THE NATURE OF LIGHT

BY ANDREW ROBINSON

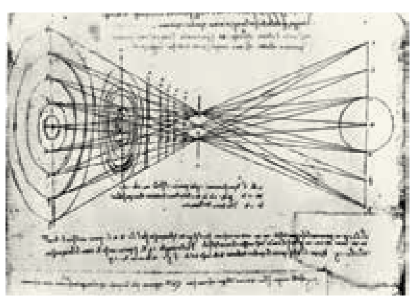
What is light? It's puzzled some of humanity's greatest thinkers for 2,000 years, especially since it appears to behave like waves as well as particles

WHAT IS LIGHT? The question has fascinated scientists – and painters, poets, writers and anyone who's ever played with a prism – since classical antiquity. Pythagoras, Euclid and Ptolemy, for example, accepted that light moved in straight lines. But rather than assuming that light rays travelled from an object to the eye, they believed the eye emitted visual rays, like feelers, which touched the object and thereby created the sensation of sight in the mind.

Drop a needle on the ground, Euclid noted in the 3rd Century BC, search for it, and wonder why the needle is not immediately visible. If light rays are emanating instantaneously from an object to the eye, he hypothesized that you should see it immediately. He decided the reason for the delay must be that the visual ray, searching the ground, is yet to touch the needle. Then, in a flash, you spot it. This ancient idea of light and sight was taught in the West in various forms until the 12th Century AD.

It was rejected by Ibn al-Haytham, a 10th Century scientist from what is now Iraq. Al-Haytham was known in the West as Alhazen, with the nicknames 'Ptolemy the Second' and 'The Physicist'. He noted that you cannot look at the Sun for long without great pain; and if you stare at a bright object for half a minute and then close your eyes, a coloured image of the object floats into view. In each case, something emitted by the object must have entered the eye.

The later translation of Alhazen's *Book Of Optics* into Latin led to its being read by, among others, artist Leonardo da Vinci, physicist Galileo Galilei, astronomer Johannes Kepler, philosopher René Descartes and mathematician Christiaan Huygens, all of whom contributed to our understanding of light and vision.



A page from one of Leonardo Da Vinci's late 15th Century notebooks, showing his musings on the nature of light

Da Vinci suggested that the eye is a camera obscura – literally, 'a darkened chamber' – into which light rays penetrate via a small aperture (the pupil) and create an inverted image of an exterior scene on the back of the eye (the retina). First adopted as a term by Kepler in 1604, the camera obscura became the dominant model of human vision in the 17th Century.

COMPETING IDEAS

Two theories of light, apparently incompatible, were in competition by 1700. The first, proposed by Huygens in 1678 and published in 1690, was an undulatory theory: light transmitted as waves. Light waves spread in all directions from a light source, and were detected by their creation of vibrations in the retina. They were regarded as analogous to sound waves spreading from a tuning fork, with the retina rather than the tympanum as detector. With sound, the undulating medium was the air; with light it was supposed to be an invisible, mysterious medium known as 'the ether'.

In contrast, Isaac Newton, who began his optical experiments in 1666, favoured a corpuscular

PHOTO: GETTY, SCIENCE PHOTO LIBRARY

This prism is both refracting light that passes through it (causing the spectrum) and reflecting it internally

> IN A NUTSHELL

Light is a somewhat confusing phenomenon, in that it can behave both as a wave *and* as a particle. This counterintuitive property of light kept some of our brightest minds (pun intended!) guessing for 2,000 years...

theory: light as particles. Light rays spread from a light source in a stream of minute particles or 'corpuscles', shooting through empty space (rather than the ether) like bullets, and were detected by their impact on the retina. That said, Newton was far from certain. He waited until 1704 before publishing his *Opticks*, and presented his ideas as a series of 'Queries' with answers that, far from being definitive, occasionally favoured the undulatory theory.

Of course, the real test of the two theories was experiment. How effective was each theory in explaining reflection, refraction and diffraction? The simplest phenomenon was the transmission of light in straight lines, as in shafts of sunlight through a cloud or solar eclipses. Such behaviour was expected for a stream of corpuscles, but not for a wave. Water waves rippling from a stone dropped into a pond could be seen to spread in all directions and bend around obstacles to some extent. Sound waves could be heard to bend. Light, however, did not appear to bend. In Newton's emphatic words: "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."

