4 OSCILLATIONS AND WAVES

Introduction

All motion is either *periodic* or *non-periodic*. In **periodic motion** an object repeats its pattern of motion at fixed intervals of time: it is regular and repeated. Wave motion is also periodic and there are many similarities between oscillations and waves; in this topic we will consider the common features but also see that there are differences.

4.1 Oscillations

Understanding

- Simple harmonic oscillations
- Time period, frequency, amplitude, displacement, and phase difference
- Conditions for simple harmonic motion

Applications and skills

- Qualitatively describing the energy changes taking place during one cycle of an oscillation
- Sketching and interpreting graphs of simple harmonic motion examples

Equations

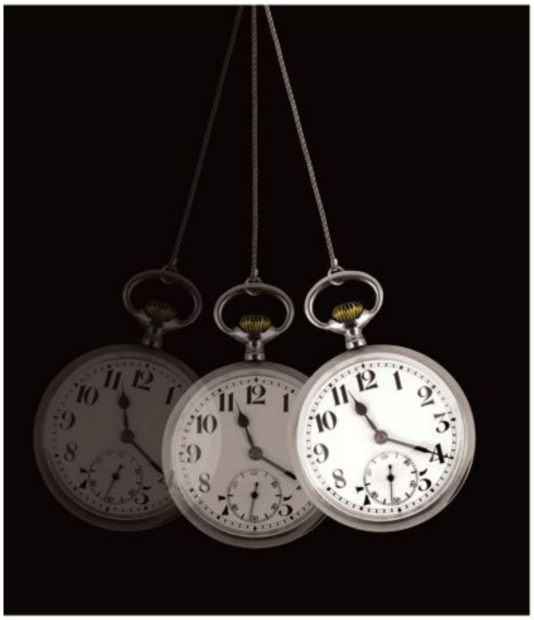
- Period-frequency relationship: $T = \frac{1}{f}$
- Proportionality between acceleration and displacement: $a \propto -x$

Nature of science

Oscillations in nature

Naturally occurring oscillations are very common, although they are often enormously complex. When analysed in detail, using a slow-motion camera, a hummingbird can be seen to flap its wings at a frequency of around 20 beats per second as it hovers, drinking nectar. Electrocardiographs are used to monitor heartbeats as hearts pulsate, pushing blood around our bodies at about one per second when we are resting and maybe two or three times this rate as we exert ourselves. Stroboscopes can be used to freeze the motion in engines and motors where periodic motion is essential, but too strong vibrations can be potentially very destructive. The practical techniques that have been developed combined with the mathematical modelling that is used to interpret oscillations are very powerful tools; they can help us to understand and make predictions about many natural phenomena.

▲ Figure 1 Hummingbird hovering over flower.



▲ Figure 2 Pocket watch under strobe light.

Isochronous oscillations

A very common type of oscillation is known as **isochronous** (taking the same time). These are oscillations that repeat in the same time period, maintaining this constant time property no matter what amplitude changes due to damping occur. It is the isochronicity of oscillations such as that of a simple pendulum that has made the pendulum such an important element of the clock. If we use a stroboscope (or strobe) we can freeze an isochronous oscillation so that it appears to be stationary; the strobe is made to flash at a regular interval, which can be matched to the oscillation. If the frequency of the strobe matches that of the oscillating object then, when the object is in a certain position, the strobe flashes and illuminates it. It is then dark while the object completes an oscillation and returns to the same position when the strobe flashes again. In this way the object appears motionless. The lowest frequency of the strobe that gives the object the appearance of being static will be the frequency of the object. If you now double the strobe frequency the object appears to be in two places. Figure 2 shows a swinging pocket watch which is illuminated with strobe light at 4 Hz, so the time interval between the images is 0.25 s. The watch speeds up in the middle and slows down at the edges of the oscillation.

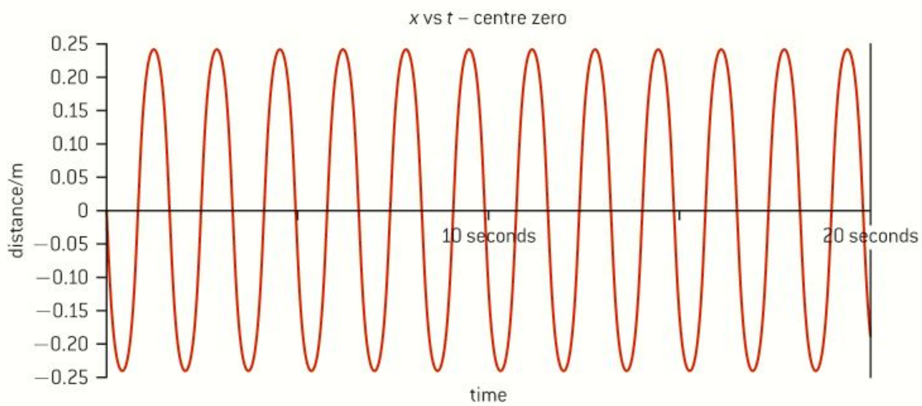
Describing periodic motion

The graph in figure 3 is an electrocardiograph display showing the rhythm of the heart of a healthy 48-year-old male pulsing at 65 beats per minute. The pattern repeats regularly with the repeated pattern being called the *cycle* of the motion. The time duration of the cycle is called the **time period** or the **period (T)** of the motion. Thus, a person with a pulse of 65 beats per minute has an average heartbeat period of 0.92 s.

▲ Figure 3 Normal adult male heart rhythm.

Let us now compare the pattern of figure 3 with that of figure 4, which is a data-logged graph of a loaded spring. The apparatus used for the datalogging is shown in figure 5 and the techniques discussed in the *Investigate!* section on p117. The graph for the loaded spring is a more straightforward example of periodic motion, obtained as the mass suspended on a spring oscillates up and down, above and below its normal rest position. There are just over 12 complete oscillations occurring in 20 seconds giving a period of approximately 1.7 s. Although the two graphs are very different the period is calculated in the same way.

As the mass passes its rest or **equilibrium position** its displacement (x) is zero. We have seen in Topics 1 and 2 that displacement is a vector



▲ Figure 4 Loaded spring.

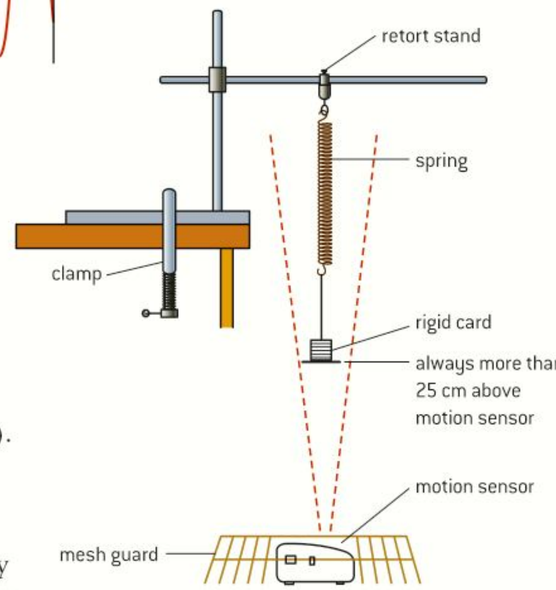
quantity and, therefore, must have a direction. In this case, since the motion is linear or one dimensional, it is sufficient to specify the direction as simply being positive or negative. The choice of whether above or below the rest position is positive is arbitrary but, once decided, this must be used consistently. In the graph of figure 4 the data logger has been triggered to start as the mass passes through the rest position. In this case positive displacements are above the rest position – so the mass is moving downwards when timing is started.

The maximum value of the displacement is called the **amplitude** (x_0). In the case of the loaded spring the amplitude is a little smaller than 0.25 m. It is much more difficult to measure the amplitude for the heart rhythm (figure 3) because of determining the rest position – additionally with no calibration of the scale it is impossible to give any absolute values. The amplitude is marked as A which is approximately 3 cm on this scale.

