CIE International A Level Physics

Topic 7

Waves

Revision Booklet

This booklet covers:

- Progressive Waves and Wave Properties
- The Wave Equation and Intensity
- Transverse and Longitudinal Waves
- The Doppler Effect
- The Electromagnetic Spectrum
- Polarisation and Malus's Law

Progressive Waves

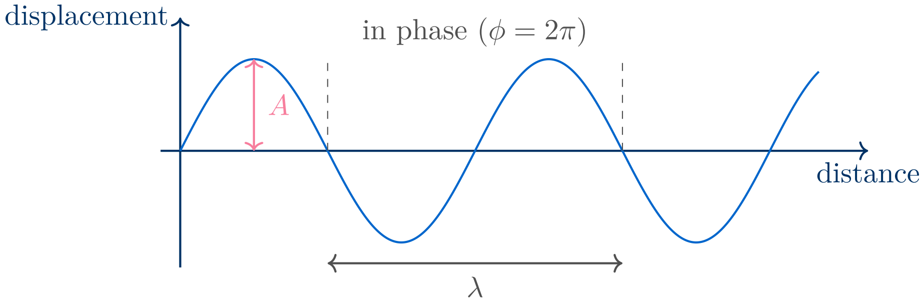
Wave Motion

A **progressive wave** transfers energy from one place to another by means of oscillations, without any net transfer of matter. The particles of the medium vibrate about their equilibrium positions.
Examples: waves in ropes, springs, ripple tanks, sound waves, electromagnetic waves.

Key Wave Terms

Displacement (x)	Distance of a particle from its equilibrium position at a given instant; can be positive or negative. Unit: m.
Amplitude (A)	Maximum displacement from equilibrium. Unit: m.
Period (T)	Time for one complete oscillation. Unit: s.
Frequency (f)	Number of complete oscillations per unit time; $f = 1/T$. Unit: Hz.
Wavelength (λ)	Distance between two adjacent points in phase (e.g. crest to crest). Unit: m.
Wave speed (v)	Speed at which the wave profile travels through the medium. Unit: m s^{-1}.
Phase difference (ϕ)	Difference in the stage of oscillation between two points. Unit: radians or degrees.

Displacement–distance graph



Phase Difference

Two points separated by a distance d along the direction of travel of a wave of wavelength λ have a phase difference:

$$\phi = \frac{2\pi d}{\lambda} \quad \text{(in radians)} \qquad \text{or} \qquad \phi = \frac{360° \cdot d}{\lambda}$$

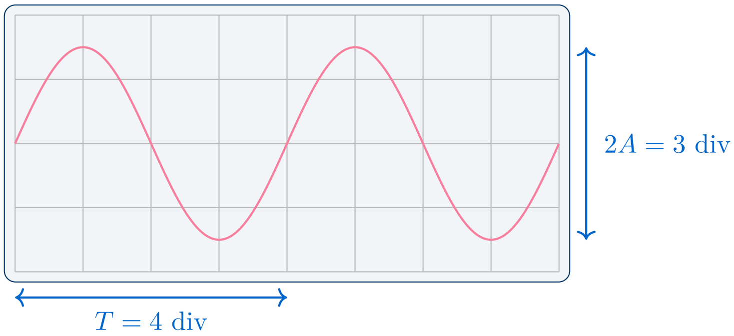
- Points separated by λ (or $n\lambda$): $\phi = 2\pi$ — **in phase**.
- Points separated by $\lambda/2$ (or $(2n-1)\lambda/2$): $\phi = \pi$ — **in antiphase**.

CRO, Wave Equation and Intensity

Using a Cathode-Ray Oscilloscope (CRO)

A CRO displays voltage against time. Two controls are used:

- **Time-base** (s div^{-1}): sets the time represented by each horizontal division. Period T = (number of divisions per cycle) × (time-base setting). Then $f = 1/T$.
- **y-gain** (V div^{-1}): sets the voltage per vertical division. Amplitude = (number of divisions from centre to peak) × (y-gain setting).



