A Brief History of Light

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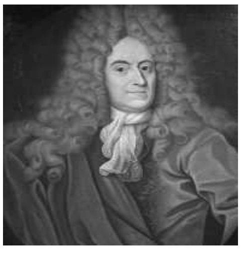
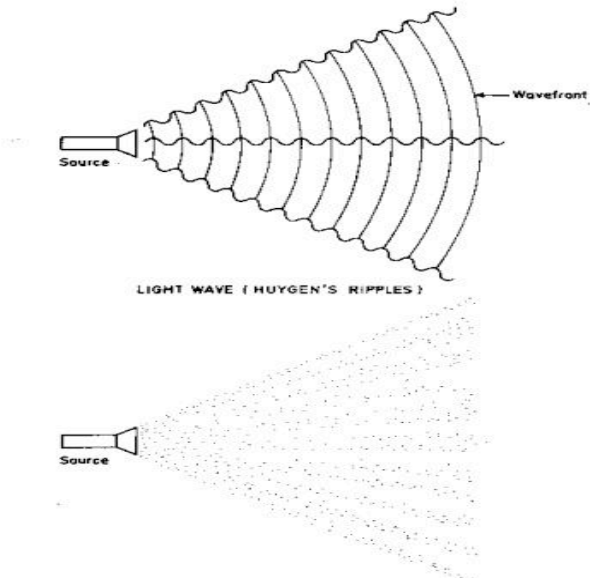
In the beginning, God said, “Let there be light”, and there was light - that’s the origin of light - according to genesis anyway. At the dawn of civilization our ancestors gazed at the ball of fire on the horizon and pondered about the wonders of the life-giving power of the light emanating from this ball. Naturally the sun, the endless cosmic source of light, was elevated to the status of godhead. The Vedic and Egyptian scriptures and even the more modern religions, such as those of the Inca, testify this status. However, for us, the mortals, light is still a ‘thing’ with which we see the world.

Our perception of the world is pre-conditioned by an acquired mental frame. We can only perceive forms or logical conclusions. If light is a ‘thing’ it must have a form; if it is an effect, there must be a cause associated with it. The enquiring minds continued the search for answers to the questions – what is the form of light or what is its cause. The questions remained un-answered for millennia. Technology advanced far ahead of science. Man had been able to make light by burning wood, candles, gas and later, by electricity. Man’s ingenuity paved the way to an epoch-making technology for producing an amazing source of light called laser. But still, to this day, the quest for an understanding of the nature of light has not ended and the light, as always, remains an enigma. The quest, however, has led us to a better understanding of the physical world and the interaction of light with itself and the material world. The fact that our vision has everything to do with light begs the philosophical question - does matter exist because we see or feel it or, is light the essence of all matter? Indeed, as some philosophers would have inferred - light is the shadow of God?

Long before Aristotle, another Greek philosopher, Empedocles saw light as ‘something’, which travels through space at a finite speed. But Aristotle did not think light to be ‘something’, which travels. According to him, light is the actuality of what is known as ‘transparency’. It is a property of the medium such as air, water, glass etc. that set in motion the property of transparency in the medium and that motion extends up to and beyond our eyes. But light emanates from the sun and the stars and travel through the vast expanse of empty space. How can it be then the property of the medium? To answer this question, the followers of Aristotle introduced the concept that the universe is not really empty but filled with a phantom, undetectable and infinitely elastic matter called ‘ether’. Light was therefore considered to be the manifestation of the property of this illusive ether. Aristotle’s concept of light was completely abandoned after the Danish scientist, Ole RÖmer, in 1679, demonstrated that light is indeed the cause of an effect, and that effect has a time lapse, i.e. the light is ‘something’ that travels with finite speed.

