HL IB Physics

Wave Phenomena

Contents

Wavefronts & Rays

Wavefronts & Rays

- Waves can travel in both two and three-dimensions:
  - A **surface wave** propagates in **two dimensions** and has **circular wavefronts** (like a circle) such as the surface of water
  - A **spherical wave** propagates in **three dimensions** and has **spherical wavefronts** (like a sphere) such as sound or light
- Waves can be represented graphically in two different ways:
  - **Wavefronts** - lines joining all the points that oscillate in phase and are perpendicular to the direction of motion (and energy transfer)
  - **Rays** - lines showing the direction of motion (and energy transfer) of the wave perpendicular to the wavefront
- Wavefronts are viewed from above and look like a series of **parallel vertical lines**
  - Peaks are often represented with a darker line
  - Troughs are represented with a fainter line
  - Some diagrams use only peak wavefronts
- The distance between successive peak wavefronts or (trough wavefronts) is equal to the wavelength of the waves

Reflection, Refraction & Transmission

Reflection, Refraction & Transmission

- When waves arrive at a boundary between two materials, they can be:
  - Reflected
  - Refracted
  - Transmitted
  - Absorbed
- In optics, a transparent material is called a **medium**
  - When referring to more than one medium these are called **media**

Reflection

- Reflection occurs when:

A wave hits a boundary between two media and does not pass through, but instead bounces back to the original medium

- The **law of reflection** states:

The angle of incidence, *i* = The angle of reflection, *r*

- When a wave is reflected, some of it may also be **absorbed** or **transmitted** through the medium
- At a boundary between two media, the **incident** ray is the ray that travels **towards** the boundary
- During reflection, the frequency, wavelength and speed of the wave does **not** change

Refraction

- Refraction is:

The change in direction of a wave when it passes through a boundary between mediums of different density

- This change of direction is caused by a **change in the speed** of different parts of the wavefront as they hit the boundary
  - In optics, the word **medium** is used to describe a transparent material

Conditions for refraction

- When a wave travels from a **less dense** medium **into a denser medium**:
  - The more optically **dense** the medium
  - The **slower** the waves travel
  - The **smaller** the angle of **refraction**
  - The light bends **towards** the normal
- When a wave travels from a **denser medium** into a **less dense medium**:
  - The less optically **dense** the medium
  - The **faster** the waves travel
  - The **greater** the angle of refraction
  - The light bends **away** from the normal
- The amount of refraction that takes place is determined by the **difference** between the angles of **incidence** (*i*) and **refraction** (*r*) of the waves at the boundary
- The angles of incidence and refraction are measured from the **normal line**
  - This is drawn at 90° to the boundary between the two media

- The amount of change in direction that takes place depends on the difference in optical **density** between the two media

- When light passes from a less dense medium to a more dense medium, (e.g. air → glass):
  - The refracted light has a **lower speed** and a **shorter wavelength** than the incident light

- When light passes from a more dense medium to a less dense medium (e.g. glass → air):
  - The refracted light has a **higher speed** and a **longer wavelength** than the incident light

- When a wave refracts, its speed and wavelength change, but its frequency remains the same
  - This is noticeable by the fact that the **colour** of the wave does **not change**

- When the light ray is incident on the boundary at **90°**:
  - The wave passes **straight through** without a change in direction
  - This is because the whole wavefront enters the boundary at the same time at the same speed

Refraction of Water Waves

- Refraction can also occur between materials of **different depths**
  - You may be asked to explain the behaviour of water waves when they refract between deep and shallow areas
- When waves pass from **deep to shallow** water there is **more friction** between the sea bed and the wave and **less space** for the wave to oscillate so the waves:
  - **Slow down**
  - The **wavelength** of the wave **decreases**
  - So the distance between **wave peaks** is **reduced**
  - Angle of refraction is less than angle of incidence, $r < i$
- If the waves hit the boundary between the change in depth at an angle then they refract towards the normal
  - So the angle of refraction < angle of incidence

Transmission

- Transmission occurs when:

  A wave passes through a substance

- **Refraction** is a type of transmission
  - Transmission is the more general term for a wave appearing on the opposite side of a boundary (the opposite of reflection)
  - Refraction is specifically the **change in direction** of a wave when it crosses a boundary between two materials that have a different density
- When passing through a material, waves can be partially **absorbed**
- The transmitted wave will have a lower amplitude if some absorption has occurred
- During transmission, the frequency or speed of the wave does **not** change
- Reflection, refraction and transmission occur for **all** types of waves, both transverse and longitudinal