The Wave Equation

Derivation: In one period T, the wave travels a distance of one wavelength λ. Speed = distance/time:

$$v = \frac{\lambda}{T} = f\lambda \qquad \text{since } f = \frac{1}{T}$$

$$v = f\lambda$$

Intensity

The **intensity** of a wave is the power transmitted per unit area perpendicular to the direction of propagation:

$$I = \frac{P}{A} \qquad \text{Unit: W m}^{-2}$$

For a progressive wave, intensity is proportional to the square of the amplitude:

$$I \propto (\text{amplitude})^2$$

So doubling the amplitude quadruples the intensity.

Common Mistake

$I \propto A^2$ means intensity is proportional to amplitude *squared*. Halving the amplitude reduces intensity to one quarter — not one half. This relationship holds for all types of progressive wave.

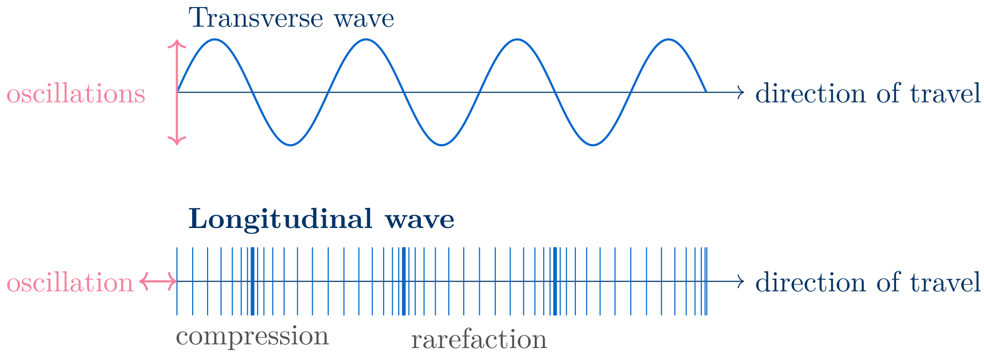
Transverse and Longitudinal Waves

Transverse Waves

In a **transverse wave**, the oscillations of particles are **perpendicular** to the direction of energy transfer (wave propagation).
Examples: waves on a rope, water ripples, all electromagnetic waves.

Longitudinal Waves

In a **longitudinal wave**, the oscillations of particles are **parallel** to the direction of energy transfer (wave propagation). The wave consists of alternating **compressions** (regions of high pressure/density) and **rarefactions** (regions of low pressure/density).
Examples: sound waves, compression waves in a spring.



	Transverse	**Longitudinal**
Oscillation direction	Perpendicular to wave travel	Parallel to wave travel
Can be polarised?	**Yes**	No
Examples	EM waves, rope waves	Sound, spring compressions
Graphical representation	Sinusoidal displacement–distance graph	Displacement–distance graph (same shape, but displacement is along wave direction)

The Doppler Effect

Doppler Effect

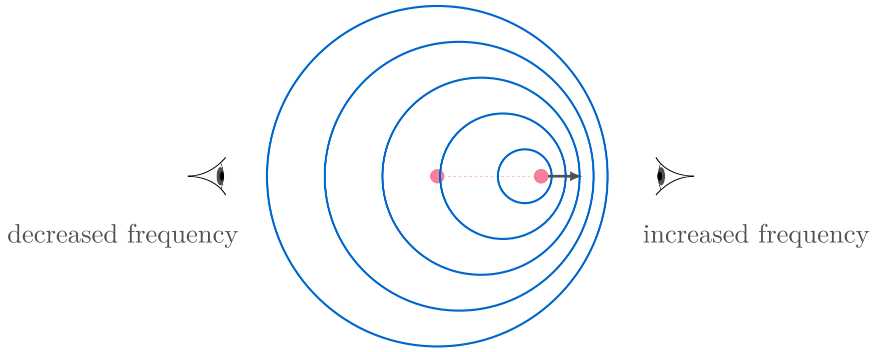
The **Doppler effect** is the change in observed frequency of a wave when the source moves relative to a stationary observer. When the source moves **towards** the observer, the observed frequency is **higher** than the source frequency; when it moves **away**, the observed frequency is **lower**.

