A Level Physics CIE

7. Waves

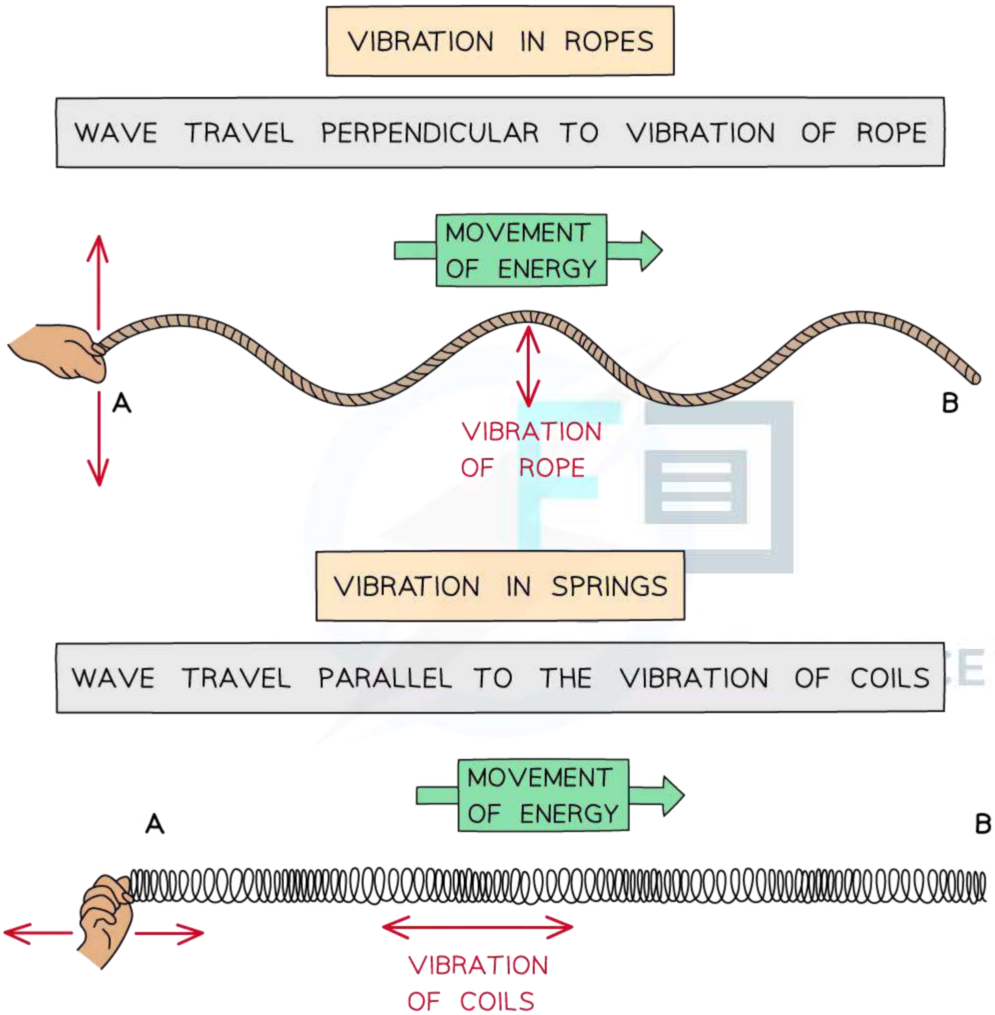
CONTENTS

7.1 Waves: Transverse & Longitudinal

7.1.1 Progressive Waves

Wave Motion

- Energy is transferred through moving **oscillations** or **vibrations**. These can be seen in vibrations of ropes or springs

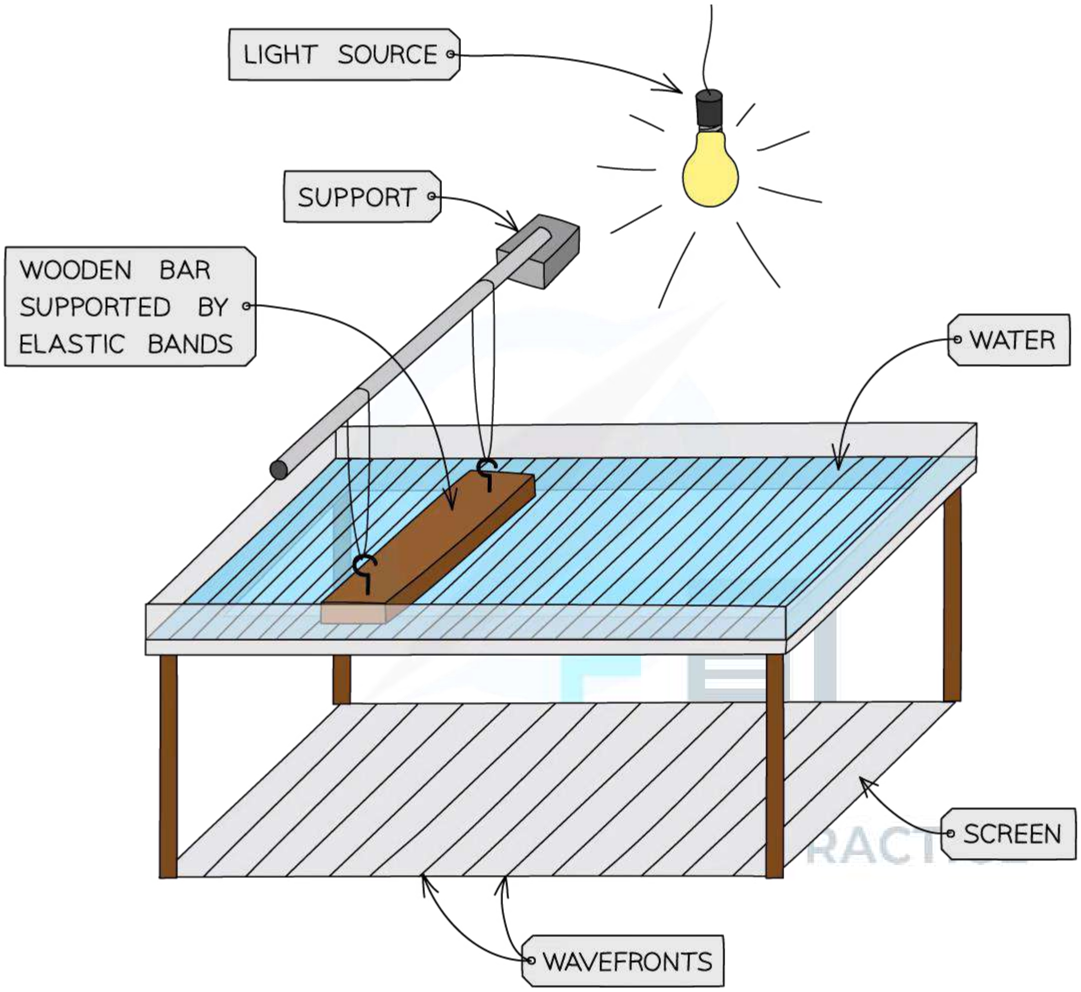


Waves can be shown through vibrations in ropes or springs

- The oscillations/vibrations can be perpendicular or parallel to the direction of wave travel:
  - When they are **perpendicular**, they are **transverse** waves
  - When they are **parallel**, they are **longitudinal** waves

Ripple tanks

- Waves can also be demonstrated by ripple tanks. These produce a combination of transverse and longitudinal waves

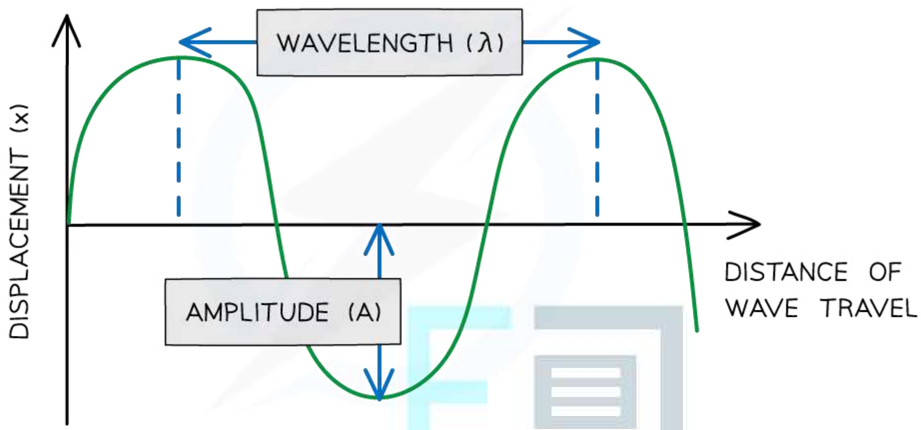


Wave effects can be demonstrated using a ripple tank

- Ripple tanks may be used to demonstrate the wave properties of reflection, refraction and diffraction

