WAVES

Overview

Waves are inherent in our everyday lives. Much of our understanding of wave phenomena has been accumulated over the centuries through the study of light (optics) and sound (acoustics). The nature of oscillations in light was only understood when James Clerk Maxwell, in his unification of electricity, magnetism and electromagnetic waves, stated that all electromagnetic fields spread in the form of waves. Using a mathematical model (Maxwell's equations), he calculated the speed of electromagnetic waves and found it to be close to the speed of light, leading him to make a bold but correct inference that light consists of propagating electromagnetic disturbances. This gave the very nature of electromagnetic waves, and hence its name.

In this bridging course, we examine the nature of waves in terms of the coordinated movement of particles. The discussion moves on to wave propagation and its uses by studying the properties of light, electromagnetic waves and sound, as well as their applications in wireless communication, home appliances, medicine and industry.

There are 4 topics in this course:

1. General Wave Properties
2. Light
3. Electromagnetic Spectrum
4. Sound

Topic 1: General Wave Properties

Content

- Describing wave motion
- Wave terms
- Longitudinal and transverse waves

Learning Outcomes

Students should be able to:

(a) describe what is meant by wave motion as illustrated by vibrations in ropes and springs

(b) compare transverse and longitudinal waves and give suitable examples of each

(c) show understanding that waves transfer energy without transferring matter

(d) define speed, frequency, wavelength, period and amplitude

(e) recall and apply the relationship velocity = frequency × wavelength to new situations or to solve related problems

(f) recall that a ripple tank can be used to demonstrate water waves

(g) state what is meant by the term wavefront

1.1 Types of wave motion

(a)	*describe what is meant by wave motion as illustrated by vibrations in ropes and springs*
(b)	*compare transverse and longitudinal waves and give suitable examples of each*
(c)	*show understanding that waves transfer energy without transferring matter*

Several kinds of wave motion occur in physics. **Mechanical waves** are produced by a disturbance, such as a vibrating object, in a material medium and are transmitted by the particles of the medium vibrating about a fixed position. Such waves can be seen or felt and include waves on a rope or spring, water waves and sound waves in air or in other materials.

A **progressive wave** or travelling wave is a disturbance which carries energy from one place to another without transferring matter. There are two types, **transverse** and **longitudinal waves**.

Transverse waves

In a transverse wave, the direction of the disturbance is at **right angles** to the direction of propagation of the wave, that is the direction in which the wave travels.

A transverse wave can be sent along a rope (or a spring) by fixing one end and moving the other rapidly up and down (Fig. 1.1). The disturbance generated by the hand is passed on from one part of the rope to the next which performs the same motion but slightly later. The humps and hollows of the wave travel along the rope as each part of the rope vibrates transversely about its undisturbed position.

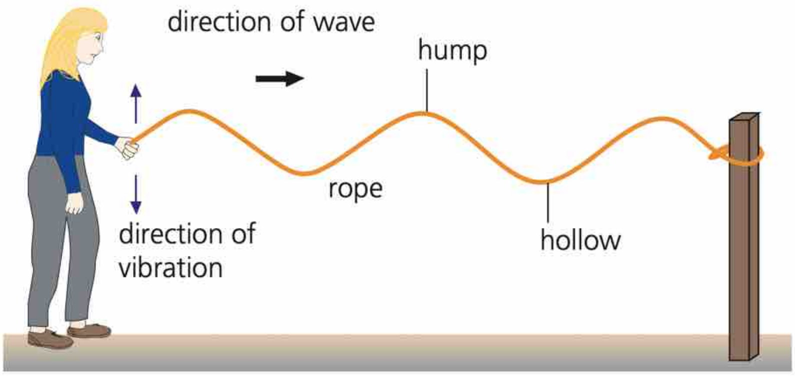


Fig. 1.1

The motion of the wave down the rope carries the energy provided by the hand towards the anchor point of the rope. The rope acts as the **medium** for the transverse wave to propagate while it remains intact, so there is no transfer of matter.

Longitudinal waves

In a progressive longitudinal wave the particles of the transmitting medium vibrate back and forth along the same line as (parallel to) that in which the wave is travelling and not at right angles to it as in a transverse wave. A longitudinal wave can be sent along a spring (or slinky), stretched out on the bench and fixed at one end, if the free end is repeatedly pushed and pulled sharply, as shown in Fig. 1.2.

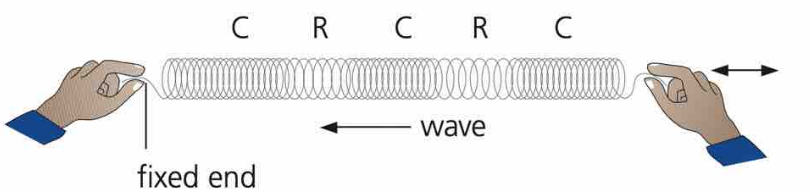


Fig. 1.2

Compressions C (where the coils are closer together) and **rarefactions** R (where the coils are further apart) travel along the spring.

The motion of the compressions and rarefactions wave down the spring carries the energy from the right hand towards the fixed end. The spring acts as the **medium** for the longitudinal wave to propagate while it remains intact, so there is no transfer of matter.

1.2 Describing Waves

(d)	*define wavelength, amplitude, period and frequency*
(e)	*recall and apply the relationship speed of wave = frequency × wavelength to new situations or to solve related problems*

Displacement–distance graph

Terms used to describe waves can be explained with the aid of a **displacement–distance graph** (Fig. 1.3). It shows, at a certain instant of time, the distance moved (sideways from their undisturbed positions) by the parts of the medium vibrating at different distances from the cause of the wave.

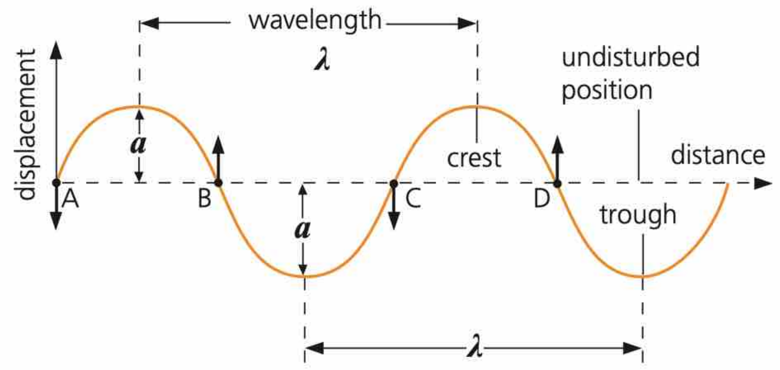


Fig. 1.3

Wavelength	The **wavelength** of a wave, represented by the Greek letter λ ('lambda'), is the distance between successive **crests** (peaks).
Amplitude	The **amplitude** a is the height of a crest or the depth of a trough measured from the undisturbed (or equilibrium) position of what is carrying the wave.

Deducing the direction of motion of points on a wave

The short arrows at A, B, C, D on Fig.1.3 show the directions of vibration of the parts of the rope at these points. How do we deduce the direction of motion of these points on the wave?

Fig. 1.4 shows a progressive transverse wave moving to the right.

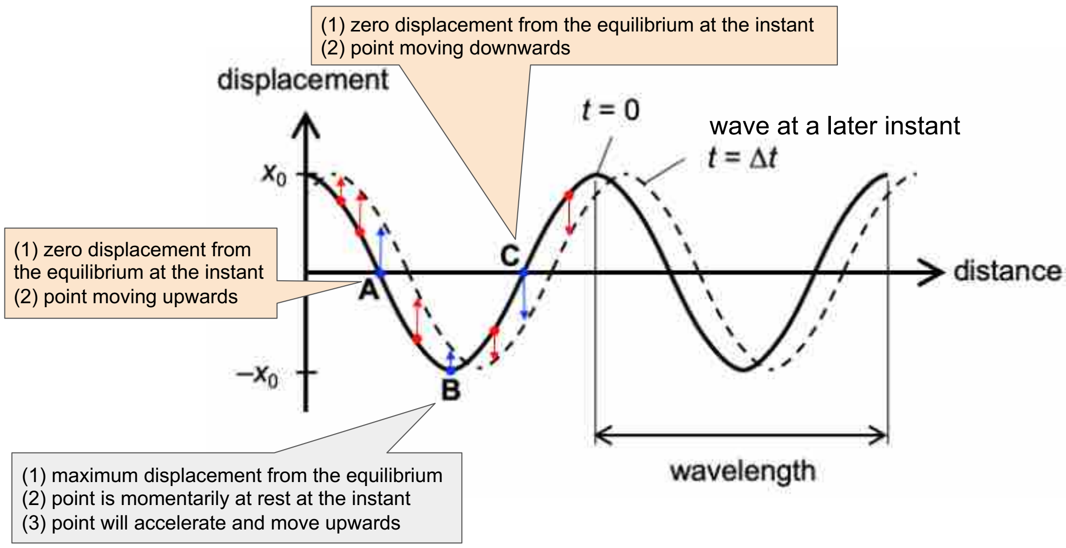


Fig. 1.4

The points on the rope A, B and C on the rope at the instant shown (solid line) must take up new positions to form the new wave at a later instant (dotted line). This method allows use to deduce the direction of motion of any points on the wave at a particular instant.

Phase

Phase	State of the vibration or oscillation of a point on a wave.

The short arrows at A, B, C, D on Fig.1.3 show the directions of vibration of the parts of the rope at these points.

- A and C have the same speed in the same direction and are **in phase**.
- B and D are also in phase with each other but they are **out of phase** with those at A and C because their directions of vibration are opposite.

In general,

Two points on a wave that are integer multiples of the wavelength (λ, 2 λ, 3λ, …) apart are **in phase**.

Displacement–time graph

If we track the displacement of a point in the medium, for example point B or D in Fig. 1.3, we obtain a **displacement–time graph** (Fig. 1.5).

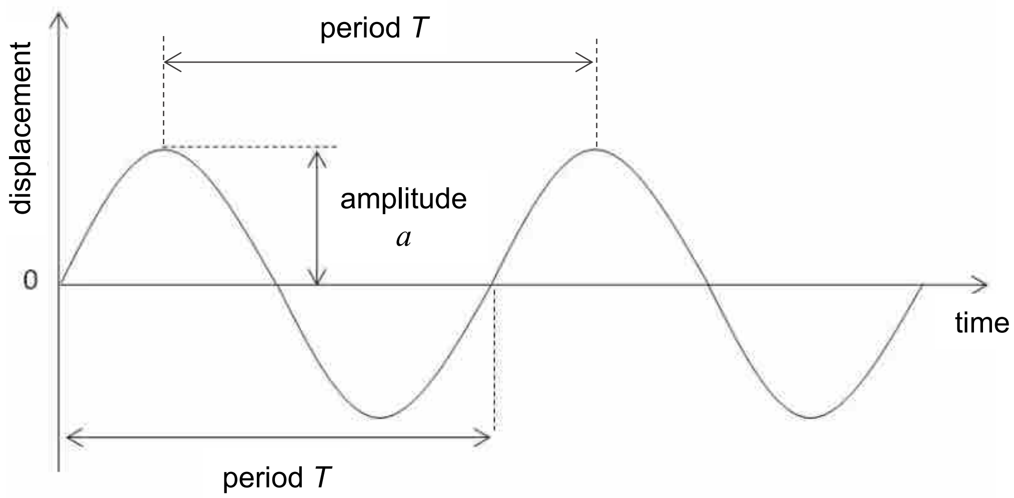


Fig. 1.5

Period	Time taken T for one complete oscillation of a point of the wave.

Frequency

Frequency	The **frequency** *f* is the number of complete waves generated per unit time. The frequency of a wave is also the number of crests passing a chosen point per unit time.

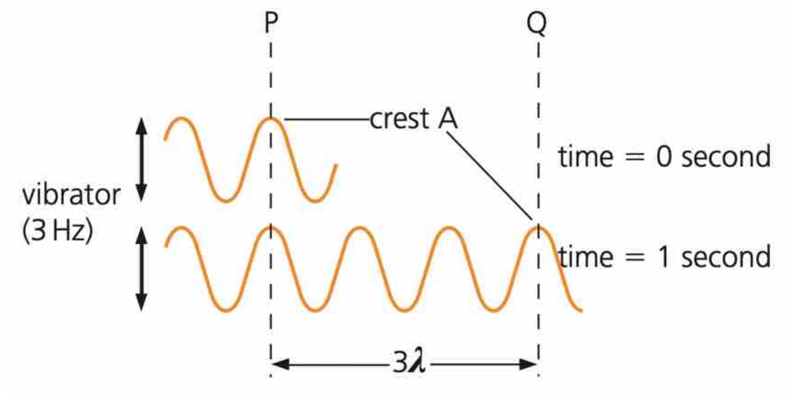


Fig. 1.6

A progressive wave propagates in a medium. Fig. 1.6 shows waves generated by a mechanical vibrator on a string at two certain instants of time, time = 0 and time = 1 second. We noticed that

- when the vibrator moves the end of a rope moved up and down three times in a second and three waves crests are produced in this time,
- three wave crests pass point P.

We say that the frequency of the wave is three vibrations per second or 3 hertz (3 Hz; the **hertz** is the unit of frequency), which is the same as the frequency of the movement of the end of the rope by the vibrator. That is, the frequencies of the wave and its source are equal.

Frequency *f* and period *T* are distinct, yet related, quantities. Frequency is a rate quantity and measured by cycles/second. Period is a time quantity and measured by seconds/cycle. From the units, it is not hard to guess that the relation between them is

$$f = \frac{1}{T} \quad \text{or} \quad T = \frac{1}{f}$$

The wave equation

The faster the end of a rope is vibrated, the shorter the wavelength of the wave produced. That is, the higher the frequency of a wave, the smaller its wavelength. There is a useful connection between *f, λ* and *v*, which is true for all types of wave.

Suppose waves of wavelength λ = 20 cm travel on a long rope and three crests pass a certain point every second. The frequency f = 3 Hz. Fig 1.5 (see above) represents this wave motion then, if crest A is at P at a particular time, 1 second later it will be at Q, a distance from P of three wavelengths, i.e. 3 × 20 = 60 cm. The speed of the wave is v = 60 cm per second (60 cm s^{-1}), obtained by multiplying *f* by λ. Hence the **wave equation** is

$$\text{speed of wave} = \text{frequency} \times \text{wavelength}$$
$$v = f\lambda$$

1.3 Water Waves and Wavefront

(f)	*recall that a ripple tank can be used to demonstrate water waves*
(g)	*state what is meant by the term wavefront*

<u>*The ripple tank*</u>

Water waves can be studied in a ripple tank. It consists of a transparent tray containing water, having a light source above and a white screen below to receive the wave images (Fig. 1.7).

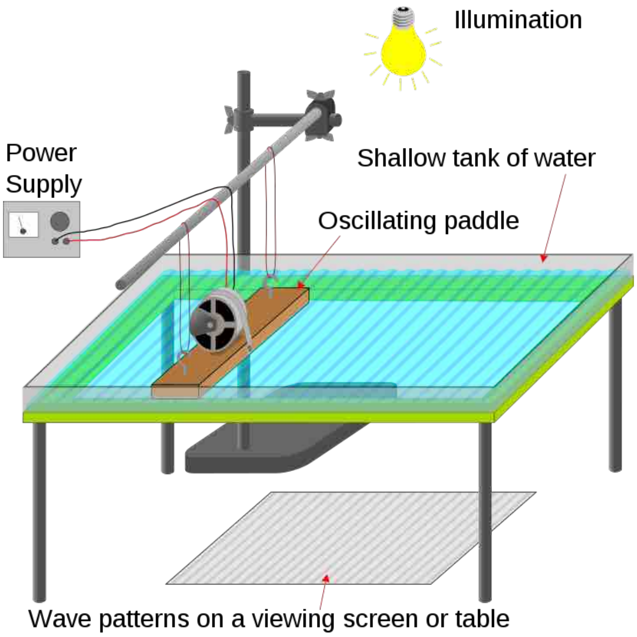


Fig. 1.7

The ripple tank can be used to observe

- **Pulses** (i.e. short bursts) of ripples are obtained by dipping a finger in the water for circular ripples and a ruler for straight ripples.

> https://youtu.be/cDt7gJICXEs
> This video shows circular ripples produced from a ripple tank.

- **Continuous ripples** are generated using an electric motor and a bar / paddle. The paddle gives straight ripples if it just touches the water or circular ripples if it is raised and has a small ball fitted to it.

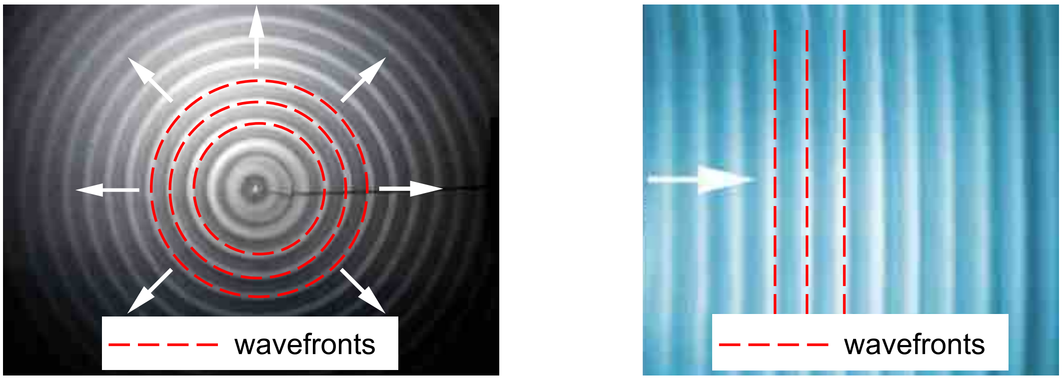
> https://youtu.be/ho2unLu-5Dw
> This video shows continuous straight ripples produced from a ripple tank.

