Topic C.2

THE WAVE MODEL

Every Formula, Trick & Trap on a Page
& IB-Style Quick Reference

Topics Covered	**Exam Relevance**
Wave quantities & $v = f\lambda$	P1 & P2 (SL + HL)
Transverse vs longitudinal	Polarisation ⇒ transverse
Sound & the EM spectrum	Order of the EM spectrum
Mechanical vs EM waves	Intensity $\propto A^2$
Wave graphs (y–x, y–t)	Read λ or T off a graph

The Big Picture — How C.2 Fits Together

THE WAVE MODEL
energy travels, matter doesn't — $v = f\lambda$

- **Wave Quantities**: λ, f, T, A; $v = f\lambda$
- **Two Types**: transverse $\perp$; longitudinal $\parallel$
- **Sound**: longitudinal; needs a medium
- **EM Waves**: transverse; vacuum; the spectrum
- **Reading Graphs**: y–$x \Rightarrow \lambda$; y–$t \Rightarrow T$

§1 — Wave Properties & Quantities

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Core Wave Equation

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

v = wave speed $(\mathrm{m/s})$; f = frequency (Hz); λ = wavelength (m); T = period (s)

TRICK In a given medium, v is fixed. If f doubles, λ halves. The wave speed does *not* change if amplitude or frequency changes.

TRICK **New medium?** The source fixes f (unchanged); the medium fixes v; so $\lambda = v/f$ changes. Source $\rightarrow f$, medium $\rightarrow v$.

Key Quantities

Amplitude A	max displacement from equil.
Period T	time for 1 complete oscillation
Frequency f	$f = 1/T \quad [\mathrm{Hz}]$
Wavelength λ	distance between in-phase pts
Wave speed v	speed of wave pattern

TRAP v is the speed of the *wave pattern*, NOT the speed of the particles. Particles oscillate about equilibrium; they do not travel with the wave.

NOTE Intensity $I \propto A^2$. Doubling amplitude → intensity $\times 4$.

Rays & Wavefronts

Wavefront: a surface (line in 2-D, sphere in 3-D) joining points that oscillate *in phase*; adjacent wavefronts are λ apart. **Ray**: line showing the direction of energy travel. **Rays are always $\perp$ (at $90°$) to wavefronts.** Point source $\Rightarrow$ circular/spherical wavefronts with radial rays; far away $\Rightarrow$ plane wavefronts with parallel rays.

FROM THE PHOTON QUESTION BANK

Draw rays exactly $90°$ to wavefronts, and read λ as the spacing between adjacent wavefronts. Wave speed depends on the medium, not the source — if f doubles at fixed v, then λ halves (show the step).

§2 — Transverse vs Longitudinal Waves

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Transverse Waves

Particle motion: *perpendicular* to direction of energy transfer

Features:
- Can be polarised
- Examples: light, all EM waves, string waves, water surface waves
- Show crests and troughs

Longitudinal Waves

Particle motion: *parallel* to direction of energy transfer

Features:
- Cannot be polarised
- Examples: sound, seismic P-waves, slinky compressions
- Show compressions and rarefactions

Compressions & Rarefactions

Compression: particles closer than normal (high pressure)

Rarefaction: particles further apart (low pressure)

Distance between adjacent compressions $= \lambda$

On a displacement–position graph:
C = zero displacement, *negative gradient*
R = zero displacement, *positive gradient*

TRAP Only transverse waves can be polarised. If a wave is polarised, it *must* be transverse. Longitudinal waves oscillate parallel to propagation — there is no plane to restrict.

FROM THE PHOTON QUESTION BANK

Locate compressions/rarefactions from a longitudinal displacement diagram and use their spacing to find λ (compression-to-compression $= \lambda$; compression-to-rarefaction $= \frac{1}{2}\lambda$). State the oscillation direction relative to energy transfer to justify the wave type.

