10 Light as a wave

10.1 Overview

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10.1.1 Introduction

Understanding waves will add to your knowledge of physics and complement your knowledge of the motion of particles. Light has always been considered a mystery from ancient times to the present. Could light be a type of wave or does it propagate and transfer energy more like a particle? In this chapter, you will investigate light as a wave as considered by Huygens, though it was considered, by Newton, to consist of particles. The refraction of light and its ability to both diffract and interfere clearly indicates that light can be modelled as a type of wave propagating at a constant speed through a variety of media. Maxwell took advantage of new knowledge in the fields of magnetism and electricity, particularly electromagnetic induction, to propose that light was in fact a self-propelled transverse wave consisting of dual electric and magnetic fields perpendicular to each other. This mathematical model of light as a wave, combined with the mathematical model of matter as a particle, seemed to make physics complete as a subject area near the end of the nineteenth century.

FIGURE 10.1 Understanding light as a wave helps to explain many physical phenomena.

10.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic you will be able to:

- describe light as an electromagnetic wave, which is produced by the acceleration of charges, which in turn produces changing electric fields and associated changing magnetic fields
- identify that all electromagnetic waves travel at the same speed, c, in a vacuum
- compare the wavelength and frequencies of different regions of the electromagnetic spectrum, including radio, microwave, infra-red, visible, ultraviolet, X-ray and gamma, and identify the distinct uses each has in society
- explain polarisation of visible light and its relation to a transverse wave model
- investigate and analyse theoretically and practically the behaviour of waves including:
  - refraction using Snell's Law: $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$ and $n_1 v_1 = n_2 v_2$
  - total internal reflection and critical angle including applications: $n_1 \sin(\theta_c) = n_2 \sin(90°)$.
- investigate and explain theoretically and practically colour dispersion in prisms and lenses with reference to refraction of the components of white light as they pass from one medium to another
- investigate and explain theoretically and practically diffraction as the directional spread of various frequencies with reference to different gap width or obstacle size, including the qualitative effect of changing the $\frac{\lambda}{w}$ ratio
- investigate and describe theoretically and practically the effects of varying the width of a gap or diameter of an obstacle on the diffraction pattern produced by light and apply this to the limitations of imaging using light
- explain the results of Young's double-slit experiment with reference to:
  - evidence for the wavelike nature of light
  - constructive and destructive interference of coherent waves in terms of path differences: $n\lambda$ and $\left(n - \frac{1}{2}\right)\lambda$ respectively
  - effect of wavelength, distance of screen and slit separation on interference patterns: $\Delta x = \frac{\lambda L}{d}$.

PRACTICAL WORK AND INVESTIGATIONS

Practical work is a central component of learning and assessment. Experiments and investigations, supported by a **Practical investigation logbook** and **Teacher-led videos**, are included in this topic to provide opportunities to undertake investigations and communicate findings.

on Resources

Digital documents Key science skills — VCAA Physics Units 1–4 (doc-#####)
Key terms glossary (doc-#####)
Practical investigation logbook (doc-#####)

studyon

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10.2 Light and its properties

BACKGROUND KNOWLEDGE

- Sources of light can be luminous or non-luminous.
- Some luminous objects are incandescent.
- Light travels very fast.

- Light travels in a straight-line path called a light ray.
- When light reflects, the angle of incidence is equal to the angle of reflection.
- Reflection can be either regular or diffuse.
- Colour is both a property of light and an aspect of human perception.

Sight is the sense by which humans and most other mammals get most of their information about the world. This sense responds to light. Questions about light naturally arise. Where does light come from? What can it do? How can its properties be explained?

Some obvious observations concerning light include the following:

- Sources of light are needed for a person to be able to see.
- Light travels very fast and appears to travel in a straight line.
- Light produces shadows.
- Light is sensed by people as exhibiting different colours.

10.2.1 Sources of light

Sources of light

When you experience darkness at night or in an enclosed room, you know that a source of light, such as the Sun or a lamp, is needed to light up the darkness. Once a lamp is turned on, you can see features in the room because the light from the lamp shines on them and is then reflected into your eyes.

This means that objects can be classified into two groups. Objects seen because they give off their own light are called **luminous** objects; those seen because they reflect light are called non-luminous objects. The Sun, torches and candles are luminous objects. Tables, chairs, cats and dogs are non-luminous objects.

FIGURE 10.2 The Pleiades open star cluster in the constellation Taurus. All stars are incandescent sources of light.

Some luminous objects produce light because they are hot. The Sun is one example. The higher the temperature, the brighter the light, and the colour also changes. These objects are called **incandescent**.

Other objects are cold and produce light in another way. This involves changes in the energy of electrons in the material brought about by either chemical or electrical processes.

10.2.2 Propagation of light

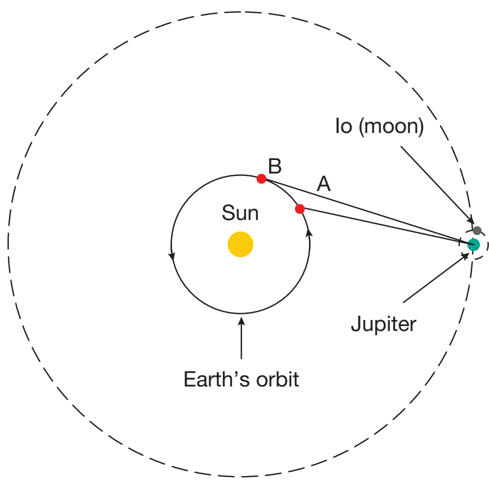
The gap experienced between seeing lightning and hearing thunder shows that sound travels relatively slowly. Light seems to travel so fast that its speed seems infinite; that is, events seem to be observed at the instant they happen.

Galileo Galilei (1564–1642) was not convinced of this. He attempted to determine the speed of light by measuring the time delay between the flash of his lamp to an assistant on a distant mountain and the return flash from his assistant's lamp. No detectable delay was observed and Galileo concluded that the speed of light was very high. A longer distance was needed to investigate such a high speed.

FIGURE 10.3 Galileo used this method to measure the speed of light. He attempted to time, with his pulse, the delay between uncovering his lantern and seeing the light from his partner's lantern, which his partner uncovered at the moment when he saw the light from Galileo's lantern.

Olaus Roemer was a Danish astronomer born two years after Galileo died. He observed that the time between eclipses of Jupiter's moons by Jupiter decreased as the Earth moved closer to Jupiter and increased as the Earth moved away. Roemer reasoned that this was because the distance the light travelled from Jupiter to Earth became greater as the Earth's orbit took it further from Jupiter, as shown in figure 10.4. Roemer used this time and the known diameter of the Earth's orbit about the Sun to estimate the speed of light. The value he obtained was $2.7 \times 10^8\ \text{m s}^{-1}$.

FIGURE 10.4 The time, as seen from the Earth, for Jupiter's moon Io to orbit Jupiter increases as the Earth moves from A to B. (The diagram is not to scale.)

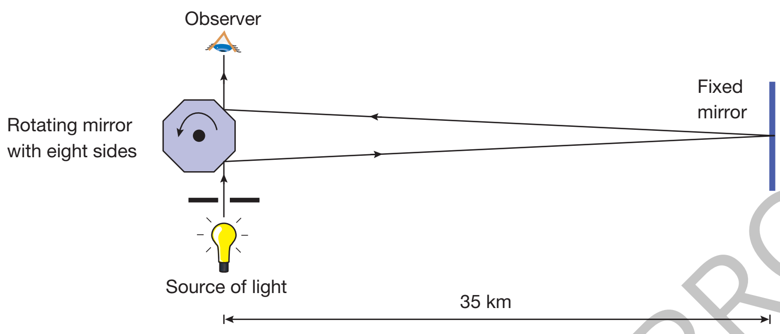


Eventually, in the nineteenth century, with stronger light sources and more precise timing devices, Galileo's method could be used, but the assistant was replaced by a mirror. The values obtained then were about $3.0 \times 10^8\ \text{m s}^{-1}$.

Early in the twentieth century, the American scientist Albert A. Michelson (1852–1931) used a rapidly rotating eight-sided mirror, as shown in figure 10.5. The light was reflected to a distant mirror about 35 kilometres away, then reflected back to the rotating mirror. For some particular rotation rates, this light is reflected by one of the sides of the rotating mirror directly to the observer. The rotation rate can be used to calculate the speed of light.

The value Michelson obtained was $2.997\ 96 \times 10^8\ \text{m s}^{-1}$. He actually measured the distance of 35 km to an accuracy of 2.5 cm. The speed of light is currently measured at $2.997\ 924\ 58 \times 10^8\ \text{m s}^{-1}$. It is rounded off to $300\ 000\ \text{km s}^{-1}$ for calculation purposes.

FIGURE 10.5 Light from the source reflects off one of the sides of the rotating mirror towards a mirror 35 kilometres away. The returning beam hits the rotating mirror. If one of the sides of the mirror is in the correct position, the light enters the eyepiece and can be seen by the observer. By measuring the speed of rotation when the beam enters the eyepiece, the speed of light can be calculated.



SAMPLE PROBLEM 1

How long does light take to travel from the Sun to the Earth?

Teacher-led video: SP1 (tlvd-XXXX)

THINK

1. To calculate the time taken for light to travel from the Sun to the Earth, the speed of light and the distance from the Sun to Earth need to be known.

2. Substitute the values for the speed of light and the distance between the Sun and Earth into the following equation and solve for time:

$$\text{speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

WRITE

speed of light $= 3.00 \times 10^8\ \text{m s}^{-1}$
distance from Sun to Earth $= 1.49 \times 10^{11}\ \text{m}$

$$\text{speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

$$\Rightarrow \text{time taken} = \frac{\text{distance travelled}}{\text{speed}}$$

$$\begin{aligned}\text{time} &= \frac{1.49 \times 10^{11}\ \text{m}}{3.00 \times 10^8\ \text{m s}^{-1}} \\ &= 0.497 \times 10^3\ \text{s} \\ &= 497\ \text{s} \\ &= 8\ \text{minutes}\ 17\ \text{seconds.}\end{aligned}$$

PRACTICE PROBLEM 1

The Moon is approximately 380 000 km from the Earth. How long would it take light to travel from a laser based on the Earth to reflect off a mirror positioned on the Moon and then return back to Earth?

SAMPLE PROBLEM 2

How far does light travel in one year (one light-year)?

Teacher-led video: SP2 (tlvd-XXXX)

THINK	WRITE
1. To calculate the distance that light travels in one year, the speed of light and the number of seconds in a year need to be known.	speed of light $= 3.00 \times 10^8$ m s^{-1} seconds in a year $= 365.25$ days year^{-1} $\times$ 24 hours day^{-1} $\times$ 3600 seconds hour^{-1}
2. Substitute the values for the speed of light and the time taken into the following equation and solve for distance: distance travelled = speed × time taken	distance travelled = speed × time taken $= 3.00 \times 10^8$ m s^{-1} $\times (365.25 \times 24 \times 3600)$ s $= 9.47 \times 10^{15}$ m $= 9.47 \times 10^{12}$ km

PRACTICE PROBLEM 2

In an optic fibre made from glass, it takes light 1.0 μs to travel a distance of 200 m. What is the speed of light in glass? Is it greater or less than the speed of light in a vacuum?

on Resources

Digital documents Investigation 10.1 Luminous or not? (doc-xxxxx)
Investigation 10.2 Luminosity and temperature (doc-xxxxx)

Teacher-led video Investigation 10.2 Luminosity and temperature (tlvd-xxxx)
Investigation 10.1 Luminous or not? (tlvd-xxxx)

10.2.3 Ray model for light

The need for sources of light, the great speed of light and the existence of sharp shadows can be described by a ray model. The model assumes that light travels in a straight-line path called a **light ray**. A light ray can be considered as an infinitely narrow beam of light and can be represented as a straight line, as shown in figure 10.6.

The bright Sun produces sharp shadows on the ground. The shape of the shadow is the same shape as the object blocking the light. This could happen only if light travels in a straight line.

FIGURE 10.6 Light rays leave a point on this pencil and travel in straight lines in all directions. The pencil is seen because of the 'bundle' of rays that enter the eye.

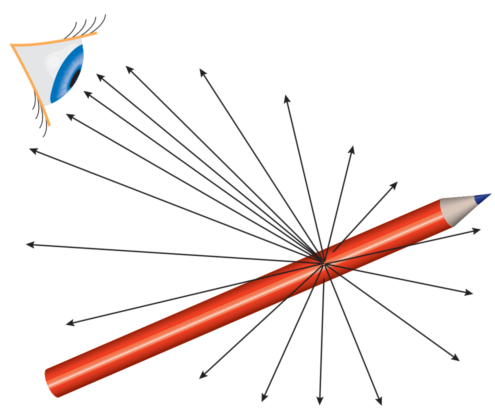


FIGURE 10.7 The straight rays passing the edge of a bird leave a sharp shadow on the ground.

10.2.4 Reflection: regular and diffuse

When you look at yourself in a plane mirror, some of the light rays from your nose, for example, travel in the direction of the mirror and reflect off in the direction of your eye. What is happening at the surface of the mirror to produce such a perfect image?

To investigate the reflection of light, the angles made by the rays need to be measured. Measurements of these angles show that, like a ball bouncing off a flat wall, the **angle of incidence** equals the **angle of reflection**.

FIGURE 10.8 Light rays from the tip of the nose reflect off the mirror and enter the eye.

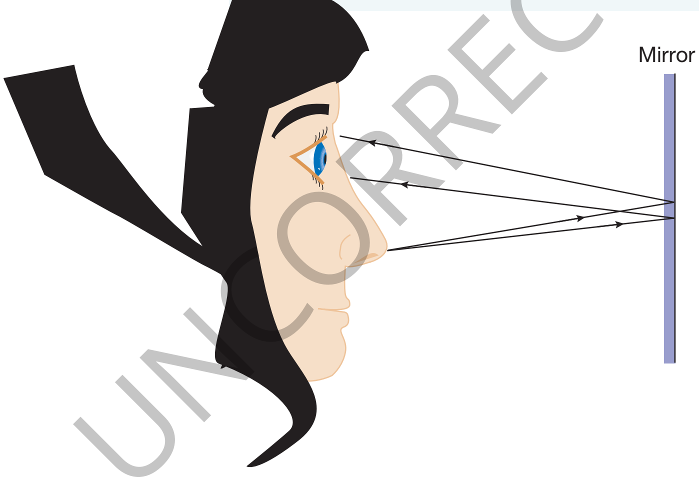
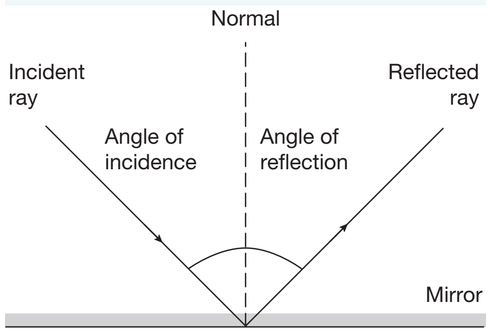


FIGURE 10.9 The ray approaching the mirror is called the incident ray. The ray leaving the mirror is called the reflected ray. The normal is a line at right angles to the mirror. The angles are measured between each ray and the normal. When the path of a light ray is traced, it is found that the angle of incidence always equals the angle of reflection.



The other seemingly trivial conclusion that can be drawn from the investigation is that the incident ray, the **normal** and the reflected ray all lie in the same plane.

Reflection from a smooth surface is called **regular** or **specular reflection**. But what happens with an irregular surface, such as this page? A page is not smooth like a mirror. At the microscopic level, ‘hills and valleys' exist. As the light rays come down into these hills and valleys, they still reflect with the two angles the same but, because the surface is irregular, the reflected rays emerge in all directions. This is called **diffuse reflection**. Light rays from diffuse reflections — from the ground, trees and other objects — enter the eye and enable the brain to make sense of the world.

FIGURE 10.10 The incident ray, the 'normal' to the surface of the mirror and the reflected ray all lie in the same plane, which is at right angles to the plane of the mirror.

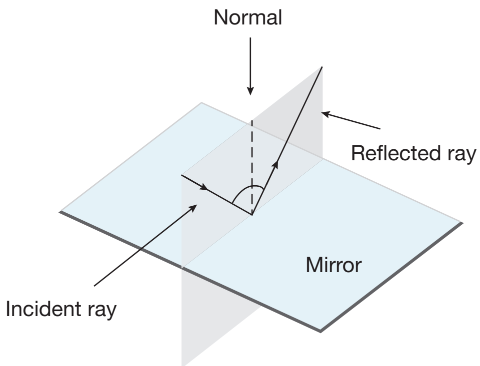
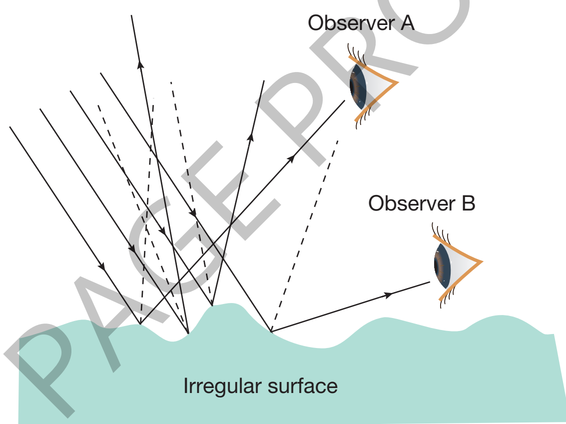


FIGURE 10.11 This is diffuse reflection. Each of the incoming parallel rays meets the irregular surface at a different angle of incidence. The reflected rays will therefore go off in different directions, enabling observers in all directions to receive light from the surface — in other words, to see the surface.



10.2.5 What is colour?

Colours are an important part of humanity's language and environment. Colours can be peaceful to the eye or very stimulating. Colours are used in language to convey feelings and emotions (for example, *fiery red, warm orange* and *icy blue*).

At first, colour may seem to be a defining part of an object, like size, shape and texture. For example, you can say *green leaves, red earth* and *blue eyes*. It is only when experiments are done with light that you can observe that the colour or appearance of an object changes with the light that is shining on it.

But what about rainbows? And the blue sky? Here it seems that colour, pure colour, is separate from any solid object. So what really is colour? It is both a property of light and an aspect of human perception. A wave model of light will assign the human perception of colour to the frequency of the light.