Diffraction of Waves

Diffraction of Waves

- Diffraction is defined as:

  The spreading out of waves after they pass through a narrow gap or around an obstruction

- Diffraction can occur when waves:
  - pass through an **aperture**
  - pass around a **barrier**

Diffraction through an aperture

- When a wave passes through a gap or aperture:
  - The waves spread out so they have curvature
  - The amplitude of the wave is less because the barrier on either side of the gap absorbs wave energy

- When the **wavelength** of the wave and the **width of the gap** is similar then diffraction occurs:
  - When the wavelength is **bigger** than the gap then **more diffraction** occurs, so the wave spreads out more after passing through
  - When the wavelength is **smaller** than the gap then **less diffraction** occurs, so the wave spreads out less after passing through
- When the **wavelength** of the wave and the **width of the gap** are not similar then diffraction does not occur:
  - For gaps that are **much smaller** than the wavelength of the wave, the wave passes over the gap easily so **no diffraction** occurs
  - For gaps that are **much bigger** than the wavelength of the wave, the majority of the wave passes straight through the gap so **no diffraction** occurs
- As the **gap size increases**, compared to the **wavelength**, the amount of **curvature** on the waves gets **less** pronounced

Diffraction around a barrier

- Diffraction can also occur when waves curve around an **edge** or **barrier**
  - The waves spread out to fill the gap behind the object
- The extent of this diffraction also depends upon the wavelength of the waves
  - The **greater** the **wavelength** then the greater the **diffraction**
- When the barrier is **larger** than the wavelength:
  - There is **some diffraction** around the barrier
  - A lot of incident waves are reflected back towards the source
  - There is a **"shadow" region** behind the barrier where no wavefronts are present
- When the barrier is the **same size** as the wavelength:
  - There is **more diffraction** around the barrier
  - There is a **smaller "shadow" region** behind the barrier where no wavefronts are present
- When the barrier is **smaller** than the wavelength:
  - **No diffraction** occurs around the barrier
  - The "shadow" region behind the barrier is **very small**

Worked example

When a wave is travelling through the air, which scenario best demonstrates diffraction?

A. UV radiation through a gate post

B. Sound waves passing a diffraction grating

C. Radio waves passing between human hair

D. X-rays passing through atoms in a crystalline solid

Answer: **D**

- Diffraction is most prominent when the wavelength is close to the aperture size

Consider option **A**:

- UV waves have a wavelength between (4×10^{-7}) and (1×10^{-8}) m so would **not** be diffracted by a gate post
- Radio waves, microwaves or sound waves would be more likely to be diffracted at this scale

Consider option **B**:

- Sound waves have a wavelength of (1.72×10^{-2}) to 17 m so would **not** be diffracted by the diffraction grating
- Infrared, light and ultraviolet waves would be more likely to be diffracted at this scale

Consider option **C**:

- Radio waves have a wavelength of 0.1 to 10^6 m so would **not** be diffracted by human hair
  - Infrared, light and ultraviolet waves would be more likely to be diffracted at this scale

Consider option **D**:

- X-rays have a wavelength of (1×10^{-8}) to (4×10^{-13}) m
  - This is a suitable estimate for the size of the gap between atoms in a crystalline solid
  - Hence X-rays could be diffracted by a crystalline solid
- Therefore, the correct answer is **D**

Worked example

An electric guitar student is practising in his room. He has not completely shut the door of his room, and there is a gap of about 10 cm between the door and the door frame.

Determine the frequencies of sound that are best diffracted through the gap.

The speed of sound can be taken to be 340 m s^{-1}

Answer:

Step 1: Optimal diffraction happens when the wavelength of the waves is comparable to (or larger than) the size of the gap

$$\lambda = 10 \text{ cm} = 0.1 \text{ m}$$

Step 2: Write down the wave equation

$$v = f\lambda$$

- Where speed of sound, v = 340 m s^{-1}

Step 3: Rearrange the above equation for the frequency *f*

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

Step 4: Substitute the numbers into the above equation

$$f = \frac{340}{0.1} = 3400 \text{ Hz}$$

- The frequencies of sound that are best diffracted through the gap are:
  $f \leq 3400$ Hz

Refraction of Waves

Snell's Law

- **Snell's law** relates the **angle of incidence** to the **angle of refraction** at a **boundary** between two media

