What is Light?

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"Light is something like raindrops.." – Richard P. Feynman

This might sound a bit poetic to you all but no, it is not. Although light enlightens us, what light itself is, has remained enigmatic since the inception of analytical thinking and scientific perception of us, the human beings. So, let us go back in time and follow the trail.

Prologue:

Before taking a peek into this spectacular journey to understand what is Light, let us understand the protocol of this quest first. The basic protocol of any scientific quest can be best represented by the following picture:

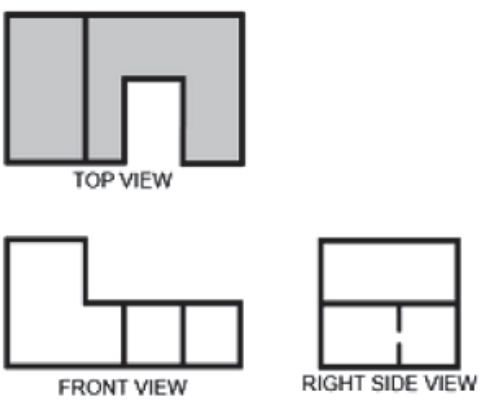

Fig 1: View of an unknown object from Top, Front and Right (Image Courtesy: Google)

So, Fig 1 represents "What we see" around us. For example, we see that Sun rises in the East and sets in the West, i.e. Sun revolves around Earth. But is that the reality? The answer, as we all know, is NO. The reality is just the contrary, i.e. it is we, or our planet Earth, that revolves around the Sun. This simple fact is enough to keep in mind that what we "see" may not be the "reality". However, what we "see" is definitely a clue, based on which we keep guessing and guessing. From the above projections of an unknown object, for example, we can conclude that the original object might look like the following (Fig 2):

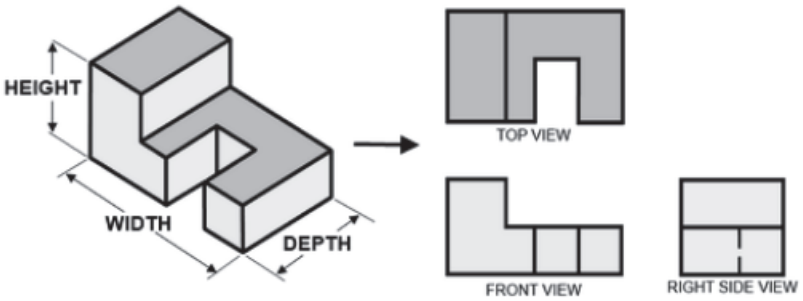

Fig 2: The original 3D object in the left panel. (Image courtesy: Google)

Our conclusion about this "original object" might change if either of the top view, front view or right-side view change upon improvised "observation" with "improvised" tools. This conclusion can also change if all on a sudden, view from a new perspective is obtained. Thus, science never comes to a halt: it turns, it twists, there are wholly unexpected corners and avenues showing up every now and then. The same thing that seemed so obvious yesterday can appear to be utter foolish and naïve supposition today. Science is a gorgeous living thing: it is still evolving to new amazements.

Ancient times: Newton's Particle

The story starts long ago. In 17th century, Pierre Gassendi, the French philosopher and scientific experimentalist, who fell among the band of truth seekers who chose to rely more on scientific evidence than on supernatural notions while trying to understand nature, proposed his integrated optics model [1]. His model explained the human vision in terms of **"atomistic"** theory of light. Light is a stream of

Fig 3: Sir Isaac Newton's experiment with prism and dispersion of light(Image Courtesy: Google)

special "image-bearing atoms" that are received and processed by the image-creating apparatus inside our body. Such school of thought finally materialized in the work of Rene Descartes, Fermat, Roemer, Robert Hooke and Sir Isaac Newton, who deduced laws of optics [2] often by analogy with mechanics and attempted to explain the speed of light, reflection, refraction, dispersion and polarization.

- Success of Atomistic Theory of Light:

  a) It gave a rough explanation of vision and color.
  b) It could explain laws of reflection.

- Failures of Atomistic Theory of Light:

  a) It could not completely explain refraction of light.
  b) The argument that explained colored vision had many question marks.

