Behaviour of light

Reflection of light

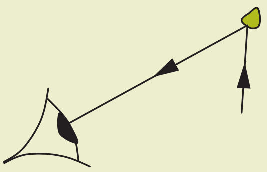
Unless it is interrupted in some way, light travels in a straight line. The direction that the light is travelling in is usually shown as an arrow and is called a *ray* of light. In practice, a ray can be thought of as a very narrow beam of light.

When light falls on to a surface, three things can happen:

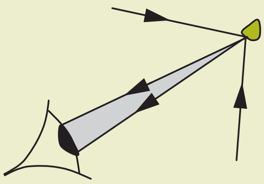
- the light can be reflected – i.e. the light is turned back into the substance (medium) in which the light was originally travelling
- the light can be transmitted – i.e. the light passes from the substance (medium) in which the light was originally travelling into a different substance; when transmission happens, there is very often some reflection as well
- the light can be absorbed – the energy the light is carrying is changed to heat by the material the surface is made from; when reflection and transmission happen, there is usually some absorption as well.

We 'see' an object only when light from that object goes into our eye. The light we use to see objects means the object is producing light (e.g. the Sun, light bulbs or flames) or light has been *reflected* off that object.

We can tell how far away an object is because there will be many rays entering the eye from an object, and the slightly different directions of these rays means that the eye will receive a *cone* of rays. The position at which we see the object is at the tip of the cone.



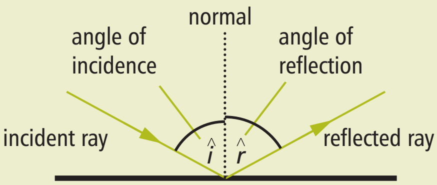
Object reflecting a light ray towards the eye



Object reflecting a cone of light towards the eye

To be able to describe the behaviour of light when it is *reflected*, it is necessary to introduce some terminology.

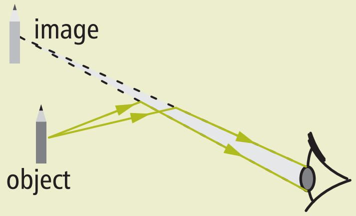
- The **incident ray** is the ray that is travelling *towards* the reflecting surface.
- The **normal** is an imaginary line that is at *right angles* to the reflecting surface and hits the reflecting surface at the same place as the incident ray.
- The **angle of incidence**, *i*, is the angle between the incident ray and the normal.
- The **reflected ray** is the ray that is travelling *away from* the reflecting surface.
- The **angle of reflection**, *r*, is the angle between the reflected ray and the normal.



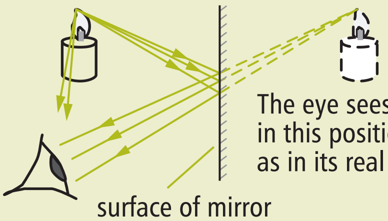
The rule which governs the way a light ray is reflected is:

angle of incidence = angle of reflection, $i = r$

In everyday life, the term *reflection* is usually used when an **image** is seen. The term *image* is used when the eye sees an object in the *wrong* position. For an image to be seen, the light must be *bent* between leaving the object and entering the eye. The brain does not know the light has been bent, so it 'sees' the object in the wrong position.



For a 'reflection' image to be seen, the reflecting surface must be smooth, such as a mirror or the flat surface of water.



If the reflecting surface was not *flat*, the reflected rays would not all meet at the *same* point, so there would be no 'position' for the flame to be seen at and so an image would not be seen.

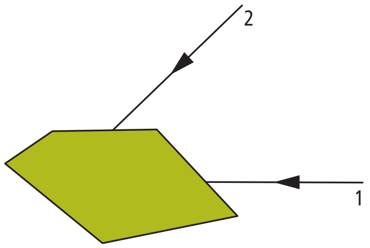
When an image of an object is seen in a plane (flat) mirror, the image has some important properties.