FIGURE 10.12 Changing the colour of the light on these flowers from white to red to blue changes one's perception of their colour.

(a) White light (b) Red light (c) Blue light

10.2 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. Calculate the longest and shortest time for a radio signal travelling at the speed of light to go from the Earth to a space probe when the space probe is:
   (a) near Mars
   (b) near Neptune.
   Data:
   $c = 3.0 \times 10^8$ m s^{-1}
   Radius of Earth's orbit about the Sun = 1.49×10^{11} m
   Radius of Mars's orbit about the Sun = 2.28×10^{11} m
   Radius of Neptune's orbit about the Sun = 4.50×10^{12} m
2. A ray of light strikes a planar mirror with an angle of incidence of 25° and regular reflection takes place.
   (a) What angle does the light ray make with the mirror surface?
   (b) What is the angle of reflection?
3. A student arranges a beam of light from a laser to strike a plane mirror such that the incident beam and the reflected beam form a right angle. What is the angle of incidence that the light from the laser makes with the mirror?

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10.3 Bending of light

KEY CONCEPTS

- investigate and analyse theoretically and practically the behaviour of waves including:
  - refraction using Snell's Law: $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$ and $n_1 v_1 = n_2 v_2$
- investigate and explain theoretically and practically colour dispersion in prisms and lenses with reference to refraction of the components of white light as they pass from one medium to another.

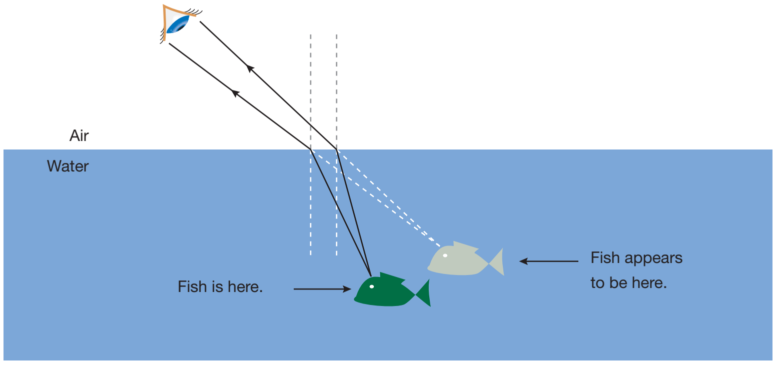
Experience shows that when you are spearing for fish in the shallows you must aim the spear below where the fish appears to be in the water. At the beach or in a pool, people standing in the shallows appear to have shorter legs. Perception is distorted, but the reason is not apparent.

When a special situation is set up, such as in figure 10.13, where a straight rod is placed in a beaker of liquids that do not mix, the idea of the change of direction of the light is apparent. This change in direction is called **refraction**. Refraction occurs when light travels from one medium to another.

The ray model can help explain observations of light. If a fish seems closer to the surface of the water, the ray of light from the fish must have bent. To your eye, the ray seems to be coming from another direction. Given that light can travel both ways along a light path, the fish will see the spear thrower further towards the vertical.

FIGURE 10.13 An example of refraction

FIGURE 10.14 The rays from the fish bend when they enter the air. To the eye, the rays appear to come from a point closer to the surface.



The ray model not only provides a way of describing your observations of the bending of light, but also of taking measurements. The angle that a ray of light makes with the normal — the angle of incidence and **angle of refraction** — can be measured and investigated.

on Resources

Digital document Investigation 10.3 Seeing is believing (doc-xxxxx)

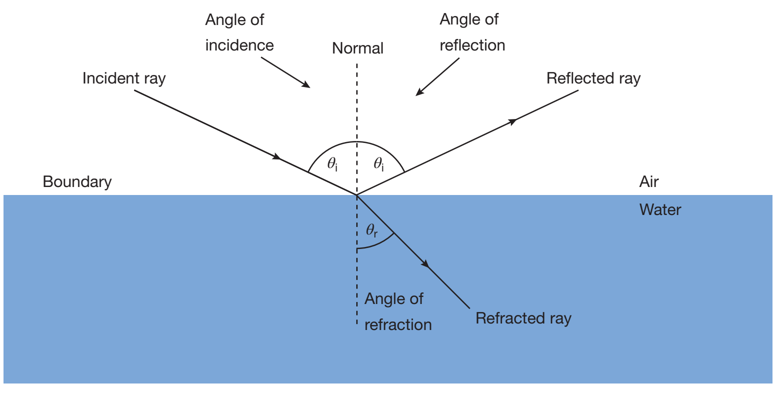
Teacher-led video Investigation 10.3 Seeing is believing (tlvd-xxxxx)

10.3.1 Snell's Law

In 1621, the Dutch physicist Willebrord Snellius (1580–1626), known in the English-speaking world as Willebrand Snell, investigated the refraction of light and found that the ratio of the sines of the angles of incidence and refraction was constant for all angles of incidence.

Figure 10.15 shows how an incident ray is affected when it meets the boundary between air and water. The normal is a line at right angles to the boundary, and all angles are measured from the normal. Some of the light from the incident ray is reflected back into air while the rest is transmitted into the water. The following ratio is a constant for all angles for light travelling from air to water:

FIGURE 10.15 The ratio $\dfrac{\sin\theta_i}{\sin\theta_r}$ is constant for all angles for light travelling from air to water.



$$\frac{\sin\ \theta_i}{\sin\ \theta_r} = \text{constant}$$

Where θ_i is the angle of incidence
θ_r is the angle of refraction.

AS A MATTER OF FACT

Snell's Law was first discovered by Abu Sa'd Ibn Sahl (*c*. 940 – *c*. 1000), a Muslim physicist in the court in Baghdad, in 984. He reported his findings in his book On burning mirrors and lenses. Ibn Sahl used the relationship to design a shape for lenses that overcame the problem of spherical aberration. Ptolemy (*c*. 100 – *c*. 170), a Greco-Egyptian mathematician, had investigated refraction much earlier, compiling a table of angles for light travelling from air into water.

Snell repeated his experiments with different substances and found that the ratio was still constant but that each substance had a different value. This suggested that different substances bend light by different amounts. (Remember that some light is always reflected.)

In fact, there is a different ratio for each pair of substances (for example: air and glass, air and water). A different ratio is obtained for light travelling from water into glass. The value of the ratio is called the **relative refractive index** because it depends on the properties of two different substances.

TABLE 10.1 Values for absolute refractive index

Material	Value
Vacuum	1.000 0
Air at 20 °C and normal atmospheric pressure	1.000 28
Water	1.33
Perspex	1.49
Quartz	1.46
Crown glass	1.52
Flint glass	1.65
Carbon disulfide	1.63
Diamond	2.42

The bending of light always involves light travelling from one substance to another. It is not possible to find the effect of a particular substance on the deflection of light without adopting one substance as a reference standard. Once you have a standard, every substance can be compared with it. A natural standard is a vacuum — the absence of any substance. The **absolute refractive index** of a vacuum is given the value of one. From this, the absolute refractive index of all other substances can be determined. Some examples are given in table 10.1. (The word 'absolute' is commonly omitted and the term 'refractive index' usually refers to the absolute refractive index.)

The refractive index is given the symbol n because it is a pure number without any units. This enables a more useful restatement of Snell's Law, for example:

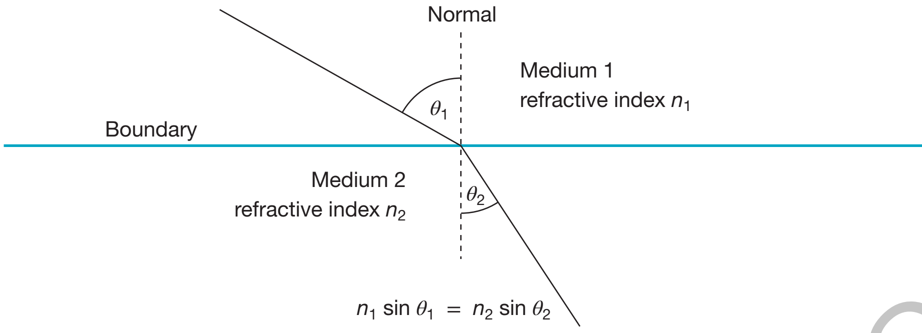
$$n_{\text{air}}\ \sin\ \theta_{\text{air}} = n_{\text{water}}\ \sin\ \theta_{\text{water}}$$

More generally this would be expressed as follows:

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

Where n_1 is the refractive index of the first medium
n_2 is the refractive index of the second medium
θ_1 is the angle of incidence
θ_2 is the angle of refraction.

FIGURE 10.16 A graphical depiction of Snell's Law for any two substances. Note that the light ray has no arrow, because the relationship is true for the ray travelling in either direction.



SAMPLE PROBLEM 3

A ray of light strikes a glass block of refractive index 1.45 at an angle of incidence of 30°. What is the angle of refraction?

Teacher-led video: SP3 (tlvd-XXXX)

THINK	WRITE
1. List the known information.	$n_{air} = 1.0; \theta_{air} = 30°; n_{glass} = 1.45; \theta_{glass} = ?$
2. Use Snell's Law, $n_1 \sin \theta_1 = n_2 \sin \theta_2$, to determine the angle of refraction.	$1.0 \times \sin 30° = 1.45 \times \sin \theta_{glass}$ $\sin \theta_{glass} = \dfrac{\sin 30°}{1.45}$ $= 0.3448$ $\Rightarrow \theta_{glass} = \sin^{-1}(0.3448)$ $\Rightarrow \theta_{glass} = 20.17°$ $\Rightarrow \theta_{glass} = 20°$

PRACTICE PROBLEM 3

A ray of light enters a plastic block at an angle of incidence of 40°. The angle of refraction is 30°. What is the refractive index of the plastic?

AS A MATTER OF FACT

Light can be bent by a strong gravitational field, such as that near the Sun. The gravitational field can act like a convex lens. Light from a distant star that is behind and blocked by the Sun bends around the Sun so that astronomers on Earth see an image of the star to the side of the Sun.

on Resources

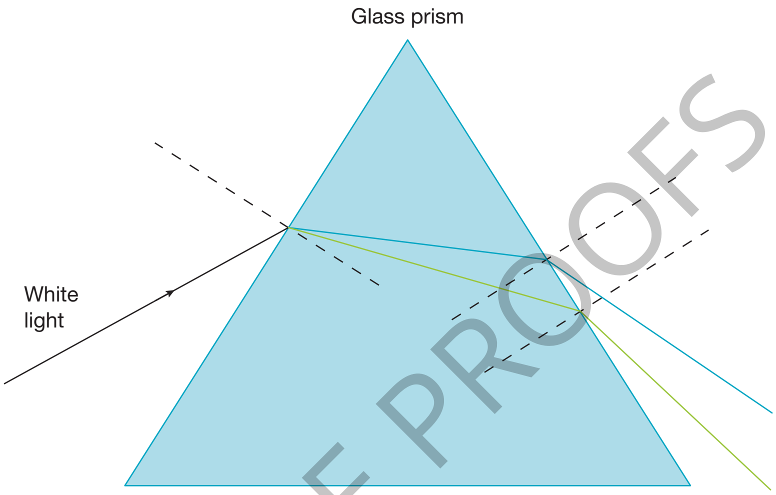
eLesson Refraction of light and Snell's Law (eles-0037)

Interactivity Refraction of light and Snell's Law (int-0056)

10.3.2 Dispersion: producing colour from white light

White light can be separated into colours using a narrow beam of light and a glass triangular prism. This phenomenon is called **dispersion**. It was first analysed in this way by Isaac Newton in 1666, although René Descartes had sought an explanation for rainbows in 1637 by working with a spherical glass flask filled with water.

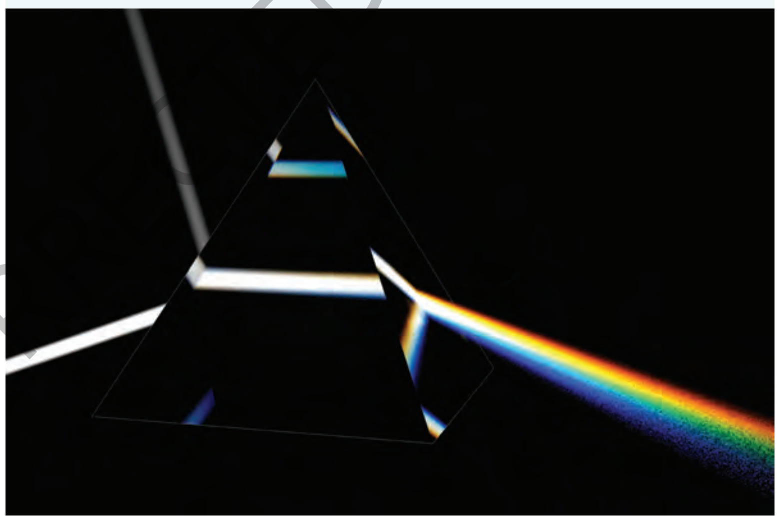
FIGURE 10.17 The colours in white light separate as they enter the glass and separate even more when they leave. At each edge, the violet is deflected more than the red.



As light enters a triangular glass prism, it is refracted towards the normal. It then travels through the prism to the other side where it is refracted away from the normal, because the light is re-emerging into the air.

The colours spread as they enter the glass and travel on different paths through the triangular prism. They are spread even more as they leave the glass. Violet is bent the most and red the least. The order of the colours, from the colour that bends least to the colour that bends most, is red, orange, yellow, green, blue, indigo, and violet.

FIGURE 10.18 A spectrum of colours is produced when white light is passed through a prism. The red light is deflected the least and each colour in the spectrum is deflected progressively more.



Each colour has a different angle of refraction. This means that the glass has a different refractive index for each colour. This can be expressed as a statement of Snell's Law, as follows:

$$n_{\text{air}} \sin \theta_{\text{i}} = n_{\text{gl (red)}} \sin \theta_{\text{red}} = n_{\text{gl (violet)}} \sin \theta_{\text{violet}}$$

For example, as shown in figure 10.19, violet light is bent more than red, so θ_{violet} is smaller than θ_{red}. This means that the refractive index of glass for violet light is greater than that for red light. This is also true for other materials (see table 10.2).

FIGURE 10.19 The angle of refraction for violet light is smaller than that for red light. This means that the refractive index of the glass is different for different colours. For violet it must be greater than that for red.

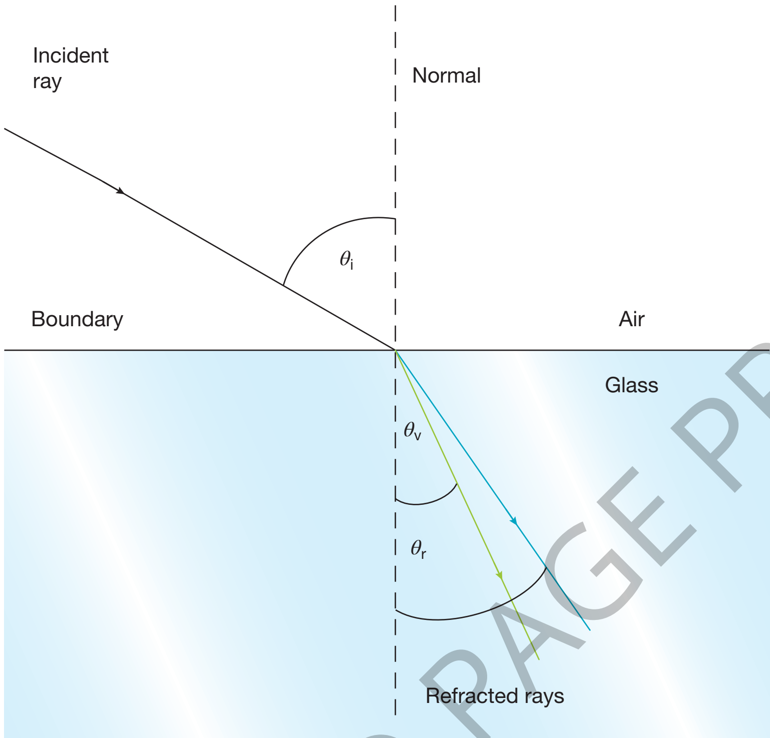


TABLE 10.2 Refractive index values vary for different coloured light.

	Index of refraction			
Colour	**Crown glass**	**Flint glass**	**Diamond**	**Water**
Red	1.514	1.571	2.410	1.331
Yellow	1.517	1.575	2.418	1.333
Deep blue	1.528	1.594	2.450	1.340

PHYSICS IN FOCUS

Sparkling physics

Diamonds are cut by a gem-maker so that, when light enters the diamond, it strikes a few faces at angles greater than the critical angle. This maximises the light path and increases the separation of the colours that occurred when the light first entered the diamond.

The appearance of white paint as white is actually due to the large amount of refraction and dispersion created by the titanium dioxide particles it contains. A large percentage of the light that hits a white surface is reflected back — the colours go in all directions and hence the surface appears white.

on Resources

- **Digital document** eModelling Using a spreadsheet to explore refraction through a prism (doc-0058)
  Investigation 10.4 Separating colours (doc-xxxxx)
- **Teacher-led video** Investigation 10.4 Separating colours (tlvd-xxxxx)
- **Interactivity** Spreading the spectrum (int-6609)

10.3.3 Limitations of the ray model

So far in this topic, the ray model has been used to describe how light is refracted. Ray diagrams illustrate Snell's Law and have allowed the visualisation of a range of optical phenomena such as mirages, and the development of technologies such as optical fibres. However, the ray model, which views light as a pencil-thin beam, does not offer an explanation of *why* light refracts. More sophisticated models are needed to provide an explanation for refraction and, in doing so, they suggest further experiments to investigate the properties of light more deeply, and to develop new technologies.

Two very different models of light were developed in the seventeenth century — one by Sir Isaac Newton (1642–1727) in England and the other by Christiaan Huygens (1627–1695) in Holland.

FIGURE 10.20 Huygens proposed that light travelled outwards from a source like circular ripples on a pond.

Newton's model was described as a 'particle model'. In his model, light consists of a stream of tiny, mass-less particles that he called corpuscles. The particles stream from a light source, like water from a sprinkler.

Huygens proposed a wave model of light, where light travels in a similar way to sound and water waves. Light leaves a source in the same way that water ripples move out from a dropped stone. The disturbance of the water surface travels outwards from the source.

