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3.3 Interference

PHYSICS

AQA A Level Revision Notes

3.3 Interference

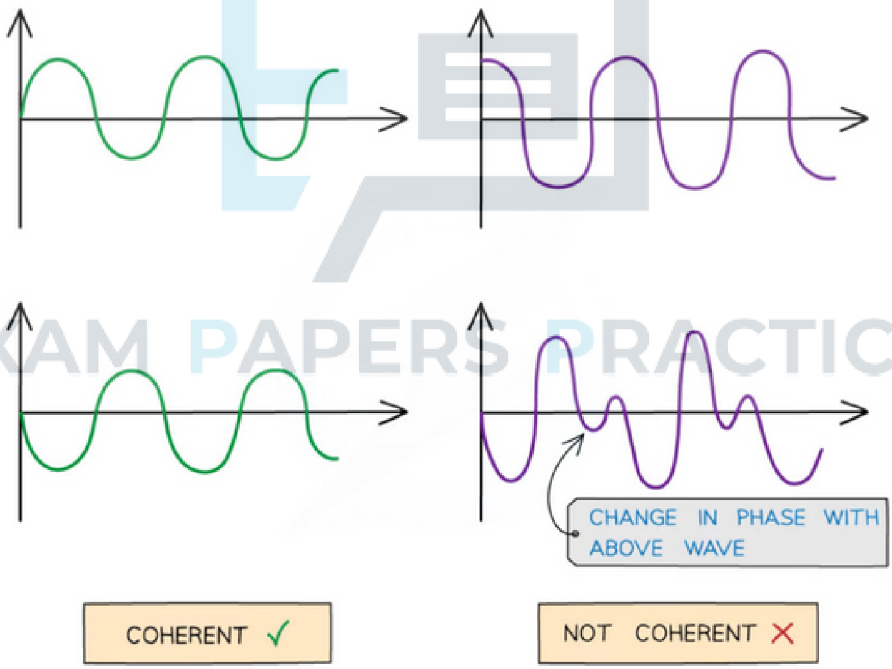
CONTENTS

Path Difference & Coherence

- Interference occurs when waves **overlap** and their resultant displacement is the **sum of the displacement of each wave**
- This result is based on the principle of superposition and the resultant waves may be smaller or larger than either of the two individual waves

Coherence

- At points where the two waves are neither in phase nor in antiphase, the resultant amplitude is somewhere in between the two extremes
- Waves are said to be **coherent** if they have:
  - The same **frequency**
  - A **constant phase difference**



Coherent v non-coherent wave. The abrupt change in phase creates an inconsistent phase difference

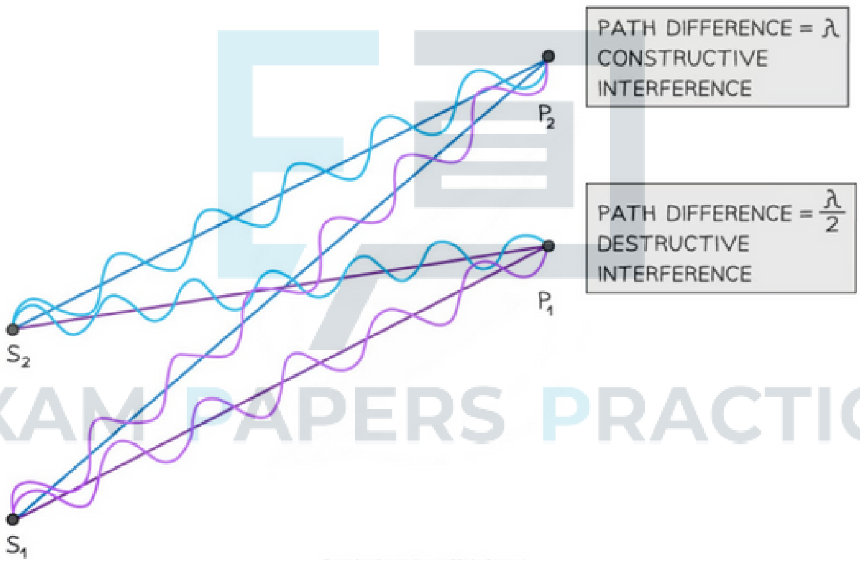
- Coherence is vital in order to produce an observable, or hearable, interference pattern
  - Laser light is an example of a coherent light source, whereas filament lamps produce incoherent light waves
  - When coherent sound waves are in phase, the sound is louder because of constructive interference

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 is generally expressed in multiples of wavelength

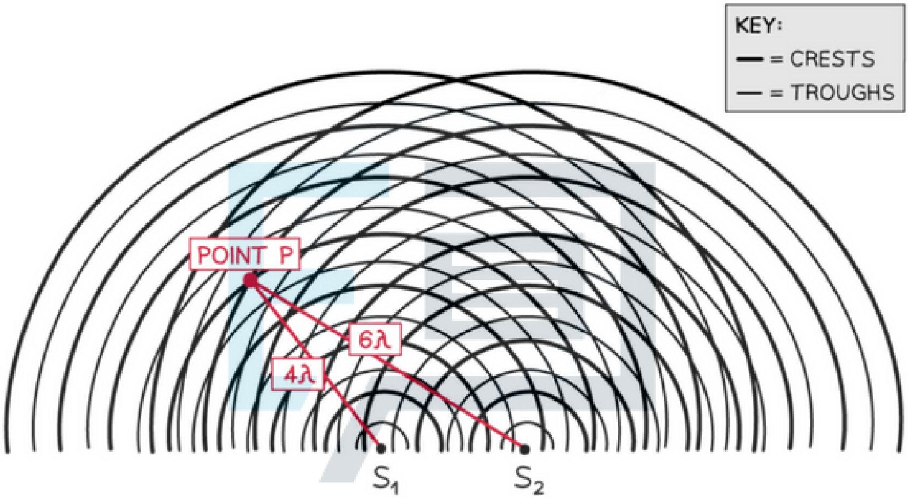


At point P_2 the waves have a path difference of a whole number of wavelengths resulting in constructive interference. At point P_1 the waves have a path difference of an odd number of half wavelengths resulting in destructive interference

- In the diagram above, the number of wavelengths between:
  - $S_1 \rightarrow P_1 = 6\lambda$
  - $S_2 \rightarrow P_1 = 6.5\lambda$
  - $S_1 \rightarrow P_2 = 7\lambda$
  - $S_2 \rightarrow P_2 = 6\lambda$

- The path difference at point P_1 is $6.5\lambda - 6\lambda =$ **$\lambda / 2$**
- The path difference at point P_2 is $7\lambda - 6\lambda =$ **λ**

