Unit 3. Waves

Y12

Table of contents

1 Wave Basics

What is a wave? How many types of waves are there? Why are they useful?

→ **Wave:** transfer of energy without matter (by transmission of oscillations):

- Mechanical: oscillations of the medium.
- Electromagnetic: oscillations of fields (electrical or magnetic).

1.1 Analysis of a Wave

- Displacement x (m): distance to the equilibrium (average) position.
- Amplitude A (m): maximum displacement of a wave.
- Frequency f (Hertz Hz): number of cycles through a point per second.
- Wavelength λ (m): distance between 2 equal waypoints (eg 2 peaks). Figure 1

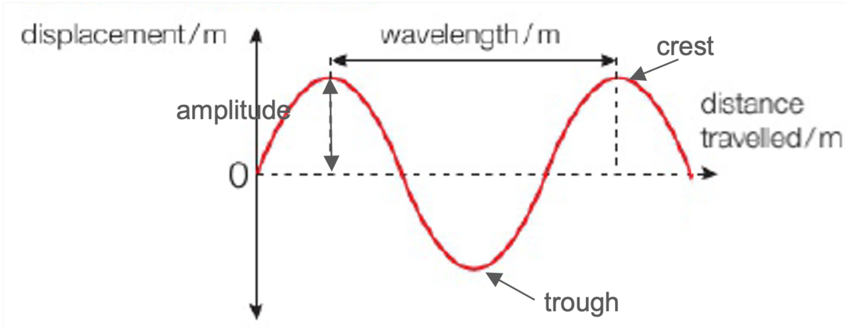

Figure 1: wave components 1

- Period T (s): time for 1 full oscillation or wavelength. Figure 2
- Phase θ (rad): stage of wave at a point (~ angle around a circle, we will see it...).
- Wave speed v (m/s): $v = \frac{d}{t}$ and also $v = f\lambda$ (Wave equation)
- Pulse-echo measurements (like bat and dolphin echolocation): emit a pulse of ultrasound (50-100kHz) and calculate $d = vt/2$ (rebound).

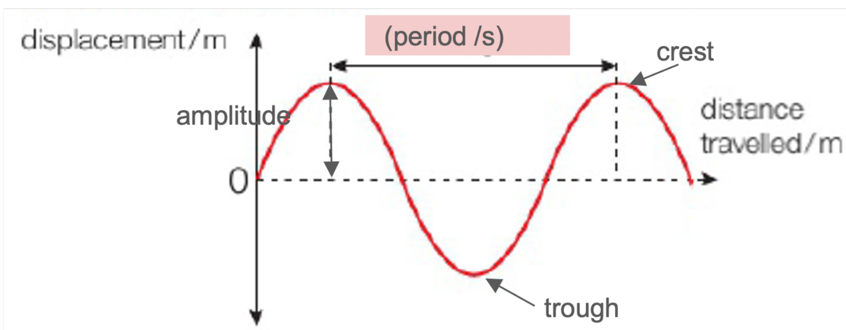

Figure 2: wave components 2

Checkpoint questions. (Extra: Read the experiment p.91, draw the wave diagram).

Answers

1. Graph from top to bottom: $0.2m$, $80m$, $5.5m$.
2. $1240m$ ($d = v \cdot t$)
3. $8.5 \cdot 10^{14} Hz$ ($f = c/\lambda$, wave equation)
4. As frequency is defined as waves per second, multipliying frequency by wavelenght is equivalent as dividing distance by time (velocity)
5. Student's own answers using $v = f \cdot \lambda$. Eg. estimated wavelenght is $5m$, estimated frequency is 1 wave every 3 seconds, so $f = 0.33Hz$. $v = f \cdot \lambda = 0.33 \times 5 = 1.7m\ s^{-1}$

2 Wave types

2.1 By oscillation plane

According to the oscillation plane, compared with wave displacement, we find transverse and longitudinal waves.

Do you know what transverse and longitudinal means?

