Index

C. Wave behaviour / C.2 Wave model

The big picture

? **Guiding question(s)**

- What are the similarities and differences between different types of waves?
- How can the wave model describe the transmission of energy as a result of local disturbances in a medium?
- What effect does a change in the frequency of oscillation or medium through which the wave is travelling have on the wavelength of a travelling wave?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

Waves are involved in every aspect of our day-to-day life. Communication, medicine, travel, cooking, art, culture and so on would not exist in the way we know them without humans understanding waves and harnessing their power. **Figure 1** shows some uses of waves. Which types of waves are being used? Can you think of any waves you have made use of today?

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Figure 1. Some Uses of Waves.

More information for figure 1

A slideshow viewer with six images, each accompanied by a descriptive text panel on the right side. The slideshow navigation bar is located at the bottom, displaying the current slide number (1/6 or 2/6) and providing buttons to move between slides. A blue progress indicator shows the position within the slideshow. In the bottom right corner, there is an expand button to view the images in full screen"

The first image shows an ultrasound scan, with a black-and-white image of a baby in the womb. The focus is on the fetus, captured through sound waves for medical imaging.

The second image displays a close-up of fiber optics, with illuminated glass fibers. The colored lights highlight the light waves traveling through the fiber optics.

The third image shows a SONAR system, with a wireframe of a boat and the beams of sound waves being emitted from it to detect objects underwater.

The fourth image features a satellite orbiting Earth, showcasing its structure in space. It is a representation of how electromagnetic waves are used for communication.

The fifth image shows a person using a tablet to connect to WiFi, with the focus on the connection symbol indicating the use of radio waves for wireless communication.

The sixth image captures a concert scene, with a crowd of people and bright stage lights. It visually represents how sound waves are amplified to reach large audiences.

Prior learning

Before you study this subtopic make sure that you understand the following:

- Velocity and displacement (subtopic A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/)).
- The concept of an oscillation (subtopic C.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43161/)).

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- Time period, frequency, amplitude, equilibrium position and displacement (subtopic C.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43161/)).

Practical skills

Once you have completed this subtopic, you can apply your knowledge of waves by going to Practical 5: Measuring the speed of sound (/study/app/math-aa-hl/sid-423-cid-762593/book/measuring-the-speed-of-sound-id-46509/).

C. Wave behaviour / C.2 Wave model

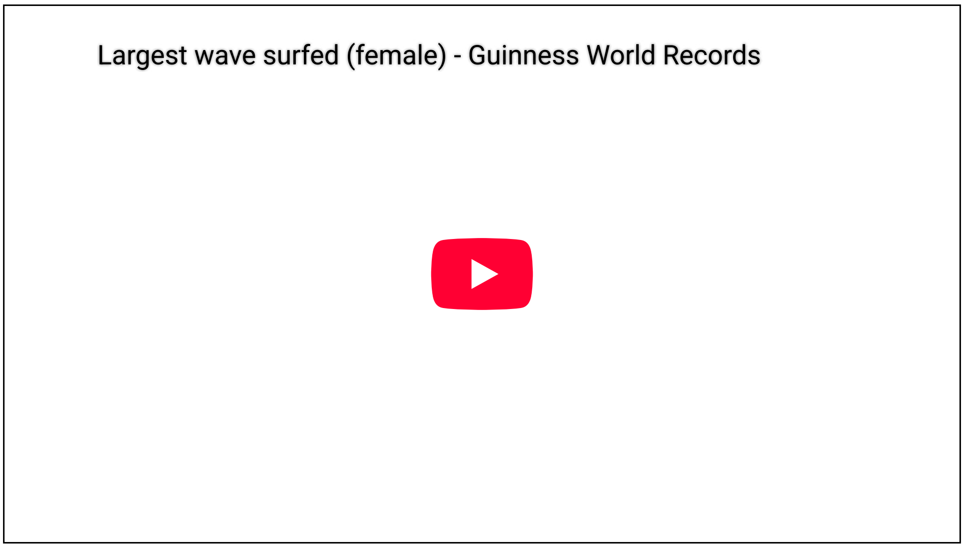
Transverse and longitudinal waves

C.2.1: Transverse and longitudinal travelling waves

Learning outcomes

By the end of this section you should be able to understand the difference between transverse waves and longitudinal waves.

Watch **Video 1** to see Maya Gabeira surf the largest recorded wave recorded by a female surfer.



Video 1. Surfing into the Guinness World Records.

More information for video 1

The video titled "Largest wave surfed (female) — Guinness World Records" captures Brazilian surfer Maya Gabeira's historic ride on a colossal 73.5-foot (22.4-meter) wave at Praia do Norte in Nazaré, Portugal, on February 11, 2020. This feat earned her the Guinness World Records title for the largest wave surfed (unlimited) — female.

In the footage, Gabeira is being towed into the massive wave by a jet ski, a common practice in big wave surfing to help surfers catch

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waves that are too large to paddle into. Once released, she expertly manoeuvres down the towering face of the wave, maintaining balance and control amidst the immense power of the ocean. The video showcases the scale of the wave, dwarfing Gabeira as she rides it, highlighting both the danger and the skill involved in such a feat.

What is a wave?

Water waves are mechanical waves. Sound waves, waves in ropes (**Figure 1**), and seismic waves are also mechanical waves. Mechanical waves need a medium to travel through.

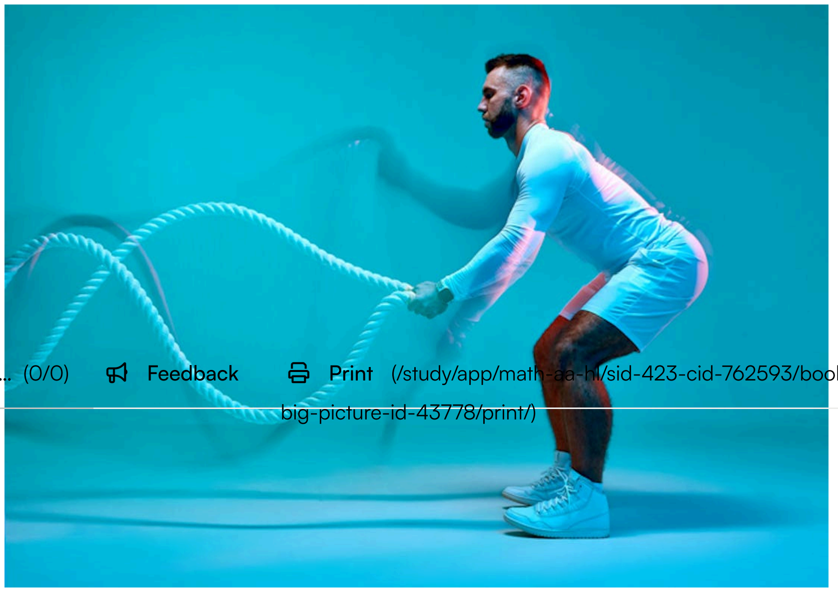

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Figure 1. A wave on a rope is a mechanical wave.

Credit: Georgii Boronin, Getty Images (https://www.gettyimages.com/detail/photo/athletic-man-training-with-rope-side-view-motion-royalty-free-image/1440578466)

A wave is an **oscillation** that transfers **energy** but not matter. All the different types of wave can be classified as longitudinal waves or transverse waves.

Transverse waves

Use the simulation in **Interactive 1** to investigate a wave on a string. Select ‘No End’ and ‘Slow Motion’. Then select ‘Oscillate’ to make a disturbance travel along the string. Move the slider for ‘Damping’ to ‘None’. Leave the other settings as they are. Press the ‘Restart’ button at the top of the screen anytime you want the wave to restart using your selected settings.

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Interactive 1. Wave on a string simulation.

More information for interactive 1

An interactive simulation titled, Wave on a string simulation, demonstrates wave motion on a string by allowing users to control various parameters and observe the resulting wave behavior. A mechanical oscillator at the left end of the string generates waves that propagate to the right. The simulation provides three wave generation modes, manual, oscillate, and pulse. Selecting "Oscillate" causes a continuous wave to form, traveling along the string. Users can modify the amplitude, frequency, damping, and tension of the wave to explore different wave behaviors.

In the "No End" setting, the wave continues propagating off the screen without reflection. The simulation features green dots on the string, which serve as reference points to highlight particle motion. These dots oscillate vertically while the wave propagates horizontally, demonstrating transverse wave motion. This means that the wave's energy moves in a direction perpendicular to the individual particle motion. The amplitude slider (ranges from 0 to 1.25 centimeter) adjusts the maximum displacement of the wave from its equilibrium position. Increasing the amplitude results in taller peaks and deeper troughs, while decreasing it makes the wave less pronounced. The frequency slider (ranges from 0 to 3 hertz) controls how many complete oscillations occur per second, affecting the wave's wavelength and speed. A higher frequency results in shorter wavelengths, while a lower frequency produces longer wavelengths.

The damping slider (ranges from none to lots) allows users to introduce energy loss in the system. Setting damping to "None" lets the wave propagate without reduction in amplitude. Increasing damping gradually reduces wave height as it moves along the string, eventually causing the wave to disappear. The tension slider (ranges from low to high) controls the tightness of the string. Higher tension results in faster wave propagation and longer wavelengths, while lower tension slows the wave and shortens the wavelength. The "Slow Motion" option slows down the wave propagation.

Through this interactive, users gain a visual and conceptual understanding of wave properties such as amplitude, frequency, wavelength, speed, and damping. It highlights the fundamental nature of transverse waves, where the oscillations occur perpendicular to the direction of energy transfer.

Look at the green dots on the string. How do they move? The green dots move up and down (oscillate), while the wave travels to the right, out of the window.

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You can see that the direction of the oscillations is at right angles (perpendicular) to the direction that the wave travels (**Figure 2**). This is how we define a transverse wave.

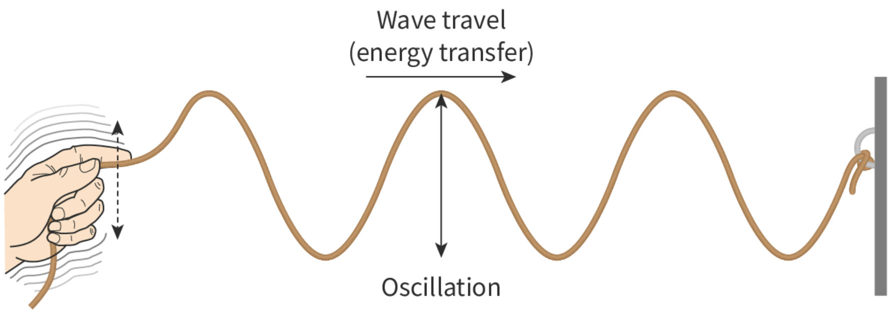

Figure 2. The directions of oscillation and energy transfer in a transverse wave.

More information for figure 2

The image illustrates a transverse wave, showing how energy travels through a medium perpendicular to the direction of oscillation. On the left, a hand grips a rope, moving it up and down to create waves. The rope waves travel horizontally from left to right, transferring energy in that direction. Above the rope, an arrow is labeled "Wave travel (energy transfer)," indicating the rightward energy transfer. Below the rope in the middle, a vertical double-headed arrow labeled "Oscillation" emphasizes that the oscillation is perpendicular to the direction of the wave travel. The wave continues until it reaches a fixed end on the right, represented by a vertical line.

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Concept

In a transverse wave, the direction of oscillation is perpendicular to the direction the wave travels (the direction of energy transfer).

Longitudinal waves

Look at the animation in **Interactive 2.** It shows the behaviour of particles in a longitudinal wave. What is the relationship between the direction of oscillations and the direction the wave travels?

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Interactive 2. The motion of particles in a longitudinal wave.

More information for interactive 2

The interactive titled, The Motion of Particles in a Longitudinal Wave demonstrates how particles oscillate in a longitudinal wave. The simulation consists of a grid of particles arranged in a structured pattern. When the wave is initiated, the particles oscillate back and forth parallel to the wave's direction of travel, forming compressions and rarefactions—regions where particles are pushed closer together or spread apart.

A red-highlighted particle serves as a reference point, allowing users to observe that individual particles do not move forward with the wave, but instead oscillate around their equilibrium positions. Users can adjust the Amplitude slider to modify the wave's strength, affecting how far the particles displace from their original positions. A higher amplitude results in more intense compressions and rarefactions, while a lower amplitude produces smaller oscillations.

The interactive helps users visualize the defining feature of longitudinal waves—that particle oscillations occur parallel to wave propagation, unlike transverse waves, where oscillations are perpendicular. This concept is fundamental to understanding sound waves, seismic P-waves, and compression waves in a slinky, reinforcing the principle that waves transfer energy without transporting matter.

The direction of the oscillations is parallel to the direction the wave travels. This is how we define a longitudinal wave.

Look at the animations in **Interactive 3.** Which shows a transverse wave and which shows a longitudinal wave? Click on 'Show or hide solution' to see the answer.

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Interactive 3. Transverse Wave or Longitudinal Wave?

More information for interactive 3

The animation illustrates two wave types using a stretched spring. In part A, the spring is pushed and pulled along its length by hand, forming compressions and rarefactions that move parallel to the wave's direction, representing a longitudinal wave.
In part B, the hand moves up and down perpendicular to the spring's length, creating peaks and troughs, representing a transverse wave.

Wave A is a longitudinal wave.

Wave B is a transverse wave.

Making connections

The particles in waves oscillate about a fixed point, and are accelerating towards that fixed point at all times. This is similar to a particle undergoing simple harmonic motion (subtopic C.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43161/)).

Drag and drop the words in **Interactive 4** to complete the sentences about transverse waves and longitudinal waves.

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Interactive 4. Direction of Waves.

Nature of Science

Aspect: Observations

Waves are categorised into two types: transverse and longitudinal. Why do you think scientists categorise their observations in this way? Does it help advance our scientific understanding, or is it just the result of us seeing patterns in the world around us?

Work through the activity in the next section to check your understanding of transverse waves and longitudinal waves.

6 section questions

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Question 1

SL HL Difficulty:

True or false?

A mechanical wave involves the transfer of matter and energy from one place to another.

False ✓

Accepted answers

False, F, false, f

Explanation

A mechanical wave only involves the transfer of energy. There is no movement of particles from one place to another.

Question 2

SL HL Difficulty:

In a 1 transverse ✓ wave, the oscillations are perpendicular to the direction of wave travel.

In a 2 longitudinal ✓ wave the oscillations are parallel to the direction of wave travel.

Accepted answers and explanation

#1 transverse

#2 longitudinal

General explanation

Transverse waves and longitudinal waves transfer energy by the oscillations of particles. When the oscillations are perpendicular to the direction of wave travel, it is a transverse wave. When the oscillations are parallel to the direction of wave travel, it is a longitudinal wave.

Question 3

SL HL Difficulty:

Which type of wave is described by the graph below?

