CAIE Physics A-level

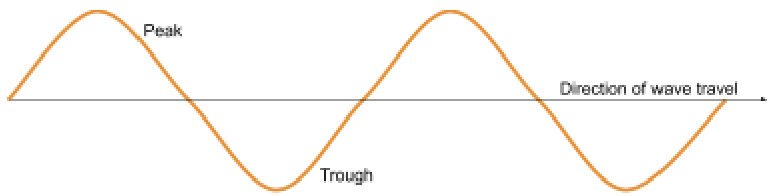
Topic 14: Waves

Notes

14 - Waves

14.1 - Progressive Waves

Wave motion can be demonstrated using the vibration of a rope:



As you can see, the wave is made up of **consecutive peaks and troughs**, which repeat continuously.

You need to be aware of the following **key terms**:

Displacement	The distance of a particle away from the equilibrium position.
Amplitude	A wave's maximum displacement from the equilibrium position.
Frequency (f)	The number of complete oscillations passing through a point per second.
Wavelength (λ)	The length of one whole oscillation (e.g. the distance between successive peaks/troughs).
Speed (v)	The distance travelled by the wave per unit time.
Phase difference	How much a wave lags behind another, (units are radians, degrees or fractions of a cycle). This value is used to compare the stages that two waves are in.
Period (T)	The time taken for one full oscillation.

The **speed (v)** of a wave is equal to the wave's frequency multiplied by its wavelength.

$$v = f\lambda$$

The above equation can be derived using the definitions of speed, frequency and wavelength as shown below:

1. Consider a wave travelling at a speed v, with a wavelength of λ m.

$$speed = \frac{distance}{time}$$

$$v = \frac{distance\ travelled\ by\ wave}{time}$$

2. A wave travels a distance equal to its wavelength during one time period, therefore:

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

3. As f = 1/T, substitute frequency into the above equation.

$$v = f\lambda$$

A **progressive wave** is a type of wave that **transfers energy without transferring material**.

Intensity is the power (energy transferred per unit time) per unit area, and can be calculated using the equation below:

$$I = \frac{P}{A}$$

Where P is the power and A is the area.

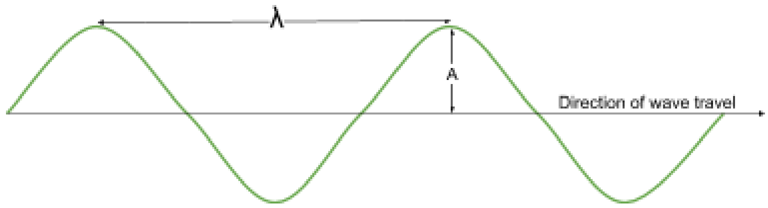
The **intensity of a wave** is **directly proportional to its amplitude squared**, as shown below:

$$Intensity \propto (amplitude)^2$$

14.2 - Transverse and longitudinal waves

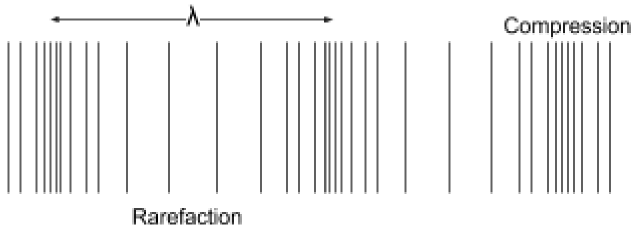
Transverse waves - the oscillations of particles (or fields) are at **right angles to the direction of energy transfer**

- All electromagnetic (EM) waves are **transverse** and travel at 3 x 10^8 ms^{-1} in a vacuum.
- Transverse waves can be demonstrated by shaking a slinky **vertically** or through the waves seen on a string, when it's attached to a signal generator.



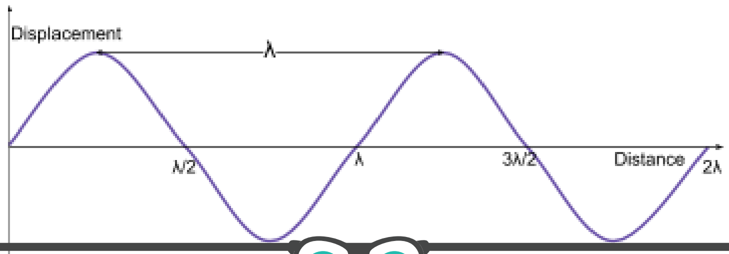
Longitudinal waves - the oscillations of particles are **parallel to the direction of energy transfer**

- These are made up of **compressions and rarefactions** and can't travel in a vacuum.
- Sound is an example of a longitudinal wave, and they can be demonstrated by pushing a slinky **horizontally**.