> http://www.falstad.com/ripple/
> This simulation shows the continuous ripples produced from a ripple tank. Select the “single source” or “plane wave” examples to see circular and plane waves respectively. You may explore other examples.

Continuous ripples are studied more easily if they are *apparently* stopped (‘frozen’) by having a light source that flashes at the same frequency as the vibrating paddle.

Wavefronts

In two dimensions, a **wavefront** is a line on which the disturbance has the same phase at all points; the crests of waves in a ripple tank can be thought of as wavefronts. A vibrating source produces a succession of wavefronts, all of the same shape. In a ripple tank, circular wavefronts are produced by a vibrating ball (a point source) and straight wavefronts are produced by a vibrating bar (a line source), as shown in Fig. 1.8.



(a) circular wave ripples　　**(b)** plane wave (straight ripples)

Fig. 1.8

The distance between two successive wavefronts is one wavelength.

Rays

A line drawn at right angles to a wavefront, which shows its direction of travel, is called a **ray**.

Fig. 1.9 shows the wavefronts and the corresponding rays.

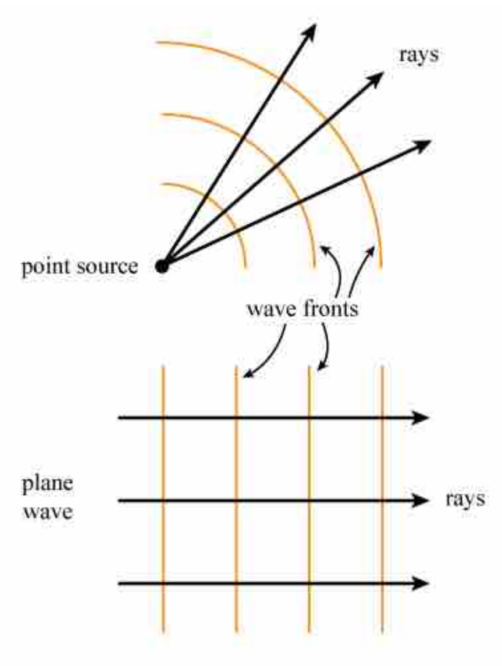
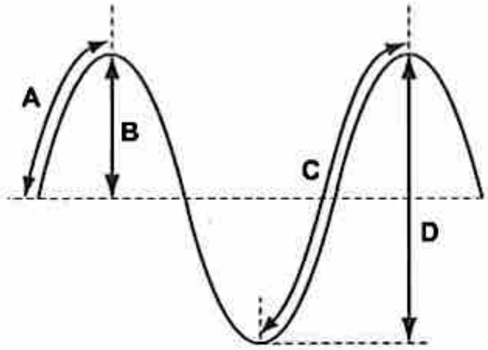


Fig. 1.9

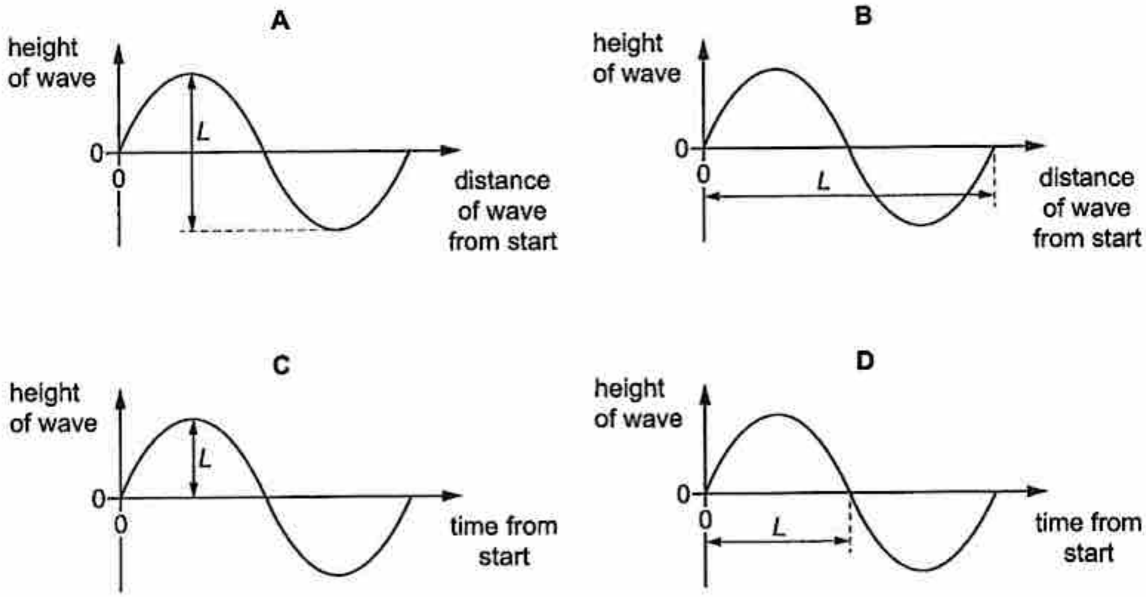
Problem Set (Topic 1)

1 What is the amplitude of the wave shown in the diagram? (2013 P1 Q25)

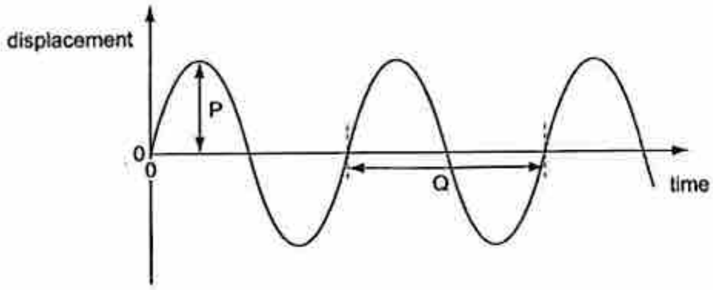


2 The graphs represent a wave on the surface of water.

On which graph does the length *L* show the wavelength of the wave? (2018 P1 Q22)



3 The diagram shows a graph of wave motion.



Which quantities are represented by P and by Q? (2012 P1 Q20)

	P	Q
A	amplitude	period
B	amplitude	wavelength
C	half the amplitude	period
D	half the amplitude	wavelength

4 A longitudinal wave travels along a spring.

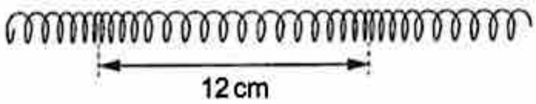
The diagram represents the position of the coils of the spring at one particular time.

The coils vibrate from side to side. Each coil completes 4.0 oscillations in 2.0 s.

Which distance is the wavelength and what is the frequency of the wave? (2016 P1 Q23)

	wavelength	frequency / Hz
A	X to Y	0.5
B	X to Y	2.0
C	Y to Z	0.5
D	Y to Z	2.0

5 The diagram shows part of a long stretched spring. A longitudinal wave is travelling along the spring.

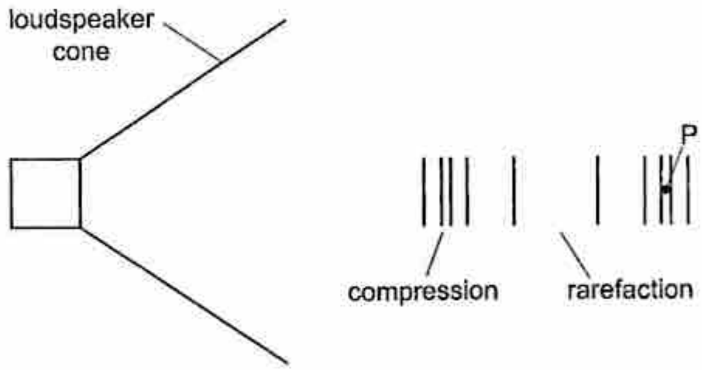


A point on the spring moves backwards and forwards between two positions that are 1.0 cm apart.

Which row describes the wave? (2020 P1 Q22)

	amplitude / cm	wavelength / cm
A	0.50	12
B	0.50	24
C	1.0	12
D	1.0	24

6 Compressions and rarefactions are sent out from a loudspeaker cone as it vibrates backwards and forwards. The frequency of vibration is 20 Hz.

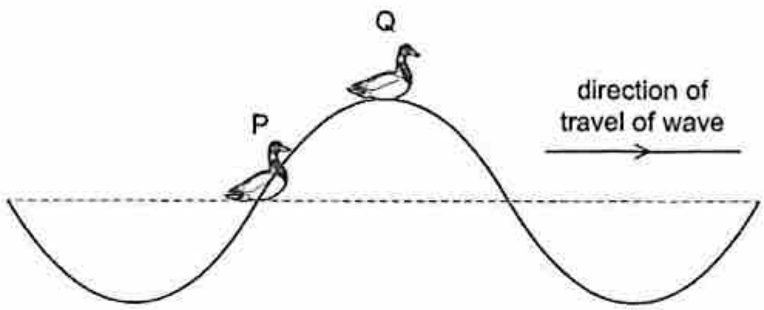


Point P is at the centre of a compression.

How much time elapses before the next rarefaction arrives at P? (2017 P1 Q21)

A 0.025 s **B** 0.050 s **C** 10 s **D** 20 s

7 The diagram shows two ducks P and Q sitting on a pond. A wave moves across the pond from left to right.



At the moment shown, duck Q is at a maximum displacement and duck P has zero displacement.

Which row describes the movement of the ducks during the next half cycle of the wave? (2018 P1 Q24)

	duck P	duck Q
A	only falls	only falls
B	falls then rises	only falls
C	falls then rises	falls then rises
D	only rises	falls then rises

8 A wave travels at a speed of 1.4 km/s and has a wavelength of 0.70 mm.

What is the frequency of the wave? (2020 P1 Q23)

A 0.98 Hz **B** 2.0 Hz **C** 2.0×10^3 Hz **D** 2.0×10^6 Hz

9 A wave moves across the surface of the water in a ripple tank. In 1.0 minute, a wavefront moves a distance of 12 wavelengths.

What is the frequency of the wave? (2015 P1 Q22)

A 0.20 Hz **B** 2.5 Hz **C** 5.0 Hz **D** 12 Hz

10 Typhoons create waves on the surface of the ocean.

Fig. 1 gives data on the speed and wavelength of some water waves. The waves travel in deep water of depth 4000 m or in shallow water of depth 10 m.

depth 4000 m	wavelength/m	10	40	100	200	300	400	500	600
	speed / m/s	4.0	7.9	12.5	17.7	21.6	25.0	27.9	30.6

depth 10 m	wavelength/m	10	40	100	200	300	400	500	600
	speed / m/s	4.0	7.6	9.3	9.7	9.8	9.9	9.9	9.9

Fig. 1

(a) For the range of wavelengths in Fig. 1, state

(i) a similarity in the speed of water waves in deep and shallow water, [1]

(ii) a difference between the speed of water waves in deep and shallow water. [1]

(b) A typhoon, 2000 km away from a stationary ship, forms quickly. It generates water waves for a short period of time.

The waves, with wavelengths between 10 and 600 m, travel across an ocean of depth 4000 m to the ship.

(i) Calculate the time taken for the first wave to reach the ship. [2]

(ii) Calculate the frequency of the first wave to reach the ship. [2]

(iii) Determine, to the nearest 100 m, the wavelength of the wave that arrives 4 hours **after** the first wave. [2]

(iv) As the first waves arrive at the ship, describe

1. the motion of the ship, [1]
2. the effect on the ship of the increase in frequency of the waves that arrive. [1]

(2012 P2B Q9)

Solutions

1	B	**2**	B	**3**	A	**4**	D	**5**	A
6	A	**7**	B	**8**	D	**9**	A		

10 **(a) (i)** At wavelengths up to about 40 m, speeds of waves are similar.

(a) (ii) Wave speed in shallow water increases with increasing wavelength to a maximum speed of 9.9 m s^{-1} and stop increasing when the wavelength is about 400 m. Wave speed in deep water continues to increase with increasing wavelength.

(b) (i) 6.5×10^4 s **(ii)** 0.051 Hz **(iii)** 400 m

Topic 2: Light

Content

- Reflection of light
- Refraction of light

Learning Outcomes

Students should be able to:

(a) recall and use the terms for reflection, including normal, angle of incidence and angle of reflection

(b) state that, for reflection, the angle of incidence is equal to the angle of reflection and use this principle in constructions, measurements and calculations

(c) define refractive index of a medium in terms of the ratio of speed of light in vacuum and in the medium

(d) recall and use the terms for refraction, including normal, angle of incidence and angle of refraction

(e) *recall and apply the relationship* $\frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2}$ *to new situations or to solve related problems*

(f) explain the terms critical angle and total internal reflection

(g) identify the main ideas in total internal reflection and apply them to the use of optical fibres in telecommunication and state the advantages of their use

2.1 Sources of light

You can see an object only if light from it enters your eyes. Some objects such as the Sun, electric lamps and candles make their own light and they are luminous sources. Most things you see do not make their own light but reflect it from a luminous source.

Light travels in straight lines. The direction of the path in which light is travelling is called a *ray* and is represented in diagrams by a straight line with an arrow on it. A beam is a stream of light and is shown by a number of rays, as in Figure 2.1. A beam may be **parallel**, **diverging** (spreading out) or **converging** (getting narrower).

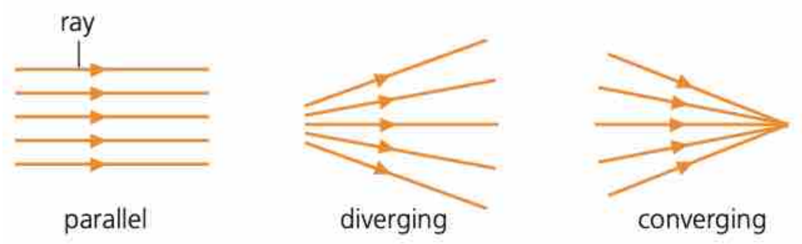


Fig. 2.1

The speed of light has a definite value; light does not travel instantaneously from one point to another but takes a certain, very small time. Its speed is 2.9979×10^8 m s^{-1} or 3.00×10^8 m s^{-1} when expressed to three significant figures.

2.2 Reflection of Light

(a)	*recall and use the terms for reflection, including normal, angle of incidence and angle of reflection*
(b)	*state that, for reflection, the angle of incidence is equal to the angle of reflection and use this principle in constructions, measurements and calculations*

Terms used in connection with reflection are shown in Fig. 2.2.

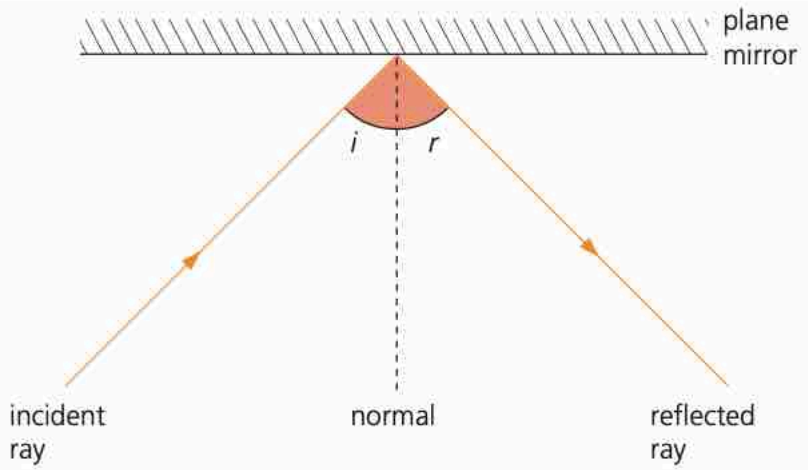


Fig. 2.2

- **Normal** line is perpendicular to a surface
- **Angle of incidence** *i* is the angle between the incident ray and the normal to a surface
- **Angle of reflection** *r* is the angle between the reflected ray and the normal to a surface

The **law of reflection** states:

The angle of incidence is equal to the angle of reflection.

The incident ray, the reflected ray and the normal all lie in the same plane. (This means that they could all be drawn on a flat sheet of paper.)

https://youtu.be/ETF2-Zz3J18
This video shows how the law of reflection can be determined experimentally.

Application

A simple *periscope* consists of a tube with two plane mirrors, fixed parallel to and facing each other. Each makes an angle of 45° with the line joining them. Light from the object is turned through 90° at each reflection and an observer is able to see over a crowd or over the top of an obstacle.