- It is the same *size* as the object.
- It is the same *way up* as the object.
- It is the same *distance* behind the mirror as the object is in front of the mirror.
- It is laterally inverted. This is why, if you look at yourself in a mirror and raise your right hand, your image appears to be raising its left hand.

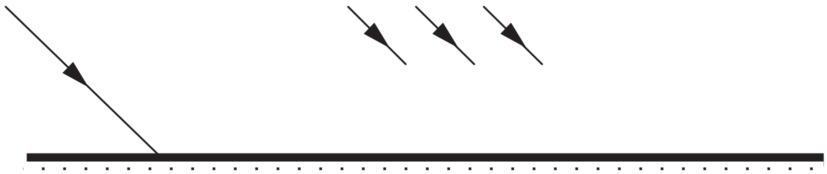
Reflection of light

Answers p. 55

1. The diagram shows two rays travelling towards an object. Accurately draw both rays after they have been reflected. On your diagram, indicate any angles that are the same size.



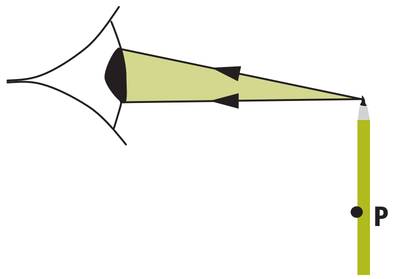
2. The diagram shows a ray of light *hitting* a flat reflecting surface.



   a. Accurately draw the ray after it has been reflected. Label your diagram.
   b. The other three rays are *parallel* to the first ray. Continue these rays and show their directions after they have been reflected.
   c. Explain why all the reflected rays are travelling in the same direction.

   d. The flat reflecting surface is replaced with a reflecting surface that is *curved*. Explain why the reflected rays will no longer be travelling in the same direction.

3. The eye sees an object because a cone of rays has travelled from each point on the object into the eye. The diagram shows the cone of rays that the eye has used to see the *point* of a pencil.

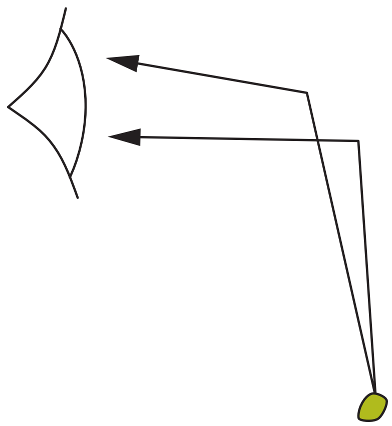


   a. Draw two rays to show the cone of rays that must *enter* the eye to see the point, **P**, on the pencil.
   b. These two rays were *reflected* off the pencil. Draw the two rays *before* they were reflected off the pencil

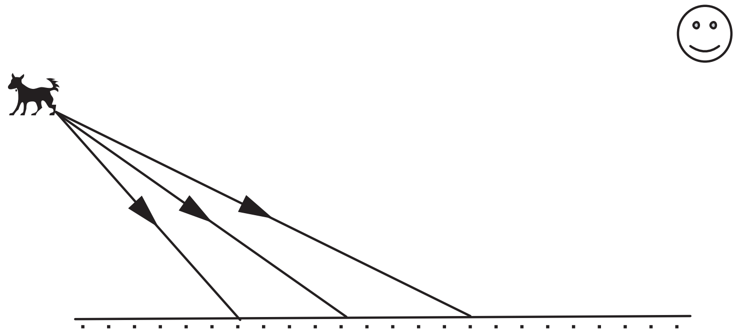
4. During the day, the rooms inside our homes are lit by light that comes in through the windows. There are many places inside a room that are *not* in direct line with a window, and yet we can see these places. We are only able to see things if light from them travels into our eyes. Explain how we are able to see objects that are not directly illuminated by light coming in through the windows. In your answer, you should consider:
   - what happens to the light that comes through the window when it hits the various surfaces in the room
   - how light can reach the regions of the room that are not directly illuminated.

