Waves

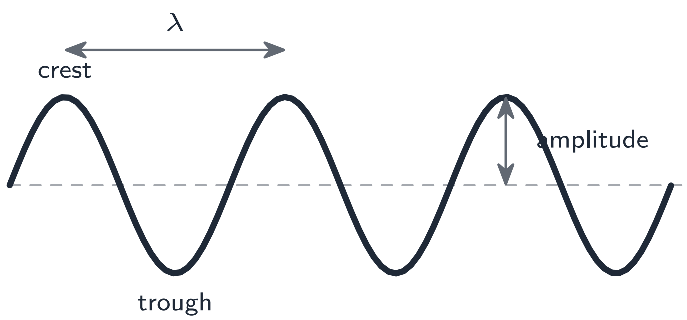
IGCSE Physics

General properties of waves

A **wave** 波 carries **energy** 能量 from place to place **without** carrying matter. For example, a water wave makes a floating cork bob up and down, but the cork does not travel along with the wave. You can make a wave on a rope by shaking one end up and down, or on a long spring by pushing one end back and forth. In a **ripple tank** 波纹水槽 (a shallow tray of water with a light above it) you can watch water waves on a screen below.

Describing a wave

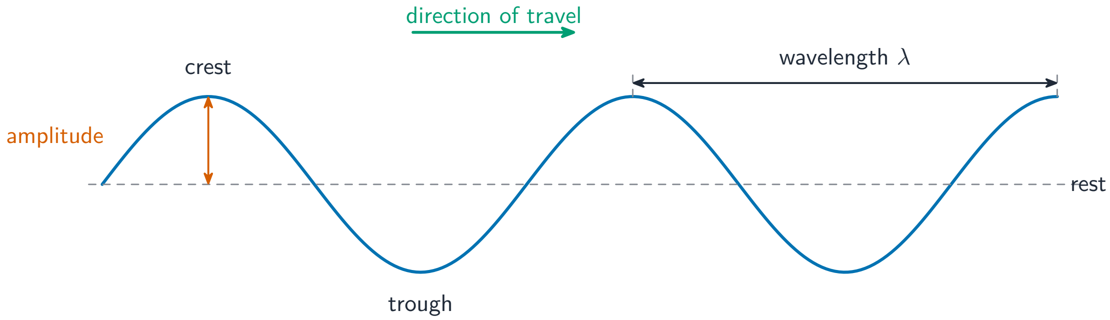
- **wavefront** 波前: a line joining points on a wave that move together (for example, the top of one ripple)
- **wavelength** 波长 (λ): the distance between two neighbouring wavefronts (one full wave)
- **frequency** 频率 (f): the number of waves passing a point each second, measured in hertz (Hz)
- **crest** 波峰 (also called the **peak** 峰, the top) and **trough** 波谷 (bottom)
- **amplitude** 振幅: the largest distance a point moves from its rest position
- **wave speed** 波速 (v): how fast a wavefront travels



The parts of a wave: wavelength, amplitude, crest and trough

These are linked by the **wave equation**:

$$v = f\lambda$$



The wavelength is the distance between two crests; the amplitude is the height from the rest position to a crest

