THE PHYSICS OF YOUR PING · TWO WAVES, ONE CABLE, AND THE 77 MS LIMIT

TWO

Every second you play League of Legends, exactly two types of wave carry information to your body: a physical sound wave in the air from your headset, and a transverse electromagnetic wave from your monitor. One requires a physical medium to travel through, whereas the other propagates through empty space.

77 ms

When you flash to evade an enemy ability, the command is registered 77 ms later on the European server. This network delay represents the time light needs to travel through the undersea glass fibres of the West Africa Cable System, crossing a physical distance of 14,530 km between South Africa and Europe.

77 ms

A geostationary satellite sits 35,786 km above Earth. This high altitude introduces a round-trip latency of nearly half a second. Low-orbit satellites like Starlink sit 65 times closer, at an altitude of 550 km — but a single satellite still can't bridge South Africa and Europe, so the signal has to relay satellite-to-satellite along the curve between them: about 10,483 km, longer than the 9,650 km you'd measure on the ground, since the relay happens on a shell 550 km up. That sets Starlink's minimum physical latency at 77 ms.

Information cannot travel faster than the speed of light. This physical limit dictates how networks operate.

The Physics of Your Ping

How signals travel to you when you connect from South Africa to Europe, and why the speed of light inside undersea glass cables determines your network latency.

Syllabus	Cambridge IGCSE Physics 0625 (2026/2027/2028) — Sections 3.3 Electromagnetic Spectrum, 3.4 Sound	**Chapter**	3.3–3.4 The Electromagnetic Spectrum and Sound
Objectives	3.3.1–3.3.10, 3.4.1–3.4.12	**Scenario**	The Physics of Your Ping

Made for **Caps** **Level** IGCSE Extended

"Games, movies and original characters created by my friends and I." — Caps

By the end, you should be able to:

- Explain what makes something a wave, and why sound needs a medium to travel while light and other EM waves don't.
- Put the seven regions of the EM spectrum in order, describe a genuine use for each, and describe a harmful effect of overexposure.
- Calculate how fast an EM wave travels through a material, and use distance, speed and time to work out real signal travel times.
- Explain why different communication systems — microwaves, radio waves, optical fibres, satellites — get chosen for different jobs, with the actual reason, not just the name.
- Describe how amplitude and frequency change loudness and pitch, and explain compression and rarefaction in a sound wave.
- Use distance, speed and time to calculate results from an echo or ultrasound measurement, including sonar depth.

> Answers to every exercise start on page 28. Try each question yourself first — quick checks can be checked immediately by flipping the page upside down.

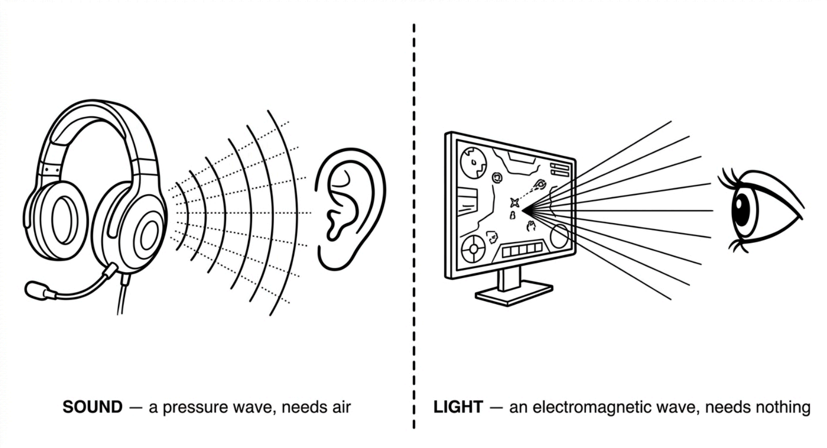
1 Two Kinds of Wave

What a wave is, and how waves are classified by their physical medium

A wave transfers energy from one location to another without transferring physical matter. A sea swell illustrates this principle clearly: water molecules move up and down in a fixed position, but do not travel from the deep ocean to the shore. Only the wave's kinetic energy moves across the surface.

When you sit down to play a game, two distinct types of wave reach you. Sound leaves your headset as a physical pressure wave. The speaker's internal diaphragm vibrates, pushing and pulling the surrounding air molecules. These molecules pass the vibration along to their neighbours, carrying the sound wave to your eardrum. In contrast, light travels from your monitor as an electromagnetic wave. This wave consists of oscillating electric and magnetic fields that require no material medium to propagate, allowing light to travel through a vacuum as easily as it travels through the air in front of your screen.

This requirement for a physical medium is the primary distinction between sound and light waves. Sound is a **longitudinal** wave. The particles of the medium vibrate back and forth along the same direction the wave travels, creating alternating regions of high and low pressure. Light is a **transverse** wave. Its fields oscillate at right angles to the direction of wave travel, mirroring the movement of a rope flicked up and down. These classifications describe how energy is transferred: longitudinal waves require a physical substance to push against, whereas transverse electromagnetic waves can travel through empty space.



The two waves that reach you every second you play: sound from your headset, light from your monitor.

KEY IDEA — What makes something a wave

A wave transfers energy from one place to another without transferring matter. In a **longitudinal** wave (like sound), the vibrations are along the same direction the wave travels — as compressions and rarefactions in a medium. In a **transverse** wave (like light), the vibrations are at right angles to the direction of travel, and no medium is needed at all.

Property	Sound	Light
Type of wave	Longitudinal	Transverse
Needs a medium?	Yes — air, water, or a solid	No — travels through a vacuum

What vibrates	Air particles (or particles in any medium)	Electric and magnetic fields
Speed in air	About 340 m/s	3.0×10^8 m/s

Sound and light are both waves, but they differ in every property that matters — including whether they need anything to travel through.

WORKED EXAMPLE 1 — The silent bell jar

Problem: A small electric bell and a lamp are sealed inside a glass jar. While air is still in the jar, you can hear the bell ringing and see the lamp lit. A pump then removes all the air from the jar. State three differences you would now notice between the bell and the lamp.

Solution:

Step 1: Identify the wave types. The bell produces sound waves, and the lamp produces light waves.

Step 2: Determine medium requirements. Sound waves require a physical medium to propagate, whereas light waves do not.

Step 3: Apply this to a vacuum. Because the pump removes the air, sound waves can no longer travel from the bell to your ears, and the bell falls silent. Light waves do not require a medium, so the lamp remains visible.

Step 4: State the physical differences. (1) The bell becomes silent, but the lamp remains lit; (2) sound waves require a medium while light waves do not; (3) sound is a longitudinal wave, whereas light is a transverse wave.

Explanation: Removing the air silences the bell because sound waves are physical vibrations of particles. Without air molecules to compress and decompress, the sound wave cannot form or transmit energy.

QUICK CHECK — READING THE PROPERTY TABLE

1. Which wave type has its vibrations at right angles to the direction of travel?

2. A speaker cone moves back and forth to make sound. Which direction do the air particles right next to it vibrate — along the direction of the sound, or across it?

Flip to check — Q1 — light (transverse). Q2 — along the direction the sound travels (that's what makes it longitudinal).