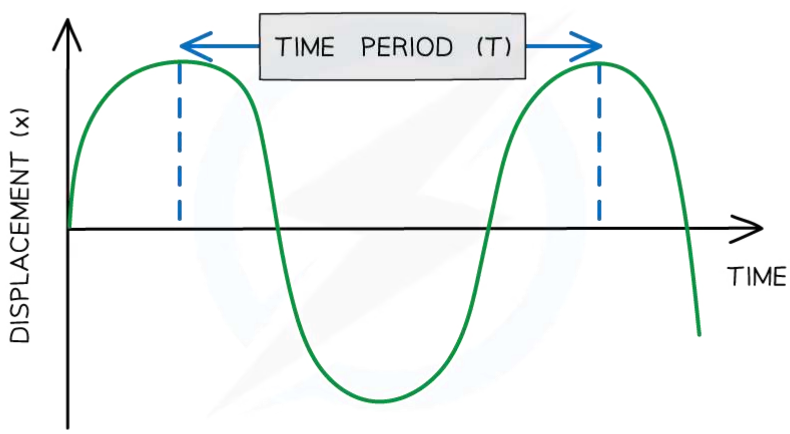
General Wave Properties

- **Displacement (*x*)** of a wave is the distance from its equilibrium position. It is a vector quantity; it can be positive or negative
- **Amplitude (A)** is the maximum displacement of a particle in the wave from its equilibrium position
- **Wavelength (*λ*)** is the distance between points on successive oscillations of the wave that are in phase
    - These are all measured in **metres (m)**



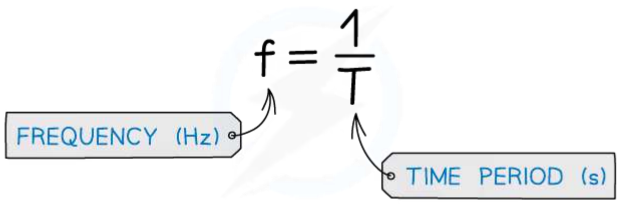
Diagrams showing the amplitude and wavelength of a wave

- **Period (*T*)** or time period, is the time taken for one complete oscillation or cycle of the wave. Measured in **seconds (s)**



Diagrams showing the time period of a wave

- **Frequency (*f*)** is the number of complete oscillations per unit time. Measured in **Hertz** (**Hz)** or **s^{-1}**



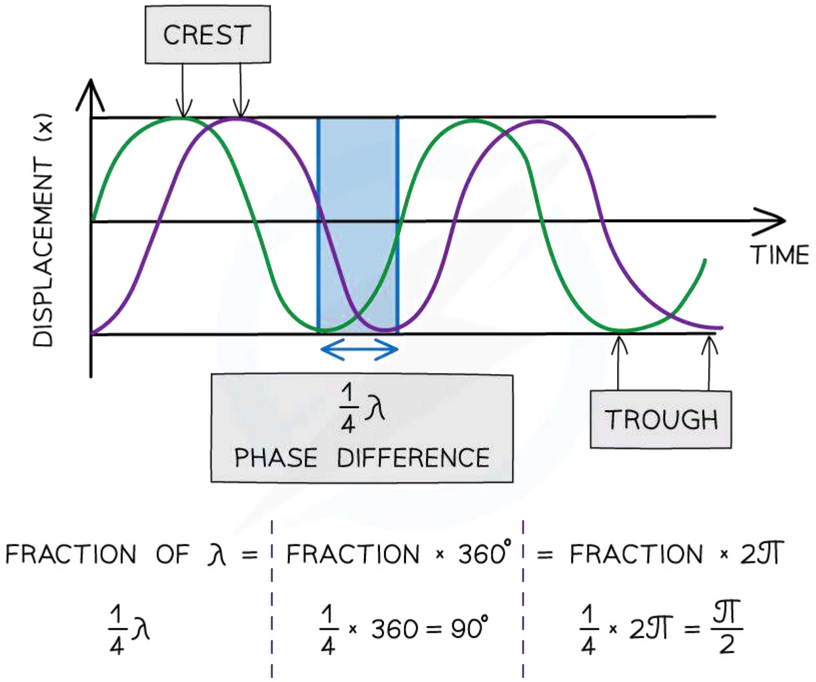
Frequency equation

- **Speed (*v*)** is the distance travelled by the wave per unit time. Measured in **metres per second ($m\ s^{-1}$)**

Phase

- The phase difference tells us **how much a point or a wave is in front or behind another**
- This can be found from the relative positive of the crests or troughs of two different waves of the same frequency
  - When the crests or troughs are aligned, the waves are **in phase**
  - When the crest of one wave aligns with the trough of another, they are in **antiphase**

- The diagram below shows the green wave **leads** the purple wave by ¼ λ

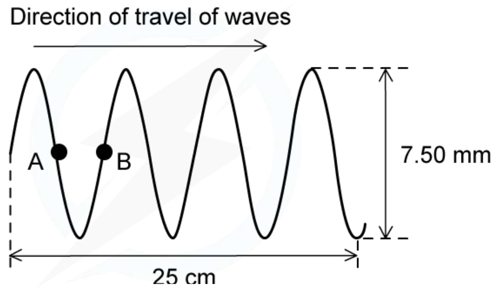


Two waves ¼ λ out of phase

- In contrast, the purple wave is said to **lag** behind the green wave by ¼ λ
- Phase difference is measured in **fractions of a wavelength, degrees** or **radians**
- The phase difference can be calculated from two different points on the same wave or the same point on two different waves
- The phase difference between two points:
  - **In phase** is **360°** or 2π radians
  - **In anti-phase** is **180°** or π radians

Worked Example

Plane waves on the surface of water at a particular instant are represented by the diagram below.



The waves have a frequency of 2.5 Hz.Determine:

a. The amplitude

b. The wavelength

c. The phase difference between points **A** and **B**

A. THE AMPLITUDE

MAXIMUM DISPLACEMENT FROM THE EQUILIBRIUM POSITION

$7.50 \text{ mm} \div 2 = 3.75 \text{ mm}$

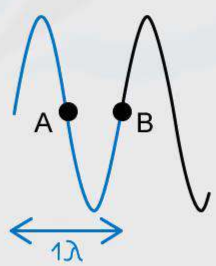
B. THE WAVELENGTH

DISTANCE BETWEEN POINTS ON SUCCESSIVE OSCILLATIONS OF THE WAVE THAT ARE IN PHASE

FROM DIAGRAM: $25\text{cm} = 3\frac{3}{4}$ WAVELENGTHS

$1\lambda = 25 \text{ cm} \div 3\frac{3}{4} = 6.67 \text{ cm}$

C. THE PHASE DIFFERENCE BETWEEN POINTS A AND B



POINTS A AND B HAVE $\frac{1}{2}\lambda$ DIFFERENCE $= \frac{1}{2} \times 360^\circ = 180^\circ$

Exam Tip

When labelling the wavelength and time period on a diagram, make sure that your arrows go from the **very top** of a wave to the very top of the next one. If your arrow is too short, you will lose marks. The same goes for labelling amplitude, don't draw an arrow from the bottom to the top of the wave, this will lose you marks too.

Wave Energy

- Waves transfer energy between points, without transferring matter
- When a wave travels between two points, no matter actually travels with it:
  - The points on the wave simply vibrate back and forth about fixed positions
- Waves that transfer **energy** are known as **progressive** waves
- Waves that do not transfer energy are known as **stationary** waves

Cathode-Ray Oscilloscope

- A Cathode-Ray Oscilloscope is a laboratory instrument used to display, measure and analyse waveforms of electrical circuits
- An A.C. current on an oscilloscope is represented as a transverse wave. Therefore you can determine its frequency and amplitude
- The x-axis is the **time** and the y-axis is the **voltage** (or **y-gain)**

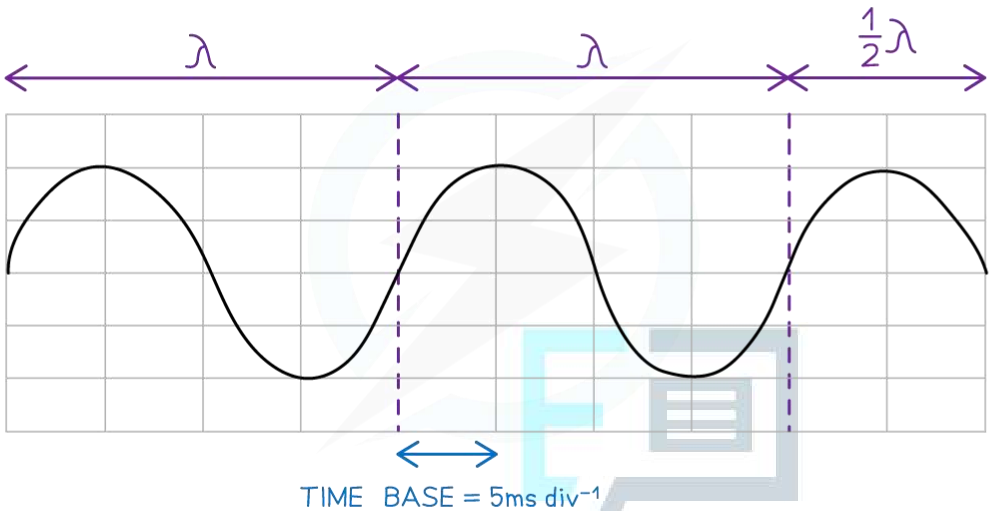
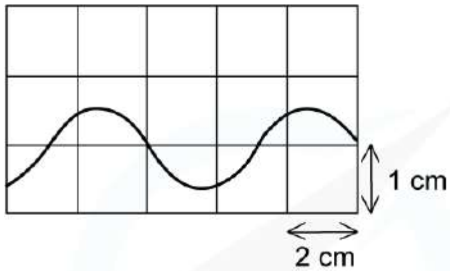


Diagram of Cathode-Ray Oscilloscope display showing wavelength and time-base setting

- The period of the wave can be determined from the **time-base** This is **how many seconds each division represents** measured commonly in **s div^{-1}** or **s cm^{-1}**
- Use as many wavelengths shown on the screen as possible to reduce uncertainties
- Dividing the total time by the number of wavelengths will give the time period *T* (Time taken for one complete oscillation)
- The **frequency** is then determined through **1/T**

Worked Example

A cathode-ray oscilloscope(c.r.o.) is used to display the trace from a sound wave. The time-base is set at 7 μs mm^{-1}.



