Physics Factsheet

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Experiments With Waves

A **ripple tank** is a simple and common way of demonstrating properties of waves, including reflection, refraction, diffraction and interference. The tank is shallow with sloping sides (to cut down on reflection when waves hit the sides) and with a transparent bottom so that a light source can be mounted below the tank, projecting a magnified image of the water waves onto a screen (usually the ceiling) above.

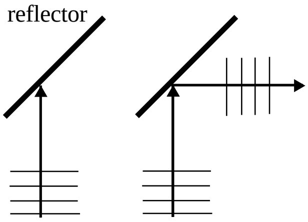
The movement of the waves can be 'stopped' for certain observations and measurements using a stroboscope – either a simple hand wheel with regularly spaced slits or an electronic stroboscope in place of the projection lamp. The stroboscope doesn't actually stop the wave movement, of course – it gives a series of 'snapshot' views of the wave timed at such a frequency that each snapshot is exactly one wave period after the previous one. This means that the viewer sees each wave crest in exactly the same position as the preceding wave – making it appear to be standing still. (Running the stroboscope slightly slower or slightly faster can give the appearance of slow forward or reverse movement of the waves – a fact well-known to cinema-goers used to seeing wagon wheels appear to spin backwards as the stagecoach slows down and the wheel movement 'strobes' with the frame frequency of the cine camera.)

Waves are usually generated by a small electric motor mounted on a wooden bar. The bar hangs by two rubber bands from a stable cross frame above one end of the tank. The motor has a weight attached to the axle, but the weight is mounted eccentrically (i.e. off-centre) so that it wobbles as it spins – and so, therefore, does the wooden bar. The bar can be lowered so that it touches the surface of the water in the tank – causing parallel plane waves to be generated at the frequency of rotation of the motor. Alternatively, one or more small plastic dippers – in the shape of small balls – can be fixed into holes in the bar and the height adjusted so that the dipper(s) just touch the surface. This produces a point source of waves which spread out as a series of concentric circles.

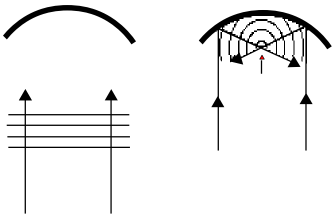
A range of accessories may then be placed in the path of the waves to demonstrate the various properties of waves.

Reflection

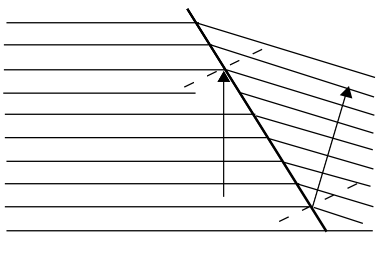
from a plane reflector



or a curved reflector

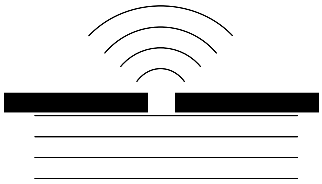


Refraction

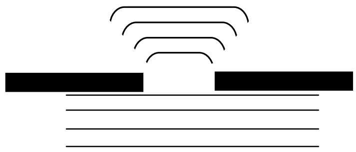


Diffraction

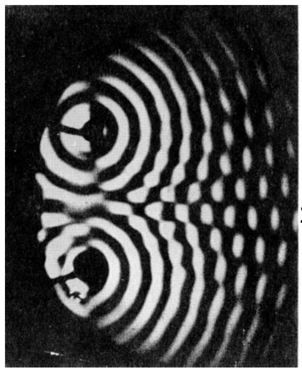
at a narrow gap

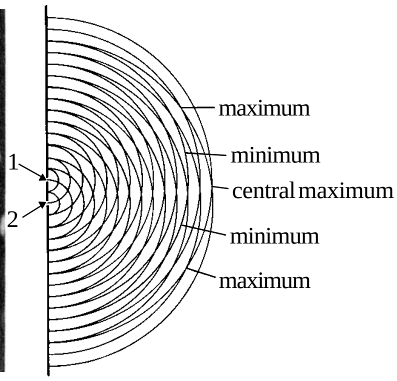


a wide gap



Interference





The ripple tank demonstrates wave properties in water waves – which have wavelengths large enough to be seen clearly. However, once the effects of wave properties have been understood, those *effects* can be recognised, observed and investigated using other types of waves even when the wavelengths involved are either too large or too small for the individual *waves* to be seen.

