HL IB Physics

Your notes

Wave Model

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* Properties of Waves
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* Electromagnetic Waves

Properties of Waves

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Properties of Waves

- **Travelling waves** are defined as follows:

Oscillations that transfer energy from one place to another without transferring matter

- Waves transfer **energy**, **not** matter
- Waves are generated by **oscillating sources**
  - These oscillations travel **away** from the source
- Oscillations can propagate through a **medium** (e.g. air, water) or in **vacuum** (i.e. no particles), depending on the type of wave

- The key properties of **travelling waves** are as follows:

Displacement

- Displacement X of a wave is the distance of a point on the wave from its equilibrium position
  - It is a vector quantity; it can be positive or negative
  - Measured in **metres** (m)

Wavelength

- Wavelength λ is the length of one complete oscillation measured from the same point on two consecutive waves
  - For example, two crests, or two troughs
  - Measured in **metres** (m)

Amplitude

- Amplitude A is the maximum displacement of an oscillating wave from its equilibrium position (x = 0)
  - Amplitude can be positive or negative depending on the direction of the displacement
  - Measured in **metres** (m)
  - Where the wave has 0 amplitude (the horizontal line) is referred to as the **equilibrium position**

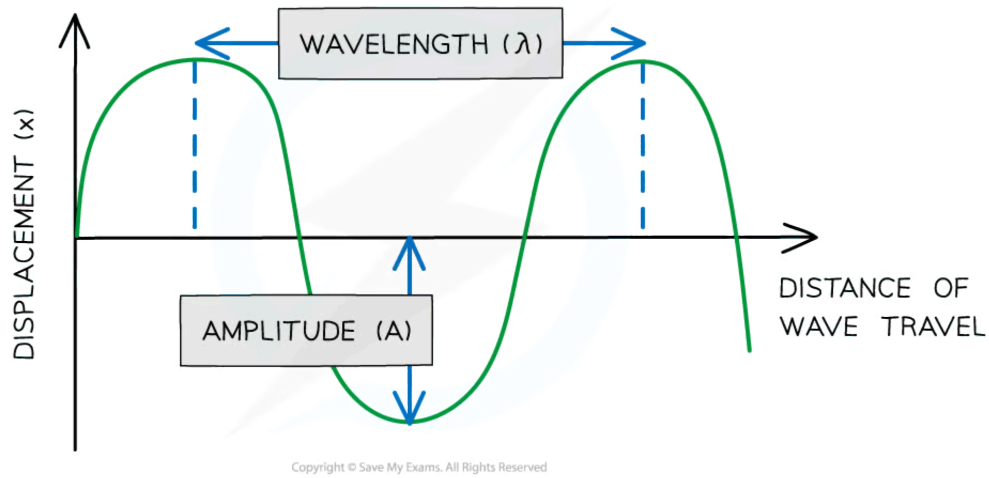

Diagram showing the amplitude and wavelength of a wave

Period & Frequency

- **Period** (*T*) is the time taken for a complete oscillation to pass a fixed point
  - Measured in **seconds** (s)
- **Frequency** (*f*) is the number of complete oscillations to pass a fixed point per second
  - Measured in **Hertz** (Hz)
- The frequency, *f*, and the period, *T*, of a travelling wave are related to each other by the equation:

$$f = \frac{1}{T}$$

- Where:
  - f = frequency (Hz)
  - T = time period (s)

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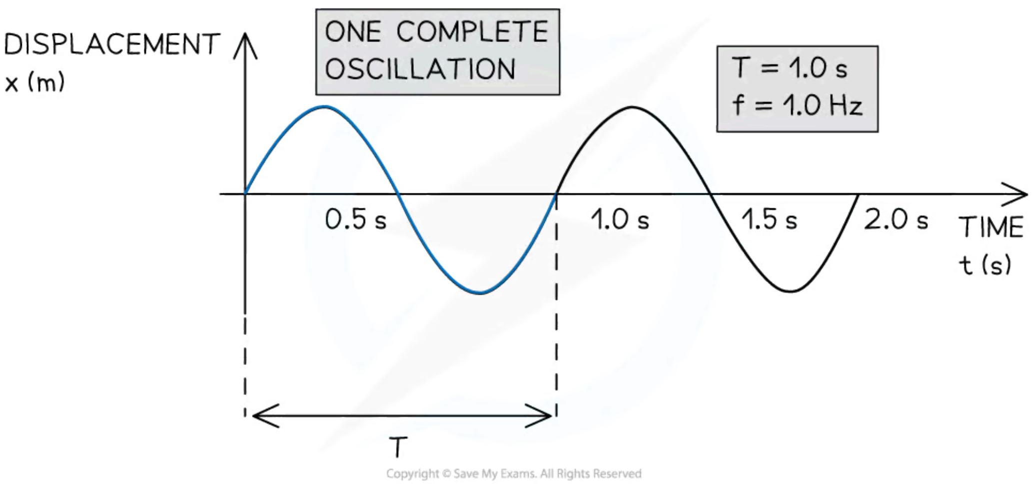

Period T and frequency f of a travelling wave

Wave speed

- **Wave speed** (v) is the distance travelled by the wave per unit time
  - Measured in **metres per second** (m s^{-1})
- The wave speed is defined by the equation:

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

- Where:
  - v = wave speed (m s^{-1})
  - λ = wavelength (m)

- This is referred to as the **wave equation**
- It tells us that for a wave of constant speed:
  - As the wavelength **increases,** the frequency **decreases**
  - As the wavelength **decreases,** the frequency **increases**

