IB DP PHYSICS

Theme C: Wave Behaviour

C.2 Wave Model

Revision Notes · Standard and Higher Level

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Original notes prepared for the IB Diploma Programme Physics course (first assessment 2025)

What the syllabus requires

C.2 builds the basic model of a travelling wave that every later wave topic (superposition, standing waves, the Doppler effect, quantum behaviour) relies on. Use this list as a final checklist before the exam.

Understanding	You should be able to...
Transverse and longitudinal waves	Define both types by comparing the direction of oscillation with the direction of energy transfer, and classify examples (rope, water, sound, seismic, light).
Wave quantities	Define and use displacement, amplitude, wavelength, period, frequency and wave speed; recall $f = 1/T$.
Wave equation	Derive and apply $v = f\lambda = \lambda/T$ in mechanical and electromagnetic contexts.
Wave graphs	Read wavelength from a displacement-distance graph and period from a displacement-time graph, and never confuse the two.
Sound	Describe sound as a longitudinal pressure wave; relate pitch to frequency and loudness to amplitude.
Electromagnetic spectrum	Order the regions by wavelength and frequency; recall that all EM waves travel at $c = 3.00 \times 10^{8}\ \text{m s}^{-1}$ in a vacuum.
Waves at boundaries	Describe reflection, transmission and absorption; know that frequency never changes at a boundary.
Intensity	Use $I \propto A^2$ and, for a point source, $I \propto 1/r^2$.

> **Exam note:** C.2 content is common to SL and HL. It is examined both directly and as the foundation of C.3 (interference), C.4 (standing waves and Doppler) and E-theme quantum physics, so weak spots here cost marks across several papers.

1. What a wave is

A **travelling (progressive) wave** is a disturbance that transfers **energy** from one place to another **without any net transfer of matter**. A cork bobbing on a pond proves the point: as ripples pass, the cork moves up and down about a fixed spot, yet the energy of the splash reaches the far bank.

The source of every wave is an **oscillation**. Each particle (or field point) repeats the motion of the source a little later than its neighbour, and this progressive phase lag is what makes the disturbance travel.

Mechanical and electromagnetic waves

	Mechanical waves	Electromagnetic waves
What oscillates	Particles of a material medium	Electric and magnetic fields
Medium required?	Yes - there must be matter to disturb	No - they travel through a vacuum
Examples	Sound, water waves, waves on strings, seismic waves	Radio, microwaves, infrared, light, UV, X-rays, gamma rays
Speed determined by	Properties of the medium (density, stiffness, tension...)	$c = 3.00 \times 10^{8}\ \text{m s}^{-1}$ in vacuum; slower in media

A mechanical wave needs a medium because its energy is stored and passed on as kinetic and potential energy of particles: each particle drags its neighbour along through intermolecular forces. Remove the particles and there is nothing to oscillate - which is why the Moon's surface is silent and why a ringing bell in an evacuated bell jar cannot be heard even though it can still be seen (light needs no medium; sound does).

Wavefronts and rays

Two standard drawing tools describe how waves spread. A **wavefront** is a line (or surface) joining neighbouring points that oscillate in phase - for ripples on a pond, the crest lines. A **ray** is an arrow drawn perpendicular to the wavefronts showing the direction of energy transfer. A point source produces circular (in 3D, spherical) wavefronts with rays pointing radially outward; far from the source the wavefronts become effectively straight and parallel (**plane waves**). Successive wavefronts are one wavelength apart, so wavefront diagrams make changes of wavelength - for example on entering a new medium - immediately visible.

2. Transverse and longitudinal waves

Waves are classified by comparing the direction in which the medium oscillates with the direction in which the wave (and its energy) travels.

- **Transverse wave:** the oscillations are **perpendicular** to the direction of energy transfer. The wave profile shows **crests** and **troughs**.
- **Longitudinal wave:** the oscillations are **parallel** to the direction of energy transfer. The medium shows **compressions** (regions of higher pressure and density) and **rarefactions** (regions of lower pressure and density).

Both types are easy to demonstrate with a stretched slinky spring. Flick the end sideways and a transverse pulse runs along it; push the end forward and back along its length and a longitudinal pulse of bunched coils (a compression) travels instead. In both cases the coils return to where they started - only the energy moves on.

