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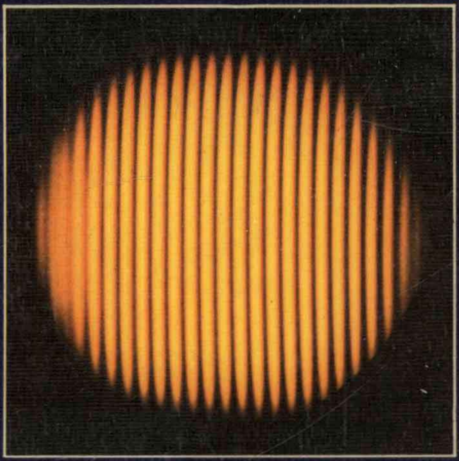

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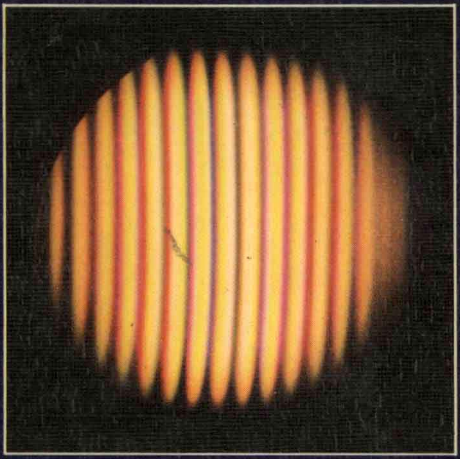

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Core
Physics

Geoff Cackett
Assistant Head Teacher, Holy Rood High School, Edinburgh

Ron Kennedy
Principal Physics Teacher, Holy Rood High School, Edinburgh

Alastair Steven
Principal Physics Teacher, Drummond High School, Edinburgh

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Core
Physics

Preface

This book is written specifically for students preparing for Scottish 'O' grade Physics but it will also be useful for 'O' level and CSE courses. The book is designed to equip the students with the understanding and basic knowledge which should provide the foundation for greater appreciation and enjoyment of the subject.

The book follows closely the order of the topics as presented in the Scottish Certificate of Education syllabus. Each chapter covers a particular topic of the syllabus with a full explanation. The practical nature of the course is emphasized by reference to many experiments with diagrams and photographs. Sample results are used to derive relationships and worked examples have been used to illustrate particular points and to help with understanding. Each chapter ends with a summary and problems, many of the problems being from past 'O' grade papers. Numerical answers have been provided to all problems; SI units are used throughout, other units being referred to only when they are in everyday use. The negative index notation for units has been used, (e.g. $\mathrm{m\ s^{-1}}$ rather than m/s), in accordance with examination requirements. Vector notation is introduced and used where essential. 'Electron flow' current convention is used and conventional current is not referred to at all, apart from a warning to students that they may encounter it in other texts.

We should like to express our appreciation to the various establishments listed on page 277 which gave permission to reproduce their drawings and photographs, and to The Scottish Certificate of Education Examinations Board for allowing us to include questions from past 'O' grade examination papers. Finally we should like to thank our families for their tolerance.

Geoff Cackett
Ron Kennedy
Alastair Stevens

Contents

1 Wave motion

1.1 Introduction

There are many different kinds of waves. One that we all recognize is the **water wave**. When a stone is thrown into a calm pond, waves spread out over the surface, Figure 1.1.
What is travelling out from the centre of the disturbance? After the wave has passed, the water settles back to its original level, so it is not the water that is travelling out. To answer the question, let us imagine a small piece of wood floating on the pond surface. The piece of wood is seen to vibrate as the wave passes. Since the wave causes the wood to move, it must be supplying energy.

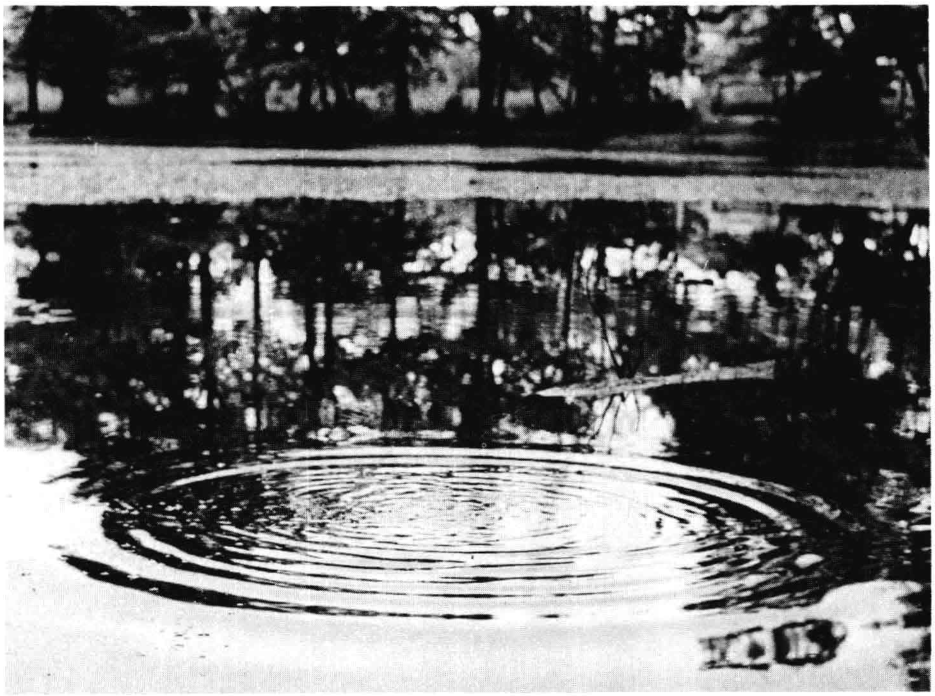
This appears to be the answer to the question. It is **energy** that is travelling out from the centre. It is even more obvious that waves carry energy if we watch waves on the sea, Figure 1.2.