The **frequency** (f) of an oscillation is the number of oscillations completed per unit time. When the time is in seconds the frequency will be in hertz (Hz). Scientists and engineers regularly deal with high frequencies and so kHz, MHz, and GHz are commonly seen. The vibrations producing sound waves range from about 20 Hz to 20 kHz while radio waves range from about 100 kHz to 100 MHz.

With **frequency** being the number of oscillations per second and **period** the time for one oscillation you may have already spotted the relationship between these two quantities:

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



▲ Figure 5 Data logger arrangement.

Worked example

A child's swing oscillates simple harmonically with a period of 3.2 s. What is the frequency of the swing?

Solution

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

$= \frac{1}{3.2} = 0.31$ Hz

Investigate!

In this investigation, a motion sensor is used to monitor the position of a mass suspended from the end of a long spring. The data logger software processes the data to produce a graph showing the variation of displacement with time. The apparatus is arranged as shown in figure 5 with the spring having a period of at least 1 second.

- The apparatus is set up as shown above.
- The mass is put into oscillation by displacing and releasing it.
- The details of the data logger will determine the setting values but data loggers can usually be triggered to start reading at a given displacement value.

- Motion sensors use ultrasound, so reflections from surroundings should be avoided.
- The software can normally be used to plot graphs of velocity and acceleration (in addition to displacement) against time.
- Similar investigations can be performed with other oscillations.

Nature of Science

"Simple" for physicists

"Simple" does not mean "easy" in the context of physics! In fact, mathematically (as discussed in Sub-topic 9.1) simple harmonic motion (SHM) is not "simple". Simple may be better thought of as *simplified* in that we make life easier for ourselves by either limiting or ignoring some of the forces that act on a body. A simple pendulum consists of a mass suspended from a string. In dealing with the simple pendulum the frictional forces acting on it (air resistance and friction between the string and the suspension) and the fact that the mass will slightly stretch the string are ignored without having any disastrous effect on the equations produced. It also means that smooth graphs are produced, such as for the loaded spring.

Simple harmonic motion

We saw that the graph produced by the mass oscillating on the spring was much less complex than the output of a human heart. The mass is said to be undergoing simple harmonic motion or SHM.

In order to perform SHM an object must have a restoring force acting on it.

- The magnitude of the force (and therefore the acceleration) is proportional to the displacement of the body from a fixed point.
- The direction of the force (and therefore the acceleration) is always towards that fixed point.

Focusing on the loaded spring, the "fixed point" in the above definition is the equilibrium position of the mass – where it was before it was pulled down. The forces acting on the mass are the tension in the spring and the pull of gravity (the weight). In the equilibrium position the tension will equal the weight but above the equilibrium the tension will be less and the weight will pull the mass downward; below the equilibrium position the tension will be greater than the weight and this will tend to pull the mass upwards. The difference between the tension and the weight provides the restoring force – the one that tends to return the mass to its equilibrium position.

We can express the relationship between acceleration a and displacement x as:

$$a \propto -x$$

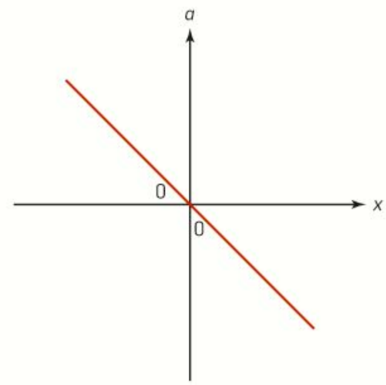
which is equivalent to

$$a = -kx$$

This equation makes sense if we think about the loaded spring. When the spring is stretched further the displacement increases and the tension increases. Because *force* = *mass* × *acceleration*, increasing the force increases the acceleration. The same thing applies when the mass is raised but, in this case, the tension decreases, meaning that the weight dominates and again the acceleration will increase. So although we cannot prove the proportionality (which we leave for HL) the relationship makes sense.

The minus sign is explained by the second bullet point "the acceleration is always in the opposite direction to the displacement". So choosing upwards as positive when the mass is above the equilibrium position, the acceleration will be downwards (negative). When the mass is below the equilibrium position (negative), the (net) force and acceleration are upwards (positive). The force decelerates the mass as it goes up and then accelerates it downwards after it stopped.

Figure 6 is a graph of a against x. We can see that $a = -kx$. takes the form $y = mx + c$ with the gradient being a negative constant.

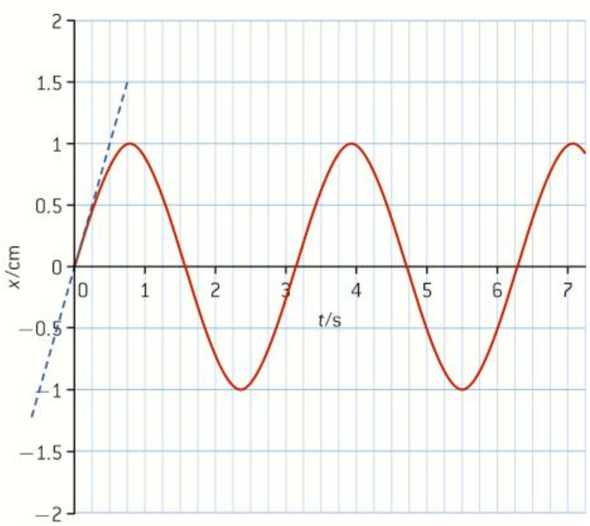


▲ Figure 6 Acceleration–displacement graph.

Graphing SHM

From Topic 2 we know that the gradient of a displacement–time graph gives the velocity and the gradient of the velocity–time graph gives the acceleration at any given time. This remains true for any motion. Let's look at the displacement graph for a typical SHM.

In figure 7 the graph is a sine curve (but if we chose to start measuring the displacement from any other time it could just as easily be a cosine, or a negative sine, or any other sinusoidally shaped graph). If we want to find the velocity at any particular time we simply need to find the gradient of the displacement–time graph at that time. With a curved graph we must draw a tangent to the curve (at our chosen time) in order to find a gradient. The blue tangent at 0 s has a gradient of +2.0 cm s^{-1}, which gives the maximum velocity (this is the steepest tangent and so we see the velocity is a maximum at this time). Looking at the gradient at around 1.6 s or 4.7 s and you will see from the symmetry that it will give a velocity of –2.0 cm s^{-1}, in other words it will be the minimum velocity (i.e. the biggest negative velocity). At around 0.8, 2.4, 3.9, and 5.5 s the gradient is zero so the velocity is zero.

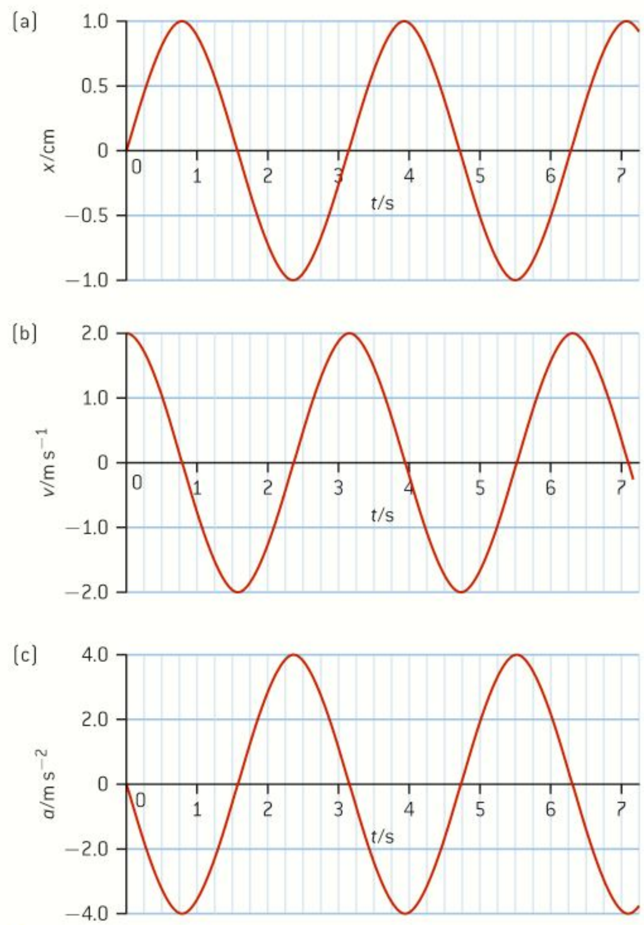


▲ Figure 7 The displacement graph for a typical SHM.