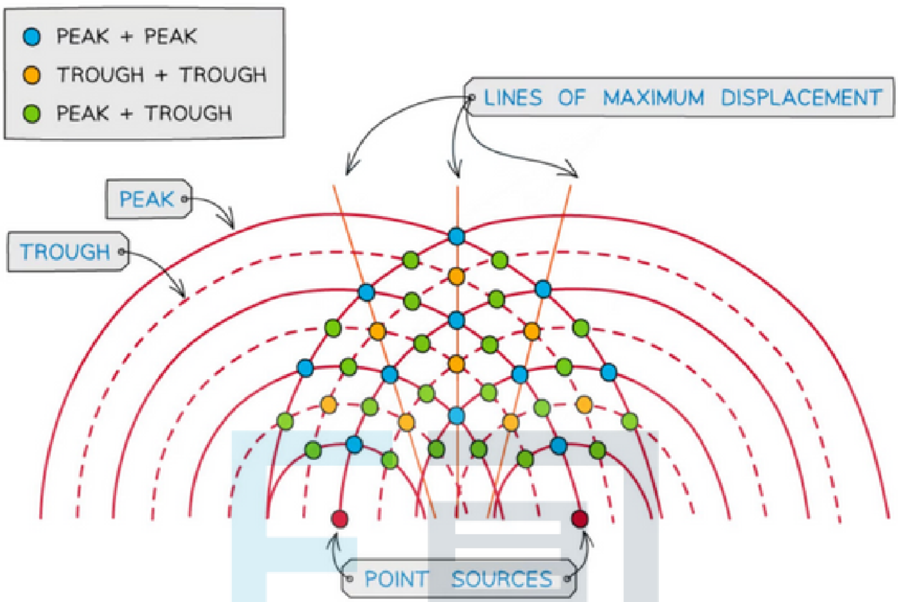
- **In general:**
  - **The condition for constructive interference is a path difference of $n\lambda$**
  - **The condition for destructive interference is a path difference of $(n + ½)\lambda$**
  - **In this case, n is an integer i.e. 0, 1, 2, 3...**



At point P the waves have a path difference of a whole number of wavelengths resulting in constructive interference

- Another way to represent waves spreading out from two sources is shown in the diagram above
- At point **P**, the number of **crests** from:
  - Source $S_1 = 4\lambda$
  - Source $S_2 = 6\lambda$

- The path difference at **P** is $6\lambda - 4\lambda =$ **2λ**
- This is a whole number of wavelengths, hence constructive interference occurs at point **P**

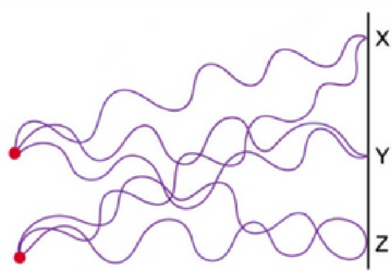


An experiment demonstrating interference of water waves.

Water ripples are generated from two red point sources. As the waves travel away from their source they interfere with each other. When the peaks from each wave meet at the same blue point constructive interference occurs and the water is highest. When the troughs from each wave meet at the same orange point constructive interference occurs and the water is most shallow. When the peak from one wave meets the trough of another destructive interference occurs and the water here is flat.

Worked Example

The diagram shows the interferences of coherent waves from two point sources.



Which row in the table correctly identifies the type of interference at points **X**, **Y** and **Z**.

	X	Y	Z
A	Constructive	Destructive	Constructive
B	Constructive	Constructive	Destructive
C	Destructive	Constructive	Destructive
D	Destructive	Constructive	Constructive

ANSWER: B

- At point **X**:
  - Both peaks of the waves are overlapping
  - Path difference = $5.5\lambda - 4.5\lambda = \lambda$
  - This is **constructive** interference and rules out options **C** and **D**
- At point **Y**:
  - Both troughs are overlapping
  - Path difference = $3.5\lambda - 3.5\lambda = 0$
  - Therefore **constructive** interference occurs
-
  - A peak of one of the waves meets the trough of the other
  - Path difference = $4\lambda - 3.5\lambda = \lambda / 2$
  - This is **destructive** interference
  - At point **Z**:

Exam Tip

Remember, interference of two waves can either be:

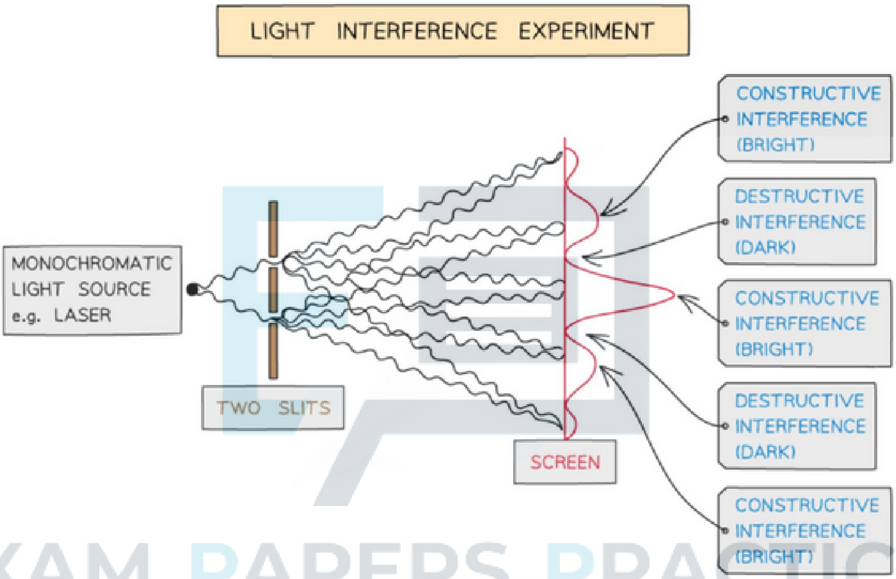
- In **phase**, causing **constructive interference.** The peaks and troughs line up on both waves. The resultant wave has double the amplitude
- In **anti-phase**, causing **destructive interference.** The peaks on one wave line up with the troughs of the other. The resultant wave has no amplitude

Think of '**constructive**' interference as '**building**' the wave and '**destructive**' interference as '**destroying**' the wave.

