

AQA Physics A-level

Section 3: Waves

Notes

3.3.1 Progressive and stationary waves

3.3.1.1 - Progressive Waves

A **progressive wave transfers energy without transferring material** and is made up of particles of a medium (or field) **oscillating** e.g. water waves are made of water particles moving up and down

Amplitude	A wave's maximum displacement from the equilibrium position (units are m)
Frequency, f	The number of complete oscillations passing through a point per second, (units are Hz)
Wavelength, λ	The length of one whole oscillation (e.g. the distance between successive peaks/troughs) (units are m)
Speed, c	Distance travelled by the wave per unit time, (units are m/s)
Phase	The position of a certain point on a wave cycle, (units are radians, degrees or fractions of a cycle)
Phase difference	How much a particle/wave lags behind another particle/wave, (units are radians, degrees or fractions of a cycle)
Period, T	Time taken for one full oscillation, (units are s)

Two points on a wave are **in phase** if they are both at the same point of the wave cycle, they will have the **same displacement and velocity** and their **phase difference will be a multiple of 360°** (2π radians), they do not need the same amplitude, only the same frequency and wavelength.

Two points are **completely out of phase** when they're an **odd integer of half cycles apart** e.g. 5 half cycles apart where one half cycle is 180° (π radians).

The **speed** of a wave is equal to the wave's frequency multiplied by its wavelength:

$$c = f\lambda$$

The **frequency** of a wave is equal to 1 over its **period**:

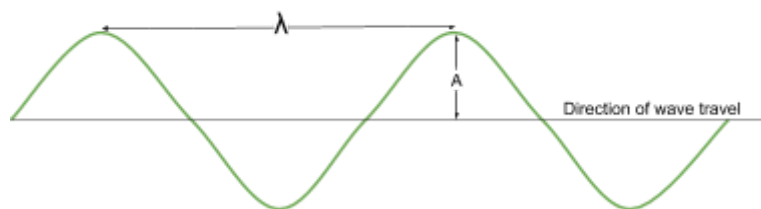
$$f = \frac{1}{T}$$

3.3.1.2 - Longitudinal and Transverse Waves

Transverse waves - oscillation of particles (or fields) is at **right angles to the direction of energy transfer**

- All electromagnetic (EM) waves are **transverse** and travel at $3 \times 10^8 \text{ ms}^{-1}$ in a vacuum.

- Transverse waves can be demonstrated by shaking a slinky **vertically** or through the waves seen on a string, when it's attached to a signal generator.



Longitudinal waves - oscillation of particles is **parallel to the direction of energy transfer**

- These are made up of **compressions and rarefactions** and can't travel in a vacuum.
- Sound is an example of a longitudinal wave, and they can be demonstrated by pushing a slinky **horizontally**.



A **polarised wave oscillates in only one plane** (e.g only up and down), **only transverse waves can be polarised**. Polarisation provides **evidence for the nature of transverse waves** because polarisation can only occur if a wave's oscillations are perpendicular to its direction of travel (as they are in transverse waves).

Polaroid sunglasses are an application of polarisation. They reduce glare by **blocking partially polarised light** reflected from water and tarmac, as they only allow oscillations in the plane of the filter, making it easier to see.

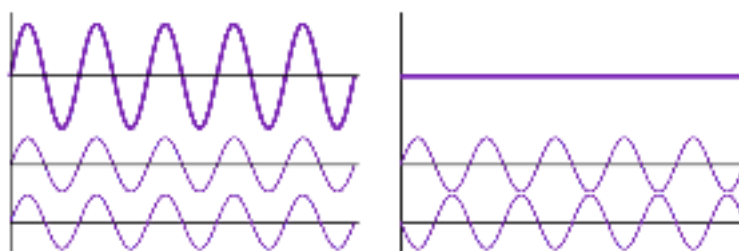
Another application of polarisation is **TV and radio signals**, which are usually plane-polarised by the orientation of the rods on the transmitting aerial, so the receiving aerial must be aligned in the same plane of polarisation to receive the signal at **full strength**.

