C.2 Wave model

Guiding questions

- What are the similarities and differences between different types of waves?
- How can the wave model describe the transmission of energy as a result of local disturbances in a medium?
- What effect does a change in the frequency of oscillation or medium through which the wave is travelling have on the wavelength of a travelling wave?

What is a wave?

SYLLABUS CONTENT

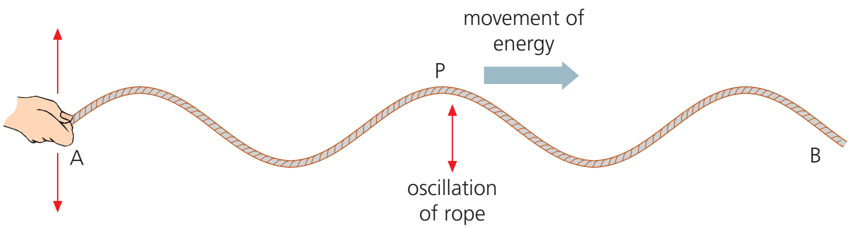
▶ The differences between mechanical waves and electromagnetic waves.

■ **Figure C2.1** Circular waves spreading out on a pond

When we think of waves the first example that comes to mind is probably that of waves on the surface of water, like those seen in Figure C2.1.

When the equilibrium of the surface is disturbed (for example by a falling drop, or touching it with a finger), it results in oscillations of the water surface at that point. Because of the forces between water molecules, the oscillations are transferred to neighbouring molecules a short time later, and then they spread outwards as a two-dimensional wave on the water surface.

A simpler, one-dimensional, example is shown in Figure C2.2: in this example the waves are produced by continuously shaking one end of the rope. Point A is the oscillating source of the wave energy, which travels to the other end, point B. All points on the rope, point P for example, oscillate up and down (as shown)..



■ **Figure C2.2** Creating a wave by shaking the end of a rope

◆ **Wave (travelling)** A wave that transfers energy away from a source. Sometimes called a progressive wave.

◆ **Propagation (of waves)** Transfer of energy by waves.

◆ **Medium (of a wave)** Substance through which a wave is passing.

These two examples are both **travelling waves**. Another kind of wave (a standing wave) is discussed in Topic C.4.

Scientists describe the motion of a wave away from its source as **propagation** of the wave. The matter through which the waves pass is called the **medium** of the wave.

All waves involve oscillations and they can be described as being either 'mechanical' or 'electromagnetic':

◆ **Wave (mechanical)** A wave which involves oscillating masses (including sound).

◆ **Wave (electromagnetic)** A transverse wave composed of perpendicular electric and magnetic oscillating fields travelling at a speed of $3.0 \times 10^8\,\mathrm{m\,s^{-1}}$ in free space.

Mechanical waves involve the oscillations of masses.

Electromagnetic waves, such as light, involve the oscillations of electric and magnetic fields.

The first part of this topic will deal with mechanical waves. Electromagnetic waves are discussed later.

A mechanical travelling wave can be described as an oscillating disturbance that travels away from its source through the surrounding medium (solid, liquid or gas) transferring energy from one place to another. Most importantly, waves transfer energy without transferring the matter itself.

■ **Figure C2.3** Ocean waves transferring a large amount of energy at Brighton, England – there is no continuous net movement of the water itself

For example, ocean waves may 'break' and 'crash' on to a shore or rocks, transferring considerable amounts of energy (that they got from the wind), but there is no net, continuous movement of water from the ocean to the land. A wooden log floating on a lake will simply oscillate up and down as waves pass (unless there is a wind).

Examples of mechanical waves

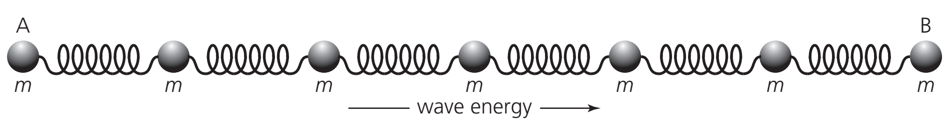
- waves on strings, ropes and springs
- waves on water
- sound (and similar waves in liquids and solids)
- earthquake waves.

Models of mechanical waves

SYLLABUS CONTENT

▶ Transverse and longitudinal travelling waves.

In order to understand more about the propagation of mechanical waves it is convenient to visualize the *continuous* medium in which they are travelling as being composed of *separate* (discrete) *particles* of mass, m, separated by springs representing the restoring forces that arise when the medium is disturbed from is equilibrium position. See Figure C2.4. The wave can be produced by shaking the end A, the wave then travels along the system to B.



■ **Figure C2.4** Wave model of masses and springs

Experiments can confirm that the speed of the wave along the system increases if the masses are smaller, or if the springs are stiffer.

There are two different ways in which A can be shaken: left–right–left–right, or up–down–up–down (as shown). This identifies the two basic kinds of mechanical wave: transverse and longitudinal.

◆ **Transverse wave** A wave in which the oscillations are perpendicular to the direction of transfer of energy.

◆ **Crest** Highest part of a transverse mechanical wave.

◆ **Trough** Lowest point of a transverse mechanical wave.

◆ **Longitudinal wave** Waves in which the oscillations are parallel to the direction of transfer of energy.

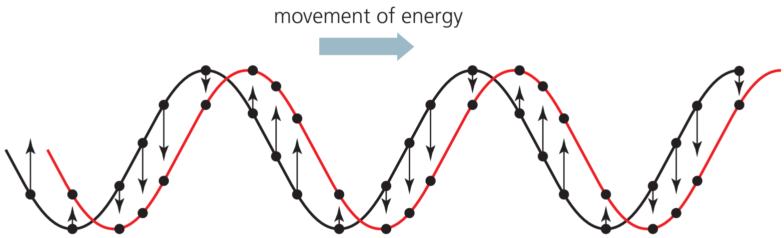
◆ **Compressions (in a longitudinal wave)** Places where there are increases in the density and pressure of a medium as a wave passes through it.