What about reflection? When light strikes a mirror, the angle of incidence is equal to the angle of reflection. In the corpuscular theory, the explanation was straightforward: the corpuscles must behave like billiard balls bouncing off the cushion of a billiard table at equal angles. The undulatory theory, too, had no real difficulty. Once Huygens assumed that a light ray could be mathematically modelled as the path of a point on a wave front, he could easily deduce the law of reflection.

Refraction was a more decisive test. When light strikes the surface of water and passes through it, the

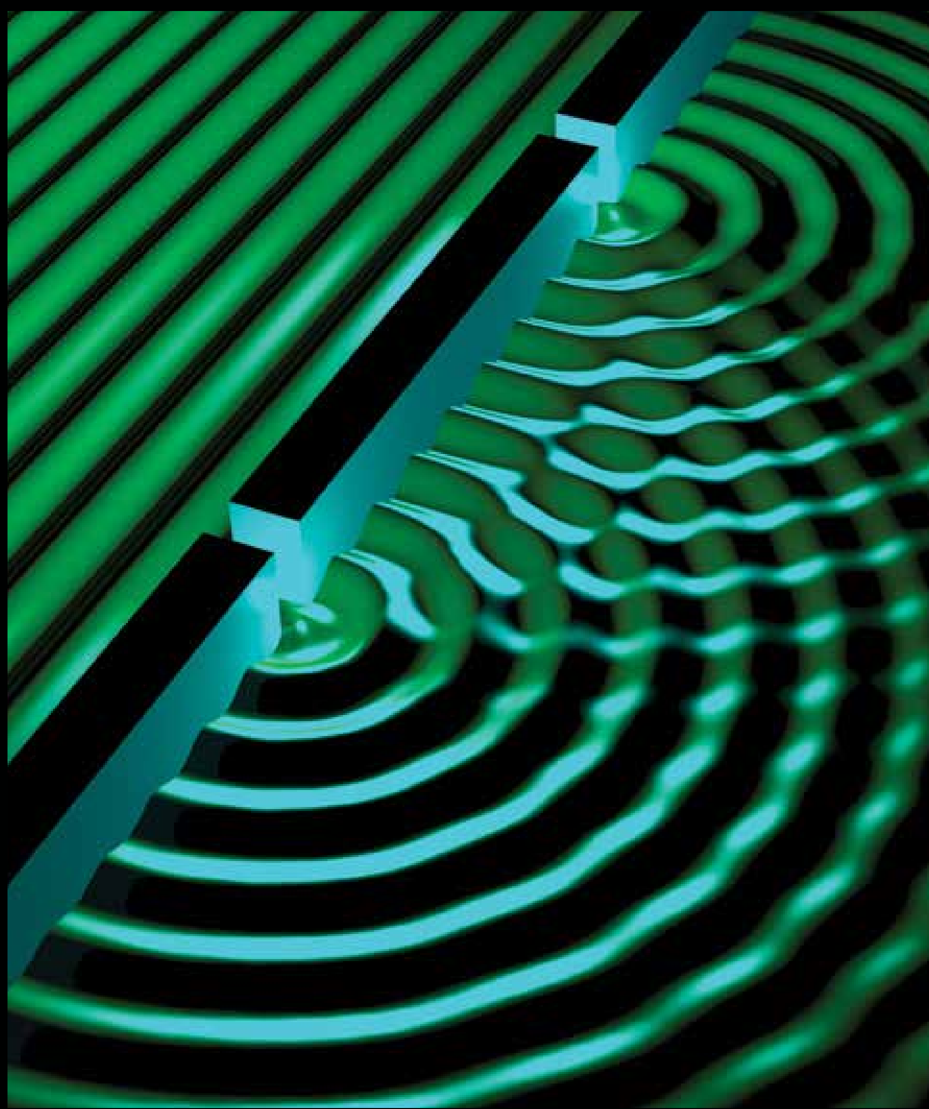
THE KEY EXPERIMENT

The interference of water waves on a pond's surface is a familiar phenomenon. Thomas Young showed that the same thing happens with beams of light

IN 1802, IN a lecture at London's Royal Institution, Thomas Young demonstrated a new device now known as a ripple tank. Its basic principle is that water is stirred up in a trough with a glass bottom illuminated from below, so that the water waves and their patterns cast shadows onto a white screen above the trough. When two sets of ripples are created, they interfere with each other, producing a pattern of agitated water known as constructive interference – where the wave peaks coincide. A pattern of smooth water is known as destructive interference – where a wave peak is cancelled by a wave trough.