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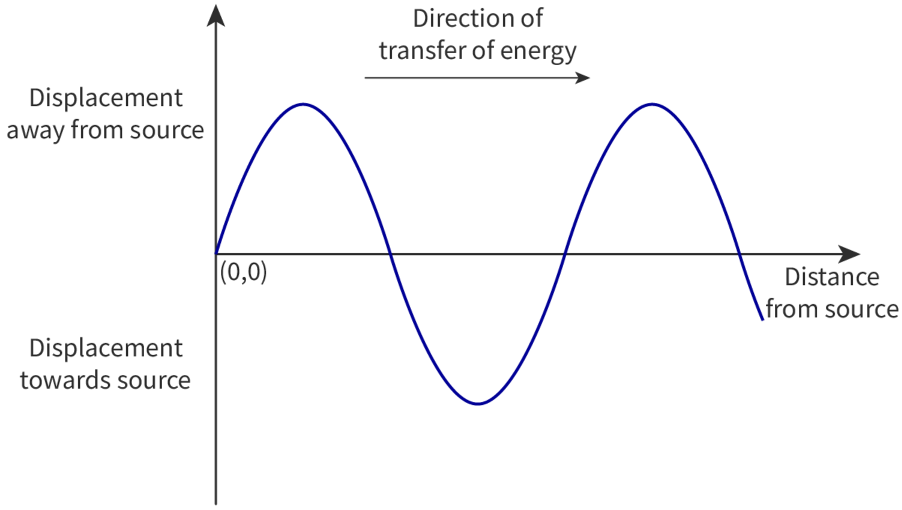

More information

1 Longitudinal ✓

2 Transverse

3 Could be either longitudinal or transverse

4 Cannot tell from this graph

Explanation

The displacement (shown by the *y*-axis) is either towards or away from the source, in other words parallel to the direction of energy transfer. So this must be a longitudinal wave.

Question 4

SL HL Difficulty:

A transverse wave is propagating through water. The distance between the centre of one crest and the adjacent trough is 0.14 cm. What is the wavelength of the wave?

1 0.28 cm ✓

2 0.14 cm

3 0.07 cm

4 0.56 cm

Explanation

The distance between one crest and the adjacent trough is half of a wavelength. One complete wavelength would then be 2 × 0.14 cm = 0.28 cm.

Question 5

SL HL Difficulty:

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Which of the following describes longitudinal but **not** transverse waves?

1 Can be considered in one dimension ✓

2 Transfers energy away from the source

3 Involves oscillations

4 Can be produced mechanically in a spring

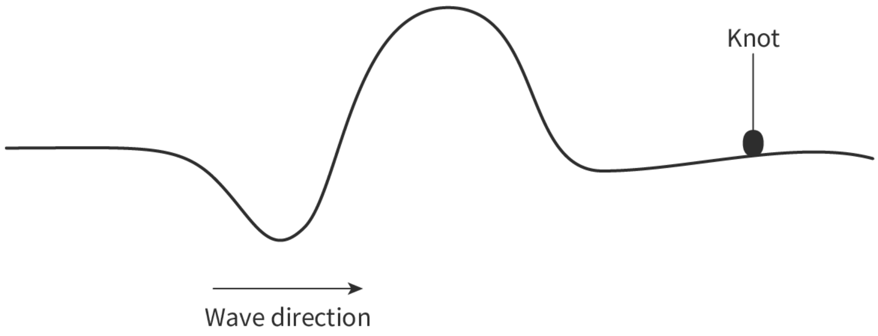
Explanation

Longitudinal waves oscillate parallel to the direction of energy transfer. In other words, the oscillations are in the same dimension as the direction of propagation of the wave, and so there is only one dimension to consider. Transverse waves must, by their definition, exist in two dimensions.

Question 6

SL HL Difficulty:

A wave on a string is moving to the right as shown in the diagram.



More information

How will the knot on the string move as the wave passes it?

1 Up, down, then up again ✓

2 Up, then down

3 Forwards then backwards

4 Forwards, backwards, then forwards again

Explanation

As the wave is transverse, particles move at right angles to the direction of wave travel. So the knot can only move up and down. The knot starts at the equilibrium position (subtopic (https://app.kognity.com/study/app/class/sid-423-cid-0/book/the-big-picture-id-43161)C.1 (https://app.kognity.com/study/app/class/sid-423-cid-0/book/the-big-picture-id-43161)). The knot first moves up (as the 'top' of the wave passes) then down (as the 'bottom' of the wave passes), then back up (to the equilibrium position).

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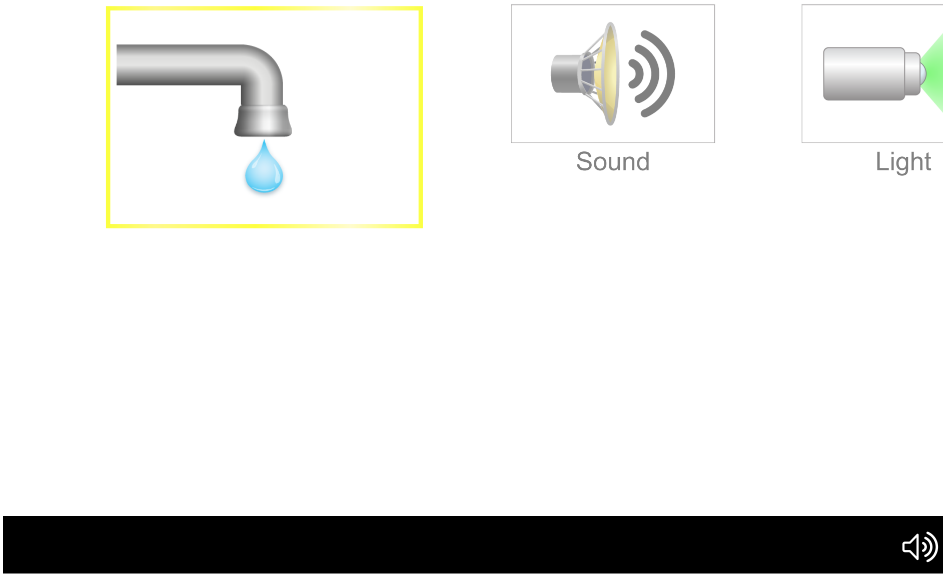
C. Wave behaviour / C.2 Wave model

Activity: Water waves and sound waves

C.2.1: Transverse and longitudinal travelling waves



Interactive 1. Water waves and sound waves simulation.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Pair activity

You are going to investigate water waves and sound waves using the simulation in **Interactive 1**.

Task 1:

1. Select ‘Water’, then select ‘Side View’. Click on the ‘Graph’ button. Move the ‘Frequency’ and ‘Amplitude’ sliders to their maximum values. Then click on the green button on the tap to make the water drip to produce a wave. What type of wave is this?

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2. Pause the simulation and use the tape measure to measure the wavelength. What is the most accurate way to do this? To measure one wavelength, or to measure several wavelengths and divide by the number of wavelengths? Record your value for the wavelength.
3. Use the stopwatch to determine the frequency of the waves. Start the stopwatch as you press the green button and record the time taken for 10 drips to fall. Calculate frequency using $f = \frac{10}{t}$.
4. Multiply the wavelength by frequency to calculate the speed of the wave (section (/study/app/math-aa-hl/sid-423-cid-762593/book/describing-waves-id-44906/)C.2.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/describing-waves-id-44906/)).
5. Reduce the amplitude of the waves using the ‘Amplitude’ slider. Repeat Steps 2 to 4. Have the wavelength and frequency values changed? What about the wave speed?

Task 2:

1. Select ‘Sound’, then select ‘Both’ (particles and waves). Click on the green button to start the sound wave. If you cannot hear any sound, check the sound settings on your device.
2. What do you notice about the direction of travel of the particles and the direction of travel of the wave? What type of wave is this?
3. Look at one red particle. How does its motion link to simple harmonic motion (subtopic (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43161/)C.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43161/))?
4. Select ‘Play Tone’ and listen to the sound. Then change the amplitude of the wave and listen to the sound again. How does the sound change? Do the particles move differently when you change the amplitude of the wave?

C. Wave behaviour / C.2 Wave model

Describing waves

C.2.2: Wave motion

Learning outcomes

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

- Describe the motion of a wave using the terms wavelength, frequency and time period.
- Determine the speed of a wave using the equations:

$$v = f\lambda \text{ and } v = \frac{\lambda}{T}$$

The wave that Maya Gabeira surfed that got her into the Guinness World Records was 20.72 m (section C.2.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/transverse-and-longitudinal-waves-id-44904/)). What does it mean when we say the wave is 20.72 m (**Figure 1**)? What property of the wave is being measured? What other terminology can we use to describe waves?

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Figure 1. Surfing a huge wave.

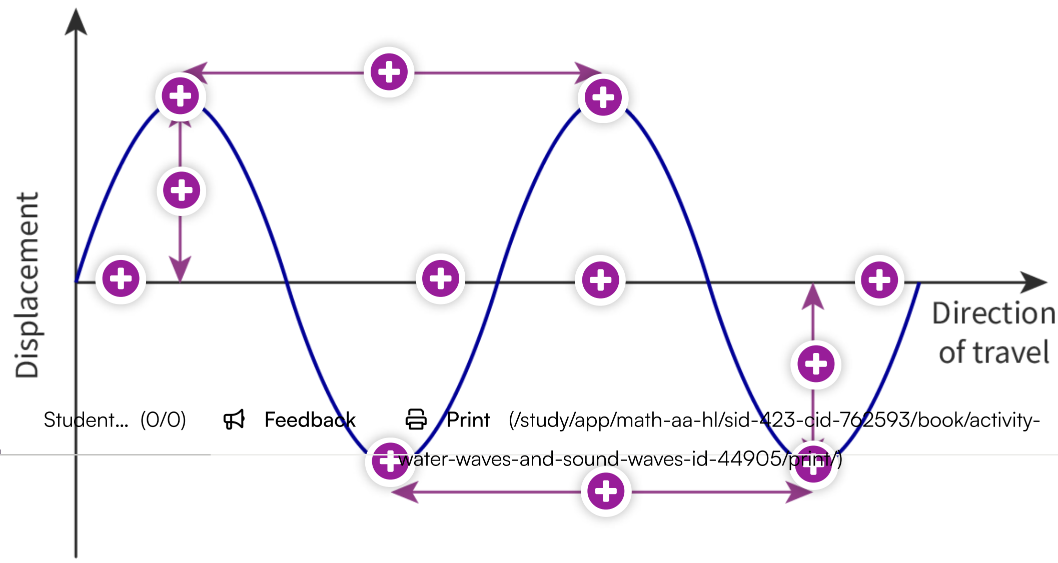
Credit: Warren Ishii / 500px, Getty Images

Amplitude and wavelength

The amplitude, x_0, of a wave is the distance to the crest or trough of a wave, measured from the **equilibrium position.**

The wavelength, λ, of a wave is the distance between two adjacent similar points on a wave.

Hover over the hotspots in **Interactive 1** to find out about amplitude and wavelength.



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Interactive 1. Amplitude and Wavelength.

More information for interactive 1

The interactive graph represents a transverse wave traveling in a specific direction. The vertical axis shows displacement, while the horizontal axis represents the direction of travel. The wave oscillates perpendicular to its direction of motion, forming crests and troughs. Arrows indicate movement at different points. Vertical arrows show displacement, and horizontal arrows represent wave travel.

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Points along the wave are marked, emphasizing how different parts of the medium move as the wave travels forward.There are multiple hotspots represented by plus signs that provide additional information when clicked.

Hotspots 1 and 12 (along horizontal arrows): Wavelength - the distance between two adjacent similar points on a wave.

Hotspots 2 and 3 (at wave crests): Crest - the top of a (transverse) wave.

Hotspots 4 and 9 (along vertical arrows): Amplitude - the distance from equilibrium position to the crest or trough of a wave.

Hotspots 10 and 11 (at wave troughs): Trough - the bottom of a (transverse) wave.

Hotspots 5, 6, 7, and 8 (along the equilibrium line): Equilibrium position - the position of the undisturbed particles.

Time period and frequency

The time period, T, is the time it takes for one complete wave to travel past a point (section C.1.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/simple-harmonic-motion-shm-id-44869/)). Imagine swimming in the sea, and feeling yourself rise up with the crest of a wave. If you start a stopwatch at that point, and stop it when the next crest passes underneath you, you will have measured the time period of a transverse wave.

A longitudinal wave does not have crests or troughs. Instead, there are regions where the particles are closer together, called compressions, and regions where the particles are more spread out, called rarefactions (Figure 2).

The frequency, f, is the number of waves that pass a point in one second (section C.1.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/simple-harmonic-motion-shm-id-44869/)).

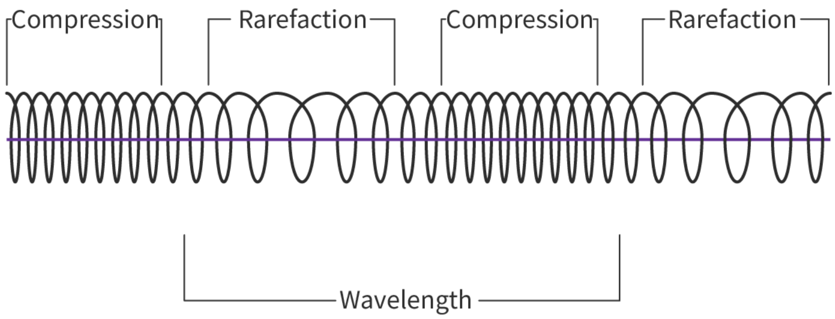

Figure 2. Longitudinal wave showing compressions, rarefactions and wavelength.

More information for figure 2

The image is a diagram illustrating a longitudinal wave. It shows a series of parallel, alternating compressed and spread-out sections, representative of compressions and rarefactions respectively. Compressions are marked where the wave particles are closest together, and rarefactions are where the particles are most spread out. The diagram includes labels for these compressions and rarefactions. Additionally, the wavelength is denoted as the distance between two successive compressions or rarefactions. This visually demonstrates how energy moves through a medium in a longitudinal wave, illustrated as a coiled spring moving horizontally with an oscillating motion.

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For a longitudinal wave, the time period is the time it takes for one complete wave to travel past a point. In this case, it is the time interval between adjacent compressions, or adjacent rarefactions. You can see the motion of particles in transverse waves and longitudinal waves in this link (https://www.acs.psu.edu/drussell/demos/waves/wavemotion.html).

Drag and drop the terms into the correct columns in the table in **Interactive 2** to show whether they can be used to describe transverse waves, longitudinal waves, or both.

Transverse	Longitudinal	Both

Wave speed	Trough	Frequency
Amplitude	Time period	Compression
Crest	Rarefaction	Wavelength

Check

Interactive 2. Understanding Transverse waves, Longitudinal waves, or Both.

Theory of Knowledge

It is important to have a common language in science when describing observations. Are scientific terms always based on logical root words? Who decides which terms are used? Can you think of any instances where scientific language has failed to keep up with changes in our scientific understanding?

