Cambridge AS & A Level · Physics (9702) · Notes

Waves AS

Read online at pastopic.com/cambridge/physics-9702/notes/waves

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Read first: Physical quantities and units

What you need to know

By the end of this topic you should be able to:

1. **Describe wave motion** using examples you can see: a rope or slinky spring shaken at one end, and ripples on water in a ripple tank.
2. **Understand and use the terms** displacement, amplitude, phase difference, period, frequency, wavelength and speed.
3. **Use a cathode-ray oscilloscope (CRO)**: read the time-base and the y-gain to find the frequency and the amplitude of a signal.
4. **Derive** $v = f\lambda$ from the definitions of speed, frequency and wavelength.
5. **Recall and use** $v = f\lambda$.
6. **Understand that a progressive wave transfers energy** (not matter) from one place to another.
7. **Recall and use** intensity $= \dfrac{\text{power}}{\text{area}}$ and intensity $\propto$ (amplitude)^2 for a progressive wave.
8. **Compare transverse and longitudinal waves.**
9. **Analyse and interpret graphs** of transverse and longitudinal waves.
10. **Understand the Doppler effect for sound**: when a source moves relative to a stationary observer, the observed frequency differs from the source frequency. (A moving observer with a still source is not required.)
11. **Use** $f_o = \dfrac{f_s v}{v \pm v_s}$ for the observed frequency from a moving source of sound.
12. **State that all electromagnetic waves are transverse** and travel at the same speed c in free space.
13. **Recall the approximate wavelength range** of each principal region of the electromagnetic spectrum, from radio waves to γ-rays.
14. **Recall that wavelengths from 400 nm to 700 nm** in free space are visible to the human eye.
15. **Understand that polarisation happens only with transverse waves**, and use **Malus's law**, $I = I_0 \cos^2 \theta$, for plane-polarised light passing through one polarising filter or several. (The effect of a filter on **unpolarised** light is not required.)

Colour from IGCSE is assumed. Superposition, stationary waves, diffraction and interference are in the next topic, Superposition; many Paper 2 questions start here and continue there.

Understand it

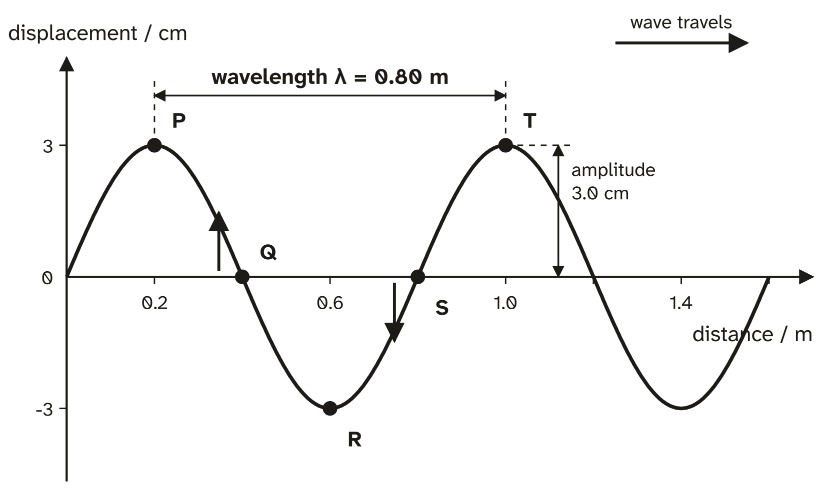
What a wave is

Tie one end of a long rope to a post and flick the other end up and down: a hump runs along the rope, but each bit of rope only moves up and down and ends up where it started. Push and pull one end of a slinky spring and a squashed region runs along it, while each coil just moves back and forth. Dip a vibrating bar into a ripple tank and circular ripples spread out, while a floating cork only bobs up and down.

In every case a **progressive wave** carries **energy** from the source outwards, and the medium itself goes nowhere: each particle oscillates about a fixed **equilibrium position**.

The words for describing a wave

- **Displacement** x (or y): how far a particle is from its equilibrium position, in a given direction (it can be negative).
- **Amplitude** A: the **maximum** displacement from the equilibrium position. It is measured from the middle line to a crest, **not** crest to trough.
- **Wavelength** λ: the distance between two neighbouring points that are **in phase**, such as crest to crest or compression to compression.
- **Period** T: the time for one complete oscillation of a particle.
- **Frequency** f: the number of oscillations per unit time, in hertz (Hz $=$ s^{-1}). $f = \dfrac{1}{T}$: a period of 2.5 ms is a frequency of $\dfrac{1}{2.5 \times 10^{-3}} = 400$ Hz.
- **Speed** v: the distance a wavefront (a crest, say) moves per unit time.
- **Phase difference**: how far one oscillation is ahead of another, as an **angle** in degrees (one whole cycle $=$ 360°). Points one wavelength apart are in phase (0° or 360°); points half a wavelength apart are in **antiphase** (180°).



Q moves up, S moves down (each copies the point just behind it).
Phase difference from P: Q 90°, R 180°, T 360° (in phase).

For points a distance Δx apart along the wave, or a time Δt apart in the same particle's motion:

$$\text{phase difference} = \frac{\Delta x}{\lambda} \times 360^\circ = \frac{\Delta t}{T} \times 360^\circ$$

Two points 0.50 m apart on the wave above are $\dfrac{0.50}{0.80} \times 360^\circ = 225^\circ$ out of phase. The phase difference between two fixed points never changes as the wave passes.

Two kinds of graph

- **Displacement against distance** is a snapshot of the whole wave at one instant. From it you read the **wavelength** and the amplitude.
- **Displacement against time** follows **one** particle. From it you read the **period** (and so the frequency) and the amplitude.

Having both lets you find the speed: $v = \dfrac{\lambda}{T}$. Mixing them up (calling a time a wavelength) is a common error.