◆ **Rarefactions (in a longitudinal wave)** Places where there are reductions in the density and pressure of a gas as a wave passes through it.

Transverse and longitudinal mechanical waves

In a **transverse wave**, each part of the medium oscillates *perpendicularly* to the direction in which the wave is transferring energy.

The waves shown in Figure C2.1, C2.2 and C2.3 are transverse waves. The black line in Figure C2.5 represents the positions of the particles in a continuous medium which is transferring wave energy to the right. The arrows show which way the particles are moving at that moment. The red line represents their positions a short time later. Each particle is oscillating with the same amplitude and frequency, but each particle is slightly out of phase with its neighbour.



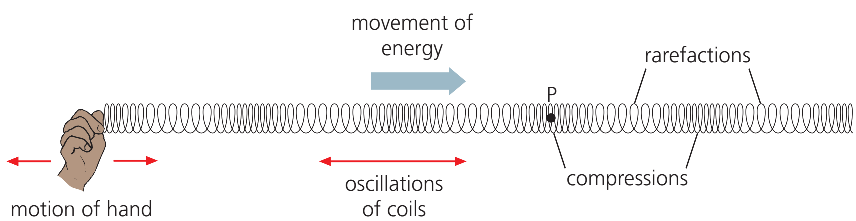
■ **Figure C2.5** Movement of particles as a transverse wave moves to the right

The tops of transverse waves are often called **crests**, while the bottoms of the waves are called **troughs**.

Mechanical waves on strings, ropes and water surfaces are all transverse in nature.

In a **longitudinal wave**, each part of the medium oscillates *parallel* to the direction in which the wave is transferring energy.

Stretched springs are often used to demonstrate waves. They are more massive than strings and this reduces the wave speed, so that the waves can be observed more easily. Stretched 'slinky' springs are particularly useful for demonstrating longitudinal waves. See Figure C2.6, which shows the characteristic **compressions** and **rarefactions** of longitudinal waves on a 'slinky'. Longitudinal waves are sometimes called compression (or pressure) waves.



■ **Figure C2.6** Oscillations of a spring transferring a longitudinal wave

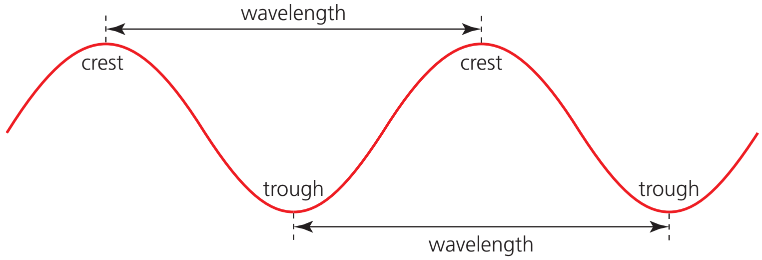
Sound travelling through air is a good example of a longitudinal wave (more details below). Longitudinal compression waves can travel through solids and liquids. Earthquakes are a combination of longitudinal and transverse waves. Transverse mechanical waves cannot travel through gases (or liquids) because of the random nature of molecular movements.

Terms used to describe all types of waves

SYLLABUS CONTENT

- Wavelength, λ, frequency, f, time period, T, and wave speed, v, applied to wave motion as given by: $v = f\lambda = \frac{\lambda}{T}$

The concept of wavelength, λ, is central to the study of waves. See Figure C2.7.



■ **Figure C2.7** One wavelength of a transverse wave

◆ **Wavelength, λ** The distance between two adjacent crests of a wave. More precisely: the shortest distance between two points moving in phase.

◆ **Time period, T** The time taken for one complete wave to pass a point.

◆ **Wave speed, v** The speed at which energy is transferred by a wave.

One **wavelength**, λ, is the shortest distant between two crests, or two troughs. Or the shortest distance between two compressions or rarefactions in a longitudinal wave. More generally, it is defined as the shortest distance between two points moving in phase (SI unit: m).

Displacement, amplitude, time period and frequency have all been discussed before (Topics A.2 and C.1) and are defined in a similar way in the study of waves:

The *amplitude* of a wave is the maximum displacement of the medium from its equilibrium position.

We saw in Topic C.1 that the energy of an oscillation was proportional to its amplitude squared. So, speaking generally, waves with greater amplitude transfer more energy. (We will see in Topic C.3 that the *intensity* of a wave is proportional to its amplitude squared.)

The **time period** of a wave, T, is the time for one oscillation of a particle within the medium, or the time it takes for one complete wave to pass a particular point (unit: second).

The frequency of a wave, f, is the number of oscillations per second of a particle within the medium, or the number of waves to pass a particular point in one second (SI unit: hertz). The following equation is repeated from Topic C.1:

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

A wave travels forward one wavelength, λ, every time period, T.

Therefore:

wave speed, $v = \dfrac{\lambda}{T}$

Since $T = 1/f$, we can write:

$$\text{wave speed, } v = f\lambda \left(\text{or } v = \frac{\lambda}{T}\right)$$

WORKED EXAMPLE C2.1

Water waves are passing into a harbour. Five crests are separated by a distance of 9.6 m. An observer notes that 12 waves pass during a time of one minute. Determine:

a the wavelength

b the period

c the frequency

d the speed of the waves.

Answer

a $\lambda = \dfrac{9.6}{4} = 2.4\,\text{m}$

b $T = \dfrac{60}{12} = 5.0\,\text{s}$

c $f = \dfrac{1}{5.0} = 0.20\,\text{Hz}$

d $v = f\lambda = 0.20 \times 2.4 = 0.48\,\text{m}\,\text{s}^{-1}$

1 Consider Figure C2.1. Explain why the amplitude of the waves decreases as they spread away from the central point.

2 Consider Figure C2.2.
  a State the type of wave which is travelling along the rope.
  b If the wave speed is $1.7\,\mathrm{m\,s^{-1}}$, calculate the wavelength produced by shaking the end seven times every 10 seconds.
  c If the rope was replaced by a thinner one, would you predict that the wave speed would increase, or decrease (under the same conditions)? Explain your answer.