> **Directions with SHM**
>
> In many situations it is helpful to think about the magnitude of the velocity i. e. speed.
>
> For SHM organize a table for an object oscillating between $+A$ and $-A$. In your table show where the magnitudes of the position, velocity, acceleration and force are (a) zero and (b) maximum. Once you have done that mark in the directions of these these vectors at $+A$, $-A$ and zero. By doing this you should be thinking physics before algebra.

Using these values you will see that, overall, the velocity is going to change as shown in figure 8(b); it is a cosine graph in this instance.

You may remember that the gradient of the velocity–time graph gives the acceleration and so if we repeat what we did for displacement to velocity, we get figure 8(c) for the acceleration graph. You will notice that this is a reflection of the displacement–time graph in the time axis i.e. a negative sine curve. This should be no surprise, since from our definition of simple harmonic motion we expect the acceleration to be a negative constant multiplied by the displacement.

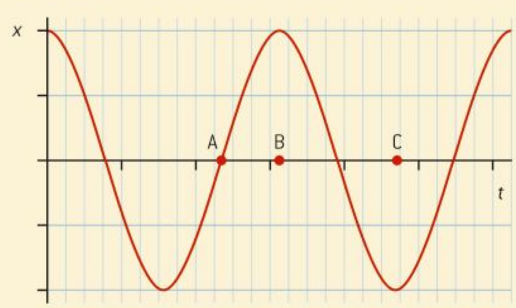


▲ Figure 8 The variation with time of displacement, velocity, and acceleration.

Worked examples

1 On a sheet of graph paper sketch two cycles of the displacement–time ($x - t$) relationship for a simple pendulum. Assume that its displacement is a maximum at time 0 seconds. Mark on the graph a time for which the velocity is maximum (labeled **A**), a time for which the velocity is zero (labeled **B**) and a time for which the acceleration is a maximum (labeled **C**).

Solution



Note

- This is a sketch graph so no units are needed – they are arbitrary.
- **A**, **B**, and **C** are each labelled on the time axis – as this is what the question asks.
- There are just two cycles (two complete periods) marked – since this is what the question asks.
- **A** is where the gradient of the displacement–time graph is a maximum.
- **B** is where the gradient of the displacement–time graph is a zero.
- **C** is where the displacement is a minimum – because $a = -kx$ this means that the acceleration will be a maximum.

2 The equation defining simple harmonic motion is $a = -kx$.

a) What are the units of the constant k?

b) Two similar systems oscillate with simple harmonic motion. The constant for system S_1 is k, while that for system S_2 is $4k$. Explain the difference between the oscillations of the two systems.

Solution

a) Rearranging the equation we obtain

$$k = -\frac{a}{x}$$

Substituting the units for the quantities gives unit of $k = -\frac{\text{ms}^{-2}}{\text{m}} = \text{s}^{-2}$

So the units of k are s^{-2} or per second squared – this is the same as frequency squared (and could be written as Hz^2).

b) Referring to the solution to (a) we can see that for S_2 the square of the frequency would be 4 times that of S_1. This means that S_2 has $\sqrt{4}$ or twice the frequency (or half the period) of S. That is the difference.

Phase and phase difference

Referring back to figures 8 a, b, and c we can see that there is a big similarity in how the shapes of the displacement, velocity, and acceleration graphs change with time. The three graphs are all sinusoidal – they take the same shape as a sine curve. The difference between them is that the graphs all start at different points on the sine curve and continue like this. The graphs are said to have a **phase difference**.

When timing an oscillation it really doesn't matter when we start timing – we could choose to start at the extremes of the oscillation or the middle. In doing this the shape of the displacement graph would not change but would look like the velocity graph (quarter of a period later) or acceleration graph (half a period later). From this we can see that the phase difference between the displacement–time graph and the velocity–time graph is equivalent to quarter of a period or $\frac{T}{4}$ (we could say that velocity leads displacement by quarter of a period). The phase difference between the displacement–time graph and the acceleration–time graph is equivalent to half a period or $\frac{T}{2}$ (we could say that acceleration leads displacement by half a period or that displacement leads acceleration by half a period – it makes no difference which).

Although we have discussed phase difference in term of periods here, it is more common to use angles. However, transferring between period and angle is not difficult:

Period T is equivalent to 360° or 2π radians,

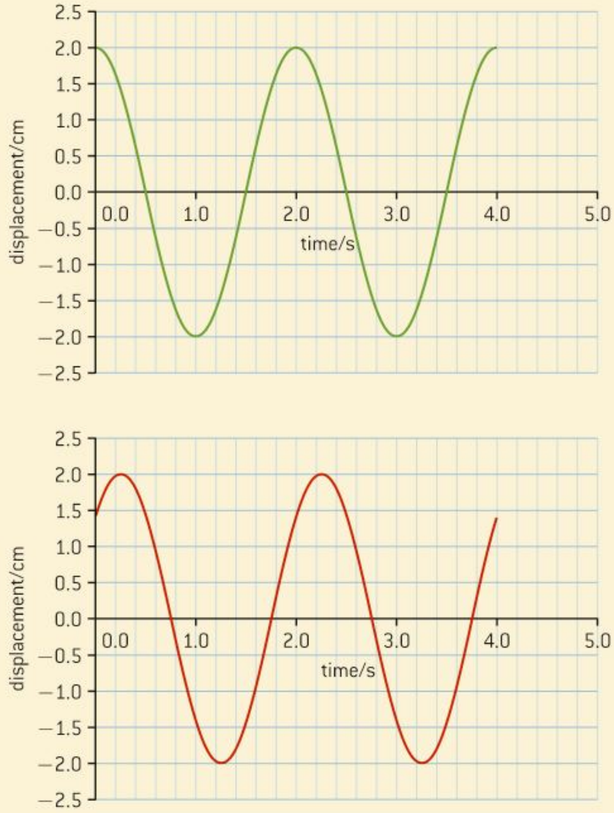
so $\frac{T}{2}$ is equivalent to 180° or π radians

and $\frac{T}{4}$ is equivalent to 90° or $\frac{\pi}{2}$ radians.

When the phase difference is 0 or T then two systems are said to be oscillating **in phase**.

Worked example

1 Calculate the phase difference between the two displacement–time graphs shown in figure 9. Give your answers in a) seconds b) radians c) degrees.



▲ Figure 9

Solution

a) It can be seen from either graph that the period is 2.0 s.