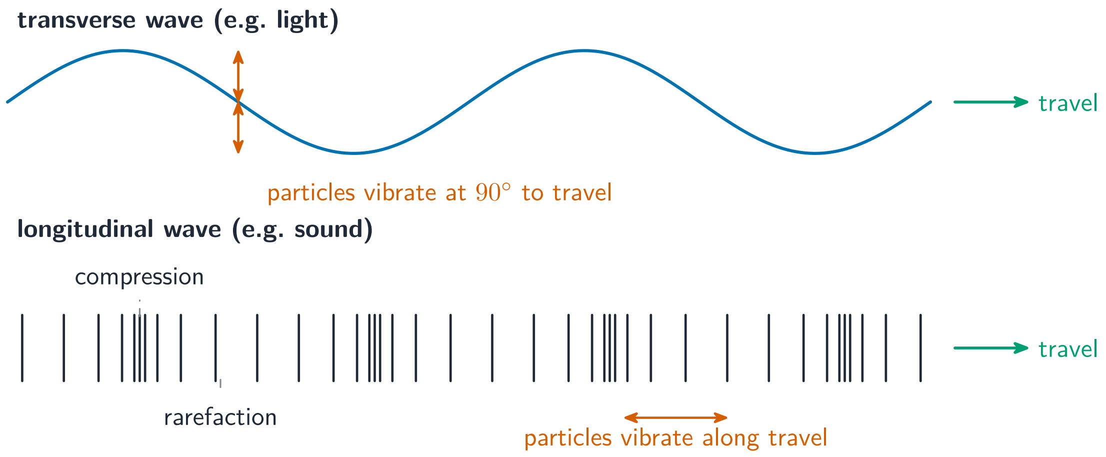
Worked example. A sound wave travels at 340 m/s and has a frequency of 170 Hz. Find its wavelength.

Rearranging $v = f\lambda$ gives $\lambda = \dfrac{v}{f}$:

$$\lambda = \frac{340}{170} = 2.0\ \text{m}$$

Two types of wave

- In a **transverse wave** 横波 the particles vibrate at right angles (90°) to the direction the wave travels (its **propagation** 传播). Light, water waves and seismic S-waves (the sideways shaking in an earthquake) are transverse.
- In a **longitudinal wave** 纵波 the particles vibrate along the same direction as the wave travels. Sound and seismic P-waves are longitudinal.

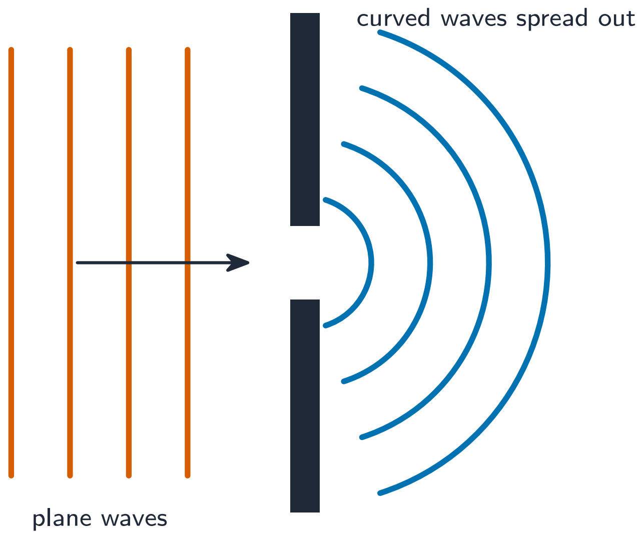


In a transverse wave the particles vibrate across the travel direction; in a longitudinal wave they vibrate along it, making compressions and rarefactions

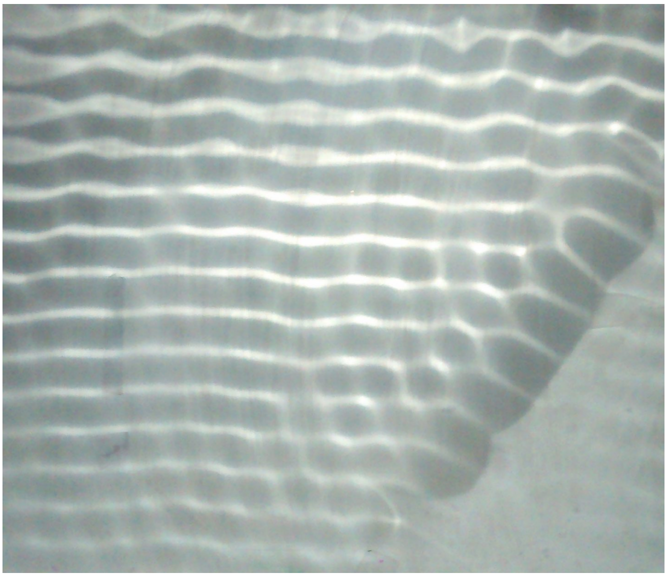
Wave behaviour

All waves can show three behaviours, which you can see in a ripple tank:

- **reflection** 反射: the wave bounces off a surface.
- **refraction** 折射: the wave changes speed (and usually direction) when it enters a different material or depth.
- **diffraction** 衍射: the wave spreads out after passing through a gap or around an edge. The spreading is greatest when the gap is about the same size as the wavelength.