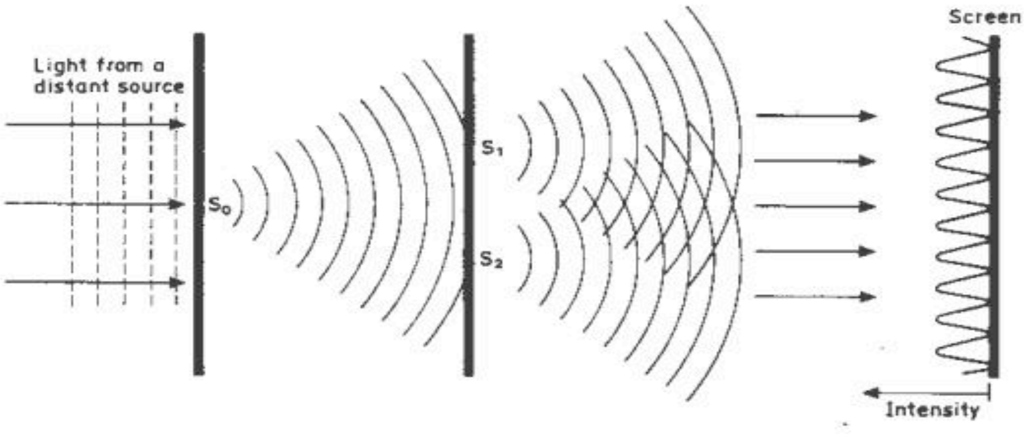


The inquiry into that ‘something’ was first made on a scientific basis by the Dutch physicist, Christiaan Huygens, in a small treatise on optics published in 1678. His vision of light was that it is a form of ripple emanating from every point in a source. The Swiss scientist Leonard Euler was the first to propose, in 1768, that just as the wavelength of sound waves determines its pitch, the wavelength of the light ripples determines the colour of that light. But the concept of light as a propagating ripple or some kind of wave did not stand up against the corpuscular theory of light propounded by the British scientist Isaac Newton.



Newton’s concept of light as a stream of particles or ‘corpuscle’ having different colour properties was not based upon any scientific experiments. He did not try to provide any explanation to many observed effects produced as a result of the interaction of light with matter. To some of the observed phenomena, he simply made some conjectures. For example, the phenomenon of partial reflection from glasses or water surfaces was interpreted in terms of correct fit of the light corpuscles with the particle or the voids of the matter. The diffused shadow of a sharp edge (diffraction pattern) was explained in terms of the motion of the wiggly motion (like that of a snake or an eel) of the so-called light particles. However woolly and non-scientific Newton’s interpretation of the interaction of light with matter was, his authority on the scientific world was so great that almost a century went by before enough experimental evidence was gathered to challenge Newton’s corpuscular theory of light.

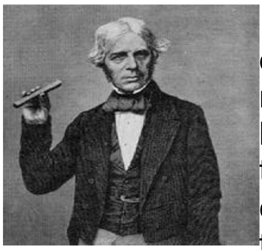
In 1801, a British medical doctor, Thomas Young, created a landmark in the scientific world by his famous ‘light and two-slit’ experiment. He observed that when light emanating from a slit (a point source) is allowed to pass through two slits on to a screen, a bright and dark pattern, called fringes, appeared on the screen or on the photographic plate placed behind the plate containing the two slits. Only spherical waves emerging from the two slits could produce such a pattern and this observation firmly established the wave nature of light. Young considered that this wave must need a medium to propagate and the concept of so-called ‘ether’ was an ideal medium for light to travel through. He also tried to give some non-scientific explanation to phenomena related to the interaction of light with matter.



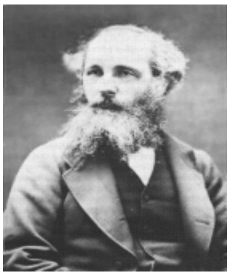
YOUNG'S DOUBLE SLIT EXPERIMENT

Newton imposed the doctrine that the theory of light must finally be based on the particulate (corpuscular) nature of light and Young contradicted this by conclusive and easily reproducible evidence that light is a kind of wave. A wave and a beam of particles are very different things. A particle can exist at one point only at a specific instant of time, whereas, a wave pervades a volume of space at any instant of time. It was proved latter that the ‘wave’ and ‘particle’ need not be taken as mutually exclusive, but that sort of duality concept did not exist in the 19 th century.

