Optics 2: Waves and their Properties

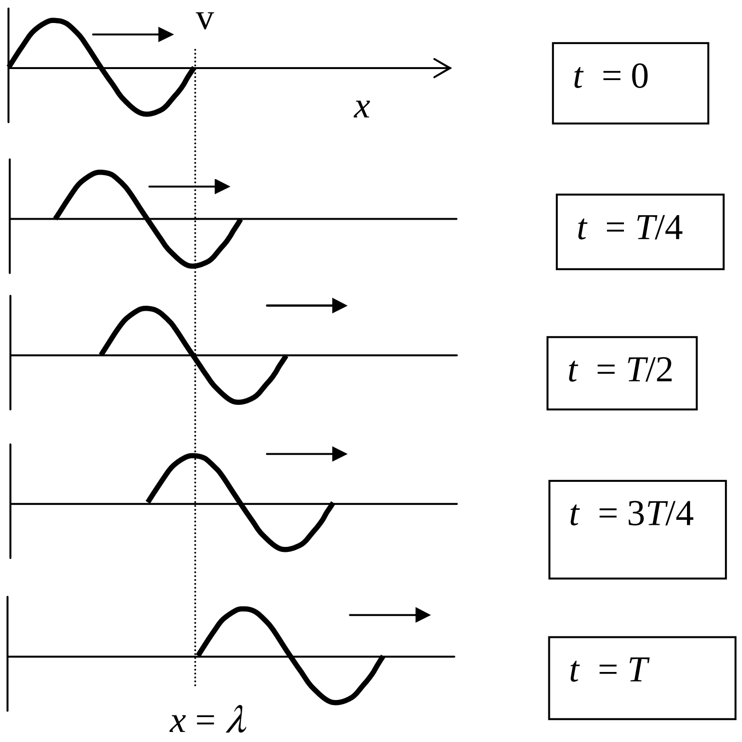
Waves start as a disturbance (source) and propagate energy, perhaps to a detector.

- *transverse waves* - the vibration is *perpendicular* to the direction of propagation (e.g. ripples on water).

- *longitudinal waves* - the vibration is in the *same direction* as the propagation of the wave (e.g. sound).

Light is a kind of transverse wave so we will focus on these.

Suppose a wave travels down a rope at a velocity v ms^{-1}:

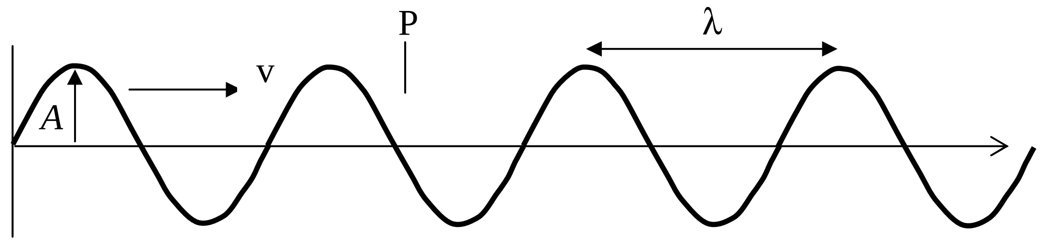


The length of one full cycle of the wave is called the wavelength λ m. Travelling at velocity v it takes a time T s given by

$$T = \frac{\lambda}{\mathrm{v}}, \qquad (1)$$

where T is called the period of the wave.

Usually we will deal with continuous waves.



Here the distance between crests is the easiest way of measuring the wavelength. The number of crests that pass an arbitrary point P in one second is termed the *frequency, f*, and is usually expressed in Hertz (Hz), or cycles/second. If one crest passes point P in time T seconds, then the number of crests passing in one second is the frequency f

$$f = \frac{1}{T} \quad . \qquad (2)$$

Combining Eqs. (1) and (2) , the velocity, wavelength and frequency are related by

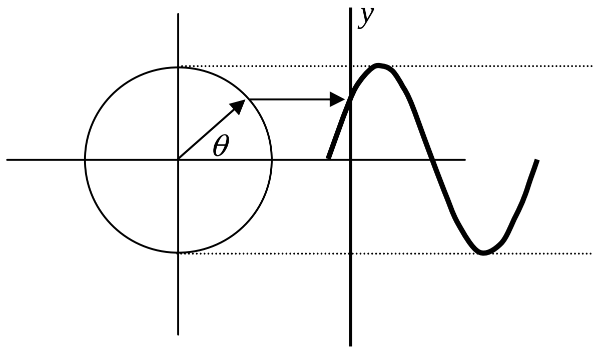
$$\mathrm{v} = \lambda f \quad . \qquad (3)$$