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Displacement—distance graphs

We can use graphs to describe the motion of waves. Imagine walking along a row of hills. As you walk, you move higher or lower than you were before. You could describe your motion by drawing a graph of your vertical displacement (from your equilibrium position) against your horizontal displacement (horizontal distance from your starting point) (subtopic A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/)).

Figure 3 shows a displacement–distance graph for a particle in a transverse wave. You can see the crests and troughs of the transverse wave.

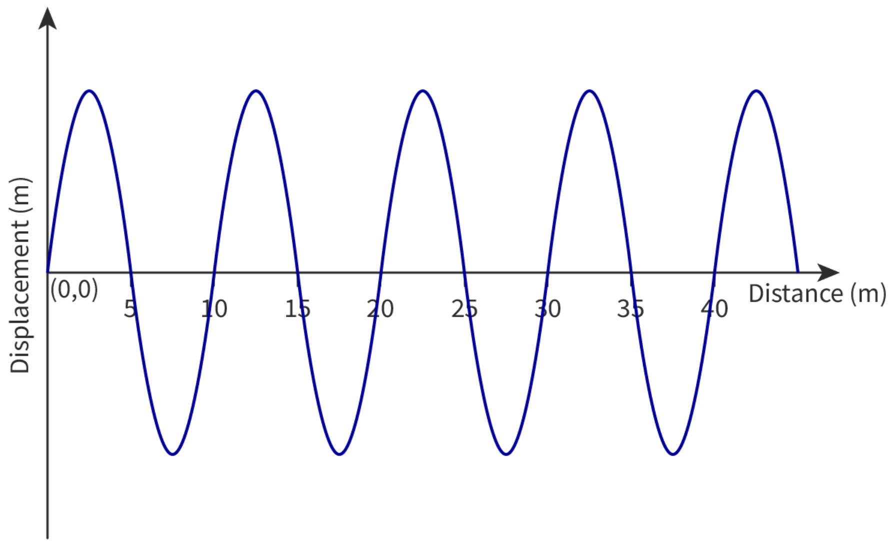

Figure 3. Displacement—distance graph for a particle in a transverse wave.

More information for figure 3

The graph depicts the displacement versus distance for a particle in a transverse wave. The X-axis is labeled 'Distance (m)' and ranges from 0 to 40 meters in increments of 5 meters. The Y-axis is labeled 'Displacement (m)' and has marks at regular intervals. The wave pattern consists of repeating crests and troughs.

The first crest occurs at 5 meters on the X-axis and the first trough at 10 meters. A complete wave cycle is measured starting from 0 displacement at 0 meters, reaching a peak at 5 meters (positive displacement), back to 0 at 10 meters, down to a trough at 15 meters (negative displacement), and returns to 0 at 20 meters. This pattern repeats such that each complete wave cycle spans 10 meters.

The graph helps in determining the wavelength, which is calculated as 10 meters, the distance between two successive points of the same displacement level (0 displacement). The crests and troughs represent the maximum and minimum displacements of the wave respectively, indicating the amplitude of the wave.

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We can use the graph to determine the wavelength of the wave. The distance between the point on the graph at 0 m displacement to the next point (one full wave) on the graph at 0 m displacement is 10 m, so the wavelength is 10 m.

A displacement–distance graph can also represent a longitudinal wave. However, it is impossible to tell from a displacement–distance graph which type of wave is being described, unless the y-axis is labelled with a direction. All we know from the graph above is the displacement at various points along the wave. We do not know whether that displacement is parallel to or perpendicular to the direction the wave is travelling.

Concept

Displacement—distance graphs can be used to describe transverse waves and longitudinal waves. Displacement—distance graphs look like transverse waves, but they might be describing the motion of longitudinal waves.

Imagine a transverse wave travelling to the right. The displacement–distance graph in **Figure 4** shows the initial position of the wave. Which direction will particle X move as the wave travels? Click on 'Show or hide solution' to see the answer.

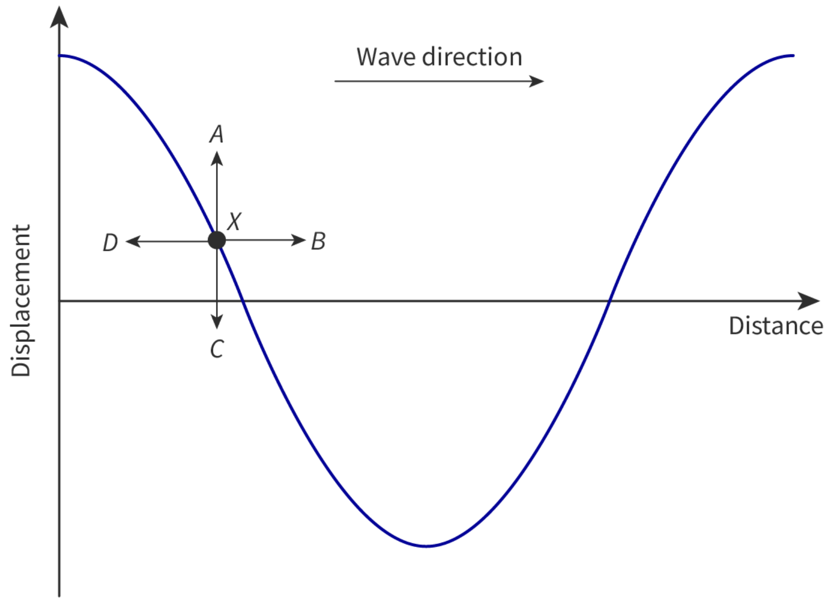


Figure 4. Which way will particle X move as the wave travels?

More information for figure 4

The image shows a graph of a transverse wave traveling to the right, represented by a sinusoidal curve. The X-axis is labeled 'Distance', and the Y-axis is labeled 'Displacement'. The wave direction is indicated by an arrow pointing right above the graph.

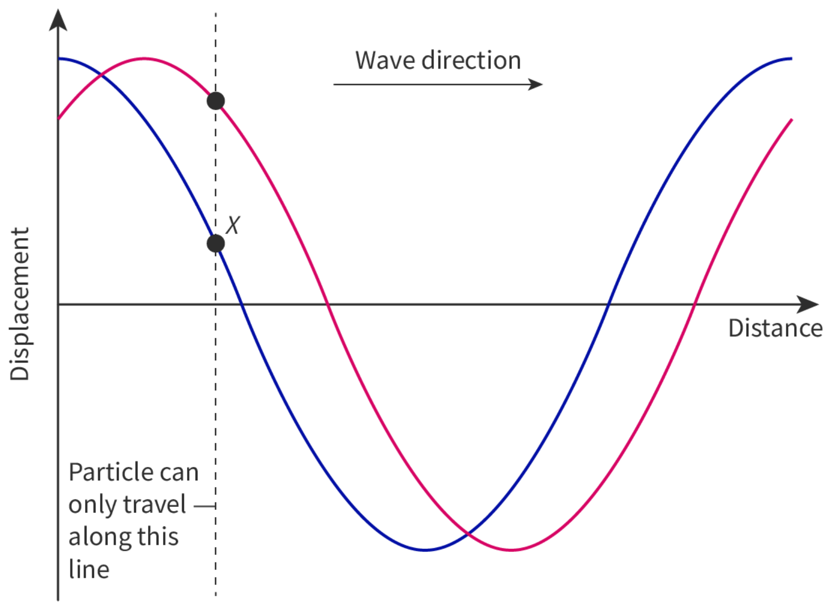
Student view

At a point on the wave, labeled 'X', four directional arrows are emanating labeled 'A', 'B', 'C', and 'D'. These likely represent potential directions in which particle 'X' might move. The particle is located at the center of the coordinate system where the wave intersects the vertical axis.

The wave shape above the axis starts with an upward curve, reaches a peak, and then curves downward crossing the horizontal axis to a trough before rising again. The point 'X' is situated on a rising portion of the curve.

[Generated by AI]

The graph below shows the wave some time later. The oscillation of particles in a transverse wave are at right angles to the direction of wave travel, so particle X can only move along the vertical red line. As the wave travels to the right, the particle is displaced upwards, so it moves in the direction of arrow A.



The equilibrium position for a particle is fixed – it is the place the particle returns to once the wave has passed through a medium. A particle can ‘move’ up and down the *y*-axis of a displacement–distance graph when a wave passes through the medium – its **position** and **displacement** can change. But the particle does not travel to the left or the right, so it has the same *x*-axis position – it stays the same distance away from the source of the waves.

Student view

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Study skills

When a transverse wave travels through a medium, the displacement of a particle from its equilibrium position can change but its distance from the source of the wave does not change. This is not true for an oscillating particle on a longitudinal wave, for which the distance from the source does change.

The displacement–distance graph in **Figure 5** shows the initial position of a wave (blue curve), then its position at a later time Δt (red curve).

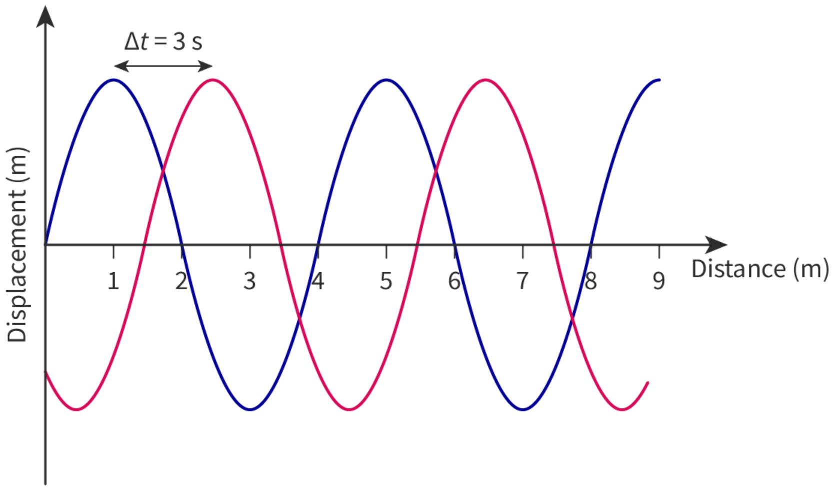

Figure 5. Displacement—distance graph showing position of wave after time Δt.

More information for figure 5

The image is a graph illustrating displacement versus distance for a wave. The X-axis represents "Distance (m)", labeled from 0 to 9 meters, showing distances in meter increments. The Y-axis represents "Displacement (m)" without specific numerical values but indicating a range for displacement.

Two sinusoidal curves are displayed on the graph: a blue curve and a red curve. The blue curve represents the initial position of the wave, while the red curve shows the wave's position after a time interval of Δt = 3 seconds. The two curves are shifted relative to one another, demonstrating the progression of the wave over time. The image depicts the temporal phase shift of the wave by showing a horizontal distance between similar points on the two curves.

Overall, the graph is used to illustrate how a wave travels a certain distance over a given period, which can be used to calculate the speed of the wave as mentioned in the surrounding context.

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We can use the graph to calculate the speed of the wave using the equation for speed (subtopic A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/)). The wave has travelled a distance of 1.5 m in 3 s:

$$\begin{aligned} v &= \frac{s}{t} \\ &= \frac{1.5}{3} \\ &= 0.5\ \mathrm{m\ s^{-1}} \end{aligned}$$

Worked example 1

Look at the wave in the displacement–distance graph in **Figure 6**. The time period of the wave is 12 s. Determine:

(a) the wave speed, and

(b) the average speed of a particle in the wave.

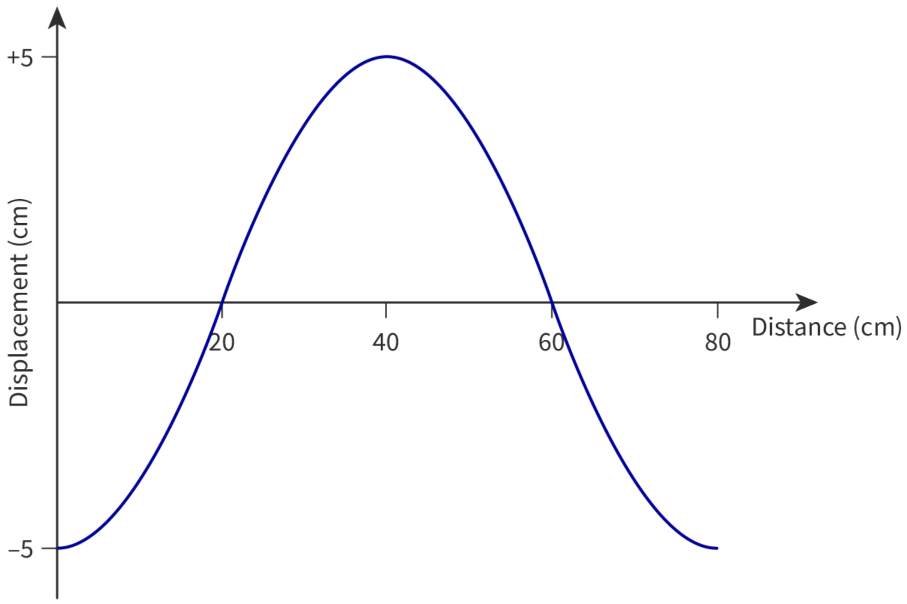

Figure 6. Determine the wave speed and the average speed of a particle in the wave.

More information for figure 6

The graph represents the displacement of a wave over distance in centimeters. The X-axis, labeled as "Distance (cm)", ranges from 0 to 80 cm. The Y-axis, labeled as "Displacement (cm)", ranges from -5 cm to +5 cm. The graph shows a single smooth sinusoidal curve representing the wave. It begins at 0 cm and follows an upward then downward pattern, peaking at approximately +5 cm displacement at around 40 cm distance, and reaching a minimum displacement of -5 cm around 80 cm distance. The pattern indicates one full cycle of a wave as it progresses along the distance axis, typical of a sine wave.

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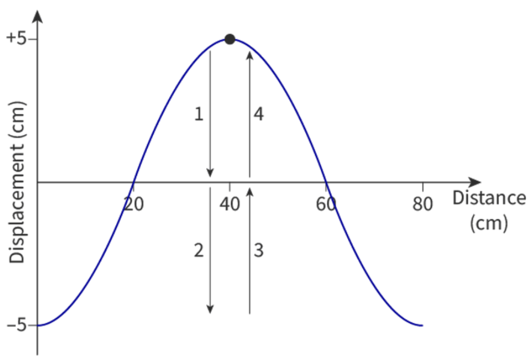
Student view

(a) To calculate the wave speed:

Solution steps	Calculations
Step 1: Use the graph in **Figure 6** to determine the wavelength of the wave.	$\lambda = 80\text{ cm}$ $= 0.80\text{ m}$
Step 2: Use the wave equation linking wave speed, wavelength and period (given in the data booklet) to calculate the wave speed.	$v = \dfrac{\lambda}{T}$ $= \dfrac{0.80}{12}$ $= 0.067\text{ m s}^{-1}(2\text{ s.f.})$

(b) To calculate the average speed of the particle in the wave:

Solution steps	Calculations
Step 1: Identify a strategy.	In one time period, T, the particle will complete one full oscillation. Imagine a particle on the crest of the wave and think about how it will move
Step 2: Identify the movement of the particle.	The particle will move: (1) down to the equilibrium position: 5 cm (2) down to the trough: 5 cm (3) up to the equilibrium position: 5 cm (4) up to the crest: 5 cm 

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Solution steps	Calculations
Step 3: Determine the speed of the particle and state the answer with appropriate units and the number of significant figures used in rounding.	The particle has travelled a distance of 20 cm and the period of the wave is 12 s. $s = 20\text{ cm} = 0.2\text{ m}$ $t = 12\text{ s}$ $v = \frac{s}{t} = \frac{0.20}{12} = 0.016666 = 0.017\text{ m s}^{-1}\ (2\text{ s.f.})$

Displacement—time graphs

Figure 7 shows a displacement–time graph for a particle.

