Wave motion and sound

Unit 8

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8.3 Properties of waves (page 221)	• State the wave equation and use it to solve problems. • Describe the characteristic properties of waves, including reflection, refraction, diffraction and interference. • Define the terms diffraction and interference.
8.4 Sound waves (page 228)	• Identify sound waves as longitudinal mechanical waves and describe how they are produced and how they propagate. • Compare the speed of sound in different materials and determine the speed of sound in air at a given temperature. • Define the intensity of a sound wave and solve problems using the intensity formula. • Explain the meaning of the terms echo, reverberation, pitch, loudness and quality. • Explain the reflection and refraction of sound and describe some applications.

Water waves are a common sight, either on the sea, in rivers or even in the bath. But have you ever really thought about what the term wave means? Maybe words like ripples, vibrations and energy spring to mind.

Waves enable us to see and to hear, and can even be used to monitor the health of unborn babies. Waves have a dangerous side too. The devastating tsunami on 26 December 2004 demonstrated some of the power of waves.

This unit looks at the different types of waves, their characteristics and behaviour and some of their uses.

8.1 Wave propagation

By the end of this section you should be able to:

- Define the terms wave and wave pulse.
- Describe longitudinal and transverse waves.
- Define the terms compression and rarefaction.

Figure 8.1 *Waves are a common sight on water.*

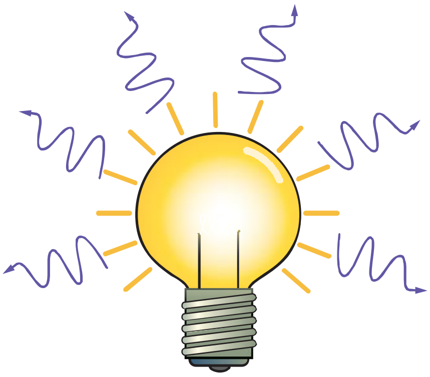


Figure 8.2 *Rays of light travel out as waves from a light bulb.*

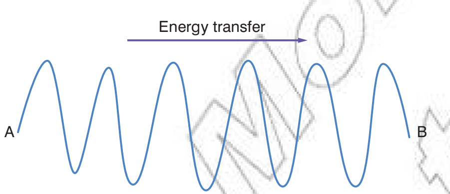


Figure 8.3 *Waves transfer energy from A to B.*

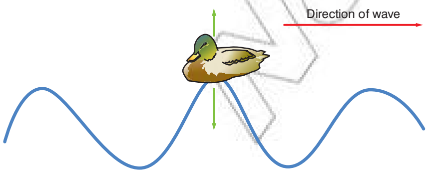


Figure 8.4 *A duck floating on the water just moves up and down as the waves go past.*

What are waves?

Waves can be thought of as a series of **vibrations** that travel through a **medium** (a medium is another way of describing the material through which the wave is travelling).

All waves transfer **energy** from one place to another. Light waves travelling out from a light bulb transfer energy from the bulb to your eye. Sound waves transfer energy from a speaker to your ear.

Although waves transfer energy from one place to another there is no transfer of **matter**. The material the wave is travelling through does not move along with the wave. In other words, when waves travel through water the water does not travel along with the wave.

This can be seen by observing a duck (or any object that floats) sitting on the water. As the wave moves past the duck it just bobs up and down. It does not travel along with the wave.

Unless it is a gas, the particles inside any medium are pretty much stationary. They move around a little and are always vibrating a little but essentially they remain in their **equilibrium positions**. When a wave passes through the material the particles in the medium simply **vibrate** from side to side.

This vibration could be up and down, left to right or any variation, but the particles always move back and forth past their equilibrium position.

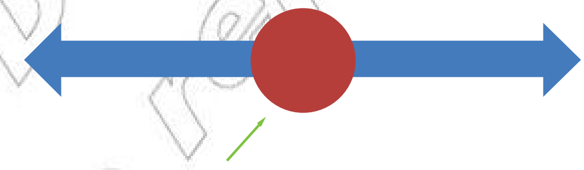


Figure 8.5 *The particles vibrate back and forth past their equilibrium position.*

If you plot a graph of the particle's **displacement** from its equilibrium position against time you would get a graph similar to Figure 8.6.

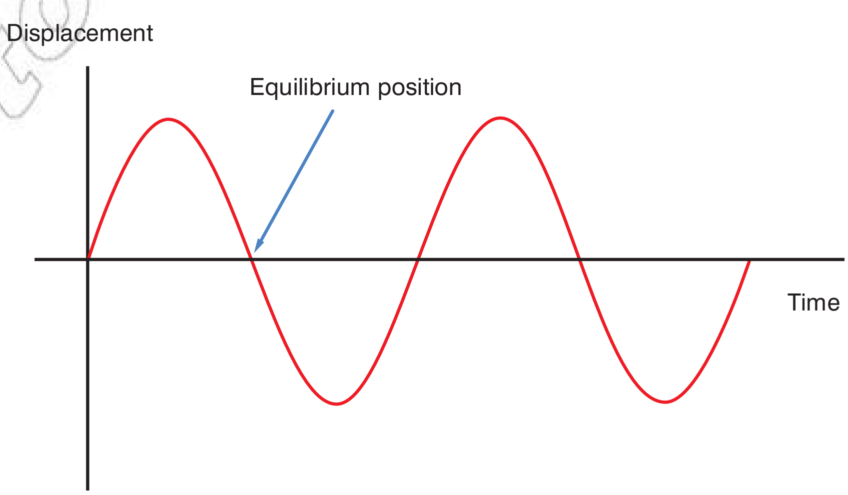


Figure 8.6 *Particle's displacement against time*

It's starting to look like a wave!

Wave pulses and continuous waves

Poke a stick into some water and you can see water waves (ripples) travelling away from the stick. The stick acts as a **source** for the waves.

If you just poke the stick once into the water a single ripple travels outwards. This is referred to as a **wave pulse**. You can see the same thing with some rubber tubing.

Here you can see that there are no repeated vibrations, just one short pulse.

If instead of just poking the stick into the water once you were to move it in and out you would create a series of ripples. New ripples would be created every time the stick went into and out of the water. This is referred to as a **continuous wave**.

As long as the source of the wave continues to vibrate a continuous wave will travel out from it.

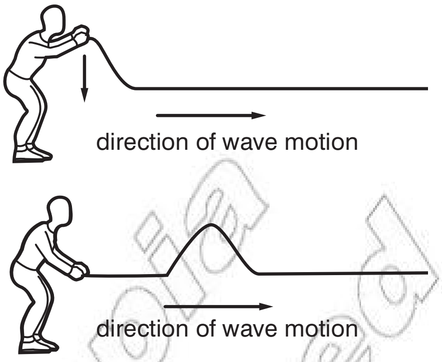


Figure 8.7 A simple wave pulse

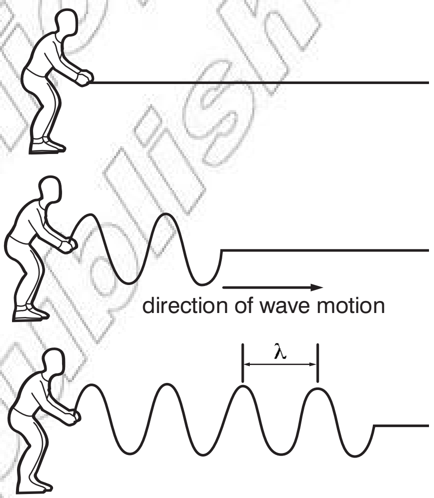


Figure 8.8 A simple continuous wave

Activity 8.1: Waves on stretched rubber tubing

- Tie one end of a long piece of rubber tubing to a fixed point in the room.
- Hold the other end, so that the tubing is taut (stretched tightly).
- Move your hand up and down briefly (Figure 8.9). Watch the wave pulse travel along the tubing. Does it reflect at the fixed end?
- Repeat, moving your hand from side to side.
- Try moving your hand up and down at a steady rate; try different frequencies. What do you observe?

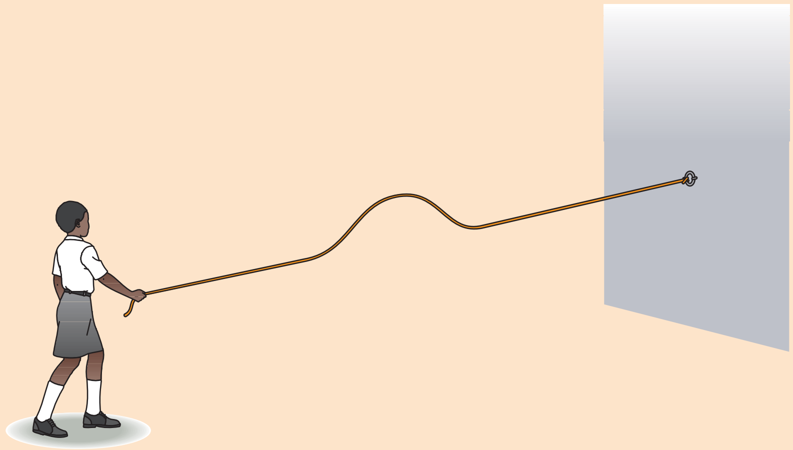


Figure 8.9 Sending a wave pulse along a taut rubber tube

Longitudinal and transverse waves

There are two main types of wave. These types are classified by the direction of vibrations in relation to the direction of

KEY WORDS

equilibrium position *the central point about which vibrations occur*

matter *a physical substance*

medium *material or substance*

vibrate *to move up and down, or side to side, about a central point*

vibrations *oscillations about a central equilibrium point*

waves *a series of vibrations that travel through a medium*

continuous wave *a wave with repeated vibrations*

source *the cause of the wave*

wave pulse *a wave with no repeated vibrations*

KEY WORDS

wave movement *the direction in which the wave is travelling*

crests *the maximum points of a transverse wave*

transverse waves *where the vibrations are perpendicular to the direction of wave motion*

troughs *the minimum points of a transverse wave*

wave movement. Remember, in both cases the material only vibrates from side to side; it does not travel along the wave.

Transverse

These are the waves most people think of. They go up and down (or left to right) in a sinusoidal motion.

In a **transverse** wave the vibrations are at *right angles* to the direction of wave movement (or energy transfer). This might be up and down or side to side.

A transverse wave is defined as a wave where the:

- **Vibrations are perpendicular (at right angles) to the direction of wave motion.**

This can be seen in Figure 8.10.

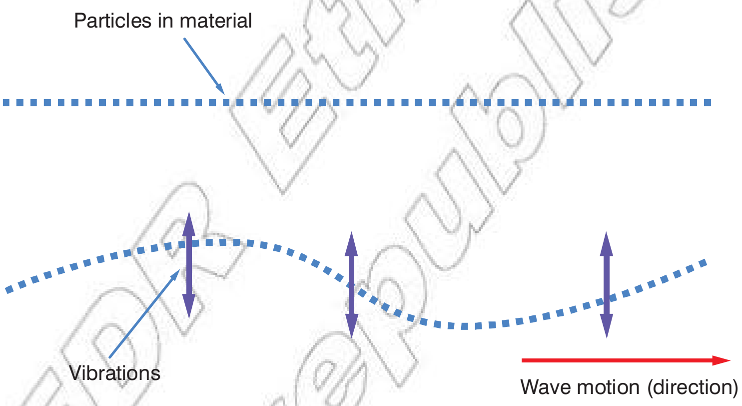


Figure 8.10 *Vibrations in a transverse wave*

Examples of transverse waves include:

- all electromagnetic waves – more on these in Section 8.2
  light
  microwaves
  radio waves
  X-rays
  etc.
- S-waves in earthquakes
- waves on strings
- waves on the surface of deep water.

All transverse waves comprise a series of **crests** (or peaks) and **troughs**.

Think about this...

It is easy to remember that transverse waves are the sinusoidal type. If you look carefully at the word **transverse** it has a transverse wave in the middle!

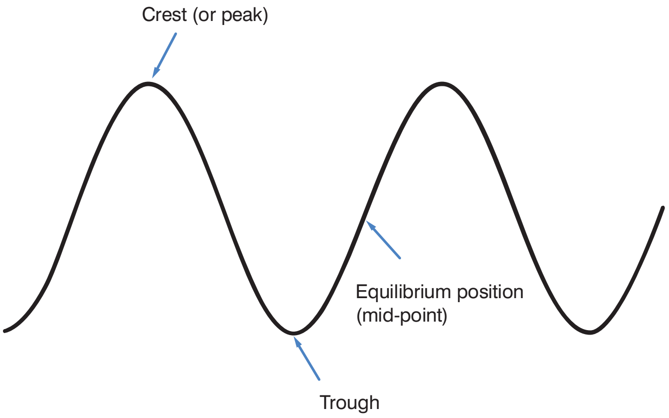


Figure 8.11 *Crests and troughs*

Like ripples on a pond, the crests travel outwards in the same direction as the wave motion.