3.3.2 Demonstrating Interference

Interference & Diffraction of a Laser

- Interference and diffraction of lasers can be demonstrated with slits or diffraction gratings
- For light rays, such as a laser light through two slits, an interference pattern forms on the screen

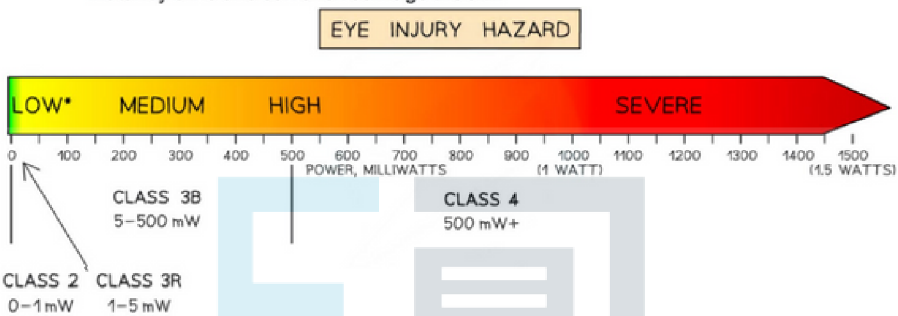


Laser light interference experiment

- Constructive interference is shown as bright fringes on the screen
  - The highest intensity is in the middle
- Destructive interference is shown as the dark fringes on the screen
  - These have zero intensity

Safety Issues with Lasers

- Lasers produce a very high energy beam of light
- This intense beam can cause **permanent eye damage** or even blindness
- In schools, only class 2 lasers are allowed - these are lasers with a power output of less than 1 mW
    - However, more powerful lasers can reach outputs of more than 500 mW
    - These are known as class 4 lasers. They are so powerful they can make a person instantly blind and can even damage the skin



The four classes of laser: In a school laboratory, only Class 2 lasers may be used

Precautions

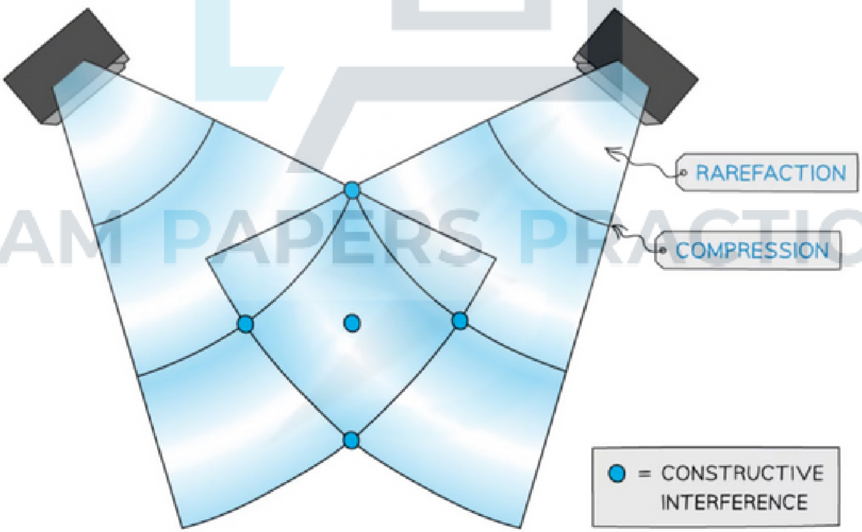
- It's important to use lasers safely and follow the guidelines:
    - **Never** look directly at a laser or its reflection
    - Don't shine the laser towards a person
    - Don't allow a laser beam to reflect from shiny surfaces into someone else's eyes
    - Wear laser safety goggles
    - Place a 'laser on' warning light outside the room
    - Stand behind the laser

Placing a laser warning sign outside of the door is one precaution that can be taken when using lasers

Sound & EM Wave Interference

Using Sound Waves

- Two-source interference of sound can be demonstrated with two speakers

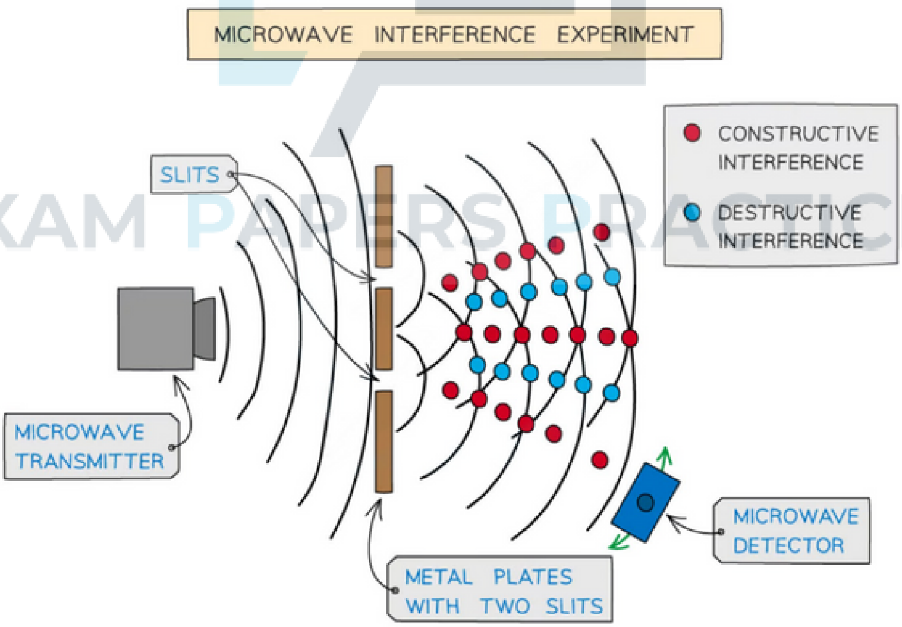


Sound wave interference from two speakers

- Sound waves are longitudinal waves so are made up of **compressions** and **rarefactions**
- Constructive interference occurs when the compression and rarefactions line up and the sound appears louder
- Destructive interference occurs when the compression lines up with a rarefaction and vice versa. The sound is quieter
  - This is the technology used in noise-cancelling headphones
- The two waves interfere causing areas of constructive and destructive interference

Using Microwaves

- Two source interference for microwaves can be detected with a moveable microwave detector



Microwave interference experiment

- Constructive interference: regions where the detector picks up a maximum amplitude
- Destructive interference: regions where the detector picks up no signal

Worked Example

Two speakers are set up in a room and play a note of frequency 280 Hz. The waves are in phase as they leave the speaker. A student walks 3.0 m between two speakers and hears quiet and loud spots as she moves. Calculate the number of quiet spots the student hears as she walks. Speed of sound in air = 340 m s^{-1}

Step 1: Calculate the wavelength

Wave equation: $v = f\lambda$

$$\lambda = \frac{v}{f} = \frac{340}{280} = 1.2 \text{ m}$$

Step 2: Write down the condition for destructive interference

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

Step 3: Calculate the smallest path difference

- The shortest path difference occurs when n = 0
  - Shortest path difference = $\frac{\lambda}{2} = \frac{1.2}{2} = 0.6$ m
- Therefore, the first quiet spot is at 0.6 m

