Edexcel International A Level (IAL) Physics

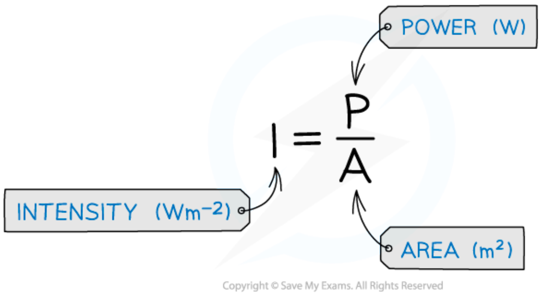
Your notes

Refraction, Reflection & Polarisation

Contents

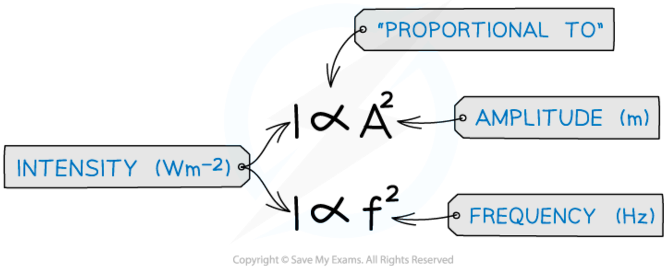
Equation for the Intensity of Radiation

- Progressive waves transfer **energy**
- The amount of energy passing through a unit area per unit time is the **intensity** of the wave
- Therefore, the **intensity** is defined as **power per unit area**



Intensity is equal to the power per unit area

- The **area** the wave passes through is **perpendicular** to the direction of its **velocity**
- The **intensity** of a progressive wave is also **proportional** to its **amplitude squared** and **frequency squared**

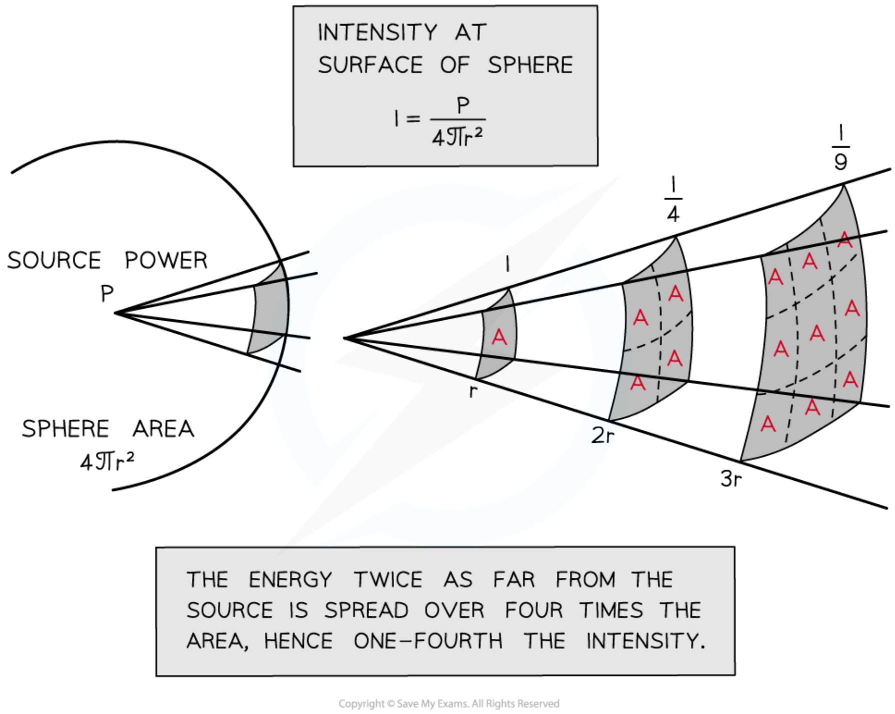


Intensity is proportional to the amplitude^2 and frequency^2

- This means, if the frequency or the amplitude is doubled, the intensity increases by a factor of 4 (2^2)

Spherical Waves

- A **spherical wave** is a wave from a point source that **spreads out equally** in all directions
- The area the wave passes through is the **surface area** of a sphere: $4\pi r^2$
- As the wave travels further from the source, the energy it carries passes through increasingly larger areas as shown in the diagram below:



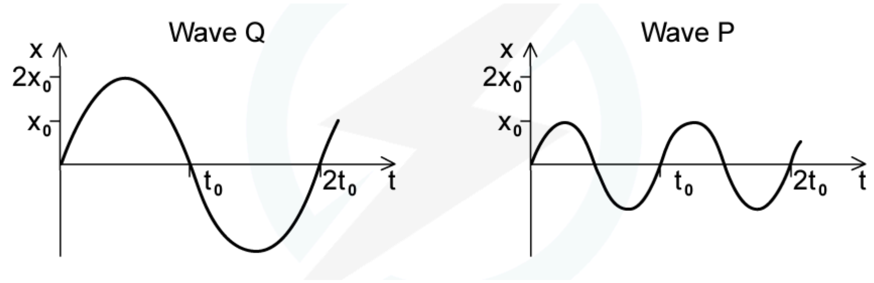
Intensity is proportional to the amplitude squared

- Assuming there's no absorption of the wave energy, the **intensity I decreases** with **increasing distance** from the source
- Note the intensity is proportional to $1/r^2$
  - This means when the source is twice as far away, the intensity is 4 times less
- The $1/r^2$ relationship is known in physics as the **inverse square law**

Worked Example

The intensity of a progressive wave is proportional to the square of the amplitude of the wave. It is also proportional to the square of the frequency. The variation with time t of displacement x of particles when two progressive waves Q and P pass separately through a medium are shown on the graphs

Your notes



The intensity of wave Q is I_0. What is the intensity of wave P?