3 Describe how the point P on the slinky spring shown in Figure C2.6 moves as the wave passes through it.

4 If you watch waves coming into a beach, you will notice that they get closer to each other.
  a State and explain how their wavelength is changing.
  b Suggest what has caused the waves to change speed.

5 After an earthquake, the first wave to reach a detector 925 km away arrived 149 s later. This type of wave is called a P wave (pressure wave).
  a Suggest whether this is a longitudinal or transverse wave.
  b Calculate the average speed of the wave ($\mathrm{m\,s^{-1}}$).
  c Suggest why your calculation produces an 'average' speed.
  d If the wave had a period of 11.21 s, what was its wavelength?

Tool 2: Technology

Generate data from models and simulations

Some time after a Primary (longitudinal) wave is received from an earthquake, a different kind of wave will be detected. This is called a Secondary (transverse) wave. If the delay between the detection of the two waves is measured and the speeds of both waves are known, the distance to the original earthquake can be determined.

Set up a spreadsheet that will calculate the distance to the source of an earthquake (dependant variable) for various time delays (independent variable). Assume speeds of waves are $5500\,\mathrm{m\,s^{-1}}$ and $3200\,\mathrm{m\,s^{-1}}$.

LINKING QUESTION

- How can the length of a wave be determined using concepts from kinematics?

This question links to understandings in Topic A.1.

Representing waves graphically

Waves can be represented by displacement–position or displacement–time graphs. They both have similar sinusoidal shapes.

Figure C2.8 shows how the displacements of particles (from their mean positions) vary with *distance* from a fixed point (position). x_0 is the amplitude of their oscillations. It may be considered as a 'snapshot' of the wave at one particular moment.

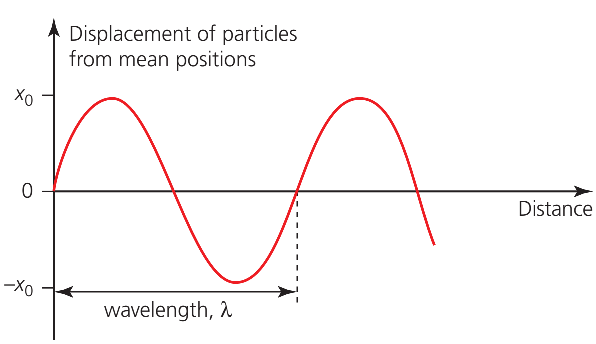


Figure C2.8 Displacement–distance graph for a wave

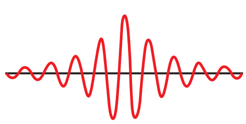
Figure C2.9 shows how the displacement of a certain particle (from its mean position) varies with time at one precise location. It could be considered as a video of that part of the medium.

Common mistake

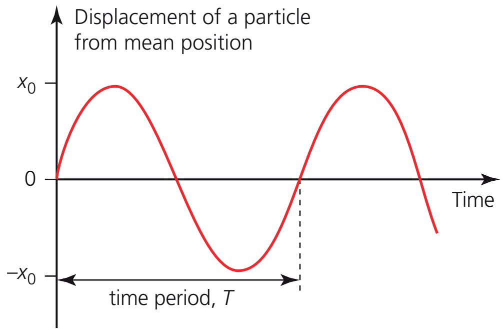
Graphs like these can be used to represent *both* transverse and longitudinal waves. Because of their shape, it is a common mistake to think that they only represent transverse waves. The direction of the displacements shown on the vertical axes of these graphs are not specified, so they could be either

- in the direction of wave travel (longitudinal waves), or
- perpendicular to wave travel (transverse waves).

◆ **Pulse (wave)** A travelling wave of short duration.



■ **Figure C2.10** Wave pulse



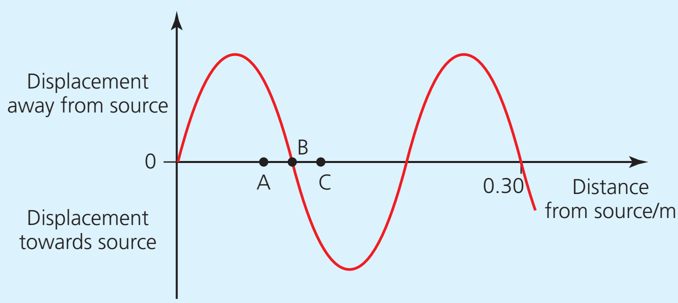
■ **Figure C2.9** Displacement–time graph for a wave

Pulses

A short duration oscillating disturbance passing through a medium may be described as a wave **pulse**. See Figure C2.10 for a simplified representation.

6 Sketch a displacement–time graph for a transverse wave of frequency 4.0 Hz and an amplitude of 2.0 cm. Assume that the wave has its maximum positive displacement at time $t = 0$. Continue the graph for a duration of 0.5 s.

7 Figure C2.11 represents a longitudinal wave.



■ **Figure C2.11** A longitudinal wave

a State its wavelength.

b Describe the instantaneous movement of a particle which is

i at a distance A from the source

ii at a distance C from the source.

c Is there a compression, a rarefaction, or neither, at position B?

8 A wave pulse is made on a water surface by touching it once with a fingertip. Sketch a possible displacement–position graph of the resulting disturbance spreading out on the surface.