A completely different approach was needed to achieve this understanding, and it came out of intense research on electricity and magnetism. It was discovered that electricity and magnetism were inexorably inter-related - one can be created from the other. The question of how these forces exert their influence on a neighbouring body through the space was raised. It was therefore necessary to have a word to denote the state of the space surrounding a magnetic pole or an electric charge. The word, ‘field’ was coined. The ‘field’ was thought to be the manifestation or the actuality of a state of tension or a motion in the so called ‘ether’ that would not be there if the agent producing these were removed. It was also discovered that the density of electric charges determines the strength of the electric field and the magnitude of a current flow determines the strength of the magnetic field.



The English physicist, Michael Faraday, after successfully demonstrating the relationship between the electricity and magnetism also succeeded in demonstrating the relationship between light and magnetism in 1845. A beam of light was first transmitted through a transparent material having uniquely oriented crystal structure (polarizer). It was then passed through between the poles of a very strong electromagnet. It was found that light intensity changed when viewed through another similar polarizer (now called analyser) as soon as the electromagnet is switched on. However, a similar experiment by Faraday, using a strong electric field failed to show the connection between the electric field and the transmittance of light. Later it was proved that such a relationship does indeed exist but the strong electric field needed to demonstrate this was not available at that time.



Twenty years later, a Scottish scientist, Clarke Maxwell transformed Faraday's dream of connecting the electric field, magnetic field and the light into reality through a grand mathematical theory – electromagnetic theory of light. He did not do any experiment, but collected the existing knowledge obtained though experiments and expressed the interrelation of the electric and magnetic fields by a set of four equations.

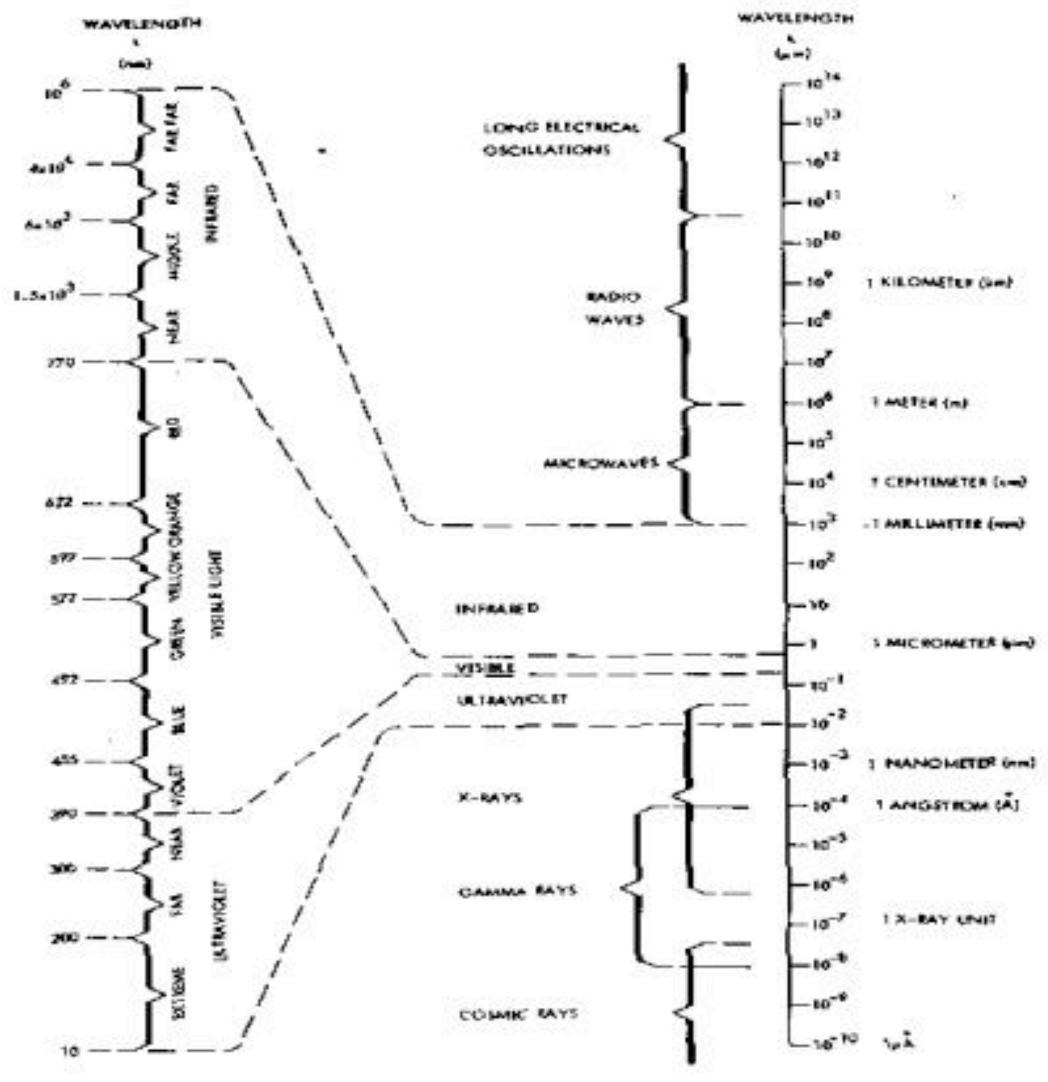
$\nabla . \mathbf{E} = \rho/\varepsilon_0$: relates electric field intensity (E) to electric charge density (ρ);
$\nabla . \mathbf{B} = 0$: relates magnetic field strength (B) to magnetic charge (does not exist, hence zero);
$\nabla \times \mathbf{E} = \delta \mathbf{B} / \delta \mathbf{t}$: a changing magnetic field produces an electric field;
$\nabla \times \mathbf{B} = \varepsilon_0\mu_0\, \delta \mathbf{E}/\delta \mathbf{t} + \mu_0 \mathbf{J}$: a changing electric field or a static electric current produces a magnetic field.