EXERCISE 1 — WAVE WARM-UP

3. Complete the sentence: “Sound waves are made of vibrating ____________.” [1 mark]

4. A student says “light is a longitudinal wave, just like sound, because both need something to vibrate.” Is the student correct? Explain your answer. [2 marks]

5. An astronaut on the Moon’s surface claps her hands 2 metres from a colleague. State, with a reason, whether the colleague hears the clap. [2 marks]

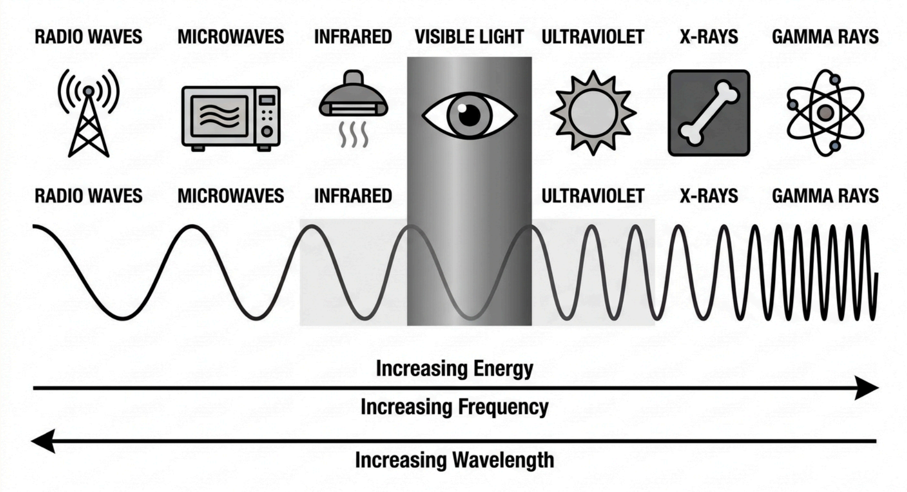
2 The EM Ladder

The seven regions of the electromagnetic spectrum, ordered by frequency

Visible light represents only a small portion of a much larger wave family. The electromagnetic spectrum consists of seven named regions. All seven are identical in wave type: they are transverse waves, require no medium, and travel at the same top speed in a vacuum (3.0×10^8 m/s). They differ only in frequency and wavelength. Ordered by increasing frequency (and decreasing wavelength), the spectrum consists of: radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays. Visible light sits in the middle of this spectrum, serving as a helpful reference point. Every other region is either a lower-frequency, longer-wavelength relative of visible light, or a higher-frequency, shorter-wavelength one.

Each region has practical engineering applications. Wi-Fi routers transmit data using microwaves, monitors emit visible light, and wireless controllers connect using radio waves. These regions are selected for specific tasks because of how their wavelengths interact with physical obstacles and electronic components.

The safety risks of electromagnetic waves vary across the spectrum. At normal levels, radio waves and visible light do not damage human cells, which is why standing near a radio antenna or a lightbulb is safe. However, higher doses of microwaves cause internal heating of body cells, and infrared radiation can burn skin. Ultraviolet light damages surface cells and eyes, which can lead to skin cancer and eye conditions. X-rays and gamma rays carry enough energy to mutate or destroy cells directly. Wavelengths interact with human tissue in specific physical ways, meaning danger depends on the specific region rather than frequency alone.



The seven regions of the EM spectrum — a typical use for each, and how wavelength shortens as frequency and energy increase.

KEY IDEA — The seven regions, in order

The EM spectrum runs, in order of increasing frequency: radio waves → microwaves → infrared → visible light → ultraviolet → X-rays → gamma rays. All seven travel at the same speed in a vacuum (3.0×10^8 m/s) — only their frequency and wavelength differ.

▸ **Watch: "GCSE Physics - Electromagnetic Waves - Frequency | Wavelength | Where They Come From"** (Cognito)

https://www.youtube.com/watch?v=zx0UIMA2-bA

Scan the code with your phone camera, or type the link.

The seven regions of the EM spectrum, in order of increasing frequency and decreasing wavelength.

QUICK CHECK — ORDERING THE SPECTRUM

1. Which has the higher frequency: ultraviolet or infrared?

2. Which travels faster through a vacuum: an X-ray or a radio wave?

Flip to check — Q1 — ultraviolet. Q2 — neither; they travel at the same speed, 3.0×10^8 m/s.

Region	Example use	Harmful effect of overexposure
Radio waves	TV and radio transmission · astronomy · RFID tags	— none specified

Microwaves	Satellite TV · mobile phones · microwave ovens	Internal heating of body cells
Infrared	Electric grills · remote controls · intruder alarms · thermal imaging · optical fibres	Skin burns
Visible light	Vision · photography · illumination	— none specified
Ultraviolet	Security marking · detecting fake banknotes · sterilising water	Damage to surface cells and eyes — skin cancer, eye conditions
X-rays	Medical scanning · security scanners	Mutation or damage to cells
Gamma rays	Sterilising food and medical equipment · detecting and treating cancer	Mutation or damage to cells

Uses and harmful effects of the seven EM regions, from the Cambridge IGCSE Physics syllabus.

> Radio waves and visible light have no harmful effects listed in the syllabus at normal exposure levels, which is why standing near a radio antenna or a lit lamp is safe. Standard precautions against exposure to high-energy waves like X-rays and gamma rays include using lead shielding (such as lead aprons or lead-lined screens) and limiting exposure time. This is why medical staff step behind protective screens when operating medical scanning equipment.

EXERCISE 2 — MATCH THE REGION

3 Put these regions in order of increasing frequency: X-rays, radio waves, ultraviolet, infrared. [2 marks]

4 Which statement about the electromagnetic spectrum is correct? [1 mark]

- ☐ **A** X-rays travel faster than radio waves in a vacuum.
- ☐ **B** Gamma rays and visible light travel at the same speed in a vacuum.
- ☐ **C** Microwaves travel faster than gamma rays in air.
- ☐ **D** Infrared travels slower than visible light in a vacuum.

5 Match each region to its example use. No region is used twice. [4 marks]

Regions
1. Ultraviolet
2. Radio waves
3. Infrared
4. Gamma rays

Uses (i) Optical fibres
(ii) Sterilising medical equipment
(iii) Security marking / detecting fake banknotes
(iv) TV transmission and astronomy

6 State one harmful effect on people of excessive exposure to gamma rays. [1 mark]

3 Digital or Analogue? Two ways to encode information in a signal

A signal carries information, such as a changing electrical voltage representing a sound wave. There are two primary ways to encode this information. An **analogue** signal varies continuously, taking any value within a range. This is similar to a light dimmer switch, which can adjust smoothly to any level between fully off and fully on. In contrast, a **digital** signal only takes specific, fixed values — usually just two levels, representing 0 and 1.

Sound can be transmitted using either method. A microphone initially produces an analogue electrical signal because it responds to continuously varying air pressure. This signal can be transmitted as an analogue waveform, or converted into a sequence of digital 0s and 1s. This digital conversion is used to transmit voice-chat across networks.

Digital signals offer two key advantages over analogue systems. First, they transmit data at a higher rate because the receiver only needs to distinguish between a small number of fixed levels, rather than measure a continuously varying signal precisely. Second, digital signals travel long distances more reliably. Although a digital signal picks up background noise in transit, the receiver only needs to decide if the signal is closer to 0 or closer to 1. This allows each relay station to regenerate a clean, exact copy of the original signal. Analogue signals cannot be regenerated this way, meaning noise accumulates continuously over distance.