Which way is a particle moving? Picture the snapshot shifted a little in the direction of travel. For a wave moving to the right, each point takes the displacement of the point just behind it (to its left). In the diagram, the point just behind Q is higher, so Q is moving **up**; the point behind S is lower, so S is moving **down**. P and R, at a crest and a trough, are momentarily at rest.

- A particle moves **fastest** as it passes through zero displacement and is **at rest** at maximum displacement.
- In each full period a particle travels a total distance of $4A$ (up A, down $2A$, up A), however far the wave itself moves. With $A = 3.0$ cm and $f = 5.0$ Hz, in 2.0 s a particle makes 10 oscillations and travels $10 \times 4 \times 3.0 = 120$ cm.

The wave equation $v = f\lambda$

In one period T, the source makes one complete oscillation and the wave moves forward by one wavelength λ. So

$$v = \frac{\text{distance}}{\text{time}} = \frac{\lambda}{T} = f\lambda \qquad \left(\text{since } f = \tfrac{1}{T}\right)$$

(Equally: in time t the source makes $n = ft$ oscillations, and the wave travels $n\lambda$; $v = \frac{n\lambda}{t} = f\lambda$.) A sound of frequency 425 Hz in air where $v = 340$ m s^{-1} has $\lambda = \dfrac{340}{425} = 0.80$ m. The **speed depends on the medium**, not on the source: a higher frequency in the same medium means a shorter wavelength.

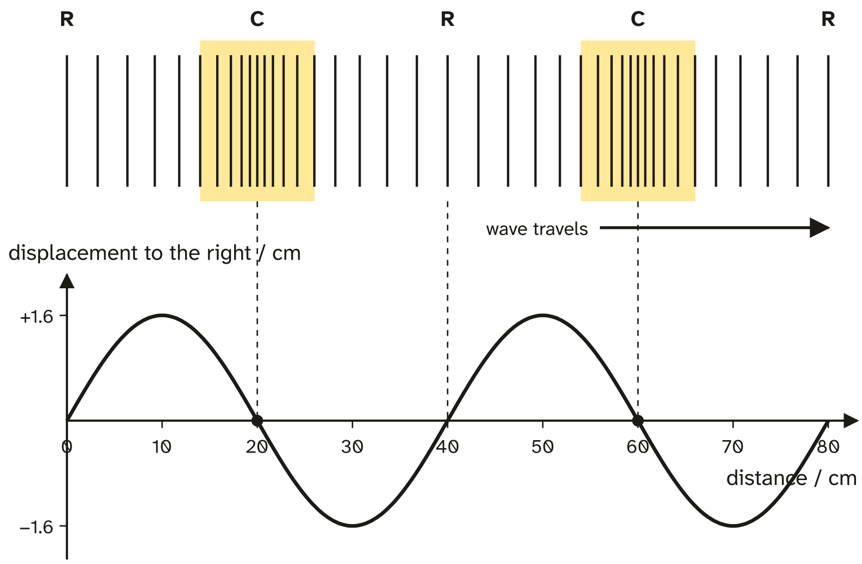
Transverse and longitudinal waves

- **Transverse**: the particles oscillate **at right angles** to the direction in which the wave transfers energy. Examples: waves on a rope or string, water ripples, all electromagnetic waves. They have crests and troughs.

- **Longitudinal**: the particles oscillate **parallel** to the direction in which the wave transfers energy. Examples: sound, and push-pull waves on a slinky. They have **compressions** (particles bunched together, higher pressure) and **rarefactions** (spread out, lower pressure).

Both kinds transfer energy, obey $v = f\lambda$, and can be reflected, refracted and diffracted, interfere and form stationary waves. Only **transverse** waves can be **polarised**. Sound needs a medium; electromagnetic waves can also travel through a vacuum.

A plucked guitar string carries **transverse** waves along the string; the string pushes on the air, sending **longitudinal** sound waves to your ear.



C: graph crosses zero going down. R: crosses zero going up.
Compression to next compression = λ = 40 cm

A longitudinal wave is usually drawn as a **displacement-distance graph** with displacement to the right plotted upwards. It looks exactly like a transverse wave, so read the labels. On it:

- At a **compression**, the graph crosses zero going **down**: the particles just to the left have moved right (positive) and those just to the right have moved left (negative), so they crowd together.
- At a **rarefaction**, it crosses zero going **up**: the neighbours have moved apart. Pressure is **lowest** here.
- Particles at a crest or trough of the graph have their largest displacement, but they are at normal spacing.

Energy and intensity

A wave carries energy, so it delivers power to any surface it hits. The **intensity** is the power per unit area, measured on an area at right angles to the direction of travel:

$$I = \frac{P}{A} \qquad (\text{unit W m}^{-2})$$

A beam carrying 0.12 W spread over 3.0 cm² $= 3.0 \times 10^{-4}$ m² has an intensity of $\dfrac{0.12}{3.0 \times 10^{-4}} = 400$ W m⁻².

For a given frequency, the intensity is proportional to the **square of the amplitude**:

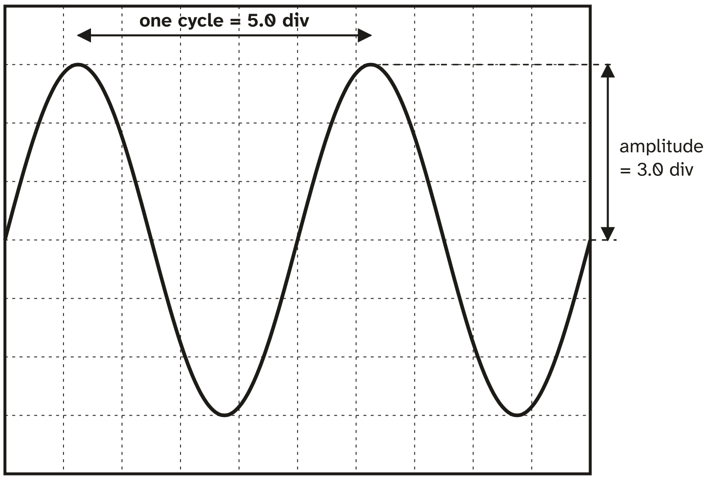
$$I \propto A^2$$

Triple the amplitude and the intensity is $3^2 = 9$ times bigger. Halve the intensity and the amplitude falls to $\dfrac{1}{\sqrt{2}} = 0.71$ of its value. The power arriving on a surface is intensity $\times$ area, so $P \propto A^2 \times$ area.