During stormy weather, the energy carried by the waves has often resulted in great damage, Figure 1.3.
This energy comes from winds moving over the surface of the sea. Figure 1.4 is a photograph of a device which can convert wave energy to useful electrical energy.

When we considered the effect of the water wave on the floating piece of wood, we saw that the actual vibrations of the water were in a **vertical** direction, while the energy was transmitted in a **horizontal** direction along the water surface.

A wave in which the vibrations are at right angles to the direction in which the wave is moving is called a **transverse** wave.

Figure 1.1 A circular wave on a pond



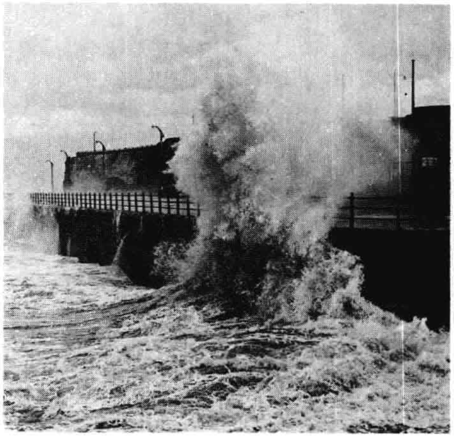
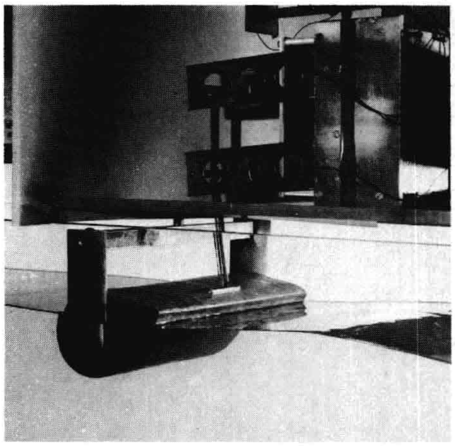


Figure 1.2 Waves smashing against a breakwater

Figure 1.3 A damaged pier

Figure 1.4 A device for converting wave energy to electricity



1.2 Transverse waves and pulses

Transverse waves can be investigated using a long 'slinky' spring stretched out on a bench. One end is held in a fixed position and the other end is moved with your hand, Figure 1.5.

By moving your hand once from side to side, you would generate what is called a **wave pulse** which would travel down the spring. It can be seen that the actual disturbance is **at right angles** to the direction of the wave pulse.

Another method of showing transverse waves is to use a wave machine, Figure 1.6.

The beads can be made to move up and down and give the impression that a wave is travelling at right angles to that direction.

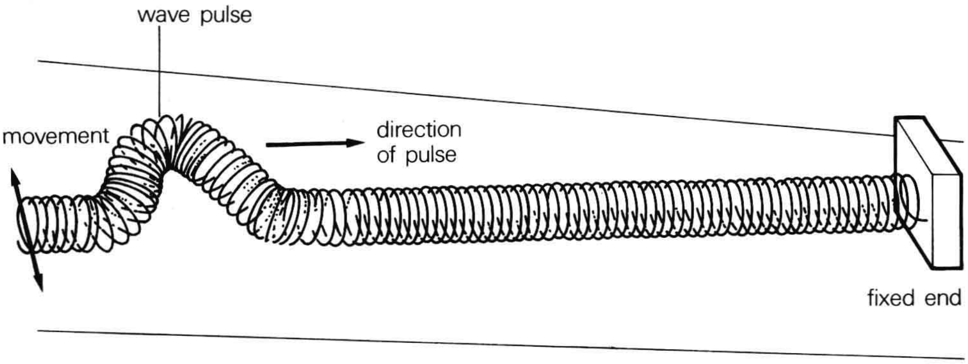


Figure 1.5 A wave on a 'slinky'

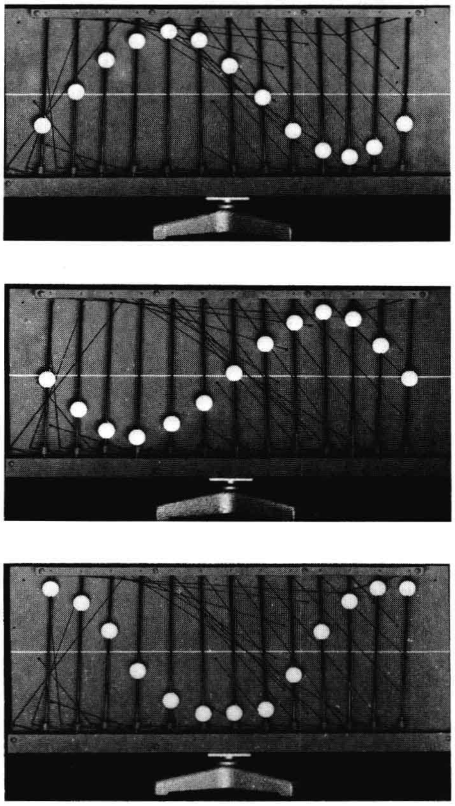


Figure 1.6 A wave machine

1.3 Quantities to describe waves

Various quantities are required to describe waves: they can be investigated using a length of rubber tubing on a bench. A travelling wave (often called a **continuous** wave) can be made by continuously moving your hand from side to side, Figure 1.7.