Drawing vertical lines through the peaks of the two curves shows the phase difference. This appears to be between 0.25–0.26 s so we will go with (0.25 ± 0.01) s.

b) The period (2.0 s) is equivalent to 2π radians, so taking ratios:

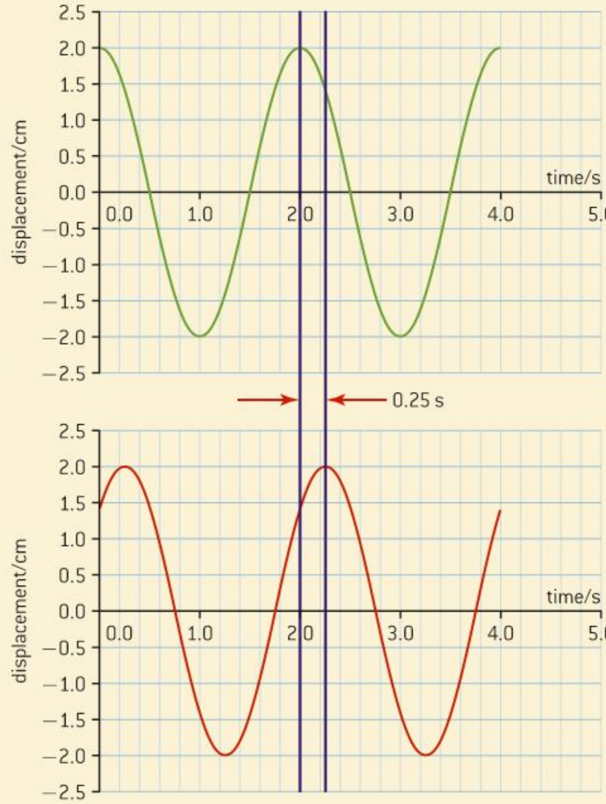
$\frac{2.0}{2\pi} = \frac{0.25}{\phi}$ (where ϕ is the phase difference in radians)

This gives a value for ϕ of 0.79 radian.

c) The period (2.0 s) is equivalent to 360°, so taking ratios:

$\frac{2.0}{360} = \frac{0.25}{\phi}$ (where ϕ is the phase difference in degrees)

This gives a value for ϕ of 45°.



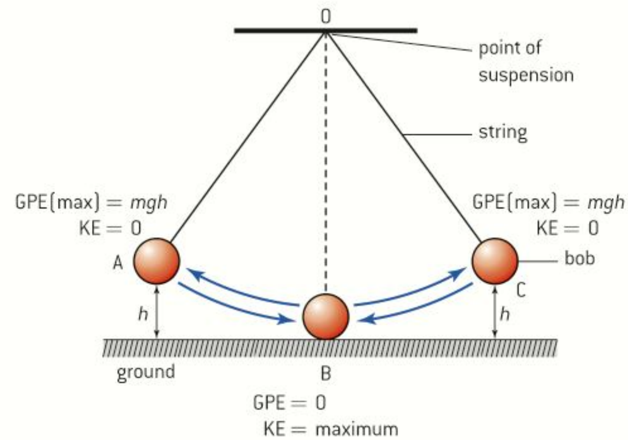
▲ Figure 10

Energy changes in SHM

Let's think of the motion of the simple pendulum of figure 11 as an example of a system which undergoes simple harmonic motion. For a pendulum to oscillate simple harmonically the string needs to be long and to make small angle swings (less than 10°). The diagram is, therefore, not drawn to scale. Let's imagine that the bob just brushes along the ground when it is at its lowest position. When the bob is pulled to position A, it is at its highest point and has a maximum gravitational potential energy

(GPE). As the bob passes through the rest position B, it loses all the GPE and gains a maximum kinetic energy (KE). The bob now starts to slow down and move towards position C when it briefly stops, having regained all its GPE. In between A and B and between B and C the bob has a combination of KE and GPE.

In a damped system over a long period of time the maximum height of the bob and its maximum speed will gradually decay. The energy gradually transfers into the internal energy of the bob and the air around it. Damping will be discussed in Option B.4.



▲ Figure 11 simple pendulum.

4.2 Travelling waves

Understanding

- → Travelling waves
- → Wavelength, frequency, period, and wave speed
- → Transverse and longitudinal waves
- → The nature of electromagnetic waves
- → The nature of sound waves

Applications and skills

- → Explaining the motion of particles of a medium when a wave passes through it for both transverse and longitudinal cases
- → Sketching and interpreting displacement – distance graphs and displacement – time graphs for transverse and longitudinal waves
- → Solving problems involving wave speed, frequency, and wavelength
- → Investigating the speed of sound experimentally

Equation

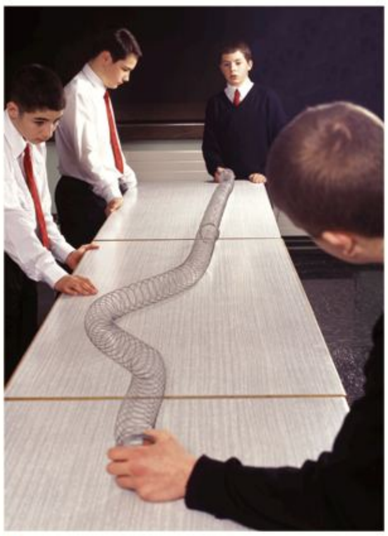
- → The wave equation: $c = f\lambda$

Nature of science

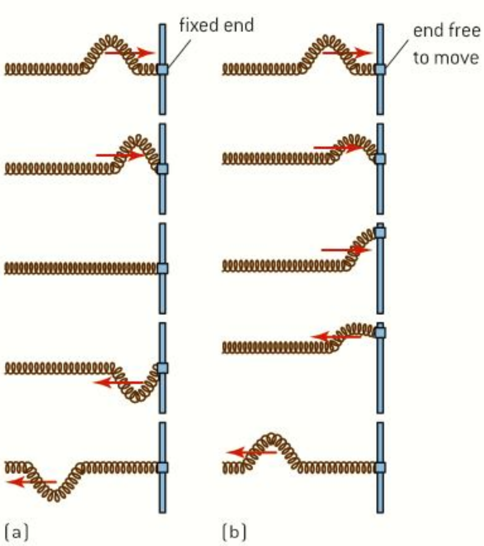
Patterns and trends in physics

One of the aspects of waves that makes it an interesting topic is that there are so many similarities with just enough twists to make a physicist think. Transverse waves have many similarities to longitudinal waves, but there are equally many differences. An electromagnetic wave requires no medium through which to travel, but a mechanical wave such a sound does need a medium to carry it; yet the intensity of each depends upon the square of the amplitude and the two waves use the same wave equation. Physicists enjoy patterns but at the same time they enjoy the places where patterns and trends change – the similarities give confidence but the differences can be thought-provoking.

▲ Figure 1 Ripples spreading out from a stone thrown into a pond.



▲ Figure 2 Slinky spring being used to demonstrate travelling waves.



▲ Figure 3 Reflection of wave pulses.

Introduction

When you consider waves you probably immediately think of the ripples on the surface of a lake or the sea. It may be difficult to think of many examples of waves, but this topic is integral to our ability to communicate and, since life on Earth is dependent on the radiation that arrives from the Sun, humankind could not exist without waves.

Waves are of two fundamental types:

- **mechanical waves**, which require a material medium through which to travel
- **electromagnetic waves**, which can travel through a vacuum.

Both types of wave motion can be treated analytically by equations of the same form. Wave motion occurs in several branches of physics and an understanding of the general principles underlying their behaviour is very important. Modelling waves can help us to understand the properties of light, radio, sound ... even aspects of the behaviour of electrons.

Travelling waves

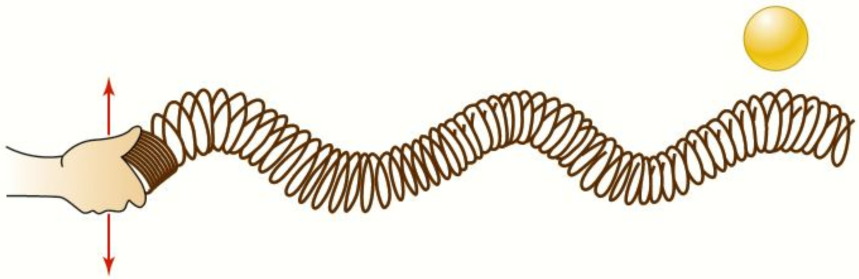
Figure 2 shows a slinky spring being used to demonstrate some of the properties of travelling waves.

With one end of the stretched spring fixed (as in figure 3(a)), moving the other end sharply upwards will send a pulse along the spring. The pulse can be seen to travel along the spring until it reaches the fixed end; then it reflects and returns along the spring. On reflection the pulse changes sides and what was an upward pulse becomes a downwards pulse. The pulse has undergone a phase change of 180° or π radians on reflection. When the end that was fixed is allowed to move there is no phase change on reflection as shown in figure 3(b) and the pulse travels back on the same side that it went out.