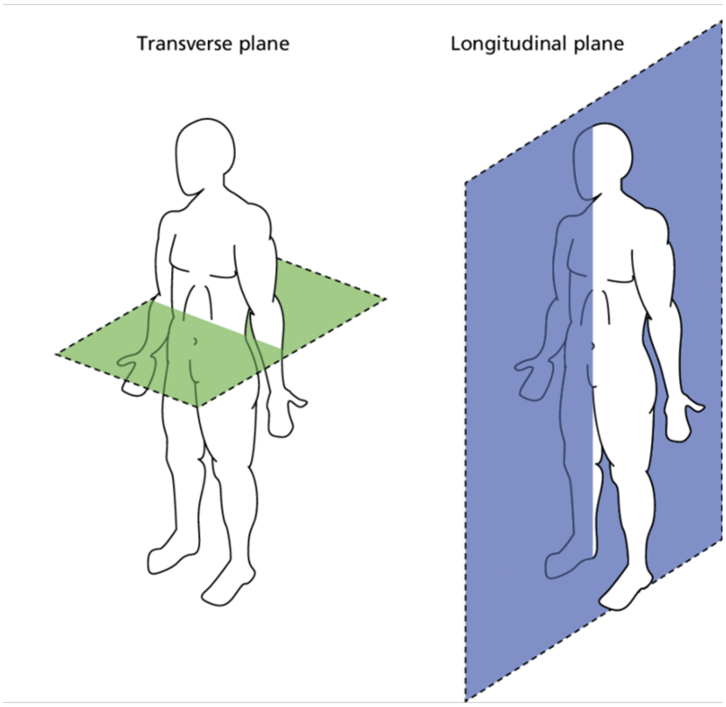

Figure 3: Transverse and longitudinal planes

→ Transverse wave: motion is perpendicular to displacement (up/down). Eg ropes, electromagnetic waves (light), earthquake S-waves.

→ Longitudinal wave: motion is parallel to displacement (front-back). Eg sound waves (compressions vs rarefactions), earthquake P-waves.

Both kinds of waves are represented in the same graphs.

- Compression: area at higher pressure (molecules closer together).
- Rarefaction: area at lower pressure (molecules further apart).

Watch this video

Minipractical: flick a string on top of the table and let it stop. Waves should remain visible. Measure the time for 10 "flicks" (oscillations) to calculate the frequency ($\frac{1}{T}$), and with a ruler the amplitude and wavelength. From this calculate the speed.

3 Wave Phase, Superposition

What is the phase in a wave? Why is it useful?

What is superposition? How can superposition apply to waves?

3.1 Phase

Phase (φ in radians) measures the wave position compared to a circular movement.

- Phase of 1 cycle (wavelength, λ) = 360° or $2\pi rad$.

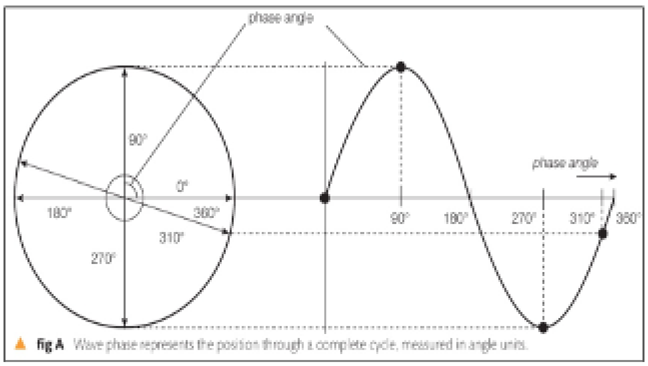

Figure 4: Phase compared to circular movement

- More than 1 cycle is expressed as the equivalent of the first cycle Eg: $450^\circ = 360^\circ + 90^\circ \rightarrow 90^\circ$; $2.5\pi\ rad = 2\pi\ rad + 0.5\pi\ rad \rightarrow 0.5\pi\ rad$.

  The phase between two point can be measured_ $\Delta\varphi_{twopoints} = 2\pi\frac{\Delta d(m)}{\lambda}$. Figure 7 and Figure 8

Watch this video.

3.2 Interference

- **Wavefront:** lines/surfaces with the wave at the same point Perpendicular to displacement of the wave.
- **Superposition:** if waves coincide in the same point, the amplitude of the different waves add. $Amplitude_T = \sum A_i$. But displacement does not change.

