

# OCR A Physics A-level

## Topic 4.4: Waves

### Notes



# Wave motion

## Progressive waves

A progressive wave is an **oscillation** that travels through matter (or in some cases a vacuum), **transferring energy** from one place to another, but not transferring any matter. The particles in the matter vibrate as the wave passes through them, but they do not move along with the wave.

There are two types of progressive waves. In a **transverse** wave, the oscillations are **perpendicular** to the direction of wave travel, such as electromagnetic waves and waves on the surface of water. The waves have peaks and troughs at the maximum and minimum points of displacement.

In a **longitudinal** wave, the oscillations are **parallel** to the direction of energy transfer, such as sound waves. They have areas of compression, where particles are closer together, and areas of rarefaction, where particles are more spread out.

## Key wave definitions and equations

- Displacement – the distance from the equilibrium position in a particular direction
- Amplitude – the maximum displacement from the origin
- Wavelength – the minimum distance between two adjacent points on a wave oscillating in phase
- Period – the time taken for a full oscillation of one wavelength to pass a given point
- Frequency – the number of complete oscillations passing a given point per unit time
- Wave speed – the distance travelled by a wave per unit time

Phase difference is the **difference in displacement** of particles along a wave, or in 2 different waves, measured in radians. If particles oscillate in step with each other, they are **in phase**, and their phase difference will be a multiple of  $2\pi$ . If particles oscillate out of phase, then the equation  $\frac{x}{\lambda} \times 2\pi$ , where  $x$  is the separation in wavelengths between the two particles, can be used to calculate the phase difference. When two particles are oscillating with a phase difference of  $\pi$ ,  $\frac{\lambda}{2}$  a wavelength out of step with each other, they are said to be **in antiphase**.

The period of the wave,  $T$ , is the **reciprocal** of the wave's frequency,  $f$ . To find the frequency of a wave, the formula  $f = \frac{1}{T}$  can be used.

The wave equation states the relationship between wave speed,  $v$ , wavelength,  $\lambda$ , and frequency,  $f$ . Using the equation  $speed = \frac{distance}{time}$ , we can derive the equation  $wave\ speed = \frac{wavelength}{period}$ . Because the period of the wave is the reciprocal of the wave's frequency, we can write this equation as

$$v = f\lambda$$



### Techniques to determine frequency

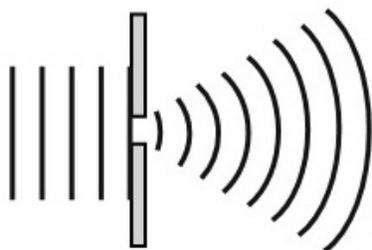
To determine the frequency of a wave, an **oscilloscope** is fed a signal, usually using a microphone. The **timebase** on the oscilloscope can be set on the x axis to represent time and on the y axis to represent the amplitude. The time taken to complete one full oscillation can be measured, and then used to find the frequency.

### Reflection, refraction, diffraction, and polarisation

All progressive waves can be reflected, refracted, and diffracted.

Reflection occurs when a wave **changes direction at a boundary** between two media, remaining in the **original** medium. An example of this is light reflecting off a mirror. The angle of the incident ray to the normal of the boundary between the two media is the same as the angle of the reflected ray to the normal. The wavelength and frequency of the wave remain the same.

Refraction occurs when a wave **changes direction as it changes speed**, when it enters a new medium. In the new medium, the frequency of the refracted waves remains constant, but the speed of the wave changes – sound waves speed up in denser materials whereas electromagnetic waves slow down. The **wavelength** of the wave **changes as a result**. There will always be some **partial reflection** at the boundary between the two media.



Diffraction is the **spreading out of a wave front** as it passes through a gap. The wavelength and frequency of the wave are not altered. Maximum diffraction will occur when the gap the wave passes through is the **same size** as the wavelength of the incident wave.

Polarisation is a property **unique to transverse waves**. It occurs when the oscillation of a wave is restricted to one place only – this type of wave is said to be **plane polarised**. Longitudinal waves cannot experience polarization, as the direction of energy transfer is already in one plane only, whereas in transverse waves, the oscillations occur in many planes, at right angles to the direction of travel.

### Techniques to demonstrate wave effects

A ripple tank can be used to demonstrate wave properties. A wave is made using an **oscillating paddle** connected to an electric motor. The depth of the tank can be adjusted to show refraction. A slit can be added to show diffraction.

To demonstrate polarization of visible light, **polarizing filters** can be used. Two polarizing filters are placed on top of each other. As one of the filters is rotated by  $90^\circ$ , the light intensity will decrease down to a minimum as the light polarized in one filter can't pass through the filter which is polarized in the perpendicular direction.





