



# SL IB Physics



Your notes

## Wave Phenomena

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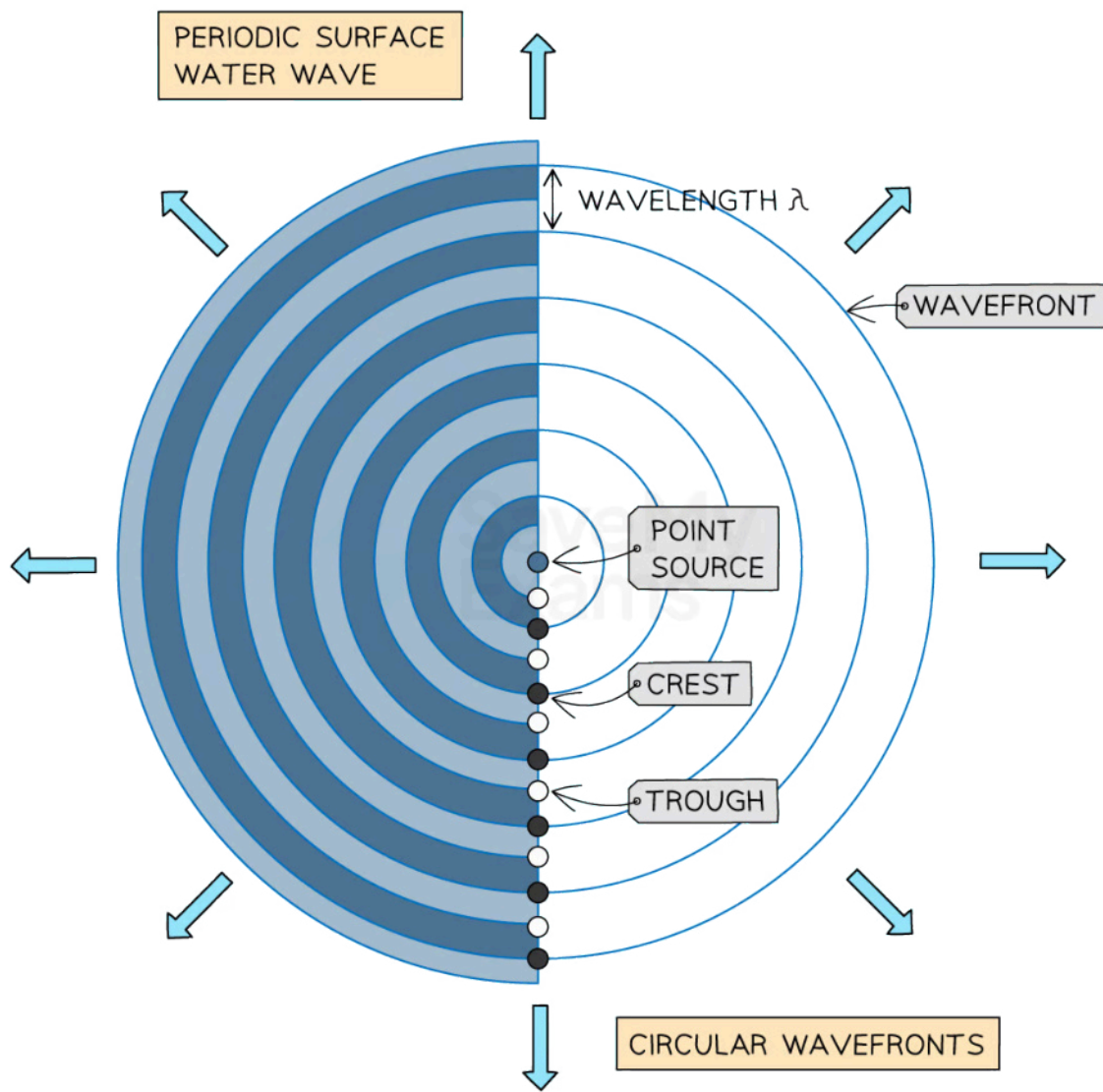


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## Wavefronts & Rays


### Wavefronts & Rays

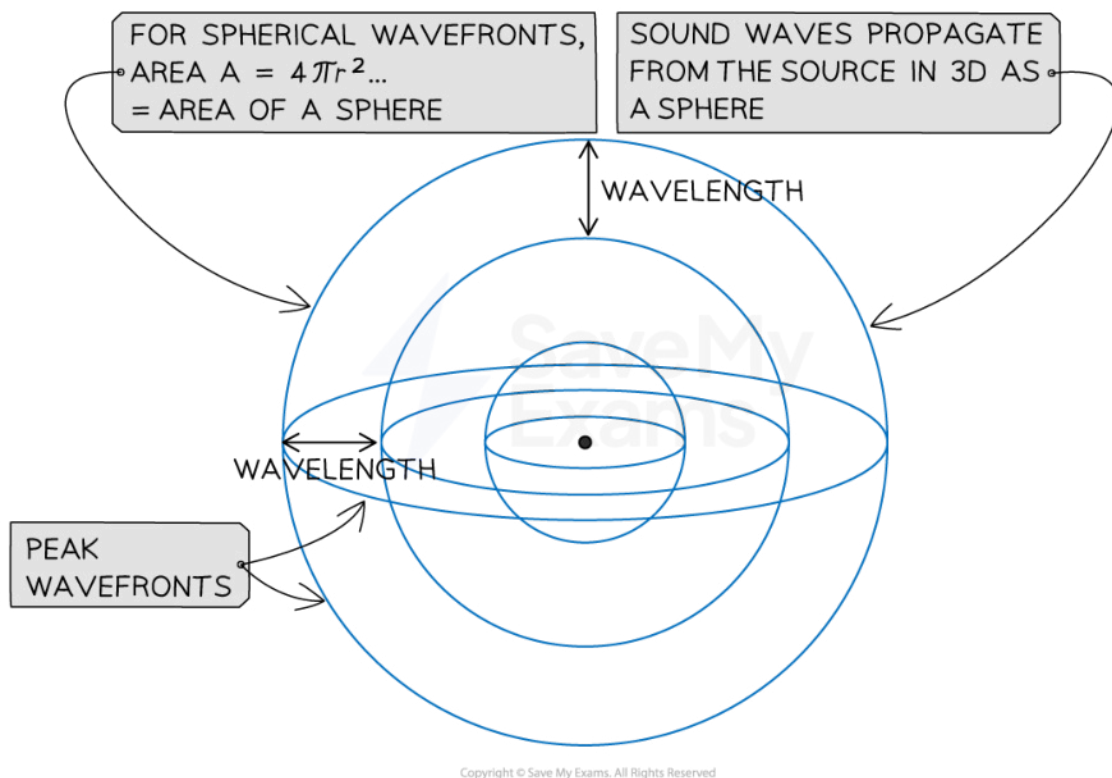
- Waves can travel in both two and three-dimensions:
  - A **surface wave** propagates in **two dimensions** and has **circular wavefronts** (like a circle) such as the surface of water
  - A **spherical wave** propagates in **three dimensions** and has **spherical wavefronts** (like a sphere) such as sound or light



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**A surface wave has circular wavefronts and moves in two-dimensions propagating outwards from the point source**

  
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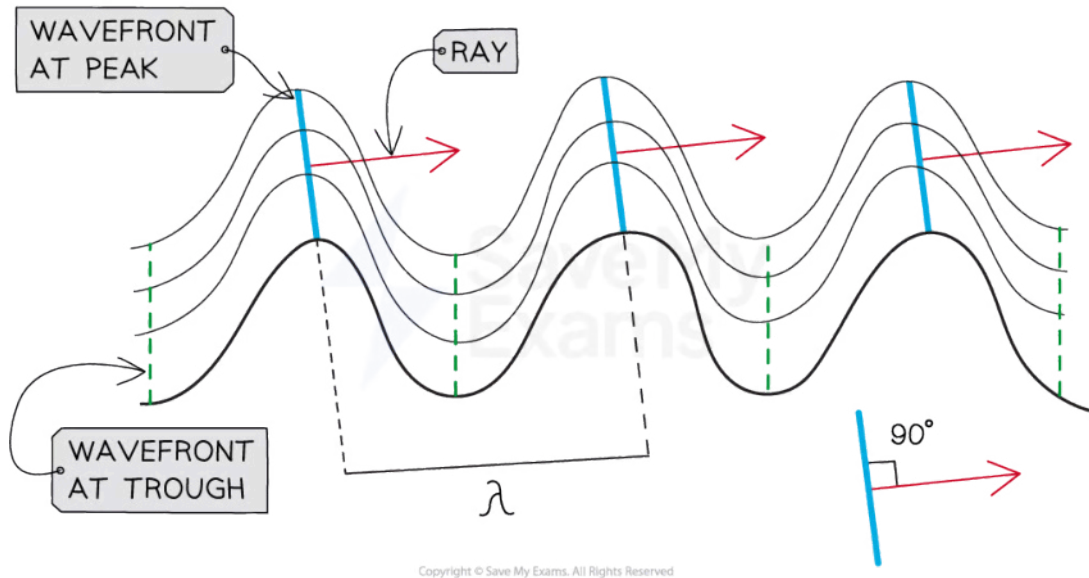


**A three dimensional wave moves with spherical wavefronts in three dimensions like a sphere**

- Waves can be represented graphically in two different ways:
  - **Wavefronts** - lines joining all the points that oscillate in phase and are perpendicular to the direction of motion (and energy transfer)
  - **Rays** - lines showing the direction of motion (and energy transfer) of the wave perpendicular to the wavefront

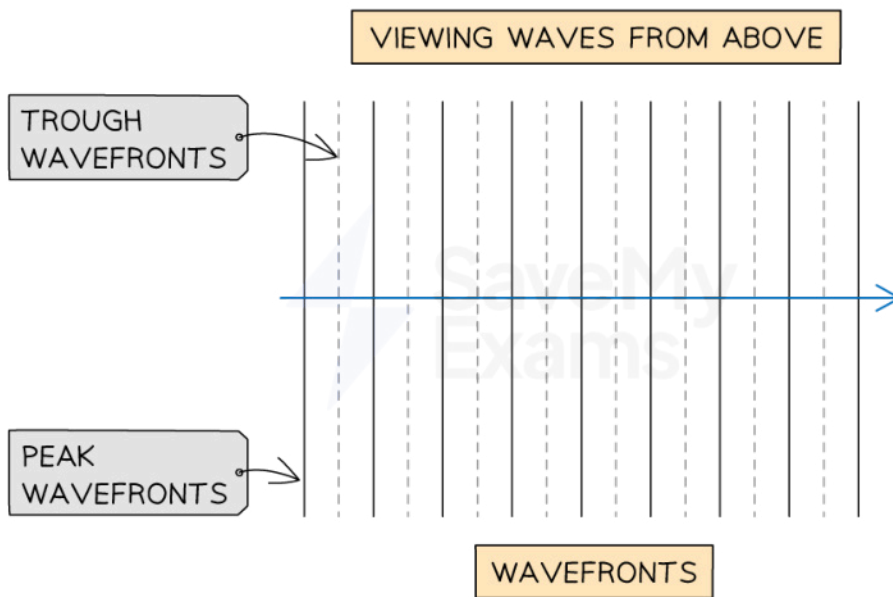


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**Wavefronts and rays for transverse waves travelling in a horizontal plane**

- Wavefronts are viewed from above and look like a series of **parallel vertical lines**
  - Peaks are often represented with a darker line
  - Troughs are represented with a fainter line
  - Some diagrams use only peak wavefronts





**Waves can be represented using wavefronts, sometimes diagrams show peak wavefronts and trough wavefronts**

- The distance between successive peak wavefronts or (trough wavefronts) is equal to the wavelength of the waves

### Examiner Tip

Understanding the difference between circular and spherical wavefronts is tricky. Remember that a circle is a 2D shape, so circular wavefronts are 2D and a sphere is a 3D shape, so spherical wavefronts are 3D.

Exam questions may ask you to sketch or interpret wavefronts and rays. Make sure you draw these with a **ruler** to ensure your lines are straight. Unclear or sloping diagrams are unlikely to get full marks!



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## Reflection, Refraction & Transmission

### Reflection, Refraction & Transmission

- When waves arrive at a boundary between two materials, they can be:
  - Reflected
  - Refracted
  - Transmitted
  - Absorbed
- In optics, a transparent material is called a **medium**
  - When referring to more than one medium these are called **media**

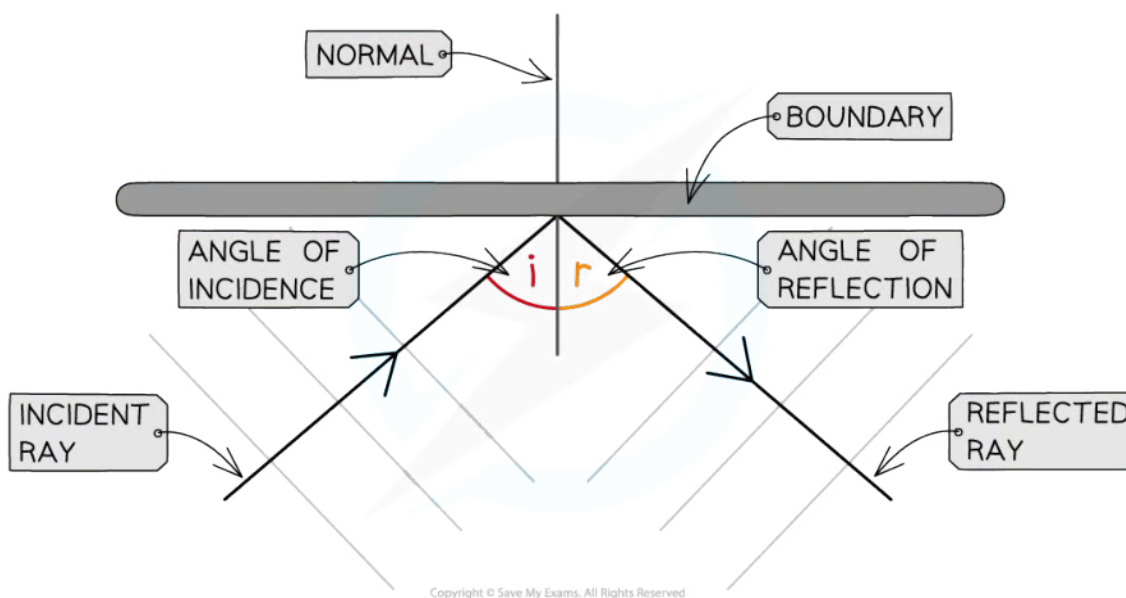
### Reflection

- Reflection occurs when:

A wave hits a boundary between two media and does not pass through, but instead bounces back to the original medium

- The **law of reflection** states:

The angle of incidence,  $i$  = The angle of reflection,  $r$



**Reflection of a wave at a boundary**

- When a wave is reflected, some of it may also be **absorbed** or **transmitted** through the medium
- At a boundary between two media, the **incident** ray is the ray that travels **towards** the boundary
- During reflection, the frequency, wavelength and speed of the wave does **not** change



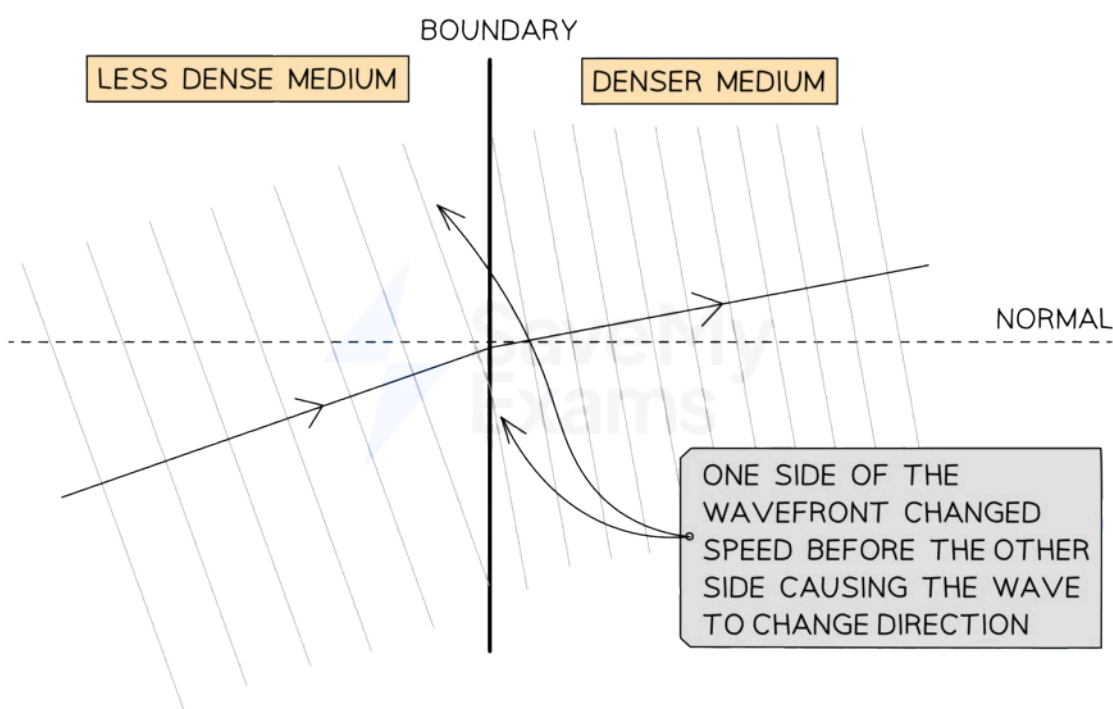
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## Refraction