Answer:

STEP 1

INTENSITY EQUATION

$I \propto A^2$

$I \propto f^2$

STEP 2

CALCULATE HOW MUCH THE AMPLITUDE HAS INCREASED/DECREASED

WAVE P IS HALF THE AMPLITUDE OF WAVE Q

$A_P = \frac{1}{2^2} A_Q$

WAVE $P = \frac{1}{4} I_0$ OF WAVE Q

STEP 3

CALCULATE HOW MUCH THE FREQUENCY HAS INCREASED/DECREASED

WAVE P IS DOUBLE THE FREQUENCY OF WAVE Q

$f_P = 2^2 f_Q$

WAVE $P = 4I_0$ OF WAVE Q

STEP 4

SUBSTITUTE BACK INTO INTENSITY EQUATION

$I_0(P) \propto \left(\frac{1}{4} \times 4\right) I_0(Q)$

INTENSITY OF WAVE P = INTENSITY OF WAVE Q $= I_0$

Examiner Tips and Tricks

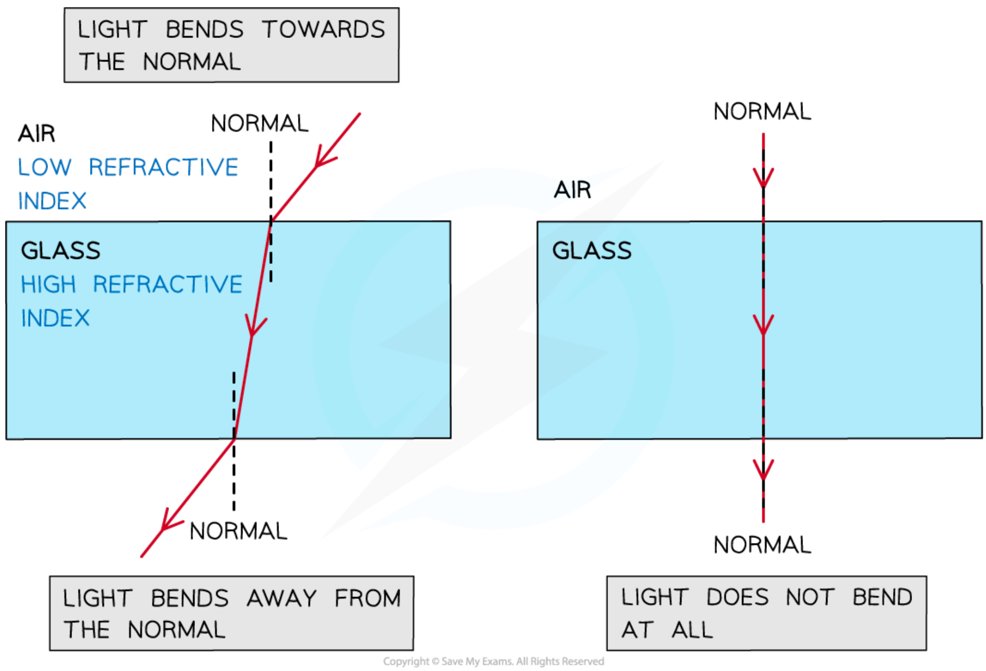
Your notes

> The key concept with intensity is that it has an inverse square relationship with distance (not a linear one). This means the energy of a wave decreases very rapidly with increasing distance

Your notes

Refraction & Refractive Index

- Refraction occurs when light passes a boundary between two different transparent media
- At the boundary, the rays of light undergo a **change in direction** and **a change in speed**
- The change in direction is caused by the change in speed
  - Entering a **more dense** medium **slows** the light down and it bends **towards** the normal
    - In the denser medium there are more particles closer together providing more friction to the passing of the light through the material
  - Entering a **less** dense medium **speeds** the light up and it bends **away** from the normal
  - When passing **along the normal** (perpendicular) the light does **not** change direction
  - Its speed does still change, as it is passing through a medium with a different refractive index



Refraction of light through a glass block

Calculating Refractive Index

- The refractive index, *n*, is a property of a material which measures how much light slows down when passing through it

