Edexcel

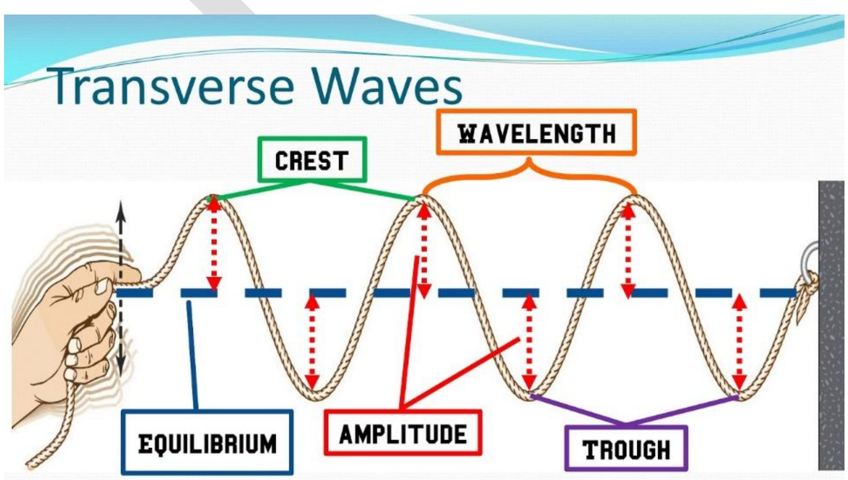
AS level

Physics

CODE: (4BI1)

Topic 3-Waves and particle nature of light

3A- 3B-3C



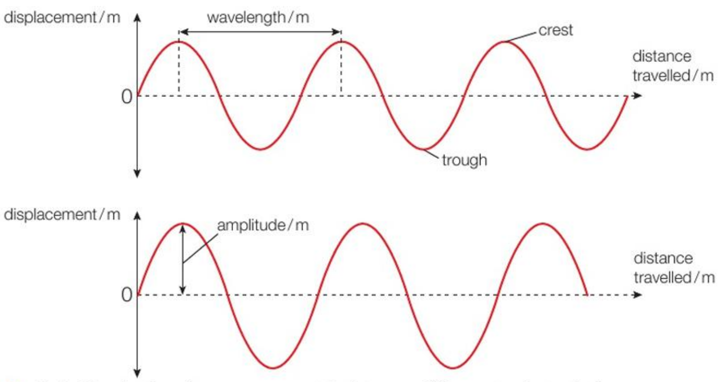
3A.1 – Wave basics

Energy transfers

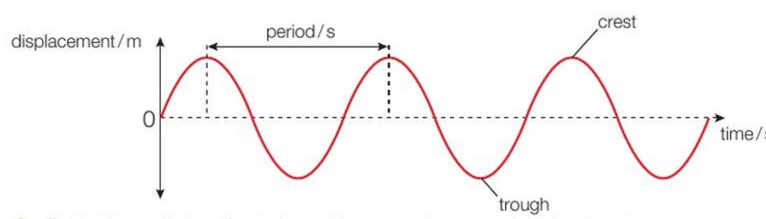
Waves transfer energy through oscillations, without causing net movement of matter. Mechanical waves require a material medium, like air molecules, while electromagnetic waves transfer energy through electric and magnetic fields. Interaction between waves and matter generally slows their transfer, as light travels more slowly in water than in a vacuum.

Graphing waves

Wave motions can be plotted on graphs. A plot of the displacement against distance travelled for a wave, as in fig A, shows the physical scale of the oscillations and the movement of the energy. Alternatively, a plot of the displacement versus time, as in fig B, shows how the vibrations occur over time.



▲ **fig A** The vibration of a wave over a certain distance, as if frozen at an instant in time.



▲ **fig B** The oscillation of a single particle or point in a wave plotted against time.

Wave measurements

Displacement: the position of a particular point on a wave, at a particular instant in time, measured from the mean (equilibrium) position. (Symbol: various, often x; SI units: m.)

Amplitude: the magnitude of the maximum displacement reached by an oscillation in the wave. (Symbol: A; SI units: m.)

Frequency: the number of complete wave cycles per second. This may sometimes be measured as the number of complete waves passing a point per second. (Symbol: f; SI units: hertz, Hz.)

Wavelength: the distance between a point on a wave and the same point on the next cycle of the wave, for example, the distance between adjacent wave peaks. (Symbol: A; SI units: m.)

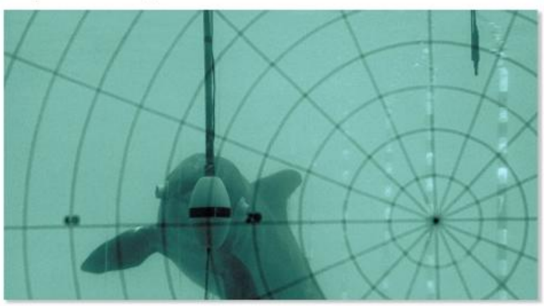
Period: the time taken for one complete oscillation at one point on the wave. This will also be the time taken for the wave to travel one wavelength. (Symbol: T; SI units: s.)

Phase: the stage a given point on a wave is through a complete cycle. Phase is measured in angle units, as a complete wave cycle is considered to be the same as travelling around a complete circle, that is 360° or 2π radians. (No standard symbol; SI units: rad.)

Wave speed: the rate of movement of the wave - the same as speed in general. (Symbol: v, or c for speed of electromagnetic waves; SI units: ms1.)

Pulse – echo measurements

Bats, native to woodlands, use their echolocation system to detect insects. They use high-frequency sound pulses to sense their location, providing a detailed perception of the world at distances of less than 5 meters. Bats make a chirp through their nose, which is reflected back to their ears, allowing them to accurately measure the time between making the sound and hearing the echo. The bat's brain also calculates the distance to the reflecting object using the equation distance = speed x time. Dolphins also use a similar echolocation system, but they can build an image of nearby objects using sound.



▲ **fig D** Dolphin echolocation is good enough to make out the shapes of objects in murky waters.

SUBJECT VOCABULARY

wave a means for transferring energy via oscillations
displacement the position of a particular point on a wave, at a particular instant in time, measured from the mean (equilibrium) position
amplitude the magnitude of the maximum displacement reached by an oscillation in the wave
frequency the number of complete wave cycles per second:

$$\text{frequency (Hz)} = \frac{1}{\text{time period (s)}}$$

$$f = \frac{1}{T}$$

wavelength the distance between a point on a wave and the same point on the next cycle of the wave
period (also **time period**) the time taken for one complete oscillation at one point on the wave:

$$\text{time period (s)} = \frac{1}{\text{frequency (Hz)}}$$

$$T = \frac{1}{f}$$

phase the stage a given point on a wave is through a complete cycle, measured in angle units, rad
wave speed the rate of movement of the wave (not the rate of movement within oscillations)
wave equation:

$$\text{wave speed (m s}^{-1}) = \text{frequency (Hz)} \times \text{wavelength (m)}$$

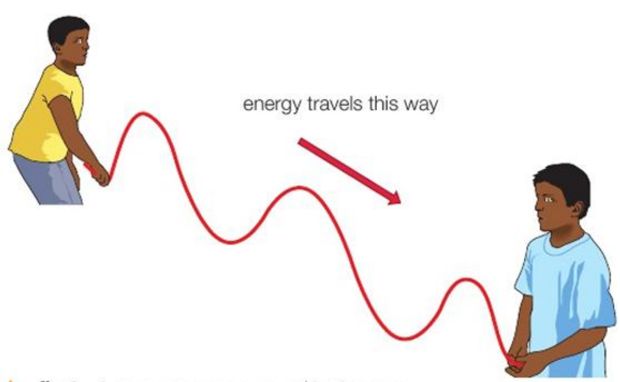
$$v = f\lambda$$

twin-beam oscilloscope an oscilloscope with two inputs. It displays each as a line on the screen, and both are shown at the same time to compare the inputs

3A.2 – Wave types

Transverse waves

A **transverse wave** is an electromagnetic wave where particles move up and down, while energy travels forward. In a fig A, a student vibrates a rope, causing particles to pull their neighbors up and down, passing vibrations through intermolecular forces. This results in the wave moving along the rope.



▲ **fig A** A transverse wave on a skipping rope.

Longitudinal waves

A **longitudinal wave** in a fluid, such as air, is generated by squashing particles together and then stretching them apart from each other, repeatedly - thus vibrating them 'longitudinally'. The areas of higher pressure cause the particles to push apart from each other, but this makes the particles move and squash their neighbours.

This higher pressure - a **compression** - then pushes them away to squash their neighbours. Similarly, the areas where there are too few particles (compared with the uniform spread of the particles when the wave is not present) cause particles to move into the vacant space - this is known as the **rarefaction** - filling the vacant space up, but causing a vacancy behind these particles, and the wave moves along.

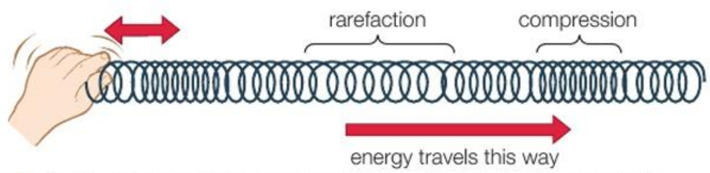


fig B A longitudinal wave generated in a long spring by repeatedly squashing and stretching one end. Areas of higher pressure are called compressions, and areas of lower pressure are called rarefactions.

Graphing waves

The text explains how waves can be represented on a graph of displacement versus distance, with transverse waves being easier to visualize. Wavelength and amplitude can be found by measuring along the graph's x-axis from one point on a wave cycle to the next. Longitudinal waves are less easy to visualize and can be difficult to measure. Fig C illustrates how longitudinal waves can be represented on a graph of displacement versus distance, making measurements easier.

