9 Properties of mechanical waves

9.1 Overview

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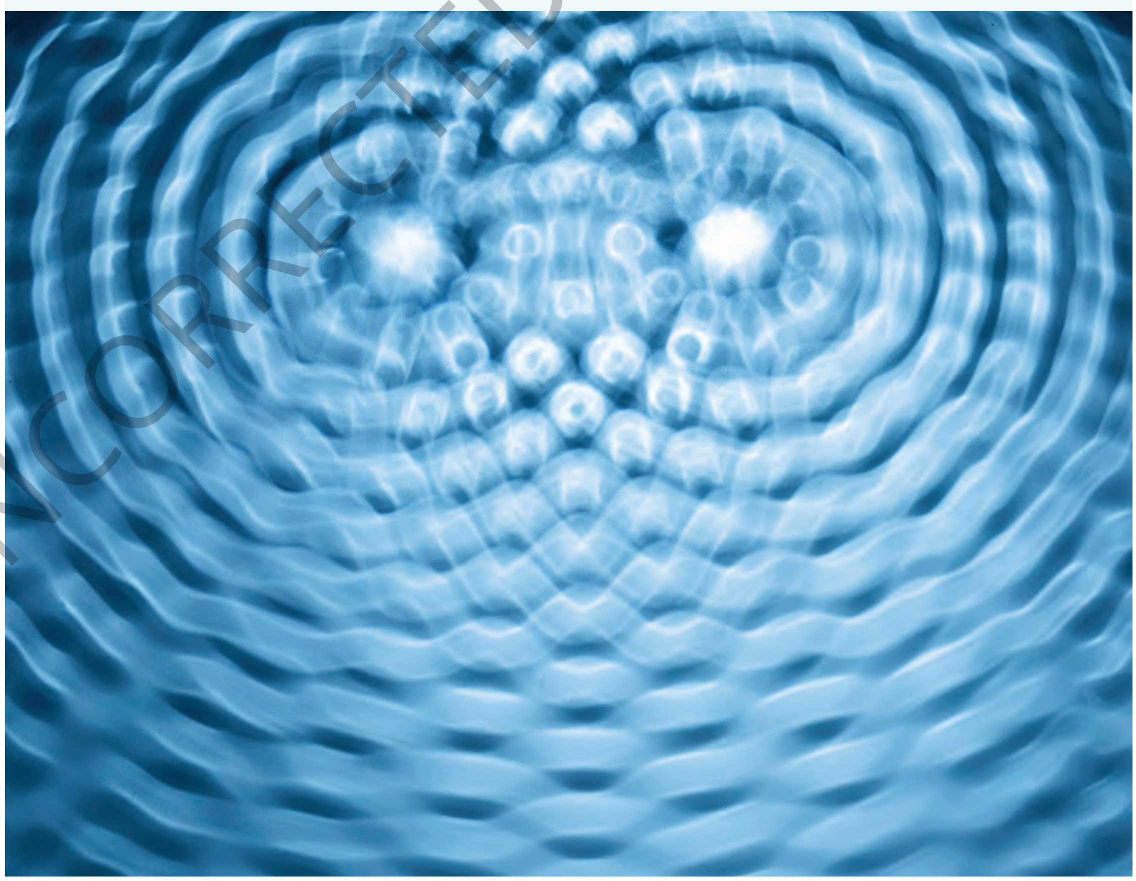
9.1.1 Introduction

In unit 3 we learned that Newton's laws of motion and kinematics, with minor corrections described by Einstein's Theory of Special Relativity along with the theory of fields, explains a great deal of the natural world. Examples include collisions between cars, orbiting planets, the forces acting on charged particles in electric and magnetic fields, and the transfer of energy from one circuit to another circuit using a transformer, to name but a few. Yet there is another common phenomenon — the behaviour of waves. Consider the ripple of waves on the surface of water, waves on a string such as a guitar, the propagation of sound through a medium, and the properties of light.

FIGURE 9.1 The study of waves reveals many important concepts in physics.



Waves can also transfer energy from one place to another. They seem to travel or propagate at a fixed speed in a medium regardless of the energy they contain. Waves have a tendency to spread out in all directions, unlike a beam of particles. Waves can pass through each other: they don't collide with each other in the same way particles collide; instead, they combine and interfere. In short, waves do things that particles can't, and particles do things that waves can't.

Waves can diffract, interfere, propagate through a medium, reflect and refract. They have a frequency, a wavelength and amplitude. All these new words need to be understood in order to appreciate and explain the behaviour of waves and their interactions with other waves. We'll see in unit 4 that we need both a wave and a particle model to better understand natural phenomena.

9.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic, you will be able to:

- explain a wave as the transmission of energy through a medium without the net transfer of matter
- distinguish between transverse and longitudinal waves
- identify the amplitude, wavelength, period and frequency of waves
- calculate the wavelength, frequency, period and speed of travel of waves using: $v = f\lambda = \frac{\lambda}{T}$
- explain qualitatively the Doppler effect
- explain resonance as the superposition of a travelling wave and its reflection, and with reference to a forced oscillation matching the natural frequency of vibration
- analyse the formation of standing waves in strings fixed at one or both ends
- investigate and analyse theoretically and practically constructive and destructive interference from two sources with reference to coherent waves and path difference: $n\lambda$ and $\left(n - \frac{1}{2}\right)\lambda$ respectively

PRACTICAL WORK AND INVESTIGATIONS

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

on Resources

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

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9.2 Waves — energy transfer without matter transfer

KEY CONCEPTS

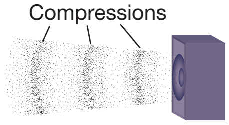
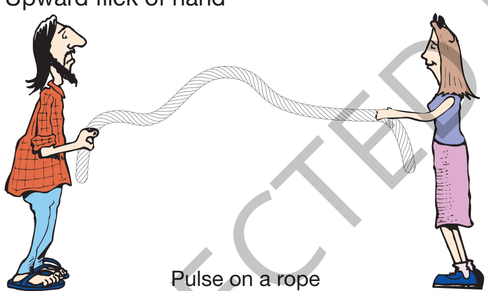
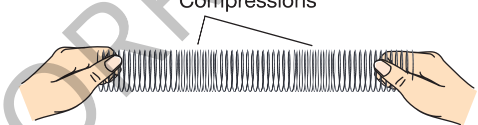
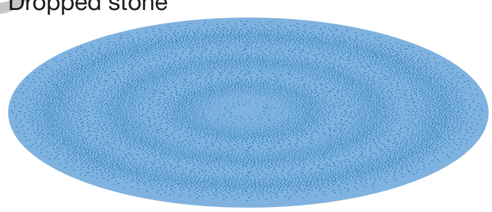
- explain a wave as the transmission of energy through a medium without the net transfer of matter
- distinguish between transverse and longitudinal waves

A **wave** is a disturbance that travels through a medium from the source to the detector without any movement of matter. Particles of the matter vibrate up and down or back and forth about their rest position, transferring energy from one place to another. Waves therefore transfer energy without any net movement of particles. **Periodic waves** are disturbances that repeat themselves at regular intervals. Periodic waves propagate by the disturbance in part of a medium being passed on to other parts of the medium. In this way, the disturbance travels but the medium stays where it is.

Looking at the examples in table 9.1, two different types of waves can be identified. For the pulse on the rope and the ripples on the water surface, the disturbance is at right angles to the direction the wave is travelling. These types of waves are called **transverse waves**.

In the examples of the sound wave travelling through air and the compression moving along the spring, the disturbance is parallel to the direction the wave is travelling. These types of waves are called **longitudinal waves**.

TABLE 9.1 Some examples of waves

Wave	Source	Medium	Detector	Disturbance	Type
Sound	Push/pull of loudspeaker  	Air	Ear	Increase and decrease in air pressure	Longitudinal
Rope	Upward flick of hand  Pulse on a rope	Rope	Person at other end	Section of rope is lifted and falls back	Transverse
Stretched spring	Push of hand  Compressions moving along a stretched spring	Coils in the spring	Person at other end	Bunching of coils	Longitudinal
Water	Dropped stone  Ripples on water	Water	Bobbing cork	Water surface is lifted and drops back	Transverse

9.2 EXERCISE

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1. (a) How is a periodic wave different from a single pulse moving along a rope?
   (b) How is a periodic longitudinal wave different from a transverse wave?
2. Ripples on a pond are caused when drops of water fall on the surface at the rate of 5 drops every 10 seconds. Calculate the following:
   (a) the period of the ripples
   (b) the frequency of the ripples
   (c) the type of wave generated when drops of water fall onto the surface of a pond.
3. What is the speed of sound in air if it travels a distance of 996 m in 3.0 s?

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9.3 Properties of waves

KEY CONCEPTS

- identify the amplitude, wavelength, period and frequency of waves
- calculate the wavelength, frequency, period and speed of travel of waves using: $v = f\lambda = \frac{\lambda}{T}$
- explain qualitatively the Doppler effect

9.3.1 Wavelength, frequency and speed

The **frequency** of a periodic wave is the number of times that it repeats itself every second. Frequency is measured in hertz (Hz) and 1 Hz = 1 s^{-1}. Frequency can be represented by the symbol f.

The **period** of a periodic wave is the time it takes a source to produce a complete wave. This is the same as the time taken for a complete wave to pass a given point. The period is measured in seconds and is represented by the symbol T.

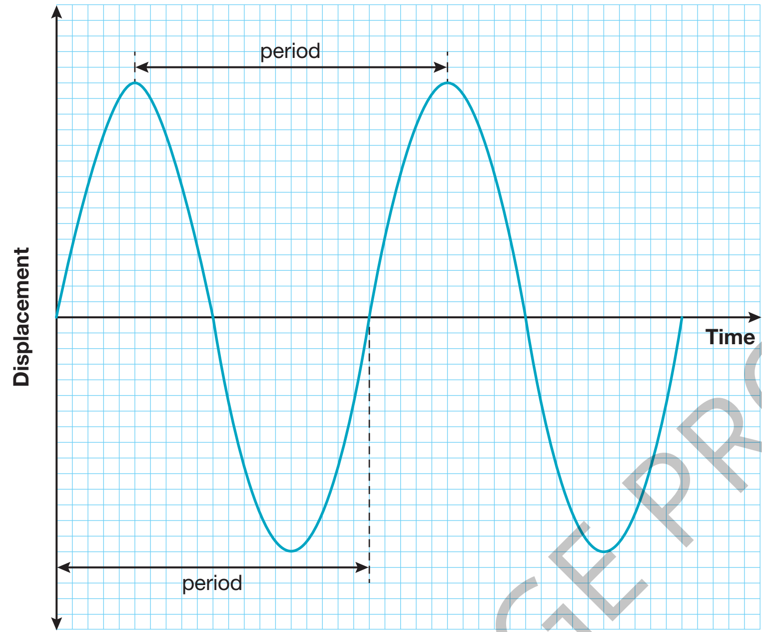
The period of a wave is the reciprocal of its frequency. For example, if five complete waves pass every second, that is, f = 5.0 Hz, then the period (the time for one complete wavelength to pass) is $\frac{1}{5.0} = 0.2$ seconds. In other words,

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

where f is the frequency of the wave
T is the period of the wave.

A displacement–time graph, as shown in figure 9.2, tracks the movement of a single point on a transverse wave over time as the wave moves through that point. In other words, it shows how the displacement of a single point on the wave varies over time. The period of the wave can be easily identified from this graph.

FIGURE 9.2 Displacement–time graphs: the movement of a single point on a transverse wave over time

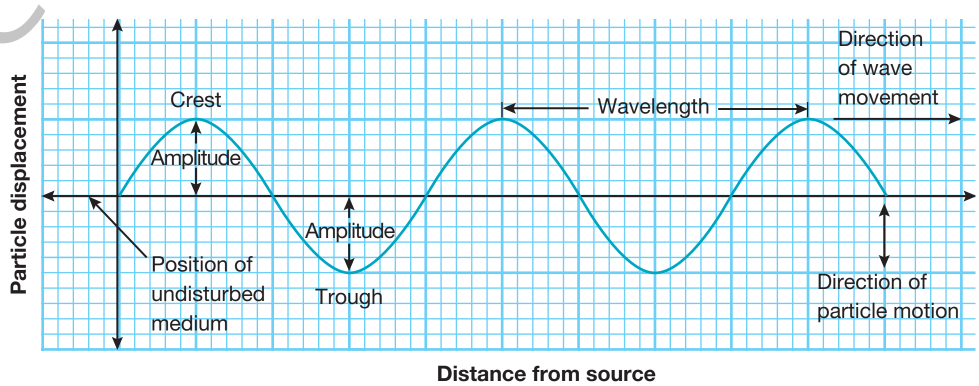


The **amplitude** of a wave is the size of the maximum disturbance of the medium from its normal state. The units of amplitude vary from wave type to wave type. For example, in sound waves the amplitude is measured in the units of pressure, whereas the amplitude of a water wave would normally be measured in centimetres or metres.