Your notes

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

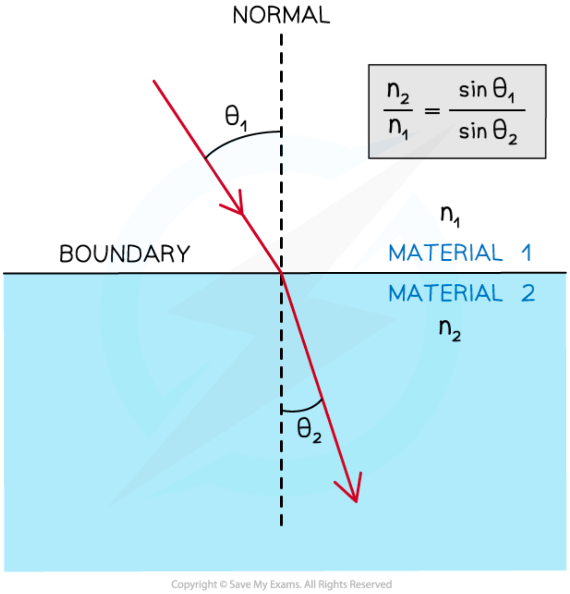
- Where:
  - c = the speed of light in a vacuum (m s^{-1})
  - v = the speed of light in a substance (m s^{-1})
- Light travels at different speeds within different substances depending on their refractive index
  - A material with a high refractive index is called **optically dense**, such material causes light to travel **slower**
- Since the speed of light in a substance will always be less than the speed of light in a vacuum, the value of the n is **always greater than 1**
- In calculations, the refractive index of air can be taken to be approximately **1**
  - This is because light does not slow down significantly when travelling through air (as opposed to travelling through a vacuum)

Snell's Law

- Snell's law relates the **angle of incidence** to the **angle of refraction**, it is given by:

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

- Where:
  - n_1 = the refractive index of material 1
  - n_2 = the refractive index of material 2
  - θ_1 = the angle of incidence of the ray in material 1 (°)
  - θ_2 = the angle of refraction of the ray in material 2 (°)

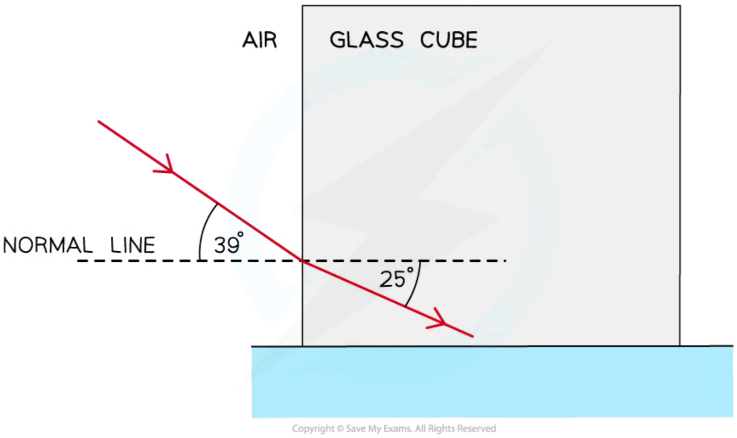


Snell's Law is used to find the refractive indices or the angles to the normal at a boundary

- θ_1 and θ_2 are always taken from the **normal**
- Material 1 is always the material in which the ray goes through **first**
- Material 2 is always the material in which the ray goes through **second**

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° and the angle of refraction is 25° as shown in the diagram.



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

Answer:

Your notes

Your notes

Step 1: Write down the known quantities

- Refractive index of air, n_1 = 1
- Refractive index of glass = n_2
- Angle of incidence, θ_1 = 39°
- Angle of refraction, θ_2 = 25°

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

Examiner Tips and Tricks

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 will not be given in the question. Always assume that n_{air} = 1.

Always check that the angle of incidence and refraction are the angles between the normal and the light ray. Remember the normal line is not really there - it has been drawn in to give you a place to measure from.

Your notes

Critical Angle

- As the angle of incidence at the boundary between a more dense and a less dense medium is increased, the angle of refraction also increases until it gets to 90°
- When the angle of refraction is exactly 90° the light is refracted along the boundary (if the boundary is straight)
  - At this point, the angle of incidence is known as the **critical angle C**
  - This can only occur when light passes from a **more dense** to a **less dense** material
- This angle can be found using the formula:

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

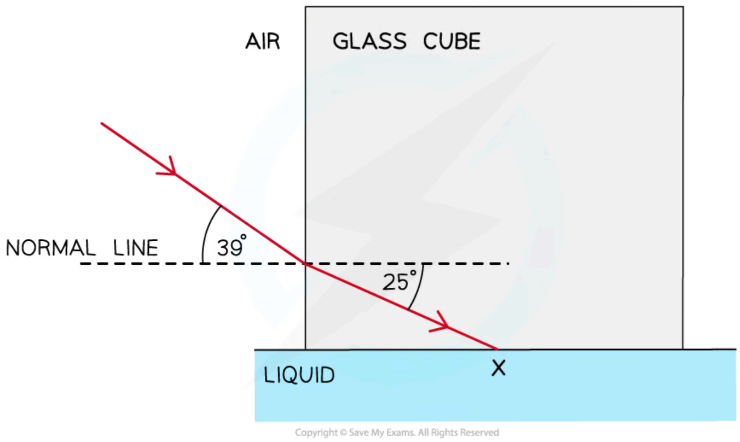
- This can easily be derived from Snell's law:

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

- Where:
  - $\theta_1 = C$
  - $\theta_2 = 90°$
  - $n_1 = n$
  - $n_2 = 1$ (air)

Worked Example

A glass cube is held in contact with a liquid and a light ray is directed at the vertical face of the cube. The angle of incidence at the vertical face is 39° and the angle of refraction is 25° as shown in the diagram. The light ray is totally internally reflected at **X**. The refractive index of the glass cube is 1.45 and the refractive index of the liquid is 1.32.