Refractive Index

- The refractive index, *n* of a material tells us how optically dense it is
- The refractive index of **air is *n* = 1**
  - Media that are **more optically dense** than air will have a refractive index of ***n* > 1**
  - Media that are **less optically dense** than air will have a refractive index of ***n* < 1**
- The higher the refractive index of a material then the more optically dense and hence the slower light will travel through it
- The refractive index of a material is calculated using the equation:

$$n = \frac{c}{v}$$

- Where:
  - *n* = absolute refractive index of the medium
  - c = speed of light in a vacuum in metres per second ($m\ s^{-1}$), $3.00 \times 10^8\ m\ s^{-1}$, as given in the data booklet
  - *v* = speed of light in the medium in metres per second ($m\ s^{-1}$)

- Note that, being a ratio, the absolute refractive index is a **dimensionless** quantity
  - This means that it has no units

Snell's Law

- **Snell's law** is given by:

$$\frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1} = \frac{v_2}{v_1}$$

- Where:
  - n_1 = the refractive index of material 1
  - n_2 = the refractive index of material 2
  - θ_1 = the angle of incidence of the ray in material 1
  - θ_2 = the angle of refraction of the ray in material 2
  - v_1 = the speed of the wave in material 1
  - v_2 = the speed of the wave in material 2
- Snell's Law describes the angle at which light meets the boundary and the angle at which light leaves the boundary, so that the light travels through the media in the least amount of time

- Light can travel through medium 1 at a speed of v_1 due to the optical density n_1 of that medium
  - Light will approach the boundary at angle θ_1

- This is the angle of **incidence**
- Light can travel through medium 2 at a speed of v due to the optical density n of that medium
  - Light will leave the boundary at angle θ
  - This is the angle of **refraction**
- Snell's Law can also be given in a more convenient form:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

Worked example

Light travels from air into glass. Determine the speed of light in glass.

- Refractive index of air, $n_1 = 1.00$
- Refractive index of glass, $n_2 = 1.50$

Answer:

Step 1: Write down the known quantities

- $n_1 = 1.00$
- $n_2 = 1.50$
- From the data booklet, $c = 3 \times 10^8$ m s^{-1} (speed of light in air)

Step 2: Write down the relationship between the refractive indices of air and glass and the speeds of light in air (v_1) and glass (v_2)

$$\frac{n_1}{n_2} = \frac{v_2}{v_1}$$

Step 3: Rearrange the above equation to calculate v_2

$$v_2 = \frac{n_1}{n_2} v_1$$

Step 4: Substitute the numbers into the above equation

$$v_2 = \frac{1.00}{1.50} \times \left(3 \times 10^8\right)$$

$$v_2 = 2 \times 10^8 \text{ m s}^{-1}$$

Critical Angle & Total Internal Reflection (TIR)

- As the angle of incidence (*i*) is increased, the angle of refraction (*r*) also increases until it gets closer to 90°
- When the angle of refraction is exactly 90° the light is refracted along the boundary between the two material
  - At this point, the angle of incidence is known as the **critical angle** θ_c

Critical Angle

- The larger the refractive index of a material, the smaller the critical angle
- When light is shone at a **boundary** between two materials, different angles of incidence result in different angles of refraction
  - As the angle of incidence is increased, the angle of refraction also increases
  - Until the **angle of incidence** reaches the **critical angle**
- When the **angle of incidence = critical angle** then:
  - Angle of refraction = 90°
  - The refracted ray is refracted **along the boundary** between the two materials
- When the **angle of incidence < critical angle** then:
  - the ray is refracted and exits the material
- When the **angle of incidence > critical angle** then:
  - the ray undergoes **total internal reflection**

Critical Angle Equation

- The critical angle of material 1 is found using the equation:

$$\sin \theta_c = \frac{n_2}{n_1}$$

- Where:
  - θ_c = critical angle of material 1 (°)
  - n_1 = absolute refractive index of material 1
  - n_2 = absolute refractive index of material 2
- The **two conditions** for total internal reflection to occur are:
  - The refractive index of the **second** medium must be **less** than the refractive index of the first, $n_2 < n_1$
  - The angle of **incidence** must be **greater** than the **critical** angle, $\theta_i > \theta_c$

Total Internal Reflection

- Total internal reflection is a special case of refraction that occurs when:
  - The **angle of incidence** within the denser medium is **greater** than the **critical angle** ($I > \theta_c$)
  - The incident refractive index $\mathbf{n_1}$ is **greater** than the refractive index of the material at the boundary $\mathbf{n_2}$ ($n_1 > n_2$)
- Total internal reflection follows the law of reflection

angle of incidence = angle of reflection

- A **denser medium** has a **higher refractive index**
  - For example, the refractive index of glass, n_g > the refractive index of air, n_a
- Light rays inside a material with a **higher refractive index** are more likely to be **totally internally reflected**

Worked example

Light travels from a material with refractive index 1.2 into air.