Step 4: Calculate the next smallest path differences

- When n = 1:
  - Path difference = $\frac{3\lambda}{2} = \frac{3 \times 1.2}{2}$ = 1.8 m
- When n = 2:
  - Path difference = $\frac{5\lambda}{2} = \frac{5 \times 1.2}{2}$ = 3.0 m

Step 5: Write a concluding sentence

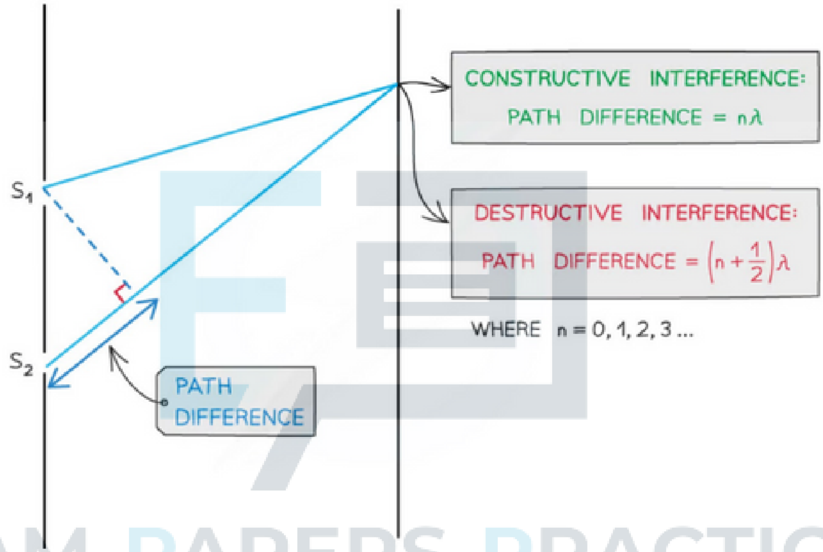
Therefore, in 3.0 m, the student hears 3 quiet spots

3.3.3 Young's Double-Slit Experiment

Double Slit Interference

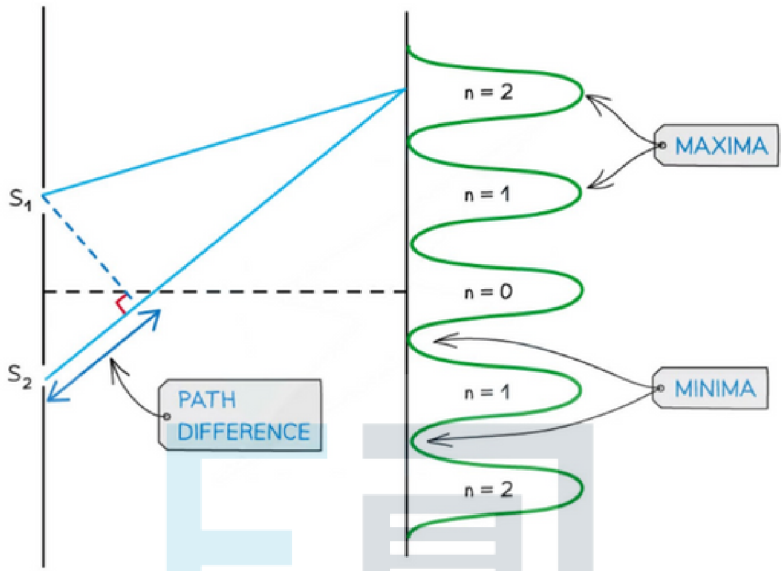
Two Source Interference

- For two-source interference fringes to be observed, the sources of the wave must be:
  - **Coherent** (constant phase difference)
  - **Monochromatic** (single wavelength)
- When two waves interfere, the resultant wave depends on the **phase difference** between the two waves
  - This is proportional to the **path difference** between the waves which can be written in terms of the wavelength λ of the wave
- As seen from the diagram, the wave from slit S_2 has to travel slightly further than that from S_1 to reach the same point on the screen
  - The difference in this distance is the **path difference**



Path difference of constructive and destructive interference is determined by wavelength

- For **constructive** interference (or maxima), the difference in wavelengths will be an **integer number of whole wavelengths**
- For **destructive** interference (or minima) it will be an **integer number of whole wavelengths plus a half wavelength**
  - *n* is the order of the maxima/minima since there is usually more than one of these produced by the interference pattern
- An example of the orders of maxima is shown below:

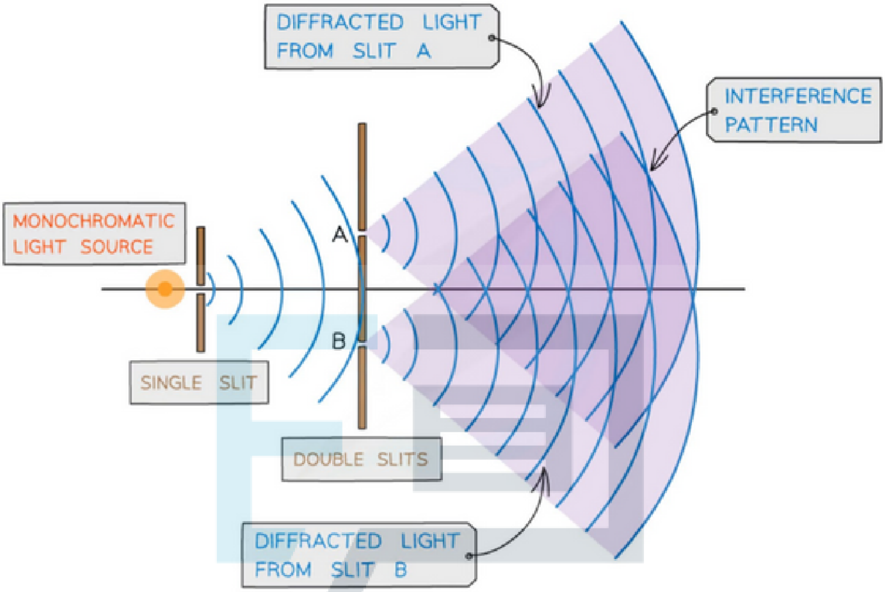


Interference pattern of light waves shown with orders of maxima

- $n = 0$ is taken from the middle, $n = 1$ is one either side and so on

Young's Double Slit Experiment

- Young's double-slit experiment demonstrates how light waves can produce an **interference pattern**
- The setup of the experiment is shown below:

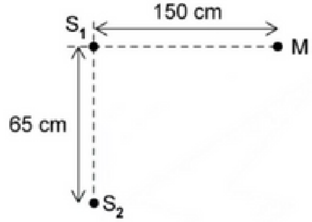


Young's double-slit experiment arrangement

- When a monochromatic light source is placed behind a single slit, the light is diffracted producing two light sources at the double slits **A** and **B**
- Since both light sources originate from the same primary source, they are **coherent** and will therefore create an observable interference pattern
- Both diffracted light from the double slits create an interference pattern made up of bright and dark fringes

Worked Example

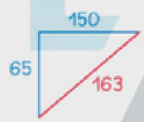
Two coherent sources of sound waves S_1 and S_2 are situated 65 cm apart in air as shown below.