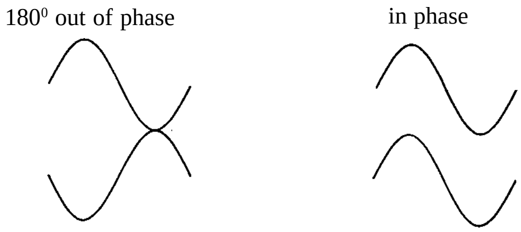
Wave properties in light waves - using a laser

A laser produces a convenient narrow, strong, sharply focussed beam of light – and so in reflection and refraction experiments it can replace the simple ray which uses a low voltage electric lamp. However, the laser really comes into its own when used in diffraction and interference experiments.

> ***Safety note:** The typical popular (science fiction) understanding of a laser is that it will cut through a sheet of metal. Although such lasers exist, you will be pleased or disappointed to find that the one you will use does not produce anything like this sort of power. It is, however, powerful enough to do serious and permanent damage to the retina of the eye if you look directly into the beam. Don't try it – and make sure the experimental set-up doesn't allow anybody else to try it either, intentionally or otherwise! If the beam reflects off a highly reflective surface (like a mirror or glass window) it can be just as dangerous.*

For interference between two wave sources to be observed, those sources need to be **coherent**. Two waves are said to be coherent when they have the same wavelength and frequency and a *constant phase relationship* to one another.

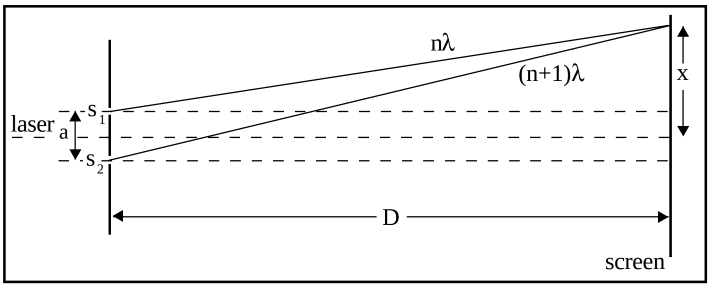
The phase relationship refers to the relative position of peaks and troughs of two waves. If the peaks of both waves occur at the same position, then the waves are said to be *in phase*. If the peaks of one wave coincide with the troughs of the other, then they are exactly *out of phase*, or *180° out of phase*.



Producing two coherent sources of water waves is not too difficult – using the ripple tank arrangement described above, the wooden bar simply has two plastic dippers placed in it, both touching the surface of the water. When the motor wobbles, so does the bar and so do the dippers – all together. Producing two coherent sound waves is not too difficult either – just connect two loudspeakers to the same amplifier output (i.e. mono, not stereo!). However, two coherent light sources are a different problem altogether. An ordinary light bulb of the type used in a laboratory ray box emits a wide range of light frequencies. Even passing the light through a colour filter still leaves a range of frequencies too wide for interference effects to be seen. The effect of interference at one frequency is alongside the same effect for a slightly different frequency – and each effect would be masked by all of the others.

To make a comparison with sound waves, the light bulb is like hitting all the notes on a piano at the same time – producing a noisy chord (or discord!) of lots of different frequencies all at once. To hear clear sound effects, it is necessary to pick out a single frequency – like a single note on the piano, or better still a tuning fork. The laser is rather like a tuning fork for light waves – it emits a very pure, narrow frequency of light. Even so, buying two similar lasers and putting them alongside one another would not guarantee coherent waves. A simple but clever trick is to shine one laser beam through two narrow, parallel slits, usually mounted in a projector slide (the arrangement is known as *Young's slits*, named after the inventor). The light waves diffract (spread out slightly) as they pass through the slits and become two beams and, since they have come from the same single source, they **must be** coherent.