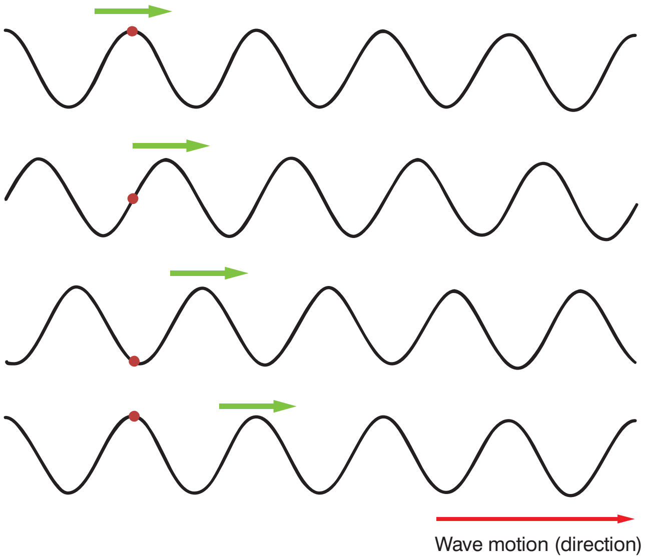


Figure 8.12 *Crests travel along with the transverse wave.*

It is important to remember that the particles just move up and down past their equilibrium position. This can be seen by the red particle; it just moves up and down as the wave travels from left to right.

Longitudinal

In a **longitudinal wave** the vibrations are in the *same direction* as the direction of wave movement (or energy transfer). This means the vibrations are forwards and backwards along the wave.

A longitudinal wave is defined as a wave where the:

- **Vibrations are parallel to (in the same direction of) the direction of wave motion.**

This can be seen in Figure 8.13.

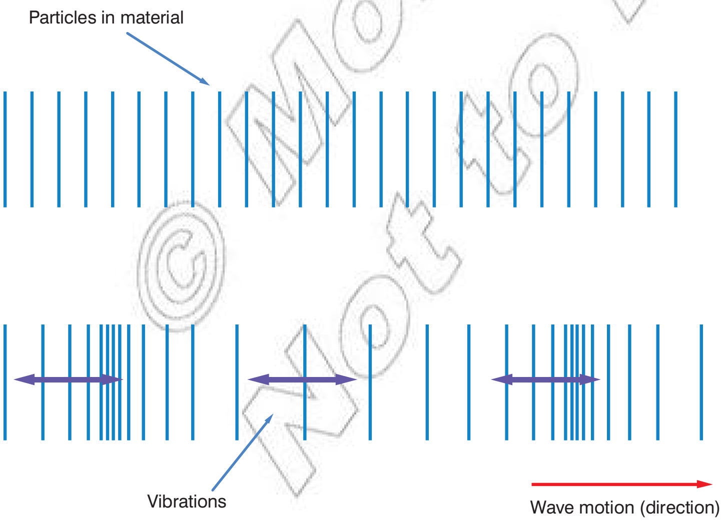


Figure 8.13 *Vibrations in a longitudinal wave*

As you can see, these are much more difficult to draw! You tend to see the particles replaced with vertical lines so the wave motion is easier to make out.

Activity 8.2: The human transverse wave

You need about ten people for this activity.

Form a line standing shoulder to shoulder and link arms tightly at the elbow.

The person at the end of the line acts as the wave source and moves forwards and backwards (only a few steps are needed).

You should be able to see the vibration travel down the line of people.

This is a transverse wave as the vibrations are at right angle to the direction of wave motion.

KEY WORDS

longitudinal waves *waves where the vibrations are parallel to the direction of wave motion*

Think about this...

Sound waves are often drawn to look like transverse waves. This is because plotting a graph of displacement against time produces exactly the same shape no matter which type of wave it is. This makes comparing them and describing their features much easier. However, they are most definitely longitudinal waves!

Examples of longitudinal waves include:

- sound waves
- pressure waves
- waves forwards and backwards through a spring
- P-waves in earthquakes.

When longitudinal waves travel through a material the particles bunch up then move further apart, then bunch up again. You can see this in Figure 8.14.

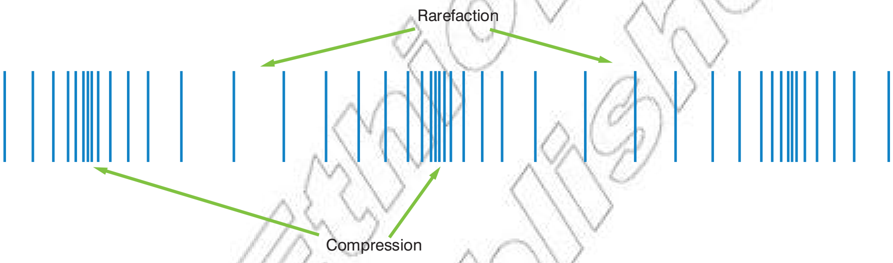


Figure 8.14 Compressions and rarefactions in a longitudinal wave

Regions where the particles are pushed together are called **compressions**. Regions where the particles are more spread out are called **rarefactions**. Compressions can be thought of as the longitudinal version of a crest and a rarefaction is the equivalent of a trough.

If the longitudinal wave is travelling through a gas then a compression can be thought of an area of **higher pressure** and a rarefaction an area of **lower pressure**. Compressions appear to travel through the material as the wave travels through it.

KEY WORDS

compressions *regions of a wave where the particles are pushed together*

higher pressure *comparatively greater pressure*

lower pressure *comparatively smaller pressure*

rarefactions *regions of a wave where the particles are spread out*

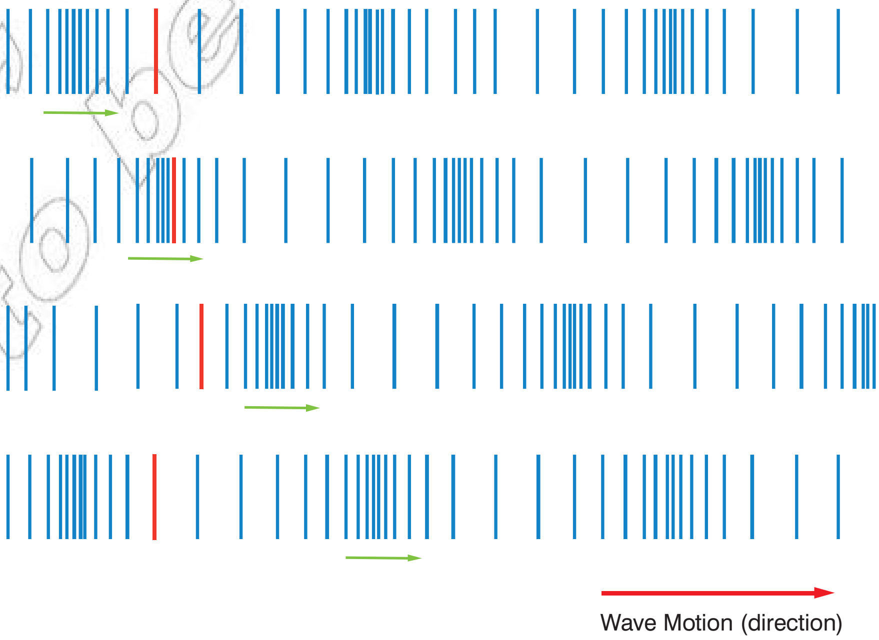


Figure 8.15 Compressions travel along a longitudinal wave.

It is important to remember that the particles just move forwards and backwards (look at the red line in the diagram).

DID YOU KNOW?

In an explosion a shock wave (a compression) travels outward from the centre of the blast. It is this area of higher pressure that causes damage.

Both transverse and longitudinal waves can also been seen using a long spring.

Activity 8.4: Waves on a spring

Use a slinky spring. Lay it carefully on a long bench or table. Ask your partner to hold one end firmly.

- As in the previous experiment, move your hand from side to side to send a wave pulse along the spring (Figure 18.6(a)). Send a continuous series of waves along the spring.
- There is a second way in which you can send a wave along a stretched spring. Push the end backwards and forwards, along the length of the spring (Figure 8.16(b)). Watch as the segments of the spring move back and forth.

Can you observe both types of wave reflecting at the fixed end of the spring?

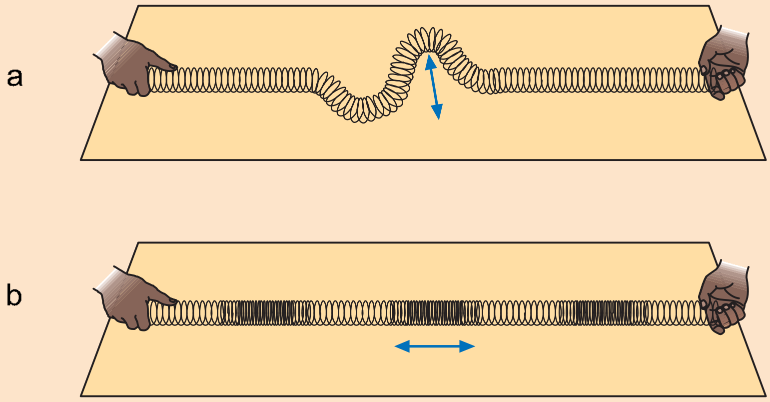


Figure 8.16 *Two types of wave on a stretched spring: (a) transverse, and (b) longitudinal*

Activity 8.3: The human longitudinal wave

Just like before you need about ten people for this activity. Again form a line standing shoulder to shoulder and link arms tightly at the elbow.

This time the person at the end of the line (still acting as the wave source) moves from side to side.

You should be able to see the vibration travel down the line of people and notice areas of compression and rarefaction. This time it is a longitudinal wave as the vibrations are in the same direction as the wave motion.

Summary

In this section you have learnt that:

- A wave transfers energy from one place to another as a series of vibrations.
- A wave pulse is a wave with no repeated vibrations.
- The particles in the medium vibrate from side to side; they do not travel through the medium with the wave.
- There are two types of wave, longitudinal and transverse.
- In a transverse wave the vibrations are perpendicular to the direction of wave motion.
- A transverse wave comprises a series of crests and troughs.
- In a longitudinal wave the vibrations are parallel to the direction of wave motion.
- A longitudinal wave comprises a series of compressions and rarefactions.
- In a compression the particles are closer together and in a rarefaction they are more spread out.

Review questions

1. Explain the difference between a continuous wave and a wave pulse.
2. Describe what happens to particles when a wave passes through a medium.
3. Explain what is meant by a transverse wave and give three examples.
4. Explain what is meant by a longitudinal wave and give three examples.

8.2 Mechanical waves

By the end of this section you should be able to:

- Define and identify the flowing features of a wave: crest, trough, wavelength, frequency, amplitude and time period.
- Distinguish between mechanical waves and electromagnetic waves.
- Identify transverse and longitudinal waves in a mechanical media.

Waves characteristics

No matter what the type of wave all waves share some characteristics. These are terms you've probably heard before. However, each has a very specific meaning:

Wave speed (v)

Wave speed is defined as:

- **The distance the wave travels in one second.**

This is the same as the distance one peak or one compression travels in one second. It's given the symbol v (or c for electromagnetic waves) and like all speeds it is measured in metres per second (m/s).

Amplitude (a)

Amplitude is defined as:

- **The maximum displacement from the equilibrium position.**

In simple terms it's the maximum height of the wave. If you plot a graph of particle displacement against distance along the wave the amplitude can be easily determined.

DID YOU KNOW?

Nothing can travel faster than the speed of light through a vacuum. This is the ultimate speed limit. It is equal to 300 000 000 m/s (or 3×10^8 m/s). That's fast enough to go around the world just under 8 times per second.

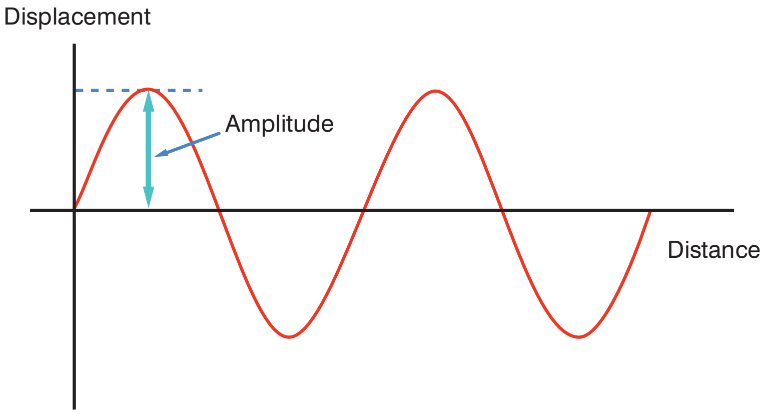


Figure 8.17 Amplitude

Notice that it is from the equilibrium position (mid-point), it is not the distance from top to bottom.

