Waves

Properties of waves and the wave equation, reflection, refraction and total internal reflection of light, thin lenses and the eye, dispersion, the electromagnetic spectrum and its uses and dangers, and sound including ultrasound.

3.1 General properties of waves

A wave is a vibration that transfers **energy without transferring matter**. A wave on a rope or a spring, or a water wave, shows this: the water or rope moves up and down but does not travel along with the wave.

Features of a wave

- **Crest (peak)** and **trough**: the highest and the lowest points of a transverse wave.
- **Amplitude**: the maximum distance of a point on the wave from its mean (rest) position.
- **Wavelength** λ: the distance between two consecutive identical points on the wave, such as two crests.
- **Frequency** f: the number of wavelengths that pass a point per unit time (the number of waves per second). It is measured in hertz (Hz).
- **Wavefront**: a line joining points on the wave that are at the same stage of vibration (for example, the crests on a water surface).
- **Wave speed** v: the distance the wave travels per unit time.

> wave speed = frequency × wavelength**, that is** $v = f\lambda$**.**

> **TRY IT**
>
> A water wave has a frequency of $5.0\ \text{Hz}$ and a wavelength of $0.20\ \text{m}$. Find its speed.

$v = 5.0 \times 0.20 = 1.0\ \text{m/s}$

> **TRY IT**
>
> A radio wave has a speed of $3.0 \times 10^8\ \text{m/s}$ and a frequency of $1.0 \times 10^8\ \text{Hz}$. Find its wavelength.

$\lambda = \frac{v}{f} = \frac{3.0\times10^8}{1.0\times10^8} = 3.0\ \text{m}$

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Transverse and longitudinal waves

	Transverse	Longitudinal
direction of vibration	at right angles to the direction of energy transfer	parallel to the direction of energy transfer
examples	light and all electromagnetic waves, water surface waves, seismic S-waves (secondary)	sound waves, seismic P-waves (primary)

What waves can do

- **Reflection** at a plane surface: the wave bounces off.
- **Refraction**: the wave changes direction when its speed changes.
- **Diffraction**: the wave spreads out as it passes through a gap or round an edge.

Diffraction through a gap. The effect is greatest when the gap is about the same size as the wavelength. A gap much wider than the wavelength gives little spreading. A longer wavelength diffracts more. Diffraction at an edge also increases with wavelength.

The ripple tank

A ripple tank is a shallow tray of water with a vibrating bar that makes straight waves.

- *Reflection:* waves hitting a straight barrier bounce off at the same angle.
- *Refraction:* put a flat piece of glass in the tank to make the water shallower. The waves slow down, the wavelength gets shorter, and the waves bend where they cross the boundary. The frequency does not change.
- *Diffraction through a gap:* waves spread out after passing through a gap, most when the gap is narrow.
- *Diffraction at an edge:* waves bend round the edge of a barrier.

3.2.1 Reflection of light

- The **normal** is a line at right angles to the surface at the point where the ray hits it.
- The **angle of incidence** i is the angle between the incident ray and the normal.
- The **angle of reflection** r is the angle between the reflected ray and the normal.

> **Law of reflection. The angle of incidence equals the angle of reflection: $i = r$. The incident ray, the reflected ray and the normal are in the same plane.**

Always measure angles from the normal, not from the surface.

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A ray of light hits a plane mirror at $30°$ to the surface of the mirror. What is the angle of reflection?

The angle between the ray and the normal is $90° - 30° = 60°$, so the angle of incidence is $60°$. The angle of reflection is therefore $60°$.

Experiment to show the law. Place a plane mirror upright on a sheet of paper. Draw a normal. Shine a narrow ray along a line at some angle, mark points along the incident and reflected rays, and remove the mirror. Draw the rays, measure the angles, and repeat with other angles.

The image in a plane mirror

The image formed by a plane mirror is:

- the **same size** as the object,
- **as far behind the mirror** as the object is in front,
- **virtual**: it cannot be shown on a screen, because the light only appears to come from the image.

Experiment. Stand a pin in front of a mirror (the object). Place two more pins behind where the image appears, in line with it, viewed from different angles. Mark the positions, then find where the lines cross. Measure the distance of the object and image from the mirror and compare.