Sound waves

SYLLABUS CONTENT

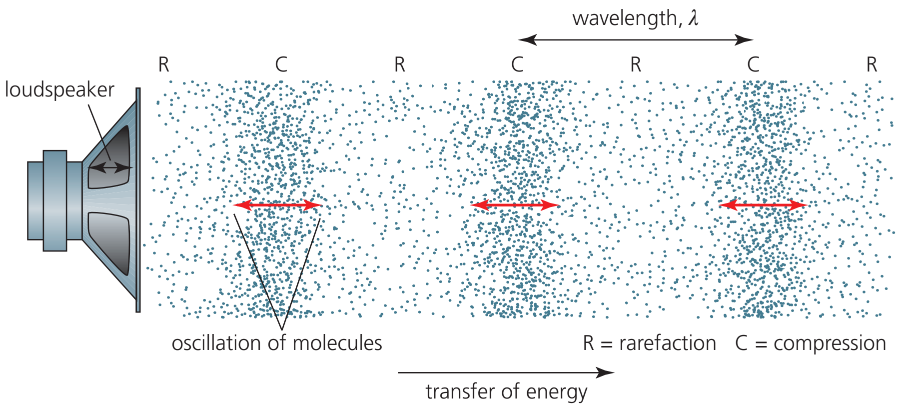
▶ The nature of sound waves.

◆ **Sound** Longitudinal waves in air or other media that are audible to humans.

◆ **Ultrasound** Frequencies of sound above the range that can be heard by humans (approximately 20 kHz).

A vibrating surface will disturb its surroundings and propagate longitudinal waves through the air. The human ear is capable of detecting this type of wave if the frequency falls within a certain range (approximately 20 Hz to 20 kHz). What we hear is called **sound**. Higher frequencies of the same type of wave, which we cannot hear, are called **ultrasound**. (Lower frequencies are called infrasound.)

Figure C2.12 shows how the surface of a loudspeaker can produce longitudinal waves in air. The random arrangement of molecules changes as the wave passes through the air. The compressions and rarefactions result in small periodic changes of air pressure.



■ **Figure C2.12** Arrangement of molecules in air as sound passes through

If the graphs shown in Figure C2.8 and C2.9 represented sound waves, the vertical axes could also be changed to represent variations of air pressure (above and below average air pressure).

Speed of sound

Sound is a mechanical wave involving oscillating particles and, as such, needs a medium to travel through. Sound cannot pass through a vacuum.

Generally, we would expect that sound will travel faster through a medium in which:

- the particles are closer together
- there are stronger forces between the particles.

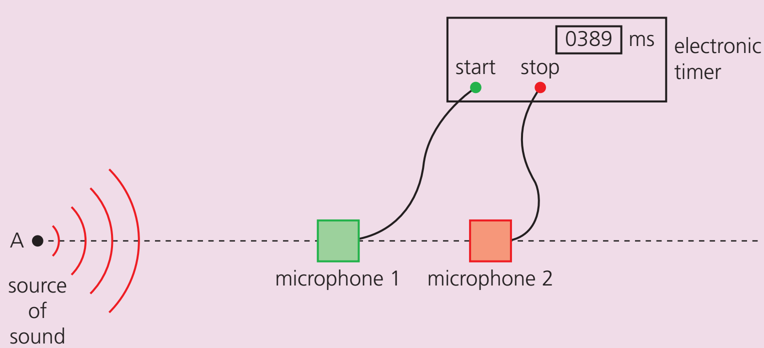
This means that sound usually travels faster in solids than liquids, and slowest in gases, such as air.

The speed of sound in the air around us increases slightly with temperature because then the molecules move faster.

Inquiry 1: Exploring and designing

Designing

Figure C2.13 shows an electronic method for determining the speed of sound.



■ **Figure C2.13** Laboratory experiment to determine the speed of sound

Design an experiment and a valid methodology using this apparatus to determine a value for the speed of sound. Suggest improvements to the design shown in Figure C2.13 so that the speed of sound in air is measured as accurately as possible.

◆ **Pitch** The sensation produced in the human brain by sound of a certain frequency.

◆ **Loudness** A subjective measure of our ears' response to the level of sound received.

◆ **Logarithmic scale (on a graph)** Instead of equal divisions (for example, 1, 2, 3, …), with a logarithmic scale each division increases by a constant multiple (for example, 1, 10, 100, 1000 …).

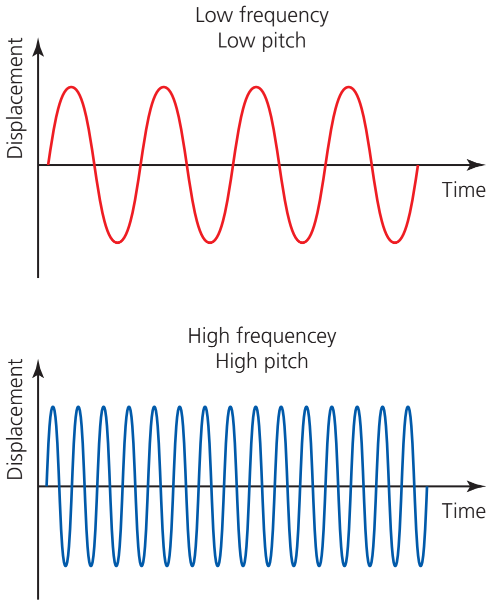
◆ **Decibel** A measure of sound level.

Pitch and loudness of sound

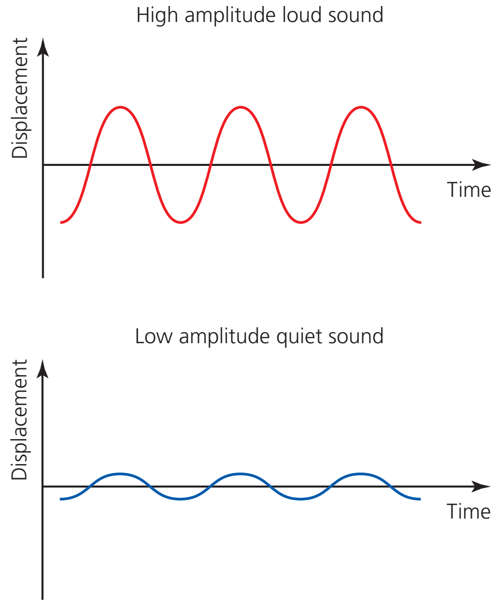
The sounds that arrive at our ears at any one time usually include a range of waves with different frequencies and amplitudes. The oscillations are transferred to our eardrums and our brain interprets them as sounds of different **pitch** and **loudness** (volume).

