

ESAT

Physics

Waves

Free lesson notes

Covers	P6.1 to P6.5
Format	Lesson, worked examples, self-check
Price	Free

About this lesson

Waves are everywhere: the ripples on a pond, the sound of a voice, the light by which you read this page, the radio signal that reaches a phone. They look very different, but they share one idea. A **wave** is a way of carrying *energy* from one place to another without anything having to travel the whole way. The water in a pond does not rush to the shore with the ripples; it just bobs up and down, and the energy moves on.

Because all waves obey the same few rules, one small toolkit solves an enormous range of ESAT problems. We start with the two kinds of wave and the quantities used to describe them (amplitude, wavelength, frequency, period), and derive the wave equation $v = f\lambda$. Then we study what waves *do*: they reflect (and we use that for plane mirrors), they refract when they change speed, and they show the Doppler effect when the source or observer moves. The last two sections cover sound (pitch, loudness, echoes, ultrasound) and the electromagnetic spectrum from radio waves to gamma rays.

How to use it. Cover each worked example and try it before reading the solution. There is no calculator in the real ESAT, so the numbers here are friendly: practise doing the arithmetic by hand. We use a speed of sound in air of 340 m/s and a speed of light of 3×10^8 m/s. Finish with the self-check, then the practice set.

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1 What is a wave? Transverse and longitudinal (P6.1)

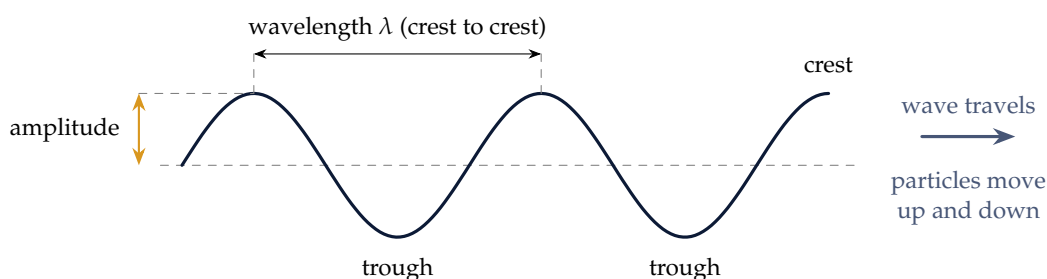
Hold one end of a long rope and flick it up and down. A hump runs along the rope towards the far end. Nothing has travelled along the rope except the *disturbance*: each piece of rope simply moves up and then back down, passing the motion to its neighbour. This is the essential nature of a wave:

a wave transfers energy (and information) from place to place, without transferring matter.

You can see this with a cork floating on a pond. As ripples pass, the cork bobs up and down, but it does not drift towards the shore.

There are two ways a medium can be disturbed, which gives two kinds of wave.

Transverse waves. The particles of the medium vibrate *at right angles* to the direction in which the wave travels. A wave on a rope, ripples on water and all electromagnetic waves (light, radio waves, X-rays and so on) are transverse. A transverse wave has high points called **crests** and low points called **troughs**.

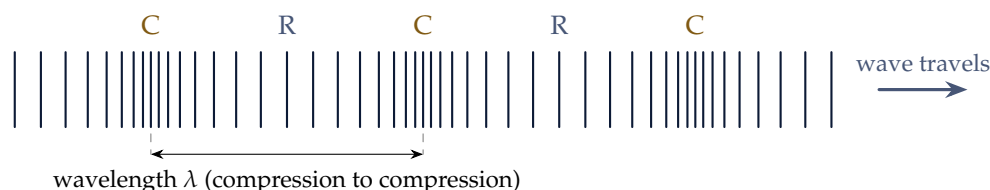


The dashed line is the rest position. The **amplitude** is the maximum displacement from the rest position (not the crest-to-trough height, which is twice as big). The **wavelength** λ (the Greek letter lambda) is the distance from any point on the wave to the next identical point, for example crest to crest. It is measured in metres.

Longitudinal waves. The particles vibrate *parallel* to the direction of travel. Push and pull one end of a stretched slinky spring along its length and you see bunched-up regions called **compressions** and stretched-out regions called **rarefactions**.

travelling along it. Sound is a longitudinal wave: the air particles are pushed together into compressions and then spread out in rarefactions.

C = compression (particles close together), R = rarefaction (particles spread out)



In the picture each vertical line is a layer of particles. Where lines are close together the pressure is high (C); where they are far apart it is low (R). The wavelength is the distance from one compression to the next. The particles themselves only shuffle a short way back and forth; the *pattern* moves to the right.