The cathode-ray oscilloscope

A microphone turns sound into a varying voltage, and a CRO draws that voltage against time: a **displacement–time graph** of the signal.

- The **time-base** is the **time per division** across the screen (for example ms div^{-1}).
- The **y-gain** is the **voltage per division** up the screen (for example mV div^{-1}).



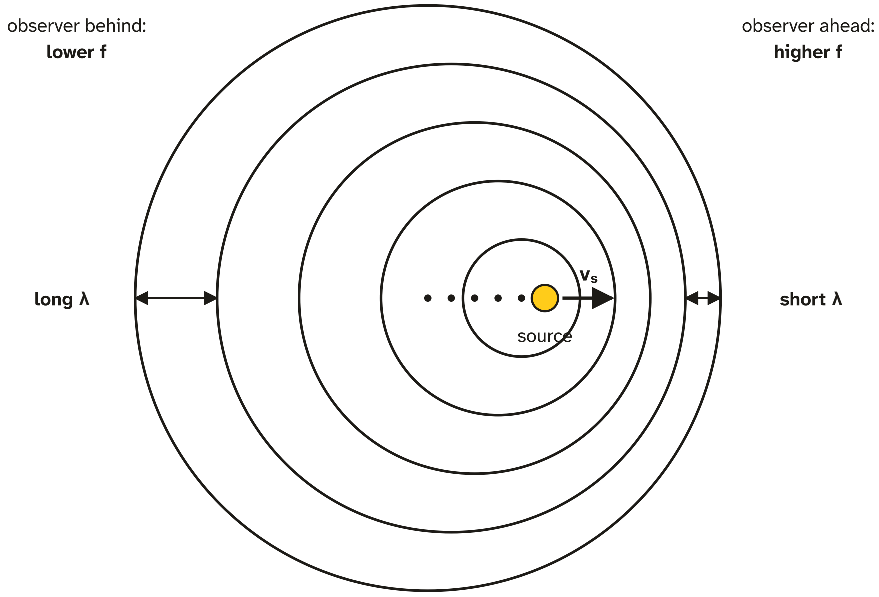
time-base 0.20 ms div^{-1} (across) y-gain 5.0 mV div^{-1} (up)

period T = 5.0 × 0.20 ms = 1.0 ms, f = 1/T = 1000 Hz
amplitude = 3.0 × 5.0 mV = 15 mV

Period $=$ (divisions for one cycle) $\times$ time-base; then $f = \frac{1}{T}$. Amplitude $=$ (divisions from the centre line to a peak) $\times$ y-gain. To fit more cycles on the screen, **increase** the time-base; to make a trace that runs off the top fit on the screen, **increase** the y-gain (more volts per division makes the trace shorter).

The Doppler effect

When a source of sound moves, the frequency heard by a stationary observer is different from the frequency it emits. Each wavefront spreads out at the speed of sound v from wherever the source was when it sent it out. In one period the source moves $v_s T$, so in front of it the wavefronts are bunched: the wavelength is $(v - v_s)T$. Behind, they are spread: $(v + v_s)T$.



Sound speed v is the same both ways; only the spacing of the wavefronts changes.

The sound still travels at v, so the observer receives $f_o = \dfrac{v}{\lambda}$ wavefronts per second:

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

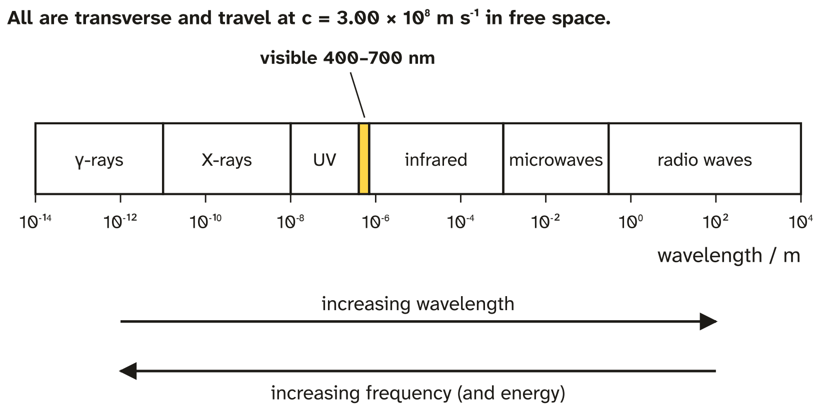
- **Minus** for a source moving **towards** the observer (smaller denominator, **higher** frequency).
- **Plus** for a source moving **away** (lower frequency).

A source of 620 Hz moving at 20 m s^{-1} in air where $v = 340$ m s^{-1} is heard at $\dfrac{620 \times 340}{340 - 20} = 659$ Hz as it approaches and $\dfrac{620 \times 340}{340 + 20} = 586$ Hz as it moves away. The source's own frequency does not change, and neither does the speed of sound.

- A source moving at **constant velocity** straight towards you gives a **constant** higher frequency, not a rising one. It drops to a constant lower one after it passes.
- Only the part of the source's velocity **along the line to the observer** counts. A source going round a circle gives the highest frequency when it moves straight towards the observer and the lowest when it moves straight away.
- The Doppler effect happens with all waves, including light; this topic only needs it for sound.

The electromagnetic spectrum

Electromagnetic waves are oscillating electric and magnetic fields, not vibrating particles. They are all **transverse**, and in free space (a vacuum) they all travel at the same speed, $c = 3.00 \times 10^8$ m s^{-1}, whatever their wavelength. So $c = f\lambda$ links frequency and wavelength: the longer the wavelength, the lower the frequency.



