Physics Units 1 & 2

Chapter 1 — Electromagnetic radiation and the wave model

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Chapter 1 Electromagnetic radiation and the wave model — 1A Describing waves: amplitude, wavelength, period and frequency

Theory

What a wave is. Drop a pebble into still water and a ring of ripples spreads out from where it landed. Flick one end of a skipping rope up and down and a bump travels along it to the other end. In each case a **disturbance** moves away from the place where it was created. The water at the surface moves up and down as the ripple passes, but it is not carried outward with the ring; a leaf floating on the pond simply bobs in place. What travels outward is **energy**, not matter.

A **wave** is a disturbance that travels and transfers energy from one place to another without transferring matter. The material the disturbance travels through is called the **medium** — for ripples the medium is water, for a rope wave the medium is the rope, and for sound the medium is the air. Later in this chapter the same ideas are applied to light and the rest of the electromagnetic spectrum.

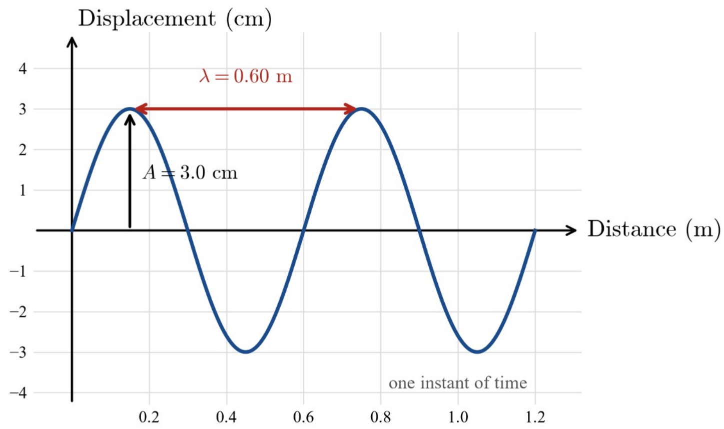
An **oscillation** (or vibration) is a repeated to-and-fro or up-and-down motion about a fixed position. A source that oscillates repeatedly produces a **periodic wave**: a wave whose pattern repeats itself at regular intervals, like the waves drawn in this section.

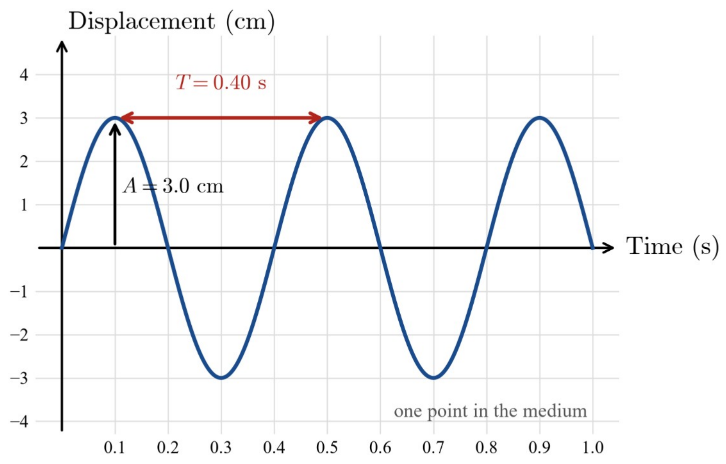
Displacement, crests and troughs. The **displacement** of a point in the medium is how far, and in which direction, that point is from its undisturbed (rest) position. On a water wave, a point at the top of its motion is at a **crest** and a point at the bottom is at a **trough**.

Two ways to draw a wave. There are two different graphs used to describe a wave, and they answer different questions.

- A **displacement–distance graph** is a snapshot of the whole wave at one instant of time. It shows how displacement varies with position along the wave.
- A **displacement–time graph** is the history of one single point in the medium. It shows how the displacement of that one point varies as time passes.

The four quantities used to describe any wave — amplitude, wavelength, period and frequency — are read from these two graphs.





Amplitude. The **amplitude**, A, is the maximum displacement of a point in the medium from its rest position — the height of a crest above the rest position, or the depth of a trough below it. Amplitude is measured in metres (m). The amplitude tells you the size of the disturbance: a wave with a larger amplitude carries more energy. On the snapshot graph above, the amplitude is read from the rest position (the axis) up to a crest.

Wavelength. The **wavelength**, λ (the Greek letter lambda), is the length of one complete copy of the repeating pattern. It is the distance between two neighbouring points that are in exactly the same state of oscillation — most easily, from one crest to the next crest, or from one trough to the next trough. Wavelength is measured in metres (m). The wavelength is read from a displacement–distance graph; it is *not* found on a displacement–time graph.

Period. The **period**, T, is the time taken for one complete oscillation at a point. On a displacement–time graph it is the time between two neighbouring crests (or two neighbouring troughs) at that point. Period is measured in seconds (s).

Frequency. The **frequency**, f, is the number of complete oscillations made each second. Frequency is measured in **hertz** (Hz): one hertz is one complete oscillation per second, so $1\,\mathrm{Hz} = 1\,\mathrm{s}^{-1}$. Frequency is read from a displacement–time graph by counting how many oscillations occur in a measured time.

Frequency and period describe the same oscillation, so they are reciprocals of each other:

$$f = \frac{1}{T} \text{ and } T = \frac{1}{f}.$$

A wave with a short period oscillates many times each second and has a high frequency; a wave with a long period oscillates few times each second and has a low frequency.

Quantity	Symbol	Unit	Meaning
Amplitude	A	metre (m)	maximum displacement from the rest position
Wavelength	λ	metre (m)	length of one complete wave pattern
Period	T	second (s)	time for one oscillation at a point
Frequency	f	hertz (Hz)	number of oscillations per second

The speed of a wave and the wave equation. The wave pattern itself travels along at the **speed of travel** of the wave, v, measured in metres per second ($\mathrm{m\ s}^{-1}$). In one period T the pattern moves forward by exactly one wavelength λ, so

$$v = \frac{\lambda}{T}.$$

Using $f = 1/T$ gives the **wave equation**:

$$v = f\lambda.$$

In the key knowledge of the study design this relationship is written in the equivalent form

$$\lambda = \frac{v}{f} = vT,$$

and $v = f\lambda$ also appears on the formula sheet. All four of v, f, λ and T can be calculated from it once the other quantities are known. The wave speed is the speed at which the *pattern* moves along — it is not the speed at which any one point of the medium moves up and down.

Units and SI multipliers. Physics calculations are done in SI units: metres for distance, seconds for time, hertz for frequency and $\mathrm{m\ s^{-1}}$ for speed. Real waves are often described using multiples and submultiples of these units, so you need to be fluent with the SI multipliers before substituting into any formula.

Prefix	Symbol	Multiplier
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}

For example, $1\,\mathrm{km} = 10^{3}\,\mathrm{m}$, $1\,\mathrm{MHz} = 10^{6}\,\mathrm{Hz}$, $1\,\mathrm{nm} = 10^{-9}\,\mathrm{m}$ and $1\,\mathrm{ms} = 10^{-3}\,\mathrm{s}$. Note that the symbol m is used both for the unit metre and for the prefix milli — the context, and the position of the symbol, tells you which is meant: mm is millimetres, $\mathrm{m\ s^{-1}}$ is metres per second.

A reliable routine for every calculation is: **(1)** convert every quantity to SI units first; **(2)** rearrange the equation for the unknown; **(3)** substitute the numbers with their units; **(4)** check that the unit of your answer is the unit expected.

Significant figures. Every measurement is a limited statement: an instrument can only ever tell you a value to some number of reliable digits. The reliable digits in a value are its **significant figures**. Calculations must not pretend to be more precise than the measurements they are built from, so significant figures must be handled consistently. The VCE Physics Study Design ("Terms used in this study", © VCAA) states: *"Significant figures should be considered in all calculations. The following guidelines apply to VCE Physics:"*

1. *"all digits in numbers expressed in standard form are significant, e.g.* 4.320×10^{-6} *has 4 significant figures"*
2. *"all non-zero numbers are significant, e.g.* 42.3 *has 3 significant figures"*
3. *"zeros between two non-zero numbers are significant, e.g.* 4.302 *has four significant figures"*
4. *"leading zeros are not significant, e.g.* 0.0043 *has 2 significant figures"*
5. *"trailing zeros to the right of a decimal point are significant, e.g.* 42.00 *has 4 significant figures"*
6. *"for numbers less than 1,* 0.4 *has 1 significant figure,* 0.04 *also has 1 significant figure whereas* 0.40 *has 2 significant figures and* 0.400 *has 3 significant figures"*
7. *"whole numbers written without a decimal point will have the same number of significant figures as the number of digits, with the assumption that the decimal point occurs at the end of the number, e.g.* 400 *has 3 significant figures. Therefore, a measured distance of* $100\,\mathrm{m}$ *will be considered as having three significant figures."*

(Standard form, also called scientific notation, writes a number as a value between 1 and 10 multiplied by a power of ten: for example $650\,000 = 6.5 \times 10^5$.)

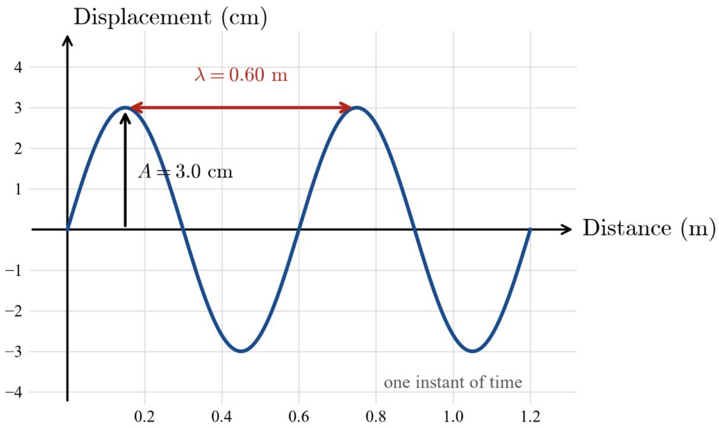
When you calculate with measured values, round your final answer to the same number of significant figures as the measured value with the *fewest* significant figures that you used. Exact numbers — counts such as “12 crests”, and defined conversion factors — do not limit the number of significant figures.

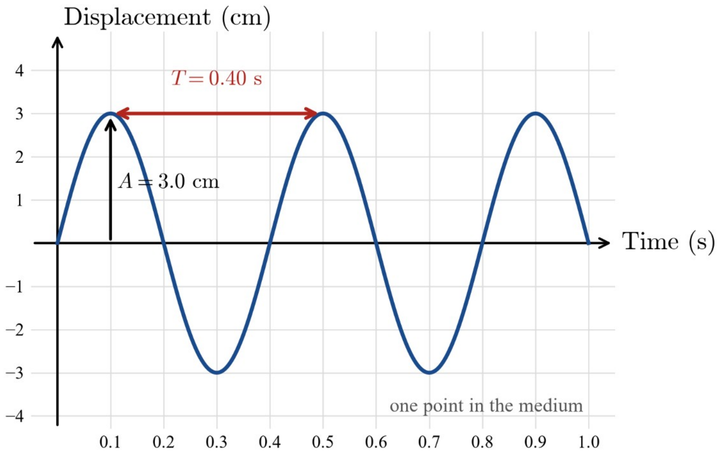
Units 3 & 4 preview. At Units 3 & 4 the wave model is applied to light, and the calculations there assume you can move fluently between wavelength and frequency using $v = f\lambda$, across many powers of ten, without revision of this section. Content under this banner is not assessed in this book’s topic tests or practice examinations.

Worked examples

Example 1 — scaffolded

A water wave in a ripple tank is shown in the two graphs below. The first is a snapshot of the wave at one instant of time; the second is the displacement–time graph of one point on the water surface as the wave passes.





(a) Identify the amplitude, wavelength and period of the wave.
(b) Calculate the frequency of the wave.
(c) Calculate the speed of travel of the wave.

Working	Comment
From the snapshot graph: $A = 3.0\,\text{cm}$, $\lambda = 0.60\,\text{m}$.	Amplitude is the maximum displacement from the rest position; wavelength is the distance from one crest to the next.
From the displacement–time graph: $T = 0.40\,\text{s}$.	Period is the time between two neighbouring crests at one point.
$f = \dfrac{1}{T} = \dfrac{1}{0.40} = 2.5\,\text{Hz}$	Frequency and period are reciprocals.

Working	Comment
$v = f\lambda = 2.5 \times 0.60 = 1.5\,\text{m s}^{-1}$	The wave equation. (Check: $v = \frac{\lambda}{T} = \frac{0.60}{0.40} = 1.5\,\text{m s}^{-1}$. ✓)

Note that the amplitude is not needed to find the speed: amplitude describes the size of the disturbance, while v, f, λ and T describe its timing and spacing.

Example 2 — scaffolded

The red light from a laser pointer has a wavelength of $650\,\text{nm}$. Light travels at $3.0 \times 10^{8}\,\text{m s}^{-1}$. Calculate the frequency of this light. Give your answer to two significant figures.

Working	Comment
$\lambda = 650\,\text{nm} = 650 \times 10^{-9}\,\text{m} = 6.5 \times 10^{-7}\,\text{m}$	Convert to SI units first: nano means 10^{-9}.
$v = f\lambda \Rightarrow f = \frac{v}{\lambda}$	Rearrange the wave equation for the unknown.
$f = \frac{3.0 \times 10^{8}}{6.5 \times 10^{-7}} = \frac{3.0}{6.5} \times 10^{8+7} = 0.46 \times 10^{15} = 4.6 \times 10^{14}\,\text{Hz}$	Divide the numbers and the powers of ten separately, then write the result in standard form.
$f = 4.6 \times 10^{14}\,\text{Hz}$ (2 significant figures)	Both values used have 2 significant figures, so the answer is rounded to 2.

Example 3 — unscaffolded

The note A above middle C — the tuning note an orchestra uses — has a frequency of $440\,\text{Hz}$. Sound travels through the air of the concert hall at about $340\,\text{m s}^{-1}$. Calculate (a) the wavelength of this sound in air and (b) its period. Give each answer to two significant figures.

The wavelength comes from the wave equation rearranged for λ:

$$\lambda = \frac{v}{f} = \frac{340}{440} = 0.7727\ldots\,\text{m}.$$

Rounding to two significant figures, $\lambda = 0.77\,\text{m}$. The period is the reciprocal of the frequency:

$$T = \frac{1}{f} = \frac{1}{440} = 0.00227\ldots\,\text{s} = 2.3 \times 10^{-3}\,\text{s},$$

again to two significant figures. (Check: $v = f\lambda = 440 \times 0.7727 = 340\,\text{m s}^{-1}$. ✓)

∴ the wavelength of the sound is $0.77\,\text{m}$ and its period is $2.3 \times 10^{-3}\,\text{s}$.

Example 4 — unscaffolded

ABC Radio Melbourne broadcasts AM radio at a frequency of $774\,\text{kHz}$. Radio waves travel at $3.00 \times 10^{8}\,\text{m s}^{-1}$. (a) Calculate the wavelength of the broadcast. (b) Calculate the period of one oscillation of the wave. Give each answer to three significant figures.

First convert the frequency to SI units: $774\,\text{kHz} = 774 \times 10^{3}\,\text{Hz} = 7.74 \times 10^{5}\,\text{Hz}$, since kilo means 10^{3}. The wavelength follows from the wave equation:

$$\lambda = \frac{v}{f} = \frac{3.00 \times 10^{8}}{7.74 \times 10^{5}} = \frac{3.00}{7.74} \times 10^{8-5} = 0.3876 \times 10^{3} = 388\,\text{m}$$

to three significant figures. The period is the reciprocal of the frequency:

$$T = \frac{1}{f} = \frac{1}{7.74 \times 10^{5}} = 1.29 \times 10^{-6}\,\mathrm{s}$$

to three significant figures. (Check: $v = f\lambda = 7.74 \times 10^{5} \times 387.6 = 3.00 \times 10^{8}\,\mathrm{m\ s^{-1}}$. ✓)

∴ the wavelength of the broadcast is $388\,\mathrm{m}$ and the period of one oscillation is $1.29 \times 10^{-6}\,\mathrm{s}$.

Practice questions

Question 1 A student shakes one end of a long rope up and down and sends a wave along it. A snapshot of the rope shows crests $2.0\,\mathrm{m}$ apart and a maximum displacement of $15\,\mathrm{cm}$. One point on the rope completes 4 oscillations in $5.0\,\mathrm{s}$. (a) Identify the amplitude and the wavelength of the wave. (b) Calculate the frequency of the wave. (c) Calculate the period of the wave. (d) Calculate the speed of travel of the wave.

Question 2 Convert the following to SI units. (a) $0.045\,\mathrm{m}$ to millimetres (b) $2.4\,\mathrm{GHz}$ to hertz (c) $620\,\mathrm{nm}$ to metres (d) $1500\,\mathrm{kHz}$ to megahertz

Question 3 (a) State the number of significant figures in each of the following: (i) 0.0340; (ii) 5.006; (iii) 2.4×10^{7}; (iv) 300; (v) 0.0006. (b) A student calculates 2.4×3.65 and writes 8.76. State the answer as it should be recorded, with the correct number of significant figures, and explain your reasoning.

Question 4 Water waves in a tank have a frequency of $5.0\,\mathrm{Hz}$ and a wavelength of $0.40\,\mathrm{m}$. (a) Calculate the period of the waves. (b) Calculate the speed of the waves. (c) Calculate the distance the wave pattern travels in $3.0\,\mathrm{s}$. (d) A small cork floats on the surface of the water. Describe the motion of the cork as the waves pass, and explain why the cork is not carried along with the waves.

Question 5 Sound travels through the air of a room at about $340\,\mathrm{m\ s^{-1}}$. A loudspeaker produces a note of frequency $170\,\mathrm{Hz}$. (a) Calculate the wavelength of the note. (b) Calculate the period of the note. (c) The loudspeaker then produces a note of frequency $340\,\mathrm{Hz}$. The speed of sound in the room is unchanged. Calculate the wavelength of the new note, and state what has happened to the wavelength compared with the first note.

Question 6 One point on a rope is watched as a wave passes. Its displacement reaches a maximum of $8.0\,\mathrm{cm}$ above the rest position at times $0.10\,\mathrm{s}$, $0.50\,\mathrm{s}$ and $0.90\,\mathrm{s}$. (a) Identify the period of the wave. (b) Calculate the frequency of the wave. (c) Identify the amplitude of the wave. (d) If the wavelength of the wave is $1.2\,\mathrm{m}$, calculate its speed of travel.

Question 7 The green light from a laser pointer has a wavelength of $532\,\mathrm{nm}$. Light travels at $3.00 \times 10^{8}\,\mathrm{m\ s^{-1}}$. Calculate the frequency of this light. Give your answer to three significant figures.

Question 8 A sound wave travelling through water has a period of $0.020\,\mathrm{s}$ and a speed of $1.5 \times 10^{3}\,\mathrm{m\ s^{-1}}$. (a) Calculate the frequency of the wave. (b) Calculate the wavelength of the wave.

Question 9 In deep ocean, a tsunami can have a wavelength of about $2.0 \times 10^{5}\,\mathrm{m}$ and travel at about $2.0 \times 10^{2}\,\mathrm{m\ s^{-1}}$. (a) Calculate the period of such a tsunami wave. (b) Calculate its frequency.

Question 10 Two students look at a displacement–distance graph of a wave. Student A says: "A point of the medium moves from one crest to the next, travelling one wavelength every period." Student B disagrees. State which student is correct, and explain your reasoning.

Question 11 A fishing boat at anchor rocks up and down as ocean swell passes, bobbing 6 times in $20\,\mathrm{s}$. (a) Calculate the frequency and the period of the swell. (b) A crew member says the swell will eventually push the boat towards the shore, since the waves are clearly moving that way. With reference to what a wave carries, explain why this reasoning is wrong.

Question 12 A student standing at the end of a pier counts 12 wave crests passing a post in $40\,\mathrm{s}$, and estimates the distance between neighbouring crests to be $6.0\,\mathrm{m}$. (a) Calculate the frequency of the waves. (b) State their wavelength. (c) Calculate the speed of the waves.

Question 13 A radio wave has a frequency of $40\,\mathrm{kHz}$. A student calculates its period and writes: "$T = 1/f = 1/40 = 0.025\,\mathrm{s}$". Identify the error in this working, and calculate the correct period.

Question 14 Violet light has a frequency of $7.5 \times 10^{14}\,\mathrm{Hz}$. Light travels at $3.0 \times 10^{8}\,\mathrm{m\,s^{-1}}$. Calculate the wavelength of violet light in metres, and then express your answer in nanometres. Give each answer to two significant figures.

