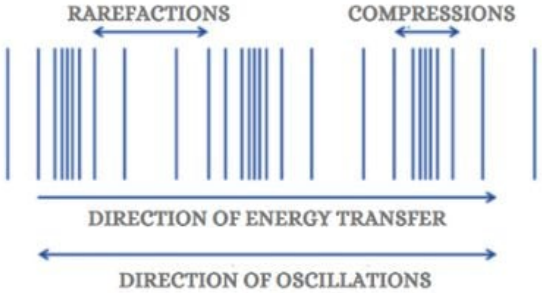
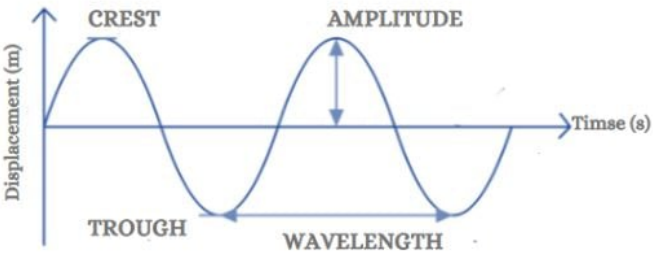


4.4 - Waves

Wave Motion

Waves transfer energy from one place to another without any net transfer of matter. These can be longitudinal or transverse:

Longitudinal	• Maxima at compressions and minima at rarefactions. • Particles move parallel to the direction of energy travel. • 
Transverse	• Maxima at peaks and minima at troughs. • Particles move perpendicular to the direction of energy travel. • E.g. electromagnetic waves. 

Waves that move away from a source are called progressive waves. However, this regards only the movement of **energy** - particles oscillate in place.

Wave Terminology

Displacement	The distance traveled by a wave from its rest position.
--------------	---

Amplitude	The maximum displacement of oscillating particles in a wave.
Wavelength	The distance between two successive identical points of a wave.
Time period	The time taken for a wave to complete one pattern of oscillation.
Frequency	The number of oscillations at any point per unit time. Reciprocal of time period.
Phase difference	A measure of the difference in pattern of oscillation between two points of a wave. Measured in radians from 0 to 2π .
Path difference	The difference between the distances traveled by two waves arriving at the same point. Usually measured in terms of wavelength, as path difference resets to 0m at a path difference equal to one wavelength.

Oscilloscopes

An oscilloscope displays a voltage-time signal. It can be used to measure the output from a microphone or signal generator.

Each horizontal division represents a unit of time. The unit of time per division is determined with the time base - e.g. 0.002 s/div. This can help you determine time period.

Each vertical division represents a unit of voltage. The unit of voltage per division is determined with the sensitivity - e.g. 20 V/div (less sensitive) to 5 mV/div (far more sensitive). The more sensitive, the easier it is to determine the precise points where the wave crosses the axis, as the slope appears steeper and the peaks are more defined. However, it also increases the risk of the signal moving off-screen.

Wave Equations

$$v = f\lambda$$

... where v is wave velocity, f is wave frequency, and λ is wave wavelength. For EM waves in a vacuum, $v = 3.00 \times 10^8$. For sound waves, $v = 330$.

$$I = \frac{P}{A}$$

... where I is the wave intensity (Wm^{-2}), P is the wave power, and A is the surface area of the source (e.g. $4\pi r^2$ for a sphere like the Sun).

Wave intensity is defined as the rate at which energy is transferred from one location to another as the wave travels through space. **It is proportional to the square of its amplitude** - e.g. if the amplitude decreases by a factor of 2, intensity reduces by a factor of $2^2 = 4$.

EM Spectrum

Waves in the EM spectrum are transverse waves that can travel through a vacuum. They all have a magnetic and an electrical wave interlocked and at right angles to each other. In a vacuum, they travel at $c = 2.98 \times 10^8 \text{ ms}^{-1}$.