Figure C2.14 shows pure sound waves of two different frequencies. We describe these sounds arriving at our ears as high pitched and low pitched.

Figure C2.15 shows two waves of the same frequency, but different amplitudes. The wave of larger amplitude transfers more energy and we describe the effects of this as a louder sound.



■ **Figure C2.14** Sounds of different frequency / pitch



■ **Figure C2.15** Sounds of different amplitude / loudness

Tool 3: Mathematics

Logarithmic graphs and power laws

Sound intensity is the power that is carried perpendicularly by sound waves through unit area. It is easily measured by electronic meters, and apps for mobile devices are commonplace.

A normal human ear is capable of detecting sounds with a very wide range of intensities. This makes showing them all on a linear chart impossible. To get over this problem, we use a **logarithmic scale**. On a logarithmic scale (on a chart or a graph) each equal increment represents the fact that the quantity has been multiplied by the same factor (usually 10). As an example, we will consider the **decibel** scale. See Figure C2.16.

A student may wish to investigate the relationship between the intensity of sound (of a constant frequency) and the thickness of material placed between the source and the detector. The student may have no idea what this relationship will be.

Carry out calculations involving logarithmic and exponential functions

Sometimes there is no 'simple' relationship between two variables, or we may have no idea what the relationship may be. So, in general, we can write that the variables x and y are connected by a relationship of the form: $y = kx^p$, where k and p are unknown constants. That is, y is proportional to x to the power p.

Taking logarithms of this equation we get:

$$\log y = (p \times \log x) + \log k$$

Compare this to the equation for a straight line, $y = mx + c$.

If a graph is drawn of $\log y$ against $\log x$, it will have a gradient p and an intercept of $\log k$.

Using this information, a mathematical equation can be written to describe the relationship. Note that logarithms to the base 10 have been used in the above equation, but natural logarithms (ln) could be used instead.

The decibel scale is widely used to compare the intensity of a sound to a reference level. Each additional 10 on the scale represents an increase by a factor of 10 in sound intensity. So, for example, a sound of 50 dB intensity is 10× more intense than a sound of 40 dB. A sound of 60 dB intensity is 100× more intense than a sound of 40 dB, and so on.

Of course, sound intensities decrease with distances from their sources, which are not stated in Figure C2.16, so the numbers should be seen as just a rough guide.

Displaying all parts of the electromagnetic spectrum (later in this topic) is done with a logarithmic scale for the same reason.

Decibels	Example
0	Silence
10	Breathing, ticking watch
20	Rustling leaves, mosquito
30	Whisper
40	Light rain, computer hum
50	Quiet office, refrigerator
60	Normal conversation, air conditioner
70	Shower, toilet flush, dishwasher
80	City traffic, vacuum cleaner
90	Music in headphones, lawnmower
100	Motorcycle, hand drill
110	Rock concert
120	Thunder
130	Stadium crowd noise
140	Aircraft taking off
150	Fighter jet aircraft taking off
160	Gunshot
170	Fireworks
180	Rocket launch

Figure C2.16 An approximate guide to sound levels in decibels

ATL C2A: Research skills

Evaluating information sources for accuracy, bias, credibility and relevance

Find three websites that enable you to check your hearing and follow their instructions. Compare the results and write a short review of your findings.

Were there any differences in the results for each website?

What might account for those differences?

Evaluate the sites in terms of their reliability.

WORKED EXAMPLE C2.2

a Calculate the wavelength of a sound of frequency 196 Hz if the speed of sound in air is $338\,\text{m}\,\text{s}^{-1}$.

b If a longitudinal compression wave of the same frequency has a wavelength of 26.1 m in steel, determine the speed of the wave.

c Explain why the wave speed is greater in steel than in air.

Answer

a $\lambda = \frac{v}{f} = \frac{338}{196} = 1.72\,\text{m}$

b $v = f\lambda = 196 \times 26.1 = 5.12 \times 10^3\,\text{m}\,\text{s}^{-1}$

c Because the particles are closer together and there are stronger forces between them.

TOK

Knowledge and the knower

- What criteria can we use to distinguish between knowledge, belief and opinion?
- How do we distinguish claims that are contestable from claims that are not?
- How do our interactions with the material world shape our knowledge?

‘If a tree falls in a forest and no one is around to hear it, does it make a sound?

Figure C2.17 A fallen tree in a forest

This well-known philosophical question can be answered in different ways, depending on the perspective we take on what is meant by ‘sound.’

◆ **Audible range** Range of sound frequencies that can be heard by humans.

If we think of sound only as an effect in the human ear and brain, then the answer is clearly ‘no’, although there will still be longitudinal waves in the air. If we define sound as a hearable (**audible**) oscillation (regardless of whether anyone is there to hear it), then the answer is ‘yes’.

Consider how the knowledge questions above relate to this problem. You may also find the following guiding questions useful:

- Should we believe in things that we have not personally seen / observed / experienced?
- Can we assume that an unobserved event behaves in exactly the same way as an observed event?
- Does observation affect / change the event being observed?
- If the fall of a tree, and any consequential effects, are never observed, is this the same as saying that the tree never fell at all?

9 **a** Sketch a graph to show the air pressure variations (from normal) for a duration of 0.2 s at a certain point through which a sound wave of frequency 100 Hz is passing. Mark one time where there is a compression and one time where there is a rarefaction.

b Determine a value for the period of the wave and show it on the graph.

10 Outline an experiment using hand-held stopwatches to determine a value for the speed of sound in air.

11 Many people know that you can estimate the distance to a storm centre by counting the number of seconds between a flash of lightning and hearing the thunder: about one kilometre for every three seconds. Explain the physics behind this idea.