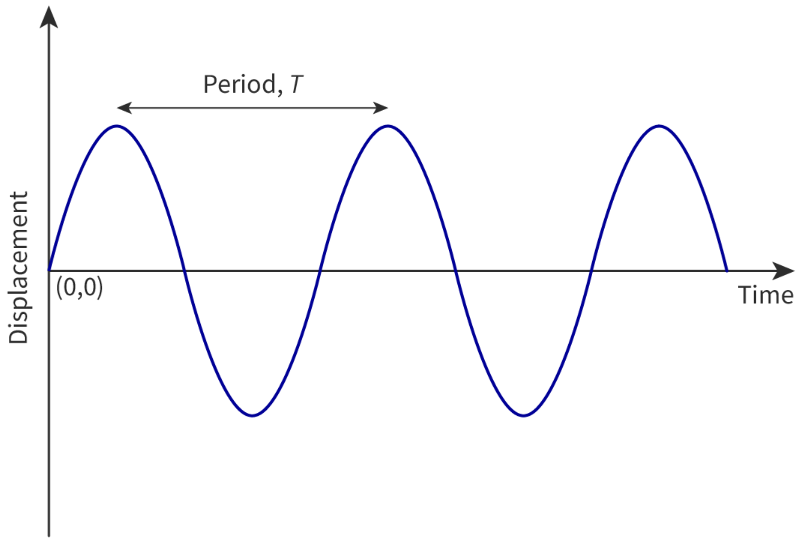

Figure 7. Displacement—time graph for a particle.

More information for figure 7

The image is a displacement-time graph for a particle. The X-axis represents time, while the Y-axis represents displacement. The graph shows a sinusoidal wave pattern beginning at the origin (0,0). Each cycle, starting with a crest, continues through a trough before repeating. The graph is marked with the time period (T), which is the distance between two consecutive crests. This period is illustrated with a horizontal arrow spanning one full cycle of the wave. This represents how long it takes for the particle to complete one full oscillation.

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We can use a displacement–time graph to find time period, T. The time period is the time taken for a particle on the wave to complete one full oscillation. On a displacement–time graph, this is the time interval between one crest and the next crest, or one trough and the next trough, etc.

Displacement–time graphs can also be used to display longitudinal waves. It is impossible to tell whether a wave represented on a displacement–time graph is transverse or longitudinal. The graph tells us how the displacement of a given point on the wave changes with time, but it does not tell us whether the displacement is parallel or perpendicular to the direction of wave travel.

Finding the speed of a wave

We can use a displacement–distance graph to find the wavelength of a wave and a displacement–time graph to find the time period of a wave (**Figure 8**). We can combine this information to find the speed of a wave.

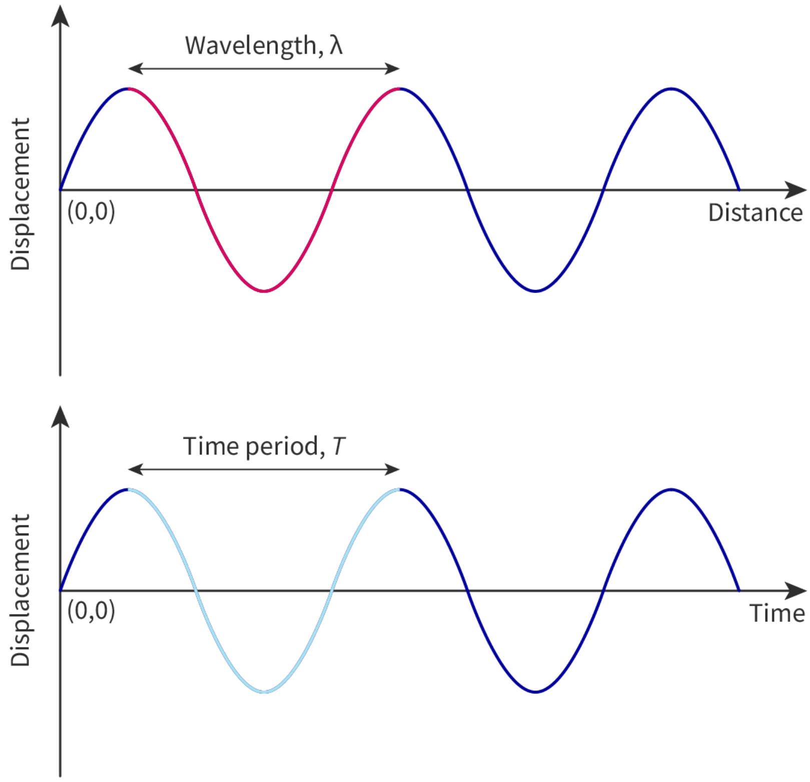

Figure 8. Displacement—distance graph and displacement—time graph.

More information for figure 8

The image consists of two separate graphs. The first graph is labeled "Displacement vs Distance" with the horizontal axis marked as "Distance" and the vertical axis marked as "Displacement." The graph shows a sine wave starting at the origin (0,0), extending across one complete wavelength labeled as "Wavelength, λ."

The second graph is labeled "Displacement vs Time" with the horizontal axis marked as "Time" and the vertical axis marked as "Displacement." This graph also displays a sine wave starting at the origin (0,0), representing one full cycle of a periodic wave. This wave extends over a time interval labeled as "Time period, T." Both graphs visually represent the relationships between wave displacement, distance, and time using sinusoidal curves.

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We know the following:

- The red section on the displacement–distance graph represents one complete wave. Its length, measured along the x-axis, represents the wavelength of the wave.
- The light blue section on the displacement–time graph represents one complete wave. Its length, measured along the x-axis, represents the time period of the wave.

The equation for speed is (subtopic A.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43128/)):

$$\text{speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

$$v = \frac{s}{t}$$

For a wave, wavelength, λ, is distance travelled, s, and time period, T, is time taken, t.

So:

$$\text{speed of a wave} = \frac{\text{wavelength}}{\text{time period}}$$

This gives the equation for the speed of a wave in **Table 1**.

Table 1. Equation for speed of a wave.

Equation	Symbols	Units
$v = \frac{\lambda}{T}$	v = wave speed	metres per second (m s^{-1})
	λ = wavelength	metres (m)
	T = time period	seconds (s)

We know that $f = \frac{1}{T}$ (subtopic C.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43161/)), which gives the other equation for wave speed in **Table 2**.

Table 2. Equation for speed of a wave.

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Equation	Symbols	Units
$v = f\lambda$	v = wave speed	metres per second (m s^{-1})
	f = frequency	hertz (Hz)
	λ = wavelength	metres (m)

The equation in **Table 2** is known as the **wave equation**.

Concept

The wave equation describes the speed of a **wave** through a medium. It does not describe the speed of the particles in a medium. The particle speed (and direction) varies during one cycle of a wave (section C.1.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/position-and-velocity-hl-id-44871/)). This speed is governed by simple harmonic motion (SHM). The wave equation describes the speed with which energy propagates through a medium.

Exercise 1

Click a question to answer

Worked example 2

A tuning fork is marked as 262 Hz. When the tuning fork is struck, the sound takes 0.15 s to travel across a 55 m concert hall. Determine the wavelength of the sound.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$s = 55 \text{ m}$ $t = 0.15 \text{ s}$ $f = 262 \text{ Hz}$
Step 2: Determine the speed of a particle.	$v = \frac{s}{t}$ $= \frac{55}{0.15}$ $= 366.67 \text{ m s}^{-1}$

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Solution steps	Calculations
Step 3: Write out the equation and rearrange to find λ.	$v = f\lambda$ $\lambda = \frac{v}{f}$
Step 4: Substitute the values given.	$= \frac{366.67}{262}$
Step 5: State the answer with appropriate units and the number of significant figures used in rounding.	$= 1.4\ \text{m}\ (2\ \text{s.f.})$

Worked example 3 shows how to answer a common IB physics style of question.

Worked example 3

Wave A has twice the wavelength and four times the speed of wave B. What is the ratio?:

$$\frac{\text{frequency of wave A}}{\text{frequency of wave B}}$$

Solution steps	Calculations
Step 1: Write out the wave equation and rearrange to find.	$v = f\lambda$ $f = \frac{v}{\lambda}$
Step 2: Determine the values of speed and wavelength of wave A in terms of the speed and wavelength of wave B.	$v_A = 4v_B$ $\lambda_A = 2\lambda_B$
Step 3: Use the wave equation to determine the ratio of the two frequencies, and substitute in the values for A.	$\frac{f_A}{f_B} = \frac{v_A}{\lambda_A} \times \frac{\lambda_B}{v_B}$ $\frac{f_A}{f_B} = \frac{4v_B}{2\lambda_B} \times \frac{\lambda_B}{v_B}$
Step 4: Cancel common terms and solve.	$\frac{f_A}{f_B} = \frac{4}{2}$ $= 2$

Work through the activity to check your understanding of graphs of wave motion.

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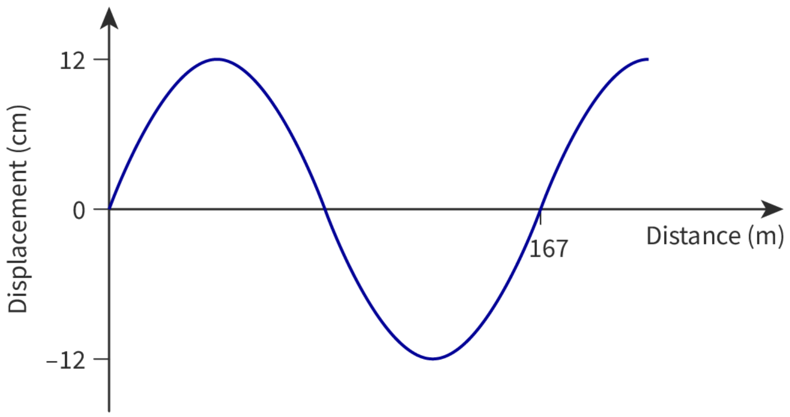
Activity

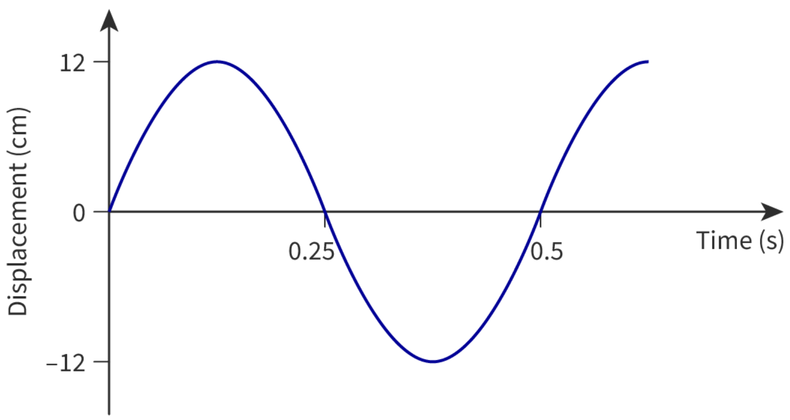
- **IB learner profile attribute:**
  - Knowledgeable
  - Communicator
- **Approaches to learning:**
  - Thinking skills — Applying key ideas and facts in new contexts
  - Communication skills — Using terminology, symbols and communication conventions consistently and correctly
- **Time required to complete activity:** 20 minutes
- **Activity type:** Pair activity

Task 1:

A wave has an amplitude of 12 cm, a time period of 0.5 s, and a wave speed of 334 m s^{-1}.

Draw a displacement—distance graph for the wave at a moment in time. Then, draw a displacement—time graph for a particle affected by the wave. Remember to label your axes.





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Displacement—distance graph for the wave and displacement—time graph for a particle affected by the wave.

Task 2:

Figure 9 shows two graphs.

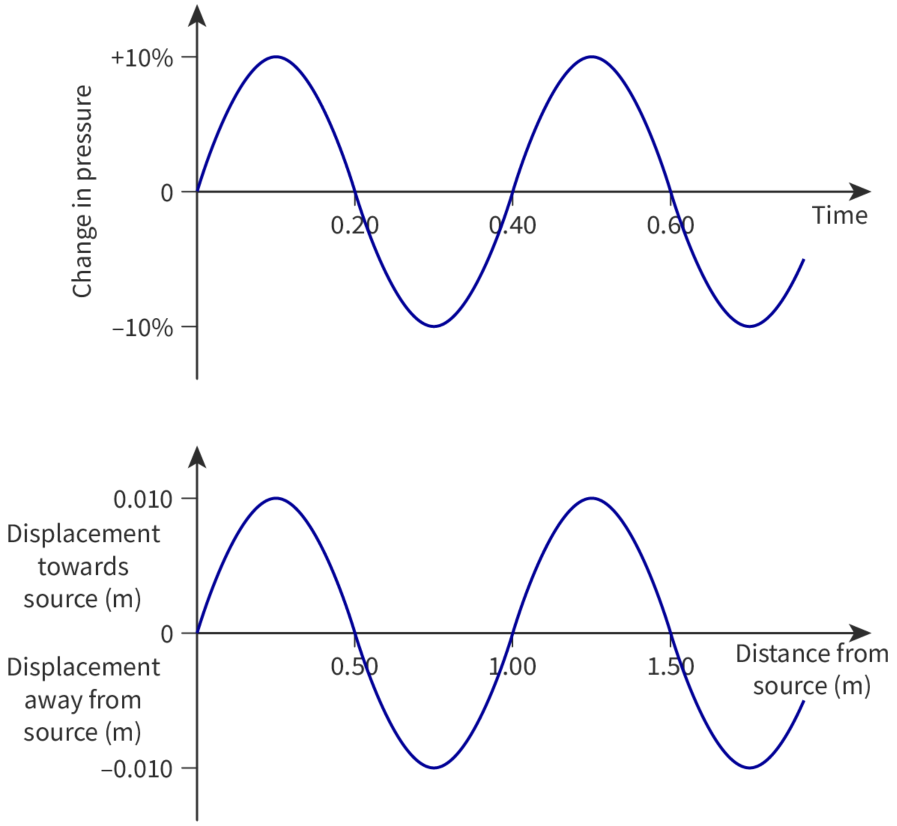

Figure 9. Two graphs for a wave.

