19 Wave motion

Types of waves

*A **pulse** is a single disturbance that propagates from one point to a next.* As the pulse passes, as in the rope or slinky spring in Figure 19.1, for example, each particle mimics the vibration at the source.

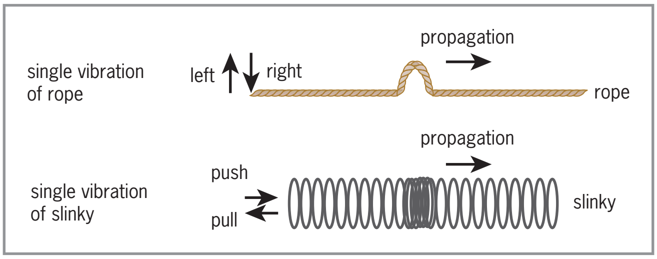

Figure 19.1 *A pulse in a rope and in a slinky*

*A **wave** is a continuous stream of regular disturbances.*

Transverse and longitudinal waves

Waves may be classified as being either transverse or longitudinal.

*A **transverse wave** is one that has vibrations perpendicular to its direction of propagation.*

Examples of transverse waves

- The wave produced in a rope or slinky lying on a horizontal surface and vibrated from one end, perpendicularly to its length (see Figures 19.2 and 19.3).
- The wave produced in water by an object vibrated perpendicularly into and out of its surface.
- An electromagnetic wave, for example light.

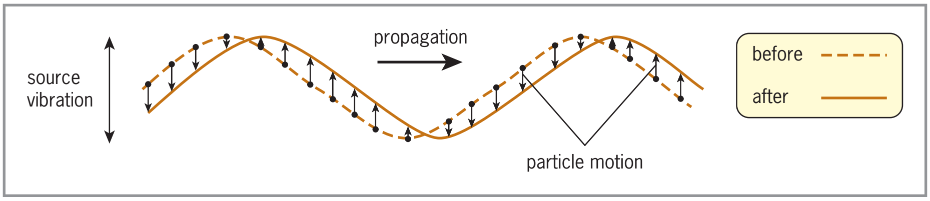

Figure 19.2 *Particle motion in a transverse wave*

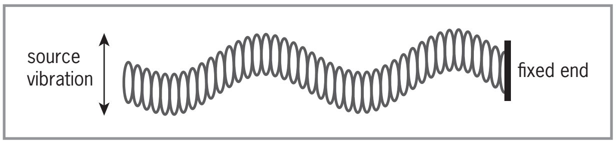

Figure 19.3 *Transverse wave in a slinky*

*A **longitudinal wave** is one that has vibrations parallel to its direction of propagation.*

Longitudinal waves are characterised by regions of high pressure (**compressions**) and regions of low pressure (**rarefactions**), indicated by C and R in Figures 19.4 and 19.5.

Examples of longitudinal waves

- The sound wave produced in a solid, liquid or gas (see Figure 19.4).
- The wave produced in a slinky lying straight on a horizontal surface and vibrated parallel to its length from one end (see Figure 19.5).

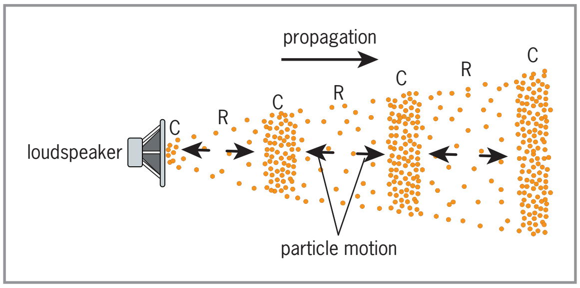

Figure 19.4 *Particle motion and pressure variation in a longitudinal sound wave*

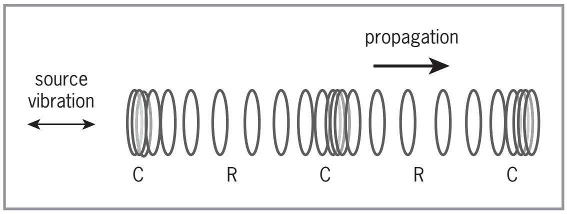

Figure 19.5 *Longitudinal wave in a slinky*

Progressive and stationary waves

Waves may also be classified is either being progressive or stationary.