Finally, a distinction that matters later. Sound and water waves need a material to travel through (a **medium**). Electro-magnetic waves do not: light reaches us from the Sun across empty space.

Key ideas

- A wave transfers energy without transferring matter.
- **Transverse**: vibration $\perp$ direction of travel (rope, water ripples, all electromagnetic waves).
- **Longitudinal**: vibration $\parallel$ direction of travel, with compressions and rarefactions (sound).
- Amplitude = maximum displacement from rest. Wavelength = length of one complete wave.

Worked example: which kind of wave?

State whether each is transverse or longitudinal, and whether it can travel through a vacuum: (a) sound from a loudspeaker, (b) a radio wave, (c) a wave on a guitar string.

(a) Longitudinal; it needs air (or some other medium), so it cannot cross a vacuum. (b) Transverse, as all electromagnetic waves are; it can travel through a vacuum. (c) Transverse: the string moves at right angles to the way the wave runs along it. A string is a medium, so no vacuum.

Common mistakes

- Saying the *matter* travels with the wave. Only the energy does; the particles oscillate about fixed positions.
- Giving the amplitude as the distance from trough to crest. It is measured from the *rest position* to a crest (or to a trough).
- Thinking sound is transverse because it is drawn as a wavy line. A graph of pressure against distance looks like a transverse wave, but the air particles move along the line of travel.

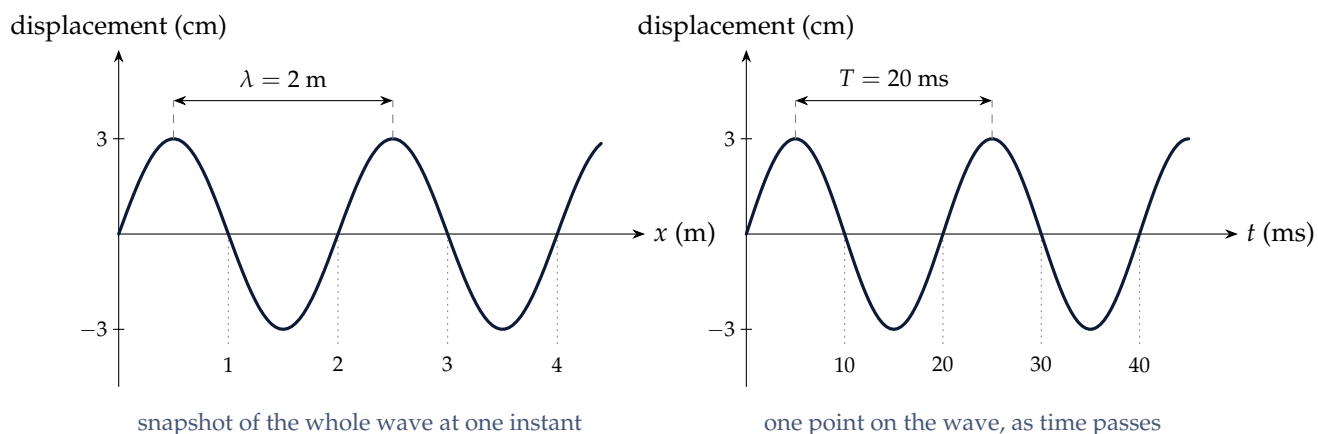
2 Frequency, period and the wave equation (P6.1)

Two more quantities describe how rapidly a wave oscillates. The **frequency** f is the number of complete waves passing a point (or complete oscillations of one particle) per second. It is measured in **hertz** (Hz): 1 Hz is one wave per second. The **period** T is the time taken for one complete wave to pass, measured in seconds. If f waves pass each second, each takes $1/f$ of a second:

$$T = \frac{1}{f} \quad \text{and} \quad f = \frac{1}{T}.$$

A frequency of 50 Hz means a period of $1/50 = 0.02$ s (that is, 20 ms). Prefixes help with large frequencies: 1 kHz = 1000 Hz, 1 MHz = 10^6 Hz, 1 GHz = 10^9 Hz.

Two graphs that look the same but are not. A wave can be shown in two ways. A *displacement–distance* graph is a snapshot of the whole wave at one instant, and the horizontal gap between crests is the *wavelength*. A *displacement–time* graph follows one point as time passes, and the horizontal gap between crests is the *period*. Always check which quantity is on the horizontal axis.



Both graphs above show the same wave: wavelength 2 m in the left graph, period 20 ms in the right, and amplitude 3 cm in each.