To demonstrate polarization of microwaves, a **metal grille** can be used. A microwave transmitter and receiver are placed on opposite sides of the grille, and microwaves are transmitted which are plane polarized with the electric field oscillating in the vertical plane. With the metal grille in the vertical orientation, the microwaves can pass through it and the maximum signal will be received. As the grille is **rotated around** to the horizontal orientation, the signal received will fall to a minimum, as the vertically plane polarized microwaves will be absorbed by the free electrons within the metal bars of the grille, greatly reducing transmission.

### Intensity of a progressive wave

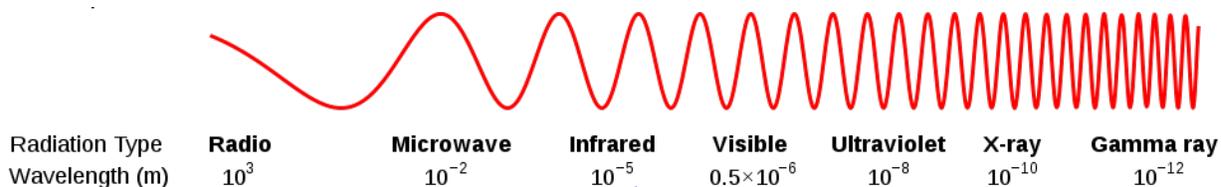
The intensity of a progressive wave is defined as the **radiant power** passing at **right angles** through a surface **per unit area**,  $= \frac{P}{A}$ . It has units of watts per metre squared,  $\text{Wm}^{-2}$ . As light from a point source spreads out in a sphere, the area in this formula can be taken as the **surface area of a sphere**,  $4\pi r^2$ . The intensity of the light is therefore inversely proportional to the square of the radius. The intensity of a wave can also be related to the amplitude of the wave, Intensity  $\propto$  Amplitude<sup>2</sup>.

## Electromagnetic waves

### The electromagnetic spectrum

Electromagnetic waves are **transverse progressive** waves, consisting of **magnetic and electric fields** which oscillate at right angles to each other. They can travel through a vacuum, and all travel at the speed of  $3.0 \times 10^8 \text{ ms}^{-1}$ . Visible light is just one small part of the spectrum of electromagnetic waves.

Typical wavelengths of electromagnetic waves:



### Refraction of light

A ray of light incident at an angle to a boundary between two transparent media will experience reflection and refraction. Refraction occurs because when the ray enters the new medium, its speed changes. The **refractive index**,  $n$ , can be used to determine the angle of refraction in to the medium.

$$n \text{ (refractive index)} = \frac{c \text{ (speed of light)}}{v \text{ (speed of light in medium)}}$$





For a ray of light leaving a medium with refractive index  $n_1$ , at an angle of  $\theta_1$ , in to a new medium with refractive index  $n_2$ , we can use the following formula to determine the angle of refraction in to the new medium,  $\theta_2$ .

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

where the incidence and refracted angles are measured **relative to the normal** to the two media.

### Total internal reflection

Total internal reflection occurs at a boundary between two transparent media, with **no refraction** – all of the light incident on the boundary is reflected back in to the original medium. Total internal reflection occurs only when two conditions are met. Firstly, the light must be travelling from a material with a higher refractive index, to a material of lower refractive index. Secondly, the angle of incidence of the ray to the normal must be **above the critical angle**. The formula

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

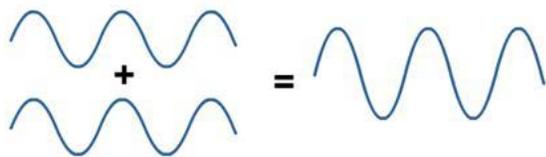
can be used, where C is the critical angle to the normal, and n is the refractive index of the material the ray is travelling in to. This formula is only true for refraction occurring where the original material is air.

## Superposition

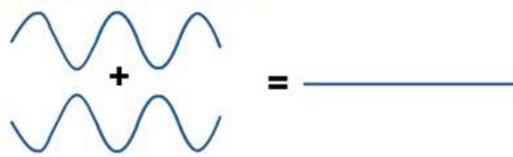
### The principle of superposition

When two or more progressive waves meet and overlap, they superpose, producing a **single wave**. The principle of superposition states *when two waves meet at a point, the resultant displacement of the wave at that point is equal to the **sum of the displacements** of the individual waves*. The resultant displacement depends on if there is constructive interference (where the individual displacements are both in the same direction, and add together) or destructive interference (where the individual displacements are in opposite directions, and counteract each other).