Question 15 Two water waves, P and Q, have the same frequency and travel at the same speed, but wave P has twice the amplitude of wave Q. State what is different about the two waves and what is the same, and explain what the larger amplitude tells you about the energy carried by wave P.

Question 16 A student makes waves travel along a stretched spring by moving one end up and down. The end completes 20 oscillations in $5.0\,\mathrm{s}$, and the wavelength of the waves is measured to be $0.85\,\mathrm{m}$. Calculate the speed of the waves.

Question 17 A wave generator in a ripple tank produces waves of frequency $10\,\mathrm{Hz}$ and wavelength $3.0\,\mathrm{cm}$. The generator is then adjusted so that it produces waves of frequency $20\,\mathrm{Hz}$, and the speed of the waves is unchanged. Use calculations to justify what happens to the wavelength.

Question 18 Two corks float $4.0\,\mathrm{m}$ apart on a pond, in line with the direction in which waves are travelling. At one instant, one cork is at the top of a crest while the other is at the bottom of a trough, and there is no other crest or trough between them. (a) Deduce the wavelength of the waves. (b) If the frequency of the waves is $0.25\,\mathrm{Hz}$, calculate their speed.

Answers

Question 1 (a) $A = 15\,\text{cm}$, $\lambda = 2.0\,\text{m}$; (b) $0.80\,\text{Hz}$; (c) $1.3\,\text{s}$; (d) $1.6\,\text{m s}^{-1}$. **Question 2** (a) $45\,\text{mm}$; (b) $2.4 \times 10^{9}\,\text{Hz}$; (c) $6.2 \times 10^{-7}\,\text{m}$; (d) $1.5\,\text{MHz}$. **Question 3** (a) (i) 3; (ii) 4; (iii) 2; (iv) 3; (v) 1; (b) 8.8 — the value 2.4 has only 2 significant figures, so the answer is limited to 2. **Question 4** (a) $0.20\,\text{s}$; (b) $2.0\,\text{m s}^{-1}$; (c) $6.0\,\text{m}$; (d) see solution. **Question 5** (a) $2.0\,\text{m}$; (b) $0.0059\,\text{s}$; (c) $1.0\,\text{m}$ — the wavelength has halved. **Question 6** (a) $0.40\,\text{s}$; (b) $2.5\,\text{Hz}$; (c) $8.0\,\text{cm}$; (d) $3.0\,\text{m s}^{-1}$. **Question 7** $5.64 \times 10^{14}\,\text{Hz}$. **Question 8** (a) $50\,\text{Hz}$; (b) $30\,\text{m}$. **Question 9** (a) $1.0 \times 10^{3}\,\text{s}$ (about 17 minutes); (b) $1.0 \times 10^{-3}\,\text{Hz}$. **Question 10** Student B; see solution. **Question 11** (a) $0.30\,\text{Hz}$, $3.3\,\text{s}$; (b) see solution. **Question 12** (a) $0.30\,\text{Hz}$; (b) $6.0\,\text{m}$; (c) $1.8\,\text{m s}^{-1}$. **Question 13** The frequency was used in kHz instead of Hz; $T = 2.5 \times 10^{-5}\,\text{s}$. **Question 14** $4.0 \times 10^{-7}\,\text{m} = 400\,\text{nm}$. **Question 15** See solution. **Question 16** $3.4\,\text{m s}^{-1}$. **Question 17** The wavelength halves, from $3.0\,\text{cm}$ to $1.5\,\text{cm}$; see solution. **Question 18** (a) $8.0\,\text{m}$; (b) $2.0\,\text{m s}^{-1}$.

Fully-worked solutions

Question 1 $\lambda = 2.0\,\text{m}$, maximum displacement $15\,\text{cm}$, 4 oscillations in $5.0\,\text{s}$. (a) The amplitude is the maximum displacement from the rest position, so $A = 15\,\text{cm}$. The crests are $2.0\,\text{m}$ apart, so $\lambda = 2.0\,\text{m}$. (b) Frequency is the number of oscillations per second. The count of 4 is exact, so $f = \frac{4}{5.0} = 0.80\,\text{Hz}$ (2 significant figures). (c) $T = \frac{1}{f} = \frac{1}{0.80} = 1.25\,\text{s}$, which rounds to $1.3\,\text{s}$ (2 significant figures). (Equivalently, $T = \frac{5.0}{4} = 1.25\,\text{s}$.) (d) $v = f\lambda = 0.80 \times 2.0 = 1.6\,\text{m s}^{-1}$.

Question 2 (a) milli means 10^{-3}, so $1\,\text{m} = 10^{3}\,\text{mm}$: $0.045\,\text{m} = 0.045 \times 10^{3} = 45\,\text{mm}$. (b) giga means 10^{9}: $2.4\,\text{GHz} = 2.4 \times 10^{9}\,\text{Hz}$. (c) nano means 10^{-9}: $620\,\text{nm} = 620 \times 10^{-9}\,\text{m} = 6.2 \times 10^{-7}\,\text{m}$. (d) kilo means 10^{3} and mega means 10^{6}, so $1\,\text{MHz} = 10^{3}\,\text{kHz}$: $1500\,\text{kHz} = 1.5\,\text{MHz}$.

Question 3 (a) (i) 0.0340: the two leading zeros are not significant (rule 4); the digits 3, 4 and the final zero after the decimal point are (rules 2 and 5) — **3 significant figures**. (ii) 5.006: the two zeros sit between non-zero digits (rule 3) — **4 significant figures**. (iii) 2.4×10^{7}: all digits of a number in standard form are significant (rule 1) — **2 significant figures**. (iv) 300: a whole number written without a decimal point has as many significant figures as digits (rule 7) — **3 significant figures**. (v) 0.0006: the leading zeros are not significant; only the 6 is — **1 significant figure**. (b) $2.4 \times 3.65 = 8.76$ on the calculator, but 2.4 has only 2 significant figures while 3.65 has 3, so the answer is limited to 2 significant figures: 8.8.

Question 4 $f = 5.0\,\text{Hz}$, $\lambda = 0.40\,\text{m}$. (a) $T = \frac{1}{f} = \frac{1}{5.0} = 0.20\,\text{s}$. (b) $v = f\lambda = 5.0 \times 0.40 = 2.0\,\text{m s}^{-1}$. (c) distance $= vt = 2.0 \times 3.0 = 6.0\,\text{m}$. (d) The cork bobs up and down about one fixed spot on the surface as the waves pass; it is not carried along with the wave pattern. A wave transfers energy from one place to another without transferring matter: the water (and the cork floating in it) oscillates locally, while only the disturbance and its energy travel on.

Question 5 $v = 340\,\text{m s}^{-1}$, $f = 170\,\text{Hz}$. (a) $\lambda = \frac{v}{f} = \frac{340}{170} = 2.0\,\text{m}$. (b) $T = \frac{1}{f} = \frac{1}{170} = 0.0059\,\text{s}$ (2 significant figures). (c) With the speed unchanged, $\lambda = \frac{v}{f} = \frac{340}{340} = 1.0\,\text{m}$. The frequency has doubled, so the wavelength has halved: at a fixed speed, $v = f\lambda$ means wavelength and frequency are in inverse proportion.

Question 6 Maxima at $0.10\,\text{s}$, $0.50\,\text{s}$, $0.90\,\text{s}$; maximum displacement $8.0\,\text{cm}$. (a) Neighbouring maxima are separated by one period: $T = 0.50 - 0.10 = 0.40\,\text{s}$. (Check: $0.90 - 0.50 = 0.40\,\text{s}$. ✓) (b) $f = \frac{1}{T} = \frac{1}{0.40} = 2.5\,\text{Hz}$. (c) The amplitude is the maximum displacement from the rest position: $A = 8.0\,\text{cm}$. (d) $v = f\lambda = 2.5 \times 1.2 = 3.0\,\text{m s}^{-1}$.

Question 7 $\lambda = 532\,\text{nm} = 532 \times 10^{-9}\,\text{m} = 5.32 \times 10^{-7}\,\text{m}$; $v = 3.00 \times 10^{8}\,\text{m s}^{-1}$.

$$f = \frac{v}{\lambda} = \frac{3.00 \times 10^8}{5.32 \times 10^{-7}} = \frac{3.00}{5.32} \times 10^{8+7} = 0.5639 \times 10^{15} = 5.64 \times 10^{14}\,\mathrm{Hz}$$

to three significant figures. (Check: $v = f\lambda = 5.639 \times 10^{14} \times 5.32 \times 10^{-7} = 3.00 \times 10^8\,\mathrm{m\,s^{-1}}$. ✓)

Question 8 $T = 0.020\,\mathrm{s}$, $v = 1.5 \times 10^3\,\mathrm{m\,s^{-1}}$. (a) $f = \frac{1}{T} = \frac{1}{0.020} = 50\,\mathrm{Hz}$. (b) $\lambda = vT = 1.5 \times 10^3 \times 0.020 = 30\,\mathrm{m}$. (Equivalently, $\lambda = \frac{v}{f} = \frac{1.5 \times 10^3}{50} = 30\,\mathrm{m}$. ✓)

Question 9 $\lambda = 2.0 \times 10^5\,\mathrm{m}$, $v = 2.0 \times 10^2\,\mathrm{m\,s^{-1}}$. (a) $\lambda = vT$, so $T = \frac{\lambda}{v} = \frac{2.0 \times 10^5}{2.0 \times 10^2} = 1.0 \times 10^3\,\mathrm{s}$ — about 17 minutes between successive crests. (b) $f = \frac{1}{T} = \frac{1}{1.0 \times 10^3} = 1.0 \times 10^{-3}\,\mathrm{Hz}$. The very low frequency matches the very long period: a tsunami oscillates on a time scale of minutes, not the fractions of a second of ordinary water waves.

Question 10 Student B is correct. A point of the medium does not travel along with the wave: it oscillates about one fixed position, returning to where it started once every period. What moves forward is the wave *pattern* — the positions of the crests and troughs — carrying energy with it. In one period the pattern advances one wavelength, which is probably what Student A has half-noticed; but it is the pattern that advances that distance, not any point of the medium. Waves transfer energy without transferring matter.

Question 11 6 oscillations in $20\,\mathrm{s}$ (the count of 6 is exact). (a) $f = \frac{6}{20} = 0.30\,\mathrm{Hz}$; $T = \frac{1}{f} = \frac{1}{0.30} = 3.3\,\mathrm{s}$ (2 significant figures). (b) A wave transfers energy through the water without transferring the water itself: the surface moves in local oscillations while the disturbance travels on. The boat, like a floating cork, bobs about one spot as the swell passes; the energy of the swell moves towards the shore, but the water beneath the boat is not carried there, so the swell does not steadily push the boat in.

Question 12 12 crests in $40\,\mathrm{s}$ (the count of 12 is exact); crest spacing $6.0\,\mathrm{m}$. (a) $f = \frac{12}{40} = 0.30\,\mathrm{Hz}$. (b) The distance between neighbouring crests is the wavelength: $\lambda = 6.0\,\mathrm{m}$. (c) $v = f\lambda = 0.30 \times 6.0 = 1.8\,\mathrm{m\,s^{-1}}$.

Question 13 The error is a unit error: the student substituted the frequency as 40, keeping it in kHz, but the period in seconds requires the frequency in hertz. $40\,\mathrm{kHz} = 40 \times 10^3\,\mathrm{Hz} = 4.0 \times 10^4\,\mathrm{Hz}$, so

$$T = \frac{1}{f} = \frac{1}{4.0 \times 10^4} = 2.5 \times 10^{-5}\,\mathrm{s}$$

to two significant figures — one thousand times shorter than the student's value. (Check: converting every quantity to SI units before substituting would have prevented the mistake.)

Question 14 $f = 7.5 \times 10^{14}\,\mathrm{Hz}$, $v = 3.0 \times 10^8\,\mathrm{m\,s^{-1}}$.

$$\lambda = \frac{v}{f} = \frac{3.0 \times 10^8}{7.5 \times 10^{14}} = \frac{3.0}{7.5} \times 10^{8-14} = 0.40 \times 10^{-6} = 4.0 \times 10^{-7}\,\mathrm{m}$$

to two significant figures. Converting to nanometres: $4.0 \times 10^{-7}\,\mathrm{m} = 4.0 \times 10^{-7} \times 10^9\,\mathrm{nm} = 4.0 \times 10^2\,\mathrm{nm} = 400\,\mathrm{nm}$.

Question 15 The same: the two waves have the same frequency (given) and the same speed (given), so they must also have the same wavelength, since $\lambda = v/f$. The different: wave P has twice the amplitude of wave Q, so points of the medium in wave P reach twice the maximum displacement from the rest position — its crests are twice as high and its troughs twice as deep. The larger amplitude means wave P carries more energy than wave Q: amplitude is the measure of the size of the disturbance, and a larger disturbance transfers more energy.

Question 16 20 oscillations in $5.0\,\text{s}$ (the count of 20 is exact); $\lambda = 0.85\,\text{m}$. $f = \frac{20}{5.0} = 4.0\,\text{Hz}$. Then $v = f\lambda = 4.0 \times 0.85 = 3.4\,\text{m s}^{-1}$.

Question 17 First find the speed of the waves from the generator's original setting, converting the wavelength to metres: $\lambda_1 = 3.0\,\text{cm} = 0.030\,\text{m}$.

$$v = f_1\lambda_1 = 10 \times 0.030 = 0.30\,\text{m s}^{-1}.$$

The speed is unchanged, so for the new frequency $f_2 = 20\,\text{Hz}$:

$$\lambda_2 = \frac{v}{f_2} = \frac{0.30}{20} = 0.015\,\text{m} = 1.5\,\text{cm}.$$

The wavelength halves, from $3.0\,\text{cm}$ to $1.5\,\text{cm}$. This is what $v = f\lambda$ requires when v is constant: doubling the frequency must halve the wavelength.

Question 18 (a) A crest and the neighbouring trough are separated by half a wavelength. The corks are $4.0\,\text{m}$ apart with no other crest or trough between them, so $\frac{\lambda}{2} = 4.0\,\text{m}$, giving $\lambda = 8.0\,\text{m}$. (b) $v = f\lambda = 0.25 \times 8.0 = 2.0\,\text{m s}^{-1}$.

Theory

Waves so far. In Section 1A every wave was described with the same four quantities — amplitude, wavelength λ, period T and frequency f — linked by the wave relationship $\lambda = v / f = v\,T$, where v is the speed of the wave. That model is not limited to waves on ropes or springs. This section applies it to light and to the much larger family of waves that light belongs to: **electromagnetic waves**.

What an electromagnetic wave is. An electromagnetic wave is a travelling disturbance made up of an oscillating (repeatedly changing) **electric field** and an oscillating **magnetic field** that move together through space. A **field** is a way of describing a physical influence spread through a region of space: an electric field is a region in which electric charges experience a force, and a magnetic field is a region in which magnets experience a force. In an electromagnetic wave the electric field oscillates in one direction, the magnetic field oscillates at right angles to it, and both are at right angles to the direction in which the wave is travelling.

Because the oscillations are at right angles to the direction of travel, all electromagnetic waves are **transverse waves**. This contrasts with a **longitudinal wave**, such as a sound wave, in which the oscillations are back and forth *along* the direction of travel.

No medium is needed. A **medium** is the material through which a wave travels. Mechanical waves — sound waves, water waves, and waves on a rope or a spring — are oscillations *of* a medium: if there is no matter to oscillate, there is no wave. A ringing bell inside a jar goes silent when the air is pumped out, and no sound travels through the emptiness of space. Electromagnetic waves are different. Because electric and magnetic fields can exist in empty space, electromagnetic waves **do not require a medium** and can propagate (travel) through a **vacuum**, a region containing no matter at all. This is how energy from the Sun reaches the Earth across empty space. It is also why astronauts on a spacewalk can see one another perfectly well but must still talk by radio: light crosses the vacuum, while sound cannot.

The speed of electromagnetic waves. In a vacuum, *all* electromagnetic waves — radio waves, visible light, X-rays and everything in between — travel at exactly the same speed, the **speed of light**, c:

$$c = 3.00 \times 10^{8}\ \mathrm{m\ s^{-1}}.$$

That is about $300\,000\ \mathrm{km}$ every second, fast enough to circle the Earth about seven and a half times in one second. Electromagnetic waves travel slightly more slowly through matter such as air, water and glass, but air slows them so little that in this course the speed in air is also taken to be c. (How the change in speed at a boundary between two materials bends light is taken up in Section 1C.)

Because electromagnetic waves are waves, the wave relationship of Section 1A applies to them. In a vacuum, and to a very good approximation in air,

$$c = f\,\lambda,$$

so that

$$f = \frac{c}{\lambda} \text{ and } \lambda = \frac{c}{f}.$$

Because c is a fixed value, frequency and wavelength are locked together: the longer the wavelength, the lower the frequency, and the shorter the wavelength, the higher the frequency.

Frequency is measured in **hertz** (Hz), where $1\ \mathrm{Hz}$ is one oscillation per second. Across the electromagnetic spectrum the numbers become very large or very small, so the SI prefixes are used:

Prefix	Symbol	Multiplier
giga	G	10^{9}

Prefix	Symbol	Multiplier
mega	M	10^{6}
kilo	k	10^{3}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}

For example, $2.45\,\text{GHz} = 2.45 \times 10^{9}\,\text{Hz}$, $774\,\text{kHz} = 774 \times 10^{3}\,\text{Hz}$, and $550\,\text{nm} = 550 \times 10^{-9}\,\text{m} = 5.50 \times 10^{-7}\,\text{m}$.

The electromagnetic spectrum. Radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays are all electromagnetic waves. They differ from one another *only* in their wavelength and frequency. Together they make up the **electromagnetic spectrum**, which spans more than ten orders of magnitude in wavelength. The table lists the seven regions in order of increasing frequency (which is the same as decreasing wavelength). The boundaries are approximate: neighbouring regions blend into one another, and different sources quote slightly different values.

Region	Typical wavelength range	Typical frequency range
Radio	longer than about $10^{-1}\,\text{m}$	below about $3 \times 10^{9}\,\text{Hz}$
Microwave	$10^{-3}\,\text{m}$–$10^{-1}\,\text{m}$	3×10^{9}–$3 \times 10^{11}\,\text{Hz}$
Infrared	$7 \times 10^{-7}\,\text{m}$–$10^{-3}\,\text{m}$	3×10^{11}–$4 \times 10^{14}\,\text{Hz}$
Visible	$4 \times 10^{-7}\,\text{m}$–$7 \times 10^{-7}\,\text{m}$	4×10^{14}–$7.5 \times 10^{14}\,\text{Hz}$
Ultraviolet	$10^{-8}\,\text{m}$–$4 \times 10^{-7}\,\text{m}$	7.5×10^{14}–$3 \times 10^{16}\,\text{Hz}$
X-ray	$10^{-11}\,\text{m}$–$10^{-8}\,\text{m}$	3×10^{16}–$3 \times 10^{19}\,\text{Hz}$
Gamma	shorter than about $10^{-11}\,\text{m}$	above about $3 \times 10^{19}\,\text{Hz}$

Visible light is only a very narrow slice of the spectrum. Within it, red light has the longest wavelength (about $7 \times 10^{-7}\,\text{m}$) and the lowest frequency, and violet light has the shortest wavelength (about $4 \times 10^{-7}\,\text{m}$) and the highest frequency, with orange, yellow, green and blue in between.

Uses in society. Each region of the spectrum is put to work in everyday life. Some of the most important uses are:

Region	Uses in society
Radio	radio and television broadcasting; communication with ships, aircraft and emergency services
Microwave	mobile phones and Wi-Fi; satellite communication and radar; microwave ovens
Infrared	remote controls; heaters and heat lamps; thermal imaging cameras, which form pictures from the infrared radiation given out by warm objects; signals carried along optical fibres (Section 1E)
Visible	human vision; lighting; photography
Ultraviolet	sterilising drinking water and surfaces; security inks that glow when lit by ultraviolet lamps
X-ray	medical imaging, for example checking for broken bones; security scanners at airports
Gamma	treating cancer by destroying tumours; sterilising medical instruments

The higher-frequency regions can damage living tissue. Too much ultraviolet exposure burns the skin and can damage the eyes, which is why sun protection matters. X-rays and gamma rays can pass through matter and harm cells inside the body, so their medical and industrial uses are carefully controlled with shielding and short exposure times.

Electromagnetic radiation from the Sun. The Sun gives out electromagnetic radiation across almost the whole spectrum, but the radiation it emits is **mainly ultraviolet, visible and infrared**. The largest share of this energy is infrared, but per unit wavelength the Sun's output peaks in the visible — our eyes detect the very region of the spectrum that the Sun emits most strongly. The infrared in sunlight is felt as warmth on the skin, and most of the Sun's ultraviolet radiation is absorbed by ozone high in the atmosphere before it reaches the surface. Chapter 2 returns to the question of how warm objects give out electromagnetic radiation, and how an object's temperature decides which part of the spectrum most of its radiation falls in.