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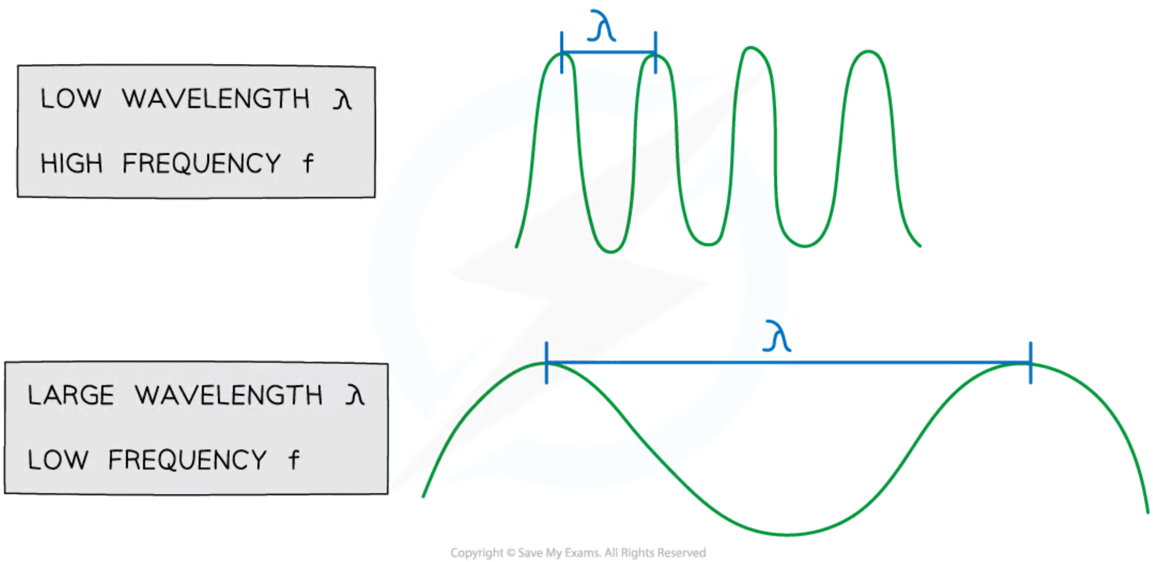
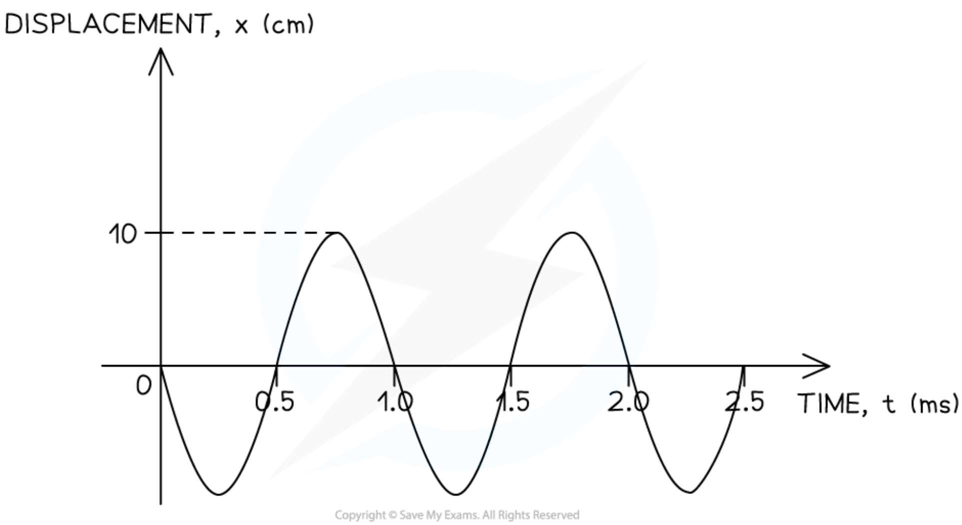


The relationship between the frequency and wavelength of a wave

Your notes

Worked example

The graph below shows a travelling wave.



Determine:

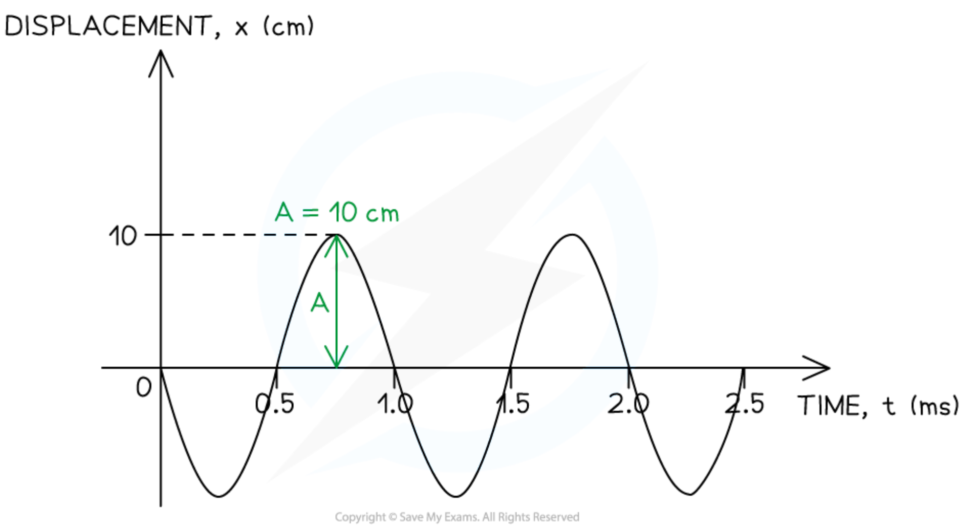
(a) The amplitude *A* of the wave, in m.

(b) The frequency *f* of the wave, in Hz.

