### I. DIFFERENT TYPES OF WAVES
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- B. WAVE PULSES AND TRAVELLING WAVES
- C. SOUND AND WATER WAVES

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### I. DIFFERENT TYPES OF WAVES
- A. TRANSVERSE AND LONGITUDINAL WAVES
B. WAVE PULSES AND TRAVELLING WAVES

Source: Physics for the IB Diploma, 5th Ed, Tsokos
EXAMPLE 1
The diagram shows a transverse wave on a string. The wave is moving from right to left. In the position shown, point X has zero displacement and point Y is at a position of maximum displacement. Describe the subsequent direction of motion of point X and of point Y (upward, downward, right, left...).

EXAMPLE 2
A wave travels along a stretched string. The diagram shows the variation with distance along the string of the displacement of the string at a particular instant in time. A small marker is attached to the string at the point labelled M. The undisturbed position of the string is shown as a dotted line.

a) On the diagram:
(i) draw an arrow to indicate the direction in which the marker is moving.
(ii) indicate, with the letter A, the amplitude of the wave.
(iii) indicate, with the letter λ, the wavelength of the wave.
(iv) draw the displacement of the string a time T/4 later, where T is the period of oscillation of the wave. Indicate, with the letter N, the new position of the marker.

b) The wavelength of the wave is 5.0 cm and its speed is 10 cm s⁻¹. Determine
(i) the frequency of the wave. [2.0 Hz]  
(ii) how far the wave has moved in T/4 s. [1.3 cm]
C. SOUND AND WATER WAVES

Sound = a series of successive high/low air pressure zones (longitudinal wave) also called compressions (high pressure) and rarefactions (low pressure).

Speed of waves depends on the properties of the medium (material) through which they are travelling. Lighter spring = faster wave speed. Hot air carries sound more quickly than cold!

DEMO: Musical instruments. Tuning forks though air and through table/solids.

Water waves: neither transverse nor longitudinal. Water particles near the surface move in a circular path, giving the water particles both transverse and longitudinal components. But we treat water waves as transverse in nature.

DEMO: Water in a tank with a light.

II. DEFINING TERMS

Source: Physics, 8th Ed, Cutnell & Johnson
Source: Physics, 8th Ed, Cutnell & Johnson
Source: Physics for the IB Diploma, 5th Ed, Tsokos
There are several key features of waves you need to know:

1. **Amplitude (A)**: The maximum displacement of the particle in the wave from the equilibrium/mean position (which is not always zero).

2. **Displacement (s)**: The change in distance (+ or -) that takes place on a particle from the wave passing through it.

3. **Frequency (f)**: The number of oscillations that take place in one second (the number of complete waves that pass through a fixed point in one second; \( f = \frac{1}{T} \)).

4. **Period (T)**: The time taken for one complete oscillation (time taken for one complete wave to pass a fixed point; \( T = \frac{1}{f} \)).

5. **Wavelength (\( \lambda \))**: The horizontal length of one cycle of the wave (distance between successive crests/troughs).

6. **Wave speed (v)**: Speed at which the wave fronts pass a fixed point.

7. **Intensity (I)**: The power per unit area that is received through the wave (\( I = \frac{\text{Power}}{\text{Area}} \)). Intensity is proportional to \( A^2 \).

It should be clear that:

**EXAMPLE 3**
The crests on a long surface water wave are 20.0 m apart, and in 1 minute 10 crests pass by. What is the speed of these waves? \[3.4 \text{ ms}^{-1}\]

**EXAMPLE 4**
In the diagram below, the distance between points A and B on water waves is 5.0 meters.

a) What is the wavelength of these water waves? \[2.0 \text{ ms}^{-1}\]

b) If 5 waves pass point B every 15 seconds, what are the frequencies of these waves? \[0.3 \text{ Hz}\]

c) What is the period of one wave? \[3.0 \text{ s}\]

d) What is the speed of one wave? \[0.6 \text{ ms}^{-1}\]
EXAMPLE 5
A radio wave, a form of electromagnetic wave, has a frequency of 99.5 MHz (99.5 x 10^6 Hz). What is its wavelength? [3.0 ms]

EXAMPLE 6
Water waves in a lake travel 4.4 m in 1.8 s. The period of oscillation is 1.2 s. What is the speed of the water waves? What is their wavelength? [2.4 ms^-1, 2.9 m]