The coherent waves are projected onto a screen several metres away from



the laser – which could be the opposite wall – and maxima and minima are observed as clear patches of bright light and darkness. These represent the positions where the waves are exactly in phase or exactly out of phase respectively – just as seen with the ripple tank interference experiment above. This equation describes the relationship between the various measurements which may now be taken, where:

The equation: $\lambda = \dfrac{ax}{D}$ *describes this relationship*

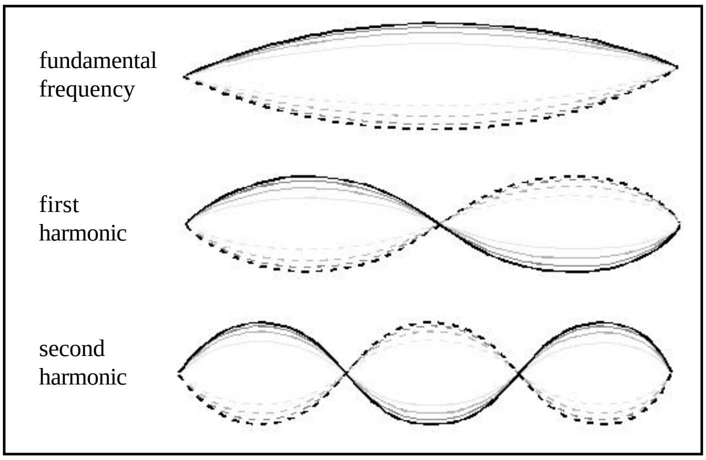
where: λ = wavelength
a = *separation of the slits (m)*
(distance between the centres of the two slits)
x = *distance between successive fringes*
D = *distance from the slits to the screen (m)*

Stationary waves experiments

Stationary waves offer a number of interesting experimental possibilities. They enable certain key measurements to be taken with a degree of accuracy difficult or impossible when dealing with travelling waves. A stationary wave can arise when a wave travelling in one direction along, or through, a particular medium, interferes with a second wave, similar in every respect to the first but travelling in the opposite direction. In practice, the 'second' wave is often in fact the first wave returning after reflection from an end or fixed point of the wave guide or wave medium.

The stationary wave has fixed nodes – positions of zero amplitude – and antinodes – positions of maximum amplitude. Often, we have a situation where only certain clearly defined frequencies can exist in a stationary wave.

Example – a vibrating string, fixed at both ends (like a guitar string)



A simple experimental way to investigate standing waves with two fixed ends is to set up a stretched cord between two fixed points several metres apart. This can be thin rubber cord, square or circular in cross-section and of about 5mm diameter fixed to two rigid supports (which might be clamp stands clamped tightly, to the benchtop); or it might be thin string, in which case at least one end needs to run over a pulley and then be loaded with a small mass – the mass may then be adjusted to change the tension in the string, one of the factors affecting the fundamental frequency of vibration.

Close to one of its ends, the string needs to pass through the top of a vibration generator which is driven by a signal generator producing a sine wave output of variable frequency.

The string will resonate (vibrate with large amplitude – as shown in the diagram showing 'fundamental frequency) when the driving frequency is equal to the fundamental frequency of the string set-up. In this condition, the stationary wave has only two nodes – the two ends of the string – and one central antinode. The wavelength is easily calculated, since the full length of the string is exactly equal to half of one wavelength. The frequency of the vibrations may be measured by feeding the output of the signal generator into an oscilloscope or a frequency meter; or by the use of a calibrated stroboscope. (The flash rate of the stroboscope is increased slowly until the vibrations appear to 'stand still'.)

The wave equation (speed = frequency × wavelength) may be used to calculate the speed of wave travel along the string. A number of investigations are possible with this set-up, by changing the tension in the string, or the mass per unit length of the string, or the length of the string.