Determine the critical angle of the material.

Answer:

Step 1: Write down the known quantities

- Refractive index of material 1, $n_1 = 1.2$
- Refractive index of air, $n_2 = 1.0$

Step 2: Write down the equation for the critical angle θ_c

$$sin\theta_c = \frac{n_2}{n_1}$$

Step 3: Substitute the numbers into the above equation

$$sin\theta_c = \frac{1.0}{1.2}$$

$$sin\theta_c = 0.83$$

Step 4: Calculate θ_c by taking $\sin^{-1}$ of the above equation

$$\theta_c = \sin^{-1} 0.83$$

$$\theta_c = 56°$$

Superposition of Waves

Superposition of Waves

- When two or more waves arrive at the same point and overlap, their amplitudes combine
  - This is called **superposition**
- The **principle of superposition** states that:

When two or more waves overlap at a point, the displacement at that point is equal to the sum of the displacements of the individual waves

- The superposition of **surface water waves** shows the effect of this overlap
  - There are areas of zero displacement, where the water is flat
  - There are areas of increased displacement, where the water waves are higher

- It is possible to analyse superposition clearly when the waves are drawn on a vertical displacement (amplitude)-displacement graph

- **Interference** is the effect of this overlap
  - This is explained in the next Interference of Waves
- Individual wave displacements may be positive or negative and are **combined** in the same way as other **vector** quantities
- It is possible to analyse superposition clearly when the waves are drawn on a displacement-time graph

- Superposition can also be demonstrated with **two pulses**
  - When the pulses meet, the resultant displacement is also the **algebraic sum** of the displacement of the individual pulses
  - After the pulses have interacted, they then carry on as normal

Interference of Waves

Double Source Interference

- Double-source interference involves producing a **diffraction** and an **interference pattern** using either:
  - The interference of two **coherent** wave sources
  - A single wave source passing through a **double slit**
- Examples of double-source interference include:
  - A **laser beam** that creates bright and dark fringes on a screen
  - **Two speakers** emitting a coherent sound
  - **Microwaves** diffracted through two slits

Interference

- Interference is the effect observed due to the **superposition** of two or more waves
  - It can be seen clearly when waves overlap completely in **phase** or **antiphase**
- The **maximum** amount of superposition occurs when two waves are in **phase**
  - They meet either **peak-to-peak** or trough-to-trough
  - This results in the two waves **adding together**
  - This is called **constructive interference**
- The **minimum** amount of superposition occurs when two waves are in **antiphase**
  - They meet **peak-to-trough**
  - This results in the two waves **cancelling** each other out and having zero effect (there is an effect - that they cancel out)
  - This is called **destructive interference**
- Constructive and destructive interference occurs when waves are **coherent**

Coherence

- For waves to be coherent they must have:
  - The same **frequency**
  - A **constant phase difference**
- At points where two waves are neither in **phase** nor in **antiphase**, the resultant amplitude is somewhere in between the two extremes
- Examples of interference from coherent light sources are:
  - Monochromatic **laser** light
  - Sound waves from two nearby **speakers** emitting sound of the same frequency

Constructive & Destructive Interference

- Whether waves are in phase or antiphase is determined by their **path difference**

Path Difference

- Path difference is defined as:

The difference in distance travelled by two waves from their sources to the point where they meet

- Path difference vs phase difference
  - **Phase difference** compares the **distance** between the **phases** (peaks and troughs) of waves that are normally travelling parallel to each other at a point
  - **Path difference** compares the amount of **progress** made by waves along a **path**, so the difference in the distance travelled by the two waves

Conditions for Constructive and Destructive Interference

- In general, for waves emitted by two coherent sources very close together:
- The condition for **constructive interference** is:

$$\textbf{path difference} = n\lambda$$

- The condition for **destructive interference** is:

$$\textbf{path difference} = \left(n + \frac{1}{2}\right)\lambda$$

- Where:
  - λ = wavelength of the waves in metres (m)
  - n = 0, 1, 2, 3... (any other integer)