The wave equation. How fast does the wave travel? In one period T the wave moves forward exactly one wavelength λ (each crest has just moved into the place of the crest ahead). Speed is distance divided by time, so

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

So **wave speed = frequency × wavelength**, with v in m/s, f in Hz and λ in m. For the wave in the figure, $v = \lambda/T = 2/0.020 = 100 \text{ m/s}$, and also $f\lambda = 50 \times 2 = 100$.

Two facts about this equation are used constantly. First, the *source* sets the frequency (your hand shaking the rope at 2 Hz makes a 2 Hz wave). Second, the *medium* sets the speed. So when a wave enters a different medium its frequency stays the same, and the wavelength changes in proportion to the speed.

Worked example: water waves

A paddle makes ripples of wavelength 0.40 m at a frequency of 2.5 Hz. Find the speed of the ripples and their period.

$$v = f\lambda = 2.5 \times 0.40 = 1.0 \text{ m/s}. \quad T = 1/f = 1/2.5 = 0.40 \text{ s}.$$

Worked example: radio wave

A radio station broadcasts at 100 MHz. Radio waves travel at $3 \times 10^8 \text{ m/s}$. What is their wavelength?

$$\lambda = \frac{v}{f} = \frac{3 \times 10^8}{100 \times 10^6} = \frac{3 \times 10^8}{10^8} = 3 \text{ m}.$$

Common mistakes

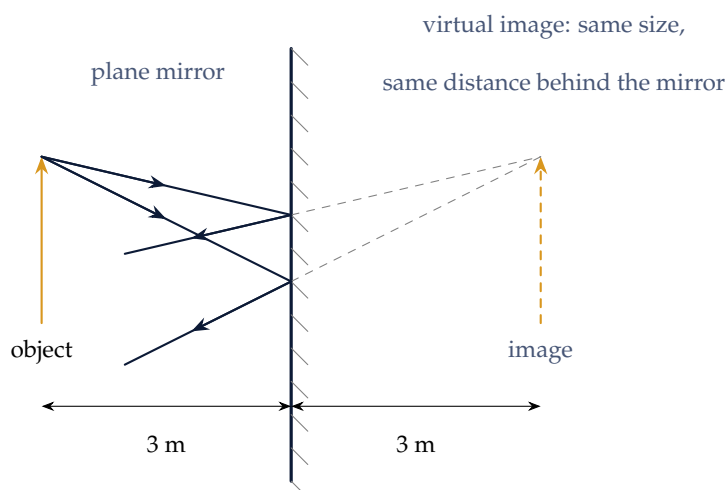
- Reading the period off a displacement–distance graph (or the wavelength off a displacement–time graph). Check the horizontal axis label.
- Using $v = f/\lambda$ or $\lambda = fv$. Write $v = f\lambda$ and rearrange: $f = v/\lambda$, $\lambda = v/f$.
- Forgetting the prefix: 100 MHz is 10^8 Hz , not 100.

3 Reflection and plane mirrors (P6.2, P6.3)

When a wave meets a boundary it can bounce back. This is **reflection**. To describe it we draw a line called the **normal** at right angles to the surface at the point where the ray hits. Angles are always measured from the normal, never from the surface.

The law of reflection: the angle of incidence equals the angle of reflection, $i = r$. The incident ray, the reflected ray and the normal all lie in one plane. This holds for every kind of wave: light off a mirror, sound off a wall, water ripples off a barrier.

Images in a plane mirror. Your eye cannot tell the true direction a ray came from; it only sees the direction it arrives in, and works out where the object must be by tracing the ray backwards in a straight line. In the diagram two rays leave the tip of the object, strike the mirror and reflect. Traced backwards (dashed lines) they appear to come from a single point behind the mirror.



That point is the image. A plane (flat) mirror gives an image that is

- the **same size** as the object,
- the **same distance behind** the mirror as the object is in front,
- **virtual**: the light does not actually pass through the image, so it cannot be caught on a screen,
- **laterally inverted** (left and right are swapped).

So you and your image are always *twice* your distance from the mirror apart.

Rotating a mirror. Because the angle between the incident and reflected rays is $2i$, turning the mirror by an angle θ about the point where the ray hits changes the angle of incidence by θ and so turns the reflected ray through 2θ (the incident ray stays fixed).

Worked example: how far from my image?

A girl stands 1.5 m in front of a plane mirror. How far is she from her image? She then steps back 0.5 m. How far apart are they now?

The image is 1.5 m behind the mirror, so the distance is $1.5 + 1.5 = 3.0$ m. After stepping back she is 2.0 m from the mirror, so the distance is $2 \times 2.0 = 4.0$ m.