12 The ultrasound waves used in a medical scanner had a frequency of 9.6 MHz.

a If the wavelength was 0.16 mm, determine the speed of ultrasound waves in the body.

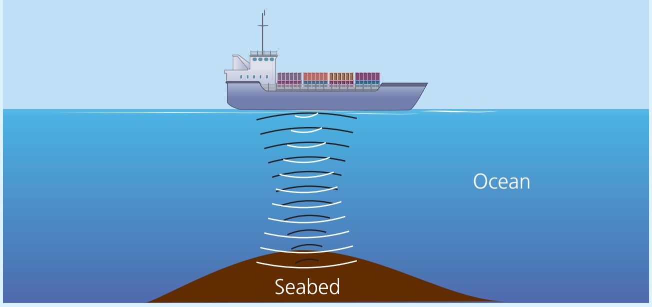
b Suggest three properties of ultrasound that make it useful for obtaining scans from inside the human body.

13 Figure C2.18 shows the use of ultrasound waves (**sonar**) to detect the depth of the ocean below a boat. Waves are produced in a **transducer** and a pulse is directed downwards. The transducer has a diameter of 3 cm. Some wave energy is reflected back from the seabed and then received and detected at the same transducer a short time later. The time delay is used to calculate the depth of the water.

a If the speed of sound waves in sea water is $1520\,\mathrm{m\,s^{-1}}$, calculate the depth of water if the delay between the pulses is 29 ms.

b To limit the spreading of the waves emitted by the transducer it is required that wavelength is much smaller than the size of the transducer. Show that this is true if the waves have a frequency of 214 kHz.

c Suggest why the system uses wave pulses rather than continuous waves.



■ **Figure C2.18** Boat using sonar

14 The speed of sound in helium gas is much greater than in air, which is mostly nitrogen (for the same temperature and pressure).
Use knowledge from Topic B.2 to discuss reasons for this difference.

◆ **Sonar** The use of reflected ultrasound waves to locate objects.

◆ **Transducer** Device that converts one form of energy to another. The word is most commonly used with devices that convert to or from changing electrical signals.

◆ **Vacuum** A space without any matter. Also called free space.

◆ **Free space** Place where there is no air (or other matter). Also called a vacuum.

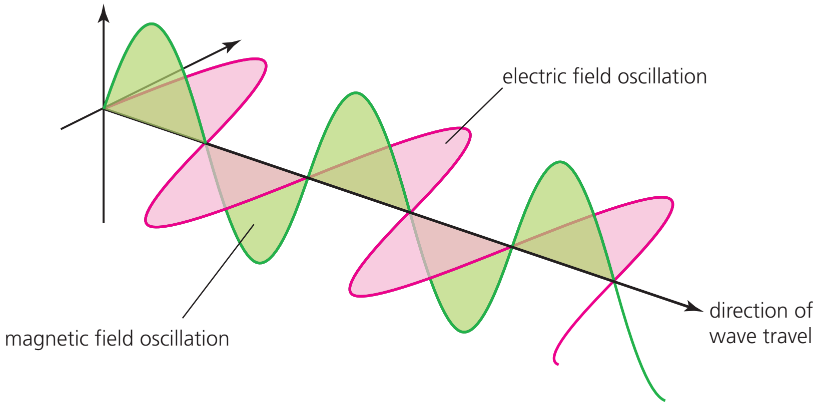
Light waves

In Topic B.1 we described the range of thermal radiations (including light) emitted from various surfaces and 'black bodies' at different temperatures. The true nature of light was not discussed in B.1, but it was a major issue among scientists for hundreds of years.

In the seventeenth century, Isaac Newton believed that a beam of light consisted of particles ('corpuscles'), others thought that light could travel as waves. The wave nature of light was not demonstrated until 1801, when the English physicist Thomas Young showed that light could 'interfere'. This famous experiment and the nature of interference are explained and discussed in Topic C.3.

Light is a transverse electromagnetic wave but, unlike mechanical waves, it does not require a medium to travel through. Light can travel across a **vacuum**, sometimes called '**free space**'. Light travelling from the Sun, through space, to arrive at the Earth is an obvious example.

Visualizing the oscillations of light waves is more difficult than the models of *mechanical* waves that we discussed earlier in this topic. Figure C2.19 shows that light oscillations are high frequency periodic variations in the strength of electric and magnetic fields (which are perpendicular to each other). Electric and magnetic fields are discussed in Theme D.



■ **Figure C2.19** Light and other electromagnetic waves are combined electric and magnetic fields

■ **Figure C2.20** Spectrum of visible light

The speed of light in a vacuum is $3.00 \times 10^8\,\mathrm{m\,s^{-1}}$ (more accurately: $299\,792\,458\,\mathrm{m\,s^{-1}}$). It is given the unique symbol 'c'.

In **transparent** materials light travels at slightly slower speeds. For example, light travels at almost the same speed in air ($299\,970\,500\,\mathrm{m\,s^{-1}}$) as in free space, but at $2.26 \times 10^8\,\mathrm{m\,s^{-1}}$ in water.

The **continuous spectrum** of visible **white light**, from red to violet, is a familiar sight (Figure C2.20). The different colours that we see are created by waves of different frequencies.

Red light has the lowest frequency, violet light has the highest frequency. 'White light' is not a precise scientific term, but it can be assumed to be the same as the light received in the black-body radiation from the Sun on a cloudless day.

◆ **Transparent** Describes a medium that transmits light without scattering or absorption.

◆ **Continuous spectrum** The components of radiation displayed in order of their wavelengths, frequencies or energies (plural: spectra).

◆ **White light** Light which contains all the colours of the visible spectrum with approximate equal intensity.

The fundamental property of a light wave is its *frequency*. If a light wave enters a different medium and then travels more slowly, its frequency cannot change, but its wavelength will decrease ($\lambda = v/f$). However, when we quote data for light waves, it is common to use wavelengths, rather than frequencies. This is because light wavelengths are easier to visualize and measure.