The Wave Strikes!

So what could be the possible alternative? Why.. the wave! Thus Huygens came up with his argument in 1678 AD. Huygens proposed the concept of secondary wavelets originating from the points on the surface of a primary wavefront. The secondary wavelets move with the same speed and their envelope, after moving for a while, give us the next wavefront after the certain time interval. If you are not from Physics background, please take a look at Fig. 4.

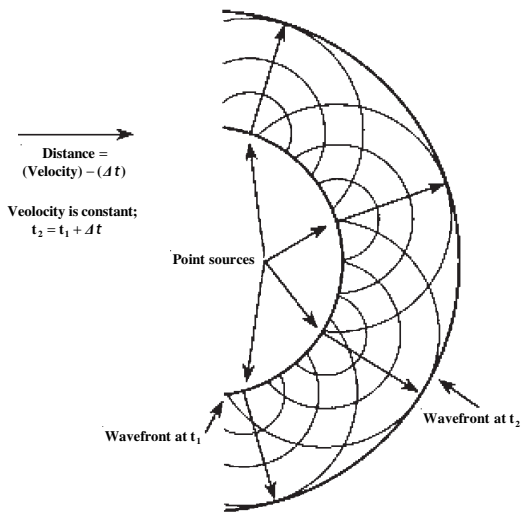

Fig 4: Huygens theory of propagation of light in terms of Wave (Image Courtesy: Google)

However, owing to various ambiguities and mainly because the name behind atomistic theory of light was Newton, the matter could not be settled or sealed. The main ambiguities of this wave theory were:

Light travels from Sun to Earth, that is through vacuum (?). If light is a wave, what is the medium of this wave? What type of wave is this? What about its speed?

The Rise of Aether

Now physicists had reached an impasse where particle theory of light was weighed against the wave theory. Both theories stood good chance of acceptance and explained various properties of light quite well and bore at the same time, several loop holes (Fig 5 and 6).

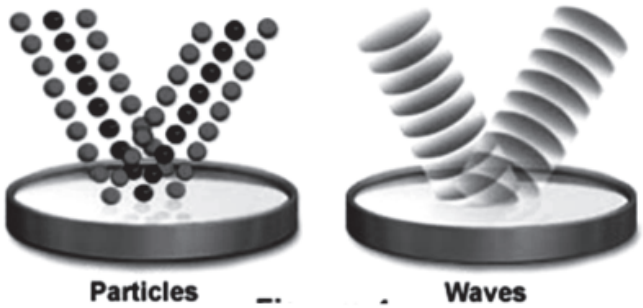

Fig 5: Reflection of light according to particle and wave theory (Image Courtesy: Google)

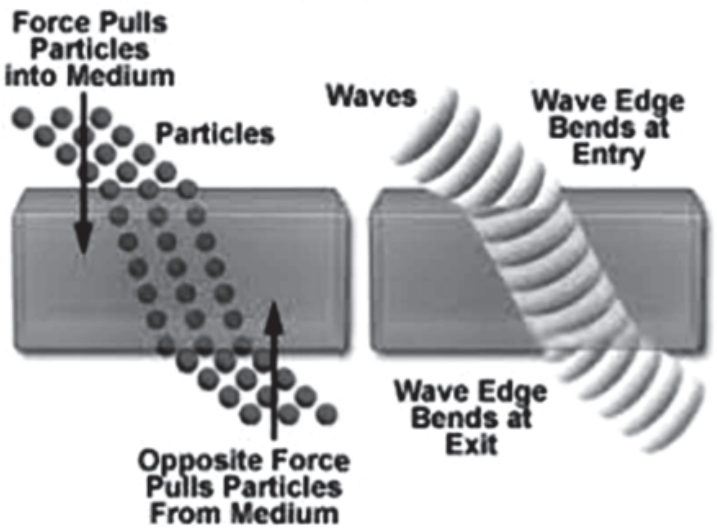

Fig 6: Refraction of light according to Particle and Wave theory(Image Courtesy: Google)