#### Constructive Interference



#### Destructive Interference



### Interference and coherence

Two waves are **coherent** when they are emitted with a **constant and unchanging phase difference** (e.g  $\pi$  radians). Interference is the superposition occurring between two coherent waves. When two coherent waves interfere, the maximum resultant displacement occurs when the phase difference is an even multiple of  $\pi$ , so the two crests of the wave combine. The



minimum resultant displacement occurs when the phase difference is an odd multiple of  $\pi$ , so one crest and one trough act to cancel each other out.

### Techniques to investigate superposition and wavelength

For **sound waves**, two **audio signal generators** can be used to investigate superposition. They will both emit coherent waves in all directions, which will overlap and form an **interference pattern**. When a microphone connected to an oscilloscope is moved parallel to the speakers, regions of loud and quiet noise will be detected.

The **Young double-slit experiment** can be used to investigate superposition in **light**, and also to determine the wavelength of the light source used. A laser which produces monochromatic light (light of a single wavelength) is placed behind a sheet with two small slits in it, a distance ' $a$ ' apart. The two coherent waves produced by the slits **overlap and superpose**, creating alternating bright (maxima) and dark (minima) fringes on a screen. The distance between two adjacent maxima is ' $x$ ', and the distance between the double slits and the screen is ' $d$ '. The equation

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

can then be used to determine the wavelength of the light used. This setup and formula can also be used when investigating superposition in microwaves.

The wavelength of a light source can also be investigated using a **diffraction grating**. A diffraction grating is a piece of transparent material with many opaque lines scratched in to it. The light is able to pass through the transparent slit between the scratches, and produces an interference pattern with bright and dark maxima and minima. The number of slits is usually given per cm, and this must be converted in to the value ' $d$ ', the distance, in metres, between each slit. The **order of maxima** (whether it is the original, first, second etc. bright maxima) is referred to as ' $n$ ', and  $\theta$  is the angle between the 0<sup>th</sup> and  $n$ th maxima. The formula

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

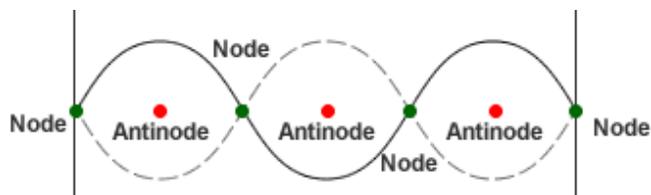
can then be used to determine the wavelength of the light source.

## Stationary waves

### Stationary waves

**Stationary waves** are formed when two progressive waves with the **same frequency** (and ideally the same amplitude), travelling in **opposite directions**, superpose. The stationary wave formed has a series of alternating nodes and antinodes. **Nodes** are points which always have **zero amplitude**, and **antinodes** are points which always have **maximum displacement**. Two adjacent nodes are half a wavelength apart. The frequency of the wave is the same at all points, except for the node where it is 0. The phase difference between two points on the wave is given by  $180^\circ n$ , where  $n$  is the number of nodes between the two points. Stationary waves do not transfer energy, they store it.





### Producing stationary waves

To produce a stationary wave in a **stretched string**, the string is held taut over a pulley. A **vibration generator** is used to oscillate the string in a coherent manner, with the frequency being adjusted until a stationary wave is produced. The initial wave produced is **reflected** at the pulley and, producing two waves with the same frequency, travelling in opposite directions, which superpose to make a stationary wave. The transmitter and pulley ends will be nodes, with a node-antinode pattern along the string.

To produce a stationary wave with **microwaves**, a **microwave transmitter** can be used to produce a wave, which is reflected off a metal plate. The incident and reflected waves superpose to make a stationary wave. A **microwave receiver** can be moved between the transmitter and the plate and will observe a minima, maxima pattern.

Stationary waves can be produced with **sound** in an **air filled tube**. A tuning fork is used to produce a loud sound, and is then held over the end of the tube. The length of the tube can be adjusted (e.g. by placing one end in water) until a stationary wave is produced. The stationary wave formed will vary depending on the air column – if the column is open at both ends, then there will be an antinode at each end, but if the column is open at one end only, then the open end will have an antinode, and the closed end will have a node.

The number of nodes produced in the stationary wave depends on the **frequency of the vibration**. The **fundamental frequency** of the stationary wave is the lowest frequency of vibration for a given arrangement. When the wave vibrates at this frequency, it is called **the first harmonic**. As the frequency increases, the vibration pattern will alter as new harmonics are produced. At frequencies other than multiples of the fundamental frequency, stationary waves will not be formed.

Harmonic	Shape	Frequency / Hz	Frequency as a multiple of $f_0$	Wavelength of the progressive wave (where $L$ is the length of the string)
1		20	$f_0$	$2L$
2		40	$2f_0$	$L$
3		60	$3f_0$	$\frac{2}{3}L$
4		80	$4f_0$	$\frac{1}{2}L$
5		100	$5f_0$	$\frac{2}{5}L$