Plane waves passing through a narrow gap spread out into curved waves — diffraction is strongest when the gap is about one wavelength wide



Plane waves in a ripple tank reflect off a straight barrier: the reflected wavefronts leave at the same angle they arrived

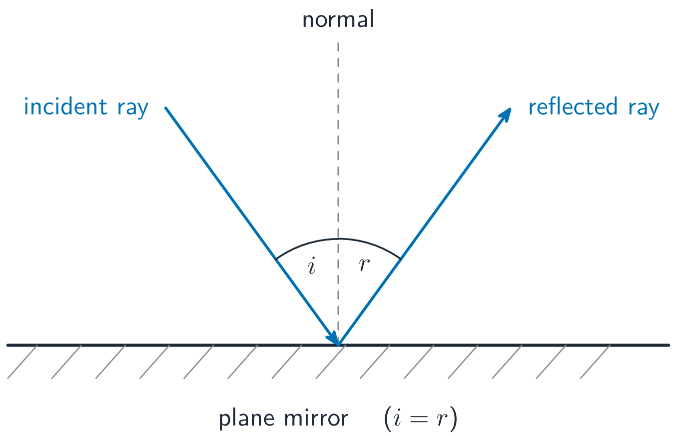
Light 光

Reflection

When light hits a mirror, it reflects. We measure angles from the **normal** 法线 (a line at 90° to the surface).

The **law of reflection**: the **angle of incidence** 入射角 equals the **angle of reflection** 反射角.

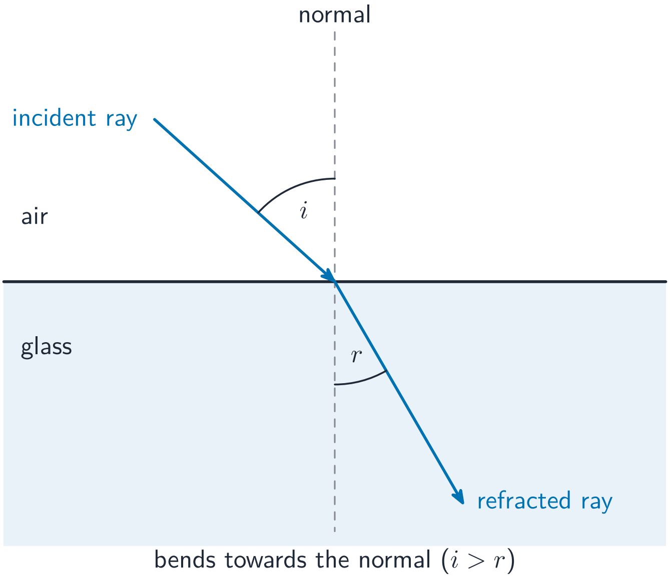
A **plane mirror** 平面镜 forms an image that is the same size as the object, the same distance behind the mirror, and **virtual** (it cannot be caught on a screen).



At a plane mirror the angle of incidence i equals the angle of reflection r, both measured from the normal

Refraction

When light passes from one material into another, it changes speed and bends. The angle in the second material is the **angle of refraction** 折射角.



Going from air into glass the light slows down and bends towards the normal, so $i > r$

Seeing refraction. Shine a narrow ray from a **ray box** 光线盒 into a rectangular glass block standing on paper. Mark the ray going in and the ray coming out, remove the block, and join the marks to draw the ray inside the glass. Draw the normal where the ray enters and measure the angle of incidence and the angle of refraction with a protractor. Repeat with a semicircular block or a prism: the ray always bends towards the normal on entering the glass and away from the normal on leaving.