Doppler Formula for a Moving Source

$$f_o = \frac{f_s v}{v \pm v_s}$$

- f_o: observed frequency (Hz).
- f_s: source frequency (Hz).
- v: speed of sound in the medium (m s^{-1}).
- v_s: speed of the source (m s^{-1}).
- Use $-$ when the source moves **towards** the observer ($f_o > f_s$).
- Use $+$ when the source moves **away** from the observer ($f_o < f_s$).

Note: this formula applies to a ***moving source*** *and stationary observer only. The Doppler effect for a stationary source and moving observer is not required.*



Sign Convention

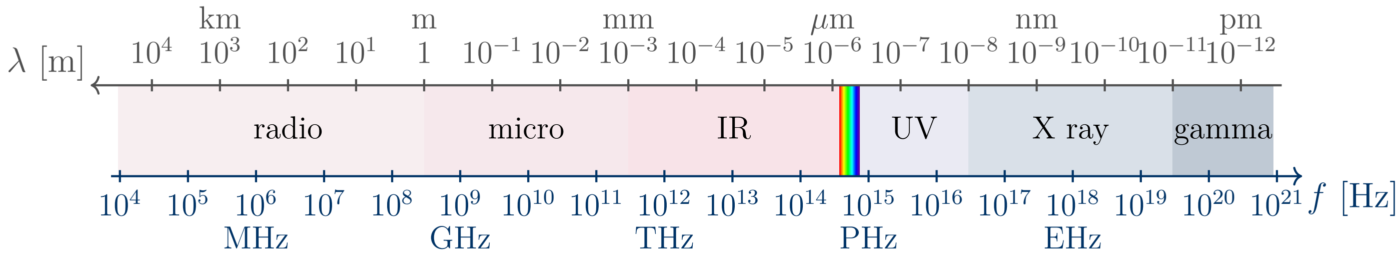
The $\pm$ in $v \pm v_s$ is a common source of error. A useful check: if the source moves towards the observer, the denominator must be *smaller* (so use $-$), making f_o *larger*. If the source moves away, the denominator is *larger* (use $+$), making f_o *smaller*. Always sanity-check your answer against this logic.

The Electromagnetic Spectrum

Properties of Electromagnetic Waves

All electromagnetic (EM) waves:

- Are **transverse** waves.
- Travel at the **same speed** in free space (vacuum): $c = 3.0 \times 10^8$ m s^{-1}.
- Require **no medium** — they can travel through a vacuum.
- Obey $v = f\lambda$ (with $v = c$ in free space).



Region	Approx. wavelength (m)	Approx. frequency (Hz)
Radio waves	$> 10^{-1}$	$< 3 \times 10^9$
Microwaves	10^{-3} to 10^{-1}	3×10^9 to 3×10^{11}
Infrared	7×10^{-7} to 10^{-3}	3×10^{11} to 4×10^{14}
Visible	4×10^{-7} to 7×10^{-7}	4×10^{14} to 7.5×10^{14}
Ultraviolet	10^{-8} to 4×10^{-7}	7.5×10^{14} to 3×10^{16}
X-rays	10^{-13} to 10^{-8}	3×10^{16} to 3×10^{21}
Gamma rays	$< 10^{-13}$	$> 3 \times 10^{21}$