Answer:

(a) Identify the amplitude *A* of the wave on the graph

- The amplitude is defined as the maximum displacement from the equilibrium position (x = 0)



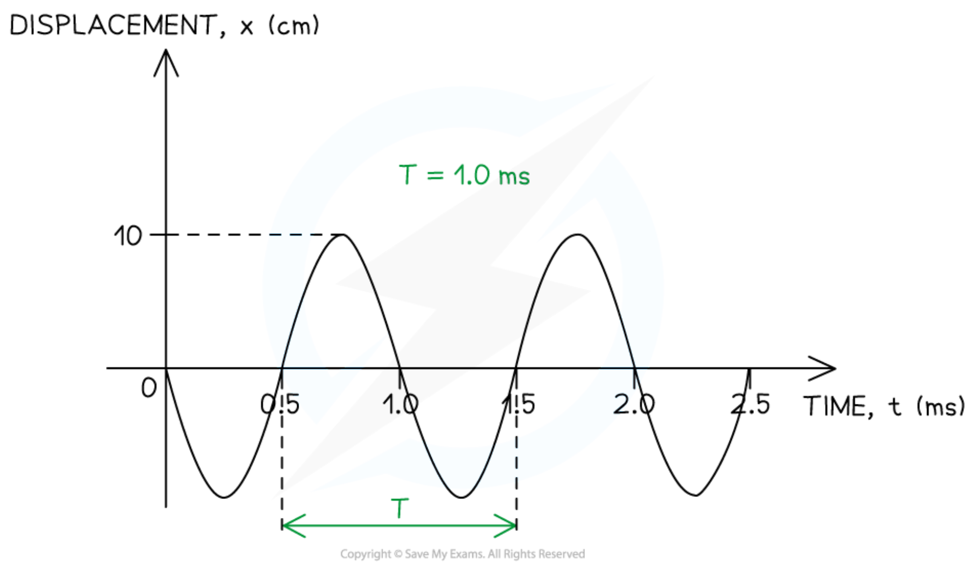
- The amplitude must be converted from centimetres (cm) into metres (m)

$$A = 0.1 \text{ m}$$

(b) Calculate the frequency of the wave

Step 1: Identify the period *T* of the wave on the graph

- The period is defined as the time taken for one complete oscillation to occur



- The period must be converted from milliseconds (ms) into seconds (s)

$$T = 1 \times 10^{-3} \text{ s}$$

Step 2: Write down the relationship between the frequency *f* and the period *T*

$$f = \frac{1}{T}$$

Step 3: Substitute the value of the period determined in Step 1

$$f = \frac{1}{1 \times 10^{-3}} = 1000 \text{ Hz}$$

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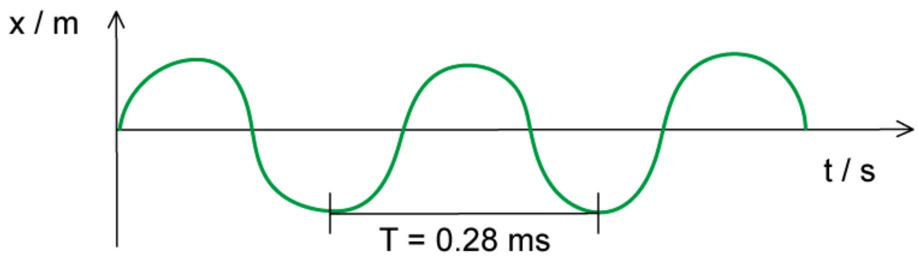
Worked example

The wave in the diagram below has a speed of 340 m s^{-1}.



Determine the wavelength of the wave.

Answer:

STEP 1

WAVE EQUATION

$v = f\lambda$

STEP 2

REARRANGE FOR WAVELENGTH

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

STEP 3

CALCULATE f

$f = \frac{1}{T} = \frac{1}{0.28 \times 10^{-3}\,s} = 3571.43 \text{ Hz}$

STEP 4

SUBSTITUTE VALUE BACK INTO WAVE EQUATION

$\lambda = \frac{340}{3571.43} = 0.095 \text{ m}$ (2 s.f.)

Your notes

Worked example

A travelling wave has a period of 1.0 μs and travels at a velocity of 100 cm s^{-1}.

Calculate the wavelength of the wave, in m.

Answer:

Step 1: Write down the known quantities

- Period, T = 1.0 μs = 1.0×10^{-6} s
- Velocity, v = 100 cm s^{-1} = 1.0 m s^{-1}

Note the conversions:

- The period must be converted from microseconds (μs) into seconds (s)
- The velocity must be converted from cm s^{-1} into m s^{-1}

Step 2: Write down the relationship between the frequency *f* and the period *T*

$$f = \frac{1}{T}$$

Step 3: Substitute the value of the period into the above equation to calculate the frequency

$$f = \frac{1}{1 \times 10^{-6}} = 1 \times 10^{6}$$

Step 4: Write down the wave equation

$$v = f\lambda$$

Step 5: Rearrange the wave equation to calculate the wavelength λ

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

Step 6: Substitute the numbers into the above equation

$$\lambda = \frac{1}{1 \times 10^{6}} = 1 \times 10^{-6}$$

Your notes

Examiner Tip

You must be able to interpret different properties of waves from a variety of graphs. You may recognise calculating the time period and wavelength look very similar (the distance for one full wave). This is the time period if the *x-axis* is **time**. If the *x*-axis is **distance**, then this distance is the wavelength.

Pay very close attention to units. If you want a frequency in Hertz, then the time period must be in **seconds** and not milliseconds etc.