The confusions were boiling up and became more complex to fit the entire story into an age-old conceptual framework of the holy grail of ancient Physics: **The Aether.**[3,4] The holy grail: Aristotle called it the fifth element. Alchemists thought it was the key to the philosopher's stone. Scientists believed it was the stuff light moved through. The imagination was something like shown in Fig 7:

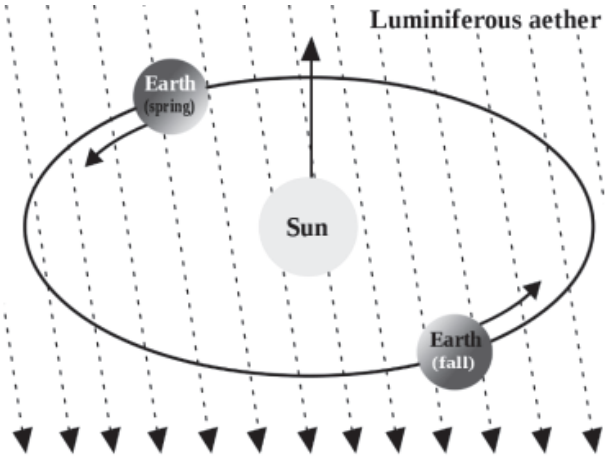

Fig 7: Aether theory of Physicists (Image Courtesy: Google)

There was no concept of vacuum. Scientists postulated that there was "something" that filled the vast expanse of interplanetary blank space. For years to come, various theories about nature and properties of so-called Aether came into place so that propagation of light and related observations could be explained. Naturally, Huygens wave also was supposed to move through this medium called Aether. But what kind of wave was this?

Maxwell's Electromagnetic Theory

This is precisely why Truth is called stranger than fiction. The answer came from a wholly unexpected corner. Electricity and magnetism were considered to be completely separate regime since 16^{th} century until the discovery of Oersted. The work of Oersted, Faraday, Bio Savart and Ampere led to the wonderful revelation that in fact both are inexorably intertwined. Around 1664 AD, James Clerk Maxwell added the final chapter to the saga of Electromagnetism and penned down four famous equations known as "**Maxwell's Equation"**and came up with the strange idea of electromagnetic wave. If that was not enough, the speed of electromagnetic wave matched with the experimentally determined value of the speed of light! Voila!

Thomas Young: A Tale of Two Slits

The never-ending debate between particle theory and wave theory brigade seemed to be resolved once and for all with this curious tale of two slits. It was nothing much: just two simple, rectangular slits cut into a sheet, held before a source of light. Now, we all have seen how lovely patterns form in the ponds and lakes during rainfall. These patterns form because water waves interact with each other and superpose on each other. This is called Interference of Waves. So pattern formation upon superposition can be considered a signature of wave aspect of any physical system. A British scientist Thomas Young, in 1801, checked to see how light behaves if it is made to "interfere". The two slits served as two sources of light and there it was for all to see. Had light been just stream of particles, no pattern should have been obtained. On the contrary, if at all any pattern could be observed, that would have settled the matter forever in favour of the Huygens wave theory of light. See the result below (Fig 8):

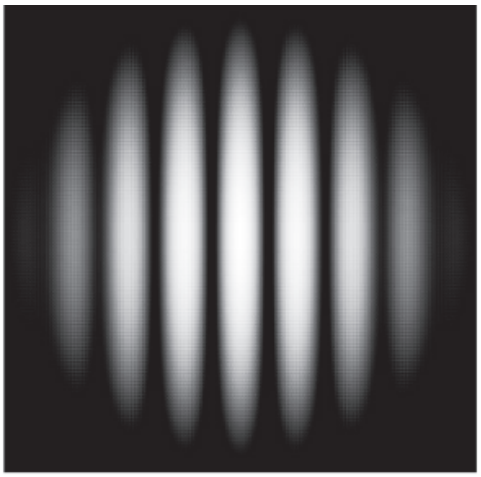

Fig 8: The pattern formed on screen when light passes through two slits before reaching the screen (Image Courtesy: Google)