The constants of proportionality, ε (epsilon) and μ(mu) are the electric (permittivity) and magnetic (permeability) constants of the medium respectively. The subscript, 0 attributes the constants to empty space.

Maxwell's equations were found to posses a class of solutions in which the time varying electric and magnetic fields – one giving rise to the other in turn, detach themselves from the charge or current that produces them and travels off into the space in the form of an electromagnetic wave with a speed given by:

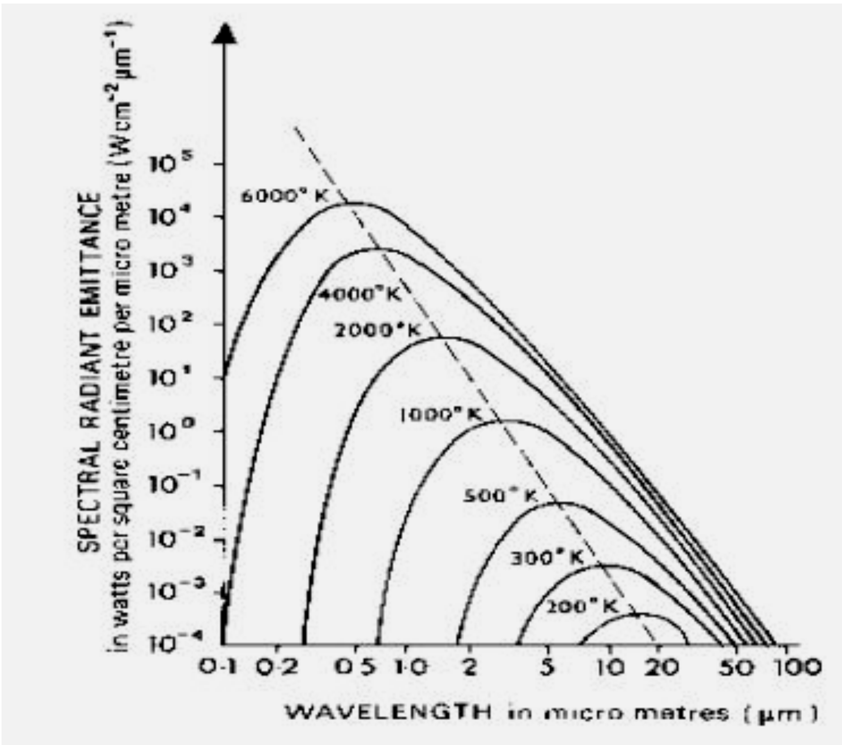
$$\mathbf{c = (1/\varepsilon\, \mu)^{1/2}}$$