Transverse & Longitudinal Waves

Your notes

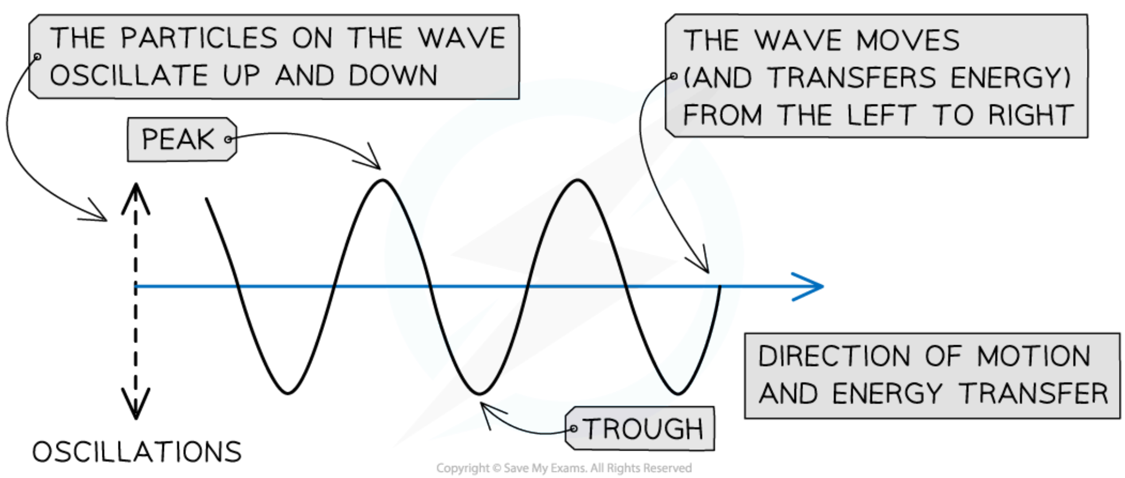
Transverse & Longitudinal Waves

- In mechanical waves, particles **oscillate** about fixed points
- There are two types of wave: **transverse** and **longitudinal**
- The type of wave can be determined by the direction of the oscillations in relation to the direction the wave is travelling

Transverse Waves

- Transverse waves are defined as follows:

  A wave in which the oscillations are perpendicular to the direction of motion and energy transfer

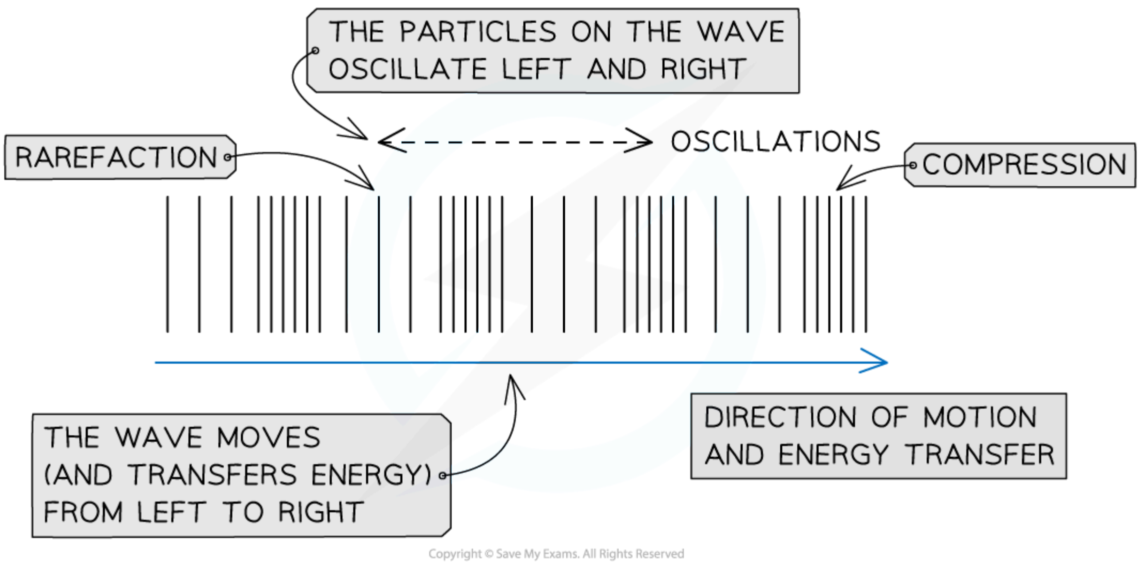


A transverse wave travelling from left to right

- This means that each particle in the wave vibrates **up** and **down**
- Transverse waves show areas of **peaks** and **troughs**
- Examples of transverse waves include:
  - Electromagnetic waves e.g. radio, visible light, UV
  - Vibrations on a guitar string
- Transverse waves transfer **energy**, even if there is no resultant displacement of the medium
  - This means transverse waves do not need particles to propagate, so they **can travel through a vacuum**
  - This is why we can still feel the UV radiation from the Sun, as it can travel through the vacuum of space

Longitudinal Waves

- Longitudinal waves are defined as follows:
  A wave in which the oscillations are parallel to the direction of motion and energy transfer