KEY IDEA — Digital vs analogue

An analogue signal varies continuously over a range of values; a digital signal only takes a small number of fixed values (usually two: 0 and 1). Digital signals carry data faster and travel further without degrading, because each relay point can regenerate an exact copy rather than just passing along an increasingly noisy original.

WORKED EXAMPLE 2 — Why voice-chat remains clear over multiple relay stations

Problem: A voice signal crosses several relay stations between two computers. Explain why the signal does not become progressively noisier at each station.

Solution:

Step 1: Identify the signal type. The system transmits the voice as a digital signal consisting of 0s and 1s.

Step 2: Explain the action of the relay stations. Each station reads the incoming signal, determines whether each pulse represents a 0 or a 1, and regenerates a clean new copy of the original sequence. It does not simply amplify the noisy signal.

Step 3: Draw a conclusion. Because each relay station regenerates a clean signal, background noise does not accumulate station by station.

Explanation: When making a physical photocopy of an image, the copier introduces slight imperfections. Copying a photocopy continuously accumulates this noise. In contrast, a digital relay does not copy the noise; it decodes the binary value (0 or 1) and retransmits a pure, clean signal.

QUICK CHECK — DIGITAL OR ANALOGUE?

1. A vinyl record groove varies continuously in depth to represent sound. Is this a digital or an analogue signal?

2. State one reason digital signals can carry data at a higher rate than analogue signals.

Flip to check — Q1 — analogue. Q2 — a receiver only has to distinguish between a small number of fixed levels, rather than measure a continuously varying value precisely.

EXERCISE 3 — SIGNAL CHECK

3. State whether a signal that only ever takes the value 0 or 1 is digital or analogue. [1 mark]

4. A teammate speaks into a microphone during a game. State whether the signal leaving the microphone is digital or analogue, and whether the signal can later be converted to the other type before it reaches you. [2 marks]

5. Explain one benefit of sending a signal digitally rather than analogue over a long distance. [2 marks]

4 Sound in Detail

Amplitude, frequency, and pressure variations in sound waves

A healthy human ear detects sounds with frequencies between 20 Hz and 20,000 Hz (20 kHz). This is the audible range of human hearing. Sound waves with a frequency above 20,000 Hz are called **ultrasound**. These waves are inaudible to humans, regardless of how loud they are. A dog whistle produces sound at approximately 25,000 Hz, which is within a dog's hearing range but silently above ours.

When a speaker diaphragm vibrates, it creates alternating pressure regions in the surrounding air. A **compression** is a region where air particles are pushed closer together, resulting in higher pressure and density. A **rarefaction** is a region where particles spread further apart, causing lower pressure and density. This repeating pattern of compressions and rarefactions travelling outward through the medium is what constitutes a sound wave.

Two properties of a sound wave determine how we hear it. **Amplitude** — the maximum distance particles vibrate from their resting position — determines loudness. A larger amplitude produces a louder sound. **Frequency** — the number of complete vibrations per second — determines pitch. A higher frequency produces a higher-pitched sound. Video games use these properties directly: as an opponent approaches, their footsteps grow louder because the amplitude increases, while the pitch remains constant. Conversely, an urgent warning ping uses a higher frequency to produce a high-pitched alert that stands out.

The speed of sound depends on the density and bonding of the medium it travels through. Sound travels fastest in solids, slower in liquids, and slowest in gases. In air, sound travels at approximately 340 m/s; in water, it travels at about 1,500 m/s; in steel, it travels at about 5,000 m/s. In a solid, tightly packed particles pass vibrations to their neighbours almost instantly. In a gas, particles are far apart and must travel to collide with one another, which slows the wave down.

An **echo** is simply a sound wave reflecting off a hard surface and returning to its source.

KEY IDEA — Compression and rarefaction

A compression is a region in a sound wave where the particles of the medium are pushed closer together than normal; a rarefaction is a region where they're spread further apart. A sound wave is a repeating pattern of compressions and rarefactions travelling through a medium.

WORKED EXAMPLE 3 — How a speaker diaphragm produces sound

Problem: Explain, in terms of compressions and rarefactions, how a headset speaker produces the sound you hear.

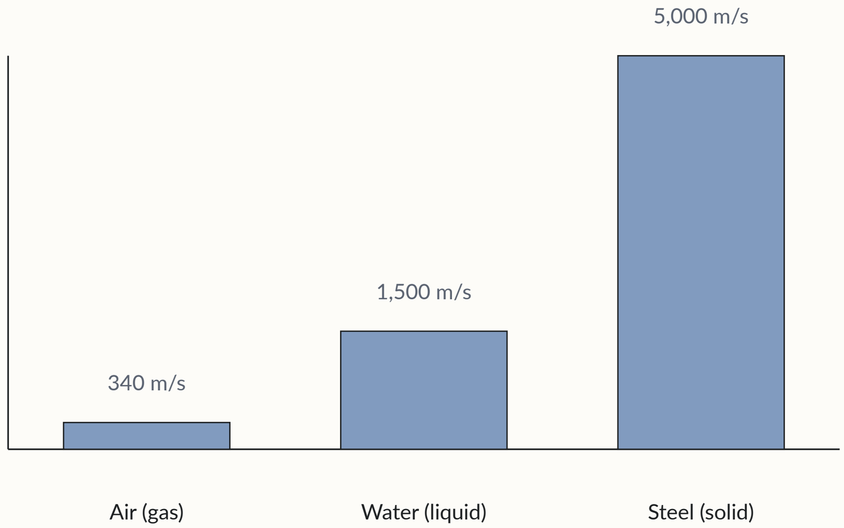
Solution:
Step 1: The speaker diaphragm vibrates back and forth.
Step 2: As the diaphragm moves outward, it pushes nearby air particles closer together, creating a compression.
Step 3: As the diaphragm pulls back inward, it leaves a region where the particles spread further apart, creating a rarefaction.
Step 4: This repeating pattern of compressions and rarefactions travels outward through the air to your ear.

Explanation: This motion shows why sound is longitudinal: the compressions and rarefactions form along the same line that the diaphragm vibrates, rather than at right angles to it.

Reference point	Frequency
Lower limit of human hearing	20 Hz
Upper limit of human hearing	20,000 Hz
Dog whistle (ultrasound)	≈ 25,000 Hz

The audible range for a healthy human ear runs from 20 Hz to 20,000 Hz; anything above that is ultrasound.

▸ **Watch: "GCSE Physics - Sound Waves and Hearing"** (Cognito)
https://www.youtube.com/watch?v=s9wZkP64rAc
Scan the code with your phone camera, or type the link.



Typical speed of sound in m/s — faster in a liquid than a gas, and faster still in a solid.

Sound	Amplitude	Frequency (Hz)	Loudness	Pitch
Enemy footsteps — far away	Small	200	Quiet	Low
Enemy footsteps — close by	Large	200	Loud	Low — unchanged
Routine alert ping	Medium	400	Medium	Low
Urgent alert ping	Medium	1200	Medium — unchanged	High

Amplitude controls loudness; frequency controls pitch — each can change independently of the other.

QUICK CHECK — READING THE REPRESENTATIONS

1. Using the reference points above: is a 25,000 Hz sound audible to a human with normal hearing?

2. Using the table of sound properties above: between the two footstep rows, which property changed, and which property stayed the same?

3. Using the bar chart above: is sound faster in water or in steel?

Flip to check — Q1 — no, it's ultrasound (above 20,000 Hz). Q2 — amplitude changed (small → large); frequency stayed the same (200 Hz), so only loudness changed, not pitch. Q3 — steel (5,000 m/s vs 1,500 m/s in water) — sound travels fastest in a solid.