What is the frequency of the sound wave?

A 2.4 Hz **B** 24 Hz

C 2.4 kHz **D** 24 kHz

ANSWER: C

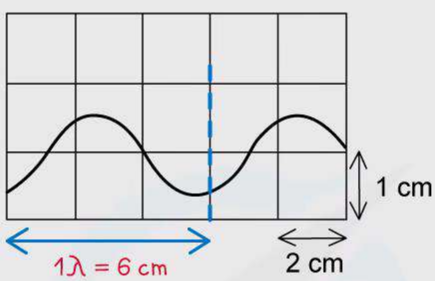
STEP 1

FREQUENCY EQUATION

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

STEP 2

CALCULATE THE TIME PERIOD FROM c.r.o.



TIME DIVISION = 7μs mm^{-1}

6 cm = 60 mm

7μs = 7×10^{-6} s

TIME PERIOD = $7 \times 10^{-6} \times 60 = 4.2 \times 10^{-4}$ s

STEP 3

CALCULATE FREQUENCY FROM EQUATION

$f = \frac{1}{4.2 \times 10^{-4} \text{ s}} = 2380.95 \text{ Hz} = 2.4 \text{ kHz}$ (2 s.f.)

Exam Tip

The time-base setting varies with units for seconds (commonly ms) and the unit length (commonly mm). Unit conversions are very important for the calculate of the time period and frequency

7.1.3 The Wave Equation

Derivation of v = f λ

- Using the definitions of speed, frequency and wavelength, the wave equation $v = f\lambda$ can be derived
- This is an important relationship between three key properties of a wave
- The derivation for this is shown below

Derivation of $v = f\lambda$

WAVELENGTH λ = DISTANCE BETWEEN POINTS ON SUCCESSIVE OSCILLATIONS OF THE WAVE THAT ARE IN PHASE (DISTANCE FROM ONE PEAK TO ANOTHER).

FREQUENCY f = NUMBER OF COMPLETE OSCILLATIONS PER UNIT TIME

TIME T = TIME TAKEN FOR ONE COMPLETE OSCILLATION

SPEED v = DISTANCE TRAVELLED BY THE WAVE PER UNIT TIME

THE SPEED OF A PARTICLE ON A WAVE IS GIVEN BY

$$\text{SPEED} = \frac{\text{DISTANCE}}{\text{TIME}}$$

FOR A WAVE

$$\text{WAVE SPEED} = \frac{\text{DISTANCE TRAVELLED BY THE WAVE}}{\text{TIME}}$$

IN ONE TIME PERIOD T, THE WAVE TRAVELS ONE FULL WAVELENGTH λ

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

FROM THE DEFINITION OF FREQUENCY

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

THEREFORE

$$v = f\lambda$$

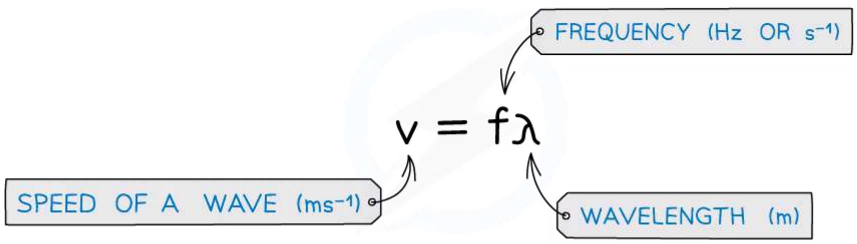
Derivation of $v = f\lambda$

Exam Tip

You will be expected to remember all the steps for this derivation (but do not need to write the full definition for each variable). If you are unsure as to where speed = distance/time comes from, make sure to revisit chapter "2. Kinematics".

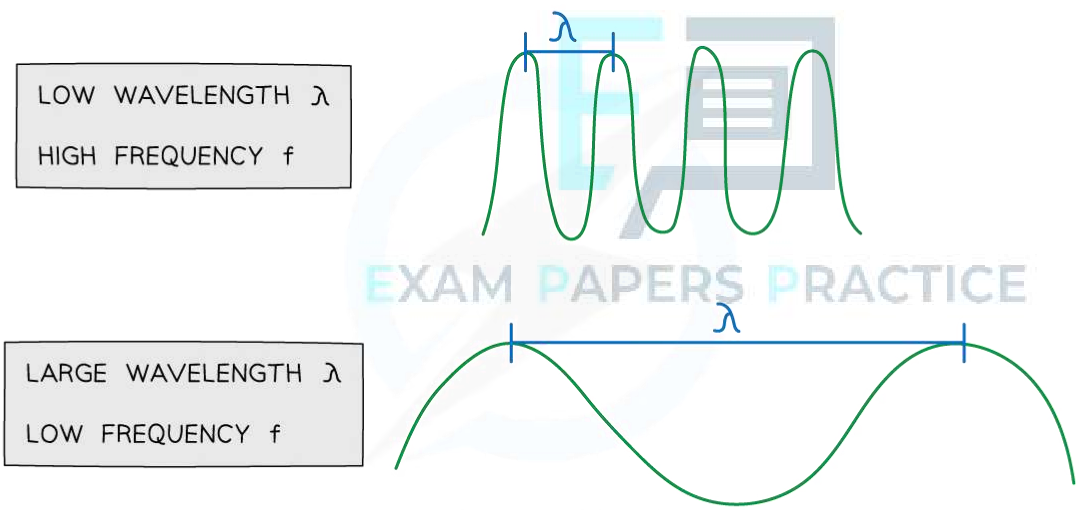
The Wave Equation

- The wave equation links the speed, frequency and wavelength of a wave
- This is relevant for both transverse and longitudinal waves



The Wave Equation

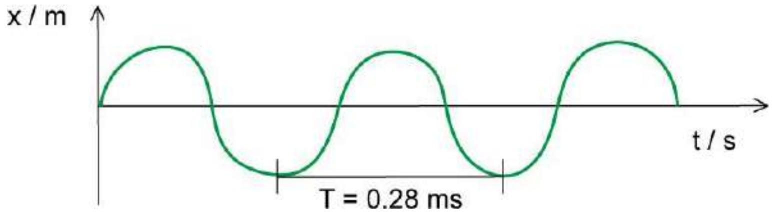
- The wave equation tells us that for a wave of constant speed:
  - As the wavelength **increases,** the frequency **decreases**
  - As the wavelength **decreases,** the frequency **increases**



The relationship between frequency and wavelength of a wave

Worked Example

The wave in the diagram below has a speed of 340 m s^{-1}.



What is the wavelength of the wave?

STEP 1

WAVE EQUATION

$v = f\lambda$

STEP 2

REARRANGE FOR WAVELENGTH

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

STEP 3

CALCULATE f

$f = \frac{1}{T} = \frac{1}{0.28 \times 10^{-3} s} = 3571.43 \text{ Hz}$

STEP 4

SUBSTITUTE VALUE BACK INTO WAVE EQUATION

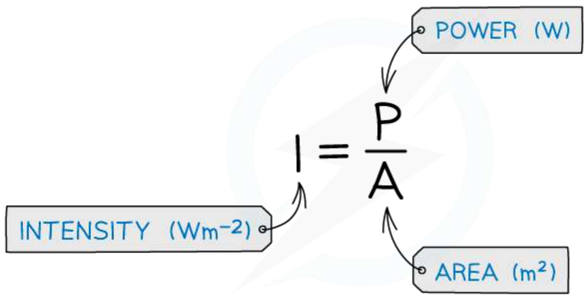
$\lambda = \frac{340}{3571.43} = 0.095 \text{ m}$ (2 s.f.)

Exam Tip

You may also see the wave equation be written as $c = f\lambda$ where c is the wave speed. However, c is often used to represent a specific speed the speed of light (3 x 10^8 ms^{-1}). Only electromagnetic waves travel at this speed, therefore it's best practice to use v for any speed that isn't the speed of light instead.