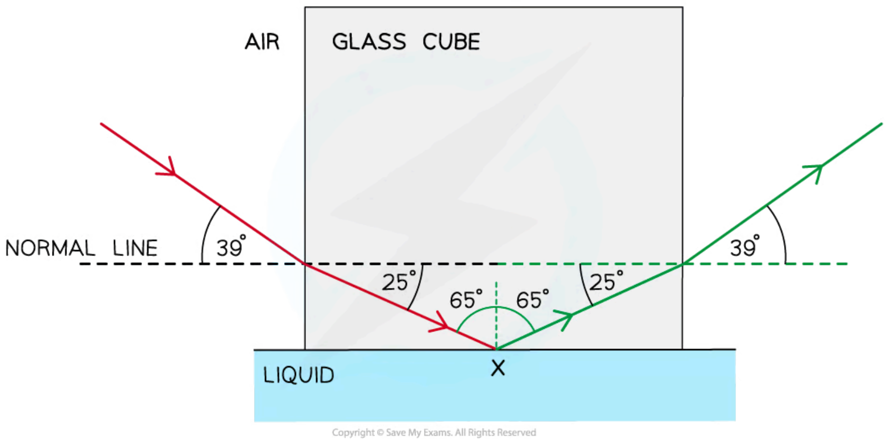
a) Complete the diagram to show the path of the ray beyond **X**

b) Calculate the critical angle for the ray at the glass-liquid boundary

Answer:

Part (a)

Complete the diagram to show the path of the ray beyond **X**



Step 1: Draw the reflected angle at the glass-liquid boundary

- When a light ray is reflected, the angle of incidence = angle of reflection
- Therefore, the angle of incidence (and reflection) is 90° – 25° = 65°

Step 2: Draw the refracted angle at the glass-air boundary

- At the glass-air boundary, the light ray refracts **away** from the normal
- Due to the reflection, the light rays are symmetrical to the other side

Part (b)

Calculate the critical angle for the ray at the glass-liquid boundary:

Step 1: Recall Snell's Law and rearrange to make critical angle the subject

Your notes

Your notes

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

$$\sin(C) = \frac{n_2}{n_1}\sin(\theta_2)$$

Step 2: Substitute in the known quantities

- n_1 = refractive index of glass cube = 1.45
- n_2 = refractive index of liquid = 1.32
- θ_1 = C
- θ_2 = 90° (The angle of refraction is 90° when at the critical angle)

$$\sin(C) = \frac{n_2}{n_1}\sin(\theta_2)$$

$$C = \sin^{-1}\left(\frac{1.32}{1.45}\right)$$

Step 3: Calculate the critical angle

$$C = 65.55°$$

Examiner Tips and Tricks

Always draw ray diagrams with a ruler, and make sure you're comfortable calculating unknown angles. The main rules to remember are:

- Angles in a right angle add up to 90°
- Angles on a straight line add up to 180°
- Angles in any triangle add up to 180°

For angles in parallel lines, such as alternate and opposite angles, take a look at the OCR GCSE maths revision notes '7.1.1 Angles in Parallel Lines'

Total Internal Reflection

- Total internal reflection (TIR) occurs 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

- Therefore, the **two** conditions for total internal reflection are:
  - The angle of incidence, θ_1 > the critical angle, C
  - Refractive index n_1 > refractive index n_2 (air)

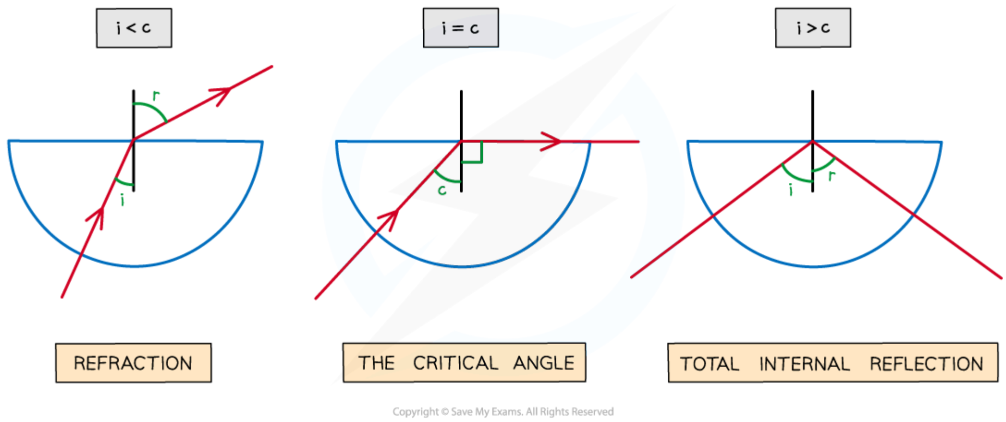
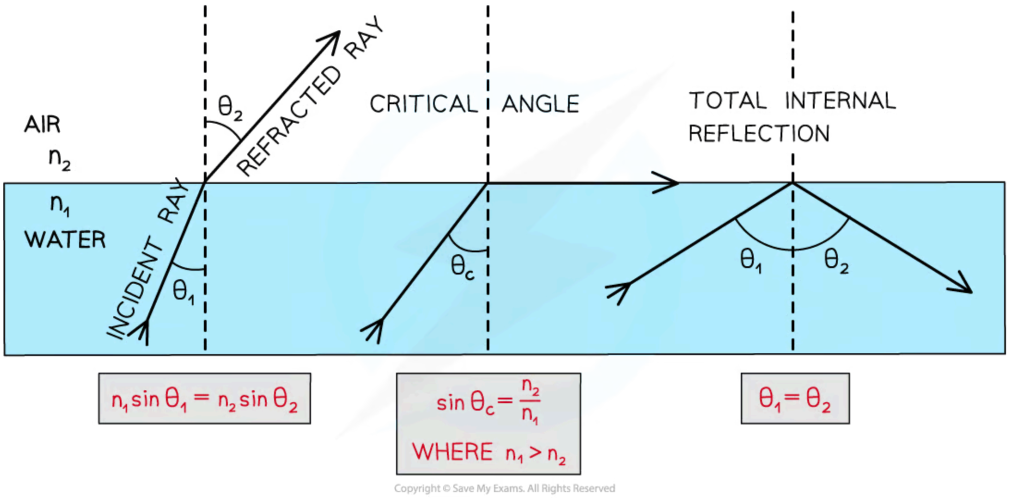