The **wavelength** is the distance between successive corresponding parts of a periodic wave. The wavelength is also the distance travelled by a periodic wave during a time interval of one period. For transverse periodic waves, the wavelength is equal to the distance between successive crests (or troughs). For longitudinal periodic waves, the wavelength is equal to the distance between two successive compressions (regions where particles are closest together) or rarefactions (regions where particles are furthest apart). Wavelength is represented by the symbol λ (lambda).

The displacement of all particles along the length of a transverse wave can be represented in a displacement–distance graph as shown in figure 9.3. A displacement–distance graph is like a snapshot of the wave at any time. The amplitude and wavelength of the wave can be easily identified from this graph.

FIGURE 9.3 Displacement–distance graphs: particle displacements along a transverse wave



The speed, v, of a periodic wave is related to the frequency and period. In a time interval of one period, T, the wave travels a distance of one wavelength, λ. Thus:

$$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{\lambda}{T} = \frac{\lambda}{\frac{1}{f}} = f\lambda$$

This relationship can be written as:

$$v = f\lambda$$

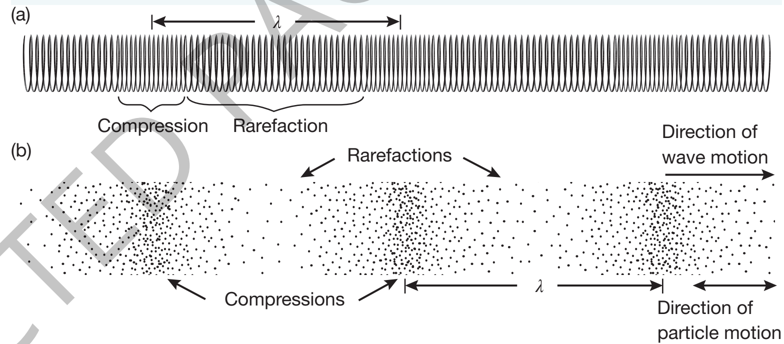
where v is the speed of the wave
f is the frequency of the wave
λ is the wavelength of the wave.

This relationship, $v = f\,\lambda$, is sometimes referred to as the universal wave equation.

The frequency of a periodic wave is determined by the source of the wave. The speed of a periodic wave is determined by the medium through which it is travelling. Because the wavelength is a measure of how far a wave travels during a period, if it can't be measured, it can be calculated using the formula $\lambda = \frac{v}{f}$.

In a longitudinal wave, as opposed to a transverse wave, the oscillations are parallel to the direction the wave is moving. Longitudinal waves can be set up in a slinky, as shown in figure 9.4a. Sound waves in air are also longitudinal waves, as shown in figure 9.4b. They are produced as a vibrating object (such as the arm of a tuning fork) first squashes the air, then pulls back to create a partial vacuum into which the air spreads.

FIGURE 9.4 Longitudinal waves in (a) a slinky (b) air



Longitudinal waves cause the medium to bunch up in places and to spread out in others. **Compressions** are regions in the medium where the particles are closer together. Referring to sound waves in air, compressions are regions where the air has a slightly increased pressure, as a result of the particles being closer together. **Rarefactions** are regions in the medium where the particles are spread out. This results in a slight decrease in air pressure in the case of sound waves.

The wavelength, λ, for longitudinal waves is the distance between the centres of adjacent compressions (or rarefactions). The amplitude of a sound wave in air is the maximum variation of air pressure from normal air pressure.

SAMPLE PROBLEM 1

What is the speed of a sound wave if it has a period of 2.0 ms and a wavelength of 68 cm?

Teacher-led video: SP1 (eles-XXXX)

THINK	WRITE
1. Note down the known variables in their appropriate units. Time must be expressed in seconds and length in metres.	$T = 2.0\text{ ms}$ $= 2.0 \times 10^{-3}\text{ s}$ $\lambda = 68\text{ cm}$ $= 0.68\text{ m}$

2. Choose the appropriate formula.

$$v = f\lambda$$
$$\Rightarrow v = \frac{\lambda}{T}$$

3. Substitute values for the wavelength and period and then solve.

$$v = \frac{0.68\ \text{m}}{2.0 \times 10^{-3}\ \text{s}}$$
$$= 340\ \text{m s}^{-1}$$

PRACTICE PROBLEM 1

What is the speed of a sound wave if it has a period of 1.5 ms and a wavelength of 51 cm?

SAMPLE PROBLEM 2

What is the wavelength of a sound of frequency 550 Hz if the speed of sound in air is 335 m s^{-1}?

Teacher-led video: SP2 (eles-XXXX)

THINK	WRITE
1. Note down the known variables in their appropriate units. Frequency must be expressed in Hertz and speed in m s^{-1}.	$f = 550$ Hz, $v = 335$ m s^{-1}
2. Choose the appropriate formula.	$v = f\lambda$ $\Rightarrow v = \frac{\lambda}{T}$
3. Substitute values for the frequency and speed and then solve.	$= \frac{335\ \text{m s}^{-1}}{550\ \text{Hz}}$ $= 0.609$ m

PRACTICE PROBLEM 2

A siren produces a sound wave with a frequency of 587 Hz. Calculate the speed of sound if the wavelength of the sound is 0.571 m.

9.3.2 The Doppler effect

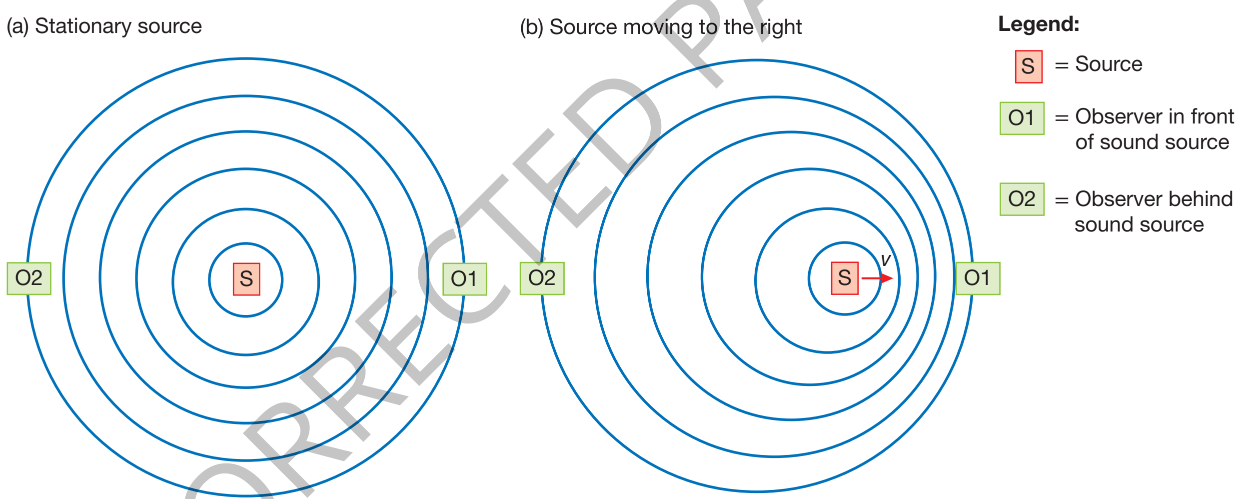
We are all familiar with the change in pitch of sound made by a car when it passes us. This is most pronounced when an emergency vehicle races by. Think of the sounds people make when mimicking passing racing cars. The sound always starts high but finishes low. This effect is called the Doppler effect, after Christian Andreas Doppler, who predicted it in 1842 before it had been observed. The Doppler effect is the result of a wave travelling at a constant speed through a medium while the source is in motion relative to the medium or if an observer is in motion relative to the medium. In either case, the frequency of the source will be different from the frequency as measured by an observer. It is the red-shift of light from distant galaxies that provides the very strong evidence for the hypothesis that the universe is expanding.

Consider a fire-engine racing to attend a fire. While it is stuck in traffic with its siren blaring, a physics student decides to measure the frequency and wavelength of the sound. The fire-engine's siren alternates between a high-pitched sound and a low-pitched sound. The student measures the high-pitched sound to have a frequency of 500 Hz and the low-pitched sound to have a frequency of 200 Hz. After determining the speed of sound to be 340 m s^{-1}, and noticing that there is no wind, the student calculates the wavelengths using $v = f\lambda$:

$$\begin{aligned}\lambda &= \frac{v}{f}\\ &= \frac{340\text{ m s}^{-1}}{500\text{ Hz}}\\ &= 0.680\text{ m for the }500\text{ Hz sound}\end{aligned}$$

$$\begin{aligned}\lambda &= \frac{v}{f}\\ &= \frac{340\text{ m s}^{-1}}{200\text{ Hz}}\\ &= 1.70\text{ m for the }200\text{ Hz sound}\end{aligned}$$

FIGURE 9.5 The Doppler effect, (a) O1 and O2 both hear the same frequency sound. (b) O1 hears a higher frequency than O2**.**



Later, the traffic jam has cleared and another fire-engine passes the physics student. The fire-engine travels at a velocity of 24 m s^{-1} relative to the road (and air). The speed of sound remains at 340 m s^{-1} through the air. The fire-engine is identical to the first one, but now the student measures the frequencies to be 538 Hz and 215 Hz as the fire-engine approaches, and 467 Hz and 187 Hz as the fire-engine moves away. The student's frequency-measuring equipment is not faulty — the student could clearly hear the pitch drop as the fire-engine passed. When the air is still, something approaching a listener will sound higher in pitch than when it is at rest relative to the listener, and will sound lower in pitch when it is moving away. Doppler cleverly predicted this result before the advent of fast fire-engines. His prediction was first confirmed experimentally by having a trumpeter play a note while passing on a 'relatively' fast-moving train.

The sound produced by the siren of the fire-engine is a series of pressure variations in the air. When the fire-engine produces a compression (region of higher than average air pressure) of the high-frequency sound, this compression moves forward at the speed of sound in air, $340\,\text{m s}^{-1}$. The next compression is produced T seconds later, where T is the period of the sound wave.

$$\begin{aligned} T &= \frac{1}{f} \\ &= \frac{1}{500\,\text{Hz}} = 0.002\,\text{s} \end{aligned}$$

At 0.002 s, the first compression has travelled the following distance:

$$\begin{aligned} d &= vt \\ &= 340\,\text{m s}^{-1} \times 0.002\,\text{s} = 0.68\,\text{m} \end{aligned}$$

In this time, the fire-engine has moved:

$$\begin{aligned} d &= vt \\ &= 24\,\text{m s}^{-1} \times 0.002\,\text{s} = 0.048\,\text{m} \end{aligned}$$

The distance between compressions is therefore:

$$\begin{aligned} \lambda &= 0.68\,\text{m} - 0.048\,\text{m} \\ &= 0.632\,\text{m} \end{aligned}$$

For the fire-engine that was stationary, the wavelength was 0.68 m. As sound is travelling at $340\,\text{m s}^{-1}$ relative to the student on the roadside, and $v = f\lambda$, the shorter wavelength from the approaching fire-engine will have a higher frequency than the stationary fire-engine. In this case, the detected frequency would be:

$$\begin{aligned} f &= \frac{v}{\lambda} \\ &= \frac{340\,\text{m s}^{-1}}{0.632\,\text{m}} = 538\,\text{Hz} \end{aligned}$$

measured by the student for the 500 Hz sound as the fire-engine approached at $24\,\text{m s}^{-1}$.

In summary, when a source of waves is approaching an observer, the frequency appears to be greater than the source frequency. When the source of waves is receding from the observer, the frequency appears to be smaller than the source frequency. Likewise, if an observer is approaching a stationary source, the frequency appears higher and, if the observer is receding from the stationary source, the frequency appears lower. The equations for calculating these changes in frequency due to motion of a source and observer relative to a medium are not examinable.

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Weblink Doppler effect applet

9.3 EXERCISE

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1. How far does a periodic wave travel in one period? Give your answer in terms of the wavelength of the periodic wave.
2. Do loud sounds travel faster than soft sounds? Justify your answer.
3. A marching band on the other side of a sports oval appears to be 'out of step' with the music. Explain why this might happen.
4. You arrive late to an outdoor concert and have to sit 500 m from the stage. Will you hear high-frequency sounds at the same time as low-frequency sounds if they are played simultaneously? Explain your answer.
5. A loudspeaker is producing a note of 256 Hz. How long does it take for 200 wavelengths to interact with your ear?
6. What is the wavelength of a sound that has a speed of 340 $m\,s^{-1}$ and a period of 3.0 ms?
7. What is the speed of a sound if the wavelength is 1.32 m and the period is 4.0×10^{-3} s?
8. The speed of sound in air is 340 $m\,s^{-1}$ and a note is produced that has a frequency of 256 Hz.
   (a) What is its wavelength?
   (b) This same note is now produced in water where the speed of sound is $1.50 \times 10^3\ m\,s^{-1}$. What is the new wavelength of the note?
9. Copy and complete the following table by using the wave formula.

v ($m\,s^{-1}$)	f (Hz)	λ (m)
	500	0.67
	12	25
1500		0.30
60		2.5
340	1000	
260	440	

10. A stationary siren is producing a sound. The siren vibrates at 100 Hz to make the sound. One observer measures the sound to have a frequency of 110 Hz. A second observer measures the sound to have a frequency of only 90 Hz. Explain why this is the case.