Region	Approximate wavelength in free space
γ-rays	shorter than about 10^{-11} m
X-rays	about 10^{-12} m to 10^{-8} m (overlaps γ-rays)
Ultraviolet	10^{-8} m to 4×10^{-7} m (10 nm to 400 nm)
Visible light	4×10^{-7} m to 7×10^{-7} m (400 nm to 700 nm; violet to red)
Infrared	7×10^{-7} m to 10^{-3} m (700 nm to 1 mm)
Microwaves	10^{-3} m to about 0.3 m (1 mm to 30 cm)
Radio waves	longer than about 0.3 m (up to kilometres)

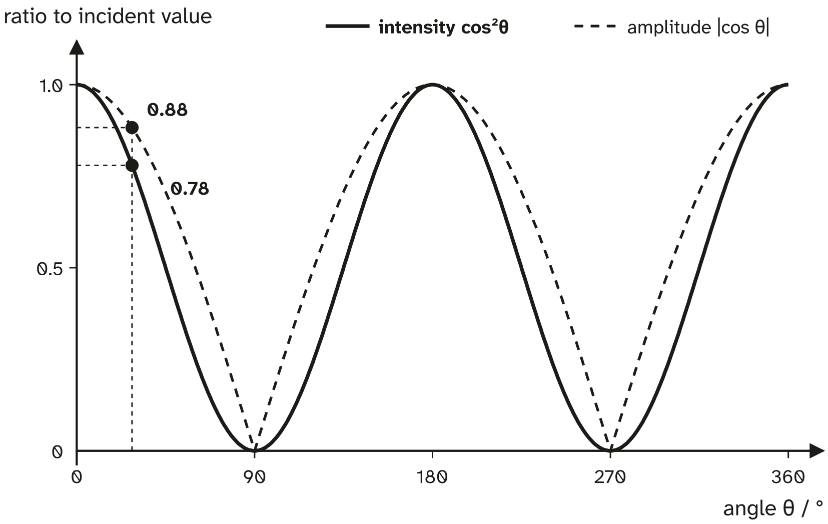
The boundaries are approximate, but learn the order and the powers of ten. A microwave of wavelength 3.0 cm has frequency $\dfrac{3.00 \times 10^8}{0.030} = 1.0 \times 10^{10}$ Hz (10 GHz).

Polarisation and Malus's law

In a transverse wave the oscillations are at right angles to the direction of travel, but they can be in any direction in that plane. A wave is **plane-polarised** when its oscillations are all in **one** direction (in one plane that contains the direction of travel). Longitudinal waves already oscillate along the direction of travel, so they **cannot** be polarised: this is how you know sound is longitudinal.

A **polarising filter** lets through only the part of the oscillation along its **transmission axis**. If plane-polarised light of amplitude A_0 meets a filter whose axis is at angle θ to the plane of polarisation, the amplitude that gets through is $A_0 \cos\theta$. Intensity is proportional to amplitude squared, which gives **Malus's law**:

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



Intensity ∝ amplitude², so I = I_0cos²θ and amplitude = A_0cos θ.
Zero at 90° and 270° (axis at right angles to the plane of polarisation).

- Axis parallel to the plane of polarisation ($\theta = 0$): all the light gets through. At right angles ($\theta = 90^\circ$): none.
- Turning a filter through 360° gives **two** maxima and **two** zeros; turning it through 180° brings it back to the same intensity.
- At $\theta = 28^\circ$, $\frac{I}{I_0} = \cos^2 28^\circ = 0.78$ and $\frac{A}{A_0} = \cos 28^\circ = 0.88$.
- **Several filters**: the light leaving each filter is polarised along **that filter's** axis. So for the next filter use the angle **between the two axes**. Vertically polarised light through a filter at 20° to the vertical and then one at 90° gives $I_0 \cos^2 20^\circ \cos^2 70^\circ = 0.10\, I_0$, even though a single filter at 90° would let nothing through.
- Microwaves can be polarised too, and a grid of parallel metal wires acts as a polarising filter for them.

Key facts and formulas

"Given" means it is on the data sheet in the exam. "Learn it" means you must remember it.

Formula	Status
$v = f\lambda$ (and $c = f\lambda$ for electromagnetic waves)	Learn it
$f = \dfrac{1}{T}$	Learn it
Phase difference $= \dfrac{\Delta x}{\lambda} \times 360^\circ = \dfrac{\Delta t}{T} \times 360^\circ$	Learn it
Intensity $I = \dfrac{P}{A}$ (W m^{-2})	Learn it
$I \propto (\text{amplitude})^2$	Learn it
Doppler effect for sound: $f_o = \dfrac{f_s v}{v \pm v_s}$	Given
Malus's law $I = I_0 \cos^2\theta$ (amplitude $A = A_0 \cos\theta$)	Learn it

Formula	Status
CRO: period $=$ divisions $\times$ time-base; amplitude $=$ divisions $\times$ y-gain	Learn it
Visible light: 400 nm to 700 nm; the order and ranges of the spectrum	Learn it
Speed of light in free space $c = 3.00 \times 10^8$ m s^{-1}	Given

Prefixes that appear here: GHz $= 10^9$ Hz, THz $= 10^{12}$ Hz, ms $= 10^{-3}$ s, μs $= 10^{-6}$ s, ns $= 10^{-9}$ s, ps $= 10^{-12}$ s, nm $= 10^{-9}$ m, pm $= 10^{-12}$ m.

How to do it

In the Paper 1 and Paper 2 questions we have tagged for this topic (198 different questions, 2021–2025; 7 more appear on two papers), the types came up this often. 22 of the 198 questions mix two or more types, so the counts add up to more than 198. Several Paper 2 questions also have parts on superposition, which the Superposition note covers.