Visible Light

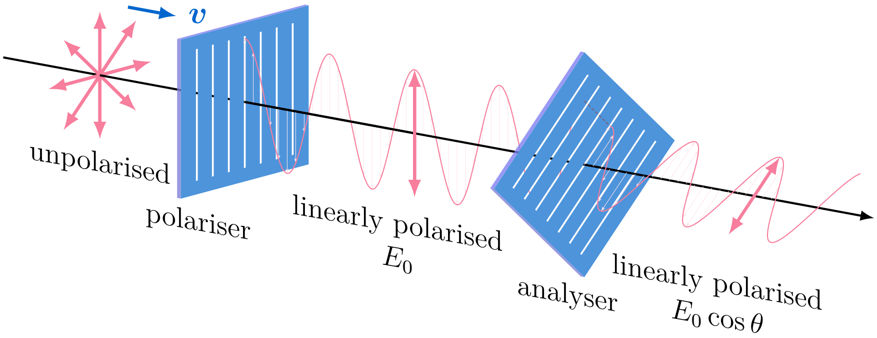
The visible spectrum occupies wavelengths from approximately **400 nm** (violet) to **700 nm** (red) in free space.

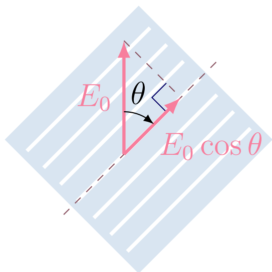
$$400 \text{ nm} = 4 \times 10^{-7} \text{ m} \qquad 700 \text{ nm} = 7 \times 10^{-7} \text{ m}$$

Polarisation and Malus's Law

Polarisation

Polarisation is a phenomenon associated with **transverse waves only**. An unpolarised transverse wave has oscillations in all planes perpendicular to the direction of travel. A **plane-polarised** wave has oscillations confined to a single plane.
Longitudinal waves *cannot* be polarised — their oscillations are already along one axis (the direction of travel).





Malus's Law

When a plane-polarised electromagnetic wave of intensity I_0 passes through a polarising filter at angle θ to the plane of polarisation:

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

- $\theta = 0°$ (filter aligned with polarisation): $I = I_0$ — maximum transmission.
- $\theta = 90°$ (filter perpendicular): $I = 0$ — complete extinction.
- $\theta = 45°$: $I = \frac{1}{2}I_0$ — half the intensity transmitted.
- **Note:** the effect of a polarising filter on an *unpolarised* wave is not required (but for reference, it halves the intensity).

Common Mistake

Malus's law ($I = I_0 \cos^2 \theta$) only applies to **already plane-polarised** light incident on a second filter. It does not apply to the first polarising filter acting on unpolarised light. Also remember θ is measured from the *transmission axis* of the filter to the plane of polarisation of the incoming wave — not between the two filters themselves unless the incoming wave was polarised along the first filter's axis.

Formula Summary Sheet

Formula	Quantity	Units
$v = f\lambda$	Wave equation	m s^{-1}
$f = 1/T$	Frequency–period	Hz
$\phi = 2\pi d/\lambda$	Phase difference	rad
$I = P/A$	Intensity	W m^{-2}
$I \propto (\text{amplitude})^2$	Intensity–amplitude	—
$f_o = f_s v/(v \pm v_s)$	Doppler effect	Hz
$I = I_0 \cos^2 \theta$	Malus's law	W m^{-2}

Key facts to recall:
All EM waves travel at $c = 3.0 \times 10^8$ m s^{-1} in free space and are transverse.
Visible light: 400 nm (violet) to 700 nm (red).
Only **transverse** waves can be polarised.
Doppler: source approaching ⇒ use − in denominator; receding ⇒ use +.

Worked Examples

Example 1 — Wave Properties from a CRO

Question: A CRO displays a wave with a period of 2.5 divisions. The time-base is set to 4.0 ms div^{-1} and the y-gain to 0.50 V div^{-1}. The wave has a peak-to-peak height of 3.0 divisions. Find (a) the frequency and (b) the amplitude.

Solution

(a) $T = 2.5 \times 4.0 \times 10^{-3} = 1.0 \times 10^{-2}$ s; $f = 1/T = 1/(1.0 \times 10^{-2}) = \mathbf{100}$ Hz

(b) Peak-to-peak = 3.0 div, so amplitude = 1.5 div. $A = 1.5 \times 0.50 = \mathbf{0.75}$ V

Example 2 — Intensity and Amplitude

Question: A loudspeaker produces a sound wave of amplitude 2.4×10^{-3} m and intensity 1.8 W m^{-2}. The amplitude is increased to 6.0×10^{-3} m. Calculate the new intensity.