Amplitude is given the symbol a (or occasionally x_o). As amplitude is a displacement it is measured in metres (m).

Wavelength (λ)

Wavelength is defined as:

- **The minimum distance between identical points on adjacent waves.**

For example, it is the distance from one peak to another, or from one compression to another. Wavelength is given the symbol λ (lambda); this is the Greek letter l.

As wavelength is a distance it is measured in metres (m).

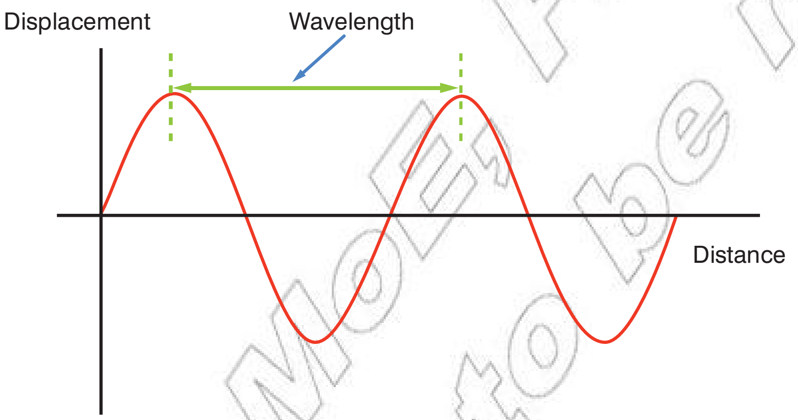


Figure 8.18 Wavelength

Again, plotting a displacement against distance graph allows wavelength to be easily determined.

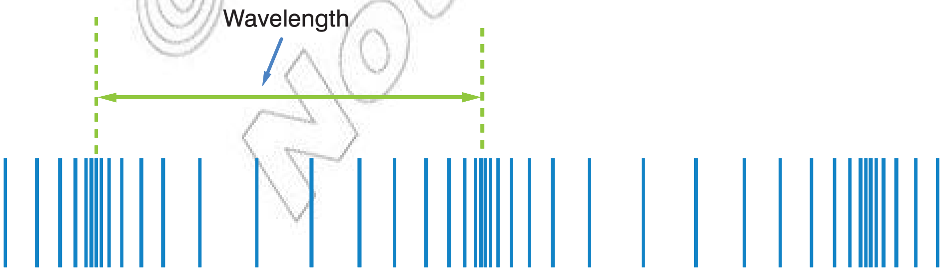


Figure 8.19 Wavelength of a longitudinal wave

Frequency (*f*)

Frequency is defined as:

- **The number of complete waves passing a given point per second.**

This can be determined by the number of crests or compressions that pass a given point per second. The higher the **frequency**, the greater the number of waves per second.

Frequency is given the symbol *f* and is measured in **hertz** (Hz). A frequency of 10 Hz would mean 10 waves per second. The hertz is the SI derived unit for frequency.

Time period (*T*)

Time period is defined as:

- **The time taken for one complete wave to pass a given point.**

This is the time taken for one complete particle vibration or oscillation. It is given the symbol *T* (or occasionally 'T').

As **time period** is just a measure of duration it is measured in seconds (s).

If you plot a slightly different graph of particle displacement (against time) then the time period is the time between two peaks.

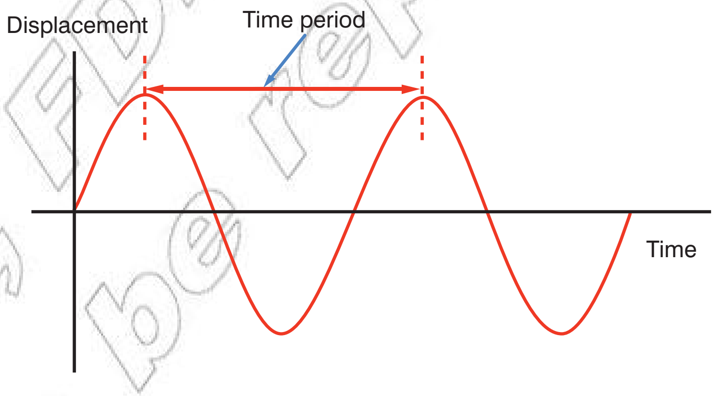


Figure 8.20 *Time period*

There are two important equations linking these terms. The first links frequency and time period.

If you consider a wave with a frequency of 4 Hz this would mean four waves passing a point per second. Each wave would therefore take 0.25 second to pass the point. The time period would be 0.25 s. The time period is the **reciprocal** of the frequency. A wave with a frequency of 10 Hz would have a time period of 1/10 or 0.1 s. In terms of an equation, we get:

- **frequency = 1 / time period**
- $f = 1 / T$

This also means $T = 1/f$.

Powers of ten prefixes are often used to describe frequencies and time periods of waves. Some common examples are listed in Table 8.1

KEY WORDS

frequency *the number of waves passing each second*
Hertz *the unit of frequency*
reciprocal *the inverse of a number which when multiplied by the original number equals 1*
time period *the time taken for a complete wave to pass a given point*
wave equation *equation relating wave speed, frequency and wavelength*
electromagnetic waves *waves that comprise vibrations of electric and magnetic fields*
mechanical waves *waves that comprise a series of vibrations of matter*
seismic waves *waves that travel through the Earth, produced by earthquakes*

DID YOU KNOW?

The reciprocal of *x* is equal to 1/*x*. For example, the reciprocal of 5 is one fifth (1/5 or 0.2), and the reciprocal of 0.25 is 1 divided by 0.25, or 4.

Activity 8.5: Time periods

Find the time period for the following waves from their frequency:

a) 20 Hz

b) 3 kHz

c) 0.2 Hz

Find the frequency of the wave from the following time periods:

a) 0.4 s

b) 0.2 ms

c) 100 s

Table 8.1 Common powers of ten prefixes

Prefix	Name	Value	Power	Example
G	Giga	×1 000 000 000	$\times 10^{9}$	6.5 GHz = 6 500 000 000 Hz
M	Mega	×1 000 000	$\times 10^{6}$	3 MHz = 3 000 000 Hz
k	Kilo	×1000	$\times 10^{3}$	4.2 kHz = 4200 Hz
m	Milli	×0.001	$\times 10^{-3}$	6 ms = 0.006 s
μ	Micro	×0.000 001	$\times 10^{-6}$	40 μs = 0.000 040 s
n	Nano	×0.000 000 001	$\times 10^{-9}$	8 nm = 0.000 000 008 m

The second equation is so important in our dealings with waves that it is often simply called the **wave equation**. It relates wave speed, frequency and wavelength.

- **Wave speed = frequency × wavelength**
- $v = f\lambda$

We will look at this in more detail in Section 8.3.

Mechanical vs. electromagnetic waves

So far whenever we've been discussing waves we have talked about particle vibrations within the medium through which the wave is travelling. However, some waves can also travel through a vacuum; there are no particles in a vacuum and so something else must be happening.

We call waves that travel through a material as vibrations of the material **mechanical waves**. Here the particles in the material (water, wood, air, etc.) vibrate. It is these vibrations that form the wave. All mechanical waves require a medium to travel through. They include sound waves, water waves and seismic waves.

Electromagnetic waves, such as light, radio and x-rays, do not require a medium to travel through. They are comprised of vibrating electric and magnetic fields. There are no particle vibrations at all. This means electromagnetic waves are able to travel through a vacuum and when they travel through a medium there are no particle vibrations inside that medium.

Examples of mechanical waves

There are lots of examples of different **mechanical waves**. We will look at sound waves in Section 8.4. In this section we will look at two types in more detail, water waves and **seismic waves**.

Water waves

Waves that travel on the surface of water can be thought of as *transverse* waves. However, there is often a slight drift in the direction of wave motion, so they are not perfect transverse waves.

If you throw a stone into a pond you can see ripples as crests and troughs travelling out from the splash. If you poke a stick up and

Activity 8.6: Electromagnetic spectrum chart

In the text, we have touched only briefly on some parts of the electromagnetic spectrum. Some aspects have been missed out almost entirely – for example, the importance of electromagnetic radiation in astronomy.

Your task, together with the rest of the class, is to produce a large, illustrated chart of the electromagnetic spectrum. Your chart will show all parts of the spectrum, and show uses, hazards, production and detection.

- Decide how you will share out the work. Perhaps different groups will take different parts of the spectrum (infra-red, visible, etc). Perhaps you will look for useful material related to different uses of radiation (industry, astronomy, medicine, etc.).
- When you have gathered images and other information, join together to make a long chart of the complete spectrum. Include on it scales of frequency and wavelength.

down in the water you can create continuous waves travelling out from the source (the stick).

Water waves arise due to the surface tension on the water. As some of the water molecules are pushed down they pull their neighbouring particles down and a trough is created; this then travels away from the source.

The speed of water waves depends on the *depth* of the water. As the depth of the water increases, so does the wave speed. In deep water, water waves can travel very fast (in hundreds of km/h).

As water waves enter shallower water their speed reduces, so the waves bunch up, the wavelength gets shorter but the amplitude increases.

An easy way to remember this is to use: SSSS Water Waves, shallower, shorter, steeper and slower.

Most water waves on the open sea are caused by the action of the wind on the surface of the water. **Tsunamis** are different types of water wave created by changes to the ocean floor or the coastline (often due to earthquakes). In deep water, tsunamis are not really noticeable. They travel very fast but have a long wavelength and small amplitude. As they approach land they slow down and can grow to massive heights.

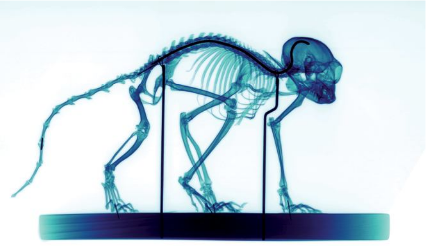


***Figure 8.21** X-ray of a marmoset monkey, taken to see how its skeleton compares with other, related species*

***Figure 8.22** Water waves on a pond*

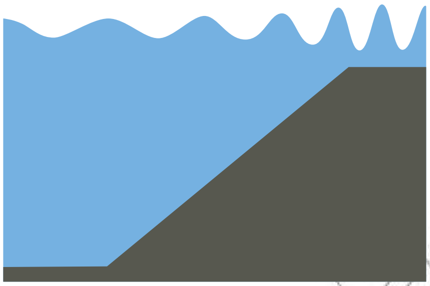


***Figure 8.23** Water waves slow down but get taller as the water gets shallower.*

DID YOU KNOW?

The speed of water waves is given by the equation; $v = \sqrt{gd}$, v = wave speed in m/s, g = gravitational field strength in N/kg = 10 N/kg and d = depth of water in m.

Seismic waves

Seismic waves are produced by earthquakes. They travel out from the **focus** in all directions throughout the Earth. It is these waves that usually cause the damage to buildings when they reach the surface.

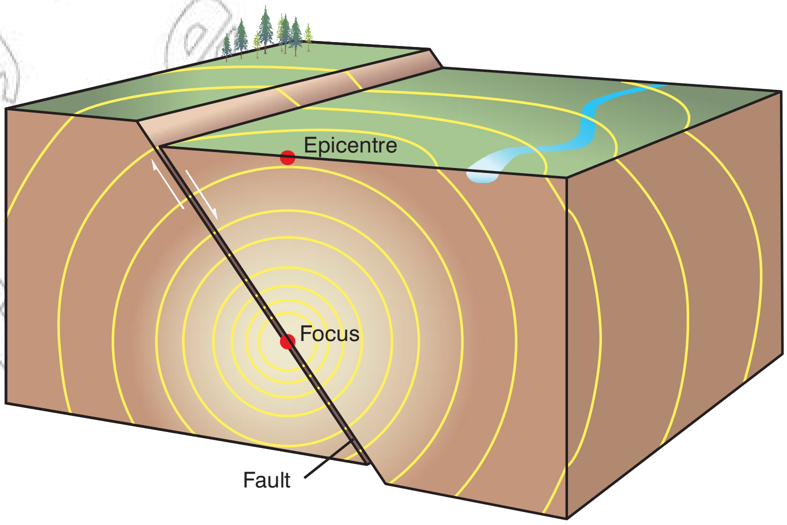


***Figure 8.24** Seismic waves travelling out from an earthquake*

There are three types of seismic waves: L-waves, P-waves and S-waves. L-waves are complex types of rolling wave, which travel along the surface of the Earth and cause the most damage to buildings.