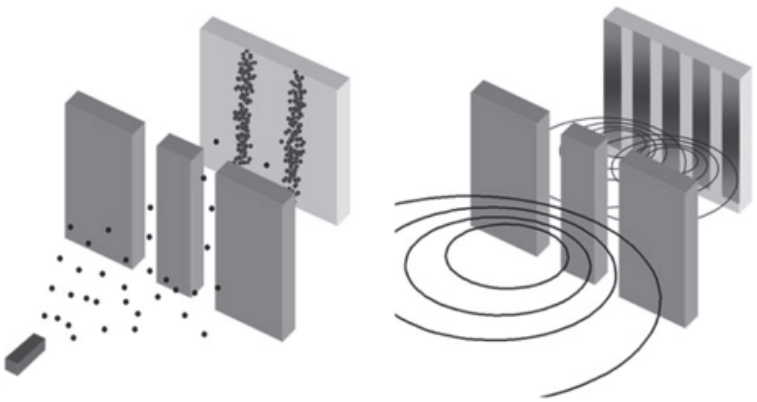

Fig 9: The scenario when particles fall on slits vs when wave falls on slits (Image Courtesy: Google)

Fig 9 tells you clearly what light must have been. It must have been Wave. The Electromagnetic Wave.

Michelson Morley: The Failed experiment that went into history

So yes, light is wave. Maxwell's wave. Maxwell fitted his theory into Aether framework, but movement of light and its speed through Aether was getting more and more complicated with newer findings. Final nail on the coffin was the famous failed experiment of Physics: The Michelson Morley experiment, 1888 AD. It tried to detect Aether, and quite conclusively, **it found nothing.**Those curious to see this apparatus that nullified a theory that held the firm belief of the Physicists for as long as two thousand years, Fig 10 is referred:

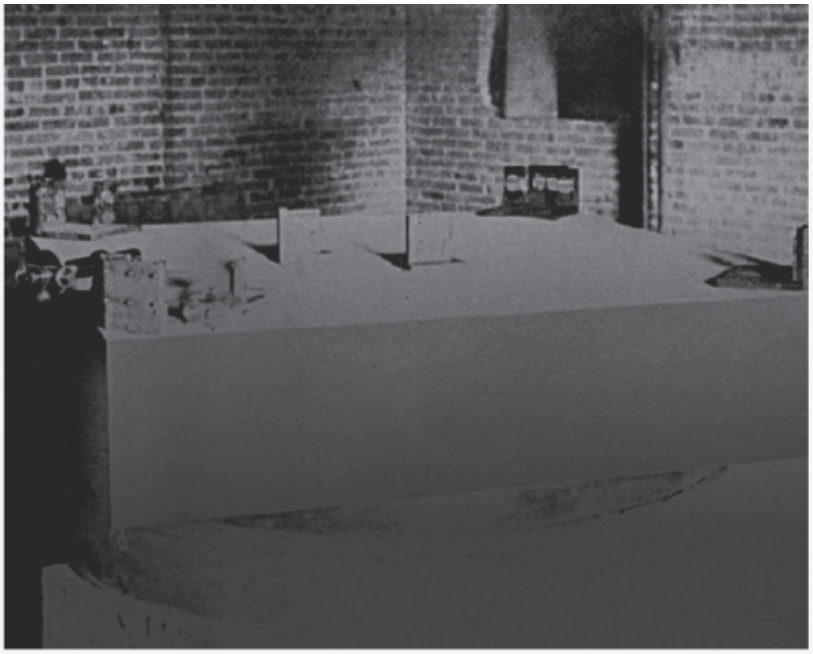

Fig 10: Michelson Morley Experimental set up (Image Courtesy: Google)

So that meant the end of the Aether theory. Light was almost reborn at the hands of Sir Albert Einstein.

Special Theory of Relativity

So there was nothing called Aether and light was an electromagnetic wave, capable of travelling through vacuum (that is, no mechanical medium was required any longer for propagation of a wave.) Then comes the question about the speed of light: it was relative to whom, if there was no medium at all? The answer lied in one of the most glamorous and celebrated theories of Physics: *Special Theory of Relativity*, developed in 1905 by a clerk working in a patent office. His name was Sir Albert Einstein.

Speed of light is universal and same for all inertial observers.