WORKED EXAMPLE C2.3

An orange light has a frequency of $4.96 \times 10^{14}\,\mathrm{Hz}$. Determine its wavelength as it passes through

a air

b a type of glass in which the speed of light has reduced to $1.94 \times 10^8\,\mathrm{m\,s^{-1}}$.

Answer

a $\lambda = \dfrac{c}{f} = \dfrac{3.00 \times 10^8}{4.96 \times 10^{14}} = 6.05 \times 10^{-7}\,\mathrm{m}$

b $\lambda = \dfrac{v}{f} = \dfrac{1.94 \times 10^8}{4.96 \times 10^{14}} = 3.91 \times 10^{-7}\,\mathrm{m}$

Different animals, birds and insects are able to detect different ranges of frequencies. For example, bees are not good at detecting the colour red, but they are able to detect higher frequencies (ultraviolet).

Red light has the longest wavelength in the visible spectrum, approximately $7 \times 10^{-7}\,\mathrm{m}$. Violet has the shortest wavelength, approximately $4 \times 10^{-7}\,\mathrm{m}$.

Use data from the previous paragraphs.

15 a Calculate a typical value for the frequency of red light in air.

b What is the frequency of the same light in glass?

16 Estimate a value for the wavelength of yellow light:

a in air **b** in water.

17 The 'light year' is widely used as a unit of distance in astronomy.
How far does light travel (km) in free space in one year?

18 Briefly outline why light waves are described as electromagnetic waves.

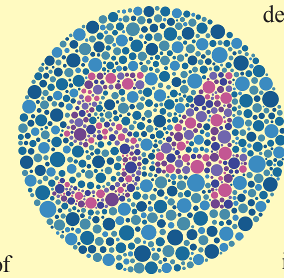
TOK

Knowledge and the knower

- How do our interactions with the material world shape our knowledge?

Perception of colour

We may all agree that light waves have a certain frequency, and whether those waves can be detected in some way by a human eye. There is no ambiguity in that, and most people would agree on the ‘colours of the rainbow’. However, how our brains process signals about the light waves detected by our eyes, and how we communicate our impressions of specific colours to other people can be problematic. ‘That dress is green’ can never be an indisputable scientific fact. ‘Colour blindness’ (see Figure C2.21) may be an unusual medical condition, but it highlights the fact that human brains can interpret signals in different ways.



■ **Figure C2.21** Test for colour blindness

Added to that, different people, societies and cultures are known to describe colours in different ways. If two people see, or describe, a colour differently, can one be ‘right’ and the other ‘wrong’?

Finally, in terms of physics, it should be pointed out that if you say that a ‘dress is green’ you probably assume it is being seen under normal lighting conditions, with white light. The colour perceived will change if the lighting is changed. For example, if a red light was used, or it was seen through a yellow filter. Even looking at the dress at night under artificial lighting could change its appearance.

◆ **Ultraviolet** Part of the electromagnetic spectrum which has frequencies just greater than can be detected by human eyes.

◆ **Electromagnetic spectrum** Electromagnetic waves of all possible different frequencies, displayed in order.

◆ **Electromagnetic radiation** Waves which consist of combined oscillating electric and magnetic fields.

Electromagnetic waves

SYLLABUS CONTENT

▶ The nature of electromagnetic waves.

The extent of a visible spectrum such as that seen in Figure C2.20 is limited by:

- the inability of the human eye to detect higher or lower frequencies, and/or
- the ability of any particular source to produce a wider range of frequencies. Light is just a small part of a much wider continuous spectrum.

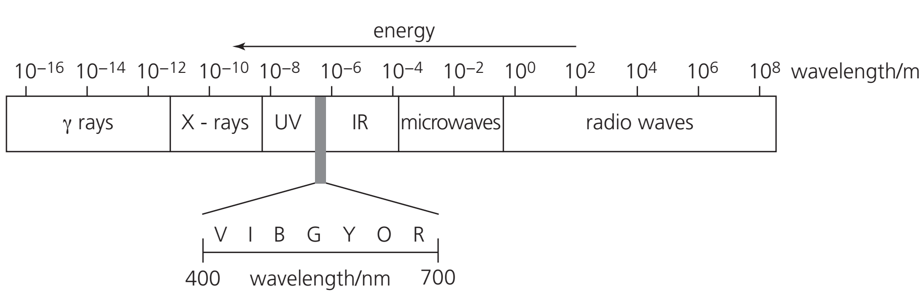
Just beyond the red end of the visible spectrum, there are waves which have longer wavelengths, called infrared. Infrared radiation was discussed in Topic B.1. Just beyond the violet end of the visible spectrum, there are waves of shorter wavelength, called **ultraviolet**.

The complete range (spectrum) of possible electromagnetic wavelengths extends from more than 100 000 km to less than 10^{-16} m. They have different origins and no single source produces all of these waves.

All electromagnetic waves travel at the same speed in vacuum, $c = 3.00 \times 10^8\,\mathrm{m\,s^{-1}}$.

They are all composed of oscillating electric and magnetic fields (Figure C2.19).

Together they are known as the **electromagnetic spectrum** (Figure C2.22). They are also described as **electromagnetic radiation**.



■ **Figure C2.22** Electromagnetic spectrum

‘Energy’ refers to the energy carried by *photons* of the radiation, as explained later in the course.

Common mistake

Remember that the spectrum is continuous and the boundaries chosen between different named sections are somewhat arbitrary.

LINKING QUESTION

- How can light be modelled as an electromagnetic wave?

This question links to understandings in Topic D.2.

Inquiry 1: Exploring and designing

Exploring

Select sufficient and relevant sources of information

After deciding on a general area of interest, for an investigation you will often need to select and research other sources of information for background knowledge and any physics needed which is beyond the IB course (if appropriate). Your teachers should be an excellent source of advice and information and, obviously, the internet has multiple sources (of various quality). Physics books, science magazines and books from libraries can all be sources of information and inspiration.