***Progressive waves** are those that transfer energy from one point to the next.*

Stationary waves do not transfer energy. These waves are not on the CSEC syllabus.

Wave parameters

- **Amplitude**, *a*: *The amplitude of a wave is the maximum displacement of the vibration or oscillation from its mean position.*

  See Figure 19.6.

  If the amplitude of a light wave increases, the light becomes *brighter*.

  If the amplitude of a sound wave increases, the sound becomes *louder*.

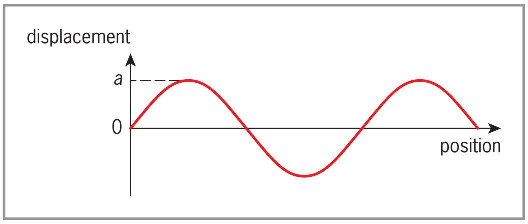

Figure 19.6 *Amplitude, a*

- **Phase**: *Points in a progressive wave are **in phase** if the distance between them along the direction of propagation is equal to a whole number of wavelengths, λ: 0λ, 1λ, 2λ, and so on.*

  See Figure 19.7.

  When points are in phase in a progressive wave they have the same displacement, direction and speed in their vibrations.

*Points in a wave are **in antiphase** (exactly out of phase), when the distance between them along the direction of propagation is equal to $\frac{1}{2}\lambda$, $1\frac{1}{2}\lambda$, $2\frac{1}{2}\lambda$, and so on.*

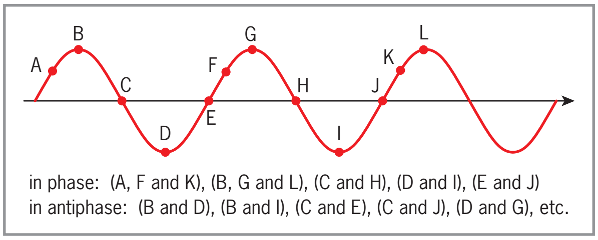

Figure 19.7 *Phase and antiphase*

- **Wavelength**, λ: *The wavelength is the distance between successive points in phase in a wave.*

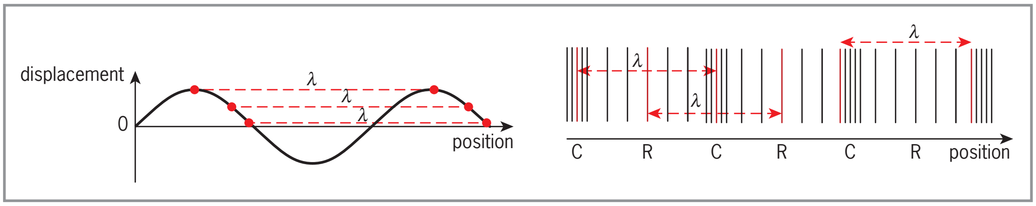

Figure 19.8 *The wavelength λ of a transverse and a longitudinal wave*

- **Period**, T: *The wave period is the time for one complete vibration.*

  In Figure 19.9 the period is 200 ms = 0.2 s.
- **Frequency**, f: *The wave frequency is the number of complete vibrations per second.*

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

T must be in seconds (s) for f to be in hertz (Hz).

If $T = 0.2\,\text{s}$ then $f = \dfrac{1}{0.2} = 5\,\text{Hz}$.

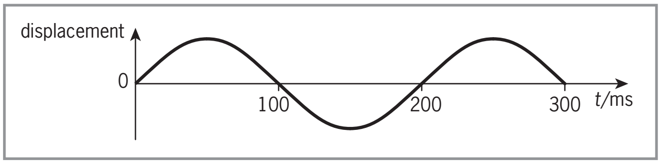

Figure 19.9 *A displacement–time graph for a wave*

The frequency of a light wave determines its *colour*. Red has the lowest frequency and violet the highest frequency of the visible spectrum.

The frequency of a sound wave determines its *pitch*. A bass note has a low frequency and a treble note has a high frequency.

- **Wavefront**: This is a line *perpendicular to the propagation* of a wave on which all points are in phase. Wavefronts are generally taken through crests of transverse waves and through compressions of longitudinal waves, as illustrated in Figure 19.10. Figure 19.11(a) shows the reflection of plane wavefronts at a barrier.