More information for figure 9

The image contains two graphs illustrating different aspects of a wave. The first graph's x-axis represents time with values from 0 to 0.60, while the y-axis shows change in pressure ranging from -10% to +10%. This graph depicts a sinusoidal wave oscillating between positive and negative pressure.

The second graph's x-axis represents distance from the source measured in meters, ranging from 0 to 1.50. The y-axis indicates displacement, showing values from -0.010 to 0.010 meters. This also forms a sinusoidal pattern, demonstrating displacement towards and away from the source.

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The same wave is being described in each graph. Describe the wave as fully as you can, giving information about:

- amplitude
- wavelength
- frequency
- time period
- wave speed.

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Based on the information provided in the graphs, determine whether the wave is transverse or longitudinal, and explain your answer.

Task 3:

The waves represented in this activity could be transverse or longitudinal. Why do we represent the waves graphically, and not draw them more realistically?

6 section questions

Question 1

SL HL Difficulty:

The distance between a crest and the equilibrium position is called the 1 amplitude ✓ . The distance between adjacent troughs is called the 2 wavelength ✓ . The time interval between successive crests is called the 3 time period ✓ .

Accepted answers and explanation

#1 amplitude

#2 wavelength

#3 time period
period

General explanation

The distance between a crest and the equilibrium position is called the amplitude. The distance between adjacent troughs is called the wavelength. The time interval between successive crests is called the time period.

Question 2

SL HL Difficulty:

The particles in a medium oscillate as a wave passes through the medium. The wave is shown in the diagram below.

Which of these quantities has different values for different particles at the instant shown in the diagram?

1 Displacement ✓

2 Amplitude

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view

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3 Frequency

4 Wavelength

Explanation

For a particular wave, amplitude, frequency and wavelength are constant. The displacement of a particle will change depending on where in the cycle the wave is at — crest, trough, etc.

Question 3

SL HL Difficulty:

Wave A has half the frequency and four times the speed of wave B.

What is the ratio $\frac{\lambda_A}{\lambda_B}$?

1 8 ✓

2 2

3 $\frac{1}{2}$

4 $\frac{1}{8}$

Explanation

$v = f\lambda$

$2f_A = f_B$

$v_A = 4v_B$

$$\frac{\lambda_A}{\lambda_B} = \frac{v_A}{f_A} \times \frac{f_B}{v_B}$$

$$\frac{\lambda_A}{\lambda_B} = \frac{4v_B}{f_A} \times \frac{2f_A}{v_B}$$

$$\frac{\lambda_A}{\lambda_B} = \frac{8}{1} = 8$$

Question 4

SL HL Difficulty:

Identify which of the following can be found from the wave shown in the graph.

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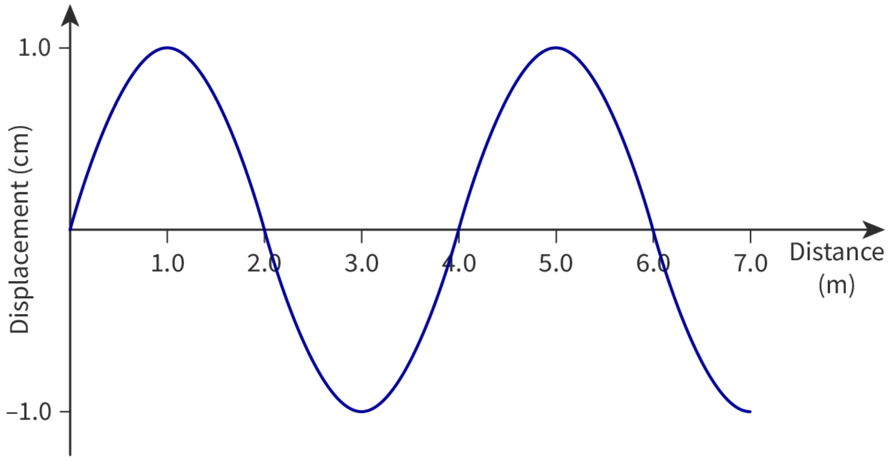


More information

1 Wavelength ✓

2 Whether the wave is transverse or longitudinal

3 Frequency

4 Period

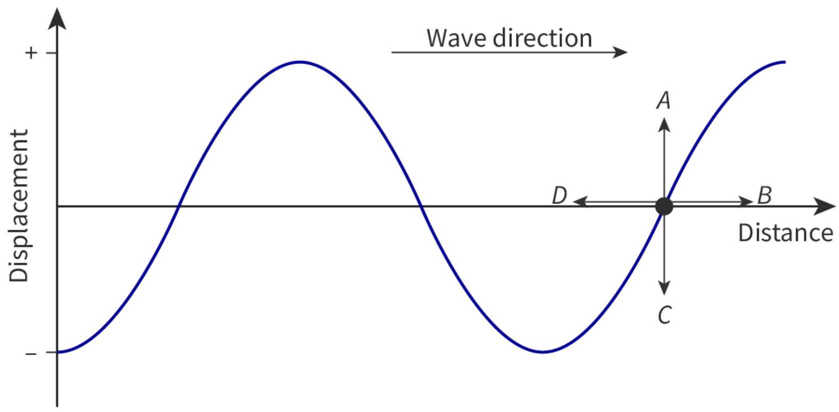
Explanation

The graph is a displacement—distance graph. It does not show time so frequency and period cannot be known. You are not told whether the displacements are parallel to or at right angles to the wave direction, so you cannot know whether the wave is longitudinal or transverse.

Question 5

SL HL Difficulty:

The graph represents a wave moving from left to right.



More information

Determine the direction the particle will move in.

1 C ✓

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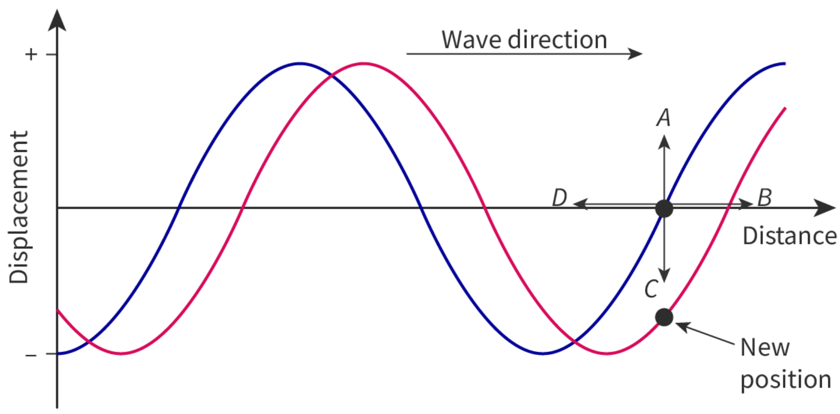
2 A

3 B

4 D

Explanation

The particle can only move along line A—C (vertically). The wave is moving to the right. The particle will have moved in the direction of C, as shown.

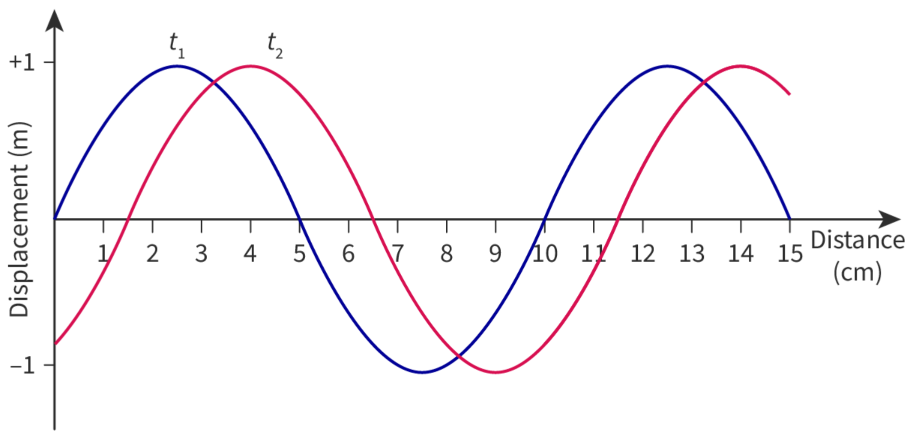


More information

Question 6

SL HL Difficulty:

The graph shows a wave at time t_1, and later at time t_2. The time interval ($t_2 - t_1$) is 0.75 s.



More information

Determine the frequency of the wave.

1 0.20 Hz ✓

2 0.13 Hz

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3 0.05 Hz

4 0.45 Hz

Explanation

Measure the wavelength from the graph:

$$\begin{aligned}\lambda &= 10 \text{ cm}\\ &= 0.1 \text{ m}\end{aligned}$$

The wave has moved a distance of 1.5 cm in 0.75 s:

$$\begin{aligned}s &= 1.5 \text{ cm}\\ &= 0.015 \text{ m}\end{aligned}$$

$$t = 0.75 \text{ s}$$

$$\begin{aligned}v &= \frac{s}{t}\\ &= \frac{0.015}{0.75}\\ &= 0.02 \text{ m s}^{-1}\end{aligned}$$

$$v = f\lambda$$

$$\begin{aligned}f &= \frac{v}{\lambda}\\ &= \frac{0.02}{0.1}\\ &= 0.2 \text{ Hz (1 s.f.)}\end{aligned}$$

C. Wave behaviour / C.2 Wave model

Sound waves and electromagnetic waves

C.2.3: Sound waves C.2.4: Electromagnetic waves C.2.5: Differences between mechanical and electromagnetic waves

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/sound-waves-and-electromagnetic-waves-id-44907/print/) Assign

Learning outcomes

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

- Describe the properties of sound waves.
- Understand the differences between mechanical waves and electromagnetic waves.
- Describe the properties of electromagnetic waves.

Student
view

Look at **Video 1.** How can sound waves shatter a glass?

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Video 1. Sound waves can cause a glass to break.

The sound waves in **Video 1** are travelling waves and transfer energy from one place to another. In this case, the energy is so great that the glass is not strong enough to withstand it, and the glass shatters.

Making connections

Resonance is responsible for shattering glass (subtopic C.4 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43788/)). Standing waves and resonance have many applications in our everyday lives.

Figure 1 shows an infrared image of galaxies captured by the James Webb Space Telescope. Infrared is an electromagnetic wave. We cannot see infrared waves, so how do telescopes capture infrared images?

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Figure 1. An infrared image of galaxies.

Source: "Stephan's Quintet taken by James Webb Space Telescope (https://commons.wikimedia.org/wiki/File:Stephan%27s_Quintet_taken_by_James_Webb_Space_Telescope.jpg)" by NASA is in the public domain

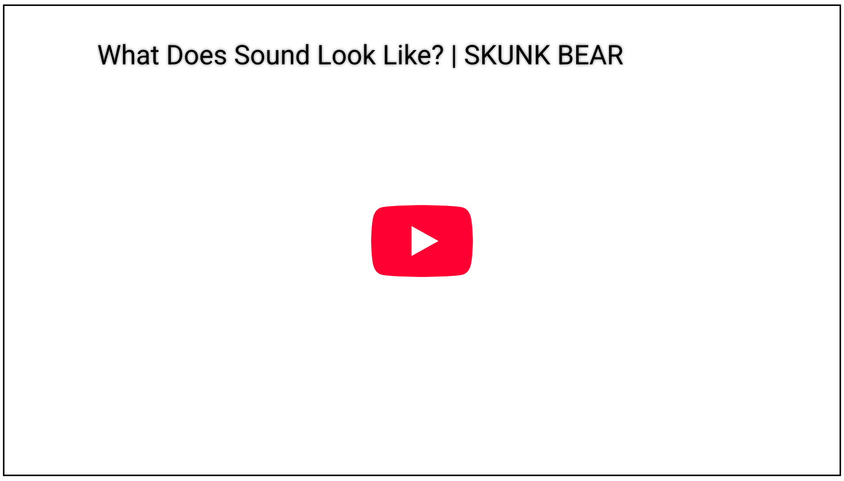
International Mindedness

The satellites, telescopes and observatories that used to examine the Earth and the skies are often the result of collaboration between international space agencies. For example, the James Webb Space Telescope, launched in 2021, is the result of collaboration between the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Canadian Space Agency. It has allowed us to see further in space and time than any telescope to date - leading to a rapid increase in our understanding of the universe.

Sound waves

Sound can be generated from different sources, such as loudspeakers, vocal chords and even the flapping of an insect's wings. What do all these sources of sound have in common? Vibrations.

Sound waves are mechanical waves and need a medium to travel through. **Video 2** shows how the particles move when a sound wave is transmitted. The video was created by a US broadcaster and so gives the speed of sound as 761 miles per hour (mph). This is equivalent to 1225 kilometres per hour (kph).



Video 2. Air particles transmitting a sound wave away from a source.

Look carefully at the particles. You will notice that the wave travels away from the source, but the particles vibrate backwards and forwards about their equilibrium position.