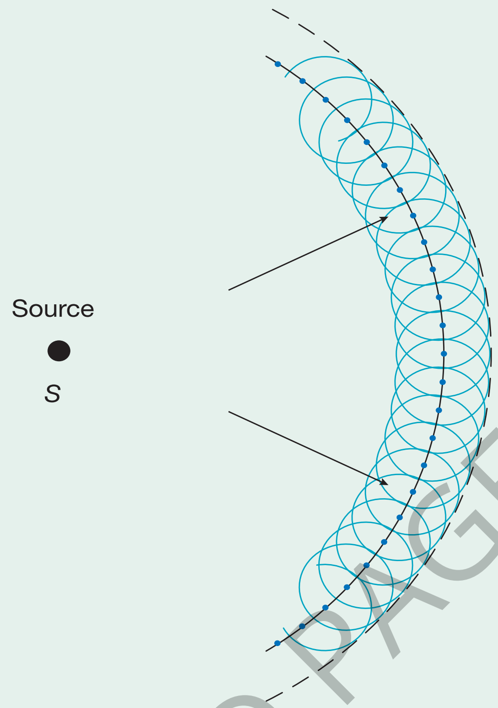
HOW DO THE TWO MODELS EXPLAIN THE PROPERTIES OF LIGHT?

How light travels

Newton's particle model: Once ejected from a light source, the particles continue in a straight line until they hit a surface.

Huygens's wave model: Huygens proposed the basic principle that 'Every point in the wavefront is a source of a small wavelet. The new wavefront is the envelope of all the wavelets.'

FIGURE 10.21 Every point in the wavefront is a source of a small wavelet. The new wavefront is the envelope of all the wavelets.



Reflection of light

Newton's particle model: As particles approach a surface, they are repelled by a force at the surface that slows down and reverses the normal component of the particle's velocity but does not change its tangential component. The particle is then reflected from the surface at an angle equal to its angle of approach. The same process happens when a billiard ball hits a cushion.

Huygens's wave model: As each part of the wavefront arrives at the surface, it produces a reflected wavelet. The new wavelets overlap to produce the next wavefront, which is travelling away from the surface at an angle equal to its angle of approach.

FIGURE 10.22 Newton's particle model of reflection

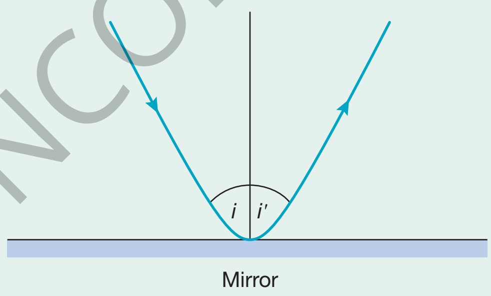
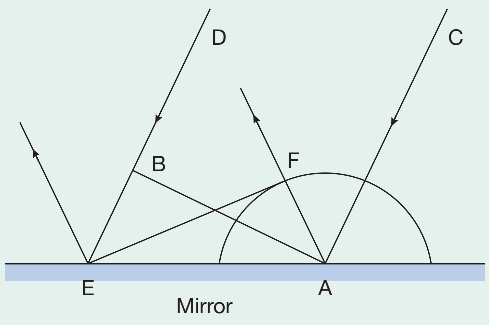


FIGURE 10.23 The wave model of reflection. Rays C and D are parallel, incoming rays, and AB is the wavefront. When ray C hits the mirror at A, a circular wavelet is produced. By the time B has reached the mirror at E, the reflected wavelet has travelled out to F. The line EF is the reflected wavefront.



Refraction of light

Newton's particle model: In approaching a denser medium, the particles experience an attractive force that increases the normal component of the particle's velocity but does not affect the tangential component. This has the effect of changing the direction of the particles, bending them towards the normal where they are now travelling faster in the denser medium. Snell's Law can be explained by this model.

Huygens's wave model: When the wavefront meets a heavier medium, the wavelets do not travel as fast as before. This causes the wavefront to change direction. In this case, the wavefront bends towards the normal when it enters a medium where the wave is slowed down. Snell's Law can be explained by this model.

FIGURE 10.24 The particle model of refraction. The particles are pulled towards the denser medium, resulting in a change in direction.

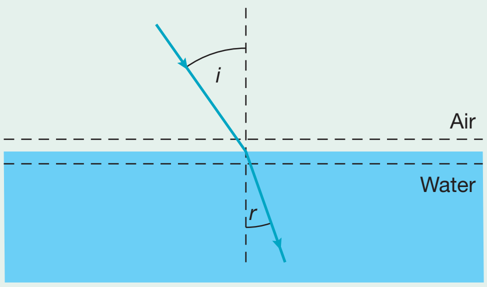
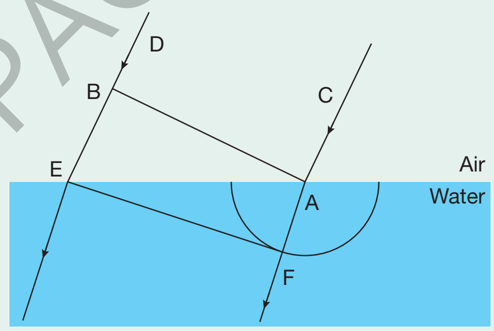


FIGURE 10.25 The wave model of refraction. The rays C and D are parallel, incoming rays. AB is the wavefront. When ray C hits the surface at A, a circular wavelet of slower speed and so smaller radius is produced. By the time B has reached the surface at E, the refracted wavelet has only gone as far as F. The line EF is the refracted wavefront, heading in a direction bent towards the normal compared to the incoming wavefront, AB.



A point of difference

Now, with these two explanations of refraction, there is a clear distinction between the two models. When light bends towards the normal as it enters water (a denser medium), the particle model says it is because light travels faster in water (the denser medium), whereas the wave model says it is because the light is travelling slower.

In the seventeenth century, scientists did not have the technology to measure the speed of light in water. However, the particle model became the accepted explanation, partly because of Newton's status and partly because Huygens's principle suggested that light should bend around corners like sound, and there was no evidence of this at the time. (Newton himself actually thought that the particles in his model needed to have some wavelike characteristics to explain some of his other observations of light and colour.)

New evidence emerges

In 1802, Thomas Young (1773–1829) showed that, in fact, light could bend around an edge. This is covered in some detail in subtopic 10.6. This was convincing evidence for the wave model, as the particle model had no mechanism to explain how particles could bend around a corner. However, the status of Newton was such that not all were convinced by Young's results. It was suggested that conclusive evidence would be to measure the speed of light in water and see if it was faster or slower than that in air. Jean Bernard Leon Foucault (1819–1868) and Hippolyte Fizeau (1819–1896) competed to measure the speed of light in water; in 1850, both showed that light was slower in water, though Foucault won by seven weeks.

on Resources

Digital documents	Investigation 10.5 Refraction of particles (doc-xxxxx)
	Investigation 10.6 Refraction of waves (doc-xxxxx)
Teacher-led videos	Investigation 10.6 Refraction of waves (tlvd-xxxxx)
	Investigation 10.5 Refraction of particles (tlvd-xxxxx)
Weblink	Huygens's principle applet

10.3.4 Speed of light in glass

Foucault and Fizeau's results, along with the work of Augustin-Jean Fresnel (1788–1827) (pronounced 'fray-NEL'), showed that the speed of light in water was less than the speed of light in air. This allowed scientists to determine the physical meaning of the refractive index:

$$\text{absolute refractive index of water} = \frac{\text{speed of light in a vacuum}}{\text{speed of light in water}}$$

In general,

The refractive index of a material is the ratio of the speed of light in a vacuum to the speed of light in the medium:

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

Where n is the refractive index of the medium
c is the speed of light in a vacuum $\left(3.0\times10^8\ \text{m s}^{-1}\right)$
v is the speed of light in the medium

The formula can be rearranged to give

$$n_{\text{water}} \times v_{\text{water}} = c$$

where c = the speed of light in a vacuum
v_{water} = the speed of light in water.

Similarly, for glass, $n_{\text{glass}} \times v_{\text{glass}} = c$, which means $n_{\text{glass}} \times v_{\text{glass}} = n_{\text{water}} \times v_{\text{water}}$, or, as a general relationship for any two materials:

$$\boldsymbol{n_1 v_1 = n_2 v_2}$$

SAMPLE PROBLEM 4

a. **The refractive index of glass is 1.5. How fast does light travel in glass?**
b. **Use the answer to (a) to determine the speed of light in water (n_{water} = 1.33).**

Teacher-led video: SP4 (tlvd-XXXX)

THINK	WRITE
a. Use the relationship $n_{\text{glass}} = \dfrac{c}{v_{\text{glass}}}$ to calculate the speed of light in glass.	**a.** $1.5 = \dfrac{3.0\times10^8}{(\text{speed of light in glass})}$ $\Rightarrow$ speed of light in glass $= \dfrac{3.0\times10^8}{1.5}$ $= 2.0\times10^8\ \text{m s}^{-1}$

b. Use the relationship $n_{glass} \times v_{glass} = n_{water} \times v_{water}$ to determine the speed of light in water.

b. $n_{glass} \times v_{glass} = n_{water} \times v_{water}$

$$1.5 \times 2.0 \times 10^8 \text{ m s}^{-1} = 1.33 \times v_{water}$$

$$\Rightarrow v_{water} = \frac{1.5 \times 2.0 \times 10^8 \text{ m s}^{-1}}{1.33}$$

$$= 2.3 \times 10^8 \text{ m s}^{-1}$$

PRACTICE PROBLEM 4

a. How fast does light travel in diamond?

b. Use the answer to (a) to determine the speed of light in carbon disulfide.

on Resources

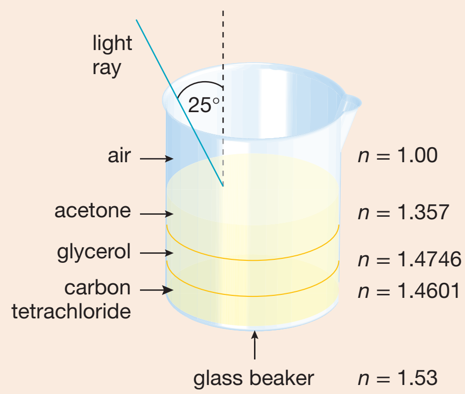
Digital document Investigation 10.7 Using apparent depth to determine the refractive index (doc-xxxxx)

Teacher-led video Investigation 10.7 Using apparent depth to determine the refractive index (tlvd-xxxxx)

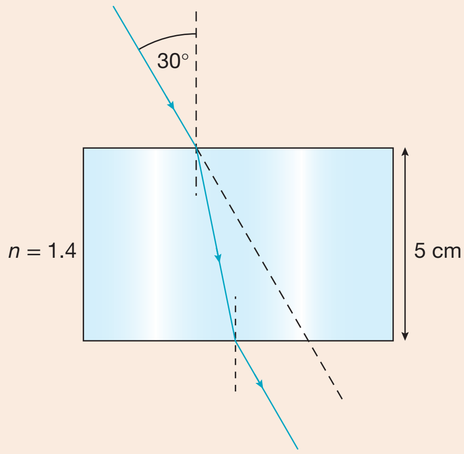
10.3 EXERCISE

To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

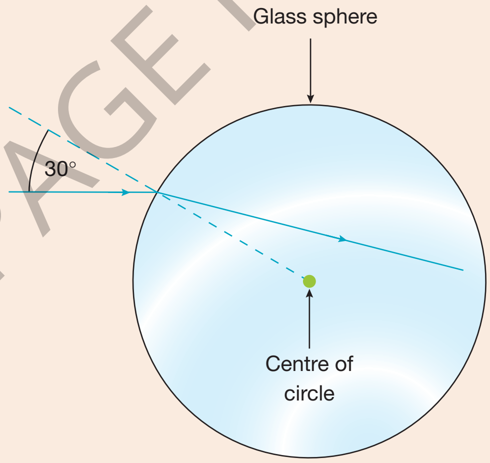
1. A ray of light in air (n_{air} = 1.00) strikes water in a pond. What is the angle of refraction in water (n_{water} = 1.33) for an angle of incidence of 40°? If the angle of incidence is increased by 10°, by how much does the angle of refraction increase?
2. A ray of light enters a plastic block at an angle of incidence of 55° with an angle of refraction of 33°. What is the refractive index of the plastic?
3. A ray of light passes from air through a rectangular glass block (n_{glass} = 1.55). The angle of incidence as the ray enters the block is 65°.
   (a) Calculate the angle of refraction at the first face of the block.
   (b) Calculate the angle of refraction as the ray emerges on the other side of the rectangular block. Comment on your answers.
4. A glass block (n_{glass} = 1.55) is immersed in a container of water (n_{water} = 1.33). A light ray passes from the water into the glass block at an angle of incidence of 28°. Determine the angle of refraction in the glass block.
5. Determine the speed of light in the following materials:
   (a) water (n_{water} = 1.33) (b) glass (n_{glass} = 1.50) (c) diamond ($n_{diamond}$ = 2.42).
6. Immiscible liquids are liquids that do not mix. Immiscible liquids will settle on top of one another, in the order of their density, with the densest liquid at the bottom. Some immiscible liquids are also transparent.
   (a) Calculate the angles of refraction as a ray passes down through immiscible layers as shown in the following diagram.
   (b) If a plane mirror was placed at the bottom of the beaker, calculate the angles of refraction as the ray reflects back to the surface. Comment on your answers.



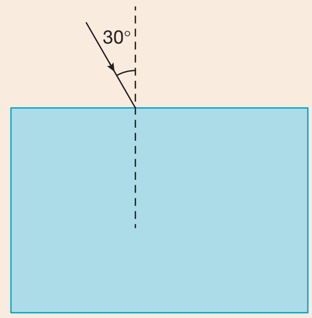
7. Calculate the sideways deflection as a ray of light goes through a parallel-sided plastic block ($n_{plastic} = 1.4$) with sides 5.0 cm apart, as in the following figure.



8. A ray of light enters a glass sphere ($n = 1.5$), as in the following figure. What happens to the ray?



9. Give the meaning of the following terms: refraction, reflection, dispersion, spectrum, refractive index, chromatic aberration.
10. (a) White light enters a crown glass rectangular prism. Sketch the path of red and deep blue light through the glass and back into air. How does the direction of the emerging coloured rays compare with that of the incoming white ray?
    (b) Suggest why a glass triangle is used to observe the visible spectrum, rather than a glass rectangle.
11. Which travels faster through crown glass — red light or violet light? What is the speed difference?
12. Green and violet light enter a triangular prism. Which is bent more?
13. A ray of white light in air strikes a rectangular glass block with an angle of incidence of 30°, as shown in the following diagram. For the glass block, the refractive index of red light is 1.514 and, for purple light, it is 1.530.
    (a) On a copy of the diagram, carefully show the path taken by red light and by purple light.
    (b) Use Snell's Law to find the angle of refraction for both the red light and the purple light.
    (c) Determine the angle between the red light ray and the purple light ray in the rectangular glass block.



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10.4 Total internal reflection

KEY CONCEPTS
- investigate and analyse theoretically and practically the behaviour of waves including:
  - total internal reflection and critical angle including applications: $n_1 \sin(\theta_c) = n_2 \sin(90°)$.

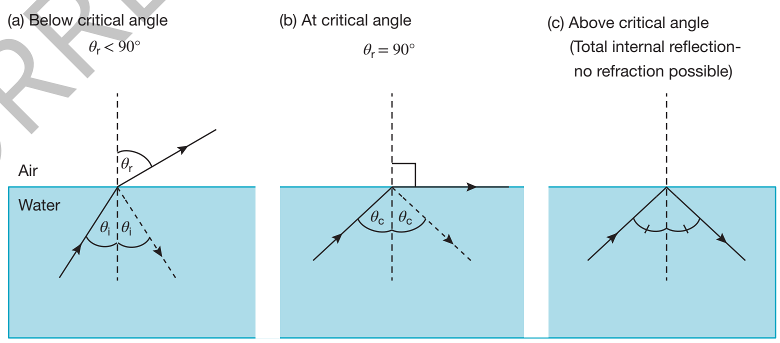
10.4.1 The critical angle

Light can play some strange tricks. Many of these involve refraction away from the normal and the effect on light of a large increase in the angle of incidence.

It has already been mentioned that some light is reflected off a transparent surface while the rest is transmitted into the next medium. This applies whether the refracted ray is bent towards or away from the normal. However, a special situation applies when the refracted ray is bent away from the normal. This is illustrated in figure 10.27. As the angle of incidence increases, the angle of refraction also increases. Eventually the refracted ray becomes parallel to the surface and the angle of refraction reaches a maximum value of 90° (see figure 10.27b). The corresponding angle of incidence is called the **critical angle**. If the angle of incidence is increased beyond the critical angle, all the light is reflected back into the water, with the angles being the same. This phenomenon is called **total internal reflection** (see figure 10.27c).

FIGURE 10.26 There are no mirrors in a fish tank but strange reflections can be seen. It appears that light is being reflected off the side of the fish tank and the water surface.

FIGURE 10.27 Three stages of refraction leading to total internal reflection



The critical angle can be calculated using Snell's Law,

$$n_1 \times \sin\theta_c = n_2 \times \sin 90°$$

Where n_1 is the refractive index of medium 1
n_2 is the refractive index of medium 2
θ_c is the critical angle for medium 1.

SAMPLE PROBLEM 5

What is the critical angle for water given that the refractive index of water is 1.3?

Teacher-led video: SP5 (tlvd-XXXX)

THINK

1. List the known information.
2. Use the relationship $n_{water} \times \sin\theta_c = n_{air} \times \sin 90°$ to determine the critical angle for water.

WRITE

$n_{\text{air}} = 1.0;\ \theta_{\text{air}} = 90°;\ n_{\text{water}} = 1.3;\ \theta_{\text{water}} = ?$

$$n_{\text{water}} \times \sin\theta_c = n_{\text{air}} \times \sin 90°$$

$$1.3 \times \sin\theta_c = 1.0 \times \sin 90°$$

$$\Rightarrow \sin\theta_c = \frac{\sin 90°}{1.3} = 0.7692$$

$$\Rightarrow \theta_c = \sin^{-1}(0.7692) = 50.28°$$

$$\theta_c = 50°$$

The critical angle is 50°.