- Refraction is:

**The change in direction of a wave when it passes through a boundary between mediums of different density**

- This change of direction is caused by a **change in the speed** of different parts of the wavefront as they hit the boundary
  - In optics, the word **medium** is used to describe a transparent material



***A wavefront changes direction when part of it hits a boundary and changes speed before the other parts***

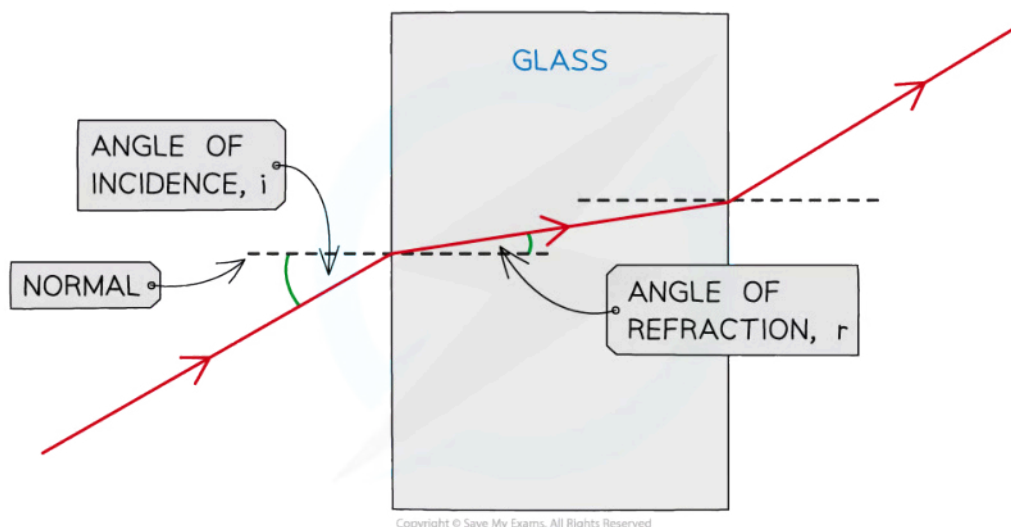
## Conditions for refraction

- When a wave travels from a **less dense** medium into a **denser medium**:
  - The more optically **dense** the medium
  - The **slower** the waves travel
  - The **smaller** the angle of **refraction**
  - The light bends **towards** the normal
- When a wave travels from a **denser medium** into a **less dense medium**:
  - The less optically **dense** the medium
  - The **faster** the waves travel



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- The **greater** the angle of refraction
- The light bends **away** from the normal
- The amount of refraction that takes place is determined by the **difference** between the angles of **incidence** ( $i$ ) and **refraction** ( $r$ ) of the waves at the boundary
- The angles of incidence and refraction are measured from the **normal line**
  - This is drawn at  $90^\circ$  to the boundary between the two media

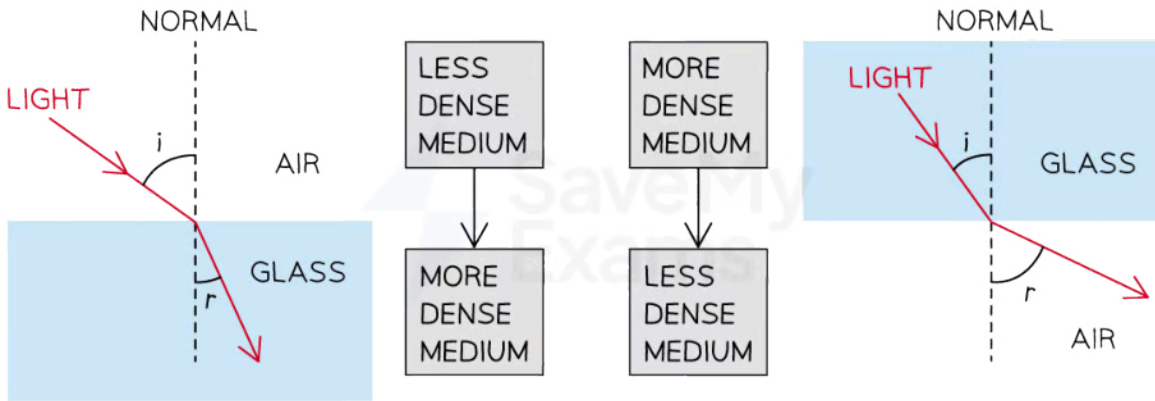


**The angle of incidence is the angle between the approaching incident ray and the normal. The angle of refraction is the angle between the ray leaving the boundary and the normal.**

- The amount of change in direction that takes place depends on the difference in optical **density** between the two media
- When light passes from a less dense medium to a more dense medium, (e.g. air  $\rightarrow$  glass):
  - The refracted light has a **lower speed** and a **shorter wavelength** than the incident light
- When light passes from a more dense medium to a less dense medium (e.g. glass  $\rightarrow$  air):
  - The refracted light has a **higher speed** and a **longer wavelength** than the incident light
- When a wave refracts, its speed and wavelength change, but its **frequency** remains the same
  - This is noticeable by the fact that the **colour** of the wave does **not change**



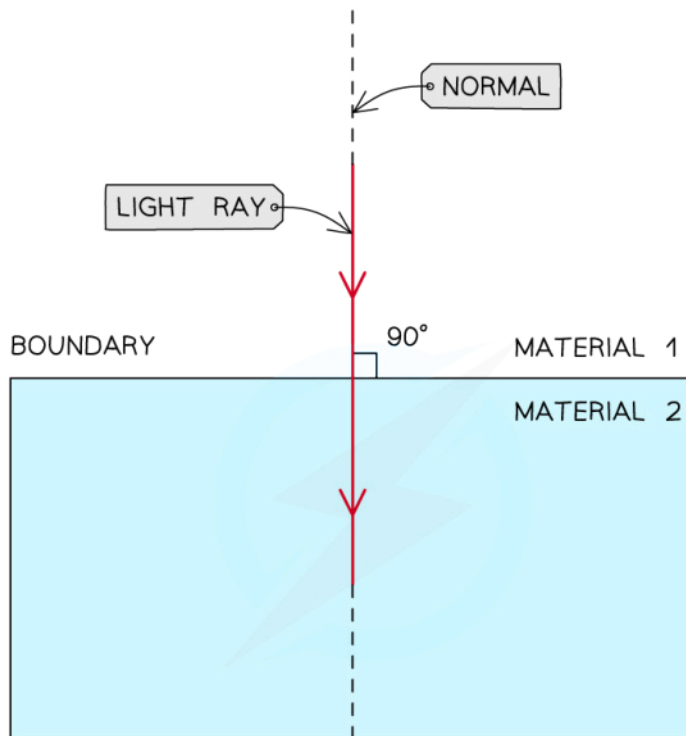
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**When light passes from a less to a more dense material the ray refracts towards the normal**

- When the light ray is incident on the boundary at  $90^\circ$ :
  - The wave passes **straight through** without a change in direction
  - This is because the whole wavefront enters the boundary at the same time at the same speed



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**Light travelling along the normal to the boundary between material 1 and material 2**

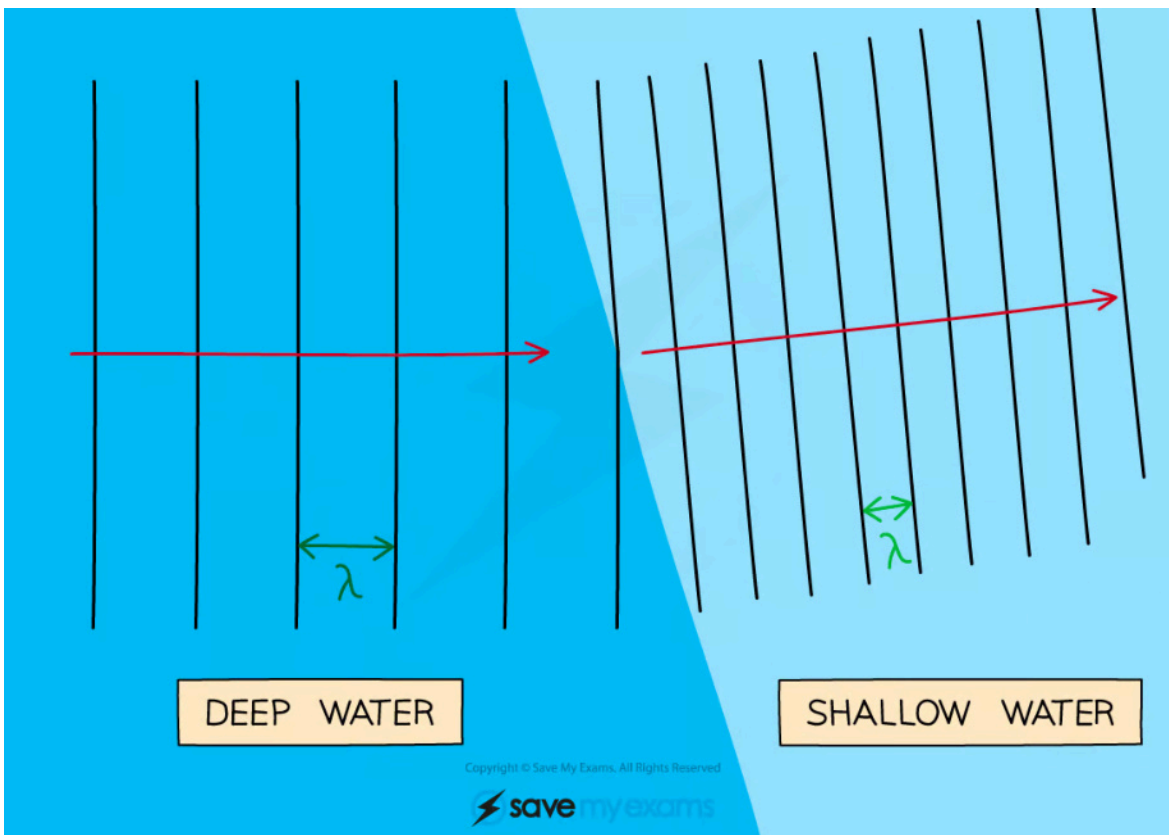
### Refraction of Water Waves

- Refraction can also occur between materials of **different depths**



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- You may be asked to explain the behaviour of water waves when they refract between deep and shallow areas
- When waves pass from **deep to shallow** water there is **more friction** between the sea bed and the wave and **less space** for the wave to oscillate so the waves:
  - **Slow down**
  - The **wavelength** of the wave **decreases**
  - So the distance between **wave peaks** is **reduced**
  - Angle of refraction is less than angle of incidence,  $r < i$
- If the waves hit the boundary between the change in depth at an angle then they refract towards the normal
  - So the angle of refraction  $<$  angle of incidence

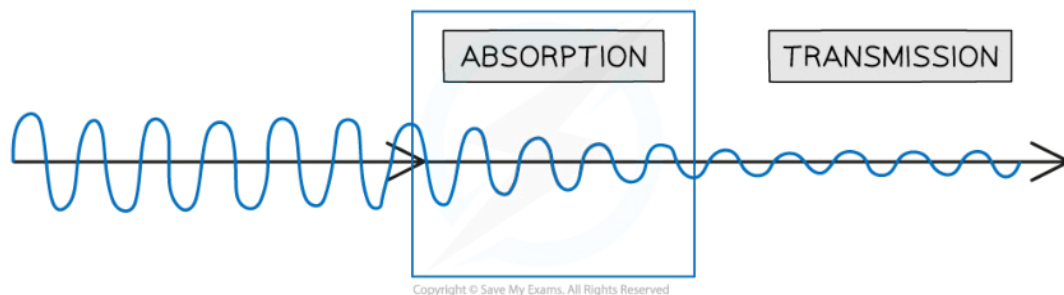


*When water waves travel from deep areas to shallow areas they slow down*

## Transmission

- Transmission occurs when:
  - **A wave passes through a substance**
- **Refraction** is a type of transmission
  - Transmission is the more general term for a wave appearing on the opposite side of a boundary (the opposite of reflection)

- Refraction is specifically the **change in direction** of a wave when it crosses a boundary between two materials that have a different density
- When passing through a material, waves can be partially **absorbed**
- The transmitted wave will have a lower amplitude if some absorption has occurred



***When a wave passes through a boundary it may be absorbed and transmitted***

- During transmission, the frequency or speed of the wave does **not** change
- Reflection, refraction and transmission occur for **all** types of waves, both transverse and longitudinal



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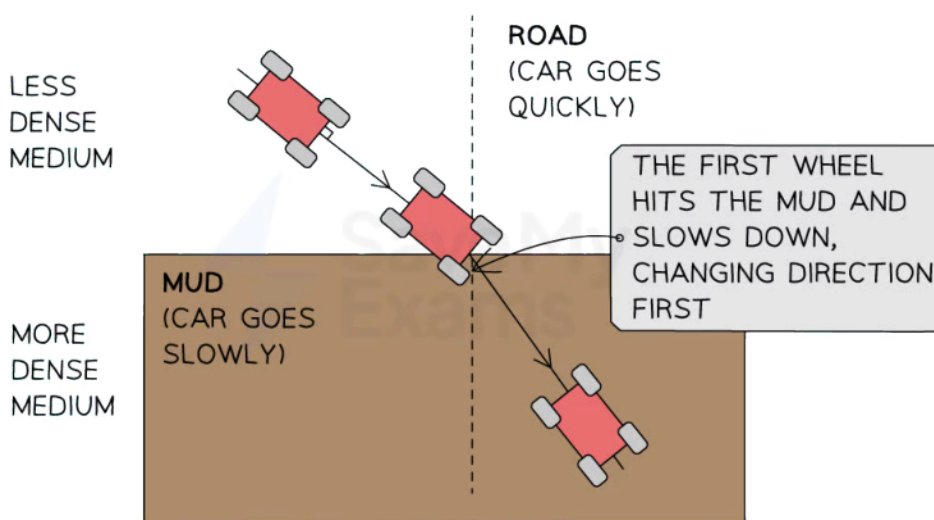


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 **Examiner Tip**

You must be able to differentiate between the different types of wave behaviour. Refraction and reflection is commonly mixed up. With refraction, there is always **transmission** and a change in direction in another medium. With reflection however, there is no transmission into another medium.

It can be tricky to understand the concept of refraction. Imagine a car driving at an angle from a road and onto a patch of mud. The wheel that hits the mud will slow down first whilst the second wheel continues to travel at the initial speed. This causes the car to turn.



In many situations in refraction, there are two boundaries to consider, the refracted ray from boundary 1 is the incident ray at boundary 2. Don't get confused with your notation in this situation. Label your diagram clearly to help.