Student
view

Sound waves are longitudinal waves (section C.2.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/transverse-and-longitudinal-waves-id-44904/)). The areas where the air particles are closer together are **compressions**, while areas where the air particles are further apart are **rarefactions** (section

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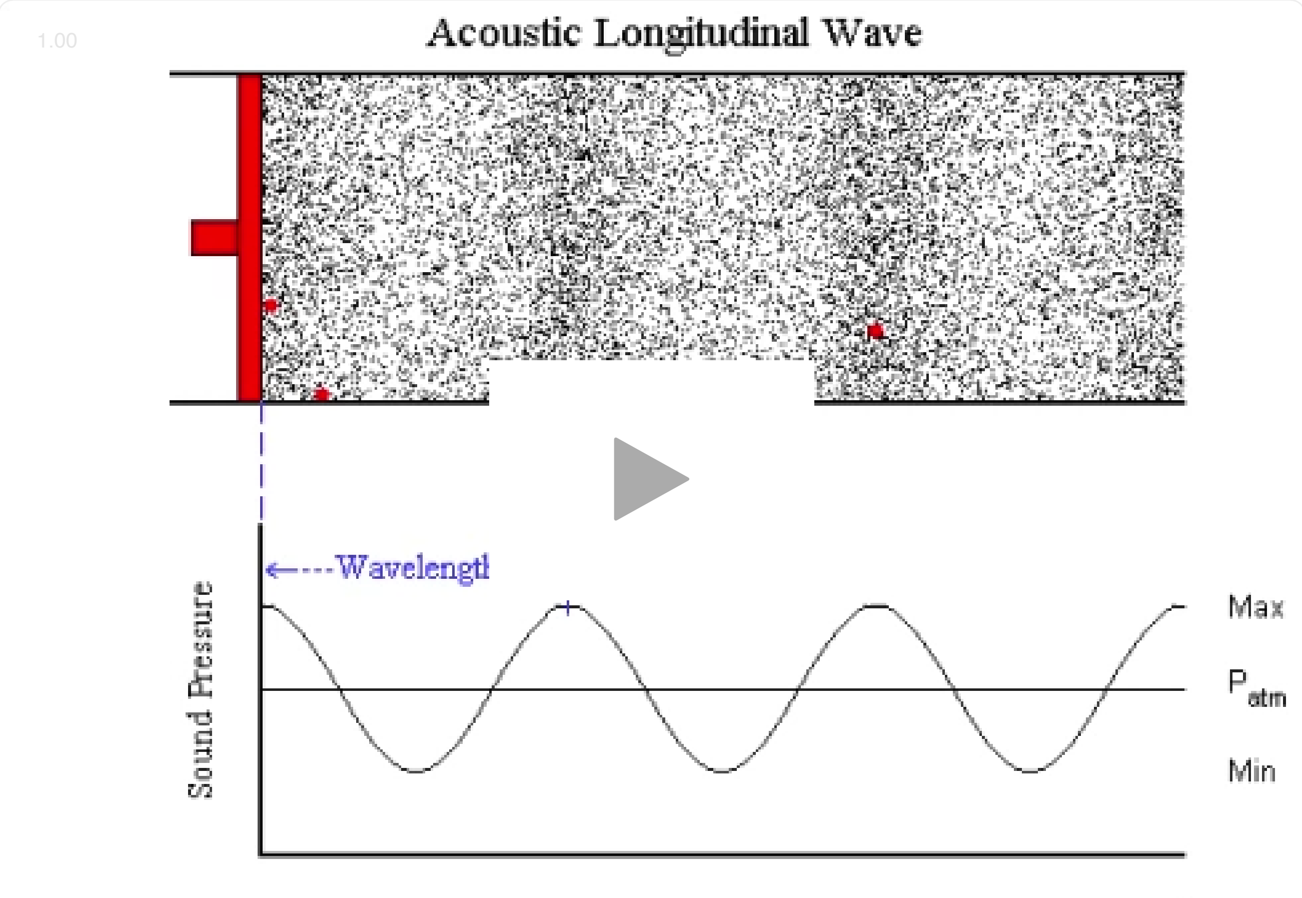
C.2.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/describing-waves-id-44906/)). These compressions and rarefactions move through the air, as the particles vibrate around their fixed positions. Compressions and rarefactions are very close to being adiabatic processes (section B.4.2a (/study/app/math-aa-hl/sid-423-cid-762593/book/the-first-law-of-thermodynamics-hl-id-44323/)).

Interactive 1 shows that the wavelength of a sound wave is the distance between two compressions (or rarefactions), and how the pressure varies along the wave.



Interactive 1. How Particles Move in a Sound Wave.

More information for interactive 1

This interactive video titled "Acoustic Longitudinal Wave" illustrates how sound waves propagate through a medium by visualizing the motion of particles and the resulting pressure variations. Individual air particles are shown as dots, oscillating back and forth about their fixed, equilibrium positions. The wave is shown traveling from left to right, while the individual red dots, highlighting some particles of the medium (such as air molecules), oscillate back and forth around their equilibrium positions. This clearly demonstrates the defining feature of longitudinal waves; particle motion that is parallel to the direction of wave travel.

As the wave moves through the medium, regions where particles are closely packed are identified as compressions (high pressure), and regions where particles are more spread out are known as rarefactions (low pressure). The wavelength is marked as the distance between two successive compressions or rarefactions, indicating the spatial periodicity of the wave.

Below the particle motion, a synchronized pressure graph dynamically shows how sound pressure varies along the wave. The vertical axis is labeled "Sound Pressure". The "*Max*" indicates the peak pressure during a compression. The "Min" marks the lowest pressure during a rarefaction. The "P_{atm}" (atmospheric pressure) serves as a baseline reference point. The pressure graph has a smooth sinusoidal shape, with peaks representing compressions (high pressure) and troughs representing rarefactions (low pressure). The wave oscillates symmetrically about the atmospheric pressure line (P_{atm}).

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This combined visualization effectively demonstrates how sound energy is transmitted through alternating regions of high and low pressure, without the net movement of particles. The simulation provides an intuitive understanding of the structure and behavior of longitudinal sound waves, including key features such as particle oscillation, wave propagation, and pressure variation over time and space.

If you have witnessed a thunderstorm, you may have noticed that the sound of thunder arrives later than the flash of lightning. This tells us that sound waves do not travel as fast as light waves.

If you stand in front of a large wall and clap your hands, you may hear an echo as the sound waves bounces off the wall (**Figure 2**). There is a time delay between making the sound and hearing the echo.

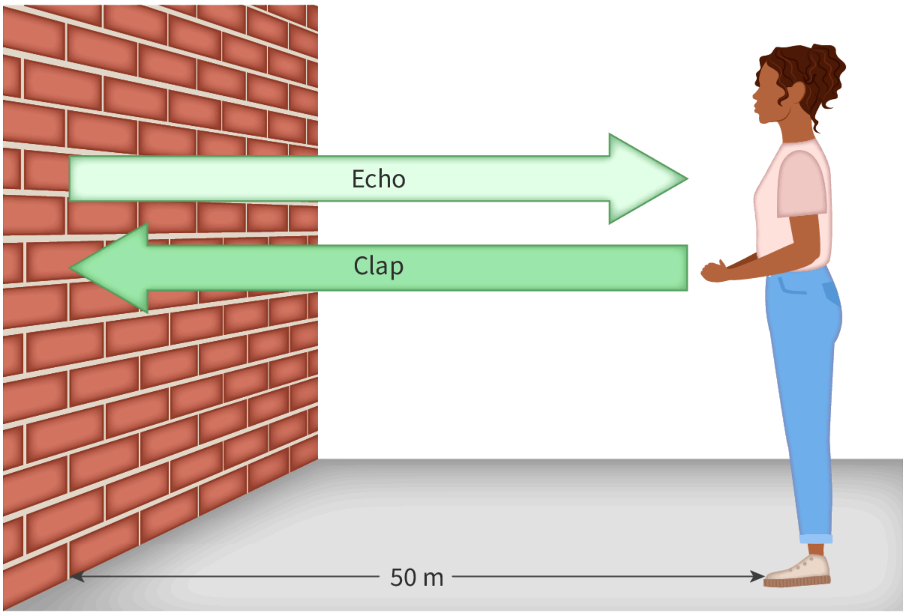

Figure 2. Clapping and hearing an echo.

More information for figure 2

The image depicts a side view illustration of a person standing at a distance from a brick wall and clapping. The person is wearing casual clothing. There are two large horizontal arrows: the arrow labeled 'Clap' points from the person towards the wall, and the arrow labeled 'Echo' points back from the wall towards the person. A distance measurement of 50 meters is shown on the ground between the person and the wall, indicating the distance over which the sound is traveling. This illustration visually represents how sound waves travel to the wall and reflect back as an echo.

[Generated by AI]

We can use the echo method to find the speed of sound in air. The time interval between the person clapping and hearing the clap can be measured.

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We can then use the equation for speed $\left(v = \frac{s}{t}\right)$ to calculate the speed of sound.

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Exercise 1

Click a question to answer

Figure 3 shows a set-up to determine the speed of sound in air. A tube of 1 m is closed at one end and has a microphone at the other end. A brief sound is made at the open end of the tube, and its echo is detected by the microphone. The microphone is connected to a laptop, which shows the output from the microphone.

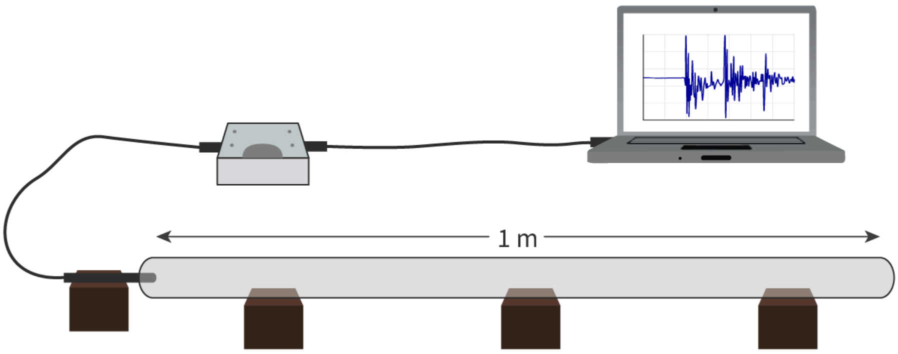

Figure 3. Set-up to determine the speed of sound in air.

More information for figure 3

The image is a diagram illustrating an experimental setup to determine the speed of sound in air. The setup includes a horizontal tube, which is 1 meter in length and closed at one end. The tube rests on several supports. A microphone is placed at the open end of the tube, and it is connected by a cable to an electronic device. This device appears to be a signal processor, which is in turn connected to a laptop computer. The screen of the laptop displays a waveform graph, presumably showing the input from the microphone. The diagram visually represents the components and their connections, emphasizing the pathway from the sound input to the digital display output.

[Generated by AI]

Worked example 1

The diagram shows a pressure–time graph for the sound and echo in **Figure 3**. The length of the tube is 1 m.

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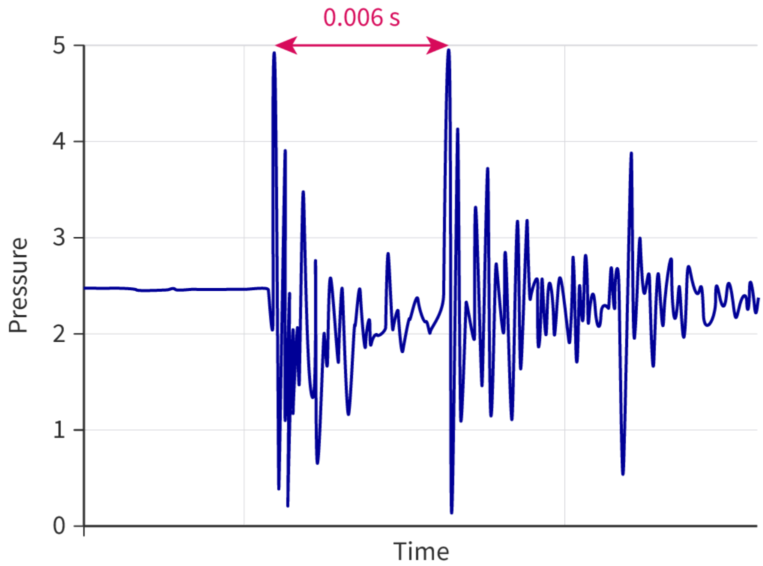

Figure 4. A pressure—time graph for sound and echo.

More information for figure 4

The image is a graph displaying pressure against time, showing the behavior of sound and its echo. The x-axis represents time, with an important segment labeled as 0.006 seconds. The y-axis represents pressure. The graph shows an initial stable pressure of around 2 units, which spikes to 5 units abruptly. This spike is followed by a decrease back to the original level, then fluctuates irregularly with smaller peaks and troughs, representing the echo effect over time.

[Generated by AI]

Determine the speed of sound in air.

Solution steps	**Calculations**
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	The sound travels to the end of the tube then back to the microphone: $$\begin{aligned} s &= 2\times1 \\ &= 2\text{ m} \end{aligned}$$ Read the time interval between the sound and the echo from the *x*-axis of the graph: $$t = 0.006\text{ s}$$
Step 2: Write out the equation.	$v = \frac{s}{t}$
Step 3: Substitute the values given.	$= \frac{2}{0.006}$

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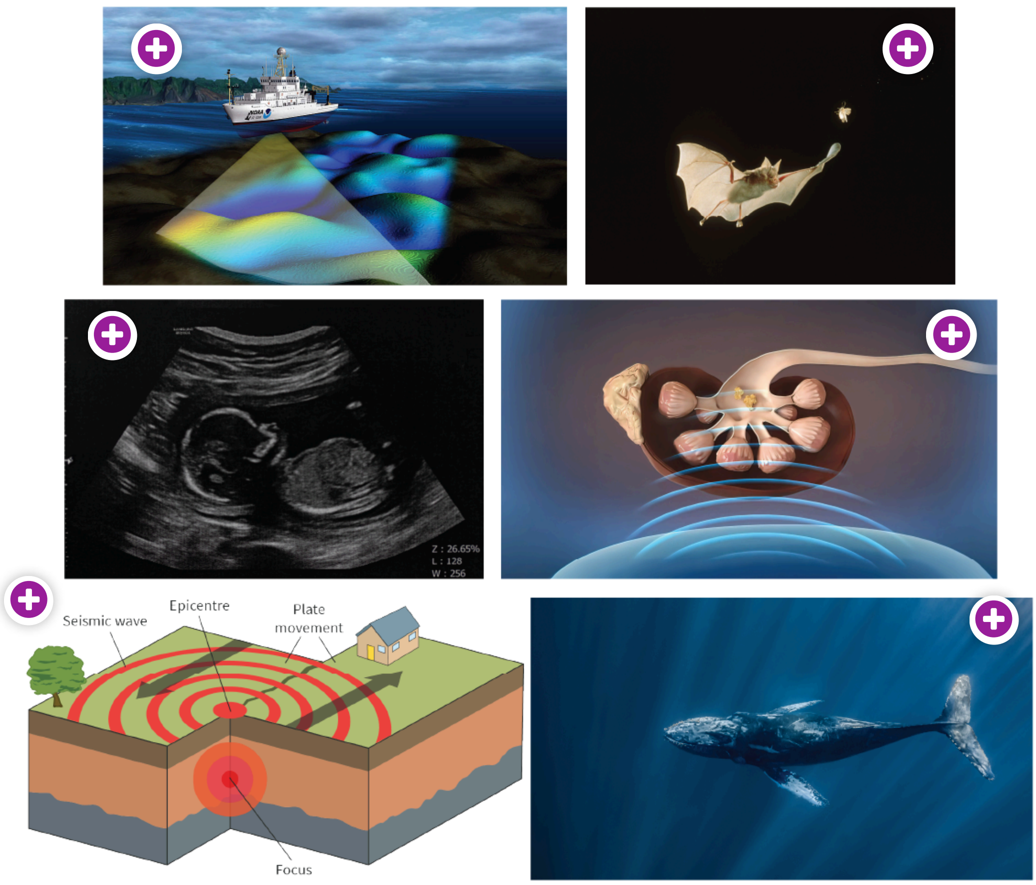
Solution steps	Calculations
Step 4: State the answer with appropriate units and the number of significant figures used in rounding.	$= 333.3 \text{ m s}^{-1} = 300 \text{ m s}^{-1} \text{ (1 s.f.)}$

The speed of the sound in air is approximately 330 m s^{-1}. The speed of sound depends on temperature and pressure, and it is different in different mediums. **Table 1** shows the speed of sound in different materials.

Table 1. Speed of sound in different materials.

Medium	Speed of sound (m s^{-1})
Air	330
Hydrogen	1270
Water	1450
Copper	3560

Click on each image in **Interactive 2** to find out how sound waves are used.