PRACTICE PROBLEM 5

A glass fibre has a refractive index of *x* and its cladding has a refractive index of *y*. What is the critical angle in the fibre?

Total internal reflection is a relatively common atmospheric phenomenon (as in mirages) and it has technological uses (for example, in optical fibres).

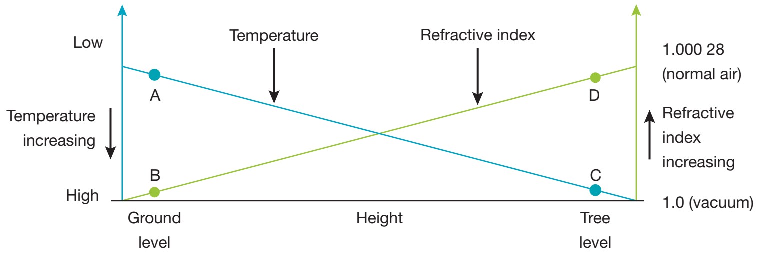
10.4.2 Mirages

There are several types of mirages that can be seen when certain atmospheric conditions enable total internal reflection to occur. These mirages appear because the refractive index of air decreases with temperature.

A common type of mirage occurs in the desert or above a road on a sunny day. As displayed in figure 10.29, at ground level the air is hot (A) with a refractive index close to 1 (B). As height increases, the temperature of the air decreases (C) and its refractive index increases (D).

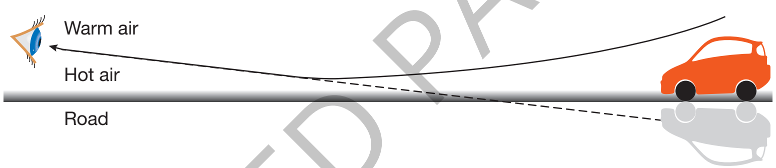
FIGURE 10.28 Mirages such as this are common on hot, sunny days.

FIGURE 10.29 Temperature and refractive index profiles for the mirage phenomenon



Rays of light from a car, for example, go in all directions. The air above the ground can be considered as layers of air. The closer to the ground, the higher the temperature and the lower the refractive index. As a ray moves into hotter air, it bends away from the normal. After successive deflections, the angle of incidence exceeds the critical angle for air at that temperature and the ray is totally internally reflected. As the ray emerges, it follows a similar path, refracting towards the normal as it enters cooler air. An image of the car can be seen below street level, as shown in figure 10.30. The mirage is upside down because light from the car has been totally internally reflected by the hot air close to the road surface.

FIGURE 10.30 The mirage of the car appears upside down due to total internal reflection in the hot air close to the ground.



Another mirage that depends on layers of air at different temperatures is known as the ‘Fata Morgana’, in which vertical streaks, like towers or walls, appear. This occurs where there is a temperature inversion — very cold at ground level and warmer above — and very stable weather conditions.

The phenomenon is named after Morgan le Fay (Fata Morgana in Italian), who was a fairy and half-sister to King Arthur of the Celtic legend. She used mirages to show her powers and, in the Italian version of the legend, lived in a crystal palace under the sea. The mirage is often seen in the Strait of Messina and over arctic ice. As shown in figure 10.31, the light rays from a distant point are each refracted by the different layers of air, arriving at different angles to the eye. The effect is that the point source (P) becomes a vertically extended source, like a tower or wall.

FIGURE 10.31 Ray paths for the Fata Morgana

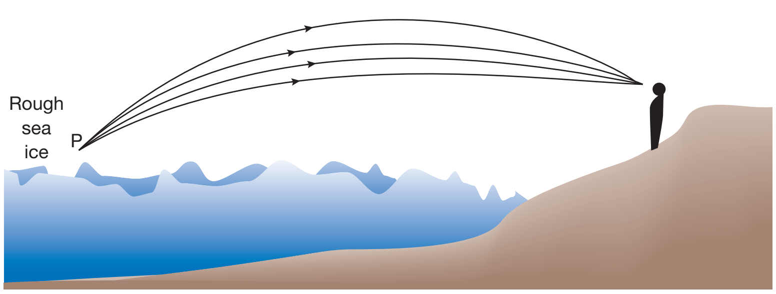


FIGURE 10.32 An example of the Fata Morgana over an ice field in the Arctic Ocean off the coast of Svalbard. The conditions that encourage the Fata Morgana are particularly common in the polar regions over ice.

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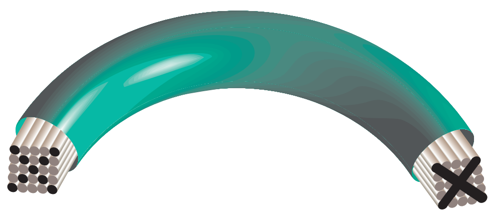
Weblink Mirages and more

10.4.3 Optical fibres

Another example of total internal reflection is in the important technological application of **optical fibres**. Optical fibres have become a feature of modern life. A thin, flexible cable containing an optical fibre can be placed inside a person's body to transmit pictures of the condition of organs and arteries, without the need for invasive surgery. The same can be done in industry when there is a problem with complex machinery.

Optical fibres are also the basis of the important telecommunications industry. They allow high-quality transmission of many channels of information in a small cable over very long distances and with negligible signal loss.

FIGURE 10.33 A bundle of optical fibres. Each fibre in the bundle carries its signal along its length. If the individual fibres remain in the same arrangement, the bundle will emit an image of the original object.



An optical fibre is like a pipe with a light shone in one end that comes out the other end. An optical fibre is made of glass that is approximately 10 micrometres (10×10^{-6} m) thick. Light travels along it, as glass is transparent, but the fibre needs to be able to turn and bend around corners. The optical fibre is designed so that any ray meeting the outer surface of the glass fibre is totally internally reflected back into the glass. As shown in

FIGURE 10.34 A light ray travels along an optical fibre through total internal reflection.

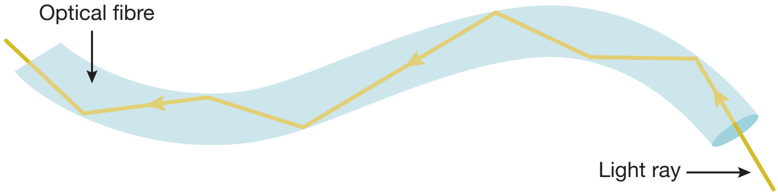


FIGURE 10.35 Light rays entering the fibre at too sharp of an angle are refracted out of the fibre.

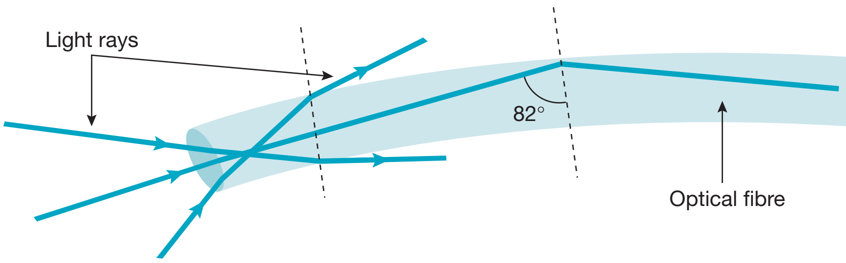


figure 10.34, the light ray meets the edge of the fibre at an angle of incidence greater than the critical angle and is reflected back into the fibre. In this way, nearly all the light that enters the fibre emerges at the other end.

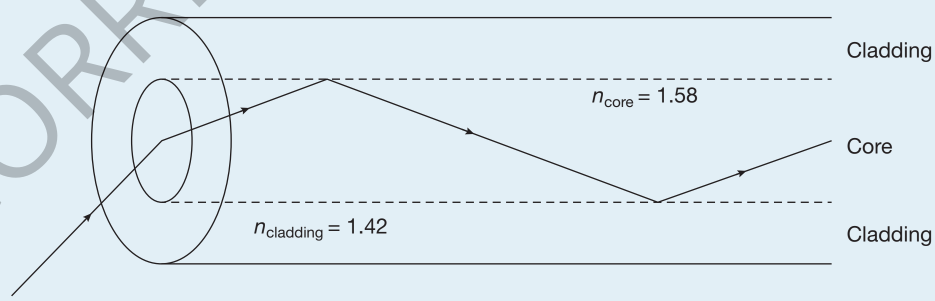
If the glass fibre is exposed to the air, the critical angle for light travelling from glass to air is 42°, which is quite small. Any angle of incidence greater than this angle will produce total internal reflection. If the fibre is very narrow, this angle is easily achieved.

However, in both medical and telecommunications uses, fibres are joined in bundles with edges touching. The touching would enable light rays to pass from fibre to fibre, confusing the signal. To overcome this, a plastic coating is put around the glass to separate the glass fibres. The total internal reflection occurs between the glass and the plastic. The critical angle for light travelling from glass to plastic is 82°. This value presents a problem because light meeting the edge of the glass at any angle less than 82° will pass out of the fibre.

This has implications for the design of the optical fibre and the beam of light that enters the fibre. The fibre needs to be very narrow and the light entering the fibre has to be a thin beam with all the rays parallel.

SAMPLE PROBLEM 6

Optical fibres transport data using light. They are constructed using transparent materials with different refractive indices. The following diagram shows a typical fibre with a cylindrical core and surrounding cladding. Laser light is shone from air in the optical fibre.



a. **Explain why it is necessary for the refractive index of the cladding to be smaller than the refractive index of the core.**
b. **Calculate the critical angle for the laser light at the core–cladding boundary.**
c. **Determine the speed of the laser light in the core of the optical fibre.**

Teacher-led video: SP6 (tlvd-XXXX)

THINK

a. Explain why it is necessary for the refractive index of the cladding to be smaller than the refractive index of the core.

WRITE

a. If the refractive index of the cladding was larger than the refractive index of the core, the light would be refracted *towards the normal* and internal reflection would not be possible. When the refractive index of the cladding is less than that of the core, the light is refracted *away from the normal* so that total internal reflection is possible if the angle of incidence is larger than the critical angle.

THINK

b. Use the relationship $n_{core} \times \sin\theta_c = n_{cladding} \times \sin 90°$ to determine the critical angle.

WRITE

b.
$$n_{core} \times \sin\theta_c = n_{cladding} \times \sin 90°$$
$$1.58 \times \sin\theta_c = 1.42 \times \sin 90°$$
$$\Rightarrow \sin\theta_c = \frac{1.42 \sin 90°}{1.58} = \frac{1.42}{1.58}$$
$$\Rightarrow \theta_c = \sin^{-1}\left(\frac{1.42}{1.58}\right)$$
$$\theta_c = 64.0°$$

The critical angle is 64.0°.

THINK

c. Analyse the refraction of the light at the entrance of the optical fibre, the air-core boundary. Use the relationship $n_{air}v_{air} = n_{core}v_{core}$.

WRITE

c.
$$n_{air}v_{air} = n_{core}v_{core}$$
$$1.00 \times \left(3.00 \times 10^8\right) = 1.58 \times v_{core}$$
$$v_{core} = \frac{3.00 \times 10^8}{1.58} = 1.90 \times 10^8 \text{ m s}^{-1}$$

The speed of the laser light in the core is 1.90×10^8 m s^{-1}.

PRACTICE PROBLEM 6

A different optical fibre is used with the same cladding ($n_{cladding} = 1.42$) as in Sample problem 6 but with a core of refractive index 1.56.

a. **Would the critical angle of this new optical fibre be larger or smaller than the previous fibre?**

b. **Calculate the critical angle for this new optical fibre.**

c. **Determine the speed of the laser light in the core of this new optical fibre. Is it larger or smaller than the speed of laser light in the previous fibre?**

on Resources

Weblink Fibre optics

10.4.4 Rainbows

Rainbows are a common example of the dispersion of light. However, they are not only seen in the sky. You can also see a rainbow when you use a garden hose. Three conditions are necessary for a rainbow to be visible:

- The Sun needs to be visible.
- Some water droplets need to be airborne.
- An observer needs to be present.

For a rainbow to be seen, the usual arrangement of these three elements is to have the Sun oriented behind the observer and the airborne water to be present in front of the observer. The water drops separate the colours in a similar way to that which occurs with the glass prism. The big difference is that, before the colours emerge from the water droplet, they are reflected from the opposite surface of the droplet.

FIGURE 10.36 Each droplet of water in the air spreads the colours. Person A sees a rainbow from raindrops in the air between droplet 2 and droplet 3. Person B sees a rainbow between droplet 1 and droplet 2.

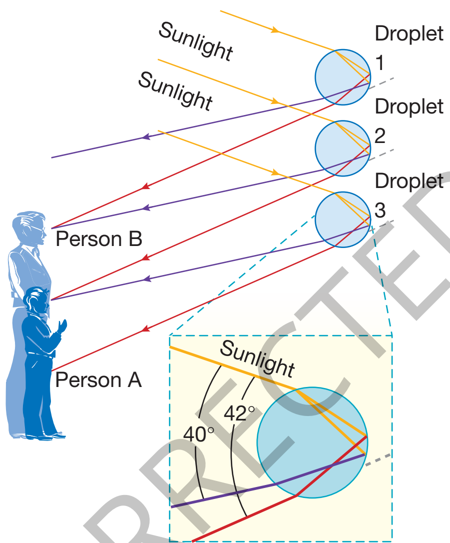
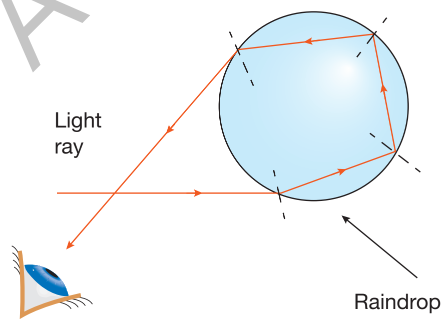


FIGURE 10.37 A light ray enters the bottom of the raindrop, is reflected twice off the wall of the raindrop, then emerges. The ray enters the eye at a higher angle than the primary rainbow. The colours are spread as they enter the raindrop and grow further apart the longer they are in the raindrop.



When you see a rainbow, each colour comes from a separate raindrop in the sky. If the red light from a raindrop enters your eye, then the violet light from that raindrop goes over your head to someone else. Each person sees his or her own personal rainbow. Your rainbow depends on raindrops in the sky being at a particular point so that the angle between you, the Sun and the raindrops is approximately 42°. The rainbow is not an image in the sky that everyone can see.

When the sky is very dark, a second, fainter rainbow may be visible on the outside of the bright one. This is due to the sunlight entering higher raindrops at the bottom and reflecting off the inside of the drop twice before emerging into the air.

10.4 EXERCISE

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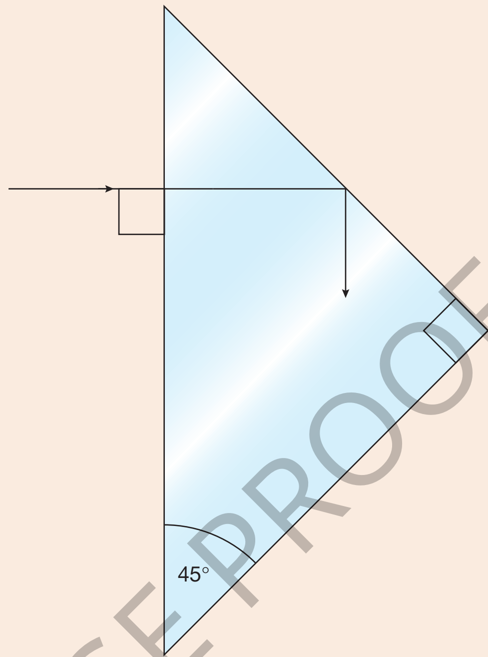
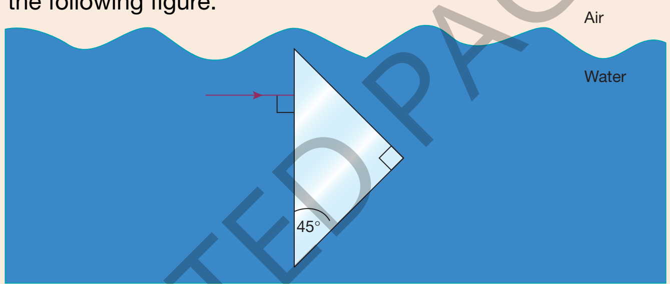
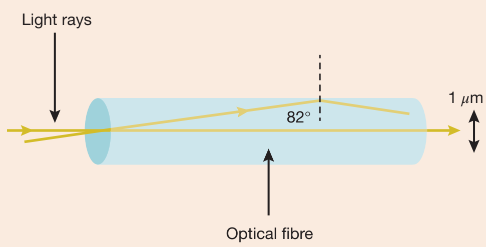
1. People enjoy the look of diamonds because they disperse white light.
   (a) Calculate the critical angle for light travelling through a diamond ($n_{diamond}$ = 2.50) towards its surface. You may assume that the diamond is in air (n_{air} = 1.00).
   (b) The diamond is now placed in water (n_{water} = 1.33). Determine the critical angle now for light at a diamond–water interface.



2. Consider the triangular prism shown in the following diagram:
   1. Calculate the refractive index of the glass triangular prism so that the light ray meets the faces at the critical angle. Is this value of the refractive index the minimum or maximum value for such a reflection?
   2. Now draw two parallel rays entering the block. Label them A and B. They emerge after propagating through the prism. Which ray of light would emerge first? Or would they emerge at the same time?
3. Calculate the refractive index of the plastic coating surrounding an optical fibre if the critical angle for glass to plastic is 82.0° and the refractive index of glass is 1.500.
4. Describe what a submerged diver would see when looking up at a still water surface.
5. A right-angled glass prism (n = 1.55) is placed under water (n = 1.33), as shown in the following figure:



   A ray of light enters the longest side along the normal. What happens to the ray of light?
6. A fish looking up at the surface of the water sees a circle, inside which it sees the 'air world'. Outside the circle it sees the reflection of the 'water world'. If the fish is 40 cm below the surface, calculate the radius of the circle (n_{water} = 1.33).
7. Light enters an optical fibre 1.0 μm in diameter, as shown in the following figure. Some light goes straight down the centre of the fibre. Another ray is angled, leaving the central line and meeting the outside edge at slightly more than the critical angle of 82°, then reflects back to the central line.