Mechanical and electromagnetic waves compared.

	Mechanical waves	Electromagnetic waves
What oscillates	particles of the medium	electric and magnetic fields
Needs a medium?	yes — cannot travel through a vacuum	no — can travel through a vacuum
Speed in a vacuum	cannot travel there	$c = 3.00 \times 10^{8}\,\mathrm{m\ s^{-1}}$
Wave type	may be transverse (waves on a rope) or longitudinal (sound)	always transverse
Examples	sound, water waves, waves on a rope or spring	radio waves, microwaves, visible light, X-rays, gamma rays

Throughout this subtopic the speed of electromagnetic waves in a vacuum, and in air, is taken as $c = 3.00 \times 10^{8}\,\mathrm{m\ s^{-1}}$.

Worked examples

Example 1 — scaffolded

A green laser pointer used in a school physics laboratory emits light of wavelength $532\,\mathrm{nm}$. Calculate the frequency of this light.

Working	Comment
$\lambda = 532\,\mathrm{nm} = 532 \times 10^{-9}\,\mathrm{m} = 5.32 \times 10^{-7}\,\mathrm{m}$.	Convert nanometres to metres: $1\,\mathrm{nm} = 10^{-9}\,\mathrm{m}$.
$c = f\,\lambda$, so rearrange to $f = \dfrac{c}{\lambda}$.	In air, light travels at (very nearly) $c = 3.00 \times 10^{8}\,\mathrm{m\ s^{-1}}$.
$f = \dfrac{3.00 \times 10^{8}}{5.32 \times 10^{-7}} = 5.64 \times 10^{14}\,\mathrm{Hz}$.	$\dfrac{3.00}{5.32} = 0.564$ and $\dfrac{10^{8}}{10^{-7}} = 10^{15}$, giving $0.564 \times 10^{15} = 5.64 \times 10^{14}$, to three significant figures.

The frequency is $5.64 \times 10^{14}\,\mathrm{Hz}$ — several hundred trillion oscillations every second.

Example 2 — scaffolded

ABC Radio Melbourne broadcasts AM radio at a frequency of $774\,\mathrm{kHz}$. Calculate the wavelength of the broadcast waves.

Source: Australian Broadcasting Corporation, ABC Radio Melbourne broadcast frequency (774 kHz AM, callsign 3LO), retrieved 2026-08-18.

Working	Comment
$f = 774\,\mathrm{kHz} = 774 \times 10^{3}\,\mathrm{Hz} = 7.74 \times 10^{5}\,\mathrm{Hz}$.	Convert kilohertz to hertz: kilo means 10^{3}.

Working	Comment
$\lambda = \frac{c}{f}$.	Rearrange $c = f\lambda$.
$\lambda = \frac{3.00\times10^{8}}{7.74\times10^{5}} = 388\,\mathrm{m}$, to three significant figures.	AM radio waves are hundreds of metres long.

For comparison, FM radio broadcasts at frequencies near $100\,\mathrm{MHz}$, giving wavelengths of only about $3\,\mathrm{m}$. Lower frequency means longer wavelength, because the speed c is the same for both.

Example 3 — unscaffolded

The mean distance from the Earth to the Sun is about $1.5\times10^{11}\,\mathrm{m}$. Calculate the time taken for sunlight to reach the Earth, in seconds and in minutes. How long would a radio signal from a spacecraft at the same distance take to reach us?

The speed of all electromagnetic waves in a vacuum is $c = 3.00\times10^{8}\,\mathrm{m\ s^{-1}}$, and speed $= \frac{\text{distance}}{\text{time}}$, so

$$t = \frac{d}{c} = \frac{1.5\times10^{11}}{3.00\times10^{8}} = 5.0\times10^{2}\,\mathrm{s}.$$

Converting to minutes, $t = \frac{500}{60} = 8.3\,\mathrm{min}$. Radio waves are electromagnetic waves too, so they travel at the same speed c; a radio signal from the same distance would also take $500\,\mathrm{s}$. When we look at the Sun we see it not as it is now, but as it was a little over eight minutes ago.

∴ the light takes $5.0\times10^{2}\,\mathrm{s}$ ($8.3\,\mathrm{min}$), and a radio signal takes the same time.

Example 4 — unscaffolded

A microwave oven heats food using electromagnetic waves of frequency $2.45\,\mathrm{GHz}$. (a) Calculate the wavelength of these waves. (b) The oven door has a window with a fine metal mesh in it. The holes in the mesh are only a millimetre or so across. Explain why the microwaves do not pass through the mesh and escape, while visible light does pass through it, so the food can be seen.

(a) Using $\lambda = \frac{c}{f}$ with $f = 2.45\,\mathrm{GHz} = 2.45\times10^{9}\,\mathrm{Hz}$:

$$\lambda = \frac{3.00\times10^{8}}{2.45\times10^{9}} = 0.122\,\mathrm{m} = 12.2\,\mathrm{cm},$$

to three significant figures.

(b) Waves do not pass effectively through openings that are much smaller than their wavelength. The $12.2\,\mathrm{cm}$ microwaves meet millimetre-sized holes, far smaller than one wavelength, so they are kept inside the oven. Visible light has a wavelength of only a few hundred nanometres, thousands of times smaller than the holes, so it passes straight through and the food can be seen.

Practice questions

Question 1 Violet light has a wavelength of $400\,\mathrm{nm}$ and red light a wavelength of $700\,\mathrm{nm}$. (a) Convert each wavelength into metres. (b) Calculate the frequency of violet light. (c) Calculate the frequency of red light, and state which colour has the higher frequency.

Question 2 An FM radio station broadcasts at a frequency of $100.0\,\mathrm{MHz}$. (a) Express this frequency in hertz. (b) Calculate the wavelength of the broadcast waves. (c) An AM station broadcasts at $1000\,\mathrm{kHz}$. Calculate its wavelength and compare it with the FM wavelength.

Question 3 A microwave oven uses electromagnetic waves of frequency $2.45\,\mathrm{GHz}$. (a) Write this frequency in hertz. (b) Calculate the wavelength of the waves. (c) The oven door contains a metal mesh with holes about a millimetre across. Explain why the microwaves do not pass through the mesh, while visible light does.

Question 4 The mean distance from the Earth to the Sun is about $1.5 \times 10^{11}\,\mathrm{m}$. (a) State the speed of light in a vacuum. (b) Calculate the time taken for sunlight to reach the Earth. (c) Calculate the distance travelled by light in $1.0\,\mathrm{s}$.

Question 5 Consider the following waves: a sound wave, a radio wave, a wave on a rope, a microwave, visible light and a water wave. (a) Sort the list into electromagnetic waves and mechanical waves. (b) State what the waves in the mechanical group have in common regarding what they need in order to travel. (c) State the speed of every electromagnetic wave in a vacuum.

Question 6 (a) List the seven regions of the electromagnetic spectrum in order of increasing frequency. (b) Identify the region with the longest wavelengths. (c) Compare infrared radiation with ultraviolet radiation: which has the shorter wavelength, and which has the lower frequency?

Question 7 A helium–neon laser of the kind used in school laboratories emits red light of wavelength $633\,\mathrm{nm}$. Calculate the frequency of this light.

Question 8 An Australian 4G mobile phone signal has a frequency of about $2.6\,\mathrm{GHz}$. Calculate the wavelength of the signal.

Question 9 A digital television broadcast has a wavelength of $1.5\,\mathrm{m}$. Calculate the frequency of the broadcast, and express your answer in megahertz.

Question 10 X-rays used for medical imaging can have wavelengths around $0.050\,\mathrm{nm}$. Calculate the frequency of such X-rays.

Question 11 The mean distance from the Earth to the Moon is about $3.84 \times 10^{8}\,\mathrm{m}$. Mission control on Earth sends a radio signal to a spacecraft orbiting the Moon. Calculate the time taken for the signal to reach the spacecraft.

Question 12 A mobile phone network operates in two bands, at $900\,\mathrm{MHz}$ and at $1.8\,\mathrm{GHz}$. Calculate the wavelength of the signal in each band, and identify which band has the shorter wavelength.

Question 13 The Sun is surrounded by the near-vacuum of space. Explain why light from the Sun reaches the Earth, but sound produced at the Sun's surface could never reach us.

Question 14 A classmate says, "Radio waves must be sound waves, because a radio plays sound." Identify two physics errors in this statement.

Question 15 All electromagnetic waves travel at the same speed c in a vacuum. Use the relationship $c = f\lambda$ to explain what happens to the frequency of an electromagnetic wave as its wavelength becomes shorter, and hence justify why X-rays have a much higher frequency than microwaves.

Question 16 Radio waves, visible light, X-rays and gamma rays have very different uses and are often talked about as if they were completely different things. Justify the claim that they are, in fact, all the same kind of wave.

Question 17 Explain why X-rays, rather than visible light, are used to produce images of broken bones, and state one precaution taken when a patient is X-rayed.

Question 18 (a) Describe the electromagnetic radiation emitted by the Sun, naming the three main regions of the spectrum involved. (b) Explain why only a small fraction of the Sun's ultraviolet radiation reaches the Earth's surface.

Answers

Question 1 (a) $4.00\times10^{-7}\,\mathrm{m}$, $7.00\times10^{-7}\,\mathrm{m}$; (b) $7.50\times10^{14}\,\mathrm{Hz}$; (c) $4.29\times10^{14}\,\mathrm{Hz}$; violet light has the higher frequency. **Question 2** (a) $1.000\times10^{8}\,\mathrm{Hz}$; (b) $3.00\,\mathrm{m}$; (c) $300\,\mathrm{m}$, one hundred times longer than the FM wavelength. **Question 3** (a) $2.45\times10^{9}\,\mathrm{Hz}$; (b) $0.122\,\mathrm{m}$ ($12.2\,\mathrm{cm}$); (c) the holes are far smaller than the microwave wavelength but far larger than the wavelength of visible light. **Question 4** (a) $3.00\times10^{8}\,\mathrm{m\ s^{-1}}$; (b) $5.0\times10^{2}\,\mathrm{s}$; (c) $3.0\times10^{8}\,\mathrm{m}$. **Question 5** (a) electromagnetic: radio wave, microwave, visible light; mechanical: sound wave, wave on a rope, water wave; (b) they all require a medium; (c) $3.00\times10^{8}\,\mathrm{m\ s^{-1}}$. **Question 6** (a) radio, microwave, infrared, visible, ultraviolet, X-ray, gamma; (b) radio; (c) ultraviolet has the shorter wavelength; infrared has the lower frequency. **Question 7** $4.74\times10^{14}\,\mathrm{Hz}$. **Question 8** $0.12\,\mathrm{m}$. **Question 9** $2.0\times10^{8}\,\mathrm{Hz}=200\,\mathrm{MHz}$. **Question 10** $6.0\times10^{18}\,\mathrm{Hz}$. **Question 11** $1.28\,\mathrm{s}$. **Question 12** $900\,\mathrm{MHz}$: $0.33\,\mathrm{m}$; $1.8\,\mathrm{GHz}$: $0.17\,\mathrm{m}$; the $1.8\,\mathrm{GHz}$ band has the shorter wavelength. **Question 13** Light is an electromagnetic wave and needs no medium; sound is a mechanical wave and cannot cross a vacuum. **Question 14** Radio waves are electromagnetic, not mechanical, and need no medium; the sound from the speaker is made by the loudspeaker, not carried from the station by the radio wave. **Question 15** Since c is fixed, f must rise as λ falls; X-ray wavelengths are billions of times shorter than microwave wavelengths, so their frequencies are billions of times higher. **Question 16** All are transverse oscillations of electric and magnetic fields, need no medium, and travel at the same speed c in a vacuum; they differ only in wavelength and frequency. **Question 17** X-rays pass through soft tissue but are absorbed by bone, while visible light does not pass through the body; for example, the rest of the body is shielded or the exposure is kept as short as possible. **Question 18** (a) Mainly ultraviolet, visible and infrared; (b) most of the ultraviolet is absorbed by ozone high in the atmosphere.

Fully-worked solutions

Question 1 $\lambda_{\text{violet}}=400\,\mathrm{nm}$, $\lambda_{\text{red}}=700\,\mathrm{nm}$, $c=3.00\times10^{8}\,\mathrm{m\ s^{-1}}$. (a) Since $1\,\mathrm{nm}=10^{-9}\,\mathrm{m}$: $400\,\mathrm{nm}=400\times10^{-9}\,\mathrm{m}=4.00\times10^{-7}\,\mathrm{m}$ and $700\,\mathrm{nm}=7.00\times10^{-7}\,\mathrm{m}$. (b) $f=\dfrac{c}{\lambda}=\dfrac{3.00\times10^{8}}{4.00\times10^{-7}}=7.50\times10^{14}\,\mathrm{Hz}$. (c) $f=\dfrac{c}{\lambda}=\dfrac{3.00\times10^{8}}{7.00\times10^{-7}}=4.29\times10^{14}\,\mathrm{Hz}$. Violet light has the shorter wavelength, so it has the higher frequency.

Question 2 $c=3.00\times10^{8}\,\mathrm{m\ s^{-1}}$. (a) $100.0\,\mathrm{MHz}=100.0\times10^{6}\,\mathrm{Hz}=1.000\times10^{8}\,\mathrm{Hz}$. (b) $\lambda=\dfrac{c}{f}=\dfrac{3.00\times10^{8}}{1.000\times10^{8}}=3.00\,\mathrm{m}$. (c) $1000\,\mathrm{kHz}=1.000\times10^{6}\,\mathrm{Hz}$, so $\lambda=\dfrac{3.00\times10^{8}}{1.000\times10^{6}}=300\,\mathrm{m}$. The AM wavelength is one hundred times longer than the FM wavelength, because the AM frequency is one hundred times lower and both travel at the same speed c.

Question 3 $f=2.45\,\mathrm{GHz}=2.45\times10^{9}\,\mathrm{Hz}$. (a) $2.45\,\mathrm{GHz}=2.45\times10^{9}\,\mathrm{Hz}$. (b) $\lambda=\dfrac{c}{f}=\dfrac{3.00\times10^{8}}{2.45\times10^{9}}=0.122\,\mathrm{m}=12.2\,\mathrm{cm}$. (c) Waves do not pass effectively through openings much smaller than their wavelength. The millimetre-sized holes are far smaller than the $12.2\,\mathrm{cm}$ microwave wavelength, so the microwaves are kept inside the oven. Visible light has a wavelength of only a few hundred nanometres, far smaller than the holes, so it passes through and the food can be seen.

Question 4 $d=1.5\times10^{11}\,\mathrm{m}$. (a) The speed of light in a vacuum is $c=3.00\times10^{8}\,\mathrm{m\ s^{-1}}$. (b) $t=\dfrac{d}{c}=\dfrac{1.5\times10^{11}}{3.00\times10^{8}}=5.0\times10^{2}\,\mathrm{s}$ (about 8.3 minutes). (c) distance $=c\times t=3.00\times10^{8}\times1.0=3.0\times10^{8}\,\mathrm{m}$.

Question 5 (a) Electromagnetic waves: the radio wave, the microwave and visible light. Mechanical waves: the sound wave, the wave on a rope and the water wave. (b) Every mechanical wave requires a medium — matter to oscillate — in order to travel; none can travel through a vacuum. (c) Every electromagnetic wave travels at $c=3.00\times10^{8}\,\mathrm{m\ s^{-1}}$ in a vacuum.

Question 6 (a) In order of increasing frequency: radio, microwave, infrared, visible, ultraviolet, X-ray, gamma. (b) Radio waves have the longest wavelengths (frequency and wavelength increase and decrease in opposite directions because $c = f\lambda$ with c fixed). (c) Ultraviolet radiation has the shorter wavelength (it sits on the high-frequency side of visible light, while infrared sits on the low-frequency side). Infrared radiation has the lower frequency.

Question 7 $\lambda = 633\,\text{nm} = 6.33 \times 10^{-7}\,\text{m}$.

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}}{6.33 \times 10^{-7}} = 4.74 \times 10^{14}\,\text{Hz},$$

to three significant figures.

Question 8 $f = 2.6\,\text{GHz} = 2.6 \times 10^{9}\,\text{Hz}$.

$$\lambda = \frac{c}{f} = \frac{3.00 \times 10^{8}}{2.6 \times 10^{9}} = 0.12\,\text{m},$$

to two significant figures.

Question 9 $\lambda = 1.5\,\text{m}$.

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}}{1.5} = 2.0 \times 10^{8}\,\text{Hz}.$$

Since mega means 10^{6}, this is $2.0 \times 10^{8}\,\text{Hz} = 200\,\text{MHz}$, to two significant figures.

Question 10 $\lambda = 0.050\,\text{nm} = 0.050 \times 10^{-9}\,\text{m} = 5.0 \times 10^{-11}\,\text{m}$.

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}}{5.0 \times 10^{-11}} = 6.0 \times 10^{18}\,\text{Hz},$$

to two significant figures — about ten thousand times higher than the frequency of visible light.

Question 11 $d = 3.84 \times 10^{8}\,\text{m}$. Radio waves are electromagnetic waves, so they travel at c:

$$t = \frac{d}{c} = \frac{3.84 \times 10^{8}}{3.00 \times 10^{8}} = 1.28\,\text{s},$$

to three significant figures.

Question 12 Using $\lambda = \dfrac{c}{f}$:

$$900\,\text{MHz}: \lambda = \frac{3.00 \times 10^{8}}{9.0 \times 10^{8}} = 0.33\,\text{m};$$

$$1.8\,\text{GHz}: \lambda = \frac{3.00 \times 10^{8}}{1.8 \times 10^{9}} = 0.17\,\text{m}.$$

Both answers are to two significant figures. The $1.8\,\text{GHz}$ band has the higher frequency and therefore the shorter wavelength.

Question 13 Model answer: Light is an electromagnetic wave — an oscillation of electric and magnetic fields — and electromagnetic waves do not need a medium, so sunlight can cross the vacuum of space between the Sun and the Earth. Sound is a mechanical wave: it is an oscillation of the particles of a medium and cannot travel where there is no matter. There is (almost) no matter between the Sun and the Earth, so any sound produced at the Sun's surface has no medium to carry it and can never reach us.

Question 14 Model answer: Two errors are: - Radio waves are electromagnetic waves, not sound waves. They are oscillations of electric and magnetic fields, not oscillations of matter, and they can travel through a vacuum; sound is a mechanical wave that needs a medium. - The sound heard from a radio is not what the radio wave "carries in" as sound. The radio wave is a signal; the loudspeaker in the radio converts that signal into a sound wave in the air of the room. The two are different waves, of different types, travelling at very different speeds.

Question 15 Model answer: In a vacuum every electromagnetic wave travels at the same speed, so $c = f\lambda$ with c fixed. Frequency and wavelength are therefore in inverse proportion: as the wavelength becomes shorter, the frequency must become higher so that the product $f\lambda$ stays equal to c. X-rays have wavelengths around $10^{-10}\,\mathrm{m}$, billions of times shorter than microwave wavelengths (around $10^{-1}\,\mathrm{m}$), so X-ray frequencies are billions of times higher than microwave frequencies.

Question 16 Model answer: They are the same kind of wave because each one is a transverse wave made of oscillating electric and magnetic fields at right angles to the direction of travel; none of them needs a medium; and in a vacuum every one of them travels at exactly the same speed, $c = 3.00 \times 10^{8}\,\mathrm{m\ s^{-1}}$. The only difference between a radio wave, visible light, an X-ray and a gamma ray is its wavelength (and therefore its frequency), and it is this difference in wavelength and frequency that gives each region its different uses.

Question 17 Model answer: X-rays are used because they can pass through the body's soft tissue but are absorbed much more strongly by bone, so an image of the bone can be formed; visible light does not pass through the body at all, so it could not produce such an image. Because X-rays can damage living tissue, precautions are taken — for example, the part of the body not being imaged is shielded, and the exposure time is kept as short as possible.

Question 18 Model answer: (a) The Sun emits electromagnetic radiation across almost the whole spectrum, but the radiation it emits is mainly ultraviolet, visible and infrared. (b) Most of the Sun's ultraviolet radiation is absorbed by ozone high in the Earth's atmosphere before it reaches the surface, so only a small fraction arrives at ground level.

Chapter 1 Electromagnetic radiation and the wave model — 1C Refraction, Snell's Law and total internal reflection

Theory

The speed of light in different media. In a vacuum, all electromagnetic waves travel at the same speed, $c = 3.0 \times 10^8\,\mathrm{m\ s^{-1}}$ (Section 1B). The speed in air is only very slightly smaller, so in this subtopic light in air is taken to travel at c. In transparent solids and liquids, light travels noticeably more slowly. The **refractive index** n of a medium is a number that measures how much that medium slows light down:

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

where v is the speed of light in the medium. The refractive index is a ratio of two speeds, so it has no units. Because light travels fastest in a vacuum, $n \geq 1$: a vacuum has $n = 1$ exactly, air has $n \approx 1.00$, and denser optical materials have larger values. A medium with a larger refractive index is said to be **optically denser** than one with a smaller refractive index. Optical density is about how slowly light travels in a material — it is *not* the same thing as mass density.