Very often, (particularly in Quantum Mechanics) the frequency is also given the symbol ν (Greek nu). But this is easily confused with the velocity

$$\mathrm{v} = \lambda \nu \quad . \qquad (4)$$

Simple Harmonic Motion and Phase

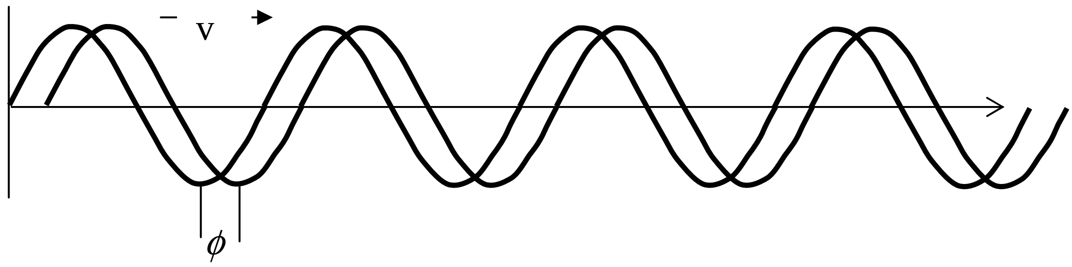
A sine wave is intimately related to circular motion:



The height $y = A\sin(\theta)$ if A is the radius of the circle. The angle θ is called the *phase angle* and can be used as a measure of position along the waveform. In this measure the full wavelength is *always* 2π radians or 360^o. There are many physical examples that can be modeled by simple harmonic motion: a pendulum, a tuning fork, a weight on the end of a spring.

Phase Difference

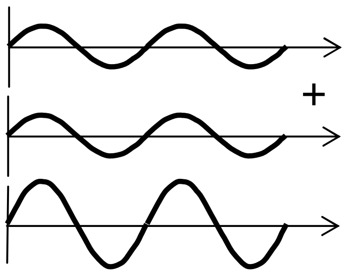
To fully specify a wave we need to say where and when it starts or give the phase at a given time and position. The waves shown below have the same amplitude, and the same frequency but a different phase. The phase difference here is ϕ and again is measured in radians or degrees.



We say that the second wave lags the first by the phase angle ϕ.

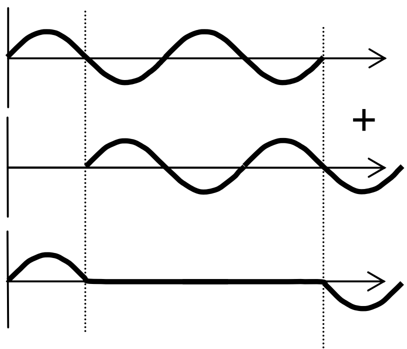
Interference

If two water waves come together in the same place they simply add together but the result depends on the phase difference.



Two waves in phase (coherent):
$\phi = 0$.

Constuctive interference



Two waves
Out of phase
$\phi = \pi$ radians

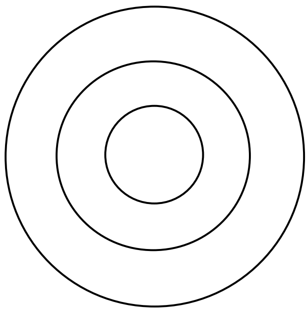
Destructive interference

Interference is responsible for the colours seen in thin films such as bubbles, phenomena such as the iridescence of opal and butterfly wings. Experiments such as Young's slits and Newton's rings depend on interference and demonstrate the wave nature of light.

Light travels in a straight line because it is the only path that *always* constructively interferes with itself. All other paths on average sum to zero.

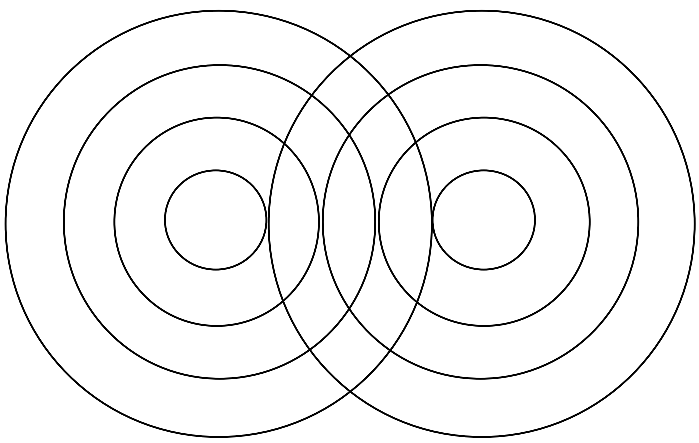
Waves in 2d and 3d

A pebble thrown into a pond makes circular 2-dimensional waves. Light from a point source spreads in all directions and makes 3-dimensional spherical waves. The spherical surfaces surrounding the source (where the electric field has a constant value) are called wavefronts. As the waves get further from the source the wave fronts become flatter. Light waves from the stars are plane waves.