Maxwell took measurements of μ and ε for space and calculated the speed of these waves to be ~ 3×10^5 km per second. This was so close to the measured speed of light that Maxwell announced that light must be a form of electromagnetic wave. His concept was very straightforward. If an electrically charged body is shaken up and down, it will produce a varying magnetic field in the direction perpendicular to the direction of the shaking. The changing magnetic field will, in turn, create a changing electric field and this process will continue as long as the shaking continues. However, the changing electric and magnetic fields will detach themselves from the charge instantly and travel across the medium or the empty space carrying the energy of the original shaking in the form of the oscillation of the electric and magnetic fields both in time and in space. According to Maxwell, these electromagnetic waves are characterized by the frequency of oscillation of the electric (or magnetic) field. Later it transpired that the electromagnetic radiation encompasses a wide range of spectrum from the high-energy gamma radiation down to low energy infrared radiation, characterized by the frequency of the field vectors. Light is simply the visible part of the spectrum between ultraviolet and infrared radiation frequencies.



Electromagnetic spectrum.

Infrared is an interesting part of the electromagnetic spectrum for a variety of reasons. It emanates from a hot body and its glow can be seen and felt as heat. Uncannily, the German physicist, Max Plank called a glowing object such as, an incandescent bulb, a red-hot metal, the sun etc. a black body. Planck took a great interest in this topic and in the year 1900, by ingenious trial and error, he put together a formula, which correctly related the observed colour (wavelength, λ) and the corresponding intensity of a glowing object, such as heated metal, with the temperature. He then tried to deduce the same formula from theoretical considerations. He found out that the only way he could derive such an equation was by making a very fundamental assumption about the way the heated atoms emit light. The assumption was that the atoms do not emit light as continuous waves but as ‘wave packets’, each carrying a definite energy, E. This energy is proportional to the frequency of vibration in the wave packet, ν (nu), i.e, $E = h\nu$. The constant of proportionality, h is known as the Plank constant. He named his ‘wave packets’ as ‘quanta’ synonymous to ‘particles’, which are also known as ‘photons’. The relationship between the frequency of Maxwell’s electromagnetic wave and the energy of the associated quanta/photon established the foundation for the unification of the wave and corpuscular concepts of light.



The German born US physicist Albert Einstein was greatly fascinated by Plank’s deduction. He was trying to make a theory of the observed photoelectric effect (ejection of electrons from metal surfaces by light). He also came to the conclusion that like blackbody radiation, the photoelectric effect also needs the light to be like a stream of particles or quanta. His theory on the photoelectric effect confirmed the corpuscular nature of light and earned him the much-coveted Noble prize in 1921. It may be noted that although Einstein is very famous for his theory of relativity, he received noble prize for his theory on the photoelectric effect and the nature of light.