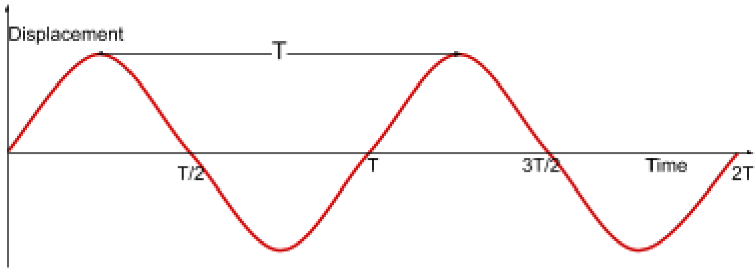


There are two types of graphs which can be used to represent waves:

➔ **Displacement-distance graphs -** these show how the displacement of a particle varies with the distance of wave travel and can be used to measure wavelength.
For a transverse wave, the displacement distance graph will look very **similar to the actual wave**, whereas for a longitudinal wave the graph will look very different from the wave.

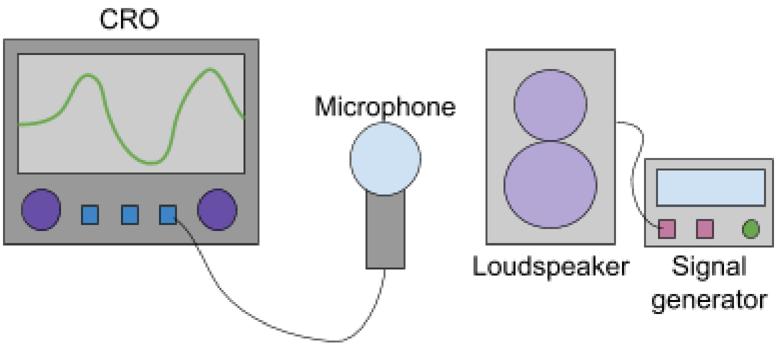


➔ **Displacement-time graphs -** these show how the displacement of a particle varies with time and can be used to measure the period of a wave.



14.3 - Determination of Frequency and Wavelength of Sound Waves

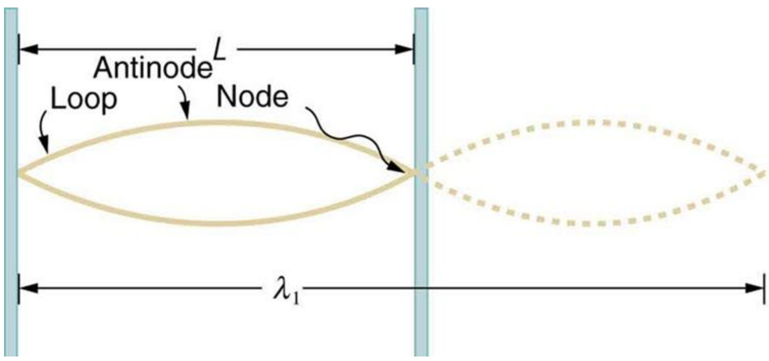
You can measure the **frequency** of a sound using a **cathode-ray oscilloscope (CRO)** as described below:



1. Connect a microphone to the CRO input and play the sound using a signal generator attached to a speaker.
2. The CRO will display the sound wave's **displacement-time** graph. In order to change the scale on the x-axis so that the waveforms fill as much of the screen as possible, adjust the time-base settings on the oscilloscope.
3. Measure the number of full waves that appear on the screen and the number of divisions they appear on. Multiply the number of divisions by the time-base to find the time taken, so that you can calculate the period of the wave (time taken for one full oscillation).
4. Finally, use the formula $f = \frac{1}{T}$ to calculate frequency.

A **stationary wave** is formed from the **superposition of 2 progressive waves**, travelling in **opposite directions** in the same plane (this is explained in further detail in section 15).

Stationary waves are formed of **nodes**, which are points of minimum displacement and **antinodes**, which are points of maximum displacement. The distance **between adjacent nodes (or antinodes) is half a wavelength**, and this fact allows stationary waves to be used to determine the wavelength.