$\rightarrow$ In pulses, waves pass through each other. Figure 5

$\rightarrow$ In continuous waves they do interfere (create a new wave, A_T). constructive ($A_T > A_i$) or destructive ($A_T < A_i$). It depends on the A_i and on the phase difference ($\Delta\theta$). Figure 6

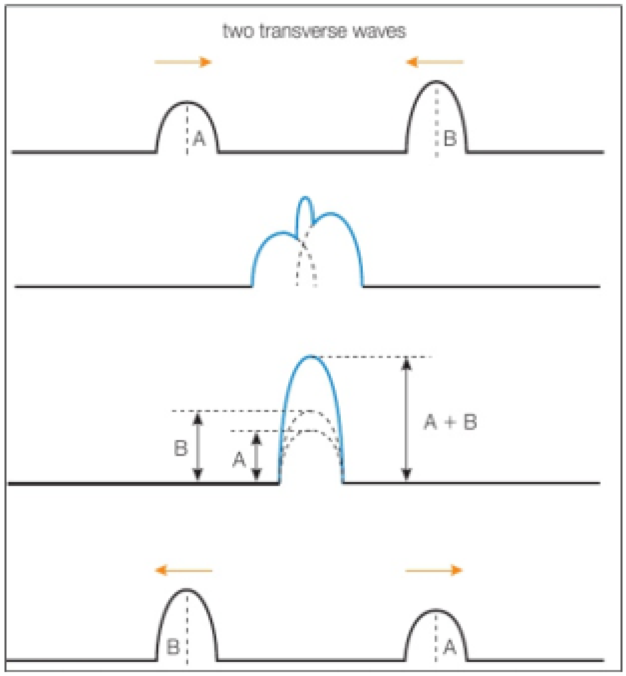

Figure 5: Waves add amplitude

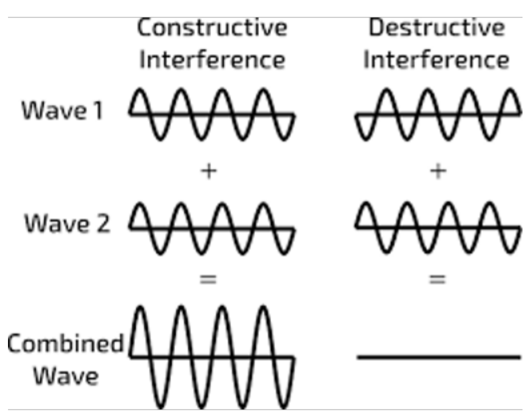

Figure 6: Constructive and destructive interference

> **!** Important
>
> **NOT REQUIRED FOR UK:** The general equation of a wave is
>
> $$y(x,t) = A \cdot sin(2\pi \frac{x - vt}{\lambda}) = A \cdot sin(2\pi \frac{x}{\lambda} \mp \omega t + \varphi_0) = A \cdot cos(2\pi \frac{x}{\lambda} \mp \omega t + \varphi_0 - \frac{\pi}{2})$$
>
> Also, $T = \frac{2\pi}{\omega} = \frac{1}{f}$ with $-$ = moving forward; $+$ = moving backward; $v = \frac{\omega\lambda}{2\pi}$.

4 Stationary waves

What are coherent waves?

Coherent waves: same frequency and "constant phase relationship" (=wavelength, so they stay in sync).

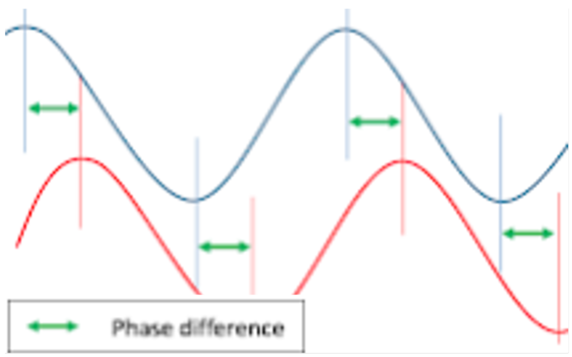

Figure 7: Constant phase shift

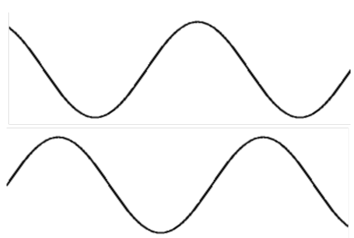

Figure 8: Constant phase in movement

Stationary ("standing") wave: superposition of opposite direction coherent waves. At points with opposite phase the interference results in no movement ("nodes"). Points with maximum amplitude are "antinodes". Total transfer of energy = 0 J (the net result is not a wave!).

