A Level Physics Edexcel

5. Waves & Particle Nature of Light

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Transverse & Longitudinal Waves

5.1 Properties of Waves

Properties of Waves

- Waves are generated by **oscillating sources**
  - These oscillations travel **away** from the source
- Oscillations can propagate through a **medium** (e.g. air, water) or in a **vacuum** (i.e. no particles), depending on the wave type

Wave Features

- In order to describe the properties of travelling waves, the following keywords need to be defined:
  - **Wavelength** λ (m) is the distance between a point on a wave and the same point on the next cycle of the wave, e.g. two crests, or two troughs
  - **Amplitude** A (m) is the magnitude of the maximum displacement reached by an oscillation in the wave
  - **Period** T (s) is the time taken for one complete oscillation at one point on the wave
  - **Frequency** f (Hz) is the number of complete wave cycles per second
  - **Wave speed c** (m s^{-1}) is the rate of movement of the wave

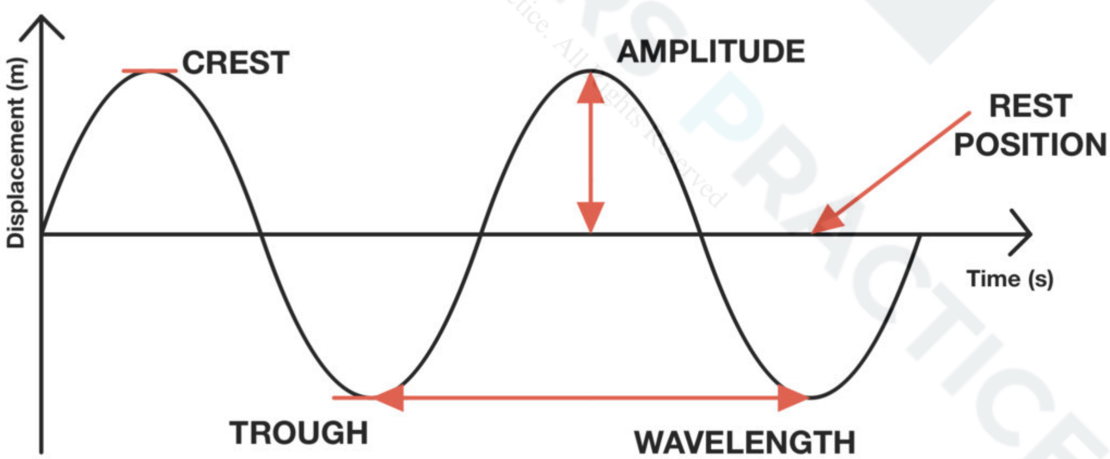
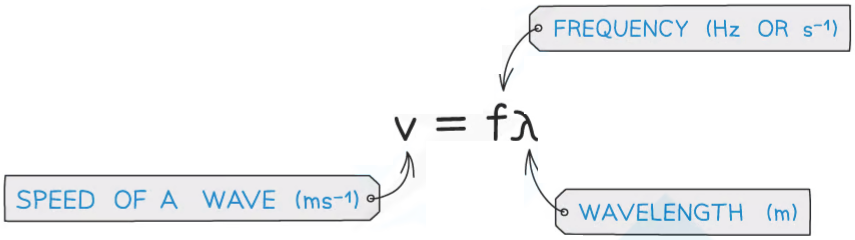


Diagram showing the amplitude and wavelength of a transverse wave

The Wave Equation

The Wave Equation

- This equation links wave speed, frequency and wavelength



- Where:
  - v = velocity of the wave (m s^{-1})
  - f = frequency of the wave (Hz)
  - λ = wavelength (m)
- The wave equation tells us that for a wave of constant speed:
  - As the wavelength **increases,** the frequency **decreases**
  - As the wavelength **decreases,** the frequency **increases**

Longitudinal Waves

Longitudinal Waves

- A longitudinal wave is one where the particles oscillate **parallel** to the;
  - Propagation of the wave
  - Direction of energy transfer
- Longitudinal waves show areas of
  - **High pressure,** called **compressions**
  - **Low pressure**, called **rarefactions**

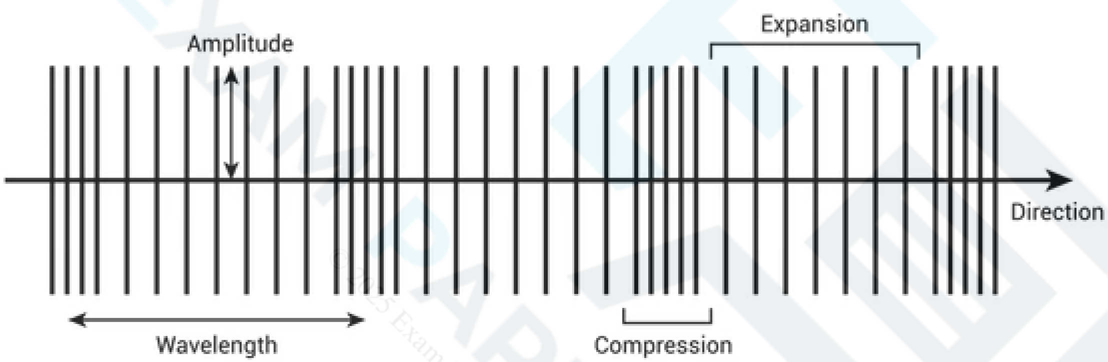
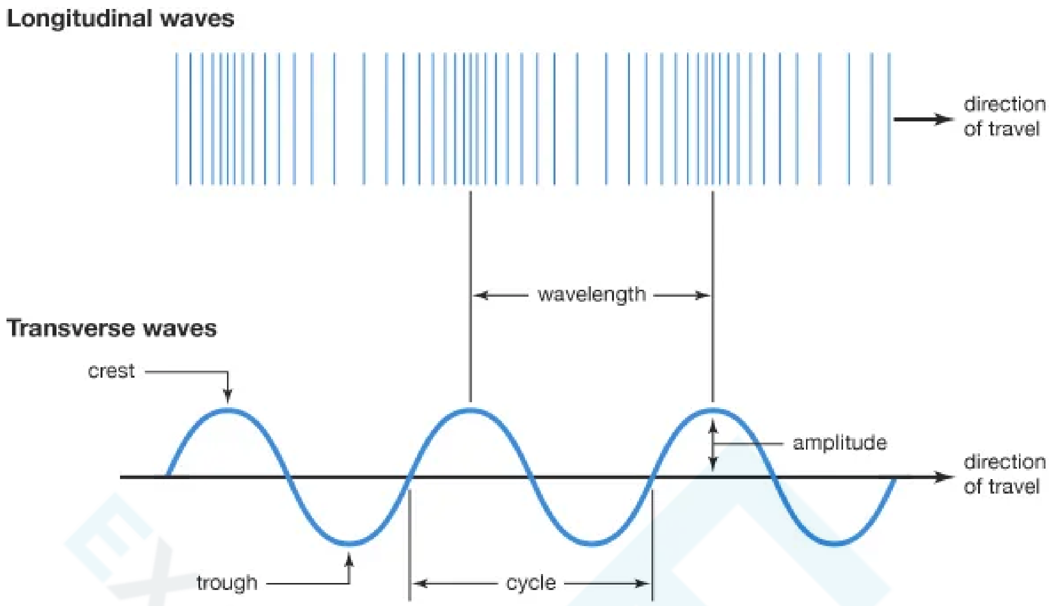


Diagram of a longitudinal wave

- Examples of longitudinal waves are:
  - Sound waves
  - Ultrasound waves
  - P-waves caused by earthquakes
- Longitudinal waves **cannot** be polarised

Labelling Longitudinal Waves

- You learned how to describe the properties of a wave, such as amplitude and wavelength at the start of this topic
  - The diagram shows a wavelength on a longitudinal wave



Wavelength is shown on a longitudinal wave

Exam Tip

Questions about longitudinal waves typically start by asking for a definition, so be ready with a statement about areas of high and low pressure and the keywords compression and rarefaction.

Be careful with graphs of waves and don't assume a sinusoidal-shaped graph represents a transverse wave. Longitudinal waves can also look sinusoidal when plotted on a graph - make sure you read the question and look for whether the wave travels **parallel** (longitudinal) or **perpendicular** (transverse) to the direction of travel to confirm which type of wave it is.

Transverse Waves

Transverse Waves

- A transverse wave is one where the particles oscillate **perpendicular** to the direction of the
  - Propagation of the wave
  - Direction of energy transfer
- Transverse waves show areas of **crests** (peaks) and **troughs**

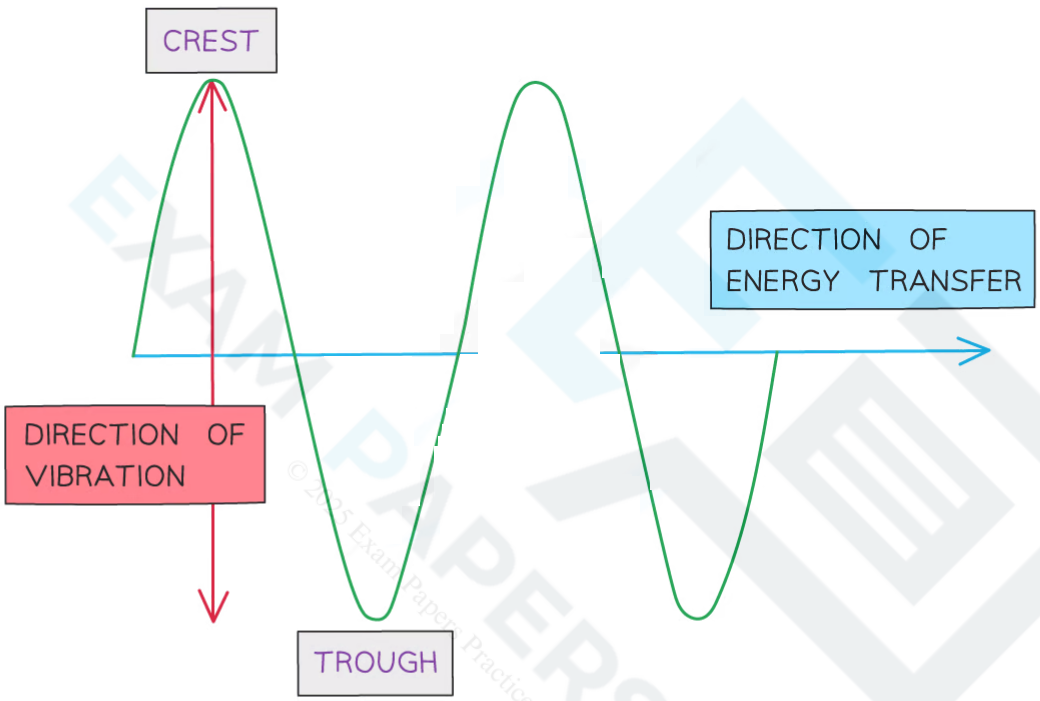


Diagram of a transverse wave

- Examples of transverse waves are:
  - Electromagnetic waves e.g. radio, visible light, UV
  - Vibrations on a guitar string
  - Waves on a rope or slinky
- Transverse waves can be polarised

Exam Tip

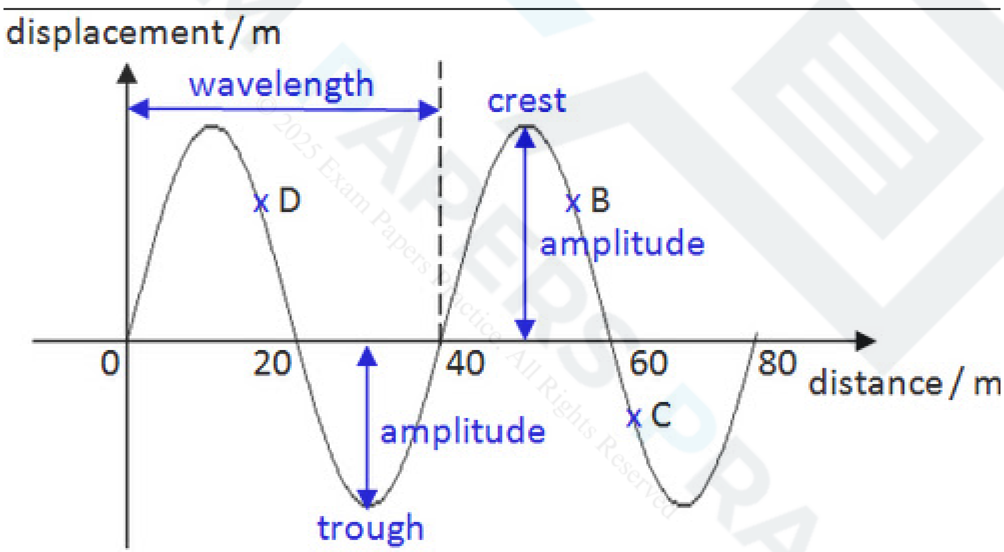
Questions about transverse waves typically start by asking for a definition, so be ready with a statement about **vibrations** or **oscillations** being perpendicular to the travel of the wave.

Graphs of Transverse & Longitudinal Waves

Graphs of Transverse Waves

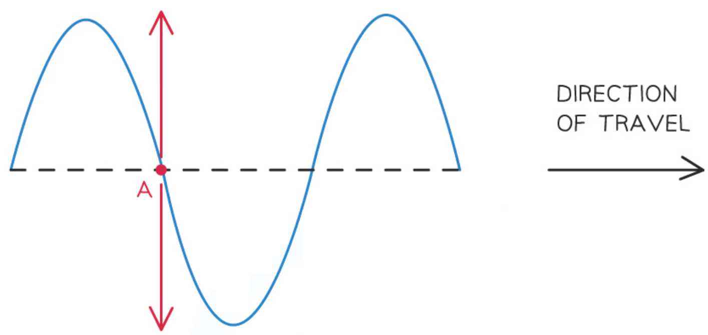
- There are two common graphs transverse waves;
  - Displacement against distance
  - Displacement against time
- These are:
  - **Similar** because they produce a **sinusoidal** shaped curve
  - **Different** because displacement against distance is showing displacement of a point on the wave, but displacement against time is showing the wave itself moving along a line

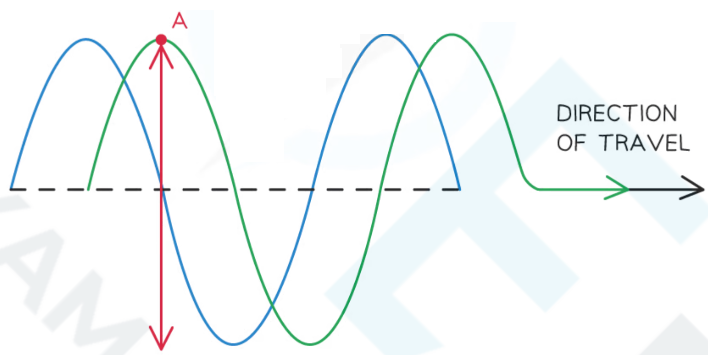
- On the **displacement-distance graph**:
  - Movement upwards from the centre line is given a positive sign and movement downwards a negative
  - The amplitude and wavelength can be found as shown below



- On the **displacement-time graph:**
  - The time period can be taken directly as shown
  - This means that frequency can be found indirectly as f = 1/T

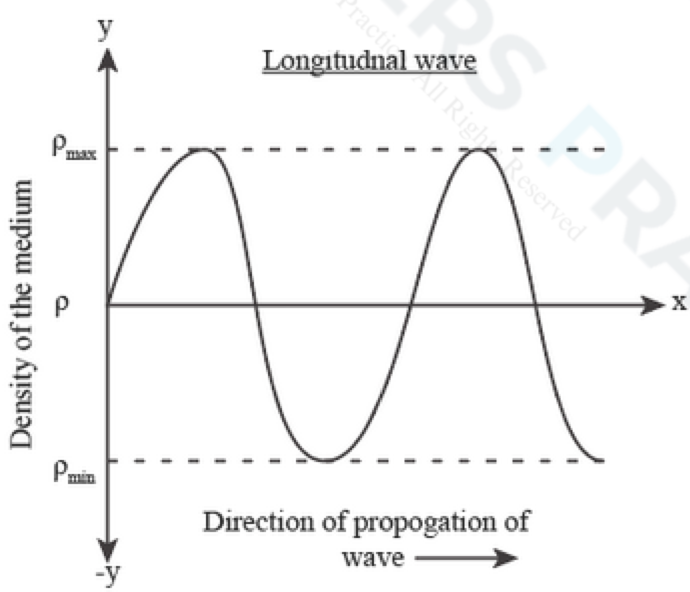
- To determine the next position of a point on the wave
  - Sketch the full wave after time has passed by looking at the direction of travel
  - Each point oscillates perpendicular to the wave, so remains on the normal line wherever the wave intersects, this is shown in red below





Graphs of Longitudinal Waves

- Plotting displacement against distance also produces a sinusoidal shaped graph
    - This can be used to show where the compressions and rarefactions will be found



Core Practical 6: Investigating the Speed of Sound

Aim of the Experiment

- To measure the speed of sound in air using an oscilloscope and a signal generator

Variables

- Independent variable = Distance
- Dependent variable = Phase of received signals
- Control variables:
  - Same location to carry out the experiment
  - For **each set of readings**, the same frequency of sound

Equipment

- Signal generator with loudspeaker
- Oscilloscope with 2-beam facility
- Microphone
- 2 metre rulers or 1 measuring tape of at least 2 m length
- Connecting leads

Method

1. Connect the microphone and signal generator to an oscilloscope, and set up the signal generator about 50 cm from the microphone
2. Set the signal to about 4 kHz
3. The oscilloscope should trigger when the microphone detects a sound, adjust the time base so that the signal from the generator and the microphone can be on the screen with about three cycles visible
4. Adjust the separation so a trough on the upper trace coincides with a peak on the lower trace (this makes judging the point where the waves coincide easier)
5. Record the distance between the microphone and signal generator (call this distance 1, d_1)
6. Move the microphone further away, watch the traces on the screen
7. When the next trough and peak coincide record the new distance (call this distance 2, d_2)
8. Repeat steps 6 and 7 as many times as possible in the available space (numbering the distances as required)
9. Calculate the mean wavelength of the sound
10. Using the oscilloscope trace find the frequency of the sound
11. Reduce the frequency to around 2 kHz (or half of the original value) and repeat steps 4–10.