Doubling the driving frequency will produce a stationary wave of the first harmonic as shown in the diagram above – the full length of the string now corresponds to one full wavelength. (This corresponds to playing a note one octave higher than the fundamental on a musical string instrument.) Three times the frequency gives the second harmonic – with three half-wavelengths fitting into the length of the string, and so on. It is relatively easy to get up to the tenth or even the fifteenth harmonic with a light string or elastic cord. Experiment with different coloured backgrounds and lighting to see the stationary waves most clearly – it is sometimes easier to see the wave pattern whilst looking along the string from one end.

Measuring the speed of sound

The speed of sound may be measured by setting up a small region of stationary sound waves inside the laboratory. Sound is produced by a signal generator driving a loudspeaker – at a fairly high audible frequency, say 3000Hz. A wooden board or convenient wall about 1.5m from the loudspeaker is used to reflect (echo) the sound waves back. A standing wave pattern now exists between the loudspeaker and the reflecting surface. A microphone is mounted in a clamp stand so that it can be moved and rested in positions between the loudspeaker and the reflector.

An oscilloscope is used to display the output from the microphone. If the microphone is slowly moved towards the loudspeaker it will be noticed that the amplitude of received sound goes through maxima and minima of amplitude. (It is worth pushing the clamp stand holding the microphone with a metre rule to cut down on reflection of sound from your arm and body.) The distance between successive maxima is one half-wavelength. (Moving the microphone through about ten successive maxima and dividing that distance to find one wavelength can reduce the error.) Frequency of the sound waves can be measured directly from the oscilloscope. The wave equation may now be used to calculate the speed of the sound waves.

Resonance in air columns

Stationary waves in air columns (such as organ pipes or other wind instruments) differ from those set up in stretched strings because different sets of harmonics are 'allowed' by the physical constraints of the medium. This is the main reason why a particular note played on a string instrument sounds different from the *same note* played on a wind instrument – the fundamental frequency is the same but the pattern of harmonics which overlay that note (at lower amplitudes) are different. This pattern of harmonics is known as the 'quality' or sometimes the 'timbre' of the note. A hollow cylinder containing a column of vibrating air is normally closed at one end and open at the other – so, whilst one end (the closed end) corresponds to a node of the stationary wave pattern, the open end corresponds to an antinode. This means that the lowest (fundamental) frequency allowed is when one *quarter* of a wavelength is contained within the air column. The first harmonic is when three-quarters of a wavelength is equal to the length of the air column, and subsequent harmonics correspond to five-quarter wavelengths, seven-quarter wavelengths and so on.

In a wind instrument, the air column is normally set vibrating by resonance from a small oscillator at one end – which may be a reed (as in some woodwind instruments) or even the musician's lips (brass instruments). This may be modelled by a tuning fork, or a small loudspeaker driven by a signal generator, placed at the open mouth of the air column.

One way to set up the air column with variable length is to have two lengths of glass tubing, one of which fits *inside* the other. The wide-bore tube is mounted vertically (supported by a clamp) and the bottom end plugged with a rubber bung or cork. The tube is then filled – not quite to the top – with water. The narrower tubing is then lowered inside the water-filled tube and the top end held with a clamp and clamp stand.

The air column to be used is then inside the narrow tube – the bottom surface being the surface of the water. The length of the air column can now be easily adjusted by simply adjusting the height of the narrow tube and re-clamping. A metre rule may be mounted outside the tubing for easy measurement of the air column length. The tuning fork or loudspeaker is placed at the top (open) mouth of the air column and the length of the column adjusted until the sound gets noticeably louder – this means that the air column is resonating. Alternatively, the air column may be left at the same length and the frequency of sound from the loudspeaker changed until resonance occurs. Once again, a variety of investigations are possible with the arrangement.

Microwave experiments

Most laboratory microwave transmitters and receivers work at a wavelength of around 3cm – which is a very convenient and measurable size for many experiments.

Receivers usually come in two forms – one with a directional collector (rather like a square funnel) and a probe type which is good for finding the strength of a signal at a point. Both types of receiver usually have an output which can be connected to a sensitive microammeter so that relative signal strength can be measured.

