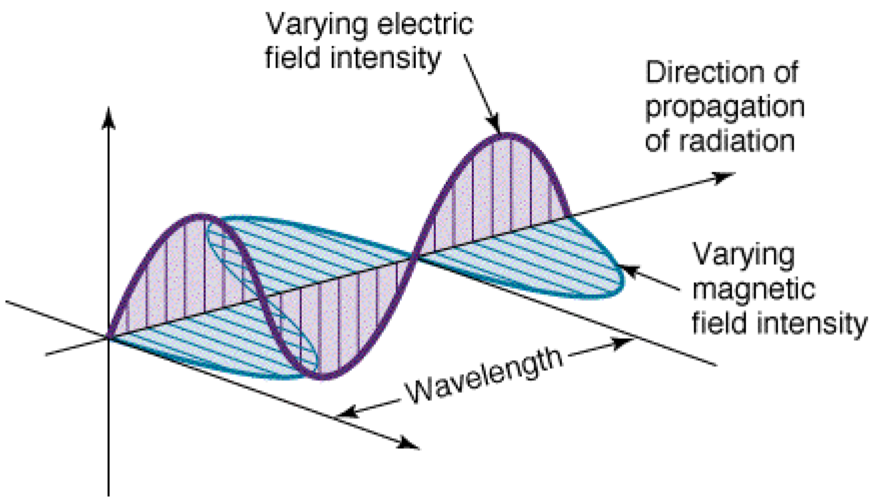
Chapter one - **The Nature and Propagation of Light**

(1-1)The Nature of Light

Light is a transverse electromagnetic wave.

In classical (i.e not quantum) picture the light is a wave of oscillating interconnected electric and magnetic fields



- EM wave is not a mechanical wave.

An Electromagnetic Wave is an alternating oscillations of the Electric (E) and Magnetic (B) fields,

Define the following properties of light:

– Speed
– Frequency
– Wavelength
– Energy

• Describe the dual nature of light, as a continuous wave and a discrete particle (photon),

1- and give examples of light exhibiting both natures

Waves have two important characteristics - wavelength and frequency. The sine wave is the fundamental waveform in nature. When dealing with light waves, we refer to the sine wave. The period (*T*) of the waveform is one full 0 to 360 degree sweep. The relationship of frequency and the period is given by the equation (see fig 1):

$$f = 1 / T \qquad (1)$$

The waveforms are always in the time domain and go on for infinity.

The amplitude of a light wave is related to its intensity.

- *Intensity* is the absolute measure of a light wave's power density.

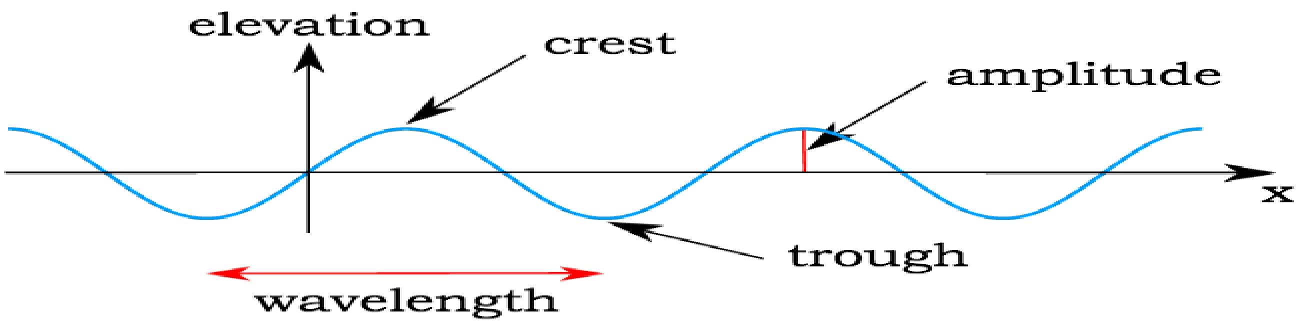


Figure (1) describe a wave

Wavelength: **This is the distance between peaks of a wave. Wavelengths are measured in units of length - meters, When dealing with light, wavelengths are in the order of *nanometres* (1×10^{-9})**