Table of Results:

TIME PERIOD / μ s	FREQUENCY / kHz	d_1 / m	d_2 / m	d_3 / m

Analysis of Results

- The speed of sound can be calculated using the equation:

$$v = f\lambda$$

- Frequency is found from the time base of the oscilloscope by using

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

Evaluating the Experiment

Systematic Errors:

- Ensure the scale of the time base is accounted for correctly
  - The scale is likely to be small (e.g. milliseconds) so ensure this is taken into account when calculating frequency
- Use the oscilloscope signal trace to find frequency to avoid relying on the dial of the signal generator

Random errors:

- Random errors in taking measurements can be reduced by doing repeat readings and taking an average
- The time interval is small so make the distance between the microphone and signal generator as large as is practical

Safety Considerations

- The voltage and current are low, so normal care with electrical equipment is sufficient (including checking the leads for any signs of damage)
- Keep sound at a normal listening volume to avoid damage to hearing

Exam Tip

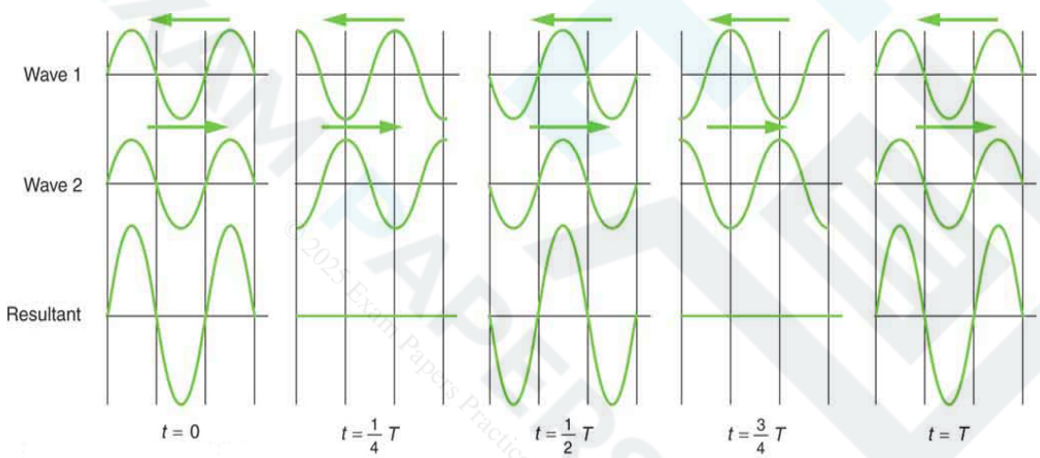
When you are answering questions about methods to measure waves, the question could ask you to comment on the accuracy of the measurements

When measuring the speed of sound, this experiment is very accurate because the timing is done automatically so reaction time is not a factor

Interference & Superposition of Waves

- **Interference** occurs whenever two or more waves combine to produce a resultant wave with a new amplitude
- **Superposition** literally means to be **positioned over** something
  - When waves interfere and combine, they do so according to the **principle of superposition**

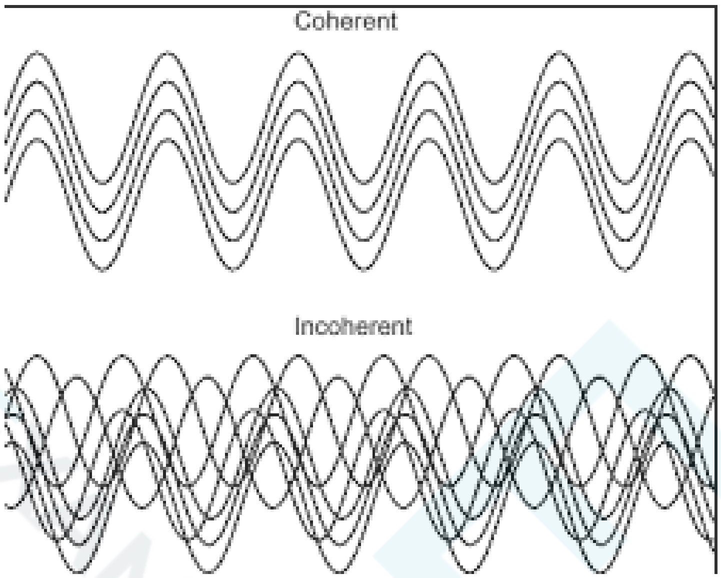
- If two wavefronts are travelling towards each other they will combine by superposition and then pass through
- The wavefronts will emerge unchanged on the other side



- Interference due to superposition can be constructive or destructive
  - **Constructive interference** happens when the resultant wave has a larger amplitude than any of the individual waves
  - **Destructive interference** happens when the resultant wave has a smaller amplitude than the individual waves

Coherence

- Interference is only observable if produced by a **coherent** source
- Waves are said to be coherent if they have:
  - A **constant phase difference**
  - The **same frequency**



Coherent waves (on the left) and non-coherent waves (on the right). The abrupt change in phase creates an inconsistent phase difference

- For example, in light, a coherent beam of light contains light waves that are **monochromatic** and have a constant phase difference
  - Monochromatic light consists of light waves of a **single frequency**
  - Laser light is an example of a coherent light source
  - Filament lamps produce incoherent light waves

Exam Tip

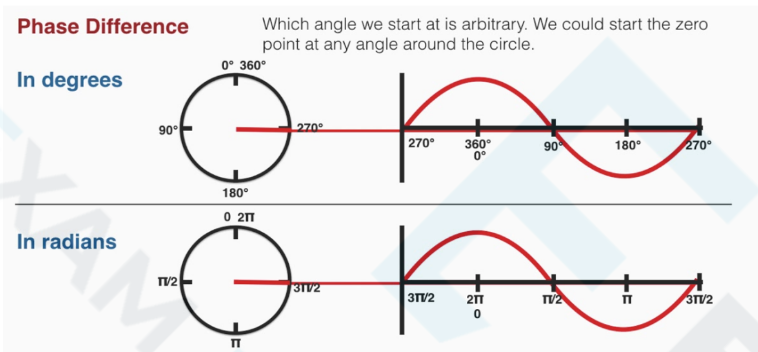
It can sometimes be tricky to identify whether constructive or destructive interference is taking place. If two waves meet at the same point on each wave e.g. two crests then the interference will be constructive, if not it will be destructive.

Phase & Path Difference

- Waves are said to be **coherent** if they have:
  - The same **frequency**
  - A **constant phase difference**

Phase Difference

- Two points on a wave, or on different waves, are in phase when they are the same point in their wave cycle
- The angle between their wave cycles is the phase difference

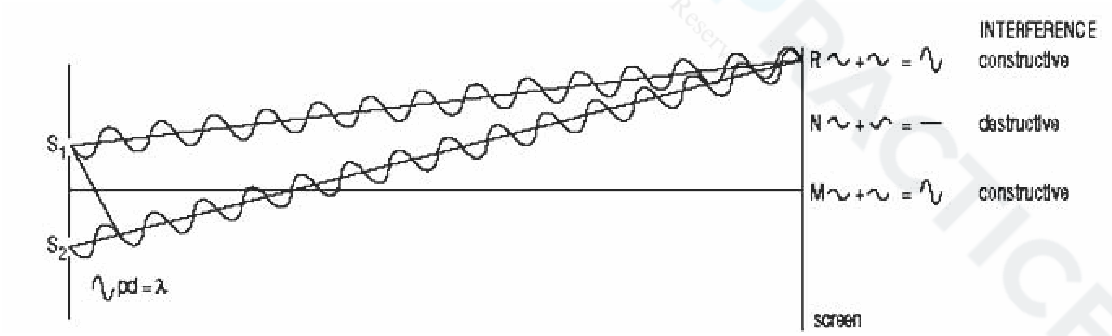


Path Difference

- The type of interference occurring at a given point (i.e. constructive or destructive) depends on the **path difference** of the overlapping waves
- Path difference is defined as:

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

- Path difference is generally expressed in multiples of wavelength

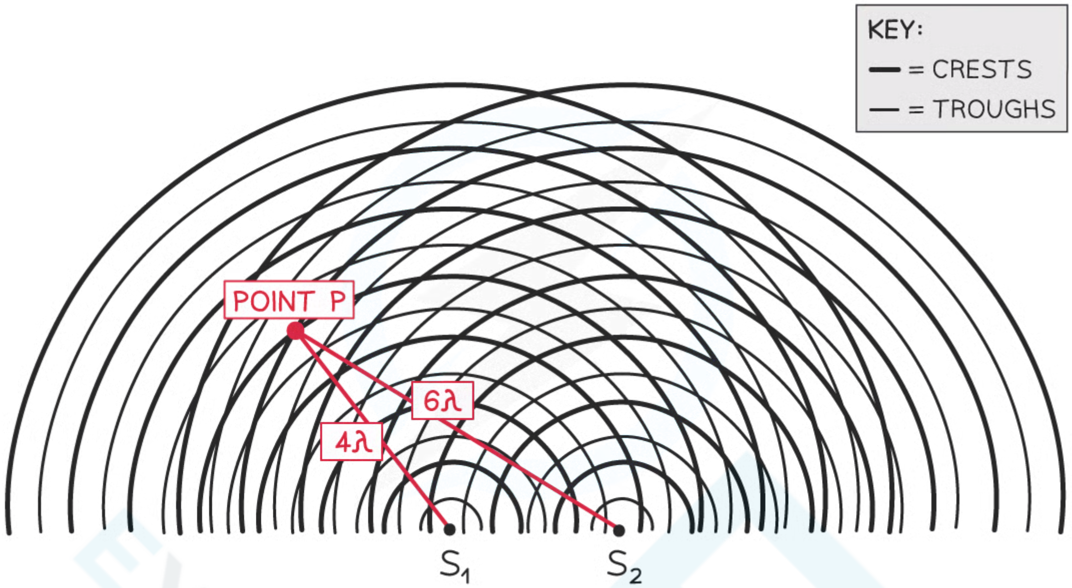


At point P_2 the waves have a path difference of a whole number of wavelengths resulting in constructive interference. At point P_1 the waves have a path difference of an odd number of half wavelengths resulting in destructive interference

- 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 at point P_1 is $6.5\lambda - 6\lambda = \boldsymbol{\lambda / 2}$
- The path difference at point P_2 is $7\lambda - 6\lambda = \boldsymbol{\lambda}$
- In general:
    - The condition for constructive interference is a path difference of $\boldsymbol{n\lambda}$
    - The condition for destructive interference is a path difference of $\boldsymbol{(n + ½)\lambda}$
    - In this case, n is an integer i.e. 0, 1, 2, 3...

- Hence:
    - **Destructive interference** occurs **at** point $\mathbf{P_1}$
    - **Constructive interference** occurs **at** point $\mathbf{P_2}$

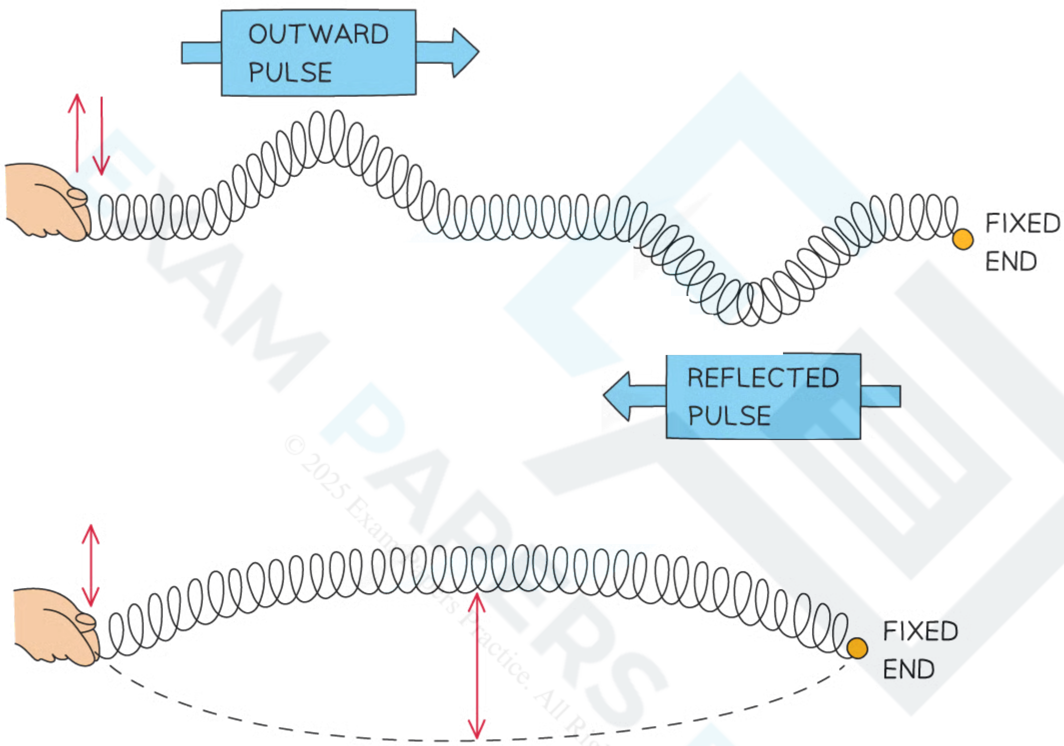


At point P the waves have a path difference of a whole number of wavelengths resulting in constructive interference

- Another way to represent waves spreading out from two sources is shown in the diagram above
- At point **P**, the number of **crests** from:
  - Source $S_1 = 4\lambda$
  - Source $S_2 = 6\lambda$
- The path difference at **P** is $6\lambda - 4\lambda =$ **2λ**
- This is a whole number of wavelengths, hence **constructive interference** occurs at point **P**

Stationary Waves

- **Stationary waves**, or standing waves, are produced by the **superposition** of two waves of the **same frequency** and **amplitude** travelling in **opposite directions**
- This is usually achieved by a travelling wave and its **reflection**. The superposition produces a wave pattern where the **peaks** and **troughs do not move**

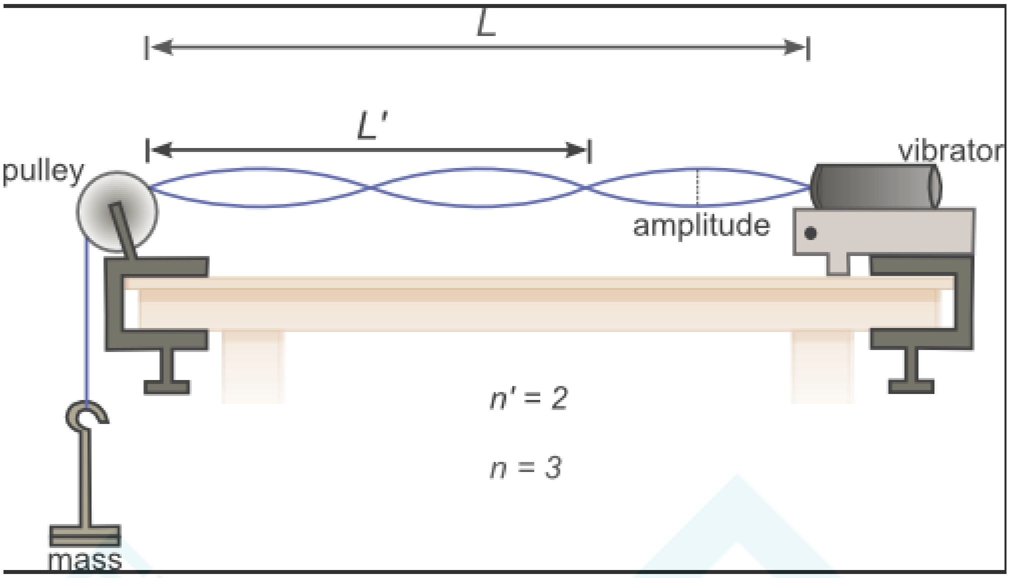


Formation of a stationary wave on a stretched spring fixed at one end

- In this section, we will look at a few experiments that demonstrate stationary waves in everyday life

Stretched Strings

- Vibrations caused by stationary waves on a stretched string produce sound
  - This is how stringed instruments, such as guitars or violins, work
- This can be demonstrated by an oscillator vibrating a length of string under tension fixed at one end:

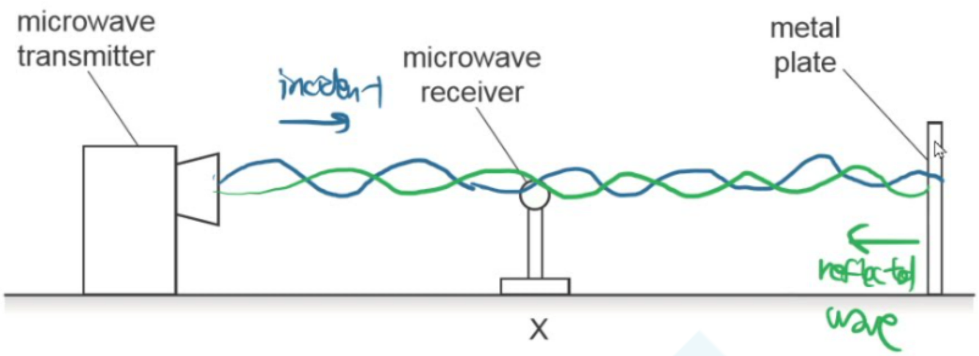


Stationary wave on a stretched string

- As the frequency of the oscillator changes, standing waves with different numbers of **minima** (**nodes**) and **maxima** (**antinodes**) form