Wave	Type	What oscillates	Notes
Wave on a rope or string	Transverse	Segments of the rope, side to side	Speed set by tension and mass per unit length
Water surface ripples	Mostly transverse	Surface water (actually small circles)	Treated as transverse at IB level
Sound in air, liquids, solids	Longitudinal	Molecules along the travel direction	A pressure wave; cannot cross a vacuum
Seismic P-waves	Longitudinal	Rock, back and forth	Fastest seismic waves; pass through solid and liquid
Seismic S-waves	Transverse	Rock, side to side	Cannot travel through liquids - evidence for Earth's liquid outer core
All electromagnetic waves	Transverse	Electric and magnetic fields	Only transverse waves can be polarised (C.3)

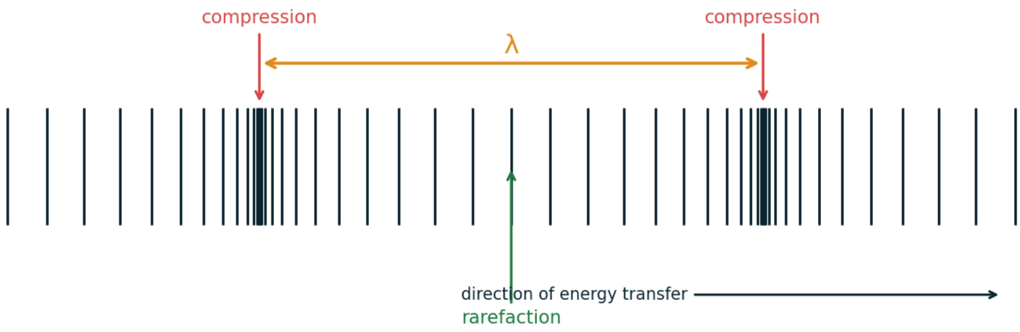

Figure 2. A longitudinal wave: particles bunch together at compressions and spread apart at rarefactions. One wavelength λ runs from one compression to the next.

Sound as a pressure wave

A loudspeaker cone pushing forward squeezes the air ahead of it into a compression; moving back it creates a rarefaction. These pressure variations travel outward at the speed of sound while each air molecule merely oscillates about a fixed position. The distance from one compression to the next is one wavelength. Sound can therefore be graphed either as particle displacement or as pressure variation against position - the two curves have the same wavelength but are a quarter of a wavelength out of step (pressure is greatest where displacement is zero).

> **Exam technique:** Definitions of transverse and longitudinal must compare the oscillation direction with the direction of **energy transfer** (or wave propagation). Saying only “up and down” or “side to side” scores nothing - a sound wave can also travel vertically!

3. The language of waves

Quantity	Symbol / unit	Definition
Displacement	x or y (m)	Distance and direction of a point in the medium from its equilibrium (rest) position at a given instant
Amplitude	A (m)	Maximum displacement from equilibrium; a wave's energy depends on amplitude, not on wavelength
Wavelength	λ (m)	Shortest distance between two points oscillating in phase, e.g. crest to adjacent crest, or compression to compression
Period	T (s)	Time for one complete oscillation of a point, equal to the time for the wave to advance one wavelength
Frequency	f (Hz)	Number of oscillations per unit time passing a point; f = 1/T
Wave speed	v (m s^{-1})	Speed at which the wave profile (and energy) travels through the medium

Deriving the wave equation

In a time of exactly one period T, every point completes one oscillation and the whole pattern moves forward by exactly one wavelength λ. Since speed = distance / time:

$$v = \lambda / T = f\lambda$$

The frequency of a wave is fixed by the **source**; the speed is fixed by the **medium**. When a wave passes into a different medium, f stays the same, so the wavelength must change in proportion to the speed.

Wave	Typical speed	Comment
Sound in air (about 20 °C)	about 340 m s^{-1}	Increases with temperature
Sound in water	about 1500 m s^{-1}	Stiffer medium → faster
Sound in steel	about 5900 m s^{-1}	Fastest in stiff solids
Ripples on deep water	a few m s^{-1}	Depends on depth and wavelength
Light and all EM waves (vacuum)	3.00×10^8 m s^{-1}	The universal constant c
Light in glass	about 2.0×10^8 m s^{-1}	Slower in denser optical media (C.3 refraction)

Worked example 1 — the wave equation

The note A4 from a tuning fork has frequency 440 Hz. Taking the speed of sound in air as 340 m s^{-1}, find (a) the wavelength in air, (b) the wavelength in water, where sound travels at 1500 m s^{-1}.