Frequency: **This is the number of peaks that will travel past a point in one second. Frequency is measured in cycles per second. The term given to this is Hertz (Hz) named after the 19th century discoverer of radio waves - Heinrich Hertz. 1 Hz = 1 cycle per second**

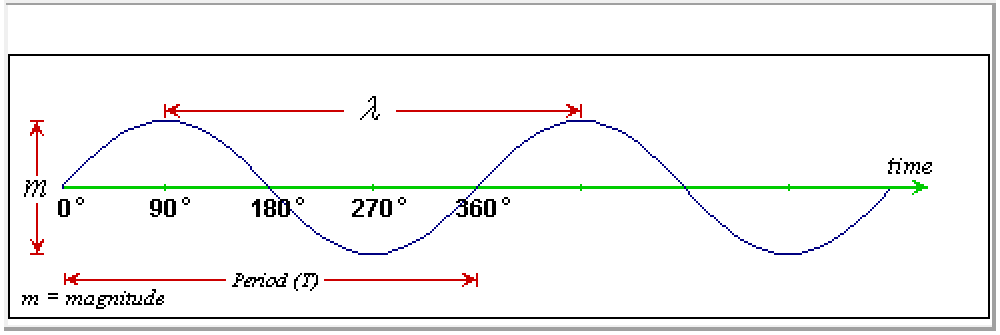


Figure 2: the sine wave is the fundamental waveform in nature

1- 2) Wave front and Rays

For an electromagnetic wave, the wave front is represented as a surface of identical phase, and can be modified with conventional optics. For instance, a lens can change the shape of optical wave fronts from planar to

A **wave front** is a surface passing through the points of a wave that have the same phase and amplitude.

Ray is a line everywhere perpendicular (normal) to the surfaces of the constant phase of the wave – wave fronts. Rays point in a local direction of the propagation of the wave.

There are two types of optical waves:

1) In a *plane wave* all rays are parallel to each other, and one can track just a single ray.
2) In *spherical wave* rays are along the radial directions and are divergent.

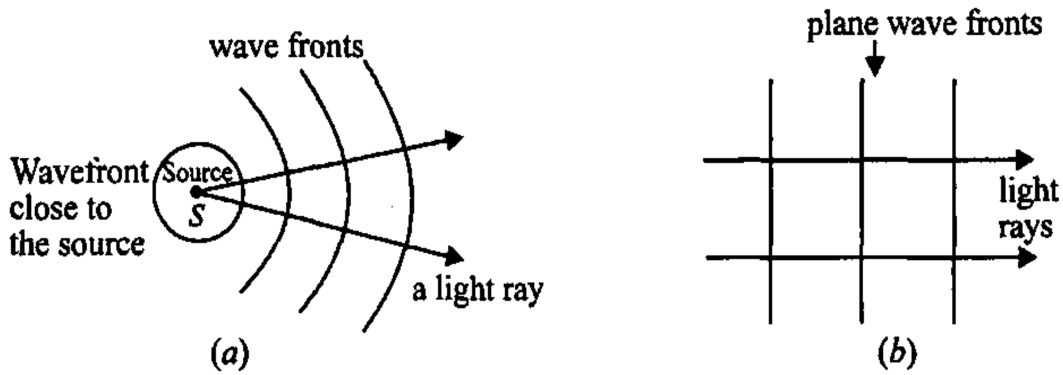


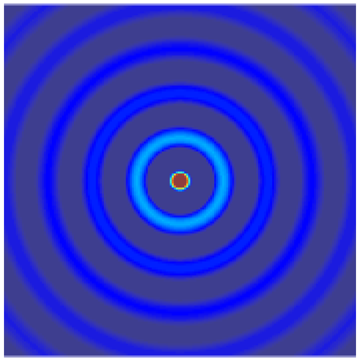
Figure (3): types of wave

In optics it is sufficient to track just the rays, if one is interested in phenomena over distances larger than a wavelength of light. This is **approximation of geometrical optics**