   (a) How much further did this second ray travel compared to the ray that travelled down the centre of the fibre?
   (b) Calculate the speed of light in the glass and hence determine the time delay between the two rays after one internal reflection. Do you think this could be a problem when transmitting data in an optical fibre? If so, when? How could the problem be overcome?

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Resources

Weblink Formation of a rainbow applet

10.5 Diffraction of light

KEY CONCEPTS

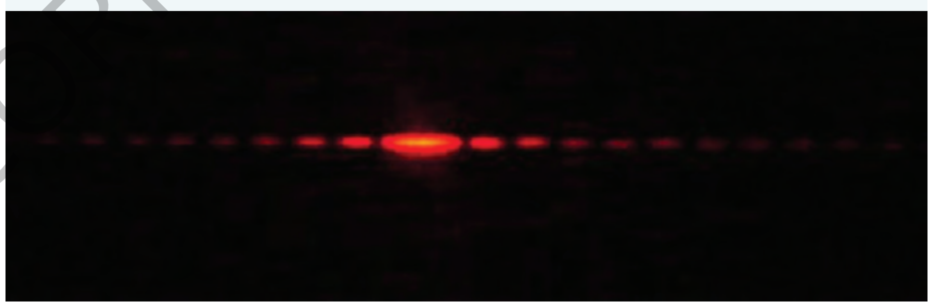
- investigate and explain theoretically and practically diffraction as the directional spread of various frequencies with reference to different gap width or obstacle size, including the qualitative effect of changing the $\frac{\lambda}{w}$ ratio
- investigate and describe theoretically and practically the effects of varying the width of a gap or diameter of an obstacle on the diffraction pattern produced by light and apply this to the limitations of imaging using light.

10.5.1 Light also diffracts

Topic 9 describes diffraction as one of the defining properties of waves. However, the word 'diffraction' was coined by Francesco Grimaldi (1618–1663) to describe a specific observation he made of light. He observed that, when sunlight entered a darkened room through a small hole, the spot was larger than would be expected from straight rays of light. He also noted that the border of the spot was fuzzy and included coloured fringes. He observed a similar effect when light passed a thin wire or a strand of hair. There is also some evidence that he repeated the experiment with two adjacent holes and observed evidence of cancellation: 'That a body actually enlightened may become obscure by adding new light to that which it has already received.' Grimaldi did not give an explanation for these observations in terms of waves or particles.

Newton was aware of Grimaldi's observation of 'diffraction'. He interpreted it using his particle model, arguing that the observed effect was due to light particles interacting with the edges of the hole as a refraction effect. He argued that if light was a wave, the bending would be much greater. Newton's conclusions on the particle model were enough for scientists even a hundred years later, in Young's time, to doubt any experimental evidence supporting the wave model.

FIGURE 10.38 Diffraction of red light



However, with improving technology, the investigation of the diffraction of light revealed more than just the observation of spreading:

- The pattern had a central bright region with narrower and less bright regions either side.
- There was a dark gap between the bright regions.
- The central region was twice as wide as the other regions, which were all about the same size.
- The pattern for red light is more spread out than that for blue light.

FIGURE 10.39 Relative intensity and diffraction patterns for (a) blue light and (b) red light

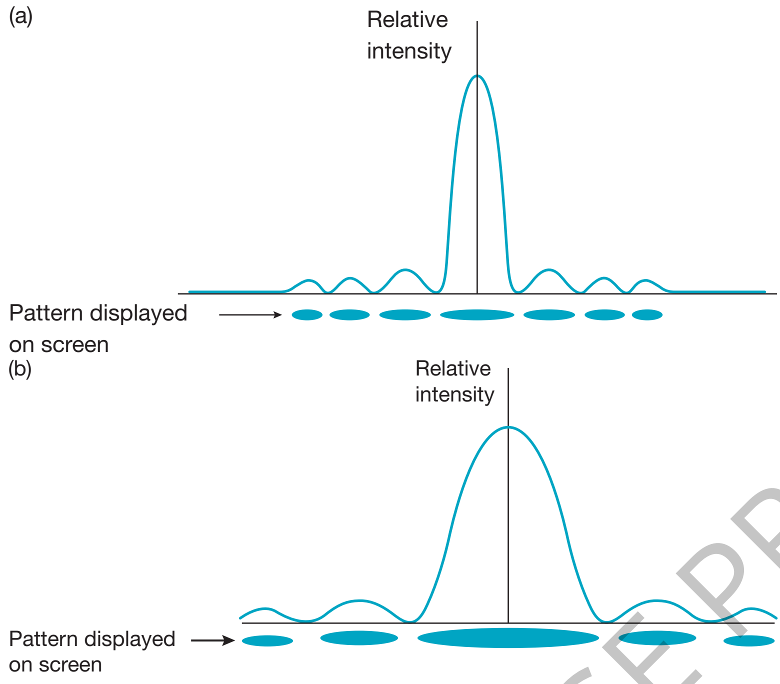


Figure 10.38 and figure 10.39 confirm that light satisfies the same relationships as other waves, that is:

- **the amount of spreading is proportional to the wavelength, λ**
- **the amount of spreading is proportional to the inverse of the gap width, $\frac{1}{w}$.**

The dark gap between the bright bands is worthy of closer examination. According to Huygens's wave model, each point on a wavefront produces circular waves that overlap to produce the next wavefront. When a straight wavefront meets a small gap, each point in the gap produces circular waves, which means the next wavefront spreads out to be wider than the gap.

Now, what happens off to the side? Consider the rays travelling at an angle θ such that:

$$\sin\theta = \frac{\lambda}{w}$$

Divide the point sources in the gap into two groups, a and b. Pairing up the top point source of group a (a_1) with the top point source of group b (b_1) shows there is a path difference of $\frac{\lambda}{2}$. Therefore, waves from a_1 and b_1 will cancel in the direction of θ. Similarly, waves from a_2 and b_2 will cancel, and so on. So for the angle θ, waves from half of the point sources in the gap will cancel with waves from the other half. This means there will be a dark band, or as it is called a first minimum, at an angle that satisfies the relationship $\sin\theta = \frac{\lambda}{w}$.

FIGURE 10.40 Diffraction patterns change with gap width. As the gap width gets smaller, coming down the figure, the pattern spreads out more.

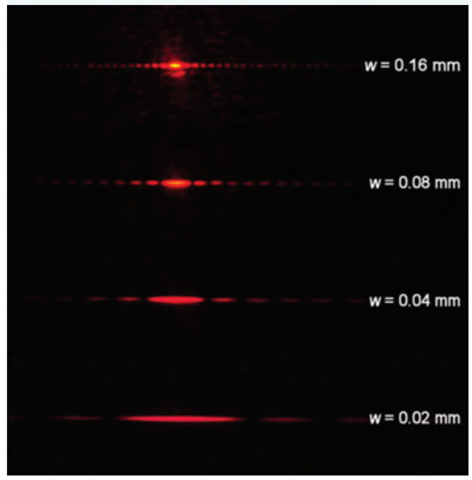
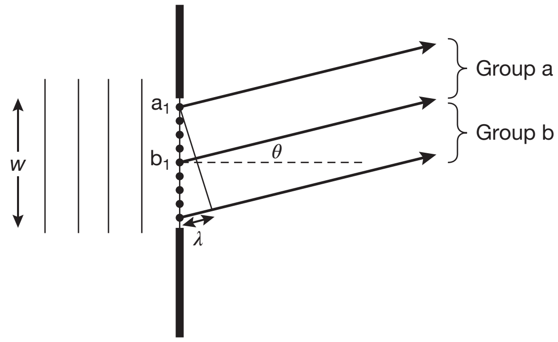


FIGURE 10.41 Point sources in a diffraction gap



This relationship provides an explanation for the observations of the diffraction of light:

- A longer wavelength ⇒ the angle of the first minimum is greater ⇒ the pattern is wider.
- A larger gap width ⇒ the angle of the first minimum is smaller ⇒ the pattern is narrower.

10.5.2 Diffraction and optical instruments

Diffraction limits the usefulness of any optical instrument, whether it be your eye, a microscope or a telescope. It even affects radio telescopes.

The pupil of your eye is the circle through which light enters the eye. The objective lens of a microscope or a telescope determines how much light the instrument captures. These all have a width, so a diffraction effect is unavoidable. Diffraction limits the instrument's capacity to distinguish two objects that are very close to each other.

In the images in figure 10.42, light from two close sources passes an optical device and produces image (a), showing two distinct spots. When the two sources are moved closer together, image (b) is produced, and the spots begin to merge. Moving the two sources even closer together produces image (c); the two spots are now one broad spot. At the separation that produces image (b), the diffraction patterns produced by the optical device begin to overlap so that the central maximum of one pattern sits on the minimum of the other. This separation is the limit of the device to resolve the detail in an image; it is called the diffraction limit or resolution of the device.

The diffraction limit of a device depends on the ratio $\frac{\lambda}{w}$. Thus, a shorter wavelength gives a better resolution, as does a larger aperture for the optical device.

FIGURE 10.42 Images produced by two point light sources as they get closer, from (a) to (c).

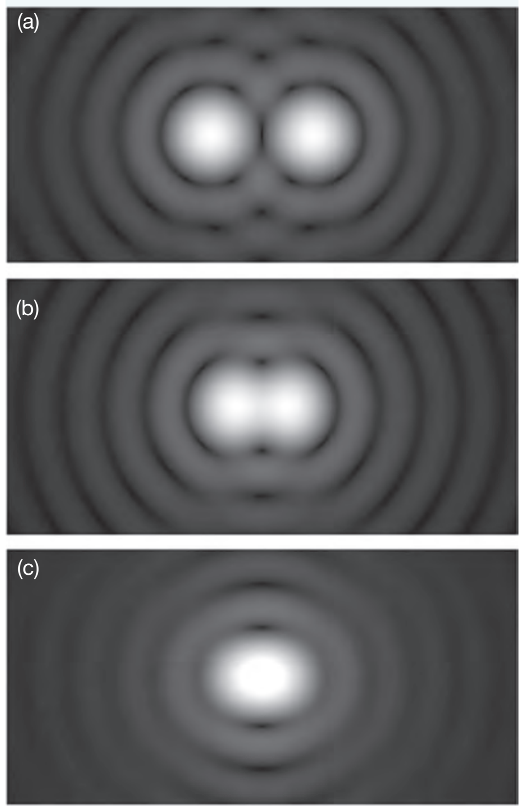
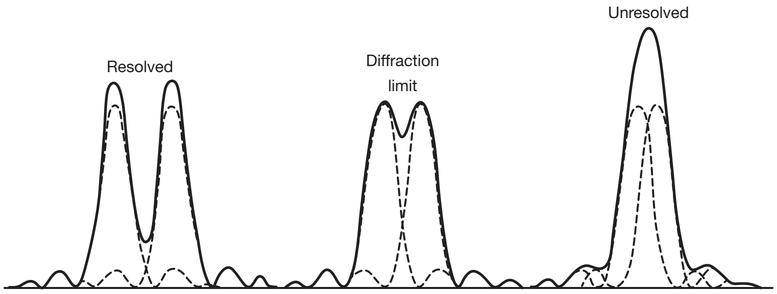


FIGURE 10.43 The diffraction patterns of two point sources overlap as the sources move closer together.

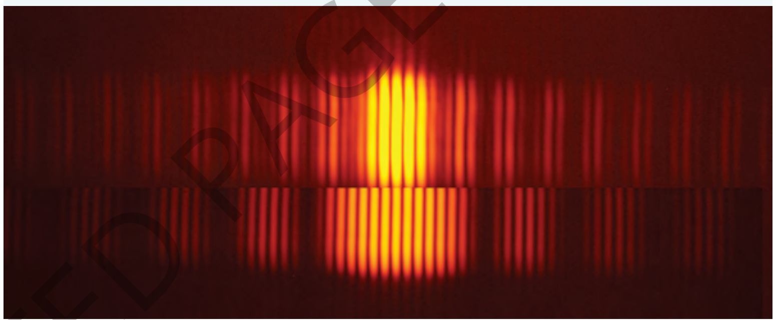


10.5.3 Linking diffraction and two-slit interference

When light from a point source illuminates a double slit, each slit produces its own diffraction pattern with a wide central maximum and smaller side maxima. If the two slits are close together, these two patterns overlap, and the light coming from each slit interferes with the light coming from the other slit. This causes light and dark bands where the two central maxima overlap and also where the side maxima overlap.

Normally, to emphasis the key features of interference, the pattern is prepared with slits that are so narrow that the central maximum fills the screen and the side maxima are not observed.

FIGURE 10.44 Interference pattern from two slits that are not extremely narrow. The slits in the bottom section of the image are narrower than those for the top section of the image because the central maximum is wider.



10.5 EXERCISE

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1. Light diffracts when it passes through a sufficiently narrow opening. Is this evidence for light being a type of wave or a stream of particles?
2. Consider the diffraction pattern produced when light passes through a narrow opening.
   (a) Explain how the first minimum from the principal axis in the pattern occurs in terms of the interference of waves passing through the narrow opening.
   (b) Sketch, on the same axes, the diffraction pattern produced by blue light and red light passing through the same narrow opening.
   (c) Repeat (b) but this time for light passing through an opening that is narrower.
3. White light consisting of all colours passes through a narrow slit and projects onto a distant screen, which shows bright and dark bands with coloured fringes.
   (a) Explain how the coloured fringes arise.
   (b) Red fringes are observed at the furthermost extent from the central white maximum. Why?
4. A beam of green light is directed at a small obstacle and a shadow is cast onto a distant screen. The shadow is not as sharp as one would expect using a ray model for light or even a particle model for light to predict the characteristics of the shadow.
   (a) Comment on why this blurred edge shadow is evidence for the wave nature of light.
   The light source is changed from green to red light and a shadow is produced on the screen.

(b) Would the shadow appear less or more sharp? Explain using your understanding of the wave nature of light.
(c) The beam of green light is restored and, this time, a smaller object is placed in it. Again a shadow is cast onto a distant screen. Would the shadow cast appear less or more sharp than that cast by the larger object?

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10.6 Interference using light

KEY CONCEPTS

- explain the results of Young's double-slit experiment with reference to:
  - evidence for the wavelike nature of light
  - constructive and destructive interference of coherent waves in terms of path differences: $n\lambda$ and $\left(n - \frac{1}{2}\right)\lambda$ respectively
  - effect of wavelength, distance of screen and slit separation on interference patterns: $\Delta x = \frac{\lambda L}{d}$.

10.6.1 Young's double-slit experiment

Thomas Young (1773–1829) was keenly interested in many things. He has been called 'the last man who knew everything'. He was a practising surgeon as well as a very active scientist. He analysed the dynamics of blood flow, explained the accommodation mechanism for the human eye and proposed the three-receptor model for colour vision. He also made significant contributions to the study of elasticity and surface tension. His other interests included deciphering ancient Egyptian hieroglyphics, comparing the grammar and vocabulary of over 400 languages, and developing tunings for the twelve notes of the musical octave. Despite these many interests, the wave explanation of the nature of light was of continuing interest to him.

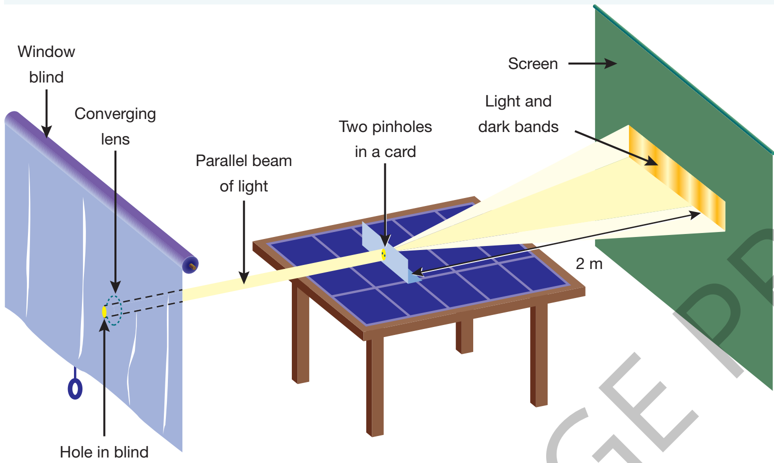
Young had already built a ripple tank to show that the water waves from two point sources with synchronised vibrations show evidence of interference. He was keen to see if he could observe interference with two beams of light. He held a fine hair close to his eye while staring past it at a distant candle. The light from the candle flame passed on both sides of the hair to reach his eyes. He did not notice a scattering of light in all directions as predicted by the particle model. Instead, a beautifully coloured pattern of bands parallel to the hair spread out across his view of the candle. Young's interpretation of what he saw was that light behaved like waves as it spread out from the candle.

> *It occurred to me that their cause must be sought in the interference of two portions of light, one reflected from the fibre, the other bending round its opposite side, and at last coinciding nearly in the direction of the former portion.*

Young described this and other experiments in lectures at the Royal Institution in London in 1801 and 1802. He did not convince his audience! His listeners were reluctant to remove their confidence from the particle model that Newton apparently supported. Young was determined to produce quantitative evidence of the phenomenon that he had observed. He analysed the published results of similar experiments performed by Newton and made further measurements of his own.

In one of his experiments, Young made a small hole in a window blind. He placed a converging lens behind the hole so that the cone of sunlight became a parallel beam of light. He then allowed light from the small hole to pass through two pinholes that he had punctured close together in a card. On a screen about two metres away from the pinholes, he again noticed coloured bands of light where the light from the two pinholes overlapped. Figure 10.45 shows Young's experimental arrangement.

FIGURE 10.45 Young's experiment



Young deliberately had just one source, the hole in the blind, because he wanted the one wavefront to arrive at the two pinholes so that light coming through one pinhole would be synchronised with the light coming though the other pinhole. Today, light coming from the two pinholes would be described as **coherent**. In the language of topic 9, the two waves are in phase. If Young had used two separate sources of light, one for each pinhole, their light would have been incoherent, with a random relationship between the light coming from the two pinholes and no discernible pattern on the screen.