Progressive waves do transfer energy. Watch here.

Harmonics: In physics, a harmonic is a sinusoidal wave with a frequency that is a positive integer multiple of the fundamental frequency of a periodic wave. The fundamental frequency is also called the 1st harmonic; the other harmonics are known as higher harmonics. As all harmonics are periodic at the fundamental frequency, the sum of harmonics is also periodic at that frequency. The set of harmonics forms a harmonic series.

Half-wavelengths that fit in a stretch of string L (Figure 9): "1st" or fundamental harmonic, $f_0 \rightarrow 0.5\lambda = L$

"2nd": $\lambda = L$

"3rd": $1.5\lambda = L$... etc.

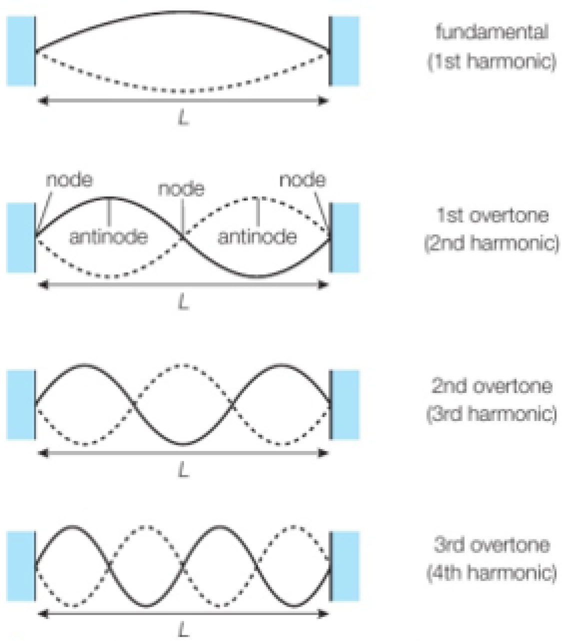

Figure 9: Harmonics

Basis for Comparison	Stationary Wave	Progressive Wave
Also called	Standing wave	Travelling wave
Basic	Energy is confined within the medium	The transfer of energy from a location to another within the medium takes place
Molecular vibration	Each particle of the wave exhibits different vibration at same instant of time	Each particle of the wave possesses similar vibration at different instant of time
Amplitude characteristic of particles	Different	Same
Motion	Not transferable among the particles	Easily transferred among the particles
Velocity at mean position	All particles have their own maximum velocity	All particles have similar maximum velocity

Basis for Comparison	Stationary Wave	Progressive Wave
Crests and Throughs	The crests and trough of the waveform appear and disappear at the initial position	The crests and troughs of the waveform move in the forward direction
Wavelength	Double the distance present between 2 consecutive nodes or anti-nodes	The distance between point of similar phase at the similar time instant

5 Diffraction

What is diffraction? Factors that affect diffraction.

How does sound spread out from a source?

Can sound go around a solid object? How?

It spreads in circles.

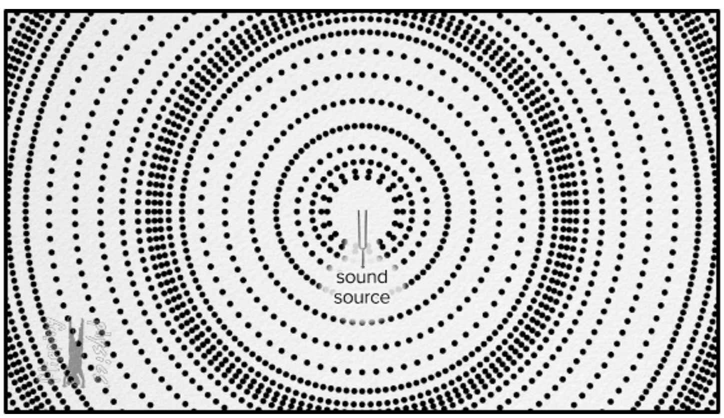

Figure 10: Circular emission

Frontwaves can go through obstacles.