Wave	Wavelength / m	Frequency / Hz
Radio	1e-1 to 1e4	3e4 to 3e9
Microwave	1e-4 to 1e-1	3e9 to 3e12
Infrared	7.4e-7 to 1e-3	3e11 to 4e14
Visible light	3.7e-7 to 7.4e-7	4e14 to 8e14
Ultra violet	1e-9 to 3.7e-7	8e14 to 3e17
X-Rays	1e-12 to 1e-7	3e15 to 3e20
Gamma rays	1e-16 to 1e-9	3e17 to 3e24

Ionising EM radiation has photons with sufficient energy to knock electrons from the shells of atoms.

99% of UV radiation is classified as UV-A, which is non-ionising. UV-B and UV-C are ionising, but UV-C is filtered out by the Earth's atmosphere, and the ionising nature of UV-B is mitigated using sunscreen creams.

Properties of Waves

Reflection	When a wave bounces off a surface.
Refraction	When a wave moves from one material into another of a different density, causing the wave to change speed and bend (unless traveling along the normal). Can be seen in glasses.
Diffraction	When a wave passes through an aperture that has a separation similar to the wave's wavelength, causing it to change direction.
Interference	When two or more waves overlap at a point, which has a particle displacement equal to the algebraic sum of all of the involved waves' displacements.

Light Refraction

Refraction occurs when a wave moves from one material into another of a different density, causing the wave to change speed and bend (unless traveling along the normal).

Every material has a refractive index. The higher this index, the stronger the effect of refraction. The refractive index is given as:

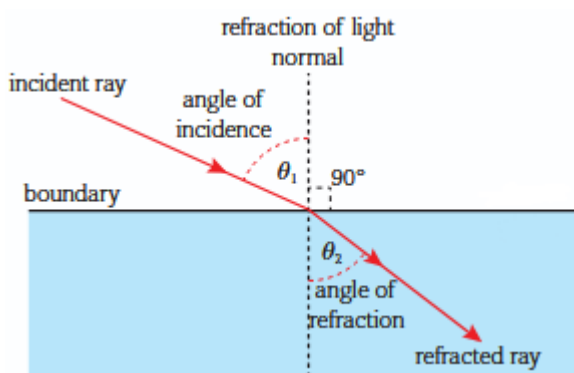
$$n = \frac{c}{v}$$

... where v is the speed of the wave in the medium.

Snell's Law

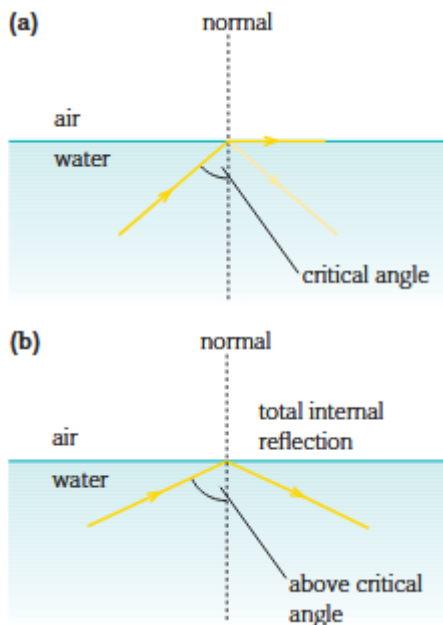
The refractive index also determines the angle at which a wave refracts, given by:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$$



Total internal reflection

This occurs when the angle of refraction (θ_2) is greater than or equal to 90 degrees. The incident angle causing a refracted angle of 90 degrees is known as the critical angle - any incident angle greater than this causes TIR. Take air and water for an example:



The critical angle is determined using:

$$\sin(C) = \frac{1}{n}$$

Polarisation

Serves as good evidence for the wave nature of light (on the particle nature, look at **4.5 - Quantum Physics**). All transverse waves can be polarised.

Light emitted from a source is unpolarised by default - the electric field of EM waves can be in any number of planes. Some crystalline materials can cause the oscillating fields to happen in only one plane. A wave with fields only one plane is known as plane polarised.