Worked example: a slanting ray

A ray strikes a plane mirror so that it makes 20° with the surface of the mirror. What is the angle of reflection, and what is the angle between the incident and reflected rays?

The normal is 90° from the surface, so the angle of incidence is $90 - 20 = 70^\circ$ (measured from the normal). The angle of reflection is also 70° . The angle between the incident and reflected rays is $70 + 70 = 140^\circ$.

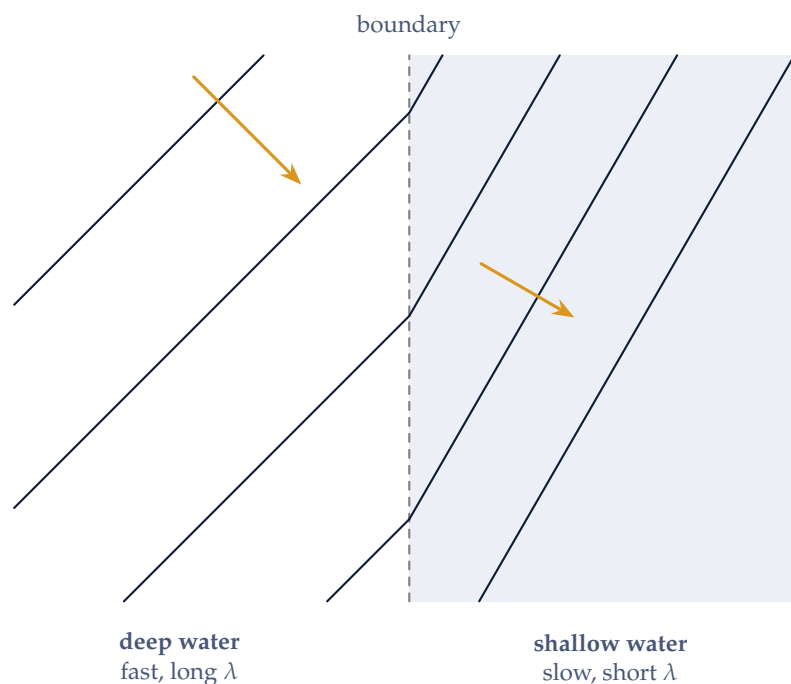
Common mistakes

- Measuring the angle from the mirror surface. The law refers to the angle from the *normal*.
- Forgetting that the object–image separation is twice the object–mirror distance.
- Drawing the image behind the mirror with solid rays. Rays behind the mirror are dashed construction lines: no light is there.

4 Refraction (P6.2, P6.3)

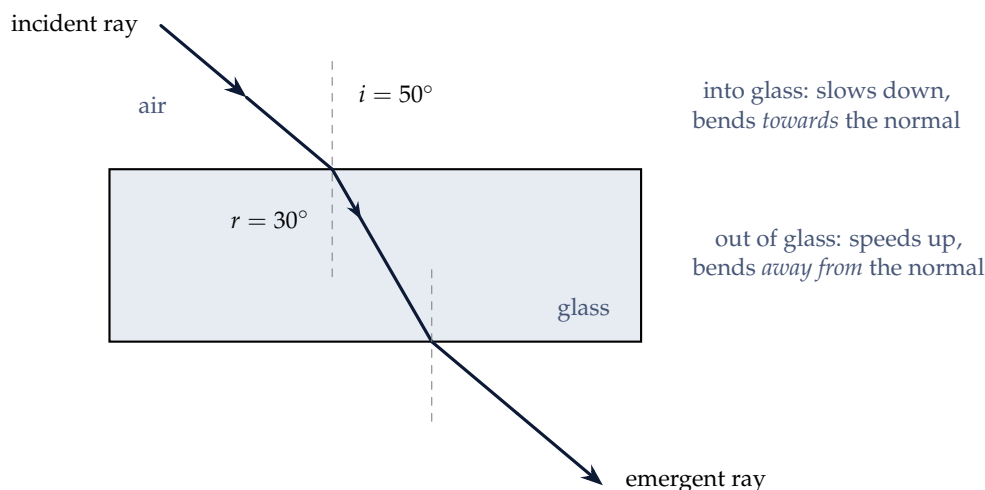
A wave travels at a speed that depends on the medium. When a wave crosses a boundary from one medium into another, its speed changes. This is **refraction**. If the wave meets the boundary at an angle, the change of speed also changes its *direction*.