EXERCISE 4 — PROPERTIES OF SOUND

4. A dog whistle produces sound at approximately 25,000 Hz. State, with a reason, whether a person with normal human hearing can hear it. [2 marks]

5. State the approximate speed of sound in air. [1 mark]

6. Which row correctly completes the table? A sound gets quieter but stays the same pitch. [1 mark]
   - ☐ **A** Amplitude decreases, frequency decreases
   - ☐ **B** Amplitude decreases, frequency stays the same
   - ☐ **C** Amplitude stays the same, frequency decreases
   - ☐ **D** Amplitude increases, frequency stays the same

7. State a definition of an echo. [1 mark]

8. Define ultrasound. [1 mark]

9. Complete the sentences: "A compression is a region of ____________________, and a rarefaction is a region of ____________________." [2 marks]

10. State how the speed of sound in water compares with the speed of sound in air. [1 mark]

✂️ *Tear this page out — keep it beside you for Sections 5–11.*

✂ **TOOLKIT — KEY TERMS**

- **Wave** — a transfer of energy from one place to another, without a net transfer of matter.
- **Longitudinal wave** — vibrations are parallel to (along) the direction of travel. Example: sound.
- **Transverse wave** — vibrations are at right angles to the direction of travel. Example: light and all other EM waves.
- **Medium** — the material a wave travels through. Sound needs one; EM waves don't.
- **Amplitude** — how far particles move from their resting position; controls loudness.
- **Frequency** — vibrations per second (Hz); controls pitch.
- **Compression** — a region where particles are pushed closer together.
- **Rarefaction** — a region where particles are spread further apart.
- **Echo** — the reflection of a sound wave off a hard surface.
- **Ultrasound** — sound with frequency above 20,000 Hz.
- **EM spectrum order (low to high frequency)** — radio, microwave, infrared, visible, ultraviolet, X-ray, gamma.
- **Speed of light/EM waves in vacuum** — 3.0×10^8 m/s.
- **Speed of sound in air** — approximately 340 m/s.
- **Digital signal** — takes only a small number of fixed values (usually 0 or 1).
- **Analogue signal** — varies continuously over a range.

End of Act 1 — the two wave types are set. Good place to stop.

your progress so far

5 The Ping Calculation

Calculating the travel time of electromagnetic waves in a medium

Electromagnetic waves travel at 3.0×10^8 m/s in a vacuum and at approximately that same speed in air. However, light slows down when it enters a transparent material like glass. As light passes through the material, it interacts with the constituent atoms; denser and more interactive materials slow the wave down more. This slowing factor is the **refractive index** (n). The speed of light in the material (v) is calculated using the formula $v = \frac{c}{n}$, where c is the speed of light in a vacuum.

Once you know the speed, you can calculate the travel time using the formula: $\text{time} = \frac{\text{distance}}{\text{speed}}$. This same relationship is used to solve echo and sonar problems.

The route of the West Africa Cable System — the actual undersea fibre this section's calculation is about.

KEY IDEA — Speed of light in a material

The speed of an EM wave in a material is $v = \frac{c}{n}$, where $c = 3.0 \times 10^8$ m/s (the speed in vacuum/air) and n is the material's refractive index. Once you know the speed, $\frac{\text{distance}}{\text{speed}} = \text{time}$. Unit conversion can go in either direction — convert the distance to metres to match a speed in m/s, or convert the speed to km/s to match a distance in km — both routes give the same answer, so use whichever leaves you with the tidier numbers.

WORKED EXAMPLE 4 — Signal travel time through glass fibre

Problem: A signal travels as light through an undersea fibre-optic cable running 14,530 km. The glass fibre has a refractive index of 1.5. Calculate the round-trip travel time.

Solution:

Step 1: Calculate the speed of light in the glass fibre using $v = \frac{c}{n}$:
$v = \frac{3.0\times10^8}{1.5} = 2.0 \times 10^8$ m/s $= 200,000$ km/s.

Step 2: Calculate the one-way travel time. Using $t = \frac{d}{v}$, divide the distance by the speed:
$t = 14, \frac{530}{200}, 000 = 0.07265$ s, or approximately 72.7 ms.

Step 3: Double this value to find the round-trip time:
$72.7 \times 2 \approx 145$ ms. This represents the physical latency, or ping, reported in a game.

WORKED EXAMPLE 4 (continued) — Alternative calculation method

Alternative method: Instead of converting the speed to km/s, convert the distance to metres and keep the speed in m/s:
$14, 530$ km $= 1.453 \times 10^7$ m.
$t = \frac{d}{v} = \frac{1.453\times10^7}{2.0\times10^8} = 0.07265$ s. This yields the identical one-way time.

Explanation: This calculation represents the absolute physical minimum travel time. A real measured network delay is slightly higher because network switches and routers along the path take time to process the data.

Step	Value
Distance (one-way)	14,530 km
Speed of light in fibre	200,000 km/s
One-way time	72.7 ms
Round-trip time	145 ms

The physics-floor calculation for a South Africa–to–Amsterdam signal, step by step.

QUICK CHECK — SAME METHOD, DIFFERENT MATERIAL

1. A different signal path uses fibre with refractive index 1.44 instead of 1.5. Calculate the new speed of light in that fibre.

Flip to check — $v = \frac{c}{n} = \frac{3.0\times10^8}{1.44} \approx 2.08 \times 10^8$ m/s.

EXERCISE 5 — CALCULATE THE FLOOR

2 A ray of light travels from an infrared remote control through air to a sensor 6.0 m away. Calculate the time taken. [2 marks]

3 A radio signal is sent from Earth to a satellite orbiting Mars, a distance of 2.25×10^8 km. Calculate the time taken for the signal to arrive, giving your answer in seconds. [3 marks]

4 Glass has a refractive index of 1.5. Calculate the speed of infrared radiation travelling through this glass. [2 marks]

6 Why Light Beats Radio

The physical properties that dictate communication system design

To understand communication systems, you must know why engineers select specific regions of the spectrum for each task. Mobile phones and Wi-Fi networks use microwaves because these waves can penetrate some walls, and because microwave receivers only require short aerials. Bluetooth devices use radio waves because they can also pass through walls and obstacles, though the signal weakens over distance. Optical fibres use visible light or short-wavelength infrared because glass is highly transparent to these wavelengths, allowing signals to carry data at an extremely high rate over long distances.

The undersea WACS cable is a direct application of this physics. Keystrokes travel across the ocean floor as pulses of light inside glass fibres because the glass is transparent to these specific wavelengths, allowing rapid and efficient data transmission.

KEY IDEA — Reasons, not labels

Naming the correct region of the spectrum earns no marks on its own at Extended level — the **because** clause is what's assessed. “Optical fibre” isn't a complete answer; “optical fibre, because glass is transparent to visible light and can carry data at a high rate” is.

WORKED EXAMPLE 5 — Explaining communication advantages

Problem: State one advantage of using optical fibres, rather than copper wires, for transmitting high-speed broadband.

Solution:

Step 1: Identify the physical property of the material. Glass is transparent to visible light and short-wavelength infrared.

Step 2: Connect this property to the transmission advantage. High-frequency light waves can carry a very high rate of data.

