Observations about Light

Light is that which illuminates: What is it?
Experiments before 1890 were consistent with the answer that light is wave motion.
What waves is vibrations of Electric and magnetic fields.
The sources of light are systems in which charges undergo acceleration: electrical oscillators, atomic systems and any phenomena which involves acceleration of electric charges.
The crucial experiment that proved light is wave motion was Young's double slit experiment – which we will discuss.
But Light also has particle properties – quanta(lumps) of energy called photons- needed to explain interaction of light with atoms and electrons in metals..

Speed of light is enormous: 30 million meters per second in vacuum – light waves can travel through “ vacuum “!
Observations about light (continued):

1. Visible Light is emitted by objects like: sun, electric bulbs, hot coals and also by fluorescent bulbs, LEDs, Lasers etc
2. Invisible light of different types is also emitted: (gamma rays, X-rays, UV, infra-red(IR), microwaves and radio waves.,
3. All of these are EM waves of different wavelengths.
4. Many objects are made visible when light shines on them – moon, lawn, clouds, blue sky. This involves phenomena such as reflection, scattering and absorption and remission. They are not usually visible at night.
5. Light intercepted by objects generally result in distinct shadows: this implies that light travels in straight lines and that light can be absorbed.
6. Light can induce photo-chemical reactions: exposing photographic film, photo-synthesis in plants through absorption in its leaves. This implies light carries energy and can deliver it to objects.
Observations about light (continued):

7. Observing a fluttering flag illuminated by sunlight suggests that all light coming from the flag originates in white light from the sun and reflecting red light in red of the flag and blue from blue dye in the flag.

8. Newton first decomposed sunlight into its colors and also recombined them to get white light.

9. Newton developed the corpuscular model of light – to explain shadows, imaging and light propagation.

10. The wave nature of light was established experimentally by Thomas Young some two centuries later by his double slit interference experiment, although it was postulated much earlier by Huyghens in his construction of light propagation.
Models for Light

Ray model

Advantage: Simplicity.

Wave model

Advantage: Color is described naturally in terms of wavelength. Required in order to explain the interaction of light with material objects of sizes comparable to or smaller than a wavelength of light.

Particle model

Required in order to explain the interaction of light with individual atoms. At the atomic level, it becomes apparent that a beam of light has a certain graininess to it.
Examples of Ray diagrams

Usually a finite number of rays are drawn.
Rays record path traveled by light – they are not objects
Rays are stopped being drawn when no new information is to be conveyed.
Huygens 's Principle

- At $t = 0$, the wave front is indicated by the plane $AA'$
- The points are representative sources for the wavelets
- After the wavelets have moved a distance $c\Delta t$, a new plane $BB'$ can be drawn tangent to the wavefronts
Ray optics is also known as Geometrical Optics

Wave optics is also called physical optics: It includes phenomena of diffraction, interference and polarization phenomena as well as dispersion and scattering.

Particle Optics covers phenomena such as photo-electric effect, scattering of light photons by electrons (Compton effect) emission and absorption of EM waves by atomic systems.
Study of Physical Optics

Light is an electromagnetic wave which propagates with a high speed. In vacuum the speed of light is \( c = 3.8 \times 10^8 \text{ m/s} \)

Frequency of light does not change when light goes from one medium to another.

The speed of light in a medium with refractive index \( n \) is \( V = \frac{c}{n} \).

The relation between \( V \), \( f \) and wavelength is

\[
V = f \lambda \\
\frac{f \lambda_{\text{medium}}}{v_{\text{medium}}} = \frac{c}{n}
\]

Wave Direction and Wave Front:

**Wave Front** = locus of points with the same phase

**Wave Direction** = (Ray direction) is the direction perpendicular (or normal) to the wave front.
A representation of an EM wave:

For an electromagnetic wave the wave amplitude is actually the value of the electric field normal to the direction of propagation.

\[ \vec{E}(x, t) \]

\[ \vec{E}(x, t) = E_m \cos(\omega t - kx + \phi_0) \]

Points with the same phase are those with \( \omega t - kx + \phi_0 = \text{constant} \)

At a time \( t = t_1 \), all points on wave front

have the same value of \( x \), \( x = x_1 \) given by

\[ x_1 = (\omega t_1 + \phi_0 - \text{constant})/k \]

This defines a plane normal to the \( x \) direction
To observe phenomena in light one uses an apparatus which generally has two main characteristics:

It has a size (size of the detector or slit or an object) “a“

The detector has a sensitivity, defined by the energy needed to make an observation. \( \Delta E \)

Also one usually specifies the frequency and light speed. Wavelength is calculated by

\[
Using the relation: velocity (V) = frequency \times \text{wavelength}(\lambda) \\
We get \( \lambda = \frac{V}{\nu} \)
That is: (i) Light shows wave behavior with $\lambda = \frac{V}{f}$ and (ii) Light shows particle like behavior, consisting of packet (called photons) of energy which is given by

$$E = hf$$

where, $h = \text{Planck's quantum of Action}$

The constant $h$, Planck's constant is energy x time = Joules seconds and is a very small number $h = 6.6 \times 10^{-34}$ Joule seconds

The three regimes are defined by the following conditions:

1. Geometrical Optics: GO
$$\lambda \ll a, hf \ll \Delta E$$

2. Wave Optics: WO
$$\lambda \approx a, hf \ll \Delta E$$

3. Quantum Optics: QO
$$\lambda \text{ very small and } hf \gg \Delta E$$
Wave nature of light was established by the double slit Experiment

Two sources (slits) are illuminated by the same light source. Light from these two sources is observed on a screen some distance away. The light waves from the two sources get superposed on the screen. There are positions where they add and positions where they cancel – these positions depend on wavelength and slit separation. The geometry is explained in the next figure.
Light Source

Opaque screen with two slits

Slit separation comparable to wavelength

Placed at a large distance from slits

Schematic for Double Slit Experiment

Screen to observe light distribution
What is seen on the screen with two slits illuminated by light of a fixed frequency is an interference pattern shown here:

Pattern of bright and dark bands produced by light shining on two horizontal slits separated by a small distance.

\[ d \approx \lambda \]
Geometry of Interference

\[
\frac{(L - L')}{d} = \sin \theta
\]

Path difference = \((L - L') = d \sin \theta\)
constructive interference when: \( L - L' = m\lambda \)
with integer \( m \) taking on positive and negative values including \( m = 0 \).

\[
\frac{\lambda}{d} = \sin \theta \approx \theta
\]

If \( \lambda \) and \( d \) are both multiplied by the same factor, for instance 5 the ratio \( \frac{\lambda}{d} \) does not change.

This is called scaling in diffraction or interference.

The photo shows this happening with ripples in a ripple tank illuminating two slits and producing an interference pattern. Can you find the pattern?
Why is it that waves emerging from the two slits produce a different pattern on the screen than that one produced by bullets?

The pattern is caused by interference of waves coming out of the two slits illuminated by a single source due to the superposition property of wave motion.

\[
\frac{\lambda}{d} = \frac{1}{1.5} = 0.667 \text{ rad} = 38.3^0
\]

\[
\frac{\lambda}{d} = 0.75/1.5 = 0.5 \text{ rad} = 28.7^0
\]