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9.4 Diffraction of waves

BACKGROUND KNOWLEDGE

- Investigate and describe theoretically and practically the effects of varying the width of a gap or diameter of an obstacle on the diffraction pattern produced by waves

Waves spread out as they pass around objects or travel through gaps in barriers. This is readily observable in sound and water waves. For example, you can hear someone speaking in the next room if the door is open, even though there is not a direct straight line between the person and your ears.

Diffraction is the directional spread of waves as they pass through gaps or pass around objects. The amount of diffraction depends on two factors: (i) the wavelength of the wave λ and (ii) the width of the gap or the size of the obstacle, for which we will use w as the variable.

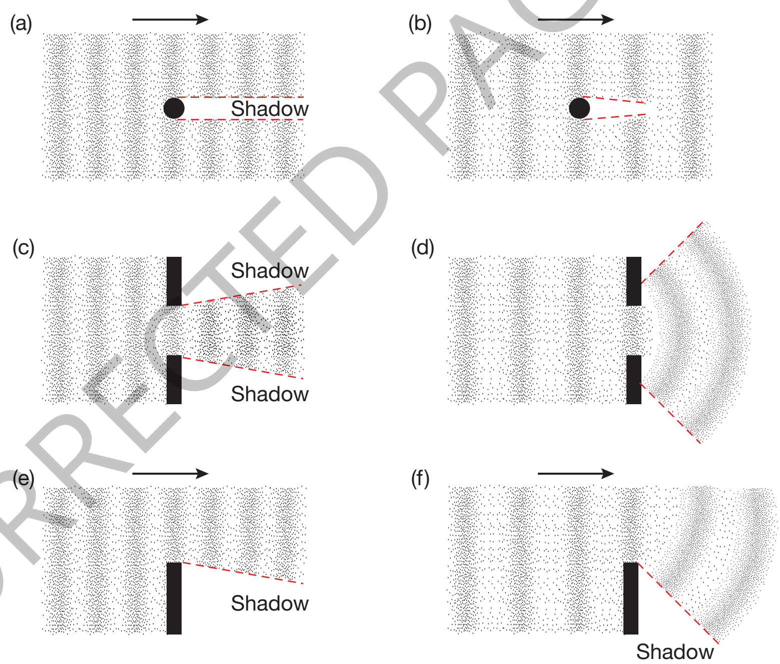
For example, the spreading out of sound from loudspeakers is the result of diffraction. The sound waves spread out as they are generated by the speaker cone of the loudspeaker. Without the effects of diffraction, hardly any sound would be heard other than from directly in front of the speaker cone. In this case, w is associated with the diameter of the speaker cone.

9.4.1 Varying the wavelength and gap width

The diffraction of sound, and indeed light, can be modelled with water waves in a ripple tank. Figure 9.6 shows the way that water waves diffract in various situations. The diagrams apply equally well to the diffraction of sound waves and light.

Importantly, the larger the wavelength λ (in figures 9.6b, d and f), the larger or more significant the amount of diffraction.

FIGURE 9.6 Diffraction of water waves: (a) short wavelength around an object, (b) long wavelength around the same object, (c) short wavelength through a gap, (d) long wavelength through the same gap, (e) short wavelength around the edge of a barrier and (f) long wavelength around the edge of the same barrier

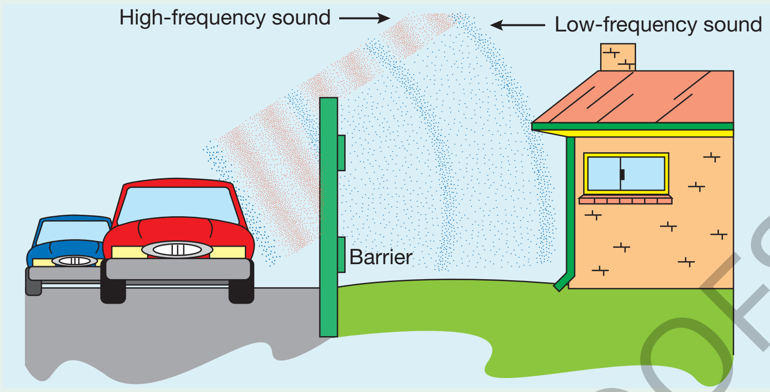


The region where waves don't travel is called a shadow. The amount of diffraction that occurs depends on the wavelength of the waves. The longer the wavelength, the more diffraction occurs. As a general rule, if the wavelength is less than the size of the object, there will be a significant shadow region.

When waves diffract through a gap of width w in a barrier, the ratio $\frac{\lambda}{w}$ is important. As the value of this ratio increases, so too does the amount of diffraction that occurs.

AS A MATTER OF FACT

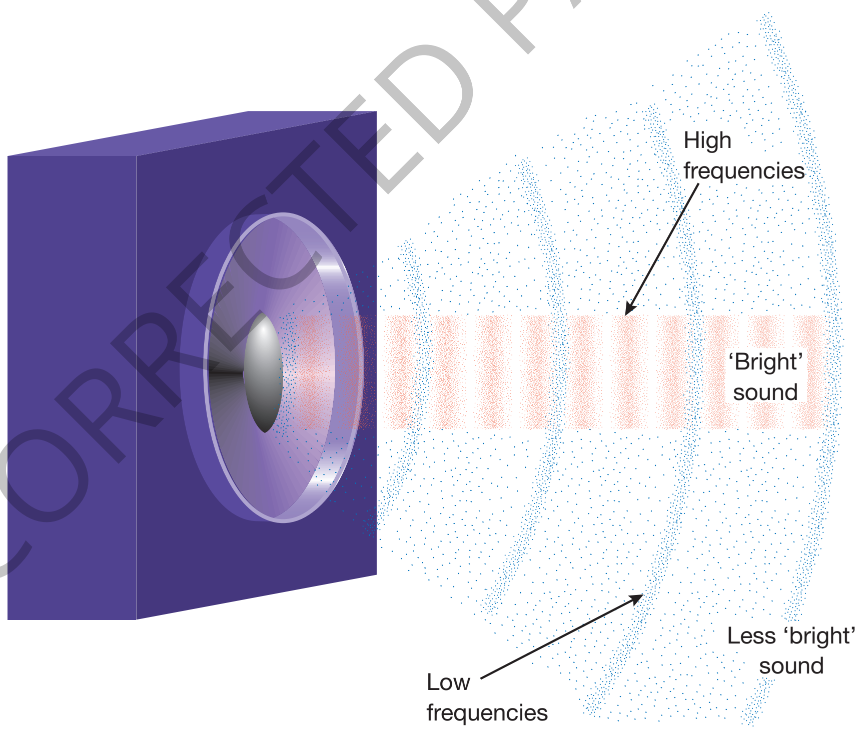
Barriers built next to freeways are effective in protecting nearby residents from high-frequency sounds as these have short wavelengths and undergo little diffraction. The low-frequency sounds from motors and tyres, however, diffract around the barriers because of their longer wavelengths.



9.4.2 Directional spread of different frequencies

The opening at the end of a wind instrument such as a trumpet, the size of someone's mouth and the size of a loudspeaker opening all affect the amount of diffraction that occurs in the sound produced. High-frequency sounds can best be heard directly in front of these devices.

FIGURE 9.7 The diffraction of high and low frequencies from a loudspeaker



When a loudspeaker plays music, it is reproducing more than one frequency at a time. Low-frequency sound waves from a bass instrument have a large wavelength; high-frequency sound waves from a trumpet have a short wavelength. Short-wavelength, high-frequency sounds do not diffract (spread out) very much when they emerge from the opening of a loudspeaker, but long wavelength sounds do. If a single loudspeaker is used, the best place to hear the sound is directly in front of the speaker.

SAMPLE PROBLEM 3

Two sirens are used to produce frequencies of 200 Hz and 10 000 Hz. Describe the spread of the two sounds as they pass through a window in a wall. The window has a width of 35 cm. Assume that the speed of sound in air is 330 m s^{-1}.

Teacher-led video: SP3 (eles-XXXX)

THINK	WRITE
1. First calculate the wavelengths of the sounds using the formula $v = f\lambda$.	200 Hz siren: $v = f\lambda$ $\lambda = \frac{v}{f} = \frac{330}{200} = 1.65\text{ m} = 165\text{ cm}$ 10 000 Hz siren: $v = f\lambda$ $\lambda = \frac{v}{f} = \frac{330}{10000} = 0.033\text{ m} = 3.3\text{ cm}$
2. Diffraction is more significant when the wavelength λ is large compared to w, in this case the width of the window.	There will be a large diffraction spread for the sound of wavelength 165 cm (200 Hz) because the wavelength is large compared with the opening: $\frac{\lambda}{w} = \frac{165}{35} = 4.7$. There will be a very small diffraction spread for the sound of wavelength 3.3 cm (10 000 Hz) because the wavelength is small compared with the opening: $\frac{\lambda}{w} = \frac{3.3}{35} = 0.094$.

PRACTICE PROBLEM 3

Two sirens are used to produce frequencies of 150 Hz and 15 000 Hz. Describe the spread of the two sounds as they pass through a doorway. The doorway has a width of 80 cm. Assume that the speed of sound in air is 330 m s^{-1}.

on Resources

Digital document Investigation 9.5 Diffraction of waves in a ripple tank (doc-18549)

Teacher-led video Investigation 9.5 Diffraction of waves in a ripple tank (eles-XXXX)

9.4 EXERCISE

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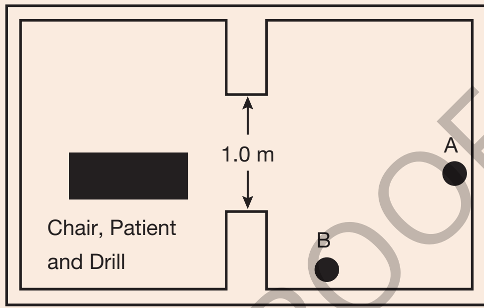
1. (a) What is diffraction?
   (b) Why is diffraction an important concept to consider when designing loudspeakers?
2. The following figure shows the design of a dentist's waiting room and surgery.
   There are two people sitting in the waiting room at points A and B. The door to the surgery is open and it has a width of 1.0 m. A drill is operating and produces a sound of 5000 Hz frequency. The patient in the surgery groans at a frequency of 200 Hz. Assume the speed of sound is 340 m s^{-1}.



   (a) What is the wavelength of the patient's groan?
   (b) What difference, if any, is there between the sound intensity levels produced by the patient's groan at points A and B? Justify your answer.
   (c) What difference, if any, is there between the sound intensity levels produced by the dentist's drill at points A and B? Justify your answer.
3. A 1500 Hz sound and an 8500 Hz sound are emitted from a loudspeaker whose diameter is $w = 0.30$ m. Assume the speed of sound in air is 340 ms^{-1}.
   (a) Calculate the wavelength of each sound.
   (b) A sound engineer wants to use a different speaker for the 8500 Hz sound so that it has the same amount of diffraction as the 1500 Hz sound has for the 0.30 m diameter speaker. Calculate the diameter of the new speaker if this is to occur. Hint: equate the ratio $\frac{\lambda}{w}$ for both situations.
4. A sound of wavelength λ passes through a gap of width w in a barrier. How will the following changes affect the amount of diffraction that occurs?
   (a) λ decreases
   (b) λ increases
   (c) w decreases
   (d) w increases

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9.5 Standing waves in strings

KEY CONCEPTS

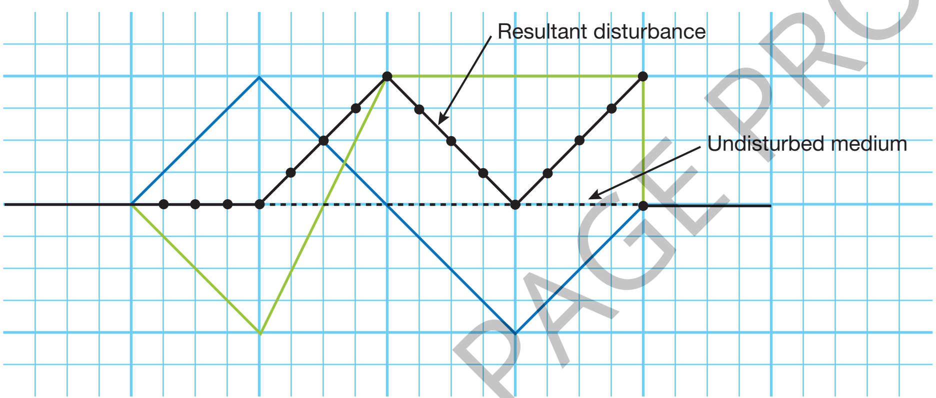
- analyse the formation of standing waves in strings fixed at one or both ends
- explain resonance as the superposition of a travelling wave and its reflection, and with reference to a forced oscillation matching the natural frequency of vibration

9.5.1 Superposition

Pulses (and periodic waves) pass through each other undisturbed. If this were not true, music and conversations would be distorted as the sound waves passed through each other. This can be observed when two pulses pass through each other on a spring. When the pulses are momentarily occupying the same part of the spring, the amplitudes of the individual pulses add together to give the amplitude of the total disturbance of the spring. This effect is known as **superposition** (positioning over) and is illustrated in the following figure.