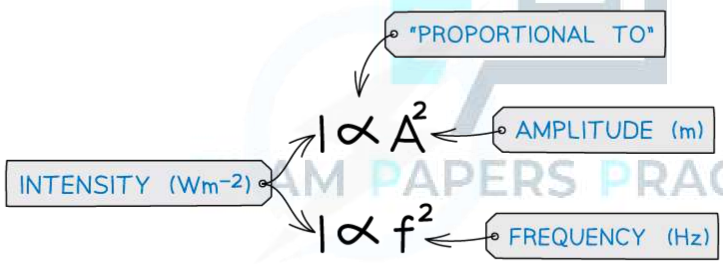
Wave Intensity

- 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

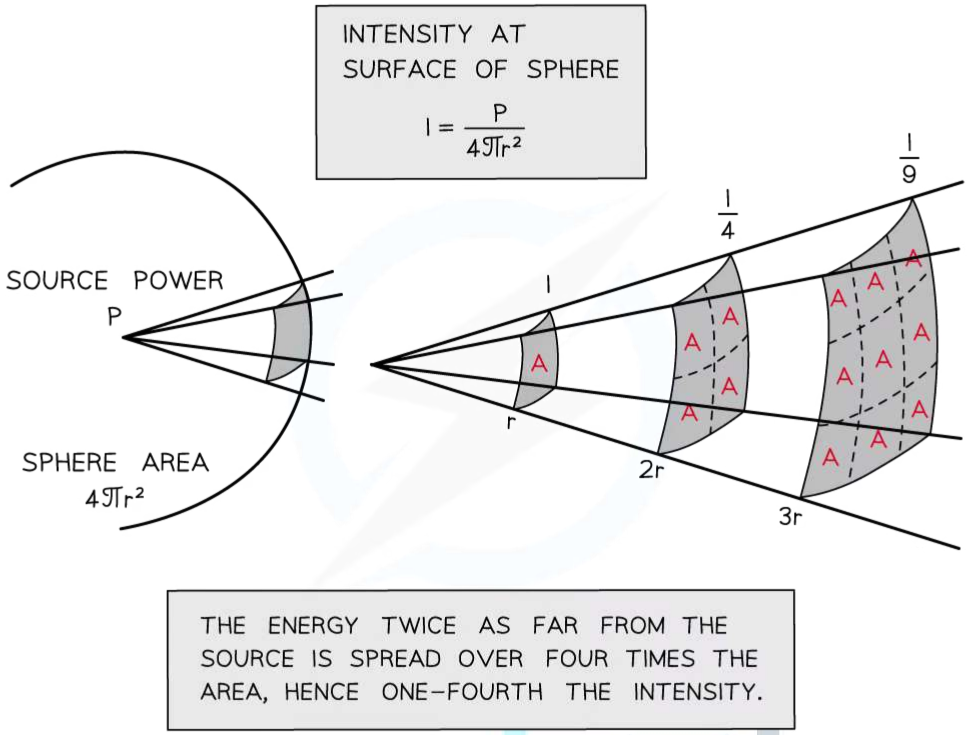


Intensity is proportional to the amplitude² and frequency²

- This means that 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 which 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:

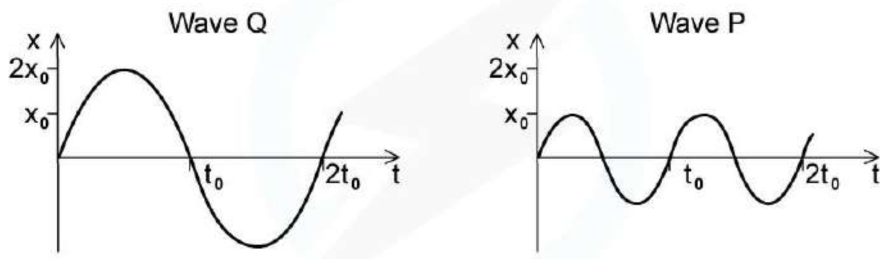


Intensity is proportional to the amplitude squared

- 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.



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

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

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

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

STEP 3

CALCULATE HOW MUCH THE FREQUENCY HAS INCREASED/DECREASED

WAVE P IS DOUBLE THE FREQUENCY OF WAVE Q

$$f_P = 2^2 f_Q$$

$$\text{WAVE P} = 4 I_0 \text{ OF WAVE Q}$$

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

Exam Tip

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

Properties of Transverse & Longitudinal Waves

- In mechanical waves, particles oscillate about fixed points
- The direction of oscillations with regards to the direction of wave travel determine what type of wave it is

Transverse waves

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

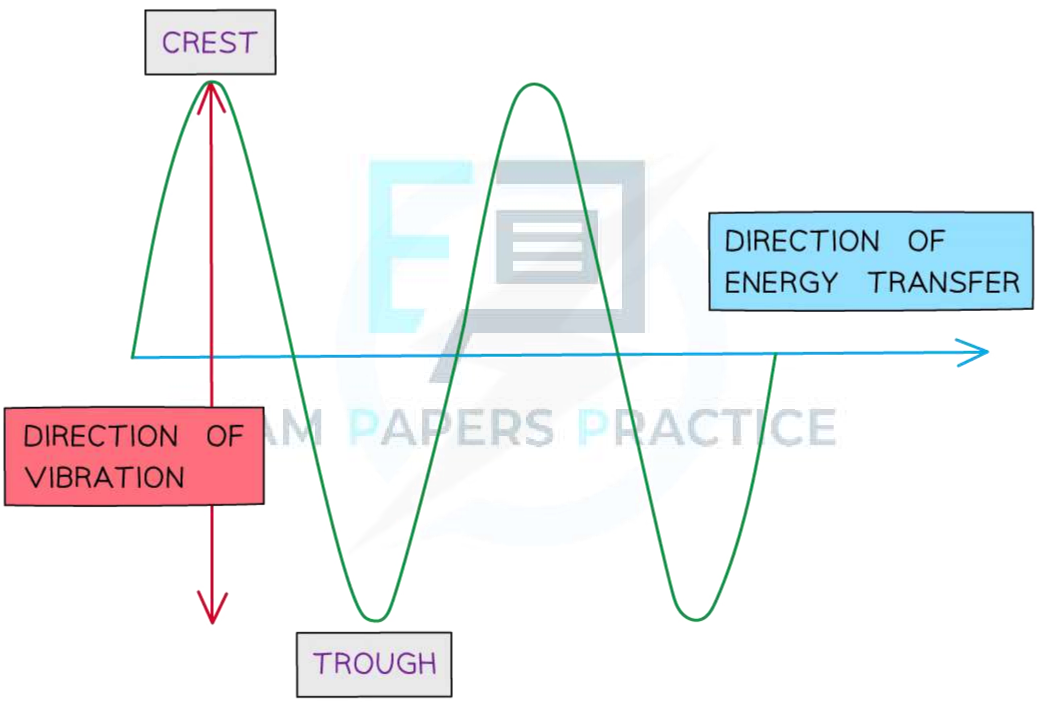


Diagram of a transverse wave

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

Longitudinal waves

- A longitudinal wave is one where the particles oscillate **parallel** to the direction of the wave travel (and energy transfer)
- Longitudinal waves show areas of **compressions** and **rarefactions**

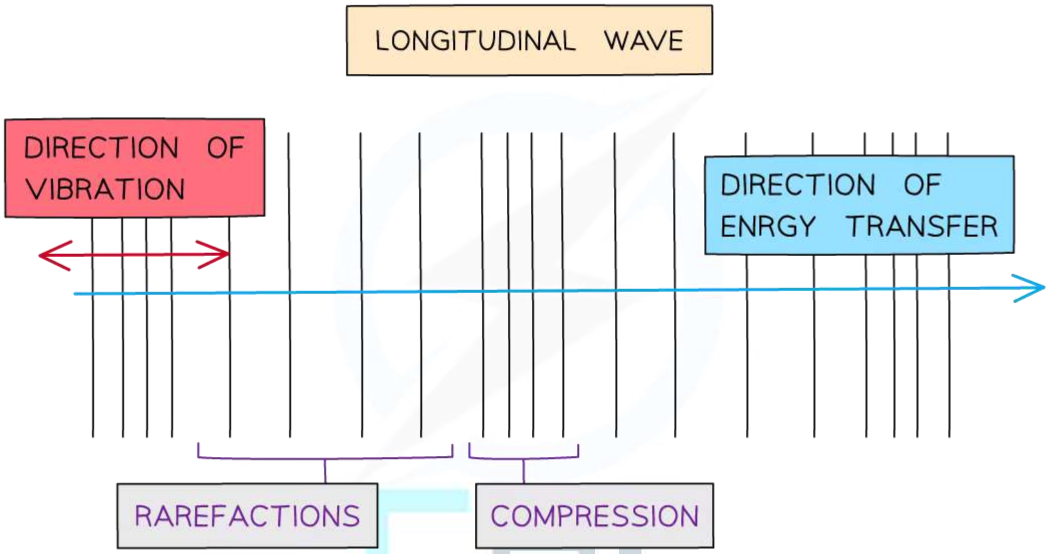
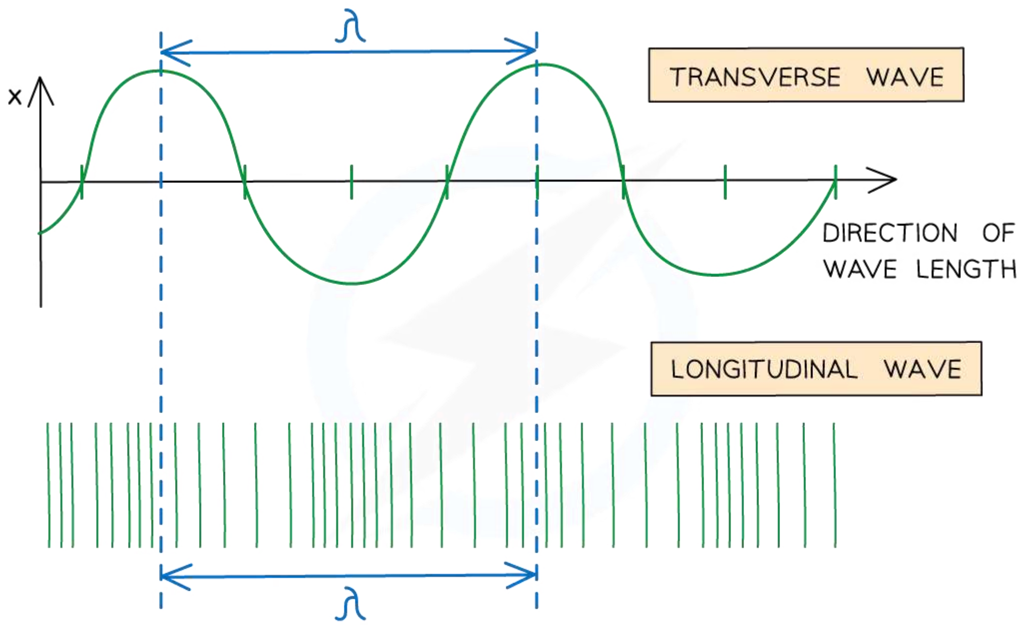