§3 — Sound Waves

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Nature of Sound

- **Mechanical** and **longitudinal**
- Requires a material medium (cannot travel in vacuum)
- Propagates as pressure variations
- Speed $\approx 340\,\mathrm{m/s}$ in air at $20\,°\mathrm{C}$
- Faster in liquids and solids than in gases
- f determines pitch; A determines loudness
- Audible range: $20\,\mathrm{Hz}$–$20\,\mathrm{kHz}$

Sound Speed in Media (approx.)

Air ($20\,°\mathrm{C}$)	$\approx 340\,\mathrm{m/s}$
Water	$\approx 1500\,\mathrm{m/s}$
Steel	$\approx 5000\,\mathrm{m/s}$

Sound is faster in solids/liquids due to stronger intermolecular forces enabling faster energy transfer.

TRICK Bell-jar experiment: as air is removed, sound fades to zero → proves sound needs a medium. Light from the bulb persists → proves EM waves do not need a medium.

TRICK **Two graphs:** y vs x is a *snapshot* $\Rightarrow$ read λ; y vs t is *one particle* $\Rightarrow$ read T. Check the axis label first, then $v = f\lambda$.

§4 — Electromagnetic Waves & EM Spectrum

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Nature of EM Waves

- **Transverse**: oscillating $\vec{E}$ and $\vec{B}$ fields, perpendicular to each other and to propagation
- Do **not** need a medium (travel through vacuum)
- All travel at $c = 3.00 \times 10^8\,\mathrm{m/s}$ in vacuum
- Obey $c = f\lambda$ in vacuum
- Slow down (but frequency unchanged) in a medium

EM Spectrum (low f → high f)

Radio	$\lambda \sim 1\,\mathrm{m}$–$1\,\mathrm{km}$
Microwave	$\lambda \sim 1\,\mathrm{cm}$
Infrared	$\lambda \sim 10\,\mathrm{\mu m}$
Visible	$\lambda \sim 400$–$700\,\mathrm{nm}$
Ultraviolet	$\lambda \sim 100\,\mathrm{nm}$
X-ray	$\lambda \sim 0.1\,\mathrm{nm}$
Gamma	$\lambda < 0.01\,\mathrm{nm}$

All travel at c in vacuum. λ decreases as f increases.

TRAP When an EM wave enters a medium: speed *decreases*, wavelength *decreases*, but frequency *stays the same*. Frequency is set by the source and does not change.

§5 — Mechanical vs. EM Waves

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Comparison Table

Property	Mechanical	EM
Medium needed?	Yes	No
Wave type	Transverse OR longitudinal	Transverse only
Speed in vacuum	Does not propagate	$c = 3.00 \times 10^8$ m/s
Speed depends on	Medium (density, elasticity)	Medium ($< c$ in material)
Polarisable?	Only if transverse	Yes (all EM waves)
Example	Sound (L), strings (T)	Light, radio, X-rays

NOTE Energy transfer: ALL travelling waves (mechanical and EM) transfer energy *without* net transfer of matter. Intensity $I = P/A$; for point source: $I \propto 1/r^2$.

§6 — Graph Interpretation Guide

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Displacement–Position (y vs x)

- Snapshot of whole wave at one instant t
- Horizontal axis $\Rightarrow$ read off λ
- Vertical axis $\Rightarrow$ read off A
- Wave moves to the right: each point will move in the direction of the *point behind it*

Displacement–Time (y vs t)

- Motion of *one particle* over time
- Horizontal axis $\Rightarrow$ read off T
- Vertical axis $\Rightarrow$ read off A
- $f = 1/T$; then use $v = f\lambda$ if needed

TRICK Distinguish the two graphs by their axes: x-axis labelled in **metres** (λ) or **seconds** (T). Never mix them up. A typical exam-style question gives one graph and asks you to read values from the other type.

FROM THE PHOTON QUESTION BANK

Read λ (and A) off a displacement–distance graph and T (and A) off a displacement–time graph; quote amplitude, never peak-to-peak. Convert a time offset between two waves to a phase difference via $\phi = (\Delta t/T) \times 360°$.

Quick Reference: All waves transfer energy. No net transfer of matter.

$v = f\lambda$ | $T = 1/f$ | $I \propto A^2$ | $c = 3.00 \times 10^8$ m/s in vacuum