Along with this, another thing was happening parallelly that was changing the face of physics forever. A thorough theoretical study of the light radiated by blackbody started to give a sense of foreboding for classical physics and the way physicists were used to perceiving the nature. The classical wave theory failed and all on a sudden, the particle "face" of wave had to be revoked. Back to the particle theory of light, to be precise.

The "photon"

So, now that there was no such thing as Aether, light is an electromagnetic wave thanks to Maxwell (Light itself would have liked to thank him for finally being granted some stability in life) that does not necessitate any medium whatsoever and proudly moves in vacuum. Now, for the light emitted by a blackbody, the experimental curve of radiation energy density as a function of wavelength looked like this (Fig 11):

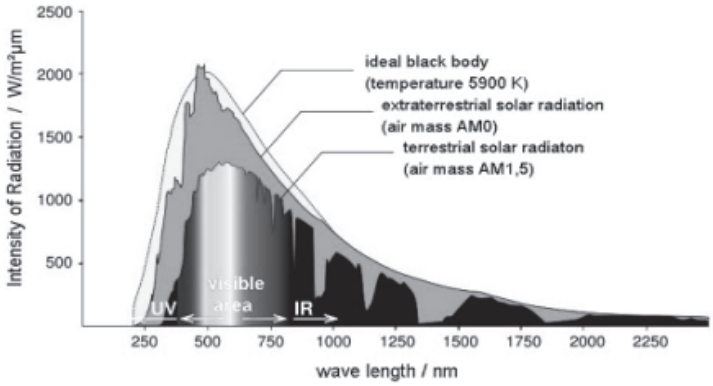

Fig 11: Blackbody radiation curve (Image Courtesy: Google)

All theoretical calculations based on wave theory failed miserably to generate this shape. How audacious the mathematics was: it unashamedly kept showing that the total energy radiated by the blackbody is infinite! After having been granted the complacency of cracking the mystery of light with Maxwellian wave, this new deadlock at the beginning of 20th century clearly signalled that science is definitely a living thing. It never stops to give surprises! Fig 12 gives you a feel about the problem:

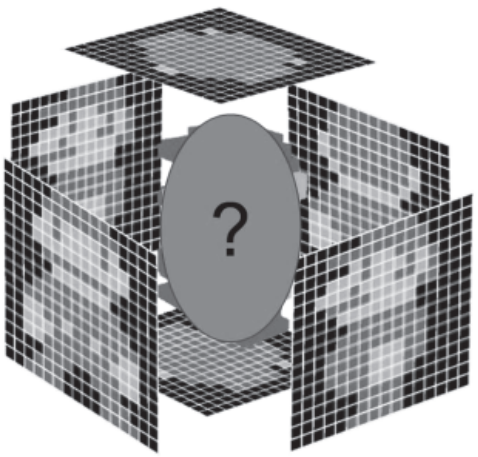

Fig 12: Based on the various chunks of experimental findings, that is various projections on the surrounding walls, figure out the actual architecture of the object inside. (Image Courtesy: Google)

The breakthrough was due to the "ad-hoc" assumption by the celebrated German Physicist Max Planck in 1900. What was that ad-hoc assumption? The energy of the radiation was emitted or absorbed not in continuity but in discreet packets, called Quanta. This feature of discreetness and localization in case of energy propagation brought back several aspects of particle theory of light. This proposal of Planck that light is emitted or absorbed in quanta was itself so strange that Planck himself was reluctant to accept the direct physical implications. But he had no way to nullify this theory either because this **quantum theory** was completely successful in explaining the experimental curve of blackbody radiation. When it comes to physical significance of quantum theory, it was Einstein who, for the first time, recognized that energy not only is absorbed or emitted but in reality, it exists and travels in quanta. Based on this theory, he was able to explain the famous Photoelectric

Effect that won him Nobel Prize in Physics. Niels Bohr also lost no time in making proper use of this theory and was able to explain for the first time the atomic spectral lines using Bohr's model. This queer little new "thing" which is streaming incessantly as "light" propagating from a source, later became popular by the name given by Gilbert Lewis, a physical chemist, in 1926: **Photon.**

Photon: What is it, after all?