5. The source of the light that comes from the sky is, of course, the Sun. In terms of the light we see at any instant, the Sun is in just one place in the sky. When light from the Sun enters our atmosphere it is, effectively, repeatedly reflected by the particles of the air so that by the time it reaches the surface of the Earth it is travelling in all directions. Explain how you know this scattering of the light has happened. In your answer, you should first consider what would happen if the light was *not* scattered.

6. The diagram shows two rays of light travelling from an object. The rays have been bent. After they have been bent, the rays form a cone that goes into a person's eye. Draw dotted lines on the diagram to show the position at which the eye would see the *image* of the object. Label the position of the image.



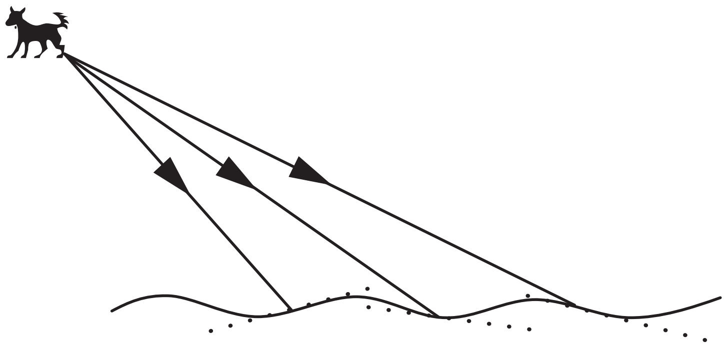
7. a. The diagram shows three rays of light travelling from a dog towards the flat surface of a pool of water.



i. Accurately draw the three reflected rays.

ii. If the three reflected rays form a cone that then goes into someone's eye, draw dotted lines on the diagram to show the position of the image of the dog that the person would see. Label the image position.

b. The surface of the water becomes ruffled. The dotted lines on the diagram show the direction of the surface of the water at each of the three positions where the rays hit the surface. Draw the reflected rays, and explain why an image will not be seen.

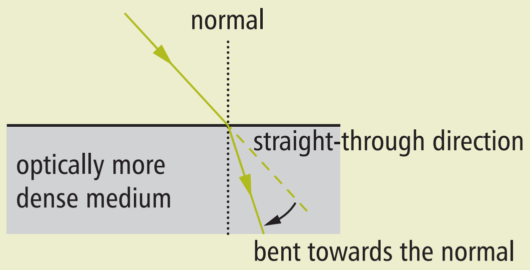


Transmission of light

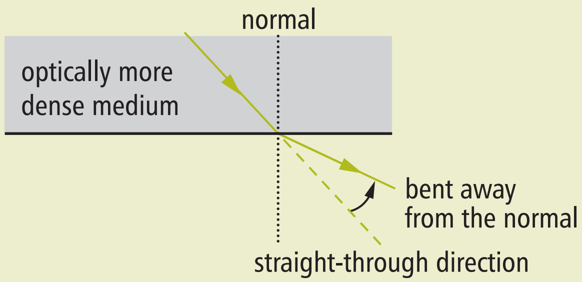
When light travels from air into another substance, such as glass, it slows down. All substances that light can travel through have an **optical density**. The *more* optically dense a substance is, the more *slowly* light will travel in that substance.

Because the *speed* of light changes as it goes from one substance into another, if the light strikes the boundary between the two substances at an *angle*, its *direction* will also change as it passes from one substance into the other. The *more* the light changes its speed at a boundary, the more the light is *bent*. The *bending* of light when it travels from one substance into another it is called **refraction**.

- Light is bent *towards* the normal if the light *slows* down when it enters the second substance (the second substance has a *greater* optical density).