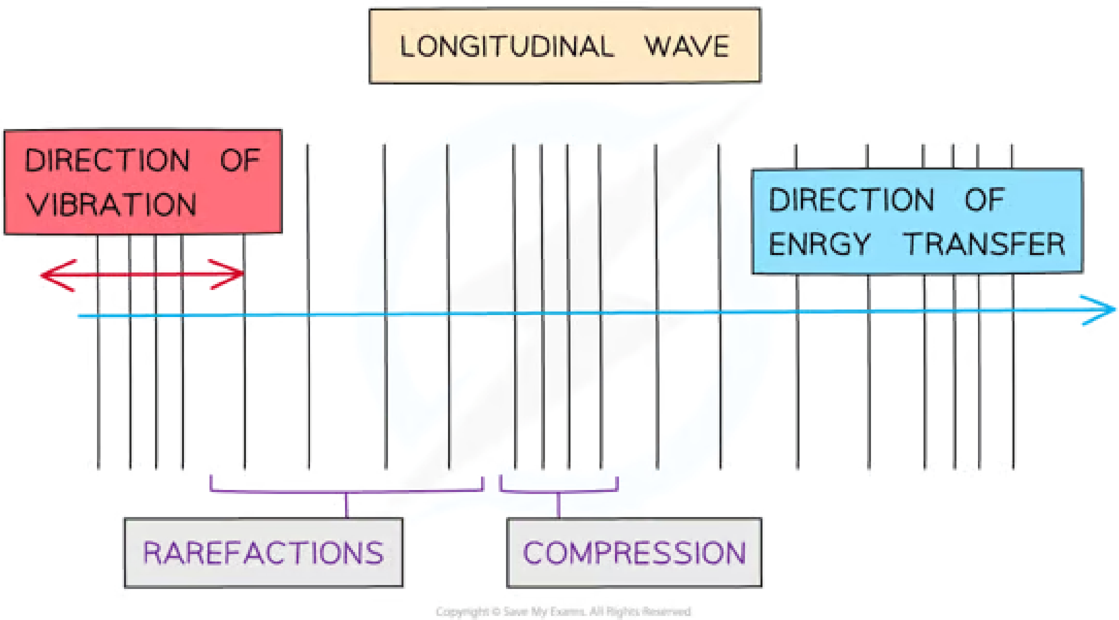


A longitudinal wave travelling from left to right

- This means that each particle in the wave only vibrates **left** and **right**
- As a longitudinal wave propagates, areas of low and high pressure can be observed:
  - A **rarefaction** is an area of low pressure, with the particles being further apart from each other
  - A **compression** is an area of high pressure, with the particles being closer to each other

Your notes

Your notes

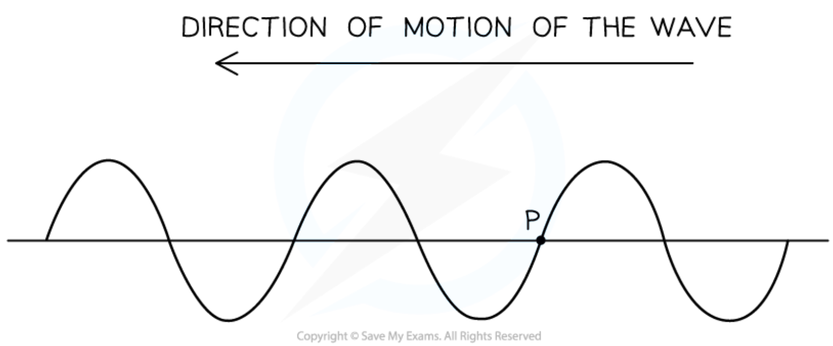


Rarefactions and compressions on a longitudinal wave

- **Sound waves** are an example of longitudinal waves
- Longitudinal waves need **particles** to propagate, so they **cannot travel through a vacuum**
  - This is why you cannot hear anything in the vacuum of outer space

Worked example

The diagram below represents a transverse wave at time t = 0. The direction of motion of the wave is shown. Point **P** is a point on the wave. State in which direction point **P** will move immediately after the time shown.



Answer:

Step 1: Determine the possible directions that point P can travel in

- In transverse waves, the particles oscillate perpendicular to the direction of motion
- This transverse wave travels from right to left
- Oscillations will either be up or down
- Hence point **P** will either move up or down

Step 2: Determine the next direction of point P

- Since the wave is moving from right to left, a crest (i.e. a point of maximum displacement above the equilibrium position) will be approaching point P immediately after the time shown
- Point P will be moving **upwards**

Your notes

Examiner Tip

Exam questions will focus on the description of the motion of particles of a medium when a wave passes through it, for both types. Make sure you remember the difference between them:

- Particles in a transverse wave move up and down
- Particles in a longitudinal wave move left and right

The particles do **not** travel 'along' the wave, they are just in one position, and can only move either vertically or horizontally. All the particles have the same motion, but are displaced slightly, creating the illusion that the whole **wave** is moving together.