Question type	Questions
Wave terms, graphs, phase difference and $v = f\lambda$	47
The electromagnetic spectrum	45
The Doppler effect	43
Transverse and longitudinal waves	28
Polarisation and Malus's law	27
The cathode-ray oscilloscope	20
Intensity, power and amplitude	15

1. Wave terms, graphs, phase difference and $v = f\lambda$ (47 questions)

1. **Check which graph it is**: displacement against **distance** (read λ) or against **time** (read T). Read the amplitude from the middle line to a peak.
2. **Convert units**: cm → m, ms → s, kHz → Hz.
3. **Use** $v = f\lambda$, $f = \frac{1}{T}$, or phase difference $= \frac{\Delta x}{\lambda} \times 360^\circ$.

Variations you will meet:

- **Definitions** (one mark each): wavelength is the distance between neighbouring points in phase (crest to crest); period is the time for one oscillation; frequency is the number of oscillations per unit time; amplitude is the maximum displacement from equilibrium; a progressive wave transfers energy (without transferring matter).
- **Derive** $v = f\lambda$: the wave moves one wavelength in one period, so $v = \frac{\lambda}{T}$, and $f = \frac{1}{T}$ gives $v = f\lambda$. Say each definition in words.

- **Speed from two graphs**: λ from the distance graph, T from the time graph, $v = \frac{\lambda}{T}$.
- **Phase difference from a diagram**: count the wavelengths between the points (use quarter-wavelengths: crest to next zero is $\frac{1}{4}\lambda = 90^\circ$), then $\times 360^\circ$. The answer can be more than 360° if the question counts that way; otherwise take away 360° as needed.
- **Phase difference from data**: find $\lambda = \frac{v}{f}$ first, then $\frac{\Delta x}{\lambda} \times 360^\circ$. Or the smallest distance for a given phase difference: $\Delta x = \frac{\phi}{360^\circ}\lambda$.
- **Direction a point is moving**: the point copies the one just behind it (on the side the wave is coming from). Crest and trough points are at rest; zero-displacement points move fastest.
- **Graph of one point against time**: start from the point's present displacement and direction; for a **velocity–time** graph, velocity is zero at a crest or trough and greatest at zero displacement, so it is a quarter-cycle ahead of the displacement.
- **Total distance moved by a particle** in time t: number of oscillations ft, times $4A$. Not the distance the wave moves.
- **Kinetic energy of a particle** is greatest at zero displacement and zero at maximum displacement, so it peaks twice in each period.
- **Points with the same displacement and direction** repeat every λ.
- **Changing frequency in the same medium**: v stays the same, so $\lambda \propto \frac{1}{f}$.

2. The electromagnetic spectrum (45 questions)

1. **Get the wavelength in metres** (from $\lambda = \frac{c}{f}$ if you are given a frequency or period; $f = \frac{1}{T}$).
2. **Compare with the table**; write it as a power of ten to place it.
3. **State the region** with its full name.

Variations you will meet:

- **Order** of regions by wavelength or frequency (γ, X, UV, visible, IR, micro, radio in order of **increasing** wavelength, which is **decreasing** frequency).
- **Is it visible?** Only 400–700 nm. Convert: 4.8×10^{-7} m $= 480$ nm (visible); 3.0×10^{-6} m (infrared) is not.
- **Frequency or period in a given unit** (GHz, THz, ps): calculate in Hz or s, then divide by the prefix.
- **Statements**: all EM waves are transverse, can be polarised, travel at c in a vacuum (so red, green and blue light from one flash arrive together), and consist of oscillating electric and magnetic fields, not vibrating atoms. Frequency is inversely proportional to wavelength.
- **Wavelength compared with a size** (a microorganism, a surface bump): convert both to the same unit and compare with 400–700 nm.
- **Different radiation, same speed**: X-rays and microwaves both travel at c in free space; only λ and f differ.

3. The Doppler effect (43 questions)

1. **Decide the direction**: towards the observer → minus (higher f_o); away → plus (lower f_o).

2. **Write the formula with symbols**, then substitute: $f_o = \dfrac{f_s v}{v \pm v_s}$. f_s is what the source **emits**; f_o is what the observer **hears**.
3. **Rearrange** for the unknown, and give the number of significant figures asked for.

Variations you will meet:

- **Find the source speed**: $v \pm v_s = \frac{f_s v}{f_o}$. If $f_o > f_s$ the source is approaching. You can also check each option in a multiple-choice question.
- **Find the source frequency** from what is heard: $f_s = \frac{f_o(v \pm v_s)}{v}$.
- **Find the speed of sound**: from $f_o(v - v_s) = f_s v$, get $v = \frac{f_o v_s}{f_o - f_s}$ (approaching).
- **Approach then recede**: the change in frequency heard is $f_{\text{towards}} - f_{\text{away}}$; work out both.
- **Two frequencies heard, speed unknown**: divide the two equations: $\frac{f_1}{f_2} = \frac{v+v_s}{v-v_s}$, then solve for v_s.
- **Source on a circle** (swung on a rope, on a rotating platform, a vehicle on a track, a swing): maximum f_o when the source moves straight towards the observer at full speed, minimum when straight away. The time from minimum to maximum is half the period of the circle. f_o against t is a smooth curve between the two values.
- **Qualitative**: constant velocity towards → a constant higher frequency; speeding up towards → rising frequency; after passing → lower frequency. A source passing at the side changes frequency gradually. The Doppler effect needs the source to move; a louder sound or a reflected sound doesn't shift the frequency. Wavelength ahead of the source is **shorter**.
- **Falling source** (dropped from a window, heard from above): find its speed with $v^2 = u^2 + 2as$, then use the plus sign (moving away).
- **Time for the sound to arrive**: distance ÷ speed of sound.