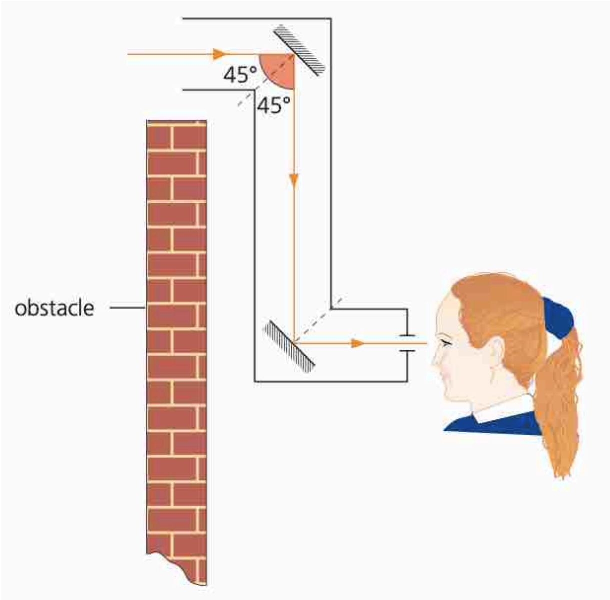


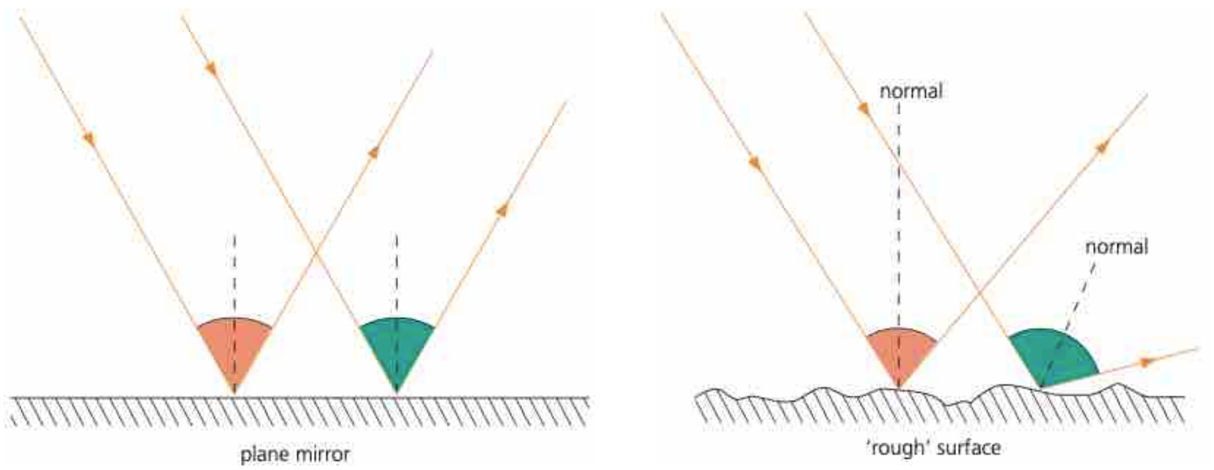
Fig. 2.3

In more elaborate periscopes like those used in submarines, prisms replace mirrors (section 2.3).

https://youtu.be/gwvI7KTgQSk
The video explains how a periscope works using the law of reflection.

Application (Regular and diffuse reflection)

If a parallel beam of light falls on a plane mirror it is reflected as a parallel beam (Fig. 2.4a) and regular reflection occurs. Most surfaces, however, reflect light irregularly and the rays in an incident parallel beam are reflected in many directions (Fig. 2.4b), this is known as diffuse reflection.



(a) **(b)**

Fig. 2.4

Real and virtual images

When you look into a plane mirror on the wall of a room you see an image of the room behind the mirror; it is as if there were another room.

A **real image** is one which can be produced on a screen (refer to Fig. 2.5 for a pinhole camera) and is formed by rays that actually pass through the screen.

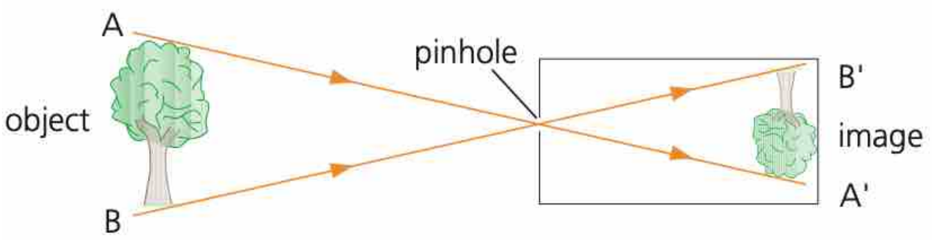


Fig. 2.5

A **virtual image** cannot be formed on a screen. The virtual image is produced by rays which seem to come from it but do not pass through it. The image in a plane mirror is virtual. Rays from a point on an object are reflected at the mirror and appear to our eyes to come from a point behind the mirror where the rays would intersect when extrapolated backwards (Fig. 2.6). IA and IB are construction lines and are shown as broken lines.

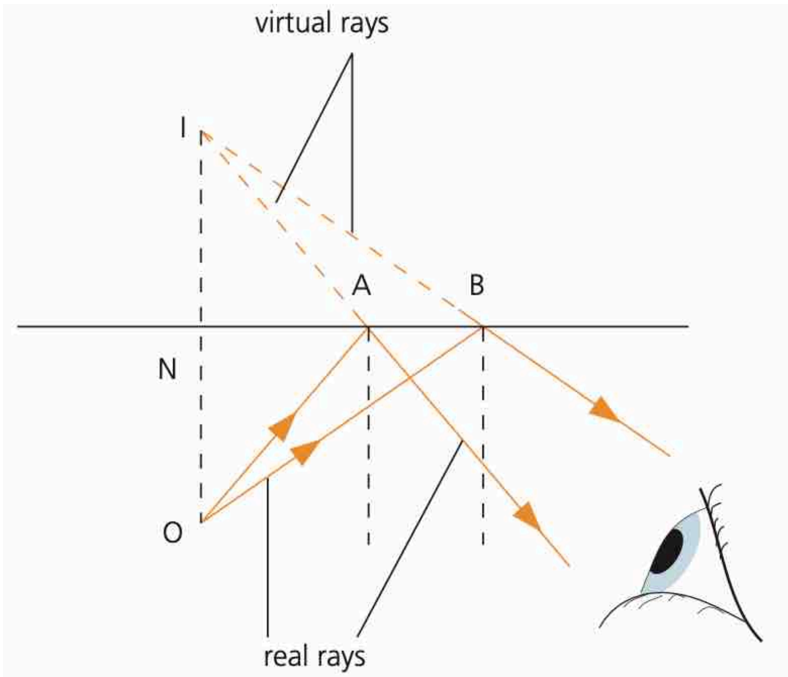


Fig. 2.6

The image in a plane mirror is

(i) as far behind the mirror as the object is in front, with the line joining the same points on object and image being perpendicular to the mirror

(ii) the same size as the object

(iii) virtual.

https://youtu.be/NeTqaDfdINc
The video explains what is a virtual image.

2.3 Refraction of light

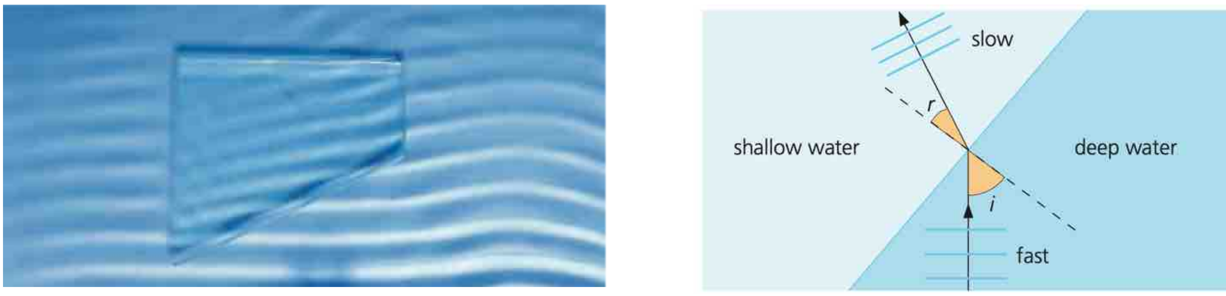
(A) Refraction of water waves in ripple tank

(c)	*define refractive index of a medium in terms of the ratio of speed of light in vacuum and in the medium*

If a glass plate is placed in a ripple tank so that the water over the glass plate is about 1 mm deep but is 5 mm deep elsewhere, continuous straight waves in the shallow region are found to have a shorter wavelength than those in the deeper parts, i.e. the wavefronts are closer together (Fig. 2.7). Both sets of waves have the frequency of the vibrating bar and, since $v = f\lambda$, if λ has decreased so has v, since f is fixed. Hence *waves travel more slowly in shallow water.*

Fig. 2.7

When the plate is at an angle to the waves (Fig. 2.8a), their direction of travel in the shallow region is bent towards the normal (Fig. 2.8b). The change in the direction of travel of the waves, which occurs when their speed and hence wavelength changes, is termed **refraction**.



(a) **(b)**

Fig. 2.8

https://youtu.be/Sar8jV8gm8Q
Video on angled refraction in a ripple tank.

Although light travels in straight lines in a transparent material, such as air, if it passes into a different material, such as water, it changes direction at the boundary between the two, i.e. it is bent. The water wave analogy allows us to define the property that results in the bending of light.

Refractive index n of a medium is the ratio of speed of light in vacuum and in the medium.

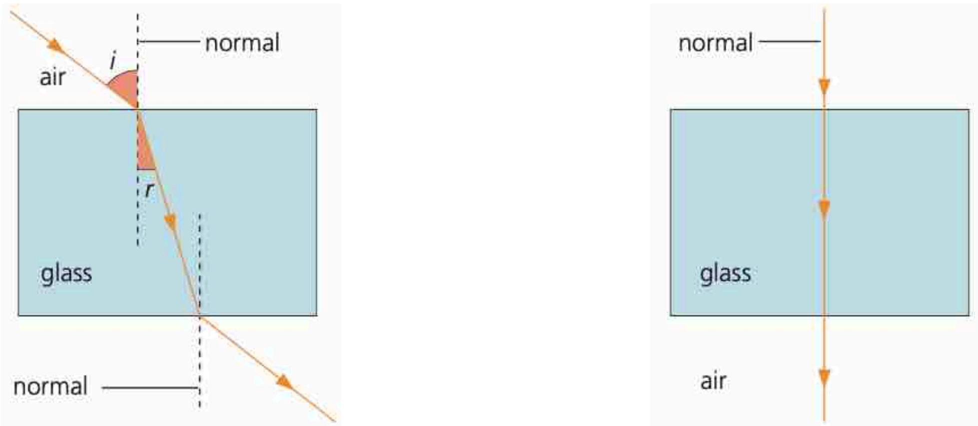
$$n = \frac{v_{\text{vacuum}}}{v_{\text{medium}}}$$

The refractive index of air is about 1.0003 which is usually taken to be equal to 1.

(B) Refraction of light

(d)	*recall and use the terms for refraction, including normal, angle of incidence and angle of refraction*
(e)	*recall and apply the relationship* $\frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2}$ *to new situations or to solve related problems*

Terms used in connection with refraction are shown in Fig. 2.9a.



(a) (b)

Fig. 2.9

- **Normal** line is perpendicular to a surface
- **Angle of incidence** *i* is the angle between the incident ray and the normal to a surface
- **Angle of refraction** *r* is the angle between refracted ray and the normal to a surface

https://youtu.be/XTMbYDrMr0w
This video shows how the refraction is investigated.

Facts about refraction:

(i) A ray of light is bent *towards* the normal when it enters an optically denser medium at an angle, for example from air to glass as in Fig. 2.9a. So the angle of refraction *r* is smaller than the angle of incidence *i*.

(ii) A ray of light is bent *away from* the normal when it enters an optically less dense medium, for example from glass to air.

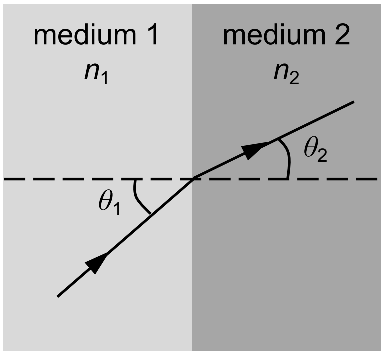
(iii) A ray emerging from a parallel-sided block is *parallel* to the ray entering, but is *displaced sideways*, like the ray in Fig. 2.9a.

(iv) A ray travelling along the normal direction at a boundary is *not refracted* (Fig. 2.9b).

Note: that 'optically denser' means having a greater refraction effect; the actual density may or may not be greater.

When light propagating in medium 1 (refractive index n_1) enters medium 2 (refractive index n_2),

$$\frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2}$$

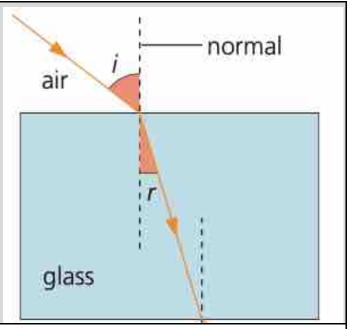


Application

The figure shows a solid, transparent block of glass in air.

The refractive index for the glass is 1.6.

Calculate the angle of refraction *r* for an angle of incidence *i* of 24°.



Solution

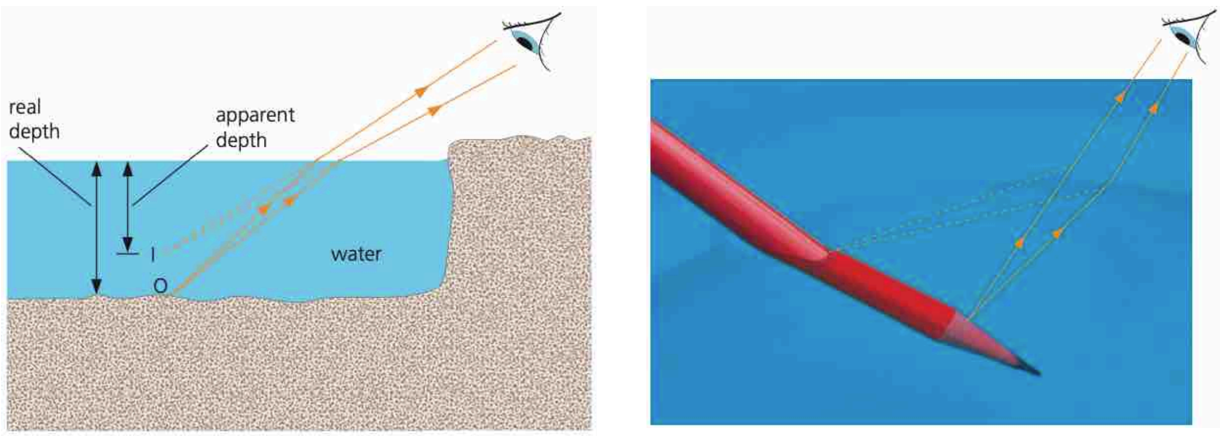
$$\frac{n_{\text{glass}}}{n_{\text{air}}} = \frac{\sin i}{\sin r} \Rightarrow \frac{1.6}{1} = \frac{\sin 24°}{\sin r} \Rightarrow \sin r = \frac{\sin 24°}{1.6}$$

$$r = 15°$$

Application (Real and apparent depth)

Rays of light from a point O on the bottom of a pool are refracted away from the normal at the water surface because they are passing into an optically less dense medium, i.e. air (Fig. 2.10a). On entering the eye, they appear to come from a point I that is *above* O; I is the virtual image of O formed by refraction.

The apparent depth of the pool is less than its real depth. Similarly, rays from the submerged part of the pencil in Fig. 2.10b are refracted at the water surface.



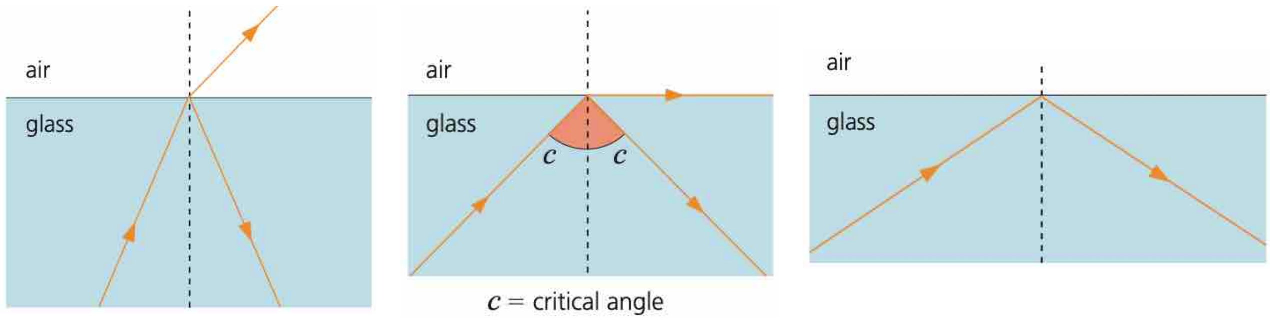
(a) **(b)**

Fig. 2.10

https://youtu.be/i8BNEuhDP6s
This video explains the concept of apparent depth.