FIGURE 10.46 Light waves in Young's experiment

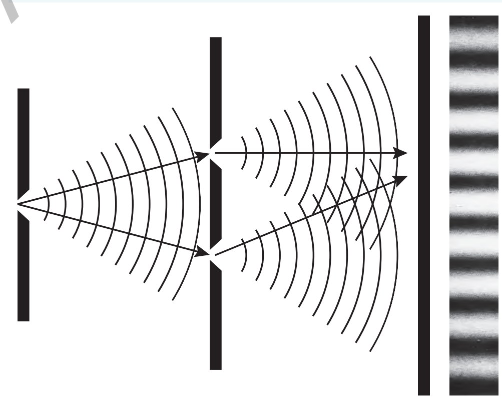
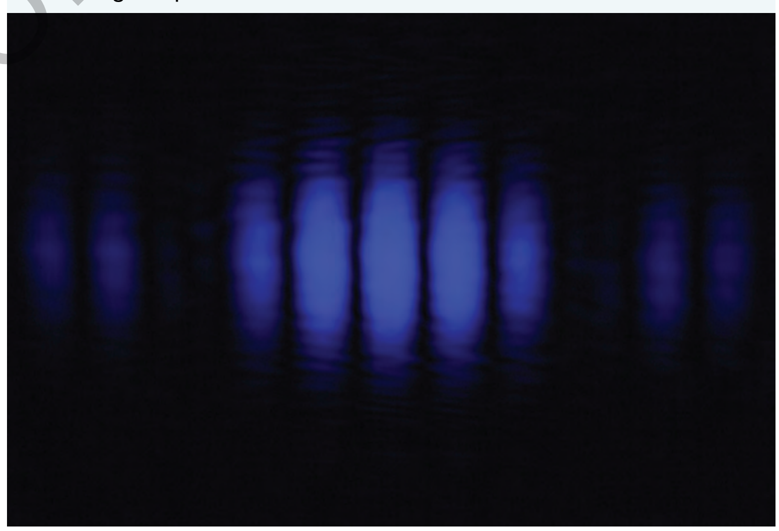


FIGURE 10.47 A light pattern produced by a modern performance of Young's experiment



Resources

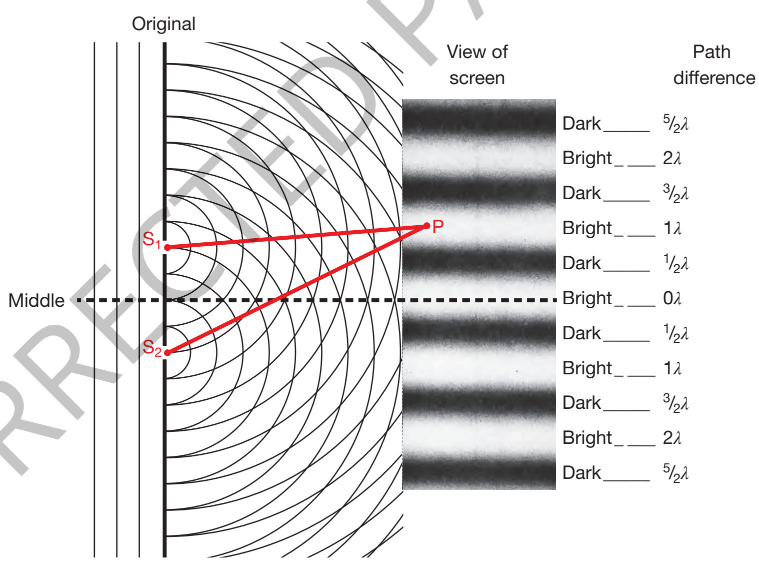
eLesson Young's experiment (interference effects with white light) (eles-0027)

Interactivity Young's experiment (interference effects with white light) (int-0051)

10.6.2 Interpreting Young's experiment

Young used the wave model for light to analyse his observations. Each hole in the window blind is a source of spherical waves. When these waves pass through the pinholes, each pinhole becomes a source of spherical waves. Waves from the two pinholes overlap on the screen, and their effects add together to produce the pattern. In reaching a particular point on the screen, waves have travelled from the source along two alternative routes, through one pinhole or the other. The difference between the lengths of the two paths is called the **path difference**. If the path difference results in the crests of the wave from one pinhole always meeting the troughs of the wave from the other pinhole (that is, exactly out of phase) then destructive interference occurs and that place on the screen is a dark band. Destructive interference occurs when the path difference is a whole number, minus one half, multiplied by the wavelength of the light: $(n - 0.5)\lambda$ where $n = 1, 2, \ldots$ is the number of bright bands from the central bright band. A bright band occurs when, in spite of a path difference, the waves are in phase: crests reinforcing crests and troughs meeting troughs.

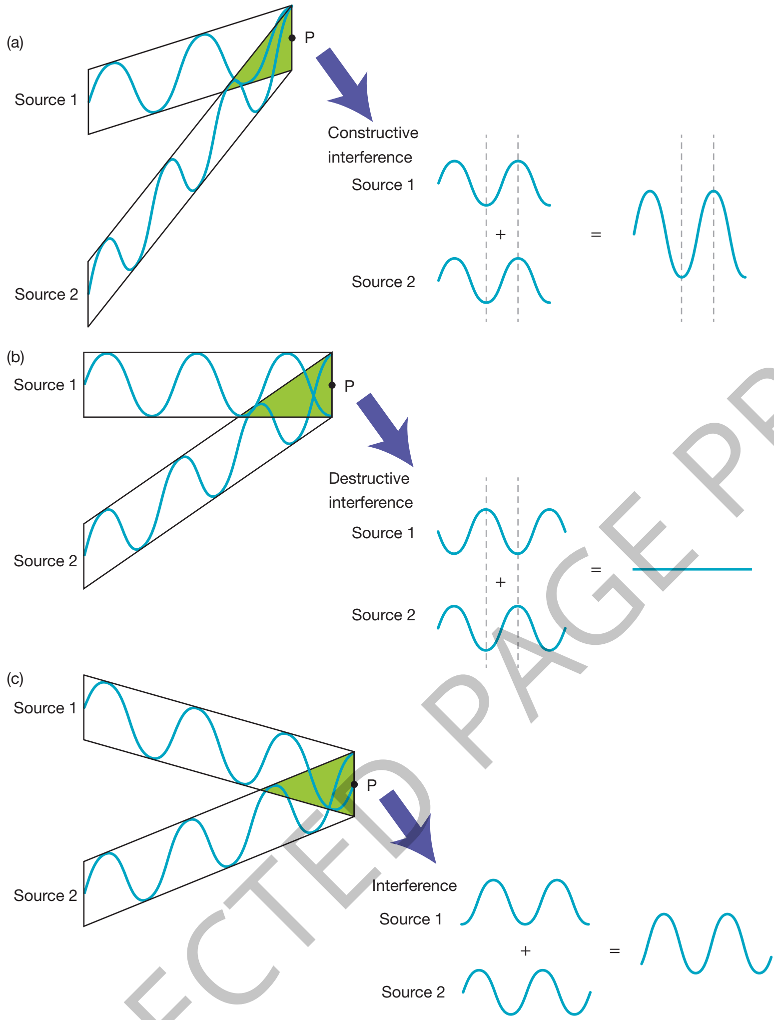
FIGURE 10.48 The wave model describes the two-slit interference pattern. Maximum intensity occurs for the maximum amplitude light wave, because of constructive interference. At P, $S_2P - S_1P = \lambda$.



This constructive interference occurs when the path difference is a whole number multiple of the wavelength of the light, n, again where $n = 1, 2, \ldots$ is the number of bright bands from the central bright band.

Think about performing Young's experiment with a light source emitting light of only one wavelength, say 600 nm (6×10^{-7} m) in the richly yellow part of the spectrum. Constructive interference will occur if the path difference between the two routes to the screen is 0, 600 nm, 1200 nm, 1800 nm, . . . $n \times 600$ nm, where n is an integer. However, if the path difference is 300 nm, 900 nm, 1500 nm . . . $(n - 0.5) \times 600$ nm, where n is an integer, then there will be destructive interference.

FIGURE 10.49 (a) Constructive interference of waves arriving in phase, (b) destructive interference of waves arriving exactly out of phase, and (c) interference of two waves slightly out of phase



SAMPLE PROBLEM 7

Red light of wavelength 640 nm is passed through a pair of slits to produce an interference pattern.

a. What is the path difference for the third bright band from the central bright band?

b. Consider the second dark band from the central bright band. How much further is S_2 than S_1 from the second dark band?

c. Red light is replaced with purple light. What happens to the interference pattern?

Teacher-led video: SP7 (tlvd-XXXX)

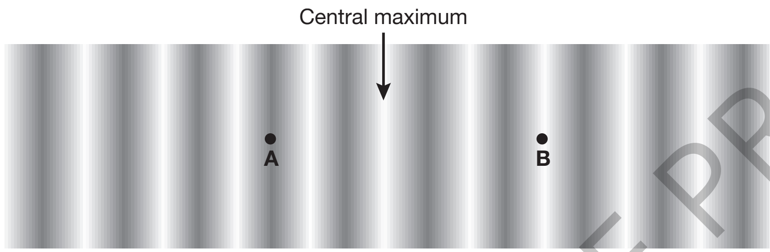
THINK	WRITE
a. The third bright band has a path difference of 3λ.	**a.** The path difference is: $3 \times 640 = 1920$ nm.
b. The second dark band arises because of destructive interference where the path difference is $\frac{3\lambda}{2}$.	**b.** S_2 is further away from this dark band than S_1 by the following distance: $\frac{3\lambda}{2} = \frac{3 \times 640}{2} = 910\,\text{nm}$

c. The wavelength for purple light is less than for red light.

c. The pattern is now more compact or compressed due to the smaller wavelength of the purple light.

PRACTICE PROBLEM 7

A student creates an interference pattern using green light of wavelength 530 nm. The pattern is shown in the following illustration.



a. Calculate the path difference for the points marked A and B.
b. The student increases the distance between the two slits. Describe what happens to the pattern.
c. She now changes the light source from green to red. Describe what happens to the pattern now.
d. Explain why the interference pattern is strong evidence for the wave nature of light.

on Resources

Weblink The atomic lab: wave interference

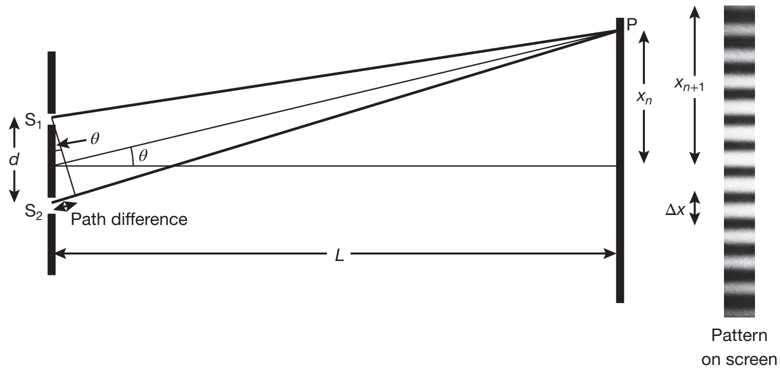
10.6.3 Spacing of bands in an interference pattern

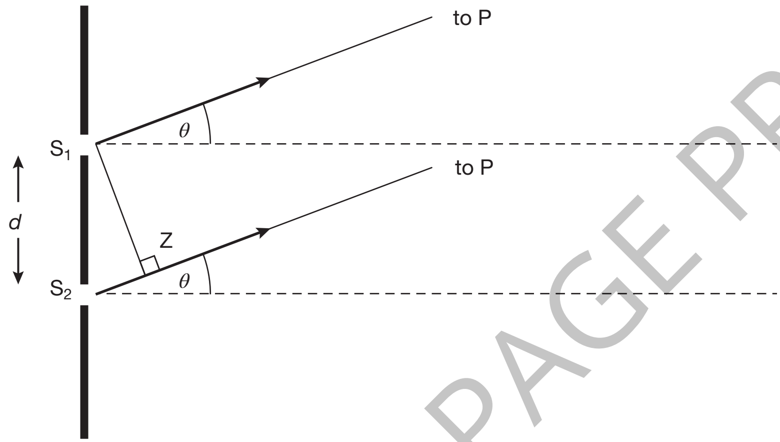
The previous section developed expressions relating the path difference to the light and dark bands in an interference pattern. These expressions are important in understanding Young's experiment, but the path difference cannot be measured. What can be measured in this experiment is:

- the separation of the two slits, d
- the wavelength, λ
- the distance of the screen from the two slits, L
- the spacing between alternate bands in the pattern (either the bright or dark bands), x.

A relationship between these four quantities would be useful. It could be used to calculate the wavelength of an unknown light source from a slide with a known slit separation, or to calculate an unknown slit separation with light of a known wavelength.

If the separation of the two slits, d, is very much less than the distance L, then the two lines S_1P and S_2P are effectively parallel, as shown in the following two diagrams. Typically, d is about 1 mm and L is about 2 metres.





In the second of the two diagrams, S_1Z is a line drawn across the two light paths at right angles. The distances from S_1 to P and from Z to P will be equal to each other. This means the path difference is S_2Z. From the right-angled triangle with corners at S_1, Z and S_2, and a right angle at Z, $\sin\theta = \dfrac{\text{path difference}}{d}$, or path difference $= d\sin\theta$.

For bright lines, $d\sin\theta = n\lambda$, where $n = 1, 2, 3, \ldots$

From the second of the two diagrams, $\tan\theta = \dfrac{x_n}{L}$, but for small angles less than 10°, $\tan\theta$ and $\sin\theta$ have similar values to within about 1%.

So, for small angles, $\dfrac{n\lambda}{d} = \dfrac{x_n}{L}$, giving $x_n = \dfrac{n\lambda L}{d}$, and for n + 1, $x_{n+1} = \dfrac{(n+1)\lambda L}{d}$.

The spacing between adjacent bright lines, $x_{n+1} - x_n = \Delta x$ is given by:

$$\Delta x = \frac{\lambda L}{d}$$

where Δx is the spacing between bands (either light or dark)
λ is the wavelength of the light waves
L is the distance of the screen from the slits
d is the slit separation.

SAMPLE PROBLEM 8

Sodium light of wavelength 589 nm is directed at a slide containing two slits that are 0.500 mm apart. What will be the spacing between the bright bands in the interference pattern on a screen that is 1.50 m away?

Teacher-led video: SP8 (tlvd-XXXX)

THINK	WRITE
1. List the known information.	$\lambda = 589$ nm; $L = 1.50$ m; $d = 0.500 \times 10^{-3}$ m; $\Delta x = ?$
2. Use the relationship $\Delta x = \dfrac{\lambda L}{d}$ to calculate the spacing between bright bands.	$\Delta x = \dfrac{\lambda L}{d}$ $= \dfrac{5.89 \times 10^{-9} \times 1.50}{0.500 \times 10^{-3}}$ $= 0.001\,77$ m $= 1.8$ mm

PRACTICE PROBLEM 8

Interference bands are formed on a screen that is 2.00 m from a double slit with separation 1.00 mm. The bands are measured to be 1.30 mm apart.

a. What is the wavelength of the light?

b. What is its colour?

c. How would the pattern change if blue light was used?

d. How could the experimental design be changed to make it easier to measure the line spacing in the pattern?

EXERCISE 10.6

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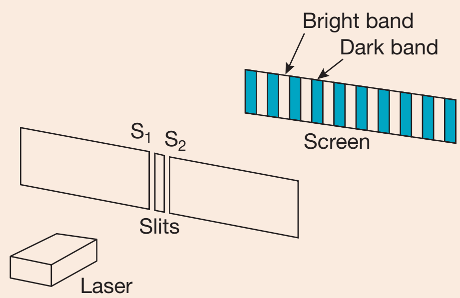
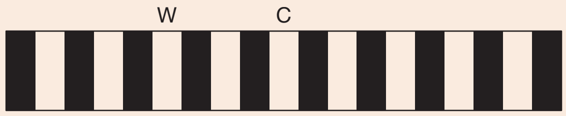
1. Young's double-slit experiment was a significant experiment in the development of understanding about light and matter.
   (a) What has been learned about the nature of light from Young's experiment?
   (b) When light is passed through a pair of narrow closely spaced slits, an interference pattern is formed. What is an interference pattern and how is it formed?
2. Jill and William are studying the effect of passing laser light of wavelength 530 nm through a pair of slits and forming a pattern on a screen several metres away.
   The following diagram shows the experimental arrangement:

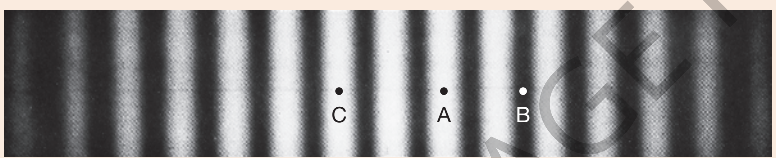


   Part of the interference pattern observed by Jill and William is shown in the next diagram. Point C represents the position of the central maximum (bright band), and point W represents the second maximum (bright band) from the centre of the pattern.



(a) Is the pattern on the screen evidence for the wave nature of light or for the particle nature of light? Explain your choice.
(b) Is W a point where constructive or destructive interference is occurring?
(c) What is the path difference $|S_1C - S_2C|$?
(d) What is the path difference $|S_1W - S_2W|$?
(e) State the three smallest path differences that would give rise to dark regions on the screen.
(f) How many dark regions are there in between C, the central maximum, and W, the second maximum from the central maximum?

3. A student shines a helium–neon laser, which produces light with a wavelength of 633 nm, through two slits and produces a regular pattern of light and dark patches on a screen as shown in the following diagram. The centre of the pattern is the band marked A. Using a wave model, light can be described as having *crests* and *troughs*.



(a) Use these terms to explain:
  i. the bright band labelled A in the diagram
  ii. the dark band labelled B.
(b) What is the path difference in the distance light has travelled from the two slits to:
  i. the bright band labelled A
  ii. the dark band labelled B
  iii. the bright band labelled C?
(c) Using the same experimental setup, but replacing the laser with a green argon ion laser emitting 515 nm light, what changes would occur to the interference pattern?
(d) The helium–neon laser is set up again. The distance between the two slits is now increased. What changes to the interference pattern shown in the diagram would occur?
(e) The screen on which the interference pattern is projected is moved further away from the slits. What changes to the interference pattern shown in the diagram would occur?

4. Infra-red radiation can be passed through a pair of narrow slits and an interference pattern produced.
(a) List several different path differences that would produce constructive interference for infra-red radiation with a wavelength of 1.06 μm.
(b) Now list several path differences that would produce destructive interference.