The **refractive index** 折射率 n compares the speed of light in the two materials:

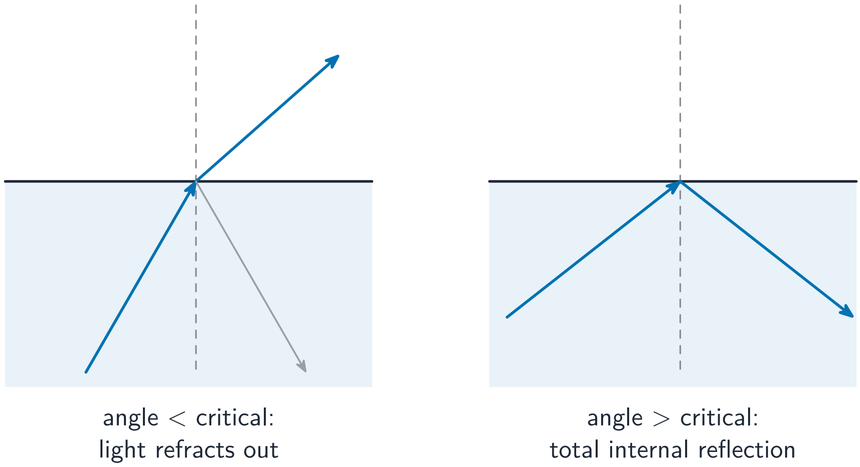
$$n = \frac{\sin i}{\sin r}$$

Worked example. A ray of light passes from air into glass. The angle of incidence is 60° and the angle of refraction is 35°. Find the refractive index of the glass. (Take $\sin i = 0.87$ and $\sin r = 0.57$.)

$$n = \frac{\sin i}{\sin r} = \frac{0.87}{0.57} = 1.5$$

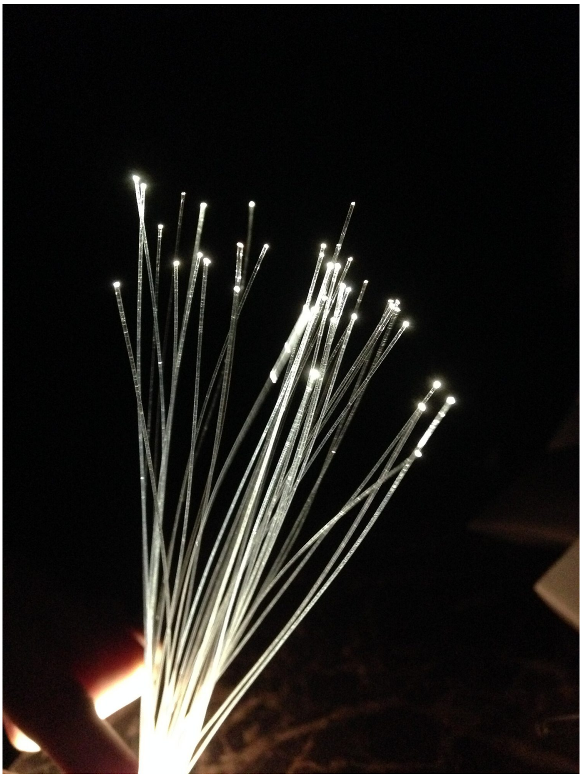
When light tries to leave glass or water and the angle is too large, it cannot get out and instead reflects completely. This is **total internal reflection** 全反射. It happens when the angle inside is bigger than the **critical angle** 临界角 c:

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



Below the critical angle the light refracts out; above it the light is totally internally reflected