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## Diffraction of Waves

### Diffraction of Waves

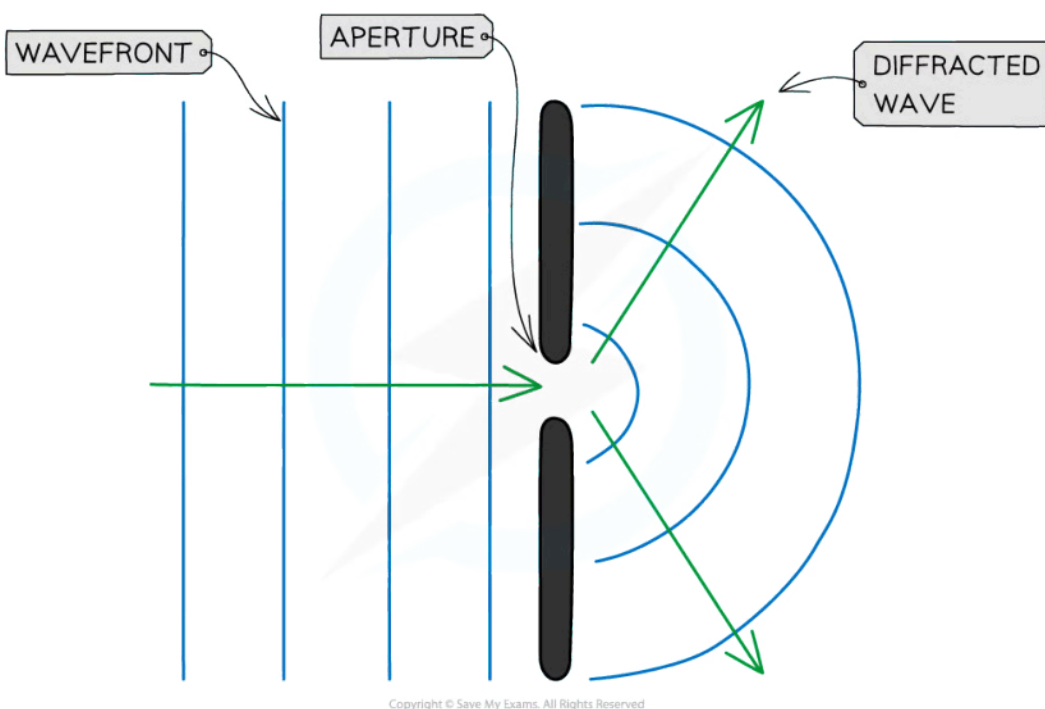
- Diffraction is defined as:  
**The spreading out of waves after they pass through a narrow gap or around an obstruction**
- Diffraction can occur when waves:
  - pass through an **aperture**
  - pass around a **barrier**



*Water waves diffract through a gap in a barrier such as in a harbour*

### Diffraction through an aperture

- When a wave passes through a gap or aperture:
  - The waves spread out so they have curvature
  - The amplitude of the wave is less because the barrier on either side of the gap absorbs wave energy



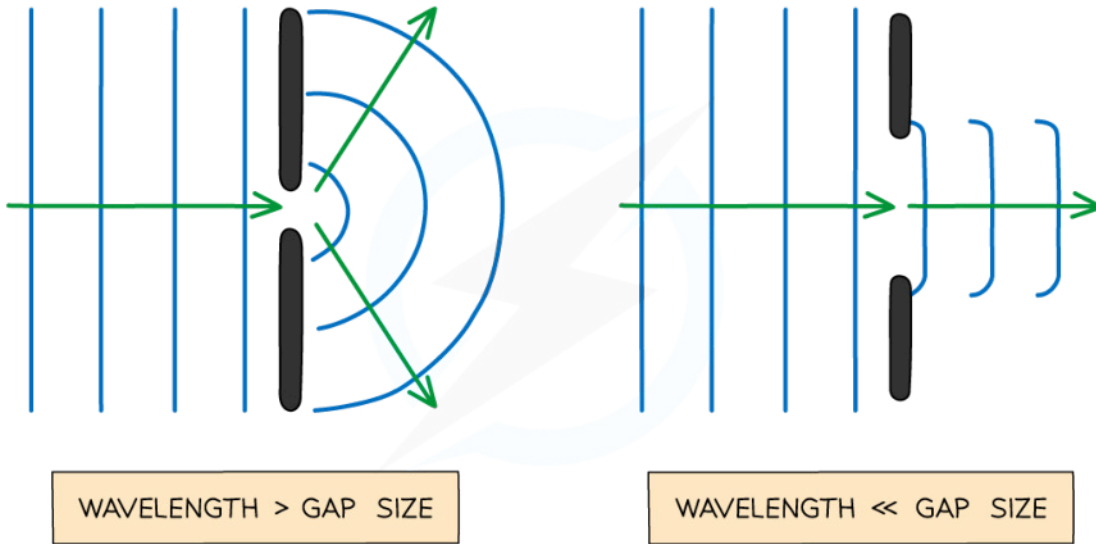
**Diffraction causes waves to spread out and become curved after passing through a narrow gap**

- When the **wavelength** of the wave and the **width of the gap** is similar then diffraction occurs:
  - When the wavelength is **bigger** than the gap then **more diffraction** occurs, so the wave spreads out more after passing through
  - When the wavelength is **smaller** than the gap then **less diffraction** occurs, so the wave spreads out less after passing through
- When the **wavelength** of the wave and the **width of the gap** are not similar then diffraction does not occur:
  - For gaps that are **much smaller** than the wavelength of the wave, the wave passes over the gap easily so **no diffraction** occurs
  - For gaps that are **much bigger** than the wavelength of the wave, the majority of the wave passes straight through the gap so **no diffraction** occurs
- As the **gap size increases**, compared to the **wavelength**, the amount of **curvature** on the waves gets **less pronounced**

**Effect of aperture size on diffraction**



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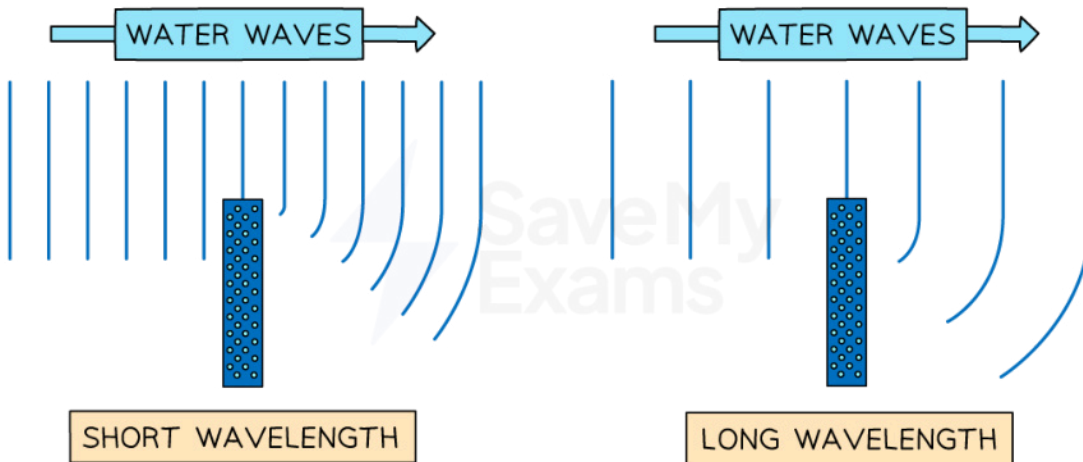


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*The size of the gap (compared to the wavelength) affects how much the waves spread out when diffracted through a gap*

### Diffraction around a barrier

- Diffraction can also occur when waves curve around an **edge** or **barrier**
  - The waves spread out to fill the gap behind the object
- The extent of this diffraction also depends upon the wavelength of the waves
  - The **greater** the **wavelength** then the greater the **diffraction**



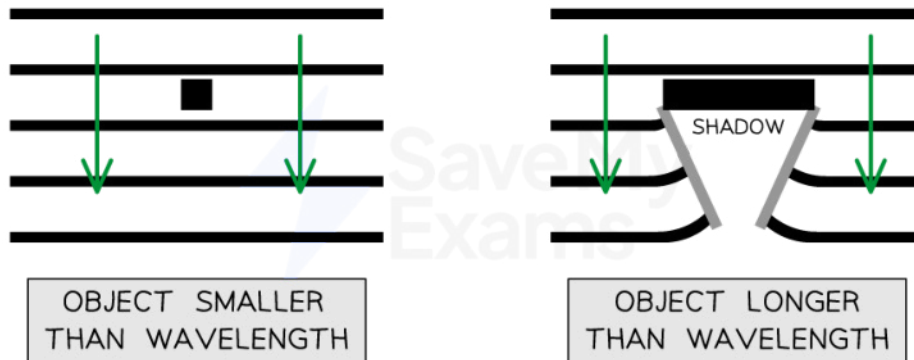
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**When a wave goes past the edge of a barrier, the waves can curve around it. Shorter wavelengths undergo less diffraction than longer wavelengths**

- When the barrier is **larger** than the wavelength:
  - There is **some diffraction** around the barrier
  - A lot of incident waves are reflected back towards the source
  - There is a **"shadow" region** behind the barrier where no wavefronts are present
- When the barrier is the **same size** as the wavelength:
  - There is **more diffraction** around the barrier
  - There is a **smaller "shadow" region** behind the barrier where no wavefronts are present
- When the barrier is **smaller** than the wavelength:
  - **No diffraction** occurs around the barrier
  - The "shadow" region behind the barrier is **very small**



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**The size of the barrier in relation to the wavelength affects how the waves diffract around it**



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### Worked example

When a wave is travelling through the air, which scenario best demonstrates diffraction?

- A. UV radiation through a gate post
- B. Sound waves passing a diffraction grating
- C. Radio waves passing between human hair
- D. X-rays passing through atoms in a crystalline solid

**Answer: D**

- Diffraction is most prominent when the wavelength is close to the aperture size

Consider option **A**:

- UV waves have a wavelength between  $(4 \times 10^{-7})$  and  $(1 \times 10^{-8})$  m so would **not** be diffracted by a gate post
- Radio waves, microwaves or sound waves would be more likely to be diffracted at this scale

Consider option **B**:

- Sound waves have a wavelength of  $(1.72 \times 10^{-2})$  to 17 m so would **not** be diffracted by the diffraction grating
- Infrared, light and ultraviolet waves would be more likely to be diffracted at this scale

Consider option **C**:

- Radio waves have a wavelength of 0.1 to  $10^6$  m so would **not** be diffracted by human hair
  - Infrared, light and ultraviolet waves would be more likely to be diffracted at this scale

Consider option **D**:

- X-rays have a wavelength of  $(1 \times 10^{-8})$  to  $(4 \times 10^{-13})$  m
  - This is a suitable estimate for the size of the gap between atoms in a crystalline solid
  - Hence X-rays could be diffracted by a crystalline solid
- Therefore, the correct answer is **D**



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### Worked example

An electric guitar student is practising in his room. He has not completely shut the door of his room, and there is a gap of about 10 cm between the door and the door frame.

Determine the frequencies of sound that are best diffracted through the gap.

The speed of sound can be taken to be  $340 \text{ m s}^{-1}$

**Answer:**

**Step 1: Optimal diffraction happens when the wavelength of the waves is comparable to (or larger than) the size of the gap**

$$\lambda = 10 \text{ cm} = 0.1 \text{ m}$$

**Step 2: Write down the wave equation**

$$v = f\lambda$$

- Where speed of sound,  $v = 340 \text{ m s}^{-1}$

**Step 3: Rearrange the above equation for the frequency  $f$**

$$f = \frac{v}{\lambda}$$

**Step 4: Substitute the numbers into the above equation**

$$f = \frac{340}{0.1} = 3400 \text{ Hz}$$

- The frequencies of sound that are best diffracted through the gap are:

$$f \leq 3400 \text{ Hz}$$

### Examiner Tip

When drawing diffracted waves, take care to keep the wavelength (the distance between each wavefront) constant.



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## Refraction of Waves

### Snell's Law

- **Snell's law** relates the **angle of incidence** to the **angle of refraction** at a **boundary** between two media

### Refractive Index

- The refractive index,  $n$  of a material tells us how optically dense it is
- The refractive index of **air is  $n = 1$** 
  - Media that are **more optically dense** than air will have a refractive index of  **$n > 1$**
  - Media that are **less optically dense** than air will have a refractive index of  **$n < 1$**
- The higher the refractive index of a material then the more optically dense and hence the slower light will travel through it
- The refractive index of a material is calculated using the equation:

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

- Where:
  - $n$  = absolute refractive index of the medium
  - $c$  = speed of light in a vacuum in metres per second ( $\text{m s}^{-1}$ ),  $3.00 \times 10^8 \text{ m s}^{-1}$ , as given in the data booklet
  - $v$  = speed of light in the medium in metres per second ( $\text{m s}^{-1}$ )
- Note that, being a ratio, the absolute refractive index is a **dimensionless** quantity
  - This means that it has no units

### Snell's Law

- **Snell's law** is given by:

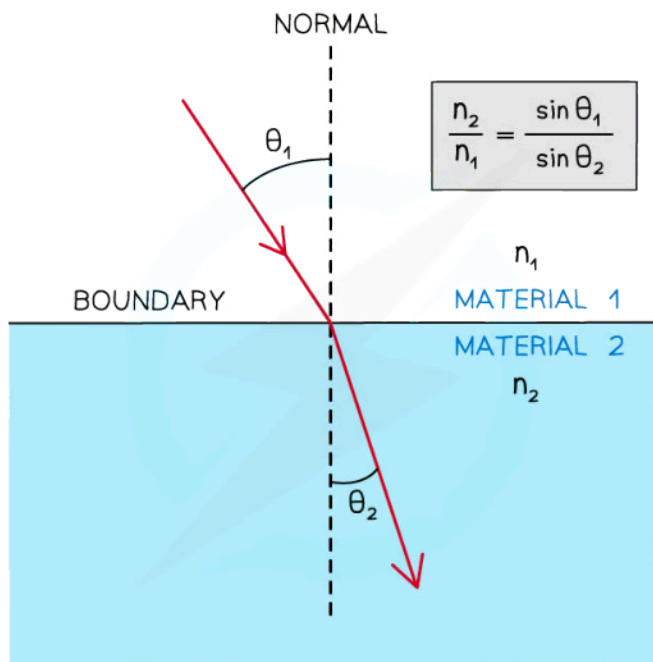
$$\frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1} = \frac{v_2}{v_1}$$

- Where:
  - $n_1$  = the refractive index of material 1
  - $n_2$  = the refractive index of material 2
  - $\theta_1$  = the angle of incidence of the ray in material 1
  - $\theta_2$  = the angle of refraction of the ray in material 2
  - $v_1$  = the speed of the wave in material 1
  - $v_2$  = the speed of the wave in material 2
- Snell's Law describes the angle at which light meets the boundary and the angle at which light leaves the boundary, so that the light travels through the media in the least amount of time
- Light can travel through medium 1 at a speed of  $v_1$  due to the optical density  $n_1$  of that medium
  - Light will approach the boundary at angle  $\theta_1$

- This is the angle of **incidence**
- Light can travel through medium 2 at a speed of  $v_2$  due to the optical density  $n_2$  of that medium
  - Light will leave the boundary at angle  $\theta_2$
  - This is the angle of **refraction**



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### Snell's Law

- Snell's Law can also be given in a more convenient form:

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

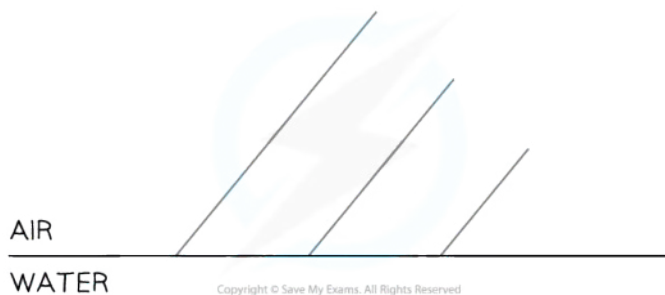




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 **Worked example**

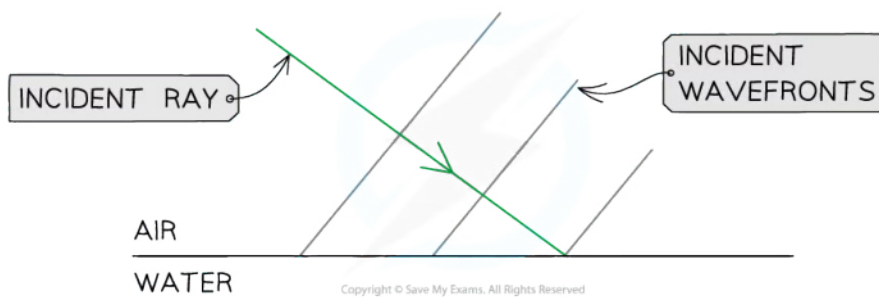
Wavefronts travel from air to water as shown. Add the refracted wavefronts to the diagram.