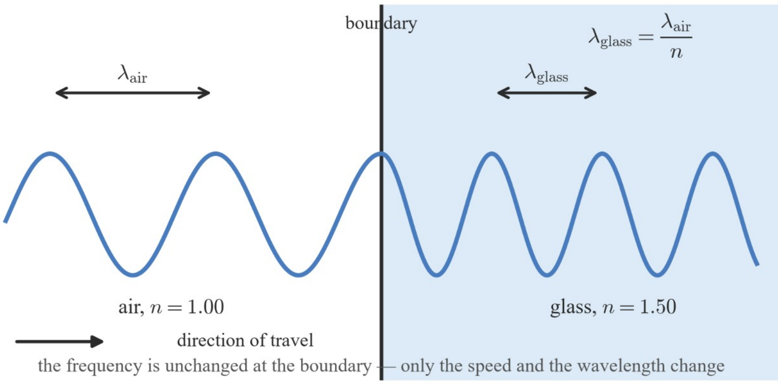
Medium	Refractive index n
vacuum	1.000
air	1.00
ice	1.31
water	1.33
glycerol	1.47
olive oil	1.47
acrylic (Perspex)	1.49
crown glass	1.52
cubic zirconia	2.16
diamond	2.42

Frequency, speed and wavelength — what changes at a boundary? When a wave crosses from one medium into another, three quantities behave differently:

- The **frequency does not change**. The frequency is determined by the source of the wave: each oscillation of the source releases one wave crest, and the boundary between two media cannot create or destroy crests, so the number of crests arriving at the boundary each second must equal the number leaving it. The frequency is therefore the same on both sides.
- The **speed changes**. The speed is determined by the medium the wave is in, $v = c / n$, so it is smaller in a medium with a larger refractive index.
- The **wavelength changes as a result**. From $v = f\lambda$ (Section 1A), $\lambda = v / f$. With f unchanged and v smaller by a factor of n, the wavelength is smaller by the same factor:

$$\lambda_{\text{medium}} = \frac{\lambda_{\text{air}}}{n}.$$

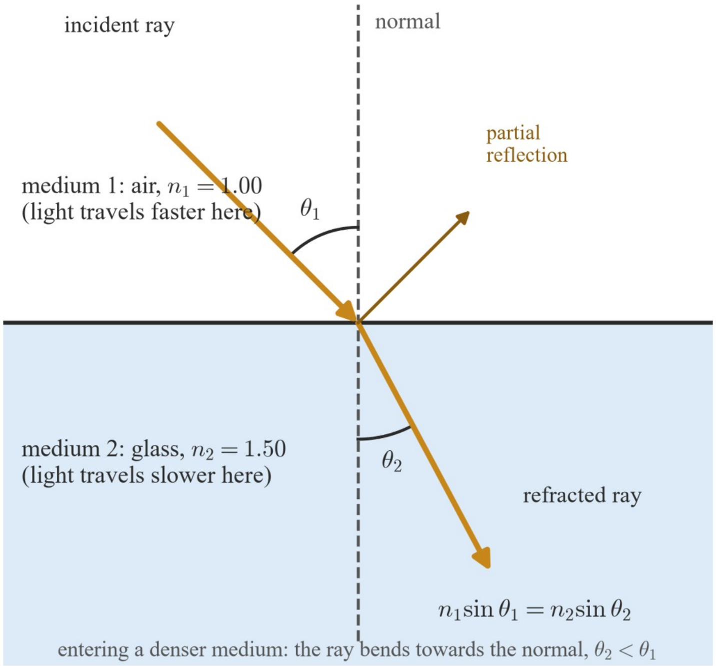
For light, the colour is connected to the frequency, so the colour of a ray does not change when it enters a new medium — only its speed and wavelength do.



Refraction. Refraction is the change in direction of a wave as it crosses the boundary between two media at an angle, caused by the change in its speed. To describe refraction precisely, three terms are used:

- the **normal**: a construction line drawn at right angles to the boundary, at the point where the ray meets it;
- the **angle of incidence** θ_1: the angle between the incoming (incident) ray and the normal;
- the **angle of refraction** θ_2: the angle between the ray in the second medium (the refracted ray) and the normal.

Angles are always measured **from the normal**, never from the surface itself.



The direction of bending follows the change in speed:

- entering an optically denser medium ($n_2 > n_1$), the light slows down and bends **towards the normal**, so $\theta_2 < \theta_1$;
- entering a less dense medium ($n_2 < n_1$), the light speeds up and bends **away from the normal**, so $\theta_2 > \theta_1$;
- a ray travelling **along the normal** ($\theta_1 = 0$) slows down but does not change direction.

The bending can be pictured with wavefronts. A wavefront arriving at the boundary at an angle has one end enter the slower medium first; that end slows down while the rest of the wavefront keeps moving at the original speed, so the wavefront swings around and the ray changes direction — like a line of walkers hitting a patch of soft sand at an angle. Note also that at every boundary some of the light is reflected as well as refracted.

Snell's Law. The exact relationship between the angles and the refractive indices is given by Snell's Law:

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

where the subscript 1 refers to the medium the light is leaving and 2 to the medium it is entering. Since $n = c / v$, multiplying each refractive index by the speed of light in that medium gives $n v = c$ for every medium, which yields a second, equivalent form relating the speeds:

$$n_1 v_1 = n_2 v_2.$$

Together these give a useful ratio form,

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} = \frac{v_1}{v_2},$$

which says the sines of the angles are in the inverse ratio of the refractive indices and in the same ratio as the speeds.

Snell's Law can be rearranged for any one of its four quantities. The two most common arrangements are:

$$\sin\theta_2 = \frac{n_1}{n_2}\sin\theta_1 \text{ and } n_2 = \frac{n_1 \sin\theta_1}{\sin\theta_2}.$$

To find an angle from its sine, use the inverse sine function, $\sin^{-1}$, on the calculator.

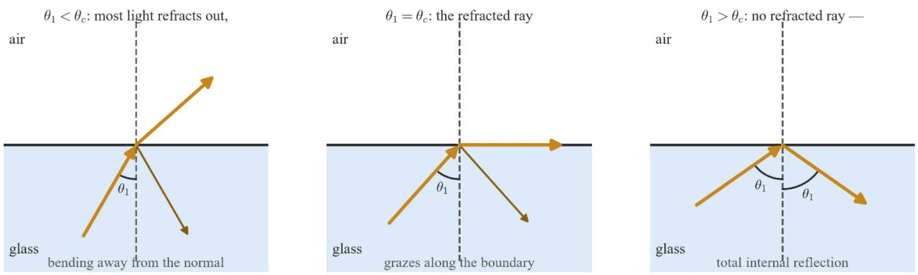
Total internal reflection and the critical angle. When light travels from an optically denser medium into a less dense one ($n_1 > n_2$), it bends away from the normal, so θ_2 is larger than θ_1. As the angle of incidence is increased, the angle of refraction increases faster and reaches 90° first. The angle of incidence for which the refracted ray just emerges at 90° — grazing along the boundary — is called the **critical angle**, θ_c. Setting $\theta_1 = \theta_c$ and $\theta_2 = 90^\circ$ in Snell's Law gives

$$n_1 \sin\theta_c = n_2 \sin 90^\circ, \text{so} \sin\theta_c = \frac{n_2}{n_1} (n_1 > n_2).$$

For angles of incidence *greater* than θ_c, no refracted ray exists at all. The boundary acts like a perfect mirror and **all** of the light is reflected back into the denser medium. This is **total internal reflection**. It happens only when two conditions are both met:

1. the light is travelling from a medium of larger refractive index into one of smaller refractive index ($n_1 > n_2$);
2. the angle of incidence is greater than the critical angle ($\theta_1 > \theta_c$).

At total internal reflection, the angle of reflection equals the angle of incidence, as for any reflection.



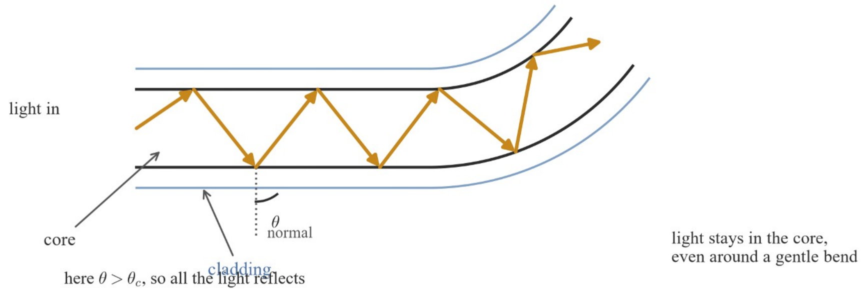
glass $\rightarrow$ air, $n_1 = 1.50$, $n_2 = 1.00$: $\sin\theta_c = n_2/n_1$, so $\theta_c \approx 42^\circ$

Some critical angles against air:

Boundary	Critical angle
water–air	48.8°
crown glass–air	41.1°
diamond–air	24.4°

Applications of total internal reflection.

- **Gemstones.** Diamond has a very small critical angle (24.4°), so light inside a cut diamond strikes the faces at angles greater than θ_c almost everywhere and is totally internally reflected from face to face until it leaves through the top of the stone. This returned light is what makes a diamond sparkle. Glass, with a much larger critical angle (41.8°), lets more light escape through the bottom and looks far less brilliant.
- **Prisms.** Right-angled glass prisms use total internal reflection to turn rays through 90° or 180° inside binoculars, periscopes and cameras. A 45° angle of incidence inside glass is greater than the glass–air critical angle of 41.8°, so the reflection is total — brighter than a mirrored surface.
- **Optical fibres.** An optical fibre is a thin strand of glass or plastic with a **core** of larger refractive index surrounded by a **cladding** of smaller refractive index. Light entering one end strikes the core–cladding boundary at angles greater than the critical angle and is totally internally reflected again and again, travelling along the fibre even around gentle bends. Optical fibres carry telephone and internet traffic and are used in medicine to look inside the body. The transmission of light through fibres for communication is investigated in Section 1E.



Investigating refraction practically. The behaviour above can be investigated in the laboratory, as the study design requires. A standard method for refraction:

1. Shine a narrow ray from a ray box at a rectangular transparent block and mark the incident and emergent rays on paper beneath.
2. Remove the block, draw its outline and the ray path inside it, and measure the angle of incidence θ_1 and the angle of refraction θ_2 with a protractor, both from the normal.
3. Repeat for a range of angles of incidence.
4. Analyse the data as a table of $\sin\theta_1$ and $\sin\theta_2$, and plot $\sin\theta_1$ against $\sin\theta_2$. Snell's Law predicts a straight line through the points whose gradient is n_2 / n_1 — equal to the refractive index of the block if it is surrounded by air.

For the critical angle, a semicircular block is used. The ray is directed from *inside* the block towards the centre of the flat face, so it crosses the curved face along a radius and enters without bending. The angle of incidence at the flat face is increased until the refracted ray just grazes the face: that angle is θ_c. Slightly beyond it, the refracted ray disappears and total internal reflection is observed.

Sources of error include the finite width of the ray, reading angles to the nearest degree, and the block not being exactly aligned with its drawn outline. Repeating each measurement and averaging improves precision. Record the method, the raw data and any changes to the procedure in your logbook.

Throughout this subtopic the speed of light in a vacuum is taken as $c = 3.0 \times 10^8\ \mathrm{m\ s^{-1}}$, and refractive indices are taken from the table above unless a question states otherwise.

Worked examples

Example 1 — scaffolded

A ray of light travelling in air strikes the surface of a swimming pool at an angle of incidence of 35°. The refractive index of water is 1.33. Calculate the angle of refraction and state which way the ray bends.

Working	Comment
$n_1 = 1.00$ (air), $n_2 = 1.33$ (water), $\theta_1 = 35^\circ$.	List the data; the light moves from air into water.
$n_1 \sin\theta_1 = n_2 \sin\theta_2$, so	Rearrange Snell's Law before substituting.
$\sin\theta_2 = \dfrac{n_1}{n_2}\sin\theta_1 = \dfrac{1.00}{1.33} \times \sin 35^\circ = \dfrac{0.57358}{1.33} = 0.43126$.	
$\theta_2 = \sin^{-1}(0.43126) = 25.5^\circ$.	Use the inverse sine function to recover the angle.
$\theta_2 < \theta_1$, so the ray bends **towards the normal**.	Water is optically denser than air: the light slows down and bends towards the normal.

Example 2 — scaffolded

Sodium street lights emit yellow light of wavelength $589\,\mathrm{nm}$ in air. The light from one such lamp falls on a shop window made of crown glass, refractive index 1.52. Calculate the speed of the light in the glass, its frequency, and its wavelength inside the glass.

Working	Comment
$v = \dfrac{c}{n} = \dfrac{3.00 \times 10^8}{1.52} = 1.97 \times 10^8\,\mathrm{m\ s^{-1}}$.	The refractive index is defined by $n = c / v$.
$f = \dfrac{c}{\lambda} = \dfrac{3.00 \times 10^8}{589 \times 10^{-9}} = 5.09 \times 10^{14}\,\mathrm{Hz}$.	Use $v = f\lambda$ in air, where the speed is c.
The frequency in the glass is unchanged: $f = 5.09 \times 10^{14}\,\mathrm{Hz}$.	The frequency is determined by the source, not by the medium, so it is the same on both sides of the boundary.
$\lambda_{\text{glass}} = \dfrac{v}{f} = \dfrac{1.974 \times 10^8}{5.093 \times 10^{14}} = 3.88 \times 10^{-7}\,\mathrm{m} = 388\,\mathrm{nm}$.	The wavelength shrinks in the same proportion as the speed. Check: $\lambda / n = 589 / 1.52 = 388\,\mathrm{nm}$. ✓

Example 3 — unscaffolded

A student investigating refraction measures an angle of incidence of 48.0° in air and an angle of refraction of 31.0° inside a block of transparent plastic. Calculate the refractive index of the plastic and the speed of light in it.

The light moves from air ($n_1 = 1.00$) into the plastic (n_2), so Snell's Law rearranged for the unknown refractive index gives

$$n_2 = \frac{n_1 \sin\theta_1}{\sin\theta_2} = \frac{1.00 \times \sin 48.0^\circ}{\sin 31.0^\circ} = \frac{0.7431}{0.5150} = 1.4429.$$

The speed follows from the definition of refractive index:

$$v = \frac{c}{n_2} = \frac{3.00 \times 10^8}{1.4429} = 2.079 \times 10^8\,\mathrm{m\ s^{-1}}.$$

∴ the refractive index of the plastic is 1.44 and light travels through it at $2.08 \times 10^8\,\mathrm{m\ s^{-1}}$.

Example 4 — unscaffolded

Diamond has a refractive index of 2.42 and cubic zirconia, a material used to imitate diamond, has a refractive index of 2.16. Calculate the critical angle for each material against air, and use the results to explain why a well-cut diamond returns more light to a viewer's eye than an identically cut cubic zirconia stone.

For each material the light would be travelling from the gem (n_1) into air ($n_2 = 1.00$), so

$$\sin\theta_c = \frac{n_2}{n_1}.$$

For diamond:

$$\theta_c = \sin^{-1}\left(\frac{1.00}{2.42}\right) = \sin^{-1}(0.4132) = 24.4^\circ.$$

For cubic zirconia:

$$\theta_c = \sin^{-1}\left(\frac{1.00}{2.16}\right) = \sin^{-1}(0.4630) = 27.6^\circ.$$

The critical angle of diamond is smaller. A ray inside either stone is totally internally reflected only if it strikes a face at an angle greater than the critical angle, so the smaller critical angle of diamond means a wider range of ray paths are trapped by total internal reflection. Light entering a cut diamond bounces from face to face and is directed back out through the top of the stone, whereas more of the light entering the cubic zirconia escapes through its lower faces.

∴ the critical angles are 24.4° (diamond) and 27.6° (cubic zirconia); diamond's smaller critical angle gives it more total internal reflection and so more sparkle.

Practice questions

Question 1 A ray of light travelling in air strikes the flat surface of a glass block, refractive index 1.50, at an angle of incidence of 40°. (a) Calculate the angle of refraction. (b) Calculate the speed of light in the glass. (c) State whether the ray bends towards or away from the normal, and explain this in terms of the speed of light.

Question 2 A helium–neon laser emits red light of wavelength $632\,\text{nm}$ in air. The beam shines into a block of acrylic (Perspex), refractive index 1.49. (a) Calculate the frequency of the light in air. (b) State the frequency of the light inside the acrylic, giving a reason for your answer. (c) Calculate the wavelength of the light inside the acrylic.

Question 3 Light travelling inside water, refractive index 1.33, reaches a flat water–air boundary. (a) Calculate the critical angle for the water–air boundary. (b) State and explain what happens to a ray that strikes the boundary at an angle of incidence of 50°. (c) State the condition on the refractive indices of the two media that must be satisfied before total internal reflection is possible.

Question 4 The speed of light in olive oil is $2.04\times10^{8}\,\text{m s}^{-1}$. (a) Calculate the refractive index of olive oil. (b) A ray in air strikes the surface of the oil at an angle of incidence of 55°. Calculate the angle of refraction in the oil. (c) Light of wavelength $600\,\text{nm}$ in air enters the oil. Calculate its wavelength in the oil.

Question 5 A student investigates the refraction of light by a rectangular glass block using a ray box and a protractor, and obtains the results below.

Angle of incidence θ_1	10°	20°	30°	40°	50°
Angle of refraction θ_2	6.6°	13.2°	19.5°	25.4°	30.7°

(a) Copy the table and add two rows showing $\sin\theta_1$ and $\sin\theta_2$ for each pair of readings.

(b) Plot a graph of $\sin\theta_1$ (on the vertical axis) against $\sin\theta_2$ (on the horizontal axis) and draw the line of best fit.
(c) Use the gradient of your line to determine the refractive index of the glass, given that the block is surrounded by air.

Question 6 An optical fibre has a core of refractive index 1.46 surrounded by cladding of refractive index 1.41. (a) Calculate the critical angle for the core–cladding boundary. (b) A ray inside the core strikes the core–cladding boundary at 70° to the normal. State, with a reason, whether this ray is totally internally reflected. (c) Explain how a ray can travel along the fibre from one end to the other even when the fibre is gently bent.

Question 7 A ray of light in air strikes the flat surface of an ice sheet, refractive index 1.31. The ray makes an angle of 60° with the surface of the ice. Calculate the angle of refraction.

Question 8 Light travels through a transparent liquid at a speed of $2.00\times10^{8}\,\mathrm{m\ s^{-1}}$. Calculate the refractive index of the liquid and the critical angle for the liquid–air boundary.

Question 9 Violet light of wavelength $400\,\mathrm{nm}$ in a vacuum enters a diamond, refractive index 2.42. Calculate the frequency, the speed and the wavelength of this light inside the diamond.

Question 10 A ray of light passes from medium A, refractive index 1.60, into medium B. The angle of incidence in A is 35° and the angle of refraction in B is 47°. Calculate the refractive index of medium B, and state in which medium light travels faster, giving a reason.

Question 11 Calculate the critical angle for a boundary between glass, refractive index 1.52, and water, refractive index 1.33, and state in which medium the light must be travelling for total internal reflection to be possible at this boundary.

Question 12 A ray travelling inside a glass block, refractive index 1.50, strikes the inside surface of the block at an angle of incidence of 45°. Determine, with a calculation, what happens to the ray, and find the angle that the resulting ray makes with the normal.

Question 13 Explain why the frequency of light does not change when it passes from air into glass, while its wavelength does change. Your answer should refer to $v=f\lambda$.

Question 14 A ray of light travels from water into air, striking the boundary at a non-zero angle. Explain why the ray bends away from the normal, making reference to the change in the speed of the light.

Question 15 A person standing at the edge of a swimming pool judges the pool to be shallower than it really is. Use refraction to explain why the bottom of the pool appears closer to the surface than it actually is.

Question 16 A diamond, refractive index 2.42, sparkles brightly when light falls on it, but an identically shaped piece of glass, refractive index 1.50, does not. Use the concept of critical angle to explain this difference.

Question 17 A student says: “Total internal reflection can happen when light travelling in air reaches the surface of water.” Evaluate this claim, making reference to the conditions needed for total internal reflection.

Question 18 Evaluate the statement: “When light enters a new medium, it always bends towards the normal.” Use the relationship $n_1 v_1 = n_2 v_2$ or the relative refractive indices in your answer.