Amplitude

The greater the movement of your hand, the greater is the size of the disturbance which travels down the tubing.

The **amplitude** of a wave is the size of the maximum disturbance measured from the 'zero' position, Figure 1.8.

Figure 1.7 A wave travelling along rubber tubing

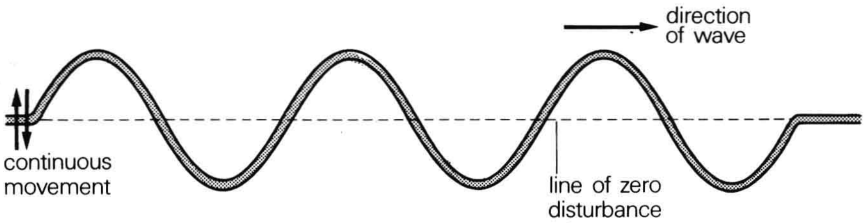
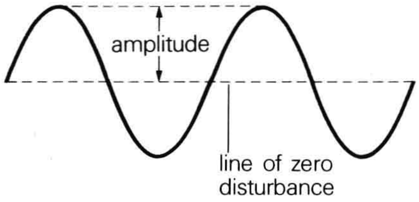


Figure 1.8 Amplitude



Wavelength (symbol λ)

The wave can be seen to repeat itself after a certain distance.

The **wavelength** of a wave is the minimum distance in which a wave repeats itself.

The SI unit for measuring wavelength is the metre (m). Another unit often used is the centimetre (cm). The wavelength may be measured between any two points at which the wave repeats itself, Figure 1.9.

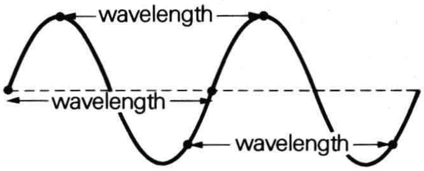


Figure 1.9 Wavelength

Frequency (symbol f)

The faster the movement of your hand, the greater is the number of waves produced in a given time.

The **frequency** of a wave is the number of complete wavelengths produced in one second.

The SI unit for measuring frequency is the hertz (Hz). The word hertz can be thought of as meaning 'per second'. For example if a wave has a frequency of 2 Hz, then two complete wavelengths are produced per second. Hertz was a German physicist who discovered radio waves in 1888. Our unit of frequency is named after him, Figure 1.10.

Figure 1.10 Heinrich Hertz

Wave speed (symbol v)

The wave travelled along the tubing at a constant speed. The **wave speed** is the distance travelled by the wave in one second.

The SI unit for measuring wave speed is the metre per second ($m\ s^{-1}$). Another unit often used is the centimetre per second ($cm\ s^{-1}$).

1.4 A wave equation

The diagrams in Figure 1.11 show how three waves of different frequencies but the same wavelength appear 1 s (one second) after they are started.

When the frequency is 1 Hz, one wavelength (λ) leaves the starting point in 1 s. Hence the distance travelled by this wave in 1 s is $1 \times \lambda$.

When the frequency is 2 Hz, two wavelengths leave the starting point in 1 s. Hence the distance travelled by this wave in 1 s is $2 \times \lambda$.

When the frequency is 3 Hz, three wavelengths leave the starting point in 1 s. Hence the distance travelled by this wave in 1 s is $3 \times \lambda$.

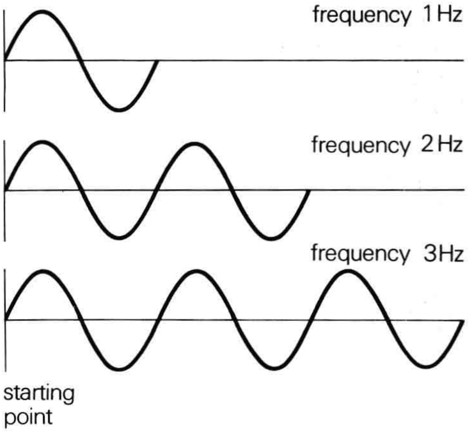
If the frequency is f Hz, f wavelengths leave the starting point in 1 s. And so the distance travelled by the wave in 1 s is $f \times \lambda$.

But the distance travelled in 1 s is the wave speed (v). Hence,

$$v = f \times \lambda$$

wave speed = frequency × wavelength
($m\ s^{-1}$) (Hz or s^{-1}) (m)

Figure 1.11



Example 1

Waves on a spring are produced at the rate of 20 wavelengths every 5 s.
a) Calculate the frequency of the wave motion.
b) If the wavelength of the waves is 0·01 m, find the speed of the waves.

a) $\text{frequency} = \dfrac{\text{number of complete wavelengths}}{\text{time taken}}$

$\Rightarrow \quad f = \dfrac{20}{5}$

$\Rightarrow \quad f = 4$ **The frequency of the wave motion is 4 Hz**

b) wave speed = frequency × wavelength

$\Rightarrow \quad v = 4 \times 0{\cdot}01$

$\Rightarrow \quad v = 0{\cdot}04$ **The speed of the waves is 0·04 $m\ s^{-1}$.**

Example 2

A water wave travels 12 m in 4 s.
a) Calculate the speed of the wave.
b) If the vibrations producing the wave have a frequency of 2 Hz, find the wavelength of the wave.

a) $\text{speed} = \dfrac{\text{distance travelled}}{\text{time taken}}$

$$\Rightarrow \quad v = \frac{12}{4}$$

$$\Rightarrow \quad v = 3$$

The speed of the wave is $3\ \text{m s}^{-1}$

b) speed = frequency × wavelength

$\Rightarrow \quad 3 = 2 \times \lambda$ multiply both sides of the equation by $\frac{1}{2}$

$$\Rightarrow \frac{1}{2} \times 3 = \frac{1}{2} \times 2 \times \lambda$$

$$\frac{3}{2} = \lambda$$

The wavelength of the wave is 1·5 m.