So, what is this photon like? In the light of Quantum Theory and Special Theory of Relativity (around 1905), the final picture stood like this:

- Light is a stream of particle-like things, called Photons. The energy propagation is characterized by localization and discreetness in space.
- Photons are massless, yet they have momentum and energy.
- It is moving with a universal speed, whose value in vacuum with respect to all inertial observers is given by universal constant c.
- The probability of finding a photon at any point in space is determined by the electromagnetic wave associated with the source.
- In spite of their localization in space like particles and ability to undergo elastic collisions with other particles like electrons (Compton Scattering), photons are able to undergo interference and create patterns as already seen in Young's double slit experiment.
- This is possible due to the fact that, energy of photon is localized like that of a particle (Photoelectric Effect) but position probability of a photon is delocalized like that of a wave (Young's double slit experiment).
- Reality of photon is not absolute. It depends on how you are looking at the photon. If we place a detector at the double slit, the interference pattern vanishes.

What is light? It is both.

So light has a dual nature: it is both. It is double-faced (no matter whether we like it or not) and which face it will show you will depend upon the experimental situation at hand. This is called Wave Particle Duality and it is not only the golden rule followed by Photons but it is the golden reality of Nature itself. Nature itself behaves like this.

Photo of Photon

The story doesn't end here. Human brain finds it hard to accept duality. It wants to know for sure which one of these two light is actually is, or photon is actually is. However, experiments have repeatedly shown that it is defiantly both at the same time. The quest is on and even today we are coming up with newer and stronger evidences in support of this. In 2012, scientist Alberto Puzzo developed a quantum delayed-choice experiment in which both particle and wave behaviours were investigated simultaneously [5]. Finally, in 2015, F. Carbonneet al were successful in imaging the duality of photons using EPFL's ultrafast energy-filtered transmission electron microscope – one of the two in the world [6]. The apparatus and the photograph are shown below in Fig 13:

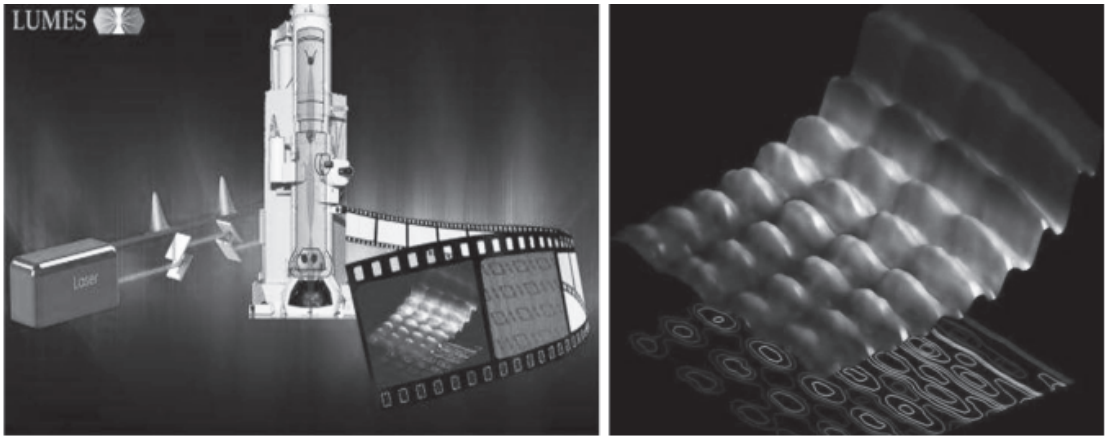

Fig 13: In the left panel, the apparatus at EPFL can be seen. In the right panel we can see the image of the duality. (Image Courtesy: Google)

Future chapters in the Life of a Photon

Photon, with all its grandeur and charismatic confusion, has opened up entire new branches of Physics like Photonics, Quantum optics and Lasers, Quantum Entanglement and so on. We have been able to entangle the quantum states of two photons. We can generate, control and detect photons with such a staggering efficiency that 21st century is going to be of Photonics in the same way as 20th century has been of Electronics. An article published in Nature on 3rd March 2020 shows how to give a veritable booster to the photonic quantum computer technology by introducing many-photon quantum circuits into a programmable nanophotonic chip [7]. The physics of photons finally has been well established but who knows, deep in the labyrinth of the mysterious future, what awaits us?

Reference:

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