P-waves and S-waves travel through the Earth. It is the different properties of these two waves that enable us to not only determine the exact location of the earthquake but also the structure of the interior of the Earth.

The P in P-waves stands for **primary**, or **pressure**. P-waves are an example of **longitudinal** waves and travel very fast (around 7000 m/s, depending on the medium). They often arrive first (hence primary waves) as they are faster than S-waves.

P-waves are able to travel through both the solid and liquid parts of the Earth's interior.

The S in S-waves stands for **secondary**, or **shear**. S-waves are an example of **transverse** waves and still travel fast (around 4000 m/s, depending on the medium), just not as fast as P-waves.

S-waves are only able to travel through the solid parts of the Earth's interior.

Different stations around the Earth record when the P-waves and S-waves arrive. The time delay between the waves and data collected from other stations can be used to work out the exact location of the focus. For example, if three stations A, B and C calculate the focus is 1000 km, 800 km and 500 km away from them, respectively, the exact position can be determined through **triangulation**.

In addition to determining the location, we said earlier that the differences between P- and S-waves allow us to determine information about the structure of the Earth.

This is a very complex process but it relies on the fact that S-waves are only able to travel through solid, whereas P-waves can travel through solids and liquids.

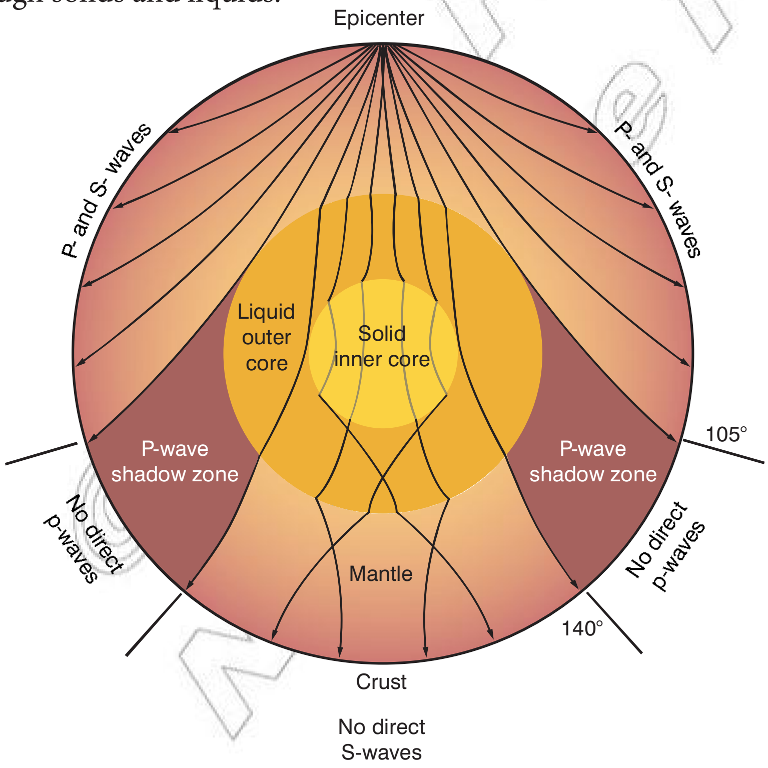


Figure 8.27 Using seismic waves to determine to structure of the Earth

As the waves travel through the Earth differences in the **density** of the medium cause the waves to bend. It is this bending and the

Think about this...

When water waves approach the coastline friction with the sea bed changes their characteristics. This leads to the wave rolling over itself and breaking onto the sea front (in this case it ceases to be a transverse wave).

DID YOU KNOW?

The fastest documented tsunami was created by an earthquake in Chile in May 1960. The waves travelled the 11 000 km to New Zealand in around 12 hours. That's an average speed of around 900 km/h!

***Figure 8.25** Understanding earthquakes might help predict them and so save lives.*

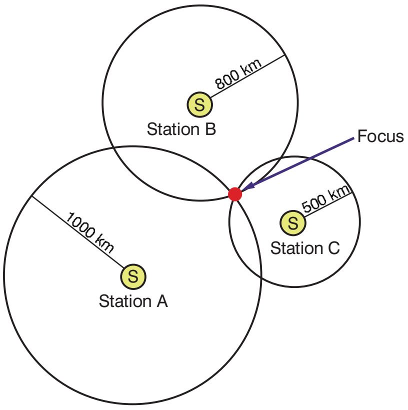


***Figure 8.26** Using triangulation to determine the location of the focus*

complete lack of S-waves on the opposite side of the Earth that allows scientists to deduce that Earth must have a liquid outer core and a solid inner core. Complex mathematics is used to determine the dimensions of the core and the changes in density between different layers inside the Earth.

DID YOU KNOW?

Other examples of mechanical waves include vibrations on strings and springs. These vibrations are used in musical instruments.

KEY WORDS

focus *the underground point of origin of an earthquake*

tsunamis *huge water waves on the open sea often caused by earthquakes*

P-waves (primary or pressure) *a type of longitudinal seismic wave that can travel through the solid and liquid parts of the Earth's structure*

S-waves (secondary or shear) *a type of transverse seismic wave that can only travel through the solid parts of the Earth's structure*

triangulation *using measurements from three positions to work out an exact point*

Summary

In this section you have learnt that:

- The amplitude of a wave is the maximum displacement from the equilibrium position.
- The wavelength of a wave is the minimum distance from two identical points on adjacent waves (e.g. peak to peak).
- The frequency of a wave is the number of waves passing a given point per second.
- The time period of a wave is the time taken for one complete wave to pass a given point.
- Mechanical waves are waves that comprise a series of vibrations of matter.
- Examples of mechanical waves include water waves, sound waves and seismic waves.
- Electromagnetic waves comprise vibrations of electric and magnetic fields. No particles are required and so electromagnetic waves can travel through a vacuum.
- Electromagnetic waves form a family of waves called the electromagnetic spectrum.

Review questions

1. Define the terms amplitude, wavelength, frequency and time period.
2. Make a scale drawing of a wave with amplitude 2 cm and wavelength 8 cm. Mark the amplitude and the wavelength.
3. Look at the wave shown in Figure 8.28. What are the values of its amplitude and wavelength?

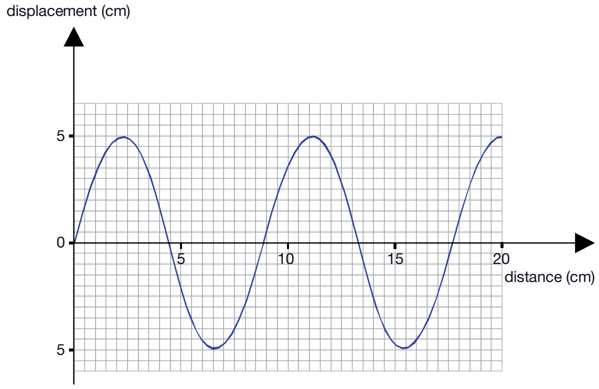


Figure 8.28

4. Look at the wave shown in Figure 8.29. What are the values of its amplitude and period?

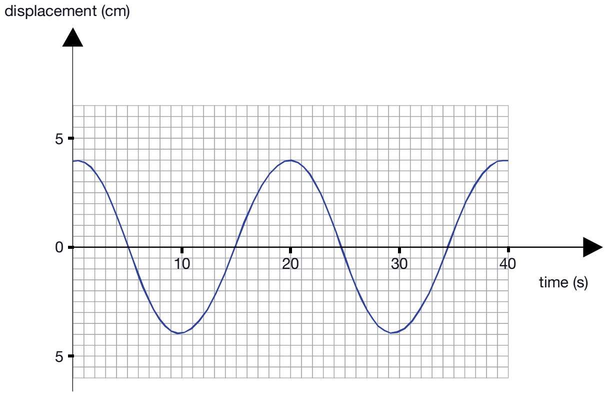


Figure 8.29

5. A wave has a frequency of 400 Hz. What is its period? Give your answer in seconds and milliseconds.
6. A wave has a period of 20 μs (microseconds). What is its frequency?
7. Describe an electromagnetic wave.
8. Describe the similarities and differences between P-waves and S-waves.

8.3 Properties of waves

By the end of this section you should be able to:

- State the wave equation and use it to solve problems.
- Describe the characteristic properties of waves, including reflection, refraction, diffraction and interference.
- Define the terms diffraction and interference.

The wave equation

We met the wave equation back in Section 8.2.

wave speed = frequency × wavelength

$v = f\lambda$

v = wave speed in m/s.

f = frequency in Hz.

λ = wavelength in m.

This equation can't be derived in the traditional sense but it is more a case of working it through logically from the definitions of v, f and λ.

If a wave has a frequency of 10 Hz it will produce 10 waves per second. If the wavelength of each wave is 2 m then it follows logically that the train of waves created in one second would be 20 m long.

KEY WORDS

diffraction *the spreading out of waves when they pass through a gap or around an obstacle*

interference *when two or more waves pass through the same point and combine to either add up or cancel each other out*

reflection *when waves bounce off a fixed surface and change direction*

refraction *when waves change speed as they travel from one medium to another and hence change direction*

wave fronts *lines used to represent wave crests*

This is the distance travelled by the wave in one second, or the wave speed.

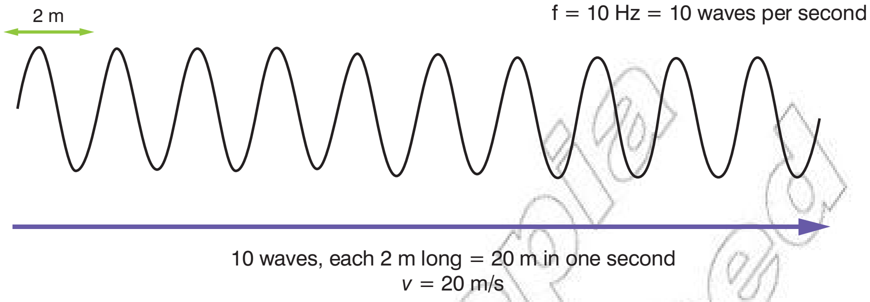


Figure 8.30 *Showing how* $v = f\lambda$

For example, if a wave has a wavelength of 3 cm and a frequency of 11 kHz its speed can be determined:

$v = f\lambda$ *State principle or equation to be used (the wave equation)*

$v = 11\,000 \text{ Hz} \times 0.03 \text{ m}$ *Substitute in known values and complete calculation*

$v = 330 \text{ m/s}$ *Clearly state the answer with unit*

Notice that wavelength must be in m and frequency in Hz.

Worked example

The two students in Figure 8.31 measure the waves passing the end of a pier. They measure the wavelength as 5 m and there were nine waves passing the pier per minute. To calculate the wave speed we must first determine the frequency. Nine waves in one minute means nine waves in 60 seconds so:

9 / 60 = 0.15 waves per second, so the frequency is 0.15 Hz.

We can now use the standard wave equation:

$v = f\lambda$ *State principle or equation to be used (the wave equation)*

$v = 0.15 \text{ Hz} \times 5 \text{ m}$ *Substitute in known values and complete calculation*

$v = 0.75 \text{ m/s}$ *Clearly state the answer with unit*

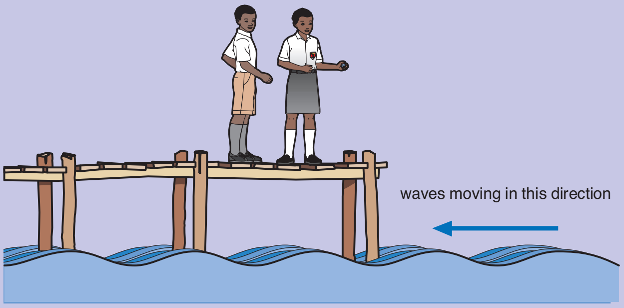


Figure 8.31 *These students are calculating the speed of the waves as they pass the pier*

Activity 8.7: Using the wave equation

Complete the following table:

Wave speed (m/s)	Frequency (Hz)	Wavelength (m)	Time period (s)
	400	2	
360		4.5	
1200			0.005

The wave equation may be also applied to electromagnetic waves, in which case the equation changes slightly to:

$c = f\lambda$

c = speed of light in a vacuum (3×10^8 m/s).

Worked example

A water wave travels at a speed of 80 m/s with a wavelength of 20 m. Calculate the time period of the wave.