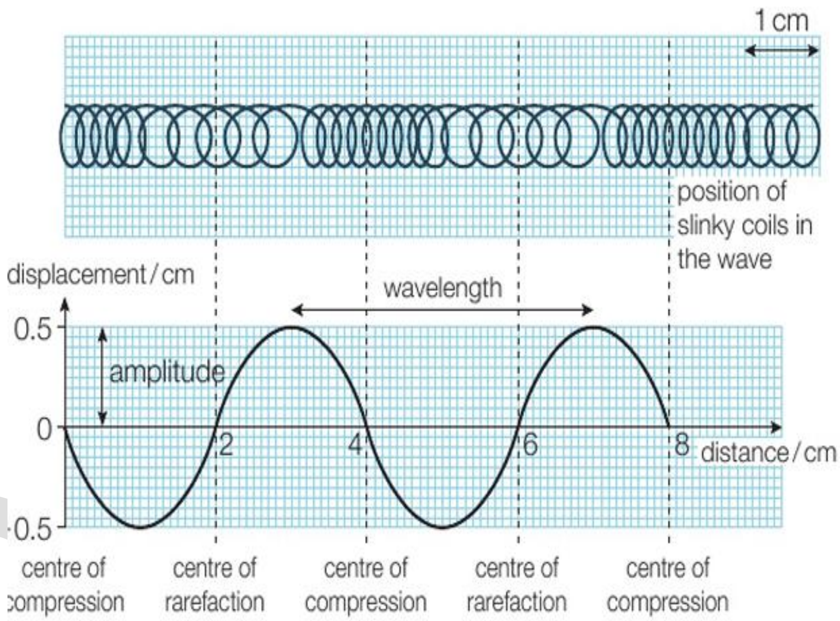


fig C A longitudinal wave can be easier to measure if it is drawn on a displacement–distance graph.

Longitudinal waves in action

Sound waves are caused by oscillations of particles of the medium (in fig D the medium is air), causing compressions and rarefactions along the line of movement of the wave. Areas of higher pressure and lower pressure in the air continue the movement of the vibrations. An area of higher pressure, a compression, will occur when the particles on either side are displaced towards it. This means particles are displaced in opposite directions towards each other to squash together and increase the pressure, as shown in fig E.

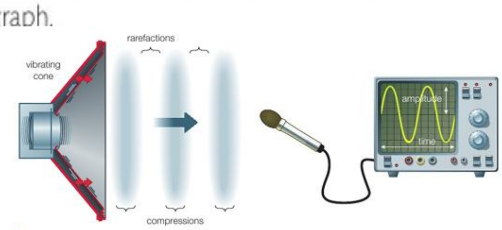


fig D A loudspeaker produces sound waves by moving its cone back and forth to set up vibrations of air molecules in line with the direction of movement of the sound wave energy – the oscilloscope shows the vibrations over time.

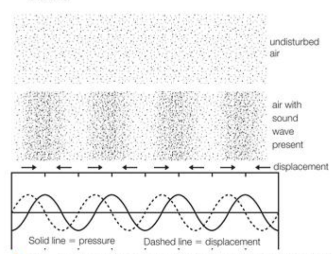


fig E Sound waves are the result of areas of increased pressure moving through a body of particles by vibrating the particles back and forth.

Earthquake waves, also called seismic waves, come in different types. Fig F shows Primary, or 'P', waves and Secondary, or 'S', waves. These are the standard longitudinal and transverse seismic waves, with P-waves travelling faster, and arriving first, leading to their name.

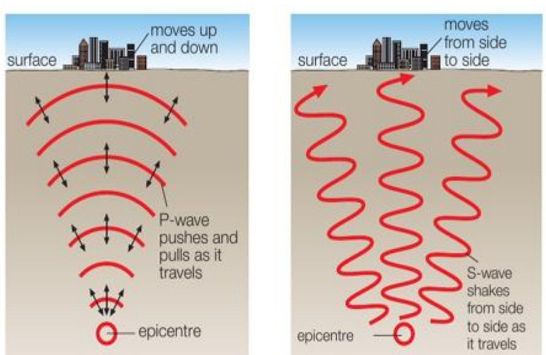


fig F Seismic waves can vibrate the rock particles of the Earth's crust in different ways.

3B The behavior of waves

3B.1 – Wave base and superposition

Phase

Waves have a cycle of oscillation, with points at specific positions called peaks, troughs, compressions, or rarefactions. The remaining points are important but not named. Positions are described by phase, with a complete cycle equivalent to 360° rotation, and a phase position is an angle measurement. There are too many points to name them all.

It is quite common to measure phase in the alternative angle units of radians, where one complete cycle is 2 π rad. Table A shows common phase positions in the two equivalent angle units, along with the fraction of a complete wavelength that they represent. As waves are, by definition, a repetitive cyclic process, phases of more than 360° could be reduced to their equivalent value within a first cycle.

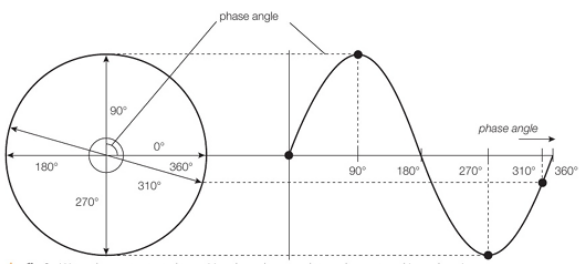


fig A Wave phase represents the position through a complete cycle, measured in angle units.

WAVE CYCLE POSITION	START	$\frac{1}{4}$ OF A CYCLE	$\frac{1}{2}$ OF A CYCLE	$\frac{3}{4}$ OF A CYCLE	A WHOLE CYCLE	1.5 CYCLES	2 COMPLETE CYCLES
PHASE / °	0	90	180	270	360	540	720
PHASE / RAD	0	$\frac{\pi}{2}$	π	$\frac{3\pi}{2}$	2π	3π	4π
NUMBER OF WAVELENGTHS	0	$\frac{\lambda}{4}$	$\frac{\lambda}{2}$	$\frac{3\lambda}{4}$	λ	1.5λ	2λ

table A Phase angles in degrees and radians, and also compared to wavelengths.

Wavefronts

Diagrams of waves are often drawn as lines, as in fig B, where all the points on a line represent points on the wave that are at the same phase position, perhaps a wave crest. These lines are called **wavefronts**. They are how the sea might look observe from a helicopter, where the troughs are all in shadow and so appear darker.

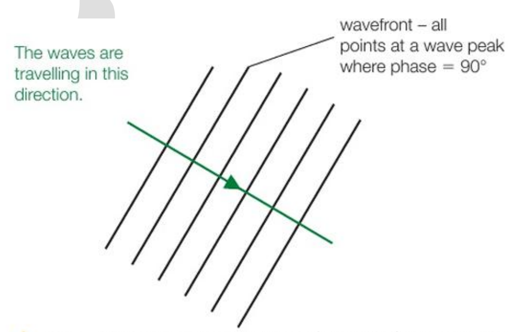


fig B All points on each wavefront (black lines) are in the same phase position: 90°, or $\pi/2$. The green line showing direction of travel is called a ray. Rays must be perpendicular to wavefronts.

Wave superposition

Wave superposition refers to the vector sum of displacements caused by individual waves when they meet, resulting in the overall displacement. As energy progresses in the same direction, each wave continues past each other, as illustrated in wave pulses passing each other.

Wave superposition is a phenomenon where waves in different directions meet at the same point, causing a sudden large wave to disappear quickly. When wave pulses A and B meet, they lift the water slightly, causing it to rise even higher. This effect is believed to explain sailors' tales of sudden waves disappearing quickly. The combined displacement of waves in wave superposition can cause a significant displacement, which then drops again as they continue past each other.

fig C When waves meet, the displacements would add to each other to give the overall displacement for each location.

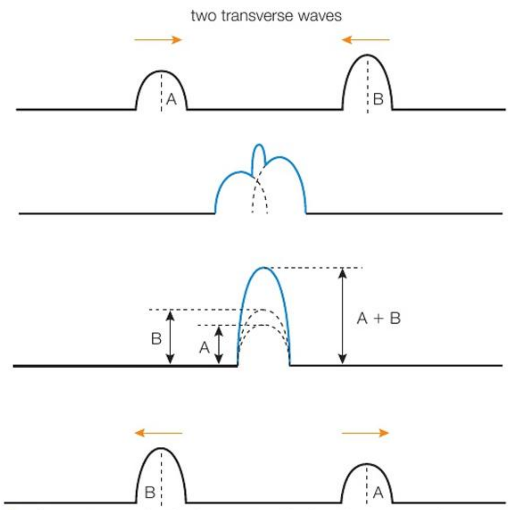


fig D Wave pulse displacements add when they meet in the same location.

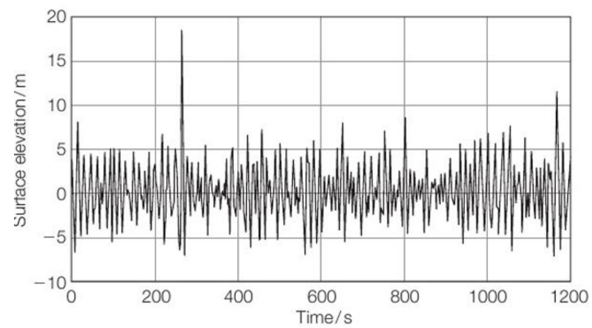


fig E Multiple small waves coinciding in the same location can lead to a brief very large displacement. This graph is of sea surface height at the Draupner North Sea Oil Platform on 1st January 1995, showing a freak 18 m wave.

Superposition of continuous waves

If, rather than a single point along the path of the waves, we consider waves superposing over a large space, the outcome is a continuous wave that is the sum of the displacements over time in each location. If the two waves are in phase, their effect will be to produce a larger-amplitude resultant wave. This is known as **constructive interference.** If identical waves meet and are exactly out of phase - if their phase difference is 180° or radians - then the resultant is a zero-amplitude wave. This idea of complete **destructive interference** can be confusing.

It is important to know the phase difference between two waves, to determine what will happen as a result of their superposition. Waves that constructively interfere, as with the top pair in **fig F,** must be in phase, which means they have a phase difference of zero.