1.5 Phase

Let us think about the way the particles of water move in a water wave. First we need two new words, Figure 1.12. A **crest** is the part of the wave above the line of zero disturbance. A **trough** is the part of the wave below the line of zero disturbance.

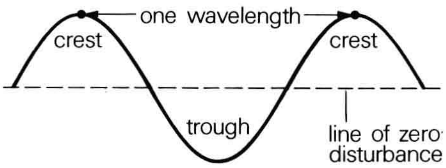


Figure 1.12

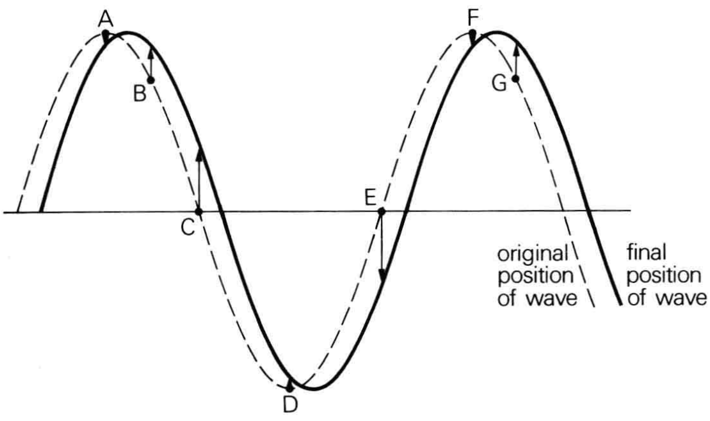
Figure 1.13 represents a wave that has travelled from the position shown by the dotted line to the position shown by the continuous line. The vertical arrows show how the particles at A, B, C, etc. have moved.

Particle A has moved down. Particle F, exactly one wavelength along, has also moved down by exactly the same amount. Particles A and F are said to be **in phase**. Particles B and G are one wavelength apart and have moved up by exactly the same amount so they are also in phase with each other.

Points in a wave separated by a whole wavelength are said to be in phase.

Particle C has moved up, while particle E (exactly one half wavelength along) has moved down, but by exactly the same amount. Particles C and E are said to be exactly out of phase. Particles A and D are half a wavelength apart and are also exactly out of phase since particle A has moved up while particle D has moved down by the same amount. Points in a wave separated by half a wavelength are said to be exactly out of phase.

Figure 1.13 Phase



1.6 Energy changes in a wave

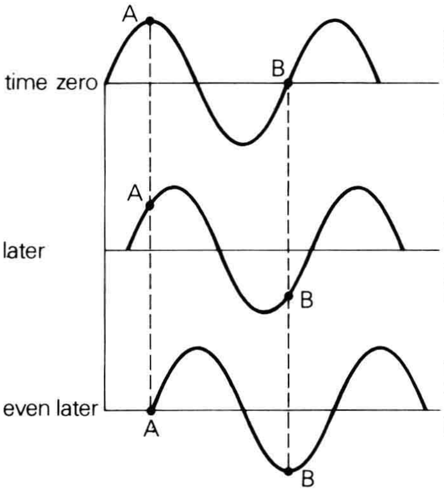
The transmission of waves involves energy changes. When a particle is displaced, it is forced back towards the line of zero disturbance. For example, in water waves the water tends to level out. In waves on rubber tubing, the displaced tubing tends to spring back to its original position.

The existence of a force on the particle trying to move it back to the line of zero disturbance means that it has **potential energy** (stored energy). When a particle is moving, it has **kinetic energy** (movement energy).

The greater the displacement of the particle, the greater is the force and the greater is its potential energy.

The faster the particle is moving, the greater is its kinetic energy.

As the wave travels along, the particles vibrate about the line of zero disturbance and there are continuous energy changes which are represented in Figure 1.14.



Particle A has maximum potential energy but no kinetic energy.

Particle B has no potential energy but maximum kinetic energy.

Particle A has some potential energy and some kinetic energy.

Particle B has some potential energy and some kinetic energy.

Particle A has no potential energy but maximum kinetic energy.

Particle B has maximum potential energy but no kinetic energy.

Figure 1.14

Finally let us see how displacement and speed are related to potential energy and kinetic energy, Figure 1.15.

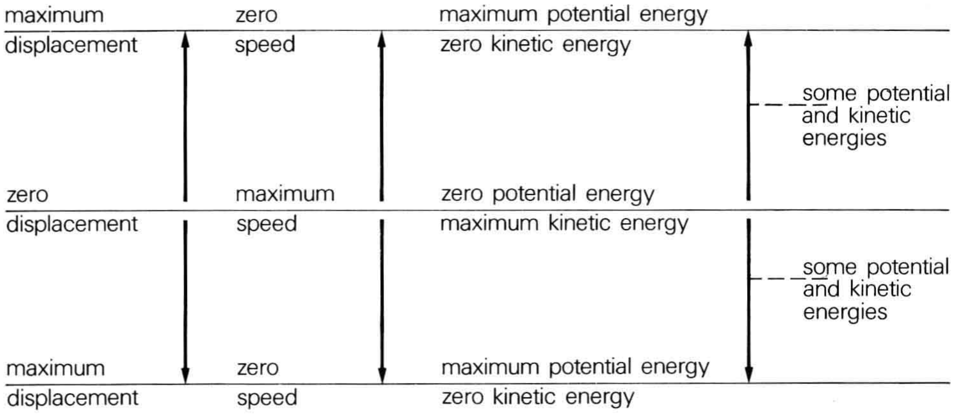


Figure 1.15

The total amount of energy in the vibration (potential energy + kinetic energy) stays constant.