5. Light of wavelength 430 nm falls on a double slit of separation 0.500 mm. What is the distance between the central bright band to the first, second and third bright band respectively in the pattern on a screen placed 1.00 m from the double slit?

6. A group of students is planning to measure the wavelength of light emitted from a laser. They do this by producing an interference pattern cast onto the wall of a classroom. The wall is 3.8 m away from the pair of slits, and they locate the central maximum and measure the distance from it to the first bright fringe immediately opposite the central maximum to be 1.9 cm. Their teacher informs them that the slits are separated by a distance of 0.134 mm.
(a) Determine the wavelength of the laser light.
(b) Describe any changes in the pattern if the slits were separated by 0.100 mm.

7. A double slit is illuminated by light of two wavelengths, 600 nm and the other unknown. The two interference patterns overlap with the third dark band of the 600 nm pattern coinciding with the fourth bright band from the central band of the pattern for the light of unknown wavelength. What is the value of the unknown wavelength?

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10.7 Light as a transverse electromagnetic wave

KEY CONCEPTS

- describe light as an electromagnetic wave, which is produced by the acceleration of charges, which in turn produces changing electric fields and associated changing magnetic fields
- identify that all electromagnetic waves travel at the same speed, c, in a vacuum
- compare the wavelength and frequencies of different regions of the electromagnetic spectrum, including radio, microwave, infra-red, visible, ultraviolet, X-ray and gamma, and identify the distinct uses each has in society
- explain polarisation of visible light and its relation to a transverse wave model.

10.7.1 Electromagnetic waves

Young had shown that the behaviour of light passing through narrow slits could be explained using the ideas of waves. He had even measured the wavelengths of light in the visible spectrum, but he did not know what sort of wave might explain light. James Clerk Maxwell (1831–1879) provided the answer in 1864. He began with the ideas of electric and magnetic interactions where a changing magnetic flux in time gave rise to an induced voltage and associated electric field. From these ideas, he developed a theory predicting that an oscillating electric charge would produce an oscillating electric field, together with a magnetic field oscillating at right angles to the electric field. These inseparable fields would travel together through a vacuum like a wave, and the speed of the wave would be the same, whether the oscillations were rapid (high frequency and a short wavelength) or very slow (low frequency and a long wavelength). Maxwell predicted their speed, using known electric and magnetic properties of a vacuum, to be 3×10^8 m s^{-1}. This is the speed of light! Maxwell had produced a theory that explained how light was produced and travelled through space as electromagnetic waves. This applied not only to visible light, but also to other radiation that people cannot see, such as infra-red and ultraviolet radiation. Furthermore, his electromagnetic model of light indicated that light could be described as a transverse wave.

FIGURE 10.50 An electromagnetic wave. The electric and magnetic fields are uniform in each plane but vary along the direction of the motion of the wave.

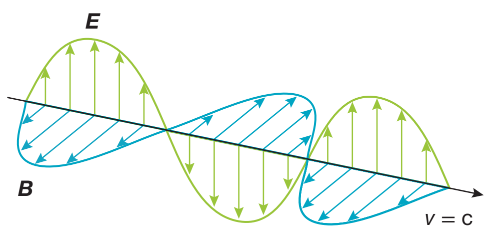


FIGURE 10.51 Forms of radiation and their place in the electromagnetic spectrum. The visible portion of the spectrum is shown enlarged in the upper part of the diagram.

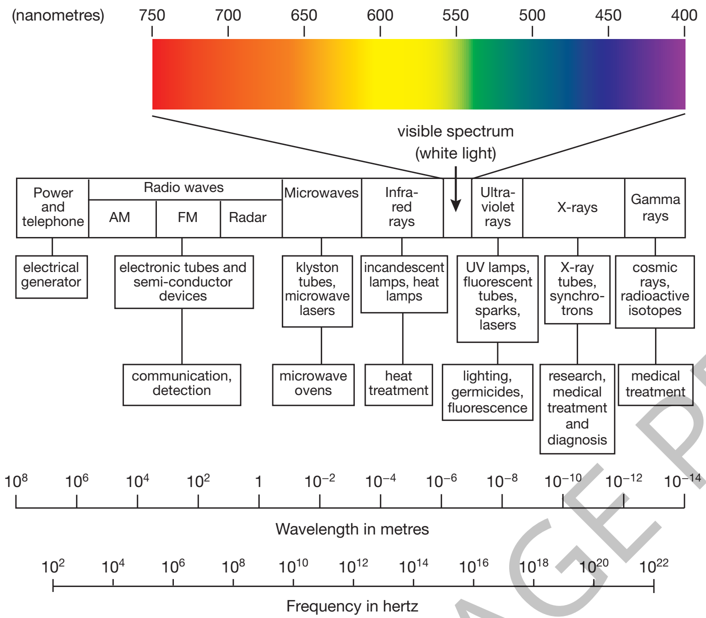


TABLE 10.3 Frequency and wavelength of colours

	Red	Orange	Yellow	Green	Blue	Violet
Frequency ($\times 10^{12}$ hertz)	430	480	520	570	650	730
Wavelength (nanometres)	700	625	580	525	460	410

SAMPLE PROBLEM 9

When light with a frequency of 5.6×10^{14} Hz travels through a vacuum, what are the values of the following?

a. Its period

b. Its wavelength (in nanometres)

The speed of light in a vacuum is 3.0×10^8 m s^{-1}.

Teacher-led video: SP9 (tlvd-XXXX)

THINK	WRITE
a. The period of a wave is the reciprocal of its frequency.	**a.** $T = \frac{1}{f}$ $= \frac{1}{5.6 \times 10^{14}}$ $= 1.8 \times 10^{-15}$ s The period of the light is 1.8×10^{-15} s.

b. 1. Use the relationship $\lambda = \dfrac{c}{f}$ to determine the wavelength.

b. $\lambda = \dfrac{c}{f}$

$= \dfrac{3.0 \times 10^{8}}{5.6 \times 10^{14}}$

$= 5.4 \times 10^{-7}\ \text{m}$

2. The wavelength of visible light is usually expressed in nanometres (nm) where $1\ \text{nm} = 1 \times 10^{-9}\ \text{m}$.

$\lambda = \dfrac{5.4 \times 10^{-7}}{1 \times 10^{-9}}\ \text{nm}$

$= 5.4 \times 10^{2}\ \text{nm}$

The wavelength of the light is 540 nanometres.

PRACTICE PROBLEM 9

Find the frequency and period of light with a wavelength of 450 nm.

The frequency of a light ray is determined by the source (that is, the object producing the light). The speed of the light is determined by the material the light is passing through. (The refractive index is a measure of how much the light is slowed down by the material.) This means that, when light passes from air into water, the frequency stays the same, the speed decreases and the wavelength must also decrease.

When you are under water and you look around, the objects you see still have the same colour. This means that your eye is responding to the frequency of the light ray and not to its wavelength. The world would be a strange place if the eye's response was the other way round.

10.7.2 Polarisation

The transverse wave model of electromagnetic radiation developed by James Maxwell in 1873 proposes that light and other electromagnetic waves travel in many planes. Two hundred years earlier, the wave model of Christiaan Huygens proposed that light travelled as longitudinal waves — like sound.

Figure 10.52 shows what happens when a transverse wave in a vertical plane passes through a vertical slit. A transverse wave in a horizontal plane is unable to pass through a vertical slit. If transverse waves in many planes were to approach the slit, only the waves in the vertical plane would pass through. This blocking of waves except for those in a single plane is called **polarisation**.

Figure 10.53 shows how a longitudinal wave can pass through both slits. Longitudinal waves cannot be polarised.

Observations of the polarisation of light show that light is a transverse wave rather than a longitudinal wave, as longitudinal waves cannot be polarised. The polarisation of light is observed when it passes through some materials. These materials, which allow light waves in one plane to pass while blocking light in all other planes, are called polarising filters.

FIGURE 10.52 Waves in a vertical plane pass through the slit. The waves in a horizontal plane cannot pass through.

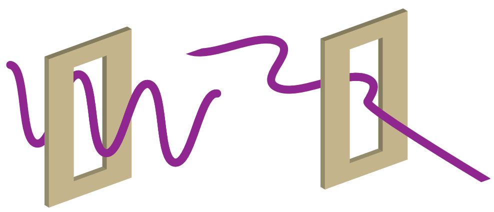


FIGURE 10.53 Longitudinal waves can pass through both vertical and horizontal slits.

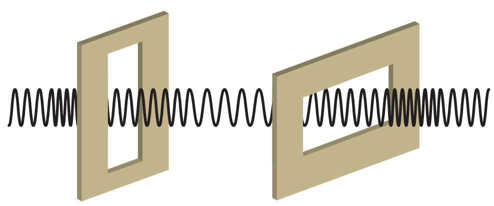


FIGURE 10.54 Light passed through crossed polarisers — polarising filters at right angles to each other

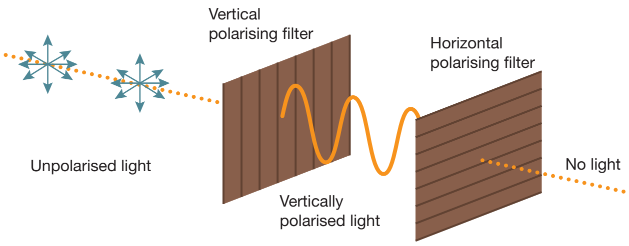
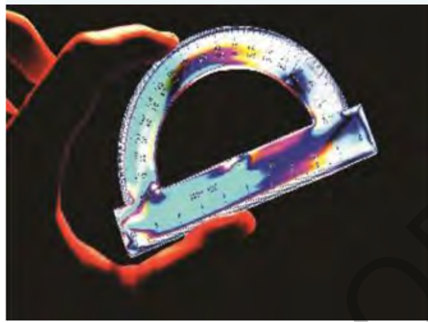


FIGURE 10.55 A protractor seen through crossed polarisers



AS A MATTER OF FACT

- Sunglasses with polarising lenses cut out the glare from reflective surfaces such as water and roads. Reflected light is polarised in the horizontal direction, so putting the plane of the polarising filter in the vertical direction cuts out glare.
- Bees can see the polarisation pattern of the sky and use it to locate sources of pollen. In fact, many insects, fish, amphibians, arthropods and octopi use the polarisation of light to their benefit.
- Stresses in transparent objects can be detected using polarisation. To do this, the object is placed between crossed polarisers. Light passes through the object towards a camera. Normally, no light would pass through the crossed polarisers. However, regions under stress can rotate the plane of polarisation. This allows some light to get through, creating a photographic image that reveals the stresses.

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Weblinks Polarisation

Polarised light applet

10.7 EXERCISE

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For this exercise, take the speed of light in a vacuum as $c = 3.0 \times 10^8$ m s^{-1}.

1. Calculate the period of orange light, which has a frequency of 4.8×10^{14} Hz.
2. Microwaves have a frequency ranging from 1.0×10^{10} through to 1.0×10^{12} Hz. Determine the range of wavelengths associated with microwaves.
3. X-rays used by dentists have a wavelength of 2.7×10^{-11} m. What is the frequency and hence the period of the X-rays produced?
4. Place the following types of electromagnetic waves in order of ascending frequency: gamma rays, radio waves, visible light, microwaves and ultraviolet rays.
5. Power lines that carry electrical energy use an AC current. These cables emit electromagnetic radiation with a period of 20 ms.
   (a) What is the frequency of the radiation emitted by power lines?
   (b) What is the wavelength of this radiation?
6. Which radio waves, AM or FM, would be more susceptible to the effects of diffraction? Explain your answer.
7. When blue light of frequency 6.5×10^{14} Hz travelling through the air meets a glass prism, its speed decreases from 3.0×10^8 m s^{-1} to 2.0×10^8 m s^{-1}. Calculate the following:
   (a) the wavelength of the blue light in the air
   (b) the wavelength of the blue light in the glass
   (c) the frequency of the blue light in the glass
   (d) the refractive index of the glass used.

8. Explain, with the aid of a diagram, why polarisation would not be possible if light behaved like a longitudinal wave.
9. Glare at the beach is partly caused by polarised light reflected from the sand and the water. The light is polarised in the horizontal plane of the two surfaces. What should be the orientation of polaroid sunglasses to block out the glare?
10. 3D movies are shown at cinemas where patrons use special glasses. Research and give a simple description of how the system works, focusing on the ability of light to be polarised.
11. Describe how a moving charged particle that changes its motion produces an electromagnetic wave. Your answer should relate to both electric and magnetic fields around a moving charged particle.

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10.8 Review

10.8.1 Summary

- Light bends as it travels from one medium to another. A measure of a medium's capacity to bend light is given by its refractive index.
- If light travels into a medium of a higher refractive index, the light is bent towards the normal. If light travels into a medium of a lower refractive index, the light is bent away from the normal. This change in direction is summarised in Snell's Law. Snell's Law can be expressed as $n_1 \sin\theta_1 = n_2 \sin\theta_2$.
- Light consists of a mixture of colours and, when these colours enter a material, they refract at different angles. This means that a material has a different refractive index for each colour. The resulting separation of light into different colours is called dispersion.
- The speed of light in a uniform medium is a constant and is given by the equation $v = \frac{c}{n}$, where c is the speed of light in a vacuum and n is the refractive index of the medium. The greater the refractive index, the lower the speed of light is in that medium.
- When light passes from medium 1 into medium 2, the respective refractive indices and speeds are related by the equation $n_1 v_1 = n_2 v_2$.
- When light travels into a medium of a lower refractive index, there will be an angle of incidence for which the angle of refraction is 90°. This angle of incidence is called the *critical angle*. For angles of incidence greater than the critical angle, all the light is reflected back into the medium. This phenomenon is called *total internal reflection*.
- The amount of diffraction is determined by the ratio $\frac{\lambda}{w}$, where λ is the wavelength and w is the width of a slit or size of an obstacle.
- The amount of diffraction is related to the wavelength of light and the size of an opening or obstacle. The greater the wavelength, the more evident are the diffraction effects. The smaller the size of an opening or obstacle, the more evident are the diffraction effects also.
- Interference patterns resulting from light passing through two narrow slits can be explained using the wave principles of constructive and destructive interference of waves that are in phase and out of phase respectively. This interference results from a path difference to a point from each of the slits.
- In an interference pattern, a region of intense light, or maxima, results from a path difference of $0, \lambda, \pm 2\lambda, \pm 3\lambda, ...$

- In an interference pattern, a region of no light, or minima, results from a path difference of $\pm\frac{1}{2}\lambda, \pm\frac{3}{2}\lambda, \pm\frac{5}{2}\lambda, \ldots$..
- The behaviour of light, particularly refraction, diffraction and two-slit interference, is strong evidence for the wavelike properties of light.
- The speed of electromagnetic waves in a vacuum is $c = 3.0 \times 10^8$ m s^{-1}. The wave equation is $v = f\lambda$ where f is the frequency and λ is the wavelength.
- Maxwell produced a mathematical model that represents light as a transverse wave consisting of perpendicular in-phase electric and magnetic fields. The wave propagates at a unique speed in uniform media. These waves are called electromagnetic waves. This model explained all the known observations of light up to the late nineteenth century.
- Visible light is a form of electromagnetic radiation that can be modelled as transverse waves with colours differing in frequency.
- Radio waves, microwaves, infra-red rays, ultraviolet rays, X-rays and gamma rays are all examples of electromagnetic radiation, differing only in frequency.
- Transverse waves, including light, can be polarised. Polarisation is the blocking of transverse waves except for those in a single plane.

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10.8.2 Key terms

The **absolute refractive index** of a substance is the relative refractive index for light travelling from a vacuum into the substance. It is commonly referred to as the refractive index.
The **angle of incidence** is the angle between an incident ray and the normal.
The **angle of reflection** is the angle between a reflected ray and the normal.
The **angle of refraction** is the angle between a refracted ray and the normal.
Two waves are **coherent** if there is a constant relative phase between them.
The **critical angle** is the angle of incidence for which the angle of refraction is 90°. The critical angle exists only when light passes from one substance into a second substance with a lower refractive index.
Diffuse reflection is reflection from a rough or irregular surface.
Dispersion is the separation of light into different colours as a result of refraction.
Incandescent objects are luminous objects that produce light because they are hot. The higher the temperature, the brighter the light, and the colour also changes.
A **light ray** can be considered as an infinitely narrow beam of light and can be represented as a straight line
Luminous objects are objects that are seen because they give off their own light.
The **normal** is a line that is perpendicular to a surface or a boundary between two surfaces.
An **optical fibre** is a thin tube of transparent material that allows light to pass through without being refracted into the air or another external medium.
Path difference is the difference between the lengths of the paths from each of two sources of waves to a point.
Polarisation is the blocking of transverse waves except for those travelling in a single plane.
Refraction is the bending of light as it passes from one medium into another.
Regular reflection (also referred to as specular reflection) is reflection from a smooth surface.
Relative refractive index is a measure of how much light bends when it travels from any one substance into any other substance.
Total internal reflection is the total reflection of light from a boundary between two substances. It occurs when the angle of incidence is greater than the critical angle.