4. Transverse and longitudinal waves (28 questions)

- **Definitions with energy**: transverse, oscillations **perpendicular** to the direction of energy transfer; longitudinal, oscillations **parallel** to the direction of energy transfer. Mention the particles' oscillations and the energy; "the wave moves along" is not enough.
- **Which statements are true for both?** Energy transfer, $v = f\lambda$, reflection, diffraction, interference, stationary waves. Only transverse: polarisation. Only waves that need a medium: sound and other mechanical waves.
- **Examples**: sound is longitudinal; light, all EM waves, and waves on strings are transverse; a slinky can carry either.
- **Longitudinal graph**: axes are displacement (to the right) against distance. The centre of a **compression** is where the graph crosses zero going **down**; a **rarefaction** is where it crosses going **up** (the lowest pressure). The wavelength is compression to compression.
- **Drawing the particles from a graph (or the reverse)**: move each particle right for a positive displacement and left for a negative one.

- **A particle in a sound wave**: it oscillates back and forth along the direction of travel. A particle with positive displacement that is about to return is moving back towards (left); use the "copy the point behind" rule for direction.

5. Polarisation and Malus's law (27 questions)

1. **Find** θ: the angle between the plane of polarisation **arriving** at the filter and the filter's transmission axis. For vertically polarised light and an axis "at 35° to the horizontal", $\theta = 55^\circ$.
2. $I = I_0 \cos^2 \theta$. For an **amplitude**, use $A = A_0 \cos \theta$ (or $\frac{A}{A_0} = \sqrt{\frac{I}{I_0}}$).
3. **Two or more filters**: after each filter the light is polarised along that filter's axis. Multiply one $\cos^2$ factor per filter, each using the angle from the previous axis.

Variations you will meet:

- **Find the angle**: $\cos \theta = \sqrt{\frac{I}{I_0}}$. For a second filter, find the angle between the axes, then add the first filter's angle to get the angle to the vertical.
- **Sketch** I **against the angle turned**: a $\cos^2$ curve between 0 and I_0 with a period of 180°. If the axis starts **parallel**, begin at I_0 (peaks at $0^\circ, 180^\circ, 360^\circ$); if it starts **perpendicular**, begin at 0 (peaks at 90° and 270°).
- **Two filters turned together or in opposite directions**: work out the angle between the axes (and to the incoming plane) at each position.
- **"Returns to the same intensity"**: the same $\cos^2 \theta$ again at $\theta \to 180^\circ - \theta$ or $180^\circ + \theta$; find the smallest rotation that gets there.
- **Why sound can't be polarised**: sound is longitudinal; polarisation needs transverse oscillations. Light, radio waves, microwaves and X-rays can all be polarised.
- **Meaning of polarisation**: the oscillations are in one direction only, in a plane that contains the direction of travel (or: at right angles to it in only one direction).
- **A detector reading** (voltmeter proportional to intensity, or a CRO trace proportional to amplitude): use $\cos^2$ for the intensity reading and $\cos$ for the amplitude reading.
- **A filter at** 45° to the plane of polarisation halves the intensity ($\cos^2 45^\circ = 0.5$); nothing else about the pattern changes.

6. The cathode-ray oscilloscope (20 questions)

1. **Count the divisions** for one whole cycle (peak to peak along the time axis, or use several cycles and divide).
2. **Period** $=$ divisions $\times$ time-base; **frequency** $= \frac{1}{T}$.
3. **Amplitude** $=$ divisions from centre line to peak $\times$ y-gain (half the peak-to-peak height).

Variations you will meet:

- **Find the time-base** from a known frequency: time-base $= \frac{T}{\text{divisions for one cycle}}$.

- **Which settings to change**: to see more cycles, increase the time-base; to make the trace fit vertically, increase the y-gain (in V div^{-1}).
- **What can be found from the screen alone**: the period (and frequency) from horizontal distances, the amplitude of the voltage from vertical ones. The wavelength or speed needs extra information.
- **Comparing screens with different settings**: work out each period in seconds before comparing.
- **New trace after a change**: a new intensity changes the height by $\sqrt{\text{intensity ratio}}$ and leaves the period unchanged. A Doppler shift changes the period: a **longer** period means a **lower** frequency (source moving away).
- **Wavelength of the sound**: $\lambda = \frac{v}{f}$ with the frequency from the trace. For an EM signal, use c.

7. Intensity, power and amplitude (15 questions)

1. **Intensity** $= \frac{\text{power}}{\text{area}}$ with the area at right angles to the wave, in m² (cm² $\times 10^{-4}$, mm² $\times 10^{-6}$; a circle πr^2).
2. **Ratios**: $\frac{I_2}{I_1} = \left(\frac{A_2}{A_1}\right)^2$ at the same frequency. Read both amplitudes from the graph (centre to peak).

Variations you will meet:

- **Power on a surface**: $P = I \times \text{area}$. If the amplitude and area both change, $P \propto A^2 \times \text{area}$: amplitude $\times 2$ and area $\times \frac{1}{3}$ gives $4 \times \frac{1}{3} = 1.3$ times the power.
- **Intensity changes, find the amplitude**: amplitude $\times \sqrt{\text{factor}}$. A ninth of the intensity means a third of the amplitude.
- **Sketching A against distance** when you are given I: at each point, $\frac{A}{A_0} = \sqrt{\frac{I}{I_0}}$ (so the curve falls more slowly than the intensity curve).
- **Efficiency with intensity** (a solar panel): input power $= I \times$ area, efficiency $= \frac{\text{useful output}}{\text{input}}$. A smaller panel gets less input power; for the same output its efficiency must be higher.
- **Statements**: intensity is proportional to amplitude squared (not amplitude); amplitude is not related to wavelength.

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **A1** accuracy mark: for a correct answer; it needs the M mark before it.
- **B1** mark for a correct result on its own, with no method needed.

Example 1

A microphone is connected to a cathode-ray oscilloscope. The trace shows a sine wave in which one complete cycle occupies 3.2 divisions horizontally and the vertical distance from a peak to a trough is 5.0 divisions. The time-base is set to 0.25 ms div^{-1} and the y-gain to 20 mV div^{-1}.