1.7 Stationary waves

Consider a wave pulse travelling along a spring. If the far end of the spring is firmly held, the incident pulse is **reflected** back along the spring, Figure 1.16. Before reflection we call the pulse an **incident** pulse. After reflection we call it a **reflected** pulse.

It is seen that, if the incident pulse is a crest, then the reflected pulse is a trough. This is called a **change of phase**.

If a continuous wave is sent along the spring instead of a pulse, the incident wave meets the reflected wave coming back in the opposite direction. The result of the combination of these two waves is called a **standing** wave (or a **stationary** wave). It is called a stationary wave because, although there are still vertical vibrations, there is no obvious motion of a wave along the spring. The displacement of any part of the spring is the result of the combination of the incident and reflected waves.

A typical stationary wave could appear as shown in Figure 1.17.

There are parts of the wave where there is no displacement. These are called **nodes** and are labelled N in Figure 1.17.

At points midway between nodes the vibrations are of maximum displacement. These are called **antinodes** and are labelled A in Figure 1.17.

The distance between nodes is **half** a wavelength, Figure 1.18.

At an antinode there is a continuous conversion of potential energy to kinetic energy to potential energy etc., because that point of the spring vibrates from one side to the other, Figure 1.19.

Figure 1.20 shows the production of stationary waves on an elastic string by means of a signal generator and vibrator.
The frequency of the vibrations can be varied by changing the frequency at which the signal generator operates. Stationary waves are found to be set up only at certain frequencies, Figure 1.21.

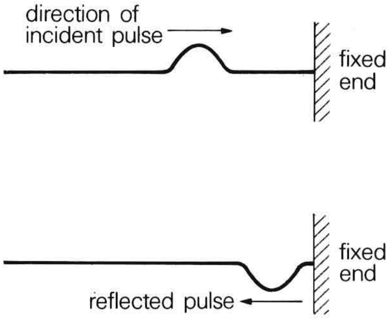


Figure 1.16 Reflection of a pulse

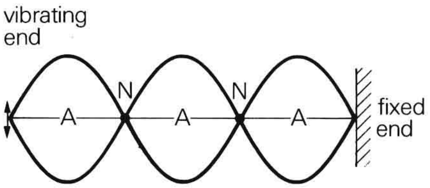


Figure 1.17 A stationary wave

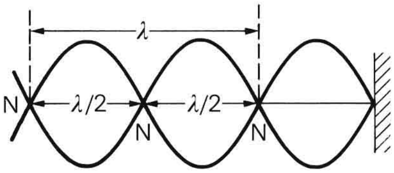


Figure 1.18

Figure 1.20

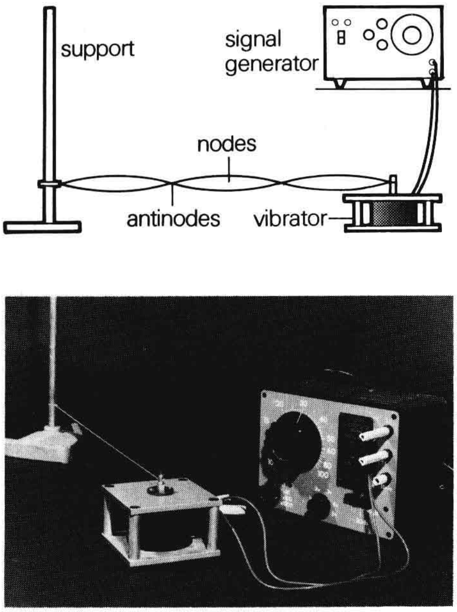
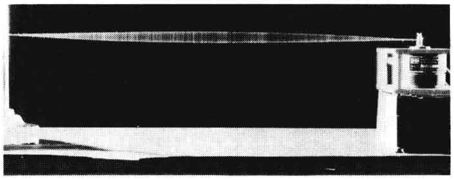
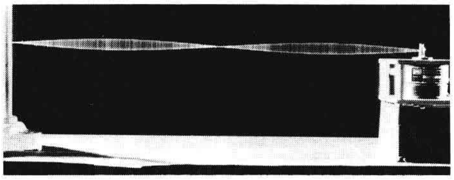


Figure 1.21 Frequency f



Frequency $2f$



Frequency $3f$

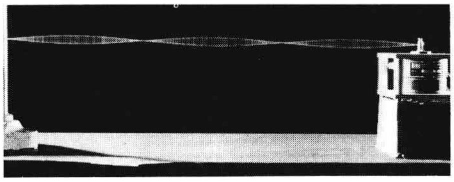
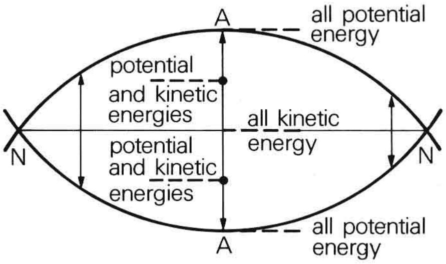


Figure 1.19



Summary

A travelling wave transmits energy.

The vibrations in a transverse wave are at right angles to the direction of travel.

The amplitude of a wave is the size of the maximum disturbance, measured from the line of zero disturbance.