(C) Critical angle and total internal reflection

(f)	*explain the terms critical angle and total internal reflection*
(g)	*identify the main ideas in total internal reflection and apply them to the use of optical fibres in telecommunication and state the advantages of their use*



(a) **(b)** **(c)**

Fig. 2.11

When light passes at small angles of incidence from an optically dense to a less dense medium, such as from glass to air, there is a strong refracted ray and a weak ray reflected back into the denser medium (Fig. 2.11a). As well as refraction, some *internal reflection* occurs. Increasing the angle of incidence increases the angle of refraction.

At a certain angle of incidence, called the **critical angle** *c* the angle of refraction is 90° (Fig. 2.11b) and the refracted ray passes along the boundary between the two media. For angles of incidence greater than *c*, the refracted ray disappears and all the incident light is reflected inside the denser medium (Fig. 2.11c). The light does not cross the boundary and is said to undergo **total internal reflection**.

> https://youtu.be/d7U3k2XtzVU
> Video on critical angle and total internal reflection.

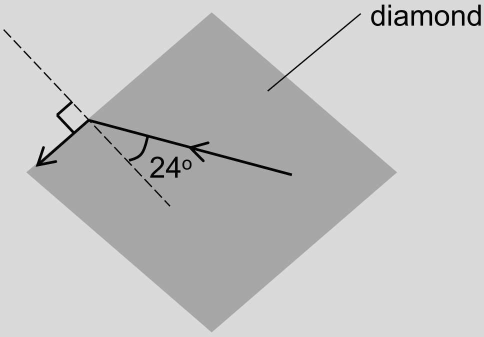
Definition

Critical angle *c* angle of incidence which produces an angle of refraction of 90°

Total internal reflection occurs when a light ray does not cross the boundary between two media; it is totally reflected at the boundary

Application

A diamond is in air. Light travelling in the diamond has a critical angle of 24°.



Calculate its refractive index of diamond.

Solution

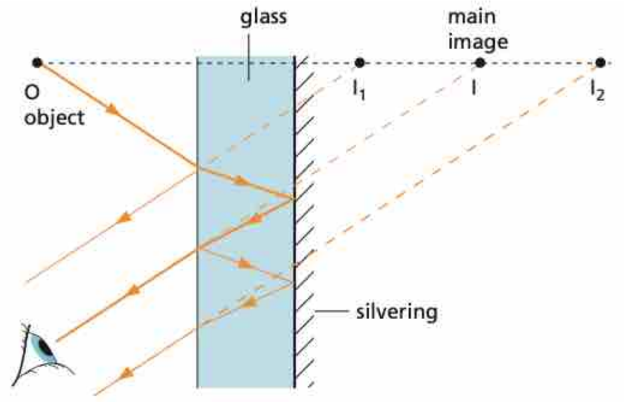
$$\frac{n_{\text{diamond}}}{n_{\text{air}}} = \frac{\sin 90^\circ}{\sin 24^\circ} \Rightarrow \frac{n_{\text{diamond}}}{1} = \frac{1}{\sin 24^\circ}$$

$$n_{\text{diamond}} = 2.5$$

Application (Multiple images in a mirror)

An ordinary mirror silvered at the back forms several images of one object, because of multiple reflections inside the glass (Fig. 2.12a). These blur the main image I (which is formed by one reflection at the silvering), especially if the glass is thick. The problem is absent in front-silvered mirrors but such mirrors are easily damaged.

(a)

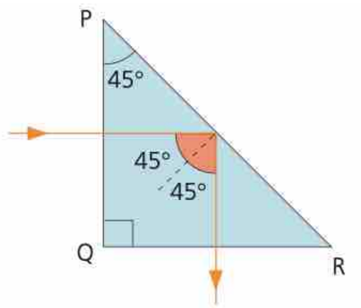


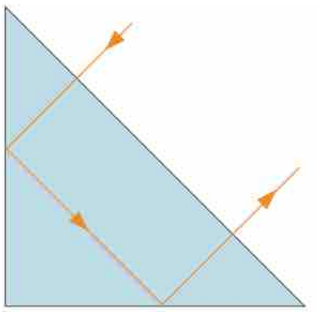
(b)

Fig. 2.12

Application (Totally reflecting prisms)

The defects of mirrors are overcome if 45° right-angled glass prisms are used. The critical angle of ordinary glass is about 42° and a ray falling normally on face PQ of such a prism hits face PR at 45°. Total internal reflection occurs and the ray is turned through 90°. Totally reflecting prisms replace mirrors in good periscopes. Light can also be reflected through 180° by a prism.



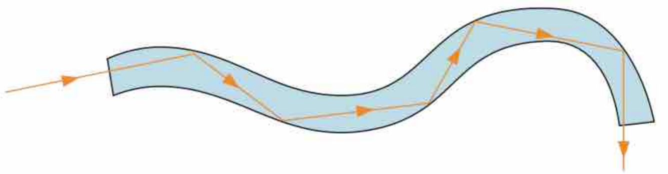


https://youtu.be/53ZrheeWre8
Demonstration of different total internal reflection that occurs in prisms.

Fig. 2.13

Application (Optical fibres)

Light can be trapped by total internal reflection inside a bent glass rod. A single, very thin glass fibre, an **optical fibre**, behaves in the same way.



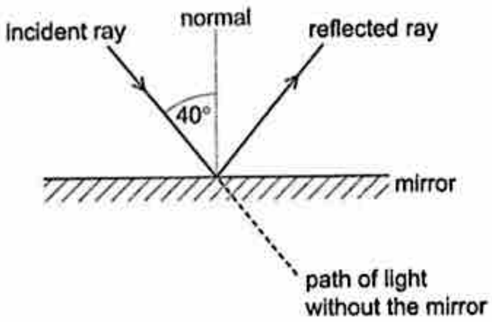
https://youtu.be/Lic3gCS_bKo
Video on optical fibre demonstration.

Fig. 2.13

Optical fibres are being used to carry telephone, high-speed broadband internet and cable TV signals as pulses of visible or infrared light. The advantages over copper cables for telecommunication purposes are (1) information can be transmitted at a higher rate, and (2) the data is more secure because they are unaffected by electronic interference. So, they can be used over longer distances (since they have lower power loss), are made of cheaper material and, as they are lighter and thinner, are easier to handle and install. However, they are not as strong as copper cables and can break if bent too much.

Problem Set (Topic 2)

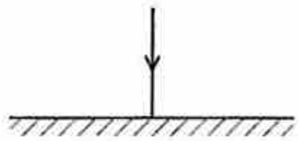
1 A mirror is placed in the path of a ray of light.



Through which angle does the direction of the ray of light change? (2014 P1 Q22)

A 40° **B** 90° **C** 100° **D** 140°

2 A ray of light is incident on a horizontal plane mirror, as shown. The light is reflected straight back the way it came.

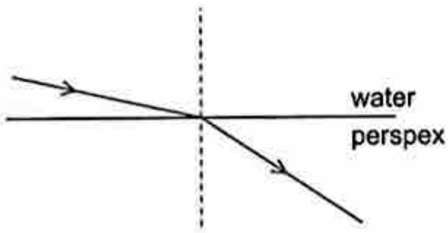


The mirror is tilted through an angle of 10°.

What is now the angle between the incident ray and the reflected ray? (2019 P1 Q25)

A 5° **B** 10° **C** 15° **D** 20°

3 A ray of light passes from water into perspex.



What is the correct explanation of the refraction? (2014 P1 Q23)

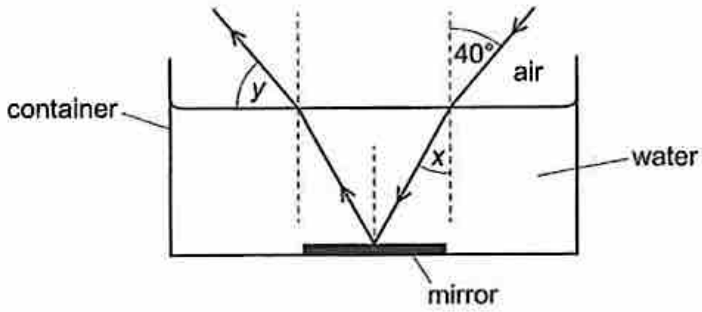
A The ray refracts away from the normal because the speed of light is greater in perspex than in water.

B The ray refracts away from the normal because the speed of light is less in perspex than in water.

C The ray refracts towards the normal because the speed of light is greater in perspex than in water.

D The ray refracts towards the normal because the speed of light is less in perspex than in water.

4 The diagram shows a ray of light passing from air into water. The angle of incidence is 40°. The ray of light reflects off a mirror that has been placed at the bottom of the container.



The refractive index of water is 1.34.

What are the angles *x* and *y*? (2018 P1 Q26)

	x / °	*y* / °
A	29	40
B	29	50
C	30	40
D	30	50

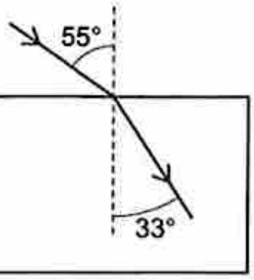
5 When light passes from air to glass with an angle of incidence of 30°, the angle of refraction is 20°.

The angle of incidence is increased to 60°.

What is the new angle of refraction? (2014 P1 Q24)

A 29° **B** 36° **C** 40° **D** 50°

6 Light in a vacuum strikes a glass surface at an angle of incidence of 55°.



In the glass, the angle of refraction is 33°.

What is the speed of light in glass? (2016 P1 Q25)

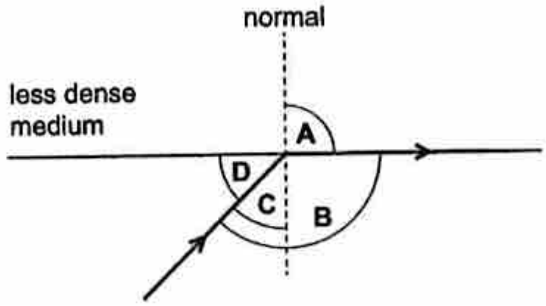
A 1.8×10^8 m/s **C** 3.0×10^8 m/s

B 2.0×10^8 m/s **D** 4.5×10^8 m/s

7 Light travels from one medium towards a less dense medium.

It is refracted along the boundary between the media, as shown.

Which angle is the critical angle? (2019 P1 Q26)



8 A ray of light in a glass block is incident on a boundary with air at an angle of incidence of 40°. The critical angle at this boundary is 43°.

What happens to the ray of light at the boundary? (2012 P1 Q23)

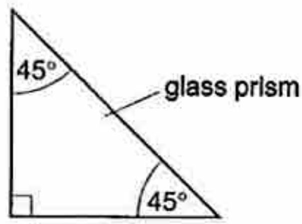
A It is partly reflected back into the glass and partly refracted along the boundary.

B It is partly reflected back into the glass and partly refracted into the air.

C It is totally reflected back into the glass.

D It is totally refracted into the air.

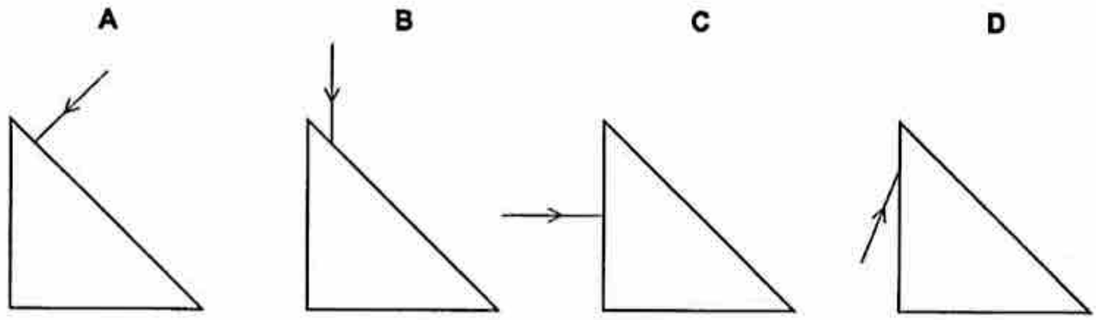
9 A glass prism has angles of 45°, 90° and 45°.



The critical angle for glass is 42°.

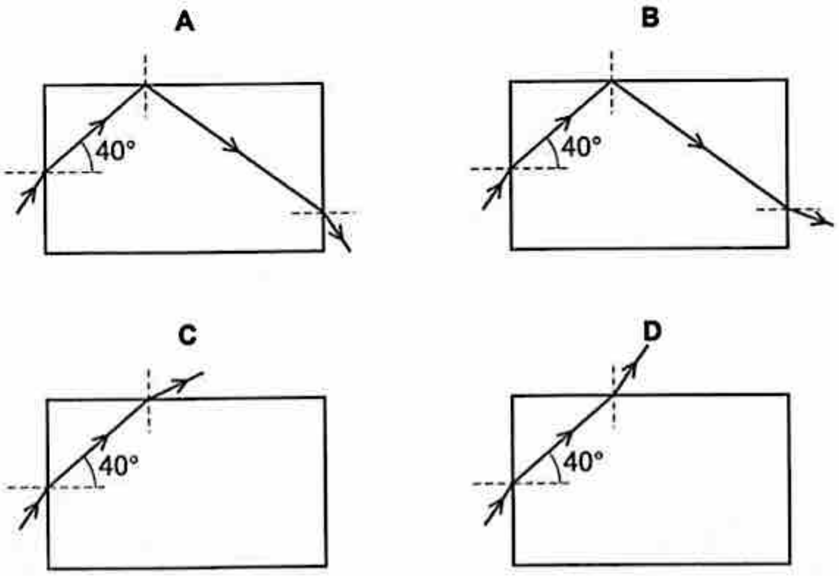
A narrow beam of light is directed onto the prism.

Which arrangement makes the beam undergo total internal reflection twice before any light leaves the prism? (2019 P1 Q28)



10 A ray of light is incident on one side of a rectangular block. The angle of refraction is 40° in the block. The critical angle for light in the block is 44°.

Which diagram shows the path of this ray? (2016 P1 Q26)



11 **(a)** A high-quality periscope uses two identical prisms.

An incomplete diagram of the periscope is shown in Fig. 3.1. Only one of the prisms is shown.

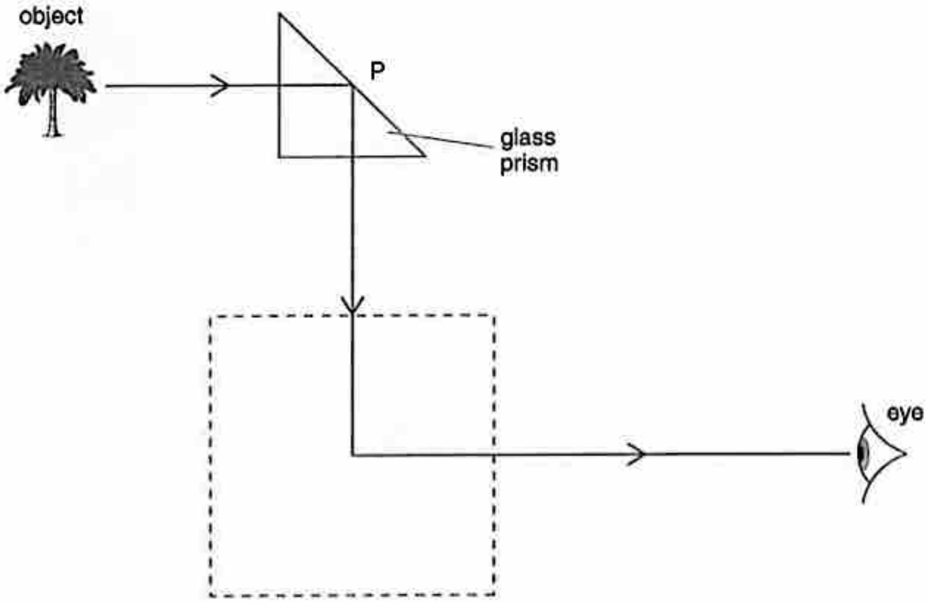


Fig. 3.1 (not to scale)

A ray of light travels from the object to the eye.

Total internal reflection occurs in both prisms.

(i) On Fig. 3.1, complete the diagram of the periscope by drawing the other prism in the dotted box, so that the ray is reflected as shown. [1]

(ii) Explain why total internal reflection occurs at P.

.... [1]

(b) Some periscopes use mirrors instead of prisms. The mirrors have a reflecting surface behind a layer of glass, as shown in Fig. 3.2.

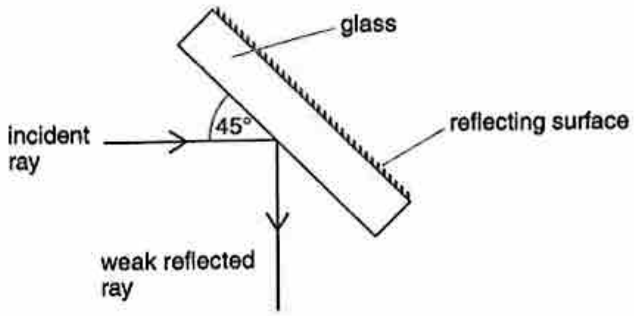


Fig. 3.2

A ray of light strikes the glass at an angle of 45° to the surface. A weak reflected ray is formed but most of the light refracts into the glass. The refractive index of the glass is 1.5.