3.3.1.3 - Principle of Superposition of waves and formation of stationary waves

Superposition is where the **displacements** of two waves are combined as they pass each other, the resultant displacement is the **vector sum** of each wave's displacement. There are two types of interference that can occur during superposition:

- **Constructive interference** occurs when 2 waves have displacement in the **same direction**
- **Destructive interference** occurs when one wave has positive displacement and the other has negative displacement, if the waves have equal but **opposite** displacements, **total destructive interference** occurs

Image source: [Haade, CC BY-SA 3.0](#), Image is recoloured



A **stationary wave** is formed from the **superposition of 2 progressive waves**, travelling in **opposite directions** in the same plane, with the **same frequency, wavelength and amplitude**.

No energy is transferred by a stationary wave.

- Where the waves meet **in phase**, **constructive interference** occurs so **antinodes** are formed, which are regions of maximum amplitude.
- Where the waves meet **completely out of phase**, **destructive interference** occurs and **nodes** are formed, which are regions of no displacement.

A string fixed at one end, and fixed to a driving oscillator at the other gives a good example of the formation of a stationary wave:

- A wave travelling down the string from the oscillator will be reflected at the fixed end of the string, and travel back along the string causing superposition of the two waves, and because the waves have the same wavelength, frequency and amplitude, a stationary wave is formed. (Labelled combined wave on diagram).

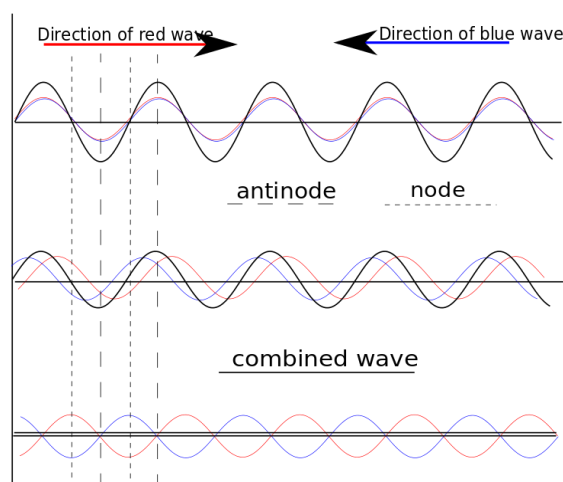


Image source: [Wjh31, CC0 1.0](#), Image is cropped

The lowest frequency at which a stationary wave forms is the **first harmonic**, which forms a stationary wave with two nodes and a single antinode. The **distance between adjacent nodes (or antinodes) is half a wavelength** (for any harmonic).

You can calculate this frequency by using this formula:

$$f = \frac{1}{2L} \sqrt{\frac{T}{\mu}}$$

Where **L** is the length of the vibrating string, **T** is the tension and **μ** is the mass per unit length.

You can double the first harmonic frequency to find the second harmonic where there are 2 antinodes, you triple the first harmonic frequency to get the third harmonic where there are 3 antinodes, and so on for the nth harmonic.

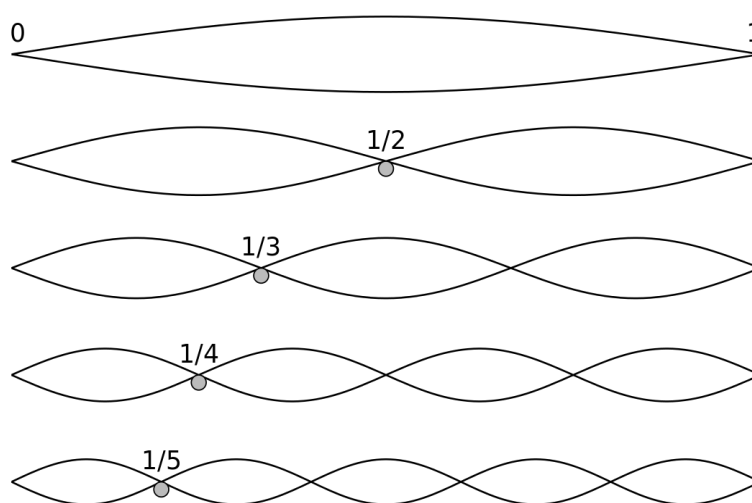


Image source: [Qef](#), [CC0 1.0](#), Image is cropped

There are several examples of stationary waves:

- **Stationary microwaves** can be formed by reflecting a microwave beam at a metal plate, to find the nodes and antinodes use a **microwave probe**.
- **Stationary sound waves** can be formed by placing a speaker at one end of a closed glass tube, lay powder across the bottom of the tube, it will be shaken at the antinodes and settle at the nodes. The distance between each node is half a wavelength, and the frequency of the signal generator to the speaker is known so by **c=fλ** the speed of sound in air can be found.

3.3.2 Refraction, diffraction and interference

3.3.2.1 - Interference

Path difference is the difference in the distance travelled by two waves.

A **coherent** light source has the **same frequency and wavelength** and a **fixed phase difference**.

Lasers are an example of light which is coherent and monochromatic, meaning they emit a single (or small range of) wavelength(s) of light. Lasers are usually used as sources of light in diffraction experiments as they form clear interference patterns.

Young's double slit experiment demonstrates interference of light from two-sources. In this experiment you can use two coherent sources of light or you could use one coherent source and a double slit in order to form an interference pattern. If you do not have a coherent source of light for example a light bulb, you could place a single slit before the double slit to make the light have a fixed path difference, and a filter to make the light monochromatic. Below is a brief procedure to describe Young's double slit experiment:

- Shine a coherent light source through 2 slits about the **same size as the wavelength** of the laser light so the light **diffracts**
- Each slit acts as a **coherent point source** making a pattern of light and dark fringes. Light fringes are formed where the light meets in phase and interferes constructively, this occurs where the path difference between waves is a **whole number** of wavelengths ($n\lambda$, where n is an integer). Dark fringes are formed where the light meets completely out of phase and interferes destructively, this occurs where the path difference is a whole number and a half wavelengths ($(n+\frac{1}{2})\lambda$).

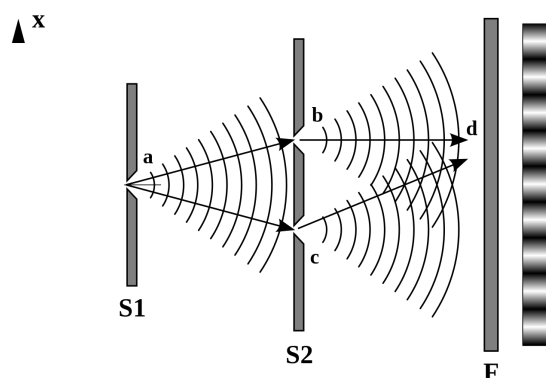


Image source: [Stannered](#), [CC BY-SA 3.0](#)

The formula associated with the above experiment is: $w = \frac{\lambda D}{s}$ Where w is the fringe spacing, λ is the wavelength of light used, D is the distance between the screen and slits, and s is slit separation.

Using **white light** instead of monochromatic laser light gives **wider maxima** and a **less intense diffraction pattern** with a **central white fringe** with alternating bright fringes which are spectra, violet is closest to the central maximum and red furthest.

Lasers can permanently damage your eyesight therefore, when using lasers there are several safety precautions, which must be followed:

- Wear **laser safety goggles**
- **Don't** shine the laser at **reflective surfaces**
- Display a **warning sign**
- Never shine the laser at a person

The type of interference described above can also be demonstrated in sound waves through a very similar process, however instead of using a double slit, you could use two speakers connected to the same signal generator. And the intensity of the wave can be measured using a microphone to find the maxima (equivalent to light fringes), and minima (equivalent to dark fringes).