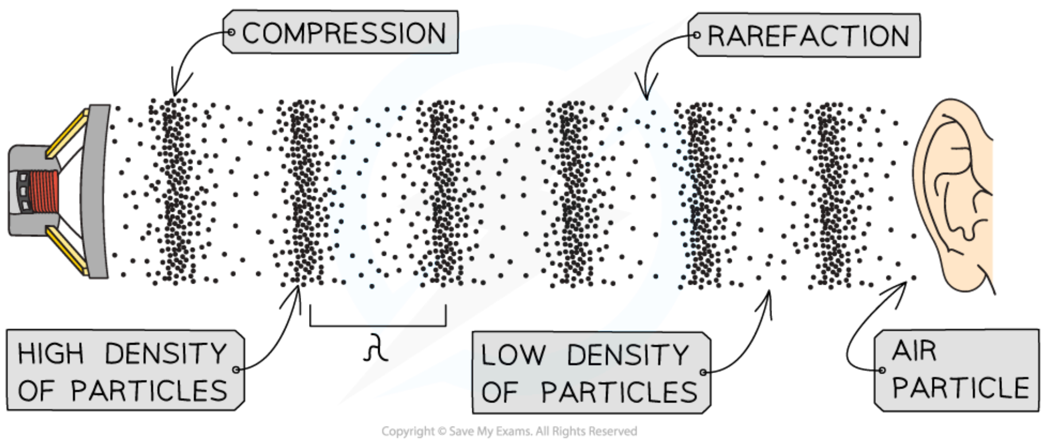
Your notes

Your notes

Sound Waves

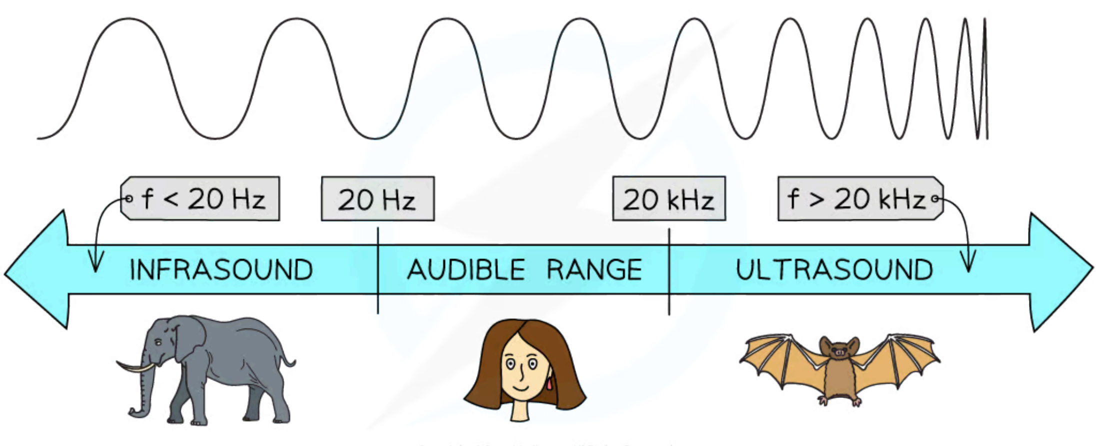
Sound Waves

- Sound waves are **longitudinal waves** and, as such, require a **medium** in which to propagate
- Sound waves are generated by oscillating sources, which produce a change in **density** of the surrounding medium
- The sound wave then travels with a series of **compressions** and **rarefactions**



A sound wave travelling through air

- Sound waves form a continuous **spectrum** based on their frequency



The spectrum of sound waves

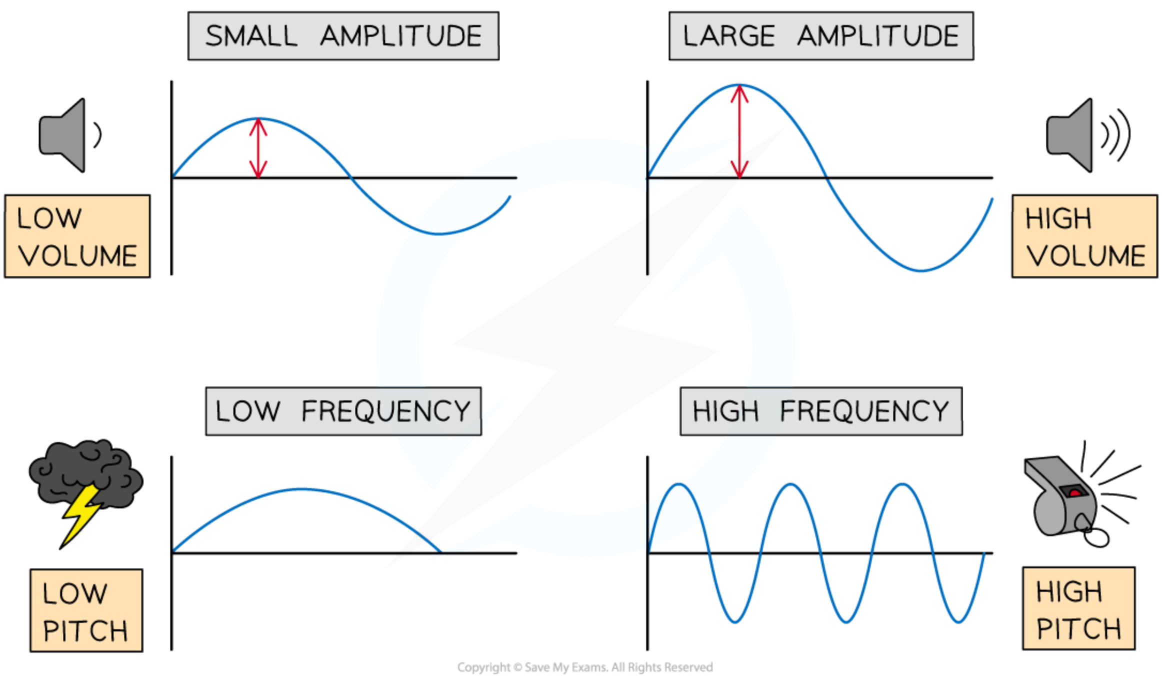
- Humans can only hear sounds with frequencies in the range 20 Hz - 20 kHz, known as the **audible range**

- Sounds with frequencies below and above this range cannot be detected by the human ear

Pitch & Volume

- The frequency of a sound wave is related to its **pitch**
  - Sounds with a **high** pitch have a **high** frequency (or short wavelength)
  - Sounds with a **low** pitch have a **low** frequency (or long wavelength)

- The amplitude of a sound wave is related to its **volume**
  - Sounds with a **large** amplitude have a **high** volume
  - Sounds with a **small** amplitude have a **low** volume



Pitch and amplitude of sound

Speed of Sound

- Sound waves travel at a speed of about 340 m s^{-1} in air at room temperature
  - The higher the air temperature, the greater the speed of sound
  - The is because the average kinetic energy of the particles is higher

- Sound travels the **fastest** through **solids**, since solid particles are closely packed and can pass the oscillations onto their neighbours much faster
- Sound travels the **slowest** in **gases**, since gas particles are spread out and less efficient in transferring the oscillations to their neighbours