3.2.2 Refraction of light

Light changes speed when it passes from one transparent material to another. If it enters at an angle, it changes direction. This is **refraction**.

- Going into a **denser** material (for example, air into glass), light slows down and bends **towards** the normal.
- Going into a **less dense** material, it speeds up and bends **away from** the normal.
- Along the normal, light does not bend.

The **angle of refraction** r is the angle between the refracted ray and the normal.

Refractive index $n = \dfrac{\sin i}{\sin r}$, where i is the angle in the air and r is the angle in the material. It has no unit.

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A ray enters glass from air with an angle of incidence of $50°$. The angle of refraction is $31°$. Find the refractive index of the glass.

$$n = \frac{\sin 50^\circ}{\sin 31^\circ} = \frac{0.766}{0.515} = 1.49$$

Experiment. Put a rectangular glass block on paper and draw round it. Shine a ray into it at an angle. Mark the ray going in and the ray coming out, remove the block and join the points. Measure i and r. A ray goes through a rectangular block and comes out parallel to the incident ray, but shifted sideways. A prism or a semicircular block bends the ray in other ways.

Critical angle and total internal reflection

When light travels from a denser material (such as glass) to a less dense one (such as air), it bends away from the normal. As the angle of incidence increases, the angle of refraction grows towards $90°$.

- The **critical angle** c is the angle of incidence in the denser material for which the angle of refraction is $90°$.
- If the angle of incidence is **greater than the critical angle**, there is no refracted ray. All the light is reflected inside the material. This is **total internal reflection**.

Total internal reflection needs light going from the denser to the less dense material, and an angle of incidence greater than c.

$$n = \frac{1}{\sin c}$$

TRY IT

The refractive index of glass is 1.5. Find the critical angle.

$$\sin c = \frac{1}{1.5} = 0.667 \quad \Rightarrow \quad c = 42°$$

Optical fibres

An optical fibre is a very thin strand of glass. Light entering at one end hits the wall at an angle greater than the critical angle, so it is totally internally reflected again and again along the fibre.

Optical fibres are used in telecommunications (telephone and internet signals sent as pulses of light) and in medicine (endoscopes). Advantages compared with copper cables: they carry far more information, they lose less signal over long distances, and they are not affected by electrical interference.

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3.2.3 Thin lenses

- A **converging (convex)** lens is thicker in the middle. It brings a parallel beam of light together to a point.
- A **diverging (concave)** lens is thinner in the middle. It spreads a parallel beam out so it appears to come from a point.

Term	Meaning
principal axis	the line through the centre of the lens at right angles to it
principal focus (focal point) F	for a converging lens, the point where rays parallel to the principal axis meet after passing through the lens
focal length f	the distance from the centre of the lens to the principal focus

Ray diagrams for a converging lens

Draw two of these three rays from the top of the object. Where they meet is the top of the image.

1. A ray parallel to the principal axis goes through the principal focus on the other side.
2. A ray through the centre of the lens carries straight on.
3. A ray through the principal focus on the object side comes out parallel to the principal axis.

Object position	Image
beyond $2F$	real, inverted, smaller
between F and $2F$	real, inverted, larger
closer than F	virtual, upright, larger, on the same side as the object

A **real image** is formed where rays actually meet, and can be shown on a screen. A **virtual image** is formed where rays only appear to come from, and cannot be shown on a screen.

$$\text{linear magnification} = \frac{\text{image length}}{\text{object length}}$$ **. It has no unit.**

TRY IT

An object $2.0\ \text{cm}$ tall gives an image $6.0\ \text{cm}$ tall. Find the magnification.

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$\frac{6.0}{2.0} = 3.0$

The magnifying glass

A converging lens is a magnifying glass when the object is **closer to the lens than the principal focus**. The image is virtual, upright and larger.

The eye

In the normal eye, the cornea and the lens together focus light from the object on the retina, producing a real, inverted image.

- **Short sight.** The eye can see near objects clearly but not distant ones. The eyeball is too long, or the lens is too powerful, so light from distant objects focuses in front of the retina. It is corrected with a **diverging** lens.
- **Long sight.** The eye can see distant objects clearly but not near ones. Light from near objects focuses behind the retina. It is corrected with a **converging** lens.