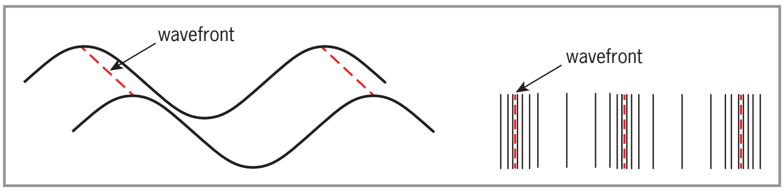

Figure 19.10 *Wavefronts of transverse and longitudinal waves*

- **Speed**, v: This is the rate at which the wavefronts of a wave propagate, and it depends on the medium of propagation. At a boundary between media the speed changes and the wave undergoes **refraction** (Figure 19.11(b)).

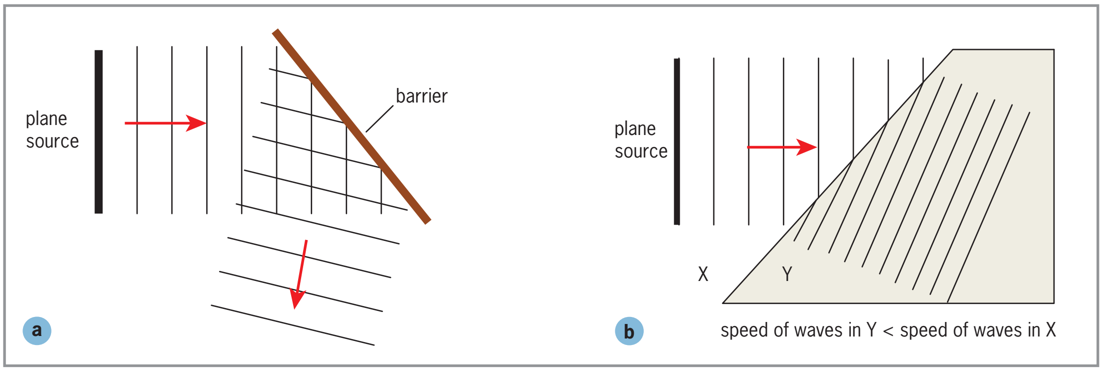

Figure 19.11 *Reflection and refraction of plane wavefronts*

Variation of the speed of waves

The speed of light is *greater in media of lesser density*. Light therefore travels fastest in a vacuum or in air and slower in water or glass.

The speed of sound is *greater through gases of lesser density*. Molecules of lesser mass respond more readily to vibrations than those of greater mass. Sound therefore travels faster through air than through carbon dioxide.

The speed of sound is *greatest through solids*, less in liquids and least in gases. The *closer packing* of the particles and the *rigidity of the bonds* in a solid allows vibrations to transfer more readily. See Table 19.1.

The speed of sound through gases is *greater at higher temperatures* because the *increased kinetic energy* allows the vibrations to be passed on more readily.

The speed of a water wave is *greater across a deeper region*.

Table 19.1 *Speed of sound in steel, water and air*

	steel	water	air at 0 °C
Speed/m s^{-1}	5100	1500	330

General wave equations

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

$$\frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{\sin\theta_1}{\sin\theta_2} = \frac{\eta_2}{\eta_1}$$

where η represents the **refractive index** of a medium (see Chapter 24), and θ_1 and θ_2 are as shown in Figure 19.12.

Figure 19.12 shows in detail the change in direction of wavefronts when the wave is refracted. Note the following:

- θ_1 and θ_2 are the angles (of incidence and refraction respectively) between RAYS and the NORMAL or between WAVEFRONTS and the INTERFACE.

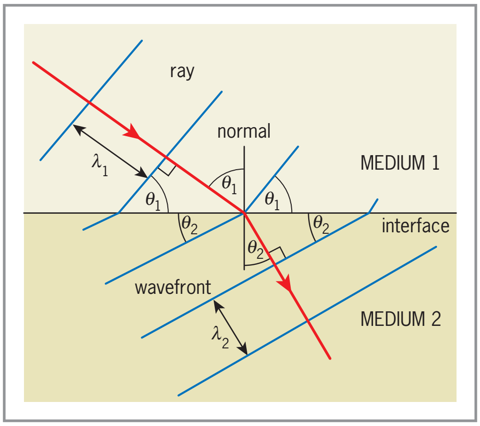

Figure 19.12 *Change in direction of waves on refraction*

- The speed, v, wavelength, λ, and sin θ, all *change by the same proportion* when the wave goes into a new medium. If v doubles, then λ and sin θ also double. The angle θ will not double, but will increase.
- T and f *do not change* when a wave passes from one medium to the next.
- When using the equations in calculations it is a good idea to use relevant letters as subscripts rather than numbers – for example, v_w for the speed in water and v_g for the speed in glass. This reduces errors due to incorrect substitution into an otherwise correct equation.
- In the third equation above, the ratio of refractive indices has its subscripts inverted relative to the other three ratios.