Why does the direction change? Think of a line of marching soldiers heading from a hard road into thick mud at an angle. The soldier who reaches the mud first slows down while the others are still marching quickly, so the line swings round. A wavefront behaves in exactly the same way. The ripple-tank picture shows crests (the lines) crossing from deep water into shallow water, where waves travel more slowly.



Three things happen at the boundary of the shaded region. (i) The waves **slow down**. (ii) Because the frequency cannot change (the same number of crests arrive at the boundary each second as leave it), $v = f\lambda$ tells us the **wavelength becomes shorter** (the lines are closer together). (iii) The wavefronts turn so that the direction of travel moves **towards the normal**. Going the other way, from slow to fast, the wave speeds up, the wavelength grows and the ray bends **away from the normal**. A wave that hits a boundary along the normal (at 0°) slows down but does not change direction.

Light in glass. Light travels at 3×10^8 m/s in air (very nearly the same as in a vacuum) but only about 2×10^8 m/s in glass. A ray going from air into glass therefore bends towards the normal. In a rectangular glass block the ray bends towards the normal on entering and bends back away from the normal by exactly the same amount on leaving, so the **emergent ray is parallel to the incident ray** but shifted sideways.



The glass block in the diagram has an angle of incidence of 50° and an angle of refraction of 30° inside the glass. At the second face the ray leaves at 50° again, which is why the exit ray is parallel to the entry ray. (The specification asks you to draw and interpret such ray diagrams, not to calculate angles from a formula.)

Key ideas

- Refraction is a change of wave *speed* on entering a new medium, which changes direction if the wave arrives at an angle.
- Frequency does not change. $v = f\lambda$, so wavelength changes in proportion to speed.

- Slower medium (e.g. air → glass): bends **towards** the normal. Faster medium: bends **away from** the normal.
- Rectangular block: the emergent ray is parallel to the incident ray.

Worked example: wavelength in glass

Red light of wavelength 600 nm in air (speed 3×10^8 m/s) enters glass, where its speed is 2×10^8 m/s. Find its frequency and its wavelength in the glass.

Frequency: $f = \frac{v}{\lambda} = \frac{3 \times 10^8}{6 \times 10^{-7}} = 5 \times 10^{14}$ Hz, and it is unchanged in the glass. In glass, $\lambda = \frac{v}{f} = \frac{2 \times 10^8}{5 \times 10^{14}} = 4 \times 10^{-7}$ m = 400 nm. (Shortcut: λ is proportional to v , so $600 \times \frac{2}{3} = 400$.)

Worked example: ripples going shallow

Ripples of wavelength 6 cm travel at 24 cm/s in deep water, and slow to 16 cm/s in shallow water. What is the wavelength in the shallow water?

Frequency = $24/6 = 4$ Hz, unchanged. Shallow: $\lambda = 16/4 = 4$ cm.