Evidence for the **wave nature of light** was provided by Young's double slit experiment because **diffraction** and **interference** are wave properties, and so proved that **EM radiation must act as a wave** (at least some of the time). However, this was not what people always thought, there were theories which suggested light was formed of tiny particles, however this experiment disproved that theory. **Knowledge and understanding of any scientific concept changes over time in accordance to the experimental evidence gathered** by the scientific community.

3.3.2.2 - Diffraction

Diffraction is the **spreading out** of waves when they pass through or around a gap. The greatest diffraction occurs when the gap is the **same size** as the wavelength. When the gap is smaller than the wavelength most waves are **reflected**, whereas when it is larger there is less noticeable diffraction. When a wave meets an **obstacle** you get diffraction round the edges, the **wider** the obstacle compared to the wavelength, the **less diffraction**.

Monochromatic light can be diffracted through a single slit onto a screen, which forms an interference pattern of light and dark fringes. The pattern has a **bright central fringe**, which is double the width of all other fringes, with alternating dark and bright fringes on either side, the bright fringes are caused by **constructive interference** where the waves meet **in phase** and the dark fringes are caused by **destructive interference** where waves arrive **completely out of phase**. The intensity of the fringes decreases from the central fringe as shown below:

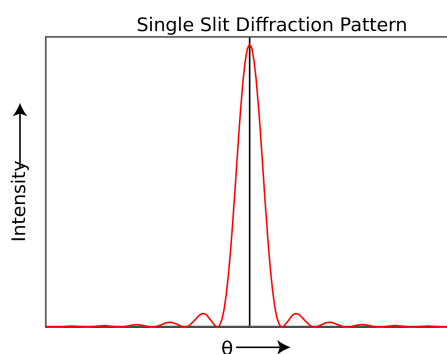


Image source: [Nmurdoch, CC0 1.0](#)

White light could be used instead of monochromatic light and the diffraction pattern you'd see would be quite different. As **white light** is made up of all colours, therefore all different wavelengths of visible light, the **different wavelengths of light are all diffracted by different amounts** so you get a **spectrum** of colour in the diffraction pattern. The diffraction pattern for white light has a **central white maximum** with alternating bright fringes which are **spectra**, **violet is closest to the central maximum and red furthest away**. Below are the diffraction patterns for white light (on the left), and red light (on the right):

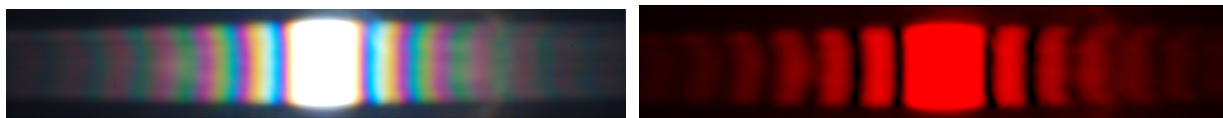


Image source: [Pieter Kuiper, CC0 1.0](#)

In order to vary the width of the central maximum, you can vary **slit width** and **wavelength**:

- **Increasing** the **slit width decreases the amount of diffraction** so the central maximum becomes **narrower** and its intensity **increases**.
- **Increasing** the light **wavelength increases the amount diffraction** as the slit is closer in size to the light's wavelength, therefore the central maximum becomes **wider** and its intensity **decreases**.

A **diffraction grating** is a slide containing many **equally spaced slits very close together**. When **monochromatic light** is passed through a diffraction grating the interference pattern is much **sharper and brighter** than it would be after being passed through a double slit like in Young's double slit, this is because there are many more rays of light reinforcing the pattern. This means measurements of slit widths are much more accurate as they are easier to take.

Below you can see how the intensity of an interference pattern varies as the number of slits increases: the red graph shows the pattern with a grating with 50 slits, while the green shows the pattern with a grating with 20 slits.