**Answer:**

**Step 1: Add the incident ray to mark the direction of the incident waves**

- The incident ray must be perpendicular to all wavefronts
- Remember to add an arrow pointing towards the air-water boundary

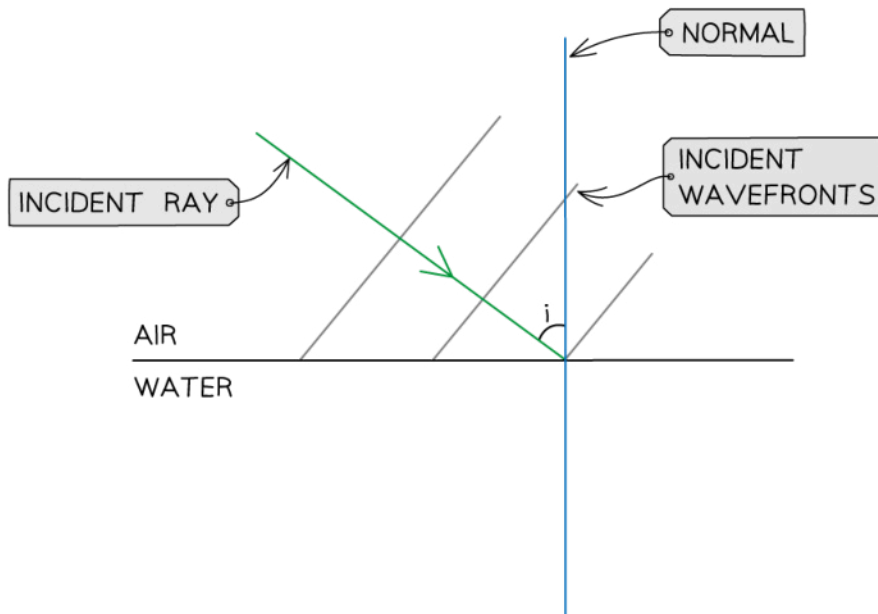


**Step 2: Add the normal at the point of incidence**

- Mark the angle of incidence ( $i$ ) between the normal and the incident ray

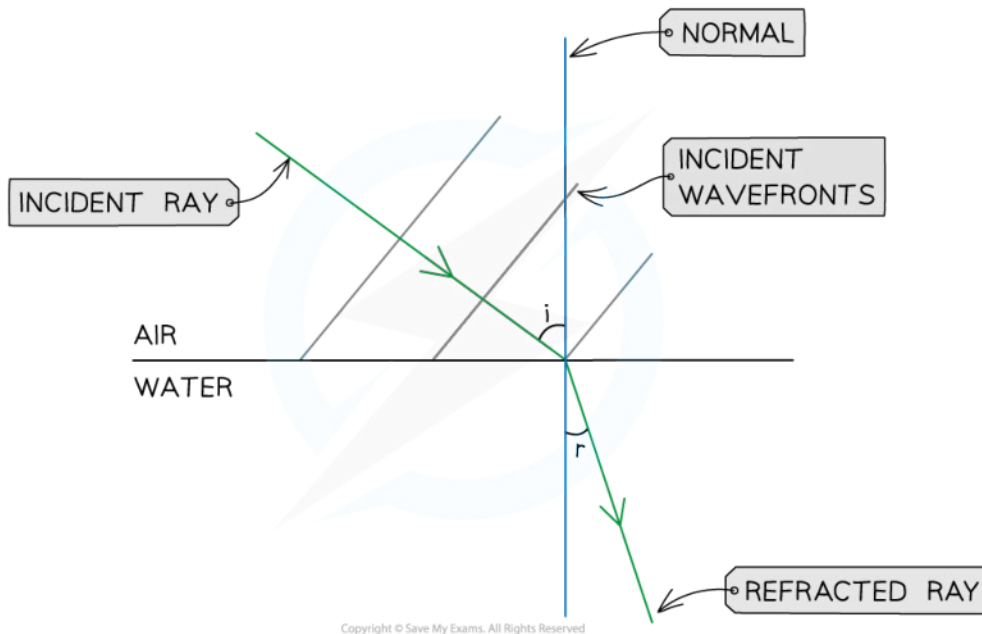


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**Step 3: Draw the refracted ray into the water**

- Water is optically denser than air
- The refracted ray must bend towards the normal
- Mark the angle of refraction ( $r$ ) between the normal and the refracted ray
- By eye,  $i > r$



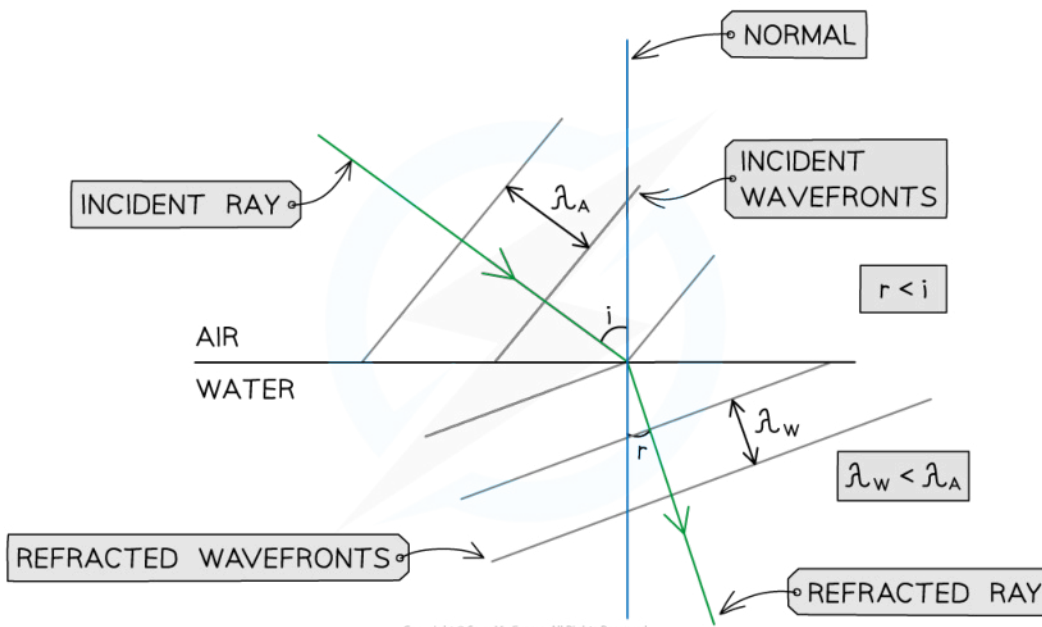
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**Step 4: Add three equally spaced wavefronts, all perpendicular to the refracted ray**

- The refracted wavefronts must be closer to each other than the incident wavefronts, since:
  - The speed  $v$  of the waves decreases in water
  - The frequency  $f$  of the waves stays the same
  - The wavelength  $\lambda$  of the waves in water is shorter than the wavelength of the waves in air  $\lambda_w < \lambda_A$ , since  $v = f\lambda$





Your notes

### Worked example

Light travels from air into glass. Determine the speed of light in glass.

- Refractive index of air,  $n_1 = 1.00$
- Refractive index of glass,  $n_2 = 1.50$

**Answer:**

**Step 1: Write down the known quantities**

- $n_1 = 1.00$
- $n_2 = 1.50$
- From the data booklet,  $c = 3 \times 10^8 \text{ m s}^{-1}$  (speed of light in air)

**Step 2: Write down the relationship between the refractive indices of air and glass and the speeds of light in air ( $v_1$ ) and glass ( $v_2$ )**

$$\frac{n_1}{n_2} = \frac{v_2}{v_1}$$

**Step 3: Rearrange the above equation to calculate  $v_2$**

$$v_2 = \frac{n_1}{n_2} v_1$$

**Step 4: Substitute the numbers into the above equation**

$$v_2 = \frac{1.00}{1.50} \times (3 \times 10^8)$$

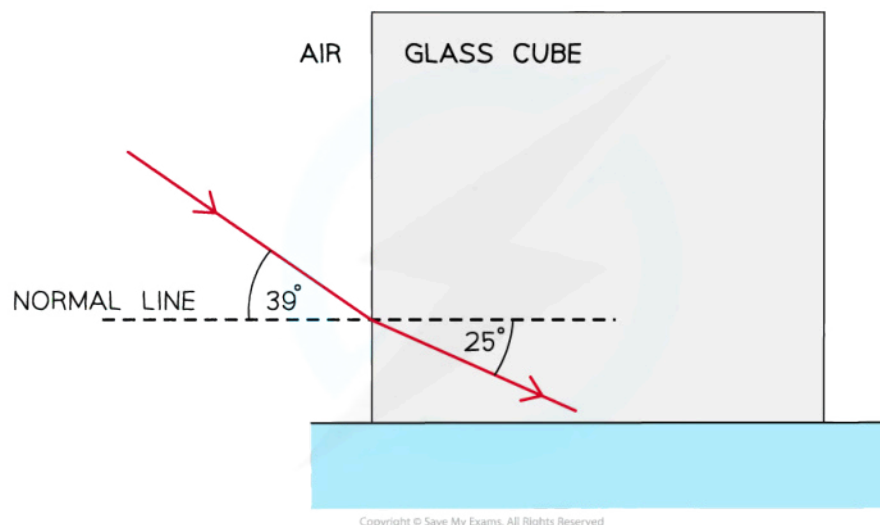
$$v_2 = 2 \times 10^8 \text{ m s}^{-1}$$



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### Worked example

A light ray is directed at a vertical face of a glass cube. The angle of incidence at the vertical face is  $39^\circ$  and the angle of refraction is  $25^\circ$  as shown in the diagram.



Show that the refractive index of the glass is about 1.5.

Answer:

#### Step 1: Write down the known quantities

- Refractive index of air,  $n_1 = 1$
- Refractive index of glass =  $n_2$
- Angle of incidence,  $\theta_1 = 39^\circ$
- Angle of refraction,  $\theta_2 = 25^\circ$

#### Step 2: Write out Snell's Law

$$\frac{n_2}{n_1} = \frac{\sin \theta_1}{\sin \theta_2}$$

**Step 3: Calculate the refractive index of glass**

$$n_2 = \frac{\sin 39}{\sin 25} = 1.489 = 1.5 \text{ (2 s.f.)}$$

- Note that in a "show that" question, the answer should be to at least one more significant figure than the value given in the question



Your notes

** Examiner Tip**

Always double-check if your calculations for the refractive index are greater than 1. Otherwise, something has definitely gone wrong in your calculation! The refractive index of air might not be given in the question. Always assume that  $n_{\text{air}} = 1$

Make sure your calculator is always in **degrees** mode for calculating the sine of angles!

Always check that the angle of incidence and refraction are the angles between the normal and the light ray. If the angle between the light ray and the boundary is calculated instead, calculate  $90 - \theta$  (since the normal is perpendicular to the boundary) to get the correct angle



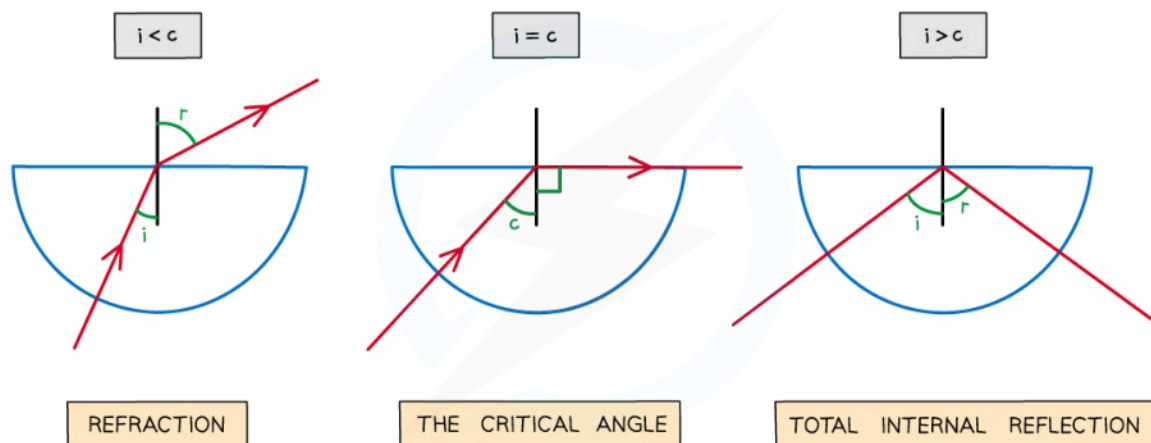
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## Critical Angle & Total Internal Reflection (TIR)

- As the angle of incidence ( $i$ ) is increased, the angle of refraction ( $r$ ) also increases until it gets closer to  $90^\circ$
- When the angle of refraction is exactly  $90^\circ$  the light is refracted along the boundary between the two material
  - At this point, the angle of incidence is known as the **critical angle**  $\theta_c$

### Critical Angle

- The larger the refractive index of a material, the smaller the critical angle
- When light is shone at a **boundary** between two materials, different angles of incidence result in different angles of refraction
  - As the angle of incidence is increased, the angle of refraction also increases
  - Until the **angle of incidence** reaches the **critical angle**
- When the **angle of incidence = critical angle** then:
  - Angle of refraction =  $90^\circ$
  - The refracted ray is refracted **along the boundary** between the two materials
- When the **angle of incidence < critical angle** then:
  - the ray is refracted and exits the material
- When the **angle of incidence > critical angle** then:
  - the ray undergoes **total internal reflection**



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*As the angle of incidence increases it will eventually exceed the critical angle and lead to the total internal reflection of the light*



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### Critical Angle Equation

- The critical angle of material 1 is found using the equation:

$$\sin \theta_c = \frac{n_2}{n_1}$$

- Where:
  - $\theta_c$  = critical angle of material 1 ( $^\circ$ )
  - $n_1$  = absolute refractive index of material 1
  - $n_2$  = absolute refractive index of material 2
- The **two conditions** for total internal reflection to occur are:
  - The refractive index of the **second** medium must be **less** than the refractive index of the first,  $n_2 < n_1$
  - The angle of **incidence** must be **greater** than the **critical** angle,  $\theta_i > \theta_c$

### Total Internal Reflection

- Total internal reflection is a special case of refraction that occurs when:
  - The **angle of incidence** within the denser medium is **greater** than the **critical angle** ( $i > \theta_c$ )
  - The incident refractive index  $n_1$  is **greater** than the refractive index of the material at the boundary  $n_2$  ( $n_1 > n_2$ )
- Total internal reflection follows the law of reflection

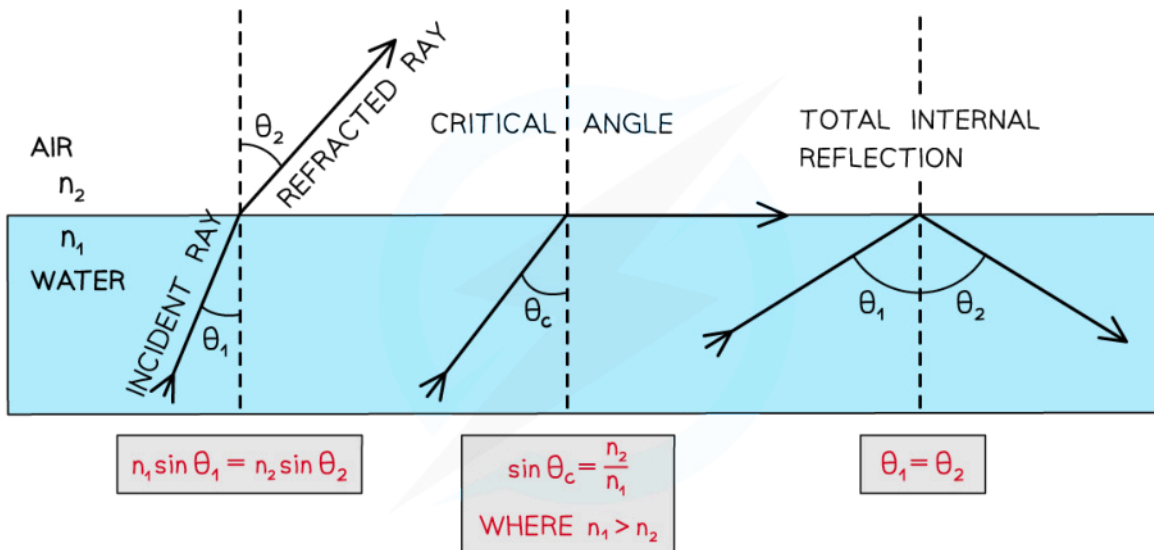
**angle of incidence = angle of reflection**

- A **denser medium** has a **higher refractive index**
  - For example, the refractive index of glass,  $n_g >$  the refractive index of air,  $n_a$
- Light rays inside a material with a **higher refractive index** are more likely to be **totally internally reflected**





Your notes



Angles of incidence, reflection and refraction to satisfy the conditions for total internal reflection



Your notes

### Worked example

Light travels from a material with refractive index 1.2 into air.