The two sources vibrate in phase but have different amplitudes of vibration. A microphone M is situated 150 cm from S1 along the line normal to S_1 and S_2. The microphone detects maxima and minima of the intensity of the sound. The wavelength of the sound from S_1 to S_2 is decreased by increasing the frequency. Determine which orders of maxima are detected at M as the wavelength is increased from 3.5 cm to 12.5 cm.

STEP 1

CALCULATE THE PATH DIFFERENCE



FROM PYTHAGORAS' THEOREM

$\sqrt{65^2 + 150^2} = 163$

PATH DIFFERENCE $= 163 - 150 = 13$ cm

STEP 2

MAXIMA ARE CAUSED BY CONSTRUCTIVE INTERFERENCE

STEP 3

CONSTRUCTIVE INTERFERENCE:

PATH DIFFERENCE $= n\lambda$ $\quad n = 0, 1, 2, 3...$

STEP 4

$13 = n\lambda$

$n = 0 \quad \lambda = 0$

$n = 1 \quad \lambda = \frac{13}{1} = 13$ cm

$n = 2 \quad \lambda = \frac{13}{2} = 6.5$ cm

$n = 3 \quad \lambda = \frac{13}{3} = 4.3$ cm

$n = 4 \quad \lambda = \frac{13}{4} = 3.3$ cm

ONLY THESE TWO ORDERS ARE WITHIN THE WAVELENGTH RANGE.

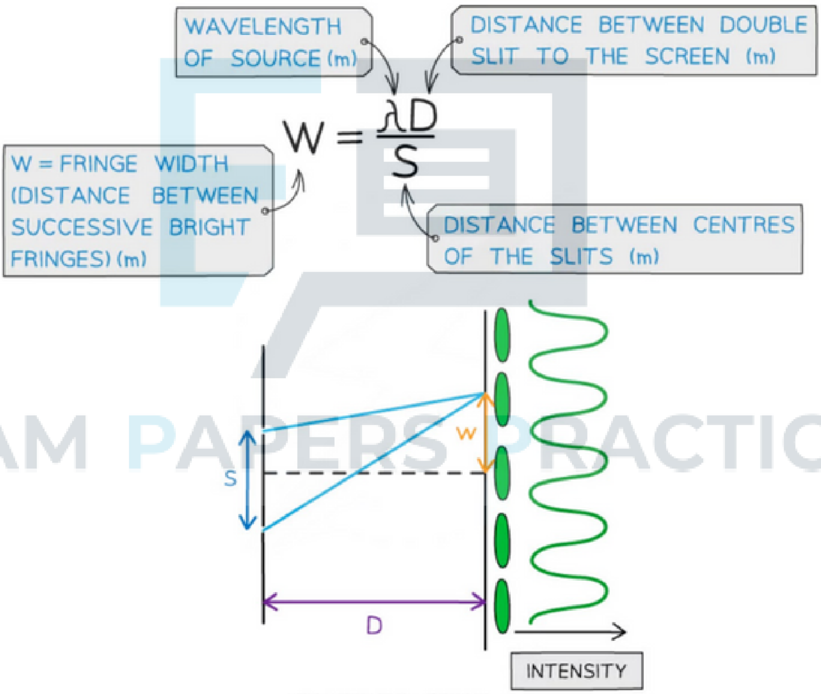
WAVELENGTHS OF 6.5 cm AND 4.3 cm ARE WHERE MAXIMA ARE DETECTED.

Exam Tip

The path difference is more specifically how much longer, or shorter, one path is than the other. In other words, the **difference** in the distances. Make sure not to confuse this with the distance between the two paths.

Fringe Spacing Equation

- The fringe spacing can be calculated from the interference pattern and the experimental setup
  - These are related using the double-slit equation:

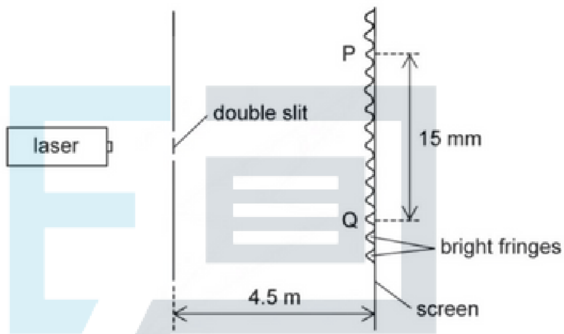


Double slit interference equation with w, s and D represented on a diagram

- The interference pattern on a screen will show as 'fringes' which are dark or bright bands
  - **Constructive** interference is shown through **bright** fringes with varying intensity (most intense in the middle)
  - **Destructive** interference is shown from **dark** fringes where no light is seen
- The distance between fringes is very small due to the short wavelength of visible light
  - A monochromatic light source makes the fringes easier to observe

Worked Example

A laser is placed in front of a double-slit as shown in the diagram below.



The laser emits light of frequency 750 THz. The separation of the maxima P and Q observed on the screen is 15 mm. The distance between the double slit and the screen is 4.5 m. Calculate the separation of the two slits.