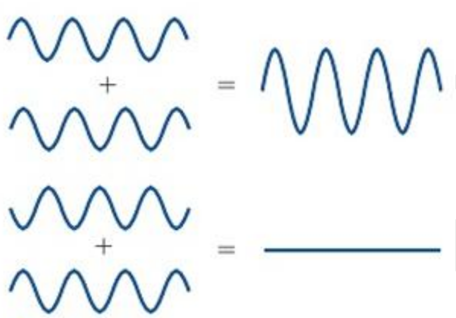


fig F Constructive and destructive interference.

SUBJECT VOCABULARY

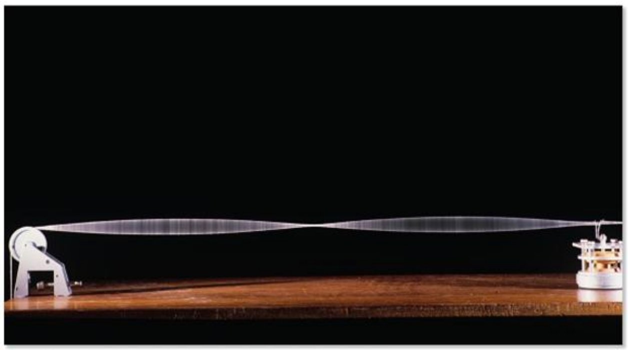
wavefronts lines connecting points on the wave that are at exactly the same phase position
superposition when more than one wave is in the same location, the overall effect is the vector sum of their individual displacements at each point where they meet
constructive interference the superposition effect of two waves that are in phase, producing a larger amplitude resultant wave
destructive interference the superposition effect of two waves that are out of phase, producing a smaller amplitude resultant wave

3B.2 Stationary waves

Standing waves

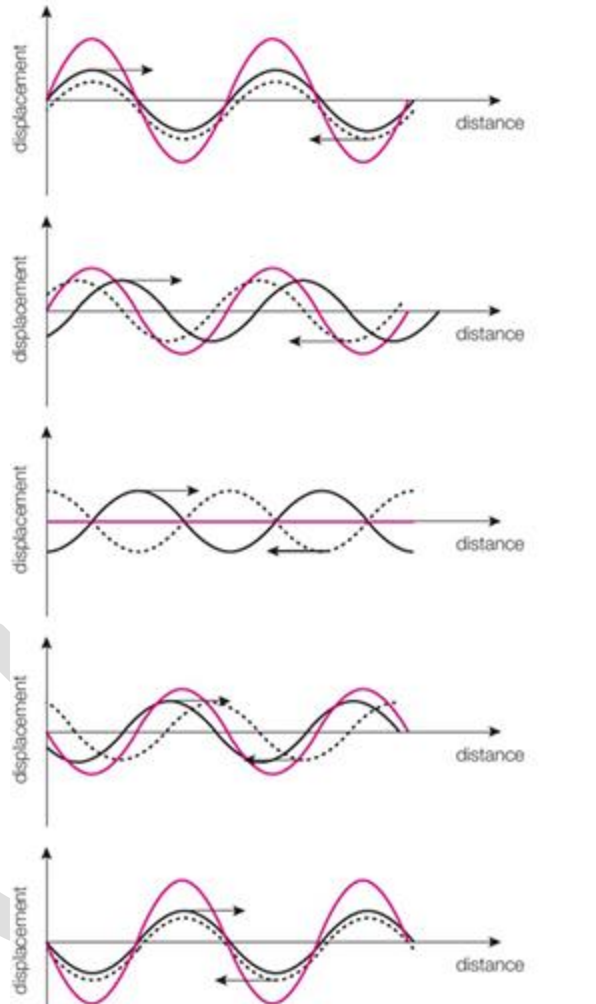
Continuous waves travelling in opposite directions will superpose continuously, and this can set up a **stationary wave** pattern, also known as a **standing wave**. The waves need to be of the same speed and frequency, with similar amplitudes, and have a constant phase relationship. Waves with the same frequency and a constant phase relationship are said to be **coherent.**

Stationary waves have this name because the profile of the wave does not move along, it only oscillates. This also means that wave energy does not pass along a standing wave, so they do not meet our strict definition of waves, which do transfer energy and are more precisely called **progressive waves.** There are points where the resultant displacement is always zero. These points never move and are called **nodes**. The points of maximum amplitude are called **antinodes**.



▲ **fig A** When coherent waves meet, a stationary wave is set up with points of zero amplitude (nodes) and points of maximum amplitude (antinodes). This can be demonstrated in the school laboratory with a vibration generator and a rubber cord.

The standing wave pattern on a string depends on the frequency of the wave that produces it. The wavelength of the standing wave pattern depends on the wave equation. For instance, the first overtone fits one complete wave in the string's length, while the third overtone has two complete waves, halving the wavelength. The frequency in the third overtone must be double the first overtone.



▲ **fig B** As coherent waves pass through each other, the resultant wave (pink) will be stationary.

String wave speeds

Waves on a stretched spring travel at a speed that is affected by the tension in the string, 7 (in newtons) and the mass per unit length of the string, μ (in kg m-1). The equation for the speed of a wave in a string is:

$$v = \sqrt{\frac{T}{\mu}}$$

If this equation is combined with the wave equation, we get an equation that tells us how the frequency of string vibrations is affected by other factors:

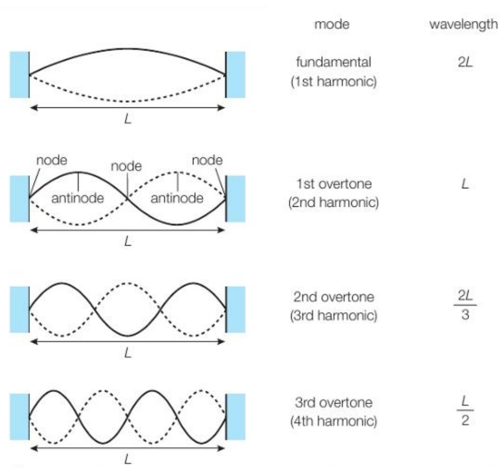
$$v = \sqrt{\frac{T}{\mu}} \quad \text{and} \quad v = f \times \lambda$$

$$\therefore \quad f \times \lambda = \sqrt{\frac{T}{\mu}}$$

$$f = \frac{1}{\lambda}\sqrt{\frac{T}{\mu}}$$

In the fundamental mode of vibration, this means the fundamental frequency, fo, depends on the length of the string, its tension and its mass per unit length from:

$$f_0 = \frac{1}{2L}\sqrt{\frac{T}{\mu}}$$



▲ **fig C** As the string is fixed at each end, these end points must always be nodes. The standing wave can only occur if its wavelength exactly allows a node at each end.

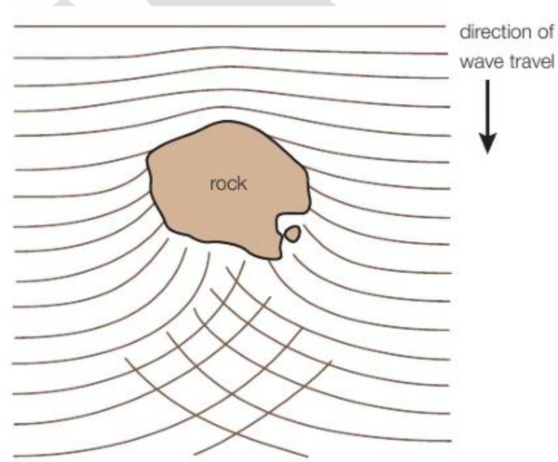
SUBJECT VOCABULARY

stationary or **standing wave** a wave which has oscillations in a fixed space, with regions of significant oscillation and regions with zero oscillation, which remain in the same locations at all times
coherence waves which must have the same frequency and a constant phase relationship. Coherent waves are needed to form a stable standing wave
progressive wave a means for transferring energy via oscillations
nodes regions on a stationary wave where the amplitude of oscillation is zero
antinodes regions on a stationary wave where the amplitude of oscillation is at its maximum
sonometer an apparatus for experimenting with the frequency relationships of a string under tension, usually consisting of a horizontal wooden sounding box and a metal wire stretched along the top of the box

3B.3 – Diffraction

Wave energy spreads behind an obstacle when it passes its edge, with small obstacles allowing wave energy to pass around both sides and continue past without shadow, as shown in fig B.

If the obstacle is larger, then there may be a shadow region behind it, but there will still be diffraction around each edge. If there are two close obstacles forming a gap, then there will be diffraction from each edge of the gap, causing the waves to spread out through the gap.



▲ **fig B** Wave energy spreads behind an obstacle.

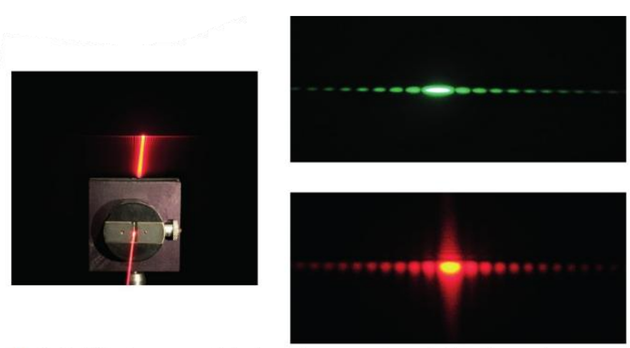
Factors affecting diffraction

Diffraction around an obstacle is determined by the size comparison between the obstacle and wave wavelength. Maximum diffraction occurs when the gap size is the same as the wavelength, with diffraction occurring most when the gap size is the same.

Wave energy can pass through gaps of different sizes, depending on the wavelength. When the wavelength matches the gap size, wave energy effectively fills the space behind, allowing us to hear around corners but not see them. The typical wavelength for audible sounds ranges from 15 centimetres to 15 meters, similar to diffracting obstacles like doorways. However, visible frequencies of light are 10-7 meters, making light only visible in direct line of sight through the gap.

Diffraction pattern

The diffraction pattern observed when light passes through a narrow slit, such as in fig E, shows a central **maximum** and then areas of darkness and then **maxima** of decreasing intensity. It can be confusing to see the areas where there is no light at all, when the diffraction through a gap suggests that the wave energy spreads out behind the gap.


▲ **fig E** Diffraction patterns of light observed on a screen show a bright, wide central maximum, surrounded by areas of darkness, and further bright spots that have decreasing brightness from the centre.