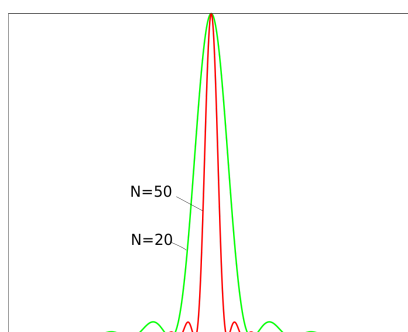
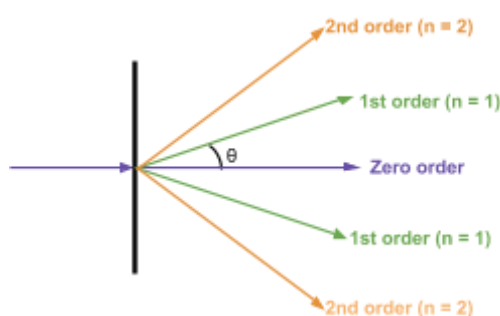


Image source: [Epzcow, CC BY-SA 3.0](#)



The ray of light passing through the centre of a diffraction grating is called the **zero order line**, lines either side of the zero order are the **first order lines**, then the lines outside the two first order lines are the **second order lines**, and so on as showcased in the diagram on the left.

The formula associated with diffraction gratings is $d \sin \theta = n\lambda$

Where d is the distance between the slits, θ is the angle to the normal made by the maximum, n is the order and λ is the wavelength. As λ increases (by for example changing the laser light from blue to red), the distance between the orders will increase because θ is larger due to the increase in diffraction as the slit spacing is closer in size to the wavelength, this means the pattern will spread out.

The maximum value of $\sin \theta$ is 1, therefore any values of n , which give $\sin \theta$ as greater than 1 are impossible.

You must be able to derive the above formula, the derivation is shown below:

1. Considering the **first order maximum**, where the **path difference between two adjacent rays of light is one wavelength** (as shown in the diagram below), name the angle between the normal to the grating and the ray of light θ .
2. As you can see a right angle triangle is formed, with side lengths d and λ . And by using the fact that a right angle is 90° , and angles in a triangle add up to 180° , you can see the upper angle in the triangle is θ (because the lower angle is $90^\circ - \theta$).
3. By using trigonometry we can see that for the first maximum $\sin \theta = \frac{\lambda}{d}$, (as $\sin \theta = \frac{\text{Opp}}{\text{Hyp}}$) which rearranges to $d \sin \theta = \lambda$, (for the first order).
4. We know that the other maxima occur when the path difference between the two rays of light is $n\lambda$, where n is an integer, therefore we can generalise the equation by replacing λ with $n\lambda$ to get: $d \sin \theta = n\lambda$.

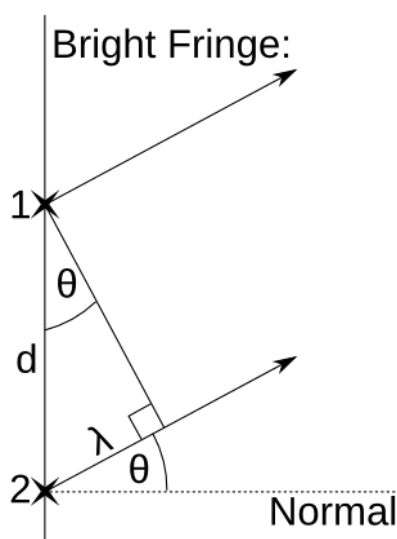


Image source: [Sjlegg](https://www.sjlegg.com), CC0 1.0, Image is cropped

There are several applications of diffraction gratings:

- You split up light from **stars** using a diffraction grating to get **line absorption spectra** which can be used to show which elements are present in the star.
- **X-ray crystallography**, which is where x-rays are directed at a thin crystal sheet which acts as a diffraction grating to form a diffraction pattern, this is because the wavelength of x-rays is similar in size to the gaps between the atoms. This diffraction pattern can be used to measure the atomic spacing in certain materials.