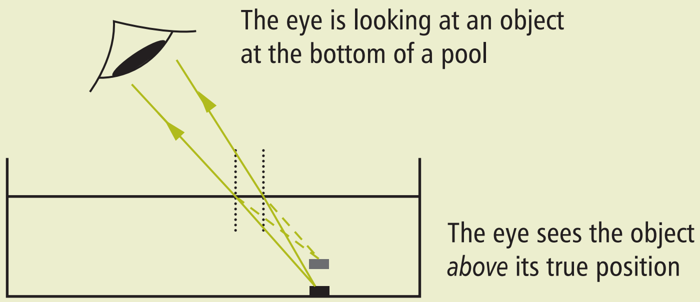


- Light is bent *away from* the normal if the light *speeds up* when it enters the second substance (the second substance has a *lesser* optical density).



If the light travels towards the boundary along the *normal* (perpendicular to the boundary), it will still change its speed as it enters the new medium, but its direction will stay the *same*.

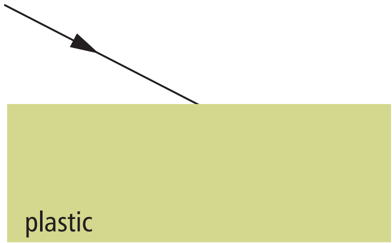
When refraction occurs, light is *bent*, so refraction can create an image.



Transmission of light

Answers p. 56

1. The diagram shows a ray of light travelling through air towards a block of plastic.

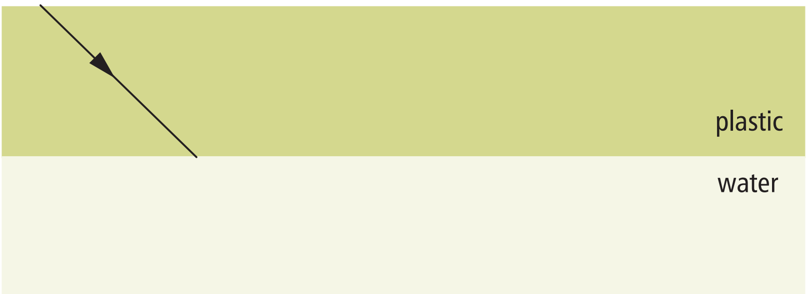


   a. Which of the two materials, *air* or *plastic*, has the greater optical density? Give a reason for your answer.

   b. In which direction will the ray that is refracted into the plastic be bent? Justify your answer in terms of what happens to the speed of the light.

   c. Continue the ray to show its direction in the plastic. Label the diagram.

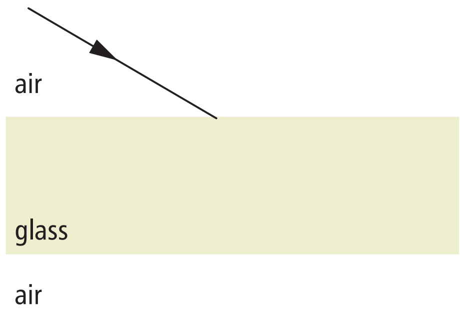
2. The diagram shows a ray of light travelling through a block of plastic towards water. The optical density of the plastic is *greater* than the optical density of the water.



   a. In which direction will the ray that is refracted into the water be bent? Give a reason, in terms of what happens to the speed of the light, for your answer.

   b. Continue the ray to show its direction when it goes into the water and then as it goes back out into air.

3. A ray of light goes from air, through a pane of glass, and back into air. The diagram shows the ray before it enters the glass.



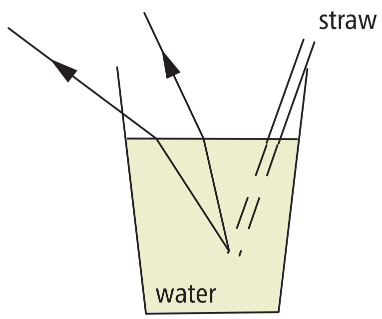
a. Draw the ray as it goes through the glass.

b. Because the ray then goes back into the same medium as it started in, the amount of bending that happened when the ray entered the glass will be the same as the amount of bending that happens when it leaves the glass.

i. Draw the ray that emerges from the glass into the air.

ii. Describe how the direction of the ray that comes out of the glass compares with the direction of the ray that goes into the glass.