The wavelength of a wave is the minimum distance in which a wave repeats itself. The unit of wavelength is the metre (m).

The frequency of a wave is the number of complete wavelengths produced in one second. The unit of frequency is the hertz (Hz).

The wave speed is the distance travelled by the wave in one second. The unit of wave speed is the metre per second (m s^{-1}).

$$v = f \times \lambda$$

wave speed = frequency × wavelength

Points in a wave separated by a whole wavelength are in phase. Points in a wave separated by half a wavelength are exactly out of phase.

Waves involve energy changes of the form

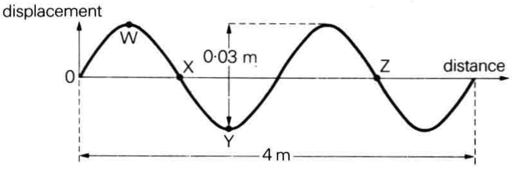
potential energy → potential energy and kinetic energy → kinetic energy → potential energy and kinetic energy → potential energy etc.

but the total amount of energy stays constant.

A stationary wave is produced when an incident wave combines with its reflected wave.

Problems

1 The diagram represents a wave 0·2 s after it has started.



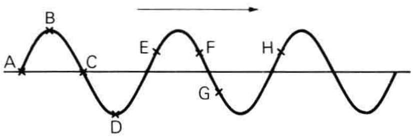
1·1 Calculate
a) the amplitude of the wave.
b) the wavelength of the wave.
c) the wave speed.
d) the frequency of the wave.
1·2 State
a) two points which are in phase.
b) two points which are exactly out of phase.
c) which point is on a wave crest.
d) which point is in a wave trough.

2 A water wave of frequency 4 Hz has a wavelength of 0·02 m. What is its speed?

3 If a wave travels with a speed of 0·1 m s^{-1} and has a wavelength of 0·05 m, what is its frequency?

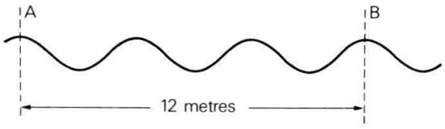
4 A wave of frequency 5 Hz has a speed of 10 cm s^{-1}. What is its wavelength?

5 In this diagram of part of a transverse wave, the arrow shows the direction in which the energy is being transferred.



5·1 Use the letters A to H to indicate:
a) a wavecrest,
b) a wave trough,
c) two points which are in phase.
5·2 Measure:
a) the wavelength in millimetres,
b) the amplitude in millimetres.
5·3 Draw a sketch of the wave and mark the directions of motion of E. *SCEEB*

6 The diagram shows a side-view of water waves in a glass-walled tank.



6·1 What is their wavelength?
6·2 If the crest at A takes 2 seconds to reach the point B, what is their frequency? *SCEEB*

2 Water waves

2.1 The ripple tank

We shall see that energy is transmitted by waves in many aspects of physics. In the first chapter we discussed water waves in a pond and in the sea. In this chapter we look more closely at the properties of water waves because they are easily observed and their wavelength and frequency are easily measured. We can then use this knowledge to study other forms of wave motion and to explain their behaviour.

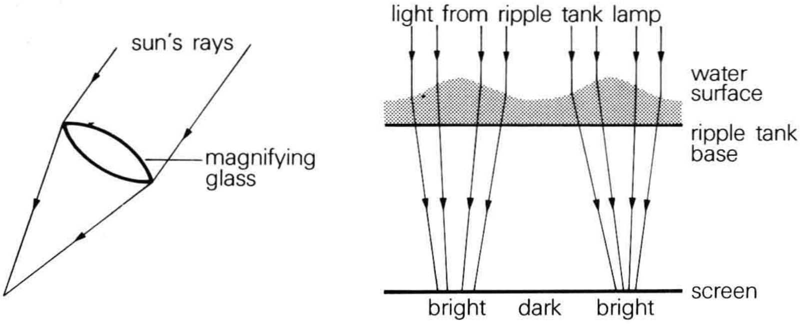
The properties of water waves are most easily studied in a ripple tank, Figure 2.1.

An image of the water waves is produced on the screen underneath the ripple tank. This image is formed by the light shining through the water on to the screen, and consists of a series of bright lines (corresponding to crests), with darker spaces in between (corresponding to troughs).

We can understand how this comes about if we consider how a magnifying glass is used to concentrate the Sun's rays, Figure 2.2. The curved lens of the magnifying glass bends the rays and brings them to a point. This process is called **focusing.**

Similarly in the ripple tank when the light from the lamp passes through the water, the curve of the water surface through which a wave is moving acts like a series of lenses and focuses the light to give a series of bright lines, Figure 2.3.

Figure 2.3



2.2 Generation of pulses

If a disturbance is created at a point on the surface of the water, a circular pulse travels out from that point. One way of creating such a disturbance is to allow a drop of water to fall on to the surface of the water, Figure 2.4. As the pulse travels out, it retains its circular shape; the boundary of this shape is called the **wavefront.**

The direction of travel of a pulse is always at right angles to the wavefront. Figure 2.5 shows a circular wavefront travelling out from O, and the arrows show the direction in which the different parts of the wavefront are travelling.

As a circular pulse spreads out, the circumference of the circle increases, and the amplitude of the wave decreases.