Microwaves

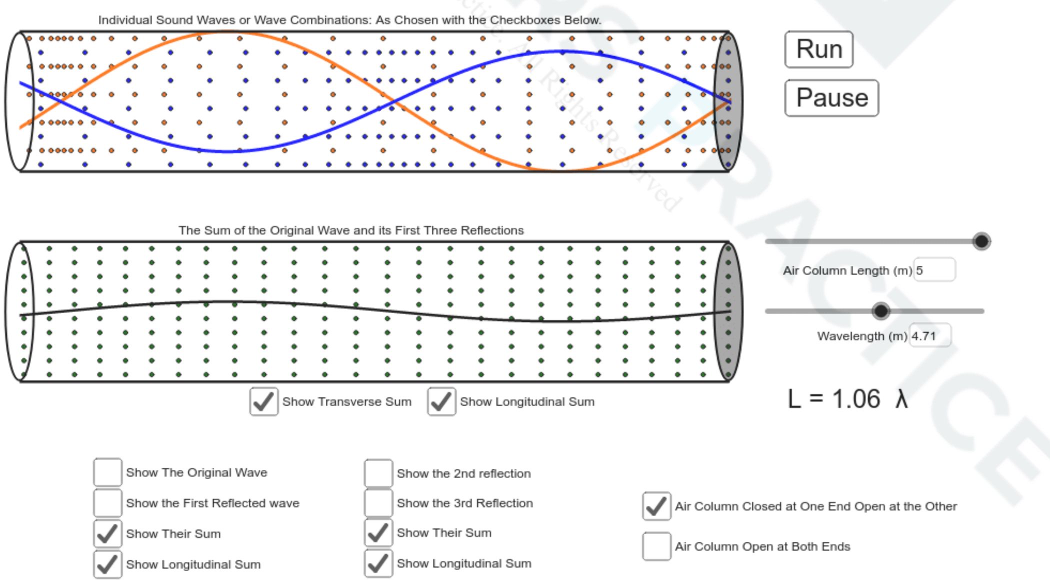
- A microwave source is placed in line with a **reflecting plate** and a small **detector** between the two
- The reflector can be moved to and from the source to vary the stationary wave pattern formed
- By moving the **detector**, it can pick up the minima (nodes) and maxima (antinodes) of the stationary wave pattern



Using microwaves to demonstrate stationary waves

Air Columns

- The formation of stationary waves inside an air column can be produced by sound waves
  - This is how musical instruments, such as clarinets and organs, work
- This can be demonstrated by placing a fine powder inside the air column and a loudspeaker at the open end
- At certain frequencies, the powder forms evenly spaced heaps along the tube, showing where there is **zero disturbance** as a result of the nodes of the stationary wave

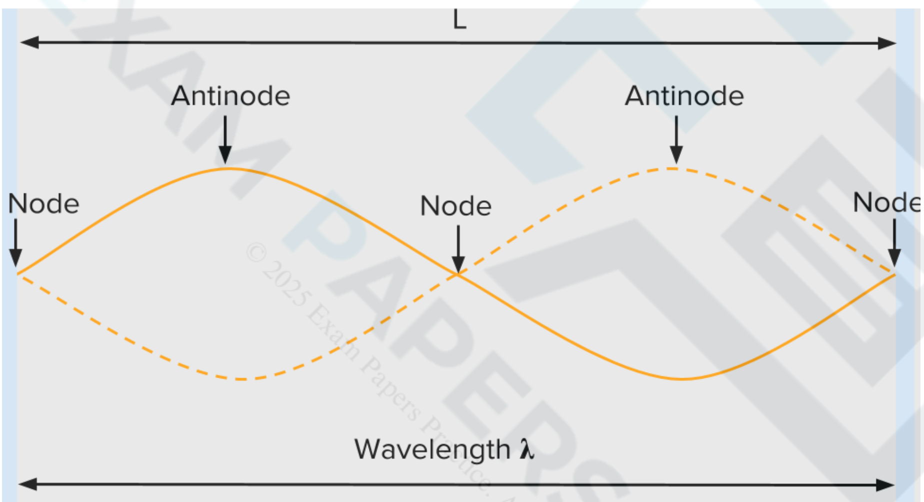


Stationary wave in an air column

- In order to produce a stationary wave, there must be a minima (node) at one end and a maxima (antinode) at the end with the loudspeaker

Nodes and Antinodes

- A stationary wave is made up **nodes** and **antinodes**
  - **Nodes** are where there is no vibration
  - **Antinodes** are where the vibrations are at their maximum amplitude
- The nodes and antinodes **do not** move along the string. Nodes are fixed and antinodes only move in the vertical direction
  - Between nodes, all points along the stationary wave are in phase
  - The image below shows the nodes and antinodes on a snapshot of a stationary wave at a point in time



- L is the length of the string
- 1 wavelength λ is only a portion of the length of the string

5.10 Wave Speed on a Stretched String

Wave Speed on a Stretched String

- The speed of a wave travelling along a string with two fixed ends is given by:

- Where:
  - T = tension in the string (N)
  - μ = mass per unit length of the string (kg m^{-1})

- At the fundamental frequency, f_0 of a stationary wave of length L, the wavelength, $\lambda = 2L$
- Therefore, according to the wave equation, the speed of the stationary wave is:

$$v = f\lambda = f \times 2L$$

- Combining these two equations leads to the equation for the **fundamental frequency** (sometimes referred to as the first harmonic):

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

- Where:
  - f = frequency (Hz)
  - L = the length of the string (m)
  - T = the tension in the string (N)
  - μ = mass per unit length (kg m^{-1})

- Mass per unit length, μ can be calculated by dividing the mass of the string by the length of the string

Core Practical 7: Investigating Stationary Waves

Aims of the Experiment

- The overall aim of the experiment is to measure how the frequency of the first harmonic is affected by changing one of the following variables:
  - The length of the string
  - The tension in the string
  - Strings with different values of mass per unit length

Variables

- Independent variable = either length, tension, or mass per unit length
- Dependent variable = frequency of the first harmonic
- Control variables
  - If length is varied = same masses attached (tension), same string (mass per unit length)
  - If tension is varied = same length of the string, same string (mass per unit length)
  - If mass per unit length is varied = same masses attached (tension), same length of the string

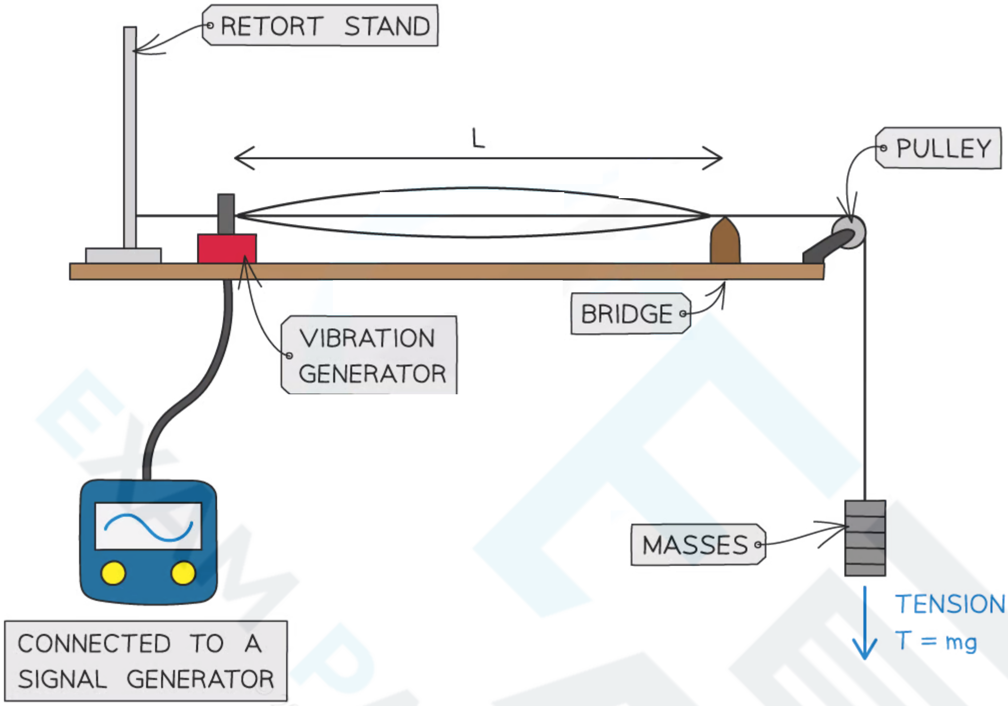
Equipment List

Apparatus	Purpose
Signal Generator	Used to operate the vibration generator and measure the frequency of the first harmonic
Vibration Generator	Connected to the signal generator to product the stationary wave
Retort Stand	To provide a stable fixed end on the table
G Clamp or 2 kg mass	To place on the retort, stand to stabilize apparatus
2.0m of string	Used to observe the stationary wave
Pulley	To allow the masses to hang vertically and introduces less friction than the edge of the table
Wooden Bridge	To provide the other fixed end which can vary the length of the string
Mass hanger + 100g masses	To hang from the pulley to vary the tension in the string
Meter ruler	To measure the length of the string
Top-pan balance	To measure the mass of the string

- Resolution of measuring equipment:
  - Metre ruler = 1 mm

- Signal generator ~ 10 nHz
- Top-pan balance = 0.005 g

Method



The setup of apparatus required to measure the frequency of the first harmonic at different values of length, tension, or mass per unit length

This method is an example of the procedure for varying the length of the string with the frequency – this is just one possible relationship that can be tested

1. Set up the apparatus by attaching one end of the string to the **vibration generator** and pass the other end over the bench pulley and secure to the mass hanger
2. Adjust the position of the bridge so that the length *L* is measured from the vibration generator to the bridge using a metre ruler
3. Turn on the **signal generator** to set the string **oscillating**
4. Increase the **frequency** of the vibration generator until the **first harmonic** (**nodes** at both ends and an **antinode** in the middle) is observed and read the frequency that this occurs at
5. **Repeat** the procedure with different lengths of *L*
6. Repeat the frequency readings at least two more times and take the **average** of these measurements
7. Measure the **tension** in the string using $T = mg$
    - Where m is the mass attached to the string and g is the gravitational field strength on Earth (9.81 N kg^{-1})
8. Measure the **mass per unit length** of the string, μ = mass of string ÷ length of string
    - Simply take a known length of the string (1 m is ideal) and measure its mass on a balance

Evaluating the Experiment

Systematic errors:

- An **oscilloscope** can be used to verify the signal generator's readings
- The signal generator should be left for about 20 minutes to stabilise
- The measurements would have a **greater resolution** if the length used is as large as possible, or as many half-wavelengths as possible
  - This means measurements should span a **suitable range**, for example, 20 cm intervals over at least 1.0 m

Random errors:

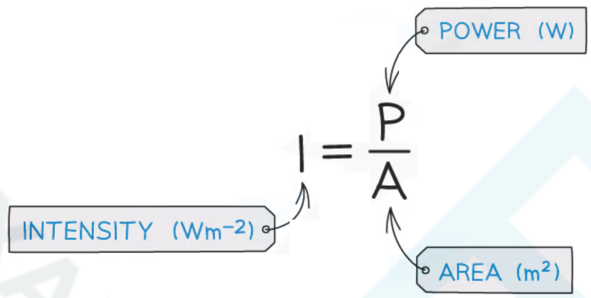
- The **sharpness** of resonance leads to the biggest problem in deciding when the first harmonic is achieved
  - This can be **resolved** by adjusting the frequency while looking closely at a node. This is a technique to gain the largest response
  - Looking at the amplitude is likely to be less reliable since the wave will be moving very fast
- When taking repeat measurements of the frequency, the best procedure is as follows:
  - Determine the **frequency** of the **first harmonic** when the largest vibration is observed and note down the frequency at this point
  - **Increase the frequency** and then gradually reduce it until the first harmonic is observed again and note down this frequency
  - If taking three repeat readings, repeat this procedure again
  - Average the three readings and move on to the next measurement

Safety Considerations

- Use a **rubber string** instead of a metal wire, in case it snaps under tension
- If using a metal wire, **wear goggles** to protect the eyes
- **Stand well away** from the masses in case they fall onto the floor
- Place a **crash mat** or a soft surface under the masses to break their fall

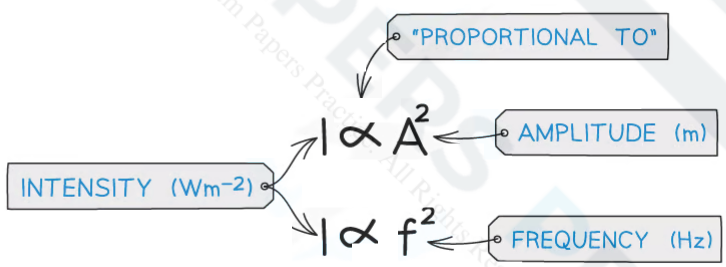
Equation for the Intensity of Radiation

- 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**

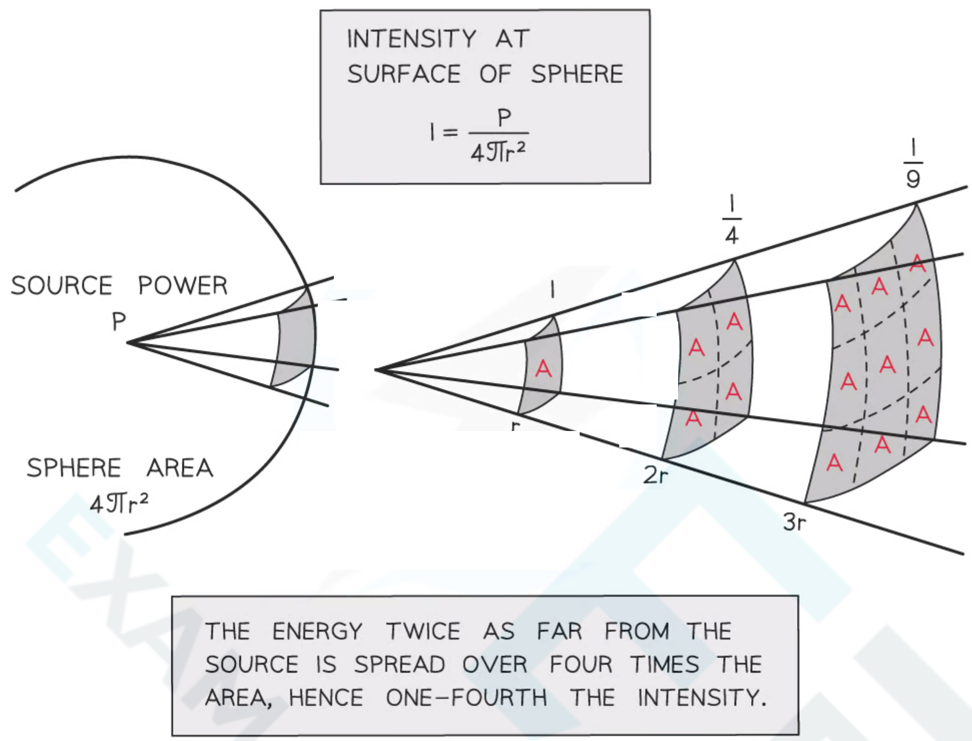


Intensity is proportional to the amplitude^2 and frequency^2

- 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:

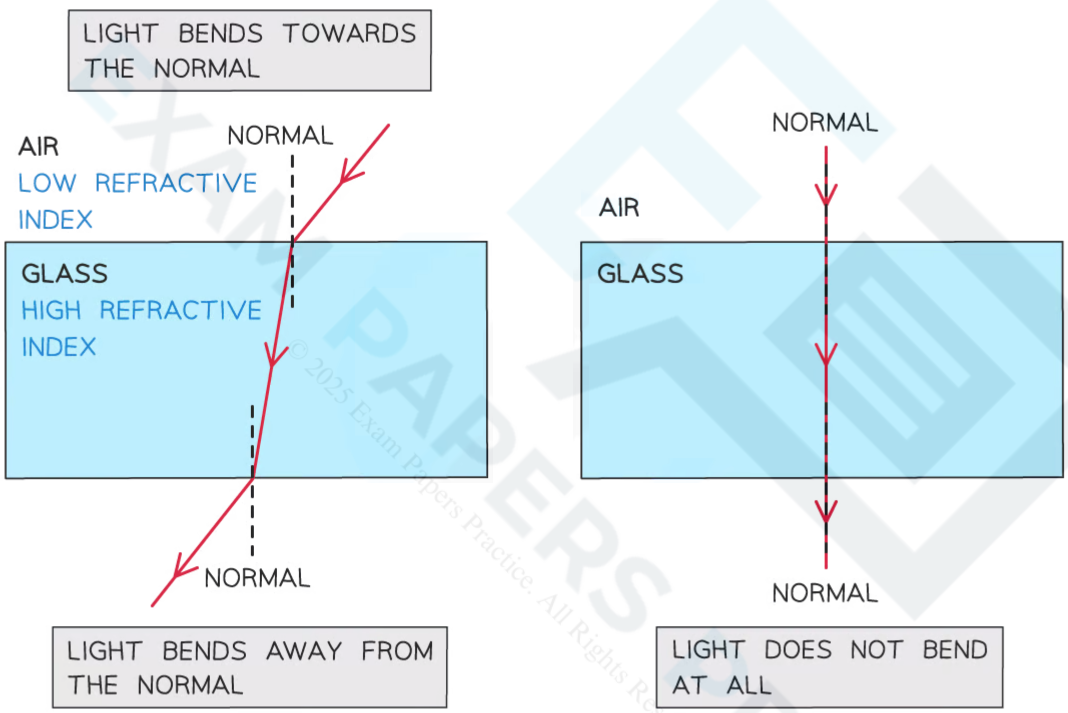


Intensity is proportional to the amplitude squared

- Assuming there's no absorption of the wave energy, the **intensity / 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**

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 speed **or** direction



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

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

- Where:
  - c = the speed of light in a vacuum (m s^{-1})
  - v = the speed of light in a substance (m s^{-1})

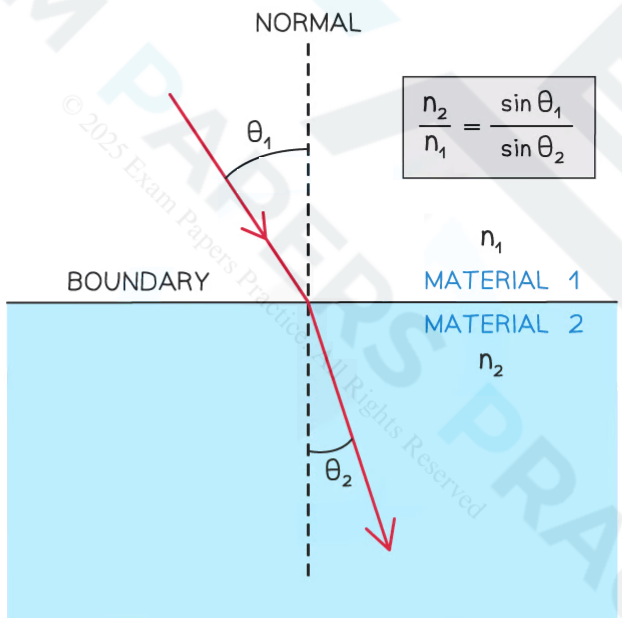
- Light travels at different speeds within different substances depending on their refractive index
  - A material with a high refractive index is called **optically dense**, such material causes light to travel **slower**
- Since the speed of light in a substance will always be less than the speed of 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**