Single slit diffraction

If we change the width of the diffraction slit, or the wavelength of the light, we will alter the diffraction pattern that we observe. A narrower slit widens the central maximum, as well as the further maxima and **minima**.

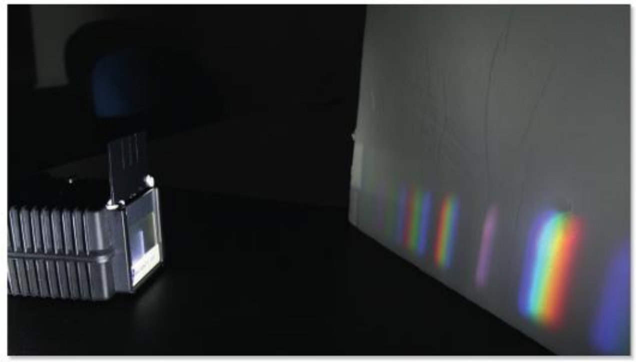
The diffraction grating

A diffraction grating is a device that will cause multiple diffraction patterns, which then overlap. These slits are parallel and have a fixed distance between each slit.

The pattern produced by each colour passing through a diffraction grating follows the equation:

$n\lambda = d \sin \Theta$

where is the angle between the original direction of the waves and the direction of a bright spot, A is the wavelength of the light used, d is the spacing between the slits on the grating, and n is called the **'order'**. The order is the bright spot number from the central maximum (which is n = 0).



▲ **fig F** Diffraction gratings can be used to examine light spectra.

▲ **fig H** CDs have a series of very close lines marked on them and act as a diffraction grating that reflects. This causes the spectrum of colours that can be seen on them from white light that hits the surface.

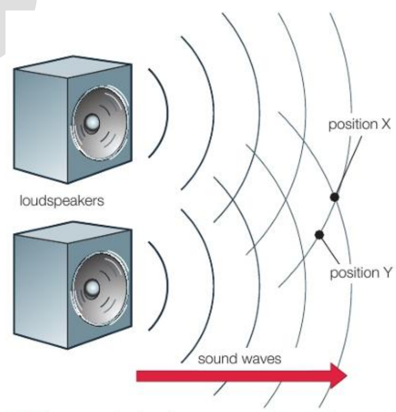
SUBJECT VOCABULARY

diffraction when a wave passes close by an object or through a gap, the wave energy spreads out.
maximum (plural **maxima**) in a diffraction or interference pattern, the bright spots
minimum (plural **minima**) in a diffraction or interference pattern, the dark spots
monochromatic containing or using only one colour. Light of a single wavelength

3B.4 – Wave interference

Two source interference

An **interference** pattern is a standing wave pattern where a wave meets its reflection, generating coherent waves with a constant phase relationship. This pattern can be generated by any combination of waves with the same frequency and phase. The relative positions of nodes and antinodes depend on the distance from speakers, their separation, and wave wavelength.

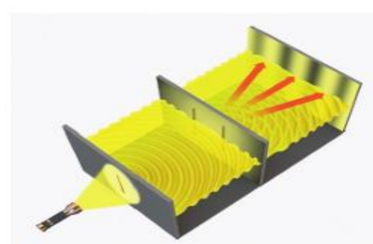


▲ **fig A** Two loudspeakers generating the same frequency sounds.

Two – slit interference

Thomas Young's 1803 experiment demonstrated an interference pattern in light, creating two coherent wave sources and a standing wave pattern. This effect, resembling nodes and antinodes in standing light waves, was based on Young's theory that light behaves as a wave, a concept that was controversial at the time.

Consider the blue line distance to X at 97 wavelengths and the red line distance at 98.5 wavelengths, with a 1.5 wavelength path difference. The waves will always be 3π radians out of phase, cancelling, and appear as a standing wave node.



▲ **fig B** Two-slit interference of torch light. An interference pattern of dark and light fringes is seen on the screen.

Note that these wavelength numbers are examples only. As light waves are so short, the numbers should be millions of wavelengths for standard laboratory distances for X.

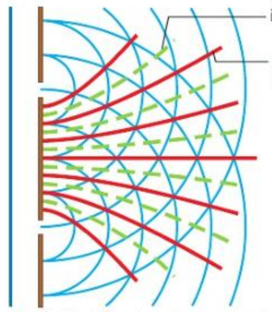


fig F All points that are exactly in phase, where the path difference is a whole number of wavelengths, $n\lambda$, will produce constructive interference. Any points where the path difference is given by $\frac{(2n+1)\lambda}{2}$ will cause destructive interference.

The connection between the phase difference and the path difference comes if we remember that each complete cycle (or wavelength) corresponds to 2π radians in phase. Waves from one slit meeting waves from the other slit at a point will each have had to travel to that point, cycling through wavelengths as they go. By comparing the path difference, this can be converted into phase differences.

Points where the path difference is equal to nλ exactly, will have a phase difference of 2nπ exactly and will be in phase, producing constructive interference.

Points where the path difference is equal to $\frac{(2n+1)\lambda}{2}$ exactly, will have a phase difference of $(2n+1)\pi$ exactly and will be in antiphase, producing destructive interference.

SUBJECT VOCABULARY

interference the superposition outcome of a combination of waves. An interference pattern will only be observed under certain conditions, such as the waves being coherent

3C – More waves properties of life

3C 1 Refraction

REFRACTION

When waves pass from one medium into another, there is a change in speed. The frequency remains constant, so the change in speed causes a change in wavelength. If the waves are approaching the interface between the two media at an angle then the change in speed causes a change in direction as well. This is called **refraction**.

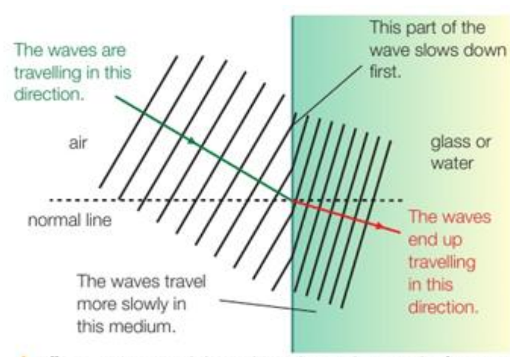


fig A Wave speed depends on the medium, and refraction is caused by a change in medium changing the wave speed.

A measure of the amount of refraction caused by different materials is called the **refractive index**, and its symbol is n. The refractive index, n, is equal to the ratio of the speed of light in a vacuum to the speed of light in the material:

$$n = \frac{c}{v}$$

Whilst it is difficult to measure the underlying change in the speed, at least for light waves, the effect on direction can be measured easily. The relationship between direction and refractive index is given by Snell's law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

fig B Refraction can alter perspective.

The values of n_1 and n_2 are the refractive indices in each medium. The values of θ_1 and θ_2 are the angles that the ray of light makes to the normal to the interface between the two media at the point the ray meets that interface, as shown in **fig C**.

DISPERSION

One of the most well known phenomena in physics is the splitting of white light into a rainbow of colours by a prism, as shown in **fig E**.

$$n_1\sin\theta_1 = n_2\sin\theta_2 \qquad n = \frac{c}{v} = \frac{c}{f\lambda}$$

If the ray enters a prism from air ($n = 1.00$) our equations become:

$$\sin\theta_1 = \frac{c\sin\theta_2}{f\lambda} \qquad \sin\theta_2 = \frac{f\lambda\sin\theta_1}{c}$$

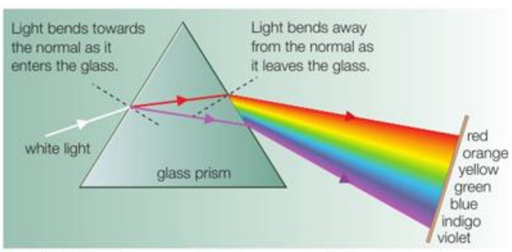


fig E Refraction affects different wavelengths (colours) differently.

On emergence from the glass prism, take care to continue with θ_1 as the angle in air:

$$\sin\theta_1 = \frac{c\sin\theta_2}{f\lambda}$$

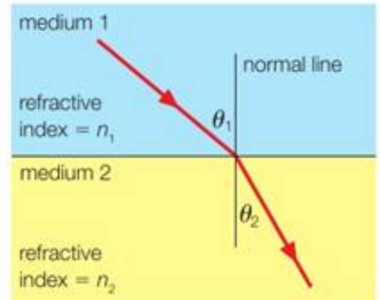


fig C Defining refraction.

SUBJECT VOCABULARY

refraction a change in wave speed when the wave moves from one medium to another. There is a corresponding change in wave direction, governed by Snell's law

refractive index, n, the amount that a material changes the speed of waves when they pass through the material from a different material:

$$\text{refractive index} = \frac{\text{speed of light in vacuum}}{\text{speed of light in the medium}} \qquad n = \frac{c}{v}$$

Snell's law the values of n_1 and n_2 are the refractive indices in each medium, and the values of θ_1 and θ_2 are the angles that the ray makes to the normal to the interface between the two media, at the point the ray meets that interface:

$$n_1\sin\theta_1 = n_2\sin\theta_2$$

3c 2 Total internal reflection

PARTIAL REFRACTION

When waves pass from one medium into another, some wave energy will pass through and some will be reflected. The proportions will depend on the amount of refraction and the angle of incidence.

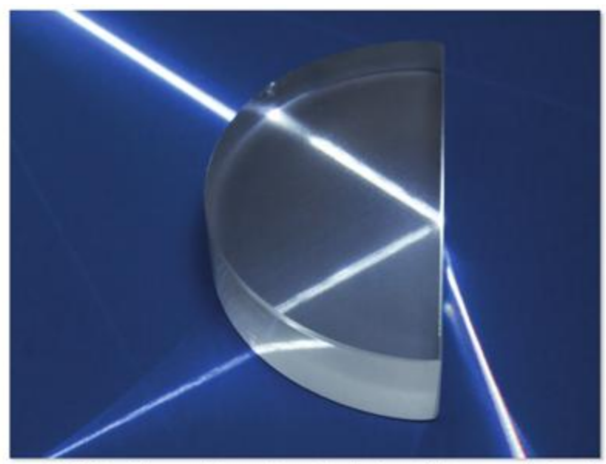


fig A Partial transmission and partial reflection of light at a media interface.