(i) Calculate the angle of refraction in the glass.

angle = ... [2]

(ii) On Fig. 3.2, draw the refracted ray inside the glass and continue the ray after it leaves the glass. [2]

(iii) Images produced by periscopes using mirrors are not as clear as images produced by periscopes using prisms. Suggest why.

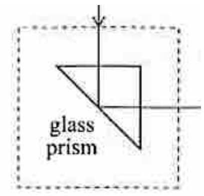
.... [1]

(2015 P2A Q6)

Solutions

1	C	**2**	D	**3**	D	**4**	B	**5**	B
6	B	**7**	C	**8**	B	**9**	A	**10**	A

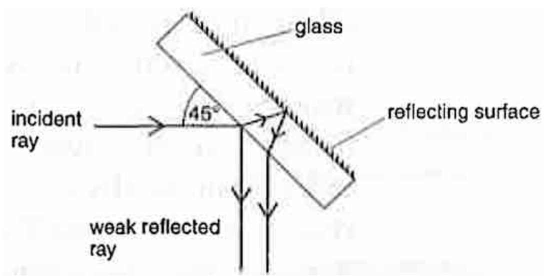
11 **(a)(i)**



(a) (ii) angle of incidence of light at P greater than critical angle of the glass

(b)(i) 28.1°

(b) (ii)



(b) (iii) From **(b)(ii)**, there will be a weak reflected image due to the weak reflected ray in addition to the main reflected image. As a result of the two images, the image is not clear.

Topic 3: Electromagnetic Spectrum

Content

- Properties of electromagnetic waves
- Applications of electromagnetic waves
- Effects of electromagnetic waves on cells and tissue

Learning Outcomes

Students should be able to:

(a) state that all electromagnetic waves are transverse waves that travel with the same speed in vacuum and state the magnitude of this speed

(b) describe the main components of the electromagnetic spectrum

(c) state examples of the use of the following components:
  (i) radio waves (e.g. radio and television communication)
  (ii) microwaves (e.g. microwave oven and satellite television)
  (iii) infra-red (e.g. infra-red remote controllers and intruder alarms)
  (iv) light (e.g. optical fibres for medical uses and telecommunications)
  (v) ultra-violet (e.g. sunbeds and sterilisation)
  (vi) X-rays (e.g. radiological and engineering applications)
  (vii) gamma rays (e.g. medical treatment)

(d) describe the effects of absorbing electromagnetic waves, e.g. heating, ionisation and damage to living cells and tissue

3.1 Properties of electromagnetic waves

(a) state that all electromagnetic waves are transverse waves that travel with the same speed in vacuum and state the magnitude of this speed

Visible light forms only a small part of a very wide spectrum of electromagnetic waves.

All types of electromagnetic radiation
- travel through a vacuum at 3×10^8 m s^{-1} and is approximately the same in air.
- exhibit reflection, refraction and have a transverse wave nature.
- obey the equation, $v = f\lambda$, where v is the speed of light, f is the frequency of the waves and λ is the wavelength. Since v is constant in a particular medium, it follows that large f means small λ.
- They carry energy from one place to another and can be absorbed by matter to cause heating and other effects. The higher the frequency and the smaller the wavelength of the radiation, the greater is the energy carried, i.e. gamma rays are more 'energetic' than radio waves.

Because of its electrical origin, its ability to travel in a vacuum (e.g. from the Sun to the Earth) and its wave-like properties, electromagnetic radiation is regarded as a *progressive transverse wave*. The wave is a combination of travelling electric and magnetic fields. The fields vary in value and are directed at right angles to each other and to the direction of travel of the wave, as shown by the representation in Fig. 3.1.

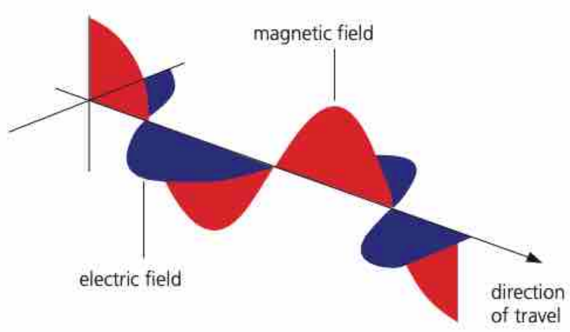


Fig. 3.1

3.2 Applications of electromagnetic waves

(b)	*describe the main components of the electromagnetic spectrum*
(c)	*state examples of the use of the following components:*
	(i) radio waves (e.g. radio and television communication)
	(ii) microwaves (e.g. microwave oven and satellite television)
	(iii) infra-red (e.g. infra-red remote controllers and intruder alarms)
	(iv) light (e.g. optical fibres for medical uses and telecommunications)
	(v) ultra-violet (e.g. sunbeds and sterilisation)
	(vi) X-rays (e.g. radiological and engineering applications)
	(vii) gamma rays (e.g. medical treatment)

Fig. 3.2 shows the main regions of the electromagnetic spectrum with their corresponding wavelengths.

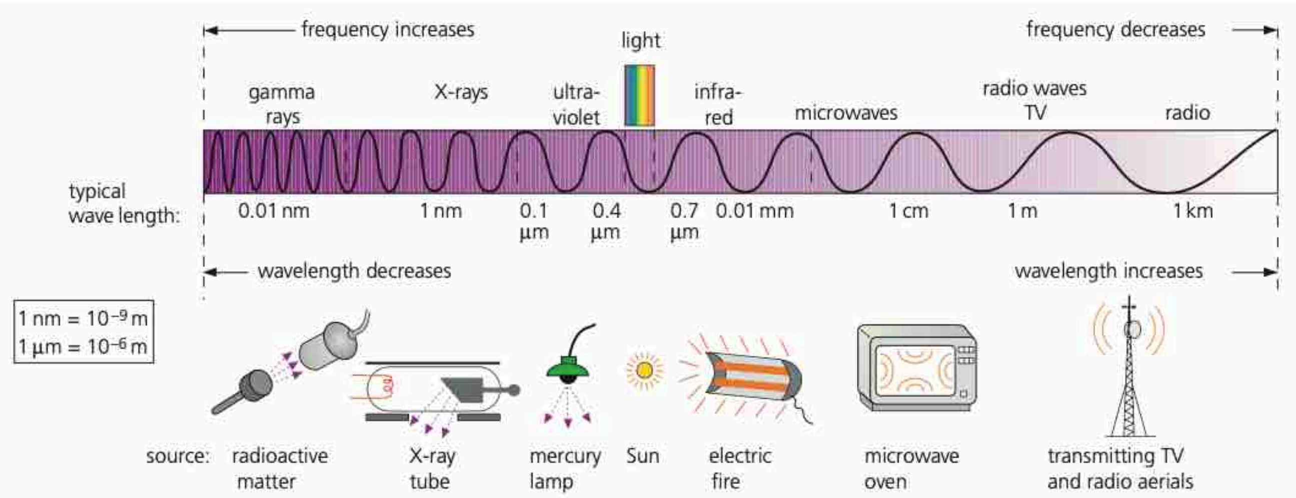


Fig. 3.2

Note that the wavelength increases from gamma rays to radio waves while the frequency increases in the reverse direction (radio to gamma). While each type of radiation has a different source, all result from electrons in atoms undergoing an energy change and all have certain properties in common.

https://youtu.be/7v2gs8rdQzU
An introduction to electromagnetic spectrum.

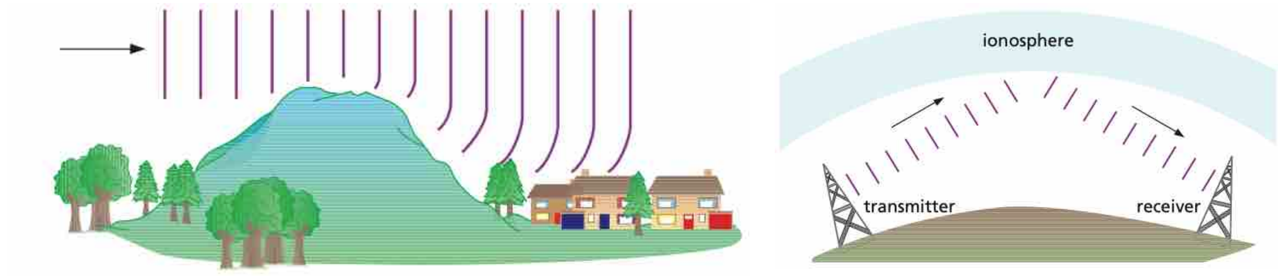
(A) Radio waves

Radio waves have the longest wavelengths in the electromagnetic spectrum. They are radiated from aerials and used to carry sound, pictures and other information over long distances.

Long, medium and short waves (wavelengths of 2 km to 10 m)

When waves propagate near an obstacle, they spread after passing around the edge of the obstacle. This is known as *diffraction*. This property is used to send signals across terrains when natural obstacles, such as hills, are blocking the source (Fig. 3.7a).

They can also be reflected by layers of electrically charged particles in the upper atmosphere (the **ionosphere**), which makes long-distance radio reception possible (Fig. 3.7b).



(a) (b)

Fig. 3.7

VHF (very high frequency) and UHF (ultra high frequency) waves (wavelengths of 10 m to 10 cm)

These shorter wavelength radio waves need a clear, straight-line path to the receiver. They are not reflected by the ionosphere. They are used for local radio and for television transmissions.

Astronomers use radio telescopes to pick up radio signals from stars and galaxies to gain information about the Universe which cannot be obtained from optical telescopes.

> https://youtu.be/Ldnh0XIMVc0
> Video on radio waves.

(B) Microwaves

Microwaves have wavelengths of a few cm.

They are used for international telecommunications and direct broadcast satellite television relay via geostationary satellites and for mobile phone networks via microwave aerial towers and low-orbit satellites. The microwave signals are transmitted through the ionosphere by dish aerials, amplified by the satellite and sent back to a dish aerial in another part of the world. Some satellite phones also use low-orbit artificial satellites.

Microwaves are also used in wireless applications, such as Bluetooth which allows short-range communication between many different types of electronic devices from mobile phones to entertainment systems.

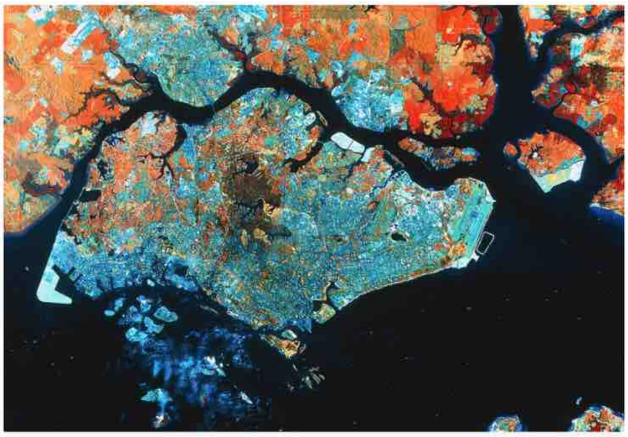
Microwaves can be used for cooking in a microwave oven since they cause water molecules in the moisture of the food to vibrate vigorously at the frequency of the microwaves. As a result, heating occurs inside the food which cooks itself.

(C) Infrared radiation

Our bodies detect *infrared* radiation (IR) by its heating effect on the skin. It is sometimes called 'radiant heat' or 'heat radiation'.

Anything which is hot but not glowing, i.e. below 500°C, emits IR alone. At about 500°C a body becomes red hot and emits red light as well as IR – the heating element of an electric fire, a toaster or an electric grill are examples. At about 1500°C, things such as lamp filaments are white hot and radiate IR and white light, i.e. all the colours of the visible spectrum.

Infrared is also used in thermal imaging cameras, which show hot spots and allow images to be taken in the dark. Infrared sensors are used on satellites and aircraft for weather forecasting, monitoring of land use (Fig. 3.5), assessing energy loss from buildings and locating victims of earthquakes. One type of intruder alarm activates an alarm when its sensor detects the infrared radiation emitted by a nearby moving body. An alternative type uses a transmitter to send an infrared beam to a receiver. When the path of the beam is broken by an intruder, an alarm is activated.



In the infrared range, green vegetation is orange, forests are brown, buildings are light blue/grey & water is black.

Fig. 3.5

The remote control for an electronic device contains a small infrared transmitter to send signals to the device, such as a television or DVD player. These are short range communication applications. Infrared is also used to carry data in long range optical fibre communication systems.

https://youtu.be/ow26-5UirSc
Video on microwaves and infrared.

(D) Visible light waves

Frequency and wavelengths of visible like

For the visible light part of the electromagnetic spectrum,

- red light has the longest wavelength, which is about 7×10^{-7} m = 0.0007 mm = 0.7 μm = 700 nm, while violet light has the shortest wavelength of about 4×10^{-7} m = 0.0004 mm = 0.4 μm = 400 nm. Colours between these in the spectrum of white light have intermediate values.

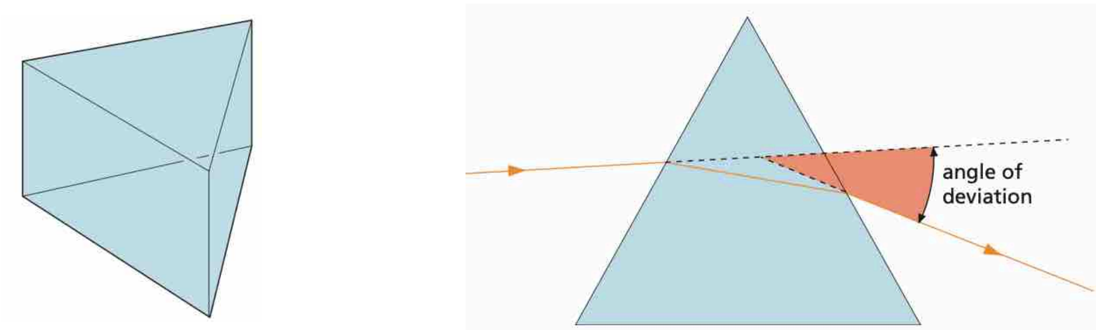
- Since $v = f\lambda$ for all waves including light, it follows that red light has a lower frequency than violet light since **(i)** the wavelength of red light is greater and **(ii)** all colours travel with the same speed 3×10^8 m s^{-1} in a vacuum.

- It is the frequency of light which decides its colour.

https://youtu.be/KnIualWf6Rs
An introduction to white light and how we see colours.

Dispersion of white light

In a triangular glass prism (Fig. 3.3), the bending of a ray due to refraction at the first surface is added to the bending of the ray at the second surface; the overall change in direction of the ray is called the *deviation*.



(a) **(b)**

Fig. 3.3

When white light (e.g. from the sun) falls on a triangular glass prism (Fig. 3.4), a band of colours called a **spectrum** is obtained. This effect is known as *dispersion*.

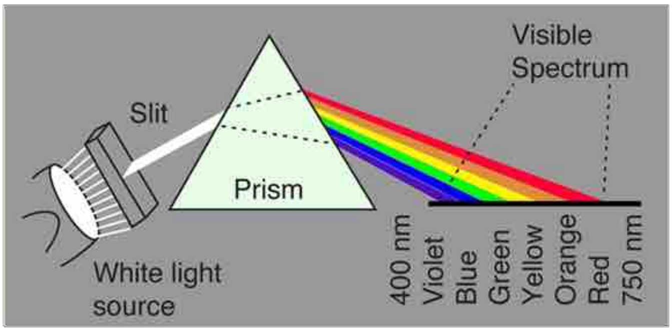


Fig. 3.4

https://youtu.be/JGqsi_LDUn0
Demonstration of the dispersion of white light using a prism.

Dispersion arises because

- white light is a mixture of wavelengths between about 400 nm (violet) and 700 nm (red)
- each frequency travels at different speed through the glass i.e. the refractive index of glass is different for each frequency (greatest for violet light):
    - red light has the longest wavelength in the optical spectrum and hence the lowest frequency and is refracted least by the prism
    - violet light has the shortest wavelength and the highest frequency in the optical spectrum and is refracted most by the prism
- the bendings of the ray do not cancel out as they do in a parallel-sided block (refer to Fig. 2.9 in topic 2 where the emergent ray, although displaced, is parallel to the incident ray), so the dispersed wavelengths do not recombine into white light.

Visible light is the type of electromagnetic radiation used by our eyes to form images of the world around us. In addition to vision, light is used for illumination and photography. Cameras and optical instruments, from microscopes to telescopes, make use of the properties of light to form images of near and distant objects.