Diagram showing refraction, the critical angle and total internal reflection

- Two conditions are necessary for total internal reflection to occur:
  - The light must be going from a **more dense medium** into a **less dense** one
  - The **angle of incidence** must be **greater** than the **critical angle**



Your notes

Examiner Tips and Tricks

If asked to name the phenomena make sure you **give the whole name** - Total Internal Reflection. Remember: Total Internal Reflection occurs when going from a **more dense to** a **less dense** material and **ALL** of the light is reflected. If asked to explain what is meant by the **critical angle**, you can draw the diagram above (showing the three semi-circular blocks).

Measuring Refractive Index

Aim of the Experiment

- To investigate the **refraction** of light through a **perspex block**

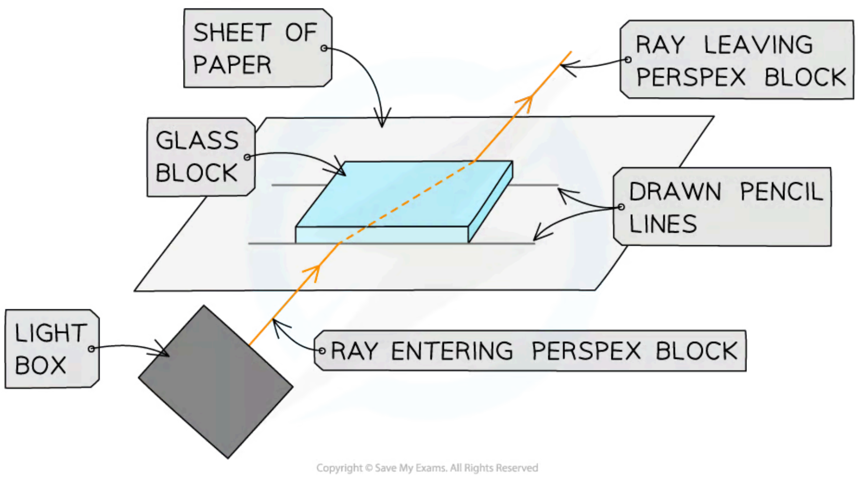
Equipment

- Ray Box - to provide a narrow beam of light to refract through the perspex box
- Protractor - to measure the light beam angles
- Sheet of paper - to mark with lines for angle measurement
- Pencil - to make perpendicular line and angle lines on paper
- Ruler - to draw straight lines on the paper
- Perspex block - to refract the light beam

Variables

- Dependent variable = angle of refraction , *r*
- Control variables:
  - Use of the same perspex block
  - Width of the light beam
  - Same frequency / wavelength of the light

Method



Apparatus to investigate refraction

1. Place the **perspex block** on a **sheet of paper**, and draw around it using a pencil

Your notes

2. Switch on the **ray box** and direct a beam of light at the **side face** of the block
3. **Mark** on the paper with a small 'x':
    - A point on the ray close to the ray box
    - The point where the ray enters the block
    - The point where the ray exits the block
    - A point on the exit light ray which is a distance of about 5 cm away from the block
4. **Draw** a dashed line **normal** (at right angles) to the outline of the block
5. Remove the block and **join the points** marked 'x' with three straight lines
6. Replace the block within its outline and **repeat** the above process for a ray striking the block at **different angles** of incidence

- An example of the data collection table is shown below:

Angle of incidence, I	Angle of refraction, r
30°	
45°	
60°	
90°	

Analysis of Results

- *i* and *r* are always measured from the **normal**
- For light rays **entering** perspex block, the light ray refracts **towards** the central line:

$$i > r$$

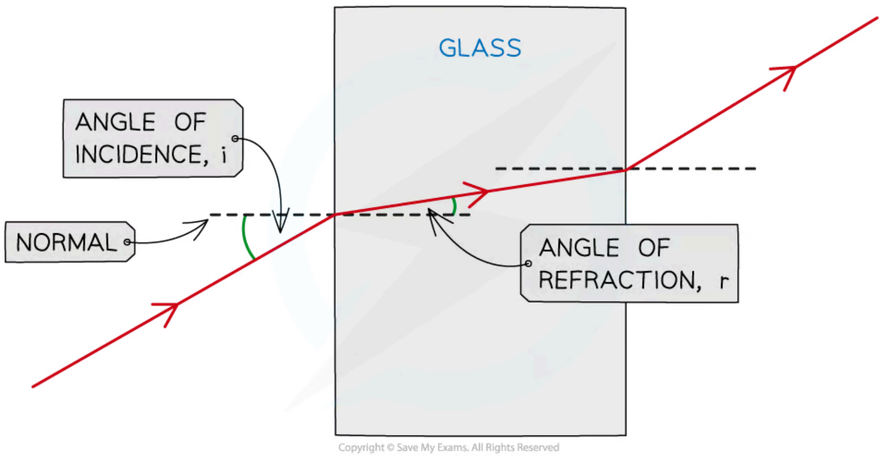
- For light rays **exiting** the perspex block, the light ray refracts **away** from the central line:

$$i < r$$

- When the angle of incidence is 90° to the perspex block, the light ray does **not** refract, it passes straight through the block:

$$i = r$$

- If the experiment was carried out correctly, the angles should follow the pattern, as shown below:



How to measure the angle of incidence and angle of refraction

Safety Considerations

- The ray box light gets **hot** and could **burn** if touched
  - Run burns under cold running water for at least five minutes
- Looking directly into the light may **damage** the **eyes**
  - Avoid looking directly at the light
  - Stand behind the ray box during the experiment
- Keep all **liquids away** from the electrical equipment and paper
- Take care using the perspex
  - Damage to the perspex block can affect the outcome of the experiment

Examiner Tips and Tricks

In your examination you could be asked about the method for this experiment or given a set of results and asked how accurate they are or how they can be improved.

Your notes

Plane Polarisation

- Transverse waves can oscillate in **any** plane perpendicular to the direction of motion (and energy transfer) of the wave
  - Such waves are said to be **unpolarised**
- When a wave is plane polarised:

Particle oscillations occur in a single plane perpendicular to the direction of wave propagation

- Polarisation can only occur in transverse waves
  - This is because transverse waves oscillate in **any plane** perpendicular to the propagation direction

Your notes

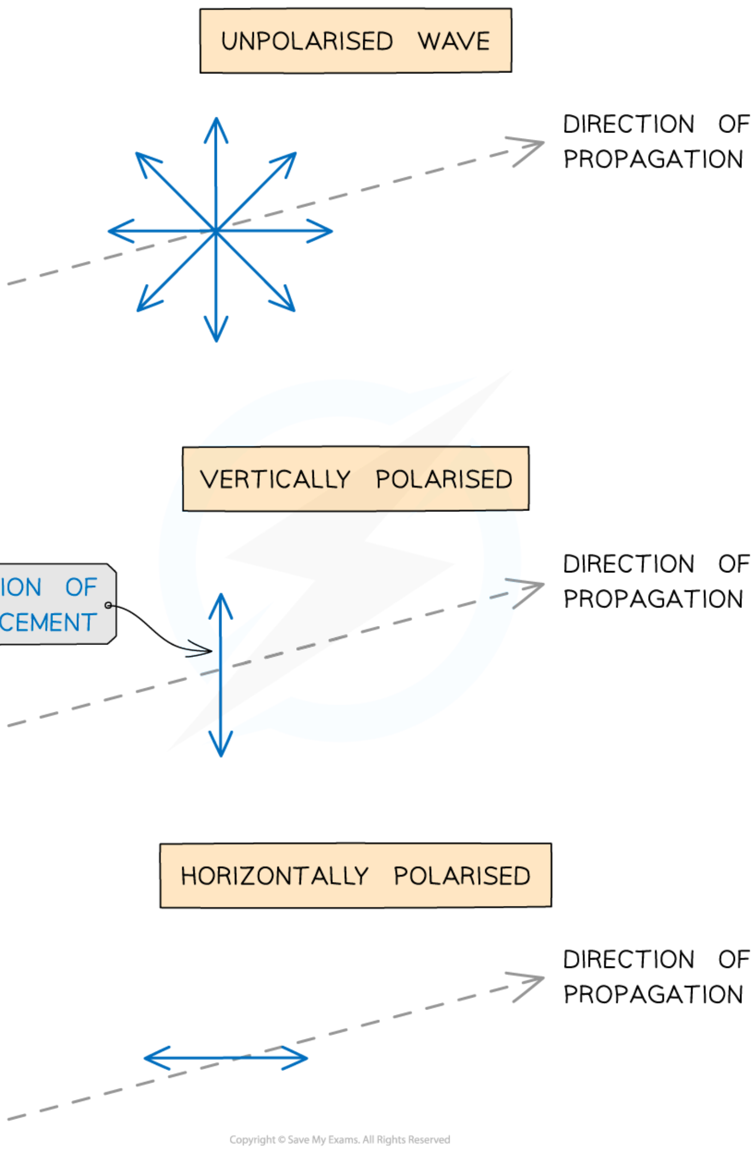


Diagram showing the displacement of unpolarised and polarised transverse waves

- Since longitudinal waves oscillate in the same direction as the direction of motion of the wave, **polarisation of longitudinal waves cannot occur**
- Methods of polarisation include
  - polarising filters
  - reflection (from a non-metallic plane surface)
  - refraction