Step 3: Formulate your final answer. "Optical fibres carry data at a much higher rate than copper wires because visible light and infrared waves can be modulated (switched on and off) far more rapidly than electrical signals in a wire."

Explanation: Simply stating that optical fibres are faster repeats the question without explaining the physics. Full marks require explaining the underlying physical mechanism.

EXERCISE 6 — MARK THIS WORK

1. A student was asked: "State two advantages of using optical fibres, rather than copper wires, for transmitting high-speed broadband." Here is their answer, below. Exactly one issue makes it uncreditable as written, even though it isn't factually wrong in spirit — identify the issue, and rewrite the answer so it would score both marks. [2 marks]

> A STUDENT'S ANSWER
>
> "Optical fibres are used because they are the fastest cable. They also don't have as many problems as normal cables."

2. State one advantage of using microwaves, rather than radio waves, to transmit a signal to a mobile phone. [1 mark]

3. A wireless controller connects to a games console using Bluetooth. State which region of the EM spectrum Bluetooth uses, and one reason for choosing it. [2 marks]

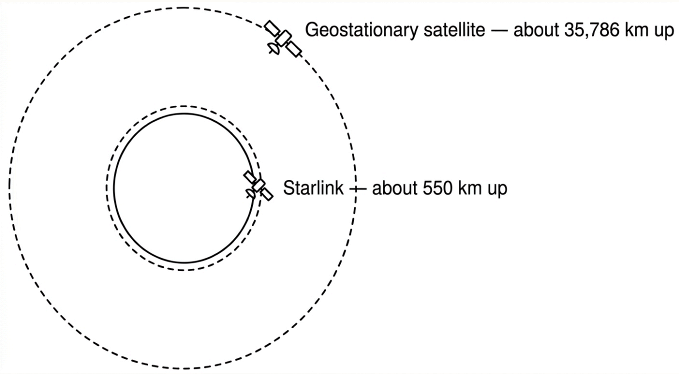
7 Satellites — Ground Station in the Sky

How satellite orbital altitude determines signal delay

Satellite communication systems rely almost entirely on microwaves. Some satellite networks use low-orbit satellites, while others use geostationary satellites that remain fixed above a single point on Earth's surface. The key trade-off between these two systems depends entirely on distance.

A geostationary satellite orbits at an altitude of 35,786 km. This height allows a single satellite to see both South Africa and Europe simultaneously. However, this extreme distance sets a high minimum travel time. The signal takes roughly 477 ms to complete a round trip, creating a delay of nearly half a second before any network hardware processes the data. This high latency makes geostationary satellite connections unsuitable for real-time applications like gaming.

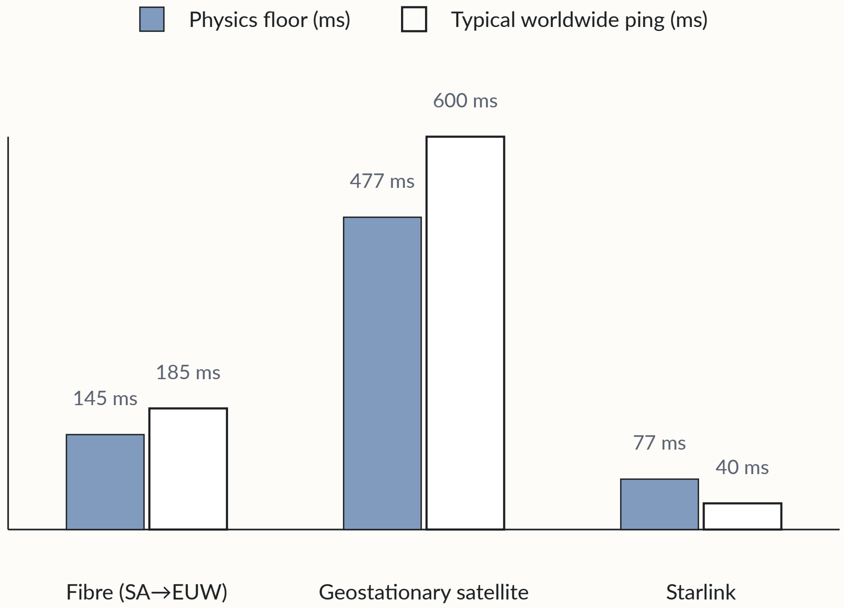
Low-orbit satellites, such as Starlink, orbit at an altitude of approximately 550 km. While they are 65 times closer to Earth, a single satellite cannot bridge the gap between South Africa and Europe. The signal must instead relay satellite-to-satellite along the Starlink mesh — and because that relay happens on a shell 550 km above the ground, the path is longer than the 9,650 km great-circle distance you'd measure between the two cities on a map: about 10,483 km. This extra distance brings the minimum round-trip time for a low-orbit connection to about 77 ms. Although this is far lower than a geostationary delay, it is not 65 times smaller, because the signal must still traverse the physical distance between the two continents.



Starlink's low orbit compared with a geostationary orbit, drawn to scale — the altitude difference behind this section's whole calculation.

KEY IDEA — Orbit distance sets the latency floor

A satellite signal makes two round trips (request and reply), each covering the distance to the satellite and back, plus — if the satellite can't see both ends of the link — the distance the signal has to relay across in between. Round-trip time $\approx 4 \times \left(\frac{\text{altitude}}{\text{speed of light}}\right)$, plus twice the relay distance ÷ speed of light if one satellite can't reach both ends. A closer orbit only gives a smaller unavoidable delay once that relay distance is accounted for.



*Round-trip time in milliseconds. The fibre and geostationary bars compare a physics floor against a real-world measurement on the **same** route. Starlink's "typical" bar is a generic, shorter-hop figure, not measured on this route — it sits below Starlink's own corrected floor because it isn't the same journey: a real South Africa-to-Amsterdam Starlink connection would have to clear 77 ms, not undercut it.*

Calculating the geostationary travel time: one-way travel time $= 35,\frac{786}{300},000 = 0.1193$ s, or 119.3 ms. The complete path has four legs (up and down for both query and response), giving $4 \times 119.3 \approx 477$ ms — a single geostationary satellite is high enough to see both South Africa and Europe, so no extra relay distance is needed. For Starlink: one-way local hop $= \frac{550}{300},000 = 1.83$ ms. However, because a single low-orbit satellite cannot span the gap, the signal must relay satellite-to-satellite along the mesh instead. The ground-level great-circle distance (9,650 km) subtends a central angle $\theta = \frac{9650}{6371} \approx 1.515$ rad (Earth's radius = 6,371 km). Starlink's relay satellites sit on a shell of radius $6371 + 550 = 6921$ km, so covering that same angle at that radius gives a relay path of $6921 \times 1.515 \approx 10,483$ km — longer than the ground distance because the relay happens on a bigger circle. (A single straight-line laser link can't shortcut this: the chord between the two satellites would dip to within 5,029 km of Earth's centre — inside the planet — so the signal must hop along the curve.) The total path distance is $550 + 10,483 + 550 = 11,583$ km. At the speed of light, this takes 0.0386 s, or 38.6 ms. The round-trip time is $2 \times 38.6 \approx 77.2$ ms ≈ 77 ms. Both values represent the physical limit of the medium; real-world routing hardware adds additional processing delay.

QUICK CHECK — WHICH ORBIT FOR GAMING?

1. State which type of satellite orbit — low or geostationary — would be more suitable for a real-time application like online gaming, and give one reason.