If light were a wave, Young thought that it, too, might demonstrate constructive and destructive interference. A year or two after his lecture, working at home, Young split a beam of light using two narrow slits. As the two beams were diffracted by the slits, they interfered with each other and created a pattern of bright and dark stripes on a screen. Thus, light added to light could produce more light or, more surprisingly, darkness.

To Einstein, Young's experiment was "the next great theoretical advance" after Newton's work on optics, while physicist Richard Feynman said it was the "heart of quantum mechanics".



Young's double-slit experiment at the turn of the 19th Century proved decisive in showing that light can behave like a wave

PHOTO: SCIENCE PHOTO LIBRARY, SCIENCE & SOCIETY X4, THINKSTOCK angles of incidence and refraction differ. The angle of refraction is less than the angle of incidence, and so a ray is bent towards the normal (the perpendicular). Although their relationship had been formulated in 1621 as Snell's Law, it still required a physical explanation.

Newton's attempt was not very convincing. He proposed that light's velocity in water was faster than in air – a counter-intuitive idea, given that water is a denser medium. Once they entered the water, said Newton, the corpuscles were acted upon by a force which increased their velocity and altered the direction of their motion. However, the nature of this force was inexplicable, and it had no supporting evidence from other phenomena.

Huygens, by contrast, assumed that light travelled more slowly in water than in air. He then used the undulatory theory in a direct and simple way, without postulating any new force, to calculate Snell's Law. But this verdict was by no means conclusive. What precisely was the velocity of light in air and in water? Ole Rømer made the first modern estimate of light's velocity in the 1670s using astronomical measurements, but not until 1850 was it measured accurately enough to prove that light moves more slowly in water than in air, as Huygens had assumed.

FRINGE THEORIES

Finally, there was diffraction, a phenomenon first observed by Francesco Grimaldi in the mid-17th Century. He allowed a beam of light into a darkened room through a small circular aperture, then passed it through a second aperture and onto a screen. He noticed that the spot of light on the screen was slightly larger than the second aperture, and had coloured fringes. When he placed a thin obstacle in the beam, its shadow was not sharp: there were bright bands, very narrow and coloured, following the outer edge of the shadow. In other words, light could be bent – diffracted – by apertures and obstacles, even if only very slightly.

When Newton repeated Grimaldi's experiments, he too observed coloured fringes. Perplexed, he claimed that the edges of an aperture or obstacle interfered with the paths of the corpuscles. Although the undulatory theory could not

CAST OF CHARACTERS

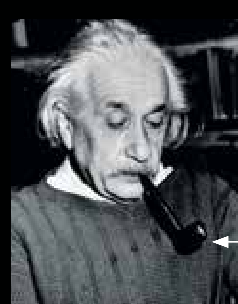
Five great minds who contributed to our understanding of how light behaves

Christiaan Huygens (1629-95) This mathematician, physicist and astronomer came from a rich and influential Dutch family. He is perhaps best known for his invention of the pendulum-regulated clock, but also improved the lenses of his telescope and discovered the rings of Saturn. His greatest achievement was his wave theory of light.

Isaac Newton (1642-1727) This farmer's son became president of the Royal Society and needs no introduction as a mathematician and physicist. His laws of mechanics and theory of gravitation are his lasting monument, but his research into optics was also highly influential, despite his dogged adherence to the corpuscular theory of light.

Thomas Young (1773-1829) This child prodigy born in modest circumstances to English Quakers became probably the greatest polymath of his age. 'The last man who knew everything' was a London physician by profession, but his reputation was made in physics, the physiology of the eye and colour vision, and Egyptology.

James Clerk Maxwell (1831-79) Maxwell was a Scottish physicist who founded the Cavendish Laboratory at Cambridge. He made key contributions to thermodynamics, the kinetic theory of gases and colour vision, but he's principally remembered for his field equations of electromagnetism, which defined light as an electromagnetic wave.



Albert Einstein (1879-1955) Einstein is generally regarded as the greatest physicist since Newton, for his General Theory of Relativity and for his contributions to quantum theory. Born in Germany, he worked in Switzerland as a patent clerk, returned to his homeland as a professor and finally emigrated to the United States to avoid Nazi persecution of Jews.

TIMELINE

It took centuries to arrive at our current understanding of light – even today, the picture isn't entirely clear

11TH CENTURY

Ibn al-Haytham shows that vision depends on light rays reflected from objects, not visual rays emitted by eyes. His work is translated into Latin in the 13th Century, influencing later European thinkers.