Determine the critical angle of the material.

**Answer:**

#### Step 1: Write down the known quantities

- Refractive index of material 1,  $n_1 = 1.2$
- Refractive index of air,  $n_2 = 1.0$

#### Step 2: Write down the equation for the critical angle $\theta_c$

$$\sin\theta_c = \frac{n_2}{n_1}$$

#### Step 3: Substitute the numbers into the above equation

$$\sin\theta_c = \frac{1.0}{1.2}$$

$$\sin\theta_c = 0.83$$

#### Step 4: Calculate $\theta_c$ by taking $\sin^{-1}$ of the above equation

$$\theta_c = \sin^{-1} 0.83$$

$$\theta_c = 56^\circ$$

### Examiner Tip

You do not need to remember the derivation for the critical angle, but you must understand and remember the critical angle formula, as this is **not** given in your data booklet.



Your notes

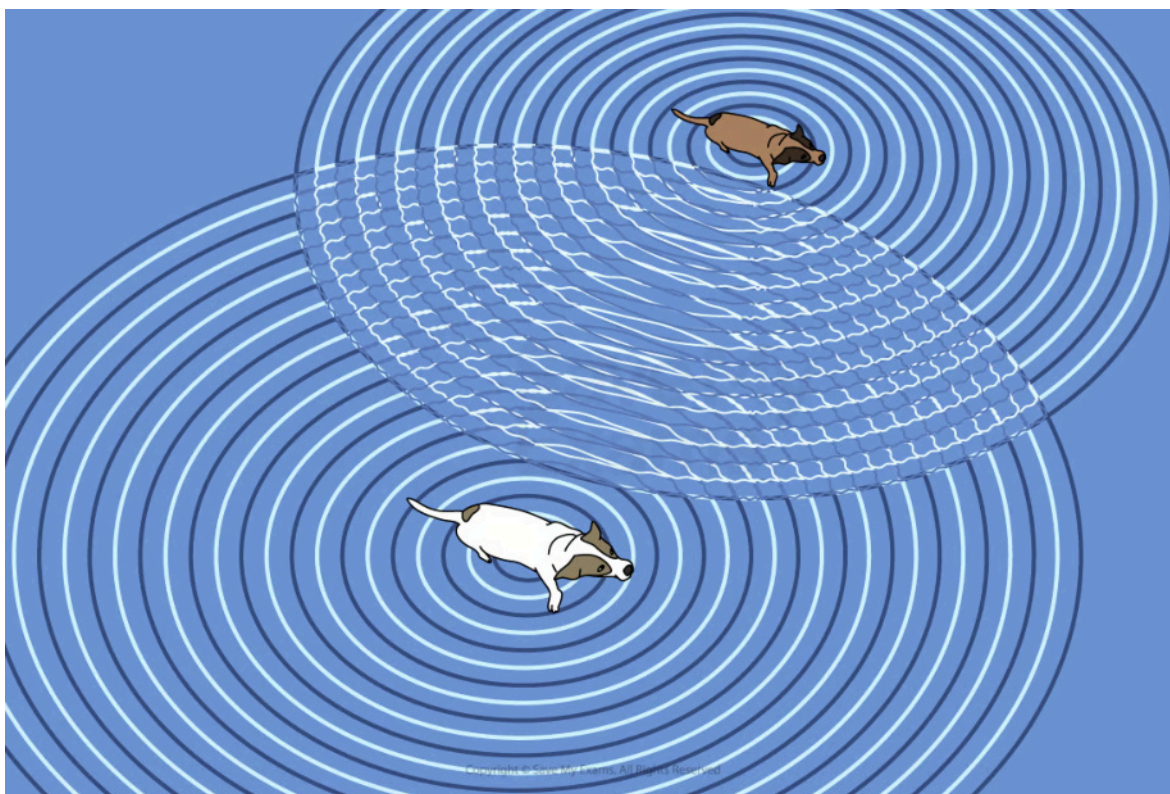
## Superposition of Waves

### Superposition of Waves

- When two or more waves arrive at the same point and overlap, their amplitudes combine
  - This is called **superposition**
- The **principle of superposition** states that:

**When two or more waves overlap at a point, the displacement at that point is equal to the sum of the displacements of the individual waves**

- The superposition of **surface water waves** shows the effect of this overlap
  - There are areas of zero displacement, where the water is flat
  - There are areas of increased displacement, where the water waves are higher

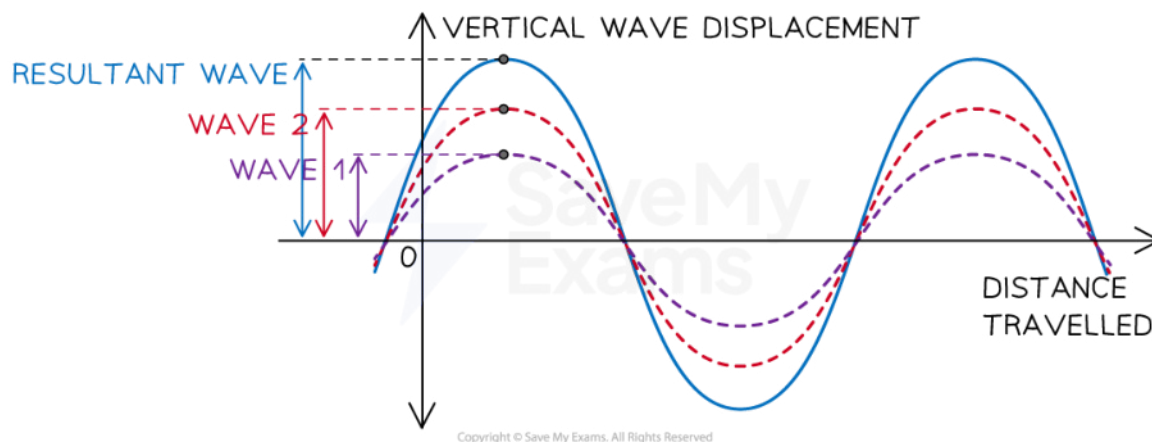


**The dogs make waves in the water which superimpose to give areas of both zero and increased displacement.**

- It is possible to analyse superposition clearly when the waves are drawn on a vertical displacement (amplitude)-displacement graph



Your notes

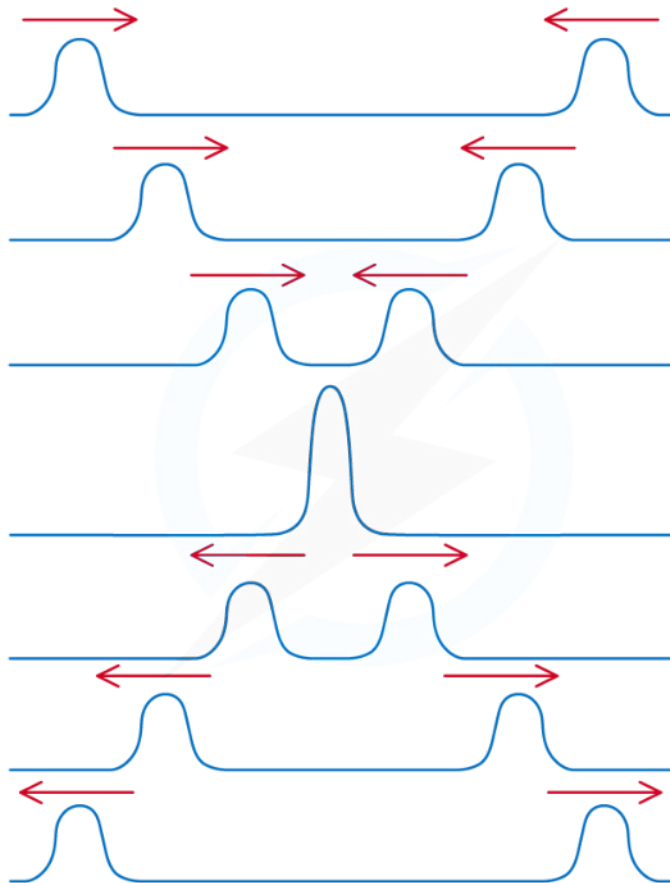


**Waves can superimpose so their amplitudes are added together often creating a larger resultant amplitude**

- **Interference** is the effect of this overlap
  - This is explained in the next [Interference of Waves](#)
- Individual wave displacements may be positive or negative and are **combined** in the same way as other **vector** quantities
- It is possible to analyse superposition clearly when the waves are drawn on a displacement-time graph
- Superposition can also be demonstrated with **two pulses**
  - When the pulses meet, the resultant displacement is also the **algebraic sum** of the displacement of the individual pulses
  - After the pulses have interacted, they then carry on as normal



Your notes



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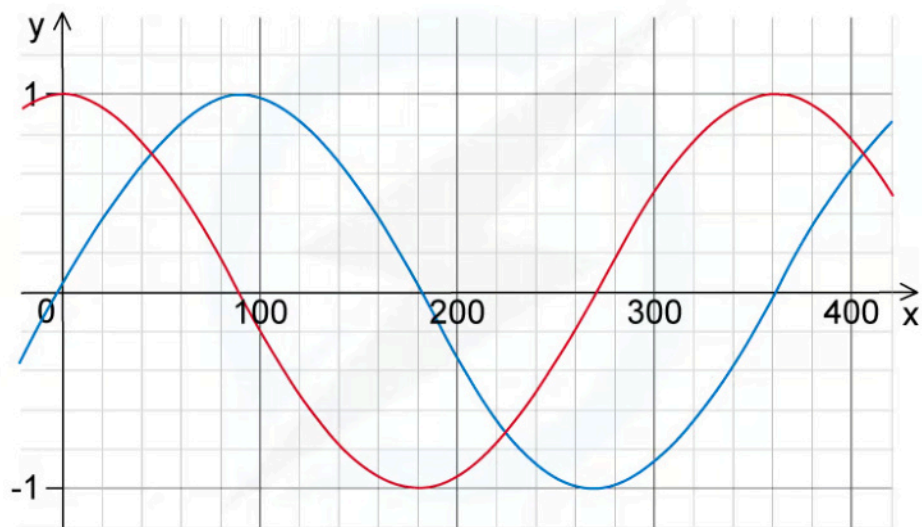
**When two pulses overlap their displacements combine to form a resultant displacement**



Your notes

 **Worked example**

Two overlapping waves of the same type travel in the same direction. The variation with  $x$  and  $y$  displacement of the wave is shown in the figure below.



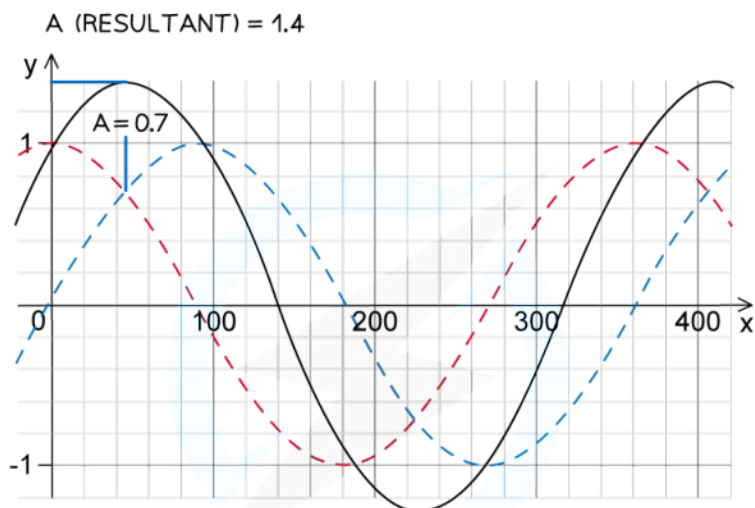
Use the principle of superposition to sketch the resultant wave.

**Answer:**



Your notes

THE GRAPH OF THE SUPERPOSITION OF BOTH WAVES IS SHOWN IN BLACK BELOW:



TO PLOT THE CORRECT AMPLITUDE AT EACH POINT, SUM THE AMPLITUDE OF BOTH GRAPHS AT THAT POINT.

e.g. AT POINT A – EACH GRAPH HAS A VALUE OF 0.7. THEREFORE THE SAME POINT WITH THE RESULTANT SUPERPOSITION IS  $0.7 \times 2 = 1.4$

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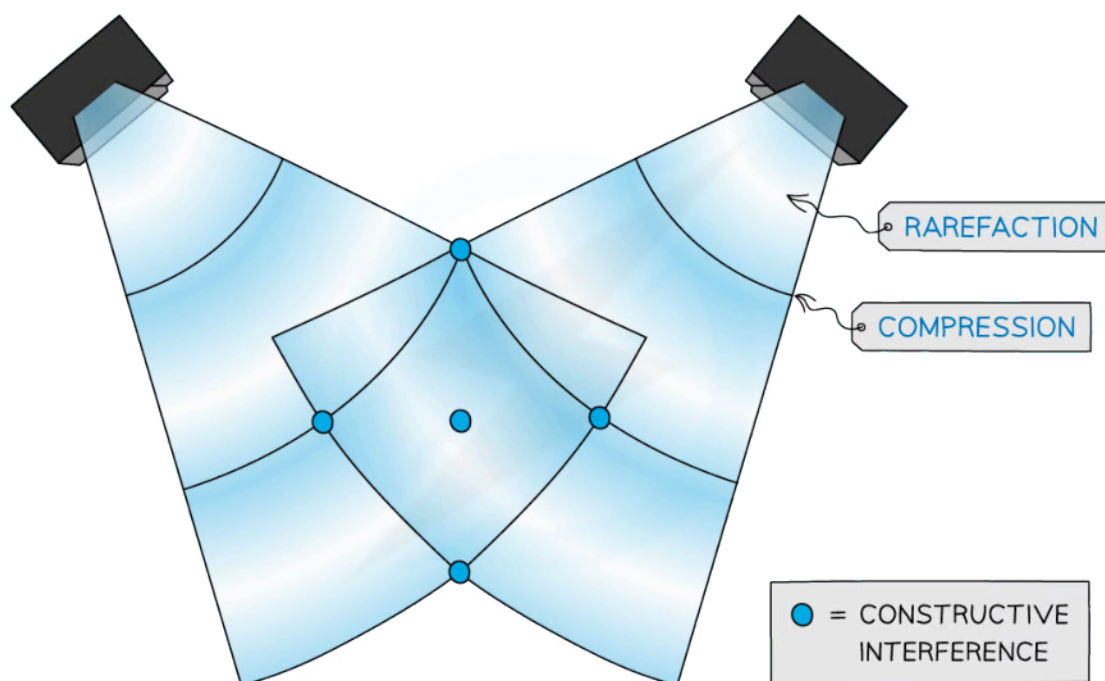


Your notes

## Interference of Waves

### Double Source Interference

- Double-source interference involves producing a **diffraction** and an **interference pattern** using either:
  - The interference of two **coherent** wave sources
  - A single wave source passing through a **double slit**
- Examples of double-source interference include:
  - A **laser beam** that creates bright and dark fringes on a screen
  - **Two speakers** emitting a coherent sound
  - **Microwaves** diffracted through two slits