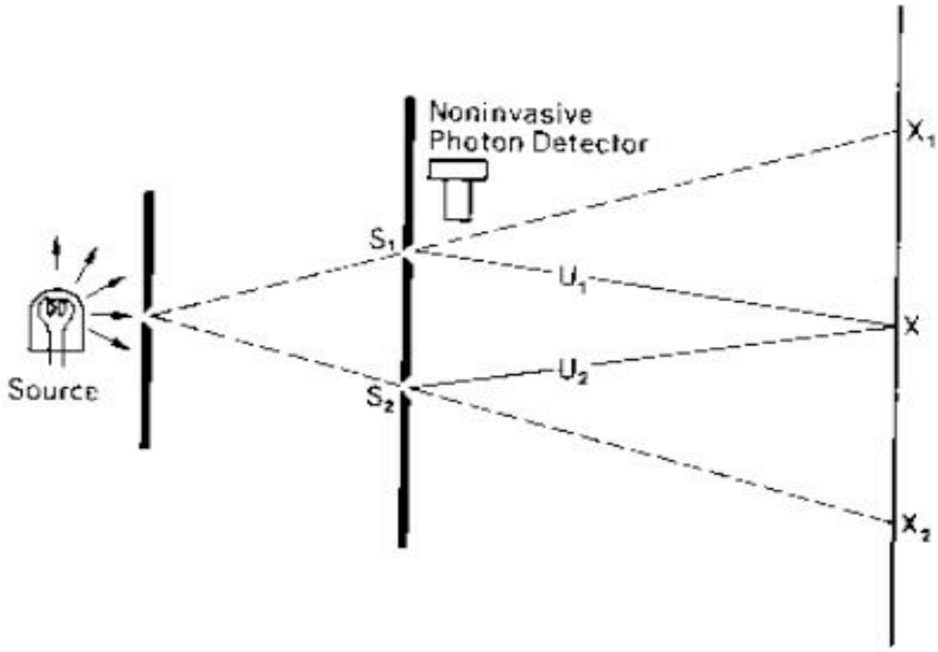
As time went by, the hypothesis of light quanta or photon began to be taken seriously. Arthur Compton, a US physicist, in 1922, performed an experiment with x-ray scattering. He concluded that x-ray did bounce off electrons just like the billiard balls do from one another. This implied that x-rays are also a part of the electromagnetic spectrum having frequencies much higher than that of the visible light and behave like Plank's quanta. The question was soon asked: can an event generated by a single photon be observed? A single photon is a quantum of energy ($h\nu$) uniquely and discreetly (hence quantized) defined by the Plank's constant. This means that the electromagnetic field is quantized with discrete frequency intervals. It did not take long before sensitive photomultipliers were developed which could detect photoelectric current generated by a single photon. A photo detector can be wired up to produce a click sound as soon as a photon hits its surface. Now if we do an experiment and reduce the intensity of the light source (in a dark enclosure) we will find that the rate at which the clicks goes off reduces in proportion to the intensity of the light, but the intensity of the sound click remains the same. From commonsense, it would appear that if the light was a wave form then there would not be any clicks but a continuous buzz and, moreover, the level of the sound intensity would go down as the light level is made lower and lower. These facts provided solid proof that light is nothing but a stream of photons.

Nothing was lacking to prove that the light is simply a stream of particles called photons, albeit having an attribute of a localized frequency. On the other hand, Young's experiment, showing that light is a flow of wave, had been refined and repeated during more than a century and the evidence that light was a form of all pervading wave was still convincing. The situation was unprecedented in the history of science. Simple experiments, requiring no subtleties of interpretation yielded clear but entirely contradictory conclusions about the nature of light. It was hard to imagine how either Einstein or Young could be wrong or their concepts on light could be reconciled. Perhaps, light is simultaneously both a flow of wave and a stream of particles. If that would be true for light, it may also be true for real particles such as electrons, protons, neutrons, alpha particles etc. These may also have associated wave properties. Such inquiries were purely hypothetical until 1925, when the French scientist, Lois de Broglie asserted that the nature favours symmetry and if the light wave has corpuscular properties, the matter must also have wave like properties. In analogy to Plank's formula he wrote a simple relation linking the momentum of a particle, p (mass $\times$ velocity) with an associated wavelength, λ (lambda) of the so called 'matter wave', $p = h/\lambda$, h being the familiar Plank constant. Later experiments provided conclusive evidence that matter such as electrons; protons, hydrogen atoms etc. do behave like waves giving diffraction pattern on a screen or photographic plate following propagation through crystal lattices. A diffraction pattern is a series of bright and dark patches resulting from the constructive and destructive combination of two or more waves having different phase angles. The wavelengths calculated from such diffraction patterns confirmed the theory proposed by de Broglie and they are called de Broglie waves.