Answers

Question 1 (a) 25.4°; (b) $2.00 \times 10^8\,\mathrm{m\,s^{-1}}$; (c) towards the normal; light slows down in the glass. **Question 2** (a) $4.75 \times 10^{14}\,\mathrm{Hz}$; (b) $4.75 \times 10^{14}\,\mathrm{Hz}$ — the frequency is set by the source and is unchanged at a boundary; (c) $424\,\mathrm{nm}$. **Question 3** (a) 48.8°; (b) total internal reflection — 50° is greater than the critical angle; (c) $n_1 > n_2$ (light must travel from the optically denser into the less dense medium). **Question 4** (a) 1.47; (b) 33.9°; (c) $408\,\mathrm{nm}$. **Question 5** (a) see solution; (b) straight line of best fit; (c) $n \approx 1.50$. **Question 6** (a) 75.0°; (b) no — 70° is less than the critical angle, so some light refracts into the cladding; (c) see solution. **Question 7** 22.4°. **Question 8** $n = 1.50$; $\theta_c = 41.8^\circ$. **Question 9** $7.50 \times 10^{14}\,\mathrm{Hz}$; $1.24 \times 10^8\,\mathrm{m\,s^{-1}}$; $165\,\mathrm{nm}$. **Question 10** $n_B = 1.25$; faster in B, which has the smaller refractive index. **Question 11** 61.0°; the light must be travelling in the glass. **Question 12** Total internal reflection; the reflected ray makes 45° with the normal. **Question 13** See solution (frequency is set by the source; v falls, so $\lambda = v/f$ falls). **Question 14** See solution (light speeds up leaving water, so the wavefront swings away from the normal). **Question 15** See solution (rays from the bottom bend away from the normal on leaving the water; the eye traces them back in straight lines to a point above the real bottom). **Question 16** See solution (diamond's smaller critical angle gives more total internal reflection). **Question 17** The claim is false; total internal reflection requires $n_1 > n_2$, and air has the smaller refractive index. **Question 18** The statement is false; light bends towards the normal only when it enters a medium of larger refractive index, and away when it enters one of smaller refractive index.

Fully-worked solutions

Question 1 $n_1 = 1.00$, $n_2 = 1.50$, $\theta_1 = 40^\circ$. (a) Snell's Law: $\sin\theta_2 = \dfrac{n_1}{n_2}\sin\theta_1 = \dfrac{1.00}{1.50}\sin 40^\circ = \dfrac{0.6428}{1.50} = 0.4285$, so $\theta_2 = \sin^{-1}(0.4285) = 25.4^\circ$. (b) $v = \dfrac{c}{n} = \dfrac{3.00 \times 10^8}{1.50} = 2.00 \times 10^8\,\mathrm{m\,s^{-1}}$. (c) The ray bends **towards the normal**. The glass is optically denser than air, so the light slows down on entering it; Snell's Law then gives $\theta_2 < \theta_1$.

Question 2 $\lambda = 632\,\mathrm{nm} = 632 \times 10^{-9}\,\mathrm{m}$, $n_{\text{acrylic}} = 1.49$. (a) In air the speed is c, so $f = \dfrac{c}{\lambda} = \dfrac{3.00 \times 10^8}{632 \times 10^{-9}} = 4.75 \times 10^{14}\,\mathrm{Hz}$. (b) The frequency inside the acrylic is the same, $4.75 \times 10^{14}\,\mathrm{Hz}$. The frequency is determined by the source and is unchanged when a wave crosses a boundary — the boundary cannot create or destroy wave crests. (c) $\lambda_{\text{acrylic}} = \dfrac{\lambda_{\text{air}}}{n} = \dfrac{632}{1.49} = 424\,\mathrm{nm}$.

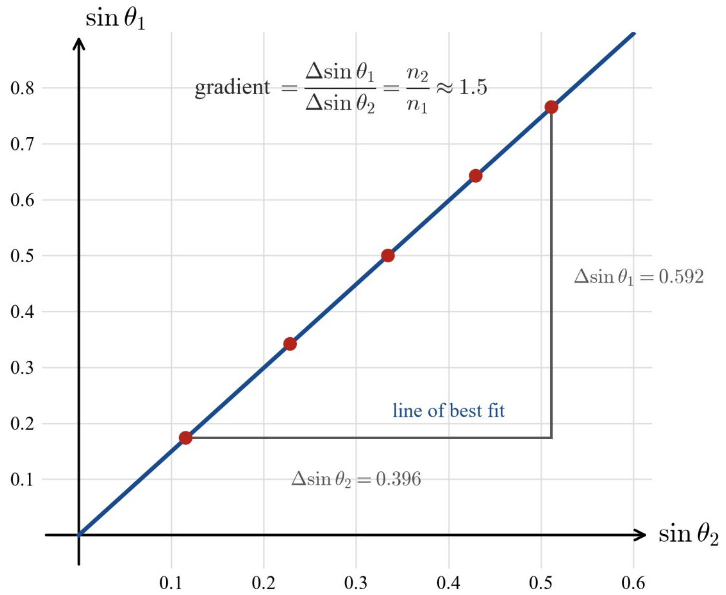
Question 3 $n_1 = 1.33$ (water), $n_2 = 1.00$ (air). (a) $\sin\theta_c = \dfrac{n_2}{n_1} = \dfrac{1.00}{1.33} = 0.7519$, so $\theta_c = \sin^{-1}(0.7519) = 48.8^\circ$. (b) The angle of incidence 50° is greater than the critical angle 48.8°, and the light is travelling from the optically denser medium (water) into the less dense one (air), so the ray undergoes **total internal reflection**: it is reflected back into the water and no light leaves through the boundary. (c) Total internal reflection is possible only when the light travels from a medium of larger refractive index into one of smaller refractive index: $n_1 > n_2$.

Question 4 $v_{\text{oil}} = 2.04 \times 10^8\,\mathrm{m\,s^{-1}}$. (a) $n = \dfrac{c}{v} = \dfrac{3.00 \times 10^8}{2.04 \times 10^8} = 1.47$. (b) $\sin\theta_2 = \dfrac{n_1}{n_2}\sin\theta_1 = \dfrac{1.00}{1.4706}\sin 55^\circ = \dfrac{0.8192}{1.4706} = 0.5570$, so $\theta_2 = \sin^{-1}(0.5570) = 33.9^\circ$. (c) $\lambda_{\text{oil}} = \dfrac{\lambda_{\text{air}}}{n} = \dfrac{600}{1.4706} = 408\,\mathrm{nm}$.

Question 5 (a) The sine values (to three significant figures) are:

θ_1	10°	20°	30°	40°	50°
$\sin\theta_1$	0.174	0.342	0.500	0.643	0.766
θ_2	6.6°	13.2°	19.5°	25.4°	30.7°
$\sin\theta_2$	0.115	0.228	0.334	0.429	0.511

(b) Plotting $\sin\theta_1$ on the vertical axis against $\sin\theta_2$ on the horizontal axis gives points lying close to a straight line of gradient about 1.5.



(c) Snell's Law gives $n_1\sin\theta_1 = n_2\sin\theta_2$, so $\sin\theta_1 = (n_2/n_1)\sin\theta_2$: the gradient of the graph is n_2/n_1. With air around the block, $n_1 = 1.00$, so $n_2 = \text{gradient} \times 1.00$. Taking two well-separated points on the line of best fit,

$$\text{gradient} = \frac{0.766 - 0.174}{0.511 - 0.115} = \frac{0.592}{0.396} = 1.49,$$

so the refractive index of the glass is approximately 1.50.

Question 6 $n_1 = 1.46$ (core), $n_2 = 1.41$ (cladding). (a) $\sin\theta_c = \frac{n_2}{n_1} = \frac{1.41}{1.46} = 0.9658$, so $\theta_c = \sin^{-1}(0.9658) = 75.0^\circ$. (b) No. The angle of incidence (70°) is *less* than the critical angle (75.0°), so total internal reflection does not occur: most of the light refracts into the cladding, where it is lost, and only a partial reflection occurs. (c) In use, light travels along the fibre in directions close to the fibre's axis, so rays strike the core–cladding boundary at angles close to 90° — well above the critical angle — and are totally internally reflected at every contact. When the fibre is gently bent, the angles at which the rays meet the boundary remain greater than the critical angle, so the light continues to be guided along the fibre.

Question 7 $n_1 = 1.00$ (air), $n_2 = 1.31$ (ice). Angles are measured from the normal, not from the surface, so the angle of incidence is $\theta_1 = 90^\circ - 60^\circ = 30^\circ$. Then

$$\sin\theta_2 = \frac{n_1}{n_2}\sin\theta_1 = \frac{1.00}{1.31}\sin 30^\circ = \frac{0.5000}{1.31} = 0.3817,$$

so $\theta_2 = \sin^{-1}(0.3817) = 22.4^\circ$.

$\therefore$ the angle of refraction is 22.4°.

Question 8 $v = 2.00 \times 10^8\ \text{m s}^{-1}$. The refractive index is

$$n = \frac{c}{v} = \frac{3.00 \times 10^8}{2.00 \times 10^8} = 1.50.$$

For the liquid–air boundary, with the light travelling from the liquid into air,

$$\sin\theta_c = \frac{n_{\text{air}}}{n_{\text{liquid}}} = \frac{1.00}{1.50} = 0.6667,$$

so $\theta_c = \sin^{-1}(0.6667) = 41.8^\circ$.

∴ the refractive index is 1.50 and the critical angle is 41.8°.

Question 9 $\lambda = 400\,\text{nm} = 400 \times 10^{-9}\,\text{m}$ in a vacuum, $n = 2.42$. The frequency, determined by the source, is the same everywhere:

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^8}{400 \times 10^{-9}} = 7.50 \times 10^{14}\,\text{Hz}.$$

The speed in diamond is

$$v = \frac{c}{n} = \frac{3.00 \times 10^8}{2.42} = 1.24 \times 10^8\,\text{m s}^{-1},$$

and the wavelength inside the diamond is

$$\lambda_{\text{diamond}} = \frac{v}{f} = \frac{1.24 \times 10^8}{7.50 \times 10^{14}} = 1.65 \times 10^{-7}\,\text{m} = 165\,\text{nm}.$$

(Equivalently, $\lambda / n = 400 / 2.42 = 165\,\text{nm}$. ✓)

∴ inside the diamond the light has frequency $7.50 \times 10^{14}\,\text{Hz}$, speed $1.24 \times 10^8\,\text{m s}^{-1}$ and wavelength $165\,\text{nm}$.

Question 10 $n_A = 1.60$, $\theta_1 = 35^\circ$, $\theta_2 = 47^\circ$. Snell's Law gives

$$n_B = \frac{n_A \sin\theta_1}{\sin\theta_2} = \frac{1.60 \times \sin 35^\circ}{\sin 47^\circ} = \frac{1.60 \times 0.5736}{0.7314} = 1.25.$$

Light travels faster in **medium B**. From $n_1 v_1 = n_2 v_2$, the medium with the smaller refractive index has the larger speed, and $n_B = 1.25$ is smaller than $n_A = 1.60$ — consistent with the ray bending away from the normal.

∴ $n_B = 1.25$, and light is faster in medium B.

Question 11 Total internal reflection requires the light to start in the optically denser medium, so take $n_1 = 1.52$ (glass) and $n_2 = 1.33$ (water):

$$\sin\theta_c = \frac{n_2}{n_1} = \frac{1.33}{1.52} = 0.8750,$$

so $\theta_c = \sin^{-1}(0.8750) = 61.0^\circ$.

∴ the critical angle is 61.0°, and total internal reflection is possible only for light travelling in the glass.

Question 12 The critical angle for the glass–air boundary is

$$\theta_c = \sin^{-1}\left(\frac{n_{\text{air}}}{n_{\text{glass}}}\right) = \sin^{-1}\left(\frac{1.00}{1.50}\right) = \sin^{-1}(0.6667) = 41.8^\circ.$$

The angle of incidence, 45°, is greater than the critical angle of 41.8°, and the light is travelling from the optically denser medium (glass) towards air, so both conditions for total internal reflection are met: **no light leaves the block**, and the ray is reflected back into the glass. The angle of reflection equals the angle of incidence.

∴ the ray is totally internally reflected and the reflected ray makes an angle of 45° with the normal.

Question 13 Model answer points:

- The frequency is determined by the source of the light. At the boundary, wave crests cannot be created or destroyed, so the number of crests arriving per second equals the number leaving per second: the frequency is the same in air and in glass.
- The speed is determined by the medium: light travels more slowly in glass than in air ($v = c / n$ with $n_{\text{glass}} > 1$).
- From $v = f\lambda$, with f unchanged and v smaller in the glass, the wavelength $\lambda = v / f$ must also be smaller in the glass.

Question 14 Model answer points:

- Water is optically denser than air ($n_{\text{water}} > n_{\text{air}}$), so light speeds up as it leaves the water and enters the air.
- A wavefront reaching the boundary at an angle has one end enter the faster medium first; that end speeds up while the rest of the wavefront is still moving at the slower speed in the water.
- The wavefront therefore swings around, and the ray bends away from the normal ($\theta_2 > \theta_1$), as required by Snell's Law with $n_2 < n_1$.

Question 15 Model answer points:

- Rays of light leaving a point on the bottom of the pool travel from water into air, so they speed up and bend away from the normal at the surface.
- The eye assumes that light has travelled in straight lines, so it traces the arriving rays back in straight lines to where they appear to come from.
- Traced back, the rays meet at a point above the real position of the bottom, so the bottom appears closer to the surface than it really is and the pool looks shallower than it is.

Question 16 Model answer points:

- The critical angle against air is $\sin\theta_c = 1 / n$: for diamond $\theta_c = \sin^{-1}(1 / 2.42) = 24.4^\circ$, while for glass $\theta_c = \sin^{-1}(1 / 1.50) = 41.8^\circ$.
- Diamond's much smaller critical angle means that rays inside the diamond strike the faces at angles greater than the critical angle over a wider range of directions, so they undergo total internal reflection rather than escaping.
- The trapped light reflects from face to face and is eventually directed back out through the top of the stone towards the viewer. In the glass, with its larger critical angle, more rays strike faces at angles below the critical angle and escape through the sides and bottom, so far less light returns to the viewer and the glass does not sparkle.

Question 17 Model answer points:

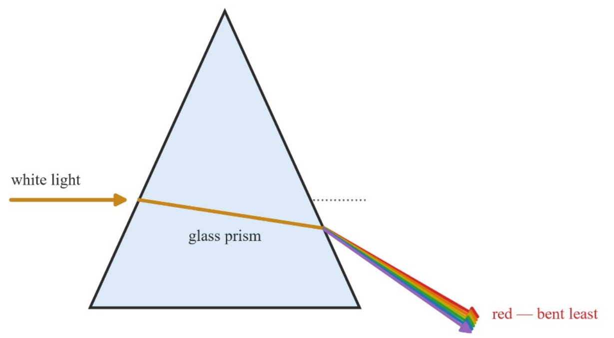
- The claim is **false**.
- Total internal reflection has two conditions: the light must travel from a medium of larger refractive index into one of smaller refractive index ($n_1 > n_2$), and the angle of incidence must exceed the critical angle.
- For light in air reaching water, $n_1 = 1.00$ and $n_2 = 1.33$, so $n_1 < n_2$: the light is travelling into the optically denser medium, and it slows down and bends *towards* the normal. No critical angle exists for this direction ($n_2 / n_1 > 1$ has no sine solution), and total internal reflection cannot occur.
- Total internal reflection at a water surface happens only for light travelling *from the water towards the air*, at angles greater than 48.8°.

Question 18 Model answer points:

- The statement is **false**: the direction of bending depends on the relative refractive indices of the two media, not simply on the fact that the medium changes.
- From $n_1 v_1 = n_2 v_2$, if $n_2 > n_1$ then $v_2 < v_1$: the light slows down and bends **towards** the normal ($\theta_2 < \theta_1$).
- If instead $n_2 < n_1$, then $v_2 > v_1$: the light speeds up and bends **away from** the normal ($\theta_2 > \theta_1$).
- There are also cases with no bending at all: a ray travelling along the normal ($\theta_1 = 0$), or crossing between media of equal refractive index, continues in a straight line without bending. The statement is therefore only true in the first of these cases.

Theory

Sunlight looks white, and the light from a globe or a torch looks white too. In Section 1B you met the visible spectrum: the narrow band of electromagnetic waves that the human eye can detect, running from red (longest wavelength, lowest frequency) through to violet (shortest wavelength, highest frequency). **White light** is not a single colour of light at all — it is a mixture of *all* the colours of the visible spectrum travelling together. Under ordinary conditions those colours stay mixed, so your eye registers the combination as white. They can, however, be separated, and that separation is the subject of this section.



dispersion: glass slows violet light more than red, so violet is bent more — the white light fans into a spectrum

Dispersion. When light crosses from one medium to another it refracts — Section 1C covered this using Snell's Law, $n_1 \sin\theta_1 = n_2 \sin\theta_2$. The **refractive index** n of a medium measures how much it slows light down: $n = c / v$, where c is the speed of light in a vacuum and v is its speed in the medium. In a vacuum every colour of light travels at the same speed c, but in a transparent material such as glass or water the different colours travel at *slightly* different speeds. Violet light (higher frequency) is slowed a little more than red light (lower frequency), so a medium has a slightly larger refractive index for violet light than for red light. Because the refractive index is different for each colour, Snell's Law gives a different angle of refraction for each colour: violet light bends more, red light bends less. **Dispersion** is the separation of white light into its component colours that results from this wavelength-dependent refraction as the light passes from one medium to another.

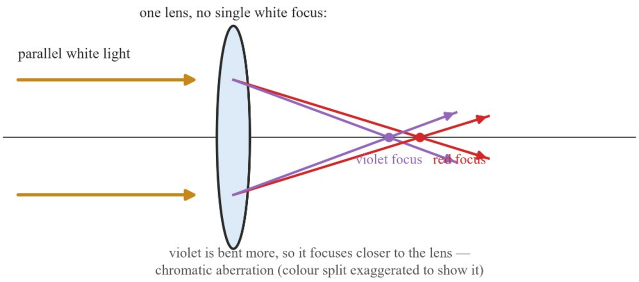
Typical refractive indices are shown below. The values for air and water are almost the same for every colour; the values for glass depend noticeably on the colour, which is why glass shows dispersion strongly and air shows it only weakly.

Medium	n (red light)	n (violet light)
Vacuum	1 (exactly, all colours)	1 (exactly, all colours)
Air	1.00	1.00
Water	1.331	1.343
Crown glass	1.514	1.532

Remember from Section 1C that the frequency of a wave is set by the source and does **not** change when the wave enters a new medium. It is the speed that is set by the medium — and since $v = f\lambda$ (Section 1A), the wavelength in the medium changes with the speed. Violet light travels more slowly in glass than red light does, so in the glass it also has the shorter wavelength.

Prisms. A triangular glass **prism** disperses white light very effectively because the light refracts *twice*: once entering the glass and again leaving it. At each surface the violet component bends more than the red component, so the two refractions add together and the colours fan out into a band called a **spectrum**. In the 1660s Isaac Newton used glass prisms to show that the colours come *from* the white light itself: a prism was not colouring the light, because a second prism could spread the spectrum further but could never create a colour that was not already there, and a lens (or a second prism turned the other way) could recombine the spectrum back into white light.

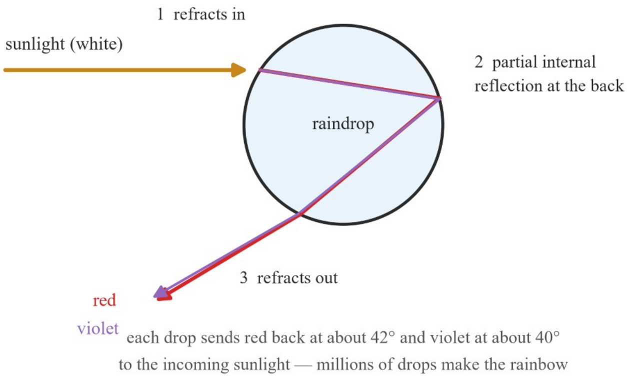
Dispersion in lenses. A lens works by refraction: it bends incoming rays so that they meet at a focus. Because different colours are refracted by different amounts, they come to a focus at slightly different positions — violet light, refracted most, focuses a little closer to the lens than red light. This effect is called **chromatic aberration**. In a camera, a telescope or the human eye it shows up as faint coloured fringes around the edges of objects in an image. Lens designers reduce chromatic aberration by combining lenses made from different types of glass, whose dispersions partly cancel each other. Dispersion is a nuisance for lenses, but it is exactly what makes prisms useful: instruments that spread light into a spectrum let scientists identify what a light source is made of — an application you will meet again if you study the astronomy options in Chapter 13.