In the diagrams of fig B we can see a ray of light trying to leave an optically more dense medium. In these examples, the partial reflection is not drawn. The first diagram shows simple refraction, for which we could use Snell's law to make some calculations. The angle in the less dense medium is greater than the incident angle inside the more dense medium. In the second diagram, the incident angle has been increased. From Snell's law, we find that at this **critical angle**, the ray would emerge in the less dense medium at an angle of 90° - it would emerge exactly along the interface.

This is not refraction, as that requires a change in medium. This means that Snell's law cannot apply. In this case, what happens is that all the wave energy is reflected inside the more dense medium, and the angles follow the law of reflection. This is **total internal reflection (TIR).**

CRITICAL ANGLE CALCULATIONS

From Snell's law, we could find the critical angle for a material:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

If we take medium 1 to be the optically more dense material, then θ_2 must be 90° when the light is at the critical angle, θ_c, in medium 1.

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

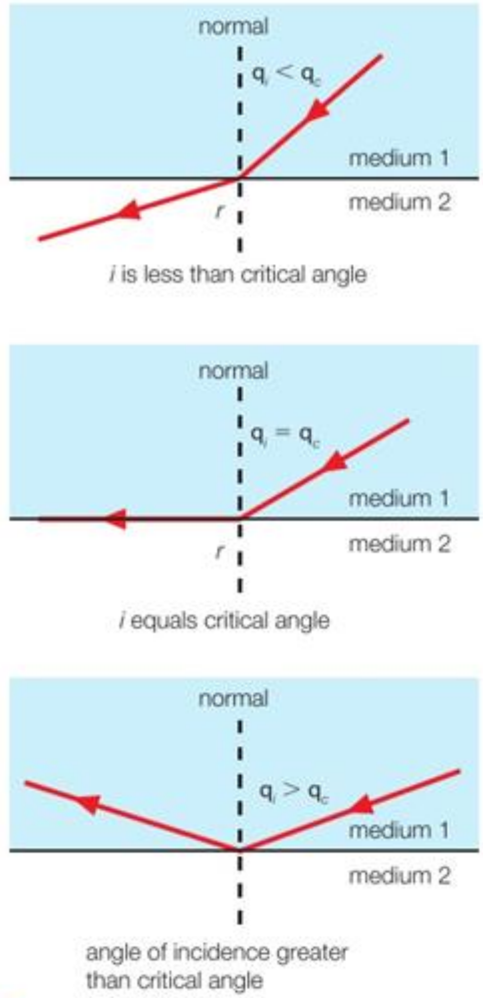
$$n_1 \sin\theta_c = n_2 \sin 90°$$

$$\sin 90° = 1$$

$$\therefore \quad n_1 \sin\theta_c = n_2 \qquad \sin\theta_c = \frac{n_2}{n_1}$$

If the situation involves a light ray emerging into air, then the equation becomes: $\sin\theta_c = \frac{1}{n_1}$

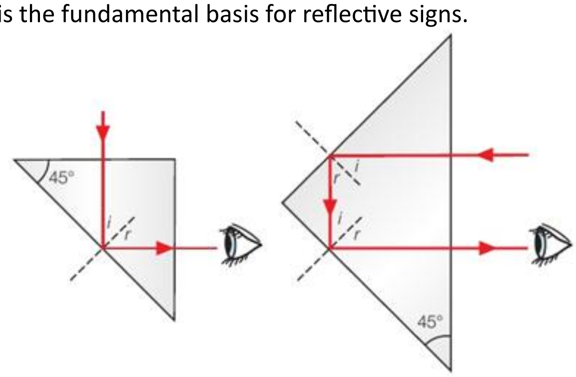
If we know the critical angle, then that will give us the refractive index for the material: $n_1 = \frac{1}{\sin\theta_c}$



▲ **fig B** Moving from refraction to total internal reflection.

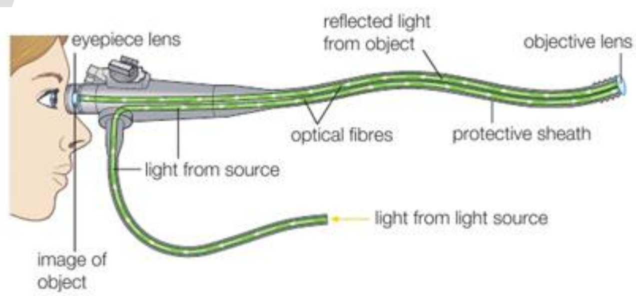
APPLICATIONS OF TIR

Fig C shows the movement of light through 45° prisms. The left-hand example is commonly used in periscopes, and the right-hand diagram is the fundamental basis for reflective signs.



▲ **fig C** Total internal reflection helps us direct light usefully.

A more complex use for TIR is in fibre optics. A thin glass fibre can guide light along its length by the repeated TIR at the internal edges. This may just be used for decorative lighting. Fibre optics can be used to guide sunlight to the interior of large buildings. Alternatively, optical fibres can be used to carry information as light pulses (as in fibre broadband) or as actual images (in uses such as a medical endoscope – see **fig E**).



▲ **fig E** A medical endoscope is used to view the body's internal organs without cutting the patient open. Light is sent in along one optic fibre, and the reflection is carried away along the other for viewing by medical staff.

SUBJECT VOCABULARY

critical angle the largest angle of incidence that a ray in a more optically dense medium can have and still emerge into a less dense medium. Beyond this angle, the ray will be totally internally reflected

total internal reflection (TIR) waves reflect back into the same medium at a boundary between two media. This requires two conditions to be met:

- the ray is attempting to emerge from the more dense medium
- the angle between the ray and the normal to the interface is greater than the critical angle

3C 3 Polarization

PLANE POLARISATION

Transverse waves have oscillations at right angles to the direction of motion. In many cases, the plane of these oscillations might be in one fixed orientation. Fig A shows the electric (red) and magnetic (blue) fields in an electromagnetic wave. In this example of a light wave, the electric fields only oscillate in the vertical plane. The wave is said to be plane polarised or, more precisely, vertically plane polarised. For electromagnetic waves, the plane of the electric field's oscillations is the one that defines its plane of **polarisation**.

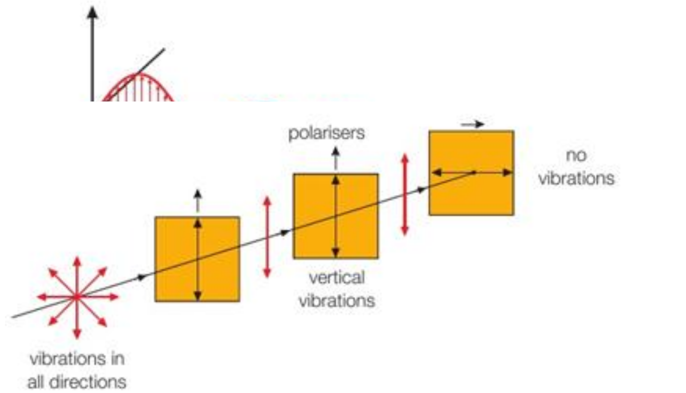


fig B Polaroid filters transmit light waves if their plane of polarisation matches with the orientation of the filter.

POLARISING FILTERS

Polarising filters filter unpolarised radiation by allowing only polarised waves to pass through. For light waves, a Polaroid sheet is used, soaked with chemicals, to ensure electric field oscillations are oriented in one direction, allowing only polarised waves to pass.

POLARISATION BY REFLECTION AND REFRACTION

When unpolarised light reflects from a surface, such as a road, the waves will become polarised. The degree of polarisation depends on the angle of incidence, but it is always tending towards horizontal plane polarisation, as shown in fig E. Sunglasses often have lenses with Polaroid filters. The Polaroid filters will block light that is horizontally polarised. If a driver has these, then they will block polarised light reflected from the road. This makes it easier for a driver to see clearly.

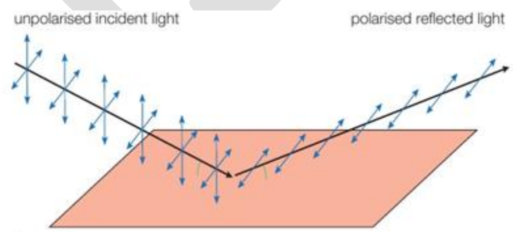


fig E Reflection can polarise waves.

Light waves incident on a surface into which they can refract (see **Section 3C.1**), such as a pond, will reflect partially horizontally polarised light as in **fig E**, but will also transmit partially vertically polarised light into the new medium, as in **fig F**.

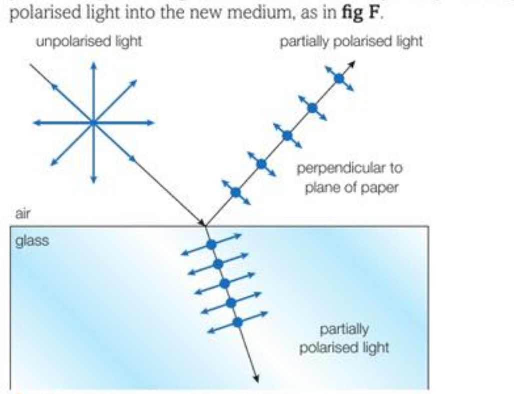


fig F Refraction can polarise waves.

POLARISATION BY CHEMICAL SOLUTIONS

The analysis of stress concentrations investigated above works because different parts of the plastic model have different effects on polarised light. This is also the case with some chemicals, such as sugar solution. The amount of the concentration of the sugar solution varies the angle to which it rotates the polarisation of the light. We can use Polaroid filters to analyse the strength of the sugar solution, by measuring the angle at which the light polarisation emerges after passing through the solution.

fig G Sugar solutions can rotate the plane of polarisation. The degree of polarisation on a particular wavelength (colour) depends on the concentration of the solution, and how far the light has had to pass through it. This gives rise to the changing colours seen along the length of this tube of sugar solution.