Diagram of a longitudinal wave

- Examples of longitudinal waves are:
  - Sound waves
  - Ultrasound waves

- These can be shown on a slinky spring
- Longitudinal waves **cannot** be polarised
- You will have learned how to analyse the properties of a wave, such as amplitude and wavelength, in "General Wave Properties"
- The diagram below shows the equivalent of a wavelength on a longitudinal wave



Wavelength shown on a longitudinal wave

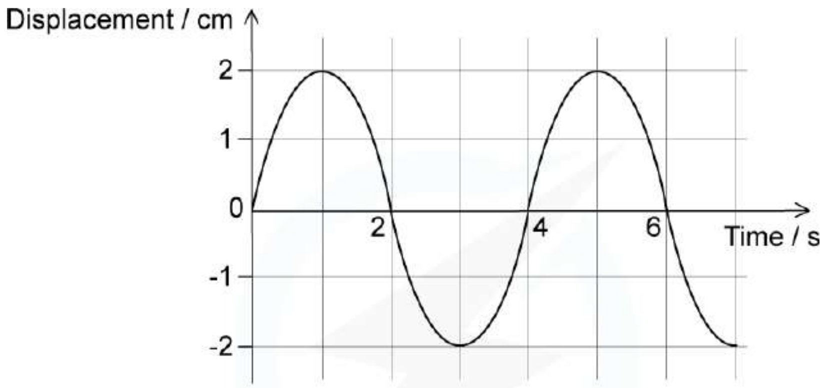
Exam Tip

The definition of transverse and longitudinal waves are often asked as exam questions, make sure to remember these definitions by heart!

Graphical Representations of Transverse & Longitudinal Waves

Worked Example

The graph shows how the displacement of a particle in a wave varies with time.



Which statement is correct?

A. The wave has an amplitude of 2 cm and could be either transverse or longitudinal.

B. The wave has an amplitude of 2 cm and has a time period of 6 s.

C. The wave has an amplitude of 4 cm and has a time period of 4 s.

D. The wave has an amplitude of 4 cm and must be transverse.

ANSWER: A

THE WAVES AMPLITUDE IS THE DISPLACEMENT FROM THE EQUILIBRIUM POSITION

FROM THE GRAPH, THIS IS 2 cm

THE GRAPH IS DISPLACEMENT AGAINST TIME, NOT DISPLACEMENT AGAINST DIRECTION OF WAVE TRAVEL

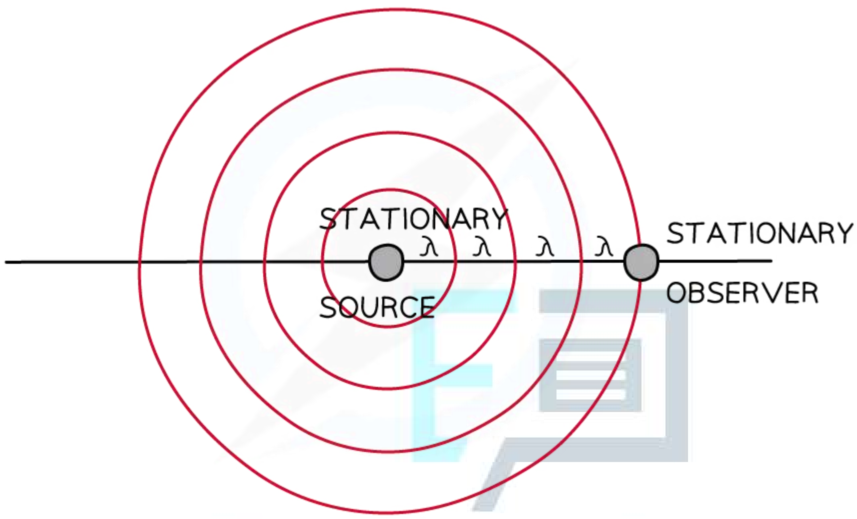
THEREFORE, THE WAVE COULD BE EITHER TRANSVERSE OR LONGITUDINAL

Exam Tip

Both transverse and longitudinal waves can look like transverse waves 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.

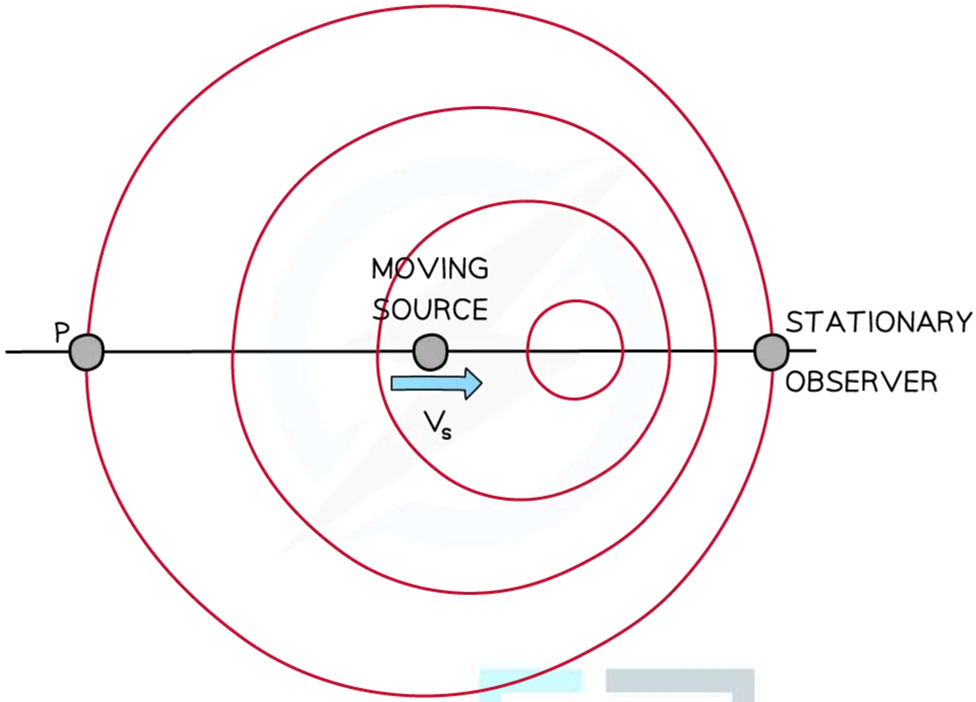
Doppler Shift of Sound

- The whistle of a train or the siren of an ambulance appears to decrease in frequency (sounds lower in pitch) as it moves further away from you
- This frequency change due to the relative motion between a source of sound or light and an observer is known as the **doppler effect** (or **doppler shift**)
- When the observer (e.g. yourself) and the source of sound (e.g. ambulance siren) are both **stationary**, the waves are at the **same** frequency for both the observer and the source



Stationary source and observer

- When the source starts to move **towards** the observer, the wavelength of the waves is **shortened**. The sound therefore appears at a **higher** frequency to the observer



Moving source and stationary observer

- Notice how the waves are closer together between the source and the observer compared to point P and the source
- This also works if the source is moving away from the observer. If the observer was at point P instead, they would hear the sound at a lower frequency due to the wavelength of the waves **broadening**

- The frequency is **increased** when the source is moving **towards** the observer
- The frequency is **decreased** when the source is moving **away** from the observer

Worked Example

A cyclist rides a bike ringing their bell past a stationary observer.Which of the following accurately describes the doppler shift caused by the sound of the bell?

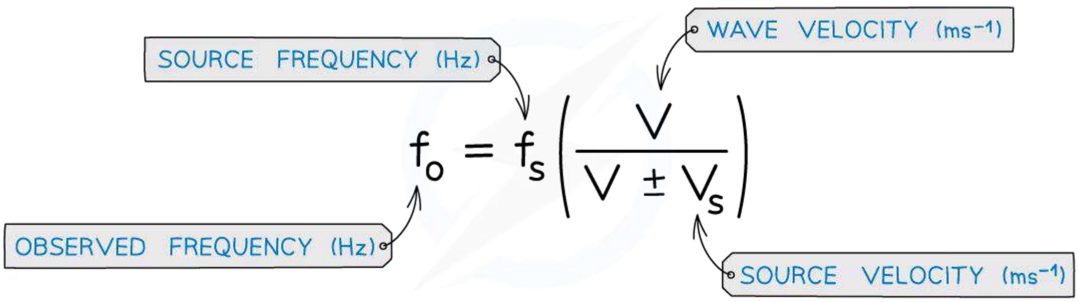
	Wavelength	Frequency	Sound pitch
A	Shorter	Higher	Lower
B	Longer	Lower	Higher
C	Shorter	Lower	Higher
D	Longer	Lower	Lower

ANSWER: D

- If the cyclist is riding past the observer, the wavelength of sound waves are going to become longer
  - This rules out options A and C
- A longer wavelength means a lower frequency (from the wave equation)
- Lower frequency creates a lower sound pitch
  - Therefore, the answer is row D

Calculating Doppler Shift

- When a source of sound waves moves relative to a stationary observer, the observed frequency can be calculated using the equation below:



$$f_o = f_s \left(\frac{v}{v \pm v_s} \right)$$

Doppler shift equation

- The wave velocity for sound waves is 340 ms^{-1}
- The ± depends on whether the source is moving towards or away from the observer
    - If the source is moving **towards**, the denominator is $v - v_s$
    - If the source is moving **away**, the denominator is $v + v_s$

Worked Example

A police car siren emits a sound wave with a frequency of 450 Hz. The car is travelling away from an observer at speed of 45 m s^{-1}. The speed of sound is 340 m s^{-1}.