Path Difference and Wavefront Diagrams

- Wavefront diagrams show the interference between waves more clearly

Young’s Double-Slit Experiment

Young's Double Slit Experiment

- Young's double-slit experiment produces a **diffraction** and an **interference pattern** using either:
  - The interference of two **coherent** wave sources
  - A single wave source passing through a **double slit**
- Lasers are the most common sources used in Young's double slit experiment because the waves must be:
  - **Coherent** (have a constant phase difference and frequency)
  - **Monochromatic** (have the same wavelength)
- In this typical set up for Young's double slit experiment:
  - The light source is placed behind the **single slit**
  - The light is then diffracted to produce two sources in the double slit at **A** and **B**
  - The light from the double slits is then diffracted, producing a **diffraction pattern** made up of bright and dark fringes on a screen

Diffraction Pattern

- The **diffraction pattern** from the interference of the two sources can be seen on the screen when it is placed far away
  - **Constructive interference** between light rays forms bright strips, also called **fringes**, interference fringes or **maxima**, on the screen
  - **Destructive interference** forms dark strips, also called dark **fringes** or **minima**, on the screen

Interference Pattern

- The Young's double slit interference pattern shows the regions of constructive and destructive interference:
  - Each **bright fringe** is a peak of equal **maximum intensity**
  - Each **dark fringe** is a a trough or minimum of **zero intensity**
- The **maxima** are formed by the **constructive interference** of light
- The **minima** are formed by the **destructive interference** of light

- Remember the conditions for interference as explained in the previous revision note on double source interference
  - For **constructive** interference (or maxima):

$$\textbf{path difference} = n\lambda$$

  - For **destructive** interference (or minima):

$$\textbf{path difference} = \left(n + \frac{1}{2}\right)\lambda$$

- For the maxima in the interference pattern:
  - There is usually more than one produced
  - ***n*** is the **order** of the maxima or minima; which represents the position of the maxima away from the central maximum
  - ***n* = 0** is the **central** maximum
  - *n* = 1 represents the first maximum on either side of the central, *n* = 2 the next one along....

Double Slit Equation

- The spacing between the bright or dark fringes in the diffraction pattern formed on the screen can be calculated using the **double-slit** equation:

$$s = \frac{\lambda D}{d}$$

- Where:
  - *s* = separation between successive fringes on the screen (m)
  - λ = wavelength of the waves incident on the slits (m)
  - *D* = distance between the screen and the slits (m)
  - *d* = separation between the slits (m)

Single-Slit Diffraction (HL)

Single Slit Intensity Pattern

Single Slit Diffraction Pattern

- The **diffraction pattern** of monochromatic light passing through a single rectangular slit, is a series of light and dark fringes on a faraway screen
- This is similar to a double slit diffraction pattern:
  - The **bright fringes** are also areas of **maximum intensity,** produced by the **constructive interference** of each part of the wavefront as it passes through the slit
  - The **dark fringes** are also areas of zero or minimum **intensity,** produced by the destructive interference of each part of the wavefront as it passes through the slit

- However, the single and double-slit diffraction patterns are **different**
- The **central maximum** of the diffraction pattern is:
  - Much **wider and brighter** than the other bright fringes
  - Much wider than that of the double-slit diffraction pattern
- On either side of the wide central maxima for the single slit diffraction pattern are much **narrower and less bright** maxima
  - These get **dimmer** as the **order increases**

Single Slit Intensity Pattern

- If a laser emitting blue light is directed at a single slit, where the slit width is similar in size to the wavelength of the light, its intensity pattern will be as follows:

- The features of the **single slit intensity** pattern are:
  - The **central bright fringe** has the **greatest intensity** of any fringe and is called the **central maximum**
  - The **dark fringes** are regions with **zero intensity**
  - Moving away from the central maxima either side, the **intensity** of each bright fringe **gets less**

Changes in Wavelength

- When the **wavelength** passing through the gap is increased then the wave **diffracts** more
- This increases the **angle of diffraction** of the waves as they pass through the slit
  - So the **width** of the **bright maxima** is also **increased**
- **Red** light
  - Which has the **longest wavelength** of visible light
  - Will produce a diffraction pattern with **wide fringes**
  - Because the angle of diffraction is wider
- **Blue** light
  - Which has a much **shorter wavelength**
  - Will produce a diffraction pattern with **narrow fringes**
  - Because the angle of diffraction is narrower