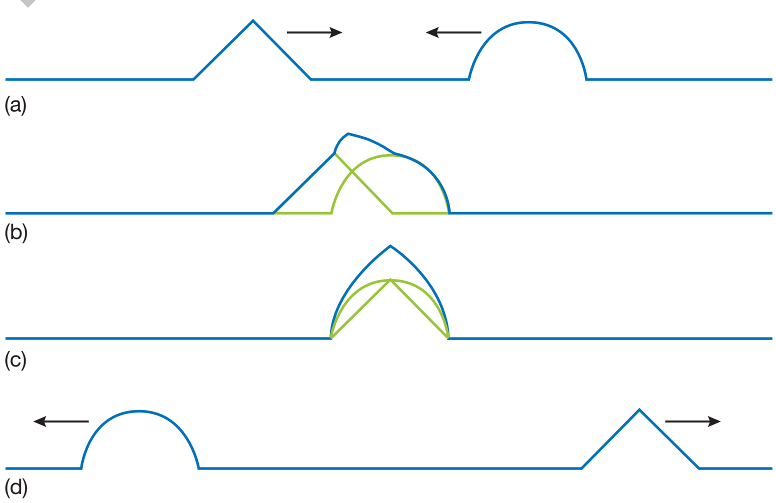
The shape of the resultant disturbance can be found by applying the superposition principle: '*The resultant wave is the sum of the individual waves*'. For convenience, we can add the individual displacements of the medium at regular intervals where the pulses overlap to get the approximate shape of the resultant wave. Displacements above the position of the undisturbed medium are considered to be positive and those below the position of the undisturbed medium are considered to be negative. This is illustrated in figure 9.8, in which two pulses have been drawn in red and blue with a background grid. The sum of the displacements on each vertical grid line is shown with a dot and the resultant disturbance, drawn in black, is obtained by drawing a smooth line through the dots.

FIGURE 9.8 How to obtain the shape of a resultant disturbance.



Figures 9.9a, b, c and d show that it is possible for a part or whole of a pulse to be 'cancelled out' by another pulse. When this effect occurs, **destructive superposition**, or destructive interference, is said to occur. When two pulses superimpose to give a maximum disturbance of a medium, constructive superposition, or **constructive interference**, is said to occur. This effect is shown in figure 9.9c.

FIGURE 9.9 (a) Two pulses of different shapes approach each other on a spring. (b) The pulses begin to pass through each other. (c) As the pulses pass through each other, the amplitudes of the individual pulses add together to give a resultant disturbance. (d) After passing through each other, the pulses continue on undisturbed.



9.5.2 Reflection of waves

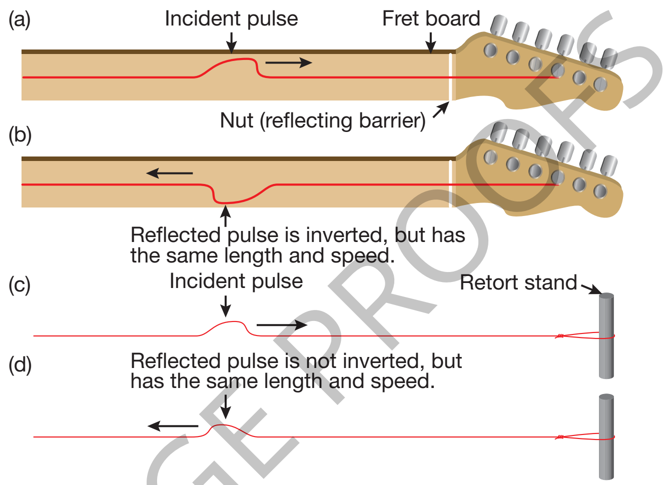
When waves arrive at a barrier, reflection occurs. Reflection is the returning of a wave into the medium in which it was originally travelling. When a wave strikes a barrier, or comes to the end of the medium in which it is travelling, at least a part of the wave is reflected.

A wave's speed depends only on the medium, so the speed of the reflected wave is the same as for the original (incident) wave. The wavelength and frequency of the reflected wave will also be the same as for the incident wave.

Reflection of transverse waves in strings

When a string has one end fixed so that it is unable to move (for example, when it is tied to a wall or is held tightly to the 'nut' at the end of a stringed instrument), the reflected wave will be inverted. This is called a change of phase. If the end is free to move, the wave is reflected upright and unchanged, so there is no change of phase. These situations are illustrated in the figure 9.10.

FIGURE 9.10 Reflection of a transverse pulse on a string when (a) and (b) the end of the string is fixed (as in a guitar), and when (c) and (d) the end of the string is free to move (as with a loop supported by a retort stand)



Resources

Digital document Investigation 9.3 Reflection of pulses in springs (doc-18547)

Teacher-led video Investigation 9.3 Reflection of pulses in springs (eles-XXXX)

9.5.3 Standing waves

Standing waves are an example of what happens when two waves pass through the same point in space. They can either interfere constructively or destructively. Interference is explained more in chapter 10. The phenomenon of standing waves is an example of interference in a confined space. The restriction may be a guitar string tied down at both ends, or a trumpet closed at the mouthpiece and open at the other end, or even a drum skin stretched tightly and secured at its circumference.

A couple of questions need to be asked, though. How and where do the nodes and antinodes form? And, what does this imply about what we hear?

Transverse standing waves in strings or springs

When two symmetrical periodic waves of equal amplitude and frequency (and therefore wavelength), but travelling in opposite directions, are sent through an elastic one-dimensional medium like a string, spring or a rope, constructive interference and destructive interference occur. In fact, destructive interference occurs at evenly spaced points along the medium and it happens all the time at these points. The medium at these points never moves. Such points in a medium where waves cancel each other at all times are called nodes. In between the **nodes** are points where the waves reinforce each other to give a maximum amplitude of the resultant waveform. This is caused by constructive interference. Such points are called **antinodes**.

When this effect occurs, the individual waves are undetectable. All that is observed are points where the medium is stationary and others where the medium oscillates between two extreme positions. There seems to be a wave but it has no direction of motion. When this occurs, it is said to be a stationary or standing wave.

Figure 9.11 shows how standing waves are formed in a string by two continuous periodic waves travelling in opposite directions. It is important to note that the wavelength of the waves involved in the standing wave is twice the distance between adjacent nodes (or adjacent antinodes).

FIGURE 9.11 The formation of a standing wave

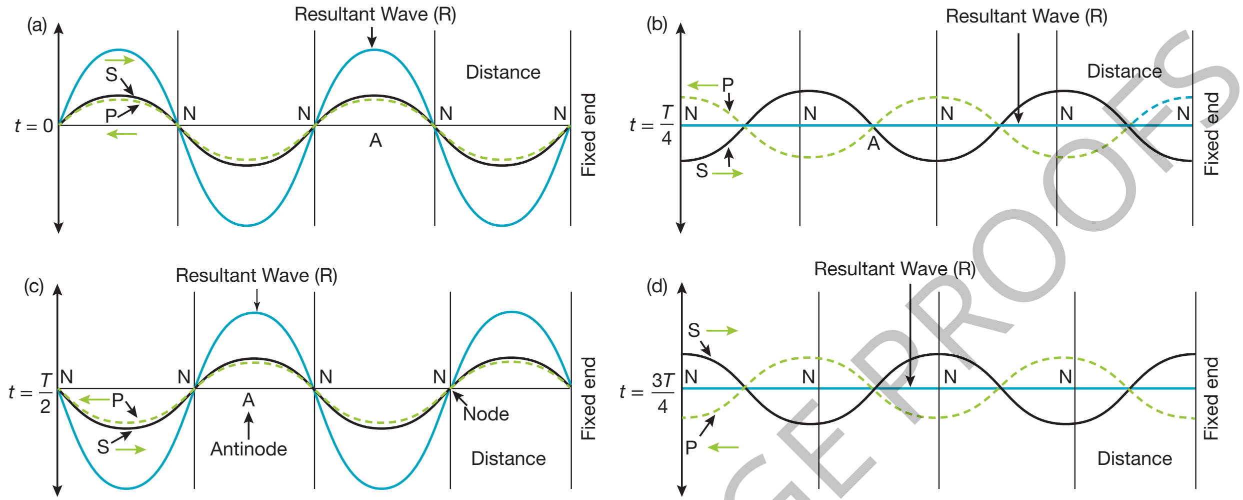
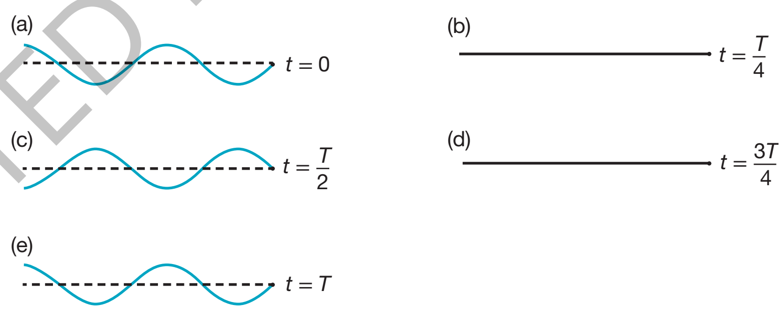


Figure 9.12 shows the motion of a spring as it carries a standing wave. It shows the shape of the spring as it completes one cycle. The time taken to do this is one period (T). Note that (i) at $t = \frac{T}{4}$ and at $t = \frac{3T}{4}$, the medium is momentarily undisturbed at all points, and (ii) that adjacent antinodes are opposite in phase — when one antinode is a crest, those next to it are troughs.

FIGURE 9.12 A standing wave over one cycle



9.5.4 Harmonics associated with standing waves

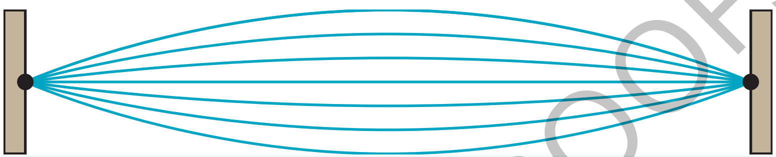
One important application of standing wave theory is that standing waves are produced on a medium fixed at both ends. This can be applied to guitar and violin stings, for example, or to water waves reflecting off a barrier, even to suspension bridges with the road fixed to a pylon at both ends. The important physics here is that when waves are generated, in the case of a guitar by plucking, a violin by using a bow, or by air passing over a bridge, travelling waves in both directions are produced and will reflect off the fixed ends. The reflected waves interfere with each other, and standing waves will be created. In all cases, the medium will only resonate at fixed frequencies that are dependent on the speed of the travelling waves and the distance between the two ends of the medium.

Resonance is the vibration of an object caused when a forced oscillation matches the object's natural frequency of vibration. Every object has one or more natural frequencies of vibration. For example, when a crystal wine glass is struck with a spoon, a distinct pitch of sound is heard. If the resonant frequency is produced by a sound source near the glass, the glass will begin to vibrate.

Let's consider a string under tension of length L fixed at both ends, and capable of resonating — that is, capable of supporting a variety of frequencies. What would be the values of the allowable frequencies?

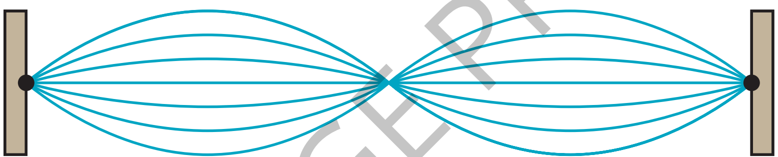
The answer lies in the fact that the ends of the string must be nodes. The longest wavelength occurs when half the wavelength can fit onto a string of length L, that is $L = \frac{\lambda}{2}$ or $\lambda = 2L$. We will call the frequency and associated wavelength of this standing wave the fundamental frequency and fundamental wavelength respectively and use the symbols f_1 and λ_1. Using the wave equation $v = f\lambda$, it follows that if $\lambda_1 = 2L$ then $f_1 = \frac{v}{2L}$. This is the fundamental frequency for a standing wave on a medium of length L fixed at both ends. Importantly, this standing wave is known as the 1st harmonic.

FIGURE 9.13 The first harmonic



The next possible standing wave that could be made occurs when two half-wavelengths, or one whole wavelength, fits onto a string of length L — that is $\lambda = L$ for this standing wave.