For a discussion about wave propagation and how the Huygens Principle works, see here.

Diffraction: bending of waves around obstacles or through gaps into the "shadow areas" (behind the obstacle). Diffraction is maximum if $L_{gap} = \boldsymbol{\lambda}$ (waves bend most); this means that he smaller the wavelenght, the smaller has to be the slit for the diffraction effect to be noticeable.

Diffraction patterns are created by wave interference (adding and subtracting of waves when they interact.

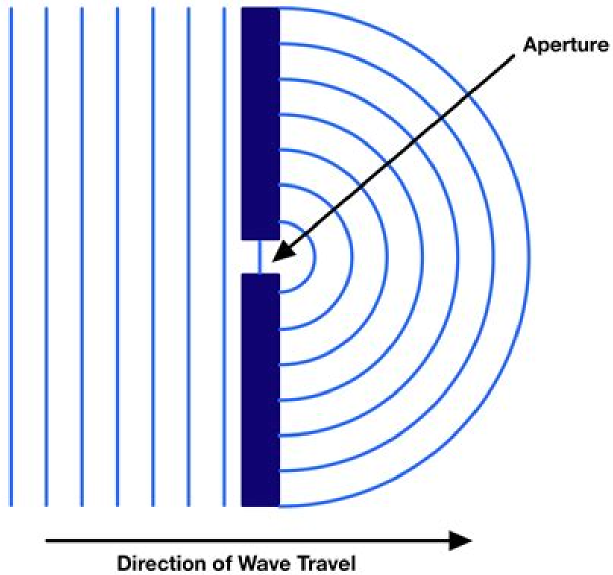

Figure 11: Diffraction through a slit

Maxima $\rightarrow$ intense points. Brightness of each maxima decreases as we move away from the center.

Minima $\rightarrow$ dark/low points.

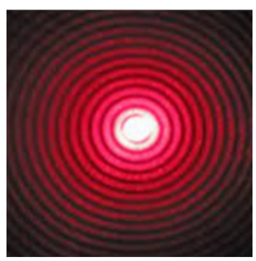

Figure 12: Diffraction patterns

To generate different patterns we use diffraction grating: many parallel slits at exact same distances to maximise separation of different colours (due to different λ).

$sin\ \theta = N\frac{\lambda}{d}$, where θ is the angle between the horizontal and the measured maxima ($N = 1, 2 ...$), N is the order of the maxima and d the separation distance for the grating. As you can see, the higher is λ, the more the ray bends (Figure 13).

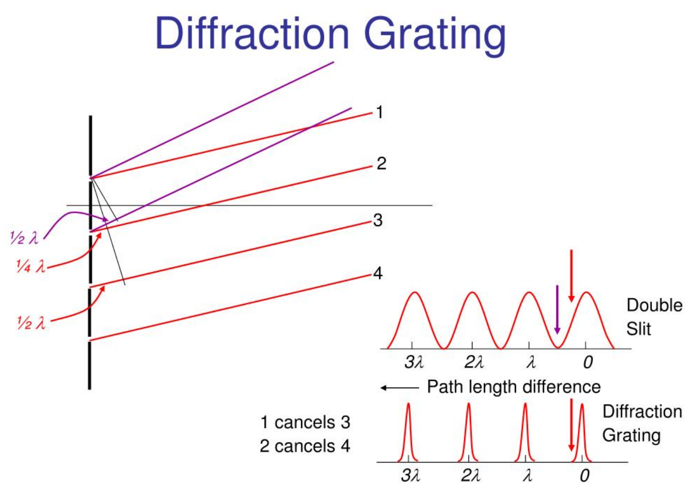

Figure 13: Diffraction grating