(a) $\lambda = v / f = 340 / 440 =$ **0.77 m**.

(b) The frequency is set by the fork and does not change: $\lambda = 1500 / 440 =$ **3.4 m**. Faster medium → longer wavelength, same frequency.

Worked example 2 — counting waves

A student watches water waves pass a mooring post. 12 complete waves pass in 30 s, and the distance between adjacent crests is 1.5 m. Find the frequency, period and speed of the waves.

$f = 12 / 30 =$ **0.40 Hz**; $T = 1/f =$ **2.5 s**.

$v = f\lambda = 0.40 \times 1.5 =$ **0.60 m s^{-1}**.

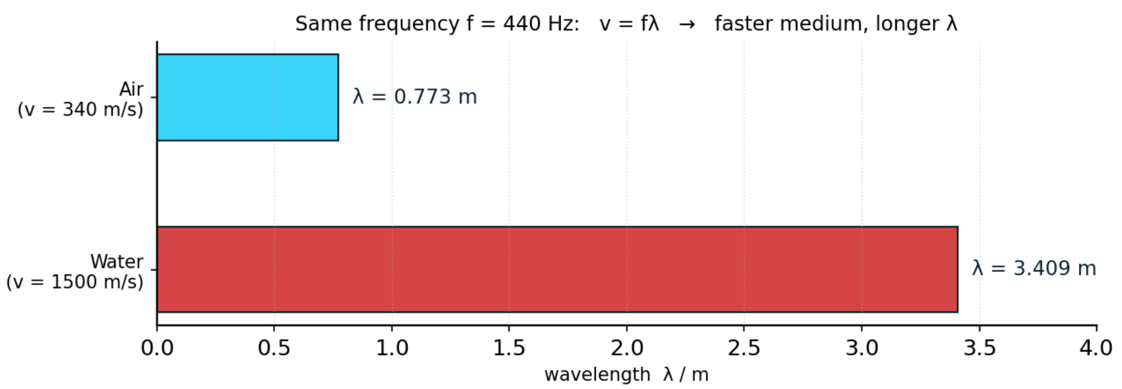

Figure 3. The wave equation $v = f\lambda$ with the frequency fixed at f = 440 Hz. The faster medium has the longer wavelength: in air (v = 340 m s^{-1}) $\lambda \approx 0.77$ m, in water (v = 1500 m s^{-1}) $\lambda \approx 3.41$ m.

Phase

Two points on a wave are **in phase** if they are doing exactly the same thing at the same time - same displacement, same velocity. Points separated by a whole number of wavelengths (λ, 2λ, 3λ...) are in phase. Points separated by half a wavelength (or any odd multiple of $\lambda/2$) are in **antiphase**: one is at a crest while the other is at a trough. Intermediate separations give intermediate phase differences. This vocabulary becomes central in C.3, where waves that meet in phase reinforce and waves in antiphase cancel.

4. The two wave graphs — and how not to mix them up

Two different graphs describe the same wave, and confusing them is the single most common error in this topic. Both look like identical sine curves; only the **horizontal axis** tells them apart, so read the axis label before anything else.

	Displacement–distance graph	Displacement–time graph
What it shows	A photograph (snapshot) of the whole wave at one instant	The motion of one single point of the medium as time passes
Horizontal axis	Position along the medium, x (m)	Time, t (s)
Repeat distance gives	Wavelength λ	Period T
Vertical axis peak gives	Amplitude A	Amplitude A
What it cannot tell you	The period or frequency	The wavelength

Neither graph alone gives the wave speed. You need one piece of information from each (λ from the snapshot, T or f from the time graph) and then $v = f\lambda$.

Worked example 3 — combining both graphs

For a wave on a long spring, a snapshot graph shows that adjacent crests are 2.4 m apart. A displacement–time graph for one coil of the spring repeats every 0.60 s. Find the frequency of the wave and its speed.

From the snapshot: $\lambda = 2.4$ m. From the time graph: $T = 0.60$ s, so $f = 1/0.60 =$ **1.7 Hz**.