Critical Angle

- As the angle of incidence 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
  - At this point, the angle of incidence is known as the **critical angle C**
- This angle can be found using the formula:

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

- This can easily be derived from Snell's law where:
  - $\theta_1 = C$
  - $\theta_2 = 90°$
  - $n_1 = n$
  - $n_2 = 1$ (air)

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)

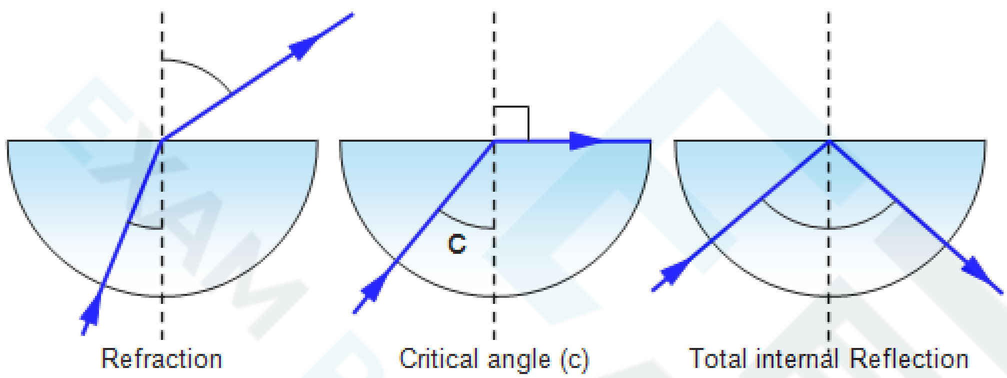
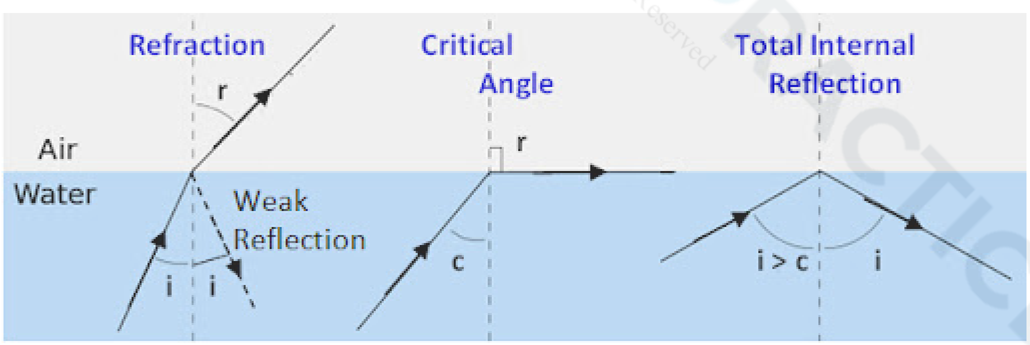


Diagram showing refraction, the critical angle and total internal reflection

- 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**



Exam Tip

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**

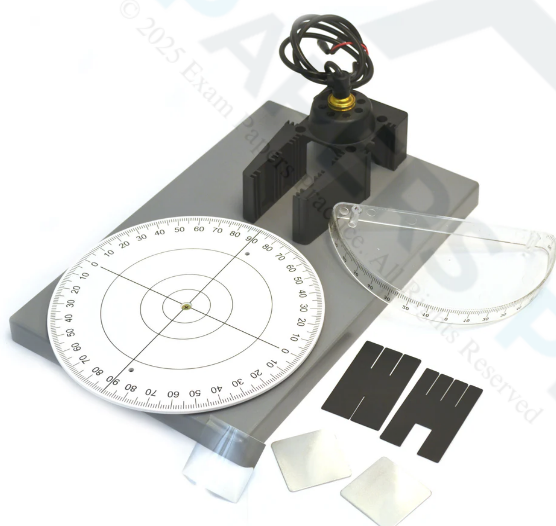
Equipment

- 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
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

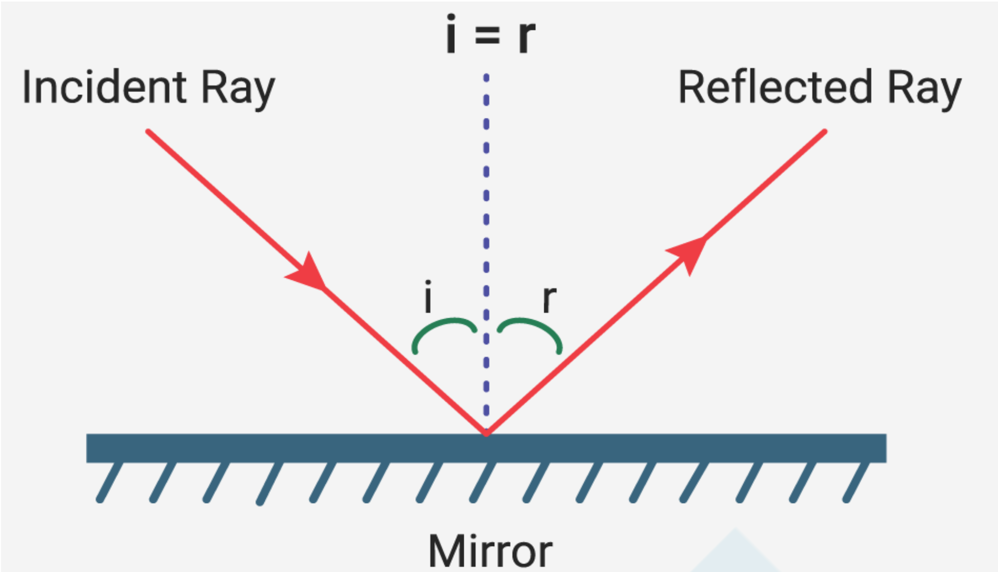
- For light rays **exiting** the perspex block, the light ray refracts **away** from the central line:

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

Exam Tip

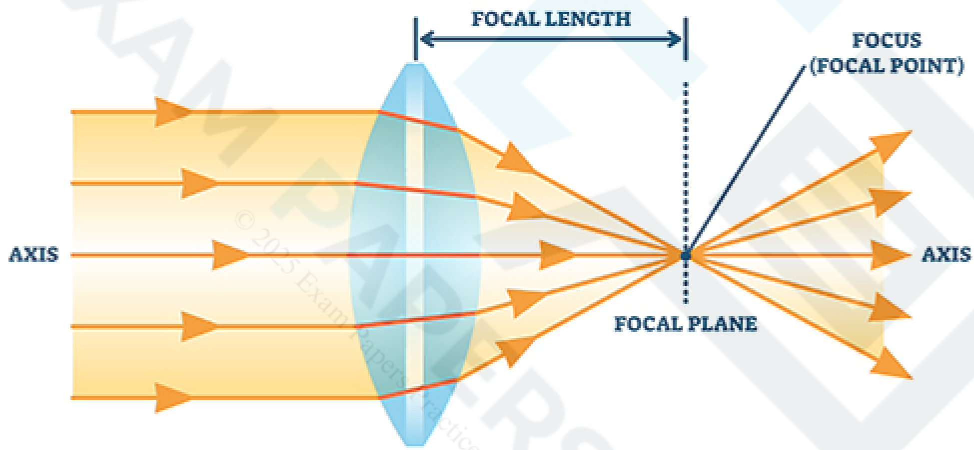
In your examination you could be asked about the method for this experiment or given a set of results and asked how accurate they are or how they can be improved.

Converging & Diverging Lenses

- A lens is a piece of equipment that forms an image by **refracting** light
- There are two types of lens:
  - Convex
  - Concave

Convex Lenses

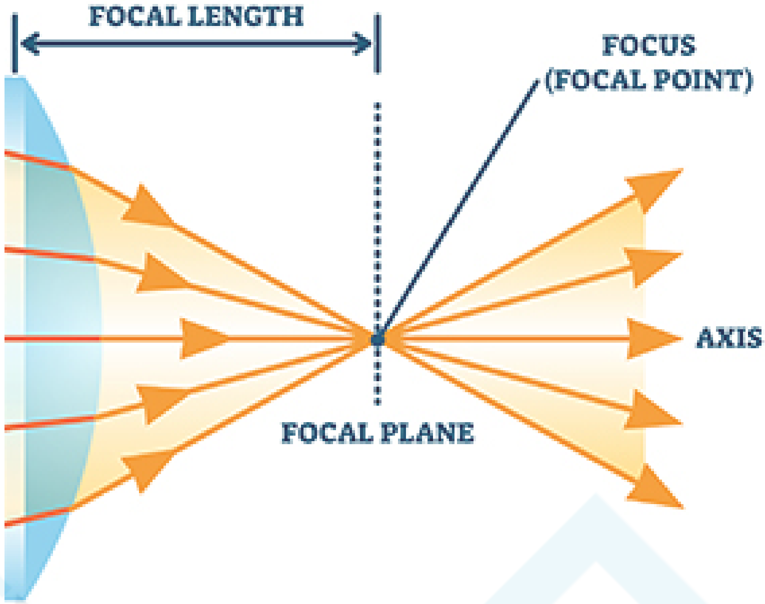
- In a convex lens, parallel rays of light are brought to a focus by refraction
  - This point is called the **principal focus**
- This lens is sometimes referred to as a **converging** lens
- The distance from the lens to the principal focus is called the **focal length**
  - This depends on how **curved** the lens is
  - The **more** curved the lens, the **shorter** the focal length



The focal length is the distance from the lens to the principal focus

Concave Lenses

- In a concave lens, parallel rays of light are made to diverge (spread out) from a point
  - This lens is sometimes referred to as a **diverging** lens
- The principal focus is now the point from which the rays appear to diverge from



Parallel rays from a concave lens appear to come from the principal focus

Exam Tip

To remember which lens is converging or diverging, think of the following: Con**v**ex lens = Con**v**erging

To remember which lens is which, a concave lens goes in at the middle, like a cave. Okay, not a very exciting cave, but all the same...

Using Ray Diagrams

Describing images formed by lenses

- Images are described using three concepts
- They are either:
  - **Real** or **virtual**
  - **Bigger** than, the **same size** as or **smaller** than the object
  - **Inverted** or the **same way up** as the object
- A **real image** is one formed by the **convergence of rays** of light (the rays meet)
  - A real image can be projected onto a screen
- A **virtual image** is seen but not formed on a screen
  - The rays of light have not met, they have been perceived by the eye
  - An image viewed through a **magnifying glass** is a virtual image
- Lenses can be used to form images of objects placed in front of them
- The location (and nature) of the image can be found by drawing a ray diagram:

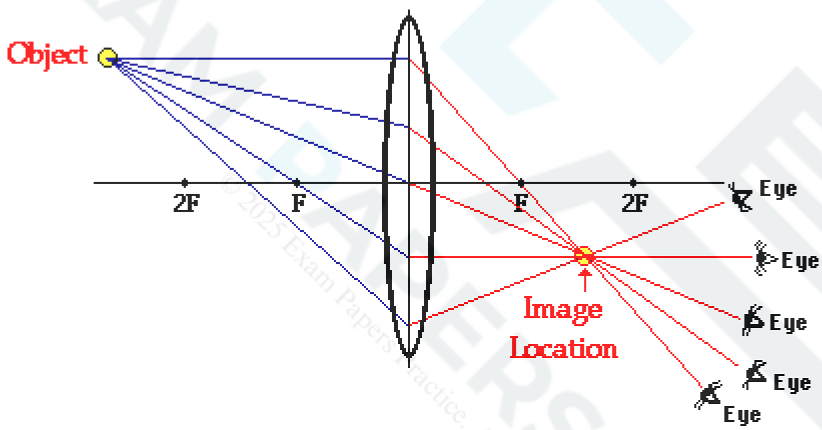


Diagram showing the formation of a real image by a lens

Drawing a Ray Diagram

1. Start by drawing a **ray going from the top** of the object **through the centre** of the lens. This ray will continue to travel in a straight line
2. Next draw a **ray going from the top of the object**, travelling **parallel to the axis** to the lens. When this ray emerges from the lens it will travel directly towards the principal focus
3. The image is found at the point where the two rays meet

- The above diagram shows the image that is formed when the object is placed at a distance between one focal length (f) and two focal lengths (2f) from the lens
- In this case, the image is:
  - **Real**
  - **Enlarged**
  - **Inverted**

* The following diagram shows what happens when the object is more distanced – further than twice the focal length (2f) from the lens:

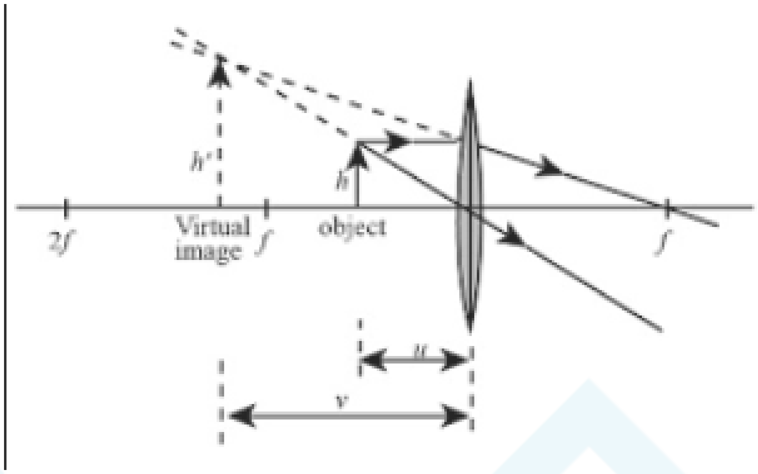


Diagram showing the formation of a real image by a lens with the object at distance

* In this case the image is:
  * **Real**
  * **Diminished (smaller)**
  * **Inverted**
* If the object is placed at exactly twice the focal length (2f) from the lens:

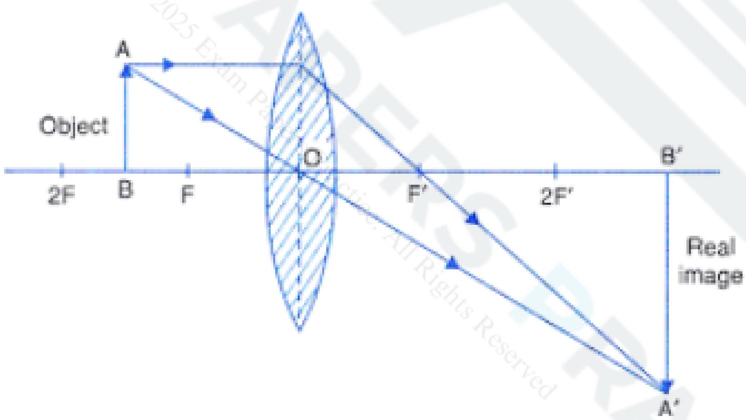


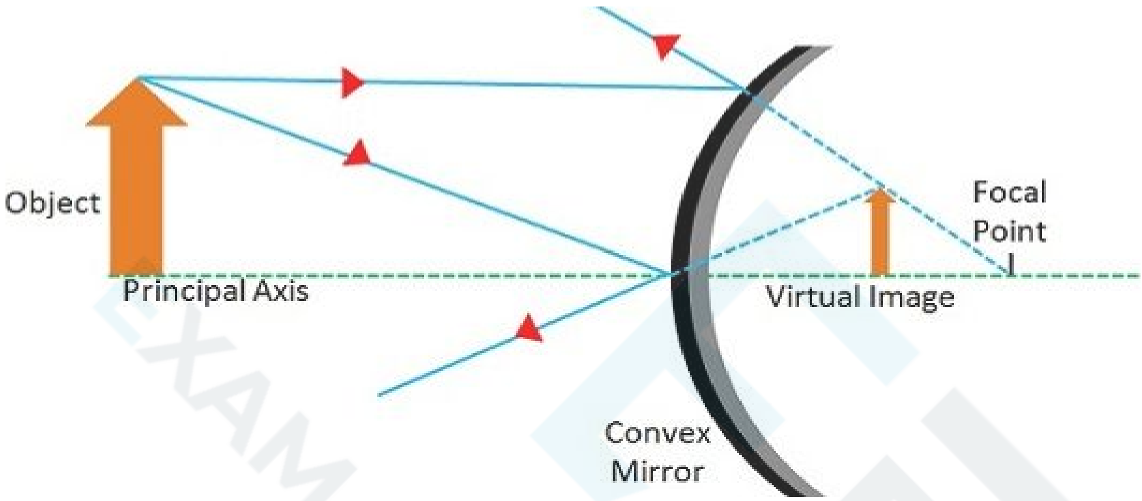
Diagram showing the formation of a real image with the object at 2f

* In this case the image is:
  * **Real**
  * **Same size as the object**
  * **Inverted**

Magnifying glasses

* If the object is placed **closer** to the **lens** than the **focal length**, the emerging **rays diverge** and a **virtual image** is formed

- When viewed from the right-hand side of the lens, the emerging rays appear to come from a point on the left. This point can be found by extending the rays backwards (creating virtual rays)
- A **virtual image** will be seen at the point where these virtual rays cross



A virtual image is formed by the divergence of rays from a point

- In this case the image is:
  - **Virtual**
  - **Enlarged**
  - **Upright**

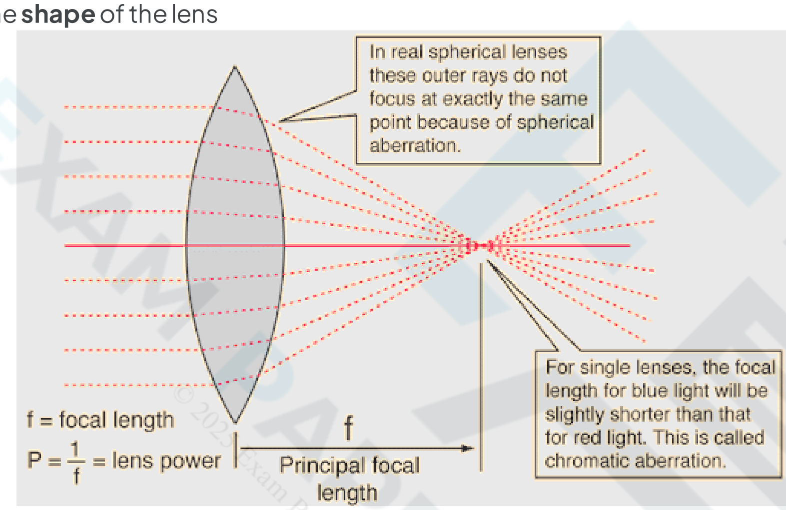
- Using a lens in this way allows it to be used as a **magnifying glass**
- When using a magnifying glass, the lens should always be held close to the object

Exam Tip

It is important to understand how the images are formed in both examples, as well as the type of image formed. You should practice drawing accurate lens diagrams. They are harder than they look!