Interactive 2. Uses of Sound Waves.

Student view

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More information for interactive 2

This interactive collage presents six distinct images, each illustrating a real-world application of sound waves. Users can click on hotspots embedded in each image to reveal informative pop-ups that explain how sound is used in different contexts; from nature and medicine to technology and geology.

- Top Left — Sonar Mapping with a Research Vessel

A research ship is shown emitting sound waves into the ocean, which reflect off the seafloor. These echoes are used to generate a map of the ocean bed.

Hotspot Text:

Sonar (sound navigation and ranging) is used to map the ocean floor, locate shoals of fish, and help submarines navigate and avoid obstacles.

- Top Right — Bat Using Echolocation

A bat is depicted mid-flight, using ultrasound pulses to detect a flying insect in the dark. Wave patterns illustrate the emitted sounds and returning echoes.

Hotspot Text:

Bats navigate using ultrasound (mechanical waves with frequency is too high to be detected by the human ear - above 20 kHz). They interpret the echoes from their high-frequency clicks and squeaks to fly through the dark and catch insects in mid-air.

- Middle Left — Ultrasound in Medical Imaging

A grayscale ultrasound scan of a fetus is displayed, representing the use of high-frequency sound waves in diagnostic imaging.

Hotspot Text:

Ultrasound provides a real-time, moving image of a subject, such as a fetus. It exposes the subject to less harm than X-rays.

Middle Right — Ultrasound for Kidney Stone Treatment

An anatomical illustration shows a kidney being targeted by focused sound waves, referencing medical ultrasound therapy.

Hotspot Text:

Kidney stones can be treated using ultrasound. The stones absorb the wave energy, which causes them to break up into smaller pieces, so they can pass out painlessly through the body.

Bottom Left — Seismic Activity and Infrasound

A cross-section of the Earth illustrates an earthquake's origin at the focus, with seismic waves spreading outward in red rings. Arrows indicate tectonic plate movement and a house and tree show human and environmental impact.

Hotspot Text:

Earthquakes generate infrasound (mechanical waves whose frequency is too low to be detected by the human ear — below 20 Hz). Monitoring stations detect infrasound. By measuring the time waves arrive at three stations, scientists can determine the epicenter of the earthquake.

- Bottom Right — Whale Communication Underwater

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A whale is shown swimming in the ocean, with arcs representing sound waves used in long-distance communication and sonar-like navigation.

Hotspot Text:

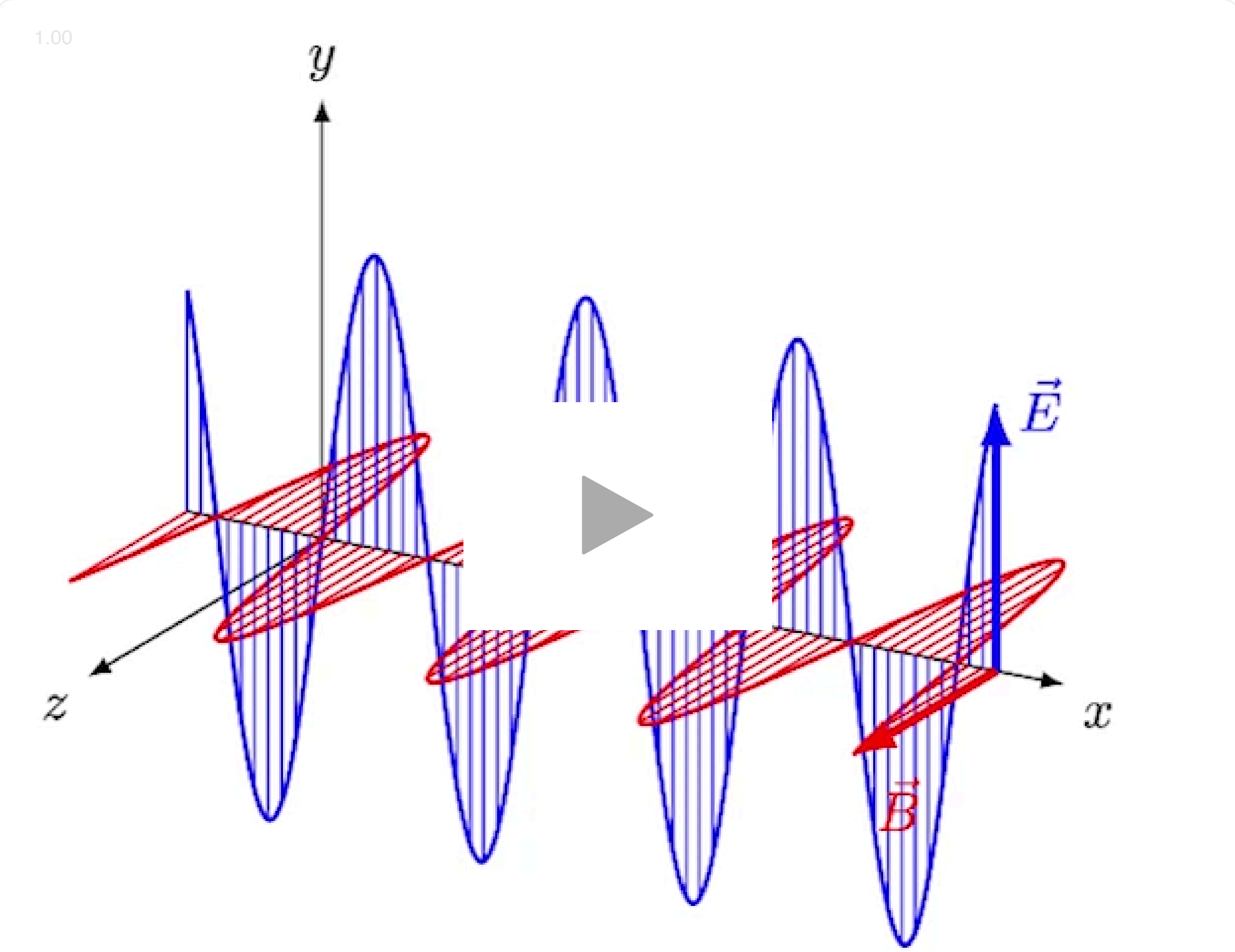
Whales communicate with each other underwater, over vast distances, using sound waves. Whales also use sonar to identify predators and navigate through the oceans.

This interactive collage offers a rich, multi-contextual understanding of how sound waves (both audible and inaudible) play vital roles across nature, healthcare, industry, and science. Each example connects core physics concepts with their real-world relevance, enhancing student engagement and curiosity.

Electromagnetic waves

Water waves and sound waves are mechanical waves, and need a medium to travel through. Electromagnetic waves are non-mechanical waves and do not need a medium to travel through. Mechanical waves cannot travel through a vacuum, but electromagnetic waves can.

Electromagnetic waves are oscillations in the electric and magnetic fields that exist throughout the universe. The two fields are at right angles to one another. In **Interactive 3**, the red arrows represent a magnetic field and the blue arrows represent an electric field.



Interactive 3. An Electromagnetic Wave.

Student
view

More information for interactive 3

This interactive features a short video that demonstrates the oscillations of electric and magnetic fields in an electromagnetic wave. The video illustrates the two fields, with the electric field represented by the blue arrows **(E)** and the magnetic field represented by the red arrows **(B)**. Both fields oscillate at right angles to each other, as shown in the visual.

In the video, the oscillations of the fields are represented along the x, y, and z axes. The electric field oscillates along the y-axis, while the magnetic field oscillates along the z-axis, with the direction of wave propagation indicated along the x-axis. This helps illustrate the perpendicular nature of electric and magnetic fields in an electromagnetic wave.

This interactive provides a clear visual understanding of the behavior of electromagnetic waves. It effectively demonstrates the relationship between the electric and magnetic fields, their oscillations, and their perpendicular orientation in space, key characteristics of electromagnetic waves.

The electromagnetic spectrum is a continuous spectrum of all the wavelengths (frequencies) of electromagnetic waves from gamma rays to radio waves. The waves are organised into groups depending on wavelength (frequency). **Figure 5** shows the groups in the electromagnetic spectrum and the ranges of their wavelengths.

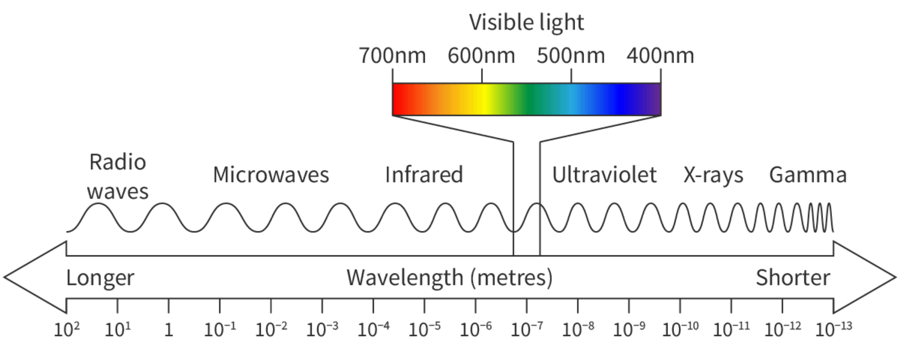


Figure 5. The electromagnetic spectrum.

More information for figure 5

The diagram illustrates the electromagnetic spectrum with a horizontal arrow indicating wavelength in meters, ranging from longer waves on the left (10^2 meters) to shorter waves on the right (10^-13 meters). It includes labeled sections for different types of waves, such as radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays. Each wave type is represented with a wavy line showing increasing frequency from radio waves to gamma rays. The visible light spectrum is highlighted with colors ranging from red at 700nm to violet at 400nm.

[Generated by AI]

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The energy of electromagnetic waves is proportional to the waves' intensity, hence to the square of their amplitude. The amplitude here is the maximum field strength of the oscillating electric and magnetic

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fields. You might think that waves on the high-frequency end of the electromagnetic spectrum (i.e. X-rays or gamma rays) are more harmful than electromagnetic waves with a lower frequency (i.e. microwaves); however, this is not always the case, indeed a high intensity microwave may be far more harmful than a low intensity X-ray. It is the energy of the photon (i.e. the quantum of light) that depends on the frequency.

All electromagnetic waves travel at the speed of light, c, in a vacuum: 3.00×10^8 m s^{-1}. The speed of light is given by the equation:

$$c = f\lambda$$

As the speed of light, c, is constant, then wavelength, λ, is inversely proportional to frequency, f, for an electromagnetic wave:

- The shorter the wavelength, the higher the frequency
- The longer the wavelength, the lower the frequency.

Creativity, activity, service

Strand: Service
Learning outcome: Demonstrate how to initiate and plan a CAS experience

Different people are more or less sensitive to different types of waves. People with hearing impairment may find it difficult to sense sound waves, and bright lights or flashing lights can affect others.

Identify a group of people in your community who are more or less sensitive to a type of wave, and plan a service project to support them. This could include enhancing signage, working with a facilities manager to include adjustable lighting or providing education for the rest of the community.

Gamma rays have the shortest wavelengths and the highest frequencies. Radio waves have the longest wavelengths and the lowest frequencies.

Humans can see only 0.0035% of the electromagnetic spectrum – visible light. Some animals can ‘see’ infrared and ultraviolet. Bees can ‘see’ patterns on flowers that are only visible in ultraviolet, while rattlesnakes (pit vipers) can sense and combine infrared and visible images.

Humans can use different materials which are sensitive to different wavelengths of light in order to form images using wavelengths of light which we cannot see. The James Webb telescope, for example, uses infrared sensors as well as visible light sensors in order to capture a wider range of images of the universe.

Student view

Electromagnetic waves can be produced in lots of ways and by many different sources. The Sun emits visible light, infrared and ultraviolet. In space, quasars (supermassive black holes) emit radio waves, and supernovae (exploding stars) can emit X-rays. On the Earth, X-rays are generated by rapidly decelerating fast moving electrons, while radio waves can be generated by oscillating electrons in long metal conductors.

Electromagnetic waves have lots of uses. Click on each image in **Interactive 4** to learn about uses of electromagnetic waves.

Rights of use

Interactive 4. Uses of Electromagnetic Waves.

More information for interactive 4

A collage of nine images, each representing different applications of electromagnetic waves. Each image has a hotspot that reveals more information when clicked.

The first image in the top-left corner shows a deep-space photograph featuring numerous galaxies, stars, and celestial objects. The hotspot reads, An image taken by the James Webb Space Telescope in the infrared part of the electromagnetic spectrum. The spiral galaxy is more than a billion light-years from Earth.

The second image in the top row depicts a person using a thermal imaging camera in an indoor setting. The camera screen displays a heat map of the surrounding environment, highlighting different temperatures in varying colors. The hotspot reads, Thermal imaging using infrared is used to detect illness at airports, locate earthquake survivors, examine houses for thermal efficiency, and rescue people lost at sea.

The third image in the top row is an old X-ray scan of a human hand, showing the skeletal structure along with a visible metal ring on one of the fingers. This is a historical X-ray image from the early days of the technology. The hotspot reads, The first X-ray was taken in 1895. Wilhelm Röntgen discovered X-rays, and used them to image the hand of his wife.

The first image in the middle row presents a weather radar visualization of a hurricane. The swirling pattern of the storm is visible, with

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colors representing different intensities of precipitation and wind. The hotspot reads, Radar images, like this image of a hurricane just before landfall in Puerto Rico, help scientists track and predict the path of hurricanes.

The second image in the middle row showcases an artistic depiction of a black hole or neutron star emitting powerful energy jets into space. The image represents a high-energy astrophysical event. The hotspot reads, Pulsars are fast-spinning stars that emit an intense beam of radio waves that can be detected on Earth.

The third image in the middle row captures a medical radiation therapy procedure. A patient lies on a treatment bed under a large machine that directs precisely targeted radiation beams for cancer treatment. The hotspot reads, Radiotherapy uses high energy gamma rays to target cancerous tumours. The radiation ionises the cells and destroys them.

The first image in the bottom row features a glass prism dispersing white light into a spectrum of colors, illustrating the concept of light refraction and dispersion. The hotspot reads, Visible light is the part of the electromagnetic spectrum we can see. Our eyes are sensitive from about 400 nm (violet light) up to about 700 nm (red light).

The second image in the bottom row is a close-up of Guatemalan currency, highlighting security features such as holograms and UV-visible elements used to prevent counterfeiting. The hotspot reads, Ultraviolet light can be used to sterilise equipment by killing bacteria, and can cause phosphorescence in bank note dyes to detect forgeries.

The final image in the bottom row is a black and white icon of a Wi-Fi signal, representing wireless communication technology. The hotspot reads, Wifi uses microwaves and radio waves at frequencies of 2.5 GHz and 5.0 GHz. Information can be quickly and safely sent from device to device.

International Mindedness

New technology, such as Wifi coverage from satellites, is shared between countries, but research is often driven by countries with the most resources. Should countries share knowledge and technology with other countries? It is morally wrong not to share it?