$v = \lambda / T = 2.4 / 0.60 =$ **4.0 m s^{-1}**.

Neither graph alone could give this answer — examiners exploit exactly this point.

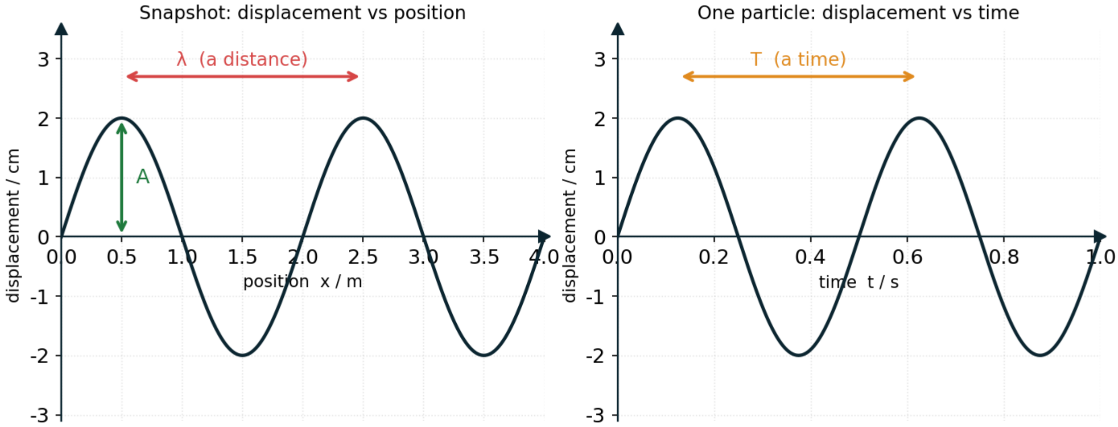

Figure 1. Left — a snapshot (displacement against position): the repeat distance is the wavelength λ and the peak height is the amplitude A. Right — the motion of one particle against time: the repeat is the period T. So λ is a distance (metres) while T is a time (seconds). Here λ = 2.0 m and T = 0.5 s, giving f = 1/T = 2.0 Hz and v = fλ = 4.0 m s^{-1}.

A 10-second identification routine

1. Read the horizontal axis label: metres → snapshot, seconds → single-point time graph. 2. Label the repeat length λ or T accordingly. 3. Read the amplitude from the peak of either graph. 4. If the question asks for speed, look for the second graph (or a stated f, T or λ) - one graph is never enough.

> **Common misconception:** On a snapshot graph the curve between two crests is **not** “one second of motion” — it is one wavelength of space. If the x-axis reads metres, the repeat length is λ; if it reads seconds, the repeat length is T. Write λ or T on the graph the moment you identify it.

5. Particle motion vs wave motion

The wave profile travels steadily at speed v, but no particle travels with it. Each particle of the medium oscillates about its equilibrium position with the period T of the source. Its velocity is continually changing: greatest as it passes through equilibrium, zero at maximum displacement (crest or trough) — exactly like a mass on a spring.

Predicting particle motion from a snapshot

A classic exam task: a snapshot of a transverse wave moving to the **right** is given, and you must state the direction a marked particle is about to move. The trick: in a short time the whole pattern slides right, so each particle will next do **what its left-hand neighbour is doing now**. Equivalently, slide the curve slightly to the right and see whether the marked point ends up higher or lower.

- Particle on the front (right-hand) side of a crest, wave moving right: it is moving **upward**.
- Particle on the back (left-hand) side of a crest, wave moving right: it is moving **downward**.
- Particle exactly at a crest or trough: instantaneously **at rest**.
- For a wave moving left, reverse every conclusion (copy the right-hand neighbour instead).

Worked example 4 — which way does P move?

A snapshot shows a transverse wave travelling to the right. Point P is on the x-axis (zero displacement), with a trough just to its left and a crest just to its right. State and explain the direction of P's velocity, and where its speed is greatest.

Slide the pattern slightly right: the trough moves toward P, so P moves **downward**. (P copies its left neighbour, which is in the trough.)

P is at zero displacement, so its speed is at its **maximum** right now; it will be momentarily zero when it reaches maximum displacement.