Power of a Lens

- The **power** of a lens is a measure of its ability to **refract** light
  - The **more** refraction a lens causes, the **higher** its power
- The **power** of a lens measures how strongly it focuses the light
  - The **more** curved the lens, the **shorter** the focal length
  - The **shorter** the focal length, the **greater** the power of the lens
- The **power** of a lens is related to:
  - The **focal length** of the lens
  - The **shape** of the lens



The power of a lens depends on its focal length

Calculate the power of a lens

- The power of a lens, *P* is calculated using the following equation:

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

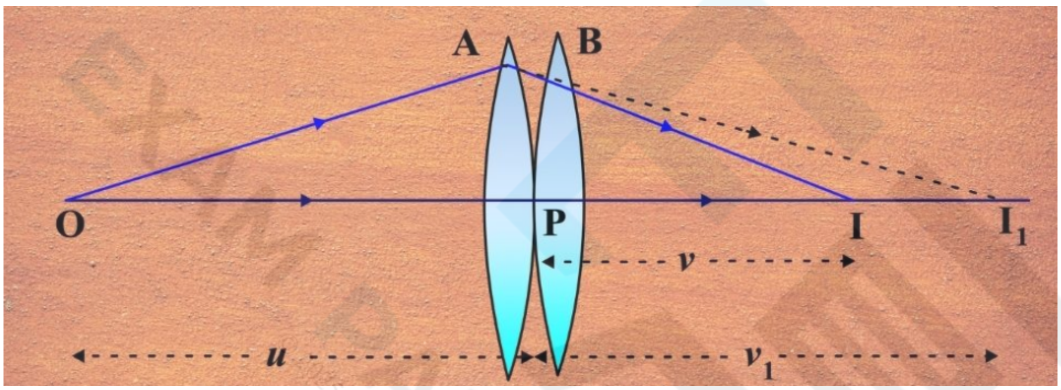
- Where:
  - P = power (dioptres, D)
  - f = focal length of the lens (m)
- **Power** is **inversely proportional** to **focal length**
- For a **concave mirror**, where the focal length is negative, power has a negative value

Thin Lenses in Combination

- When **multiple lenses** are used in **series** (one after the other) this is called a **compound lens**
- To find the **total power** of a compound lens, find the **sum of the powers** of the **individual lenses**

$$P_{Total} = P_1 + P_2 + \dots P_n$$

- Where:
  - P_{Total} = Total power of all the lenses (dioptre, D)
  - P_1 = power of lens 1 (dioptre, D)
  - P_2 = power of lens 2 (dioptre, D)

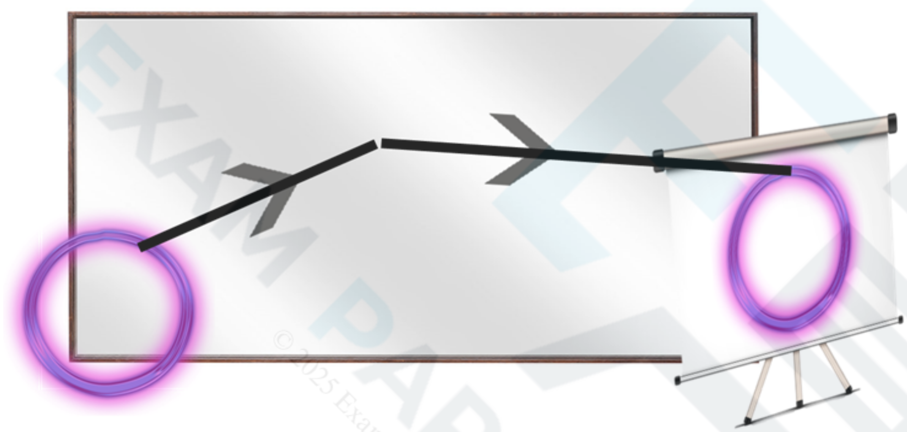


- In this case the image is:
  - Virtual
  - Diminished
  - Upright
- The lenses should be:
  - Arranged so that their principle axes line up
  - Touching or very close

Real & Virtual Images

Real Images

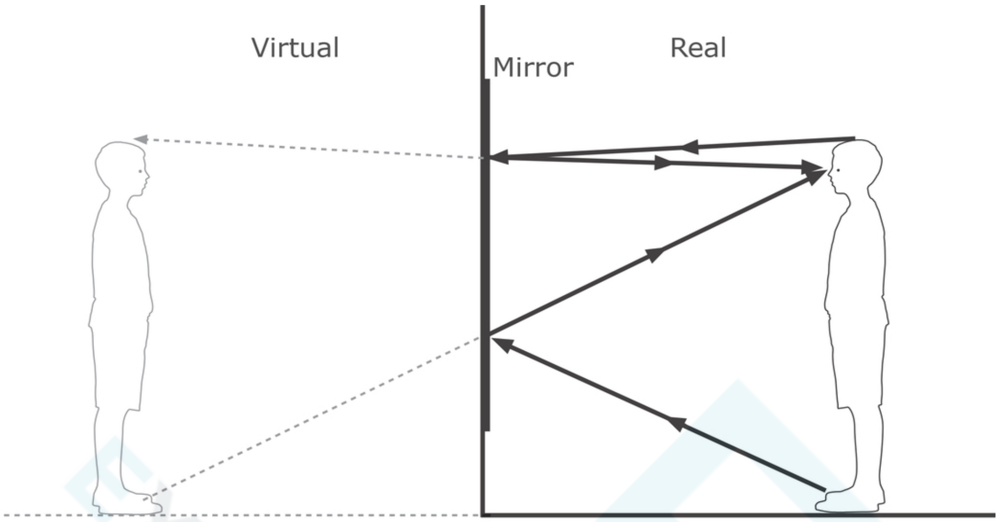
- Are formed when light rays from a point on an object **pass through another point** in space
  - The light rays are **really there**
- Can be **formed on a screen**
- Are seen in ray diagrams at the point where **rays cross**
- Examples include:
  - Pictures projected onto a wall or screen
  - The image formed on the retina



A real image can be projected onto a screen

Virtual Images

- Virtual images are formed when light rays from a point on an object **appear** to have come from another point in space
- The light rays are **not really** where the image appears to be
- The image **cannot be formed on a screen**
- Examples include:
  - Images seen through a **magnifying glass**
  - **All** images formed by a **diverging** (concave) lens
  - Reflections in a mirror



A reflection in a mirror is an example of a virtual image

Ray diagrams

- Ray diagrams can be used to show whether an image will be real or virtual
- If the rays from the object naturally cross the image will be real
- If the rays have to be extended backwards to make them cross, the image is virtual
  - To signal virtual rays they are drawn as dashed lines rather than solid ones

Ray diagram for a real image in a converging lens

1. Start by drawing a ray going from the top of the object through the centre of the lens. This ray will continue to travel in a straight line
2. Next draw a ray going from the top of the object, travelling parallel to the axis to the lens. When this ray emerges from the lens it will travel directly towards the principal focus
3. The image is found at the point where the above two rays meet

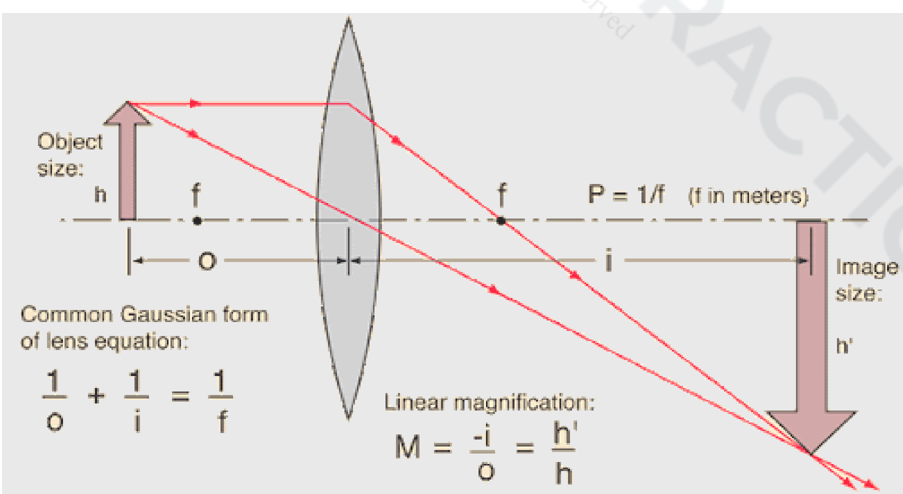
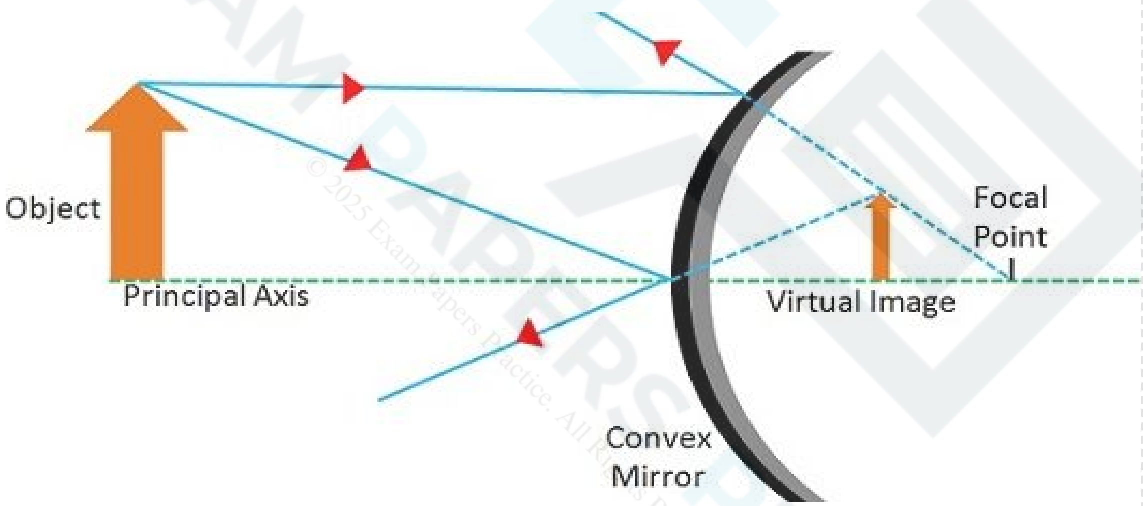


Diagram showing the formation of a real image by a lens

- The above diagram shows the image that is formed when the object is placed at a distance between one focal length (f) and two focal lengths (2f) from the lens
- In this case, the image is:
  - **Real**
  - **Enlarged**
  - **Inverted**

Ray diagram for a virtual image in a converging lens

- If the object is placed closer to the lens than the focal length, the emerging rays diverge and a real image is no longer formed
- When viewed from the right-hand side of the lens, the emerging rays appear to come from a point on the left. This point can be found by extending the rays backwards (creating virtual rays)
- A virtual image will be seen at the point where these virtual rays cross



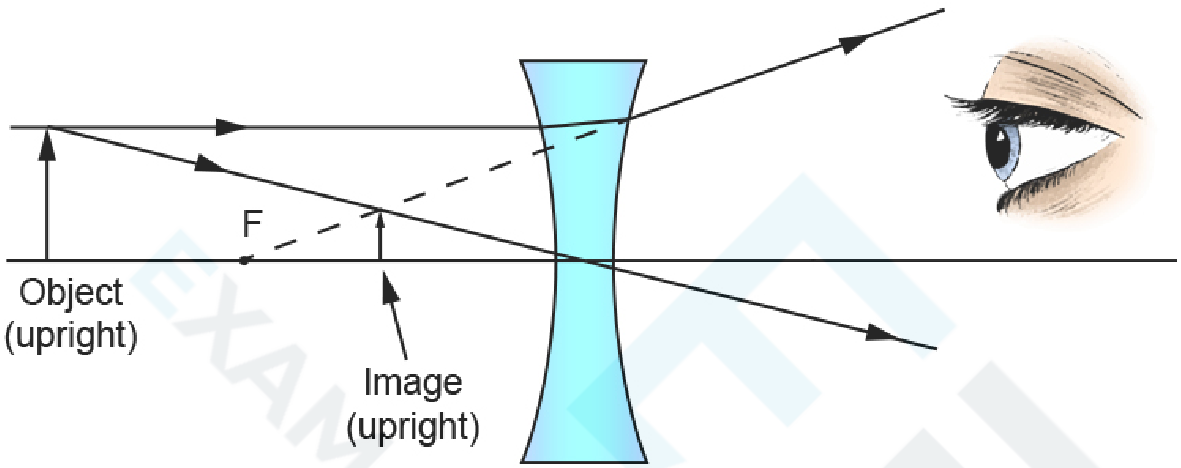
A virtual image is formed by the divergence of rays from a point

- In this case the image is:
  - **Virtual**
  - **Enlarged**
  - **Upright**

- Using a lens in this way allows it to be used as a **magnifying glass**
- When using a magnifying glass, the lens should always be held close to the object

Ray diagram for a virtual image in a diverging lens

- The image formed by a diverging lens is always virtual
- To draw this diagram draw two rays from the top of the object
    - One ray passes through the centre of the lens with no refraction
    - The second is drawn parallel to the principal axis until it meets the centre of the lens
    - The ray refracts through the principal focus
    - To make the rays cross the line will need to be extended, forming a virtual meeting point



Concave lenses only produce virtual images

- In this case the image is:
    - **Virtual**
    - **Diminished**
    - **Upright**

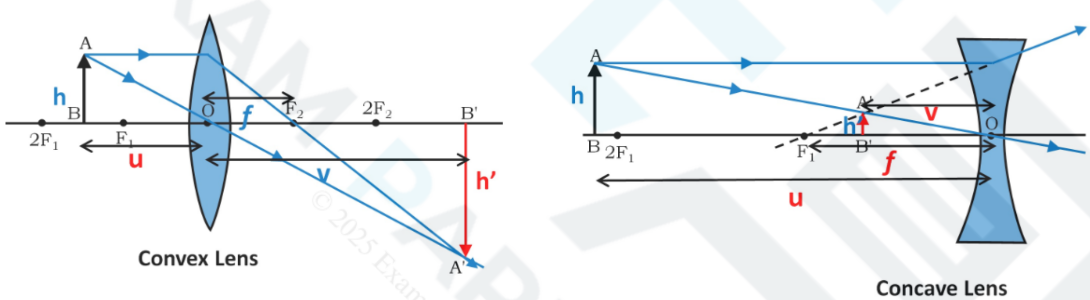
5.22 The Lens Equation

The Lens Equation

- This equation can be applied to all **thin converging** and **diverging** lenses
- The equation relates the **focal length** of the lens to the **distances** from the **lens** to the **image** and the **object**

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

- Where:
  - f = focal length (m)
  - v = image distance from lens (m)
  - u = object distance from lens (m)



Lens Formula: $$\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$$

Magnification $$m = \frac{Height\ of\ image}{Height\ of\ Object}$$

$$m = \frac{v}{u}$$

- This equation only works for **thin** converging or diverging lenses
  - The values are **positive** if the image is **real**

5.23 Magnification

Magnification

Magnification as a Ratio of Heights

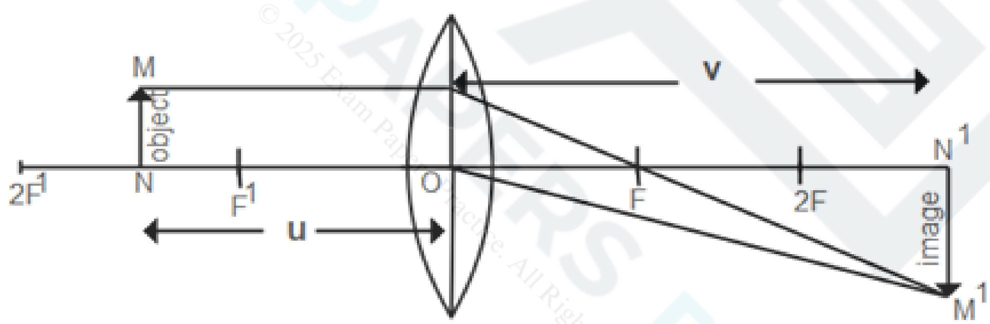
- Magnification means how much larger the image is than the object
  - This is the ratio of the image/object height

$$m = \frac{h_i}{h_o}$$

- Where:
  - m = magnification
  - h_i = image height (m)
  - h_o = object height (m)

Magnification as a Ratio of Distances

- A diagram of an object and its real image will produce similar triangles
  - Therefore, the ratio of magnification is also represented by comparing distance from the lens to the object and the image



  - Where:
    - m = magnification
    - v = distance from lens to object (m)
    - u = distance from lens to image (m)
- Since magnification is a **ratio**, it has **no units**

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**
- **Polarisation** occurs when

> **Particles are only allowed to oscillate in one of the directions perpendicular to the direction of wave propagation**

- When a transverse wave is polarised, its **electric field** is only allowed to oscillate in **one fixed plane** perpendicular to the direction of motion of the wave
    - For EM waves it is the **plane** of the **electric fields** oscillation that defines its **plane of polarisation**
- A transverse wave can be vertically polarised, horizontally polarised, or polarised in any direction in between