All these brilliant ideas and experiments did nothing to establish the fundamental connection between the wave that exist in a region of space at any instant of time and the particle that is confined to a point mass at any instant of time. The wave-particle duality remained a puzzle and a subject of discord until scientists came to terms with the fact that the conventional mental picture of the physical world to explain observed phenomena needed to be abandoned. A theory based on a completely different formalism, which is not supported by any pre-conceived model of the physical world in terms of particle or wave, was needed to reconcile the wave-particle duality. In the early 1930s, Heisenberg, Schrödinger, Dirac and many other lesser mortals, developed such a theory based on a hitherto unknown and unheard of wave concept. This theory describes the position of electrons in an atom in terms of a wave function. This wave function is, in fact, a mathematical formalism describing the position of an electron in terms probability distribution. This wave is not a representation of the motion of an electron around the nucleus of an atom, but this 'wave' is the electron as much as Maxwell's electromagnetic wave is to the photon – a particle. But there must be a way to reconcile the concept of a real world particle with a phantom wave. Not all electrons are confined to an atomic sphere and are immune from physical observation and manipulation. It was well known that free electrons, away from their atomic shells, move from one place to another, get influenced by electric fields and cause counters to register their arrival at particular locations and at particular moments. It describes its trajectory in a cloud chamber and its charge can be measured by simple laboratory experiments. Polish born German Physicist, Max Born addressed this dilemma in 1926. According to his vision this phantom wave does not describe the exact behaviour of a particle, but gives us the probability of finding it at a given point in space at any instant of time. Max Born states, "Paradoxically the motion of an elementary particle obeys the laws of probability, while the probability itself is governed by the casual law". The name coined for this wave is, 'probability wave', characterized by a function with two parameters: amplitude (strength) and phase (angular direction in space) in analogy with real waves.

When all conventional concepts of wave and particles are abandoned and the physical world is analysed by a mathematical procedure called, 'quantum mechanics', it transpires that the motion of a photon can also be adequately described by this probability wave. Additionally, all the interaction processes between light and matter (e.g. electrons) can be predicted by the use of this mathematical procedure, known as Quantum Electro Dynamics (QED).

The QED is a magic box, which came into existence out of the confusion amongst the thinkers of the 19^{th} century regarding the wave-particle duality. This magic box may be considered to have a shattered opening for light to enter. If a photo detector is put into this dark magic box and the shutter is opened to let some light in, the detector registers the arrival of photons. However, if two slits and a photographic screen replace the photo-detector and the shutter is opened to let the light in, the photographic film will record the interference of two light waves emanating from the two slits. This paradox was put into a firm mathematical foundation by the Danish physicist, Niels Bohr and others in around 1927 during a workshop at Copenhagen and is known famously as the Copenhagen interpretation. This simply interprets light propagating as wave and interacting with matter as particles (wave function collapses to a singularity at the point of interaction). The paradox is simply interpreted for the layman as follows:



Let us consider a double-slit experiment where the photons (emitted at a very low rate, i.e. very low intensity source) are allowed to go through any of the two slits, S_1 and S_2. Let the wave functions of the photons passing through them be U_1 and U_2 respectively. In this thought experiment we now introduce a photo detector near one of the slit (say S_1), which is capable of detecting a photon when it passes by (not into) it. Let p be the probability that the detector will detect when a photon is passing by. The QED gives an expression for the intensity, I_x at a point x on the screen due to the arrival of the photon (which is the square of the probability amplitude):

$$I_x = |\sqrt{(1 - p^2)}\, U_2 + U_1|^2 + p^2 |U_2|^2$$

Let us consider two scenarios:

i. Perfect detector: p = 1, i.e. every time a photon passes by, it registers its presence. The above equation then reduces to:

$I_x = |U_1|^2 + |U_2|^2$ → the effect on the screen is due to

Contributions from the two particles are only represented by two different wave functions and establishing the particular nature of light.

ii. Detector does not work (or removed) : p = 0, the equation is then:

$I_x = |U_1|^2 + |U_2|^2 + 2|U_1 * U_2|$ → the effect on the screen

has a contribution from an interference effect represented by the cross term establishing the wave nature of light.

As time went on, most physicists learnt to get along with the paradox of the quantum theory. Albert Einstein was not one of them. He believed, to the end of his life, that the probability based doctrine of Niels Bohr or the Copenhagen interpretation is a superficial resolution and the true nature of light is still unresolved and the truth lies deeper. He declared that God does not play dice.

In the final analysis, it does not matter what light truly is, as long as we can use it and explain its interactions with itself and matter, albeit using the wonderful magic box called, ‘QED’. Perhaps light is the essence of all matter and God created it for us to marvel in it but not to comprehend it, like the ‘Holy Grail’ for all ages - to be quested in romance and adventure and never to be found out or understood. Who knows? Perhaps light is indeed the shadow of God.