(a) Calculate the frequency of the sound. **[2]**

(b) Determine the amplitude of the signal. **[1]**

(c) The speed of sound in air is 340 m s^{-1}. Calculate the wavelength of the sound. **[2]**

(d) The intensity of the sound is doubled without changing its frequency. The amplitude of the trace is proportional to the amplitude of the sound. Describe the new trace. **[2]**

Solution

(a) $T = 3.2 \times 0.25 = 0.80$ ms **C1** $f = \dfrac{1}{0.80 \times 10^{-3}} = 1250$ Hz. **A1**

(b) Amplitude $= \frac{5.0}{2} \times 20 = 50$ mV. **A1**

(c) $\lambda = \dfrac{v}{f}$ **C1** $= \dfrac{340}{1250} = 0.27$ m. **A1**

(d) $I \propto A^2$, so the amplitude goes up by $\sqrt{2}$: $2.5 \times \sqrt{2} = 3.5$ divisions from the centre to a peak (peak to trough 7.1 divisions). **B1** The frequency is unchanged, so one cycle still occupies 3.2 divisions. **B1**

Example 2

A car sounds its horn, which emits a note of frequency 520 Hz, as it travels at a constant 25 m s^{-1} along a straight road that passes through the place where a pedestrian is standing. The speed of sound in air is 340 m s^{-1}.

(a) Calculate the frequency heard by the pedestrian as the car approaches. **[2]**

(b) Calculate the frequency heard after the car has passed and is moving away. **[1]**

(c) Explain why the frequency heard as the car approaches is higher than 520 Hz. **[2]**

(d) On another day the pedestrian hears the same horn at 540 Hz as the car approaches. Calculate the speed of the car. **[2]**

Solution

(a) $f_o = \dfrac{f_s v}{v - v_s}$ **C1** $= \dfrac{520 \times 340}{340 - 25} = 561$ Hz. **A1**

(b) $f_o = \dfrac{520 \times 340}{340 + 25} = 484$ Hz. **A1**

(c) The car moves forward between sending out one wavefront and the next, so the wavefronts in front of it are closer together: the wavelength is shorter. **B1** The sound travels at the same speed, so more wavefronts reach the pedestrian each second: a higher frequency. **B1**

(d) $340 - v_s = \dfrac{520 \times 340}{540} = 327.4$ **C1** $v_s = 12.6$ m s^{-1}. **A1**

Example 3

A beam of vertically polarised light of intensity 12 W m^{-2} passes normally through two polarising filters. The transmission axis of the first filter is at 25° to the vertical and that of the second filter is at 75° to the vertical.

(a) State why a beam of sound cannot be polarised. **[1]**

(b) Calculate the intensity of the light leaving the first filter. **[2]**

(c) Calculate the intensity of the light leaving the second filter. **[2]**

(d) Calculate the ratio $\dfrac{\text{amplitude of light leaving the second filter}}{\text{amplitude of the incident light}}$. **[2]**

(e) The second filter is rotated so that the angle between its axis and the vertical increases. State the smallest angle it must be turned through for no light to leave it. **[1]**

Solution

(a) Sound is a longitudinal wave, and only transverse waves can be polarised. **B1**

(b) $I = I_0 \cos^2\theta = 12\cos^2 25^\circ$ **C1** $= 9.86$ W m^{-2}. **A1**

(c) The light arriving is polarised at 25°, so the angle to the second axis is $75^\circ - 25^\circ = 50^\circ$. **C1** $I = 9.86\cos^2 50^\circ = 4.07$ W m^{-2}. **A1**

(d) $\dfrac{A}{A_0} = \sqrt{\dfrac{I}{I_0}}$ **C1** $= \sqrt{\dfrac{4.07}{12}} = 0.583$ (or $\cos 25^\circ \times \cos 50^\circ$). **A1**

(e) Zero intensity needs the second axis at 90° to the first, that is 115° to the vertical: a turn of 40°. **B1**

Example 4

(a) Use the definitions of speed, frequency and wavelength to show that $v = f\lambda$. **[2]**

(b) A transverse wave of frequency 12 Hz travels along a rope at 4.8 m s^{-1}. The amplitude of the wave is 1.5 cm.

(i) Calculate the wavelength. **[1]**

(ii) Calculate the phase difference between the oscillations of two points on the rope 0.15 m apart. **[1]**

(iii) Calculate the total distance moved by a point on the rope in 0.75 s. **[2]**

(c) The amplitude of the wave falls to 0.90 cm; the frequency is unchanged. Calculate the new intensity as a fraction of the original intensity. **[2]**

Solution

(a) Frequency is the number of oscillations per unit time, so one oscillation takes $T = \frac{1}{f}$; in that time the wave moves one wavelength, the distance between neighbouring points in phase. **B1** Speed $= \dfrac{\text{distance}}{\text{time}} = \dfrac{\lambda}{T} = f\lambda$. **B1**

(b)(i) $\lambda = \dfrac{4.8}{12} = 0.40$ m. **A1**

(ii) $\dfrac{0.15}{0.40} \times 360^\circ = 135^\circ$. **A1**

(iii) Number of oscillations $= 12 \times 0.75 = 9$ **C1** distance $= 9 \times 4 \times 1.5 = 54$ cm. **A1**

(c) $I \propto A^2$ **C1** $\dfrac{I_2}{I_1} = \left(\dfrac{0.90}{1.5}\right)^2 = 0.36$. **A1**