4. The diagram shows a straw in a glass of water. The dashed part is the *true* position of the straw. A cone of rays has been drawn from the end of the straw.



a. The cone of rays goes into someone's eye. On the diagram, draw dotted lines to show where the eye sees the position of the end of the straw to be.

b. Complete the diagram to show how the rest of the straw would be seen.

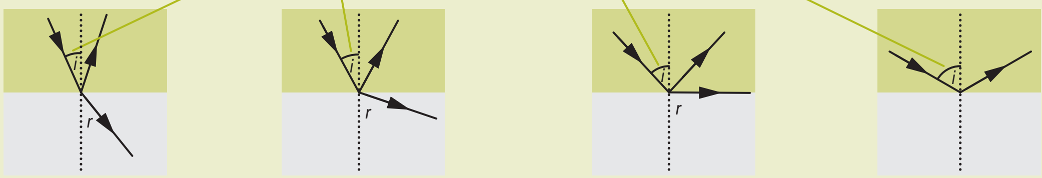
5. Explain why, when you look down into a swimming pool, it looks shallower than it really is. In your answer you should consider:
   - what happens to a cone of rays that comes from the bottom of the pool into your eye
   - how your brain could be deceived by this cone of rays.

   Draw a diagram to support your explanation.

Total internal reflection

When light goes at an angle from one substance into another, its direction bends. If the optical density of the second substance is *less* than the optical density of the first substance, the direction of the light bends *away* from the normal. As the angle of incidence increases, the angle of refraction also increases. Eventually, the angle of refraction reaches 90°. When this happens, the angle of incidence is called the **critical angle**. If the angle of incidence is increased again, there will be no more refraction; the light will be reflected only. This is called **total internal reflection**.

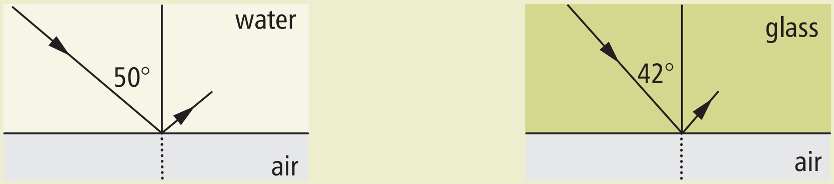
In each diagram the angle of incidence, *i*, is increasing



Angle of refraction is *r* | Angle of refraction, *r*, has increased | Angle of refraction, *r*, has increased to 90° | No refraction, just reflection

During this increase in the angle of incidence, the relative brightness of the reflected ray *increases* while the relative brightness of the refracted ray *decreases*.

When we see the effects of total internal reflection, it is often because light has gone from either glass or water into air. The diagrams following show the size of the critical angle for both these substances.



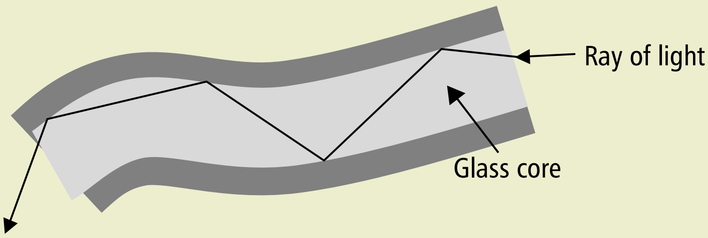
As can be seen in the diagrams, the angle of incidence does not have to be very large before total internal reflection occurs. The diagrams also show that the *greater* the optical density (glass has a greater optical density than water), the *smaller* the critical angle.