The transmitter and receiver arrangement can be used for many kinds of wave experiment – including investigation of reflection (microwaves will reflect well off a metal sheet), refraction, diffraction and interference. The convenient wavelength of the microwaves usually means that measurements of suitable accuracy may be made with simple apparatus such as a metre rule. Apparatus suitable for diffracting and refracting microwaves are usually available from the supplier of the 3cm wave transmitting and receiving equipment.

Practice Questions

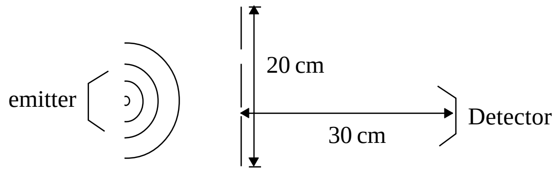
1. A pair of parallel slits are illuminated with light from a sodium vapour lamp of frequency 5.09×10^{14}Hz. A series of light and dark fringes is projected on to a screen 1m from the slits.
   (a) Explain why a bright fringe is always found at the centre of the pattern [3]

   (b) The distance between the central bright fringe and the adjacent bright fringe is 1mm. How far apart are the slits? ($c = 3 \times 10^8 \text{ms}^{-1}$) [4]

2. (a) 'Waves from two sources can only combine to form a stable interference pattern if they are coherent.' What does 'coherent' mean? [2]

   (b) A student sets up two loudspeakers to perform an experiment on the interference of sound. The loudspeakers produce sound waves with the same frequency, which is known to be below 1kHz. She finds a point of annulment, i.e. a point where the noise level is very low, at 3m from one speaker and 2m from the other. Determine all possible frequencies at which the speakers could have been oscillating. Take the speed of sound in air as *340ms*$^{-1}$ [4]

3. Microwaves with a wavelength of 6cm are directed towards a metal plate. The plate is 20cm wide and has two parallel slits in it. An interference pattern is formed on the far side of the plate.



   (a) A microwave detector is placed 30cm directly in front of one of the slits. The detector gives a zero reading.
      (i) Comment on the phase difference between the waves from each slit at this point and hence explain why the detector gave a reading of zero [2]

      (ii) Calculate the distance between the slits [4]

   (b) What would happen to the interference pattern if the plate was rotated through an angle of 90^0? Explain your answer [3]

4. (a) Explain the difference in terms of energy, between progressive (travelling) and stationary (standing) waves [2]

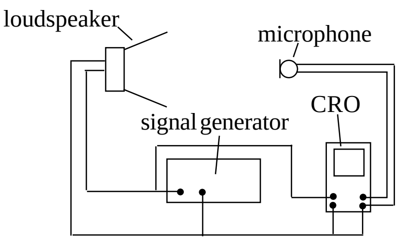
   (b) The velocity v of a transverse wave on a stretched string is given in the formula: $$v^2 = \frac{T}{\mu}$$
   where T is the tension in the string and μ is the mass per unit length. Use this equation to derive an expression for the fundamental frequency of a vibrating wire in terms of T, μ and its length, L[2]

   (c) A violin string is 35 cm long and has a mass of 2.25 g. It produces a note of frequency 256 Hz when sounding its first overtone. Find the tension in the string [4]

Exam Workshop

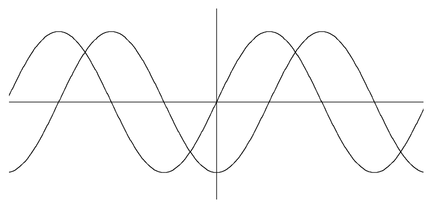
This is a typical weak student's answer to an exam question. The comments explain what is wrong with the answers and how they can be improved. The examiners' mark scheme is given below.

The equipment shown in the diagram is set up for an experiment.



(a) The CRO displays two traces: one directly from the signal fed to the loudspeaker, the other from the microphone.

(i) Draw a labelled diagram of a typical display you would expect to see on the CRO **[3]**



2/3

Correct! but the student hasn't *labelled* the diagram – a common mistake!