Far from the source the wave is planar

the crests of the wave form planes (in 3D) or straight lines (in 2D)

- Planar wave has well-defined direction of propagation, thus we can think about **light rays**
  Physicists say "we can use **geometrical optics** approximation here"

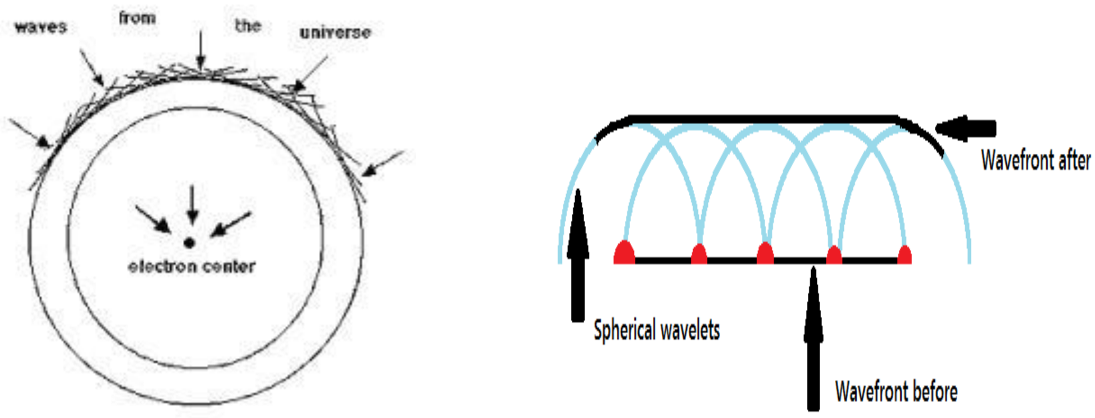


Point source emits spherical waves.

- Far from the source, segment of spherical surface looks like plane and we speak about **rays** . EM waves from distant stars is very planar !

(1-3) Huygens' Principle

- The wave theory says that every point on the wave front is taken as source secondary spherical wavelets.
- Each point on the wave front radiates spherical waves which interfere to preserve it during propagation (see fig 4).



(a) (b)

Figure 4: a) Source of Spherical In-Waves, b) Huygens Principle

To brief of Huygens' wave theory of light

- Each point in a source of light sends out waves in all directions in hypothetical medium called "ETHE form of energy
- Light travels in the form of waves.
- Light waves have very short wave length

(1-4) Speed of light

The ancient beliefs believed that light traveled with an infinite speed, but in 1849 the French physicist Fizeau Became the first man to measure the speed of light here on earth.

An intense beam of light from a source S is first reflected from a half-silvered mirror *G* and then brought to a focus at the point *0* by means of lens L_1• The diverging beam from *0* is made into a parallel beam by lens L_2. After traveling a distance of 8.67 km to a distant lens L3 and mirror *M*, the light is reflected back toward the source. This returning beam retraces its path through L_2, *O*, and Lt, half of it passing through *G* and entering the observer's eye at *E*.