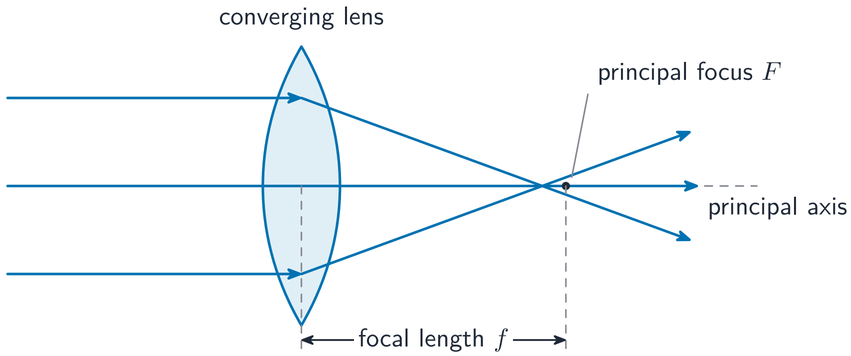
This effect is used in **optical fibres** 光纤, thin glass threads that carry light signals for telephones and the internet.



Total internal reflection keeps light bouncing along each fibre until it shines out at the tip

Lenses

A **converging lens** 凸透镜 (fat in the middle) bends parallel rays inwards to a point called the **principal focus** 焦点. The **principal axis** 主光轴 is the straight line through the centre of the lens at right angles to it; the principal focus lies on this axis. The distance from the centre of the lens to the principal focus is the **focal length** 焦距. A **diverging lens** 凹透镜 (thin in the middle) spreads parallel rays out, as if they came from a focus on the incoming side.



A converging lens bends parallel rays to meet at the principal focus; the focal length f is the lens-to-focus distance

A converging lens can form a **real image** 实像 (rays really meet; can be shown on a screen) or, when the object is very close, a **virtual image** 虚像 (rays only seem to come from it). Used close to the eye, a converging lens is a **magnifying glass** 放大镜.

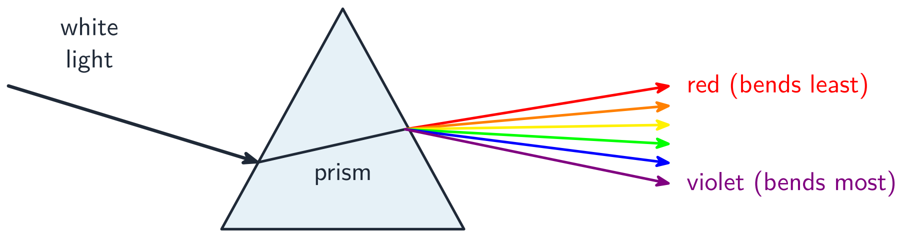
Describe an image with three pairs of words: **enlarged** 放大的 or **diminished** 缩小的 (or the same size), **upright** 正立 or **inverted** 倒立 (upside down), and real or virtual. An object far beyond the focus gives a diminished, inverted, real image (as in a camera). An object between the focus and the lens gives an enlarged, upright, virtual image (a magnifying glass).

Correcting sight. A person with **short-sightedness** 近视 sees near things clearly but distant things are blurred: the eye focuses the light in front of the **retina** 视网膜 (the back of the eye). A diverging lens in front of the eye spreads the rays out first, so they focus on the retina. A person with **long-sightedness** 远视 sees distant things clearly but near things are blurred: the eye focuses the light behind the retina. A converging lens brings the rays together a little before they enter the eye.

Held away from the eye, a converging lens forms a real image – here the houses behind it appear upside down