Example 1

Calculate the wavelength of the broadcast from a radio station which emits waves of frequency 104.1 MHz, given that the speed of the wave is 3.0×10^8 m s^{-1}.

$$v = \lambda f$$

$$3.0 \times 10^8 = \lambda \times 104.1 \times 10^6$$

$$\frac{3.0 \times 10^8}{104.1 \times 10^6} = \lambda$$

$$2.9\,\text{m} = \lambda$$

Example 2

A water wave has a speed of 3.0 m s^{-1} and its crests are 5.0 m apart. It approaches a reef at an angle of incidence of 60°. On passing over it, the distance between its crests reduces to 4.0 m. Determine for the wave:

a the frequency in the deeper water

b the period in the deeper water

c the frequency as it passes over the reef (shallow)

d the period as it passes over the reef

e the speed as it passes over the reef

f the angle of refraction on reaching the reef

g the refractive index on travelling from the deep to the shallow.

a

$$v = \lambda f$$

$$3.0 = 5.0f$$

$$\frac{3.0}{5.0} = f$$

$$0.60\text{ Hz} = f$$

b

$$T = \frac{1}{f} = \frac{1}{0.60}$$

$$T = 1.67\text{ s (1.7 s to 2 sig. fig.)}$$

c 0.60 Hz (frequency does not change)

d 1.7 s (period does not change)

e Using s for 'shallow' and d for 'deep':

$$\frac{v_s}{v_d} = \frac{\lambda_s}{\lambda_d}$$

$$\frac{v_s}{3.0} = \frac{4.0}{5.0}$$

$$v_s = \frac{4.0}{5.0} \times 3.0$$

$$v_s = 2.4\text{ m s}^{-1}$$

f $\frac{\sin\theta_s}{\sin\theta_d} = \frac{\lambda_s}{\lambda_d}$

$\frac{\sin\theta_s}{\sin 60} = \frac{4.0}{5.0}$

$\sin\theta_s = \frac{4.0}{5.0} \times \sin 60$

$\theta_s = 44°$

g When referring to refractive index of one medium relative to the next, the second medium must be in the numerator.

$\frac{\eta_s}{\eta_d} = \frac{\lambda_d}{\lambda_s}$

$\frac{\eta_s}{\eta_d} = \frac{5.0}{4.0}$

$\frac{\eta_s}{\eta_d} = 1.25$

Graphs of waves

Displacement–position graph

A displacement–position graph relates the displacement of each point in a wave to the distance or position from some reference point at ONE INSTANT IN TIME (the time is held fixed). See Example 3.

Example 3

Figure 19.13 shows a wave of speed 32 m s^{-1} at an instant in time. Determine:

a the amplitude **b** the wavelength **c** the frequency **d** the period

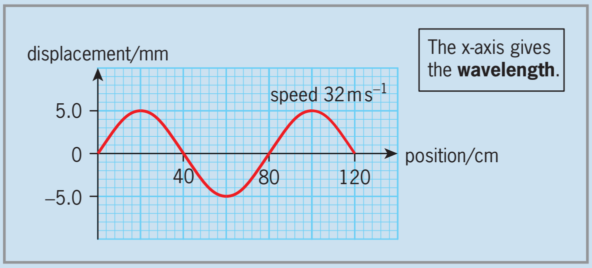

Figure 19.13

a Amplitude = 5.0 mm

b Wavelength = 80 cm or 0.80 m

c Frequency *f*:

$v = \lambda f$

$f = \frac{v}{\lambda} = \frac{32}{0.80} = 40\text{ Hz}$

d Period *T*:

$T = \frac{1}{f} = \frac{1}{40} = 0.025\text{ s}$

Displacement–time graph

A displacement–time graph relates the displacement of ONE POINT in the wave as time continues (the position is held fixed). See Example 4.