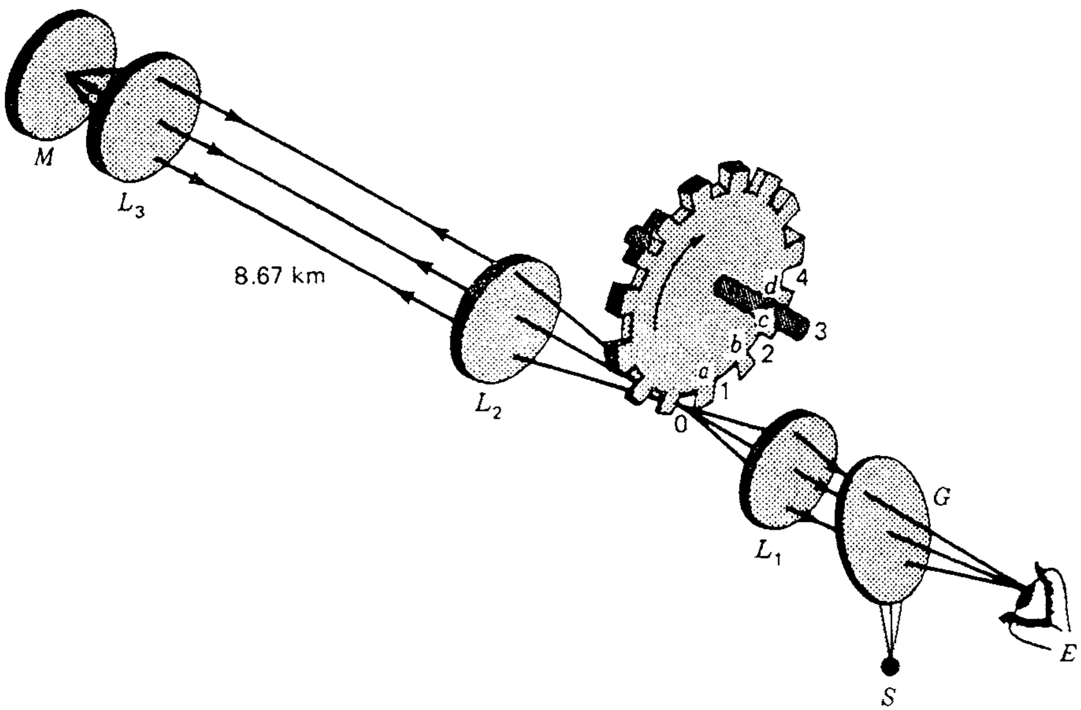


Figure 5: Experimental arrangement described by the French physicist Fizeau, with which
He determined the speed of light in air in 1849. Since the wheel contained 720 teeth, Fizeau found the maximum intensity to occur when its speed was 25 rev/s. The time required for each light pulse to travel over and back could

be calculated by *(1/720)(1/25)* = 1/18,000 s. From the measured distance over and back of 17.34 km, this gave a speed of

$$v = \frac{d}{t} \; \frac{17.34\ km}{\frac{1}{18000}s} = \ 312{,}000\ \text{km}/s$$

The speed of light, although quite fast, is not infinite. Over 40 years later the American physicist Michelson (first American Nobel laureate 1907)measured the speed of light in air The speed of light in a vacuum is expressed as ***c* = 2.99 × 108 m/s**. Light travels in a vacuum at a constant speed, and this speed is considered a universal constant.

$$\boldsymbol{c = \lambda f}$$

Example (1): The wavelength of a diagnostic x-ray is only 0.01 nm. What frequency does the doctor's machine operate with?

Solution:

$$\boldsymbol{c = \lambda f}$$

$$\boldsymbol{f = \frac{c}{\lambda} = \frac{3x10^{8} m/s}{0.01x10^{-9}} = 3x10^{19} Hz}$$

c = 2.99792458 × 10^{8} m/s .

Speed of light in vacuum is a fundamental physical constant

The EM wave travels in vacuum at a constant speed

$$V = c = 3 \times 10^{8} m/s$$

$$f\lambda = c \qquad (1)$$

(1-5) Photon

The particle-like nature of light is modeled with photons. A photon has no mass and no charge.

A beam of light is modeled as a stream of photons, each carrying a well-defined energy that is dependent upon the wavelength of the light. The energy of a given photon can be calculated by: $E = \hbar f$. $\hbar$ is called *the Planck's constant* and is another fundamental constant of nature.