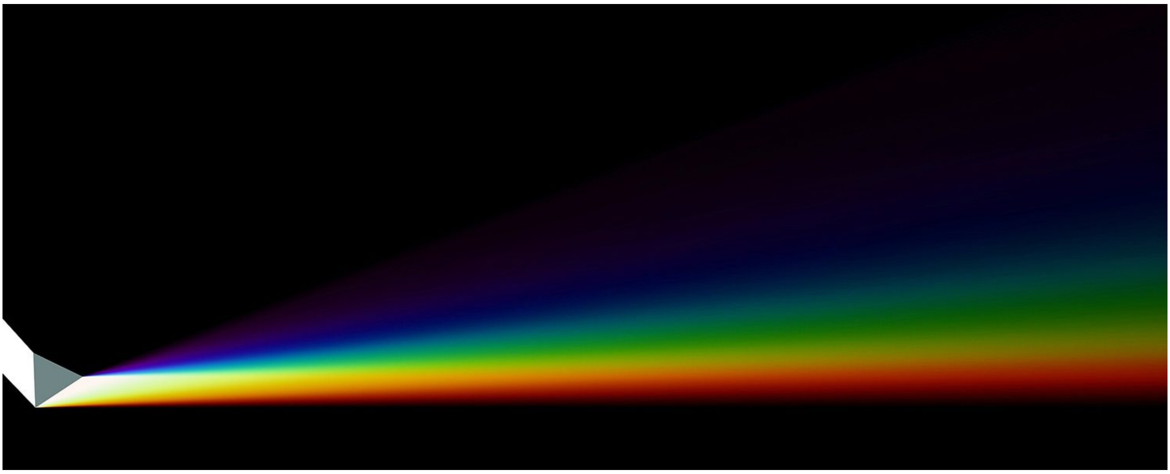
Dispersion

A glass **prism** 棱镜 splits white light into the colours of the **spectrum** 光谱. This splitting is called **dispersion** 色散.



A prism refracts violet light most and red light least, so white light spreads into a spectrum

The order of colours is red, orange, yellow, green, blue, indigo, violet. Red light has the longest wavelength and the lowest frequency; violet is the opposite. Light of a single frequency (one pure colour) is **monochromatic** 单色.



White light entering a real glass prism spreads into the full spectrum of colours

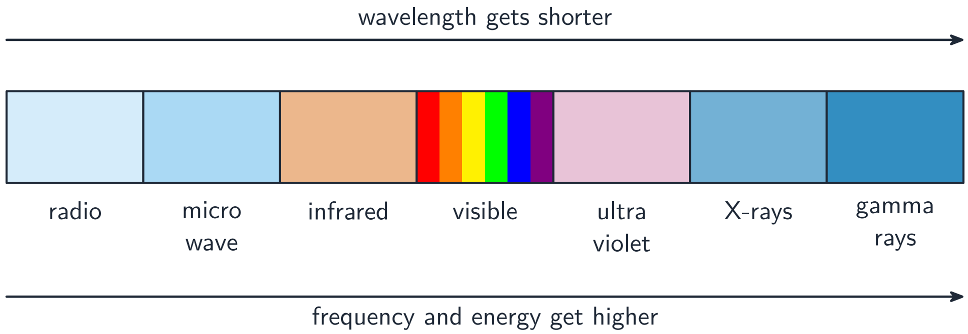
The electromagnetic spectrum 电磁波谱

The **electromagnetic spectrum** is a family of waves that all travel at the same high speed in a **vacuum** 真空, 3.0×10^8 m/s. In order from longest wavelength (lowest frequency) to shortest:

Region	A typical use	Danger from too much
radio waves 无线电波	radio and TV signals, astronomy, RFID tags	—
microwaves 微波	mobile phones, satellite TV, cooking	heating of body cells
infrared 红外线	remote controls, thermal imaging, grills, optical fibres	skin burns
visible light	seeing, photography	—
ultraviolet 紫外线	sterilising water, checking bank notes	skin cancer, eye damage
X-rays X 射线	medical and security scans	damage to cells
gamma rays 伽马射线	sterilising equipment, treating cancer	mutation of cells

As you go from radio waves to gamma rays, the frequency rises, the wavelength falls, and the energy (and danger) rises. The speed of electromagnetic waves in air is almost the same as in a vacuum.

Satellites. Communication with **artificial satellites** 人造卫星 mainly uses microwaves, because they pass through the atmosphere. Some satellite phones use satellites in **low orbit** 低轨道, close to the Earth. Other satellite phones, and direct broadcast satellite television, use satellites in **geostationary orbit** 地球静止轨道, which stay above the same point on the Earth.