Flip to check — Low orbit — because the shorter distance to the satellite means a shorter physics-floor round-trip time.

EXERCISE 7 — ORBIT COMPARISON

2 A satellite phone user in a remote area can choose a low-orbit or a geostationary satellite service. State which region of the EM spectrum both services use, and explain why a low-orbit service gives a shorter delay than a geostationary one. [3 marks]

8 Mixed Practice

Identifying and solving different question types

Questions in this chapter generally fall into one of four distinct categories:

1. **Region ID:** Naming or ordering parts of the electromagnetic spectrum.
2. **Speed & medium facts:** Calculating wave speed and identifying medium requirements.
3. **Communication reasoning:** Explaining the physical mechanisms behind engineering choices.
4. **Sound properties:** Analyzing wave characteristics such as amplitude, frequency, compressions, and rarefactions.

The following exercise mixes these categories. Before you answer each question, identify which category it belongs to.

Category	What it means	Example objective
Region ID	Naming or ordering an EM region	3.3.1 / 3.3.3
Speed & medium facts	How fast a wave travels and what it needs	3.3.2 / 3.3.6 / 3.4.4 / 3.4.5 / 3.4.11
Communication reasoning	Why a system uses that region — the “because” clause	3.3.5 / 3.3.7 / 3.3.8–10
Sound properties	Amplitude, frequency, compression, rarefaction	3.4.2 / 3.4.7 / 3.4.10

The four kinds of question in this topic — decide which one you’re facing before you answer.

EXERCISE 8 — WHICH KIND IS IT?

1 Which kind is it? A signal travels from a phone to a Wi-Fi router. State the region of the EM spectrum used, and one reason for choosing it. [2 marks]

2 Which kind is it? State which travels faster in a vacuum: a gamma ray or a radio wave. [1 mark]

3 Which kind is it? A speaker cone vibrates, alternately pushing air particles together and letting them spread apart. Name the two regions this creates. [2 marks]

4 Which kind is it? Put these EM regions in order of increasing wavelength: visible light, gamma rays, radio waves. [2 marks]

5 Which kind is it? A toy inside a sealed glass jar has all the air pumped out. State what happens to a bell ringing inside it, and why. [2 marks]

6 Which kind is it? A microphone converts sound into a continuously varying voltage. State whether this signal is digital or analogue. [1 mark]

7 Which kind is it? Two sounds have the same frequency, but one is played twice as loud. State which property of the wave has changed. [1 mark]

Reflection: How sure do you feel about telling these four kinds apart before you've even read the whole question? If you're confident — move on to Section 9. If any of Q1, Q2, Q5, or Q6 above tripped you up, that's a "speed & medium facts vs. communication reasoning" mix-up — go back to Section 6's Key Idea ("Reasons, not labels") and try one more question from Exercise 6 before continuing.

End of Act 2 — the EUW case study is done. Good place to stop.

your progress so far

9 The Challenge

Measuring the speed of sound experimentally using echoes

The relationship used to calculate signal travel times ($\frac{\text{distance}}{\text{speed}} = \text{time}$) can be rearranged to find the speed of sound if you measure both distance and time. Standing a known distance from a large, flat wall allows you to calculate the speed of sound by timing how long a sound wave takes to return as an echo.

To conduct this experiment, stand a known distance from a large, flat wall. Clap your hands at a steady pace and adjust your rhythm until each new clap coincides exactly with the returning echo of the previous one. When aligned, the time between claps equals the time required for sound to travel to the wall and back. Because timing a single echo precisely is difficult, measure the total time for twenty consecutive claps and divide by twenty. This distributes any timing or reaction-time error across twenty separate intervals. Since the sound must travel to the wall and back, you must double the physical distance in your calculation: $v = \frac{2 \times d}{t}$.

KEY IDEA — Distance, speed, and the ÷2 for an echo

For any echo measurement: $v = \frac{2 \times d}{t}$ — speed equals twice the distance to the reflecting surface, divided by the time for the sound to go there and back. The factor of 2 exists because the sound covers the distance twice — once out, once back — a piece of reasoning that reappears exactly in Section 10′s sonar calculation.

WORKED EXAMPLE 6 — Speed of sound echo experiment

Problem: A student stands 50 m from a large flat wall and claps in time with the returning echo. Twenty claps take a total of 6.06 s. Calculate the measured speed of sound.

Solution:

Step 1: Calculate the time for a single round trip by dividing the total time by the number of intervals:

$\frac{6.06}{20} = 0.303$ s.

Step 2: Determine the total distance the sound wave travelled. Since the wave must travel to the wall and back, double the distance:

$2 \times 50 = 100$ m.

Step 3: Calculate the speed of sound using the formula $v = \frac{d}{t}$:

$\frac{100}{0.303} \approx 330$ m/s.

Explanation: A value of 330 m/s is close to the standard speed of 340 m/s. The small discrepancy represents normal experimental error, such as human reaction-time delay in operating the stopwatch or minor inaccuracies in measuring the physical distance.

Distance to wall (m)	Time for 20 intervals (s)	Time per interval (s)	Calculated speed (m/s)
50	6.06	0.303	330

Trial data from the worked clap-echo measurement above.

QUICK CHECK — SAME METHOD, NEW NUMBERS

1 A different trial is done at a distance of 80 m. Twenty claps take 9.6 s. Calculate the speed of sound from this trial.

Flip to check – time per interval $= \frac{9.6}{20} = 0.48$ s; *speed* $= \frac{2\times 80}{0.48} \approx 333$ m/s.

EXTENSION — GO AND CLAP

This is the one place in the kit where you measure the $\times\, 2$ *in* $v = \frac{2\times d}{t}$ *yourself, instead of only reading about it. If you get about 330 m/s at a real wall (rather than the neat 340 m/s in a table), that difference is your reaction-time error, not a rounding error.*

Find a large, flat, hard wall with open space in front of it — a school hall wall or the side of a building works. Pace out or measure a distance of 30–50 m. Clap steadily and adjust your rhythm until each clap lands exactly on the echo of the one before. Time twenty claps on your phone, divide by twenty, and calculate your own speed of sound using $v = \frac{2\times d}{t}$. Compare it to the accepted value of about 340 m/s — if it's off by more than about 10%, check whether your distance was paced accurately, and try again.

EXERCISE 9 — MEASURING SOUND

2 Describe an experiment, using a measurement of distance and time, that could be used to determine the speed of sound in air. [4 marks]

3 A tuning fork produces a note at 340 Hz. Sound travels at 340 m/s in the air in the room. Calculate the wavelength of the note. [2 marks]

10 Full Circle — Ultrasound and Sonar

Applying echo calculations to underwater depth measurement

Ultrasound waves have frequencies above 20,000 Hz. They are used for three main tasks: testing materials without damaging them, imaging soft tissue in medicine, and measuring depth or distance underwater using sonar. All three applications rely on the same principle: a transmitter sends a sound pulse, a receiver records the time taken for the echo to return, and the system uses the speed of sound to calculate the distance travelled.

This uses the same division-by-two logic as the clap-echo experiment. A sonar pulse travels to the seabed and back again, meaning the total distance covered is twice the actual depth. To find the depth, you must halve the calculated distance: $\text{depth} = \frac{v \times t}{2}$.

KEY IDEA — Sonar depth calculation

$\text{depth} = \frac{v \times t}{2}$, where v is the speed of sound in the medium and t is the time for the pulse to return. The ÷2 is there because $v \times t$ gives the total distance travelled (down and back); depth is only half of that.