Note

You should discuss with fellow students how Newton's second and third laws of motion apply to the motion of the far end of the spring.

Observing the motion of a slinky can give much insight into the movement of travelling waves. To help focus on the motion of the spring, it is useful if one of the slinky coils is painted to make it stand out from the others. The coils are being used to model the particles of the medium through which the wave travels – they could be air or water molecules. If a table tennis ball is placed beside the spring, it shoots off at right angles to the direction of the wave pulse. This shows that this is a **transverse wave** pulse – the direction of the pulse being perpendicular to the direction in which the pulse travels along the slinky. When the slinky is vibrated continuously from side to side a transverse wave is sent along the spring as shown in figure 4 overleaf.



▲ Figure 4 Transverse waves on a slinky spring.

From observing the wave on the spring and water waves on a pond we can draw the following conclusions:

- A wave is initiated by a vibrating object (the source) and it travels away from the object.
- The particles of the medium vibrate about their rest position at the same frequency as the source.
- The wave transfers energy from one place to another.

A slinky can generate a different type of wave called a **longitudinal wave**. In this case the free end of a slinky must be vibrated back and forth, rather than from side to side. As a result of this the coils of the spring will vibrate about their rest position and energy will travel along the spring in a direction parallel to that of the spring's vibration as shown in figure 5.

▲ Figure 5 Longitudinal waves on a slinky spring.

Describing waves

When we describe wave properties we need specialist vocabulary to help us:

- **Wavelength** λ is the shortest distance between two points that are in phase on a wave, i.e. two consecutive **crests** or two consecutive **troughs**.
- **Frequency** f is the number of vibrations per second performed by the source of the waves and so is equivalent to the number of crests passing a fixed point per second.
- **Period** T is the time that it takes for one complete wavelength to pass a fixed point or for a particle to undergo one complete oscillation.
- **Amplitude** A is the maximum displacement of a wave from its rest position.

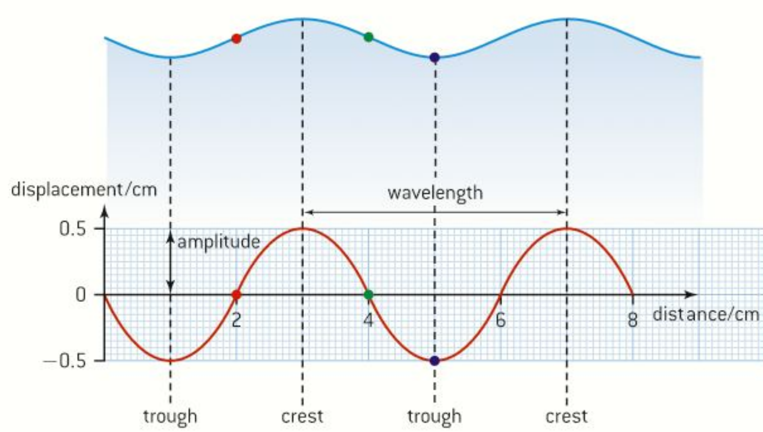
These definitions must be learned, but it is often easier to describe waves graphically. There are two types of graph that are generally used when describing waves: displacement–distance and displacement–time graphs. Such graphs are applicable to every type of wave.

For example *displacement* could represent:

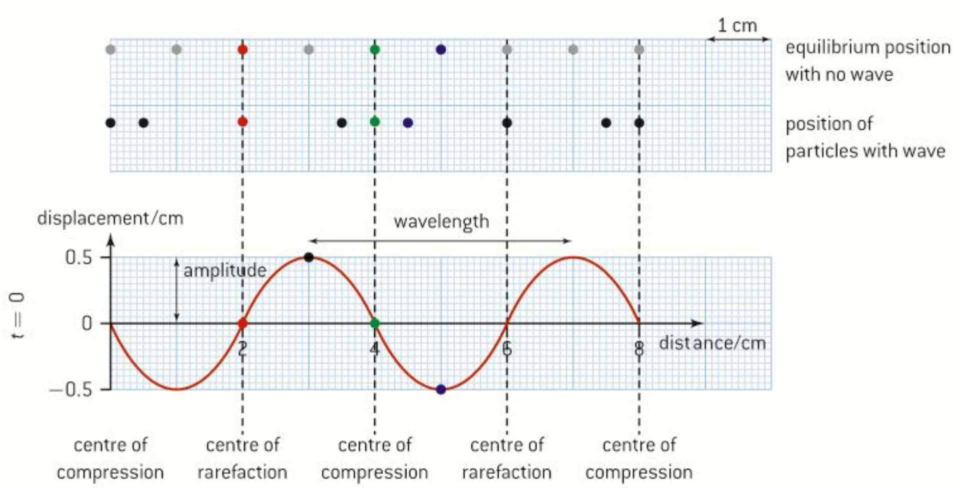
- the displacement of the water surface from its normal flat position for water waves
- the displacement of air molecules from their normal position for sound waves
- the value of the electric field strength vector for electromagnetic waves.

Displacement–distance graphs

This type of graph is sometimes called a wave profile and represents the displacement of many wave particles at a particular instant of time. On figure 6 the two axes are perpendicular but, in reality, this is only the case when we describe transverse waves (when the graph looks like a photograph of the wave taken at a particular instant). For longitudinal waves the actual displacement and distance are parallel. Figure 7 shows how the particles of the medium are displaced from the equilibrium position when the longitudinal wave travels through the medium forming a series of **compressions** (where the particles are more bunched up than normal) and **rarefactions** (where the particles are more spread out than normal). In this case the particles that are displaced to the left of their equilibrium position are given a negative displacement, while those to the right are allocated a positive displacement.



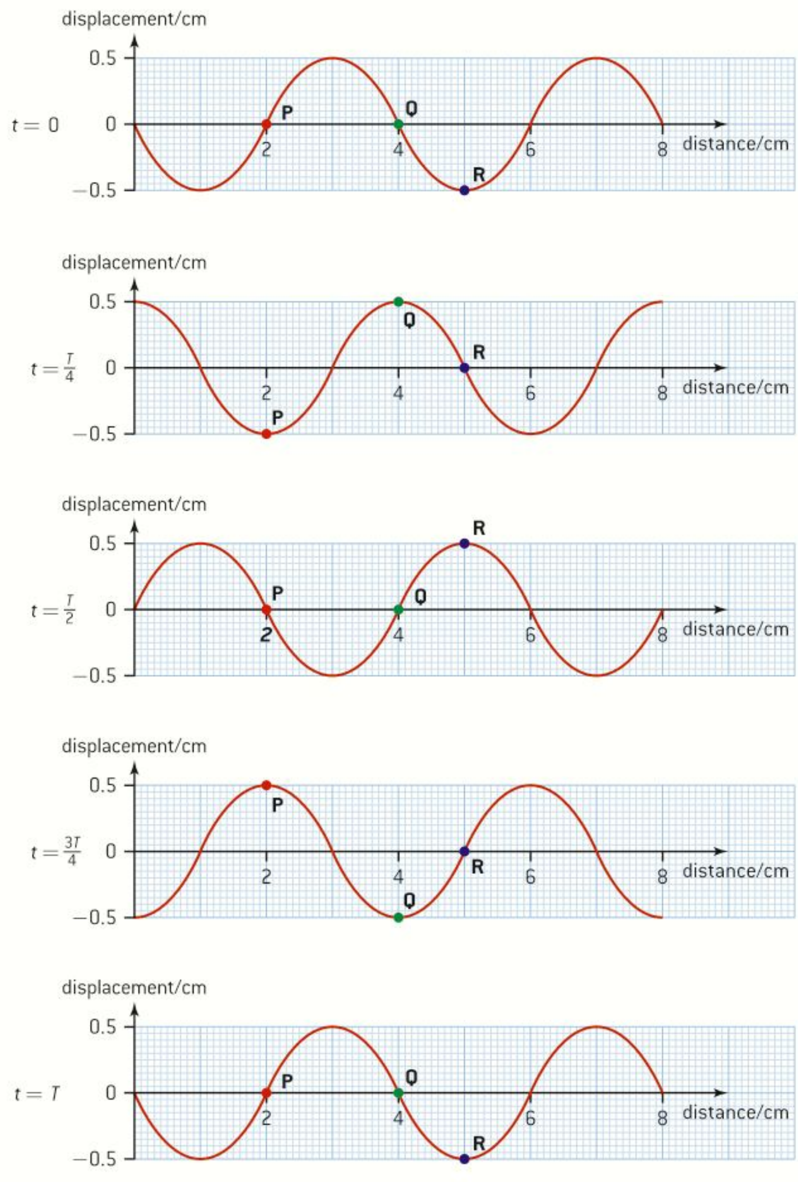
▲ Figure 6 Transverse wave profile.