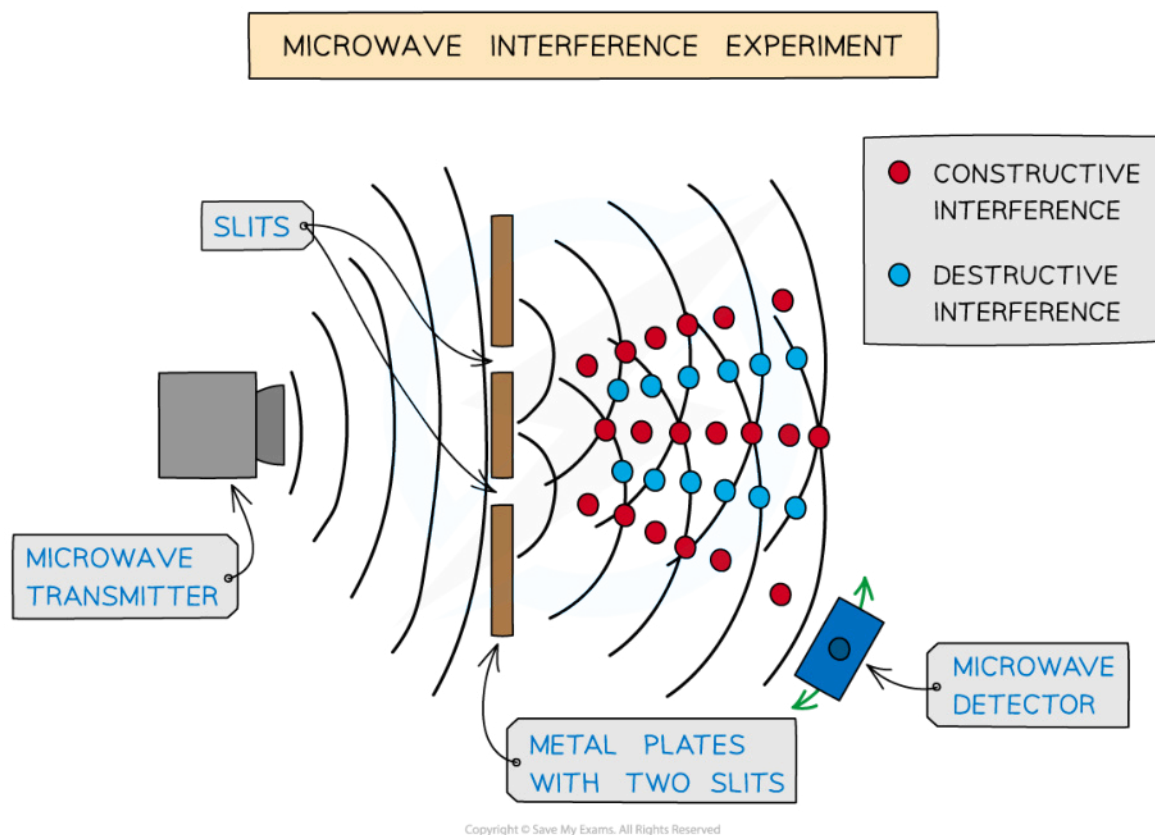
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*Sound wave interference from two speakers emitting a coherent sound*





Your notes



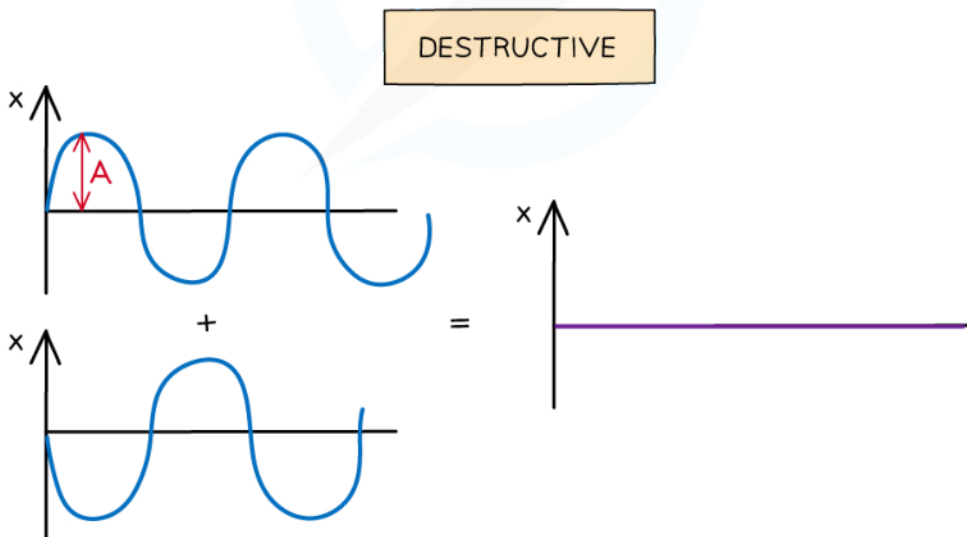
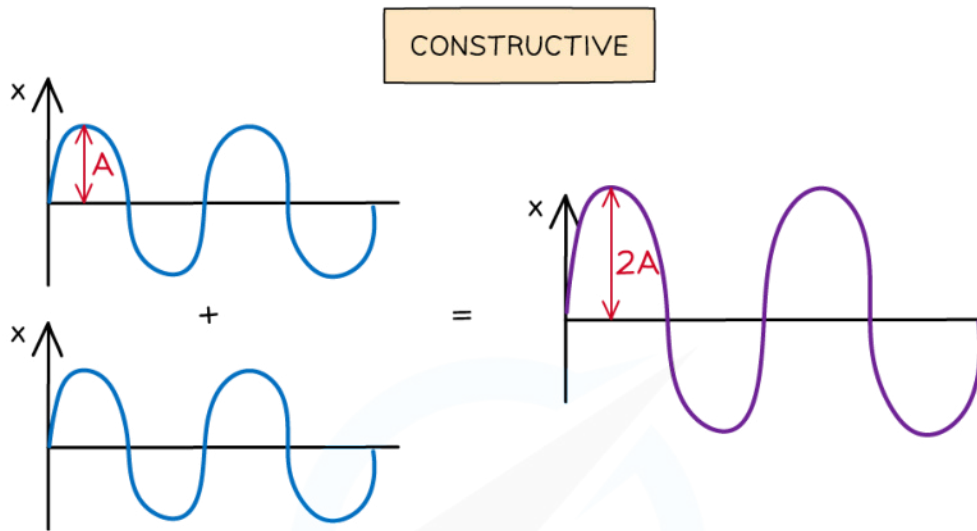
***A microwave interference experiment creates a diffraction pattern with regions where microwaves are and are not detected***

## Interference

- Interference is the effect observed due to the **superposition** of two or more waves
  - It can be seen clearly when waves overlap completely in **phase** or **antiphase**
- The **maximum** amount of superposition occurs when two waves are in **phase**
  - They meet either **peak-to-peak** or **trough-to-trough**
  - This results in the two waves **adding together**
  - This is called **constructive interference**
- The **minimum** amount of superposition occurs when two waves are in **antiphase**
  - They meet **peak-to-trough**
  - This results in the two waves **cancelling** each other out and having zero effect (there is an effect - that they cancel out)
  - This is called **destructive interference**
- Constructive and destructive interference occurs when waves are **coherent**



Your notes



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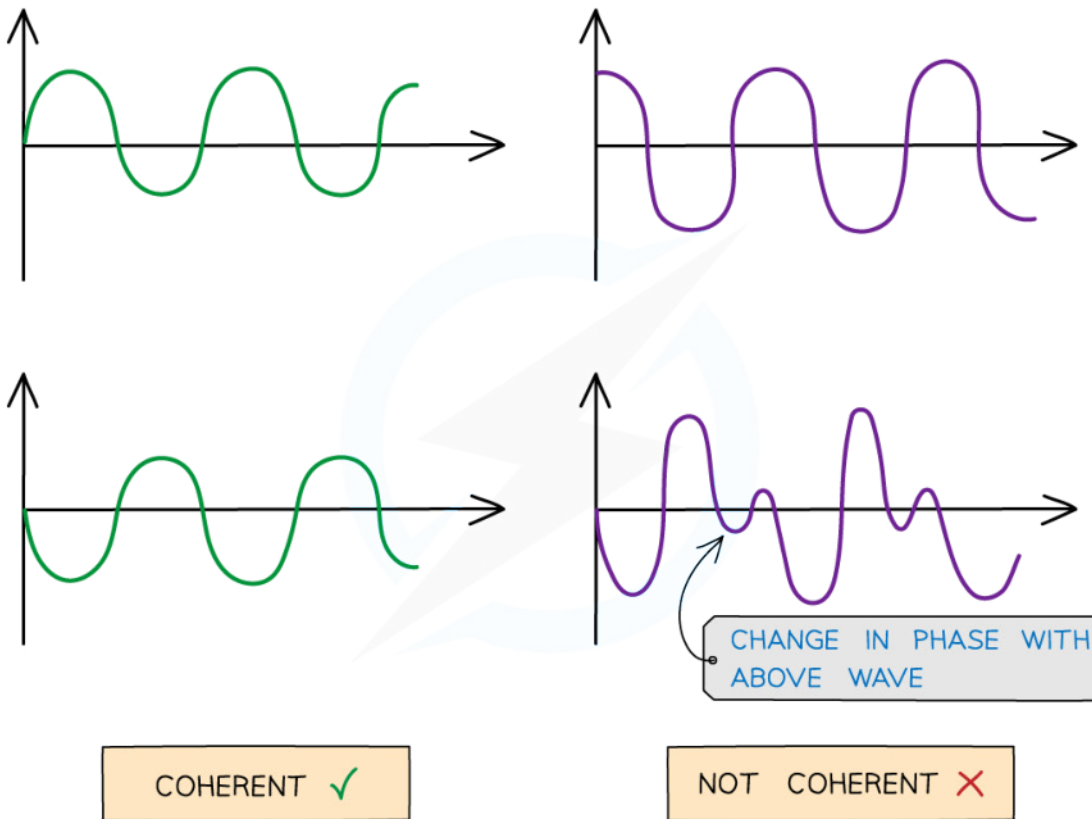
*Waves undergo the maximum amount of constructive and destructive interference when they are in phase or antiphase*

### Coherence

- For waves to be coherent they must have:
  - The same **frequency**
  - A **constant phase difference**



Your notes



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**Coherent vs. non-coherent waves. The abrupt change in phase creates an inconsistent phase difference.**

- At points where two waves are neither in **phase** nor in **antiphase**, the resultant amplitude is somewhere in between the two extremes
- Examples of interference from coherent light sources are:
  - Monochromatic **laser** light
  - Sound waves from two nearby **speakers** emitting sound of the same frequency



Your notes

## Constructive & Destructive Interference

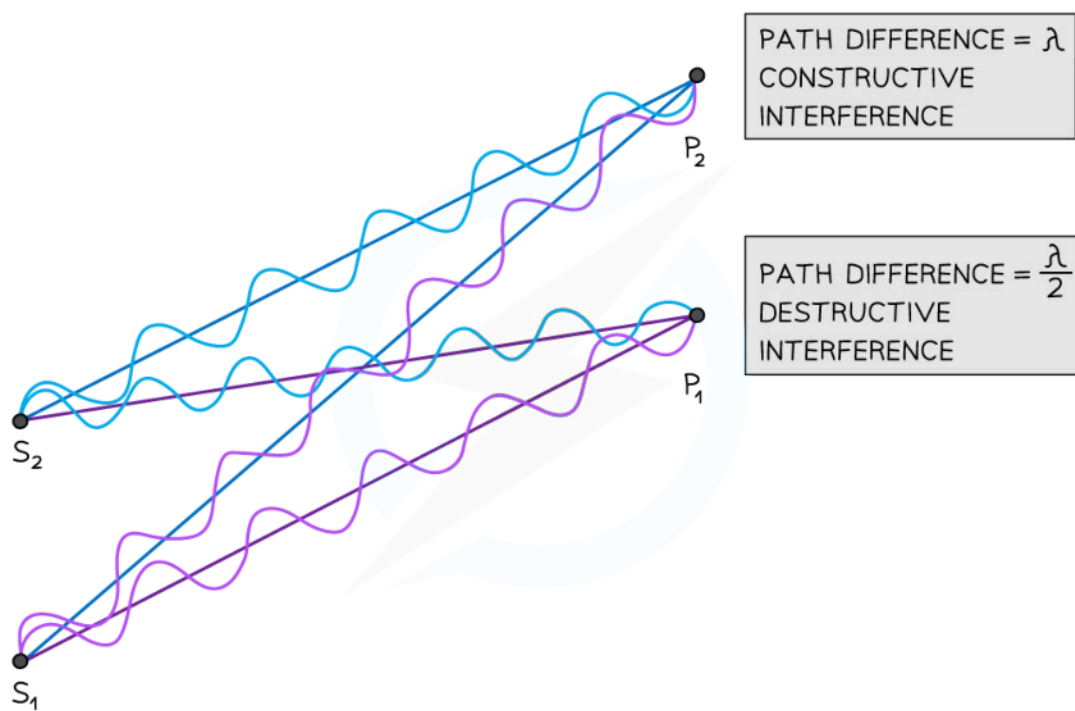
- Whether waves are in phase or antiphase is determined by their **path difference**

### Path Difference

- Path difference is defined as:

**The difference in distance travelled by two waves from their sources to the point where they meet**

- Path difference vs phase difference
  - Phase difference** compares the **distance** between the **phases** (peaks and troughs) of waves that are normally travelling parallel to each other at a point
  - Path difference** compares the amount of **progress** made by waves along a **path**, so the difference in the distance travelled by the two waves



PATH DIFFERENCE =  $\lambda$   
CONSTRUCTIVE INTERFERENCE

PATH DIFFERENCE =  $\frac{\lambda}{2}$   
DESTRUCTIVE INTERFERENCE

**At point  $P_2$  the waves have a path difference of a whole number of wavelengths resulting in constructive interference. At point  $P_1$  the waves have a path difference of an odd number of half wavelengths resulting in destructive interference**

- In the diagram above, the number of wavelengths between:
  - $S_1 \rightarrow P_1 = 6\lambda$
  - $S_2 \rightarrow P_1 = 6.5\lambda$
  - $S_1 \rightarrow P_2 = 7\lambda$
  - $S_2 \rightarrow P_2 = 6\lambda$
- The path difference is:

- $(6.5\lambda - 6\lambda) = \frac{\lambda}{2}$  at point P<sub>1</sub>
- $(7\lambda - 6\lambda) = \lambda$  at point P<sub>2</sub>
- Hence:
  - **Destructive interference** occurs at point P<sub>1</sub>
  - **Constructive interference** occurs at point P<sub>2</sub>

### Conditions for Constructive and Destructive Interference

- In general, for waves emitted by two coherent sources very close together:
- The condition for **constructive interference** is:

$$\text{path difference} = n\lambda$$

- The condition for **destructive interference** is:

$$\text{path difference} = \left(n + \frac{1}{2}\right)\lambda$$

- Where:
  - $\lambda$  = wavelength of the waves in metres (m)
  - $n = 0, 1, 2, 3, \dots$  (any other integer)

### Path Difference and Wavefront Diagrams

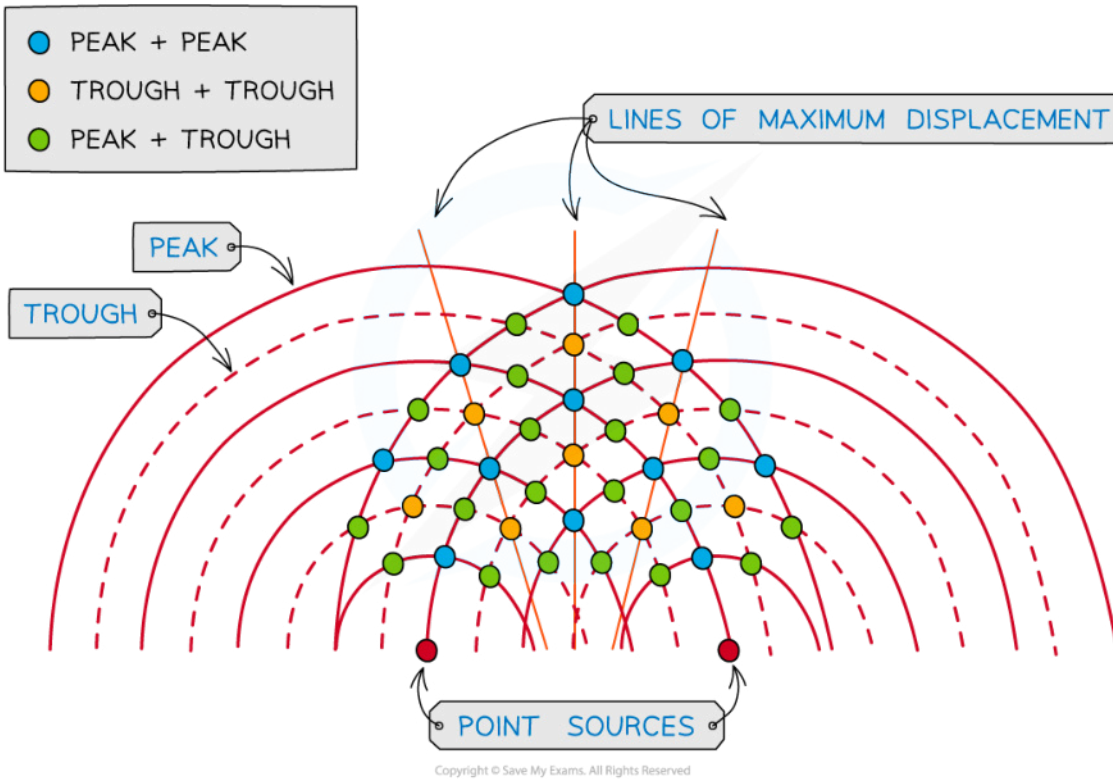
- Wavefront diagrams show the interference between waves more clearly