Solution

Since $I \propto A^2$:

$$\frac{I_2}{I_1} = \left(\frac{A_2}{A_1}\right)^2 = \left(\frac{6.0 \times 10^{-3}}{2.4 \times 10^{-3}}\right)^2 = (2.5)^2 = 6.25$$

$$I_2 = 6.25 \times 1.8 = \mathbf{11.3}\ \text{W m}^{\mathbf{-2}}$$

Example 3 — Doppler Effect

Question: An ambulance siren emits sound at $f_s = 850$ Hz. The ambulance approaches a stationary observer at 22 m s^{-1}. The speed of sound is 340 m s^{-1}. Calculate the frequency heard by the observer (a) as the ambulance approaches and (b) as it recedes.

Solution

(a) Approaching (use −):

$$f_o = \frac{f_s v}{v - v_s} = \frac{850 \times 340}{340 - 22} = \frac{289\,000}{318} = \mathbf{909}\ \text{Hz}$$

(b) Receding (use +):

$$f_o = \frac{f_s v}{v + v_s} = \frac{850 \times 340}{340 + 22} = \frac{289\,000}{362} = \mathbf{798}\ \text{Hz}$$

Example 4 — Malus's Law

Question: Plane-polarised light of intensity 24 W m^{-2} is incident on a polarising filter. The filter's transmission axis makes an angle of 35° with the plane of polarisation. Calculate the transmitted intensity.

Solution

$$I = I_0 \cos^2\theta = 24 \times \cos^2(35°) = 24 \times (0.819)^2 = 24 \times 0.671 = \mathbf{16.1}\ \text{W m}^{\mathbf{-2}}$$

Practice Exam Questions

Section A — Short Answer Questions

Q1. Define the terms (a) amplitude, (b) frequency, (c) wavelength and (d) phase difference.

[4 marks]

Q2. A water wave has frequency 3.5 Hz and wavelength 0.24 m. Calculate its speed. Two points on the wave are separated by 0.18 m in the direction of travel. Calculate the phase difference between them.

[4 marks]

Q3. Distinguish between transverse and longitudinal waves. Give one example of each. Explain why polarisation is evidence that light is a transverse wave.

[4 marks]

Q4. State three properties common to all electromagnetic waves. Sketch the electromagnetic spectrum, labelling each region and giving an approximate wavelength range for visible light.

[5 marks]

Section B — Longer Structured Questions

Q5. A source of sound has frequency 640 Hz and moves towards a stationary observer at 15 m s^{-1}. The speed of sound in air is 340 m s^{-1}.

(a) Calculate the frequency heard by the observer.

[2 marks]

(b) The source then moves away from the observer at the same speed. Calculate the new observed frequency and the change in observed frequency between the two situations.

[3 marks]

(c) Explain in terms of wavefronts why the observed frequency is higher when the source approaches.

[2 marks]

Q6. A plane-polarised beam of light of intensity I_0 is incident on a polarising filter.

(a) The filter's transmission axis is at 50° to the plane of polarisation. Calculate the transmitted intensity as a fraction of I_0.

[2 marks]

(b) The filter is rotated to 90°. State the transmitted intensity and explain your answer.

[2 marks]

(c) The intensity of the incident beam is now doubled to $2I_0$ and the filter is returned to 50°. Calculate the new transmitted intensity.

[1 mark]

Q7. A loudspeaker emits sound of frequency 500 Hz and produces an intensity of 3.2×10^{-3} W m^{-2} at a distance of 4.0 m.

(a) The amplitude of the sound wave at this distance is A_1. The speaker power is increased so that the amplitude doubles to $2A_1$. Calculate the new intensity.

[2 marks]

(b) Calculate the wavelength of the sound wave. (Speed of sound = 340 m s^{-1}.)

[2 marks]

(c) Two points in the sound wave are 0.51 m apart along the direction of travel. Calculate the phase difference between them.