3.2.4 Dispersion of light

White light is a mixture of colours. When it passes through a glass prism, each colour is refracted by a different amount (violet the most, red the least), so the white light spreads out into a spectrum. This is **dispersion**.

The seven traditional colours, in order, are red, orange, yellow, green, blue, indigo, violet.

- In order of **increasing frequency**: red to violet.
- In order of **increasing wavelength**: violet to red.

3.3 Electromagnetic spectrum

Electromagnetic waves are transverse waves that need no medium. In order of **increasing frequency** (and decreasing wavelength):

> radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, gamma rays

All electromagnetic waves travel at 3.0×10^8 m/s in a vacuum. The speed in air is about the same.

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Region	Uses
radio waves	radio and television broadcasting, communications, astronomy
microwaves	satellite television, mobile (cell) phones, Bluetooth, microwave ovens
infrared	household appliances (grills, toasters), remote controllers, intruder alarms, thermal imaging, optical fibres
visible light	photography, vision
ultraviolet	security marking, detecting counterfeit bank notes, sterilising water
X-rays	medical imaging in hospitals, security scanners, killing cancer cells, finding cracks in metal
gamma rays	detecting and killing cancer cells, sterilising food and medical equipment, finding cracks in metal

Dangers of electromagnetic radiation

- **Excessive exposure to microwaves and infrared** heats soft tissue and can cause burns.
- **Ultraviolet, X-rays and gamma rays** are **ionising**: they can damage or mutate cells. Ultraviolet causes skin cancer and cataracts. X-rays and gamma rays cause cell mutation and cancer.

3.4 Sound

Sound is produced by a **vibrating source**, such as a guitar string, a loudspeaker cone or vocal cords.

- Sound is a **longitudinal wave**. The vibrating source pushes the air particles together, making a **compression** (high pressure), and then leaves a gap, making a **rarefaction** (low pressure). The pattern spreads through the air.
- Sound needs a medium, so it **cannot travel in a vacuum**. **Experiment:** a ringing bell inside a bell jar. As the air is pumped out, the sound fades away, though the clapper is still seen to hit the bell.
- The range of frequencies that humans can hear is about **20 Hz to 20 000 Hz**.

Loudness and pitch

- A bigger **amplitude** gives a **louder** sound.
- A higher **frequency** gives a **higher pitch**.

On an oscilloscope screen, a louder sound is a taller trace and a higher pitch is a trace with more waves close together. Different instruments playing the same note give different trace shapes. This difference in quality is the **timbre**.

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Echoes and the speed of sound

An **echo** is sound reflected from a hard surface. Reflection of sound can be shown by a sound travelling along a tube towards a hard board, which reflects it into a second tube.

Measuring the speed of sound in air. Stand a measured distance (for example $100\ \text{m}$) from a large wall and make a sharp sound, such as a clap. Time the interval between the clap and its echo. The sound travels there and back, so

$$\text{speed} = \frac{2 \times \text{distance to the wall}}{\text{time}}$$

Repeat and average the times to reduce errors.

> **TRY IT**
>
> A student stands $85\ \text{m}$ from a wall. The echo of a clap comes back after $0.50\ \text{s}$. Find the speed of sound.

$$v = \frac{2 \times 85}{0.50} = 340\ \text{m/s}$$

The speed of sound in air is about 330 to $350\ \text{m/s}$. Sound travels faster in **solids** than in **liquids**, and faster in liquids than in **gases**, because the particles are closer together and pass the vibration on more quickly.

Ultrasound

Ultrasound is sound with a frequency above $20\ \text{kHz}$, which is higher than humans can hear. Uses:

- **Cleaning** delicate objects such as jewellery: the vibrations shake dirt loose.
- **Medical scanning**, including before birth: ultrasound reflects from boundaries between different tissues, and a computer builds up a picture from the echoes.
- **Sonar**: a ship sends out a pulse and times the echo from the sea bed or a shoal of fish.

> **TRY IT**
>
> A ship sends an ultrasound pulse down and receives the echo $0.80\ \text{s}$ later. The speed of sound in sea water is $1500\ \text{m/s}$. Find the depth of the sea.

The pulse travels down and back, so the one-way time is $0.40\ \text{s}$:

$$\text{depth} = 1500 \times 0.40 = 600\ \text{m}$$

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