Your notes

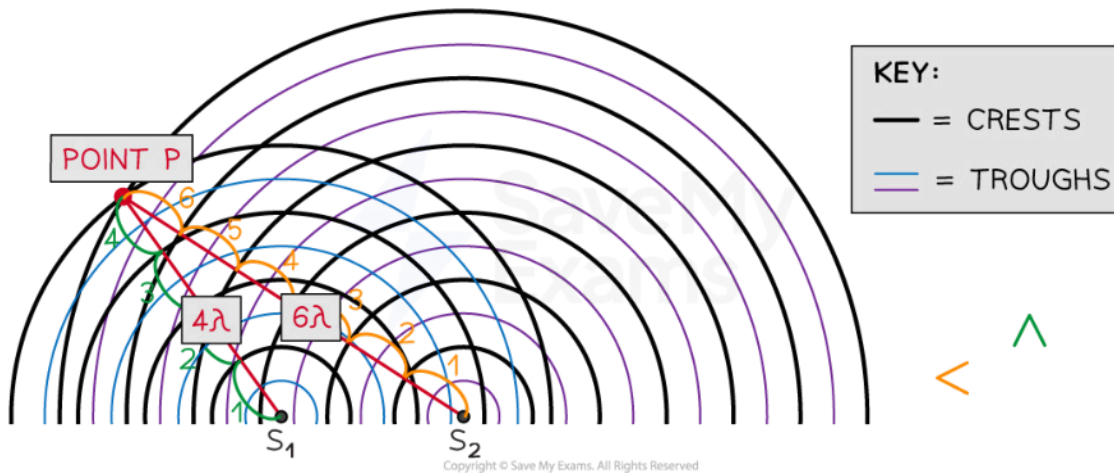


Your notes



At the blue dot where the peak of two waves meet, constructive interference occurs. At the yellow dot where two troughs meet, constructive interference also occurs. Constructive interference occurs along the lines of maximum displacement. At the green dot, where a peak and a trough meet, destructive interference occurs

- On a wavefront diagram, it is possible to **count** the number of wavelengths to determine whether constructive or destructive interference occurs at a certain point



***At point P the waves have a path difference of a whole number of wavelengths, resulting in constructive interference***

- At point **P**, the number of **crests** from:
  - Source  $S_1 = 4\lambda$
  - Source  $S_2 = 6\lambda$
- So the path difference at **P** is  $6\lambda - 4\lambda = 2\lambda$
- This is a whole number of wavelengths, hence, constructive interference occurs at point **P**



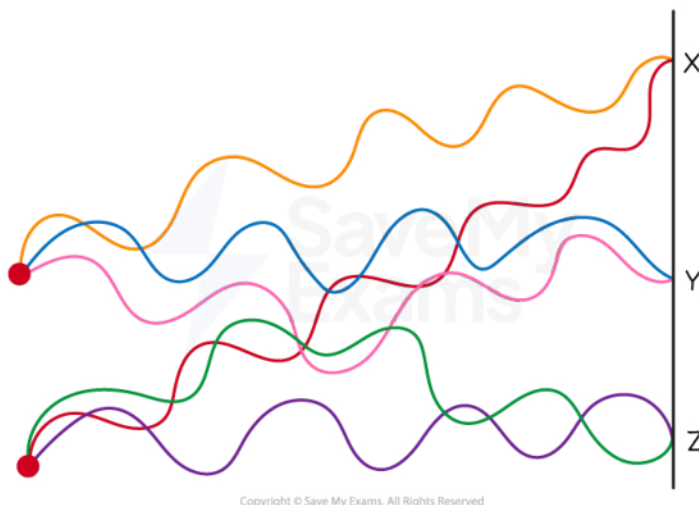
Your notes



Your notes

### Worked example

The diagram shows the interferences of coherent waves from two-point sources.



Which row in the table correctly identifies the type of interference at points X, Y and Z?

	X	Y	Z
A	Constructive	Destructive	Constructive
B	Constructive	Constructive	Destructive
C	Destructive	Constructive	Destructive
D	Destructive	Constructive	Constructive

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#### ANSWER: B

- At point X:
  - Both peaks of the waves are overlapping
  - Path difference =  $5.5\lambda - 4.5\lambda = \lambda$
  - This is **constructive** interference and rules out options C and D
- At point Y:
  - Both troughs are overlapping
  - Path difference =  $3.5\lambda - 3.5\lambda = 0$
  - Therefore **constructive** interference occurs



- At point **Z**:
  - A peak of one of the waves meets the trough of the other
  - Path difference =  $4\lambda - 3.5\lambda = \lambda / 2$
  - This is **destructive** interference

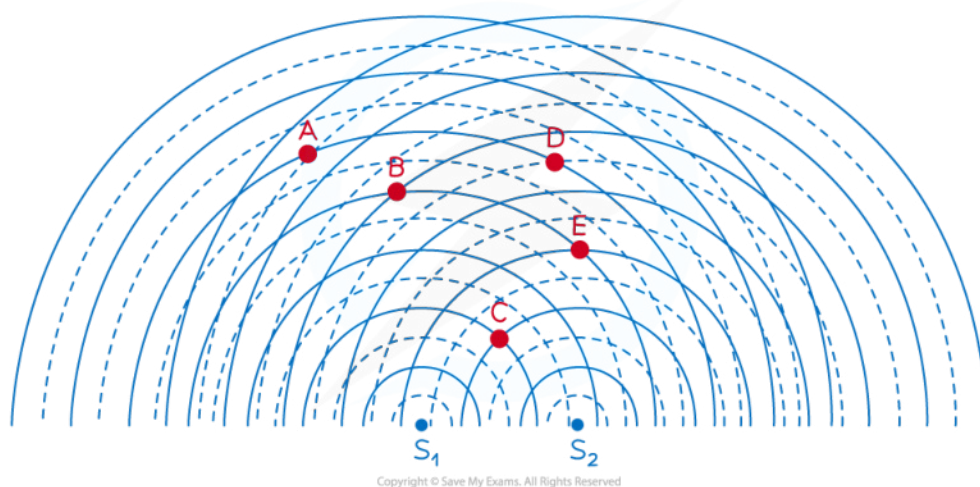


Your notes

### Worked example

The diagram below is a snapshot of overlapping wavefronts resulting from the interference of coherent waves diffracted by two narrow slits  $S_1$  and  $S_2$ .

KEY: — = CRESTS    - - - = TROUGHS



For each of the points A, B, C, D and E, determine:

- The path difference from the sources
- The value of  $n$  in the path difference formula
- Whether they are locations of constructive or destructive interference

**Answer:**

**Step 1: Count the number of wavelengths between each source and the desired point**

- For example, the number of wavelengths between:
  - $S_1 \rightarrow A = 5\lambda$
  - $S_2 \rightarrow A = 6.5\lambda$

**Step 2: Determine the path difference by subtracting the distances of the point from the two sources**

- For example, path difference at A =  $(6.5\lambda - 5\lambda) = 1.5\lambda$

**Step 3: Compare the path difference calculated in Step 2 with the condition for constructive or destructive interference and give the value of  $n$**

- For example, path difference at A =  $1.5\lambda = (n + \frac{1}{2})\lambda \rightarrow n = 1$

**Step 4: Decide whether the point is a location of constructive or destructive interference**

- For example, at A, destructive interference occurs
- Point A:



Your notes

- Path difference =  $(6.5\lambda - 5\lambda) = 1.5\lambda$
- $n = 1$
- Destructive interference
- Point B:
  - Path difference =  $(5\lambda - 4\lambda) = \lambda$
  - $n = 1$
  - Constructive interference
- Point C:
  - Path difference =  $(2\lambda - 2\lambda) = 0$
  - $n = 0$
  - Constructive interference
- Point D:
  - Path difference =  $(5\lambda - 4.5\lambda) = 0.5\lambda$
  - $n = 0$
  - Destructive interference
- Point E:
  - Path difference =  $(4\lambda - 3\lambda) = \lambda$
  - $n = 1$
  - Constructive interference

### Examiner Tip

Remember, interference of two waves can either be:

- In **phase**, causing **constructive interference**. The peaks and troughs line up on both waves. The resultant wave has double the amplitude
- In **antiphase**, causing **destructive interference**. The peaks on one wave line up with the troughs of the other. The resultant wave has no amplitude

Think of '**constructive**' interference as '**building**' the wave and '**destructive**' interference as '**destroying**' the wave.

You are not required to memorise the specific conditions for constructive and destructive interference, as these are given in the data booklet.

You must be able to determine the path difference of waves from two sources (or two narrow slits) at a given point. You can then compare this with the given conditions for constructive and destructive interference, to decide which type of interference occurs at the point you are considering.

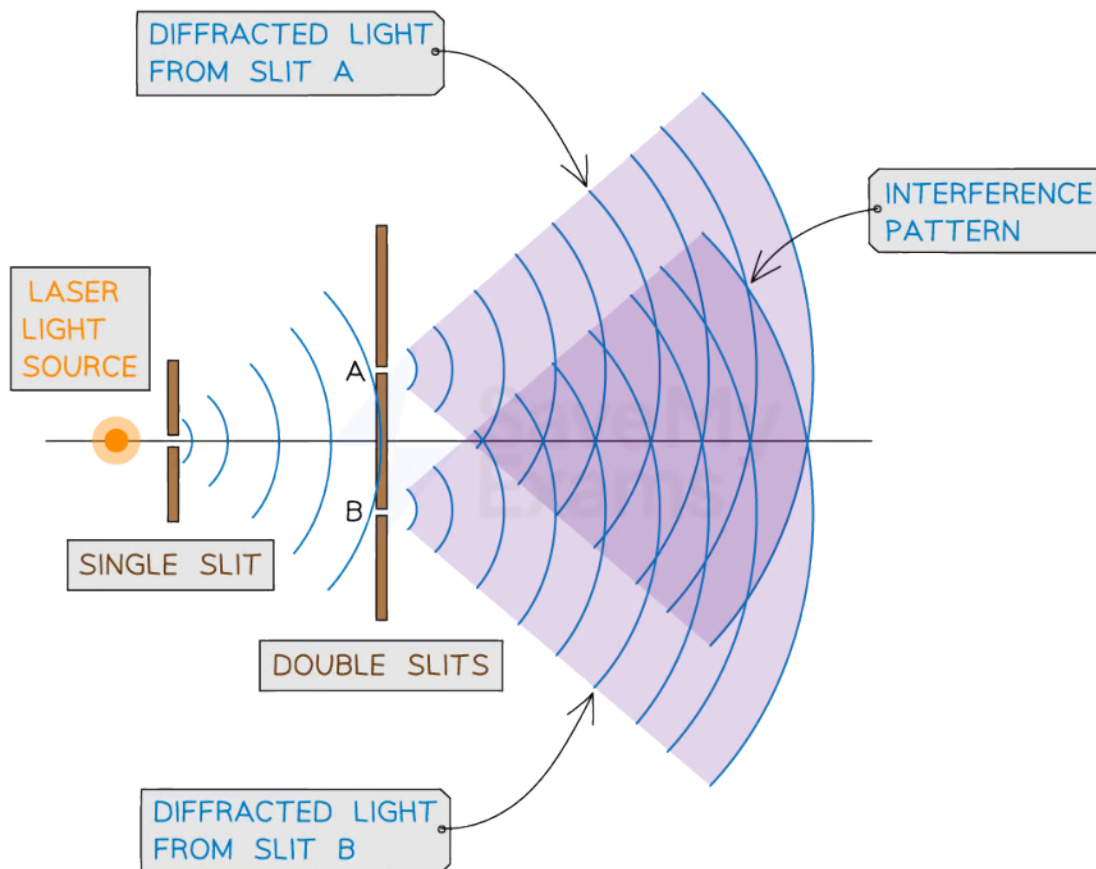


Your notes

## Young's Double-Slit Experiment

### Young's Double Slit Experiment

- Young's double-slit experiment produces a **diffraction** and an **interference pattern** using either:
  - The interference of two **coherent** wave sources
  - A single wave source passing through a **double slit**
- Lasers are the most common sources used in Young's double slit experiment because the waves must be:
  - Coherent** (have a constant phase difference and frequency)
  - Monochromatic** (have the same wavelength)
- In this typical set up for Young's double slit experiment:
  - The light source is placed behind the **single slit**
  - The light is then diffracted to produce two sources in the double slit at **A** and **B**
  - The light from the double slits is then diffracted, producing a **diffraction pattern** made up of bright and dark fringes on a screen



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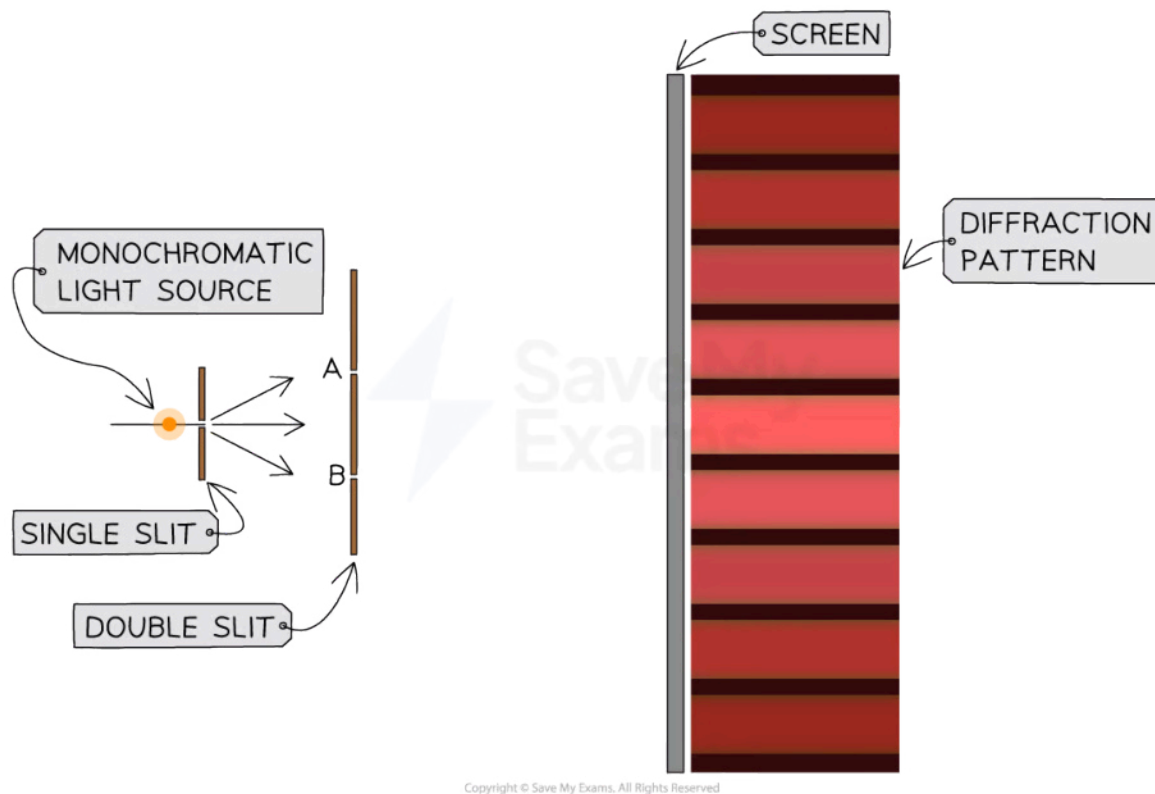
*The typical arrangement of Young's double slit experiment*



