NATURE OF LIGHT

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THE NATURE OF LIGHT

Until the beginning of the 19th century, light was considered to be a stream of particles, emitted by a light source, which stimulated the sense of sight on entering the eye. The chief architect of the particle theory of light was Newton. With this theory, he provided simple explanations of some known experimental facts concerning the nature of light, such as the laws of reflection and refraction.

According to Newton, the particles emitted by a source travelled in a straight line until the boundary of a new medium was encountered. He derived a relationship that predicted that the speed of light in a medium such as water would be greater than its speed in air.

This is exactly the opposite of the result predicted by the wave theory. Foucault later found a value for the velocity of light in a medium that showed that Newton's prediction was incorrect. This played a large part in discrediting the so-called *corpuscular theory of light.*

Most scientists initially accepted Newton's particle theory of light. However, during Newton's lifetime, another theory was proposed. In 1678, a Dutch physicist and astronomer, Christian Huygens (1629-1695), showed that a wave theory of light could also explain the laws of reflection and refraction. In addition, his theory could account for the fact that light entering a medium from air at an angle would be bent.

The wave theory did not receive immediate acceptance for several reasons. All the waves known at the time (e.g. sound and water waves) travelled through some sort of medium; but light from the Sun could travel to Earth through empty space. Furthermore, it was argued that if light were some form of wave, it would bend around obstacles; hence, we should be able to see around corners. It is now known that light does indeed bend around the edges of objects. This phenomenon, known as *diffraction,* is not easy to observe because light waves have such short wavelengths. Even though experimental evidence for the diffraction of light had been discovered by Francesco Grimaldi (1618-1663) around 1660, for more than a century most scientists rejected the wave theory and adhered to Newton's particle theory. This was partly due to Newton's great reputation as a scientist.

The first clear demonstration of the wave nature of light was provided by 1801 by Thomas Young (1773-1829), who showed that under appropriate conditions, light exhibits interference behaviour. That is, at certain points in the vicinity of two sources, light waves can combine. They can even cancel each other by destructive interference. Such behaviour could not be explained by a particle theory. A few years later, and building on Young's experimental work, Augustin Fresnel (1788-1827) definitely signalled the end of 18th century physics and the birth of modern optics. He extended the wave theory of light to a large class of optical phenomena and developed the theoretical framework that became the foundation of modern optics.

The most important development concerning the theory of light was the work of James Clark Maxwell, who in 1865 predicted that light was a form of high-frequency electromagnetic wave. His theory predicted that these waves should have a speed of 3×10^8 m/s. This value is in agreement with the experimentally measured speed.

Light is transmitted in the form of transverse waves. In the diagram below we see that the electric and magnetic vectors associated with an electromagnetic wave are at right angles to each other and also to the direction of wave propagation.

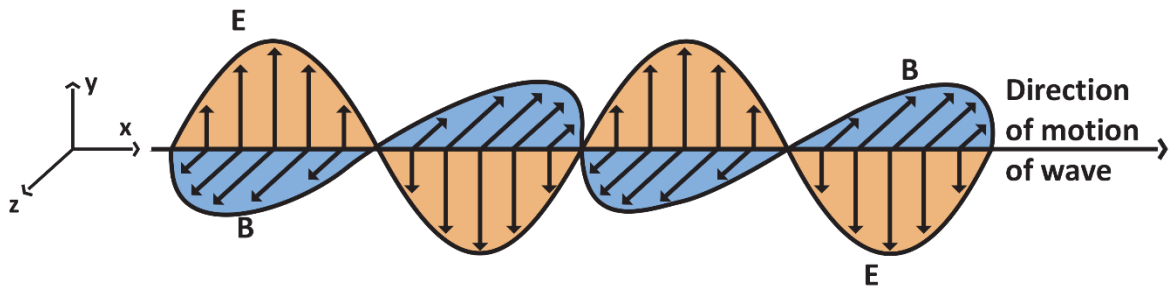


Figure 1.1: *Schematic diagram of an electromagnetic wave propagating in the x direction. The electric field vector E vibrates in the xy plane, and the magnetic field vector B vibrates in the xz plane*

Although the classical theory of electricity and magnetism explained most known properties of light, some subsequent experiments could not be explained by the assumption that light was a wave. The most striking of these was the *photoelectric effect*, discovered by Hertz. Hertz found that clean metal surfaces emit charges when exposed to ultra-violet light.