III. GRAPHS OF WAVES

A. DISPLACEMENT-TIME GRAPHS

B. DISPLACEMENT-POSITION GRAPHS
Note that the equilibrium position is not always at $y = 0$. Why not?

**DEMO:** Vernier probe – $d$-$t$ graph for pendulum, mass on a spring

**DO HW #3**

**IV. WAVEFRONTS AND RAYS**

For a 2D wave:

- **Wavefronts** = vertical planes going through waves
- **Rays** = lines at right angles to wavefronts in the direction of wave travel

For waves made by a point source (stone dropping in water):

- Circles are wavefronts, radial vectors are rays

**DEMO** in ripple tank

*Source: Physics for the IB Diploma, 5th Ed, Tsokos*
V. ELECTROMAGNETIC (EM) WAVES

A. THE WAVE EQUATION FOR EM WAVES

Electromagnetic waves (EM waves) behave like any other waves. Radio waves and light are two examples of EM waves. Visible light is simply one small part of a larger 'electromagnetic spectrum' of EM waves. The frequency of the waves in this small part determines the color we see.

EM waves are created by an oscillating electric charge which produces varying electric and magnetic field at right angles to each other. Propagate as a transverse wave and are able to move through a vacuum, since no particles are involved. The speed of EM waves is $2.99792458 \times 10^8 \text{ m/s}$.

B. THE ELECTROMAGNETIC SPECTRUM

Source: Physics, 8th Ed, Cutnell & Johnson

Source: Physics, 8th Ed, Cutnell & Johnson
White light = light having all the colors of the spectrum.

Sun emits in all frequencies. Spectrum curve for sun:

DEMO: White light through a prism

VI. WHEN WAVES HIT BOUNDARIES BETWEEN TWO MEDIA
A. REFLECTION AND TRANSMISSION

EXAMPLE 7
The speed of radio waves in vacuum (equal to the speed of light) is $3.00 \times 10^8$ m/s. Find the wavelength for

a) An AM radio station with frequency 1070 kHz

[281 m]

b) An FM radio station with frequency 91.7 Mhz

[3.27 m]

Source: Physics for the IB Diploma, 5th Ed, Tsokos
B. SNELL’S LAW

**Snell’s Law**

The speed of light in a vacuum, c, is 3.0 x 10^8 m/s. In all other media, v < c.

**V** depends on the optical density of the media through which light is passing.

Because it slows down, it also changes direction when transmitted through another medium.

**Define:**

**Refraction** = the change in direction of a wave when travelling from one medium to another due to a change in speed of the wave.

All waves refract. f does not change, but v changes. Therefore, λ changes.

Water waves change direction from one depth to another.

**DEMO**

If v_1 > v_2, wave bent towards the normal.
If v_1 < v_2, wave bent away from the normal.

**Therefore, for light:**

The wave is always bent towards the normal if going from less dense to more dense media.

Usually some of the wave is reflected and some is refracted.

Snell’s Law:

For light: every optically transparent material has an index of refraction given by:

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

derive?

In your data booklet:

NOTE: n must always be greater than 1.

n depends on λ, so rays with same angle of incidence but different λs will be bent differently. Called ‘dispersion’.

**DEMO**

Source: Physics for the IB Diploma, 5th Ed, Tsokos

Source: Physics, 8th Ed, Cutnell & Johnson

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**Table 26.1 Index of Refraction**

for Various Substances

<table>
<thead>
<tr>
<th>Substance</th>
<th>Index of Refraction, n</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solids at 20°C</strong></td>
<td></td>
</tr>
<tr>
<td>Diamond</td>
<td>2.419</td>
</tr>
<tr>
<td>Glass, crown</td>
<td>1.523</td>
</tr>
<tr>
<td>Ice (0 °C)</td>
<td>1.309</td>
</tr>
<tr>
<td>Sodium chloride</td>
<td>1.544</td>
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<tr>
<td>Quartz</td>
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</tr>
<tr>
<td>Crystalline</td>
<td>1.544</td>
</tr>
<tr>
<td>Fused</td>
<td>1.458</td>
</tr>
<tr>
<td><strong>Liquids at 20°C</strong></td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
<td>1.501</td>
</tr>
<tr>
<td>Carbon disulfide</td>
<td>1.632</td>
</tr>
<tr>
<td>Carbon tetrachloride</td>
<td>1.461</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>1.362</td>
</tr>
<tr>
<td>Water</td>
<td>1.333</td>
</tr>
<tr>
<td><strong>Gases at 0 °C, 1 atm</strong></td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>1.000 293</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>1.000 45</td>
</tr>
<tr>
<td>Oxygen, O₂</td>
<td>1.000 271</td>
</tr>
<tr>
<td>Hydrogen, H₂</td>
<td>1.000 139</td>
</tr>
</tbody>
</table>