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Digital document Key terms glossary (doc-#####)

10.8.3 Practical work and investigations

online only

Investigation 10.1
Luminous or not?
Aim: To determine, from a list, which items are luminous and which items are non-luminous
Digital document: doc-xxxxx
Teacher-led video: tlvd-xxxxx

FPO

Investigation 10.2
Luminosity and temperature
Aim: To investigate the change in colour and brightness with temperature
Digital document: doc-xxxxx
Teacher-led video: tlvd-xxxxx

FPO

Investigation 10.3
Seeing is believing
Aim: To observe the bending of light
Digital document: doc-xxxxx
Teacher-led video: tlvd-xxxxx

FPO

Investigation 10.4
Separating colours
Aim: To determine which colour is bent the most by a prism
Digital document: doc-xxxxx
Teacher-led video: tlvd-xxxxx

FPO

Investigation 10.5
Refraction of particles
Aim: To measure the refraction of particles using surfaces at different heights
Digital document: doc-xxxxx
Teacher-led video: tlvd-xxxxx

FPO

Investigation 10.6
Refraction of waves
Aim: To observe the wavelength and refraction of waves travelling from deep to shallow water
Digital document: doc-xxxxx
Teacher-led video: tlvd-xxxxx

FPO

Investigation 10.7
Using apparent depth to determine the refractive index
Aim: To determine the refractive index using apparent depth
Digital document: doc-xxxxx
Teacher-led video: tlvd-xxxxx

FPO

10.8 Exercises

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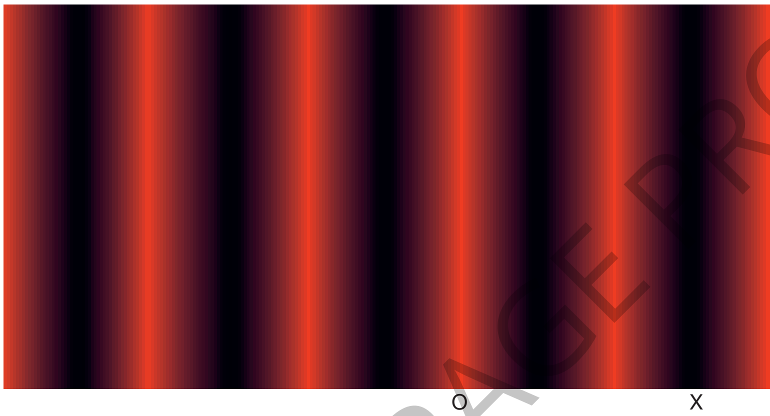
10.8 Exercise 1: Multiple choice questions

1. A group of students is trying to measure the speed of light on a sports oval. They have placed a mirror 120 m from a laser source and light sensor, both of which are connected to a timer. The timer starts when the laser is switched on and stops when a pulse arrives at the sensor. Light from the laser strikes the mirror and is reflected directly back to the sensor. Which one of the following do the students accurately measure the time to be?
   - A. 4.0×10^{-7} s
   - B. 1.6×10^{-6} s
   - C. 8.0×10^{-6} s
   - D. 8.0×10^{-7} s
2. In a practical session, students use a semicircular prism to investigate the refraction of light. When a narrow beam of light has an angle of incidence of 35°, the angle of refraction is 26°. Which one of the following is the refractive index of the prism?
   - A. 1.34
   - B. 1.28
   - C. 0.75
   - D. 0.85
3. A ray of light inside a rectangular block of glass ($n_{glass} = 1.53$) makes on angle of incidence of 47.0°. The rectangular block is immersed in water ($n_{water} = 1.33$). Calculate the angle of refraction for the ray of light as it exits into the water from the glass block.
   - A. 39.8°
   - B. 57.3°
   - C. 43.6°
   - D. 48.7°
4. Consider two optical fibres each of length 10 m. Optical fibre X has a core refractive index of 1.54 whereas optical fibre Y has a core refractive index of 1.58. Which one of the following statements is correct regarding the propagation of pulses of light sent down both fibres?
   - A. It will take a shorter time for the light pulse to pass down optical fibre Y than optical fibre X.
   - B. It will take the same time as the fibres have the same length, and the speed of light in both fibres is the same for all observers.
   - C. It will take a shorter time for the light pulse to pass down optical fibre X than optical fibre Y.
   - D. It will take a different amount of time but one that is not possible to determine.
5. Students are asked to calculate the critical angle for light propagating inside a transparent crystal. Their teacher tells them that the refractive index for the crystal is 1.387. Which one of the following is the critical angle for this crystal when placed in air?
   - A. 47.3°
   - B. 45.4°
   - C. 48.5°
   - D. 46.1°
6. White light is incident on an air–glass interface. Due to dispersion, the white light separates into colours. Which one of the following statements is correct?
   - A. Blue light will have an angle of refraction that is greater than the angle of refraction of red light.
   - B. Red light will have an angle of refraction that is greater than the angle of refraction of green light.
   - C. Green light will have an angle of refraction that is greater than the angle of refraction of yellow light.
   - D. Orange light will have an angle of refraction that is greater than the angle of refraction of red light.

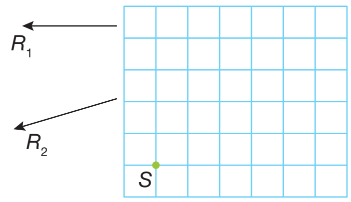
7. A student attempts to illustrate the diffraction of light. She makes a single slit of width 3.0 mm, and no significant diffraction is observed when she uses green light. Which one of the following statements offers the best advice to her so that diffraction can be observed?
   A. Advise the student to use blue light instead of green light.
   B. Advise the student to make the slit narrower, closer to the wavelength of green light.
   C. Advise the student to make the slit wider, closer to the wavelength of green light.
   D. Advise the student to use red light instead of green light.
8. An interference pattern like the one shown in the following image is cast onto a screen as students do a practical task on interference. They use laser light of wavelength 650 nm passing through a closely spaced narrow double slit. The bright fringe O is identified as the central maximum.



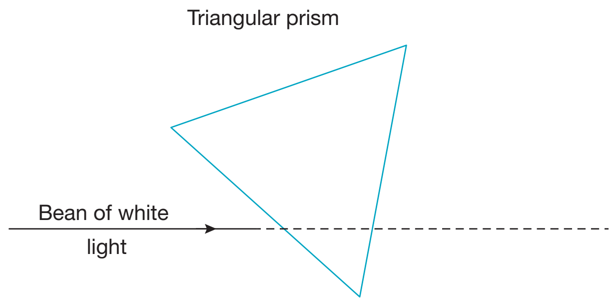
   The point X is a region on the screen where there is no light. What is the path difference from each of the slits to the point X?
   A. 975 nm
   B. 325 nm
   C. 1300 nm
   D. 1625 nm
9. Students produce an interference pattern using a green light laser. They cast a pattern onto a screen that is 2.5 m from the slits. The narrow slits are separated by 0.075 mm. A member of the group measures the distance between two adjacent bright fringes to be 1.60 cm. Which one of the following wavelengths of green light is the one used?
   A. 420 nm
   B. 440 nm
   C. 460 nm
   D. 480 nm
10. Which one of the following statements is correct regarding an observation about light and a model for light?
   A. Interference demonstrates that light is a type of transverse wave.
   B. Polarisation of light demonstrates that light is a type of transverse wave.
   C. Interference demonstrates that light is a type of longitudinal wave.
   D. Polarisation of light demonstrates that light is a type of longitudinal wave.

10.8 Exercise 2: Short answer questions

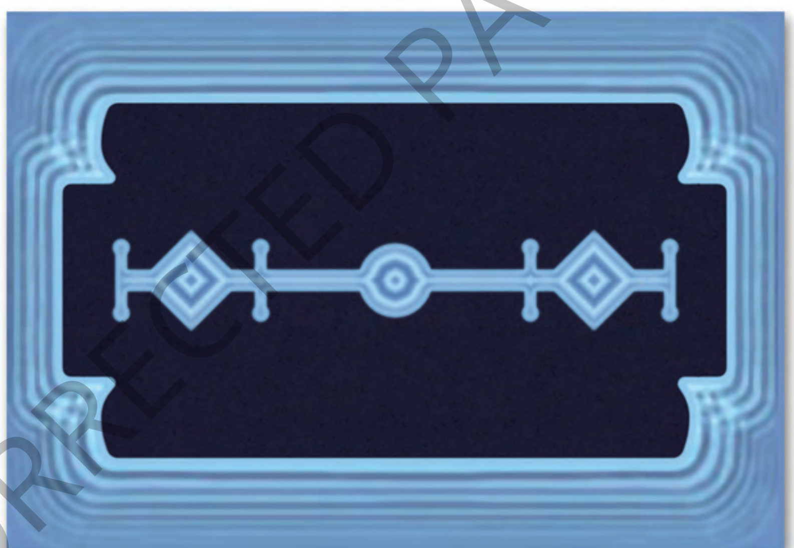
1. The following diagram shows a light source S placed in front of a plane mirror that is not shown. Two light rays R_1 and R_2 that are reflected from the mirror are shown.



   a. On a copy of the diagram, locate the position of the image **S** and mark that point with the letter **I**.
   b. Draw in the location of the plane mirror using a straight line to represent the mirror.
2. Blue light has a frequency of 6.5×10^{14} Hz, and yellow light has a frequency of 5.2×10^{14} Hz.
   a. Determine the wavelength of both blue and yellow light in air. Take the speed of light in air to be 3.0×10^{8} m s^{-1}.
   b. Determine the wavelength of both blue and yellow light, this time in glass with a refractive index of 1.50 for both colours.
3. Lasers can be rapidly switched on and off to produce a pulse of light. A particular pulse of blue light (6.5×10^{14} Hz) consists of 1.0×10^{6} complete cycles. What is the distance between the start and end of this particular pulse? Hint: how much time would it take to produce this pulse?
4. Consider a ray of light incident on an air–perspex interface such that the angle of refraction is 16° when the angle of incidence is 22°.
   a. Calculate the refractive index of the perspex, assuming the refractive index of air is 1.00.
   b. If the angle of incidence is increase by 10°, what is the increase in the angle of refraction?
   c. Now consider a ray of light propagating from the perspex into the air with an angle of incidence of 22°. Calculate the angle of refraction and comment on your answer.
5. A group of students is investigating the refraction of light as it passes from a transparent block of carbon disulfide ($n = 1.63$) into very salty water ($n = 1.38$).
   a. Calculate the speed of light in carbon disulfide.
      Consider a ray of light passing from carbon disulfide into very salty water.
   b. Will the light speed up or slow down in the very salty water compared to its speed in carbon disulfide?
   c. Will the light bend towards the normal or away from the normal at the interface between carbon disulfide and the very salty water?
   d. If the angle of incidence is 45°, calculate the angle of refraction.
6. Consider a ray of white light incident on an air–flint glass interface with an angle of incidence of 25°. The refractive index for red light in flint glass is 1.571 and, for blue light, the refractive index is 1.594. The refracted beam disperses as it passes into the glass.
   a. Explain what is meant by the word 'disperses' in this context.
   b. Determine the angle between the refracted red light and the refracted blue light in the flint glass.
      The angle of incidence is now increased from 25° to 50°.
   c. What is the angle between the red and blue refracted rays now?
7. A beam of white light is fired at a triangular prism as shown in the following diagram. The dotted line gives the direction of the incident beam as a reference line for your drawing.
   By drawing onto a copy of the diagram, show how the white light is dispersed as it passes through the prism. Clearly indicate on your diagram both the red and violet end of the spectrum produced by white light passing through the prism.

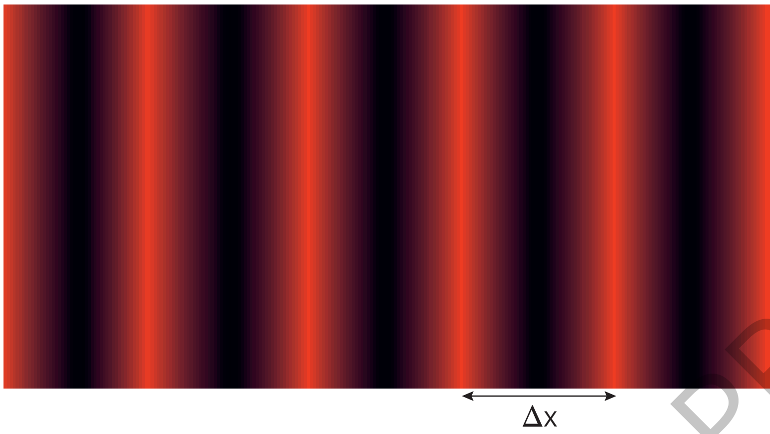


8. Consider three different types of glass X, Y and Z. Their refractive indices are $n_X = 1.53$, $n_Y = 1.55$ and $n_Z = 1.57$ respectively.
   a. Of the three different types of glass, state the glass with the smallest critical angle.
   b. Using your choice for part (a), determine the critical angle for light.
      Now, consider glass Z making an optical interface with glass X.
   c. Determine the critical angle for this arrangement.
9. The following image shows the shadow produced when light has passed the edge of a razor blade. Explain why the shadow is not sharp and why there are regions of bright and dark light. Use the words *diffraction* and *interference* in your answer.



10. When light passes through a narrow slit, a diffraction pattern is produced and can be displayed on a screen. State two ways in which the amount of diffraction can be increased so that the pattern appears to be more spread out.
11. Using your knowledge of interference, explain why a pattern consisting of many bright and dark regions appears on a screen when light from a single source passes through two closely spaced, narrow slits.
12. The path difference to the third dark fringe in a standard two-slit interference pattern is 1250 nm.
    a. What is the wavelength of the light used to make the interference pattern?
    b. What is the path difference for the second bright fringe?

13. A two-slit interference pattern is constructed by a group of students, and a clear pattern like the one shown in the following image is cast onto the wall of a classroom. The distance between two adjacent bright fringes is shown as Δx.

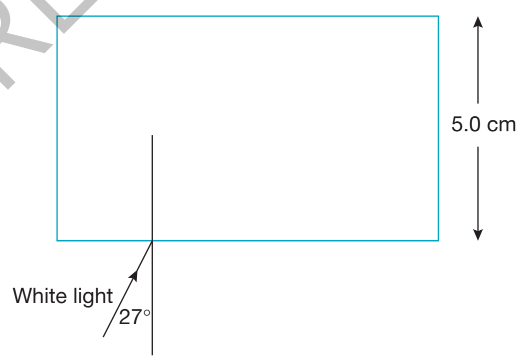


State three different ways in which the spacing Δx could be increased by a factor of 2.

14. A group of students is using a laser that emits light of wavelength 650 nm. They point the beam at a pair of slits that they know has a slit separation of 0.10 mm. They wish to produce a two-slit interference pattern, where the bright fringes are separated by 2.0 cm, as part of a display for an open day at their school. Calculate the distance they must position the screen from the pair of slits to achieve this.
15. Would it be possible to polarise microwaves? Discuss.

10.8 Exercise 3: Exam practice questions

1. A narrow beam of white light makes an angle of incidence with a rectangular prism having a width of 5.0 cm, as shown in the following diagram. The refractive index for red light in the prism is $n_{\text{red}} = 1.530$, and for blue light, the refractive index is $n_{\text{blue}} = 1.548$.

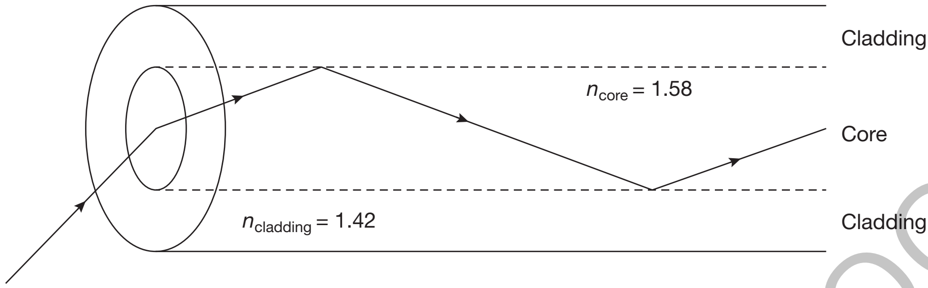


   a. Onto a copy of the diagram, carefully draw rays to indicate the propagation of red and blue light through the block of glass. For each path, indicate two points where refraction occurs and one where a reflection also occurs.

   The narrow beam of white light makes an angle of incidence with the air–prism interface of 27°.

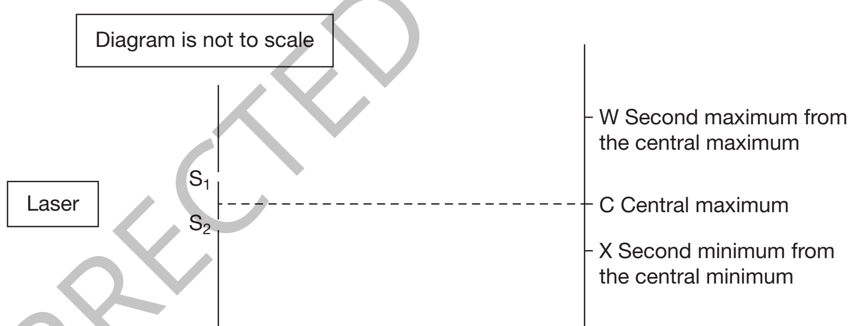
   b. Determine the angle of refraction for red light.
   c. Consider the time it takes for red light and blue light to propagate through the prism. Which colour would take the least time? Or does it take the same time?

2. Optical fibres consist of transparent materials having an inner core and an outer cladding with different refractive indices. The following diagram shows a typical optic fibre. The refractive index of the core is 1.58 and the critical angle for light at the core–cladding boundary 84°.



a. For the fibre to operate correctly, would the refractive index of the cladding be greater than, the same size as, or smaller than the refractive index of the core? Explain your choice without a calculation.
b. Calculate the refractive index of the cladding, $n_{cladding}$.
c. Determine the speed of light in the core of the fibre optic.
d. In one instance, light of wavelength 400 nm is shone from air into the optical fibre. Calculate the wavelength of the light in the core of the optical fibre.

3. William and Jill are studying laser light of wavelength $\lambda = 530$ nm passing through a pair of slits. The light forms a pattern on a screen, several metres away, consisting of bright and dark fringes. The following diagram shows the experimental arrangement.



a. Calculate the frequency of the light emitted by the laser.
b. What is the path difference $|S_2X - S_1X|$? Give your answer in metres.
c. What is the path difference $|S_2W - S_1W|$? Give your answer in metres.
d. The slits are moved further apart. Describe what happens to the spread of the light pattern on the screen.

Julian, a friend of Jill, states, 'I am confused. The pattern on the screen is not what I would expect as there are only two slits and I'd expect there to be only two bright regions on the screen.'

e. Is the pattern on the screen evidence for the wave nature of light? Use your understanding to convince Julian that the pattern, as observed, is in the terms of properties associated with waves.

4. In the late nineteenth century, light was regarded as an electromagnetic wave because of the theoretical work done by James Maxwell.
a. Explain what is meant by the phrase 'electromagnetic wave'.
b. Explain why electromagnetic waves can be polarised and yet sound waves cannot, though both are a type of wave.

Consider four different types of electromagnetic waves:
γ-rays; radio waves; UV light; microwaves

c. Match each of the four types of electromagnetic waves with the wavelengths listed in the following table.

	wavelength (m)	electromagnetic wave type
i.	1×10^{3}	
ii.	1×10^{-2}	
iii.	1×10^{-12}	
iv.	1×10^{-8}	

d. Which one of the four categories of electromagnetic waves would diffract most significantly when propagating past a building?

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