In 1905, Einstein published a paper that formulated the theory of light quanta and accounted for the photoelectric effect. He reached the conclusion that light is composed of *corpuscles,* or discontinuous quanta of energy. Furthermore, he asserted that light interacting with matter also consists of quanta, and he brilliantly worked out the implications of the photoelectric process.

More specifically, Einstein showed that the energy of a photon is proportional to the frequency of the electromagnetic wave:

$$E = h \cdot f$$

where h= 6.63 x 10^{-34} Js is *Planck's constant.* This theory contains features of both the wave and particle theories of light.

In view of these developments, light must be regarded as having a *dual nature.* That is, to best describe light's behaviour, **we need in some cases to consider light to be acting as a wave and in others to be acting as a particle.** For example, classical electromagnetic wave theory provides adequate explanations of light propagation and of the effects of interference, whereas the photoelectric effect is best explained by assuming that light is a particle.

The nature we consider light to have in a particular situation will depend on which is the most appropriate model for those circumstances.. . In this course, we consider **Physical Optics** which involves phenomena which can only be explained by reference to the nature of light, as well as phenomena which do not depend on the nature of light, but only on its path. This is commonly referred to as **Geometric Optics**.

LIGHT WAVES

In the 17th century, the Dutch physicist and mathematician Christian Huygens and many other workers had been investigating various optical phenomena. In order to explain certain effects, he suggested that light energy travels as a waveform. Essentially, the wave theory describes light as spreading outwards from a source in a homogeneous isotropic medium in the form of *spherical waves.*

A source which has negligible size in comparison to the distance to the observer is termed a *point* source, while one which has appreciable size compared to the distance between the source and the observer is called an extended source (a source viewed from a distance greater than 10 times its maximum dimension across the line of sight can be considered as a point object). A medium which has the same optical properties in all directions is an *isotropic* medium (the opposite is anisotropic). If a material is isotropic throughout its volume, it is described as *homogeneous*.

Originally, it was thought that the medium through which the light was travelling was actually formed into waves (e.g. waves in water or sound waves in air) However, later work by Maxwell confirmed that the waves are actually variations of an electromagnetic character and are not waves formed in any material substance. The following figure shows a two-dimensional illustration of spherical waves from a point source S in which the waves appear as circles called *wavefronts.*

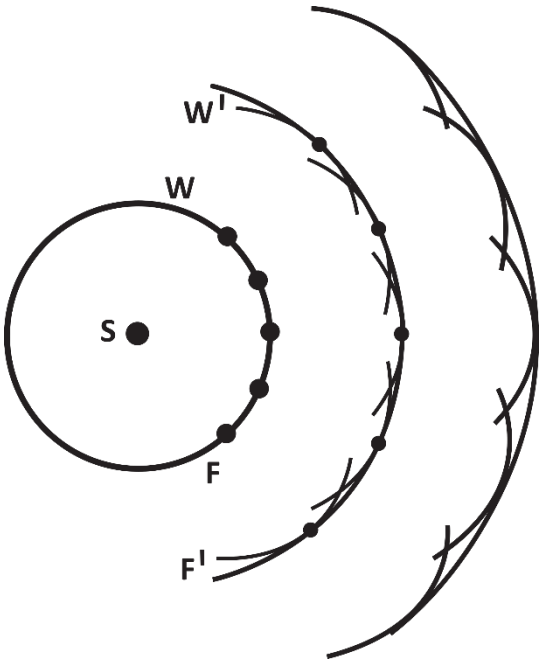


Figure 1.2: *By considering the wavefronts WF and W'F', we can visualize the waves leaving the source in two dimensions as concentric spheres (spheres with a common centre but different radii).*

A **wavefront** can be defined as a surface passing through the points on a set of waves that have the same phase and amplitude. It is the set of points in space reached by a wave or vibration at the same instant as the wave travels through a medium. Wave fronts generally form a continuous line or surface. From everyday experience, the lines formed by crests of ripples on a pond, for example, correspond to curved wave fronts.

All wave motions possess the characteristics of *wavelength, velocity, frequency,* and *amplitude*. The high points on a wave are called *crests*, the low points, *troughs*. The *amplitude* is the maximum height of a crest, or depth of a trough, relative to the normal (or equilibrium) level. The total swing from a crest to a trough is twice the amplitude. The distance between two successive crests is called the *wavelength*: λ (the Greek letter lambda). The wavelength is also equal to the distance between *any* two successive identical points on the wave. The *frequency*, *f,* is the number of crests - or complete cycles - that pass a given point per unit time (often denoted with the Greek letter ν (pronounced [nju])). The *period*, *T,* of course, is just 1/f, and is the time elapsed between two successive crests or troughs passing by the same point in space.