Double Slit Modulation

- When light passes through a double slit **two types** of interference occur:
  - The diffracted rays passing through one slit interfere with the rays passing through the other
  - Rays passing through the same slit interfere with each other
- This produces a double-slit **intensity pattern** where the single-slit intensity pattern **modulates** (adjusts) the intensity of the light on the screen
  - It looks like a **double-slit interference pattern** inscribed in the **single-slit intensity pattern**

- The **single-slit intensity pattern** has a distinctive **central** maximum and **subsequent** maxima at lower intensity
- The double-slit interference pattern has **equally** spaced intensity peaks with maxima of **equal** intensity
- Together, the combined double slit intensity pattern has equally spaced bright fringes but now within a single slit '**envelope**'

Diffraction Gratings (HL)

The Diffraction Grating

- A diffraction grating is a piece of **optical equipmen**t that also creates a **diffraction pattern** when light is passed through it
- Diffraction gratings diffract::
  - Monochromatic light into bright and dark fringes
  - White light into its different wavelength components
- A diffraction grating consists of a **large number** of very **thin**, **equally spaced parallel slits** carved into a glass plate

The Diffraction Grating Equation

- Diffraction gratings are useful because they create a **sharper pattern** than a double slit
  - This means their **bright fringes** are **narrower** and **brighter** while their dark regions are wider and darker
- Just like for single and double-slit diffraction the regions where **constructive interference** occurs are also the regions of **maximum intensity**
- Their location can be calculated using the **diffraction grating equation**
- Where:
  - n is the order of the maxima, the number of the maxima away from the central (n = 0)
  - d is the distance between the slits on the grating (m)
  - θ is the angle of diffraction of the light of order n from the normal as it leaves the diffraction grating (°)
  - λ is the wavelength of the light from the source (m)

Number of Slits

- **Increasing** the **number** of slits **increases** the **number** and **intensity** of the maxima in the intensity pattern
  - This is because **more slits** means **more diffraction** and **more constructive interference**

Slit Spacing

- Diffraction gratings come in **different sizes**
  - The sizes are determined by the number of **lines per millimetre** (lines / mm) or lines per m
  - This is represented by the symbol *N*
- *d* can be calculated from *N* using the equation
  - If *N* is given in terms of lines per mm then *d* will be in mm
  - If *N* is given in terms of lines per m then *d* will be in m

$$d = \frac{1}{N}$$

Angular Separation

- The angular separation of each maxima is calculated by rearranging the grating equation to make θ the subject
- The angle θ is taken from the centre meaning the higher orders of *n* are at greater angles of diffraction

- The angular separation between two angles is found by subtracting the smaller angle from the larger one
- The angular separation between the first and second maxima at n_1 and n_2 is $\theta_2 - \theta_1$

Orders of Maxima

- The maximum angle of diffraction with which maxima can be seen is when the beam is at right angles to the diffraction grating
  - This means $\theta = 90°$ and $\sin \theta = 1$

- The highest order of maxima visible is therefore calculated by the equation:

$$n = \frac{d}{\lambda}$$

- Since *n* is an integer number of maxima, if the value obtained is a decimal it must be rounded **down** to determine the highest-order visible
  - E.g If *n* is calculated as 2.7 then *n* = 2 is the highest-order visible

The Diffraction of White Light

- A source of white light diffracted through a diffraction grating will produce the following **diffraction pattern**:
  - It is different to that produced by a double or single slit
  - The first-order spectrum $n = 1$ is used for analysis
- The central maximum is a **very thin bright strip** because each wavelength interferes here constructively
  - It is surrounded by wide dark destructive interference fringes
- All other maxima are composed of a **spectrum**
- **Separate** diffraction patterns can be observed for each wavelength of light
  - The shortest wavelength (violet / blue) would appear **nearest** to the central maximum because it is diffracted the **least**
  - The longest wavelength (red) would appear **furthest** from the central maximum because it is diffracted the **most**
- The colours look **blurry** and further away from the central maximum, the fringe spacing gets so small that the spectra eventually merge without any space between them
  - As the maxima move **further away** from the central maximum, the wavelengths of **blue** observed **decrease** and the wavelengths of **red** observed **increase**