[2 marks]

Mark Scheme and Answers

Q1(a). Maximum displacement of a particle from its equilibrium position [1].
Q1(b). Number of complete oscillations per unit time [1].
Q1(c). Distance between two adjacent points that are in phase [1].
Q1(d). Difference in the stage of oscillation between two points on a wave [1].

Q2. $v = f\lambda = 3.5 \times 0.24 = \mathbf{0.84}$ m $\mathbf{s^{-1}}$ [2]. Phase difference: $\phi = 2\pi d/\lambda = 2\pi \times 0.18/0.24 = 2\pi \times 0.75 = \mathbf{1.5}\pi$ rad ($= 270°$) [2].

Q3. Transverse: oscillations perpendicular to direction of travel [1]; e.g. EM waves / rope [1]. Longitudinal: oscillations parallel to direction of travel [1]; e.g. sound [1]. Light can be polarised ⇒ oscillations must be perpendicular to direction of travel ⇒ transverse [bonus/mark scheme dependent on question wording].

Q4. Any three of: all transverse; travel at $c = 3 \times 10^8$ m s^{-1} in free space; require no medium; obey $v = f\lambda$ [3]. Spectrum with correct order (radio → γ) [1]; visible 400–700 nm [1].

Q5(a). $f_o = 640 \times 340/(340 - 15) = 217\,600/325 = \mathbf{669}$ Hz [2].

Q5(b). $f_o = 640 \times 340/(340 + 15) = 217\,600/355 = \mathbf{613}$ Hz [2]; change $= 669 - 613 =$ **56** Hz [1].

Q5(c). As the source approaches, successive wavefronts are emitted closer together [1]; the observer encounters more wavefronts per second, so the observed frequency is higher [1].

Q6(a). $I = I_0 \cos^2(50°) = I_0 \times (0.643)^2 = \mathbf{0.413\ I_0}$ [2].

Q6(b). $I = I_0 \cos^2(90°) = \mathbf{0}$ [1]; the transmission axis is perpendicular to the plane of polarisation so no light passes through [1].

Q6(c). $I = 2I_0 \cos^2(50°) = 2 \times 0.413\, I_0 = \mathbf{0.826\ I_0}$ [1].

Q7(a). $I \propto A^2$; amplitude doubles so I increases by factor 4: $I_2 = 4 \times 3.2 \times 10^{-3} = \mathbf{1.28 \times 10^{-2}}$ W $\mathbf{m^{-2}}$ [2].

Q7(b). $\lambda = v/f = 340/500 = \mathbf{0.68}$ m [2].

Q7(c). $\phi = 2\pi d/\lambda = 2\pi \times 0.51/0.68 = 2\pi \times 0.75 = \mathbf{1.5}\pi$ rad (270°) [2].

Revision Checklist

Use this checklist to track your understanding. Tick each box when you are confident:

	Learning Objective	Confidence (1–3)
☐	Define displacement, amplitude, period, frequency, wavelength, phase difference	
☐	Use the CRO to determine frequency and amplitude	
☐	Derive and use $v = f\lambda$	
☐	Use $I = P/A$ and $I \propto (\text{amplitude})^2$	
☐	Distinguish transverse and longitudinal waves with examples	
☐	Sketch and interpret displacement–distance graphs for both wave types	
☐	Understand the Doppler effect for a moving source	
☐	Use $f_o = f_s v/(v \pm v_s)$ with correct sign convention	
☐	State properties common to all EM waves	
☐	Recall the EM spectrum regions and approximate wavelength ranges	
☐	Recall visible light wavelength range (400–700 nm)	
☐	Explain polarisation and why it is evidence for transverse waves	
☐	Apply Malus's law $I = I_0 \cos^2\theta$ to plane-polarised light	

Key: 1 = Need more work 2 = Getting there 3 = Confident

Good luck with your revision!

Waves is one of those topics where a clear mental picture goes a long way. Sketch the wave, label the amplitude and wavelength, decide whether oscillations are parallel or perpendicular to travel — and most of the topic falls into place from there.