The **wave speed, v**, is the speed at which wave crests (or any other part of the waveform) move. It will be the product of the number of waves passing a point per second (the frequency) and the length of each wave (the wavelength). Therefore the velocity is related to other wave characteristics by the relationship:

$$\mathbf{v = f.\lambda}$$

- **v = speed of light, measured in m/s**
- λ is the wavelength in metres
- f is the frequency in Hz

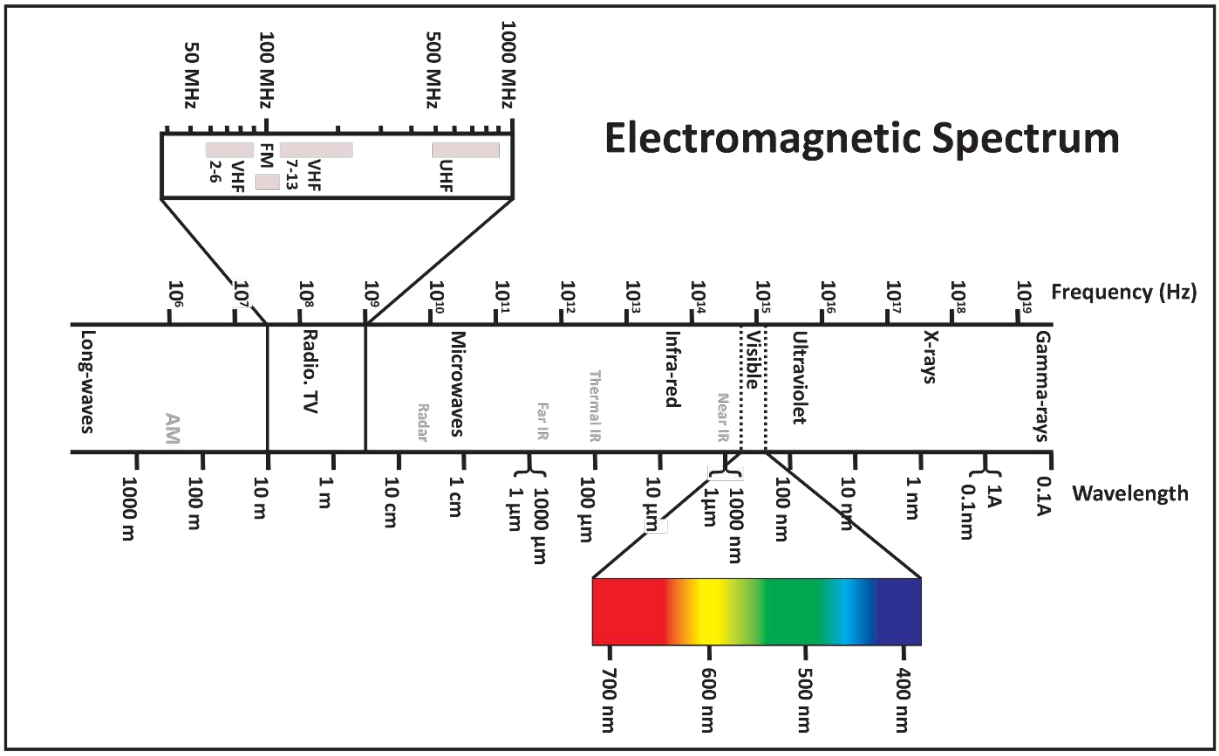
We can apply this general wave equation to light in vacuum. Since the speed of light in vacuum is usually indicated by c, the above equation becomes:

$$\mathbf{c = f.\lambda}$$

N.B. The above equation holds specifically for light travelling in <u>vacuum</u>.

VISIBLE LIGHT

There are many forms of electromagnetic waves which are distinguished from each other by their frequency, energy and wavelength. Taken together, they constitute what is known as the *electromagnetic spectrum.* The various types are indicated in the diagram.