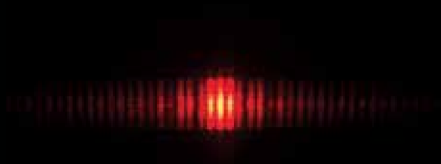
1690

Christiaan Huygens publishes a wave theory of light. It explains refraction and diffraction, but depends on the existence of an 'ether', for which there is no evidence.

1704

After decades of experimentation, Isaac Newton publishes his *Opticks*. It explains some optical phenomena (but not others) with a particle theory of light, which does not require the existence of an ether.

c.1804

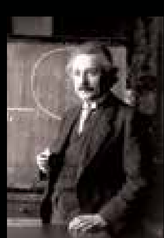


Thomas Young establishes beyond doubt that light can behave as a wave by passing a light beam through two narrow slits and observing an interference pattern on a screen.

1865

Building on the work of Michael Faraday, James Clerk Maxwell predicts the existence of electromagnetic waves of varying frequency and wavelength, including light waves.

1905



Albert Einstein's Special Theory of Relativity postulates that light moves at a speed independent of the observer and does not require Maxwell's ether. Separately, he uses the photoelectric effect to postulate light quanta.

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explain the colours, it explained diffraction better than its rival.

Nevertheless, Newton's prestige allowed his theory of light to dominate the Age of the Enlightenment. In 1771, the first edition of the *Encyclopaedia Britannica* boldly declared: "Light consists of an inconceivably great number of particles flowing from a luminous body in all manner of directions; and these particles are so small, as to surpass all human comprehension." Not until the early 19th Century were corpuscles seriously challenged by undulations.

Around 1804, Thomas Young demonstrated the interference of light, in which two overlapping beams of light produced bright and dark stripes, comparable to the interference of two water waves (see 'The Key Discovery'). Corpuscles could not produce such patterns. Subsequent experiments on polarised light by French physicist Augustin Fresnel suggested a transverse light wave. Its components oscillate at right angles to each other and to the direction of propagation, as opposed to a longitudinal wave such as sound, which oscillates only in the direction of propagation.

ELECTROMAGNETISM

In the 1830s and '40s, Michael Faraday demonstrated the inter-relationship of electric and magnetic fields of force. James Clerk Maxwell then took Faraday's fields and merged them mathematically into a single concept: an electromagnetic wave with transverse electric and magnetic components, which Maxwell calculated would propagate through the ether at a speed similar to the measured speed of light, around 300,000km/s. Different colours of light now corresponded to different wavelengths and frequencies. In the 1880s, German physicist Heinrich Hertz proved such waves' existence experimentally.

Maxwell solved one problem brilliantly, but offered no physical explanation for the ether. If light was a wave, what was vibrating? Persistent attempts to detect the ether failed during the latter part of the 19th Century. After 1905, with the arrival of Albert Einstein's Special Theory of Relativity, Maxwell's ether was abandoned as an unnecessary concept.

Relativity started with Einstein's 'thought experiment' in 1895 about chasing a light ray. Ten years later