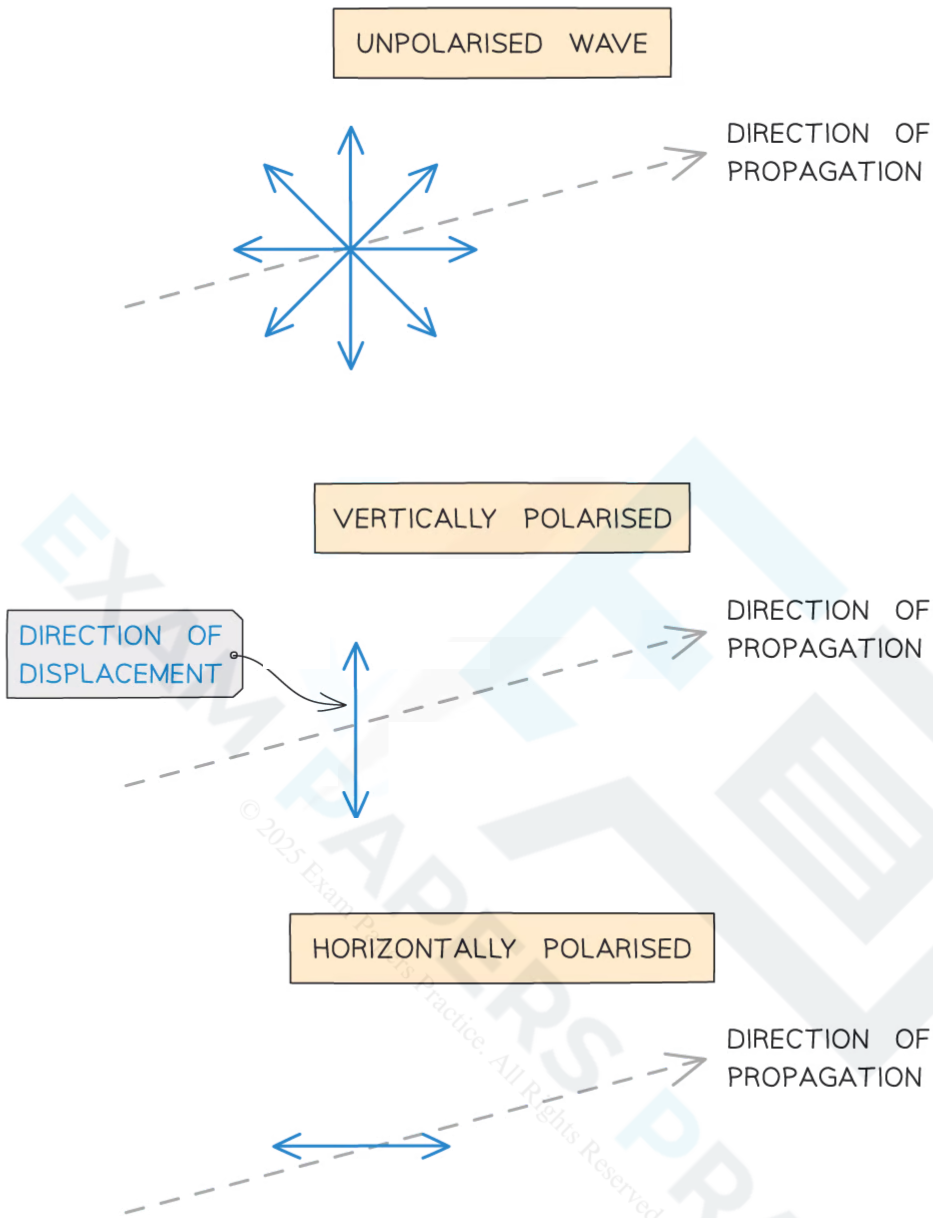


Diagram showing the displacement of unpolarised and polarised transverse waves

- 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 and reflection from a non-metallic plane surface

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

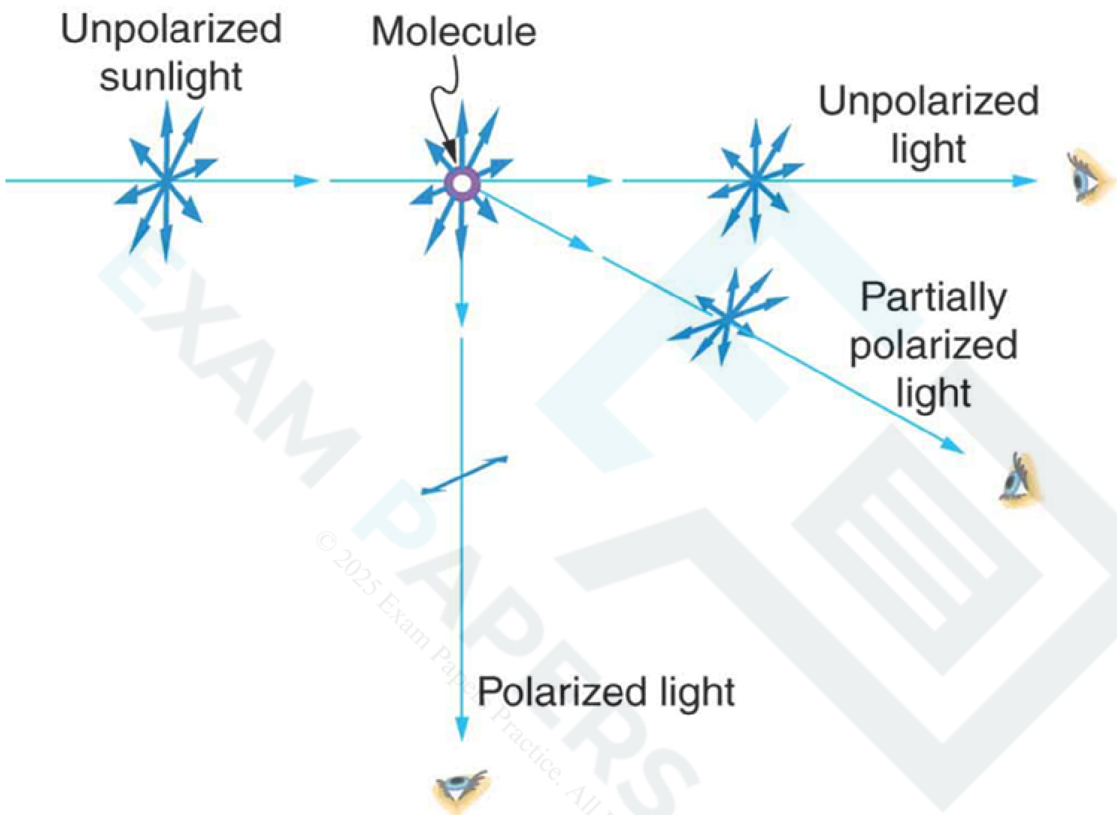


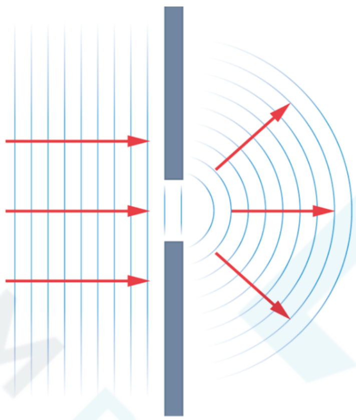
Diagram showing an unpolarised and polarised wave travelling through polarisers

Diffraction

Diffraction is the **spreading out** of waves when they pass an obstruction

Diffraction through a gap

- This obstruction is typically a narrow gap (a slit, or aperture)



as the wave goes through the gap it spreads out

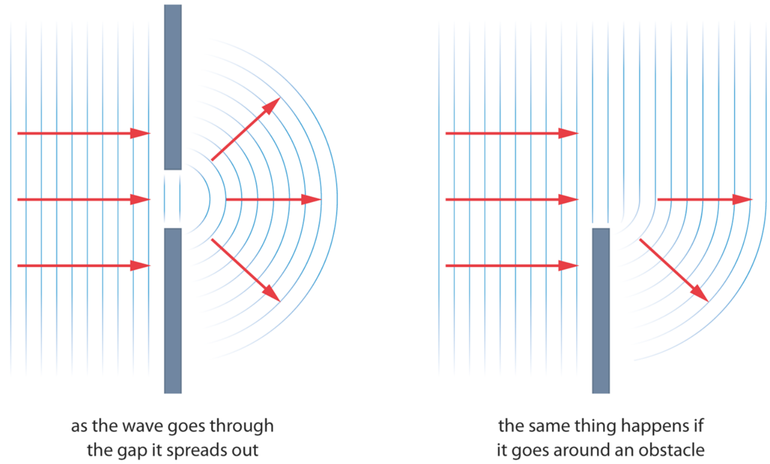
- Diffraction is usually represented by a wavefront as shown by the vertical lines in the diagrams above
- The only property of a wave that changes when its diffracted is its **amplitude**
  - This is because some energy is **dissipated** when a wave is diffracted through a gap

Diffraction around an obstacle

- The diffraction pattern for a large slit can be thought of as a wave passing two completely separate obstacles
  - This shows that when a wave meets an obstacle a diffraction pattern forms around the edges.
  - Behind the obstacle a 'shadow' forms where no part of the wave reaches

Factors that affect diffraction

- The effects of diffraction are most prominent when the gap size or obstacle is approximately the same or smaller than the wavelength of the wave
  - As the size of the gap or obstacle increases, the effect gradually gets less pronounced
  - When the gap is much larger than the wavelength, the waves are no longer spread out

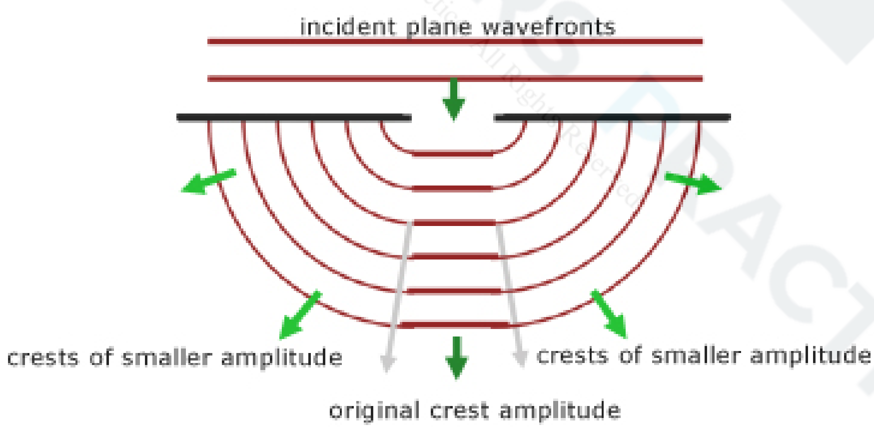


The size of the gap (compared to the wavelength) affects how much the waves spread out

Explaining diffraction

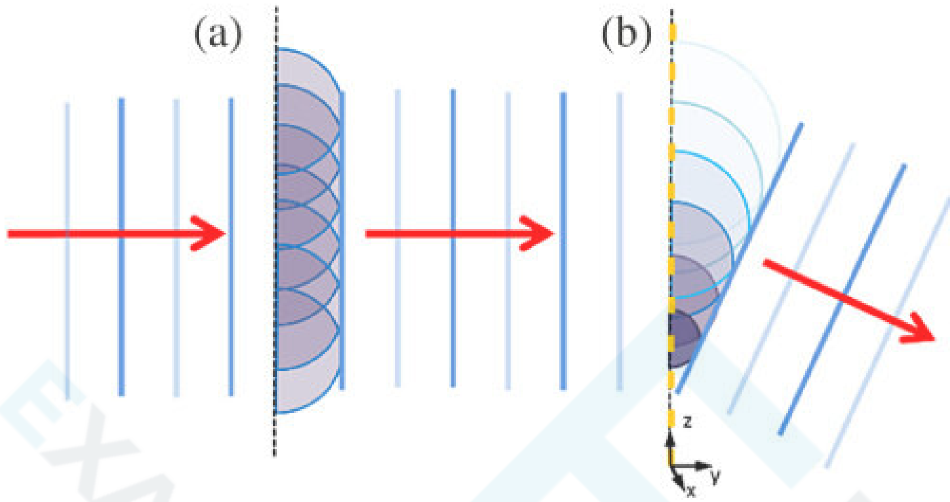
- Huygens developed a model for wave propagation which suggested that every point on a wavefront can be considered to be a point source of secondary waves (which he called wavelets)
    - This leads to a diagram, called **Huygens' construction**, which shows that new wavefronts are tangential to the secondary wavelets
    - The tangents create the curve of the new wavefront emerging either through the gap or around the obstacle

Huygens' Construction for Diffraction Through a Gap



Those point sources which pass through the gap create new wavelets on the other side, leading to the characteristic curved shape of the diffracted wave

Huygens' Construction for Diffraction Around an Obstacle



Those point sources which pass around the obstacle create new wavelets on the other side, leaving empty space where the 'shadow' is seen

The Diffraction Grating Equation

- A **diffraction grating** is a plate on which there is a very large number of parallel, identical, close-spaced slits
- When **monochromatic light** is incident on a grating, a pattern of narrow bright fringes is produced on a screen

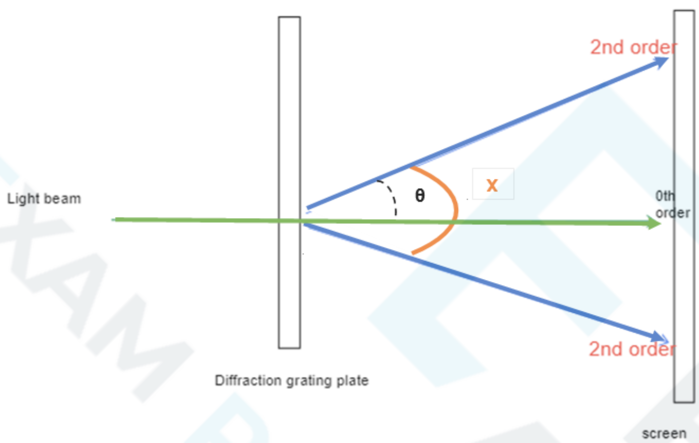
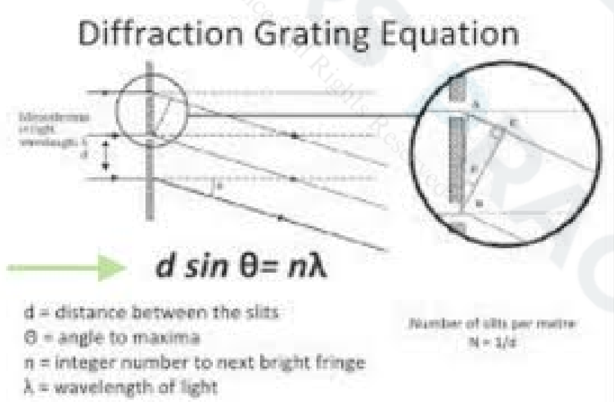


Diagram of diffraction grating used to obtain a fringe pattern

- The angles at which the maxima of intensity (constructive interference) are produced can be deduced by the diffraction grating equation



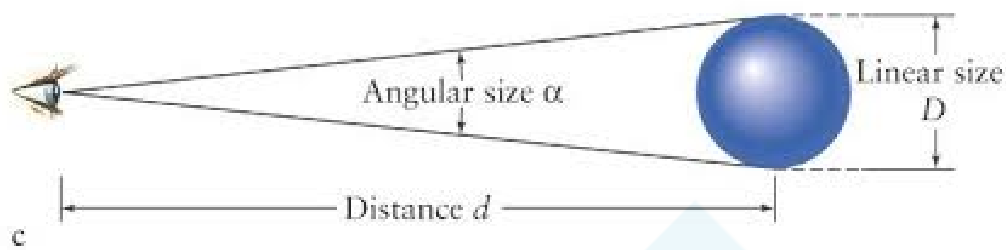
Diffraction grating equation for the angle of bright fringes

- Exam questions sometime state the **lines per m** (or per mm, per nm etc.) on the grating which is represented by the symbol *N*
- *d* can be calculated from *N* using the equation

$$d = \frac{1}{N}$$

Angular Separation

- The angular separation of each maxima is calculated by rearranging the grating equation to make θ the subject
- The angle θ is taken from the centre meaning the higher orders are at greater angles



Angular separation

- The angular separation between two angles is found by subtracting the smaller angle from the larger one
- The angular separation between the first and second maxima n_1 and n_2 is $\boldsymbol{\theta_2 - \theta_1}$

Orders of Maxima

- The maximum angle to see orders of maxima is when the beam is at right angles to the diffraction grating
  - This means $\theta = 90°$ and $\sin\theta = 1$
- The highest order of maxima visible is therefore calculated by the equation:

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

- Note that since *n* must be an integer, if the value is a decimal it must be rounded **down**
  - E.g If *n* is calculated as 2.7 then *n* = 2 is the highest order visible

Core Practical 8: Investigating Diffraction Gratings

Aim of the Experiment

- To find the wavelength of light using a diffraction grating

Variables

- Independent variable = Distance between maxima, *h*
- Dependent variable = The angle between the normal and each order, θ_n (where n = 1, 2, 3 etc)
- Control variables
  - Distance between the slits and the screen, *D*
  - Laser wavelength λ
  - Slit separation, *d*

Equipment List

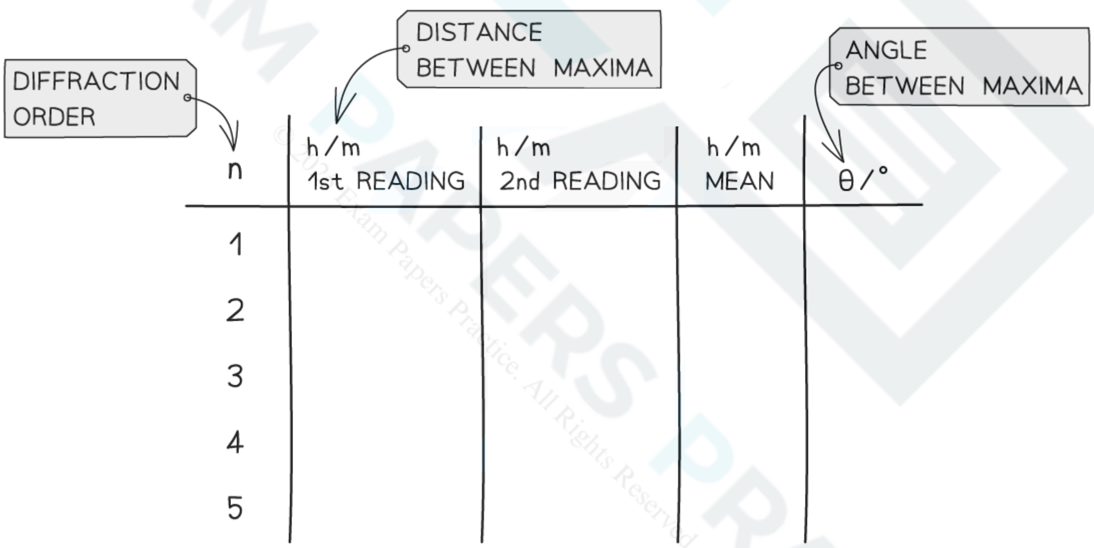
Apparatus	Purpose
Laser	To use as a source of monochromatic light
Single Slit	To focus the laser beam onto the double slit (optional)
Double Slit	To diffract the beam into two sources of coherent light
Diffraction Grating	To diffract the beam into multiple sources of coherent light
Meter Ruler	To measure the distance between the slits and the screen (D)
Vernier Calipers	To measure the fringe width (w) and slit separation (if not quoted on double slit)
Retort Stand	To support the laser and slits at the same height
White Screen	To project the interference patter on to
Set Square	To ensure all components are aligned to the normal perfectly

