HL IB Physics

Wave Model

Contents

Properties of Waves

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**

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)

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**

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

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

Transverse & Longitudinal Waves

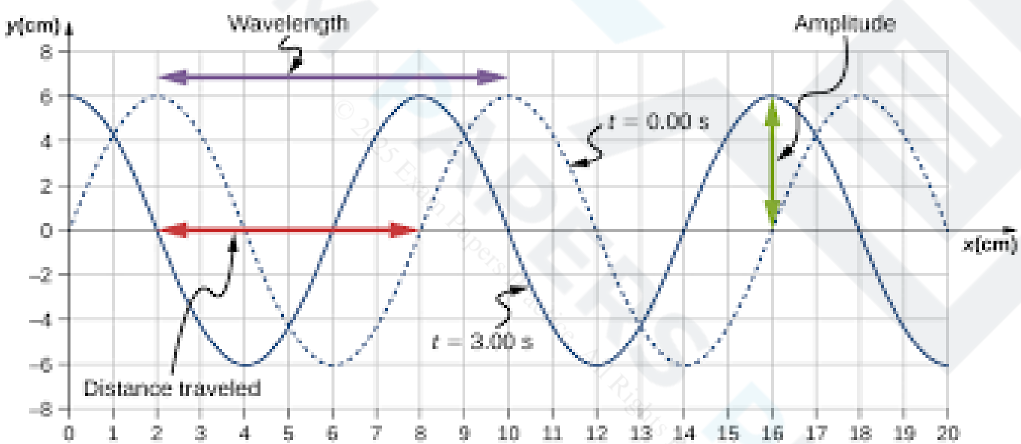
Transverse & Longitudinal Waves

- 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

- 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

- **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

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

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

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)
- 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
- 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

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

Comparing Mechanical & Electromagnetic Waves

- 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