WORKED EXAMPLE 7 — Calculating ocean depth

Problem: A ship's sonar sends an ultrasound pulse straight down. It returns after 0.08 s. The speed of sound in seawater is approximately 1,500 m/s. Calculate the depth of the water beneath the ship.

Solution:

Step 1: Calculate the total distance travelled by the pulse using $d = v \times t$:

$1500 \times 0.08 = 120$ m.

Step 2: Divide this value by two to find the depth of the water:

$\text{depth} = \frac{120}{2} = 60$ m.

Explanation: This calculation matches the structure of the clap-echo experiment. In both cases, the distance calculated from speed and time represents a round trip, which must be halved to find the distance to the reflecting boundary.

Quantity	Value
Time for pulse to return	0.08 s
Speed of sound in water	1500 m/s
Total distance travelled	120 m
Depth of water	60 m

The sonar calculation above, step by step — the same distance/speed/time logic as your own clap-echo experiment.

QUICK CHECK — ONE MORE SONAR CALC

1. A sonar pulse returns after 0.04 s, and the speed of sound in water is 1,500 m/s. Calculate the depth.

Flip to check — distance $= 1500 \times 0.04 = 60$ m; depth $= \frac{60}{2} = 30$ m.

EXERCISE 10 — SONAR AND ULTRASOUND

2. State one use of ultrasound in medicine. [1 mark]

3. A submarine sends an ultrasound pulse toward the seabed. It returns after 0.12 s. The speed of sound in water is 1,500 m/s. Calculate the depth of the seabed below the submarine. [3 marks]

11 All Done? And Where This Leads

Review your skills, then complete the examination questions

Review each of these statements before attempting the examination questions below.

- [ ] I can explain what makes something a wave, and say why sound needs a medium and light doesn't.
- [ ] I can order the EM spectrum's seven regions and give a real use and a real harmful effect for each.
- [ ] I can calculate the speed of an EM wave in a material and work out a real signal's travel time.
- [ ] I can explain — with a proper reason, not just a name — why a system uses microwaves, radio waves, or optical fibres.
- [ ] I can describe how amplitude and frequency control loudness and pitch, and explain compression and rarefaction.
- [ ] I can calculate a distance or depth from speed and time, including an echo or sonar measurement.

If you need to review any of these skills, return to the corresponding section's explanation and exercises before continuing.

EXERCISE 11 — WHERE THIS ALL LEADS

E1. State the region of the electromagnetic spectrum used for satellite television broadcasting. [1 mark]

E2 A doctor uses X-rays to examine a patient's broken arm. State one precaution that reduces the harmful effects of this exposure. [1 mark]

E3 Explain why glass optical fibres, rather than copper cables, are used for undersea internet cables. [2 marks]

E4 Calculate the time taken for a radio signal to travel 3.84×10^5 km from Earth to the Moon. [2 marks]

E5 Two identical alarm sirens are compared. Siren A is quieter and lower-pitched than Siren B. State one possible difference between the amplitude and frequency of the two sirens' sound waves. [2 marks]

E6 A ship's sonar sends a pulse toward the seabed; it returns after 0.06 s. The speed of sound in seawater is 1,500 m/s. Calculate the depth of the seabed. [3 marks]

Check your answers

Try first. Check after.

Section 1 — Wave Warm-up

- Q1: particles (of the medium, e.g. air molecules)
- Q2: No — light is transverse, and needs no medium.
- Q3: No — the Moon has no atmosphere to transmit sound waves.

Section 2 — Match the Region

- Q1: radio waves → infrared → ultraviolet → X-rays
- Q2: B
- Q3: 1–iii, 2–iv, 3–i, 4–ii
- Q4: Mutation or damage to cells

Section 3 — Signal Check

- Q1: Digital
- Q2: Analogue at the microphone; yes, can convert to digital
- Q3: Signal regeneration removes noise at each relay, giving longer range

Section 4 — Properties of Sound

- Q1: No — 25,000 Hz is above the audible upper limit of 20,000 Hz
- Q2: ≈ 340 m/s
- Q3: B
- Q4: Reflection of a sound wave off a hard surface
- Q5: Sound above 20,000 Hz
- Q6: Higher density/pressure; lower density/pressure
- Q7: Faster in water than in air

Section 5 — Calculate the Floor

- Q1: 2.0×10^{-8} s
- Q2: 750 s
- Q3: 2.0×10^{8} m/s

Section 6 — Mark This Work

- Q1: "Optical fibres carry data at a higher rate because glass is transparent to visible light and infrared, allowing high-frequency modulation; they also experience less signal loss over long distances because glass fibres have no electrical resistance."
- Q2: Only needs a short aerial
- Q3: Radio waves — passes through walls (weakened)

Section 7 — Orbit Comparison

- Q1: Microwaves; low orbit is closer, giving a shorter round-trip time

Section 8 — Which Kind Is It?

- Q1: kind: communication reasoning — microwaves, short aerial
- Q2: kind: speed & medium facts — neither, same speed

- Q3: **kind: sound properties — compressions and rarefactions**
- Q4: **kind: region ID — gamma rays → visible light → radio waves**
- Q5: **kind: speed & medium facts — silent, no medium**
- Q6: **kind: communication reasoning — analogue**
- Q7: **kind: sound properties — amplitude**

Section 9 — Measuring Sound

- Q1: **See Worked Example 6 (Section 9): measured distance from a wall, timed echo, $v = \frac{2 \times d}{t}$**
- Q2: **1.0 m**

Section 10 — Sonar and Ultrasound

- Q1: **Scanning soft tissue**
- Q2: **90 m**

Section 11 — Where This All Leads

- E1: **Microwaves**
- E2: **Limit exposure time / shielding**
- E3: **Transparency to light + high data rate**
- E4: **≈ 1.28 s**
- E5: **Smaller amplitude; lower frequency**
- E6: **45 m**

Mark scheme

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Skill legend: order = ordering the EM spectrum (3.3.1) · same speed = all EM waves travel at the same vacuum speed (3.3.2) · EM uses = uses of EM regions (3.3.3) · EM harm = harmful effects of EM exposure (3.3.4) · satellite = satellite communication, LEO vs geostationary (3.3.5) · fibre calc = speed of EM waves in a medium and travel-time calculations (3.3.6) · comm reason = the physical reason a system uses a given region (3.3.7) · signal type = digital vs analogue signals (3.3.8) · sound signal = sound as digital or analogue (3.3.9) · digital benefit = benefits of digital signalling (3.3.10) · sound source = production of sound by vibration (3.4.1) · longitudinal = longitudinal nature of sound (3.4.2) · audible range = 20 Hz–20,000 Hz human hearing range (3.4.3) · medium = sound needs a medium, light doesn't (3.4.4) · sound speed = speed of sound in air (3.4.5) · measure sound = experimental method for speed of sound (3.4.6) · loud & pitch = amplitude/frequency controlling loudness/pitch (3.4.7) · echo = echo as reflection of sound (3.4.8) · ultrasound def = definition of ultrasound (3.4.9) · compression = compression and rarefaction (3.4.10) · speed in media = sound speed in solids/liquids/gases (3.4.11) · sonar calc = ultrasound uses and sonar depth calculation (3.4.12)

Quick-check answers are printed inline on the student page (flip-to-check) and are not repeated below.