	RADIO WAVES	MICRO WAVES	INFRA RED	VISIBLE LIGHT	ULTRA VIOLET	X-RAYS	GAMMA RAYS
Wavelength:	Long ←						Short
Frequency:	Low →						High
Energy:	Low →						High

Figure 1.3: *Representation of the electromagnetic spectrum*

In order of increasing energy we have:

(a) **Radio waves** with wavelengths varying from about 1 m to as long as 1 km.

(b) **Microwaves** with wavelengths of about 1 mm to 30 cm.

(c) **Infrared radiation** with wavelengths of about 1 mm to 7 x 10^{-7} m (700 nm). These waves are readily absorbed by most materials. They usually appear as heat since their energy agitates the atoms of the body, increasing their vibrational and translational motion, which results in a temperature rise.

(d) **Visible light** which is the most familiar form of electromagnetic waves. The various wavelengths of visible light are classified with colours ranging from violet (~400 nm) to red (~700 nm) (depending on the definition of visible light, larger limits (e.g. 380-830nm) may be given). The eye's sensitivity is a function of wavelength, the sensitivity being a maximum at a wavelength of about 555 nm (yellow-green). The maximum is dependent on light conditions.

(e) **Ultraviolet radiation** covers wavelengths ranging from about 380 nm down to 60 nm.

(f) **X-rays** are electromagnetic waves with wavelengths in the range of about 10 nm down to 10^{-4} nm**.**

(g) **Gamma rays** are emitted by radioactive nuclei and during certain nuclear reactions (e.g. cosmic rays). Their wavelengths range from about 10^{-10} m to less than 10^{-14} m. They are highly penetrating and produce serious damage when absorbed by living tissues.

You can create a mnemonic to remember the radiation in order of decreasing wavelength / increasing frequency / increasing energy. For example:

***R*oyalty**	***R*adio waves**
***M*eets**	***M*icrowave**
***I*n**	***I*nfra-Red**
***V*ery**	***V*isible light**
***U*nusual**	***U*ltra-violet**
e***X*pensive**	***X*-rays**
***G*ardens**	***G*amma rays**

THE SUN'S RAYS

Approximately 43% of the radiation emitted by the sun is in the visible range. (It is assumed the reason why our eyes are most sensitive to light around 555nm is that it also corresponds to the maximum of emission of the sun when measured at the surface of the Earth).
For the rest of the sun's radiation, approximately 49% is in the near infrared range and around 7% is in the ultraviolet range. Less than 1% is X-rays, gamma rays, and radio waves.

The spectrum of electromagnetic radiation from the sun striking the Earth's atmosphere ranges from 100 to 10^6 nm. This can be divided into five regions in increasing order of wavelengths.

- **Ultraviolet C** or (UVC) range, which spans a range of 100 to 280 nm. This radiation is at higher frequency than violet light and hence also invisible to the human eye. Owing to absorption by the atmosphere, none reaches the Earth's surface. This spectrum of radiation has germicidal properties, and is emitted by germicidal lamps, and other artifical sources.
- **Ultraviolet B** or (UVB) range spans 280 to 315 nm. It is also greatly absorbed by the atmosphere but can reach the Earth's surface.
- **Ultraviolet A** or (UVA) spans 315 to 400 nm. It was been traditionally held as less damaging to the DNA than the other types of UV, however, since it penetrates deeper into the skin, it is much more hazardous than traditionally considered.
- **Visible range** spans 400 to 700 nm.
- **Infrared** range spans 700 nm to 10^6 nm [1 mm]. It is also divided into three types on the basis of wavelength:
    - Infrared-A: 700 nm to 1 400 nm
    - Infrared-B: 1 400 nm to 3 000 nm
    - Infrared-C: 3 000 nm to 1 mm.

THE RAY APPROACH

In studying geometric optics, we will make use of an important property of light. **Light travels in straight lines until it encounters a boundary between two different materials**. Based on this observation, (referred to as the principle of *rectilinear propagation of light*) we will use what is called the ray approach to represent our light waves. A ray of light is an **imaginary** line drawn along the direction of travel of the light waves. The rays are straight lines perpendicular to the wavefronts.