Which of the following is the frequency the observer hears?

A. 519 Hz **B.** 483 Hz **C.** 397 Hz **D.** 358 Hz

ANSWER: C

STEP 1

DOPPLER SHIFT EQUATION

$$f_o = f_s\left(\frac{V}{V \pm V_s}\right)$$

STEP 2

SUBSTITUTE VALUES INTO THE EQUATION

$f_s = 450\ Hz$
V = SPEED OF SOUND = $340\ ms^{-1}$
V_s = VELOCITY OF THE POLICE CAR (SOURCE) = $45\ ms^{-1}$

THE SOURCE IS MOVING AWAY FROM THE OBSERVER, SO WE USE $V + V_s$

$$f_o = 450\left(\frac{340}{340 + 45}\right) = 397\ Hz \quad (3\ s.f.)$$

Exam Tip

Be careful as to which frequency and velocity you use in the equation. The 'source' is always the object which is moving and the 'observer' is always stationary.

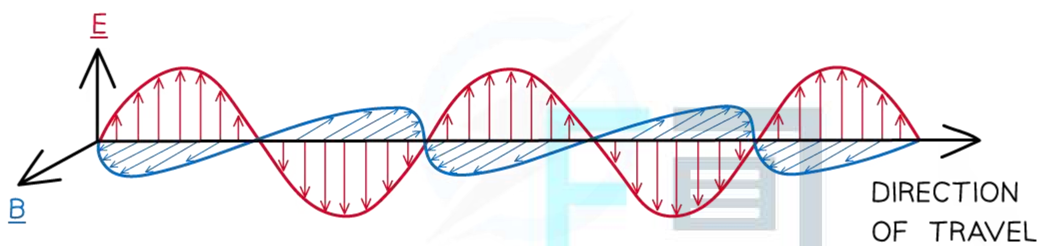
7.2 Transverse Waves: EM Spectrum & Polarisation

7.2.1 Electromagnetic Spectrum

Properties of Electromagnetic Waves

- Visible light is just one part of a much bigger spectrum: The Electromagnetic Spectrum
- All electromagnetic waves have the following properties in common:
  - They are all **transverse** waves
  - They can all travel in a **vacuum**
  - They all travel at the **same speed** in a vacuum (free space) — the speed of light **3×10^8 ms^{-1}**

- The speed of light in air is approximately the same



Oscillating electric and magnetic fields in an electromagnetic wave

- These transverse waves consist of electric and magnetic fields oscillating at right angles to each other and to the direction in which the wave is travelling (in 3D space)
- Since they are transverse, all waves in this spectrum can be reflected, refracted, diffracted, polarised and produce interference patterns

Uses of electromagnetic waves

- Electromagnetic waves have a large number of uses. The main ones are summarised in the table below

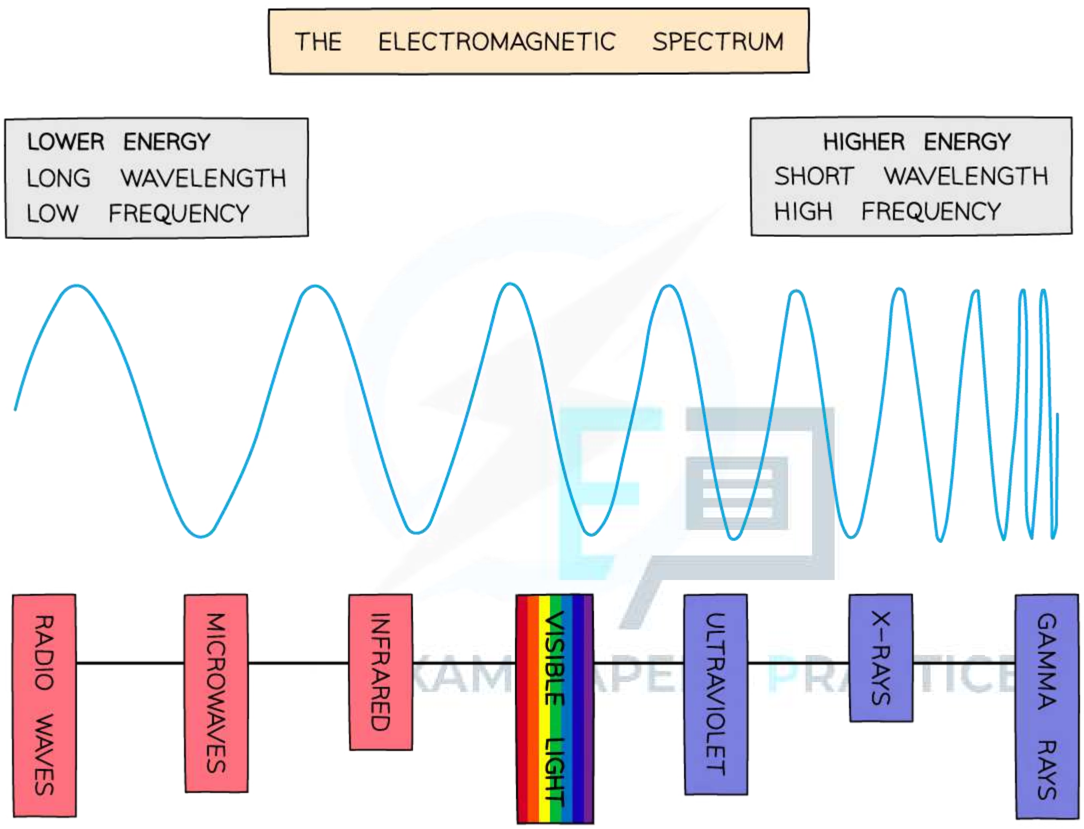
WAVE	USE
RADIO	• COMMUNICATION (RADIO AND TV)
MICROWAVE	• HEATING FOOD • COMMUNICATION (WIFI, MOBILE PHONES, SATELLITES)
INFRARED	• REMOTE CONTROLS • FIBRE OPTIC COMMUNICATION • THERMAL IMAGING (MEDICINE AND INDUSTRY) • NIGHT VISION • HEATING OR COOKING THINGS • MOTION SENSORS (FOR SECURITY ALARMS)
VISIBLE LIGHT	• SEEING AND TAKING PHOTOGRAPHS/VIDEOS
ULTRAVIOLET	• SECURITY MARKING (FLUORESCENCE) • FLUORESCENT BULBS • GETTING A SUNTAN.
X-RAYS	• X-RAY IMAGES (MEDICINE, AIRPORT SECURITY AND INDUSTRY)
GAMMA RAYS	• STERILISING MEDICAL INSTRUMENTS TREATING CANCER

Exam Tip

You will be expected to recall the common properties of all electromagnetic waves in an exam question, however the speed of light will be given on the data sheet.

From Radio Waves to Gamma Rays

- The electromagnetic spectrum is arranged in a specific order based on their wavelengths or frequencies
- This order is shown in the diagram below from longest wavelength (lowest frequency) to shortest wavelength (highest frequency)



Energy, wavelength and frequency for each part of the electromagnetic spectrum

- The higher the **frequency**, the higher the **energy** of the radiation
- Radiation with higher energy is highly ionising and is harmful to cells and tissues causing cancer (e.g. UV, X-rays, Gamma rays)
- The approximate wavelengths in a vacuum of each radiation is listed in the table below:

EM spectrum wavelengths and frequencies

Radiation	Approximate wavelength range / m	Approximate frequency range / Hz
Radio	> 0.1	< 3×10^{9}
Microwaves	$0.1 - 1 \times 10^{-3}$	$3 \times 10^{9} - 3 \times 10^{11}$
Infra-red	$1 \times 10^{-3} - 7 \times 10^{-7}$	$3 \times 10^{11} - 4.3 \times 10^{14}$
Visible	$4 \times 10^{-7} - 7 \times 10^{-7}$	$7.5 \times 10^{14} - 4.3 \times 10^{14}$
Ultra-violet	$4 \times 10^{-7} - 1 \times 10^{-8}$	$7.5 \times 10^{14} - 3 \times 10^{16}$
X-rays	$1 \times 10^{-8} - 4 \times 10^{-13}$	$3 \times 10^{16} - 7.5 \times 10^{20}$
Gamma rays	$1 \times 10^{-10} - 1 \times 10^{-16}$	$3 \times 10^{18} - 3 \times 10^{24}$

- To alternatively find the range of frequencies, convert the wavelengths using the wave equation: **$c = f\lambda$** where c is the speed of light: **3.0×10^{8} m s^{-1}**

Worked Example

A is a source emitting microwaves and B is a source emitting X-rays.The table suggests the frequencies for A and B. Which row is correct?