Section 1

Q	Answer	Skill	Marks	Notes
1	**particles (e.g. air molecules)**	sound source	1	Accept "molecules," "matter," or "air particles"; "sound" alone is not creditable.
2	**No — light is transverse and needs no medium**	longitudinal	2	Working: light's fields oscillate at right angles to travel direction. 1 mark "transverse" (not longitudinal); 1 mark "no medium needed."
3	**No sound heard**	medium	2	Working: no atmosphere on the Moon → no medium for sound. 1 mark "no"; 1 mark reason (no medium/air).

Section 2

Q	Answer	Skill	Marks	Notes
1	**radio → infrared → ultraviolet → X-rays**	order	2	1 mark if exactly one adjacent pair is swapped.
2	**B**	same speed	1	Common error: assuming higher frequency = faster in vacuum.
3	**1–iii, 2–iv, 3–i, 4–ii**	EM uses	4	1 mark per correct pair, independent of others.

4	**Mutation or damage to cells in the body**	EM harm	1	"Can cause cancer" alone (without mutation/cell damage) is not the full syllabus wording — accept as a consequence, but reward the mechanism.

Section 3

Q	Answer	Skill	Marks	Notes
1	**Digital**	signal type	1	Direct recall of the definition.
2	**Analogue at microphone; can convert to digital**	sound signal	2	1 mark analogue at source; 1 mark conversion possible.
3	**Signal regeneration; noise doesn't accumulate; longer range**	digital benefit	2	"Higher data rate" is also a fully creditable alternative benefit.

Section 4

Q	Answer	Skill	Marks	Notes
1	**No — above the 20,000 Hz upper limit**	audible range	2	1 mark "no"; 1 mark for quoting/using the 20–20,000 Hz range correctly.
2	**≈ 340 m/s**	sound speed	1	Accept any value in 330–350 m/s range.
3	**B**	loud & pitch	1	Common error: assuming loudness and pitch always change together.
4	**Reflection of a sound wave off a hard surface**	echo	1	Both "reflection" and "sound wave" required.
5	**Sound with frequency higher than 20,000 Hz**	ultrasound def	1	Numerical threshold required, not just "very high pitch."
6	**Higher density/pressure; lower density/pressure**	compression	2	1 mark per blank.
7	**Faster in water than in air**	speed in media	1	Direction of comparison is what's assessed; exact ratio not required.

Section 5

Q	Answer	Skill	Marks	Notes
1	2.0×10^{-8} **s**	fibre calc	2	Working: $t = \frac{6.0}{3.0 \times 10^8}$. 1 mark substitution; 1 mark final value + unit.

2	750 s	fibre calc	3	Working: convert km→m: 2.25×10^{11} m; $t = \frac{d}{3.0 \times 10^8}$. 1 mark unit conversion; 1 mark substitution; 1 mark final answer.
3	2.0×10^8 m/s	fibre calc	2	Working: $v = \frac{c}{n} = \frac{3.0 \times 10^8}{1.5}$. 1 mark formula/substitution; 1 mark final value.

Section 6

Q	Answer	Skill	Marks	Notes
1	**Planted error: no physical reason given (label without mechanism). Fix: "higher data rate because glass is transparent to visible/IR, which can switch fast; less signal loss than copper's electrical resistance."**	comm reason	2	This is the exact weakness the topic list flags for Extended 3.3.7 — award marks only if the rewrite supplies both an advantage AND its physical reason.
2	**Microwaves only need a short aerial**	comm reason	1	Accept "penetrates some walls" as alternative reason.
3	**Radio waves; passes through walls (weakened)**	comm reason	2	1 mark region; 1 mark reason.

Section 7

Q	Answer	Skill	Marks	Notes
1	**Microwaves; low orbit is closer → shorter round-trip time**	satellite	3	Working: shorter distance at same wave speed → shorter time. 1 mark region; 1 mark shorter distance; 1 mark link to shorter time via same speed.

Section 8

Q	Answer	Skill	Marks	Notes
1	**Microwaves; short aerial**	comm reason	2	1 mark for naming category (communication reasoning); remaining marks for the physics answer itself.
2	**Neither — same speed, 3.0×10^8 m/s**	same speed	1	Trap: higher frequency ≠ faster in vacuum.
3	**Compressions and rarefactions**	compression	2	Both terms required.
4	**Gamma rays → visible light → radio waves**	order	2	Watch for direction confusion (wavelength vs frequency).

5	**Silent — no medium in the jar**	medium	2	1 mark "silent"; 1 mark reason.
6	**Analogue**	signal type	1	Continuously varying voltage.
7	**Amplitude**	loud & pitch	1	Loudness changed, pitch didn't.

Section 9

Q	Answer	Skill	Marks	Notes
1	**Measured distance from a wall; timed echo (repeats for accuracy);** $v = \frac{2 \times d}{t}$	measure sound	4	1 mark measured distance/ hard surface; 1 mark valid timing method; 1 mark repeats/intervals for accuracy; 1 mark correct ÷2 doubling logic.
2	**1.0 m**	measure sound	2	Working: $\lambda = \frac{v}{f} = \frac{340}{340}$. 1 mark rearrangement; 1 mark final value + unit.

Section 10

Q	Answer	Skill	Marks	Notes
1	**Scanning soft tissue**	sonar calc	1	Any valid medical ultrasound use.
2	**90 m**	sonar calc	3	Working: $d = 1500 \times 0.12 = 180$; depth $= \frac{180}{2}$. 1 mark total distance; 1 mark halving; 1 mark final answer.

Section 11

Q	Answer	Skill	Marks	Notes
E1	**Microwaves**	EM uses	1	Direct recall.
E2	**Limit exposure/shielding**	EM harm	1	Any dose-reducing precaution creditable.
E3	**Transparency to light/IR + high data rate**	comm reason	2	1 mark transparency/low loss; 1 mark data rate.
E4	**≈ 1.28 s**	fibre calc	2	Working: $d = 3.84 \times 10^8$ m; $t = \frac{d}{3.0 \times 10^8}$. 1 mark conversion/ substitution; 1 mark final value.
E5	**Smaller amplitude; lower frequency**	loud & pitch	2	1 mark each correct comparison.
E6	**45 m**	sonar calc	3	Working: $d = 1500 \times 0.06 = 90$; depth $= \frac{90}{2}$. 1 mark total distance; 1 mark halving; 1 mark final answer.

QA note: All objective codes verified against Cambridge IGCSE Physics 0625 syllabus for 2026/2027/2028 (sections 3.3, pp. 25–26, and 3.4, pp. 26–27). Question formats and command words mirror the sampled Oct/Nov 2025 series (13 papers: qp_11/21/22/23/31/32/41/42/43/51/52/61/62), with all numerical values either drawn from that syllabus (c = 3.0×10^8 m/s; audible range 20 Hz–20,000 Hz; typical sound speeds) or independently sourced and cited in the personalisation map (West Africa Cable System distance — Wikipedia; geostationary and Starlink altitudes — satsig.net, orbitalradar.com). No content was reproduced from any textbook; all questions are original. Personalisation rationale: scenario (EUW gaming latency) applied only where the map identified a genuine, non-forced curriculum connection (3.3.5, 3.3.6, 3.3.7, and the closing echo/sonar pairing in Sections 9–10); objectives with no natural scenario connection (3.3.4, 3.4.3, 3.4.9, 3.4.11) were taught and tested on the curriculum content directly, per the map's own flag.