# Waves

Wave terms, using a CRO, v = f lambda, intensity, transverse and longitudinal waves, the Doppler effect for a moving source, the electromagnetic spectrum, and polarisation with Malus's law.

## Progressive waves

A **progressive wave** transfers energy from one place to another without transferring matter. You can see this on ropes, on springs and on water in a ripple tank.

### Wave terms

| Term | Meaning |
|---|---|
| Displacement $x$ | distance of a point from its rest position |
| Amplitude $A$ | maximum displacement |
| Wavelength $\lambda$ | distance between neighbouring points in phase, such as crest to crest |
| Period $T$ | time for one complete oscillation |
| Frequency $f$ | number of oscillations per unit time, $f = 1/T$ |
| Speed $v$ | distance a wavefront travels per unit time |
| Phase difference | how far one oscillation is ahead of another, in degrees or radians. One whole wavelength is 360° or $2\pi$ rad |

### Using a CRO

A cathode-ray oscilloscope displays voltage against time.

- The **time-base** setting (such as 2 ms/div) is the time per horizontal division. Measure the divisions for one cycle, multiply, and that is the period. Then $f = 1/T$.
- The **y-gain** setting (such as 5 V/div) is the voltage per vertical division. Amplitude is the divisions from the centre to a peak, multiplied by the y-gain.

> TRY IT
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> **One cycle covers 4.0 divisions with the time-base at 0.50 ms/div. Find the frequency.** $T = 4.0 \times 0.50 = 2.0$ ms, so $f = 1/(2.0 \times 10^{-3}) = 500$ Hz.

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### The wave equation

In one period $T$, a wave travels one wavelength. So $v = \lambda/T$, and since $f = 1/T$:

$$v = f\lambda$$

### Intensity

**Intensity** is the power per unit area, at right angles to the direction of travel, $I = P/A$, measured in W m$^{-2}$. For a progressive wave:

$$I \propto A^2$$

Doubling the amplitude makes the intensity four times as large. From a point source spreading out equally, $I = P/(4\pi r^2)$.

## Transverse and longitudinal waves

| | Transverse | Longitudinal |
|---|---|---|
| Oscillations | at right angles to the direction of energy transfer | parallel to the direction of energy transfer |
| Examples | light, water ripples, waves on a rope | sound, a pushed slinky |
| Features | crests and troughs | compressions and rarefactions |
| Can be polarised? | yes | no |

### Reading wave graphs

Two graphs look alike, and you must check the axis:

- **Displacement against distance** is a snapshot of the wave. It gives the **wavelength**.
- **Displacement against time** shows one point as time passes. It gives the **period**.

For a longitudinal wave, a graph of displacement against distance is still a sine curve, even though the particles move along the wave's direction. Compressions are where neighbouring particles move towards a point.

## Doppler effect for sound waves

When a source of sound moves relative to a stationary observer, the observed frequency differs from the frequency the source emits. Coming towards you, the wavefronts are bunched up, so you hear a higher frequency. Going away, they are spread out, so you hear a lower one.

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$$f_o = \frac{f_s\, v}{v \pm v_s}$$

where $v$ is the speed of sound and $v_s$ is the speed of the source. Use **minus when the source approaches** (the observed frequency goes up) and plus when it recedes.

> TRY IT
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> **A 600 Hz siren moves towards you at 30 m/s. The speed of sound is 330 m/s. What frequency do you hear?** $f_o = 600 \times 330/(330 - 30) = 660$ Hz.

## Electromagnetic spectrum

All electromagnetic waves are **transverse** and travel at the same speed in free space, $c = 3.00 \times 10^8$ m/s.

| Region | Approximate wavelength range |
|---|---|
| Radio waves | above 0.1 m (can be $10^6$ m) |
| Microwaves | $10^{-3}$ m to 0.1 m |
| Infrared | $7 \times 10^{-7}$ m to $10^{-3}$ m |
| Visible light | 400 nm to 700 nm |
| Ultraviolet | $10^{-8}$ m to $4 \times 10^{-7}$ m |
| X-rays | $10^{-13}$ m to $10^{-8}$ m |
| Gamma rays | below $10^{-11}$ m |

The X-ray and gamma-ray ranges overlap because they are named by how they are made, not just their wavelength.

## Polarisation

Polarisation can only happen to **transverse** waves. In a **plane-polarised** wave, the oscillations are all in one plane that contains the direction of travel. Unpolarised light has oscillations in many planes.

A polarising filter only transmits the component of the oscillations along its transmission axis. So the amplitude after the filter is $A_0 \cos\theta$. Since intensity depends on amplitude squared:

$$I = I_0 \cos^2\theta$$

This is **Malus's law**, where $\theta$ is the angle between the wave's plane of polarisation and the transmission axis.

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**Plane-polarised light of intensity $I_0$ passes through a filter at 60° to its plane, then through a second filter at 90° to the first. What comes out?** After the first: $I_0 \cos^2 60° = 0.25 I_0$, now polarised along the first filter's axis. After the second: $0.25 I_0 \cos^2 90° = 0$. No light gets through.

NOTE

Exam tip: Malus's law applies filter by filter, and $\theta$ is measured from the plane the light has **after** the previous filter. Rotating a single filter through 360° gives two maxima and two minima.

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