	Frequency emitted by A/Hz	Frequency emitted by B/Hz
A	$3 \times 10^{9} - 3 \times 10^{11}$	$> 10^{19}$
B	$1 \times 10^{12} - 1 \times 10^{13}$	$3 \times 10^{16} - 7.5 \times 10^{20}$
C	$3 \times 10^{9} - 3 \times 10^{11}$	$3 \times 10^{16} - 7.5 \times 10^{20}$
D	$4 \times 10^{14} - 8 \times 10^{14}$	$5 \times 10^{13} - 7 \times 10^{15}$

ANSWER: C

STEP 1

THE WAVE EQUATION

$c = f\lambda$

STEP 2

REARRANGE FOR FREQUENCY

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

STEP 3

THE RANGE OF WAVELENGTH FOR MICROWAVES IS $0.1 - 1 \times 10^{-3}$ m

USE WAVE EQUATION TO FIND EQUIVALENT FREQUENCIES FOR MICROWAVES

$f = \frac{3 \times 10^8}{0.1} = 3.0 \times 10^9$ $\quad$ $f = \frac{3 \times 10^8}{1.0 \times 10^{-3}} = 3.0 \times 10^{11}$

$f = 3.0 \times 10^9 - 3.0 \times 10^{11}$ Hz

STEP 4

THE RANGE OF WAVELENGTH FOR X-RAYS IS $1 \times 10^{-8} - 4 \times 10^{-13}$ m

USE WAVE EQUATION TO FIND EQUIVALENT FREQUENCIES FOR X-RAYS

$f = \frac{3 \times 10^8}{1 \times 10^{-8}} = 3 \times 10^{16}$ Hz $\quad$ $f = \frac{3 \times 10^8}{4 \times 10^{-13}} = 7.5 \times 10^{20}$ Hz

$f = 3 \times 10^{16} - 7.5 \times 10^{20}$ Hz

STEP 5

ROW C MATCHES BOTH OF THESE FREQUENCY RANGES

Exam Tip

You will be expected to memorise the range of wavelengths for each type of radiation, however you don't need to learn the frequency ranges by heart. Since all EM waves travel at the speed of light, you can convert between frequency and wavelength using the wave equation in an exam question.

Visible Light

- Visible light is defined as the range of wavelengths (400 - 700 nm) which are visible to humans
- Visible light is the only part of the spectrum detectable by the human eye
    - However, this is only 0.0035% of the whole electromagnetic spectrum
- In the natural world, many animals, such as birds, bees and certain fish, are able to perceive beyond visible light and can see infra-red and UV wavelengths of light

7.2.2 Polarisation

Polarisation

- Transverse waves are waves with their displacement perpendicular to their direction of travel. These oscillations can happen in **any plane** perpendicular to the propagation direction
- Transverse waves can be **polarised,** this means:
  - Vibrations are restricted to **one** direction
  - These vibrations are still **perpendicular** to the direction of propagation/energy transfer
- The difference between unpolarised and polarised waves are shown in the diagram below

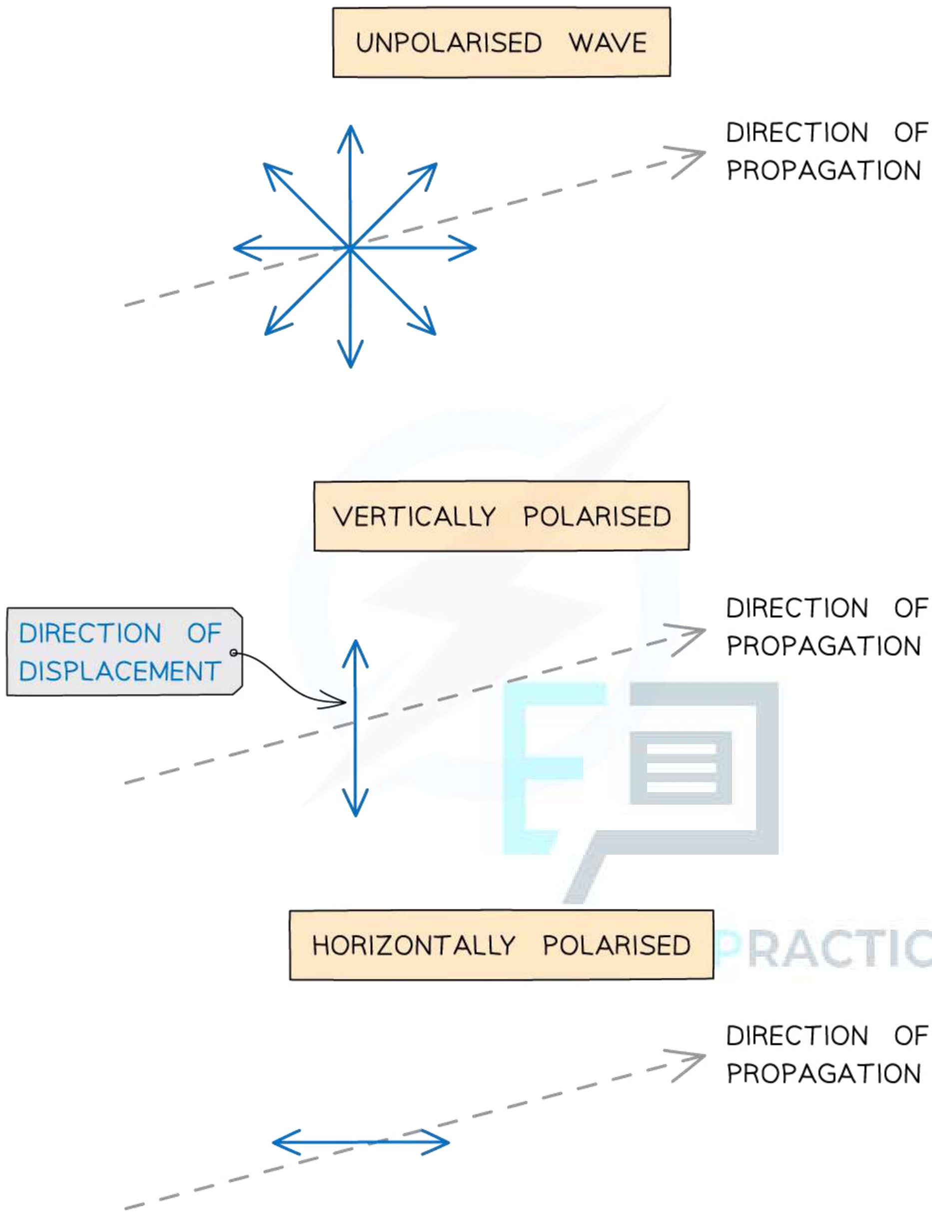


Diagram showing the displacement of unpolarised and polarised transverse waves

- Longitudinal waves (e.g. sound waves) cannot be polarised since they oscillate parallel to the direction of travel
- Waves can be polarised through a **polariser** or **polarising filter**. This only allows oscillations in a certain plane to be transmitted

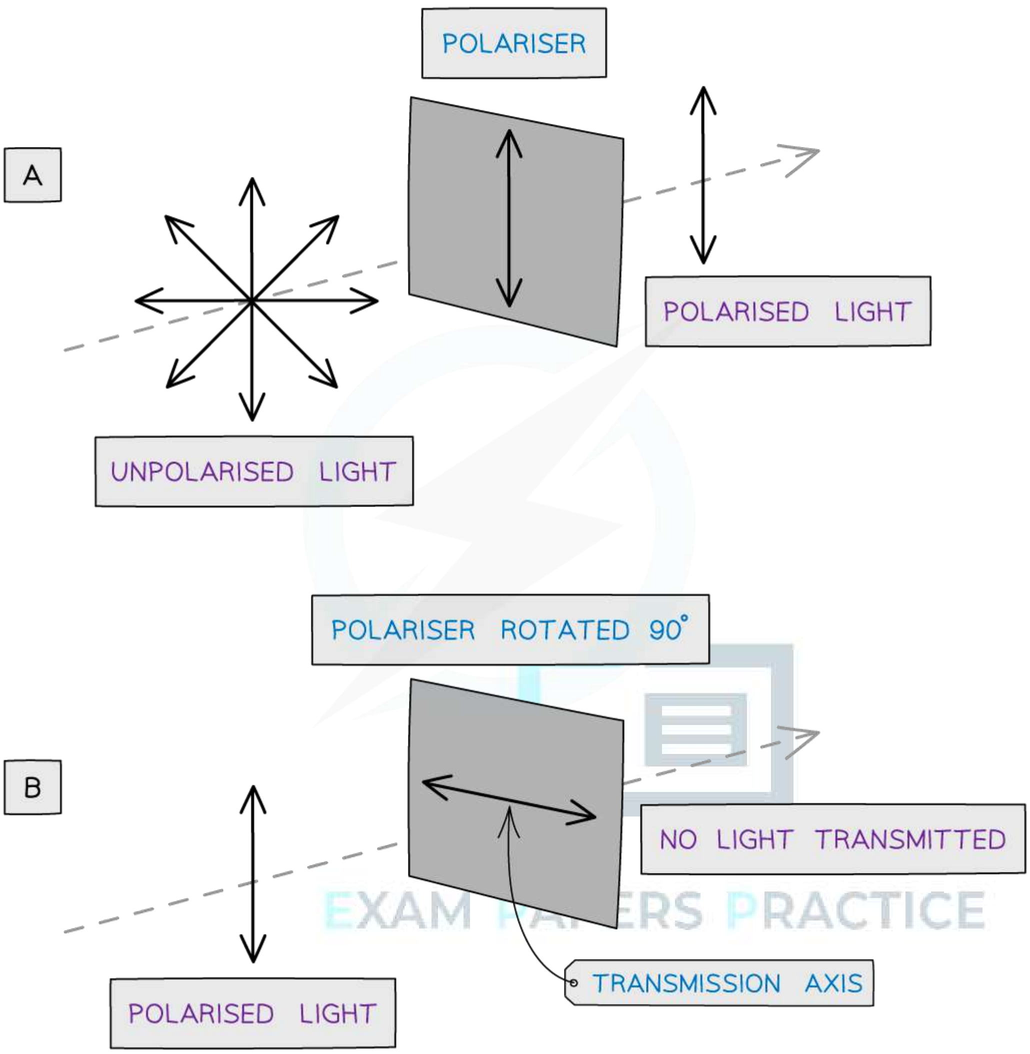


Diagram showing an unpolarised and polarised wave travelling through polarisers

- Only unpolarised waves can be polarised as shown in diagram A
- When a polarised wave passes through a filter with a transmission axis perpendicular to the wave (diagram B), none of the wave will pass through
- Light can also be polarised through reflection, refraction and scattering
- An example of polarisation in everyday life is polaroid sunglasses. These reduce glare caused by sunlight for drivers to see through windows and fishermen to see beneath the water surface more clearly

Worked Example

The following are statements about waves.Which statement below describes a situation in which polarisation should happen?