Interference on a pond.

If two pebbles are thrown simultaneously into a pond the ripples interfere to form patterns. If the lines below represent crests and the space between are troughs where are the highest and lowest points of the resulting pattern and where are the null points where the waves cancel?



Polarization

In 3 dimensions a transverse wave may oscillate in any plane perpendicular to the direction of propagation. For light this means the direction in which its electric field oscillates. There are two *independent* possibilities usually referred to as vertical and horizontal polarization. Light beams with perpendicular polarizations will not interfere with each other. The observation of two modes of light led Huygens to suggest that light was a transverse wave. Most light is a mixture of polarizations and is said to be unpolarized.

Summary

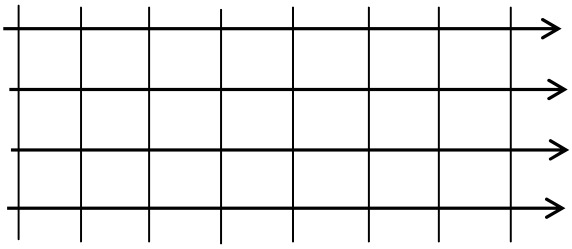
In 3 dimensions a transverse wave of known velocity is completely specified by four quantities:

- Wavelength or frequency.
- Amplitude.
- Phase.
- Polarization.

Light as a wave

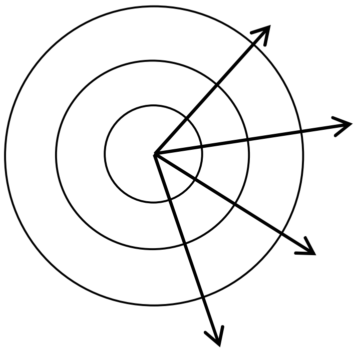
Wavefronts and Rays

At any point, in a vacuum and in isotropic materials, the direction of motion of a wave is perpendicular to the wavefront. A line drawn to correspond to this direction is called a ray and is also the direction of flow of radiant energy. Rays associated with the flat wavefronts from a distant star are parallel.

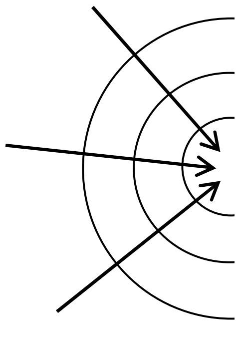


Rays perpendicular to a set of plane wavefronts

Rays from a point source are divergent.

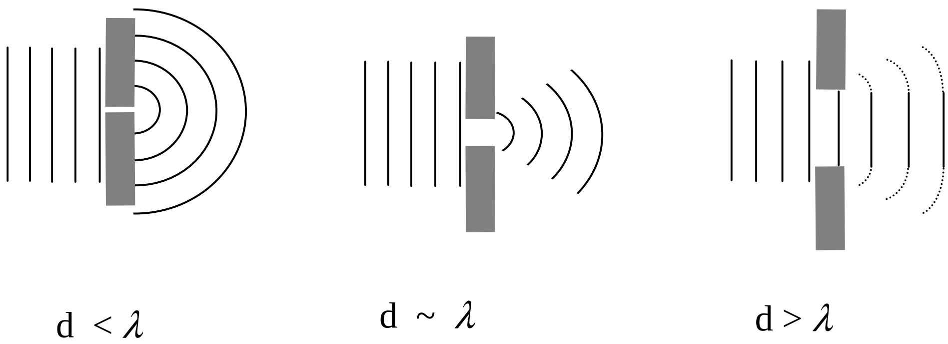


Rays for light focused by a lens are convergent.