Investigating dispersion. Dispersion can be investigated practically in the school laboratory. A narrow beam of white light from a lamp (or sunlight admitted through a narrow gap) is directed onto one face of a triangular prism, and the emerging light is caught on a white screen: the spectrum appears spread across the screen. Rotating the prism changes the angles of incidence and shows how the spread of the spectrum changes with them. Placing a second identical prism upside-down in the spectrum recombines the colours back into white light on the screen. Record your method, your observations and any changes you make in your logbook — logbook entries are required for satisfactory completion of Unit 1. **Safety:** never look directly at the Sun, and never direct sunlight through a lens or prism toward anyone's eyes; use a lamp where possible and handle glass prisms over the bench, not at its edge.

Rainbows. A rainbow is dispersion on a grand scale, produced by millions of raindrops. After a shower, with the Sun low and shining from behind you, each raindrop acts a little like a prism. Follow one ray of sunlight into one spherical drop:

1. The ray **refracts as it enters** the drop (air to water). Because the refractive index of water is slightly different for each colour, the light disperses: violet bends more than red.
2. The ray travels across the drop and strikes the inside back surface. There **part of the light reflects** back into the drop. (The angle at the back surface is smaller than the critical angle for water, about 48.8°, so this is a partial reflection — most of the light actually passes out of the back of the drop and is lost.)
3. The reflected ray **refracts again as it leaves** the drop (water to air), spreading the colours a little further.

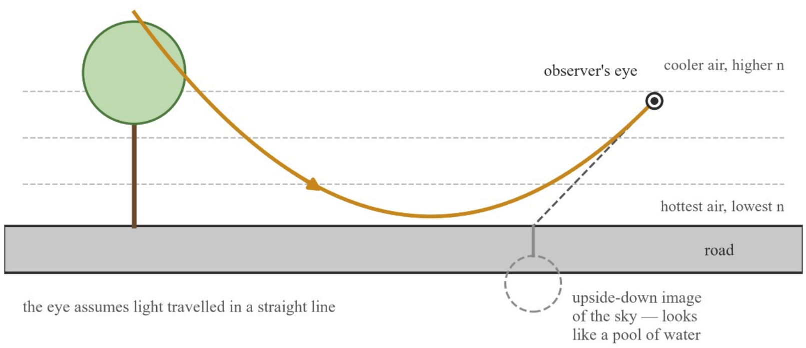


The geometry of the sphere fixes the directions in which each colour comes back out of the drop. Red light returns toward the observer at about 42° to the direction opposite the Sun (the direction in which your shadow points), and violet light at about 40°. Two consequences follow:

- **The order of colours.** Red light reaching your eye must come from drops that are *higher* in the sky than the drops sending you violet light, so in a primary rainbow red appears on top (the outer edge of the arc) and violet at the bottom (the inner edge), with the other colours in between.
- **The arc shape.** The drops that can send dispersed light back to your eye all lie at the one fixed angle (40°–42°) from the shadow direction, in every direction around it. Those positions form a circle, so the rainbow appears as an arc of a circle; the ground usually blocks the lower part. From an aeroplane, looking down on rain, a full circular rainbow can sometimes be seen.

Note that every drop sends out *all* the colours, but from any one drop only one colour is directed toward your eye — a rainbow is a combined effort of millions of drops, and two people standing side by side actually see light from different sets of drops. Because the top of a rainbow sits 42° above the shadow direction, a rainbow is only visible when the Sun is less than 42° above the horizon — early morning, late afternoon, or (in southern Australia) much of a winter's day. Occasionally a second, fainter bow appears outside the first, with the colours reversed, produced by light that reflects twice inside each drop.

Mirages. A mirage is refraction in the air itself. Air is normally a nearly uniform medium, but on a hot day a sealed road heats the air just above it, while the air higher up stays cooler. Cool air is denser than hot air, and denser air has a slightly higher refractive index — so the air above the road becomes a stack of thin layers whose refractive index increases with height.



Light from the sky (or from a distant object) travelling down toward the road keeps crossing into layers of lower refractive index, where it travels faster. At each boundary the ray bends away from the normal, so instead of travelling in a straight line it follows a curve that gradually bends back upward. Because the critical angle between the cool and hot layers is very close to 90° (see Worked Example 3), only rays that travel almost parallel to the ground — grazing rays — curve far enough to turn back up. When such a ray curves up into your eye, you see the sky appearing to come *from the ground*. Your brain assumes light travels in straight lines, so it interprets the light as a reflection of the sky in something on the road — and a blue shimmering reflection on a flat surface reads as water. The "pool" flickers because the hot air layers are constantly moving. The same physics works in reverse over very cold surfaces (such as sea ice): the air near the surface is colder, denser and of higher refractive index than the air above, rays curve downward as they cross the layers, and distant objects can appear lifted or floating above their true position.

Dispersion matters beyond prisms and rainbows. In optical fibres (Section 1E) the different speeds of different colours in glass would spread a signal out over distance, so fibre communications must manage dispersion as well as rely on total internal reflection.

Worked examples

Example 1 — scaffolded

A beam of white light in air strikes the flat face of a crown-glass prism at an angle of incidence of 55°. The refractive index of the glass is 1.514 for red light and 1.532 for violet light. Calculate the angle of refraction for red light and for violet light, and find the angular separation between the two colours inside the glass.

Working	Comment
Snell's Law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$, with $n_1 = 1.00$ (air), $\theta_1 = 55^\circ$.	From Section 1C. The incident medium is air.
Red: $\sin\theta_{\text{red}} = \dfrac{1.00 \times \sin 55^\circ}{1.514} = \dfrac{0.8192}{1.514} = 0.5411$.	Rearrange Snell's Law for the red component.
$\theta_{\text{red}} = \sin^{-1}(0.5411) = 32.8^\circ$.	Red light refracts toward the normal.
Violet: $\sin\theta_{\text{violet}} = \dfrac{1.00 \times \sin 55^\circ}{1.532} = \dfrac{0.8192}{1.532} = 0.5347$.	Same calculation with the violet refractive index.
$\theta_{\text{violet}} = \sin^{-1}(0.5347) = 32.3^\circ$.	Violet refracts more, so it bends closer to the normal (smaller angle).
Separation: $32.8^\circ - 32.3^\circ = 0.5^\circ$.	The colours are already separating inside the glass; a second surface separates them further.

Example 2 — scaffolded

A ray of sunlight strikes a spherical raindrop at an angle of incidence of 60°. The refractive index of water is 1.33. Calculate the angle of refraction as the ray enters the drop, then use the critical angle to determine whether the ray undergoes total internal reflection at the inside back surface of the drop.

Working	Comment
Snell's Law: $1.00 \times \sin 60^\circ = 1.33 \times \sin r$.	Air to water at the front surface of the drop.
$\sin r = \dfrac{0.8660}{1.33} = 0.6511$, so $r = 40.6^\circ$.	The ray bends toward the normal on entering.
Inside a sphere, the ray meets the back surface at the same angle it made inside at entry: incidence angle at the back $= 40.6^\circ$.	The triangle joining the centre of the drop to the two points on the surface is isosceles.
Critical angle: $\sin\theta_c = \dfrac{n_2}{n_1} = \dfrac{1.00}{1.33} = 0.7519$, so $\theta_c = 48.8^\circ$.	From Section 1C: $n_1 \sin\theta_c = n_2 \sin 90^\circ$.
$40.6^\circ < 48.8^\circ$, so total internal reflection does **not** occur.	The angle is below the critical angle.
Instead, most of the light passes out through the back of the drop, and part reflects back inside.	It is this partially reflected portion that goes on to form the rainbow.

Example 3 — unscaffolded

Above a hot sealed road, the cool air has refractive index 1.00029 and the hot air just above the surface has refractive index 1.00026. Calculate the critical angle for light travelling from the cool air into the hot air, and explain what the result says about the rays that produce a mirage.

For total internal reflection the light must travel from the higher-index medium (cool air) into the lower-index medium (hot air). Using the critical-angle relationship from Section 1C,

$$\sin\theta_c = \frac{n_{\text{hot}}}{n_{\text{cool}}} = \frac{1.00026}{1.00029} = 0.99997,$$

so

$$\theta_c = \sin^{-1}(0.99997) = 89.6^\circ.$$

The critical angle is only about 0.4° short of 90°, which means only rays striking the boundary almost parallel to the ground — grazing rays — can reflect back upward. Rays coming down steeply from the sky simply pass through into the hot air. This is why a mirage is seen only when looking almost along the road surface, across a long, flat stretch: the light must travel a long distance through the layers at a grazing angle before it curves far enough to turn back up toward the observer's eye.

∴ the critical angle is 89.6°; only near-grazing rays turn back up to form the mirage.

Example 4 — unscaffolded

Red light of frequency $4.6 \times 10^{14}\,\mathrm{Hz}$ and violet light of frequency $7.4 \times 10^{14}\,\mathrm{Hz}$ enter a block of crown glass, for which $n = 1.514$ (red) and $n = 1.532$ (violet). Calculate the speed and wavelength of each colour inside the glass, and state which colour is slowed more.

The frequency of each wave is set by its source and does not change at the boundary, so the speed in the glass follows from $n = c/v$, that is $v = c/n$:

$$v_{\text{red}} = \frac{3.0 \times 10^8}{1.514} = 1.98 \times 10^8\,\mathrm{m\,s^{-1}},$$

$$v_{\text{violet}} = \frac{3.0 \times 10^8}{1.532} = 1.96 \times 10^8\,\mathrm{m\,s^{-1}}.$$

The wavelength inside the glass then follows from $v = f\lambda$, that is $\lambda = v/f$:

$$\lambda_{\text{red}} = \frac{1.98 \times 10^8}{4.6 \times 10^{14}} = 4.3 \times 10^{-7}\,\mathrm{m}\,(430\,\mathrm{nm}),$$

$$\lambda_{\text{violet}} = \frac{1.96 \times 10^8}{7.4 \times 10^{14}} = 2.6 \times 10^{-7}\,\mathrm{m}\,(260\,\mathrm{nm}).$$

∴ violet light is slowed more ($1.96 \times 10^8\,\mathrm{m\,s^{-1}}$ against $1.98 \times 10^8\,\mathrm{m\,s^{-1}}$) and has the shorter wavelength in the glass. Because it travels more slowly, violet has the larger refractive index and refracts more at any surface — the origin of dispersion.

Practice questions

Question 1 A beam of white light in air strikes a flint-glass prism at an angle of incidence of 50°. The refractive index of the glass is 1.608 for red light and 1.632 for violet light. (a) Calculate the angle of refraction of the red light. (b) Calculate the angle of refraction of the violet light. (c) State which colour is refracted more, and explain how your answers show this.

Question 2 A ray of sunlight strikes a spherical raindrop at an angle of incidence of 45°. The refractive index of water is 1.33. (a) Calculate the angle of refraction as the ray enters the drop. (b) State the angle at which the ray strikes the inside back surface of the drop. (c) Calculate the critical angle for the water–air boundary, and use it to decide whether the ray undergoes total internal reflection at the back of the drop.

Question 3 On a hot day the air above a sealed road forms layers: cool air of refractive index 1.00029 above hot air of refractive index 1.00026. (a) State in which layer light travels faster, and justify your answer using $n = c/v$. (b) Calculate the critical angle for light travelling from the cool layer into the hot layer. (c) Use your answer to explain why a mirage is seen only when looking almost along the surface of a long, flat road.

Question 4 Red light of wavelength $656\,\text{nm}$ in air enters a block of crown glass of refractive index 1.514. (a) Calculate the frequency of the red light in air. (b) Calculate the speed of the red light in the glass. (c) Calculate the wavelength of the red light in the glass. (d) State what happens to the frequency of the light as it enters the glass.

Question 5 In the 1660s Isaac Newton passed sunlight through one triangular prism, producing a spectrum, and then passed that spectrum through a second identical prism turned the other way. (a) Describe what the first prism does to the sunlight, and why. (b) Predict what is seen on a screen placed after the second prism. (c) Explain what this pair of experiments shows about the nature of white light.

Question 6 A rainbow is seen when sunlight is dispersed by raindrops. (a) State where the Sun must be relative to an observer who sees a rainbow. (b) Red light returns from the drops at about 42° to the shadow direction and violet light at about 40°. Use these angles to determine which colour appears at the top of the rainbow, and explain your reasoning. (c) Explain why the rainbow appears as an arc rather than as a straight band of colour.

Question 7 The refractive index of water is 1.331 for red light and 1.343 for violet light. Calculate the speed of red light and of violet light in water.

Question 8 Violet light of wavelength $405\,\text{nm}$ travels through air and then enters water, for which the refractive index at this wavelength is 1.343. (a) Calculate the frequency of the violet light. (b) Calculate the wavelength of the violet light in the water.

Question 9 A beam of white light in air strikes a glass block at an angle of incidence of 40°. Inside the glass, two of the refracted rays make angles of 23.5° and 23.1° with the normal. Calculate the refractive index of the glass for each ray, and identify which ray is the violet light. Justify your identification.

Question 10 Above a hot road, a ray of light travelling through cool air (refractive index 1.00029) strikes the boundary with hot air (refractive index 1.00026) at an angle of 89.7° to the normal. Determine by calculation whether the ray undergoes total internal reflection.

Question 11 The top of a primary rainbow is 42° above the shadow direction. At a particular moment the Sun is 55° above the horizon. Calculate the position of the top of the rainbow relative to the horizon, and state whether a rainbow can be seen from ground level.

Question 12 Sunlight strikes the flat surface of a pond at an angle of incidence of 60°. The refractive index of the water is 1.331 for red light and 1.343 for violet light. Calculate the angle of refraction for red and for violet light, and find the angular separation between the two colours under the surface.

Question 13 Green light of wavelength $550\,\text{nm}$ in air enters glass of refractive index 1.52. (a) Calculate the frequency of the green light. (b) Calculate the speed and the wavelength of the green light in the glass.

Question 14 Explain why violet light is refracted more than red light when white light passes from air into glass. Your answer should refer to speed, refractive index and Snell’s Law.

Question 15 White light travels through a vacuum. Explain why no dispersion occurs in a vacuum, no matter how far the light travels.

Question 16 In a primary rainbow, red appears at the top of the arc and violet at the bottom. Explain how this order arises, referring to the angles at which red and violet light return from the drops. You may assume that every drop disperses the full spectrum.

Question 17 A mirage on a hot road is often described as “the sky reflected in water”. Explain, using the refraction model of the mirage, why the observer’s brain reaches that interpretation even though there is no water present.

Question 18 Mirages are seen on hot days over long, flat stretches of road, but not over short stretches and not on cold days. Explain both observations using the physics of the layered air model.

Question 19 A simple camera lens produces images with faint coloured fringes around the edges of bright objects. (a) Name this effect and explain its cause, referring to refraction of the different colours. (b) Explain why camera lenses are built from several lenses made of different types of glass.

Question 20 When light crosses from air into glass, its speed and wavelength change but its frequency does not. Explain why the frequency must remain the same, referring to what determines the frequency and what determines the speed.

Answers

Question 1 (a) 28.5°; (b) 28.0°; (c) violet — it has the smaller angle of refraction, meaning it bends further toward the normal. **Question 2** (a) 32.1°; (b) 32.1°; (c) $\theta_c = 48.8^\circ$; $32.1^\circ < 48.8^\circ$, so no total internal reflection (the reflection is partial). **Question 3** (a) the hot-air layer; lower n means larger $v = c/n$; (b) 89.6°; (c) only rays within about 0.4° of grazing can reflect, so the effect needs a long, flat road viewed nearly along the surface. **Question 4** (a) $4.6 \times 10^{14}\,\text{Hz}$; (b) $1.98 \times 10^{8}\,\text{m s}^{-1}$; (c) $433\,\text{nm}$; (d) it does not change. **Question 5** (a) it disperses the white light into a spectrum because the glass refracts each colour by a different amount; (b) white light; (c) white light is a mixture of colours, and the prism separates them rather than adding colour. **Question 6** (a) behind the observer (and low in the sky); (b) red — drops higher in the sky send red to the eye at the larger angle of 42°; (c) all drops returning light lie at a fixed angle around the shadow direction, forming a circle; the ground blocks the lower part. **Question 7** Red: $2.25 \times 10^{8}\,\text{m s}^{-1}$; violet: $2.23 \times 10^{8}\,\text{m s}^{-1}$. **Question 8** (a) $7.4 \times 10^{14}\,\text{Hz}$; (b) $302\,\text{nm}$. **Question 9** $n = 1.61$ (23.5° ray) and $n = 1.64$ (23.1° ray); the 23.1° ray is violet — smaller refraction angle means more bending, and violet is refracted most. **Question 10** $\theta_c = 89.6^\circ$; $89.7^\circ > 89.6^\circ$, so total internal reflection occurs. **Question 11** The top of the rainbow would be $42^\circ - 55^\circ = 13^\circ$ *below* the horizon; no rainbow can be seen. **Question 12** Red: 40.6°; violet: 40.2°; separation 0.4°. **Question 13** (a) $5.5 \times 10^{14}\,\text{Hz}$; (b) $1.97 \times 10^{8}\,\text{m s}^{-1}$, $362\,\text{nm}$. **Question 14** See model answer. **Question 15** See model answer. **Question 16** See model answer. **Question 17** See model answer. **Question 18** See model answer. **Question 19** See model answer. **Question 20** See model answer.

Fully-worked solutions

Question 1 $n_1 = 1.00$ (air), $\theta_1 = 50^\circ$, $n_{\text{red}} = 1.608$, $n_{\text{violet}} = 1.632$. (a) Snell's Law: $\sin\theta_{\text{red}} = \dfrac{\sin 50^\circ}{1.608} = \dfrac{0.7660}{1.608} = 0.4764$, so $\theta_{\text{red}} = \sin^{-1}(0.4764) = 28.5^\circ$. (b) $\sin\theta_{\text{violet}} = \dfrac{\sin 50^\circ}{1.632} = \dfrac{0.7660}{1.632} = 0.4694$, so $\theta_{\text{violet}} = \sin^{-1}(0.4694) = 28.0^\circ$. (c) Violet light is refracted more. Both rays bend toward the normal on entering the glass, and the violet ray's smaller angle of refraction ($28.0^\circ < 28.5^\circ$) means it bends further from its original direction. This is because violet light travels more slowly in the glass, so the glass has the larger refractive index for violet.

Question 2 $n_1 = 1.00$, $\theta_1 = 45^\circ$, $n_{\text{water}} = 1.33$. (a) $\sin r = \dfrac{\sin 45^\circ}{1.33} = \dfrac{0.7071}{1.33} = 0.5317$, so $r = \sin^{-1}(0.5317) = 32.1^\circ$. (b) Inside a spherical drop, the triangle joining the centre to the entry point and the back-surface point is isosceles, so the ray meets the back surface at the same angle: 32.1°. (c) $\sin\theta_c = \dfrac{1.00}{1.33} = 0.7519$, so $\theta_c = 48.8^\circ$. The incidence angle at the back (32.1°) is smaller than the critical angle, so total internal reflection does not occur: most light exits the back of the drop, and the small partially reflected portion is what forms the rainbow.

Question 3 Cool layer $n = 1.00029$; hot layer $n = 1.00026$. (a) Since $n = c/v$, the speed in a medium is $v = c/n$. The hot-air layer has the smaller refractive index, so light travels faster in the hot air. (b) $\sin\theta_c = \dfrac{n_{\text{hot}}}{n_{\text{cool}}} = \dfrac{1.00026}{1.00029} = 0.99997$, so $\theta_c = 89.6^\circ$. (c) The critical angle is only 0.4° short of 90°, so only rays travelling almost parallel to the ground can reflect back upward; steeper rays pass straight through the layers. For a ray to curve far enough to reach the observer's eye it must cross many layers at a grazing angle, which requires a long, flat road. That is why mirages appear only in the distance, seen nearly along the surface.

Question 4 $\lambda = 656\,\text{nm} = 656 \times 10^{-9}\,\text{m}$ in air; $n = 1.514$. (a) $f = \dfrac{c}{\lambda} = \dfrac{3.0 \times 10^{8}}{656 \times 10^{-9}} = 4.6 \times 10^{14}\,\text{Hz}$. (b) $v = \dfrac{c}{n} = \dfrac{3.0 \times 10^{8}}{1.514} = 1.98 \times 10^{8}\,\text{m s}^{-1}$. (c) The frequency is unchanged in the glass, so using the unrounded frequency from (a), $\lambda=\frac{v}{f}=\frac{1.9815\times10^{8}}{4.573\times10^{14}}=4.33\times10^{-7}\,\mathrm{m}=433\,\mathrm{nm}$. (Equivalently, $\lambda_{\mathrm{glass}}=\lambda_{\mathrm{air}}/n=656/1.514=433\,\mathrm{nm}$.) (d) The frequency does not change — it is set by the source, not by the medium.