It is *impossible* for total internal reflection to happen if light is going from a less optically dense substance into a more optically dense substance because the light will be bent *towards* the normal and so there will never be an angle of incidence at which the angle of refraction is 90°. Total internal reflection can *only* happen when light is travelling from a *more* optically dense substance into a *less* optically dense substance.

Fibre optic cabling is gradually replacing copper cabling in telecommunications, and this is having a huge effect on the speed of the internet. Fibre optic cables work by total internal reflection. The signal that is sent down the cable is a light signal and so its speed, as it travels along the cable, is much greater than the speed at which an electrical signal travels along a copper cable.

A fibre optic cable consists of a very thin core of glass sheathed in a material which has a low optical density.

A ray of light entering one end of the cable is totally internally reflected every time it hits the edge of the glass fibre. Because it is reflected back into the glass (and *not* transmitted out of the glass), it travels along the cable and out the other end.



Answers

Types of waves (page 3)

1. When the drum is hit, the skin starts to vibrate up and down. The movement of the skin pushes against air molecules, creating the compressions and rarefactions that are a sound wave.
2. Sound is a mechanical wave, so needs a medium to travel through; light and heat are both electromagnetic waves, so do not need a medium to travel through. There is a vacuum between the Earth and the Sun, and so there is no medium for sound to travel in.
3. The swimmers will rise and fall between the crests and the troughs of the waves. Amplitude is *half* the total distance between a crest and a trough. If the total distance from crest to trough is 1.2 m, the amplitude is 0.6 m.
4. **a.** For both types of wave, the local movement of the medium consists of a vibration around the position of the medium before the wave arrived.
   b. In a longitudinal wave, the direction of the vibrations of the medium is parallel to the direction in which the wave is travelling. In a transverse wave, the direction of the vibrations of the medium is perpendicular to the direction in which the wave is travelling.
5. If the ball is to be carried towards the shore, the water under the ball must move towards the shore. Because the water waves are transverse, the movement of the water under the ball is up and down, and so there is no movement of water towards the shore.
6. Storm-force winds have much more energy than gentle winds, and so more energy is used to generate the waves. The amplitude of a wave is a measure of the energy it has; so, waves generated by storm-force winds have greater amplitude.
7. If the drum is hit hard, more energy is used to create the sound wave that is produced. This means the wave will have greater amplitude, so more energy will be carried to the ear of the person who hears the sound and so the sound will be louder.

Speed of a wave (page 6)