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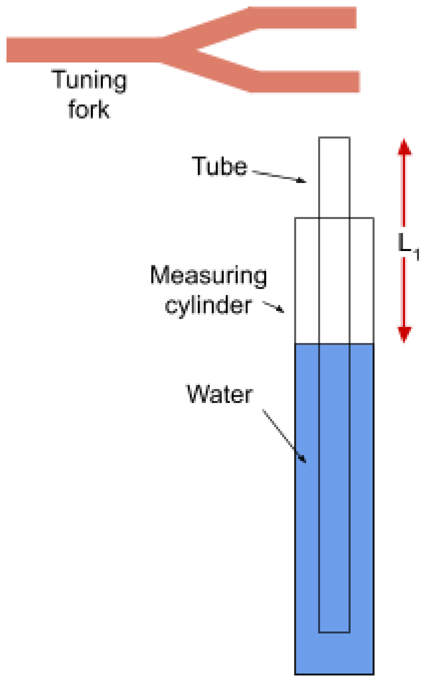
You can measure the **wavelength** of sound using **stationary waves** as described below:



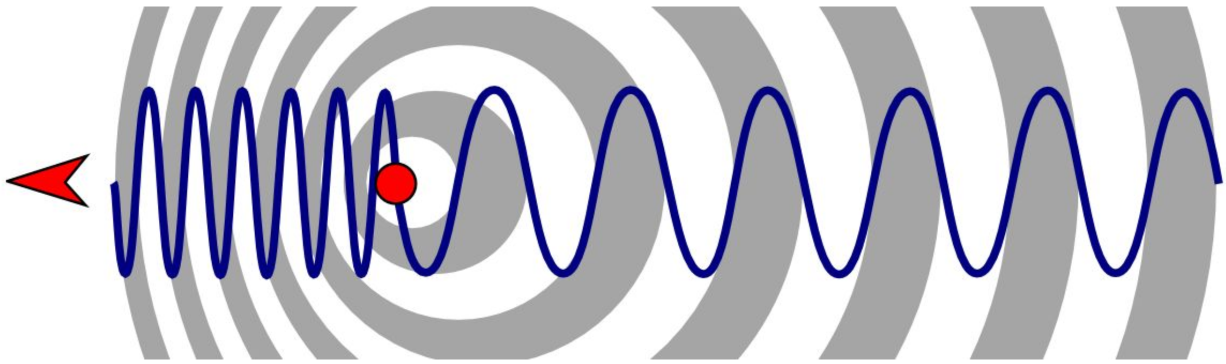
1. Fill a measuring cylinder around three quarters of the way up with water.
2. Place a tube into the measuring cylinder, as shown on the diagram to the right, and hold it in place using a clamp stand.
3. Hit a tuning fork with a hammer and hold it just above the tube and adjust the tube's height until a stationary wave is formed. When a stationary wave forms, the sound produced by the tuning fork will be noticeably amplified.
4. Measure the height of the air column in the tube (L_1) at this point.
5. Then, move the tube up again until a second stationary wave is formed. Again record the height of the air column in the tube (L_2).
6. The wavelength of the wave is equal to **$2(L_2 - L_1)$**.

Two measurements of the length of the air column in the tube are taken because the antinode formed is formed just above the top of the tube, so subtracting these measurements removes the **systematic error** that this causes.

A similar experiment can be carried out using a loudspeaker directed at a wall, changing its position until a stationary wave is formed, and using a microphone to investigate its nodes and antinodes. Then, you could measure the distance between adjacent nodes in order to calculate wavelength.

14.4 - Doppler Effect

The **Doppler effect** is the **compression or spreading out of waves** that are emitted or reflected by a **moving source**. As the source is moving, the wavelengths in front of it are compressed and the wavelengths behind it are spread out as shown in the diagram below, this leads to a **change in observed frequency**. An example of the doppler effect can be heard in the sound of a car moving past you.



You can calculate the **observed frequency (f_o)** of a moving source of sound when it moves relative to a stationary observer using the equation below:

$$f_o = \frac{f_s v}{(v \pm v_s)}$$

Where f_s is the frequency given out by the moving source, **v** is the speed of sound, and v_s is the constant speed of the source.

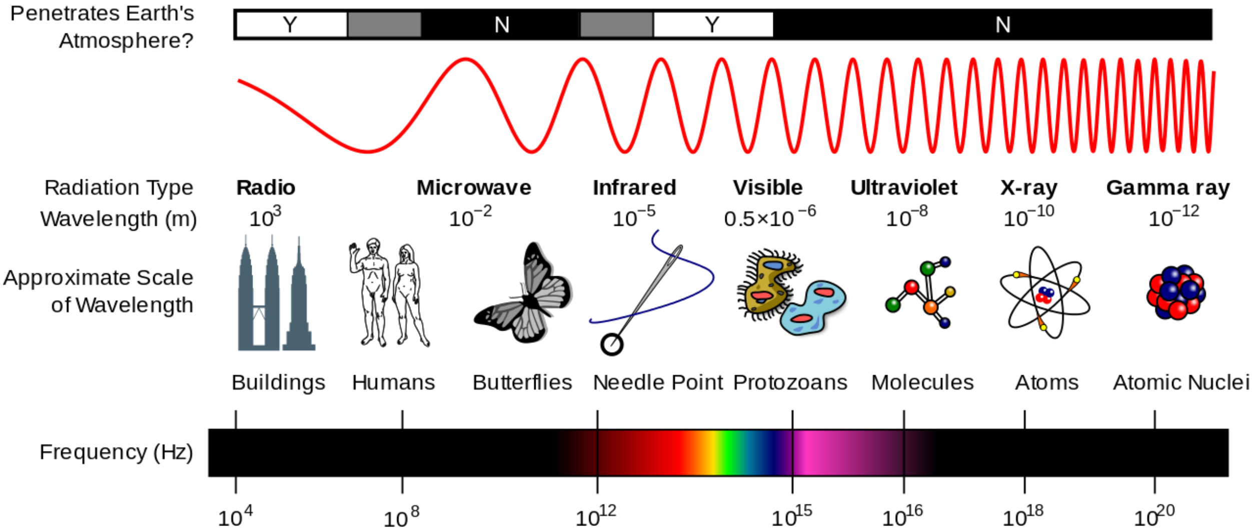
The sign on the bottom of the equation depends on whether the source is moving towards or away from the observer:

- **v_s is added** when the source is moving **away** from the observer
- **v_s is subtracted** when the source is moving **towards** from the observer.

It is important to note that **the Doppler effect is observed in all waves**, **not** only sound waves. For example, the light given out by distant objects in space will experience a Doppler shift.

14.5 - Electromagnetic Spectrum

The electromagnetic spectrum contains all electromagnetic (EM) waves; these are classified into principal categories by their wavelengths. The diagram below shows the principal categories and their associated wavelengths.



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You should be aware of the orders of magnitude (the power of ten) of the above principal categories, as shown in the table below:

EM radiation	Order of magnitude of wavelength (m)
Radio	10^3
Microwave	10^{-2}
Infrared	10^{-5}
Visible	10^{-7}

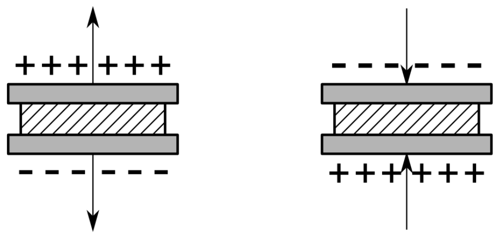
Ultraviolet	10^{-8}
X-ray	10^{-10}
Gamma ray	10^{-12}

All EM waves travel at the same speed in free space, which is **3×10^{8} ms^{-1}**, the speed of light in free space (c).

14.6 - Production and Use of Ultrasound in Diagnosis (A-level only)

An **ultrasound wave** is a **longitudinal** wave with a frequency greater than **20 kHz**, however when used for medical purposes the frequency of ultrasound waves used is usually between 1 MHz and 20 MHz.

When a **potential difference is applied** to a **piezoelectric** material (e.g. a quartz crystal), it will experience **mechanical deformation** (the reverse is also true). This is known as the **piezoelectric effect** and it is used to produce ultrasound waves.



A transducer, containing piezoelectric material is used to transmit and detect ultrasound waves, this is because:

- When an **alternating** potential difference is applied to a piezoelectric material it will cause the material to **vibrate at the same frequency as the applied p.d**. If the frequency of the alternating p.d is equal to the **natural frequency** of the piezoelectric material, there is **resonance** and the vibrations reach their **maximum amplitude**. These vibrations produce pulses of ultrasound waves that are emitted.
- When a piezoelectric material is hit by an ultrasound wave it will **deform**, producing a potential difference which can be amplified and displayed (usually on an oscilloscope).

Ultrasound is reflected when it reaches a **boundary between two mediums** and the amount of reflection that takes place depends on the **difference in acoustic impedance** of the two mediums.

The **intensities** of the reflected waves can be used to determine the **internal structure** of the target (e.g. the density of the materials within the target) being investigated.
The **time taken** for these reflected waves to return can be used to determine the **position of objects/structures** within the target.

The **specific acoustic impedance** is a measure of how difficult it is for an acoustic wave to travel through a **particular** medium (e.g inside a wind instrument).

The **intensity reflection coefficient** is a measure of the proportion of the incident ultrasound signal that is reflected when it moves between two mediums. As the amount of reflection that takes place is dependent on the **difference in acoustic impedance** of the two mediums, the **intensity reflection coefficient is dependent on the specific acoustic impedances of the two mediums**.

As ultrasound waves move through matter, they experience **attenuation** meaning that they are absorbed and scattered, **decreasing their intensity**. You can calculate the intensity of an ultrasound wave after it has travelled a distance x through a particular material using the following equation:

$$I = I_0 e^{-\mu x}$$

Where I_0 is the initial intensity, x is the distance travelled through the material, and μ is the material's linear attenuation coefficient.