STEP 1

CALCULATE THE WAVELENGTH OF THE LIGHT

$$v = f\lambda$$

STEP 2

REARRANGE FOR λ AND SUBSTITUTE IN VALUES

$$\lambda = \frac{v}{f} = \frac{3 \times 10^8}{750 \times 10^{12}} = 4 \times 10^{-7} \text{m} = 400 \text{ nm}$$

STEP 3

FRINGE SPACING EQUATION

$$W = \frac{\lambda D}{S}$$

STEP 4

REARRANGE FOR S – SEPARATION OF THE TWO SLITS

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

STEP 5

SUBSTITUTE IN VALUES

$$s = \frac{4 \times 10^{-7} \times 4.5}{15 \times 10^{-3} \div 9} = 1.08 \times 10^{-3} \text{ m} = 1.1 \text{ mm (2 s.f.)}$$

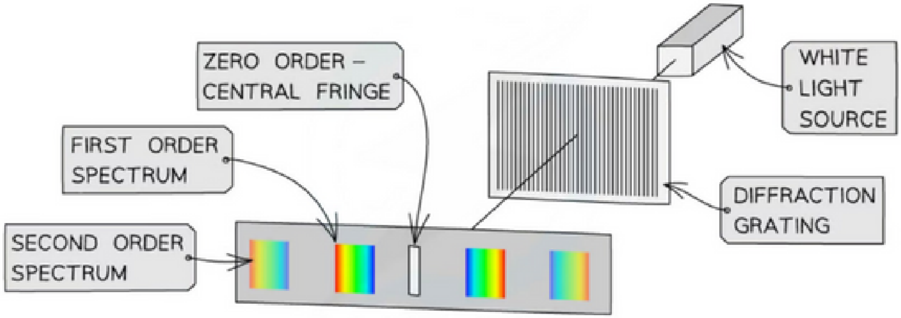
TOTAL NUMBER OF BRIGHT FRINGES

Exam Tip

Since *w*, *s* and *D* are all distances, it's easy to mix up which they refer to. Labelling the double-slit diagram as shown in the notes above will help to remember the order i.e. *w* and *s* in the numerator and *D* underneath in the denominator.

Interference Patterns

- If the monochromatic laser light is replaced with a white light source, the interference pattern observed is slightly different
- White light is composed of all the colours of visible light, so, each wavelength of white light produces its own interference pattern
- The central fringe is white because, at that position, the path difference for all wavelengths present is zero, therefore all wavelengths will arrive **in phase**
  - The central fringe is, therefore, the same colour as the source i.e. white
- The first maximum occurs when the path difference is λ
  - Since blue light has a shorter wavelength than red light, the path difference will be **smaller**, so the blue maximum will appear **closer** to the centre
- Each colour will produce a maximum in a slightly different position and so the colours spread out into a spectrum



Each fringe appears as a visible spectrum apart from the central white fringe. Red is diffracted the most, violet is diffracted the least

3.3.4 Developing Theories of EM Radiation

Developing Theories of EM Radiation

Isaac Newton (1672)

- Newton proposed that visible light is a stream of microscopic particles called **corpuscles**
- However, these corpuscles could not explain interference or diffraction effects, therefore, the view of light as a wave was adopted instead

Christiaan Huygens (1678)

- Huygens came up with the original **Wave Theory of Light** to explain the phenomena of diffraction and refraction
- This theory describes light as a series of wavefronts on which every point is a source of waves that spread out and travel at the same speed as the source wave
  - These are known as **Huygens' wavelets**

Thomas Young (1801)

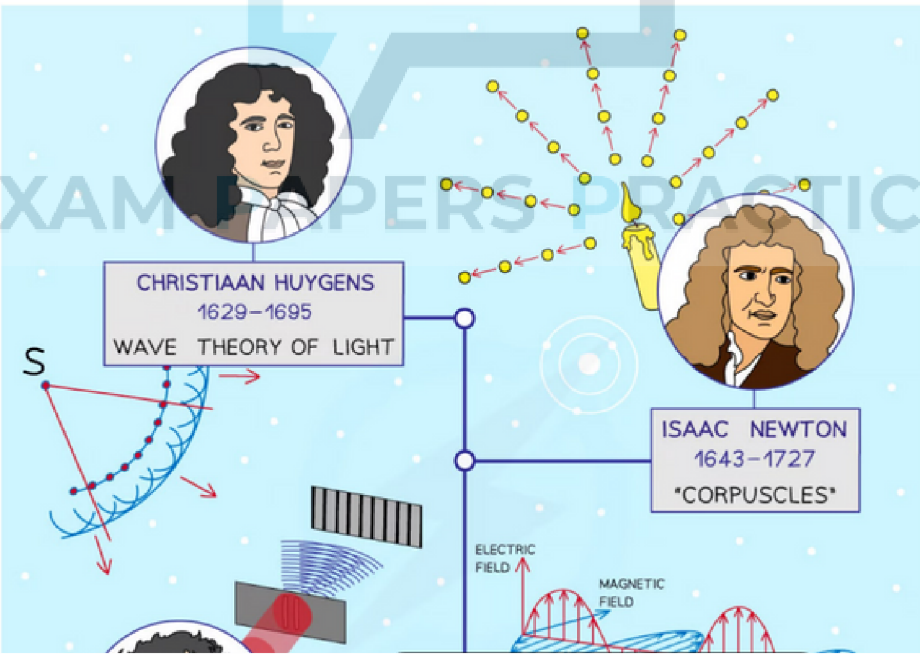
- Young devised the famous **double-slit experiment**
- This provided experimental proof that light is a wave that can undergo constructive and destructive interference

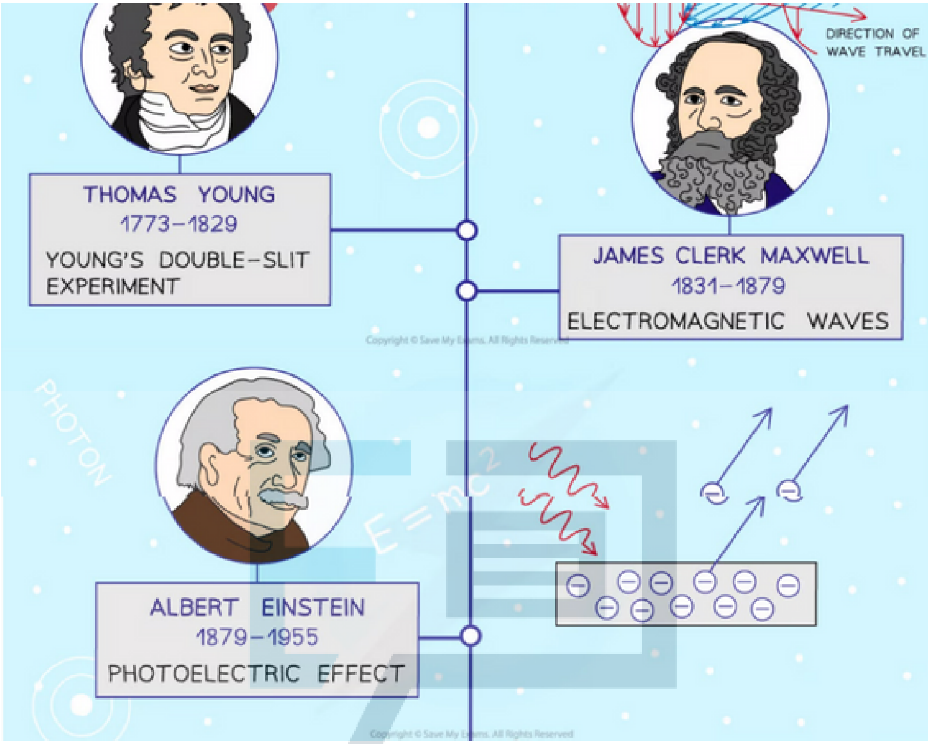
James Clerk Maxwell (1862)