1. **a.** **i.** 12 km = 12 × 1 000 m = 12 000 m
   ii. $v = \frac{d}{t} = \frac{12\ 000}{35} = 342.86 = 340 \text{ m s}^{-1}$
   b. $t = \frac{d}{v} = \frac{12\ 000}{3 \times 10^8} = 0.000040 \text{ s}$
   c. The person would count about 35 seconds, because the light effectively takes no time at all. This means there are approximately 12 sets of 3 seconds, so the estimated distance would be 12 km.
   d. $d = vt = 342.86 \times 30.6 = 10\ 491.5 = 10.5 \text{ km}$
2. **a.** $f = \frac{v}{\lambda} = \frac{3 \times 10^8}{405 \times 10^{-9}} = 7.4 \times 10^{14} \text{ Hz}$
   b. **i.** $\lambda = \frac{v}{f} = \frac{3 \times 10^8}{5.6 \times 10^{14}} = 5.4 \times 10^{-7} \text{ m}$
   ii. 540 nm
   c. **i.** The speed will slow down.
   ii. It won't affect the frequency; the frequency will stay the same.
   iii. $v = f\lambda = 4.6 \times 10^{14} \times 500 \times 10^{-9} = 2.3 \times 10^8 \text{ m s}^{-1}$
   d. Red light has a smaller frequency than green or purple, and so the light that has frequency 4.6×10^{14} Hz must be the red light.
3. **a.** $T = \frac{3.6}{10} = 0.36 \text{ s}$
   b. $f = \frac{1}{T} = \frac{1}{0.36} = 2.8 \text{ Hz}$
   c. $v = \frac{d}{t} = \frac{8}{2.5} = 3.2 \text{ m s}^{-1}$
   d. $\lambda = \frac{v}{f} = \frac{3.2}{2.8} = 1.1$ m, so the estimate was too low.
   e. If Mary is not making as many waves per second, then the frequency of the wave will decrease. The speed of the wave will not change because it is the same spring. If the frequency decreases and the speed stays the same, then the wavelength must increase ($v = f\lambda$).
4. **a.** Both colours are travelling in air, so both will have the same speed. Blue light has a higher frequency than red light, so the wavelength of the blue light will be shorter than the wavelength of the red light.
   b. Both sound waves are travelling in air, so both will have the same speed. High-pitched sound has a higher frequency than low-pitched sound, so the wavelength of the higher-pitch sound will be shorter than the wavelength of the lower-pitch sound.
5. **a.** **i.** 28 kHz = 28 000 Hz and 54 mm = 0.054 m
   ii. $v = f\lambda = 28\ 000 \times 0.054 = 1\ 512 \text{ m s}^{-1}$
   iii. $d = vt = 1\ 512 \times 0.75 = 1\ 134 \text{ m}$
   iv. The sound has to travel to the obstacle and then back again, so the total distance travelled is twice the distance to the obstacle; so, $d = \frac{1}{2} \times 1\ 134 = 567 \text{ m}$
   v. $2d = vt \Rightarrow d = \frac{1}{2} \times (1\ 512 \times 0.1) = 76 \text{ m}$
   b. The frequency of the sound wave does not affect the speed at which it travels, so does not affect the time it takes for the dolphin to hear the echo. As the dolphin uses the time to estimate the distance, the estimate will not be affected.
6. **a.** **i.** $v = \frac{d}{t} = \frac{570}{0.75} = 760 \text{ km h}^{-1}$
   ii. $760 \text{ km h}^{-1} = 760 \times 1\ 000 \text{ m h}^{-1} = \frac{760\ 000}{60 \times 60} \text{ m s}^{-1} = 210 \text{ m s}^{-1}$
   iii. $f = \frac{v}{\lambda} \frac{210}{100\ 000} = 0.0021 \text{ Hz}$
   iv. The time for one complete wave to pass under the ship is the period of the wave.
   $T = \frac{1}{f} = \frac{1}{0.0021} = 480 \text{ s} = 8.0 \text{ minutes}$
   b. $v = f\lambda = 0.0021 \times 20\ 000 = 42 \text{ m s}^{-1}$

Reflection, transmission and diffraction of a wave
(page 11)

1. a. The frequency of the light always stays the same, and so both the reflected and transmitted light will have the same frequency as the light that shone onto the sea. Because the reflected light is in the same medium as before it was reflected, it will not change its speed and so the wavelength of the light will also not change. The transmitted light will slow down, which means its wavelength must get shorter because speed is proportional to wavelength ($v = f\lambda$).
   b. The energy carried by the light that shines onto the sea has to be divided between the reflected light and the transmitted light. This means the energy of the reflected light and the energy of the transmitted light are less than the energy of the incident light. As amplitude is an indicator of the energy of a wave, the amplitude of the incident light will be greater than the amplitude of both the reflected light and the transmitted light.
2. There will only be reflection because light cannot be transmitted into the solid material of the wall.
3. If a light wave cannot go from the transmitter to the receiver, there must be a barrier in between. A light wave has a very short wavelength, and so cannot diffract around a barrier. A radio wave has a relatively long wavelength, and so it is possible for it to bend sufficiently around a barrier to be able to reach a receiver that is not in line of sight.
4. a. The wave will not change its frequency because frequency always stays the same. Because the wave is not going into a different medium it will not change its speed, and so its wavelength will also stay the same.
   b. The amount of bending that happens at each side of the gap depends on how close the width of the gap is to the wavelength of the wave. As the width of the gap gets smaller, the size of the gap gets closer to the wavelength of the wave, and so the wave is bent much further around each edge of the gap, making it more circular in shape.
5. a. Radio waves all travel at the same speed – c, the speed of light. Since $v = f\lambda$ and v is constant, the much higher-frequency digital radio waves must have much smaller wavelengths than the lower-frequency analogue waves. The greater the wavelength of a wave, the more it diffracts around a barrier. Thus lower-frequency analogue waves are better able to diffract around a barrier than higher-frequency digital radio waves.
   b. i. Digital signals are broadcast using higher frequencies. Diffraction is needed to bend signals around obstacles, and, because high-frequency waves diffract less than low-frequency waves, there will be fewer places that are able to receive the digital signal.
      ii. Because the wave from a satellite comes from above Earth and only has to pass through our atmosphere, there is far less chance of there being a barrier to stop the signal.
6. $v = f\lambda \Rightarrow \lambda_{\text{low pitch}} = \dfrac{v}{f_{\text{low}}} = \dfrac{340}{400} = 0.85$ m