(E) Ultraviolet radiation

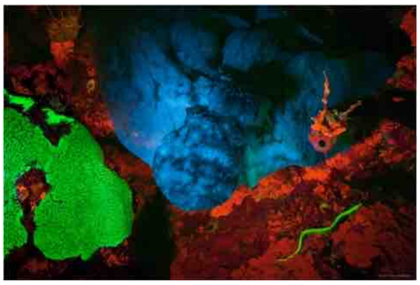
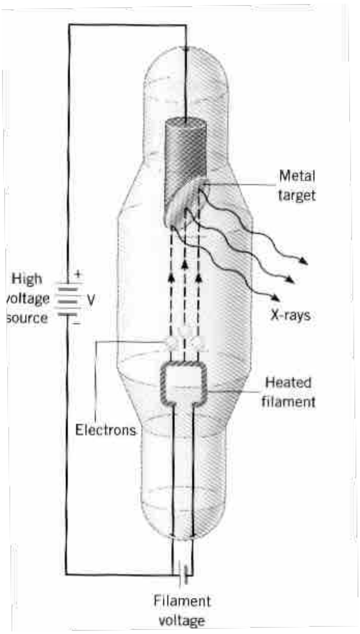


Fig. 3.6

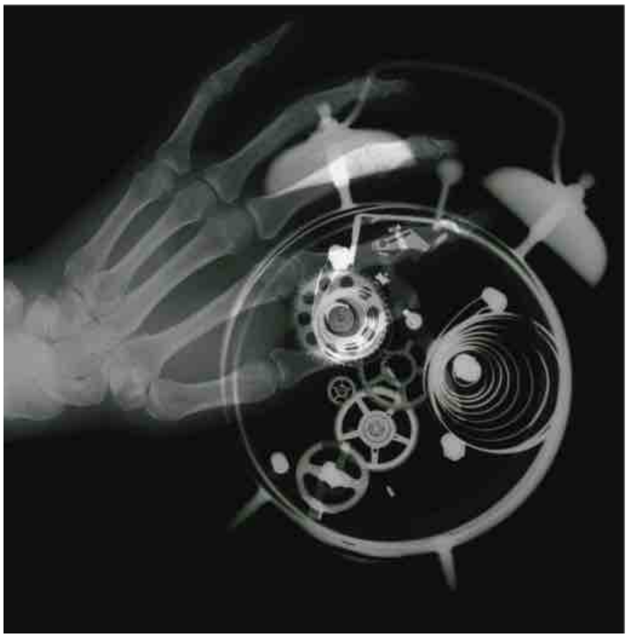
Ultraviolet (UV) rays have shorter wavelengths than light. **Ultraviolet radiation** causes fluorescent paints and clothes washed in some detergents to fluoresce. They glow by re-radiating as light the energy they absorb as UV. This effect may be used in security marking to verify ‘invisible’ signatures on bank documents and to detect fake bank notes. Water treatment plants often use UV radiation to sterilise water because the energy of UV radiation is high enough energy to kill bacteria.

https://youtu.be/q_CxKQC-zpg
Video on visible and ultraviolet light.

(F) X-rays



(a)



(b)

Fig. 3.8

X-rays are produced when high-speed electrons are stopped by a metal target in an X-ray tube. X-rays have smaller wavelengths than UV (Fig. 3.8a).

They are absorbed to some extent by living cells but can penetrate certain solid objects and affect a photographic film. With materials such as bones, teeth and metals which they do not pass through easily, shadow pictures can be taken, like that in Fig. 3.8b of a hand on an alarm clock.

They are widely used in dentistry and in medicine, for example to detect broken bones and in **radiotherapy** in high doses to kill cancerous cells. X-rays are also used in security machines at airports for scanning luggage; some body scanners, now being introduced to screen passengers, use very low doses of X-rays. In engineering applications, X-ray imaging is used to inspect welded joints and detect cracks in metal parts.

For safety reasons, X-ray machines need to be shielded with lead.

(G) Gamma rays

Gamma rays are more penetrating and dangerous than X-rays.

They are used to both diagnose and treat cancer and also to kill harmful bacteria in food and on surgical instruments. In medical diagnostics, a radioactive **tracer** (Fig. 3.9) that emits gamma rays and is detected by gamma ray camera detectors and is then used to image the distribution of the tracer.

In radiotherapy used to treat cancer, high-energy beams of gamma rays are focused directly onto a tumour in order to kill the cancerous cells.

In engineering applications, gamma-ray photography is used to detect cracks and flaws in metals.

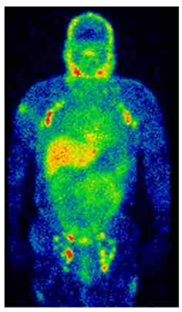


Fig. 3.9

https://youtu.be/dBFGjdgbpno
Video on X-rays and gamma rays.

3.3 Effects of electromagnetic waves on cells and tissue

(d)	*describe the effects of absorbing electromagnetic waves, e.g. heating, ionisation and damage to living cells and tissue*

High exposures to electromagnetic radiation can cause harmful effects.

Microwaves	Microwaves produce heating of soft tissue in the body when they are absorbed by the water in living cells. This can damage or kill the cells. There is some debate at present as to whether their use in mobile phones is harmful; 'hands-free' mode, where separate earphones are used, may be safer.
Infrared	Infrared radiation transfers thermal energy, so when of high intensity can cause burns to the skin.
Ultraviolet	Ultraviolet radiation causes ionisation, so when absorbed in high doses it can cause skin cancer and eye damage including cataracts. Dark skin is able to absorb more UV in the surface layers than skin of a lighter colour, so reducing the amount reaching deeper tissues. Exposure to the harmful UV rays present in sunlight can be reduced by wearing protective clothing such as a hat or by using sunscreen lotion.
X-rays and gamma rays	X-rays and gamma rays also cause ionisation of atoms in cells and cause mutation or damage to cells in the body which can lead to cancer. X-ray and gamma ray machines are shielded by lead to reduce unnecessary exposure.

https://youtu.be/d9fXDHKWy1g
Video on the dangers of electromagnetic waves.

Problem Set (Topic 3)

1 Which statement about gamma rays and ultra-violet is correct? (2016 P1 Q27)

A They have the same frequency in a vacuum.

B They have the same wavelength in air.

C They travel as longitudinal waves in air.

D They travel at the same speed in a vacuum.

2 Which representation of the electromagnetic spectrum is correct? (2017 P1 Q26)

A

visible light

X-rays	gamma rays	ultra-violet radiation		infra-red radiation	microwaves	radio waves

← increasing wavelength

B

visible light

radio waves	microwaves	infra-red radiation		ultra-violet radiation	X-rays	gamma rays

increasing wavelength →

C

visible light

X-rays	gamma rays	ultra-violet radiation		infra-red radiation	microwaves	radio waves

← increasing frequency

D

visible light

radio waves	microwaves	infra-red radiation		ultra-violet radiation	X-rays	gamma rays

increasing frequency →

3 Which row lists the applications of parts of the electromagnetic spectrum? (2012 P1 Q25)

	infra-red radiation	ultra-violet radiation	gamma rays
A	intruder alarm	toaster	sunbed
B	television controller	sunbed	treatment of cancer
C	toaster	television controller	sterilisation
D	treatment of cancer	sterilisation	television controller

4 Five components of the electromagnetic spectrum are listed.

radio waves   microwaves   visible light   X-rays   gamma rays

(a) (i) Two other components of the electromagnetic spectrum are missing from the list.

Write the names of the missing components in the appropriate row in the Table.

Table

name of component	wavelength / m
	1×10^{-7}
	1×10^{-5}

[2]

(ii) State one component of the electromagnetic spectrum that is an ionising radiation.[1]

(iii) State one use of an ionising radiation. [1]

(b) All electromagnetic waves transfer energy and travel through a vacuum at a speed of 3.0×10^{8} m s^{-1}.

(i) State one other property common to all components of the electromagnetic spectrum. [1]

(ii) The wavelength of a microwave is 2.0×10^{-2} m.

Calculate the frequency of this wave. [2]

(2020 P2A Q6)

5 Different colours of light take different paths through a drop of water. The effect can form a rainbow when white light from the Sun strikes raindrops in the air.

Fig. 6.1 shows a ray of white light incident on a raindrop and the path of red light inside the drop.

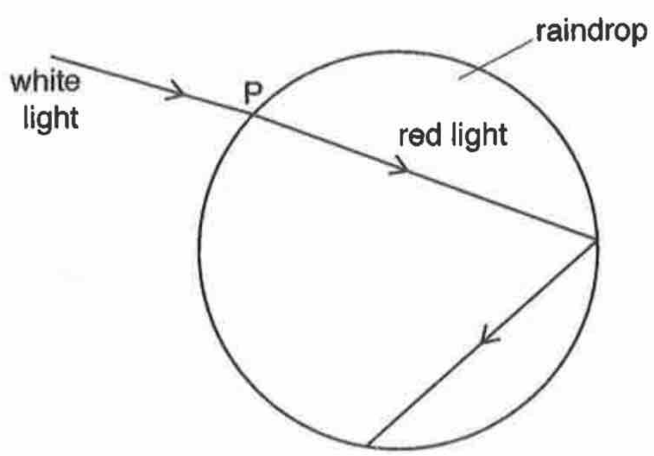


Fig. 6.1 (not to scale)

(a) On Fig. 6.1, draw, and label, the angle of incidence and the angle of refraction of the red light at the point P. [1]

(b) The refractive index of water for blue light is slightly larger than for red light.

(i) State and explain how the angle of refraction at point P for blue light compares with the angle of refraction for red light. [1]

(ii) On Fig. 6.1, draw the path of a ray of blue light inside the raindrop and **out into the air.** [2]

(c) Red light has a frequency of 4.3×10^{14} Hz and travels at a speed of 3.0×10^{8} m s^{-1} in air.

The refractive index of water for red light is 1.3.

Calculate the wavelength of the red light in **water**. [3]

(2019 P2B Q11b Or)

6 **(a)** State the type of electromagnetic radiation used

(i) in the remote control of a television set, [1]

(ii) in a sunbed. [1]

(b) X-rays are a type of electromagnetic radiation used to produce images of the inside of the human body.

State three possible effects on the living cells in the human body when X-rays are absorbed by body tissue. [3]

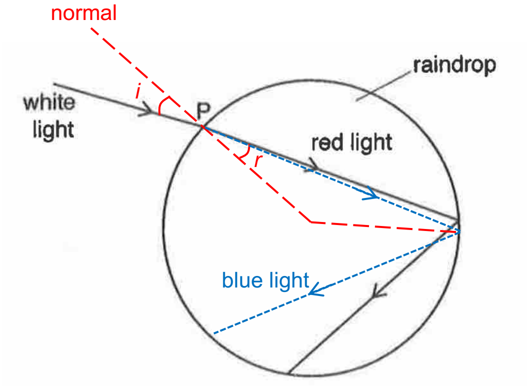
(2019 P2B Q10a,c)

Solutions

1 D **2** D **3** B

4 **(a)(i)** ultraviolet; infrared **(ii)** X-rays or gamma ray **(iii)** treatment of cancer
(b)(i) transverse wave **(ii)** 1.5×10^{10} Hz

5 **(a)** & **(b)(ii)**



i = angle of incidence
r = angle of refraction

(b)(i) angle of refraction smaller than red light because higher refractive index means light bends more towards normal

(c) $n = c / v \rightarrow v = 3 \times 10^{8}/1.3 = 2.308 \times 10^{8}$
$\lambda = 2.308 \times 10^{8}/4.3 \times 10^{14} = 5.4 \times 10^{-7}$ m

6 **(a)(i)** microwave **(ii)** ultraviolet
(b) causes cell to heat up; causes cell damage/mutation; ionisation within cell

Topic 4: Sound

Content

- Sound waves
- Speed of sound
- Use of cathode-ray oscilloscope
- Echo
- Ultrasound

Learning Outcomes

Students should be able to:

(a) describe the production of sound by vibrating sources

(b) explain that a medium is required in order to transmit sound waves and that the speed of sound differs in air, liquids and solids

(c) describe the longitudinal nature of sound waves in terms of the processes of compression and rarefaction

(d) relate loudness of a sound wave to its amplitude and pitch to its frequency

(e) describe a direct method for the determination of the speed of sound in air and make the necessary calculation

(f) describe how the reflection of sound may produce an echo, and how this may be used for measuring distances

(g) describe the use of a cathode-ray oscilloscope (c.r.o.) to display waveforms and to measure potential differences and short intervals of time (detailed circuits, structure and operation of the c.r.o. are not required)

(h) interpret c.r.o. displays of waveforms, potential differences and time intervals to solve related problems

(i) define ultrasound and describe one use of ultrasound, e.g. quality control and pre-natal scanning

4.1 Sound waves

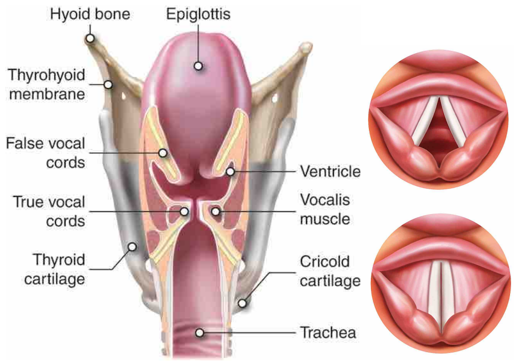
(a)	*describe the production of sound by vibrating sources*
(b)	*explain that a medium is required in order to transmit sound waves and that the speed of sound differs in air, liquids and solids*
(c)	*describe the longitudinal nature of sound waves in terms of the processes of compression and rarefaction*
(d)	*relate loudness of a sound wave to its amplitude and pitch to its frequency*

(A) Sound is produced by vibration

All sources of sound have some part that *vibrates*. A guitar has strings (Fig. 4.1a), a drum has a stretched skin (Fig. 4.1b) and the human voice has vocal cords (Fig. 4.1c).

(a)

(b)



(c)

Fig. 4.1

The sound travels through the air to our ears and we hear it. That the air is necessary may be shown by pumping the air out of a glass jar containing a ringing electric bell (Fig. 4.2).

Fig. 4.2

https://youtu.be/ce7AMJdq0Gw
A bell can be heard ringing within a bell jar. The bell jar is connected to a vacuum pump and the air is slowly removed. Once a vacuum has been achieved the pumped is turned off and air is allowed to slowly re-enter the bell jar.

Evidently sound cannot travel in a vacuum as light can. A medium is needed to transmit sound waves. In addition to air, solids and liquids are also able to transmit sound waves.

(B) Speed of sound

Sound transfers energy as a progressive **longitudinal wave**. As with transverse waves, sound waves obey the wave equation wave speed = frequency × wavelength ($v = f\lambda$).

The *speed of sound* depends on the material through which it is passing. It is faster in solids than in liquids and faster in liquids than in gases because the molecules in a solid are closer together than in a liquid and those in a liquid are closer together than in a gas. Some values are given in Fig. 4.3.

Material	air	water	concrete	steel
Speed / m s^{-1}	330 – 350	1400	5000	6000

Fig. 4.3

In air the speed *increases with temperature* and at high altitudes, where the temperature is lower, it is less than at sea level. Changes of atmospheric pressure do not affect it.

(C) Longitudinal nature of sound waves

As we saw in Topic 1, in a progressive longitudinal wave the particles of the transmitting medium vibrate back and forth along the same line as that in which the wave is travelling. In a sound wave, the air molecules move repeatedly closer together and then further apart in the direction of travel of the wave as can be seen in Fig. 4.4.

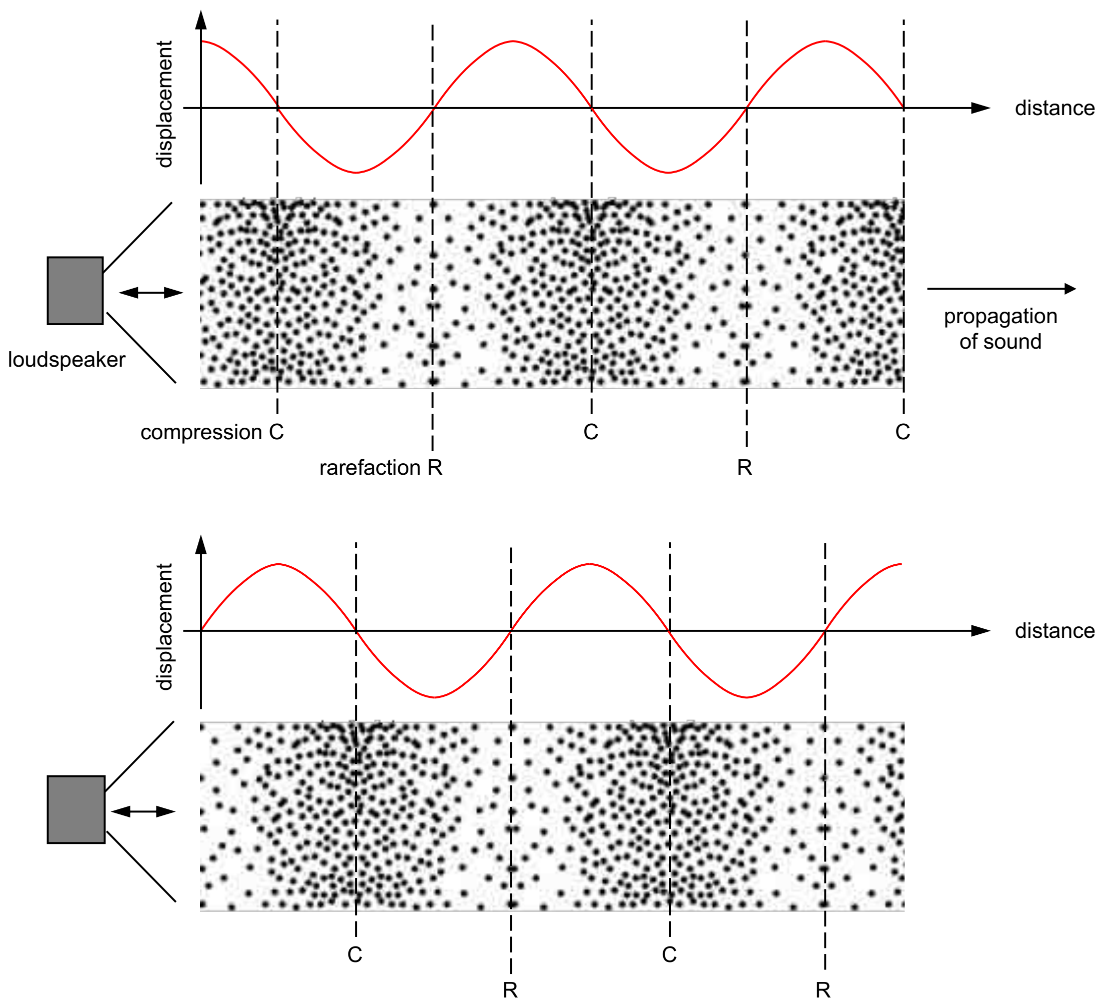


Fig. 4.4

The speaker has a cone which is made to vibrate in and out by an electric current. When the cone moves out, the air in front is compressed; when it moves in, the air is rarefied (becomes ‘thinner’). The wave progresses through the air but the air as a whole does not move. The air particles (molecules) vibrate backwards and forwards a little as the wave passes. The sound wave produced by the loudspeaker consists of a train of **compressions** C (where the air molecules are closer together) and **rarefactions** R (where the air molecules are further apart) in the air, as shown in Fig. 4.3. The atmospheric air pressure is slightly higher in a compression and lower in a rarefaction.