Technologies and ideas have developed and will continue to develop over time, and we will find new ways to transmit and gather information from waves.

Nature of Science

Aspect: Experiments

Near the end of the 19th century, physicists believed that there was a universal medium, called the *aether* that existed to enable electromagnetic waves to travel everywhere. However, no experiment could verify the existence of the aether.

A final, clever, and sensitive experiment using the properties of electromagnetic waves and performed by Albert Michelson and Edward Morley (http://galileoandeinstein.physics.virginia.edu/more_stuff/Applets/MichelsonMorley/michelsonmorley.html) over a period of many months was also unable to detect the aether. However, the experiment also enabled a turning point in our thinking about the concepts of space and time.

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Also in the late 19th century, the Scottish physicist James Clerk Maxwell developed a set of partial differential equations — known to all physicists as ‘Maxwell's equations’ — that unified theories of electricity and magnetism. Maxwell's equations describe how electric and magnetic fields are generated by charges, currents and the changes in each. The equations consolidate all electric and magnetic phenomena as being elements of a single general field description of electricity and magnetism, or as we now call it; electromagnetism.

Activity

- **IB learner profile attribute:**
  - Knowledgeable
  - Communicator
- **Approaches to learning:** Communication skills — Reflecting on the needs of the audience when creating engaging presentations
- **Time required to complete activity:** 20 minutes
- **Activity type:** Pair activity

Task 1: Effective communication is an important part of the scientific process, and this section contains many key terms. Your first task is to complete the crossword below, working with a partner if preferred.

Please note: Add a space between words where the answer contains two words. Use hyphens where needed.

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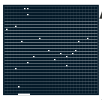
Identify these terms from their descriptions



Across

1 Radiation with wavelength of around one centimetre *(10)*

3 The number of wave cycles occurring per second *(9)*

5 v = fλ *(4,8)*

8 Mechanical waves whose frequency is too high to be detected by the human ear (above 20 kHz) *(10)*

9 Electromagnetic waves with the ability to pass through skin tissue, but not dense bone *(6)*

11 The region of the electromagnetic spectrum

Check Show solution Retry

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Interactive 5. Complete the Crossword.

More information for interactive 5

This interactive crossword puzzle helps users identify terms related to electromagnetic waves based on their descriptions. The layout features a crossword grid with both horizontal and vertical slots to fill in the correct answers. It presents two distinct lists of clues adjacent to the crossword grid: Across and Down. There are 20 clues in total—11 across and 9 down—each requiring the identification of a term that fits the given description.
Each clue requires the identification of a term that fits the given description. The crossword grid consists of blank spaces where users can type in their answers, with real-time validation to ensure mistakes can be corrected. Below the grid are three interactive buttons: "Check," which allows users to verify their answers and confirms whether each one is correct or incorrect; "Show Solution," which reveals the correct answers for all clues, enabling users to

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compare their solutions; and "Retry," which resets the puzzle to allow a fresh attempt. Additionally, a progress bar at the bottom left corner tracks the number of correct answers, and once all answers are entered correctly, a $20/20$ star rating appears to confirm completion.

Below is the full list of clues along with their respective clue number in the beginning and the number of letters in a bracket at the end.

Across:

3. Electromagnetic waves with the ability to pass through skin tissue, but not dense bone (6)

5. The region of the electromagnetic spectrum with wavelengths just a little longer than those detected by the human eye (wavelengths above 700 nm) (8)

8. An oscillation in an electromagnetic field that requires no medium (matter) to travel, and can exist in a vacuum $(15, 4)$

11. The electromagnetic waves with the shortest wavelength and highest energy $(5, 4)$

12. The region of the electromagnetic spectrum with wavelengths just a little shorter than those detected by the human eye (wavelengths below 400 nm) (11)

13. A wave whose particles oscillate parallel to the direction of energy transfer (12)

14. The number of wave cycles occurring per second (9)

15. The distance between the peak (or trough) of a wave and its equilibrium position (9)

16. The region of the electromagnetic spectrum that can be detected by the human eye (with wavelengths between 400 and 700 nm) (11)

19. The time taken for one complete cycle of a wave (6)

20. Mechanical waves whose frequency is too high to be detected by the human ear (above 20 kHz) (10)

Down:

1. The speed at which energy is transferred through a medium $(4, 5)$

2. Radiation with a wavelength of around one centimeter (10)

4. Oscillations in air that can be detected by humans (between 20Hz and 20 kHz) $(5, 4)$

6. The distance between adjacent, identical points on a wave (eg, two neighboring peaks on a transverse wave) (10)

7. The electromagnetic wave with the longest wavelength $(5, 5)$

9. A wave that requires a medium (matter) to travel $(10, 4)$

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10. A wave whose particles oscillate at right angles to the direction of energy transfer (10)

17. Mechanical waves whose frequency is too low to be detected by the human ear (above $20\,\mathrm{kHz}$) (10)

18. A wave equation where the wave speed equals the product of frequency and wavelength $(4, 8)$

This interactive crossword puzzle serves as a valuable tool for reinforcing knowledge of electromagnetic waves, their properties, and related physics concepts. By solving the puzzle, users are encouraged to recall and apply important terms, such as wave speed, wavelength, frequency, and various types of electromagnetic radiation.

Solutions

Across Answers:

3. X-RAYS

5. INFRARED

8. ELECTROMAGNETIC WAVE

11. GAMMA RAYS

12. ULTRAVIOLET

13. LONGITUDINAL

14. FREQUENCY

15. AMPLITUDE

16. VISIBLE LIGHT

19. PERIOD

20. ULTRASOUND

Down Answers:

1. WAVE SPEED

2. MICROWAVES

4. SOUND WAVE

6. WAVELENGTH

7. RADIO WAVES

9. MECHANICAL WAVE

10. TRANSVERSE

17. INFRASOUND

18. WAVE EQUATION

Note: The crossword structure is generated at random, and the clues are not necessarily in the same order.

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Task 2: Create an informative media element that you could use to teach other students about the transmission of different types of waves and how humans use them to share or gather information. It could be a recorded podcast, an information poster, a booklet, a matching card game, or a song with lyrics written by you. You may wish to focus on a theme or a particular type of wave (parts of the electromagnetic spectrum, for example).

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5 section questions

Question 1

SL HL Difficulty:

True or false?

Electromagnetic waves are mechanical waves.

False

Accepted answers

False, F, false, f

Explanation

Mechanical waves need a medium to travel through. Electromagnetic waves can travel through a vacuum, so they are not mechanical waves.

Question 2

SL HL Difficulty:

Which of the following electromagnetic waves has the highest frequency?

1 X-rays

2 Radio waves

3 Ultraviolet

4 Microwaves

Explanation

X-rays have the shortest wavelength (and the highest frequency) of the waves in the electromagnetic spectrum.

Question 3

SL HL Difficulty:

Write the two missing words in the following sequence:

Radio waves, microwaves, 1 infrared , visible light, ultraviolet waves, 2 X-rays , gamma rays.

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Accepted answers and explanation

#1 infrared

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infra-red

#2 X-rays

xrays

General explanation

The words are the seven types of electro-magnetic radiation, listed in order of decreasing wavelength. Microwaves have the second longest wavelength, so appear second, after radio waves.

Question 4

SL HL Difficulty:

A microwave oven has a frequency of 12 GHz. Determine the wavelength of the microwaves?

1 2.5 cm ✓

2 40 cm

3 4.0 cm

4 0.25 cm

Explanation

$c = 3.00 \times 10^{8}\ \mathrm{m\ s^{-1}}$

$$\begin{aligned} f &= 12\ \mathrm{GHz} \\ &= 12 \times 10^{9}\ \mathrm{Hz} \end{aligned}$$

$c = f\lambda$

$$\begin{aligned} \lambda &= \frac{c}{f} \\ &= 3.00 \times \frac{10^{8}}{12 \times 10^{9}} \\ &= 0.025\ \mathrm{m} \\ &= 2.5\ \mathrm{cm} \end{aligned}$$

Question 5

SL HL Difficulty:

A ship's sonar device emits sonic pulses that are returned from surface 1 in a time of 2.01 s, and from surface 2 in a time of 2.03 s. Determine how far apart the two surfaces are.

The speed of sound in water is 1500 m s^{-1}.

1 15 m ✓

2 30 m

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3 35 m

4 40 m

Explanation

The time interval between the two pulses arriving is 0.02 s. In this time, the sound wave travelled an extra distance, and was reflected back the same distance.

$$v = \frac{s}{t}$$

$$\begin{aligned} s &= vt \\ &= 1500 \times 0.02 \\ &= 30 \text{ m} \end{aligned}$$

This is the distance to travel the extra distance and back, so the distance between the two surfaces is:

$$\frac{30}{2} = 15m$$

C. Wave behaviour / C.2 Wave model

Summary and key terms

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/summary-and-key-terms-id-44908/print/) Assign

- There are two types of waves: transverse and longitudinal. Waves transfer energy, but not matter.
- The particles in transverse waves oscillate at right angles to the direction of energy transfer. The particles in longitudinal waves oscillate parallel to the direction of energy transfer.
- The terms wavelength, time period, frequency, amplitude and wave speed can be used to describe waves.
- Transverse waves have crests and troughs, while longitudinal waves have compressions and rarefactions.
- Sound waves are longitudinal waves, which are produced by a vibrating source. Compressions are areas of higher pressure and rarefactions are areas of lower pressure.
- Mechanical waves, such as water waves and sound waves, are waves that need a medium to travel through. Electromagnetic waves are not mechanical waves, as they do not need a medium to travel through.
- Electromagnetic waves are oscillations in electric and magnetic fields, and they travel at the speed of light in a vacuum.
- The electromagnetic spectrum is a continuous spectrum of all the wavelengths (frequencies) of electromagnetic waves, divided into groups.
- The higher the frequency of an electromagnetic wave, the greater its energy and the more harmful it can be.

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Key terms

**Review these key terms. Do you know them all? Fill in as many gaps as yo
the terms in this list.**

1. The distance between the crest (or trough) of a wave and its equilibrium position
.
2. An is an oscillation in electric and magnetic fields. It
mechanical wave and does not need a medium to travel through.
3. The is the number of waves passing a point in one
4. When the oscillations of a wave are parallel to the direction of energy transfer, th
a . When the oscillations and energy transfer are perpe
is a .
5. A is a wave that needs a medium to travel through.
6. The of a wave is the time taken for one complete cy
7. The distance between adjacent identical points on a wave, for example, two cres
compressions is called the .
8. An area of a longitudinal wave where the particles have a higher density is a
and the area where the particles have a lower density
.
9. The of a wave is the peak of a wave, where particle
greatest displacement from equilibrium.

frequency | compression | electromagnetic wave | crest | transverse wa
mechanical wave | rarefaction | time period | amplitude | longitudinal w
wavelength

Check

Interactive 1. Transverse and Longitudinal Waves: Comparison

C. Wave behaviour / C.2 Wave model

Checklist

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What you should know

After studying this subtopic, you should be able to:

- Understand the difference between transverse waves and longitudinal waves.
- Describe the motion of a wave using the terms wavelength, frequency and time period.
- Determine the speed of a wave using the equations:

$$v = f\lambda \text{ and } v = \frac{\lambda}{T}$$

- Describe the properties of sound waves.
- Understand the differences between mechanical waves and electromagnetic waves.
- Describe the properties of electromagnetic waves.

Practical skills

Once you have completed this subtopic, go to Practical 5: Measuring the speed of sound (/study/app/math-aa-hl/sid-423-cid-762593/book/measuring-the-speed-of-sound-id-46509/) in which you will use simple harmonic motion to measure the speed of sound.

C. Wave behaviour / C.2 Wave model

Investigation

Section Student… (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/investigation-id-44910/print/) Assign

- **IB learner profile attribute:** Risk-taker
- **Approaches to learning:** Thinking skills – Experimenting with new strategies for learning
- **Time required to complete activity:** 20 minutes
- **Activity type:** Individual activity

Your task

Let's look at some wave experiments you can conduct at home!

Experiment 1: 'Seeing' infrared radiation

Equipment

Student view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

1 × camera (on a mobile phone or laptop, would be fine)

1 × remote (for a television, air conditioning unit, sound system, for example)

Instructions

1. Turn on your camera.
2. Point the remote at the camera, so the bulb at the front is visible.
3. Press a button on the remote (careful you don't pause someone's favourite programme!)
4. What do you see?

What is happening?

Our eyes contain rods and cones, which detect incoming photons of radiation. However infrared photons are too low energy for our rods and cones to detect. Most cameras have a wider bandwidth sensitivity than our eyes, so can pick up higher and lower wavelengths than our eyes can. The screen then compresses this bandwidth, so that wavelengths which are too long for us to observe are made a little shorter on your screen. This makes them visible to our eyes!

Strictly speaking, you are not 'seeing' infrared radiation – this is impossible. Rather, the radiation is shifted to a wavelength you can see.

Experiment 2: Testing your range of hearing

Equipment

1 × sound generator website, such as this one (https://onlinetonegenerator.com/), or an app such as Physics Toolbox Sensor Suite. Note that the sound system of the device or headphones you use will have their own frequency range of sounds it can produce.

Instructions

1. Start at 50 Hz. Do you hear a low bass note?
   - If yes, then great! Now drop the frequency in 10 Hz steps. When can you no longer hear the note?
   - If no, then increase the frequency to 100 Hz. If you still cannot hear it then change your device or headphones and start again.
2. Restart at 12 kHz. Do you hear a high frequency note?
   - If yes, then great! Now increase the frequency in 1 kHz steps. When can you no longer hear the note?
   - If no, then decrease the frequency to 10 kHz. If you still cannot hear it then change your device or headphones and start again.
3. Use the wave equation $(c = f\lambda c = f\lambda)$ to find the wavelength of these sounds. The speed of sound in air changes, but 330 m s^{-1} is a good estimate.

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

What is happening?

In step 1, when the note becomes inaudible, this is the lower end of your range of hearing. The frequency is too low for your delicate hearing mechanisms to detect, and you are playing infra-sound.

In step 2, when the note becomes inaudible, this is the upper end of your range of hearing and you are playing ultrasound.

Remember these numbers and compare it to your friend. Whose lower range of hearing is most sensitive? Who can hear the longest wavelength? Whose upper range is most sensitive?

If possible, test your hearing on their device to see if your result changes.

C. Wave behaviour / C.2 Wave model

Reflection

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/reflection-id-47878/print/) Assign

Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

Reflection

Now that you've completed this subtopic, let's come back to the guiding questions introduced in The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43778/).

- What are the similarities and differences between different types of waves?
- How can the wave model describe the transmission of energy as a result of local disturbances in a medium?
- What effect does a change in the frequency of oscillation or medium through which the wave is travelling have on the wavelength of a travelling wave?

Student view

Overview
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With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

⚠ Once you submit your response, you won't be able to edit it.

0/2000

Submit

Rate subtopic C.2 Wave model

Help us improve the content and user experience.

Student
view