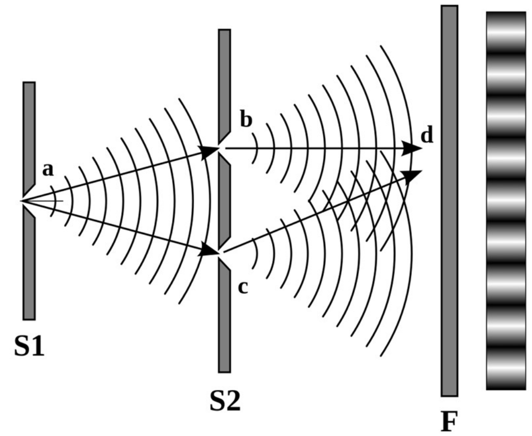
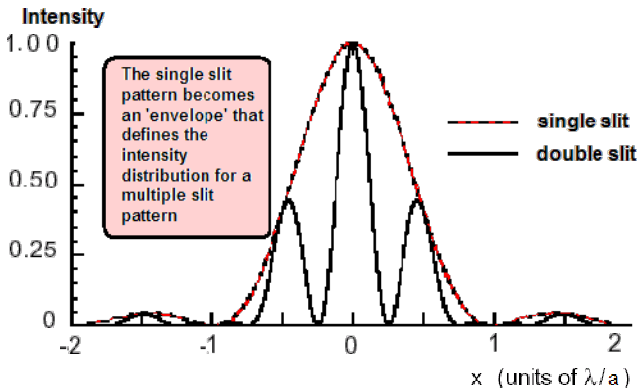
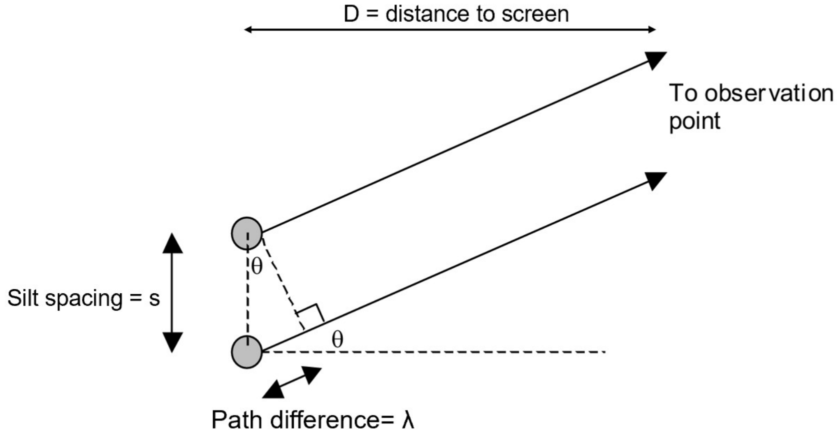
3.3.2 Refraction, diffraction and interference

3.3.2.1 Interference

- Coherence
    - Waves with a **constant phase difference** and the **same frequency and wavelength**
- Monochromatic
    - Light waves with **a single wavelength only**
- Lasers
    - **Coherent and monochromatic**
    - Usually used as sources of light in diffraction experiments as they form clear interference patterns
- Path difference
    - The difference in the distance travelled by two waves from their sources to where they meet
- Interference of monochromatic light
    - Path difference = $n\lambda$ → constructive interference, gives maximum intensity / reinforcement
    - Path difference = $\left(n+\frac{1}{2}\right)\lambda$ → destructive interference, gives 0 intensity / cancellation
- Interference of longitudinal waves (sound waves)
    - Constructive / reinforcement
        - Compression + compression / rarefaction + rarefaction → greater volume
    - Destructive / cancellation
        - Compression + rarefaction → 0 volume, used for noise cancellation
- Young's double slit experiment
    - Condition for light source
        - Monochromatic → colour filter
        - Coherent → single silt between light source and double silt
        - Laser is both monochromatic + coherent so no colour filter / single slit needed
    - Procedure
        - Shine a coherent light source through 2 slits about the same size as the wavelength laser light so the light diffracts / use 2 coherent sources
        - Each slit acts as a **coherent point source** making a pattern of light and dark fringes
        - Light fringes are formed where the light from both slits meet **in phase** and **interferes constructively** (path difference = $n\lambda$)
        - Dark fringes are formed where the light from both slits meets **completely out of phase** and **interferes destructively** (path difference = $\left(n+\frac{1}{2}\right)\lambda$)
        - 



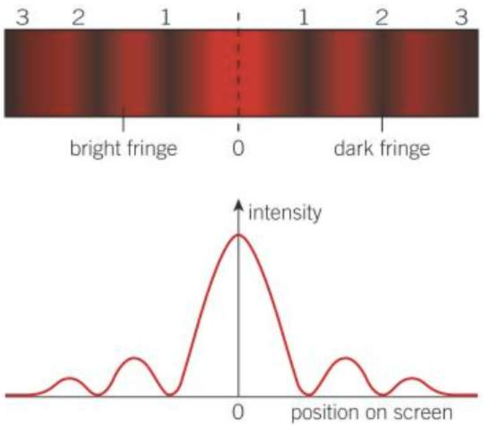
- (Bright) Fringe spacing
  - $w = \frac{\lambda D}{s} = \frac{\text{wavelength} \times \text{distance between slit and screen}}{\text{slit spacing}}$