When the wave enters your ear the compressions and rarefactions cause small, rapid pressure changes on the eardrum and you experience the sensation of sound.

Humans hear only sounds with frequencies from about 20Hz to 20000Hz. These are the **limits of audibility** in a healthy human ear; the upper limit decreases with age.

For transverse waves, the displacement-distance graph takes the same shape as the wave in the medium. For longitudinal waves, the displacement-distance graph **does not** take the same shape as the wave in the medium! The graph represents the displacement of the air particles from their equilibrium position along the same line as that in which the wave is travelling.

https://youtu.be/HhYPwj3uz14
Video on interpret the displacement-distance graph for a longitudinal wave.

(D) Terms related to sound

Irregular vibrations, such as those of motor engines, cause **noise**; regular vibrations, such as occur in the instruments, produce **musical notes** with three properties – **pitch**, **loudness** and **quality**.

Pitch

The pitch of a note depends on the frequency of the sound wave reaching the ear, i.e. on the frequency of the source of sound. A high-pitched note has a high frequency and a short wavelength.

Notes of known frequency can be produced in the laboratory by a signal generator supplying alternating electric current (a.c.) to a loudspeaker. The cone of the speaker vibrates at the frequency of the a.c. which can be varied and read off a scale on the generator.

https://youtu.be/yMGKtRcT_mM
Video on using a signal generator and speaker to product sound waves.

A set of tuning forks with frequencies marked on them can also be used. A tuning fork (Fig. 4.5) has two steel prongs which vibrate when struck; the prongs move in and out *together*, generating compressions and rarefactions.

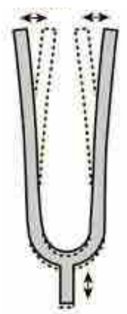


Fig. 4.5

Loudness

A note becomes louder when more sound energy enters our ears per second than before. This will happen when the source is vibrating with a larger amplitude. If a violin string is bowed more strongly, its amplitude of vibration increases, as does that of the resulting sound wave, and the note heard is louder because more energy has been used to produce it.

Quality

The same note on different instruments sounds different; we say the notes differ in **quality** or **timbre**. The difference arises because no instrument (except a tuning fork and a signal generator) emits a 'pure' note, i.e. of one frequency.

The **waveform** of a note played near a microphone connected to a **cathode ray oscilloscope** (CRO) can be displayed on the CRO screen. Those for the *same* note on three instruments are shown in Fig. 4.6. Their different shapes show that, while they have the same fundamental frequency, their quality differs because they contain additional frequencies. The 'pure' note of a tuning fork has a *sine* waveform and is the simplest kind of sound wave.

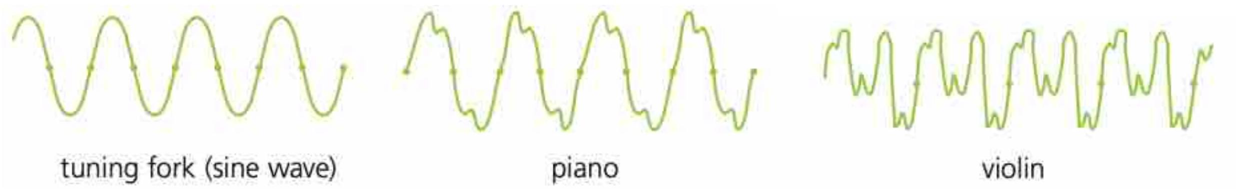


Fig. 4.6

Note while the waveform on the CRO screen is transverse, it represents a longitudinal sound wave.

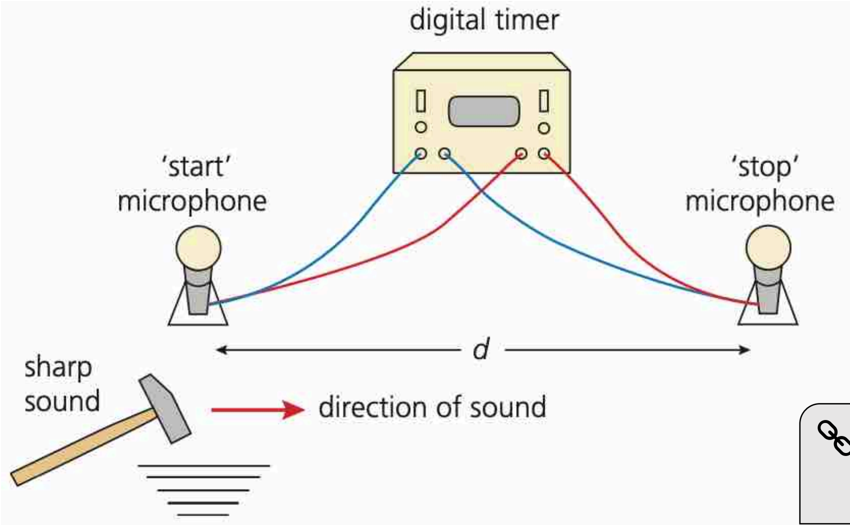
4.2 Measurement of the speed of sound

(e)	*describe a direct method for the determination of the speed of sound in air and make the necessary calculation*
(f)	*describe how the reflection of sound may produce an echo, and how this may be used for measuring distances*
(g)	*describe the use of a cathode-ray oscilloscope (c.r.o.) to display waveforms and to measure potential differences and short intervals of time (detailed circuits, structure and operation of the c.r.o. are not required)*
(h)	*interpret c.r.o. displays of waveforms, potential differences and time intervals to solve related problems*

(A) Direct method

The speed of sound in air can be found directly by measuring the time taken for a sound to travel past two microphones, as shown in Fig. 4.7.

- One microphone is attached to the 'start' and the other to the 'stop' terminal of a digital timer.
- With the small hammer and metal plate to the side of the 'start' microphone, produce a sharp sound. When the sound reaches the 'start' microphone, the timer should start; when it reaches the 'stop' microphone, the timer should stop.
- The time displayed is then the time t taken for the sound to travel the distance d.
- Repeat the experiment a few times and work out an *average* value for t.



https://youtu.be/k9Iezv8OtuY
Video on using a digital timer to measure the speed of sound.

Fig. 4.7

$$\text{speed of sound in air} = \frac{\text{distance travelled by the sound}}{\text{time taken}} = \frac{d}{t}$$

This method can also be used to find the speed of sound in different materials. For example, placing a metal bar between the microphones would allow the speed of sound in the metal to be determined.

(B) Echo method

Sound waves are reflected well from hard, flat surfaces such as walls or cliffs and obey the same laws of reflection as light. The reflected sound forms an **echo**; an echo is the reflection of a sound wave.

An estimate of the speed of sound in air can be made if you stand a distance d from a high wall or building and clap your hands. Echoes are produced. When the clapping rate is such that each clap coincides with the echo of the previous one, the sound has travelled to the wall and back in the time between two claps, i.e. one interval. By timing N intervals with a stopwatch, the time t for one interval can be found.

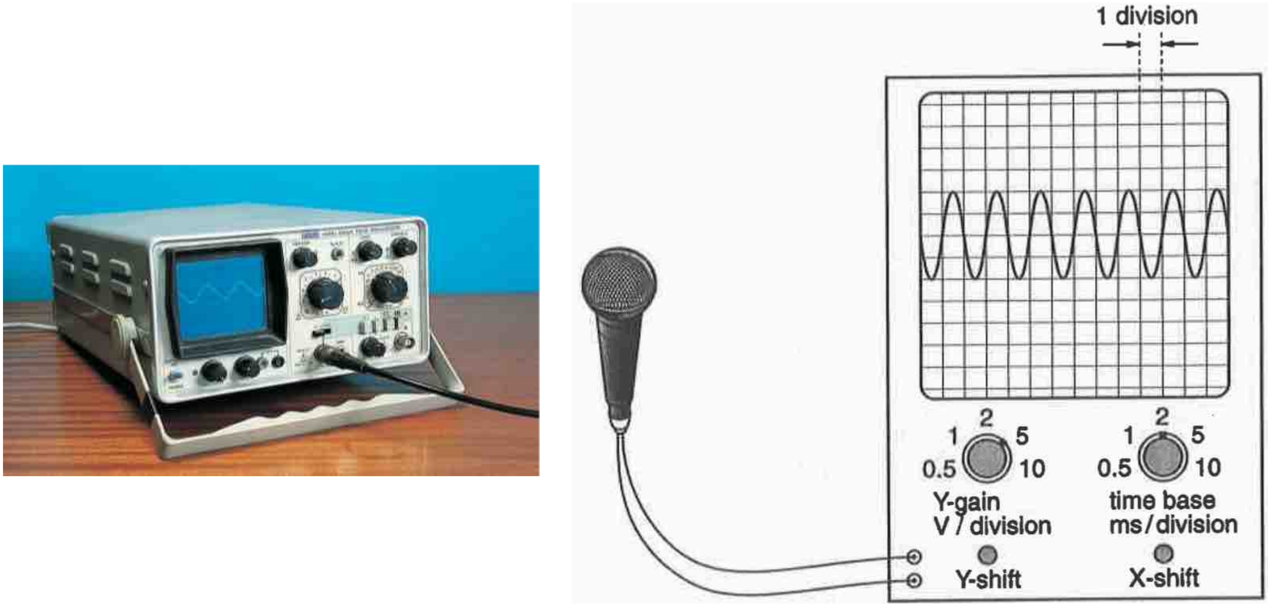
$$t = \frac{\text{timing for } N \text{ intervals}}{N}$$

$$\text{speed of sound in air} = \frac{\text{distance travelled by the sound}}{\text{time taken}} = \frac{2d}{t}$$

https://youtu.be/J97YSCnU4KM
Video on the use of echo method to estimate the speed of sound.

(C) Cathode-ray oscilloscope (c.r.o.)

A **cathode ray oscilloscope (c.r.o.)** is shown in Figure 4.8a.



(a) **(b)**

Fig. 4.8

Fig. 4.8b shows a schematic layout of the c.r.o. receiving inputs from a microphone (or any devices that produces p.d.). The controls of the c.r.o. are:

- The vertical axis on an oscilloscope screen provides a measurement of p.d. and the horizontal axis is a measure of time. The signal to be displayed or measured is connected to the Y-input terminal of the oscilloscope. The **Y-gain** control amplifies the input p.d. to make it large enough to appear a suitable size on the screen. The Y-gain setting in volts per division or V/div allows the size of the input p.d. to be measured.

- The **timebase** controls how fast the bright spot (the input signal) moves from left to right. The distance moved by the spot is directly proportional to time and so the horizontal axis becomes a time axis. The timebase setting in milliseconds per division or ms/div allows time intervals in a varying p.d. to be measured.

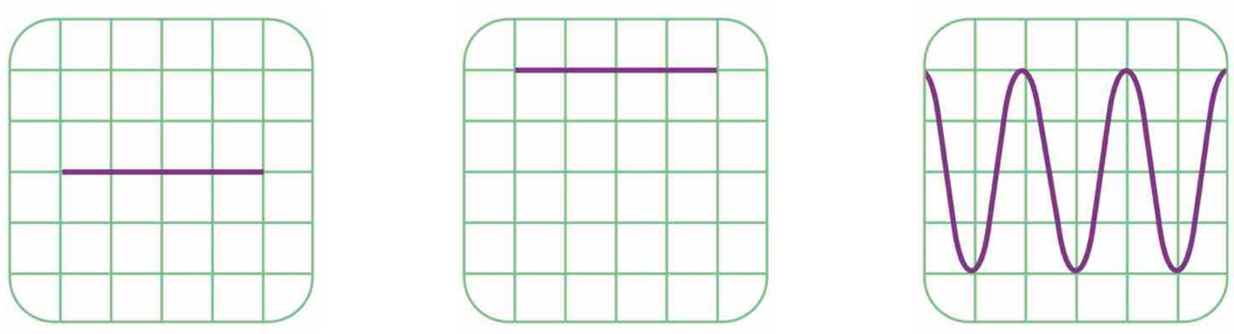
- To prepare the oscilloscope for use, the timebase is switched off. The X-shift and Y-shift are used to control the spot 'manually' over the screen in the X and Y directions, respectively to their mid-positions.

- The timebase and Y-gain controls can then be adjusted to suit the input.

When the timebase is on, the oscilloscope acts as a 'graph-plotter' to show the waveform, i.e. the variation with time, of the p.d. applied to its Y-input, as shown in Fig. 4.8b.

https://youtu.be/MzZmgk1Hjs8
Video on how the c.r.o. is used to determine the period and amplitude of a signal.

With the timebase switched on, Fig. 4.9 shows the display on an oscilloscope screen (called traces) for three different input p.d.



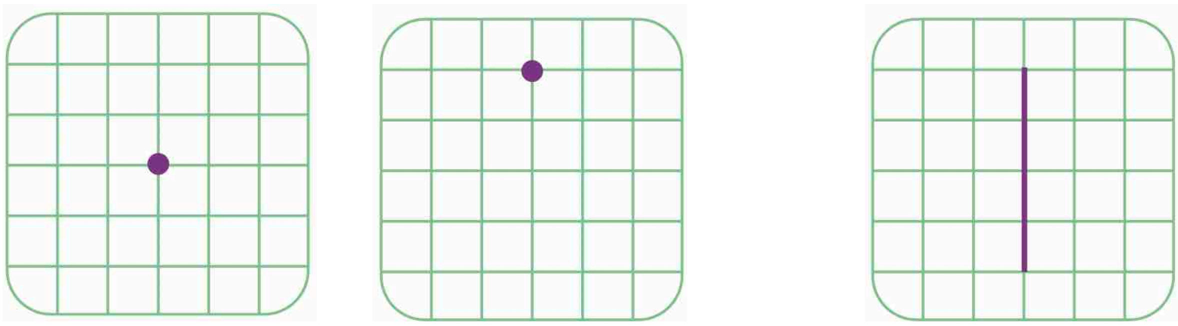
(a) The p.d. applied to the Y-input is zero, and there is a straight line across the centre of the screen.

(b) The Y-input is a constant signal and the trace is a horizontal line displaced upwards by an amount determined by the Y-gain setting.

(c) The Y-input is an alternating signal, so the p.d. is alternately positive and negative.

Fig. 4.9

When the timebase is switched off, the trace is concentrated to a spot that does not move from left to right. Figure 4.10 shows how the display appears for the different inputs from Fig. 4.9.



(a) The input p.d. is zero and the spot remains at the centre of the screen.

(b) The Y-input is a constant signal and the spot is displaced upwards.

(c) The Y-input is an alternating signal, so the p.d. is alternately positive and negative and the trace appears as a continuous vertical line whose length increases when the Y-gain is increased.

Fig. 4.10

Application

A sound wave is picked up by the microphone in Fig. 4.8b. The time base for the c.r.o. is set at 2 ms / division.

Determine the frequency of the sound emitted by the whistle.

Solution

Period of wave = 2 divisions = 4 ms

Frequency = 1 / period = 1 / 0.004 = 250 Hz

4.3 Ultrasound

(i)	*define ultrasound and describe one use of ultrasound, e.g. quality control and pre-natal scanning*

(A) Ultrasound and its production

Ultrasound is defined as sound with a frequency higher than 20kHz. The frequency of ultrasound is too high to be detected by the human ear but can be detected electronically and displayed on a cathode ray oscilloscope.