Example 4

Figure 19.14 shows a wave of speed 40 m s^{-1}. Determine:

a the amplitude of particle P **b** the displacement of particle P **c** the period

d the frequency **e** the wavelength

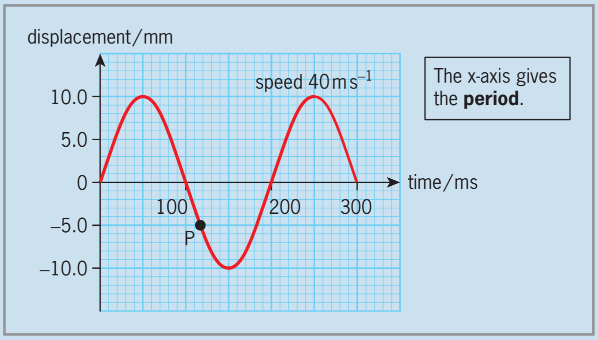

Figure 19.14

a Amplitude of P = 10.0 mm

b Displacement of P = –5.0 mm

c Period = 200 ms or 0.200 s

d Frequency f:

$$f = \frac{1}{T} = \frac{1}{0.200} = 5.00 \text{ Hz}$$

e Wavelength λ:

$$v = \lambda f$$

$$\lambda = \frac{v}{f} = \frac{40}{5.00} = 8.0 \text{ m}$$

Important notes

- Displacement–position and displacement–time graphs of waves have the shape of transverse waves, but they can represent *both transverse and longitudinal waves*. Recall that graphs are a mathematical means of relating two variables – they are not pictures.
- Pressure–position and pressure–time graphs always represent *longitudinal* waves. Recall that these waves have regions of high and low pressure – compressions and rarefactions.
- The mean value on the vertical axis of a pressure–time graph of a sound wave (see Figure 19.15) is *not zero*, as it is with a graph of displacement.

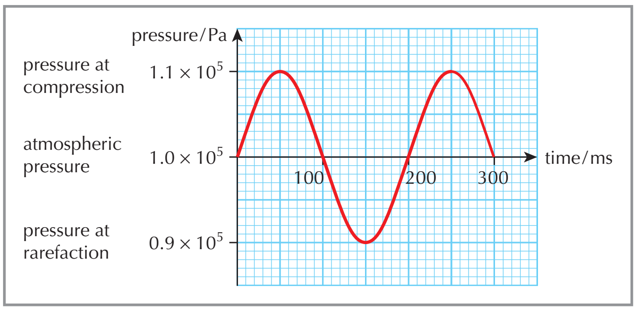

Figure 19.15 *Pressure–time graph of a sound wave*

Revision questions

1. What is meant by each of the following terms describing waves?
   - **a** longitudinal wave
   - **b** transverse wave
   - **c** progressive wave

2. Give TWO examples of a transverse wave and TWO examples of a longitudinal wave.

3. Define the following terms associated with waves:

   a wavelength **b** amplitude **c** frequency **d** period **e** wavefront

4. How does the speed of the wave change in each of the following situations?
   - **a** Light wave travels from glass to air.
   - **b** Water wave travels from a deep region to a shallow region.
   - **c** Sound wave travels from air to a denser gas.
   - **d** Sound wave travels from air to water.

5. Give reasons for your answers to 4c and 4d above.

6. Calculate the frequency of blue light in air given that its wavelength and speed are 4.0×10^{-7} m and 3.0×10^{8} m s^{-1} respectively.

7. The speed of a wave reduces from 40 m s^{-1} to 32 m s^{-1} on entering a second medium. The angle of incidence is 30° and the period of vibration is 0.40 s. Determine for the wave:
   - **a** the frequency
   - **b** the wavelength in the first medium
   - **c** the wavelength in the second medium
   - **d** the angle of refraction.

8. The wave shown in the graph of Figure 19.16 has a speed of 4.0 m s^{-1}. Determine:

   a its period **b** its frequency **c** its amplitude **d** its wavelength

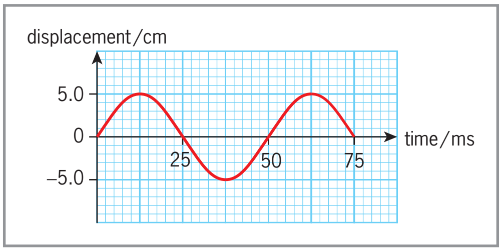

Figure 19.16