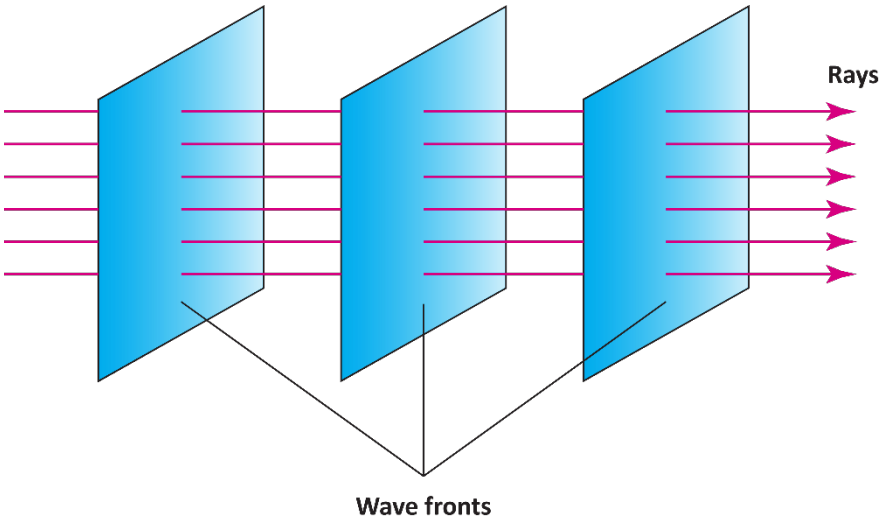


Figure 1.4: *The light rays are perpendicular to the wavefronts*

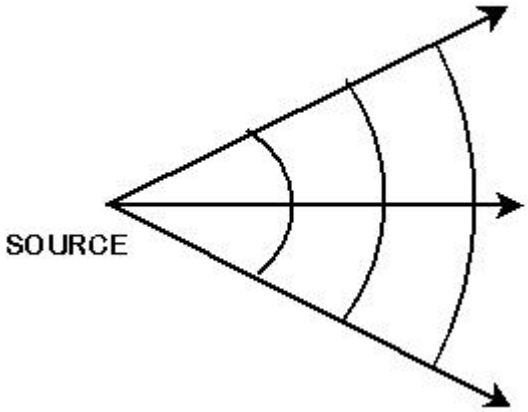
A group of light rays is referred to as a *pencil* of rays. A collection of pencils is, in turn, known as a *beam* of light.

Light rays spread out, or diverge, from point sources. In general, light is diverging from all points in all directions. Our eyes intercept small cones of these diverging rays and form images which the brain then interprets. **The direction the rays are travelling when they enter the eye indicates to us the direction to the object**.

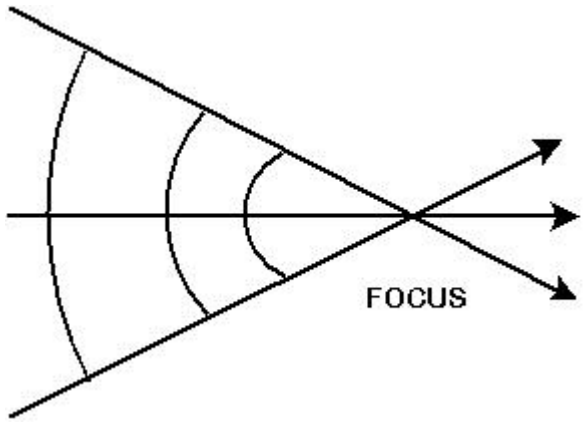
Geometric optics assumes that light travels in straight lines until it encounters a boundary between two media. Our own optical system has been trained by experience from birth to accept that the diverging light which enters the eye has travelled a straight-line path from its source. This is not always the case and can lead to illusions, like mirages.

As spherical wavefronts expand very far from the source, a small section of the front looks like a plane. Thus, **a point source a relatively large distance away can be approximated as a source of plane waves**. For example, the light from a very small bulb at a distance of a few metres, or the light from the sun or a star can be assumed to arrive as plane waves. The rays from the object will then be parallel to each other.

A DIVERGING PENCIL



A CONVERGING PENCIL



A PARALLEL PENCIL

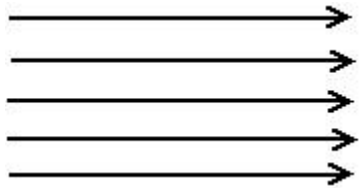


Figure 1.5: *a) A diverging pencil of rays b) a converging pencil of rays c) a parallel pencil of rays*

REFRACTIVE INDEX

The refractive index refers to the relative speed of light in a medium when compared to the speed of light in vacuum. For example, water (H_2O) has a refractive index of 1.333, meaning that light travels 1.333 times slower in water than in vacuum. The index varies with the wavelength of the light (approximately 1 to 2% for the range of visible light) and is a physical property of a material. As such, it can be used to identify a substance. The table below presents some common substances and their refractive index.