Light presents itself a sequence of particle (photons) which have energy proprtional to the frequency

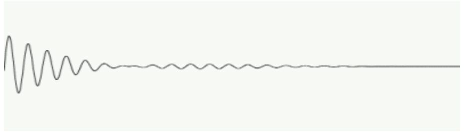
$$\text{Photon energy } (E) = hc/\lambda \qquad (2)$$

where E is in joules
h = Planck's constant = $6.625\ 10^{-34}$ J · s
c = Speed of light = 2.998 × 108 m/s
λ = Wavelength of the light in meters

Particle Properties of Light

- Light also behaves as though it comes in particles called photons.
- A photon has a wavelength and frequency associated with it.
- The Energy carried by the photon is

$$E = h\,f = \frac{h\,c}{\lambda} \quad (3)$$



In this equation, h is Planck's constant: h = 6.625 x 10^{-34} J s.

Since $f_{blue} > f_{red}$, blue photons carry more energy than red photons!

Example (2) :

Photons in a yellow light have a wavelength of 550 nm. (The symbol nm is defined as a Nanometer = 10^{-9} m.) What is the energy of this photon?

Solution:

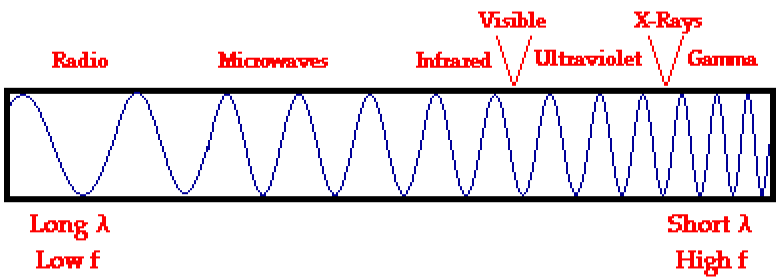
$$E = h\,f = \frac{h\,c}{\lambda}$$

H.W E= ?

(1-6) Electromagnetic spectrum

EM waves can have different frequencies and wavelength. **Distribution of light in frequency (wavelength) is EM spectrum.** EM radiation is classified into types according to the frequency of the wavelength.

$$E=hf=h\,c/\lambda$$



The diagram below depicts the electromagnetic spectrum and its various regions.

If the EM wave has wavelength in the **visible** range **400 nm < λ< 700 nm**

Our eyes interpret EM waves with different wavelengths in the visible range as different colors.

In order of long wavelength to short wavelength: red, orange, yellow, green, blue, indigo, violet