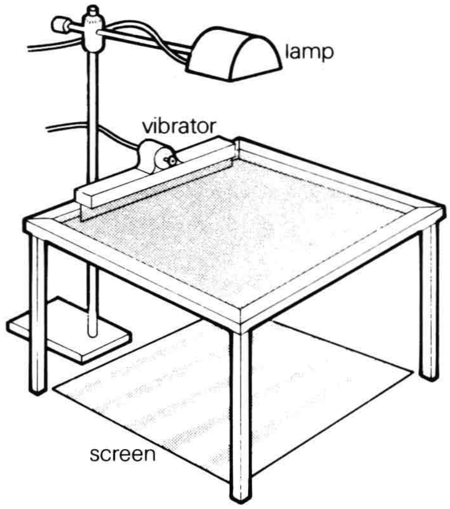


Figure 2.1 The ripple tank

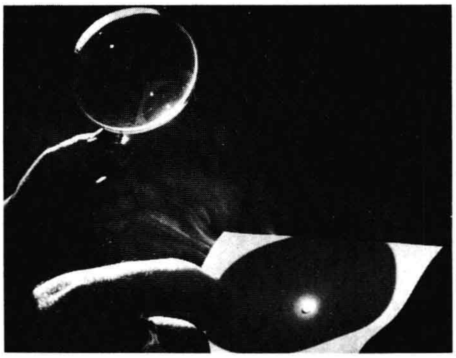


Figure 2.2

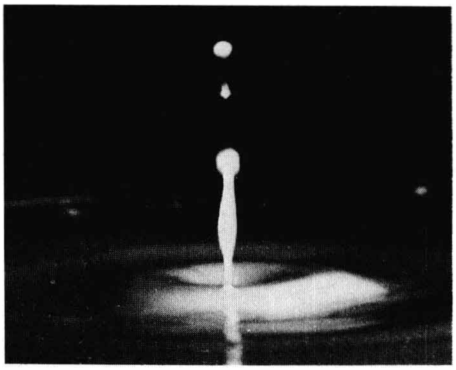
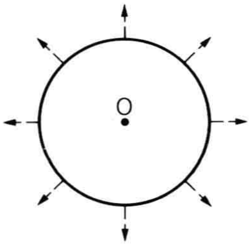


Figure 2.4

Figure 2.5



If a disturbance is created along a straight line on the surface of the water, a straight pulse is generated. This can be done by dipping a straight object into the water. The straight pulse that is generated continues to move across the surface of the water as a straight line. Again, the direction of travel is at right angles to the wave front, Figure 2.6.

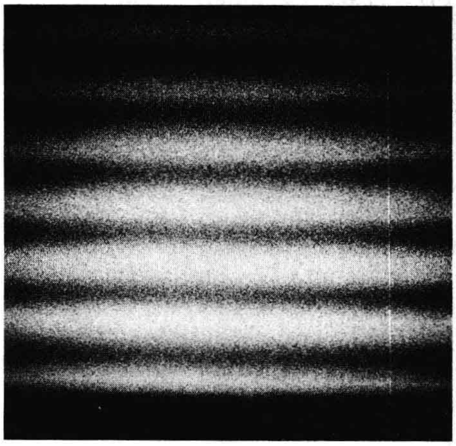


Figure 2.6

2.3 Reflection of pulses

When a barrier is placed in the path of a pulse, the pulse is reflected. Before it strikes the barrier the pulse is called the **incident pulse**; after it has been reflected the pulse is called the **reflected pulse**.

Figure 2.7 shows a circular pulse being reflected at a straight barrier. The incident pulse is circular, with a centre at O. The reflected pulse is also circular, with a centre at I. The points I and O are an equal distance from the barrier.

When a straight pulse is reflected by a straight barrier, the reflected pulse is also straight. Such a reflection is illustrated in Figure 2.8.

The **normal** is the line at right angles to the reflecting surface.

The angle between the path of the incident pulse and the normal is called the **angle of incidence** ($\angle i$).

The angle between the path of the reflected pulse and the normal is called the **angle of reflection** ($\angle r$).

Whenever a pulse is reflected, it is observed that the angle of incidence is always equal to the angle of reflection. This is called the **Law of Reflection** $\angle i = \angle r$.

Figure 2.9 shows two examples of straight pulses being reflected by curved barriers.

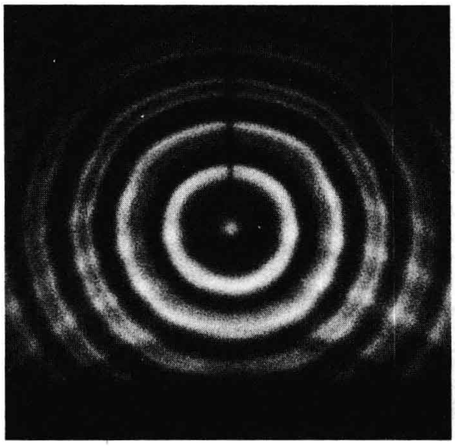


Figure 2.7

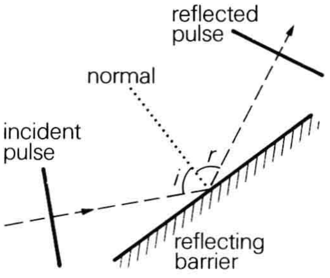
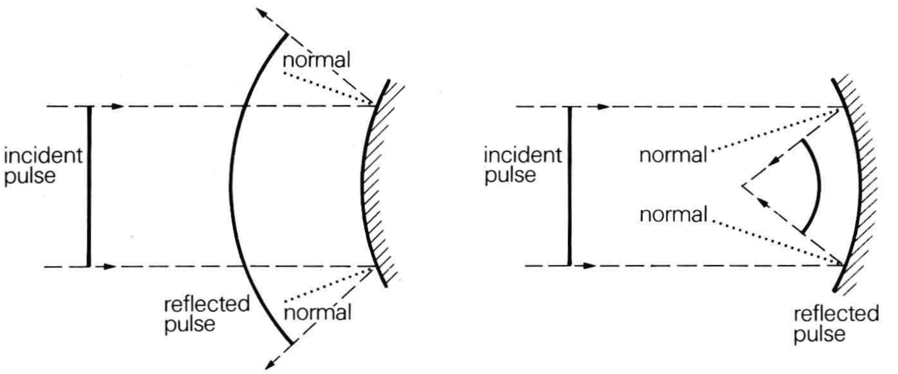