- Maxwell showed that electric and magnetic fields obeyed the wave equation. This means that light was simply waves made up of electric and magnetic fields travelling perpendicular to one another
- Later, Maxwell and Hertz discovered the full **electromagnetic spectrum**

Albert Einstein (1905)

- Einstein discovered that light behaves as a particle, as demonstrated by the **photoelectric effect**
- He described light in terms of packets of energy called **photons**
- Later the scientific community came to understand that light behaves both like a wave and a particle
  - This is known as **wave-particle duality**





3.3.5 Required Practical: Young's Slit Experiment & Diffraction Gratings

Required Practical: Young's Slit Experiment & Diffraction Gratings

Equipment List

Apparatus	Purpose
Laser	To use as a source of monochromatic light
Single Slit	To focus the laser beam onto the double slit (optional)
Double Slit	To diffract the beam into two sources of coherent light
Diffraction Grating	To diffract the beam into multiple sources of coherent light
Metre ruler	To measure the distance between the slits and the screen (D)
Vernier Callipers	To measure the fringe width (w) and slit separation (if not quoted on double slit)
Retort Stand	To support the laser and slits at the same height
White Screen	To project the interference pattern on to
Set Square	To ensure all components are aligned to the normal perfectly

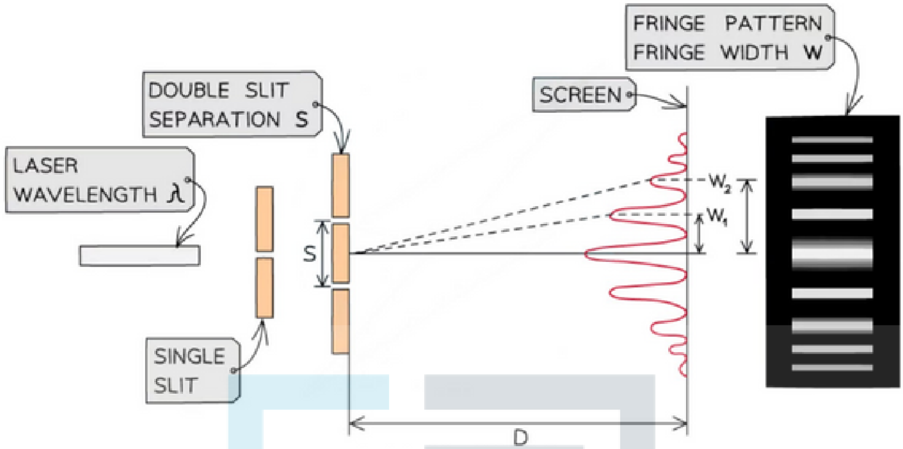
- Resolution of measuring equipment:
  - Metre ruler = 1 mm
  - Vernier Callipers = 0.01 mm

Young's Double-Slit Experiment

The overall aim of this experiment is to investigate the relationship between the distance between the slits and the screen, *D*, and the fringe width, *w*

- Independent variable = Distance between the slits and the screen, *D*
- Dependent variable = Fringe width, *w*
- Control variables
  - Laser wavelength, λ
  - Slit separation, *s*

Method



The setup of apparatus required to measure the fringe width w for different values of D

1. Set up the apparatus by fixing the laser and the slits to a retort stand and place the screen so that *D* is 0.5 m, measured using the metre ruler
2. Darken the room and turn on the laser
3. Measure from the central fringe across many fringes using the vernier callipers and divide by the number of fringe widths to find the fringe width, *w*
4. Increase the distance *D* by 0.1 m and repeat the procedure, increasing it by 0.1 m each time up to around 1.5 m
5. Repeat the experiment twice more and calculate and record the mean fringe width w for each distance *D*

- An example table might look like this:

DISTANCE BETWEEN SLITS AND SCREEN

FRINGE WIDTH

D / m	W / m 1st READING	W / m 2nd READING	W / m 3rd READING	W / m MEAN
0.5				
0.6				
0.7				
0.8				
0.9				
1.0				
1.1				
1.2				
1.3				
1.4				
1.5				

Analysing the Results

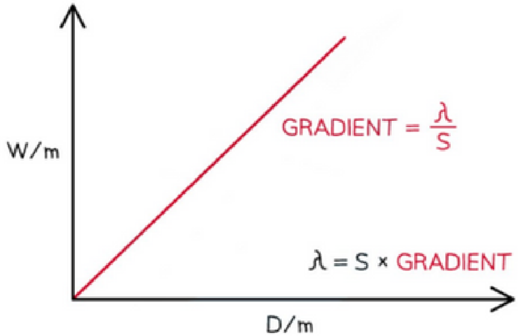
- The fringe spacing equation is given by:

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

- Where:
  - w = the distance between each fringe (m)
  - λ = the wavelength of the laser light (m)
  - D = the distance between the slit and the screen (m)
  - s = the slit separation (m)

- Comparing this to the equation of a straight line: y = mx
  - y = w (m)
  - x = D (m)
  - Gradient = λ/s (unitless)

- Plot a graph of w against D and draw a line of best fit
- The wavelength of the laser light is equal to the gradient multiplied by the slit separation, because:

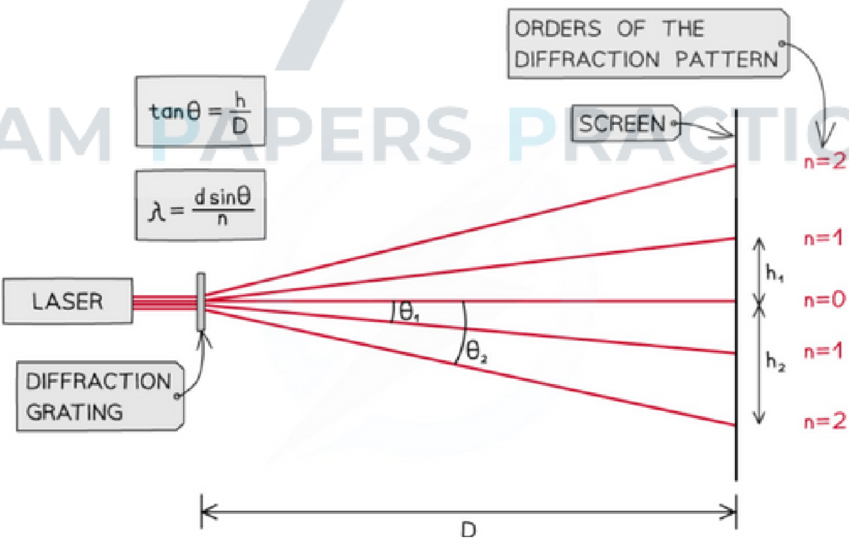


Interference by a Diffraction Grating

The overall aim of this experiment is to calculate the wavelength of the laser light using a diffraction grating