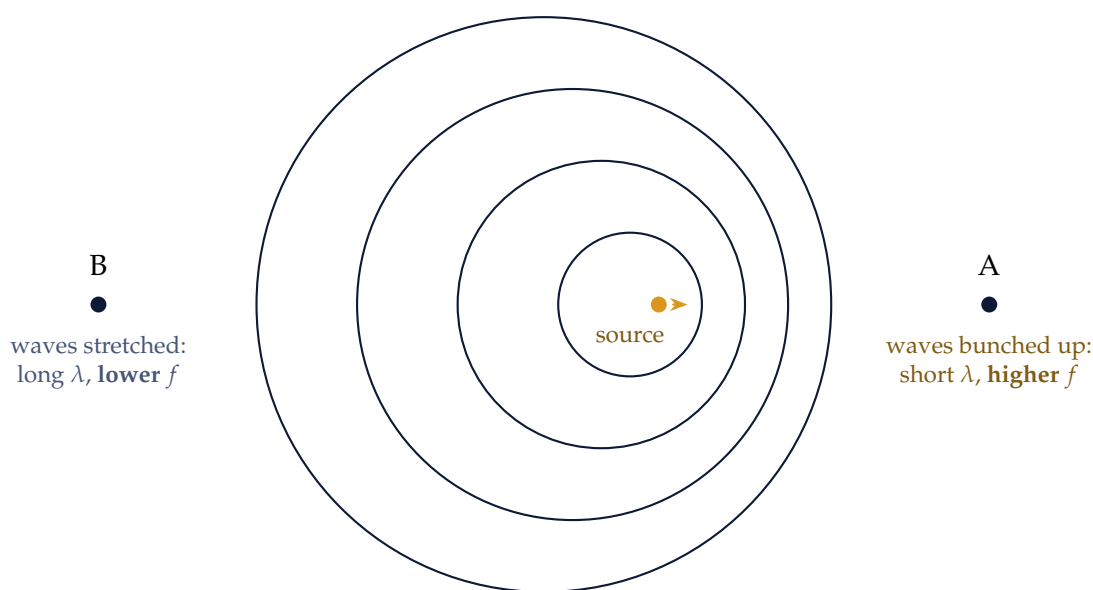
Common mistakes

- Saying that the frequency changes. It is set by the source and is the same on both sides of the boundary.
- Bending the wrong way. Remember: slowing down $\Rightarrow$ towards the normal ("slow = squash towards the normal").
- Thinking a wave on the normal stops or bends. It slows down (shorter wavelength) but carries straight on.

5 The Doppler effect (P6.2)

You have heard an ambulance siren drop in pitch as it speeds past. The siren itself does not change; what changes is the frequency the listener *receives*. This is the **Doppler effect**: when a source of waves and an observer move relative to each other, the observed frequency differs from the frequency emitted.

Why it happens. Waves spread out at a speed fixed by the medium, regardless of how the source moves. Each crest, once emitted, spreads out as a circle centred on the point where the source was when it emitted that crest. If the source is moving, those centres are *different* points, drawn in the picture as four circles.



source moving $\rightarrow$ (speed $0.4 \times$ wave speed); circles show crests emitted at equal time intervals

Ahead of the moving source the later crests are emitted from positions closer to the observer, so the circles are squeezed together: the observed wavelength is **shorter**. An observer at A receives crests more frequently, so the frequency is **higher**.

Behind the source the circles are spread out, so the wavelength is **longer** and observer B receives crests less often, so the frequency is **lower**.

What changes and what does not. For sound, higher frequency means higher pitch: the siren sounds higher as it approaches and lower as it recedes. The *true* frequency of the siren is unchanged, and the pitch heard while it approaches is constant (it does not slide upwards); the jump down happens as it passes you. The effect is stronger the faster the source moves. It occurs for all waves, including light: light from distant galaxies is shifted to longer wavelengths ("redshift"), showing that they are moving away from us, and police speed guns and medical blood-flow scans use the same idea with microwaves and ultrasound.

Counting crests (a numerical example). A source makes 2 Hz ripples on water, where ripples travel at 20 cm/s, and moves forward at 4 cm/s. The ripples are emitted every 0.5 s, and in that time the source moves $4 \times 0.5 = 2$ cm closer. The wavelength in front is $\lambda = 20 \times 0.5 - 2 = 8$ cm, so an observer in front sees frequency $f = 20/8 = 2.5$ Hz. Behind, the crests are $10 + 2 = 12$ cm apart, so $f = 20/12 \approx 1.7$ Hz.

Worked example: what an observer hears

A source emitting a steady note moves directly towards a stationary listener. Is the observed (a) wavelength, (b) frequency, (c) speed of the sound waves in air, larger, smaller or unchanged compared with a stationary source?

(a) Smaller: the crests are squeezed together. (b) Larger, since $f = v/\lambda$ with the same v and a smaller λ . (c) Unchanged: the speed of the waves is set by the air alone.

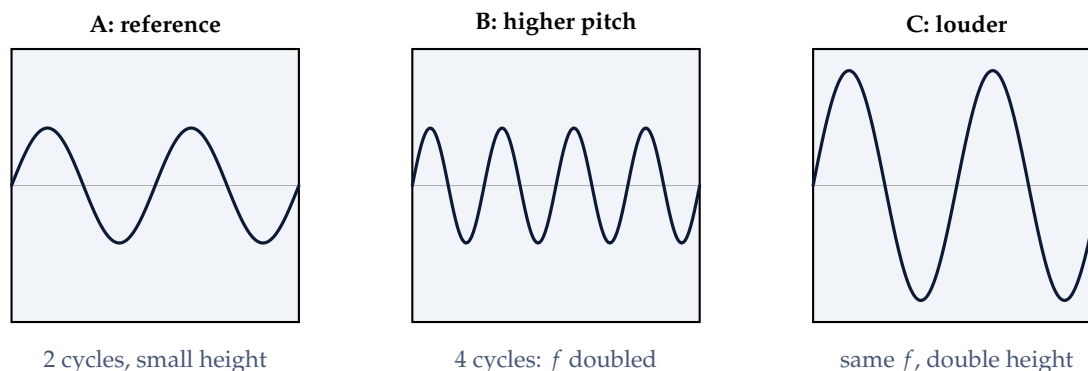
Common mistakes

- Believing that the pitch rises *gradually* as the source approaches. It is higher but steady, then lower but steady after it passes. (The *loudness* rises and falls.)
- Saying the source's own frequency changes. It is the observer's received frequency that differs.
- Saying the wave speed changes. In the medium the wave speed is fixed; wavelength and frequency change.