Figure 2.8

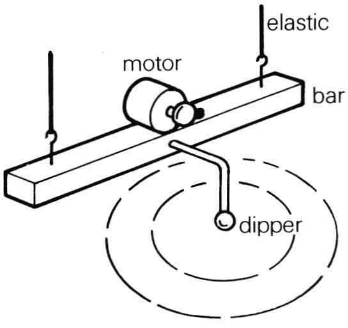
Figure 2.9


a) Reflection at a convex barrier **b)** Reflection at a concave barrier

2.4 Generation of continuous waves

Figure 2.10 shows an apparatus that can be used to generate continuous circular waves. As the electric motor rotates, it causes the bar to vibrate; these vibrations cause the dipper to move up and down in the water. The vibrations at a single point on the surface of the water generate a series of pulses which make up a continuous circular wave.

Figure 2.10



If the whole length of the bar is dipping in the water (Figure 2.11), the energy from the rotation of the motor is transmitted to the water along the length of the bar. This generates a series of straight pulses that make up a continuous straight wave.

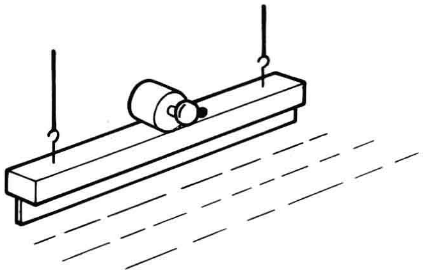


Figure 2.11

2.5 'Stopping' the wave pattern

It is difficult to observe and measure waves that are continuously on the move. One way of 'stopping' or 'freezing' the wave, when we wish to make observations, is to take a photograph and study it. In the laboratory we use a hand stroboscope to 'stop' the wave pattern. The hand stroboscope (Figure 2.12) consists of a disc with slits in it at regularly spaced intervals. If the disc is rotated in front of your eye, the scene appears whenever a slit is passing the eye but it is blocked for the rest of the time. If the stroboscope is rotated at a steady rate, you see the scene as a series of pictures separated by fixed time intervals.

Figure 2.13 shows how the stroboscope can 'stop' the wave pattern. Of course the wave does not actually stop, but to the observer it does appear to be stationary.

Figure 2.13

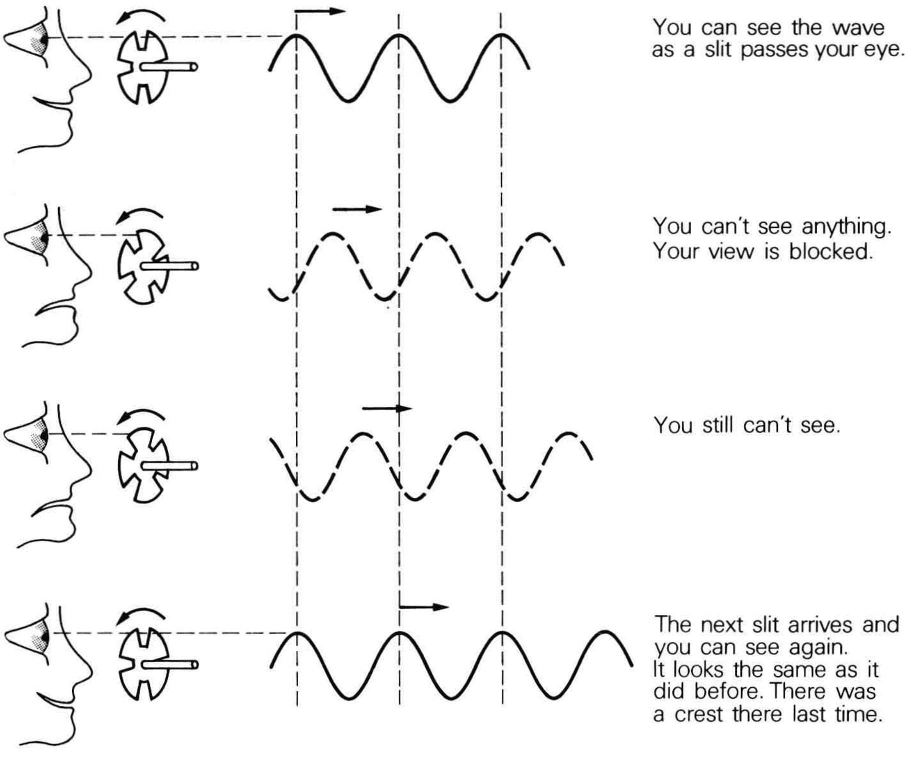


Figure 2.12 Hand stroboscope

If the frequency of the series of pictures seen by the observer is such that, whenever he sees the wave, there is a crest in the same position, the observer will see the wave standing still.

Using the ripple tank and the wave generator, we can now generate continuous waves and investigate their behaviour. In some cases it will be easier to make observations if we 'stop' the wave pattern by viewing it through a hand stroboscope. The word 'stroboscope' is often abbreviated to 'strobe'.