From radio waves to gamma rays the wavelength falls while the frequency and energy rise

Digital and analogue signals

Radio waves and microwaves carry information as signals, and a signal is either **analogue** 模拟 or **digital** 数字. An **analogue signal** varies **continuously** and can take any value; a **digital signal** is a stream of just two values, on or off (`1` or `0`). Sound can be sent as either kind of signal: a microphone gives an analogue signal, which can be turned into a digital one.

Modern communication prefers **digital** signalling for two reasons the exam asks for:

- a **higher rate** of data transmission;
- a **greater range**: a weak digital signal can be **regenerated** back to a clean `1/0` exactly, because only two levels have to be told apart, so noise picked up along the way is removed. An analogue signal cannot be cleaned up this way, so its noise builds up.

Sound 声音

Sound is made by a vibrating object. It is a **longitudinal wave**: the air is squeezed into a **compression** 压缩 (particles close together) and stretched into a **rarefaction** 稀疏 (particles far apart).

- Sound needs a **medium** 介质 (a material) to travel through, so it cannot travel through a vacuum.
- Humans can hear frequencies from about 20 Hz to 20 000 Hz.
- Sound travels much slower than light (about 340 m/s in air), and faster in liquids and solids than in gases.
- A **larger amplitude** makes a louder sound (greater **loudness** 响度); a **higher frequency** makes a higher **pitch** 音调. So a dolphin's rapid clicks are high-pitched, and a hard drum-hit (big vibration) is loud.

A reflected sound is an **echo** 回声.

Measuring the speed of sound. Two students stand a known distance apart, for example 500 m, measured with a tape or a trundle wheel. One bangs two blocks of wood together. The other starts a stopwatch when they see the blocks hit and stops it when they hear the bang. Light arrives almost at once, so the time measured is the time the sound takes, and speed = distance ÷ time. Repeat and take an average to reduce the reaction-time error. The echo method needs one person: clap at a known distance from a large wall and time the reflected sound, remembering that the sound travels there and back.

Worked example. A student stands 85 m from a large wall and claps once. The echo returns 0.50 s later. Find the speed of sound.

The sound travels to the wall and back, a distance of $2 \times 85 = 170$ m, in 0.50 s:

$$v = \frac{s}{t} = \frac{170}{0.50} = 340 \text{ m/s}$$

Ultrasound 超声波 is sound above 20 000 Hz – too high for humans to hear. Its uses rely on reflection: **sonar** measures water depth, **medical scanning** images a baby or soft tissue, and **non-destructive testing** finds cracks inside metal without cutting it open. Like an echo, an ultrasound pulse travels **there and back**, so halve the total distance to reach the object.

Worked example. A sonar pulse returns from the seabed 0.10 s after it is sent; sound travels at 1500 m/s in water. The pulse covers $s = v \times t = 1500 \times 0.10 = 150$ m there and back, so the sea is $150/2 = 75$ m deep.

A microphone converts sound vibrations in air into an electrical signal

Exam tips

- Learn $v = f\lambda$ and be ready to rearrange it. Measure all angles of incidence, reflection and refraction from the **normal** (the line at 90° to the surface), never from the surface itself.
- **Transverse** waves vibrate across the direction of travel (light, water); **longitudinal** waves vibrate along it (sound). Sound needs a **medium**, so it cannot cross a vacuum; light can.
- **Total internal reflection** happens only when light travels from a denser material to a less dense one *and* the angle inside is bigger than the critical angle.

- Know the **electromagnetic spectrum** in order — radio, microwave, infrared, visible, ultraviolet, X-ray, gamma. All travel at the same speed in a vacuum; frequency and energy rise from radio to gamma.
- Going into a denser material (air $\rightarrow$ glass) light slows down and bends *towards* the normal; leaving it (glass $\rightarrow$ air) light speeds up and bends *away*.