6 Sound (P6.4)

Sound is made when something vibrates, pushing the air next to it into a train of compressions and rarefactions. It is a longitudinal wave and needs a medium: there is no sound in a vacuum. The speed of sound in air is about 340 m/s. Sound travels faster in liquids (about 1500 m/s in water) and faster still in solids (several thousand metres per second in steel), because the particles are closer together and pass the vibration on more quickly. This is the opposite order to light, which is fastest in a vacuum.

Pitch and loudness. The **pitch** of a note is set by its frequency: high frequency, high pitch. The **loudness** is set by the amplitude: larger amplitude, louder sound. An oscilloscope turns sound into a wavy trace on a screen, so the two properties are easy to read.



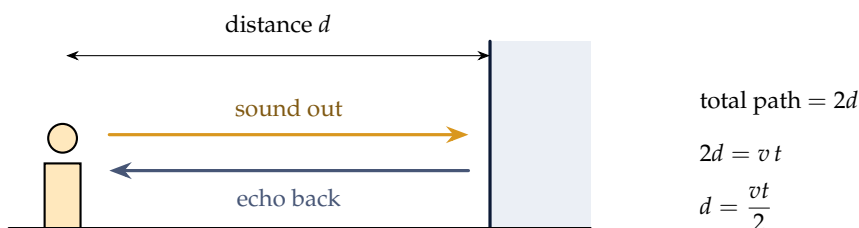
Compared with the reference trace A, trace B fits twice as many waves into the same time, so it has twice the frequency and a higher pitch (same height, so the same loudness). Trace C has the same frequency but waves of twice the height, so it is the same pitch but louder.

The range of hearing. A healthy young person hears frequencies from about 20 Hz to 20 000 Hz (20 kHz). Sound above this range is **ultrasound** and below it is **infrasound**.

Echoes. Sound reflects from hard surfaces. If a sound pulse leaves a source, reflects from a surface at distance d and

returns after a time t , the sound has travelled to the surface and back, a total of $2d$:

$$2d = vt \implies d = \frac{vt}{2}$$



The most common error is forgetting that the distance travelled is twice the distance to the surface.

Ultrasound in use. Ultrasound is not heard, so it can be used without disturbing anyone, and it reflects partially at the boundary between two different materials. Uses include medical scans (a pulse is sent into the body and the timing of the echoes from the boundaries between tissues is turned into an image, for example of a foetus, which is safer than X-rays), sonar (ships measure the depth of the sea or find shoals of fish), cleaning delicate objects (vibrations shake dirt loose), and testing for hidden cracks in metal parts.

Worked example: depth of the sea

A ship's sonar sends a pulse of ultrasound down and detects the echo from the sea bed after 0.60 s. The speed of sound in sea water is 1500 m/s. How deep is the water?

Distance travelled (down and back) = $vt = 1500 \times 0.60 = 900$ m. Depth = $900/2 = 450$ m.

Worked example: wavelength of ultrasound

An ultrasound scanner uses a frequency of 2 MHz and the speed of sound in body tissue is 1500 m/s. Find the wavelength.

$$\lambda = \frac{v}{f} = \frac{1500}{2 \times 10^6} = 7.5 \times 10^{-4} \text{ m} = 0.75 \text{ mm.}$$

Short wavelengths like this let the scanner pick out small details.

Common mistakes

- Using $d = vt$ for an echo and forgetting to halve. The sound covers the distance twice.
- Confusing pitch and loudness: pitch $\leftrightarrow$ frequency, loudness $\leftrightarrow$ amplitude.
- Thinking sound is faster in air than in water or steel. In denser media the particles are closer together, so sound travels faster.