*Measured with light whose wavelength in a vacuum is 589 nm.*
EXAMPLE 8
A ray of light is incident in water at an angle of i) 30.0 degrees and ii) 70.0 degrees on a water-glass plane surface. Calculate the angle of refraction in the glass in each case.

\[25.9^\circ, 55.3^\circ\]

EXAMPLE 9
Given the information in example 8, sketch the path of the ray in the diagram below showing all relevant angles, and calculate the angles of the ray within the glass and the water. Use a straightedge and make your diagram as neat as possible.
VII. WHEN WAVES INTERACT WITH EACH OTHER

A. THE SUPERPOSITION PRINCIPLE

When two waves meet at the same time in the same place, the resulting disturbance is the sum of the disturbances from the individual waves. All waves interfere according to this principle (water, sound, light, etc).

DEMO: Rope, slinky

Add waves 1 and 2:

Source: Physics, 8th Ed, Cutnell & Johnson

Source: Physics for the IB Diploma, Oxford
B. CONSTRUCTIVE AND DESTRUCTIVE INTERFERENCE

If resulting wave is bigger, waves reinforce each other: interact constructively

If resulting wave is smaller, waves cancel part of each other: waves interact destructively

Strictly speaking:

Constructive interference = 2 waves are in phase (the phase difference is 0) and the resultant wave has a large amplitude.

Destructive interference = 2 waves are exactly out of phase (the phase difference is ½ of a cycle, or π) and the resultant wave has zero amplitude.

Remember?? Discuss phase shifts.

Source: Mathematics for the IB Diploma, Oxford

Source: Physics for the IB Diploma, Oxford
C. INTERFERENCE: PATH AND PHASE DIFFERENCE

Consider: a string between two points $S_1$ and $S_2$, and point $P$ between them:

Send identical waves from $S_1$, $S_2$ at same time. Will they hit $P$ at the same time? NO!

What if:
- Wave from $S_1$ arrives at $P$ after 2 s.
- Wave from $S_2$ arrives at $P$ after 4 s.

When waves arrive at $P$, crests/troughs match up. Destructive interference.

In this case: $T = 4$ s, and difference in arrival times is $2$ s. Would also happen if difference in arrival times was $2$ s, $6$ s, $10$ s, etc… These are half-integer multiples of $T$.

Therefore: If difference in arrival times is a half-integer multiple of $T$, destructive interference.

Since $Tv = \lambda$, condition for destructive interference is when path difference is:

$\text{Source: Physics for the IB Diploma, Oxford}$
NOW: What if waves arrive as shown:

Resultant wave at P?

Between 4 and 6 s, only wave from S\textsubscript{1} reaches P.

But at 6 s onwards, crests/crests match up between waves from S\textsubscript{1} and S\textsubscript{2}.

Cons\textit{tructive} interference.

In this case: T = 4 s, and difference in arrival times is 4 s.

Would also happen if difference in arrival times was 4 s, 8 s, 12 s, et c…

These are \textit{integer multiples} of T.

\textbf{THEREFORE:} If difference in arrival times is an \textit{integer multiple} of T = constructive interference.

Since \( TV = \lambda \), condition for \textit{destructive interference} is when path difference is:

Source: Physics for the B Diploma, Oxford
VIII. DIFFRACTION

A. WHEN WAVES GO THROUGH OPENINGS

When waves go through openings, diffraction occurs. Diffraction is the spreading out of waves when they encounter an obstacle or go through an opening. All waves diffract, but the extent of the diffraction depends on the size of the opening compared to the wavelength of the wave:

- When \( W < \lambda \): more diffraction
- When \( W > \lambda \): little or no diffraction

Demo: Ripple tank

Can you hear sound around open doors? DIFFRACTION!

Can you see around open doors? WHY NOT?

B. WHEN WAVES GO AROUND OBSTACLES

Around corners/obstacles, the same thing happens. Size of obstacle must be about the same size as \( \lambda \) for diffraction to occur.

Sources:
- http://johnvagabondscience.wordpress.com
- http://geographyfieldwork.com
- Physics, 8th Ed., Cutnell & Johnson
- Physics for the IB Diploma, Oxford
Diffraction affects the lives of people living in mountainous areas. For example, radio waves (longer wavelength) can diffract around a hill to be received by a radio in a house, but TV waves (shorter wavelength) do not bend as much. Therefore, the house will have poor TV reception. The same principle applies for devices such as mobile phones, whose EM communications depend upon transmission/reception towers.