Graphs for longitudinal waves

Longitudinal waves are drawn using the same sinusoidal graphs, with one convention: displacements **along** the direction of travel (say, to the right) are plotted as positive, displacements the other way as negative. The graph then looks exactly like a transverse wave's, but crests do not mean sideways motion. On such a snapshot, a **compression** is centred where the displacement is zero and the particles on either side are displaced toward that point; a rarefaction is the zero-displacement point the neighbours are displaced away from. Exam questions asking you to locate a compression on a displacement graph are testing precisely this.

> **Common misconception:** “The particles travel along with the wave at speed v.” They do not. Particle speed (which varies during each cycle) and wave speed (constant, set by the medium) are different quantities and are generally unequal.

6. Sound

Sound is a longitudinal mechanical wave produced by a vibrating source — a guitar string, vocal folds, a loudspeaker cone. The vibration alternately compresses and rarefies the surrounding medium, and these pressure variations propagate outward. At the ear they set the eardrum vibrating at the same frequency.

Perceived property	Physical quantity	Detail
Pitch	Frequency	Higher f → higher pitch. Doubling f raises the note one octave.
Loudness	Amplitude / intensity	Larger amplitude → louder sound ($I \propto A^2$)
Audible range (healthy young ear)	20 Hz to 20 kHz	Upper limit falls with age; ultrasound is above 20 kHz, infrasound below 20 Hz

Speed of sound in different media

Sound travels fastest where the medium is stiff and the particles respond quickly: v(solids) > v(liquids) > v(gases). In a gas the speed rises with temperature — warmer molecules move faster and pass on the disturbance sooner (roughly 0.6 m s^{-1} per °C in air, qualitative knowledge is enough). The speed of sound in a given gas does **not** depend on the frequency: a distant orchestra stays in time.

Worked example 5 — sonar depth finding

A ship's sonar emits a pulse of ultrasound that reflects from the sea bed and returns after 0.90 s. The speed of sound in sea water is 1500 m s^{-1}. Find the depth of the water.

The pulse travels down **and back**, so the one-way time is 0.45 s.

depth = v × t = 1500 × 0.45 = **675 m** ≈ **680 m** (2 s.f.).

Forgetting to halve the echo time is the classic error in every echo problem.

Worked example 6 — medical ultrasound

A medical ultrasound scanner operates at 5.0 MHz. The speed of sound in soft tissue is about 1540 m s^{-1}. Calculate the wavelength in tissue and comment on why such a high frequency is used.

$\lambda = v / f = 1540 / (5.0 \times 10^6) = 3.1 \times 10^{-4}$ m ≈ **0.31 mm**.

A wave can only resolve detail comparable to its wavelength, so a sub-millimetre wavelength lets the scanner image fine structures inside the body. (Diffraction, the underlying reason, is developed in C.3.)

7. The electromagnetic spectrum

Electromagnetic waves are transverse oscillations of electric and magnetic fields, perpendicular to each other and to the direction of travel. They need no medium and **all travel at the same speed in a vacuum**, $c = 3.00 \times 10^8$ m s^{-1}. The spectrum is continuous; the named regions differ only in frequency and wavelength (and hence in photon energy and typical behaviour).

Region	Typical λ (vacuum)	Typical f (Hz)	Sources and uses
Radio	> 0.1 m (up to km)	$< 3 \times 10^9$	Oscillating currents in aerials; broadcasting, communication, radio astronomy
Microwave	1 mm – 0.1 m	$3 \times 10^9 – 3 \times 10^{11}$	Magnetrons, satellites; ovens, Wi-Fi, mobile links, radar
Infrared	700 nm – 1 mm	$3 \times 10^{11} – 4.3 \times 10^{14}$	All warm objects; thermal imaging, remote controls, optical fibres
Visible	about 400 – 700 nm	$4.3 – 7.5 \times 10^{14}$	Hot objects, LEDs, lasers; vision, photography (red → violet as λ falls)
Ultraviolet	10 – 400 nm	$7.5 \times 10^{14} – 3 \times 10^{16}$	The Sun, discharge lamps; sterilisation, fluorescence; causes sunburn
X-rays	0.01 – 10 nm	$3 \times 10^{16} – 3 \times 10^{19}$	Fast electrons striking metal targets; medical imaging, crystallography

Region	Typical λ (vacuum)	Typical f (Hz)	Sources and uses
Gamma rays	< 0.01 nm	> 3×10^{19}	Radioactive nuclei; cancer therapy, sterilising equipment

Ordering aids: wavelength **decreases** and frequency **increases** from radio to gamma. Since $c = f\lambda$ is fixed in a vacuum, quoting either f or λ specifies the wave completely.