SUBJECT VOCABULARY

polarisation the orientation of the plane of oscillation of a transverse wave. If the wave is (plane) polarised, all its oscillations occur in one single plane

3D 1 Wave particle duality

HUYGENS' PRINCIPLE

The Dutch scientist Christiaan Huygens came up with a principle for predicting the future movement of waves if we know the current position of a wavefront. The basic idea is to consider that any and every point on the wavefront is a new source of circular waves travelling forwards from that point. When the movement of these numerous circular waves is plotted, and then their superposition considered, the resultant wave will be the new position of the original wavefront.

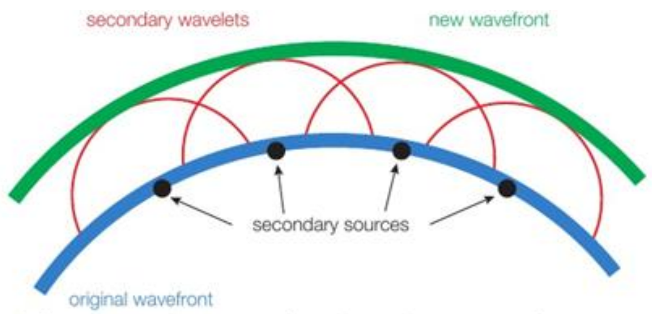


fig A Huygens' construction for explaining the movement of waves.

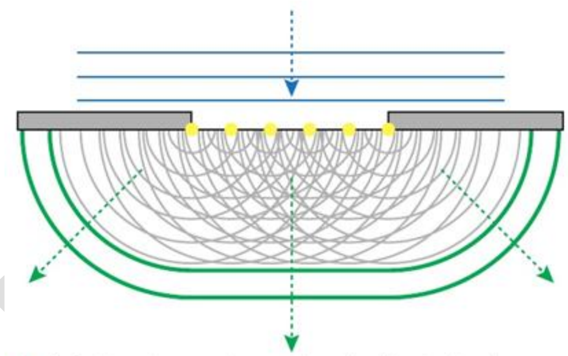


fig B Huygen's construction correctly predicts diffraction through a gap.

LIGHT IS A WAVE

We have seen numerous instances of light undergoing wave-like activities.

EVIDENCE THAT LIGHT IS A WAVE

The interference pattern produced by diffraction and Young's two-slit experiment both require the superposition of wave displacements to generate the standing wave pattern seen. This is only possible if light is behaving as a wave. It must have repeating cycles of displacement that cause this superposition. The constructive and destructive interference gives a pattern of antinodes and nodes (maxima and minima). Particles cannot superpose in this way.

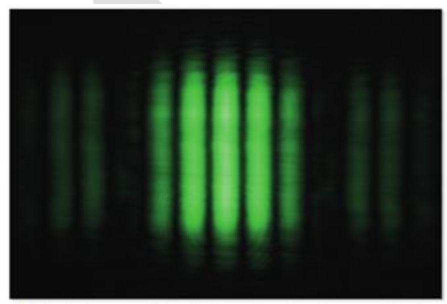


fig C Superposition effects, such as standing wave interference patterns, are only possible if light behaves as a wave.

LIGHT IS A PARTICLE

In some cases, the examples of light acting as a wave are phenomena that can only occur for waves. In Section 3D.2 we will look in detail at the photoelectric effect. This was first observed in 1887 by Heinrich Hertz (after whom the unit for frequency is named). However, it was not until the beginning of the twentieth century that an adequate explanation of the phenomenon was made. Working on the basis of Max Planck's 1901 suggestion that light could exist as quantised packets of energy called **photons**,

PHOTON ENERGY

For electromagnetic radiation, the energy of the photon can be calculated by multiplying the frequency by Planck's constant, h. This constant has an extremely small value because it represents the fundamental minimum possible step in energy. In SI units, h = 6.63 x 10-34 Js. If we work on very small scales, photons cannot have energy values that differ by less than the Planck constant. This means that there are some energy values that are impossible in our universe. Such a system of minimum sized steps is called **quantisation**.

The energy of a photon is given by the equation:

photon energy (J) = Planck's constant (J s) × frequency (Hz)

$$E = hf$$

ELECTRONS ARE PARTICLES

Experiments that produce ions can demonstrate electrons behaving as particles because a fixed lump of mass and charge is removed from the atom in order to change the atom into an ion. The charge to mass ratio is a unique identifying property of particles, and was first demonstrated for the electron by J.J. Thomson in 1897. Robert Millikan, in an experiment finally published in 1913, took this one step further to find the electron charge itself. The fact that electrons hold a fixed amount of charge and a fixed mass indicates they are localised particles.

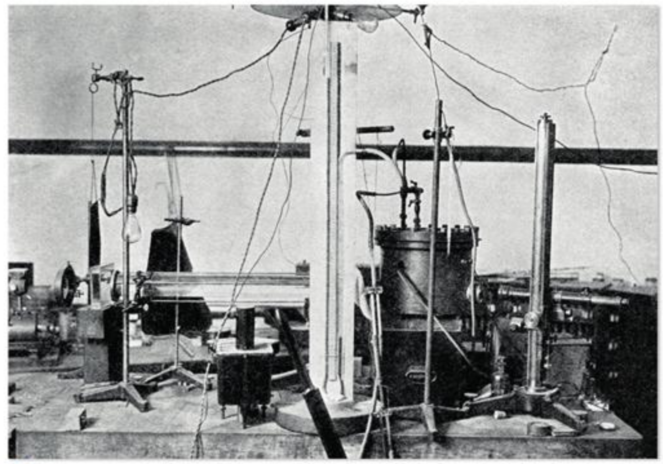


fig D Robert Millikan's oil drop apparatus showed that electrons have a fixed charge of 1.5924×10^{-19} coulombs. The difference with the currently accepted value is caused by a mistake in Millikan's calculations, because he used a slightly incorrect value for the viscosity of air.

ELECTRONS ARE WAVES

If electrons are made to travel at very high speeds, they will pass through gaps and produce a diffraction pattern. They will also interact with a double-slit apparatus to produce the interference pattern seen when waves pass through two slits. Diffraction and interference are not expected by classical particles, as they should simply travel straight through the slits. Observation of these experimental results proves that electrons can behave as waves.

WAVES OR PARTICLES?

The experimental observations highlighted in this section have suggested that both electrons and electromagnetic radiation seem to contradict our explanations of them. Physicists have good theoretical descriptions of the wave and particle natures for electrons and also for electromagnetic radiation. However, we do not have a complete and perfect single theory that explains both correctly for either electrons or EM radiation.

PHENOMENON	EVIDENCE FOR WAVES	EVIDENCE FOR PARTICLES
light	diffraction, interference, polarisation	photoelectric effect
electron	diffraction, interference	ionisation

table A Summary of the evidence for light and electrons behaving as waves or particles.

The idea that these things behave as waves under certain circumstances and as particles under other circumstances is known as **wave–particle duality**.

SUBJECT VOCABULARY

photons 'packets' of electromagnetic radiation energy where the amount of energy $E = hf$, which is Planck's constant multiplied by the frequency of the radiation: the quantum unit that is being considered when electromagnetic radiation is understood using a particle model

quantisation the concept that there is a minimum smallest amount by which a quantity can change: infinitesimal changes are not permitted in a quantum universe. The quantisation of a quantity is like the idea of the precision of an instrument measuring it

wave–particle duality the principle that the behaviour of electromagnetic radiation can be described in terms of both waves and photons

3D 2 The Photoelectric effect

photoelectrones

The **work function** of light is crucial in understanding the release of photoelectrons from negatively charged metals. The wave theory suggests that any light with a sufficiently bright amplitude can enable the release of photoelectrons. However, red light, which is the most effective in releasing photoelectrons, does not produce any photoelectrons. This is due to the maximum wavelength of light, known as the **threshold frequency**, which is the minimum frequency at which **photoelectrons** are never emitted.

The explanation for these experimental observations can be summarised as:

- Light travels as photons, with a photon's energy proportional to the frequency.

- When a photon encounters an electron, it transfers all its energy to the electron (the photon ceases to exist).

- If an electron gains sufficient energy - more than the work function - it can escape the surface of the metal as A photoelectron.

- Brighter illumination means more photons per second, which will mean a greater number of photoelectrons emitted per second.

- If an electron does not gain sufficient energy from an encounter with a photon to escape the metal surface, it will transfer the energy gained from the photon to the metal as a whole before it can interact with another photon. Thus, if the photon energy is too low, no photoelectrons are observed.

THE PHOTOELECTRIC EFFECT EQUATION

Einstein developed an equation to explain the photoelectric effect, which is based on the conservation of energy. We have previously seen that the energy of a photon can be found from $E = hf$. During the photoelectric effect, the energy of a photon is transferred to an electron. To escape a metal surface, an electron requires at least an amount of energy equal to the work function. It may also lose energy before escaping the metal due to other physical processes. Only the remaining energy will be available for the electron emission kinetic energy to be emitted from the surface. Therefore, the kinetic energy that the electron can have on emission from the metal surface is less than or equal to the difference between the photon energy and the work function. This maximum possible kinetic energy $\frac{1}{2}mv^2_{max}$ determines the maximum initial velocity v_{max} of the photoelectron. Einstein's photoelectric effect equation then is:

$$\frac{1}{2}mv^2_{max} = hf - \phi$$

Or, stated in terms of the conservation of energy, the photon energy transferred to the electron is used partly to escape the metal surface and partly for its kinetic energy on leaving the metal. So, a rearrangement of the equation is:

$$hf = \phi + \frac{1}{2}mv^2_{max}$$

THE PHOTOELECTRIC CELL EXPERIMENT

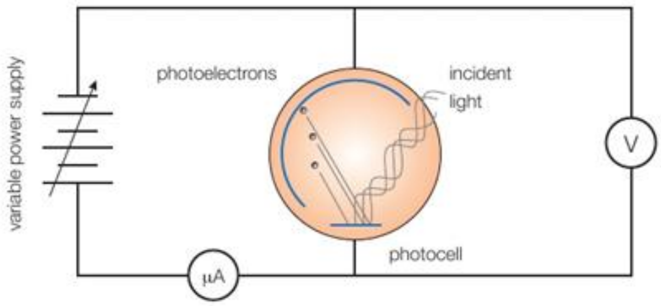


fig B A photoelectric effect cell experiment circuit.