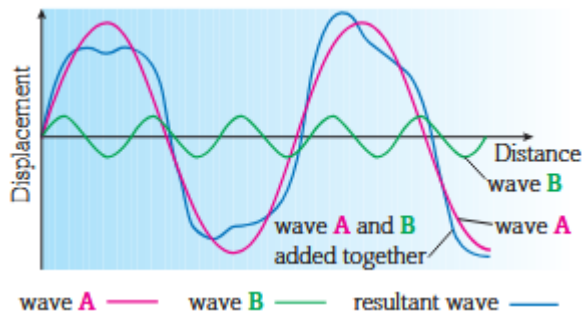
Malus' Law

When a perfect polarising filter is put in front of a polarising wave with the vertical at an angle theta to the plane, the intensity of the output is:

$$I = I_{max} \cos^2(\theta)$$

Interference and Superposition

The principle of superposition states that when two or more waves of the same type meet, the resultant wave can be found by adding the displacements of the individual waves.

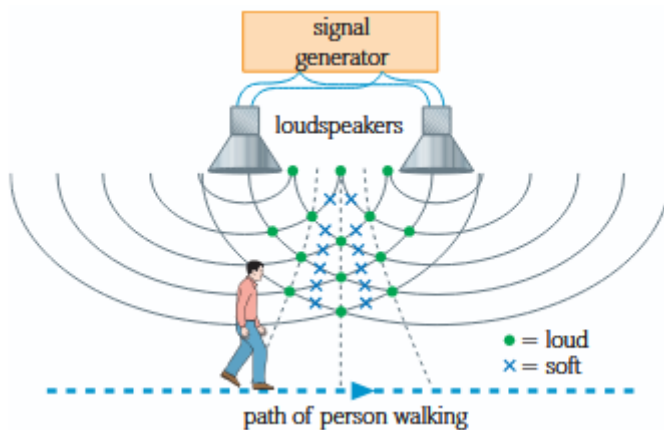


Coherent waves have a constant frequency, and thus a constant phase difference.

With two waves in phase (path difference a multiple of λ ; phase difference 0 or a multiple of 2π), total constructive interference occurs. This means the resultant wave has an increased amplitude.

With two waves out of phase (path difference an odd multiple of $\frac{1}{2}\lambda$; phase difference an odd multiple of π), total destructive interference occurs. This means the resultant wave has an amplitude of 0m.

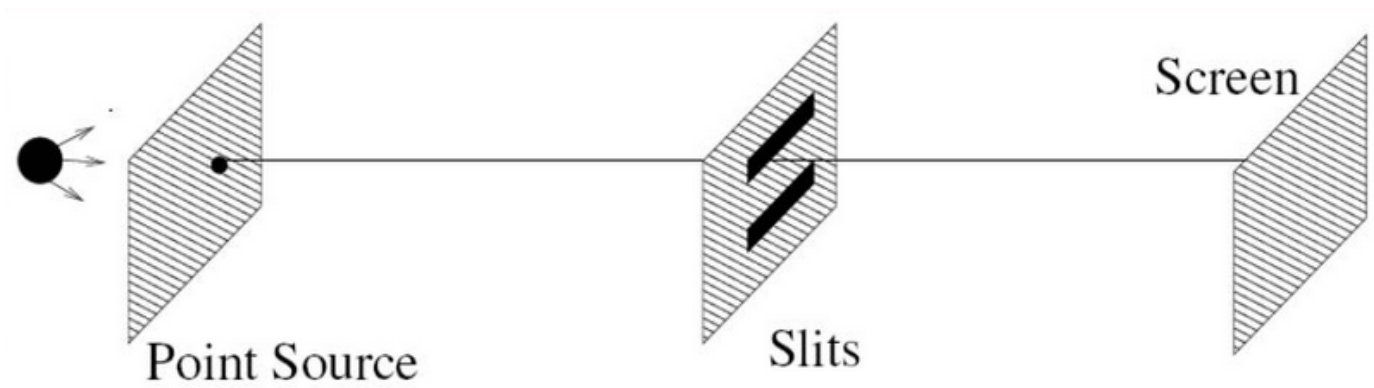
In sound/spreading waves instead of waves in a linear path:



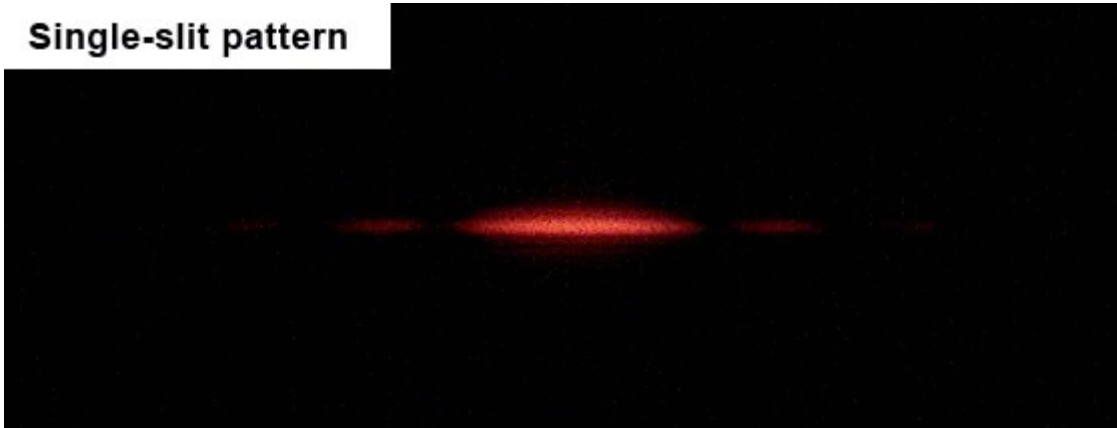
Young's Double-Slit Experiment

Involves the emission of monochromatic light waves with wavelength λ leaving a source and entering two slits with separation "a", causing diffraction. The diffracted waves travel a perpendicular distance "D" from the slits and superpose, constructively and destructively interfering to form fringes with separation "x" between maxima:

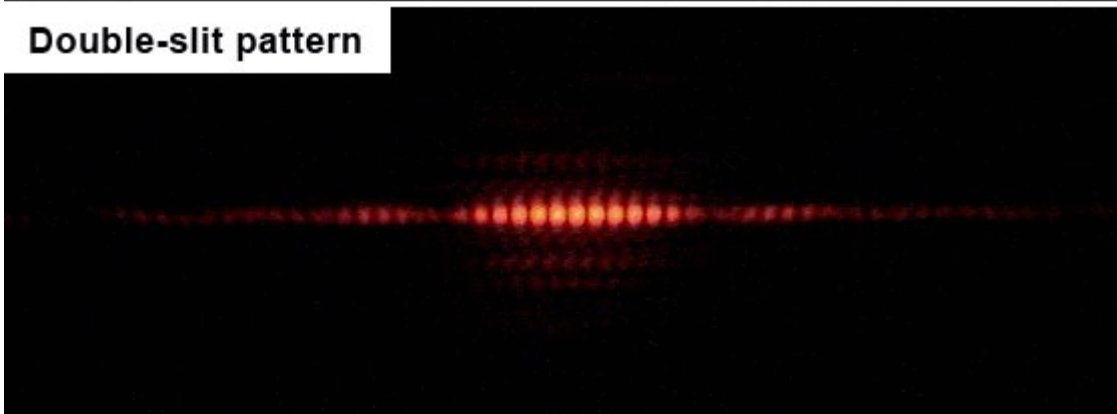
$$\lambda = \frac{ax}{D}$$



Single-slit pattern

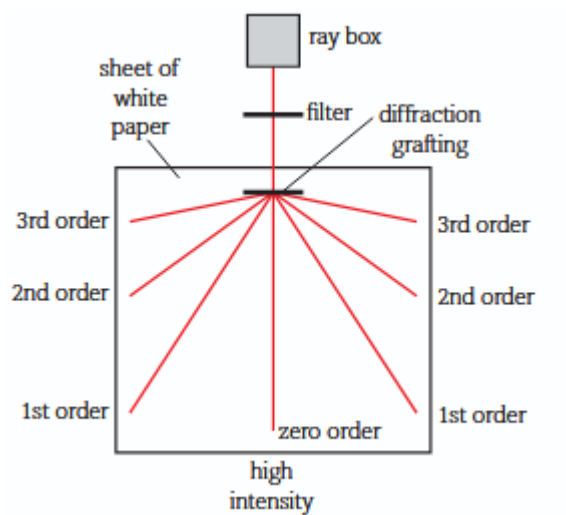


Double-slit pattern



Diffraction gratings

A diffraction grating is a piece of optical equipment made from glass, onto which hundreds/thousands of very thin, parallel, and equally spaced grooves have been accurately engraved. Measured in lines per mm. This greatly increases the resolution of interference patterns, which increases with number of slits. As you can see in the above image, a double slit pattern has much clearer fringe separations than the single slit pattern. Different orders of fringe are visible at path differences equal to multiples of λ depending on slit separation, which define where fringes are visible - e.g.:



$$n\lambda = d\sin(\theta)$$

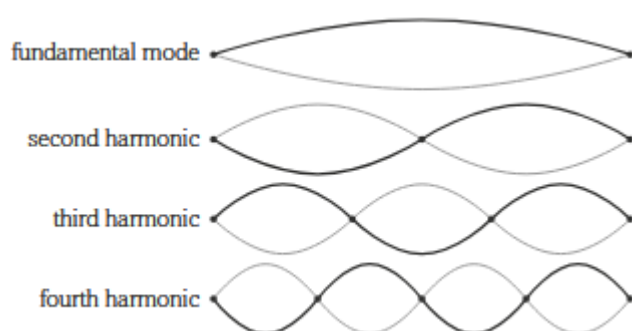
... where n is the order of the maximum (1, 2, 3), λ is the wavelength of light, d is slit separation, and θ is the angle between the beam and the grating.

Stationary Waves

Stationary waves are produced by interference in accordance with the principle of superposition. Two waves must be coherent, have roughly the same amplitude, and be traveling in opposite directions. Nodes are points of zero amplitude, where waves undergo destructive interference. Antinodes are points of maximum amplitude, where waves undergo constructive interference. Adjacent nodes and adjacent antinodes have a separation equal to half the wavelength.

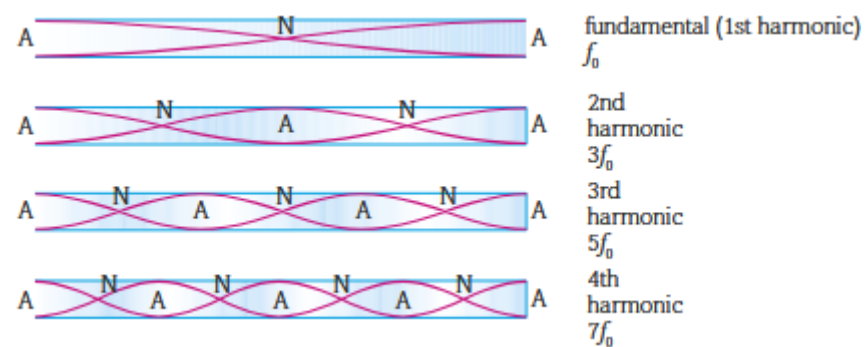
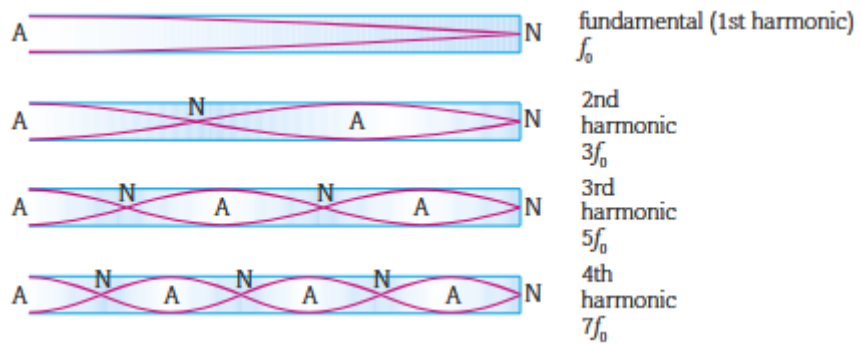
Harmonics

Depending on the frequency of the stationary wave, it may have a different mode of harmonic:



Longitudinal Waves

In tubes, there is always a node at the closed end, and an antinode at an open end. This makes the fundamental and n th harmonics look different:



Revision #5

Created 2026-02-16 18:28:31 UTC by Asad

Updated 2026-02-17 22:05:40 UTC by Asad