▲ Figure 7 Longitudinal wave profile.

It is very easy to read the amplitude and wavelength directly from a displacement–time graph. For the longitudinal wave the wavelength is both the crest-to-crest distance and the distance between two consecutive compressions or rarefactions.

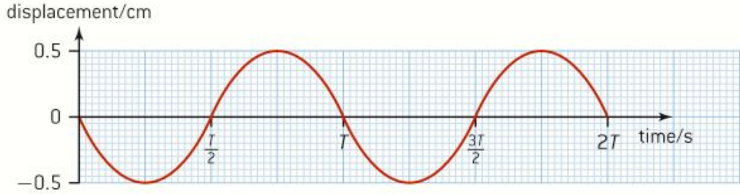
Using a sequence of displacement–distance graphs can provide a good understanding of how the position of an individual particle changes with time in both transverse and longitudinal waves (figure 8). On this diagram the wave profile is shown at a quarter period $\left(\frac{T}{4}\right)$ intervals; diagrams like this are very useful in spotting the phase difference between the particles. **P** and **Q** are in anti-phase here (i.e. 180° or π radians out of phase) and **Q** leading **R** by 90° or $\frac{\pi}{2}$ radians. You may wish to consider the phase difference between **P** and **R**.



▲ Figure 8 Sequence of displacement-distance graphs at $\frac{T}{4}$ time intervals.

Displacement–time graphs

A displacement–time graph describes the displacement of one particle at a certain position during a continuous range of times. Figure 9 shows the variation with time of the displacement of a single particle. Each particle along the wave will undergo this change (although with phase difference between individual particles).



▲ Figure 9 Displacement–time graphs.

Note

It is common to confuse displacement–distance graphs (where crest-to-crest gives the wavelength) with displacement–time graphs (where crest-to-crest gives the period).

This graph makes it is very easy to spot the period and the amplitude of the wave.

The wave equation

When a source of a wave undergoes one complete oscillation the wave it produces moves forward by one wavelength (λ). Since there are f oscillations per second, the wave progresses by $f\lambda$ during this time and, therefore, the velocity (c) of the wave is given by $c = f\lambda$.

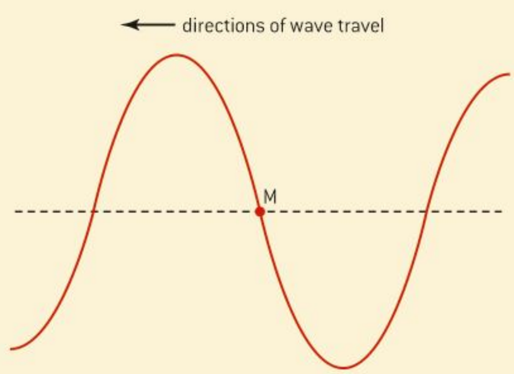
With f in hertz and λ in metres, c will have units of hertz metres or (more usually) metres per second. You do need to learn this derivation and it is probably the easiest that you will come across in IB Physics.

Worked example

The diagram below represents the direction of oscillation of a disturbance that gives rise to a wave.

a) Draw two copies of the diagram and add arrows to show the direction of wave energy transfer to illustrate the difference between (i) a transverse wave and (ii) a longitudinal wave.

b) A wave travels along a stretched string. The diagram to the right shows the variation with distance along the string of the displacement of the string at a particular instant in time. A small marker is attached to the string at the point labelled M. The undisturbed position of the string is shown as a dotted line.



On a copy of the diagram:

(i) Draw an arrow to indicate the direction in which the marker is moving.

(ii) Indicate, with the letter A, the amplitude of the wave.

(iii) Indicate, with the letter λ, the wavelength of the wave.

(iv) Draw the displacement of the string a time $T/4$ later, where T is the period of oscillation of the wave.

(v) Indicate, with the letter **N**, the new position of the marker.

c) The wavelength of the wave is 5.0 cm and its speed is 10 cm s^{-1}.

Determine:

(i) the frequency of the wave

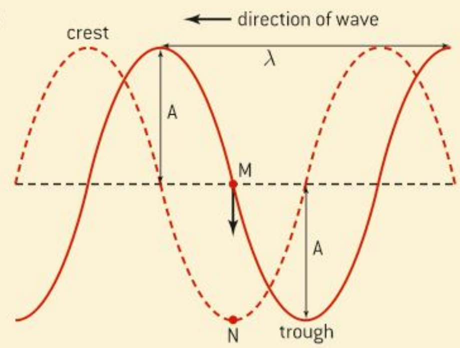
(ii) how far the wave has moved in a quarter of a period.

Solution

a) (i) The energy in a transverse wave travels in a direction perpendicular to the direction of vibration of the medium:

(ii) The energy in a longitudinal wave travels in a direction parallel to the direction of vibration of the medium:

b)



(i) With the wave travelling to the left, the trough shown will move to the left and that must mean that M moves downwards.

(ii) The amplitude (A) is the height of a crest or depth of a trough.

(iii) The wavelength (λ) is the distance equivalent to crest to next crest or trough to next trough.

(iv) In quarter of a period the wave will have moved quarter of a wavelength to the left (broken line curve).

(v) After quarter of a period the marker is now at the position of the trough (N).

c) (i) $f = \frac{c}{\lambda} = \frac{10}{5} = 2.0$ Hz (since both wavelength and speed are in cm, there is no need to convert the units)

(ii) $T = \frac{1}{f} = 0.5$ s

Because the wave moves at a constant speed $s = ct = c\frac{T}{4} = 10 \times 0.125 = 1.25$ cm

Investigate!

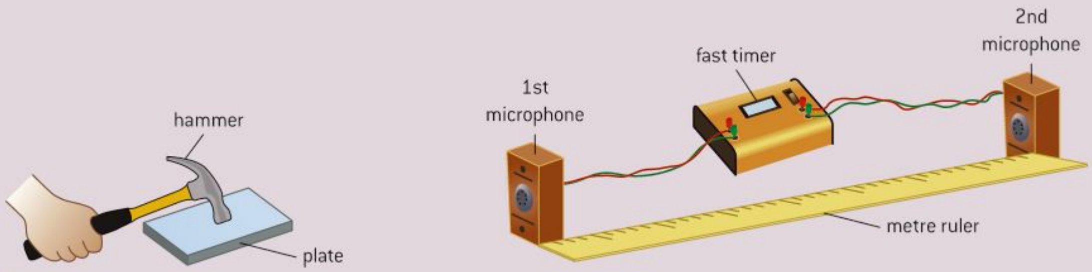
Measuring the speed of sound

Here are two of the many ways of measuring the speed of sound in free air (i.e. not trapped in a tube).

Method one – using a fast timer

This is a very simple method of measuring the speed of sound:

- Two microphones are connected to a fast timer (one which can measure the nearest millisecond or even microsecond).
- The first microphone triggers the timer to start.
- The second microphone triggers the time to stop.
- When the hammer is made to strike the plate the sound wave travels to the two microphones triggering the nearer microphone first and the further microphone second.
- By separating the microphones by 1 m, the time delay is around 3.2 ms.