Worked example 7 — across the spectrum

(a) An FM station broadcasts at 98.0 MHz. Find the wavelength. (b) A helium–neon laser emits light of wavelength 633 nm. Find its frequency.

(a) $\lambda = c / f = (3.00 \times 10^8) / (9.80 \times 10^7) =$ **3.06 m** — which is why radio aerials are metres long.

(b) $f = c / \lambda = (3.00 \times 10^8) / (6.33 \times 10^{-7}) =$ **4.74×10^{14} Hz**.

Moving up the spectrum, the waves become more penetrating and more hazardous: high-frequency ultraviolet, X-rays and gamma rays carry enough energy per photon to ionise atoms (remove electrons), which is why they damage living cells and why exposure to them is limited and shielded. Radio waves, microwaves, infrared and visible light are non-ionising.

> **Sanity check:** Visible light frequencies are around 10^{14}–10^{15} Hz and wavelengths are hundreds of nanometres. If your answer for light comes out as kilohertz or metres, a power of ten has gone astray.

8. Waves at boundaries; intensity

When a wave meets the boundary between two media, three things happen in some proportion:

- **Reflection** — part of the energy returns into the first medium (echoes, mirrors).
- **Transmission** — part passes into the second medium, generally with a different speed and therefore a different wavelength.
- **Absorption** — part of the energy is transferred to the medium itself, usually ending up as internal (thermal) energy.

Throughout all of this the **frequency never changes**: the boundary is driven at the frequency of the incoming wave, like a hand shaking the next rope. Only v and λ change together, keeping $f = v/\lambda$ constant.

Intensity

Intensity I is the power transferred per unit area perpendicular to the wave's direction of travel, measured in W m^{-2}. Because the energy of an oscillator is proportional to the square of its amplitude:

$$I \propto A^2$$

So doubling the amplitude quadruples the intensity. For a **point source** radiating power P equally in all directions with no absorption, the energy spreads over a sphere of area $4\pi r^2$:

$$I = P / (4\pi r^2) \text{ so } I \propto 1/r^2 \text{ and therefore } A \propto 1/r$$

Doubling the distance from a point source cuts the intensity to a quarter and the amplitude to a half.

Worked example 8 — inverse-square law

A small siren radiates 60 W of sound uniformly in all directions. Find the intensity (a) 2.0 m away, (b) 6.0 m away. (c) State the ratio of the wave amplitudes at the two distances.

(a) $I = P / (4\pi r^2) = 60 / (4\pi \times 2.0^2) = 60 / 50.3 =$ **1.2 W m^{-2}**.

(b) Distance × 3, so intensity ÷ 9: $I = 1.19 / 9 =$ **0.13 W m^{-2}** (or directly $60 / (4\pi \times 36) = 0.13$ W m^{-2}).

(c) $A \propto 1/r$, so A(2.0 m) : A(6.0 m) = **3 : 1**.

Scope note: The detailed geometry of reflection and refraction (Snell's law, total internal reflection) belongs to C.3 Wave Phenomena. For C.2 you need the ideas of reflection, transmission and absorption, the constancy of frequency, and the intensity relations above.

9. Common pitfalls

- Reading a period off a displacement–distance graph (or a wavelength off a displacement–time graph). Check the axis label first, always.
- Saying particles travel along with the wave. They oscillate about fixed positions; only energy travels.
- Letting the frequency change when a wave enters a new medium. Frequency is fixed by the source; v and λ change together.
- Forgetting to halve the round-trip time in echo and sonar problems.
- Defining amplitude as “crest-to-trough distance” — that is 2A. Amplitude is measured from the equilibrium position.
- Treating loudness/brightness as depending on frequency, or pitch/colour as depending on amplitude — it is the other way round.
- Doubling amplitude and doubling intensity: $I \propto A^2$, so intensity goes up four times.
- Unit slips with nm, MHz and GHz: convert to metres and hertz before using $c = f\lambda$.