Refractive index of some common materials (λ = 589.29, Temperature = 20°C)	
Air	1.001
Water	1.333
Crown glass	1.520
Flint glass	1.610
Sapphire	1.770
Diamond	2.420
Human cornea (average)	1.376

Table 1.1: *Refractive index of different common materials*

Since the refractive index of a material varies with the frequency (and thus wavelength) of light, it is usual to specify the corresponding vacuum wavelength at which the refractive index is measured. Typically, this is done at various well-defined spectral emission lines.

In the UK and the North America, refractive index is measured at present on the helium d-line (wavelength 587.56 nm) and is indicated as $\mathbf{n_d}$.

In continental Europe it is measured on the mercury e-line (wavelength 546.07 nm) and is indicated as $\mathbf{n_e}$.

You will learn more about refractive index and its importance in Chapter 3: Refraction.

PHASE DIFFERENCE

In this chapter we have discussed the nature of light and we have represented it as sinusoidal waves. They are referred to by this name since this function also represents the variation in the sine of an angle. This function repeats after 360°, or 2π radians. Thus the distance from one crest to another represents the wavelength, or a phase difference of 360° or 2π radians.

The phase concept refers to the fraction of the wave that has elapsed, relative to its origin. Two waves can be “in phase” meaning that the same fraction of the wave has elapsed since the origin for the two waves, or, to put it simply, that they are having their peaks and their troughs at the same time. Therefore, two waves that are not synchronised in their peaks and troughs will be “out of phase”. Figure 1.6 represents this concept.

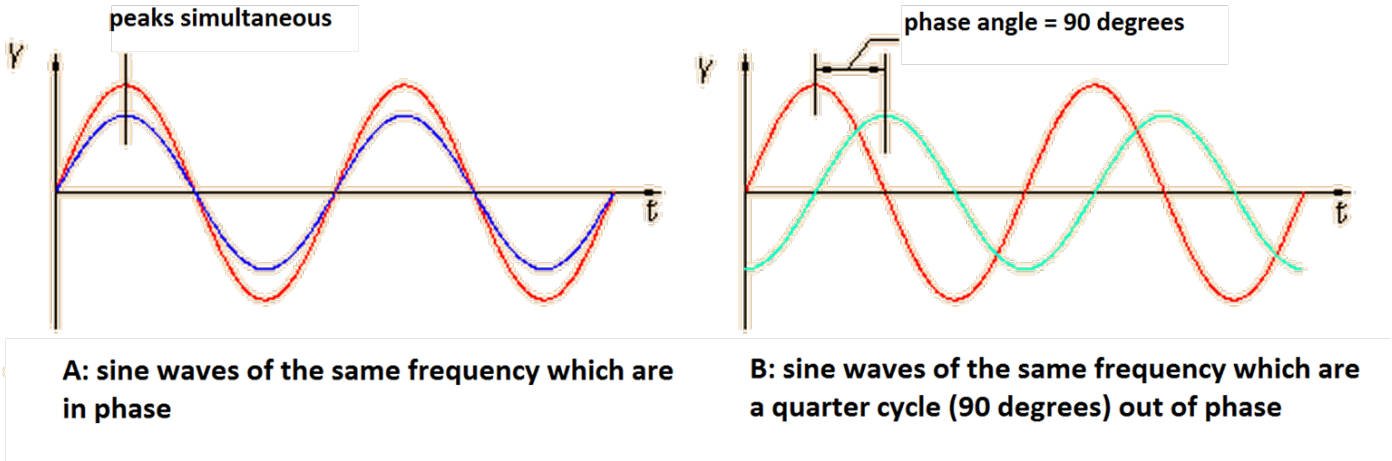


Figure 1.6: *Phase difference*

When waves are completely in phase they have a phase difference of zero degrees or (n x 360°) or (n x 2π rad), where n is an integer. This corresponds to a phase difference of either zero or a whole (integral) number of wavelengths.

When waves are completely out of phase they have a phase difference of (m x 180°) or (m x π rad), where m is an odd integer. This corresponds to a phase difference of ½ or 1½ or 2½ etc. wavelengths.

The phase differences and their implications in optics are going to be discussed in depth in Chapter 7: Interference.