Common mistakes

- **Using the time-base as the period.** The March 2025 report names this, and the March 2023 one mentions dividing by the wrong number of divisions. At 2.0 ms div^{-1}, a cycle 2.5 divisions long has $T = 5.0$ ms and $f = 200$ Hz, not $\frac{1}{0.0020} = 500$ Hz. Count the divisions for a whole cycle, and take care with ms and μs.
- **Swapping f_s and f_o in the Doppler formula.** Reports from several years say candidates put the heard frequency where the emitted one belongs. If you hear 710 Hz from a source approaching at 30 m s^{-1} ($v = 340$ m s^{-1}), the source emits $\frac{710\times310}{340} = 647$ Hz, not $\frac{710\times340}{310} = 779$ Hz. Also check the sign: approaching means a higher frequency.
- **Ignoring "to three significant figures"** in Doppler answers. Reports note this more than once.
- **Using $\cos\theta$ instead of $\cos^2\theta$** for intensity (or $\cos^2$ for an amplitude). At 62°, the intensity fraction is 0.22, the amplitude fraction 0.47.
- **Measuring the second filter's angle from the vertical.** With two filters, each angle is measured from the previous filter's axis. Reports from 2022 and 2023 say two-filter questions go badly; in one, many candidates found the angle between the filters but forgot to add the first filter's angle.
- **Thinking amplitude grows in step with intensity.** Five times the intensity is $\sqrt{5} = 2.24$ times the amplitude, not 5 times. One report describes new traces sketched with the amplitude multiplied by the intensity factor.
- **Power-of-ten slips with prefixes**: GHz, THz, ps and nm. Reports in several years mention answers given in Hz when GHz or THz was asked, or wrong conversions to ps. Write the power of ten in full before converting.
- **Vague definitions of transverse and longitudinal.** "The energy moves in the direction of the wave" earns nothing. Compare the direction of the **particles' oscillations** with the direction of **energy transfer**.

- **Not knowing the spectrum ranges.** Reports note wrong regions for given wavelengths, for example putting a visible wavelength such as 500 nm in the ultraviolet. Visible is 400–700 nm, and learn one wavelength for each region.
- **Treating phase difference as a time or a distance.** It is an angle in degrees.
- **Measuring amplitude peak to trough.** Amplitude is centre to peak.

How to get the marks

- **Definitions** (use the key words):
  - Wavelength: distance between neighbouring points **in phase** (crest to crest).
  - Frequency: number of oscillations **per unit time**. Period: time for **one** oscillation.
  - Amplitude: **maximum displacement** from the equilibrium position.
  - Progressive wave: a wave that **transfers energy**.
  - Transverse / longitudinal: particle oscillations **perpendicular / parallel** to the direction of **energy transfer**.
  - Polarisation: oscillations in **one direction only**, in a plane containing the direction of travel; it needs a transverse wave.
- **"Derive" or "use the definitions"**: state each definition (as a word equation or in symbols), then combine them. A bare $v = \frac{\lambda}{T}$ with no definitions gets little.
- **Calculations (C1 then A1)**: write the equation in symbols, substitute, then the answer with a unit. With the Doppler formula, the correct substitution alone often earns the first mark.
- **Significant figures**: match the data (usually 2 or 3); give exactly the number asked for.
- **Units**: Hz, m, m s^{-1}, W m^{-2}, degrees for phase difference. Convert to the unit the answer line asks for (GHz, THz, ps).
- **"Show that"**: every value substituted, including c, and the answer to one more significant figure than the one printed.
- **Sketches**:
  - Malus: a smooth $\cos^2$ curve between 0 and I_0, the right maxima and zeros, at least one full cycle.
  - CRO trace after an intensity change: same period, height changed by the square root of the intensity factor.
  - Doppler f against t for a source passing on a straight line: a constant high value, then a drop through f_s as it passes, then a constant low value.
- **"State and explain"**: give the result **and** the physics link, for example "higher frequency: the wavefronts in front are closer together, and the speed of sound is unchanged".
- **Multiple choice**: work it out before you look. Wrong options often use cos instead of $\cos^2$, the amplitude peak to trough, the period instead of the wavelength, or the wrong Doppler sign.

Quick check

1. An electromagnetic wave in free space has frequency 1.5×10^{15} Hz. Calculate its wavelength and name its region.
2. A sound of frequency 1100 Hz travels at 330 m s^{-1}. Calculate the phase difference between two points 0.12 m apart along the wave.
3. A source emitting 750 Hz moves directly away from a stationary observer at 15 m s^{-1}. The speed of sound is 330 m s^{-1}. Calculate, to three significant figures, the frequency heard.
4. A laser beam of power 3.0 mW has a cross-sectional area of 2.0 mm^2. Calculate its intensity. By what factor does the intensity change if the amplitude increases by 50%?
5. Vertically polarised light of intensity I_0 and amplitude A_0 is incident normally on a polarising filter whose transmission axis is at 55° to the vertical. Find the transmitted intensity and amplitude in terms of I_0 and A_0.

Answers

1. $\lambda = \dfrac{c}{f} = \dfrac{3.00 \times 10^{8}}{1.5 \times 10^{15}} = 2.0 \times 10^{-7}$ m $= 200$ nm: ultraviolet.
2. $\lambda = \dfrac{330}{1100} = 0.30$ m, so the phase difference is $\dfrac{0.12}{0.30} \times 360^\circ = 144^\circ$.
3. Moving away, so plus: $f_o = \dfrac{750 \times 330}{330 + 15} = 717$ Hz.
4. $I = \dfrac{3.0 \times 10^{-3}}{2.0 \times 10^{-6}} = 1500$ W m^{-2}. The amplitude becomes 1.5 times as big, so the intensity is multiplied by $1.5^2 = 2.25$.
5. $I = I_0 \cos^2 55^\circ = 0.33\, I_0$ and $A = A_0 \cos 55^\circ = 0.57\, A_0$.

Past questions to try

- **9702/22/F/M/24 Q5**: defining a transverse wave, naming a region of the spectrum, then a wavelength from an oscilloscope trace.
- **9702/21/O/N/22 Q4**: the meaning of polarisation, why sound can't be polarised, and Malus's law to find an angle.
- **9702/22/O/N/21 Q4**: the Doppler effect for a toy car that speeds up and then moves steadily away.
- **9702/23/O/N/22 Q4**: a longitudinal wave drawn as particles and as a graph, its speed, and how intensity depends on amplitude.