In order to find the time period we must first find the frequency of the wave:

$v = f\lambda$ *State principle or equation to be used (the wave equation)*

$f = v / \lambda$ *Rearrange equation to make f the subject*

$f = 80\ \text{m/s} / 20\ \text{m}$ *Substitute in known values and complete calculation*

$f = 4\ \text{Hz}$ *Clearly state the answer with unit*

Time period is the reciprocal of the frequency so:

$T = 1 / f$ *State principle or equation to be used*

$T = 1 / 4\ \text{Hz}$ *Substitute in known values and complete calculation*

$T = 0.25\ \text{s}$ *Clearly state the answer with unit*

Worked example

A radio station transmits at a frequency of 97.0 MHz. Calculate its wavelength.

$c = f\lambda$ *State principle or equation to be used (the wave equation applied to electromagnetic waves)*

$\lambda = c / f$ *Rearrange equation to make λ the subject*

In this case the frequency is 97.0 MHz or 97 million Hz.

$\lambda = 3 \times 10^8\ \text{m/s} / 97 \times 10^6\ \text{Hz}$ *Substitute in known values and complete calculation*

$\lambda = 3.1\ \text{m}$. *Clearly state the answer with unit*

Wave behaviour

All types of wave exhibit certain behaviour; they exhibit **reflection**, **refraction**, **diffraction** and **interference**.

Reflection

Reflection occurs when a wave reaches a fixed surface. The wave cannot pass through the surface; instead, it reflects off it, so that its direction changes. Figure 8.32 shows what happens when circular ripples in a ripple tank reflect off a straight barrier.

- The ripples spread out as circles from the source.
- After they have reflected from the barrier, they are still circular. They continue to spread out but they are travelling in the opposite direction.

In a picture like Figure 8.32, we are looking down on the ripples from above. We see the pattern of the wave crests; if we draw lines to represent these crests, we call them **wave fronts**. Figure 8.33 shows straight wave fronts reflecting off a straight barrier that is at an angle. The barrier is at 45° to the ripples arriving from the left; the reflected ripples have been reflected through 90°.

Figure 8.33 helps us to understand the first law of reflection of light – the angle of incidence equals the angle of reflection.

How are waves affected by a curved reflector? At each point on the surface of a curved reflector, the waves obey the law of reflection; that is, they reflect as if the surface at that point was flat.

Figure 8.34(a) shows the effect when plane (flat) ripples reach a concave reflector. The ripples are reflected inwards so that they converge at a point (we say that they are focused by the reflector).

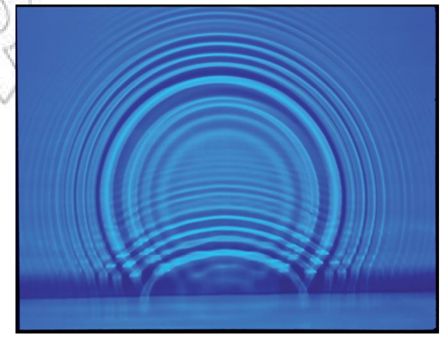


Figure 8.32 *Ripples in a ripple tank reflect off a straight barrier*

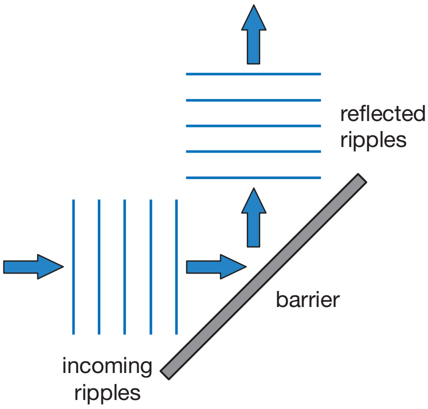


Figure 8.33 *The lines are called wave fronts; here they are reflecting off a straight barrier*

Figure 8.34(b) shows how ripples are affected by a convex reflector; in this case, the straight ripples are reflected so that they become curved. They take the form of circular ripples spreading out as though they were coming from a point on the other side of the barrier.

Figure 8.34(a) also tells us how circular ripples will be affected by a concave reflector. If they start from the focus of the reflector, they will be reflected so that they become straight ripples. (To see this, simply reverse the arrows in the diagram.)

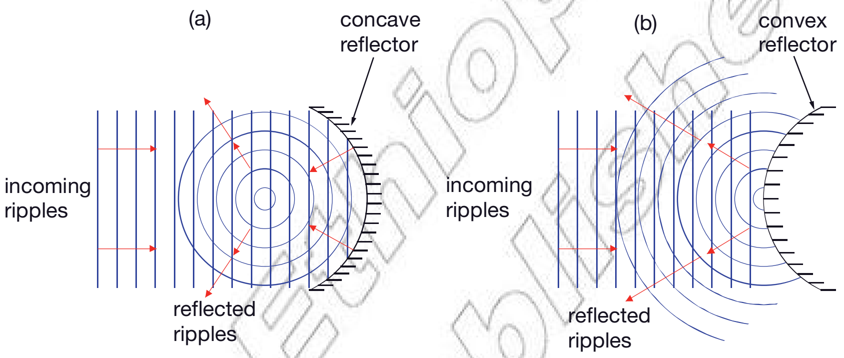


Figure 8.34 Showing how plane ripples are reflected by (a) a concave reflector; (b) a convex reflector

Refraction

The word *refraction* means *breaking*. Refraction is a property of all waves (light, sound, etc.). It happens when waves change speed as they move from one material to another.

Refraction can be shown using a ripple tank. Ripples travel more slowly in shallower water than in deeper water, because they drag on the bottom. A shallow area can be created in the tank by placing a sheet of glass in the tank; typically, the water is 8 mm deep, but only 3 mm deep above the glass.

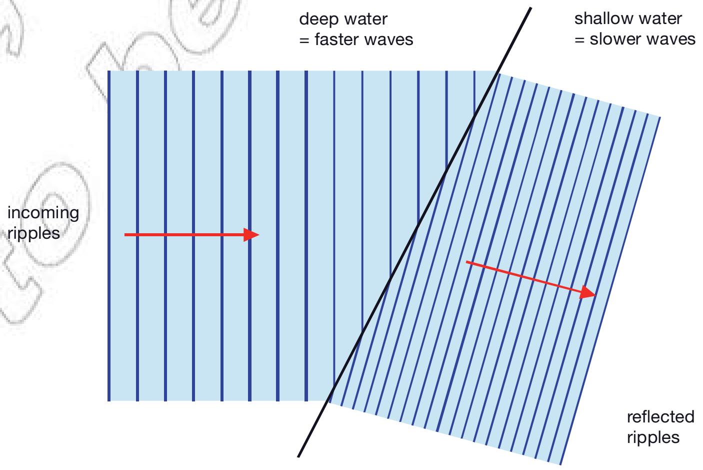


Figure 8.35 Wave fronts change direction when their speed changes

Figure 8.35 shows the pattern that results when the boundary between the deep and shallow water is at an angle to the wave fronts. Things to notice:

- The ripples change direction as they enter the shallower water.
- The ripples are closer together in the shallower water – their wavelength has decreased.

You will learn more about refraction of light in Grade 10.

Introduction to diffraction and interference

Diffraction and **interference** are behaviours totally unique to waves. Essentially diffraction is the spreading out of waves when they travel through gaps or around obstacles, whereas interference is when two waves pass through each other and either add up or cancel each other out.

Diffraction

Imagine you are sitting in a room. The door is open, and you can hear music coming from the radio in the next room. You cannot see the radio, but the sound waves it produces pass through the door and spread out into the room you are in. This spreading out is an example of a wave phenomenon called diffraction.

Diffraction occurs when a wave passes the edge of an obstacle, or through a gap. It can be investigated using a ripple tank. Figure 8.36 shows what happens when ripples reach a barrier with a gap in it. From the photographs you can see the following:

- The ripples spread out into the space beyond the gap.
- The narrow gap has more effect than the wide one – there is more spreading out with the narrower gap.

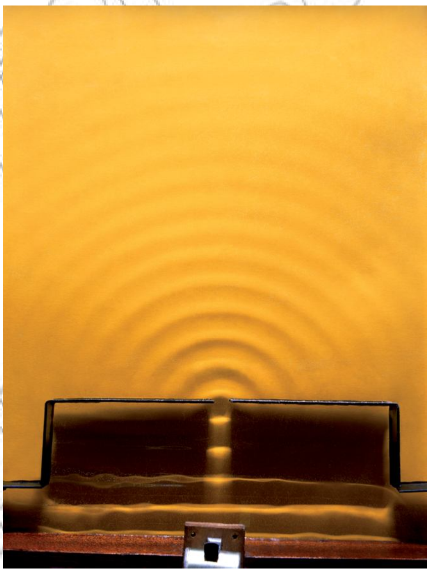
The effect of diffraction is greatest when the width of the gap is the same as the wavelength of the waves, as in Figure 8.36(a). A bigger gap has less effect.

Why do we not notice diffraction of light? The wavelength of light is very short – less than one-millionth of a metre. This means that a very tiny gap is needed to diffract light – light waves will not be noticeably diffracted as they pass through a doorway. In fact, light is diffracted by very small gaps or obstacles. Figure 8.37 shows the Moon hidden behind a church spire. The photo was taken at a time when there were many tiny grains of pollen in the atmosphere, and the light from the Moon is being diffracted by these, causing a 'halo' around it. The size of the pollen grains is similar to the wavelength of light.

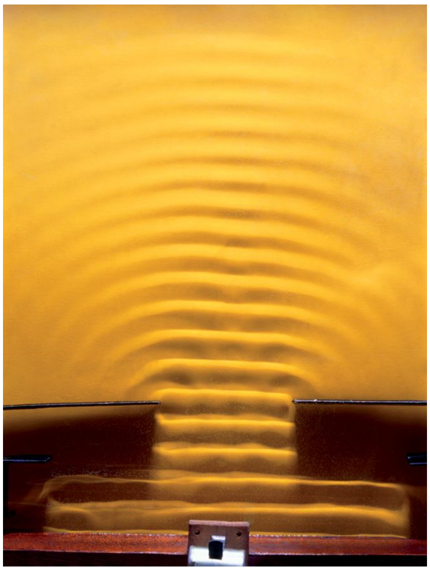
Activity 8.8: Observing diffraction of light

Grains of talcum powder are very small – similar to the wavelength of light. They can diffract light to form a pattern like the halo shown in Figure 8.37.

- Find two glass microscope slides.
- Sprinkle a very little talcum powder on one slide. Press the second slide on top of the first, and slide it around to give a thin film of powder between the two slides.
- Hold the double slide close to your eye and look at it through a distant lamp. Can you see a diffraction halo around the lamp?



(a)



(b)

Figure 8.36 *Diffraction of ripples as they pass through a gap in a ripple tank; the gap in (a) is similar in size to the wavelength of the ripples; in (b) it is much bigger.*

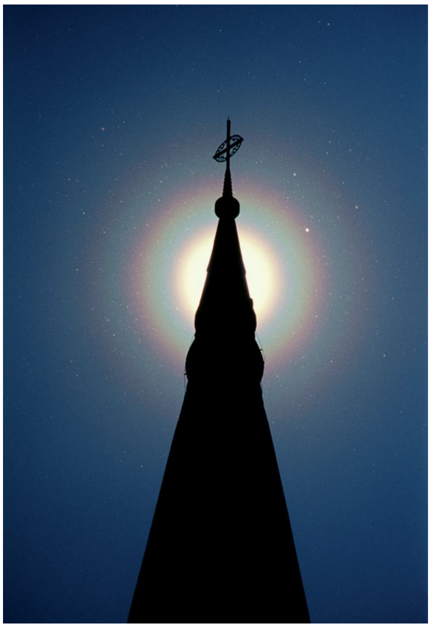


Figure 8.37 You may have seen a 'halo' like this around the Moon, or around the Sun at sunset. It is caused by tiny pollen grains or water droplets in the air, diffracting the light

Interference

What happens when two waves meet? A strange feature of waves is that they pass straight through each other. Here is an example with two sets of light waves. Switch on two torches (flashlights). Direct their beams so that they cross over. The light waves from one torch pass straight through the light waves from the other. If light was made of particles, they would bounce off each other.

Now we need to think about what happens at the point where the paths of the two sets of waves cross.

Constructive and destructive interference

To observe **interference**, we need two sets of waves. Figure 8.38 shows that there are two kinds of interference:

- If the two waves are in phase (in step) with each other, they combine to make a bigger wave, with twice the amplitude. This is called **constructive interference**.
- If the two waves are out of phase with each other, they cancel each other, so that there is no wave. This is called **destructive interference**.