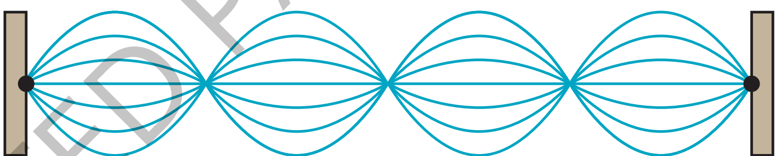
FIGURE 9.14 The second harmonic



We will call this standing wave the second harmonic. Thus $\lambda_2 = L$ and $f_2 = \frac{2v}{2L} = \frac{v}{L} = 2f_1$. The second harmonic has a frequency that is exactly twice the frequency of the first harmonic.

Let's finally look at the third harmonic and we will see a number pattern emerge for all harmonics. The third harmonic will be again fixed at both ends where 1.5 wavelengths will fit onto a string of length L — that is $L = \frac{3}{2}\lambda$, so $\lambda_3 = \frac{2L}{3}$.

FIGURE 9.15 The third harmonic



In general, the nth harmonic will have a wavelength given by

$$\lambda_n = \frac{2L}{n}$$

where λ_n is the wavelength
L is the length of the string
n is the number of the harmonic ($n = 1, 2, 3, 4, 5 \ldots$)

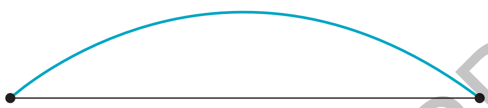
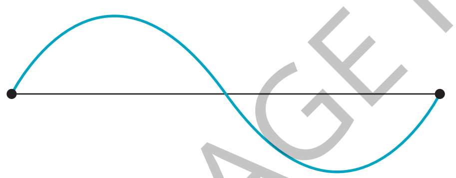
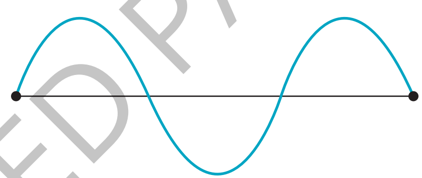
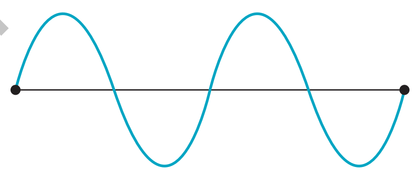
Since the nth harmonic has the wavelength $\frac{2L}{n}$, the frequency of the nth harmonic will be given by

$$f_n = \frac{nv}{2L} = nf_1$$

where f_n is the frequency of the wave
L is the length of the string
n is the number of the harmonic ($n = 1, 2, 3, 4, 5 \ldots$)
v is the velocity of the wave
f_1 is the fundamental frequency

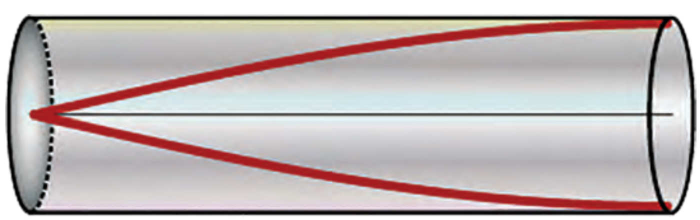
Each of these standing waves or resonances can exist independently of each other and so they give rise to the rich diversity of sound made by musical instruments, even when they are playing the same note. Each instrument will make harmonics of different intensities to produce a spectrum of frequencies unique to that instrument. Nonetheless, the resonant frequencies are governed by simple rules that rely solely on the speed of the travelling wave for the medium, v, and the length of the medium, L, fixed at both ends. This concept applies equally well to pipes used in organs and explains how a musical note can be generated in an air column.

TABLE 9.2 Standing waves on a string fixed at both ends

Harmonic	Number of nodes	Number of antinodes	Pattern	Resonant frequency: $f = \frac{v}{\lambda}$
First	2	1		$L = \frac{\lambda_1}{2}$, $f_1 = \frac{v}{2L}$
Second	3	2		$L = \frac{2\lambda_2}{2} = \lambda_2$ $f_2 = \frac{v}{L}2f_1$
Third	4	3		$L = \frac{3\lambda_3}{2}$, $f_3 = \frac{3v}{2L} = 3f_1$
Fourth	5	4		$L = \frac{4\lambda_4}{2}$, $f_4 = \frac{4v}{2L} = 4f_1$
nth	n+1	n		$L = \frac{n\lambda_n}{2}$, $f_n = \frac{nv}{2L} = nf_1$ $n = 1, 2, 3, 4, 5...$

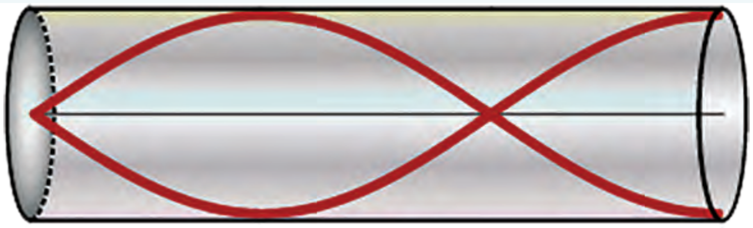
Resonances can also occur on strings fixed at one end (producing a node) but free at the other end (producing an antinode). The fundamental standing wave on such a string of length L will only be one quarter of a wavelength, $\frac{\lambda}{4}$. Here $\lambda_1 = 4L$ and hence the fundamental frequency $f_1 = \frac{v}{4L}$.

FIGURE 9.16 The first harmonic



The next possible frequency for a resonance to occur is when an additional half wavelength is added to the fundamental quarter-wavelength to make a standing wave such that $L = \frac{3\lambda}{4}$ or rearranging $\lambda_3 = \frac{4L}{3}$. In which case, the next lowest frequency $f_3 = \frac{3v}{4L}$.

FIGURE 9.17 The third harmonic

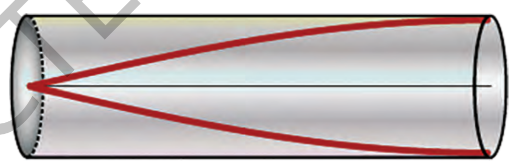
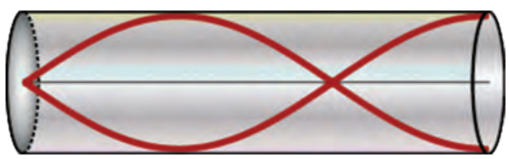


There is an important difference between resonances produced on strings fixed at both ends compared with those where the strings are fixed at one end only:

1. For a string fixed at only one end, the fundamental frequency is half the frequency of a string fixed at both ends.
2. For a string fixed at only one end, only odd harmonics are allowed; the 3rd harmonic is the second lowest frequency, the 5th harmonic is the third lowest frequency, and so on.

This is summarised in table 9.3:

TABLE 9.3 Standing waves on a string fixed at one end only

Harmonic	Number of nodes	Number of antinodes	Pattern	Resonant frequency: $f = \frac{v}{\lambda}$
1st	1	1		$L = \frac{\lambda_1}{4}$, $f_1 = \frac{v}{4L}$
3rd	2	2		$L = \frac{3\lambda_3}{4}$, $f_3 = \frac{3v}{4L} = 3f_1$
5th	3	3		$L = \frac{5\lambda_5}{4}$, $f_3 = \frac{5v}{4L} = 5f_1$

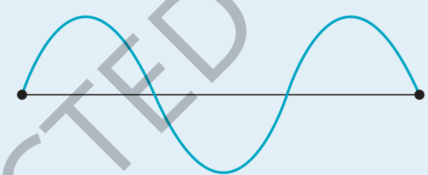
(Continued)

TABLE 9.3 Standing waves on a string fixed at one end only *(Continued)*

Harmonic	Number of nodes	Number of antinodes	Pattern	Resonant frequency: $f = \frac{v}{\lambda}$
7th	4	4		$L = \frac{7\lambda_7}{4}$, $f_3 = \frac{7v}{4L} = 7f_1$
odd *n*th	$2n - 1$	$2n - 1$		$L = \frac{n\lambda_n}{4}$, $f_3 = \frac{nv}{4L} = nf_1$, $n = 1, 3, 5, 7...$

SAMPLE PROBLEM 4

Two students have created a standing wave using wire under tension attached to two ends as part of an extended investigation. The distance between the two ends is 1.50 m. At one instant when the amplitude of the standing wave is a maximum, the wave looks like this:



a. **How many nodes are there in this standing wave (including the two fixed ends)?**
b. **How many antinodes are there?**
c. **Which harmonic of all the possible standing waves does this standing wave represent?**
d. **What is the wavelength of the standing wave?**
The students measure the frequency of the standing wave to be 4.2 Hz.
e. **What is the period of the standing wave?**
f. **What is the speed of the travelling waves on this wire that superimpose to produce this standing wave?**
g. **What would be the fundamental frequency f_1 and wavelength λ_1 for a standing wave on this wire?**

Teacher-led video: SP4 (eles-XXXX)

THINK	WRITE
a. A node can be identified as any point where the amplitude of the wave is a minimum. Count the number of nodal points, including both ends.	**a.** There are four nodes for this standing wave.
b. An antinode can be identified as any point where the amplitude of the wave is a maximum. Count the number of antinodes.	**b.** There are three antinodes for this standing wave.

c. The number of antinodes is equal to the harmonic number. There are three antinodes.

c. The wave is the 3rd harmonic for this wire.

d. The length of the wire, 1.5 m is $\frac{3}{2}$ wavelengths.

d. $L = \frac{3}{2}\lambda$ for the 3rd harmonic.

Thus: $1.5 = 1.5\lambda$

$\Rightarrow \lambda = 1.0\,\text{m}$

e. The period for the 3rd harmonic is $T = \frac{1}{f_3}$

e. $T = \frac{1}{f_3}$

$= \frac{1}{4.2}$

$= 0.2380 \approx 0.24\,\text{s}$

f. Use the equation $v = f_3\lambda_3$ and solve for v.

f. $v = f_3\lambda_3$

$= 4.2 \times 1.0$

$= 4.2\,\text{m s}^{-1}$

g. The nth harmonic is given by the expression $f_n = \frac{nv}{2L} = nf_1$ where $f_3 = 4.2\,\text{Hz}$.

g. $f_3 = 4.2 = 3 \times f_1$

$f_1 = \frac{4.2}{3} = 1.4\,\text{Hz}$

The fundamental frequency for the wire is 1.4 Hz.

PRACTICE PROBLEM 4

The tension in the wire is now increased so that the speed of travelling waves is 6.0 ms^{-1}.

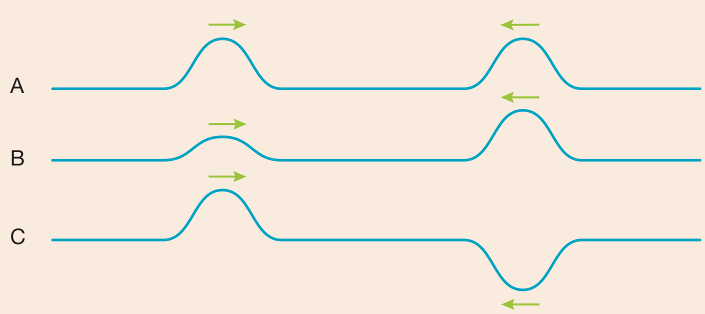
a. What will be the respective frequencies f_1, f_2 and f_3 of the first, second and third harmonic standing waves now?

b. For each of the first three harmonics, what will be the wavelengths λ_1, λ_2 and λ_3?

9.5 EXERCISE

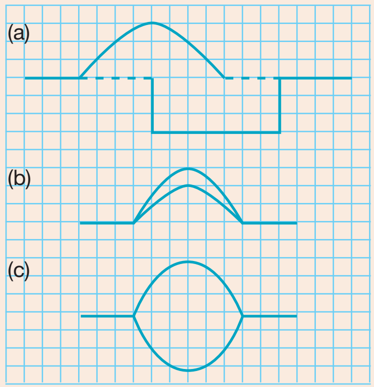
To answer questions online and to receive **immediate feedback** and **sample responses** for every question, go to your learnON title at www.jacplus.com.au.

1. In each of the following diagrams, two waves move towards each other. Identify the diagram (or diagrams) showing waves that, as they pass through each other, could experience:
   (a) only destructive interference
   (b) only constructive interference.



2. What is superposition and when does it occur?
3. What is constructive interference and when does it occur?

4. The following figure shows the positions of three sets of two pulses as they pass through each other. Copy the diagram and sketch the shape of the resultant disturbances.

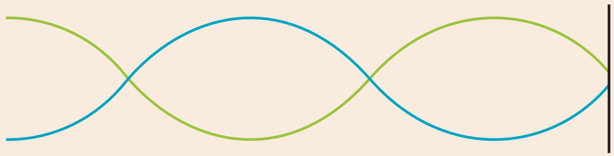


5. What is the wavelength of a standing wave if the nodes are separated by a distance of 0.75 m?
6. The following figure shows a standing wave in a string. At that instant ($t = 0$) all points of the string are at their maximum displacement from their rest positions.