Question 5 (a) The first prism disperses the white light into a spectrum. Each colour refracts on entering and leaving the glass, and because the glass slows violet light more than red light, violet is refracted more and the colours fan out. (b) A spot of white light is seen on the screen. (c) The first prism did not add colour to the light: the colours were already present in the white light as a mixture, and the prism only separated them. Recombining the separated colours with the second prism restores white light, which shows that white light *is* the mixture of all the colours of the visible spectrum.

Question 6 (a) The Sun must be behind the observer (and less than 42° above the horizon), with the rain in front. (b) Red appears at the top. Red light returns from the drops at the larger angle (42°), so the drops sending red light to the eye sit higher in the sky than the drops sending violet light (40°). Since you see red from higher drops and violet from lower drops, red forms the upper (outer) edge of the bow. (c) Every drop that can return dispersed light to the eye must lie at the one fixed angle (40°–42°) from the shadow direction, in every direction around it. The set of all such positions is a circle centred on the shadow direction, so the bow appears as an arc of that circle; the ground blocks the lower drops, so normally only the upper arc is seen.

Question 7 Using $v=c/n$: Red: $v=\frac{3.0\times10^{8}}{1.331}=2.25\times10^{8}\,\mathrm{m\ s^{-1}}$. Violet: $v=\frac{3.0\times10^{8}}{1.343}=2.23\times10^{8}\,\mathrm{m\ s^{-1}}$.

Question 8 $\lambda=405\,\mathrm{nm}=405\times10^{-9}\,\mathrm{m}$; $n=1.343$. (a) $f=\frac{c}{\lambda}=\frac{3.0\times10^{8}}{405\times10^{-9}}=7.4\times10^{14}\,\mathrm{Hz}$. (b) The frequency is unchanged in the water. The speed is $v=c/n=3.0\times10^{8}/1.343=2.23\times10^{8}\,\mathrm{m\ s^{-1}}$, so, using the unrounded values, $\lambda=v/f=3.02\times10^{-7}\,\mathrm{m}=302\,\mathrm{nm}$ (equivalently, $405/1.343=302\,\mathrm{nm}$).

Question 9 $\theta_1=40^{\circ}$, so $\sin\theta_1=0.6428$. For the 23.5° ray: $n=\frac{\sin 40^{\circ}}{\sin 23.5^{\circ}}=\frac{0.6428}{0.3987}=1.61$. For the 23.1° ray: $n=\frac{\sin 40^{\circ}}{\sin 23.1^{\circ}}=\frac{0.6428}{0.3923}=1.64$. The 23.1° ray is the violet light. It makes the smaller angle with the normal, so it has bent further from its original direction — and violet light is always the most strongly refracted component because the glass has the larger refractive index for it.

Question 10 The critical angle for the cool-to-hot boundary is

$$\sin\theta_c=\frac{1.00026}{1.00029}=0.99997\Rightarrow\theta_c=89.6^{\circ}.$$

The ray strikes the boundary at 89.7°, which is larger than the critical angle, and it is travelling from the higher-index medium into the lower-index medium, so **total internal reflection occurs**: the ray reflects back upward. This turning of grazing rays is what sends the image of the sky up into the observer's eye in a mirage.

Question 11 The shadow direction points as far below the horizon as the Sun is above it, so with the Sun 55° above the horizon, the shadow direction is 55° below it. The top of the rainbow lies 42° above the shadow direction:

$$42^{\circ}-55^{\circ}=-13^{\circ},$$

that is, 13° *below* the horizon. Since the whole bow lies below the horizon, no rainbow can be seen from ground level. (This is why rainbows need a low Sun — below 42° elevation — and are a morning or afternoon sight in summer, but can appear near midday in winter.)

Question 12 $\theta_1 = 60^\circ$, $\sin 60^\circ = 0.8660$. Red: $\sin\theta_{\text{red}} = \frac{0.8660}{1.331} = 0.6507$, so $\theta_{\text{red}} = 40.6^\circ$. Violet: $\sin\theta_{\text{violet}} = \frac{0.8660}{1.343} = 0.6448$, so $\theta_{\text{violet}} = 40.2^\circ$. Separation: $40.6^\circ - 40.2^\circ = 0.4^\circ$. The sunlight is already slightly dispersed as it enters the water.

Question 13 $\lambda = 550\,\text{nm} = 550\times10^{-9}\,\text{m}$; $n = 1.52$. (a) $f = \frac{c}{\lambda} = \frac{3.0\times10^8}{550\times10^{-9}} = 5.5\times10^{14}\,\text{Hz}$. (b) $v = \frac{c}{n} = \frac{3.0\times10^8}{1.52} = 1.97\times10^8\,\text{m s}^{-1}$, and with the frequency unchanged (using the unrounded frequency from (a)), $\lambda = \frac{v}{f} = \frac{1.974\times10^8}{5.455\times10^{14}} = 3.62\times10^{-7}\,\text{m} = 362\,\text{nm}$ (equivalently $550/1.52 = 362\,\text{nm}$).

Question 14 Model answer. In glass, violet light travels more slowly than red light, so the refractive index of the glass is larger for violet than for red ($n = c/v$). Snell's Law, $n_1 \sin\theta_1 = n_2 \sin\theta_2$, then requires a smaller angle of refraction θ_2 for the larger n_2: at the same angle of incidence, violet bends closer to the normal than red. The different bending angles for the different colours are what separate the white light into a spectrum.

Question 15 Model answer. Dispersion happens because different colours travel at different speeds in a medium, giving each colour a different refractive index. In a vacuum there is no medium: every electromagnetic wave, of every colour and frequency, travels at the one speed c. With one speed for all colours there is only one refractive index ($n = 1$), so every colour refracts identically — and in fact there are no boundaries in a vacuum at which to refract at all. White light can cross the whole vacuum of space without separating, which is why sunlight still arrives as white light.

Question 16 Model answer. Every drop disperses the full spectrum and sends all the colours back out, but only one colour from any one drop is aimed at the observer's eye. Red light returns at about 42° to the shadow direction and violet at about 40°, so the red reaching the eye must come from drops higher in the sky and the violet from drops lower down. From top to bottom the observer therefore sees red, then the intermediate colours, then violet — red on the outside of the arc and violet on the inside.

Question 17 Model answer. In the hot layered air above the road, light from the sky travelling at a grazing angle is refracted progressively as it crosses into hotter, lower-index layers, curving until it turns back upward into the observer's eye. The observer's brain assumes light always travels in a straight line, so it traces the arriving ray back along its final straight-line direction — which points down at the road. The observer therefore sees an image of the sky appearing to lie on the road surface, exactly where a reflection of the sky would appear in a pool of water. With no water present, the "reflection" is really refracted light from the sky, but the brain has no way to tell the difference.

Question 18 Model answer. A mirage needs two conditions. First, a strong temperature gradient: only a hot surface (such as sealed road in sunshine) creates a hot, low-density, low-index layer of air near the ground with cooler, higher-index air above it. On a cold day the gradient is absent or reversed, so rays do not curve upward. Second, grazing geometry: the critical angle between the layers is about 89.6°, so only rays travelling almost parallel to the ground can turn back up. Such rays must cross a long stretch of the layered air to curve far enough to reach the eye, which is why the effect appears only over long, flat distances and never over a short stretch of road.

Question 19 Model answer. (a) The effect is chromatic aberration. A lens focuses light by refraction, and because the glass refracts violet light more than red light (the refractive index is larger for violet), the colours come to a focus at slightly different distances from the lens. An image formed at one focus position is slightly out of focus for the other colours, which appear as coloured fringes at high-contrast edges. (b) Different types of glass disperse light by different amounts. By combining several lenses made from different glasses, the designer arranges for the dispersion of one lens to partly cancel the dispersion of another, bringing the colours to nearly the same focus while keeping the overall focusing power of the lens system.

Question 20 Model answer. The frequency of a wave is set by its source — it is the number of oscillations the source makes each second — and the medium the wave enters cannot change that rate. The wave arriving at the boundary makes the disturbance in the glass oscillate at exactly the same rate: the number of wave crests arriving at the boundary each second equals the number of crests moving away on the other side, so the frequency is the same in both media. The speed, by contrast, is set by the medium (light slows down in glass), so the speed changes. Since $v = f\lambda$ and f is fixed, the wavelength must change in proportion to the speed.

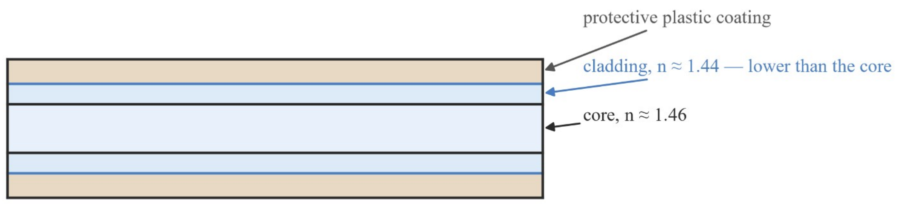
Theory

A telephone call, a streamed video and a web page are all carried as **data** — information encoded as streams of numbers. Most of this data is now sent as pulses of light guided along thin strands of very pure glass called **optical fibres**. A single fibre is roughly as thick as a human hair, yet a cable of fibres carries the internet traffic of whole cities. This subtopic examines how light is transmitted through an optical fibre, and why fibres have become the workhorse of modern communication.

The structure of an optical fibre. An optical fibre is built from two layers of glass. The inner layer, called the **core**, is the region through which the light travels. Surrounding the core is a second layer of glass called the **cladding**. The cladding has a *lower* refractive index than the core. Outside the cladding is a tough plastic coating that protects the glass from scratches and moisture. The **refractive index** n of a material is a measure of how much slower light travels in that material than in a vacuum:

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

where $c = 3.00 \times 10^8 \text{ m s}^{-1}$ is the speed of light in a vacuum and v is the speed of light in the material. The refractive index has no units. The glass used for fibre cores typically has $n \approx 1.46$, so light travels through it at about $2.05 \times 10^8 \text{ m s}^{-1}$ — roughly two-thirds of its vacuum speed.



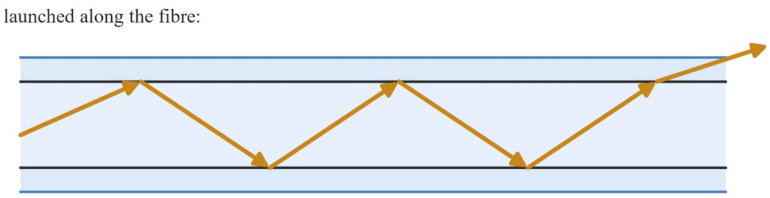
total internal reflection traps light in the core because the cladding has the lower refractive index: $\sin\theta_c = n_{clad}/n_{core}$

How light is trapped: total internal reflection. As a light pulse travels along the core it reaches the core–cladding boundary. The light is travelling from a medium of higher refractive index (the core) toward one of lower refractive index (the cladding), so total internal reflection is possible — the behaviour studied in Section 1C. When the angle of incidence at the boundary is greater than the **critical angle** θ_c, no light refracts out at all: every bit of it reflects back into the core. The pulse therefore zigzags down the fibre, reflecting again and again, guided by the boundary, even around gentle bends.

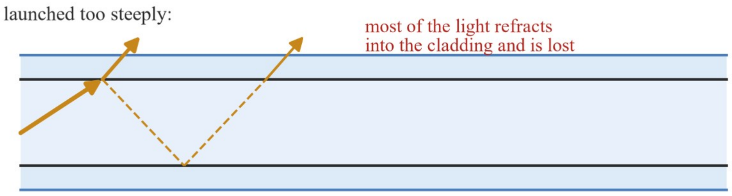
The critical angle is set by the two refractive indices. From Snell's Law with the refracted ray at 90° (Section 1C):

$$n_{\text{core}} \sin\theta_c = n_{\text{cladding}} \sin 90^\circ, \text{so} \sin\theta_c = \frac{n_{\text{cladding}}}{n_{\text{core}}}.$$

Because $n_{\text{cladding}} < n_{\text{core}}$, the ratio is less than 1 and a real critical angle exists. Rays striking the boundary at angles greater than θ_c are totally internally reflected and stay in the core; rays striking at smaller angles partly refract into the cladding and their light is lost from the signal.



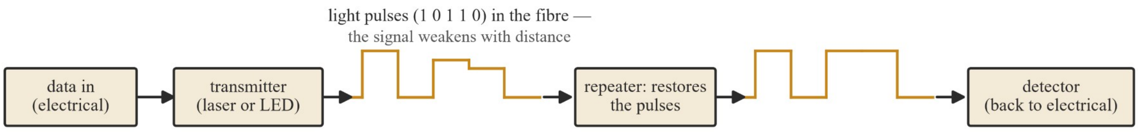
incidence angle at the boundary $> \theta_c$:
total internal reflection — the light is guided along the core



incidence angle at the boundary $< \theta_c$:
little or no total internal reflection — the signal fades quickly

Why the cladding matters. The cladding is not merely a protective wrapper; it does three jobs. First, it keeps the reflecting surface pristine: a scratch or a film of dirt on a bare core would let light leak out at the contact point. Second, it fixes a known, stable lower refractive index against the core, which sets a definite critical angle. Third, a cable contains many fibres side by side; without cladding, light could leak from one core into a neighbour wherever two bare fibres touched, and each conversation would blur into the next.

How a fibre carries information. To carry information, the light is switched on and off very rapidly. A pulse of light represents a 1 and the absence of a pulse represents a 0 — one binary digit, or **bit**, of data. At the transmitting end of a link, a **transmitter** converts the electrical data signal into pulses of light (usually produced by a laser or a light-emitting diode) and launches them into the fibre. At the receiving end, a light detector converts the arriving pulses back into an electrical signal.



an optical communication link: the data rides on the light,
and repeaters let it travel long distances without being lost

As light travels through even the purest glass, a tiny fraction of its energy is absorbed by the glass, so the pulses gradually weaken with distance. This weakening is called **attenuation**. On a link hundreds of kilometres long the pulses would become too weak and too indistinct to read, so devices called **repeaters** (or optical amplifiers) are placed at intervals along the cable to boost the signal back to full strength.

Why fibres are used for communication. Optical fibres have displaced copper wires for most long-distance communication because:

- **Large bandwidth.** The **bandwidth** of a link is the amount of information it can carry per second. Light has an extremely high frequency (about 10^{14} Hz — Section 1B), so a light beam can be pulsed billions of times each second. One fibre can carry thousands of telephone calls, television channels and internet connections at once.
- **Low attenuation.** Pulses travel much farther through glass before needing amplification than electrical signals travel through copper wire.
- **No electrical interference.** Glass is an insulator, so the light in a fibre is unaffected by nearby power lines, lightning or electrical machinery. Copper wires pick up such interference, which corrupts the signal.
- **Size and security.** Fibres are thin and light, and no light escapes from a healthy fibre, so a signal cannot be read from outside the cable without physically tampering with it.

Fibres in Australia. Optical fibres form the backbone of Australia's communications. The National Broadband Network (the NBN) connects homes and businesses across the country; in its fastest connections, called *fibre to the premises*, an optical fibre runs all the way from the local exchange into the building itself. Australia is also linked to other countries by submarine fibre-optic cables laid on the sea floor; most international data traffic to and from Australia travels through these cables rather than by satellite. The same guiding principle is also put to work in medicine: a bundle of fibres in an endoscope carries light into the body and returns an image, letting doctors look inside without surgery.

In the laboratory. The guiding of light can be investigated directly: a ray box or a low-power laser (never directed at anyone's eyes) is shone into one end of a short length of plastic optical fibre. Light emerges from the far end even when the fibre is bent into a curve, and light can be seen leaking out where the fibre is kinked sharply — evidence that the light is being reflected at the inner surface, and that this reflection fails when the bend is too tight.

Throughout this subtopic the speed of light in a vacuum is taken as $c=3.00\times10^{8}\,\mathrm{m\ s^{-1}}$.

Worked examples

Example 1 — scaffolded

An optical fibre used to carry internet traffic has a silica core of refractive index 1.460, surrounded by cladding of refractive index 1.445. (a) Calculate the critical angle for the core–cladding boundary. (b) A ray travelling in the core strikes the boundary at 85° to the normal. Determine what happens to the ray. (c) A second ray strikes the boundary at 80° to the normal. Determine what happens to this ray, and explain why this matters for communication.

Working	Comment
$n_{\text{core}}=1.460$, $n_{\text{cladding}}=1.445$; since $n_{\text{core}}>n_{\text{cladding}}$, total internal reflection is possible.	Light can only be trapped when it travels from higher to lower refractive index.
$\sin\theta_c=\dfrac{n_{\text{cladding}}}{n_{\text{core}}}=\dfrac{1.445}{1.460}=0.9897$.	From $n_{\text{core}}\sin\theta_c=n_{\text{cladding}}\sin 90^{\circ}$ (Section 1C).
$\theta_c=\sin^{-1}(0.9897)=81.8^{\circ}$.	
(b) $85^{\circ}>81.8^{\circ}$: the angle of incidence is greater than the critical angle, so the ray is totally internally reflected and stays in the core.	The condition for total internal reflection is $\theta>\theta_c$.
(c) $80^{\circ}<81.8^{\circ}$: the ray is *not* totally internally reflected; some light refracts into the cladding and is lost.	Escaping light weakens the signal, so fibres are designed so that rays always meet the boundary at angles above θ_c.

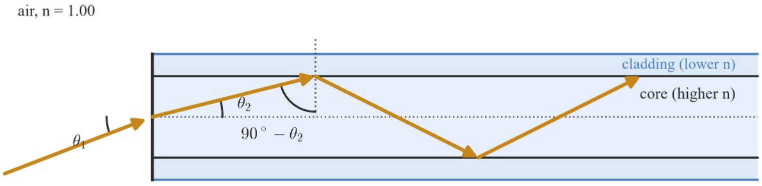
Example 2 — scaffolded

Optical fibres carry internet traffic between Melbourne and Sydney, a distance of roughly $900\,\mathrm{km}$ of fibre. The core of the fibre has refractive index 1.46. (a) Calculate the speed of light in the core. (b) Calculate the time taken for a pulse of light to travel from Melbourne to Sydney through this fibre.

Working	Comment
$n=1.46$, $L=900\,\mathrm{km}=9.00\times10^{5}\,\mathrm{m}$, $c=3.00\times10^{8}\,\mathrm{m\ s^{-1}}$.	List the data; convert km to m.
$v=\dfrac{c}{n}=\dfrac{3.00\times10^{8}}{1.46}=2.05\times10^{8}\,\mathrm{m\ s^{-1}}$.	Refractive index is defined by $n=c/v$. Light travels slower in glass than in a vacuum.
$t=\dfrac{L}{v}=\dfrac{9.00\times10^{5}}{2.05\times10^{8}}=4.38\times10^{-3}\,\mathrm{s}$.	Time = distance ÷ speed.
$t\approx4.4\,\mathrm{ms}$.	Less than a hundredth of a second — effectively instantaneous to the people on the call.

Example 3 — unscaffolded

A ray of light in air strikes the flat end of the core of an optical fibre at an angle of incidence of 15°. The core has refractive index 1.50 and the cladding has refractive index 1.44. Determine, by calculation, whether this ray will be guided along the fibre by total internal reflection.



if $90^\circ - \theta_2$ exceeds θ_c at the boundary,
the light stays trapped and is guided along the fibre

At the end face, Snell's Law gives the angle of refraction θ_2 in the core:

$$\sin\theta_2 = \frac{n_{\text{air}}\sin\theta_1}{n_{\text{core}}} = \frac{1.00\times\sin 15^\circ}{1.50} = \frac{0.2588}{1.50} = 0.1725,$$

so $\theta_2 = 9.9^\circ$. The ray now makes an angle of 9.9° with the fibre's axis, so it strikes the core–cladding boundary at an angle of incidence of $90^\circ - 9.9^\circ = 80.1^\circ$.

The critical angle for this boundary is

$$\sin\theta_c = \frac{n_{\text{cladding}}}{n_{\text{core}}} = \frac{1.44}{1.50} = 0.96 \Rightarrow \theta_c = 73.7^\circ.$$

Since $80.1^\circ > 73.7^\circ$, the ray strikes the boundary at an angle greater than the critical angle and is totally internally reflected. The same geometry repeats at every later bounce.

∴ the ray is guided along the fibre (angle of incidence at the wall, 80.1°, exceeds the critical angle, 73.7°).

Example 4 — unscaffolded

A $1.0\,\text{km}$ length of optical fibre has a core of refractive index 1.460 and cladding of refractive index 1.445. Light entering the fibre may travel straight along the axis (the shortest path) or zigzag at any angle up to the critical angle (the longest guided path). Calculate the travel time for each of these rays, and use your results to explain why pulses of light sent into the fibre must be spaced apart in time.