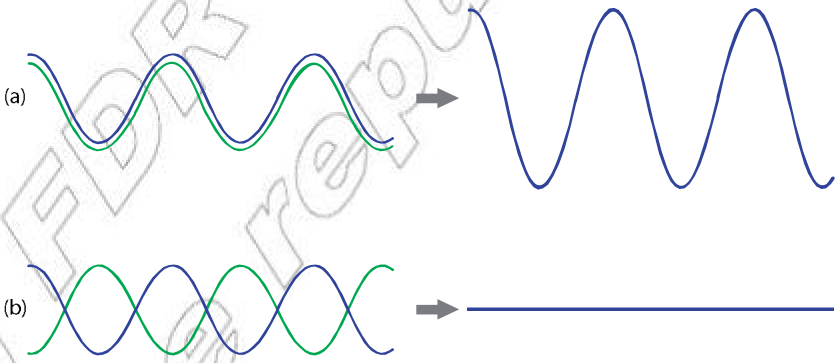


Figure 8.38 *Two waves can interfere (a) constructively, or (b) destructively*

Note that the two sets of waves must have exactly the same wavelength (and frequency) if they are to interfere like this. Also, their amplitudes should be the same if they are going to cancel exactly.

It is difficult to see interference with light. One example is the coloured patterns you see where there is a thin film of oil on a puddle of water, or if you look at the shiny surface of a compact disc (CD). Where you see a bright red colour, for example, red light waves are reflecting off the surfaces of the oil or CD and interfering constructively to produce a bright colour. Different colours interfere at different angles to produce the pattern.

Interference of ripples

A ripple tank can show the interference patterns produced when two sets of ripples meet. There are two ways to do this:

- Use two vibrating dippers to produce two sets of circular ripples. Where the ripples overlap, they produce a characteristic pattern (Figure 8.39). At some points, the ripples add together (interfere constructively) to produce a large effect. In between, they cancel out so that the surface of the water is unperturbed.
- Alternatively, use a straight vibrating source to produce parallel ripples. Direct these at a barrier with two gaps; the ripples pass through the gaps and diffract into the space beyond. Here, they overlap to produce an interference pattern similar to the one shown in the photograph.

Figure 8.39 *The two vibrating balls produce sets of ripples that overlap with each other to produce an interference pattern. At the top of the photo you can clearly see regions where the ripples are cancelling out (destructive interference). In between are regions of constructive interference*

KEY WORDS

constructive interference
where two waves are in phase with each other and combine to make a bigger wave

destructive interference
where two waves are out of phase with each other and combine to cancel each other out

Summary

In this section you learnt that:

- The wave equation is $v = f\lambda$.
- When waves bounce off a surface, this is called reflection.
- When waves travel from one medium to another, their speed may change and so they may bend. This is called refraction.
- Diffraction is the spreading out of waves when they pass through a gap or around an obstacle.
- Interference is when two or more waves pass through the same point and either add up or cancel each other out.

Review questions

1. A guitarist plays a high note; its frequency is 2000 Hz. The sound waves produced have a wavelength of 0.17 m. What is the speed of sound in air?
2. A drummer plays a note with a frequency of 85 Hz. What is the wavelength of this sound wave in air? (Speed of sound in air = 340 m s^{-1}.)
3. A radio station broadcasts an FM signal with a wavelength of 2.85 m. If the speed of radio waves is 3×10^8 m s^{-1}, what is the frequency of the FM signal?
4. Explain the terms reflection, refraction, diffraction and interference.

KEY WORDS

longitudinal mechanical waves *waves comprising vibrations in matter where the vibrations are parallel to the direction of wave motion*

audible range *the range of sound frequencies that can be detected by the ear*

ear drums *membranes in the ear that vibrate when a sound wave enters the ear canal*

Activity 8.9: To show that sound is caused by vibration

- Stretch a piece of elastic and pluck it. Note the way it moves.
- Press one end of a ruler down on a table. Twang the free end.
- Strike the prongs of a tuning fork against a rubber stopper; note how they move backwards and forwards. Let one of the prongs touch a table-tennis ball hanging on a thread. The ball moves. Touch the still surface of water with the moving prongs; ripples spread out across the surface.

Table 8.2 *Vibrations in musical instruments*

Instrument	Vibration
Drums	Drum skin
Piano	Strings
Guitar, violin, etc.	Strings and body of instrument
Trumpet and trombone	Lips (causing the air inside to vibrate)

8.4 Sound waves

By the end of this section you should be able to:

- Identify sound waves as longitudinal mechanical waves and describe how the waves are produced and how they propagate.
- Compare the speed of sound in different materials and determine the speed of sound in air at a given temperature.
- Define the intensity of a sound wave and solve problems using the intensity formula.
- Explain the meaning of the terms echo, reverberation, pitch, loudness and quality.
- Explain the reflection and refraction of sound and describe some applications.

Sound waves are **longitudinal mechanical waves**. Sound waves are produced whenever an object vibrates. When you speak your vocal cords in your throat vibrate as the air is pushed over them. Different musical instruments produce sound by making a part of the instrument vibrate.

As sound waves are mechanical waves they require a medium to travel through. Sound obviously travels through air but it also travel through other gases, as well as solids and liquids. Importantly, sound cannot travel through a vacuum.

Activity 8.10: To find whether sound can pass through a vacuum

- Hang an electric bell by cotton thread from the stopper of a bell jar (Figure 8.40). Make the bell ring. Place the jar on the plate of an exhaust pump. Can you hear the sound?
- Pump air out of the bell jar, letting the bell ring all the time inside the jar. What do you observe about the sound?
- Let air enter the bell jar again. What happens?

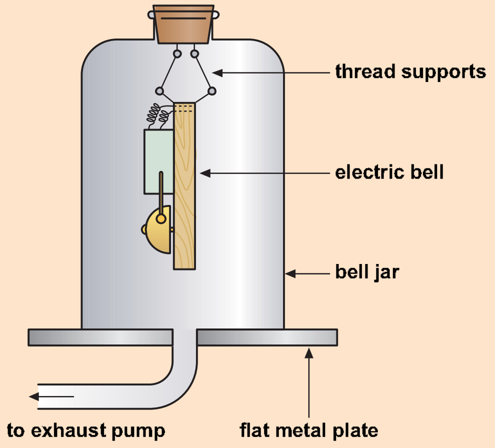


Figure 8.40 *Can sound pass through a vacuum?*

It is important to realise that sound waves are longitudinal. We often see pictures of sound waves looking like transverse waves. Remember, this is because a graph of particle displacement against distance or time for both transverse and longitudinal waves looks like Figure 8.41.

Sound waves are a series of compressions and rarefactions and we can see this by conducting a very simple experiment.

If you place a candle in front of a speaker and then play sounds through the speaker (ideally just one tone) you will see the candle flame wobble from side to side.

This shows that the vibrations are parallel to the direction of wave motion. In fact if you think about how the speaker produces the sound then it is even more obvious.

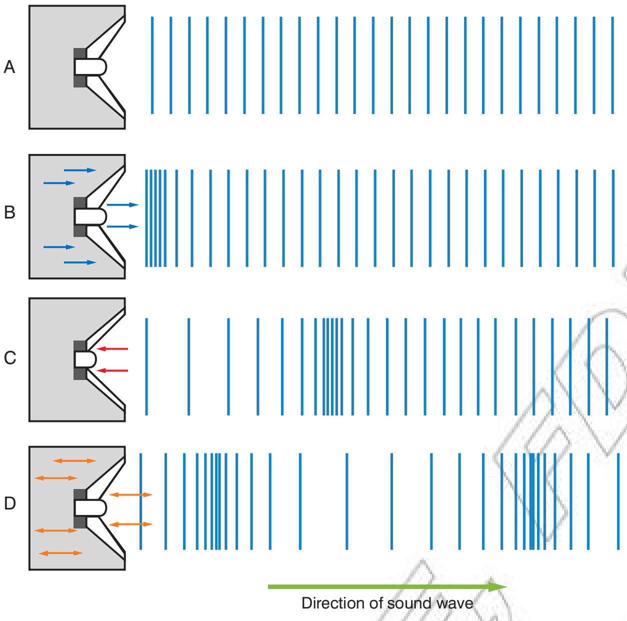


Figure 8.43 *How a speaker produces a sound wave*

If you look closely at a speaker you will see the speaker cone moving in and out. As it moves out it creates an area of higher pressure as it compresses the air (B). The cone then moves back in and so creates an area of lower pressure, and so a rarefaction (C). This process continues, creating a longitudinal wave (D).

Hearing

When these vibrations reach our ears they travel down our ear canal and make our **ear drums** vibrate. These vibrations are transmitted to special cells inside your skull, which send a signal to your brain that we interpret as sound.

When we are young we can detect a range of frequencies from around 20 Hz to 20 000 Hz. This is referred to as our **audible range**.

This varies from person to person and factors such as age and exposure to loud music dramatically changes this range. Table 8.3 on the next page shows the audible range of several other animals.

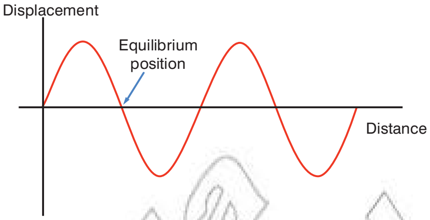


Figure 8.41 *Displacement against distance*

Activity 8.11: Sound travels through many substances

- A string telephone:

  Join the bottoms of two empty tin cans with string. Speak into one tin while a friend listens with the other tin. Keep the string tight so that it presses against the metal. Can sound pass through a string?
- Lay a ticking watch or clock at one end of a table. Now place one ear against the table, at the other end. Can you hear the ticking? Does sound travel better through wood than through air?
- Clap your hands when swimming under water. Can you hear the sound easily? This might be tricky and so it helps if you have a partner who can clap while you swim!

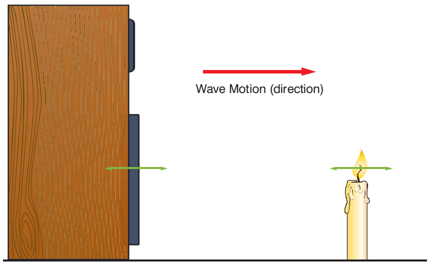


Figure 8.42 *Demonstrating sound waves are longitudinal*

Think about this...

To help remember the audible range of humans think of 20:20 vision. This is often used to represent good eyesight. Well, humans also have 20:20 hearing, that is 20 Hz to 20 kHz!

Figure 8.44 *Different animals have different audible ranges.*

Table 8.3 *Different audible ranges*

Animal	Approximate audible range (Hz)
Human	20–20 000
Bat	10–200 000
Dog	15–40 000
Dolphin	120–110 000

DID YOU KNOW?

Elephants can detect very low frequency sound waves. This is used for long-distance communication between herds. Due to its low frequency it has a range of around 10 km.

The speed of sound

The speed of sound through air is around 340 m/s; this is around 900 000 times slower than light, but still pretty fast.

In storms thunder and lightning occur at the same time. However, the light travels much faster than the sound. This means we always see the flash of lightning before the sound of thunder arrives. The greater the time delay, the further away the storm.

In fact if we assume the light arrives without any real delay, then for every second between the lightning and the thunder the storm is around 300 m away.

Activity 8.12: Investigating the range of hearing

A signal generator connected to a loudspeaker can produce sounds of a known frequency (Figure 8.45).

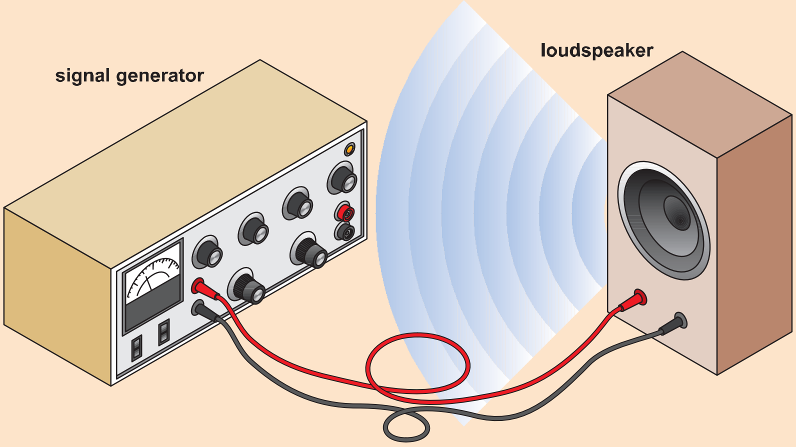


Figure 8.45 *Turning the dial on the signal generator changes the frequency of the sound from the loudspeaker.*

- Listen as the frequency becomes higher and higher. At what frequency does it become inaudible?
- Repeat as the frequency is reduced.
- Imagine that someone in your class claims to be able to hear frequencies that are higher than you can hear. How could you check that they are telling the truth?
- It is said that younger people can hear higher notes than older people. How could you test this idea?

Sound travels at different speeds through different materials. The speed of sound through water is around five times faster than in air and in metals like iron it is faster still (around 15 times).