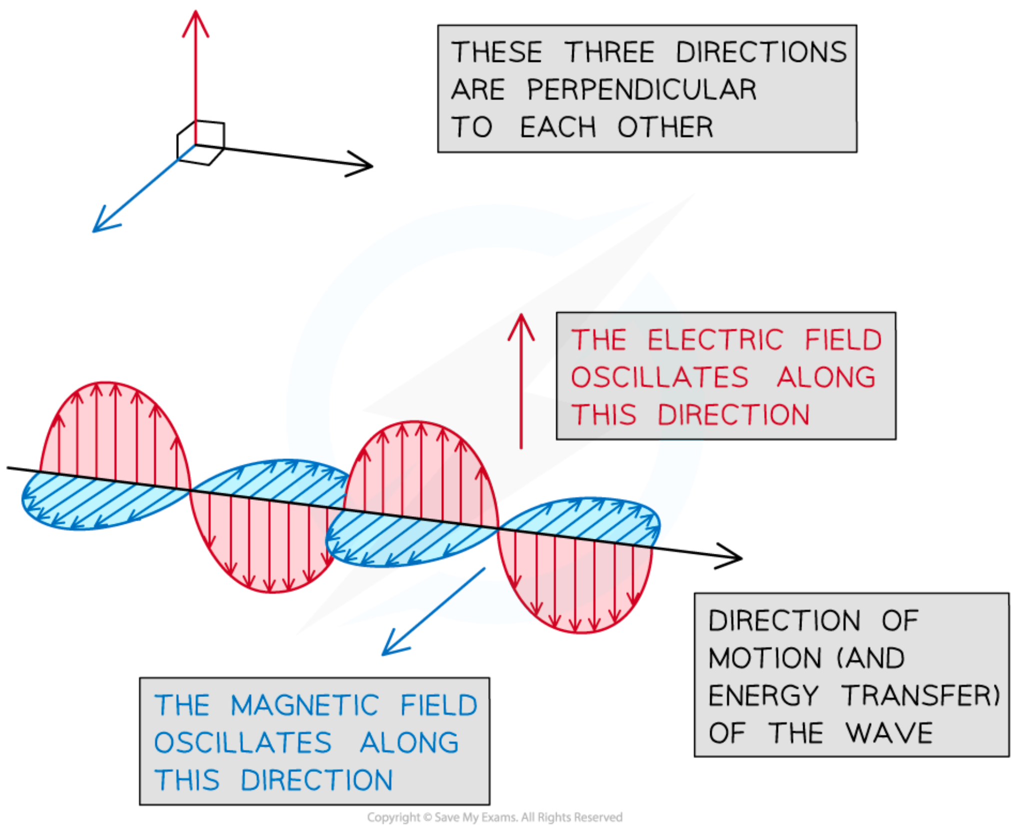
Your notes

Your notes

Electromagnetic Waves

The Electromagnetic Spectrum

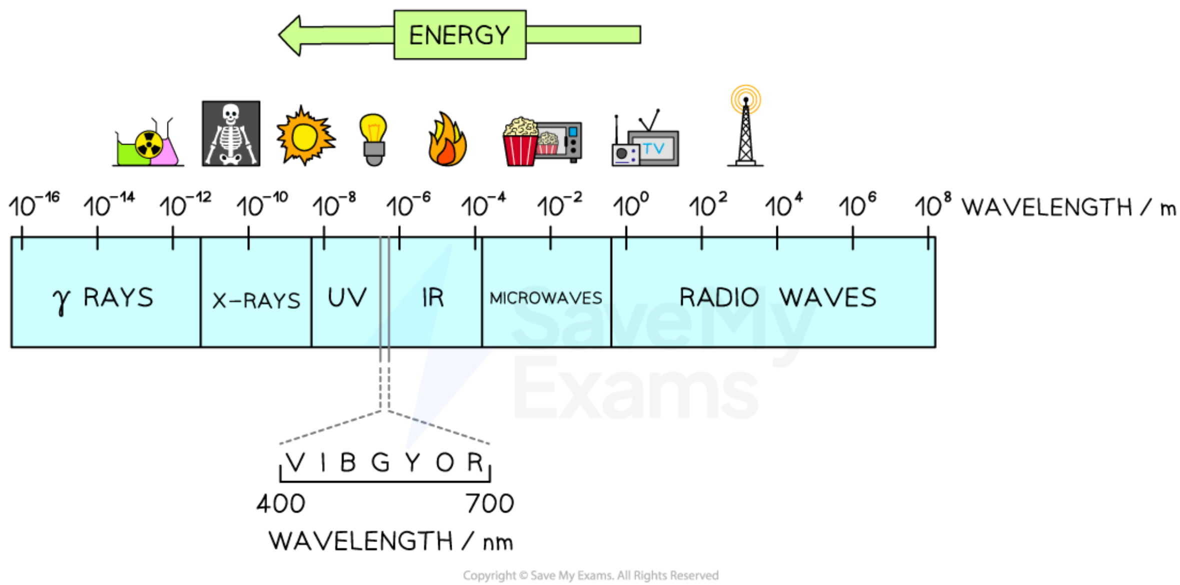
- An electromagnetic wave is generated by the combined oscillation of an **electric** and a **magnetic field**
- These fields oscillate **perpendicularly** to each other and to the direction of motion of the wave (i.e. the direction in which energy is transferred)



An electromagnetic wave is generated by the combined oscillation of an electric and a magnetic field

- Electromagnetic waves are **transverse waves** and, as such, they can travel through **vacuum**
- Regardless of their frequency, all electromagnetic waves travel at the **speed of light** $c = 3 \times 10^8$ m s^{-1} in vacuum
- Electromagnetic waves form a continuous **spectrum** based on their frequency (or wavelength)
- The shorter the wavelength, or higher the frequency, the greater the **energy** of the wave

Your notes



The electromagnetic spectrum

- Humans can only sense electromagnetic waves with wavelengths in the range 700 nm - 400 nm, which are the limits of the so-called **visible spectrum**
  - Electromagnetic waves with longer and shorter wavelengths are invisible to the human eye
- Knowing the wavelengths of electromagnetic waves, their frequencies can be calculated using
  - The wave equation
  - The fact that the speed of light ($c = 3 \times 10^8$ m s^{-1}) in a vacuum is constant

Worked example

:The wavelength of blue light falls within the range 450 nm – 490 nm.