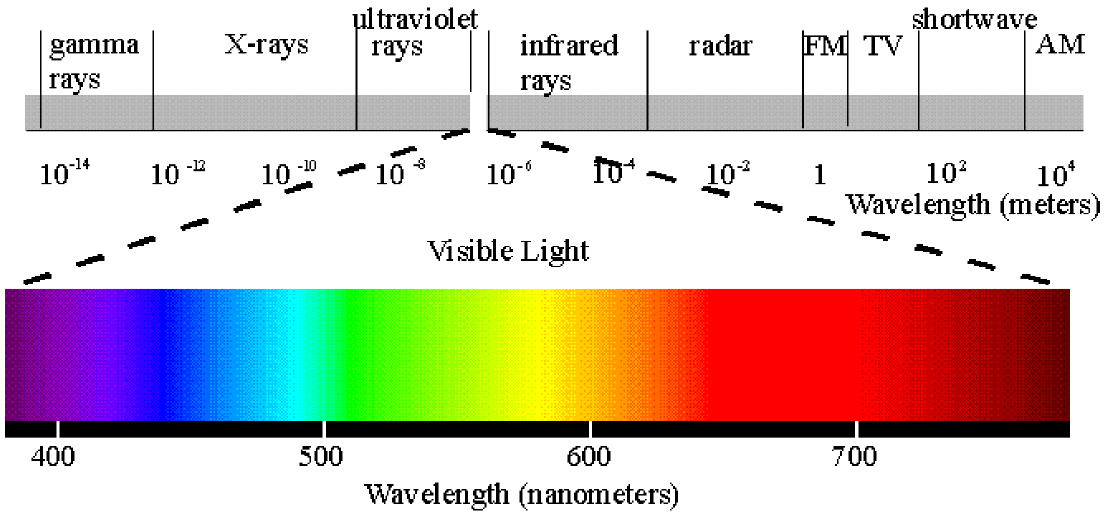


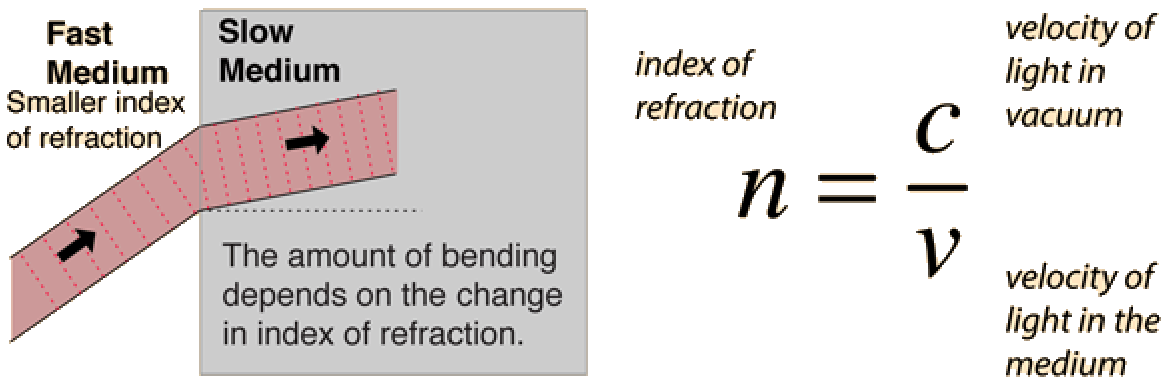
Table (1-1) : represented the wavelength and frequency ranges of the divisions of the electromagnetic spectrum.

Category	Range of Wavelengths (nm)	Range of Frequencies (Hz)
gamma rays	<1	$>3\times10^{17}$ $>3\times10^{17}$

X-rays	1–10	3×10^{16}–3×10^{17}
ultraviolet light	10–400	$7{,}5\times10^{14}$–3×10
visible light	400–700	$4{,}3\times10^{14}$–$7{,}5\times10^{14}$
Infrared	700–10^{5}	3×10^{12}–$4{,}3\times10^{14}$
microwave	10^{5}–10^{8}	3×10^{9}–3×10^{12}
radio waves	$>10^{8}$	$<3\times10^{9}$

(1-7) Refraction index

The index of refraction is defined as the speed of light in vacuum divided by the speed of light in the medium.



In the material the light always moves with speed **v** that is slower than in vacuum.

- The ration ***n = c/v*** is called **index of refraction** and is one of the most important optical properties of a material. Typical values for glasses are *n ~ 1.5-2* while for the air it is 1.0003, which is practically unity

- Index of refraction is always larger than unity **n** > **1** , equal to unity only in vacuum.

Table (1-2): shows different refractive index with various materials.

Material	**n**	**Material**	**n**
Vacuum	1.000	Ethyl alcohol	1.362
Air	1.000277	Glycerin	1.473

Water	4/3	Ice	1.31
Carbon disulfide	1.63	Polystyrene	1.59
Methylene iodide	1.74	Crown glass	1.50-1.62
Diamond	2.417	Flint glass	1.57-1.75

Example (1): The speed of light in an unknown medium is measured to be 2.76×10^8 m/s. What is the index of refraction of the medium?

Solution:

The index is found to be

$n = c/v$ = (3.00 x 108 m/s)/(2.76 x 108 m/s) = 1.09.