Table 8.4 *Speed of sound in different materials*

Medium	Speed of sound (m/s)
Dry air at 0°C	331
Dry air at 30°C	349
Moist tropical air	351
Water at 20°C	1484
Seawater at 15°C	1510
Wood	3850
Iron, steel	5000
Glass	5000

In general, the denser the material, the faster the speed of sound. This is because the particles in the medium are closer together and so the vibrations pass from particle to particle much quicker.

When sound waves travel through gases, things are a little more complex due to the motion of the particles. The density of the gas has an effect, and if two gases were at the same temperature then sound would travel faster through the denser gas. However, the temperature of the gas has a significant effect.

When a gas is at a higher temperature the average kinetic energy of the particles is higher. This means on average the particles are moving faster (see Unit 7). The faster the particles are moving, the faster the speed of sound through the gas. This can be seen in Table 8.5.

As air gets warmer the speed of sound through it increases. The speed of sound through any gas may be calculated using the equation below:

- $v = \sqrt{(\gamma R^* T)}$

γ = the adiabatic index of the gas (a constant for the gas). For air, this equals 1.4.

R^* = another constant for the gas. It equals the molar gas constant / the molar mass (R / M). For air. this is 286 m^2/s^2 K.

T = the temperature in K.

For air, this can be simplified to:

- $v = \sqrt{(kT)}$

where $k = \gamma \times R^* = 1.4 \times 286\ m^2/s^2\ K = 400\ m^2/s^2\ K$ and so:

- $v = \sqrt{(400 \times T)}$

At 25 °C the speed of sound through air may be calculated using this equation:

- $v = \sqrt{(400 \times T)}$

Figure 8.46 *A storm*

Activity 8.13: Thunder and lightning

A clap of thunder arrives five seconds after the lightning. How far away is the storm? What would happen to the time delay if the storm were moving towards you?

Table 8.5 *Speed of sound in air*

Air temperature (°C)	Speed (m/s)
–20	319
–10	325
0	331
10	337
20	343
30	349

DID YOU KNOW?

Mach numbers (named after the Austrian physicist Ernst Mach) are often used to quantify the speed of fast moving aircraft. Mach 1 represents the speed of sound, Mach 2 twice the speed of sound, etc. Aircraft travelling at speeds greater than Mach 1 are flying faster than the speed of sound and are said to be supersonic.

Figure 8.47 *Modern jet fighters are able to travel much faster than the speed of sound.*

Remember, the temperature must be in K not °C. So, 25 °C = 298 K

- $v = \sqrt{(400 \times 298 \text{ K})}$
- $v = 345$ m/s

A simple way to determine the speed of sound is to measure the time it takes for a sound wave to travel a known distance.

Activity 8.14: Measuring the speed of sound using echoes

- Stand facing a tall wall, at a distance of about 100 m (Figure 8.48). Measure the distance to the wall.
- Clap two blocks of wood together, and listen to the echo. The time interval is too short to measure accurately.
- Now clap the blocks together so that each clap coincides with the echo of the previous one. Using a stopwatch, time a sequence of 10 claps. (Count 0, 1, 2, 3 … 9, 10.)
- Now you know the time taken for the sound to travel to the wall and back ten times. Use this information to calculate the speed of sound in air.

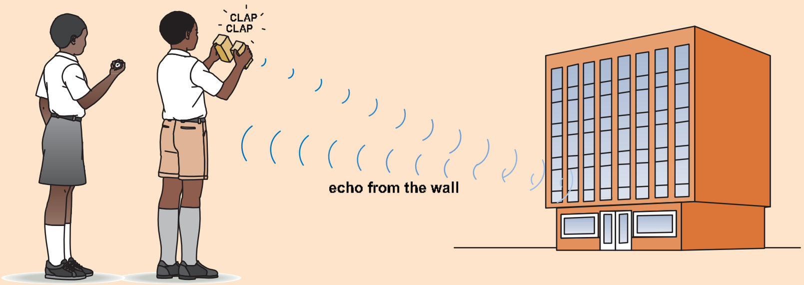


Figure 8.48 *Using echoes to measure the speed of sound*

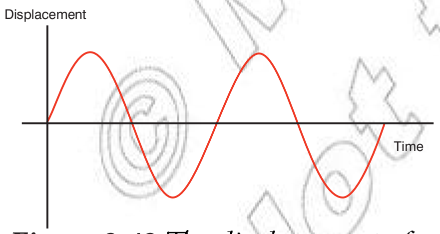


Figure 8.49 *The displacement of air particles against time*

How do we describe sound waves?

What is the difference between louder and quieter sounds? Or higher pitch and lower pitch sounds? And why does the same note sound different from a violin to a piano? In order to answer these questions we need to be able to observe what is going on in terms of the particles.

Sound waves are longitudinal mechanical waves, but we can use an oscilloscope and microphone to help ‘see’ sound waves. An oscilloscope produces a trace on the screen that varies depending on the sound entering the microphone. It is essentially a trace of the displacement of the particles against time.

Using an oscilloscope we can see the effect of changing volume and pitch.

Loudness

The **loudness** of a sound depends on the amplitude of the sound wave. The greater the amplitude, the louder the sound.

In louder sounds the particles move further from their equilibrium position.

The loudness of a sound is measured in decibels (or dB). This is a complex scale. It is logarithmic not a linear scale. In other words 40 dB is much more than twice as loud as 20 dB.

Table 8.6 The loudness of different sounds

Sound	Loudness (decibels)
Whisper	10
Leaves rustling in the wind	17
Shouting	70
Loud music	100
Jet engine	120

Pitch

The **pitch** of a sound depends on the frequency of the sound wave. The higher the frequency of the sound waves the higher their pitch.

In higher pitch sounds the particles vibrate more often past their equilibrium position per second.

Timbre (quality)

The same note played on different instruments sounds distinctly different. This difference is referred to the **timbre** (or quality) of the sound. Quality does not mean good or bad, it just refers to the difference in the sound.

You can see from Figure 8.53 above that the same note produces a different trace on the oscilloscope. This is because of the complex nature of the number of different vibrations produced by the instrument.

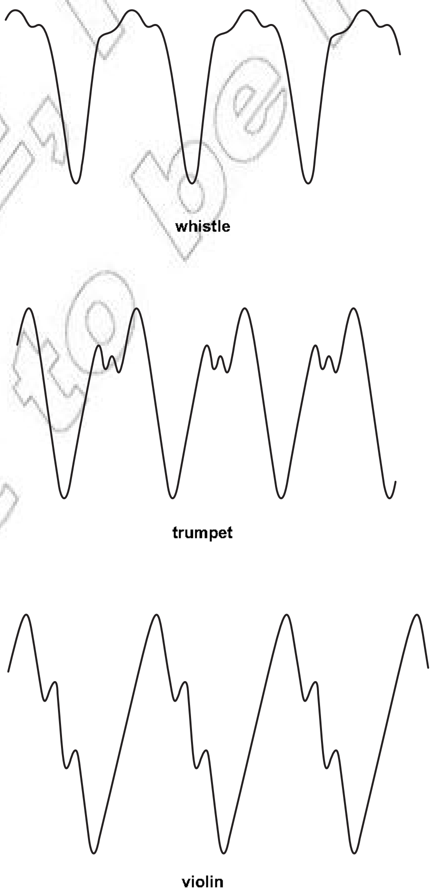


Figure 8.53 The same note produced by different instruments

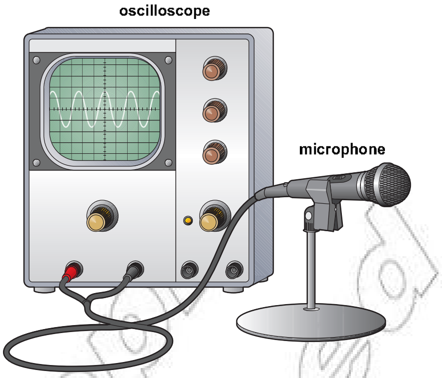


Figure 8.50 A simple oscilloscope

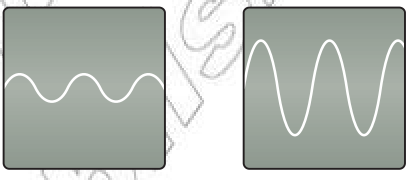


Figure 8.51 The difference between a loud sound and a quiet sound

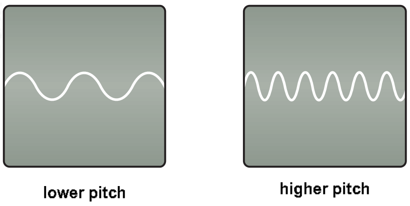


Figure 8.52 The difference between a low pitch sound and a high pitch sound

KEY WORDS

loudness the audible strength of a sound, which depends on the amplitude of the sound wave

pitch highness or lowness of a sound, which depends on the frequency of the sound wave

timbre the quality of a sound

__Figure 8.54__ Different instruments produce different quality notes.

Activity 8.15: Sounds on a scope

- Connect a signal generator to an oscilloscope and to a loudspeaker. Watch how the trace on the scope changes as the controls of the signal generator are altered.
- The sound is made louder: how does the trace change?
- The frequency is made higher: how does the trace change?
- Connect a microphone to the oscilloscope, in place of the signal generator. Make different sounds in front of the microphone and observe the traces. (Try clapping, whistling, playing an instrument.)

__Figure 8.55__ It is important to reduce the echo in recording studios.

Echoes, echoes, echoes, echoes....

Sound, like all waves, is able to reflect off surfaces. A reflection of sound is called an **echo**.

You get the best echoes off solid surfaces, like metal sheets or stone. Softer surfaces tend to absorb the sound waves and so there are reflected less. You might have noticed this inside a cave or inside a building with solid stone walls.

If the sound produced is in an enclosed space it may produce a number of echoes. It sounds like the sound is building up then slowly decaying away. This is called **reverberation**.

This is most noticeable when the source of sound stops but the reflections continue. Each time they reflect off the surface they lose some energy and so the amplitude decreases and the sound becomes quieter.

DID YOU KNOW?

"A duck's quack doesn't echo" is a much-quoted scientific myth. The truth is that a duck's quack does, it's just quite hard to hear due to the shape of the sound wave produced.

The intensity of sound waves

The further the source of sound is away from you the quieter the sound. This is because the energy is spread out over a much wider area.

This happens with all waves. If you look closely at the ripples on a pond you can see the amplitude of the wave decreases as you get further away from the source.

__Figure 8.56__ The ripples get smaller as the energy is spread out.

The **intensity** of any wave is defined as the energy received by each square metre per second. A higher intensity would mean more energy per second falling on each square metre.

- **Intensity is equal to the energy incident on each square metre of a surface per second.**

This gives us units of intensity as W/m^2, we use W as this is just energy per second.

The further away the surface the more the energy gets spread out and so the intensity falls. Imagine standing near a wall and shouting at it (I know it sounds odd!). The sound spreads out as it leaves your mouth and strikes an area of the wall.

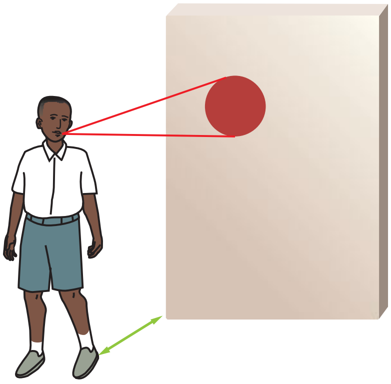


Figure 8.57 *Stand close to a wall and the intensity is higher.*

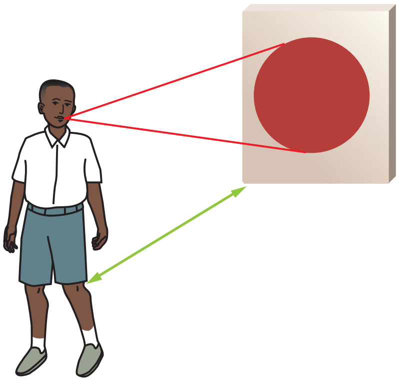


Figure 8.58 *Stand further away and the intensity drops.*

KEY WORDS

echo *a reflection of a sound wave*

intensity *the energy received by each square metre of a surface per second*

reverberation *multiple reflection of sound waves in an enclosed space so that the sound continues after the source is cut off*

inverse square *relationship where if one variable increases by a factor of x^2 then the other decreases by a factor of x^2*

However, if you stand further away the sound has to travel a greater distance before it strikes the wall and so it spreads out to cover a wider area.

The intensity is now lower as the energy per second per square metre has dropped – it's more spread out.

In all cases the intensity of a wave can be determined using the equation below.