A. Radio waves pass through a metal grid

B. Surface water waves are diffracted

C. Sound waves are reflected

D. Ultrasound waves pass through a metal grid

ANSWER: A

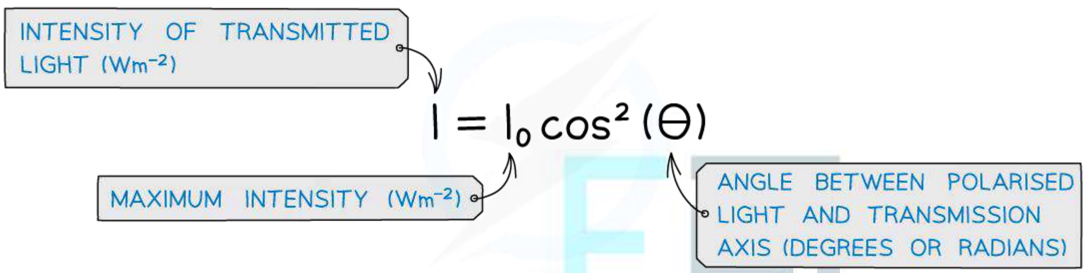
- Polarisation only occurs for transverse waves, therefore, **C** and **D** can be ruled out as sound and ultrasound are both longitudinal waves
- Waves are not polarised when diffracted, hence we can also rule out option **B**
- Radio waves are transverse waves – they can be polarised by a metal grid so only the waves that fit through the grid will be transmitted, therefore, **A** is correct

Malus's Law

- The intensity of unpolarised light is reduced as a result of polarisation
- If unpolarised light of intensity I_0 passes through a polariser, the **intensity of the transmitted polarised light falls by a half**

- The first filter that the unpolarised light goes through is the **polariser**
- A second filter placed after the first one is known as an **analyser**
  - If the analyser has the **same orientation** as the polariser, the light transmitted by the analyser has the **same intensity** as the light incident on it
  - If they have a different orientation, we must used Malus's law

- Malus's law states that if the analyser is rotated by an angle θ with respect to the polariser, the intensity of the light transmitted by the analyser is



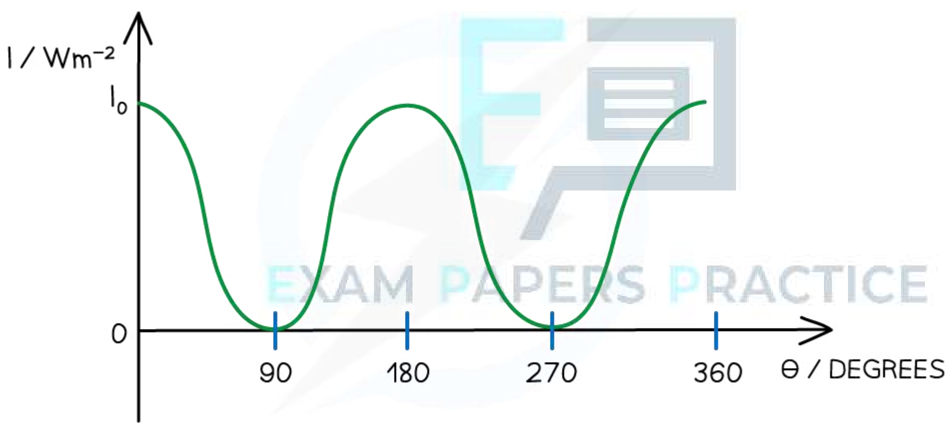
Malus's law equation

- Recall that intensity is the power per unit area and measured in **W m^{-2}**
- If the analyser is rotated by 90° with respect to the polariser (θ = 90°), the intensity of the light transmitted by the analyser will be zero, since $cos(90°) = 0$
- Malus's law also explains why, if the polariser and the analyser have the same orientation, light transmitted by the analyser has the **same intensity** as light transmitted by the polariser
  - i.e the intensity does not decrease between the polariser and the analyser
  - In fact, when θ = 0°, $cos(0°) = 1$, and $I = I_0/2$
- A polariser will only transmit light that is polarised parallel to its transmission axis
- This is seen in Malus's law by the angle θ:

Table of transmission depending on polariser orientation

Angle of transmission axis θ / degrees	Direction of transmission axis	cos²θ	Transmitted intensity I / W m−2	Max or min light intensity transmitted
0 180	↕	1	I_0	Max
90 270	↔	0	0	Min

- The change in intensity against the angle of transmission axis is shown in the graph below

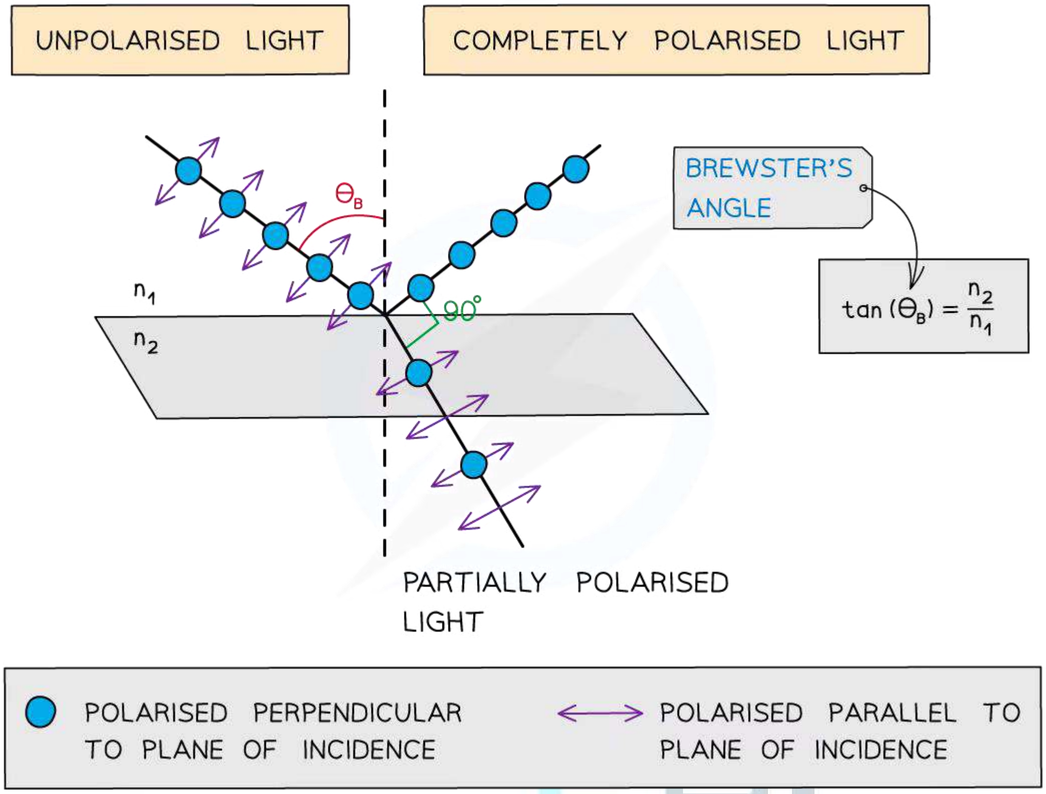


The half rule

- When unpolarised light passes through the first polariser, half the intensity of the wave is always lost ($\frac{I_0}{2}$)

Brewster's angle

- Brewster's angle is an angle of incidence at which light with a particular polarisation is perfectly transmitted through a surface



- n_1 is the refractive index of the initial material (in this case, air)
- n_2 is the refractive index of the material scattering the light

Worked Example

Unpolarised light is incident on a polariser.

The light transmitted by the first polariser is then incident on a second polariser.

The polarising(or transmission) axis of the second polariser is 30° to that of the first.The intensity incident on the first polariser is I.What is the intensity emerging from the second polariser?**A.** 0.75 I **B.** 0.38 I **C.** 0.87 I **D.** 0.43 I

ANSWER: B

STEP 1

FROM THE HALF RULE, WHEN THE LIGHT PASSES THROUGH THE FIRST POLARISER HALF OF ITS INTENSITY IS LOST

$$I_1 = \frac{1}{2}$$

STEP 2

MALUS'S LAW IS USED TO FIND THE INTENSITY OF THE POLARISED LIGHT AFTER THE SECOND POLARISER

$$I = I_0 \cos^2(\theta)$$

$$I_2 = I\cos^2(30)$$

$$I_2 = \frac{3}{4}I$$

STEP 3

COMBINE THE INTENSITY DROPS

TRANSMITTED INTENSITY $I = \left(\frac{1}{2} \times \frac{3}{4}\right) I$

$= 0.375\,I$

$= 0.38\,I$ (2 s.f.)

INTENSITIES ARE COMBINED BY MULTIPLYING THE FRACTION TRANSMITTED THROUGH EACH POLARISER

Exam Tip

Remember when using Malus's law to **square** the cosine of the angle ($\cos^2 \theta$)

Remember that the unpolarised light coming through will always halve in intensity when it becomes polarised through an polariser. Only **then** should you use Malus' law to find the intensity of the light after it has passed through the analyser. Therefore, the I and I_0 in Malus' law are the intensities of light that are already polarised.