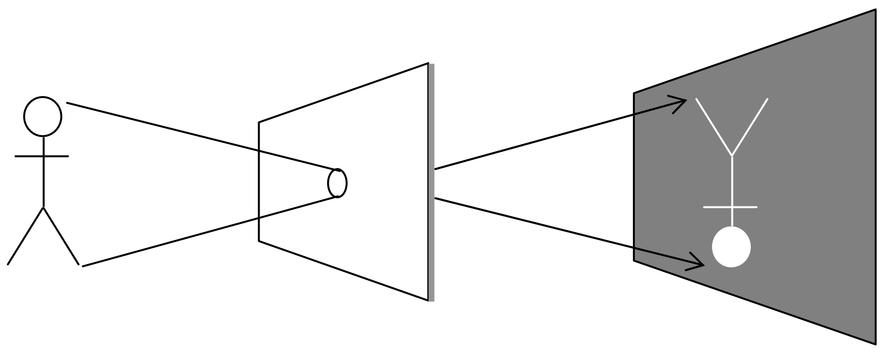


Diffraction

We classically think of light as always traveling in straight lines, but when waves pass near a barrier they tend to bend around that barrier and become spread out. Diffraction of a wave occurs when it passes by a corner or through an opening or slit that is physically the approximate size of, or even smaller than its wavelength.



Diffraction of plane waves by a pinhole (or slit). The diagrams attempt to depict something that is more complex in practice. Just like any other wave motion light is subject to diffraction and its influence can limit the focus of instruments – such as the **pinhole camera**

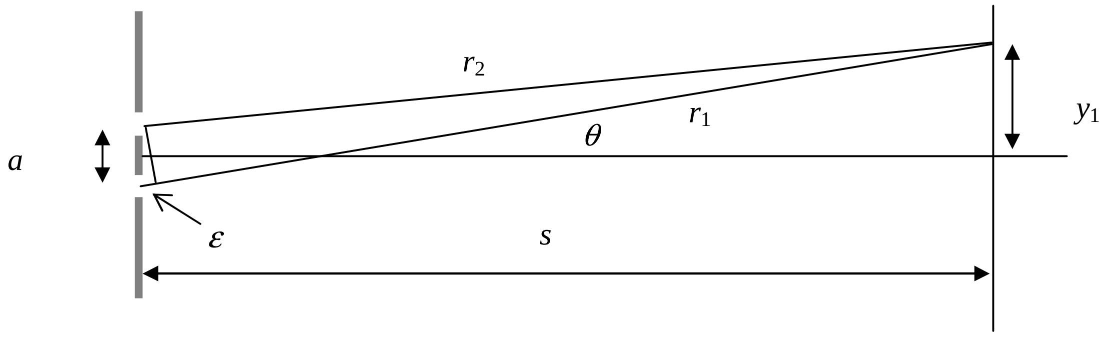


Blurring of the image happens because rays from the head (say) can pass either through the top of the hole or the bottom (this is geometric optics). Thus, the smaller the hole the better (if dimmer) the image. But if the hole is *too* small the wave properties of light become important and the image is blurred by diffraction effects.

Young's experiment

Young established the wave nature of light by demonstrating interference (~1804). In Young's experiment monochromatic light is passed through two narrow slits. Because of diffraction effects the waves spread out on the other side to act as two *coherent* sources.

A screen is placed a relatively far distance from the slits and the light falling on it shows alternating bright and dark areas due to interference between the two sources.



The path difference is

$$r_1 - r_2 = \varepsilon \approx a\sin(\theta)$$

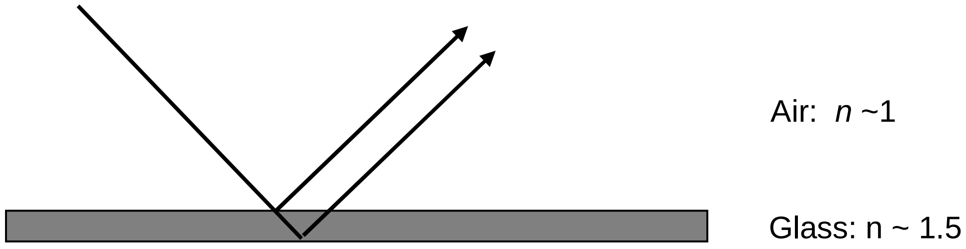
Now $\sin\theta = y_1/r_1 \approx y_1/s$ and so $\varepsilon = ay_1/s$

When $\varepsilon = m\lambda$ (m = 0, ±1, ±2, ….) the waves are in phase and there is constructive interference. In between (m = ½, $^3/_2$, …) the waves are out of phase. So we get bright fringes at

$$y_m = \frac{s}{a} m\lambda .$$

Thin Film Interference

A similar diagram and reasoning can be used to understand interference effects from thin films (oil slicks, anti-reflection coatings).



Thin films can be designed to make antireflective coatings.