(1-8) Optical path

In a medium of constant refractive index, n, the optical path length OPL for a path of physical length d ,to define a quantity called the *optical path.* The path d of a ray of light in any medium is given by the product *velocity* times *time:*

$$d = vt$$

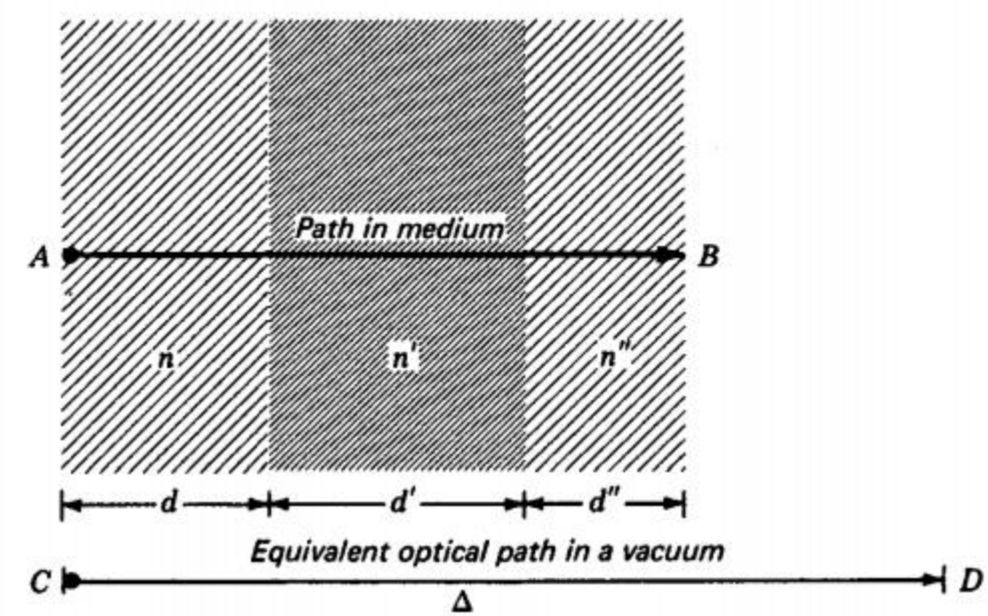
Since by definition $n = c/v$, which gives $v = c/n$, we can write the product nd is called the *optical path* Δ:

$$nd = ct$$

$$\Delta = n\, d$$

If the refractive index varies along the path, the OPL is given by

Opt= $n_1 d_1 + n_2 d_2$



Problems

Q1: Light of wavelength 589 nm in vacuum passes through a piece of fused quartz of index of refraction *n* 1.458. **(a)** Find the speed of light in fused quartz. **(b)** What is the wavelength of this light in fused quartz? **(c)** What is the frequency of the light in fused quartz?

Q2: Light with wavelength 589 nm passes through crystalline sodium chloride. In this medium, find (a) the speed of light, (b) the wavelength, and (c) the frequency of the light.
Answer (a) 1.94 108 m/s (b) 381 nm (c) 5.09 1014 Hz

3. What is Light?

Q4: How long does it take light from the sun to reach the earth? Assume the earth's distance from the sun to be 1.50 X 10^8 km
Q5: If the refractive index for a piece of optical glass is 1.5250, calculate the speed of light in the glass. *Ans.* 1.9659 x 10^8 m/s
Q6: A water tank is 62.0 cm long inside and has glass ends which are each 2.50 cm thick. If the refractive index of water is 1.3330 and of glass is 1.6240, find the overall optical path.
Q7: A beam of light passes through 285.60 cm of water of index 1.3330, then through 15.40 cm of glass of index 1.6360, and finally through 174.20 cm of oil of index 1.3870.
Find to three significant figures *(a)* each of the separate optical paths and *(b)* the total optical path.
Ans. (a) 380.7, 25.19, and 241.6 cm, *(b)* 647 cm.