   $\lambda_{\text{high pitch}} = \dfrac{v}{f_{\text{high}}} = \dfrac{340}{1\,500} = 0.2267 = 0.23$ m

   The low-pitch notes have wavelengths that are much closer to the size of the gap than the high-pitch notes. Also, the low-pitch notes have longer wavelengths than the high-pitch notes. This means the low-pitch notes will diffract much more than the high-pitch notes.

General behaviour of waves – topic questions (page 13)

1. **Sound and water waves**
   a. $T = \dfrac{1}{f}$

   $\Rightarrow T = \dfrac{1}{670}$

   $\Rightarrow T = 0.001493$ s

   period $= 0.0015$ s

   b. $9\lambda = 4.5$ m

   $\Rightarrow \lambda = \dfrac{4.5}{9}$

   $\Rightarrow \lambda = 0.50$ m

   $v = f\lambda$

   $\Rightarrow v = 670 \times 0.50$

   $= 335$ m s^{-1}

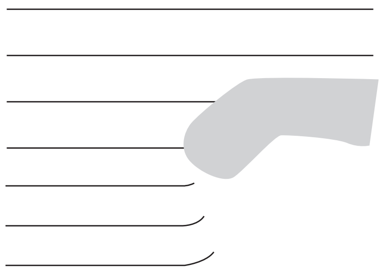
   speed $= 340$ m s^{-1}

   c. Each smoke particle will vibrate backwards and forwards in a horizontal direction. The direction of vibration is parallel to the direction of motion of the wave because a sound wave is longitudinal.
   d. If the sound was louder, the amplitude of the vibrations of the smoke particles would be greater.
   e. If the sound had a higher pitch, the frequency would be greater. Because the speed of the sound wave would stay the same, the wavelength would be less ($v = f\lambda$). The compressions and rarefactions would be closer together.
   f. 12 times a minute $= \dfrac{12}{60}$ times per second $\Rightarrow f = 0.20$ Hz
   g. $v = f\lambda$

   $\Rightarrow \lambda = \dfrac{0.80}{0.20} = 4.0$ m

   h. $v = f\lambda$, $\lambda = 0.75 \times 4.0 = 3.0$ m

   $\Rightarrow v = 0.20 \times 3.0 = 0.60$ m s^{-1}

   i. A water wave is a transverse wave. Therefore the water is moving up and down at right angles to the direction of the wave, which is horizontally across the surface. The bobbing of the wood is caused by the movement of the water. As the water does not move towards the shore, it cannot make the wood move towards the shore.
   j. 

   The diagram shows that the wavelength stays constant, and that the edge of the wave crests that have passed the rock curve inwards.

2. **Travelling waves**
   a. i. The particles vibrate up and down at right angles to the wave direction.
      ii. The particles vibrate back and forth parallel to the wave direction.
   b.