7 The electromagnetic spectrum (P6.5)

Light is only one member of a whole family of waves. **Electromagnetic (EM) waves** are transverse waves made of oscillating electric and magnetic fields, and they all share some properties: they travel through a vacuum, and they all travel at the same speed there, 3×10^8 m/s. What makes one different from another is its wavelength and frequency. Since $c = f\lambda$ with c fixed, *a longer wavelength means a lower frequency*.

	long wavelength, low frequency, low energy				short wavelength, high frequency, high energy		
	radio	micro-waves	infra-red	visible	ultra-violet	X-rays	gamma rays
λ (m)	10^3	10^{-2}	10^{-5}	5×10^{-7}	10^{-8}	10^{-10}	10^{-12}
f (Hz)	3×10^5	3×10^{10}	3×10^{13}	6×10^{14}	3×10^{16}	3×10^{18}	3×10^{20}

In order of increasing frequency (decreasing wavelength) the spectrum is: **radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, gamma rays**. Within visible light the order runs red (longest wavelength, about 700 nm) to

violet (shortest, about 400 nm). The values in the figure are typical orders of magnitude, since the bands overlap. Higher frequency also means more energy per wave packet: this is why only the last three are ionising and dangerous to living cells.

Uses and hazards.

- **Radio waves:** broadcasting radio and television, communication. Hazard: very little at normal exposure.
- **Microwaves:** cooking food, satellite and mobile-phone communication. Hazard: they heat body tissue, so internal burns at high intensity.
- **Infrared:** remote controls, heaters and grills, thermal-imaging cameras. Hazard: skin burns.
- **Visible light:** seeing, photography, optical fibres for communication. Hazard: a bright laser can damage the retina.
- **Ultraviolet:** sterilising water, security marking, fluorescent lamps. Hazard: damages skin cells and can cause sunburn, skin cancer and eye damage.
- **X-rays:** imaging bones and teeth, airport scanners. Hazard: ionising, so can damage cells and cause cancer.
- **Gamma rays:** sterilising medical equipment and food, treating cancer, medical tracers. Hazard: ionising, as for X-rays.

The detailed uses above are the standard ones; you are expected to be able to match each type of radiation with a typical use and its main hazard.

Worked example: time for light to reach us

The Sun is 1.5×10^{11} m from the Earth. How long does its light take to arrive?

$$t = \frac{d}{c} = \frac{1.5 \times 10^{11}}{3 \times 10^8} = 500 \text{ s, which is a little over 8 minutes.}$$

Worked example: radar

A radar pulse (a radio wave) is reflected from an aircraft and returns after $40 \mu\text{s}$. How far away is the aircraft?

Distance there and back = $ct = 3 \times 10^8 \times 40 \times 10^{-6} = 12\,000$ m. The aircraft is $12\,000/2 = 6\,000$ m (6 km) away.

Exam tip

For any EM-wave question, write $c = f\lambda$ with $c = 3 \times 10^8$ m/s first. To order the spectrum quickly, remember *Radio Microwave Infrared Visible Ultraviolet X-ray Gamma* (increasing frequency). Ionising radiation starts at ultraviolet.

Common mistakes

- Mixing up the order of microwaves and infrared, or of ultraviolet and X-rays.
- Saying that ultraviolet is a hazard because it is hot. It damages cells (ionisation); infrared is the one that burns.
- Thinking different EM waves travel at different speeds in a vacuum. They all travel at 3×10^8 m/s.

Check yourself

Try these without looking back, then compare with the answers on the next page.

1. Is sound transverse or longitudinal? Can it travel through a vacuum?
2. A wave has a frequency of 4 Hz and a wavelength of 3 m. Find its speed and period.
3. A man stands 3 m from a plane mirror. How far is he from his image?
4. A ray in air strikes a glass block along the normal. Does it bend? Does its speed change?
5. Waves enter shallower water and slow down. What happens to the frequency and the wavelength?
6. A fire engine approaches a stationary listener. Does the listener hear a higher or lower pitch than the driver does?
7. A shout takes 2 s to return as an echo from a cliff. The speed of sound is 340 m/s. How far away is the cliff?
8. Which has the higher frequency, an X-ray or a microwave? Which has the longer wavelength?

Answers to the self-check

1. Longitudinal; no, it needs a medium.
2. $v = f\lambda = 4 \times 3 = 12 \text{ m/s}$; $T = 1/4 = 0.25 \text{ s}$.
3. The image is 3 m behind the mirror, so 6 m.
4. No bend (angle of incidence is 0°), but it slows down.
5. Frequency is unchanged; the wavelength decreases in proportion to the speed.
6. Higher, while it approaches (lower once it has passed).
7. $d = vt/2 = 340 \times 2/2 = 340 \text{ m}$.
8. The X-ray has the higher frequency; the microwave has the longer wavelength.

Next step

Heurisco's *ESAT Physics: Waves Practice Set* has twenty original exam-style questions on this lesson, with ray and wave diagrams, in order of difficulty, with a full worked solution and a note on the trap in each.