- Resolution of measuring equipment:
  - Metre ruler = 1 mm
  - Vernier Callipers = 0.01 mm

Method

1. Place the laser on a retort stand and the diffraction grating in front of it
2. Use a set square to ensure the beam passes through the grating at normal incidence and meets the screen perpendicularly
3. Set the distance *D* between the grating and the screen to be 1.0 m using a metre ruler
4. Darken the room and turn on the laser
5. Identify the zero-order maximum (the central beam)
6. Measure the distance *h* to the nearest two first-order maxima (i.e. n = 1, n = 2) using a vernier calliper
7. Calculate the mean of these two values
8. Measure distance *h* for increasing orders
9. Repeat with a diffraction grating with a different number of slits per mm

- An example table might look like this:



Analysing the Results

The diffraction grating equation is given by:

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

- Where:
  - n = the order of the diffraction pattern
  - λ = the wavelength of the laser light (m)
  - d = the distance between the slits (m)
  - θ = the angle between the normal and the maxima

- The distance between the slits is equal to:

$$d = \frac{1}{N}$$

- Where
  - N = the number of slits per metre (m^{-1})

- Since the angle is not small, it must be calculated using trigonometry with the measurements for the distance between maxima, h, and the distance between the slits and the screen, D

$$\tan\theta = \frac{h}{D} \quad \rightarrow \quad \theta = \tan^{-1}\left(\frac{h}{D}\right)$$

- Calculate a mean θ value for each order
- Calculate a mean value for the wavelength of the laser light and compare the value with the accepted wavelength
  - This is usually 635 nm for a standard school red laser

Evaluating the Experiments

Systematic errors:

- Ensure the use of the set square to avoid parallax error in the measurement of the fringe width
- Using a grating with more lines per mm will result in greater values of *h*. This lowers its percentage uncertainty

Random errors:

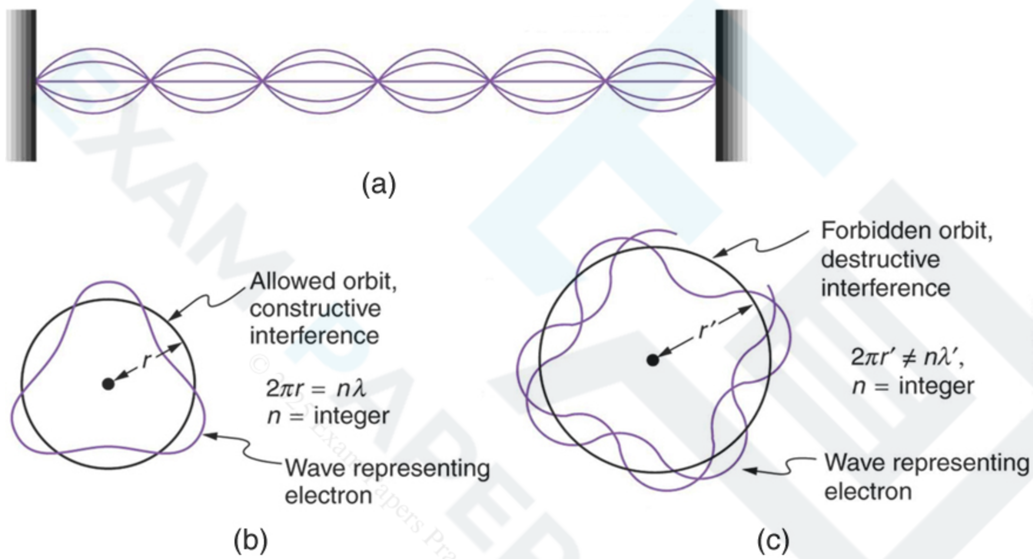
- The fringe spacing can be subjective depending on its intensity on the screen, therefore, take multiple measurements of *w* and *h* (between 3–8) and find the average
- Use a Vernier scale to record distances *w* and *h* to reduce percentage uncertainty
- Reduce the uncertainty in *w* and *h* by measuring across all visible fringes and dividing by the number of fringes
- Increase the grating to screen distance *D* to increase the fringe separation (although this may decrease the intensity of light reaching the screen)
- Conduct the experiment in a darkened room, so the fringes are clear

Safety Considerations

- Lasers should be Class 2 and have a maximum output of no more than 1 mW
- Do not allow laser beams to shine into anyone's eyes
- Remove reflective surfaces from the room to ensure no laser light is reflected into anyone's eyes

The Wave Nature of Electrons

- Electron diffraction was the first clear evidence that matter can behave like light and has wave properties
  - This is demonstrated using the electron diffraction tube
- The electrons are accelerated in an electron gun to a high potential, such as 5000 V, and are then directed through a thin film of graphite
  - The lattice structure of the graphite acts like the slits in a diffraction grating
- The electrons diffract from the gaps between carbon atoms and produce a circular pattern on a fluorescent screen made from phosphor



Electrons accelerated through a high potential difference demonstrate wave-particle duality

- In order to observe the diffraction of electrons, they must be focused through a gap similar to their size, such as an atomic lattice
- Graphite film is ideal for this purpose because of its crystalline structure
  - The gaps between neighbouring planes of the atoms in the crystals act as slits, allowing the electron waves to spread out and create a diffraction pattern
- The diffraction pattern is observed on the screen as a series of concentric rings
  - This phenomenon is similar to the diffraction pattern produced when light passes through a diffraction grating
  - If the electrons acted as particles, a pattern would not be observed, instead, the particles would be distributed uniformly across the screen
- It is observed that a larger accelerating voltage reduces the diameter of a given ring, while a lower accelerating voltage increases the diameter of the rings

The de Broglie Equation

- Using ideas based upon the quantum theory and Einstein's theory of relativity, de Broglie theorised that not only do EM waves sometimes behave as particles, but that very small, fast moving particles like electrons could also behave as waves
  - He called these **matter waves**
- The Broglie equation relates the wavelength of some particles to their mass and velocity, which combine to give their momentum
  - Hence:

$$\lambda = \frac{h}{mv} = \frac{h}{p}$$

-
  - λ = the de Broglie wavelength (m)
  - h = Planck's Constant (J s)
  - m = mass (kg)
  - v = velocity (m s^{-1})
  - p = momentum (kg m s^{-1})

Worked Example

Determine the de Broglie wavelength of a person of mass 70 kg moving at 2 ms^{-1} and comment on your answer.

Step 1: Write the known values

- Mass, m = 70 kg
- Velocity, v = 2 m s^{-1}
- Planck's constant, h = 6.63×10^{-34} Js

Step 2: Write the equation and substitute the values

$$\lambda = \frac{h}{mv} = \frac{(6.63 \times 10^{-34})}{70 \times 2} = 4.74 \times 10^{-36}$$

Step 4: Write the answer to the correct number of significant figures and include units

- de Broglie wavelength of a moving person, $\lambda = 4.7 \times 10^{-36}$ m

Step 5: think about the magnitude of the result and comment on it

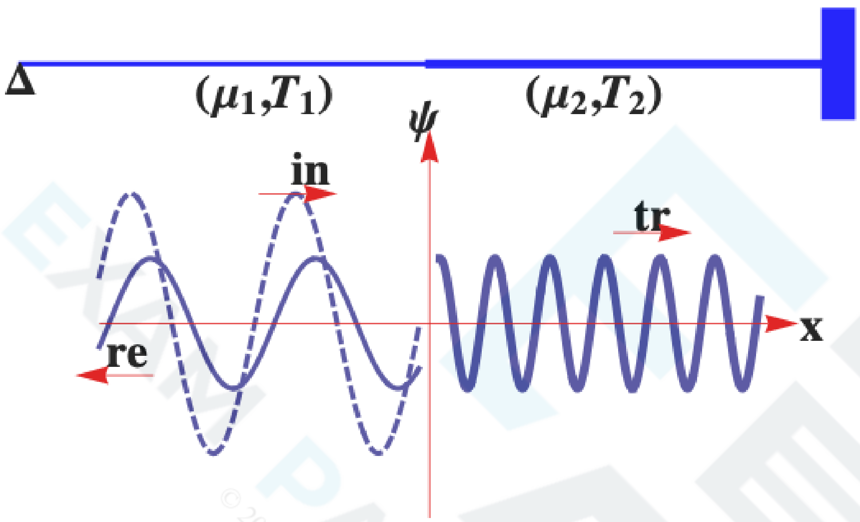
- The person does have a de Broglie wavelength but since it is about 10^{20} times smaller than a nucleus, it can be ignored
- People behave like particles, not waves

Exam Tip

If you've not been given the mass of a particle in a question, make sure to look at your data sheet which includes the rest mass of various particles

Transmission & Reflection of Waves

- When waves are incident on the interface between two different media, they are either **transmitted** or **reflected**
  - 'Incident on' simply means 'to meet'
  - The interface is also called the **boundary** between media
  - Transmitted means to pass through



- When the media have **similar** densities the energy of the wave is mostly **transmitted**
- When the media have **different** densities most of the energy is **reflected**

Reflected waves in use

- Uses of reflected waves include:
  - Medical x-rays
  - Sonar
  - Ultrasound scans

Transmitted waves in use

- In the above examples the waves have to be transmitted through one medium first, before they are reflected
  - X-rays are transmitted through soft tissue
  - Sonar is transmitted through air or water
  - Ultrasound is transmitted through a gel of similar density to the skin so that it reaches the tissues inside the body

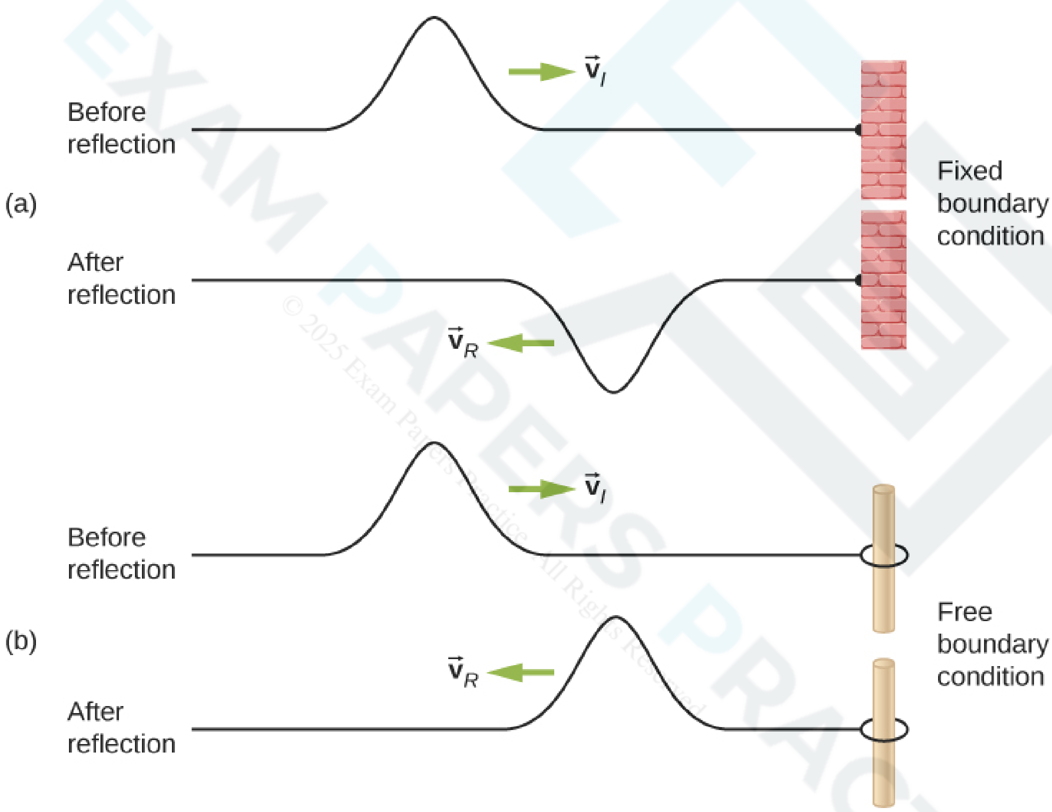
Reflection

- Reflection occurs when:

    A wave hits a boundary between two media and does not pass through, but instead stays in the original medium

- The law of reflection states:

    The angle of incidence = The angle of reflection



Reflection of a wave at a boundary

- Some of the wave may also be absorbed or transmitted
    - Echos are examples of sound waves being reflected off a surface
- **Flat** surfaces are the **most** reflective
    - The smoother the surface, the stronger the reflected wave is
- **Rough** surfaces are the **least** reflective

- This is because the light scatters in all directions

- **Opaque** surfaces will reflect light which is not absorbed by the material
  - The electrons will absorb the light energy, then reemit it as a reflected wave

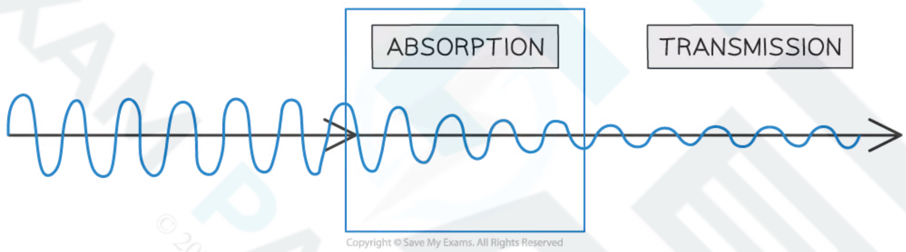
Transmission

- Transmission occurs when:

  A wave passes through a substance

- For light waves, the more transparent the material, the more light will pass through
  - Transmission can involve **refraction** but it is not exactly the same
  - For the process to count as transmission, the wave must pass through the material and **emerge** from the other side

- When passing through a material, waves are usually partially absorbed
  - The transmitted wave may have a lower **amplitude** because of some absorption
    - For example, sound waves are **quieter** after they pass through a wall



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

Pulse-Echo Technique

Foetal Scanning

- In medicine, ultrasound can be used to construct images of a **foetus** in the womb
  - An ultrasound detector is made up of a **transducer** that produces and detects a beam of ultrasound waves into the body
  - The ultrasound waves are reflected back to the transducer by different **boundaries** between tissues in the path of the beam
  - For example, the boundary between fluid and soft tissue or tissue and bone

- Using the speed of sound and the time of each echo's return, the detector calculates the distance from the transducer to the tissue boundary
- Gel is put onto the scanner so that the boundary between the instrument and the skin is of the same density as the skin, this allows the signal to be easily **transmitted**
- By taking a series of ultrasound measurements, sweeping across an area, the time measurements may be used to build up an **image**
  - Unlike many other medical imaging techniques, ultrasound is **non-invasive** and **harmless**

Ultrasound can be used to construct an image of a foetus in the womb

Sonar

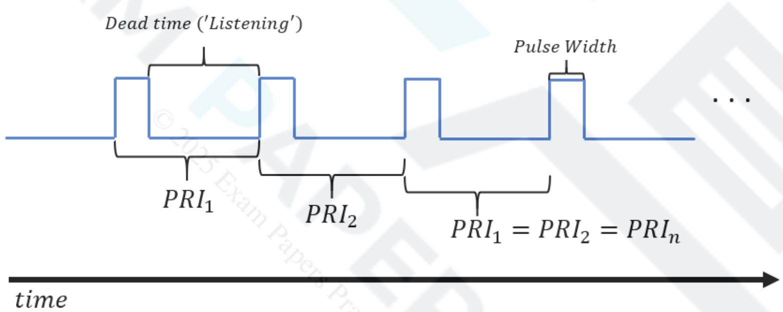
- **Sonar** uses **ultrasound** to detect objects underwater
- The sound wave is **reflected** off the object being tracked
- Examples include;
  - Finding fish by fishing fleets
  - Military uses looking for underwater vessels
  - Mapping the ocean bottom

- The **time** it takes for the sound wave to return is used to calculate the **depth** of the water
- The **distance** the wave travels is **twice the depth** of the ocean
  - This is the distance to the ocean floor plus the distance for the wave to return

Pulse Duration and Wavelength

- The amount of detail which can be captured (the **resolution**) of pulse-echo techniques depends on the wavelength
  - **Shorter** wavelengths have **smaller (better)** resolution
  - **More** detail can be seen since they diffract (spread out) less
  - More energy is needed as short wavelength waves have higher frequency
- Wavelength is chosen to be similar in size to the object that is being resolved
  - This makes best use of diffraction effects

- Pulse duration is a consideration because ultrasound transducers cannot transmit and receive pulses at the same time.
  - If incoming and outgoing pulses overlap the information is lost and image quality suffers
  - This affects the range since a longer wait time for pulses to return reduces the amount of information which can be collected



- Ultrasound pulses are very short, only a few microseconds, to reduce reflections from nearby interfaces
- The gap between pulses is relatively long, measured in milliseconds, to prevent overlapping signals
  - This combination of **short pulses** with relatively **large spaces** between them produces the **clearest** images

Worked Example

A sonar system uses ultrasound with frequency of 3.2 kHz to map the ocean floor. The speed of sound in water is 1 500 m s^{-1}.