Your notes

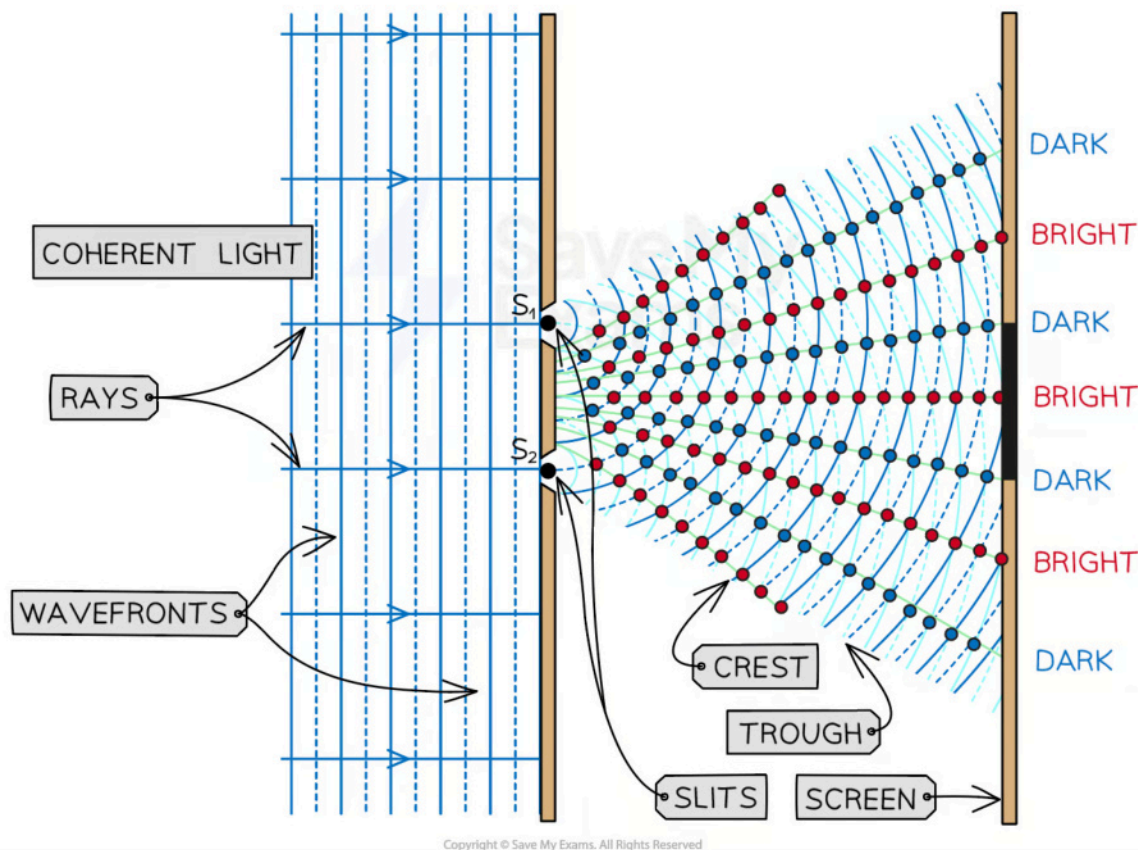
## Diffraction Pattern

- The **diffraction pattern** from the interference of the two sources can be seen on the screen when it is placed far away
  - **Constructive interference** between light rays forms bright strips, also called **fringes**, interference fringes or **maxima**, on the screen
  - **Destructive interference** forms dark strips, also called dark **fringes** or **minima**, on the screen



### *Young's double slit experiment and the resulting diffraction pattern*

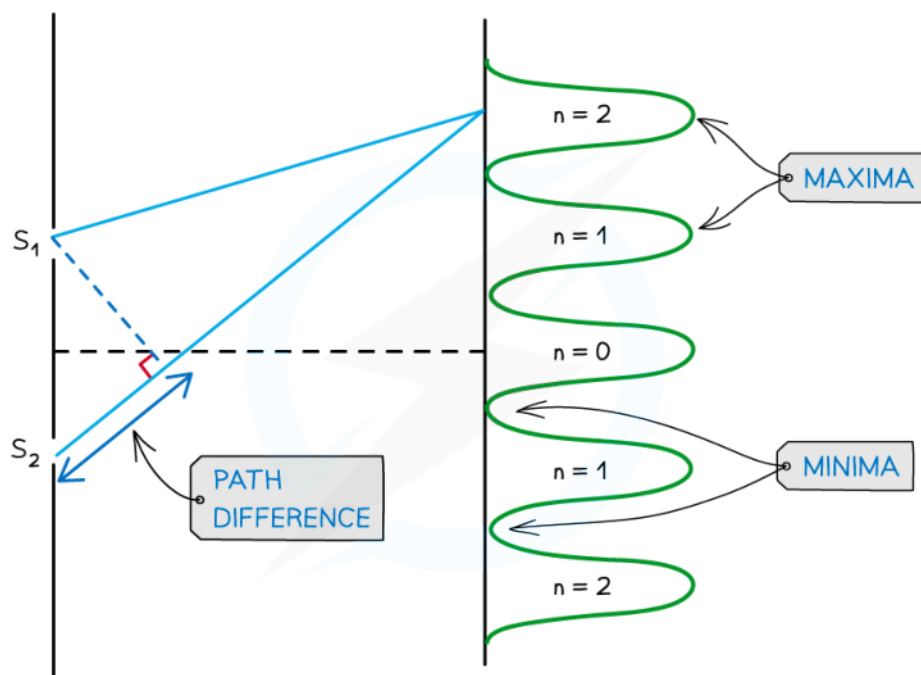
- Each bright fringe is **identical** and has the same width and intensity



The constructive and destructive interference of laser light through a double slit creates bright and dark strips called fringes on a screen placed far away

### Interference Pattern

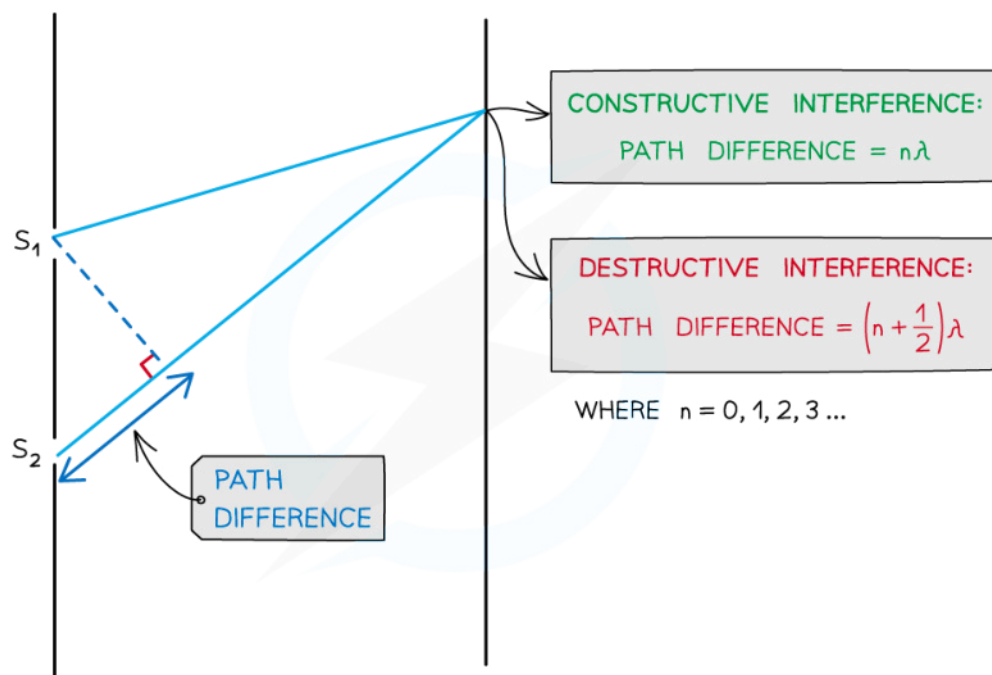
- The Young's double slit interference pattern shows the regions of constructive and destructive interference:
  - Each **bright fringe** is a peak of equal **maximum intensity**
  - Each **dark fringe** is a trough or minimum of **zero intensity**
- The **maxima** are formed by the **constructive interference** of light
- The **minima** are formed by the **destructive interference** of light



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### The interference pattern of Young's double slit diffraction of light

- When two waves interfere, the resultant wave depends on the **path difference** between the two waves
- The wave from slit  $S_2$  has to travel slightly further than that from  $S_1$  to reach the same point on the screen
  - This extra distance is the **path difference**



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The path difference between two waves is determined by the number of wavelengths that cover their difference in length

- Remember the conditions for interference as explained in the previous revision note on [double source interference](#)

- For **constructive** interference (or maxima):

$$\text{path difference} = n\lambda$$

- For **destructive** interference (or minima):

$$\text{path difference} = \left(n + \frac{1}{2}\right)\lambda$$

- For the maxima in the interference pattern:
  - There is usually more than one produced
  - $n$  is the **order** of the maxima or minima; which represents the position of the maxima away from the central maximum
  - $n = 0$  is the **central** maximum
  - $n = 1$  represents the first maximum on either side of the central,  $n = 2$  the next one along....

### Double Slit Equation

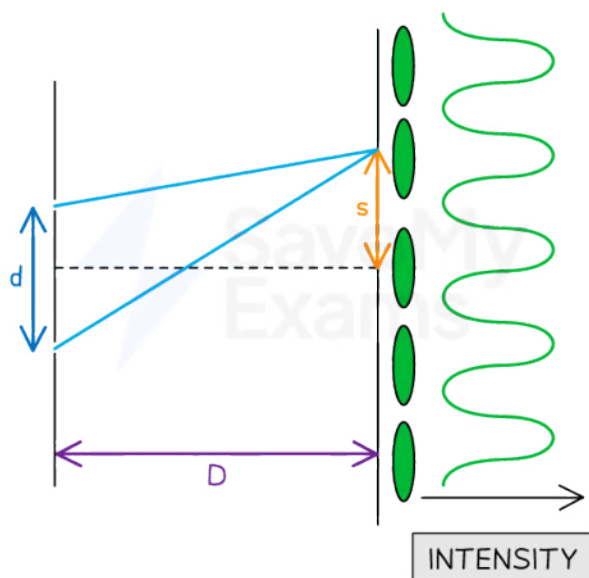
- The spacing between the bright or dark fringes in the diffraction pattern formed on the screen can be calculated using the **double-slit** equation:



$$s = \frac{\lambda D}{d}$$



- Where:
  - $s$  = separation between successive fringes on the screen (m)
  - $\lambda$  = wavelength of the waves incident on the slits (m)
  - $D$  = distance between the screen and the slits (m)
  - $d$  = separation between the slits (m)



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***Double slit interference equation with  $w$ ,  $d$  and  $D$  represented on a diagram***

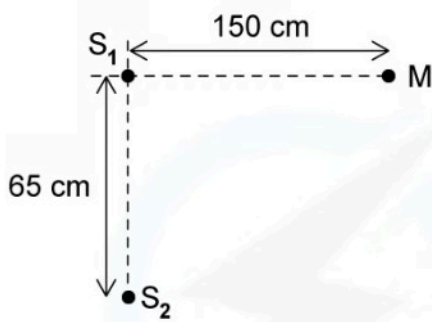
- The above equation shows that the separation between the fringes,  $s$  will **increase** if:
  - The **wavelength** of the incident light **increases**
  - The **distance** between the screen and the slits **increases**
  - The **separation** between the slits **decreases**



Your notes

### Worked example

Two coherent sources of sound waves  $S_1$  and  $S_2$  are situated 65 cm apart in air as shown below.



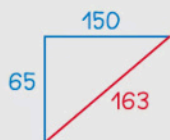
The two sources vibrate in phase but have different amplitudes of vibration. A microphone  $M$  is situated 150 cm from  $S_1$  along the line normal to  $S_1$ . The microphone detects maxima and minima of the intensity of the sound. The wavelength of the sound from  $S_1$  to  $S_2$  is decreased by increasing the frequency.

Determine which orders of maxima are detected at  $M$  as the wavelength is increased from 3.5 cm to 12.5 cm.



STEP 1

CALCULATE THE PATH DIFFERENCE



FROM PYTHAGORAS' THEOREM

$$\sqrt{65^2 + 150^2} = 163$$

$$\text{PATH DIFFERENCE} = 163 - 150 = 13 \text{ cm}$$

STEP 2

MAXIMA ARE CAUSED BY CONSTRUCTIVE INTERFERENCE

STEP 3

CONSTRUCTIVE INTERFERENCE:

$$\text{PATH DIFFERENCE} = n\lambda \quad n = 0, 1, 2, 3, \dots$$

STEP 4

$$13 = n\lambda$$

$$n = 0 \quad \lambda = 0$$

$$n = 1 \quad \lambda = \frac{13}{1} = 13 \text{ cm}$$

$$n = 2 \quad \lambda = \frac{13}{2} = 6.5 \text{ cm}$$

$$n = 3 \quad \lambda = \frac{13}{3} = 4.3 \text{ cm}$$

$$n = 4 \quad \lambda = \frac{13}{4} = 3.3 \text{ cm}$$

ONLY THESE TWO ORDERS  
ARE WITHIN THE WAVELENGTH  
RANGE.

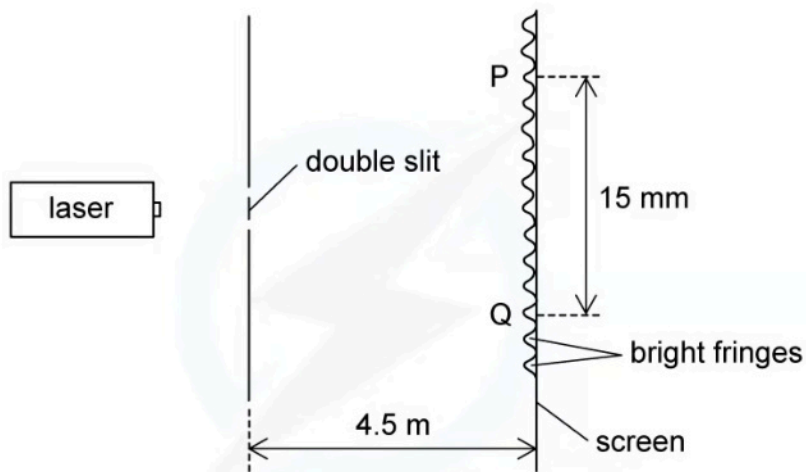
WAVELENGTHS OF 6.5 cm AND  
4.3 cm ARE WHERE MAXIMA  
ARE DETECTED.



Your notes

 **Worked example**

A laser is placed in front of a double-slit as shown in the diagram below.



The laser emits light of frequency 750 THz. The separation of the maxima P and Q observed on the screen is 15 mm. The distance between the double slit and the screen is 4.5 m.

Calculate the separation of the two slits.



Your notes

STEP 1

CALCULATE THE WAVELENGTH OF THE LIGHT

$$v = f\lambda$$

STEP 2

REARRANGE FOR  $\lambda$  AND SUBSTITUTE IN VALUES

$$\lambda = \frac{v}{f} = \frac{3 \times 10^8}{750 \times 10^{12}} = 4 \times 10^{-7} \text{ m} = 400 \text{ nm}$$

STEP 3

FRINGE SPACING EQUATION

$$w = \frac{\lambda D}{S}$$

STEP 4

REARRANGE FOR  $S$  – SEPARATION OF THE TWO SLITS

$$S = \frac{\lambda D}{w}$$

STEP 5

SUBSTITUTE IN VALUES

$$s = \frac{4 \times 10^{-7} \times 4.5}{15 \times 10^{-3} \div 9} = 1.08 \times 10^{-3} \text{ m} = 1.1 \text{ mm (2 s.f.)}$$

TOTAL NUMBER OF  
BRIGHT FRINGES

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### Examiner Tip

The path difference is more specifically how much longer, or shorter, one path is than the other. In other words, the **difference** in the distances. Make sure not to confuse this with the distance between the two paths.

Since  $d$ ,  $s$  and  $D$  are all distances, it's easy to mix up which they refer to. Labelling the double-slit diagram as shown in the notes above will help to remember the order i.e.  $d$  and  $s$  in the numerator and  $D$  underneath in the denominator.