3.3.2.3 - Refraction at a plane surface

A **refractive index (n)** is a property of a material which measures how much it slows down light passing through it. This is calculated by dividing the speed of light in a vacuum (c) by the speed of light in that substance (c_s).

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

A material with a **higher refractive index** can also be known as being **more optically dense**. As light **doesn't** slow down significantly when travelling through air (in comparison to travelling through a vacuum), the refractive index of **air** is **approximately 1**.

Refraction occurs when a wave enters a different medium, causing it to change direction, either towards or away from the normal depending on the material's refractive index.

Snell's law is used for calculations involving the refraction of light:

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

- n_1 is the refractive index of material 1,
- n_2 is the refractive index of material 2,
- θ_1 is the angle of incidence of the ray in material 1
- θ_2 is the angle of refraction of the ray in material 2

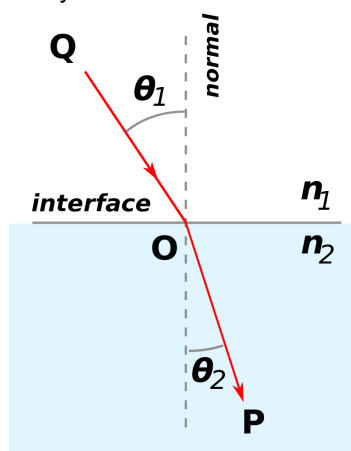


Image source: [Oleg Alexandrov, CC BY-SA 3.0](#)

As the light moves across the boundary of the 2 materials its **speed changes**, which causes its **direction** to change.

In the example above, n_2 is more optically dense than n_1 , therefore the ray of light slows down and **bends towards the normal**. However, in the case where n_2 is less optically dense than n_1 , the ray of light will **bend away from the normal**.

As the angle of incidence is increased, the angle of refraction also increases until it gets closer to 90° . When the angle of refraction is **exactly 90°** and the light is **refracted along the boundary**, the angle of incidence has reached the **critical angle (θ_c)**. This angle can be found using the following formula:

$$\sin \theta_c = \frac{n_2}{n_1} \quad \text{where } n_1 > n_2$$

Total internal reflection (TIR) can occur when the **angle of incidence is greater than the critical angle and the incident refractive index (n_1) is greater than the refractive index of the material at the boundary (n_2)**.

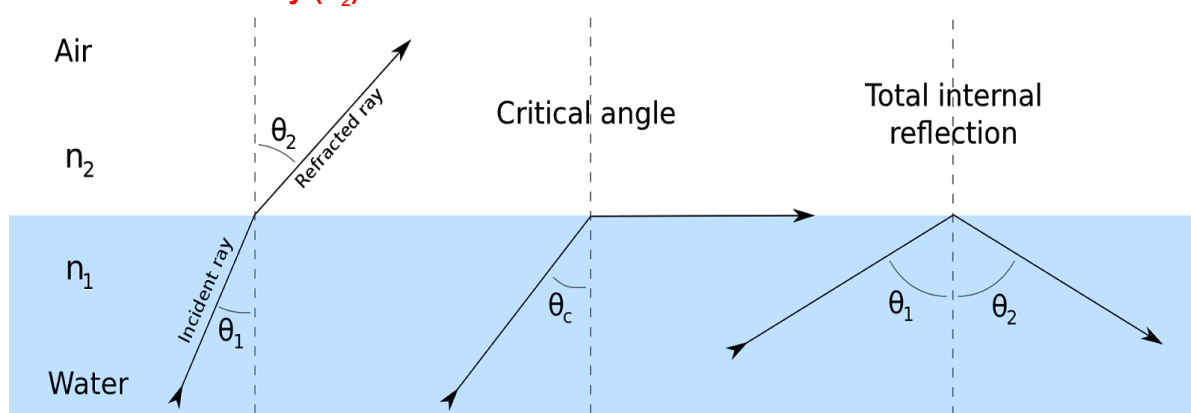


Image source: [Josell7, CC BY-SA 3.0](#)