Polarising filters

- Light waves can be polarised by making them pass through a **polarising filter** (also known as a **polariser**)

- The filter imposes its plane of polarisation on the incident light wave
- A polariser with a vertical **transmission axis** only allows vertical oscillations to be transmitted through the filter (**A**)
- If vertically polarised light is incident on a filter with a horizontal transmission axis, no transmission occurs (**B**), and the wave is blocked completely

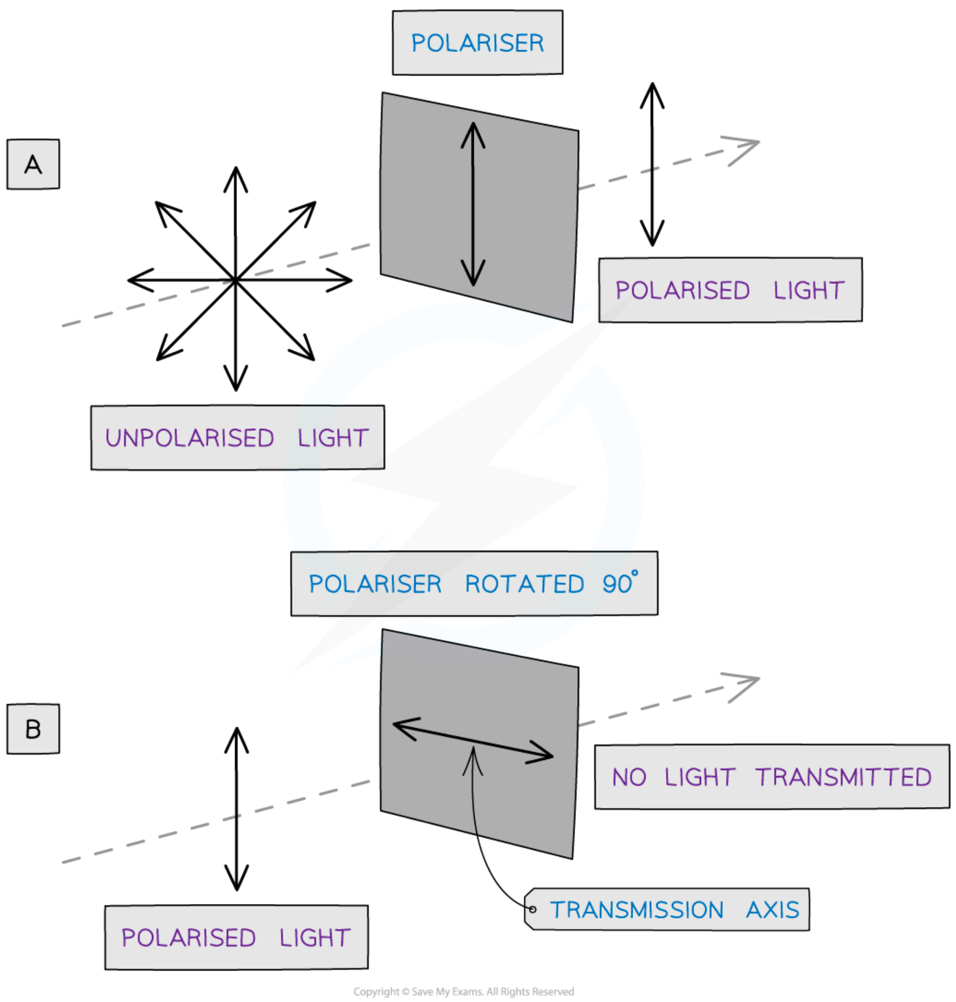


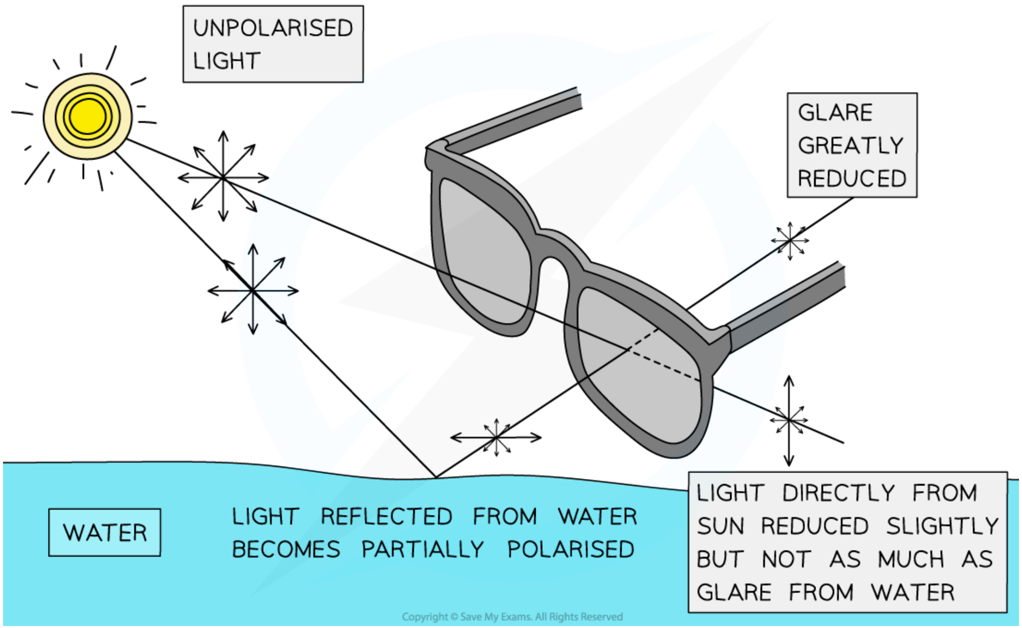
Diagram showing an unpolarised and polarised wave travelling through polarisers