(ii) State two aspects of this display that would change as the distance between the loudspeaker and microphone is increased **[2]**

the phase difference between the waves increases
the amplitude of microphone signal decreases 2/2

Correct - 2 marks

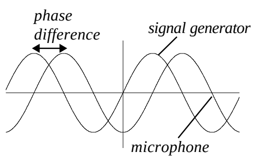
(b) Explain how the CRO measurements can be used to find the wavelength of the sound **[5]**

Gradually move microphone away for the speaker Each time traces are in phase the microphone has moved one wavelength. Count the number of wavelengths moved. Measure distance moved and calculate wavelength 4/5

Correct method, but the student did not state that the traces must be in phase before the microphone is moved

Examiner's answers

(a) (i) Two traces drawn, out of phase ✓✓
Labels shown ✓



(ii) Phase difference increases ✓
Amplitude of microphone signal decreases ✓

(b) Place microphone so traces are in phase ✓
Gradually move microphone away ✓
Each time traces are back in phase, microphone has moved one wavelength✓ Count the number of wavelengths moved ✓
Measure distance moved and calculate wavelength ✓

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Answers

1. (a) At the centre of the pattern, waves from each slit have travelled equal distances. i.e. path difference is zero ✓
This implies that the phase difference is zero ✓
Thus constructive interference will always occur at the centre of the pattern, producing a bright fringe ✓ [3]

(b) $\lambda = \frac{c}{f} = \frac{3\times10^8}{5.09\times10^{14}} = 5.89\times10^{-7}$m ✓
Let y = distance between the bright fringes
d = distance between slits
D = distance between slits and screen
m = order of the fringe counting outwards from the central bright fringe

$y = \frac{m\lambda D}{d}$

When $m = 1$, $d = \frac{\lambda D}{y}$ ✓

$d = \frac{5.89\times10^{-7}\times1}{1.0\times10^{-3}}$ ✓

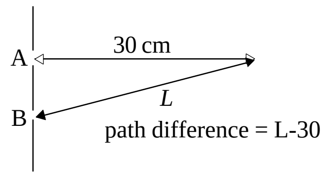
$d = 5.89\times10^{-4}$m ✓ [4]

2. (a) Waves from two sources are coherent if:
Their frequencies are equal ✓
The phase difference between them is constant ✓ [2]

(b) 'Annulment' or cancellation implies the path difference is an odd number of half wavelengths, i.e. $\lambda/2$, $3\lambda/2$, $5\lambda/2$, $7\lambda/2$, etc.; ✓
The path difference = 1m
Hence: λ = 2m, 2/3m, 2/5m, 2/7m, etc. ✓
Using $f = v/\lambda$, gives the following possible frequencies:
170Hz, 510Hz, 850Hz, 1190Hz, etc. ✓
As we know that the speakers were oscillating below 1kHz, the only possible frequencies for the sound are: 170Hz, 510Hz, 850Hz ✓ [4]

3. (a) (i) The waves from the two slits must be in anti-phase at this point✓
i.e. phase difference of π radians, giving destructive interference✓ [2]

(ii) The path difference from each of the slits must be an odd number of half wavelengths ✓



Smallest possible path difference = $\lambda/2$ = 3cm ✓
Then $AB^2 = 33^2 - 30^2$, AB = 13.75cm ✓
The next possible path difference, $3\lambda/2$ gives AB = 25cm which is greater than the width of the plate ✓ [4]

(b) The pattern would vanish. ✓ Microwaves are transverse and polarised. ✓ With the plate turned through 90°, the microwaves cannot pass through the slits ✓ [3]

4. (a) Progressive waves show net displacement of energy from one place to another✓ Stationary waves maintain energy within a boundary and hence no net displacement energy occurs ✓ [2]

(b) In fundamental mode $L = \frac{\lambda}{2}$

$\lambda = 2L$ ✓

$f = \frac{c}{\lambda} = \frac{1}{2}L\sqrt{\frac{T}{\mu}}$ ✓ [2]

(c) First overtone $L = \lambda$✓

$T = v^2u = f^2\lambda^2\mu$ ✓

$T = f^2L^2\frac{m}{L} = f^2Lm$ ✓

$T = 256^2\times0.35\times2.25\times10^{-3}$

$T = 52$N ✓ [4]