- Independent variable = Distance between maxima, *h*
- Dependent variable = The angle between the normal and each order, θ_n (where n = 1, 2, 3 etc)
- Control variables
  - Distance between the slits and the screen, *D*
  - Laser wavelength λ
  - Slit separation, *d*

Method



The setup of apparatus required to measure the distance between maxima h at different angles θ

1. Place the laser on a retort stand and the diffraction grating in front of it
2. Use a set square to ensure the beam passes through the grating at normal incidence and meets the screen perpendicularly
3. Set the distance *D* between the grating and the screen to be 1.0 m using a metre ruler
4. Darken the room and turn on the laser
5. Identify the zero-order maximum (the central beam)
6. Measure the distance *h* to the nearest two first-order maxima (i.e. n = 1, n = 2) using a vernier calliper
7. Calculate the mean of these two values
8. Measure distance *h* for increasing orders
9. Repeat with a diffraction grating with a different number of slits per mm

- An example table might look like this:

DIFFRACTION ORDER

DISTANCE BETWEEN MAXIMA

ANGLE BETWEEN MAXIMA

n	h / m 1st READING	h / m 2nd READING	h / m MEAN	θ / °
1				
2				
3				
4				
5				

Analysing the Results

The diffraction grating equation is given by:

$$n\lambda = d \sin \theta$$

- Where:
  - n = the order of the diffraction pattern
  - λ = the wavelength of the laser light (m)
  - d = the distance between the slits (m)
  - θ = the angle between the normal and the maxima
- The distance between the slits is equal to:

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

- Where
  - N = the number of slits per metre (m^{-1})

- Since the angle is not small, it must be calculated using trigonometry with the measurements for the distance between maxima, h, and the distance between the slits and the screen, D

$$\tan \theta = \frac{h}{D} \quad \rightarrow \quad \theta = \tan^{-1}\left(\frac{h}{D}\right)$$

- Calculate a mean θ value for each order
- Calculate a mean value for the wavelength of the laser light and compare the value with the accepted wavelength
  - This is usually 635 nm for a standard school red laser

Evaluating the Experiments

Systematic errors:

- Ensure the use of the set square to avoid parallax error in the measurement of the fringe width
- Using a grating with more lines per mm will result in greater values of h. This lowers its percentage uncertainty

Random errors:

- The fringe spacing can be subjective depending on its intensity on the screen, therefore, take multiple measurements of *w* and *h* (between 3–8) and find the average
- Use a Vernier scale to record distances *w* and *h* to reduce percentage uncertainty
- Reduce the uncertainty in *w* and *h* by measuring across all visible fringes and dividing by the number of fringes
- Increase the grating to screen distance *D* to increase the fringe separation (although this may decrease the intensity of light reaching the screen)
- Conduct the experiment in a darkened room, so the fringes are clear

Safety Considerations

- Lasers should be Class 2 and have a maximum output of no more than 1 mW
- Do not allow laser beams to shine into anyone's eyes
- Remove reflective surfaces from the room to ensure no laser light is reflected into anyone's eyes

Worked Example

A student investigates the interference patterns produced by two different diffraction gratings. One grating used was marked 100 slits / mm, the other was marked 300 slits / mm. The distance between the grating and the screen is measured to be 3.75 m.The student recorded the distance between adjacent maxima after passing a monochromatic laser source through each grating. These results are shown in the tables below.

300 slits/mm	h_1/cm	h_2/cm	Average h/cm	Cumulative Total h/cm
n=0 to 1	71.7	71.5	71.6	71.6
n=1 to 2	79.8	79.8	79.8	151.4

100 slits/mm	h_1/cm	h_2/cm	Average h/cm	Cumulative Total h/cm
n=0 to 1	23.8	24.0	23.9	23.9
n=1 to 2	24.0	25.0	24.5	48.4

Calculate the mean wavelength of the laser light and compare it with the accepted value of 635 nm. Assess the percentage uncertainty in this result.

Step 1: Calculate the distance between the slits

For 300 slits / mm: $d = \frac{1}{N} = \frac{1}{300 \times 10^3}$

For 100 slits / mm: $d = \frac{1}{N} = \frac{1}{100 \times 10^3}$

Step 2: Calculate the mean angle for each order

$$\theta = \tan^{-1}\left(\frac{h}{D}\right)$$

- For 300 slits / mm:

$$\theta_1 = \tan^{-1}\left(\frac{71.6}{375}\right) = 10.81°$$

$$\theta_2 = \tan^{-1}\left(\frac{151.4}{375}\right) = 21.99°$$

- For 100 slits / mm:

$$\theta_1 = \tan^{-1}\left(\frac{23.9}{375}\right) = 3.647°$$

$$\theta_2 = \tan^{-1}\left(\frac{48.4}{375}\right) = 7.354°$$

Step 3: Use the grating equation to determine the wavelengths for each order

$$n\lambda = d \sin\theta$$

- For 300 slits / mm:

$$n = 1: \ \lambda = \frac{1}{300 \times 10^3} \times \sin 10.81° = 6.25 \times 10^{-7} = 625 \text{ nm}$$

$$n = 2: \ \lambda = \frac{1}{2 \times (300 \times 10^3)} \times \sin 21.99° = 6.24 \times 10^{-7} = 624 \text{ nm}$$

- For 100 slits / mm:

$$n = 1: \ \lambda = \frac{1}{100 \times 10^3} \times \sin 3.647° = 6.36 \times 10^{-7} = 636 \text{ nm}$$

$$n = 2: \ \lambda = \frac{1}{2 \times (100 \times 10^3)} \times \sin 7.354° = 6.40 \times 10^{-7} = 640 \text{ nm}$$

Step 4: Calculate the mean wavelength

$$\text{Mean } \lambda = \frac{625 + 624 + 636 + 640}{4} = 631.25 = 631 \text{ nm}$$

Step 5: Determine the percentage uncertainty in this value

- The difference between the calculated and accepted value is:

$$635 - 631 = 4 \text{ nm}$$

$$\% \text{ uncertainty} = \frac{4}{635} \times 100\% = 0.6\%$$