A useful application of total internal reflection are **optical fibres**; these are flexible, thin tubes of plastic or glass which carry information in the form of light signals. They have an **optically dense core** surrounded by **cladding** with a lower optical density allowing TIR to occur, this **cladding** also **protects the core from damage** and prevents **signal degradation** through **light escaping the core**, which can cause information to be lost.

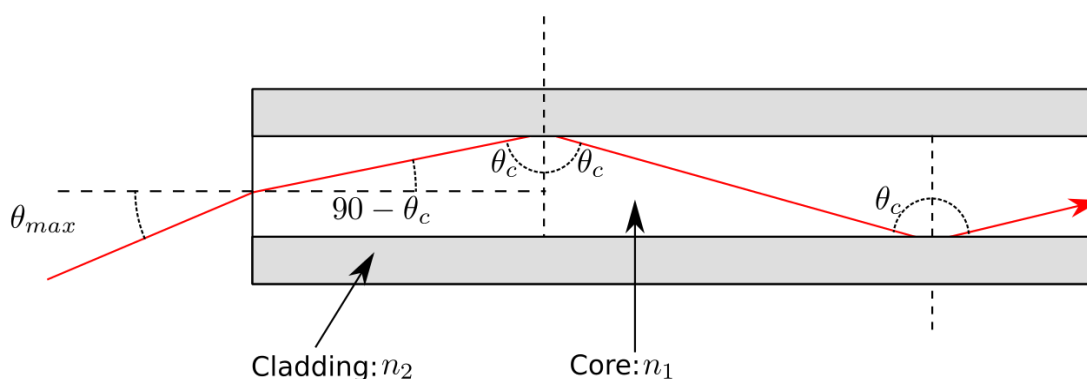
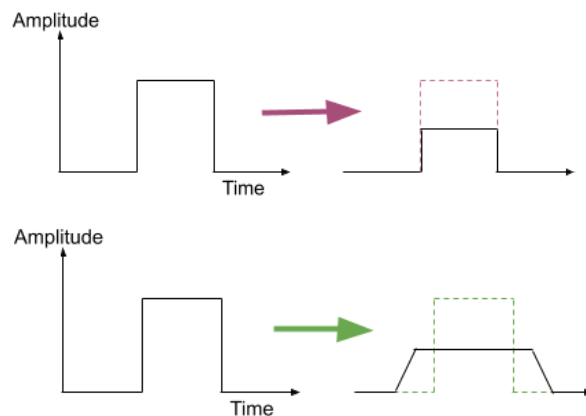


Image source: [User A1, CC BY-SA 3.0](#)



Signal degradation can also be caused by the following:

- **Absorption** - where part of the signal's energy is absorbed by the fibre, reducing the **amplitude** of the signal, which could lead to a loss of information
- **Dispersion** - this causes **pulse broadening**, which is where the received signal is broader than the original transmitted signal. Broadened signals can overlap causing loss of information. There are two types of dispersion:
 - **Modal** - caused by light rays entering the fibre at different angles, therefore they take different paths along the fibre, (for example some may travel down the middle of the fibre, while others are reflected repeatedly,) this leads to the rays taking a different amount of time to travel along the fibre, causing **pulse broadening**.
 - This can be reduced by **making the core very narrow**, therefore making the possible difference in path lengths smaller.
 - **Material** - caused by using light consisting of different wavelengths, meaning light rays will travel at different speeds along the fibre, which leads to **pulse broadening**
 - This can be prevented by using **monochromatic light**.

Both absorption and dispersion can also be reduced by using an **optical fibre repeater**, which regenerates the signal during its travel to its destination.