- intensity = power /area

If we think about the sound travelling out in all directions (in 3D) from a source we can see that the energy spreads out in the shape of a sphere. So in this case the area is the surface area of a sphere (given by $4\pi r^2$). This means the equation becomes:

- intensity = power /area
- $I = P / 4\pi r^2$

From this equation we can see that if the wave travels twice as far then the intensity falls to a quarter of its value. Three times as far and it is a ninth. This is because the energy is spread over a much larger area, double the distance and it's four times the area, as shown in Figure 8.59.

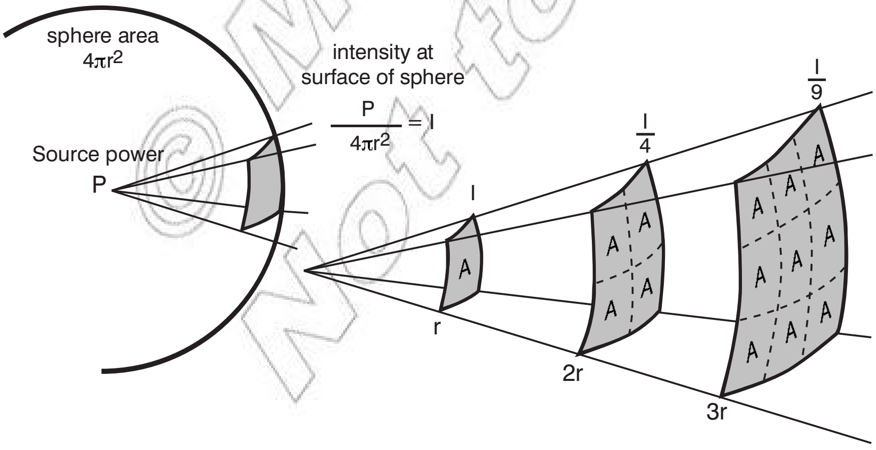


Figure 8.59 *Intensity against distance*

This kind of relationship is called an **inverse square** relationship. As the distance goes up by a factor of x, the intensity falls by x^2. This produces a graph like that in Figure 8.60 on the next page.

Think about this…

Sound waves speed up as they enter denser materials; this means when they refract they bend towards normal unlike light (which slows down in denser materials).

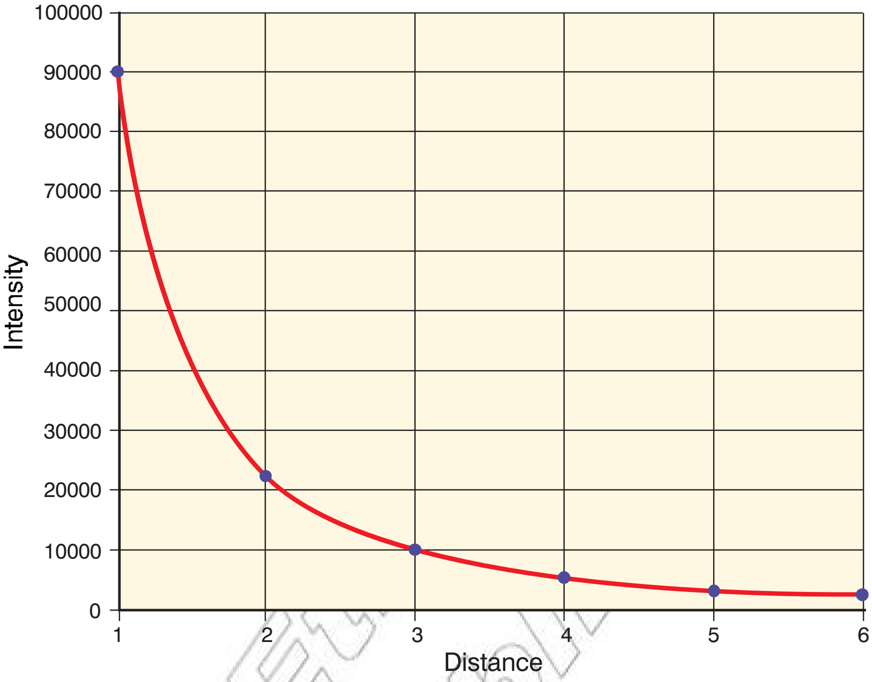


Figure 8.60 *A graph showing how intensity varies with distance from source.*

You will come across a number of inverse square relationships in the next few years.

KEY WORDS

ultrasound *high frequency sound waves, above human hearing*

hydrophones *underwater microphones*

Worked example

A speaker has a power output of 150 W. Determine the intensity of the sound 1.5 m from the speaker.

$I = P / 4\pi r^2$ *State principle or equation to be used (intensity for a point source)*

$I = 150\text{ W} / 4\pi \times (1.5\text{ m})^2$ *Substitute in known values and complete calculation*

$I = 5.3\text{ W/m}^2$ *Clearly state the answer with unit*

The intensity of a sound wave is measured to be 0.7 W/m^2 when 2.0 m from the source. Calculate the power of the source.

$I = P / 4\pi r^2$ *State principle or equation to be used (intensity for a point source)*

$P = I \times 4\pi r^2$ *Rearrange equation to make P the subject*

$P = 0.7\text{ W/m}^2 \times 4\pi \times (2.0\text{ m})^2$ *Substitute in known values and complete calculation*

$P = 35\text{ W}$ *Clearly state the answer with unit*

Uses of sound waves

Sound waves have many uses, in addition to the obvious uses in communication and music.

Most of these uses depend on the behaviour of the sound waves when they **reflect** or **refract**. Sound, like all waves, reflects off surfaces, but sound waves also reflect off the boundary between materials if there is a change in density between the materials. The greater this change in density the greater the amount of sound reflected.

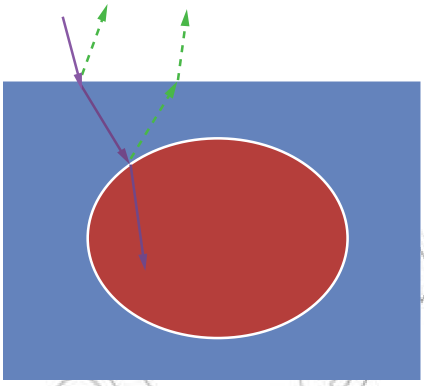


Figure 8.61 The reflection and refraction of sound through different materials

In Figure 8.61, sound waves refract as they enter a medium with a different density (the red area). You can also see the sound waves reflect off the boundary between the materials (the green arrows).

It is these reflections and refractions that can tell us a great deal about the object and so make sound very useful indeed.

In fact for most uses **ultrasound** is used instead. Ultrasound is just sound waves with a high frequency and so a relatively short wavelength. This means it does not diffract very much and so it remains as a tight focused beam.

Ultrasound is any sound above the audible range of humans. It can be defined as:

- **Sound waves with a high frequency, above human hearing, above 20 kHz.**

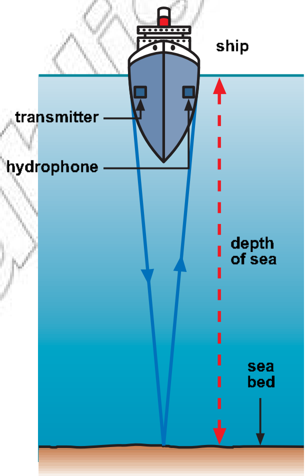


Figure 8.62 Using SONAR to determine the depth of the sea

One example of the use of sound is SONAR. This stands for SOund Navigation And Ranging, which is the sound wave equivalent of radar. It is most often used by ships to determine the depth of the sea bed, the location of a shoal of fish, or even the position of an enemy submarine.

Sound is transmitted by the ship and it travels through the water. It reflects off the sea bed and travels back up where it is detected by special underwater microphones called **hydrophones**.

It is then a relatively simple process to determine the distance travelled by the sound using distance = speed of sound through water × time taken. The depth is then half this distance as the sound has had to travel there and back!

Ultrasound is also used in pre-natal scanning. Here the ultrasound travels into the womb and reflects off the unborn baby. This sound is harmless (unlike using X-rays) and allows doctors to monitor the progress of the developing baby.

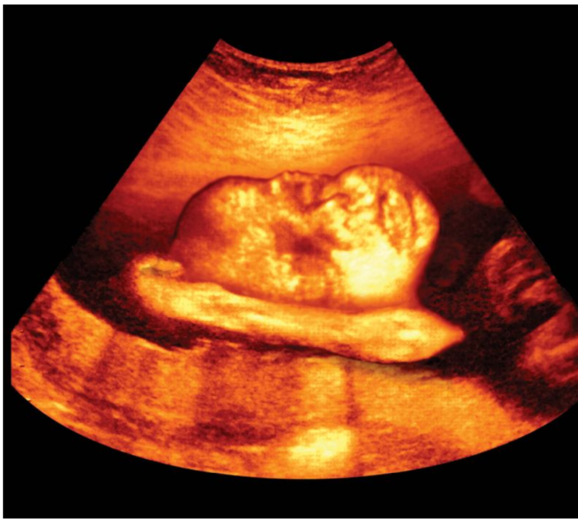


Figure 8.63 Using ultrasound to monitor a baby

Ultrasound is also used to detect flaws in metals and even to help people park their cars! In each case it is the reflection and refraction of the sound that makes the job possible.

Activity 8.16: Depth sounding

The speed of sound through sea water is around 1500 m/s. A wave pulse is sent from a ship and takes 0.7 s to return. Calculate the depth of the water.

Summary

- Sound waves are mechanical longitudinal waves produced when objects vibrate.
- Sound waves travel through different media as a series of compressions and rarefactions.
- In general, sound travels faster in denser materials; however, the warmer the gas the faster the speed of sound through it.
- The amplitude of a sound wave affects its loudness and the frequency of the sound wave its pitch.
- A reflection of sound is called an echo and if several echoes are trapped inside a room or object a reverberation may be heard.
- The intensity of a sound wave is the energy received per square metre of a surface per second.
- Sound has many uses including SONAR and pre-natal scanning. Both rely on the sound waves reflecting and refracting off different materials.

Review questions

1. Compare the speed of sound through the different materials in the Table 8.4 (speed of sound through materials). Explain the differences in the speed of sound:
   a) between solids, liquids and gases
   b) between warm air and cold air.
2. Explain the meaning of the terms loudness, pitch and timbre. Illustrate your explanations with diagrams and examples.
3. A speaker produces a sound output at a power of 500 W. Determine the intensity at:
   a) 2.0 m
   b) 4.0 m
   c) 16 m
4. The intensity of a sound source is measured 3.0 m from the source and it found to be 4.0 W/m^2. Calculate the intensity received at:
   a) 1.0 m
   b) 5.0 m
5. Describe one possible use of sound waves.

End of unit questions

1. a) In which type of wave are the vibrations at right angles to the direction of travel?
   b) What is the name given to the other type of wave?
   c) Describe the vibrations in this type of wave.
   d) Give an example of each type of wave.
   e) Describe how you would demonstrate each type of wave using a slinky spring.
2. Complete the table and draw the following waves to scale:

Wave speed (m/s)	Frequency (Hz)	Wavelength (m)	Time period (s)	Amplitude (m)
720	45			8.0
40			0.05	4.0
	6000	0.002		3.0

3. An electromagnetic wave has a wavelength of 10 nm. Calculate its frequency and identify to which part of the electromagnetic spectrum the wave belongs.
4. What wave phenomena are described here?
   a) A light wave slows down as it passes from air into water; this causes it to change direction.
   b) Waves on the sea pass between two high walls into a harbour. They spread out into the space behind the walls.
   c) Two alarm sirens are emitting a loud note; at points between the two sirens the sound is very loud, but at other points it is much fainter.
   d) An explorer shouts into a dark cave; a fraction of a second later, he hears the sound of his own voice.
5. Draw diagrams to illustrate the difference between constructive and destructive interference.
6. Two identical waves of amplitude 5 cm meet in a large ripple tank. What will be the amplitude of the combined wave at a point where they interfere constructively? And where they interfere destructively?
7. Explain why, if someone is playing a guitar in the next room, you may be able to hear the sound of the guitar through the open doorway, although you cannot see the guitarist because she is round the corner.
8. What is meant by an echo?
9. A child claps her hands together whilst facing a tall building. The echo reaches her ears after 0.6 s. How far is she from the building? (Speed of sound in air = 340 m s^{-1}.)

10. Outline a method of finding the velocity of sound in air.
11. In an experiment to measure the speed of sound in a steel rod, it is found that a sound will travel along a rod of length 2 m in a time of 0.000 4 s. What is the speed of sound in steel?
12. Explain why a flash of lightning is usually seen before the clap of thunder is heard.
13. A ship is sailing in a part of the sea where the bed is 600 m below the ship. The ship uses sonar to detect the seabed. How long will it take a pulse of sound to travel to the seabed and return to the ship? (Speed of sound in water = 1500 m s^{-1}.)