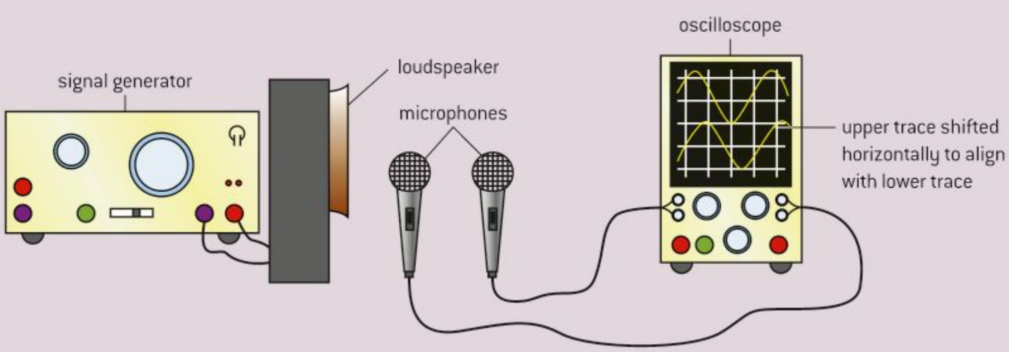


▲ Figure 10 Fast timer method for the speed of sound.

- This gives a value for the speed of sound to be $c = \frac{s}{t} = \frac{1.0}{3.2 \times 10^{-3}} \approx 310\ \text{m s}^{-1}$
- This should be repeated a few times and an average value obtained.
- You might think about how you could develop this experiment to measure the speed of sound in different media. Sound travels faster in solids and liquids than in gases – can you think why this should be the case? If the temperature in your country varies significantly over the year you might try to perform the experiment in a hot or cold corridor and compare your results.

Method two – using a double beam oscilloscope

- Connect two microphones to the inputs of a double-beam oscilloscope (figure 11).
- Connect a signal generator to a loudspeaker and set the frequency to between 500 Hz and 2.0 kHz.
- One of the microphones needs to be close to the loudspeaker, with the second a metre or so further away.
- Compare the two traces as you move the second microphone back and forth in line with the first microphone and the speaker.
- Use a ruler to measure the distance that you need to move the second microphone for the traces to change from being in phase to changing to antiphase and then back in phase again.
- The distance moved between the microphones being in consecutive phases will be the wavelength of the wave.
- The speed is then found by multiplying the wavelength by the frequency shown on the signal generator.



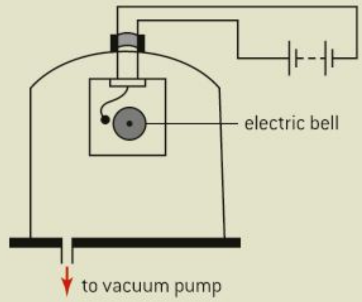
▲ Figure 11 Double beam oscilloscope method for the speed of sound.

Nature of Science

Analogies can slow down progress

You may have seen a demonstration, called the "bell jar" experiment, to show that sound needs a material medium through which to travel.

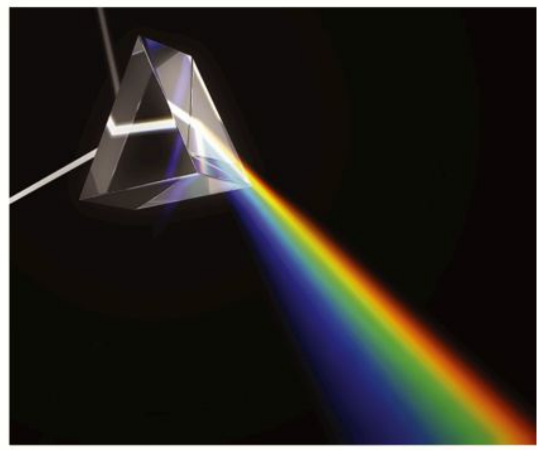
An electric bell is suspended from the mouth of a sealed bell jar and set ringing (figure 12). A vacuum pump is used to evacuate the jar. When there is no longer any air present in the jar, no sound can be heard. This experiment was first performed by Robert Boyle in 1660 although, long before this time, the Ancient Greeks understood that sound needed something to travel through. The first measurements of the speed of sound were made over four hundred years ago. These experiments were based on measuring the time delay either between a sound being produced and its echo reflecting from a distant surface or between seeing the flash of a cannon when fired and hearing the bang. From the middle to the end of the seventeenth century physicists such as Robert Hooke and Christiaan Huygens proposed a wave theory of light. In line with the model for sound, Huygens suggested that light was carried by a medium called the luminiferous ether. It was not until 1887, when Michelson and Morley devised an experiment in an attempt to detect the ether wind, that people began to realize that electromagnetic waves were very different from sound waves.



▲ Figure 12 The bell jar experiment.

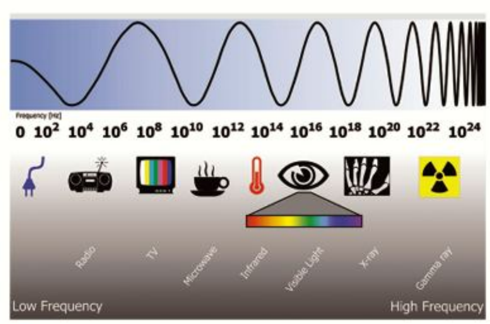
Electromagnetic waves

You may have seen the experiment shown in figure 13 in which a beam of *white* light is dispersed into the colours of the visible spectrum by passing it through a prism. The fact that what appears to be a single "colour" actually consists of multiple colours triggers the question "what happens beyond the red and blue ends of the spectrum?" The two colours represent the limit of vision of the human eye but not the limit of detection of electromagnetic radiation by the human body. Holding the back of your hand towards the Sun allows you to feel the warmth of the Sun's infra-red radiation. In the longer term, your hand will be subjected to sunburn and even skin cancer caused by the higher energy ultraviolet radiation. Figure 14 shows the full electromagnetic spectrum with the *atmospheric windows*; these are the ranges of electromagnetic waves that can pass through the layers of the atmosphere.



▲ Figure 13 Dispersion of white light using a glass prism.

All electromagnetic waves are transverse, carry energy, and exhibit the full range of wave properties. They travel at 300 million metres per second (3.00×10^8 m s^{-1}) in a vacuum. All electromagnetic waves (except gamma rays) are produced when electrons undergo an energy change, even though the mechanisms might differ. For example, radio waves are emitted when electrons are accelerated in an aerial or antenna. Gamma rays are different, they are emitted by a nucleus or by means of other particle decays or annihilation events. All electromagnetic waves consist of a time-varying electric field with an associated time-varying magnetic field. As the human eye is sensitive to the electric component, the amplitude of an electromagnetic wave is usually taken as the wave's maximum electric field strength. By graphing the electric field strength on the *y*-axes, we can use displacement–distance and displacement–time graphs to represent electromagnetic waves. In the following discussion of the different areas of the electromagnetic spectrum the range of the wavelength is given but these values are not hard and fast. There are overlaps of wavelength when radiation of the same wavelength is emitted by different



▲ Figure 14 The electromagnetic spectrum.

mechanisms (most notably X-rays and gamma rays). In addition to comparing the wavelengths of the radiations it is sometimes more appropriate to compare their frequencies (for example, radio waves) or the energy of the wave photon (for example, with X-rays and gamma rays). The frequency range is easy to calculate from wavelengths using the equation $c = f\lambda$ with $c = 3.00 \times 10^8$ m s^{-1}. Photon energies will be discussed in Topic 7. Those electromagnetic waves with frequencies higher than that of visible light ionize atoms – and are thus harmful to people. Those with lower frequencies are generally believed to be safe.