If the period of the standing wave is 0.40 s, sketch diagrams to show the shape of the string at the following times:
(a) $t = 0.05$ s
(b) $t = 0.1$ s
(c) $t = 0.2$ s
(d) $t = 0.4$ s.
7. Kim and Jasmine set up two loudspeakers in the following arrangements:
   - The speakers face each other.
   - They are 10 m apart.
   - The speakers are in phase and produce a sound of 330 Hz.

   Jasmine uses a microphone connected to a CRO and detects a series of points between the speakers where the sound intensity is a maximum. These points are at distances of 3.5 m, 4.0 m and 4.5 m from one of the speakers.
(a) What causes the maximum sound intensities at these points?
(b) What is the wavelength of the sound being used?
(c) What is the speed of sound on this occasion?
8. A standing wave is set up by sending continuous waves from opposite ends of a string. The frequency of the waves is 4.0 Hz, the wavelength is 1.2 m and the amplitude is 10 cm.
(a) What is the speed of the waves in the string?
(b) What is the distance between the nodes of the standing wave?
(c) What is the maximum displacement of the string from its rest position?
(d) What is the wavelength of the standing wave?
(e) How many times per second is the string straight?
9. A standing wave is set up by sending continuous waves from opposite ends of a string. The frequency of the waves is 2.5 Hz, the wavelength is 2.4 m and the amplitude is 0.04 m.
(a) What is the speed of the waves in the string?
(b) What is the distance between the nodes of the standing wave?
(c) What is the maximum displacement of the string from its rest position?
(d) What is the wavelength of the standing wave?
(e) How many times per second is the string straight?
10. A guitar string is capable of supporting many discrete frequencies when plucked. The length of the guitar string is 0.80 m, and travelling waves on the string have speed 650 ms^{-1}. Determine the frequency of the first three harmonics.

11. In a classroom demonstration, a teacher vibrates a string that is fixed at one end and connected to vibrating device at the other end. The vibrating device has a frequency of 200 Hz. The fixed end (right-hand end) can be considered as a node while the other end can be modelled as an antinode. In the demonstration, the pattern looks like the following diagram.



(a) Which harmonic does this pattern represent for the string?
(b) How many nodes are there in this pattern?
(c) The length of the string is 1.5 m. What is the wavelength of the standing wave?
(d) What is the speed of travelling waves on this string?
(e) What frequency would the teacher need to set the vibrating device at to produce the fundamental or first harmonic standing wave using this apparatus?

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9.6 Interference of waves

KEY CONCEPT

- investigate and analyse theoretically and practically constructive and destructive interference from two sources with reference to coherent waves and path difference: $n\lambda$ and $\left(n - \frac{1}{2}\right)\lambda$ respectively

9.6.1 Interference of waves in two dimensions

Interference of waves is best observed in a ripple tank. When two point sources emit continuous waves with the same frequency and amplitude, the waves from each source interfere as they travel away from their respective sources. If the two sources are in phase (producing crests and troughs at the same time as each other), an interference pattern similar to that shown in figure 9.18 is obtained.

Lines are seen on the surface of the water where there is no displacement of the water surface. These lines are called **nodal lines**. They are caused by destructive interference between the two sets of waves. At any point on a nodal line, a crest from one source arrives at the same time as a trough from the other source, and vice versa. Any point on a nodal line is sometimes called a local minimum, because of the minimum disturbance that occurs there.

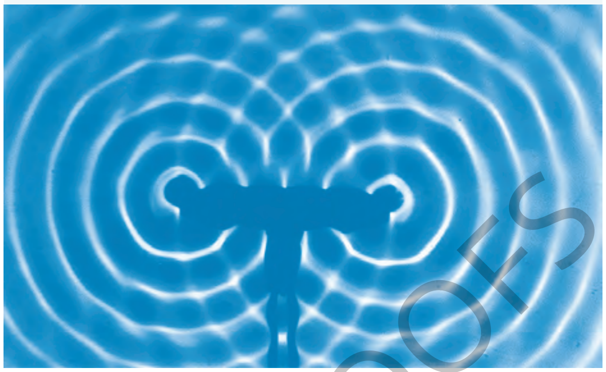
Between the nodal lines are regions where constructive interference occurs. The centres of these regions are called **antinodal lines**. At any point on an antinodal line, a crest from one source arrives at the same time as a crest from the other source, or a trough from one source arrives at the same time as a trough from the other source, and so on. Any point on an antinodal line is sometimes called a local maximum, because of the maximum disturbance that occurs there.

When the two sources are in phase, as shown in figure 9.18, the interference pattern produced is symmetrical with a central antinodal line. Note that any point on the central antinodal line is an equal distance from each source. Since the sources produce crests at the same time, crests from the two sources will arrive at any point on the central antinodal line at the same time.

Similar analysis will show that, for any point on the first antinodal line on either side of the centre of the pattern, waves from one source have travelled exactly one wavelength further from one source than from the other. This means that crests from one source still coincide with crests from the other, although they were not produced at the same time (see figure 9.19). Point P_A in figure 9.19 is on the first antinodal line from the centre of the pattern. It can be seen that point P_A is 4.5 wavelengths from S_1 and 3.5 wavelengths from S_2.

A way to establish whether a point is a local maximum is to look at the distance it is from both sources. If the distance that the point is from one source is zero or a whole number multiple of the wavelength further than the distance it is from the other source, then that point is a local maximum. This 'rule' can be re-expressed as: '*If the path difference at a point is nλ, the point is a local maximum*'.

FIGURE 9.18 An interference pattern obtained in water by using two point sources that are in phase



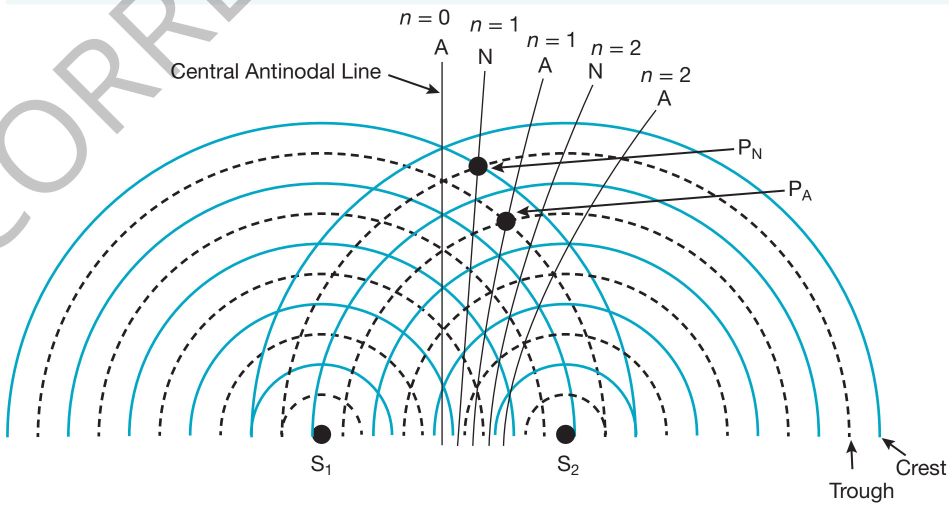
Therefore,

For a point to be an antinode:

$$d(PS_1) - d(PS_2) = n\lambda \quad n = 0, 1, 2, 3, 4, \ldots$$

where
***n* is the number of the antinodal line from the centre of the pattern**
λ is the wavelength
P is the point in question
S_1 and S_2 are the sources of the waves
$d(PS_1)$ is the distance from P to S_1
$d(PS_2)$ is the distance from P to S_2

FIGURE 9.19 Interference pattern produced by two sources in phase



Similar analysis shows that, for a point on a nodal line, the difference in distance from the point to the two sources is $\frac{1}{2}\lambda$ or $1\frac{1}{2}\lambda$ or $2\frac{1}{2}\lambda$ and so on. This means that a crest from one source will coincide with a trough from the other source, and vice versa. Point P_N in figure 9.19 is 5 wavelengths from S_1 and 4.5 wavelengths from S_2.

For a node:

$$\boldsymbol{d(PS_1) - d(PS_2) = (n - \tfrac{1}{2})\lambda \quad n = 1, 2, 3, 4, ...}$$

where
n is the number of the nodal line obtained by counting outwards from the central antinodal line
λ is the wavelength
P is the point in question
S_1 and S_2 are the sources of the waves
$d(PS_1)$ is the distance from P to S_1
$d(PS_2)$ is the distance from P to S_2

SAMPLE PROBLEM 5

Two point sources S1 and S_2 emit waves in phase in a swimming pool. The wavelength of the waves is 1.00 m. P is a point that is 10.00 m from S_1, and P is closer to S_2 than to S_1. How far is P from S_2 if:
a. P is on the first antinodal line from the central antinodal line
b. P is on the first nodal line from the central antinodal line?

Teacher-led video: SP5 (eles-XXXX)

THINK	WRITE
a. 1. $d(PS_1)$ is greater than $d(PS_2)$; $d(PS_1) = 10.00\text{ m}, \lambda = 1.00\text{ m}$	**a.** $d(PS_1) - d(PS_2) = \lambda$
2. If P is on the first antinodal line from the central antinodal line, then: $d(PS_1) - d(PS_2) = \lambda$	$d(PS_2) = d(PS_1) - \lambda = 10.00\text{ m} - 1.00\text{ m} = 9.00\text{ m}.$
b. 1. $d(PS_1)$ is greater than $d(PS_2)$; $d(PS_1) = 10.00\text{ m}, \lambda = 1.00\text{ m}$	**b.** $d(PS_1) - d(PS_2) = \frac{1}{2}\lambda$
2. If P is on the first nodal line from the central antinodal line, then: $d(PS_1) - d(PS_2) = \frac{1}{2}\lambda$	$d(PS_2) = d(PS_1) - \frac{1}{2}\lambda = 10.00\text{ m} - 0.50\text{ m} = 9.50\text{ m}.$

PRACTICE PROBLEM 5

Two point sources S1 and S_2 emit waves in phase in a swimming pool. The wavelength of the waves is 1.00 m. P is a point that is 10.00 m from S_1, and P is closer to S_2 than to S_1. How far is P from S_2 if:
a. P is on the second antinodal line from the central antinodal line
b. P is on the second nodal line from the central antinodal line?

9.6.2 Interference with sound

When two sources emit sound with the same frequency in phase, an interference pattern is produced. The pattern is three-dimensional, but its features are the same as for interference patterns produced in water.

A local antinode, or maximum, is a point where constructive interference produces a sound of greater intensity than that produced by one source alone. As the pattern is three-dimensional, there is a central antinodal plane (as opposed to a line) where all points are an equal distance from each source. In this plane, a compression from one source coincides with a compression from the other source. This is followed by a progression of coincidental rarefactions and compressions. As the waves pass through such a point, there is a maximum variation in the air pressure, resulting in a louder sound.

A local node, or minimum, is a point where destructive interference produces a sound of much less intensity than that produced by one source alone. At a point in a nodal region, compressions from one source coincide with rarefactions from the other source and vice versa. As the waves pass through such a point, there is very little variation in the air pressure, resulting in a very soft sound.

AS A MATTER OF FACT

Complete destructive interference rarely occurs, as the sounds produced from each source are usually not of equal intensity, due to the different distances travelled by the individual waves and the inverse square law that describes this variation in intensity with distance from the source.

The same formulas that were used for water waves can be used to determine whether a point is part of a nodal or antinodal region.

For a point to be an antinode,

$$d(\mathrm{PS}_1) - d(\mathrm{PS}_2) = n\lambda \quad n = 0, 1, 2, 3, 4, \ldots$$

For a point to be a node,

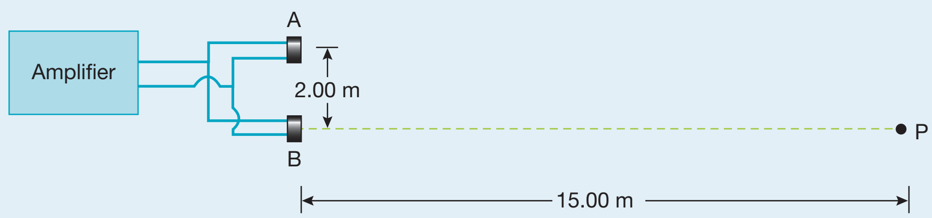
$$d(\mathrm{PS}_1) - d(\mathrm{PS}_2) = \left(n - \frac{1}{2}\right)\lambda \quad n = 1, 2, 3, 4, \ldots$$

where
n **is the number of the antinodal region from the centre of the pattern or the number of the nodal line obtained by counting outwards from the central antinodal plane.**
P is the point in question.
S_1 and S_2 are the sound sources.

SAMPLE PROBLEM 6

A student arranges two loudspeakers, A and B, so that they are connected in phase to an audio amplifier. The speakers are then placed 2.00 m apart and they emit sound that has a wavelength of 0.26 m.

Another student stands at a point P, which is 15.00 m directly in front of speaker B. The situation representing this arrangement is shown in the following figure. Describe what the student standing at point P will hear from this position.