Ultrasound waves are produced by a quartz crystal which is made to vibrate electrically at the required frequency; they are emitted in a narrow beam in the direction in which the crystal oscillates. An ultrasound receiver also consists of a quartz crystal, but it works in reverse, i.e. when it is set into vibration by ultrasound waves it generates an electrical signal which is then amplified. The same quartz crystal can act as both a transmitter and a receiver.

(B) Ultrasound echo techniques

Ultrasound waves are partially or totally reflected from surfaces at which the density of the medium changes. This property is exploited in techniques such as sonar and medical ultrasound imaging.

Application (Bat using sonar)

A bat emitting ultrasound waves can judge the distance of an object from the time taken by the reflected wave or 'echo' to return (Fig. 4.11).

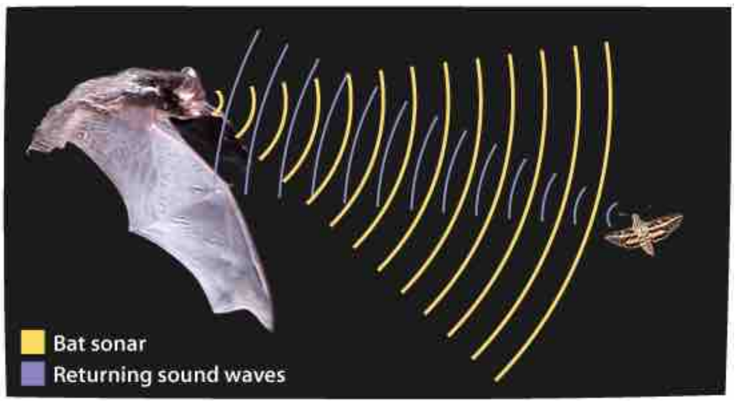


Fig. 4.11

Application (Ship using sonar)

Ships with sonar can determine the depth of a shoal of fish or the seabed (Fig. 4.12).

A research ship is using sonar to map the seabed.

How deep is the water if an ultrasound pulse reflected from the seabed takes 1.5 s to travel from transmitter to receiver?

Take the speed of sound in water to be 1400 m s^{-1}.

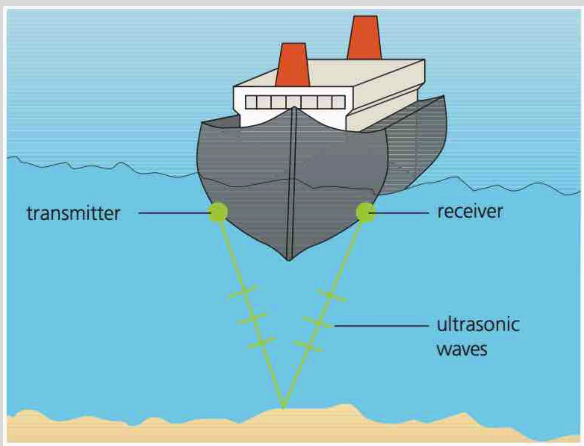


Fig. 4.12

Solution
If the depth of the seabed is d, the ultrasound must travel a distance of $2d$ during time t between the transmission and reception of the signal, then

$$2d = vt$$

$$d = \frac{1400 \times 1.5}{2} = 1050 \text{ m}$$

Additional information: motion sensors also work on this principle.

Application (Ultrasound imaging)
In medical ultrasound imaging, used in prenatal clinics to monitor the health of an unborn baby, an ultrasound transmitter/receiver is scanned over the mother's abdomen and a detailed image of the fetus is built up (Fig. 4.13). Reflection of the ultrasound pulses occurs from boundaries of soft tissue, in addition to bone, so images can be obtained of internal organs that cannot be seen by using X-rays. Less detail of bone structure is seen than with X-rays, as the wavelength of ultrasound waves is larger, typically about 1mm, but ultrasound has no harmful effects on human tissue.

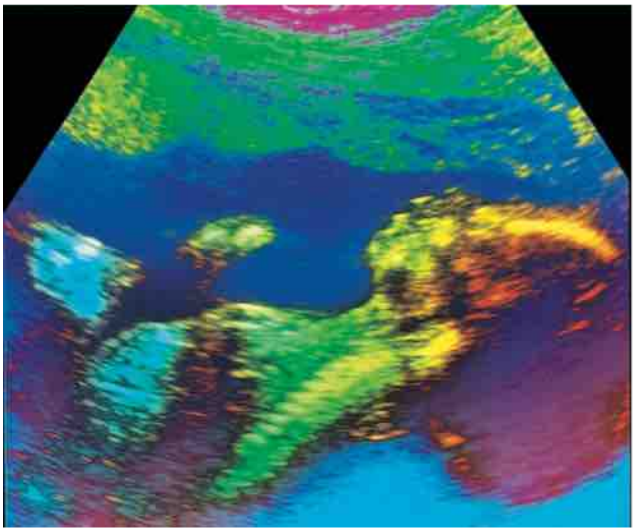


Fig. 4.13

<u>Other uses</u>

Ultrasound can also be used in cleaning. Jewellery, or objects such as street lamp covers, can be cleaned by immersion in a tank of solvent which has an ultrasound vibrator in the base.

https://youtu.be/8ixr2NQF9Dg
A brief introduction to ultrasound and its applications.

Problem Set (Topic 4)

1 The speed of sound is different in steel, water and air.

What is the correct order going from the substance with the lowest speed of sound to the substance with the highest speed of sound? (2017 P1 Q28)

A air → steel → water

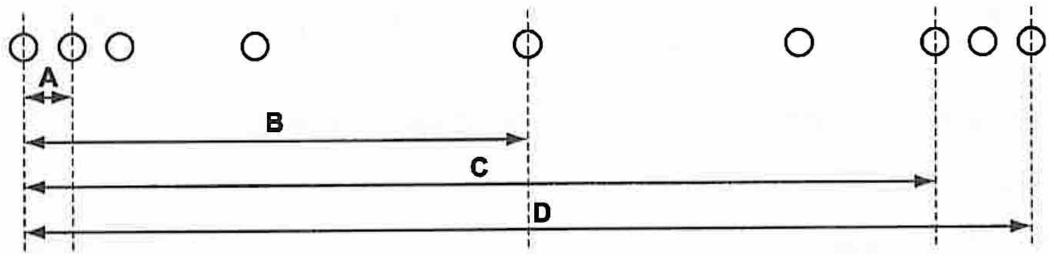
B air → water → steel

C water → air → steel

D water → steel → air

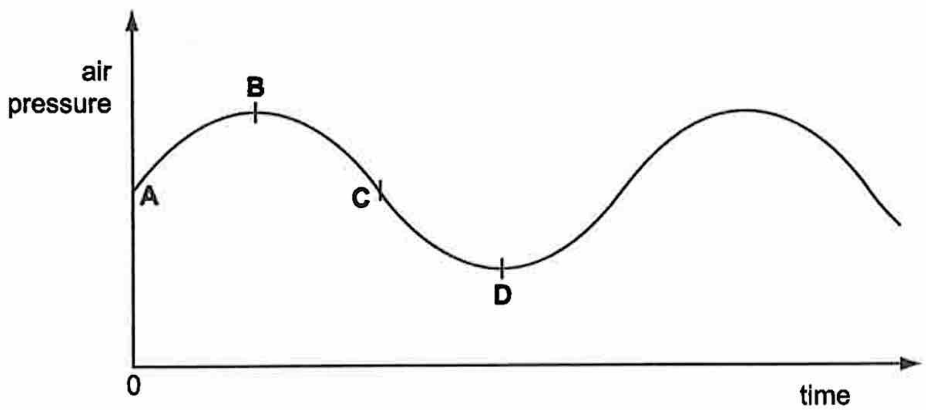
2 A sound wave passes through air. The diagram represents the arrangement of air molecules at one instant.

Which distance is the wavelength of the sound wave? (2012 P1 Q26)



3 The graph shows how the air pressure varies as a sound wave passes through air.

Which point represents a compression? (2016 P1 Q28)



4 A metal plate is oscillating up and down continuously. In 4.0 ms, it moves from the bottom position to the top position.

The oscillation of the plate causes sound waves to be generated in the surrounding air. Sound travels at a speed of 340 m/s.

What is the wavelength of these sound waves? (2019 P1 Q24)

A 0.37 m **B** 0.74 m **C** 1.4 m **D** 2.7 m

5 Which statement about sound waves is correct? (2017 P1 Q27)

A Loudness depends on amplitude and pitch depends on frequency.

B Loudness depends on frequency and pitch depends on amplitude.

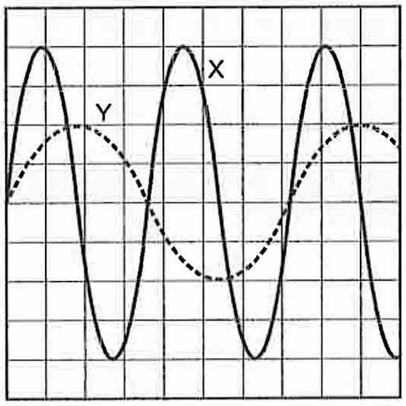
C Loudness depends on velocity and pitch depends on wavelength.

D Loudness depends on wavelength and pitch depends on amplitude.

6 A microphone is connected to a cathode-ray oscilloscope (c.r.o.).

The microphone receives sound from a loudspeaker.

The diagram shows the waveforms seen on the screen of the c.r.o. for two different sounds X and Y.



How does sound Y differ from sound X? (2018 P1 Q28)

A Y is louder and has a higher pitch.

B Y is louder and has a lower pitch.

C Y is quieter and has a higher pitch.

D Y is quieter and has a lower pitch.

7 Which does **not** involve an echo of an ultrasound signal? (2020 P1 Q26)

A bats detecting obstacles in their path

B satellites detecting objects moving towards them in space

C fishing boats measuring the depth of the sea

D doctors producing the image of an unborn baby

8 An ultrasound signal of frequency 2.0 MHz is used in a pre-natal scan.

The speed of the signal is 1.4 km/s.

What is its wavelength? (2015 P1 Q28)

A 7.0×10^{-4} m **B** 2.8×10^{-3} m **C** 0.70 m **D** 2.8 m

9 A pulse of sound is transmitted vertically downwards from an echo-sounder at the bottom of a ship. The pulse is reflected from the seabed and returns to the ship. The time taken between transmitting and receiving the pulse is 0.40 s. The speed of sound in water is 1500 m/s.

What is the depth of water under the ship? (2015 P1 Q29)

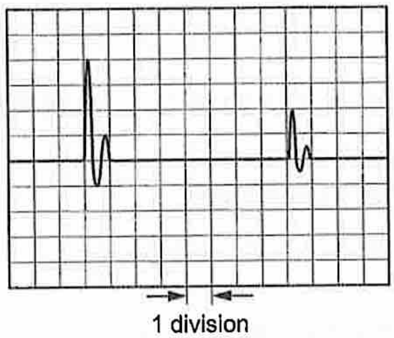
A 300 m **B** 600 m **C** 1200 m **D** 3800 m

10 A man stands in front of a wall.

There is a microphone next to him which is connected to a cathode-ray oscilloscope (c.r.o.).

He claps his hands and hears the echo.

The diagram shows what is seen on the screen of the c.r.o.



Each division on the screen represents 10 ms and the speed of sound in air is 300 m/s.

How far is the man from the wall? (2018 P1 Q27)

A 6.0 m **B** 12 m **C** 24 m **D** 1200 m

11 A teacher demonstrates the sound produced from a whistle by connecting a microphone to a cathode-ray oscilloscope (c.r.o.), as shown in Fig. 11.1. Four controls on the c.r.o. are shown.

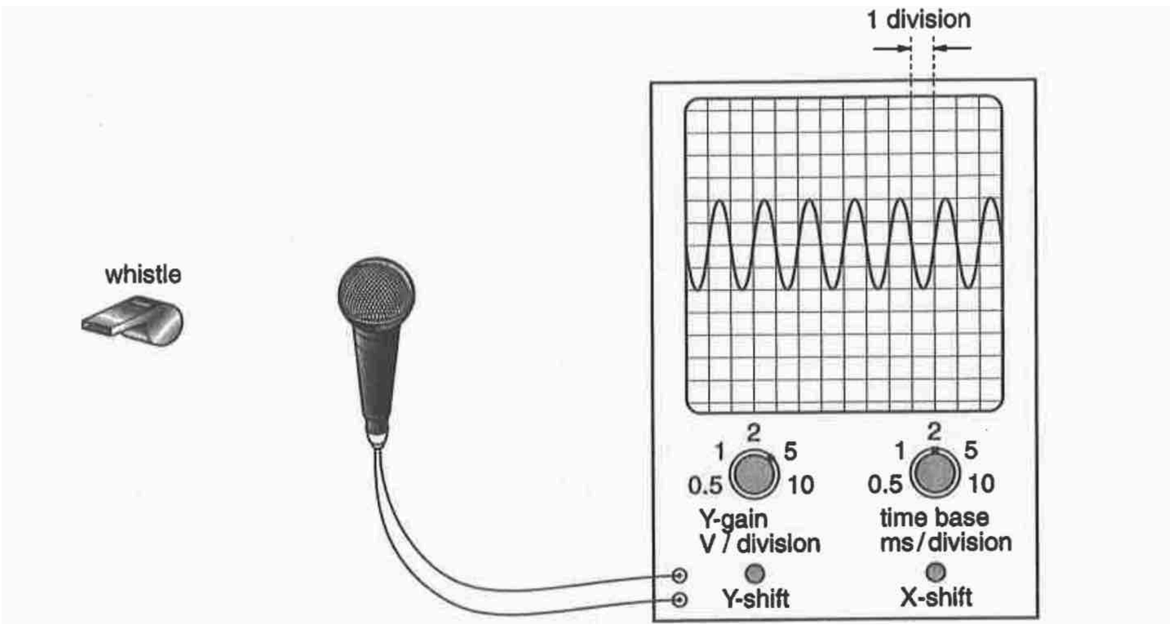


Fig. 11.1

(a) Describe how the sound is transmitted from the whistle to the microphone. You may include a diagram in your answer. [3]

(b) The time base is set at 2 ms / division. Determine the frequency of the sound emitted by the whistle. [2]

(c) The whistle is replaced with another of lower pitch. The controls on the c.r.o. are unaltered. Describe and explain what happens to the trace on the c.r.o. screen. [2]

(2013 P2A Q12a,b,c Either)

12 **(a)** A student measures the speed of sound using an echo from the cliff. She stands facing the cliff and claps her hands, as shown in Fig. 12.1.

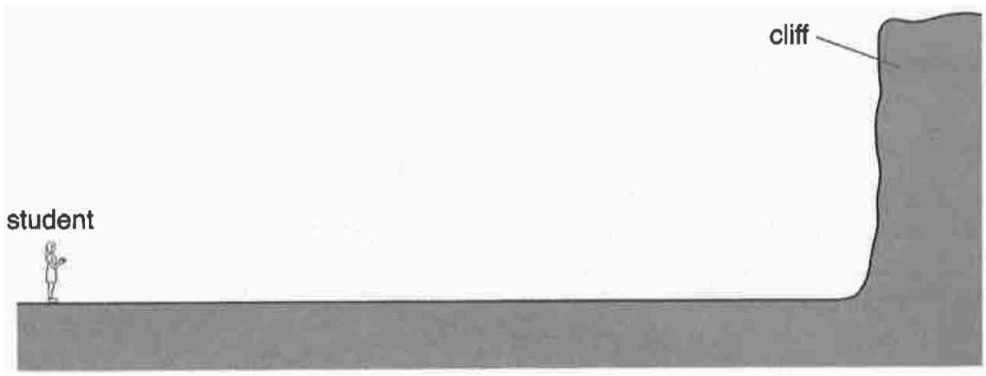


Fig. 12.1

The echo arrives 3.6 s after she claps her hands.
She walks 200 m towards the cliff and then claps her hands again. The echo now arrives 2.3 s after she claps.

Calculate the speed of sound using these data. Give your answer to an appropriate number of significant figures. [3]

(b) The student produced a musical sound. State how the sound heard changes when

(i) the amplitude of the sound decreases, [1]

(ii) the wavelength of the sound decreases. [1]

(2019 P2A Q5)

Solutions

1	B	**2**	C	**3**	B	**4**	D	**5**	A
6	D	**7**	B	**8**	A	**9**	A	**10**	B

11 **(a)** Whistle vibrate when blown causes air molecules around it to move back and forth about a fixed position.
Layers of air moving back and forth pass energy from molecule to molecule in a longitudinal wave spreading in all directions.
Some of this energy reaches and is picked up by the microphone.
(b) period = 2 divisions = 4 ms; frequency = 1 / period = 1 / 0.004 = 250 Hz
(c) Lower pitch means lower frequency, so longer period.
Less waves seen on the c.r.o. screen.

12 **(a)** $v = x / 1.8$ and $v = (x - 200) / 1.15$ where x is distance of student from the cliff originally
$x = 553.8$ m
$v = 553.8 / 1.8 = 310$ m s^{-1} (2 s.f. since times are measured to 2 s.f.)
(b) **(i)** loudness is reduced **(ii)** frequency increases, so higher pitch