The speed of light in the core is

$$v = \frac{c}{n_{\text{core}}} = \frac{3.00\times10^8}{1.460} = 2.05\times10^8\,\text{m s}^{-1}.$$

For the axial ray the path is simply $L = 1000\,\text{m}$, so

$$t_{\text{axial}} = \frac{L}{v} = \frac{1000}{2.05\times10^8} = 4.87\times10^{-6}\,\text{s}.$$

For the ray zigzagging at the critical angle, $\sin\theta_c = \dfrac{1.445}{1.460} = 0.9897$, and the path length is stretched to $L/\sin\theta_c$:

$$\text{path} = \frac{1000}{0.9897} = 1010\,\text{m},\ t_{\text{zigzag}} = \frac{1010}{2.05\times10^8} = 4.92\times10^{-6}\,\text{s}.$$

The zigzag ray arrives $4.92 - 4.87 = 0.05\,\mu\text{s}$ (about $50\,\text{ns}$) later than the axial ray.

∴ the axial ray takes 4.87×10^{-6} s and the critical-angle ray 4.92×10^{-6} s. Because rays taking different paths arrive at slightly different times, a short pulse spreads out as it travels. Pulses must therefore be spaced far enough apart that the spread-out tail of one pulse does not overlap the next — this limits how fast data can be sent down the fibre.

Practice questions

Question 1 An optical fibre has a core of refractive index 1.48 surrounded by cladding of refractive index 1.46. (a) State the relationship between the refractive index of the core and the refractive index of the cladding that is needed for the fibre to guide light by total internal reflection. (b) Calculate the critical angle for the core–cladding boundary. (c) A ray travelling in the core strikes the boundary at 82° to the normal. Determine whether the ray is totally internally reflected.

Question 2 In a school laboratory investigation, students send pulses of light through a $20\,\mathrm{m}$ length of plastic optical fibre of refractive index 1.50. (a) Calculate the speed of the light pulses in the fibre. (b) Calculate the time taken for a pulse to travel the length of the fibre. (c) Calculate the time light would take to travel the same $20\,\mathrm{m}$ through a vacuum, and hence determine the extra time the light takes because it travels in the fibre rather than in a vacuum.

Question 3 A ray of light in air strikes the flat end of the core of an optical fibre at an angle of incidence of 30°. The core has refractive index 1.50 and the cladding has refractive index 1.44. (a) Calculate the angle of refraction of the ray in the core. (b) Calculate the angle at which the ray then strikes the core–cladding boundary, measured from the normal to the boundary. (c) Determine, by calculation, whether this ray will be guided along the fibre.

Question 4 (a) Explain why the glass used for the core of a communication fibre must be extremely transparent. (b) State two functions of the cladding. (c) Explain why the refractive index of the cladding must be less than the refractive index of the core.

Question 5 A fibre-optic communication link consists of a transmitter at one end, an optical fibre, and a receiver at the other end. (a) State the role of the transmitter. (b) State the role of the receiver. (c) Explain what a repeater does, and why repeaters are needed at intervals along a link several hundred kilometres long.

Question 6 (a) State two advantages of optical fibres over copper wires for carrying telephone and internet signals. (b) Explain why the signal in an optical fibre is unaffected by electrical interference from nearby power lines or lightning. (c) Light has a frequency of about $10^{14}\,\mathrm{Hz}$, far higher than the frequencies of the radio waves used for mobile phone signals. Explain why a beam of light can carry more information than a lower-frequency radio wave.

Question 7 The core of an optical fibre has refractive index 1.52 and the cladding has refractive index 1.49. Calculate the critical angle for the core–cladding boundary.

Question 8 A pulse of light travels through $50\,\mathrm{km}$ of optical fibre whose core has refractive index 1.52. (a) Calculate the speed of light in the core. (b) Calculate the time taken for the pulse to travel the length of the fibre.

Question 9 The critical angle for the core–cladding boundary of an optical fibre is 75.0°. The cladding has refractive index 1.40. Calculate the refractive index of the core.

Question 10 A ray of light in air strikes the flat end of the core of an optical fibre at an angle of incidence of 20°. The core has refractive index 1.48 and the cladding has refractive index 1.40. Determine, by calculation, whether this ray will be guided along the fibre.

Question 11 A $2.0\,\mathrm{km}$ length of optical fibre has a core of refractive index 1.50 and cladding of refractive index 1.485. Calculate the difference between the travel time of a ray that goes straight along the axis of the fibre and the travel time of a ray that zigzags along the fibre at the critical angle.

Question 12 A fibre-optic cable can be bent around corners. Explain why the light continues to be guided around a gentle bend, and why a very sharp bend causes signal loss.

Question 13 Most of the data traffic between Australia and the rest of the world travels through submarine fibre-optic cables laid on the sea floor, rather than by communication satellite. Give two physics reasons why fibre-optic cables are preferred for this role.

Question 14 Even the purest glass absorbs a tiny fraction of the energy of the light travelling through it. Explain the effect this absorption has on a pulse of light travelling along a long fibre, and state the name given to this effect.

Question 15 Information on a fibre-optic link is sent digitally: a pulse of light represents a 1 and the absence of a pulse represents a 0. (a) Describe how the sound of a telephone call is carried along the fibre. (b) State and explain one advantage of sending information as pulses rather than as a signal that varies continuously.

Question 16 A fibre-optic link between two cities is $250\,\mathrm{km}$ long and the core of the fibre has refractive index 1.50. (a) Calculate the time taken for a pulse of light to travel from one city to the other. (b) State whether this delay would be noticeable to two people talking on a telephone call, and justify your answer.

Question 17 It is difficult to *tap* an optical fibre — to read the data it is carrying — without being detected. Explain why, with reference to the way light travels in a fibre.

Question 18 Light travels through a $10\,\mathrm{km}$ length of optical fibre whose core has refractive index 1.46. Calculate the time taken for the light to travel through the fibre, and the time light would take to travel the same $10\,\mathrm{km}$ through a vacuum. State both times and comment on the difference.

Answers

Question 1 (a) the core must have a higher refractive index than the cladding; (b) 80.6°; (c) yes — $82^{\circ} > 80.6^{\circ}$, so the ray is totally internally reflected. **Question 2** (a) $2.0 \times 10^{8}\,\mathrm{m\ s^{-1}}$; (b) $1.0 \times 10^{-7}\,\mathrm{s}$; (c) $6.7 \times 10^{-8}\,\mathrm{s}$; extra time $3.3 \times 10^{-8}\,\mathrm{s}$. **Question 3** (a) 19.5°; (b) 70.5°; (c) no — $70.5^{\circ} < \theta_c = 73.7^{\circ}$, so the ray refracts into the cladding and is lost. **Question 4** (a) so that as little light energy as possible is absorbed on the journey; (b) any two of: protects the reflecting surface, fixes a known lower refractive index (sets θ_c), stops light leaking into neighbouring fibres; (c) total internal reflection requires travel from higher to lower refractive index. **Question 5** (a) converts the electrical data signal into pulses of light launched into the fibre; (b) detects the arriving light pulses and converts them back into an electrical signal; (c) a repeater boosts the weakened pulses back to full strength; needed because absorption in the glass attenuates the signal over long distances. **Question 6** (a) any two of: larger bandwidth, lower attenuation (fewer repeaters), no electrical interference, thinner and lighter; (b) glass is an insulator, so external electric effects cannot disturb the light; (c) the higher the frequency of the carrier, the faster it can be pulsed on and off, so more bits can be sent each second. **Question 7** 78.6°. **Question 8** (a) $1.97 \times 10^{8}\,\mathrm{m\ s^{-1}}$; (b) $2.5 \times 10^{-4}\,\mathrm{s}$. **Question 9** 1.45. **Question 10** yes — angle of refraction 13.4°, angle of incidence at the wall 76.6°, critical angle 71.1°; $76.6^{\circ} > 71.1^{\circ}$, so the ray is guided. **Question 11** $1.0 \times 10^{-7}\,\mathrm{s}$ (about $100\,\mathrm{ns}$). **Question 12** at a gentle bend rays still strike the boundary at angles greater than the critical angle, so total internal reflection continues; at a sharp bend the angle of incidence falls below the critical angle and light refracts out of the core. **Question 13** any two of: fibres provide much larger bandwidth; the signal path is far shorter than a route up to a satellite and back, giving a smaller time delay and less attenuation; the signal in a cable is unaffected by weather or the atmosphere. **Question 14** the pulse loses energy and becomes weaker the farther it travels; this gradual weakening is called attenuation. **Question 15** (a) the call's electrical signal is used to switch a light source on and off, producing a stream of pulses that represents the message as bits; at the far end a detector converts the pulses back into an electrical signal; (b) weakened or distorted pulses can be rebuilt into clean pulses by repeaters, so the message does not degrade with distance. **Question 16** (a) $1.25 \times 10^{-3}\,\mathrm{s}$ ($1.25\,\mathrm{ms}$); (b) no — it is far shorter than the delays people notice in conversation (of order a tenth of a second or more). **Question 17** light is trapped in the core by total internal reflection and none escapes through the sides; reading the data requires cutting or sharply bending the fibre, which interrupts or weakens the signal and reveals the tampering. **Question 18** fibre: $4.9 \times 10^{-5}\,\mathrm{s}$; vacuum: $3.3 \times 10^{-5}\,\mathrm{s}$; the light takes about $1.5 \times 10^{-5}\,\mathrm{s}$ longer in the fibre because it travels more slowly in glass.

Fully-worked solutions

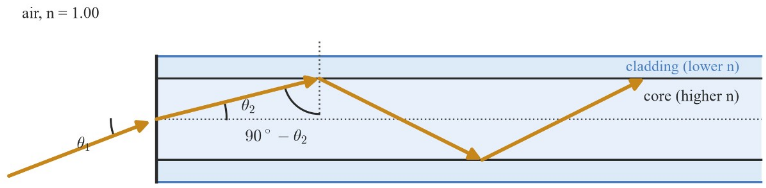
Question 1 $n_{\text{core}} = 1.48$, $n_{\text{cladding}} = 1.46$. (a) Total internal reflection can only occur when light travels from a medium of higher refractive index to one of lower refractive index, so the core must have the higher refractive index: $n_{\text{core}} > n_{\text{cladding}}$. (b)

$$\sin\theta_c = \frac{n_{\text{cladding}}}{n_{\text{core}}} = \frac{1.46}{1.48} = 0.9865\,, \theta_c = \sin^{-1}(0.9865) = 80.6^{\circ}.$$

(c) The angle of incidence is 82°, which is greater than the critical angle (80.6°), so the ray **is** totally internally reflected and remains in the core.

Question 2 $L = 20\,\mathrm{m}$, $n = 1.50$. (a) $v = \frac{c}{n} = \frac{3.00 \times 10^{8}}{1.50} = 2.0 \times 10^{8}\,\mathrm{m\ s^{-1}}$. (b) $t = \frac{L}{v} = \frac{20}{2.0 \times 10^{8}} = 1.0 \times 10^{-7}\,\mathrm{s}$. (c) In a vacuum, $t = \frac{20}{3.00 \times 10^{8}} = 6.7 \times 10^{-8}\,\mathrm{s}$. The extra time taken in the fibre is $1.0 \times 10^{-7} - 6.7 \times 10^{-8} = 3.3 \times 10^{-8}\,\mathrm{s}$ (about $33\,\mathrm{ns}$).

Question 3 $\theta_1 = 30^{\circ}$, $n_{\text{core}} = 1.50$, $n_{\text{cladding}} = 1.44$.



if $90^\circ - \theta_2$ exceeds θ_c at the boundary,
the light stays trapped and is guided along the fibre

(a) Snell's Law at the end face:

$$\sin\theta_2 = \frac{1.00 \times \sin 30^\circ}{1.50} = \frac{0.5}{1.50} = 0.3333, \theta_2 = 19.5^\circ.$$

(b) The ray makes an angle of 19.5° with the fibre axis, so it strikes the core–cladding boundary at $90^\circ - 19.5^\circ = 70.5^\circ$ to the normal.

(c) The critical angle is

$$\sin\theta_c = \frac{1.44}{1.50} = 0.96 \Rightarrow \theta_c = 73.7^\circ.$$

Since $70.5^\circ < 73.7^\circ$, the angle of incidence is smaller than the critical angle, so the ray is **not** totally internally reflected: it refracts into the cladding, and its light is lost from the signal. The ray is not guided.

Question 4 (a) The light must travel many kilometres through the core. If the glass absorbed much of the light's energy, the pulses would weaken rapidly and could not reach the far end carrying the message. Extremely transparent glass minimises this absorption, keeping attenuation small. (b) Any two of: the cladding keeps the reflecting surface clean and undamaged so that light does not leak out at scratches or dirty patches; it provides a known, stable lower refractive index, which fixes the critical angle; it prevents light leaking from one fibre into a neighbouring fibre where the two touch inside a cable. (c) Total internal reflection only occurs when light travels from a medium of higher refractive index into one of lower refractive index. With $n_{\text{cladding}} < n_{\text{core}}$ a real critical angle exists ($\sin\theta_c = n_{\text{cladding}} / n_{\text{core}} < 1$), so rays can be trapped. If the cladding's refractive index were equal to or greater than the core's, no angle of incidence could produce total internal reflection and the fibre could not guide light.

Question 5 (a) The transmitter converts the electrical data signal into pulses of light and launches them into the fibre. (b) The receiver detects the arriving light pulses and converts them back into an electrical signal. (c) A repeater boosts the weakened light pulses back to full strength (or regenerates them as clean pulses). As pulses travel through the glass, absorption attenuates them: after several hundred kilometres they would be too weak and too indistinct to read reliably, so they must be boosted at intervals along the link.

Question 6 (a) Any two of: fibres have a much larger bandwidth (they carry far more data per second); pulses travel farther before needing amplification (lower attenuation); fibres are thinner and lighter than copper cables; the signal is free of electrical interference. (b) Glass is an insulator. Interference from power lines or lightning is an electrical disturbance, and it cannot disturb a signal carried by light in an insulating glass fibre. In a copper wire the same disturbance would induce unwanted currents and corrupt the signal. (c) The information is encoded by switching the carrier wave on and off. A carrier of frequency 10^{14} Hz can be switched billions of times each second — far faster than a radio wave of much lower frequency — so many more bits can be sent each second, and many more channels can share the one fibre.

Question 7 $n_{\text{core}} = 1.52$, $n_{\text{cladding}} = 1.49$.

$$\sin\theta_c = \frac{1.49}{1.52} = 0.9803, \theta_c = \sin^{-1}(0.9803) = 78.6^\circ.$$

Question 8 $L = 50\,\text{km} = 5.0 \times 10^4\,\text{m}$, $n = 1.52$. (a) $v = \dfrac{c}{n} = \dfrac{3.00 \times 10^8}{1.52} = 1.97 \times 10^8\,\text{m s}^{-1}$. (b) $t = \dfrac{L}{v} = \dfrac{5.0 \times 10^4}{1.97 \times 10^8} = 2.5 \times 10^{-4}\,\text{s}$.

Question 9 $\theta_c = 75.0^\circ$, $n_{\text{cladding}} = 1.40$. Rearranging $\sin\theta_c = \dfrac{n_{\text{cladding}}}{n_{\text{core}}}$:

$$n_{\text{core}} = \frac{n_{\text{cladding}}}{\sin\theta_c} = \frac{1.40}{\sin 75.0^\circ} = \frac{1.40}{0.9659} = 1.45.$$

Question 10 $\theta_1 = 20^\circ$, $n_{\text{core}} = 1.48$, $n_{\text{cladding}} = 1.40$. Refraction at the end face:

$$\sin\theta_2 = \frac{1.00 \times \sin 20^\circ}{1.48} = \frac{0.3420}{1.48} = 0.2311, \theta_2 = 13.4^\circ.$$

The angle of incidence at the core–cladding boundary is $90^\circ - 13.4^\circ = 76.6^\circ$. The critical angle is

$$\sin\theta_c = \frac{1.40}{1.48} = 0.9459, \theta_c = 71.1^\circ.$$

Since $76.6^\circ > 71.1^\circ$, the ray strikes the boundary at an angle greater than the critical angle and is totally internally reflected. ∴ the ray **is** guided along the fibre.

Question 11 $L = 2.0\,\text{km} = 2000\,\text{m}$, $n_{\text{core}} = 1.50$, $n_{\text{cladding}} = 1.485$. The speed of light in the core is $v = \dfrac{3.00 \times 10^8}{1.50} = 2.00 \times 10^8\,\text{m s}^{-1}$. For the axial ray: $t_{\text{axial}} = \dfrac{2000}{2.00 \times 10^8} = 1.00 \times 10^{-5}\,\text{s}$. For the ray zigzagging at the critical angle: $\sin\theta_c = \dfrac{1.485}{1.50} = 0.9900$, so the path length is $\dfrac{2000}{0.9900} = 2020\,\text{m}$ and $t_{\text{zigzag}} = \dfrac{2020}{2.00 \times 10^8} = 1.01 \times 10^{-5}\,\text{s}$. The difference is $1.01 \times 10^{-5} - 1.00 \times 10^{-5} = 1.0 \times 10^{-7}\,\text{s}$ (about $100\,\text{ns}$).

Question 12 Light is guided by total internal reflection, which continues whenever a ray strikes the core–cladding boundary at an angle greater than the critical angle. Around a gentle bend the rays' angles of incidence change only slightly and remain greater than the critical angle, so the light keeps reflecting and follows the fibre around the corner. At a very sharp bend, however, rays strike the boundary at angles smaller than the critical angle; total internal reflection then fails, light refracts out through the cladding, and signal loss results.

Question 13 Any two physics reasons, for example: - **Bandwidth:** a fibre-optic cable provides a far larger bandwidth than a satellite link, so it can carry vastly more data at once — necessary for the huge volume of international internet traffic. - **Distance and delay:** a signal routed via a geostationary satellite must travel up to the satellite and back down again — a far longer path than the direct cable route — giving a larger time delay and greater attenuation. - **Reliability:** the signal in a cable is unaffected by weather and atmospheric conditions, which can disturb radio links to satellites.

Question 14 As the pulse travels, some of its energy is absorbed by the glass, so the pulse becomes weaker and weaker with distance. The longer the fibre, the weaker the pulse becomes when it arrives. This gradual weakening of a signal as it travels through a medium is called **attenuation**. (On long links the effect is dealt with by placing repeaters at intervals to boost the signal.)

Question 15 (a) At the transmitting end, the electrical signal from the telephone is used to switch a light source on and off very rapidly, producing a stream of light pulses — the message encoded as bits (pulse = 1, no pulse = 0). The pulses travel along the fibre by total internal reflection. At the receiving end, a light detector converts the pulse stream back into an electrical signal that reproduces the sound. (b) Pulses are either present or absent, so a weakened or slightly distorted pulse can be recognised and rebuilt into a clean, full-strength pulse by a repeater. The message therefore does not gradually degrade with distance, whereas a continuously varying signal would carry any picked-up distortion all the way to the receiver.

Question 16 $L = 250\,\text{km} = 2.50 \times 10^5\,\text{m}$, $n = 1.50$. (a) $v = \dfrac{3.00 \times 10^8}{1.50} = 2.00 \times 10^8\,\text{m s}^{-1}$, so

$$t = \frac{2.50 \times 10^5}{2.00 \times 10^8} = 1.25 \times 10^{-3}\,\text{s} = 1.25\,\text{ms}.$$

(b) No. A delay of about one millisecond is far shorter than the delays people notice in conversation, which are of order a tenth of a second or more. The fibre delay alone would not be noticeable.

Question 17 In a healthy fibre the light is trapped in the core by total internal reflection: no light escapes through the sides, so the signal cannot simply be "listened to" from outside the cable, as an electrical signal can sometimes be picked up from a copper wire. To read the data, someone must physically interfere with the fibre — cutting into it, or stripping the cladding and bending the core sharply to leak light out. Either action interrupts or noticeably weakens the transmitted signal, which alerts the network operators to the tampering.

Question 18 $L = 10\,\text{km} = 1.0 \times 10^4\,\text{m}$, $n = 1.46$. In the fibre: $v = \dfrac{3.00 \times 10^8}{1.46} = 2.05 \times 10^8\,\text{m s}^{-1}$, so

$$t_{\text{fibre}} = \frac{1.0 \times 10^4}{2.05 \times 10^8} = 4.9 \times 10^{-5}\,\text{s}.$$

In a vacuum:

$$t_{\text{vacuum}} = \frac{1.0 \times 10^4}{3.00 \times 10^8} = 3.3 \times 10^{-5}\,\text{s}.$$

The light takes about $1.5 \times 10^{-5}\,\text{s}$ (roughly $50\,\%$) longer in the fibre, because light travels more slowly in glass than in a vacuum.