Teacher-led video: SP6 (eles-XXXX)

THINK

1. In this type of question, it is important to determine whether the point is a node or antinode.
   This is done by determining the path difference and then comparing this to the wavelength.
   $\lambda = 0.26\ \text{m}, d(\text{PB}) = 15.00\ \text{m}, d(\text{AB}) = 2.00\ \text{m}$
2. $d(\text{PA})$ can be found by applying Pythagoras's theorem.
3. Calculate the path difference.
4. Compare the path difference to the wavelength.
5. Describe what the student standing at P will hear.

WRITE

2. $$d(\text{PA})^2 = 15.00\ \text{m}^2 + 2.00\ \text{m}^2 = 229\ \text{m}^2$$
   so, $d(\text{PA}) = 15.13\ \text{m}$
3. $$d(\text{PA}) - d(\text{PB}) = 15.13\ \text{m} - 15.00\ \text{m} = 0.13\ \text{m}$$
4. $$0.13\ \text{m} = \frac{1}{2}\lambda$$
5. The student is at a local minimum and will hear only a very soft sound.

PRACTICE PROBLEM 6

Consider the scenario from sample problem 6.

A third student stands at a point Q, which is 3.60 m directly in front of speaker B. Describe what the student standing at point Q will hear from this position.

9.6.3 Colour effects of interference

In the case of light, when two waves of red light meet, constructive interference would result in bright red light. Destructive interference would result in an absence of light, that is, darkness.

When light of a mixture of colours shines on a film of oil in a puddle on the road, light is reflected from the top surface of the oil, as well as from the bottom surface. However, the light from the bottom surface has further to travel, that is, twice the thickness of the oil film. Depending on how this extra distance compares with the wavelength of a particular colour, the two waves may undergo constructive or destructive interference. For example, when you look at an oil film (see figures 9.20 and 9.21), the section that looks yellow is where the thickness is just right for yellow light to undergo maximum constructive interference. Yet at the same place, other colours (which have different wavelengths) undergo destructive interference or less than maximum constructive interference. At other places on the oil film, the

FIGURE 9.20 The colours on this oil film are the result of the interference of light. The wave model of light explains this phenomenon.

thickness will be just right for maximum constructive interference for another colour. The different colours on the oil film indicate the different thicknesses of the oil as the film spreads out.

The colours that flash at you when you move the shiny surface of a CD in sunlight also appear as a result of interference (see figure 9.22). The light from adjacent ridges in the surface follows paths of ever so slightly different lengths. The waves interfere with each other. The difference between the lengths of the paths changes because the distance between adjacent ridges changes. Different colours undergo constructive and destructive interference, depending on the path difference.

FIGURE 9.21 In an oil film, the light waves reflecting from the bottom surface interfere with those reflecting from the top surface. Whether the interference is constructive or destructive depends on how the thickness of the film compares with the wavelength of the light.

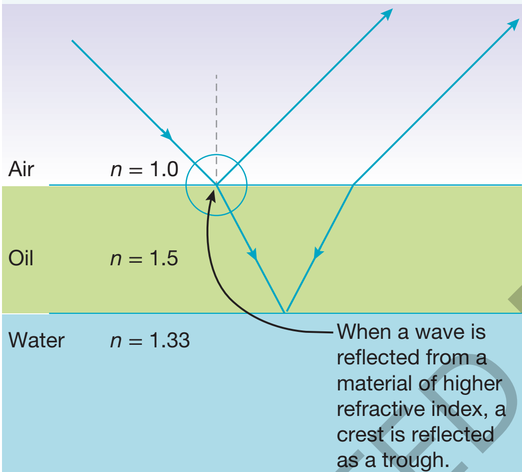


FIGURE 9.22 These colours are the result of interference.

Resources

Digital document Investigation 9.4 Thin soap films (doc-18548)

Teacher-led video Investigation 9.4 Thin soap films (eles-XXXX)

9.6 EXERCISE

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

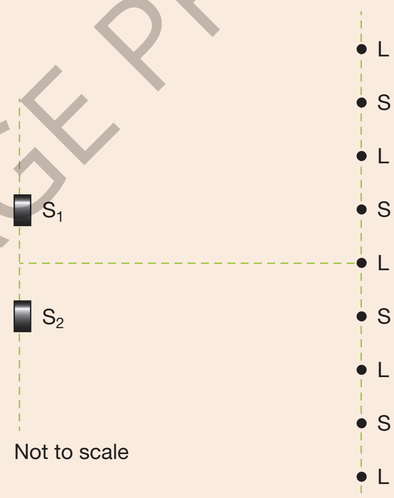
1. Describe the interference pattern produced when two sound sources produce sounds of equal frequency in phase. How can you determine whether a point on the interference pattern is a local maximum or local minimum?
2. Explain what is meant by the expression 'interference pattern' when applied to two sound sources that are in phase.
3. Two sources in phase emit sound with a wavelength of 0.90 m. Describe the loudness (louder or softer when compared to that produced by a single source) at the following positions:
   (a) at an equal distance from both sources
   (b) at a distance of 15.45 m from one source and 14.55 m from the other
   (c) at a distance of 15.75 m from one source and 16.20 m from the other.
   Justify your answers.

4. Two loudspeakers are set up on an open-air stage as shown in the following diagram.

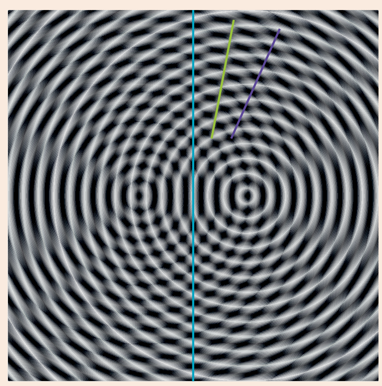
A sound engineer tests the arrangement by feeding a tone of 660 Hz through both speakers. For the following questions, assume that:
- the speakers are producing sound in phase
- the speed of sound in air is 330 m s^{-1}.

(a) What is the wavelength of the sound that is produced by each speaker?
(b) The engineer walks directly away from one of the speakers until he notices that the sound has a minimum value at point P. He accurately measures the distance from this point to the nearest speaker (S_1) and finds that it is 17.875 m. How far is he from speaker S_2? (In calculating this distance, assume that P is on the first nodal line.)
(c) How far apart are the speakers? Hint: Use Pythagoras's theorem.

5. Two loudspeakers in phase produce an interference pattern on a sports field. The set-up of the apparatus is shown further down in this question.
The speakers produce sound with a wavelength of 0.80 m. Suroor walks from point A to point I and detects either a loud or very soft sound at the points labelled in the diagram.
(a) What causes the variations in the loudness of the sound?
(b) Describe the sound (loud or soft) detected at point E. Explain your answer.
(c) Describe the sound (loud or soft) detected at point D. Explain your answer.
(d) If point D is 20.00 m from speaker S_2, how far is it from speaker S_1?
(e) Suroor stands at point D as her assistant Susie slowly increases the frequency while keeping the power of the speakers constant. Describe the loudness of the sound that Suroor detects as the frequency increases. Justify your answer.



6. Consider an interference pattern resulting from two in-phase sources in a large swimming pool where the wavelength of the waves is 0.80 m.
An overview image of the pattern is shown in the following diagram.
(a) On the diagram, label a point A where the path difference is 0.
(b) On the diagram, label a point B where the path difference 1.2 m.
(c) On the diagram, label a point C where the path difference is 2.4 m.
(d) If the source frequency was increased, the wavelength of the travelling waves would decrease. Describe what changes in the pattern would occur.



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9.7 Review

9.7.1 Summary

- Waves provide a means of energy transfer from one place to another place without matter transfer. There are many examples of waves and they can be transverse or longitudinal.
- Properties of waves that can be measured include speed, wavelength and frequency. These quantities are connected by the universal wave equation:

$$\text{speed} = \text{frequency} \times \text{wavelength, or } v = f\lambda.$$

- As a transverse wave moves through a medium, the particles vibrate perpendicularly to the direction of propagation. Surface waves on water or vibrations of a string are examples of transverse waves.
- As longitudinal waves move through a medium, the particles of the medium vibrate back and forth parallel to the direction of propagation. Sound is an example of a longitudinal wave.
- Light is a form of electromagnetic radiation that can be modelled as a type of transverse wave with different colours differing in frequency and wavelength.
- The Doppler effect is the result of a wave source moving through the medium. The waves move at constant speed relative to the medium away from the moving source, resulting in a higher frequency in front of the moving source and a lower frequency behind it.
- An observer moving towards a stationary source will measure a frequency greater than the source frequency. An observer moving away from a stationary source will measure a frequency smaller than the source frequency.
- All waves when passing through a narrow opening or around an obstacle will diffract. Diffraction is the spreading of waves. The amount of diffraction is increased when the wavelength λ is increased. The amount of diffraction is also increased when the size of the opening w is decreased or the obstacle is made smaller. The ratio $\frac{\lambda}{w}$ is useful in deciding the amount of diffraction that will occur in a given situation.
- All waves, including light, have the capacity to interfere with each other, producing constructive interference or destructive interference when and where two waves meet.
- Standing waves are caused by the superposition of two wave trains of the same frequency and amplitude travelling in opposite directions. Points of no disturbance are called nodal points or nodes and points of maximum disturbance are called antinodes.
- Standing waves on strings fixed at both ends are capable of supporting many discrete frequencies called harmonics. The first harmonic is given by: $f_1 = \frac{v}{2L}$ where v is the speed of the travelling wave and L is the length of the string, assuming both ends to be nodes. The nth harmonic is given by the expression $f_n = nf_1$ where f_1 is the fundamental frequency or first harmonic.
- For a string of length L fixed at both ends, the wavelength of the nth harmonic standing wave is $\lambda_n = \frac{\lambda_1}{n}$ where $\lambda_1 = 2L$.
- Standing waves on strings that are fixed at one end and free at the other end are capable of supporting many discrete frequencies called harmonics. The first harmonic is given by $f_1 = \frac{v}{4L}$ where v is the speed of the travelling wave and L is the length of the string. The nth harmonic is given by the expression $f_n = nf_1$ where f_1 is the fundamental frequency or first harmonic frequency and only odd numbered harmonics, $n = 3, 5, 7$ and so on, are allowed.
- For a string of length L fixed at one end, the wavelength of the nth harmonic standing wave is $\lambda_n = \frac{\lambda_1}{n}$ where $\lambda_1 = 4L$ and $n = 3, 5, 7 \ldots ..$

- When waves that are in phase pass through a pair of openings, an interference pattern is produced due to constructive and destructive interference of the two waves emerging from the opening. This pattern is called a double-slit interference pattern.
- The pattern can be explained using the concept of path difference such that regions of constructive interference occur at X when the path difference $= 0, \pm 1\lambda, \pm 2\lambda, \pm 3\lambda$ ..... or, alternatively, $|S_1X - S_2X| = n\lambda$, where $n = 0, 1, 2, 3, \ldots$ ..
- Regions of destructive interference occur at Y when the path difference $= \pm\frac{1}{2}\lambda, \pm\frac{3}{2}\lambda, \pm\frac{5}{2}\lambda$ ..... or, alternatively, $|S_1Y - S_2Y| = \left(n - \frac{1}{2}\right)\lambda$, where $n = 1, 2, 3 \ldots$ ..

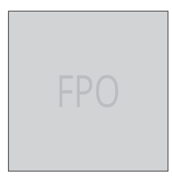
9.7.2 Key terms

The **amplitude** of a wave is the size of the maximum disturbance of the medium from its normal state.
An **antinodal line** is a line where constructive interference occurs on a surface.
An **antinode** is a point at which constructive interference takes place.
A **compression** is a region of increased pressure in a medium during the transmission of a sound wave.
Constructive interference describes the addition of two wave disturbances to give an amplitude that is greater than either of the two waves.
Destructive interference is the addition of two wave disturbances to give an amplitude that is less than either of the two waves.
Diffraction is the spreading out, or bending of, waves as they pass through a small opening or move past the edge of an object.
The **frequency** of a periodic wave is the number of times the wave repeats itself every second.
A **longitudinal wave** is a wave for which the disturbance is parallel to the direction of propagation.
A **nodal line** is a line where destructive interference occurs on a surface, resulting in no displacement of the surface.
A **node** is a point at which destructive interference takes place.
The **period** of a periodic wave is the time it takes a source to produce one complete wave.
A **periodic wave** is a disturbance that repeats itself at regular intervals.
A **rarefaction** is a region of reduced pressure in a medium during the transmission of a sound wave.
Resonance is the condition where a medium responds to a periodic external force by vibrating with the same frequency as the force.
A **standing wave** is the superposition of two wave trains at the same frequency and amplitude travelling in opposite directions. Standing waves are also known as stationary waves because they do not appear to move through the medium. The nodes and antinodes remain in a fixed position.
Superposition is the adding together of amplitudes of two or more waves passing through the same point.
A **transverse wave** is a wave for which the disturbance is at right angles to the direction of propagation.
A **wave** is a transfer of energy through a medium without any net movement of matter.
The **wavelength** is the distance between successive corresponding parts of a periodic wave.