10. Quick reference

Result	Statement
Wave	Transfers energy without net transfer of matter
Frequency and period	$f = 1/T$
Wave equation	$v = f\lambda = \lambda/T$
Transverse / longitudinal	Oscillation perpendicular / parallel to direction of energy transfer
Snapshot graph (x-axis: distance)	Read amplitude and wavelength λ
Time graph (x-axis: time)	Read amplitude and period T
At a boundary	f constant; v and λ change together; partial reflection, transmission, absorption

Result	Statement
Speed of EM waves in vacuum	$c = 3.00 \times 10^{8}$ m s^{-1} for every region of the spectrum
Intensity	$I \propto A^2$; point source: $I = P/(4\pi r^2)$, so $I \propto 1/r^2$ and $A \propto 1/r$
Audible range	about 20 Hz to 20 kHz; pitch ↔ frequency, loudness ↔ amplitude

11. Test yourself

Attempt these without notes; full answers follow. Take the speed of sound in air as 340 m s^{-1} and $c = 3.00 \times 10^{8}$ m s^{-1}.

1. Green light has a wavelength of 500 nm in a vacuum. Calculate its frequency.

2. A tuning fork of frequency 256 Hz is sounded in air and then under water ($v = 1500$ m s^{-1}). Find the wavelength in each medium and explain why the frequency does not change.

3. A displacement–time graph for one point on a wave repeats every 0.020 s. A snapshot of the same wave shows crests 6.8 m apart. Find the frequency and speed of the wave.

4. Explain why an astronaut on the Moon cannot hear a nearby rock fall, but can see it fall.

5. A microwave oven uses radiation of wavelength 12 cm. Calculate the frequency and state the region of the EM spectrum on each side of microwaves.

6. The intensity of sound from a small (point-like) source is 8.0 W m^{-2} at a distance of 1.0 m. Find the intensity at 4.0 m, and the ratio of amplitudes at the two positions.

7. A student claps her hands 170 m from a large wall and hears the echo. Calculate the time interval between the clap and the echo.

8. Seismic P-waves pass through the Earth's liquid outer core but S-waves do not. What does this tell you about the two wave types? Explain.

9. A snapshot shows a transverse wave moving to the left. Point Q sits at zero displacement with a crest immediately to its left and a trough immediately to its right. In which direction is Q moving?

10. The amplitude of a wave is doubled while its frequency is unchanged. State the effect on (a) the intensity, (b) the wave speed.

Answers

1. $f = c/\lambda = (3.00 \times 10^{8}) / (5.00 \times 10^{-7}) = 6.0 \times 10^{14}$ Hz.

2. In air: $\lambda = 340/256 = 1.3$ m. In water: $\lambda = 1500/256 = 5.9$ m. The frequency is set by the vibrating fork, which drives each medium at the same rate; only speed and wavelength depend on the medium.

3. $T = 0.020$ s so $f = 50$ Hz; $\lambda = 6.8$ m, so $v = f\lambda = 50 \times 6.8 = 340$ m s^{-1} (a sound wave).

4. Sound is a mechanical wave and needs a medium; the Moon has no atmosphere, so no sound reaches the astronaut. Light is an electromagnetic wave and travels through the vacuum, so the fall is visible.

5. $f = c/\lambda = (3.00 \times 10^{8}) / 0.12 = 2.5 \times 10^{9}$ Hz (2.5 GHz). Microwaves lie between radio waves (longer λ) and infrared (shorter λ).

6. $I \propto 1/r^2$: distance × 4, so $I = 8.0/16 = 0.50$ W m^{-2}. Amplitude $\propto 1/r$, so A(1.0 m) : A(4.0 m) = 4 : 1.

7. Round trip = 2 × 170 = 340 m; t = 340/340 = 1.0 s.

8. P-waves are longitudinal and S-waves are transverse. Liquids cannot support the sideways (shear) oscillations of a transverse wave, but can be compressed, so only the longitudinal P-waves are transmitted — evidence that the outer core is liquid.

9. The wave moves left, so Q next copies its **right-hand** neighbour, which is in the trough: Q moves downward.

10. (a) $I \propto A^2$, so the intensity becomes 4 times larger. (b) No effect — wave speed is a property of the medium, not of the amplitude.