Polarisation by reflection

- When light is reflected from a non-metallic surface e.g. the surface of water or a wet road, it undergoes **partial plane polarisation**
- Reflected light is polarised in a plane **parallel** to the reflecting surface
  - This means if the surface is horizontal, a proportion of the reflected light will oscillate more in the horizontal plane than in the vertical plane
- Sunglasses with vertically aligned Polaroid lenses can block this horizontally polarised light

Your notes

- As a result, they can reduce glare, which means
  - objects under the surface of water can be viewed more clearly
  - drivers can see the road more clearly

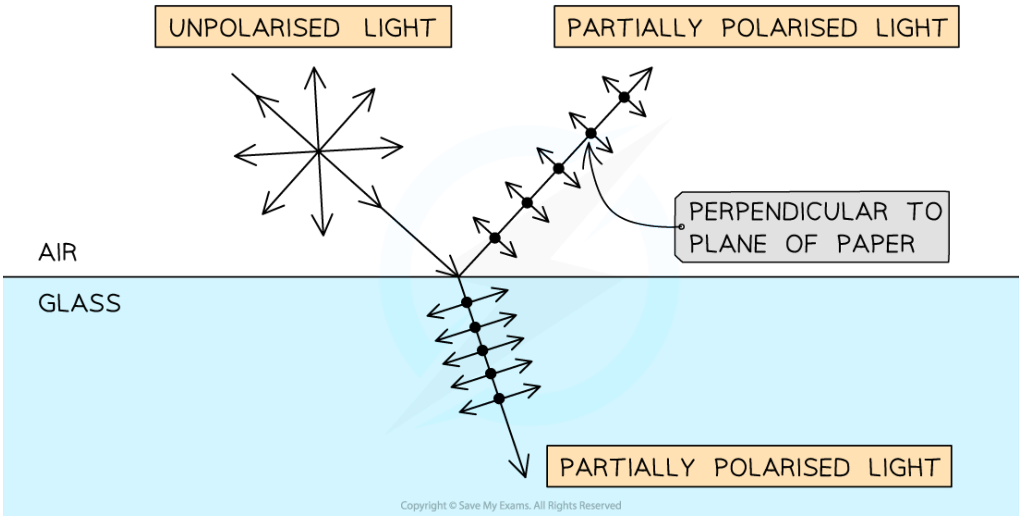


When sunlight reflects off a horizontal reflective surface, such as water, the light becomes horizontally polarised. This is where Polaroid sunglasses come in useful with their vertically aligned polarising filters

Polarisation by refraction

- Light can also become partially polarised by refraction when transmitted from one medium into another, such as from air into glass or water
- Refracted light is polarised in a plane **perpendicular** to the transmitting surface
  - This means if the surface is horizontal, a proportion of the transmitted (refracted) light will oscillate more in the vertical plane than in the horizontal plane
- When unpolarised light is incident on a horizontal surface into which it can refract:
  - some of the light is **reflected**, partially polarising it in the **horizontal** plane
  - some of the beam is **transmitted** and **refracted**, also partially polarising it, but in the **vertical** plane

Your notes



Unpolarised light can be partially polarised by both reflection and refraction at the boundary between two media, such as air and glass

Using polarisation for stress analysis

- Polarising filters can be used to observe stress concentrations in materials due to changes in refractive index
- A sample of transparent material (such as plastic) is positioned between two polarising filters with their planes at 90° to one another
  - When the material is unstressed, no light passes through
  - When the material is stressed, the plane of polarisation of the light passing through the material is rotated
- Different areas under different degrees of stress cause light to pass through at different speeds
- The result is an interference pattern with different colours revealing areas of varying stress in the material
  - The **brighter** regions represent areas under **more** stress
  - The **darker** regions represent areas under **less** stress

Using polarisation for chemical analysis

- Polarising filters can also be used to analyse the strength of chemical samples, such as sugar solutions
- In a similar way to materials under stress, chemical solutions can also rotate the plane of polarisation of the light passing through
- The degree of polarisation depends on the concentration of the solution
  - The **higher** the concentration of the sample, the **greater** the angle at which the light emerges

Your notes

- The **lower** the concentration of the sample, the **smaller** the angle at which the light emerges

Your notes