9.7.3 Practical work and investigations

online only

Investigation 9.3
Reflection of pulses in springs
Digital document: doc-18547169
Teacher-led video: eles-#####



Investigation 9.4
Thin soap films
Digital document: doc-18548
Teacher-led video: eles-#####

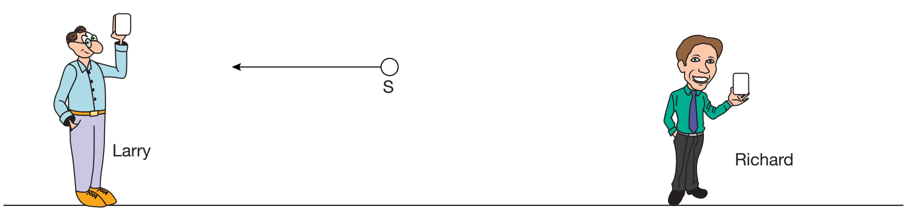
Investigation 9.5
Diffraction of waves
Digital document: doc-18549
Teacher-led video: eles-#####

9.7 Exercises

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

9.7 Exercise 1: Multiple choice questions

1. Which statement is correct?
   A. Sound is a type of transverse wave whereas surface waves on a ripple tank are a type of longitudinal wave.
   B. Sound is a type of longitudinal wave whereas surface waves on a ripple tank are a type of transverse wave.
   C. Both sound and surface waves on a ripple tank are types of longitudinal waves.
   D. Both sound and surface waves on a ripple tank are types of transverse waves.
2. The musical note A has a frequency of 440 Hz. Orchestras often use this note to tune up. Calculate the wavelength of this note in air and identify the value in the following list. The speed of sound in air is 340 m s^{-1}.
   A. 0.77 m
   B. 1.29 m
   C. 0.64 m
   D. 1.54 m
3. Consider a periodic sound wave produced by a speaker in air where the frequency is slowly increased from 440 Hz to 880 Hz. Which one of the following statements is correct?
   A. The wavelength will remain constant and the speed of the sound wave will slowly increase.
   B. The wavelength will slowly increase and the speed of the sound wave will remain constant.
   C. The wavelength will slowly decrease and the speed of the sound wave will slowly increase.
   D. The wavelength will slowly decrease and the speed of the sound wave will remain constant.
4. Consider a sound of frequency f emitted from a stationary source S moving to the left as shown in the following diagram. Two observers, Larry and Richard, each use a meter to measure the frequency of the sound — the meters are identified by f_L and f_R respectively. Both Larry and Richard are stationary.



Identify, from the following list, which relationship between f_L and f_R is correct.

A. $\frac{f_L}{f_R} > 1$

B. $\frac{f_L}{f_R} = 1$

C. $\frac{f_L}{f_R} < 1$

D. $f_R > f > f_L$

5. A group of students produces periodic waves in a ripple tank with a wavelength λ that pass through a narrow opening of width w to demonstrate diffraction. In which situation will diffraction be most significant?

A. $\lambda = 20$ mm and $w = 10$ mm
B. $\lambda = 40$ mm and $w = 10$ mm
C. $\lambda = 40$ mm and $w = 5.0$ mm
D. $\lambda = 20$ mm and $w = 5.0$ mm

6. A guitar string is tuned so that the first harmonic is 440 Hz. Which of the following are possible harmonics for that string when vibrated?

A. 110, 220, 330 Hz
B. 220, 660, 880 Hz
C. 660, 880, 1320 Hz
D. 880, 1320, 1760 Hz

7. A teacher uses a vibrating string to demonstrate standing waves to a group of students. The distance between two adjacent nodes on string is measured to be 36 cm when the frequency of the wave generator attached to the string is 120 Hz. Identify from the following list, the speed of the travelling waves on the string.

A. 43.2 m s^{-1}
B. 86.4 m s^{-1}
C. 57.6 m s^{-1}
D. 172.8 m s^{-1}

8. A teacher uses a skipping rope to demonstrate standing waves to a group of students. One end of the rope is fixed while the other end, held by the teacher, can be considered to be an antinode. The rope has a length of 2.4 m. The teacher produces the 3rd harmonic on the rope. Calculate the distance from the fixed end to the nearest node on this standing wave, and identify your answer from the following list.

A. 1.8 m
B. 3.2 m
C. 1.2 m
D. 1.6 m

9. When waves are passed through two closely spaced openings, an interference pattern results on the far side. In a student investigation into interference, periodic waves of wavelength 1.5 cm are used to study double-slit interference using a ripple tank. A region of destructive interference is observed. From the following list, identify a possible path difference for this region.

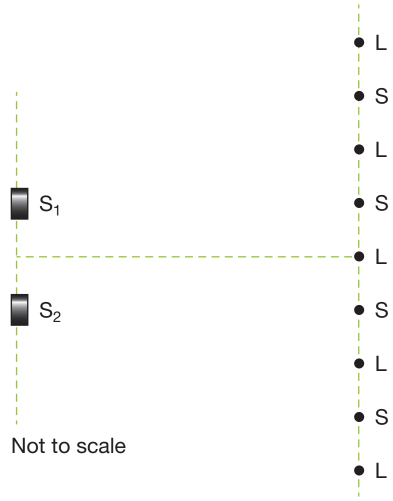
A. 1.5 cm
B. 0 cm
C. 3.0 cm
D. 0.75 cm

For Questions 10 and 11:

A double-slit interference pattern may be made with in-phase sound waves of a single frequency being produced by two speakers S_1 and S_2. This is shown in the following diagram. Regions of loud and soft sounds are shown by labels L and S respectively.

10. Which one or more statements are correct?

A. A region of loud sound is due to constructive interference of waves from S_1 and S_2.
B. A region of loud sound is due to destructive interference of waves from S_1 and S_2.
C. A region of soft sound is due to constructive interference of waves from S_1 and S_2.
D. A region of soft sound is due to destructive interference of waves from S_1 and S_2.



11. The frequency of the sound waves is now increased. Which one of the following statements is correct?
    A. The regions of loud sounds, L, will be louder than before.
    B. The distance between adjacent loud regions and soft regions will be greater than before.
    C. The regions where the sound is loud will be quieter than before
    D. The distance between adjacent loud regions and soft regions will be less than before.

9.7 Exercise 2: Short answer questions

1. Waves are capable of transferring energy from one place to another. Explain why waves require a medium to achieve this.
2. Describe the essential difference between a longitudinal wave and a transverse wave.
3. A student is studying surface waves using water at a local swimming pool. She makes waves at a rate of two every second and the ripples radiate away from the source.
    a. What is the period of the waves?
    b. The waves radiate away from the source at a speed of 2.5 m s^{-1}. What is the distance between two adjacent peaks, that is, the wavelength of the waves?
    c. If she increases the rate at which she makes waves, what will happen to the wavelength of the waves? What will happen to the speed of the waves?
4. Sound produced by an opera singer has a frequency of 926 Hz.
    a. What is the period of the sound wave?
    b. Taking the speed of sound to be 340 m s^{-1}, what is the wavelength of this sound in air?
5. Humans can hear sounds ranging from approximately 20 Hz to 20 000 Hz. What is the wavelength associated with these frequencies in air?
6. Consider an ambulance with its siren blaring at a fixed frequency as it travels along a road. Discuss the frequencies heard by the following three groups of people:
    a. those behind the ambulance, having been passed by it
    b. the driver of the ambulance
    c. those in front of the ambulance as it moves towards them.
7. Describe what diffraction is and state changes in a diffraction pattern when:
    a. the wavelength of the waves used is decreased, keeping the width constant
    b. the width of the opening is decreased, keeping the wavelength constant.
8. On a guitar, the bottom string is called the E-string. When tuned correctly, the fundamental or first harmonic note has a frequency of 82.41 Hz.
    a. When the E-string is plucked, a series of different frequencies or harmonics is produced. Determine the frequencies of the first four harmonics.

The length of the E-string on a typical acoustic guitar is 0.75 m and the string can be considered to be fixed at both ends.

b. Calculate the wavelength of the fundamental tone on the string.
c. Use your result to part b to determine the speed of the travelling waves on the string.
d. Are the waves on the string transverse or longitudinal? Explain.
e. Consider the 3rd harmonic for this string. What is the distance between two adjacent nodes on the string?

9. A student plays a note on a violin. The 4th harmonic associated with the note is 2460 Hz.
a. Determine the frequency of the fundamental associated with this note.
b. Draw the standing wave for this 4th harmonic to illustrate the location of nodes and antinodes on the violin string.

The distance between the bridge of the violin and the position of the student's finger on the string is 0.58 m.

c. Use your answer to part a to determine the speed of the travelling waves on the string.
d. Determine the distance between two adjacent antinodes on the string for the 4th harmonic.

10. A two-source interference pattern is produced in a school pool with two sources S1 and S_2, each making periodic surface waves with wavelength 0.80 m. This is shown in the following diagram with the horizontal dotted line representing where the path difference is zero for the two sources.

a. The distance $S_1A = 12.0$ m. What is the distance S_2A?
b. The point B lies on the first nodal line away from the dotted line. What is the path difference $|S_1B - S_2B|$ equal to?
c. The path difference $|S_1C - S_2C|$ is 1.6 m. At point C, are the waves from S_1 and S_2 constructively or destructively interfering? Explain your answer.
d. The path difference $|S_1D - S_2D|$ is 3.0 m and $S_1D = 14.8$ m. Calculate the distance S_2D.

11. A two-source interference experiment is produced in a ripple tank. A student locates a point of no disturbance X along the first nodal line of the pattern, as shown in the following diagram.

a. In terms of the wavelength λ, what is the path difference $|S_1X - S_2X|$?
b. The student measures the distances $S_1X = 14.8$ cm and $S_2X = 15.8$ cm. What is the wavelength of the surface waves generated in the ripple tank?
c. Waves are generated with frequency 8.0 Hz. Calculate the speed of the surface waves in the ripple tank.

9.7 Exercise 3: Exam practice questions

Question 1

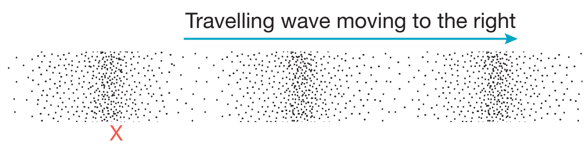
a. In what way are longitudinal waves different from transverse waves? Give an example of each type of wave in your answer.

b. Jenny states that longitudinal and transverse waves have similarities. Discuss three ways in which both types of waves are similar.

c. Sarah claims that a transverse wave will diffract when passing through a narrow opening but that a longitudinal wave will not. Her friend Tony claims that both transverse and longitudinal waves will diffract. Discuss each person's claim.

Question 2

Consider the wave pattern shown in the following diagram, which illustrates compressions and rarefactions of a sound wave at one instant progressing to the right.



a. From the diagram and using a ruler, measure the wavelength of the sound wave. Give your answer in centimetres.

b. If the speed of the wave to the right is 38 cm s^{-1}, calculate the frequency of the source of the waves.

c. Consider the compression labelled X on the diagram. Clearly mark a point on the diagram and label it Y to indicate the position of this compression 0.10 s later.

Question 3

Jimmy plucks one of the strings on his guitar. It vibrates with a fundamental frequency of 530 Hz. The length of the string is 85 cm and it is fixed at both ends.

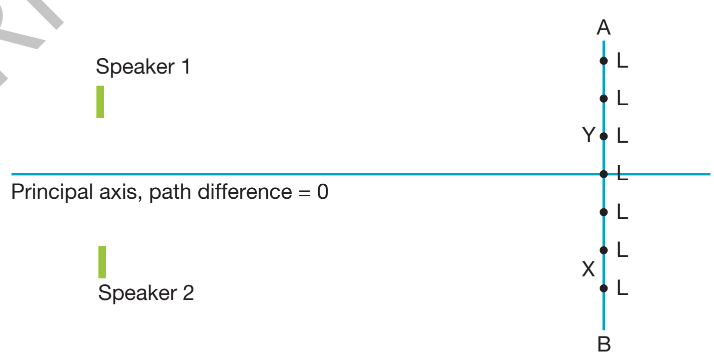
a. Calculate the speed of the travelling wave on the string.

b. Determine the first three overtones (2nd, 3rd and 4th harmonics) that could be produced when Jimmy plucks the string.

Question 4

A group of students investigating the wave nature of sound set up a pair of speakers separated by 2.80 m. Each speaker produces in-phase sound with frequency 720 Hz from a single audio amplifier. The following diagram gives an overhead view of the arrangement. A student walks along the line AB and detects a series of evenly spaced loud (L) and soft sounds.

Data: the speed of sound = 340 m s^{-1}.



a. Explain why the sound intensity varies from loud to soft at regular intervals as the student walks from A to B at a steady pace.

b. Determine the wavelength of the sound waves produced by both speakers.

c. A student positions himself at point Y, where the sound is loud. Calculate the path difference from the two speakers to this point.

d. When the student is at point X, she notes that the sound is soft and assumes she is on a nodal line. She measures the distance to speaker 2 and finds it to be 7.2 m. How far is she from speaker 1?

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