We could use the photoelectric effect equation to measure Planck's constant and the work function for a metal. In a vacuum, we place the metal as the anode in a cell that has a gap to the cathode – see **fig B**. When we shine light of a known frequency onto the anode, photoelectrons will be emitted and the current registered on the ammeter. If we slowly increase the pd across the photoelectric cell, eventually the anode will become sufficiently positive that all photoelectrons will be stopped and attracted back to it, so the photoelectric current will be zero. This **stopping voltage**, V_s, will give us the maximum kinetic energy of the photoelectrons, from the definition of voltage:

$$\frac{1}{2}mv^2_{max} = e \times V_s$$

If we use a range of light frequencies and find the stopping voltage for each, we can plot a graph of the photoelectron maximum kinetic energy, on the y-axis, against frequency, on the x-axis. Comparison with the equation for a straight line shows us that the graph should produce a straight best-fit line and the gradient will be equal to Planck's constant.

$$\frac{1}{2}mv^2_{max} = hf - \phi$$

$$y = mx + c$$

The y-intercept will represent the value of the work function, ϕ. Also, when the value of y is zero (the x-intercept) then the photon energy must equal the work function.

$$\frac{1}{2}mv^2_{max} = hf - \phi$$

$$0 = hf - \phi$$

$$\therefore \quad hf = \phi$$

This means that the value of the x-intercept will give the threshold frequency for the anode metal.

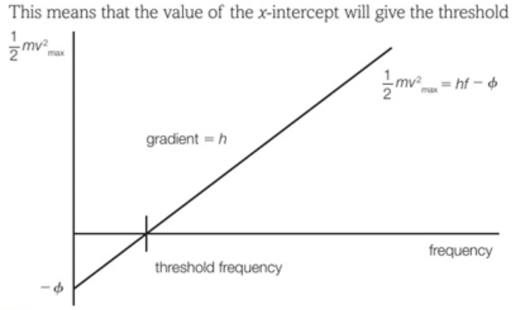


fig C Graphical analysis of results from a photoelectric cell experiment can determine Planck's constant and the work function for the anode metal.

EXAM HINT

When you have a graph with plotted data points, start by drawing a best-fit line. The question may not ask you to do this, but it will be expected.

METAL	WORK FUNCTION / eV
cadmium	4.07
caesium	2.10
iron	4.50
nickel	5.01
zinc	4.30

table A Examples of photoelectric work function values.

3D 3 Electron diffraction and interaction

ELECTRON DIFFRACTION

As a diffraction pattern is a wave phenomenon, to observe this from a beam of electrons means that they must be behaving as waves. This is true whether we are passing waves through a gap, as in fig A, or reflecting waves from a grating, as we saw in fig H of Section 3B.3.

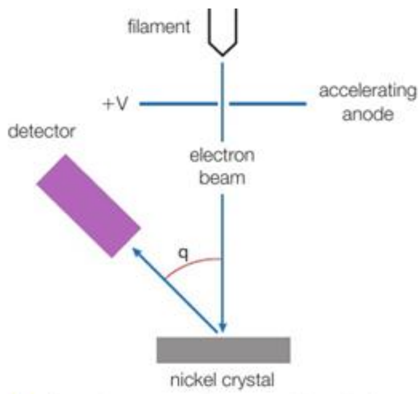


fig B Davisson and Germer reflected a beam of electrons from a nickel crystal and measured the intensity of the reflection at different angles.

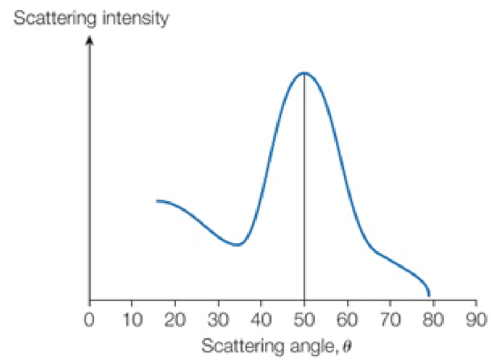


fig C Davisson and Germer's electron beam reflection from a surface of atoms, acting as a reflection grating, showed variable intensity at different angles, exactly as is observed with waves.

Not only did Davisson and Germer prove experimentally that electrons can behave as waves, but their results also allow calculation of the distance between atoms in the nickel crystal. This has given rise to advances in the study of atomic structures using electron beam crystallography.

DE BROGLIE EQUATION

In 1924, a French prince called Louis de Broglie suggested electrons could behave as waves and proposed an equation to calculate their wavelength. Their wavelength is inversely proportional to the momentum they have when considered as particles.

$$\text{electron wavelength (m)} = \frac{\text{Planck's constant (J s)}}{\text{momentum (kg m s}^{-1})}$$

$$\lambda = \frac{h}{p}$$

TWO-SLIT ELECTRON INTERFERENCE

In 1965, Richard Feynman suggested that electrons should also be able to produce the two-slit interference pattern seen with light, as they can behave as waves. Recently, this has been shown to be the case, giving further evidence for the wave nature of electrons.

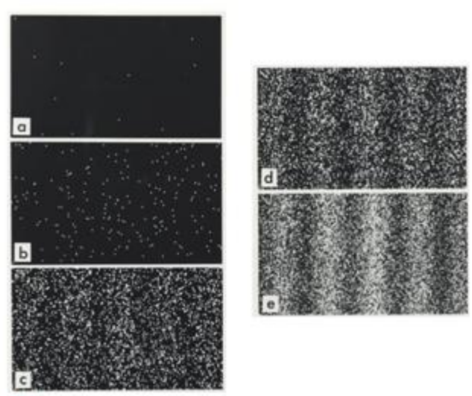


fig E Recent experiments have been able to demonstrate electrons producing an interference pattern when passed through a two-slit-type experiment. The five images here show the same image after different amounts of time. The particle electrons hit the screen in places that slowly build up the wave interference pattern.

ELECTRON MICROSCOPY

One of the most important applications of the wave nature of electrons is its use to study objects at very small scales.

Electron beams are useful for microscopy due to their ability to control wavelength by altering voltage. This allows for images of objects 1000 times smaller than visible light, as electron waves are 1000 times shorter than light waves.

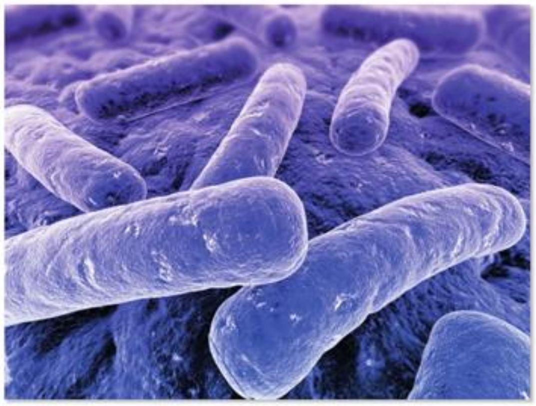


fig F Electron microscopes can have a magnification up to 10 million times. These bacteria are about 1 micrometre long.

fig G Electron microscopes have sufficient magnification to see the results of manipulation of individual atoms. This Atom Boy image was made by researchers at IBM who moved individual carbon monoxide molecules on a surface of copper metal.

3D 4 Atomic electron energies

ELECTRON ENERGY LEVELS

In **Section 4A.6** we will see that electrons in semiconductors can have varying amounts of energy, and that the energy they have can put them into the valence band or conduction band. These energy bands are wide in solids – there is a large range of values of energy that the electron could have and still be in that band. In free atoms, such as those in a gas, the energy values that the electrons could have are limited to a small number of exact values, often called energy levels.

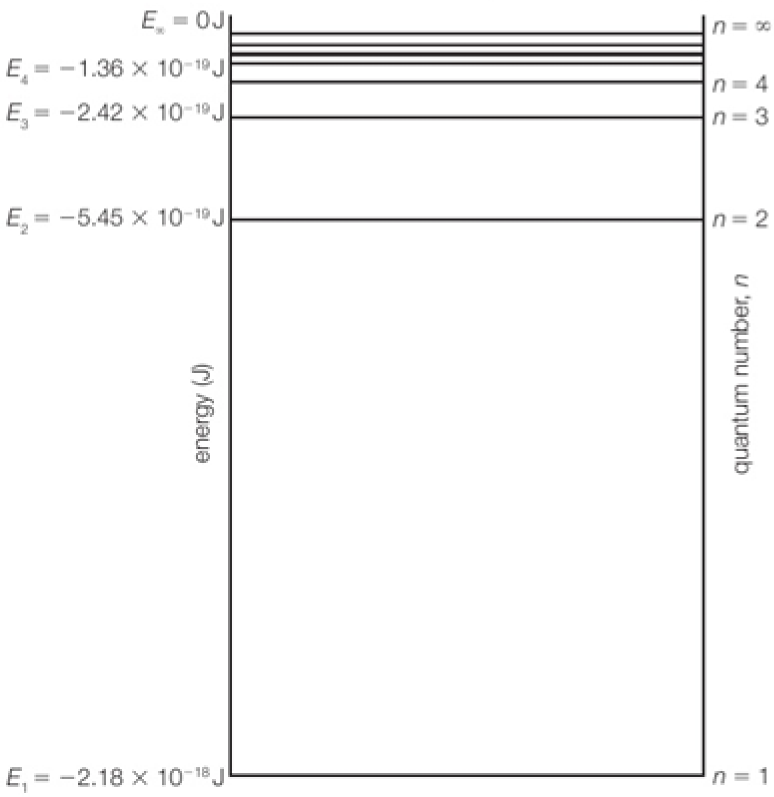


fig A An energy level diagram for hydrogen. The energy values are negative, as we have to put energy in to lift the electron up from the ground state.