An echo is detected 3.6 s after the pulse is transmitted.

a) Determine the depth of the sea at this point.

b) Suggest a resolution for this ultrasound survey of the seafloor

Part (a)

Step 1: Write the known values from the question

- Frequency, f = 3.2 kHz = 3 200 Hz
- Speed of sound, v = 1 500 m s^{-1}
- Time, t = 3.6 s

Step 2: Write the correct equation and substitute the values

- Distance;

$$d = vt = 1500 \times 3.6 = 5\,400 \text{ m}$$

Step 3: Account for the received signal being an echo

- Total distance travelled by the signal = 5 400 m
- Depth of the sea floor = 1/2 × 5 400 = 2 700 m

Part (b)

Step 1: Write the wave equation and rearrange to make wavelength the subject

$$v = f\lambda$$

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

Step 2: Calculate to find wavelength

$$\lambda = \frac{1500}{3200} = 0.47$$

Step 3: Write the final answer to correct significant figures and give units

The resolution of the signal is similar to the wavelength, and λ = 0.47 m

Wave-Particle Duality

- Light can behave as a particle (i.e. photons) **and** a wave
- This phenomenon is called the wave-particle nature of light or **wave-particle duality**
- Light interacts with matter, such as electrons, **as a particle**
  - The evidence for this is provided by the photoelectric effect
- Light propagates through space **as a wave**
  - The evidence for this comes from the diffraction and interference of light in Young's Double Slit experiment

Light as a Particle

- Einstein proposed that light can be described as a quanta of energy that behave as particles, called photons
- The photon model of light explains that:
  - Electromagnetic waves carry energy in discrete packets called photons
  - The energy of the photons are quantised according to the equation $E = hf$
  - In the photoelectric effect, each electron can absorb only a single photon - this means only the frequencies of light above the threshold frequency will emit a photoelectron
- The wave theory of light does **not** support the idea of a threshold frequency
  - The wave theory suggests any frequency of light can give rise to photoelectric emission if the exposure time is long enough
  - This is because the wave theory suggests the energy absorbed by each electron will increase gradually with each wave
  - Furthermore, the kinetic energy of the emitted electrons should increase with radiation intensity
  - However, in the photoelectric effect, this is not what is observed
- If the frequency of the incident light is above the threshold and the intensity of the light is increased, **more photoelectrons are emitted per second**
- Although the wave theory provides good explanations for phenomena such as interference and diffraction, it fails to explain the photoelectric effect

Compare wave theory and particulate nature of light

The wave theory of light suggests...	This is wrong because...
Any frequency of light can give rise to photoelectric emission if the exposure time is long enough	Photoelectrons will be released immediately if the frequency is above the threshold for that metal
The energy absorbed by each electron will increase gradually with each wave	Energy is absorbed instantaneously – photoelectrons are either emitted or not emitted after exposure to light
The kinetic energy of the emitted electrons should increase with radiation intensity	If the intensity of the light is increased, more photoelectrons are emitted per second

Development of the Theory of Wave-Particle Duality

- Ideas about the nature of light were contested by modern science for around 300 years
- The evidence to prove both theories was available
  - Some prominent scientists argued light was a wave
  - Others contested that light was a particle
- It was not until the early 20th century that scientists settled on a theory of duality

5.33 Energy of a Photon

Energy of a Photon

- Photons are fundamental particles which make up all forms of electromagnetic radiation
- A photon is a massless “packet” or a “quantum” of electromagnetic energy
- What this means is that the energy is not transferred continuously, but as discrete packets of energy
- In other words, each photon carries a specific amount of energy, and transfers this energy all in one go, rather than supplying a consistent amount of energy

Calculating Photon Energy

The Relationship between Energy (E), Frequency (υ), Wavelength (λ), and Planck’s Constant (h)

$$\boxed{E = h\upsilon} \qquad \boxed{E = \frac{hc}{\lambda}}$$

$$h = 6.626 \times 10^{-34} \text{ J·s}$$

$$c = 3.0 \times 10^{8} \text{ m/s}$$

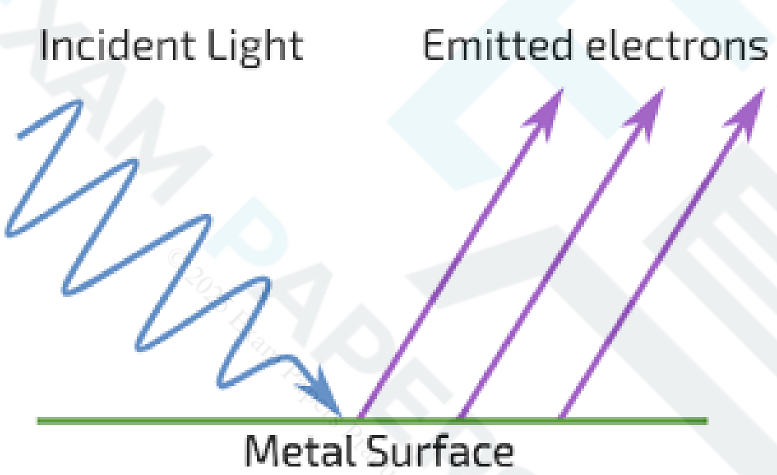
- Where:
  - E = energy of the photon (J)
  - h = Planck's constant (J s)
  - c = the speed of light (m s^{-1})
  - f = frequency (Hz)
  - λ = wavelength (m)
- This equation tells us:
  - The higher the frequency of EM radiation, the higher the energy of the photon
  - The energy of a photon is inversely proportional to the wavelength
  - A long-wavelength photon of light has a lower energy than a shorter-wavelength photon

The Photoelectric Effect & Atomic Spectra

5.34 The Photoelectric Effect

The Photoelectric Effect

- The **photoelectric effect** is the phenomena in which electrons are emitted from the surface of a metal **upon the absorption of electromagnetic radiation**
- Electrons removed from a metal in this manner are known as **photoelectrons**
- The photoelectric effect provides important evidence that light is **quantised**, or carried in discrete packets
  - This is shown by the fact each electron can absorb only a single photon
  - This means only the frequencies of light above a **threshold frequency** will emit a photoelectron



Photoelectrons are emitted from the surface of metal when light shines onto it

- The photoelectric effect can be observed on a **gold leaf electroscope**
- A plate of metal, usually **zinc**, is attached to a gold leaf, which initially has a negative charge, causing it to be repelled by a central negatively charged rod
  - This causes negative charge, or electrons, to build up on the zinc plate
- **UV light** is shone onto the metal plate, leading to the **emission** of **photoelectrons**
- This causes the extra electrons on the central rod and gold leaf to be removed, so, the gold leaf begins to fall back towards the central rod
  - This is because they become less negatively charged, and hence repel less

5.35 The Photoelectric Equation

YOUR NOTES
↓

The Photoelectric Equation

- Since energy is always conserved, the energy of an incident photon is equal to:

The work function + the maximum kinetic energy of the photoelectron

- The energy within a photon is equal to ***hf***
- This energy is transferred to the electron to release it from a material (the work function) and the remaining amount is given as kinetic energy to the emitted photoelectron
- This equation is known as the **photoelectric equation**:

$$E = hf = \Phi + \tfrac{1}{2} mv^2_{max}$$

- Where:
  - h = Planck's constant (J s)
  - f = the frequency of the incident radiation (Hz)
  - Φ = the work function of the material (J)
  - $\tfrac{1}{2} mv^2_{max}$ = KE_{max} = the maximum kinetic energy of the photoelectrons (J)
- This equation demonstrates:
  - If the incident photons do not have a high enough frequency and energy to overcome the work function (Φ), then no electrons will be emitted
  - $hf_0 = \Phi$, where f_0 = threshold frequency, photoelectric emission only just occurs
  - KE_{max} depends only on the frequency of the incident photon, and **not** the intensity of the radiation
  - The majority of photoelectrons will have kinetic energies **less than** KE_{max}

Work Function

- The work function Φ, or threshold energy, of a material, is defined as:

The minimum energy required to release a photoelectron from the surface of a metal

- Consider the electrons in a metal as trapped inside an 'energy well' where the energy between the surface and the top of the well is equal to the work function Φ
- A single electron absorbs one photon
- Therefore, an electron can only escape from the surface of the metal if it absorbs a photon which has an energy equal to Φ or higher

Graphical Representation of Work Function

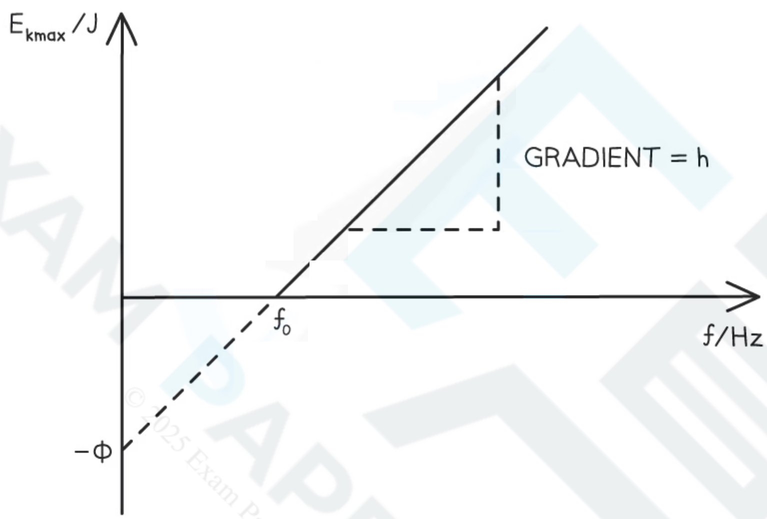
- The photoelectric equation can be rearranged into the straight line equation:

$$y = mx + c$$

- Comparing this to the photoelectric equation:

$$KE_{max} = hf - \Phi$$

- A graph of maximum kinetic energy KE_{max} against frequency f can be obtained



- The key elements of the graph:
  - The work function Φ is the **y-intercept**
  - The threshold frequency f_0 is the **x-intercept**
  - The **gradient** is equal to Planck's constant h
  - There are no electrons emitted below the threshold frequency f_0

Threshold Frequency

- The threshold frequency is defined as:

  The minimum frequency of incident electromagnetic radiation required to remove a photoelectron from the surface of a metal

The Electronvolt

- The electronvolt is a unit which is commonly used to express very small energies
- This is because quantum energies tend to be much smaller than 1 Joule
- The electronvolt is derived from the definition of potential difference:

$$V = \frac{E}{Q}$$

- When an electron travels through a potential difference, energy is transferred between two points in a circuit, or electric field
- If an electron, with a charge of 1.6×10^{-19} C, travels through a potential difference of 1 V, the energy transferred is equal to:

$$E = QV = 1.6 \times 10^{-19}\ \text{C} \times 1\ \text{V} = 1.6 \times 10^{-19}\ \text{J}$$

- Therefore, an electronvolt is defined as:

The energy gained by an electron travelling through a potential difference of one volt

$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$$

Relation to kinetic energy

- When a charged particle is accelerated through a potential difference, it gains kinetic energy
- If an electron accelerates from rest, an **electronvolt** is equal to the kinetic energy gained:

$$eV = \tfrac{1}{2}mv^2$$

- Rearranging the equation gives the speed of the electron:

$$v = \sqrt{\frac{2eV}{m}}$$

? Worked Example

Show that the photon energy of light with wavelength 700nm is about 1.8 eV.

Step 1: Write the equations for wave speed and photon energy

wave speed: $c = f\lambda \longrightarrow f = \frac{c}{\lambda}$

photon energy: $E = hf \longrightarrow E = \frac{hc}{\lambda}$

Step 2: Calculate the photon energy in Joules

$$E = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34}) \times (3.0 \times 10^{8})}{700 \times 10^{-9}} = 2.84 \times 10^{-19}\ \text{J}$$

Step 3: Convert the photon energy into electronvolts

$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$ J → eV: divide by 1.6×10^{-19}

$$E = \frac{2.84 \times 10^{-19}}{1.6 \times 10^{-19}} = \mathbf{1.78\ eV}$$

Exam Tip

- To convert between eV and J:
- eV → J: **multiply** by 1.6×10^{-19}
- J → eV: **divide** by 1.6×10^{-19}

The Particle Nature of EM Radiation

The Particle Nature of Light

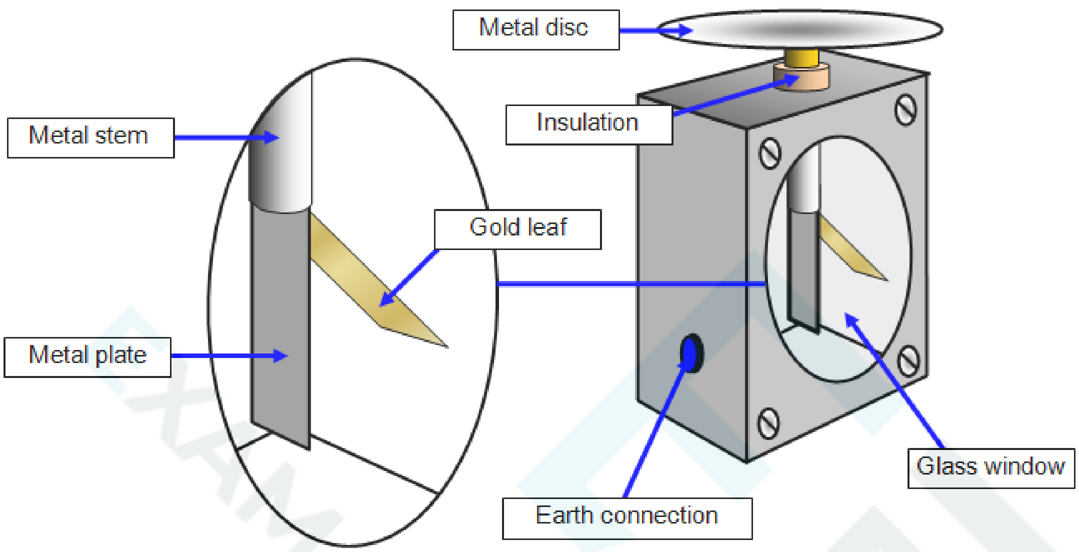
- In classical wave theory, electromagnetic (EM) radiation is assumed to behave as a wave
- This is demonstrated by the fact EM radiation exhibits phenomena such as **diffraction** and **interference**
- However, experiments from the last century, such as the **photoelectric effect** and **atomic line spectra**, can only be explained if EM radiation is assumed to behave as particles

Evidence for the Particle Nature of Light

- The best evidence for the particle nature of light comes from the photoelectric effect
- This is demonstrated using the Gold-leaf Electroscope

Observations of the Gold Leaf Experiment

- The explanation for these observations supports the theory of light as a particle, specifically a discrete packet (or photon) of energy
  - Placing the UV light source **closer** to the metal plate causes the gold leaf to **fall more quickly**
  - Using a higher frequency light source **does not change** how quickly the gold leaf falls
  - Using a filament light source causes **no change** in the gold leaf's position
  - Using a positively charged plate causes **no change** in the gold leaf's position
  - Emission of photoelectrons happens **as soon as the radiation is incident on the surface of the metal**
- Each of the observations is explained below



Typical set-up of the gold leaf electroscope experiment

Placing the UV light source closer to the metal plate causes the gold leaf to fall more quickly

- Placing the UV source closer to the plate increases the intensity incident on the surface of the metal
  - Increasing the intensity, or brightness, of the incident radiation increases the number of photoelectrons emitted per second
  - Therefore, the gold leaf loses negative charge more rapidly

Using a higher frequency light source does not change how quickly the gold leaf falls

- The maximum kinetic energy of the emitted electrons increases with the frequency of the incident radiation
  - In the case of the photoelectric effect, energy and frequency are **independent** of the intensity of the radiation
  - So, the intensity of the incident radiation affects how quickly the gold leaf falls, not the frequency

Using a filament light source causes no change in the gold leaf's position

- If the incident frequency is below a certain threshold frequency, no electrons are emitted, no matter the intensity of the radiation
  - A filament light source has a frequency below the threshold frequency of the metal, so, no photoelectrons are released

Using a positively charged plate causes no change in the gold leaf's position

- If the plate is positively charged, that means there is an excess of positive charge on the surface of the metal plate
    - Electrons are negatively charged, so they will not be emitted unless they are on the surface of the metal
    - Any electrons emitted will be attracted back by positive charges on the surface of the metal

Emission of photoelectrons happens as soon as the radiation is incident on the surface of the metal

- A single photon interacts with a single electron
    - If the energy of the photon is equal to the work function of the metal, photoelectrons will be released instantaneously

5.38 Atomic Line Spectra

Atomic Line Spectra

- An emission line spectrum is produced when:

  An excited electron in an atom moves from a higher to a lower energy level and emits a photon with an energy corresponding to the difference between these energy levels

- Each element produces a unique **emission line spectrum** due to its unique set of energy levels
  - Hot gases produce emission line spectra, such as stars
- When the atoms of a gas are **excited**, electrons gain energy and move to higher energy levels

- Electrons cannot stay in a continuous state of excitation, so they will move back to lower energy levels through **de-excitation**
  - During de-excitation, energy must be conserved, so transitions result in an **emission of photons** with discrete frequencies (or wavelengths) specific to that element
  - Since there are many possible electron transitions for each atom, there are many different radiated wavelengths
  - This creates a **line spectrum** consisting of a series of bright lines against a dark background
  - An emission line spectrum acts as a **fingerprint of the element**

An example of the emission line spectrum of hydrogen

- Each line of the emission spectrum corresponds to a different **energy level** transition within the atom
  - Electrons can transition between energy levels absorbing or emitting a **discrete amount of energy**
  - An excited electron can transition down to the next energy level or move to a further level closer to the ground state
- For example, if an atom has six energy levels:
  - At low temperatures, most electrons will occupy the ground state n = 1
  - At high temperatures, electrons may be excited to the most excited state n = 6

- The energy of a photon is given by the equation:

$$E = hf$$

- Using energy can be written as:

$$E = \frac{hc}{\lambda}$$

- Where:
  - E = energy of the photon (J)
  - h = Planck's constant(J s)
  - c = speed of light (m s^{-1})
  - f = frequency (Hz)
  - λ = wavelength (m)

- The energy required to move from one energy level to another is given by the difference of energy between the two energy levels:

$$\Delta E = E_1 - E_2$$

- Where:
  - E_1 = energy associated with the level that the electron has left (eV)
  - E_2 = energy associated with the level that the electron moves to (eV)

- The difference of energy corresponds to the energy of the absorbed (or emitted) photon:

$$\Delta E = E_1 - E_2 = hf = \frac{hc}{\lambda}$$

- For each transition, a photon will be emitted with a specific wavelength

- In the case of hydrogen, all wavelengths are in the visible range:
  - From n = 6 to n = 2 - violet
  - From n = 5 to n = 2 - blue
  - From n = 4 to n = 2 - light blue
  - From n = 3 to n = 2 - red

If the emitted photons are in the visible range, wavelengths can be represented as lines of the respective colour against a black background

- Emitted photons can have a range of wavelengths spanning the whole electromagnetic spectrum
  - The wavelength is inversely proportional to the energy level transition associated with the emitted photon