NEED TO KNOW

Key terms relating to the behaviour and study of light

1 REFRACTION

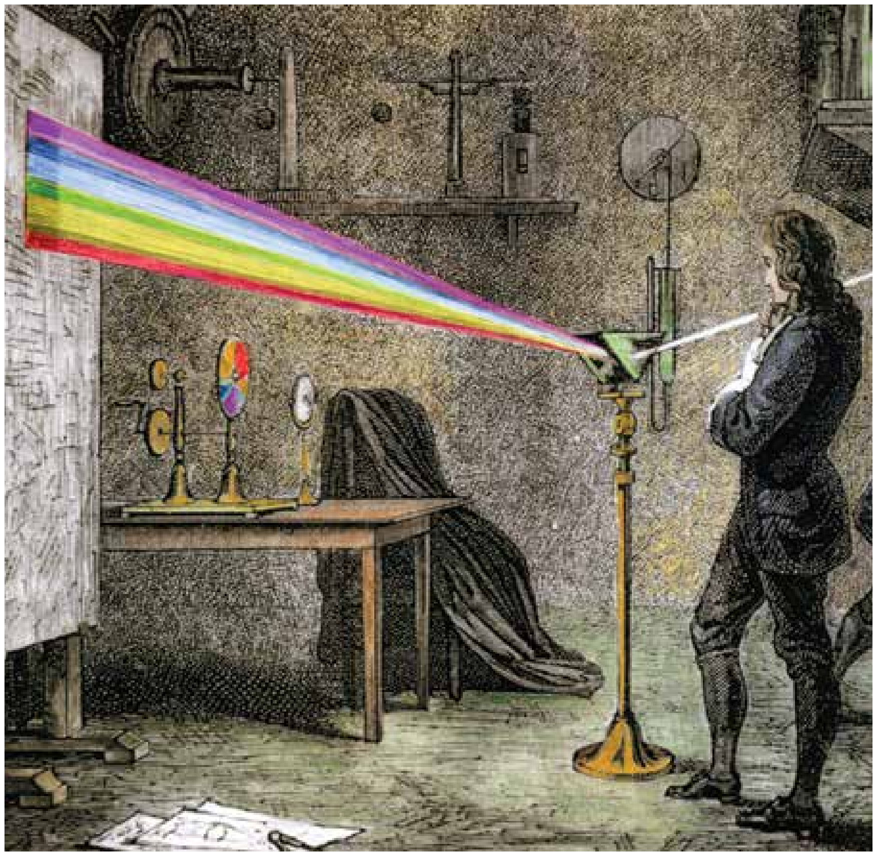
Light passing from one medium to another is bent by refraction – hence the ability of lenses to focus light rays, and the fact that a pencil placed in a half-glass of water looks bent. The refractive index of a medium is the ratio of the velocity of light in a vacuum to its velocity in the medium.

2 DIFFRACTION

Diffraction is the bending of all waves by apertures and obstacles. The diffraction of light is not so obvious in ordinary life as its refraction, but it can be observed in the iridescent colours formed by a CD or DVD under visible light. The surface of these discs is ruled with very close lines, which form a diffraction grating.

3 PHOTOELECTRIC EFFECT

High-frequency electromagnetic radiation such as X-rays can displace electrons from certain metals. However, this occurs only above a certain threshold frequency, never below it, regardless of the intensity of the radiation. The explanation for this requires the radiation to be quantised, with the energy of each quantum dependent on its frequency.



A young Isaac Newton conducting light experiments using a prism in the mid-17th Century. Newton favoured a corpuscular theory of light, and his great standing ensured that idea dominated scientific thought for many decades

he wrote: “If I pursue a beam of light with the velocity *c* (velocity of light in a vacuum), I should observe such a beam of light as a spatially oscillatory electromagnetic field at rest. However, there seems to be no such thing, whether on the basis of experience or according to Maxwell’s equations.”

Were we to travel faster than light, Einstein imagined a situation in which we might run away from a light signal and catch up with previously sent light signals. The most recently sent light signal would be detected first by our eyes, and then we’d see progressively older light signals. “We should catch them in a reverse order to that in which they were sent, and the train of happenings on our Earth would appear like a film shown backwards, beginning with the happy ending.”

The idea of catching or overtaking light was clearly absurd. Einstein postulated that the speed of light is always the same, independent of how the emitting source or the detector move, and without the need for any universal frame of reference such as the ether. If this were not radical enough, in 1905 Einstein also proposed a comeback for Newton’s corpuscular theory in a more modern form. Instead of corpuscles, there were now light ‘quanta’ (later termed photons).

In 1900, Max Planck had postulated that the electromagnetic spectra from red-hot bodies could be explained only if radiation could be emitted or absorbed in discrete packets, or ‘quanta’. Now Einstein, after considering the photoelectric effect – the way in which certain metals emit electrons when exposed to radiation – proposed that not only were the emission and absorption of light quantised (formed into quanta), light itself was quantised. Between them, Planck and Einstein launched a theory that would determine the course of 20th Century physics.

Today, physicists are compelled to accept that light behaves as both a particle and a wave, depending on how they choose to measure its phenomena. But its underlying physical nature remains a puzzle. A few years before his 1955 death, Einstein remarked: “All the 50 years of conscious brooding have brought me no closer to the answer to the question, ‘What are light quanta?’ Of course today every rascal thinks he knows the answer, but he is deluding himself.”

Since the 1980s, delicate experiments have replayed a version of Young’s key experiment and shown that a single photon can somehow interfere with itself. In his much-praised study *Catching The Light*, quantum physicist Arthur Zajonc admits: “Light remains as fundamentally mysterious as ever”. ■

ANDREW ROBINSON’s books include biographies of Einstein and Thomas Young

Find out more

Melvyn Bragg and guests discuss the life and work of James Clerk Maxwell in this episode of Radio 4’s *In Our Time* programme.
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