EXCITATION AND DE-EXCITATION

Fig A illustrates the energy values that electrons of hydrogen could have. Under normal circumstances, an electron in an atom of hydrogen would be in its **ground state**. This is the lowest energy level, with a quantum number (or level) of n = 1. In order to move up energy levels, the electron must take in some energy. This is called **excitation**. Electrons can become excited if the atom collides with another particle. Alternatively, if the electron absorbs a photon that has exactly the correct amount of energy, the electron can jump to a higher energy level. For example, the difference in energy between the ground state (-2.18×10^{-18} J) and the n = 2 state (-5.45×10^{-19} J) is 1.635×10^{-18} J.

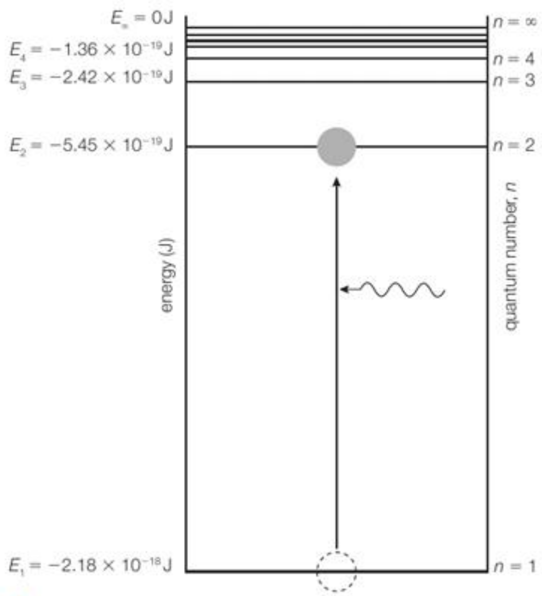


fig B Electron excitation in a hydrogen atom. For ease of reference, the energy levels are numbered with integers from $n = 1$ for the ground state, upwards.

An incident photon that does not have the energy exactly equivalent to a jump between the current position of the electron and one of the higher levels will not be absorbed – the photon and electron will not interact at all. If gas atoms are illuminated by a range of frequencies (colours), those with the correct frequency values will be absorbed, so there will be some colours missing from the light after it passes through the gas.

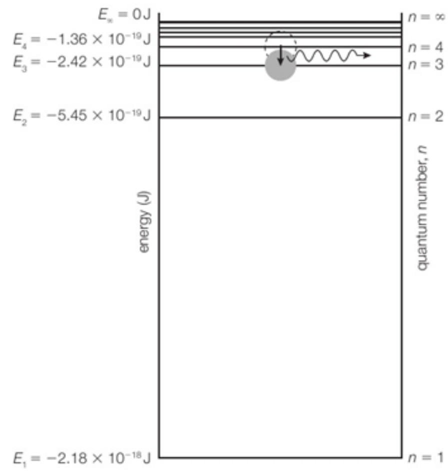


fig C Electron de-excitation in a hydrogen atom.

If an electron is already excited, after a random amount of time it will de-excite. This may involve dropping straight down to the

IONISATION

Fig A shows the ground state energy of a hydrogen atom is 2.18×10^{-18} J, which is equivalent to 13.6 electronvolts. The n = ∞ level at the top of the diagram has an energy value of zero. At this level, the electron has left the atom - the hydrogen is ionised. This means that the energy required to ionise an atom of hydrogen in its ground state, its ionisation energy, is 13.6 eV.

LINE SPECTRA

Light made up of multiple wavelengths (colours) can be split up to show which colours are present. This could be done using a diffraction grating in which the amount of diffraction is dependent on the wavelength, and so the various colours will spread different amounts. The resulting spectrum will often be a series of individual lines, if the original light contained only a few wavelengths. Such a line spectrum is the typical result of exciting the atoms of a gas, perhaps by heating the gas.

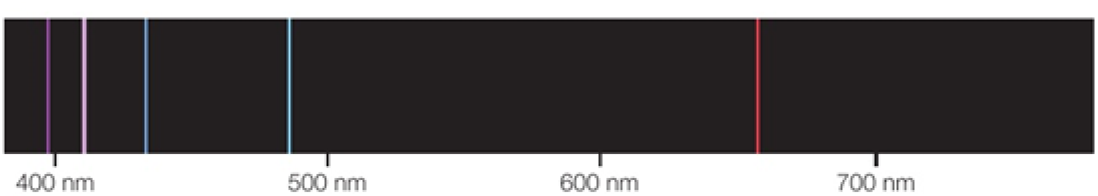


fig D Hydrogen emission line spectrum.

INTENSITY OF RADIATION

When a lamp emits light, we could measure its intensity. This is the amount of energy it carries, per unit area, and per unit time. Power is the rate of transfer of energy, so this becomes:

$$\text{intensity (W m}^{-2}\text{)} = \frac{\text{power (W)}}{\text{area (m}^2\text{)}}$$

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

SUBJECT VOCABULARY

ground state the lowest energy level for a system, for example, when all the electrons in an atom are in the lowest energy levels they can occupy, the atom is said to be in its ground state

excitation an energy state for a system that is higher energy than the ground state, for example, in an atom, if an electron is in a higher energy level than the ground state, the atom is said to be 'excited'

ionisation energy the minimum energy required by an electron in an atom's ground state in order to remove the electron completely from the atom

line spectrum a series of individual lines of colour showing the frequencies present in a light source

Revision questions

(1)(a) Some radio signals have a frequency of 218.6 MHz. Calculate their wavelength.
(b) State what is meant by:
(i) frequency
(ii) wavelength.

(2) Two students are carrying out an investigation to determine a value for the speed of sound in air. They stand 80 m from a building. One student hits two pieces of wood together to make a loud sound and a short time later an echo is heard.

The other student uses a stopwatch to measure the time interval t between the two pieces of wood being hit and the echo being heard. The procedure is repeated. The students also measure the air temperature.

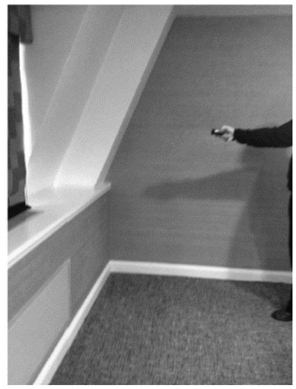
(a) Explain how a sound wave travels through air.
(b) The students repeat the investigation on a different day. The results are shown in the table.
(i) Deduce why the students thought it necessary to make a third measurement on day 2.
(ii) Calculate the percentage uncertainty in the mean value of time on day 1.

	temperature / °C	t_1 / s	t_2 / s	t_3 / s	mean t / s
Day 1	12	0.51	0.43	–	0.47
Day 2	18	0.44	0.69	0.48	0.46

(iii) Calculate the difference in the value for the speed of sound between day 1 and day 2 obtained from these results.
Difference in speed = ...

(iv) The students state that the difference in the speed of sound between day 1 and day 2 is due to the change in air temperature. Explain whether the results obtained are sufficient for this statement to be made

(3) An ultrasonic distance estimator can be used to measure the length of a room.



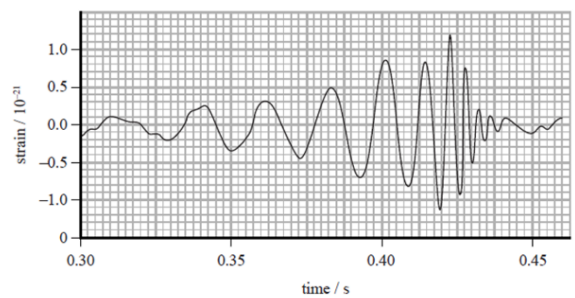
The estimator is held against one wall. It emits pulses of ultrasound and detects them when they return after reflection by the opposite wall.

(a) Explain why the ultrasound must be emitted in pulses.

(b) The shortest distance the estimator can measure is 40 cm. Calculate the longest pulse duration that would allow this distance to be measured. speed of ultrasound in air = 330 m s^{-1}

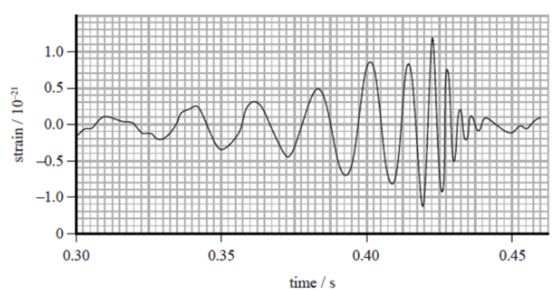
(c) When the estimator is pointed at a sloping wall, as shown in the photograph, it is unable to measure this distance. Suggest why the estimator is unable to measure the distance to the sloping wall.

(4) In 2016 scientists at the Laser Interferometer Gravitational-Wave Observatory (LIGO) announced that gravitational waves had been detected. The signal they detected is shown on the graph.
Gravitational waves travel at the speed of light. Determine the mean wavelength of the waves detected between 0.30 s and 0.35 s on the graph.



(5) In February 2013 the largest known meteor for a century exploded over the Ural region of Russia. The explosion was detected by stations monitoring infrasound, a type of sound with a frequency too low for humans to hear. Describe how infrasound travels through the air.

Gravitational waves travel at the speed of light. Determine the mean wavelength of the waves detected between 0.30 s and 0.35 s on the graph



(6) In February 2013 the largest known meteor for a century exploded over the Ural region of Russia. The explosion was detected by stations monitoring infrasound, a type of sound with a frequency too low for humans to hear.
Describe how infrasound travels through the air.

(7) Dolphins use ultrasound when hunting prey. They emit short pulses of ultrasound, known as clicks, and detect the ultrasound reflected from their prey.

(a) Describe how ultrasound travels through water.

(b) Suggest why the dolphins emit a series of clicks rather than a continuous sound.

(c) When searching for prey the dolphins emit 16 clicks per second.

(i) Show that the time between clicks when searching for prey is about 0.06 s.

(ii) Calculate the maximum distance that can be determined by the dolphin when searching for prey. speed of sound in seawater = 1530 m s−1

(iii) The dolphin increases the number of clicks per second to 125 when near to capturing its prey. Suggest why

(d) Bats use ultrasound in air when hunting prey. The ultrasound frequency and the duration of the click is the same for both bats and dolphins. Explain whether bats or dolphins would be able to locate their prey more precisely. speed of sound in air = 330 m s