Nature of Science

Infra-red radiation ($\lambda_{ir} \sim 1 - 1000$ μm)

William Herschel discovered infra-red in 1800 by placing a thermometer just beyond the red end of the spectrum formed by a prism. Today we might do the same experiment but using an infra-red detector as a modern thermometer. Objects that are hot but not glowing, i.e. below 500 °C, emit infra-red only. At this temperature objects become red-hot and emit red light in addition to infra-red. At around 1000 °C objects become white hot and emit the full visible spectrum colours. Remote controllers for multimedia devices utilize infra-red as do thermal imagers used for night vision. Infra-red astronomy is used to "see" through dense regions of gas and dust in space with less scattering and absorption than is exhibited by visible light.

Ultraviolet radiation ($\lambda_{uv} \sim 100 - 400$ nm)

In 1801, Johann Ritter detected ultraviolet by positioning a photographic plate beyond the violet part of the spectrum formed by a prism. It can also be detected using fluorescent paints and inks – these absorb the ultraviolet (and shorter wavelengths) and re-emit the radiation as visible light. Absorption of ultraviolet produces important vitamins in the skin but an overdose can be harmful, especially to the eyes. The Sun emits the full range of ultraviolet: UV-A, UV-B, and UV-C. These classifications are made in terms of the range of the wavelengths emitted (UV-A ~315–400 nm, UV-B ~280–315 nm, and UV-C ~ 100–280 nm). UV-C rays, having the highest frequency, are the most harmful but, fortunately, they are almost completely absorbed by the atmosphere. UV-B rays cause sunburn and increase the risk of DNA and other cellular damage in living organisms; luckily only about 5% of this radiation passes through the ionosphere (this consists of layers of electrically charged gases between 80 and 400 km above the Earth). Fluorescent tubes, used for lighting, contain mercury vapour and their inner surfaces are coated with powders. The mercury vapour and powders fluoresce when radiated with ultraviolet light. With the atmosphere absorbing much of the ultraviolet spectrum, satellites must be positioned above the atmosphere in order to utilize ultraviolet astronomy, which is very useful in observing the structure and evolution of galaxies.

Radio waves ($\lambda_{radio} \sim 1$ mm $- 100$ km)

James Clerk Maxwell predicted the existence of radio waves in 1864. Between 1885 and 1889 Heinrich Hertz produced electromagnetic waves in the laboratory, confirming that light waves are electromagnetic radiation obeying Maxwell's equations. Radio waves are used to transmit radio and television signals. VHF (or FM) radio waves have shorter wavelengths than those of AM. VHF and television signals have wavelengths of a few metres and travel in straight lines (or **rays**) from the transmitter to the receiver. Long-wave radio relies on reflections from the ionosphere and diffracts around obstacles on the Earth's surface. Satellite communication requires signals with wavelengths less than 10 m in order to penetrate the ionosphere. Radio telescopes are used by astronomers to observe the composition, structure and motion of astronomic bodies. Such telescopes are physically large, for example the Very Large Array (VLA) radio telescope in New Mexico which consists of 27 antennas arranged in a "Y" pattern up to 36 km across.

Microwaves ($\lambda_{micro} \sim 1$ mm $- 30$ cm)

Microwaves are short wavelength radio waves that have been used so extensively with radar, microwave cooking, global navigation satellite systems and astronomy that they deserve their own category. In 1940, Sir John Randall and Dr H A Boot invented the magnetron which produced microwaves that could be used in **radar** (an acronym for *radio detection and ranging*) to locate aircraft on bombing missions. The microwave oven is now a common kitchen appliance; the waves are tuned to frequencies that can be absorbed by the water and fat molecules in food, causing these molecules to vibrate. This increases the internal energy of the food – the container holding the food absorbs an insignificant amount of energy and stays much cooler. Longer wavelength microwaves pass through the Earth's atmosphere more effectively than those of shorter wavelength. The **Cosmic Background Radiation** is the elemental radiation field that fills the universe, having been created in the form of gamma rays at the time of the Big Bang. With the universe now cooled to a temperature of 2.73 K the peak wavelength is approximately 1.1 mm (in the microwave region of the spectrum).

X-rays ($\lambda_x \sim 30$ pm – 3 nm)

X-rays were first produced and detected in 1895 by the German physicist Wilhelm Conrad Roentgen. An X-ray tube works by firing a beam of electrons at a metal target. If the electrons have sufficient energy, X-rays will emitted by the target. X-rays are well known for obtaining images of broken bones. They are also used in hospitals to destroy cancer cells. Since they can also damage healthy cells, using lead shielding in an X-ray tube is imperative. Less energetic and less invasive X-rays have longer wavelengths and penetrate flesh but not bone: such X-rays are used in dental surgery. In industry they are used to examine welded metal joints and castings for faults. X-rays are emitted by astronomical objects having temperatures of millions of kelvin, including pulsars, galactic supernovae remnants, and the accretion disk of black holes. The measurement of X-rays can provide information about the composition, temperature, and density of distant galaxies.

Gamma rays ($\lambda_\gamma < 1$ pm)

Gamma rays were discovered by the French scientist Paul Villard in 1900. Gamma rays have the shortest wavelength and the highest frequency of all electromagnetic radiation. They are generated, amongst other mechanisms, by naturally occurring radioactive nuclei in nuclear explosions and by neutron stars and pulsars. Only extra-terrestrial gamma rays of the very highest energies can reach the surface of the Earth – the rest being absorbed by ozone in the Earth's upper atmosphere.

Nature of Science

Night vision

Humans eyes are sensitive to the electric component of a portion of the electromagnetic spectrum known as the visible spectrum; this is what we call *sight*. Some animals, in particular insects and birds, are able to see using the ultraviolet part of spectrum. However, ultraviolet consists of relatively short wavelength radiation that can damage animal tissue, yet these animals appear to be immune to these dangers. It has been speculated whether any animal eye might be adapted to be able to use the infra-red part of the electromagnetic spectrum. As these long wavelengths have low energy it might be far-fetched to believe that they can be detected visually. There are animals that have evolved ways of sensing infra-red that are similar to the processes occurring in the eye. For example, the brains of some snakes are able to interpret the infra-red radiation in a way that can be combined with other sensory information to enable them to have a better understanding of surrounding danger or food sources.

4.3 Wave characteristics

Understanding

- ➔ Wavefronts and rays
- ➔ Amplitude and intensity
- ➔ Superposition
- ➔ Polarization

Applications and skills

- ➔ Sketching and interpreting diagrams involving wavefronts and rays
- ➔ Solving problems involving amplitude and intensity
- ➔ Sketching and interpreting the superposition of pulses and waves
- ➔ Describing methods of polarization
- ➔ Sketching and interpreting diagrams illustrating polarized reflected and transmitted beams
- ➔ Solving problems involving Malus's law

Equations

- ➔ Relationship between intensity and amplitude: $I \propto A^2$
- ➔ Malus's law: $I = I_0 \cos^2 \theta$

Nature of science

Imagination and physics

"Imagination … is more important than knowledge. Knowledge is limited. Imagination encircles the world[1]."

Einstein was famous for his *gedanken* "thought" experiments and one of the qualities that makes a great physicist is surely a hunger to ask the question "what if … ?". Mathematics is a crucial tool for the physicist and it is central to what a physicist does, to be able to quantify an argument. However, imagination can also play a major role in interpreting the results. Without imagination it is hard to believe that we would have Huygens' principle, Newton's law of gravitation, or Einstein's theory of special relativity. To visualize the abstract and apply theory to a practical situation is a flair that is fundamental to being an extraordinary physicist.

[1] Viereck, George Sylvester (October 26, 1929). 'What life means to Einstein: an interview'. *The Saturday Evening Post.*

Introduction

Wavefronts and rays are visualizations that help our understanding of how waves behave in different circumstances. By drawing ray or wave diagrams using simple rules we can predict how waves will behave when they encounter obstacles or a different material medium.