Example 1: If you wish to investigate the effect that water vapour in the air has on the rate of evaporation from a water surface, you will need to learn about *humidity*.

Example 2: If you wish to investigate the world-wide use of solar heating of water, you will need to learn about the hours of sunlight in different locations, the variation in altitude of the Sun, comparative costs and so on.

Your intended investigation could be both interesting and unusual, but it needs to be realistic in terms of the apparatus that is available in your school, and the time available. So, it may be wise to check with teachers about whether an intended investigation is sensible under the circumstances.

Any sources of information should be acknowledged in the investigation report, including those which were researched but not used (with a reason given).

Task: Apart from sources on Earth, waves from all parts of the electromagnetic spectrum arrive at Earth from space. Use the internet to gather information about the origins of these waves and to what extent they are able to pass through the atmosphere and reach the Earth's surface.

The list in Table C2.1 shows some origins of electromagnetic waves and a selection of their uses.

Table C2.1 The different sections of the electromagnetic spectrum

Name	Typical wavelength / m	Origins (all are received from Outer Space)	Some common uses
radio waves	10^{2}	electronic circuits / aerials	communications, radio, television
microwaves	10^{-2}	electronic circuits / aerials	communications, mobile phones, ovens, radar
infrared (IR)	10^{-5}	everything emits IR but hotter objects emit much more than cooler objects	lasers, heating, cooking, medical treatments, remote controls
visible light	5×10^{-7}	very hot objects, light bulbs, the Sun	vision, lighting, lasers
ultraviolet (UV)	10^{-8}	the Sun, UV lamps	fluorescence
X-rays	10^{-11}	X-ray tubes	medical diagnosis and treatment, investigating the structure of matter
gamma rays	10^{-13}	radioactive materials	medical diagnosis and treatment, sterilization of medical equipment

LINKING QUESTION

- How are waves used in technology to improve society? (NOS)

This question links to understandings in Topics C.3, C.4, C.5, D.2, D.3 and D.4.

◆ **Quantum physics** Study of matter and energy at the subatomic scale. At this level quantities are quantized.

Top tip!

The fact that electromagnetic waves have some properties that could not be explained satisfactorily by their wave nature had very important consequences. A new 'particle' model for light, introduced at the start of the twentieth century, was the beginning of **quantum physics**. This is introduced in Topic E.2.

LINKING QUESTIONS

- How are electromagnetic waves able to travel through a vacuum?
- Can the wave model inform the understanding of quantum mechanics? (NOS)

These questions link to understandings in Topic E.2.

Nature of science: Experiments

Pure research

The first artificial electromagnetic (radio) waves

Heinrich Hertz (Figure C2.23) was the first to produce and detect artificial electromagnetic waves (1887 in Karlsruhe in Germany). He used high voltage electrical sparks. The electrical currents in sparks involve the necessary high frequency oscillating electric and magnetic fields. Although the distance involved was very small, it was the start of modern wireless communication. It was left to others (such as Guglielmo Marconi) to develop the technology for transmission over longer and longer distances – and then to design techniques to modify the amplitude, frequency or phase of the radio waves to transfer information, such as speech.

Figure C2.23 Heinrich Hertz

Tragically, Hertz died at the age of 36 in 1894. This was long before the far-reaching consequences of his discovery had been exploited.

Hertz had been trying to provide evidence for the electromagnetism theories of James Clerk Maxwell, and he has been widely quoted as saying that his discovery was 'of no use whatsoever'. He was not alone in that opinion at the time.

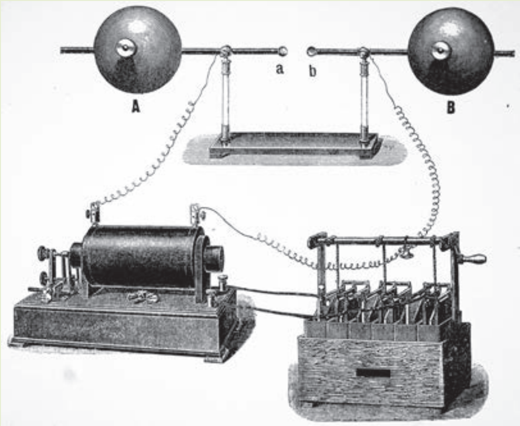


Figure C2.24 Hertz's apparatus for the first artificial production of electromagnetic waves

'Pure research' is about extending knowledge and confirming theories, it is not about solving practical problems. But there are many historical examples of pure research leading to unexpected benefits of major significance – such as radio communication.

Of course, a large number of examples of pure research have *not* produced any worthwhile gains for society. An often-asked question is 'should governments spend large amounts of money on open-ended research which has no obvious benefits (at that time)?'

In terms of laboratory investigations that you might carry out as a student: the common expectation is that they should have an 'aim', which may be answering a specific question. But maybe that is too restrictive?

19 Determine the frequency (in MHz) of a gamma ray which has a wavelength of 4.1×10^{-12} m.

20 A mobile phone network uses electromagnetic waves of frequency 1200 MHz.
- **a** Calculate their wavelength.
- **b** State which part of the electromagnetic spectrum contains these waves.
- **c** Use the internet to find out the frequency used in microwave ovens.
- **d** Suggest why our bodies are not warmed up by using mobile phones.

21 As you are reading this, which types of electromagnetic radiation are there in the room?

22 **a** State which types of electromagnetic radiation are considered to be dangerous.
- **b** What do they have in common?

23 Outline what properties of X-rays make them so useful in hospitals.

24 **a** Calculate how long it takes for a Bluetooth signal to travel from a mobile phone to a speaker which is 4.7 m away.
- **b** How much time (to the nearest minute) does it take light to reach the Earth from the Sun?
- **c** **i** How much time does it take a radio signal to travel to Mars from Earth?
  - **ii** Explain why your answer is uncertain. (Use the internet to obtain relevant data.)