Determine the range of frequencies of blue light.

Answer:

Step 1: Write down the known quantities

- Note that you must convert the values of the wavelength from nanometres (nm) into metres (m)
  - λ_{lower} = 450 nm = 4.5 × 10^{-7} m
  - λ_{higher} = 490 nm = 4.9 × 10^{-7} m

Step 2: Remember that all electromagnetic waves travel at the speed of light in vacuum

- From the data booklet, c = 3.00 × 10^8 m s^{-1}

Step 3: Write down the wave equation

$$v = f\lambda$$

Step 4: Rearrange the above equation to calculate the frequency *f*

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

Step 5: Substitute the lower and higher values of the wavelength to calculate the limiting values of the frequency of blue light

- The lower frequency f_{lower} corresponds to the higher value of the wavelength λ_{higher}

$$f_{lower} = \frac{3.00 \times 10^8}{4.9 \times 10^{-7}} = 6.1 \times 10^{14} \text{ Hz}$$

- The higher frequency f_{higher} corresponds to the lower value of the wavelength λ_{lower}

$$f = \frac{3.00 \times 10^8}{4.5 \times 10^{-7}} = 6.7 \times 10^{14} \text{ Hz}$$

Step 6: Write down the range of frequencies of blue light

$$f = 6.1 \times 10^{14} - 6.7 \times 10^{14} \text{ Hz}$$

Your notes

Examiner Tip

You don't need to memorise the order or the wavelengths of waves in the electromagnetic spectrum, as this is given in your data booklet. However, you must remember all electromagnetic waves travel at the speed of light, c.

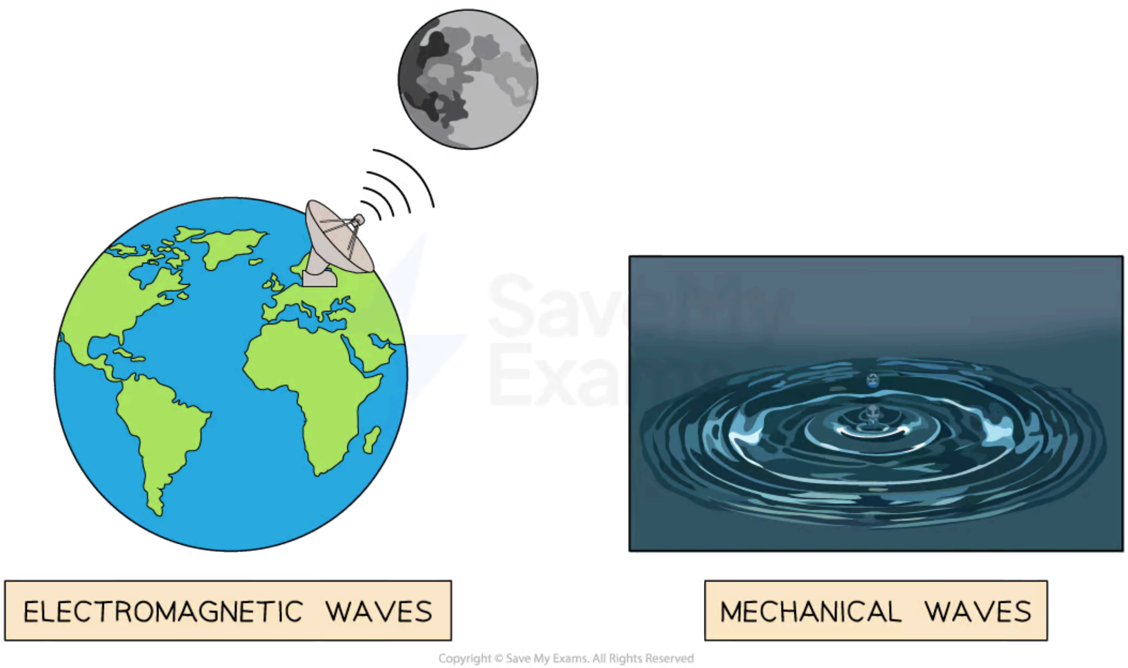
Your notes

Comparing Mechanical & Electromagnetic Waves

Your notes

- Travelling waves can be of two types, **mechanical** and **electromagnetic**

Mechanical Waves	Electromagnetic Waves
Require a medium, such as a fluid or solid to propagate through	Do not require a medium
Can be transverse or longitudinal	Are only transverse
Cannot travel through a vacuum	Can travel through a vacuum
Are produced by the oscillation of particles in a medium	Are produced by oscillating charged particles
Examples: Sound waves, waves on the surface of the ocean	Examples: Radio waves, UV rays, X-rays
Travel a lot slower than the speed of light	Travel at the speed of light



Electromagnetic waves can travel in a vacuum (such as space) whilst mechanical waves require a medium (such as water)

Examiner Tip

You must be able to identify the features of either mechanical or electromagnetic waves, depending on the question.

A common misconception is that mechanical waves are just longitudinal, like sound waves. However, they can also be transverse waves that travel through a medium such as seismic waves (created during an earthquake) and water waves.

Your notes