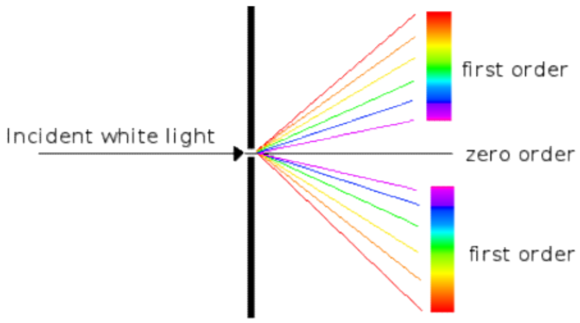


  - $\sin\theta = \frac{\lambda}{s}$
  - $\tan\theta = \frac{w}{D}$
  - When θ is small: $\sin\theta \approx \tan\theta \approx \theta$ so $\frac{\lambda}{s} = \frac{w}{D}$
  - Hence $w = \frac{\lambda D}{s}$
- Significance of Young's double slit experiment
  - **Proved the wave nature of light** since diffraction and interference are wave properties
  - Proved that EM radiation must act as a wave
  - Disproved the theories that light is formed of tiny particles
  - Knowledge and understanding of any scientific concept changes over time in accordance to the experimental evidence gathered by the scientific community
- Interference pattern with white light
  - Wider maxima
  - Less intense diffraction pattern with a central white fringe (all colours are present)
  - Alternating bright fringes which are spectra, violet is the closest to the central maximum and red is the furthest
- Safety precautions with lasers
  - Do not look directly at a laser beam even when it is reflected
  - Wear laser safety goggles
  - Don't shine the laser at reflective surfaces
  - Display a warning sign
  - Never shine the laser at a person

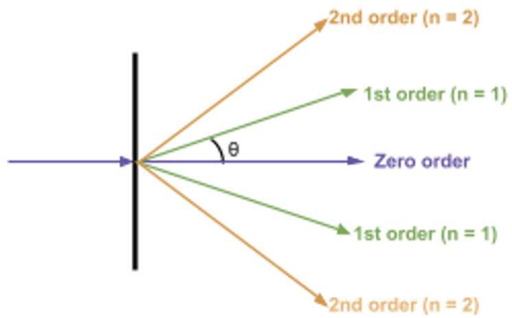
3.3.2.2 Diffraction

- Single silt diffraction
  - Monochromatic light
    - Central maximum with highest frequency
    - Decreasing intensity fringes on both sides, equally spaced
    - Central fringe is twice the width of other fringes

    - 

- White (non-monochromatic) light
    - White central maxima
    - Fringes on both sides show as spectrums
    - Red furthest, violet closest to the centre
    - 

- Narrower slit = lower intensity for all fringes + wider spacing as waves are more diffracted
- Longer wavelength = more diffracted so wider spacing and fringes

- Fringe spacing for single slit diffraction
    - $w = \frac{D\lambda}{a}$
    - Central fringe = $\frac{2D\lambda}{a}$ wide
- Diffraction grating
    - A slide containing many equally spaced slits very close together
    - When monochromatic light is passed through a diffraction grating the interference pattern is much **sharper and brighter** than it would be after being passed through a double slit
    - Light passing through each slit is diffracted
    - The diffracted light waves from adjacent slits reinforce each other in certain directions only and cancel out in all other directions
    - Distances from the centre where maxima occur $= d\sin\theta = n\lambda$ (d = distance between slits)
        - Angle of diffraction between each transmitted beam and the central beam increases if light of a longer wavelength or a grating with closer slits is used
    - 

- White light incident
    - Spectrum is seen when white light is used
    - Different colours of light have different maxima positions
    - Line absorption spectra and line emission spectra can determine the elements in a substance (photoelectric effect)
- Maximum number of orders visible

- Use $\theta = 90°$
- $n_{max} = \left\lfloor \frac{d}{\lambda} \right\rfloor$
- Measuring wavelength of light
  - Diffraction patterns are measured using a spectrometer
    - Angles measured accurate to 1 arc minute ($\frac{1}{60}°$)
  - It can be used to study light from any source and measure wavelengths very accurately
  - Angle measured using a known wavelength → grating spacing calculated
  - Grating can then be used to measure the wavelength of any light
- Applications of diffraction grating
  - Diffraction gratings can be used to observe and measure spectral lines
  - Line emission spectra can be used to identify elements in the vapour gas of the vapour lamp (similar to line absorption spectra)

3.3.2.3 Refraction at a plane surface

- Refraction
  - Change of direction and **wavelength** when a wave crosses a boundary and its speed changes
- Refractive index of a substance
  - $n = \frac{c}{c_s} = \frac{\sin i}{\sin r}$
  - Refractive index of air ≈ 1
  - Higher refractive index = light travels slower in the substance
- Snell's law
  - $n_1 \sin \theta_1 = n_2 \sin \theta_2$
- Total internal reflection (TIR)
  - For ray going from **more dense** to **less dense** substance & the angle of incidence exceeds the critical angle
  - No refracted light wave since the angle of refraction > 90° so **all the light is reflected**
- Critical angle
  - The angle of incidence at which the angle of refraction is 90°
  - $\sin \theta_c = \frac{n_2}{n_1} (n_2 > n_1)$
- Optical fibre structure
  - Cladding
    - Protects the outer surface of the core from scratching
    - Ensure that no light leaves the core
    - RI of cladding < RI of core
    - Similar RI between cladding and core: larger critical angle → less reflection → less modal dispersion
    - RI of cladding much smaller than core: smaller critical angle → less light escape → more light collected
  - Core
    - The transmission medium for EM waves to progress
- Types of optical fibre
  - Step index fibre
    - The refractive index of each component increases moving from the outside to the centre of the fibre
    - The refractive index within each component is **uniform**
  - Graded index fibre
    - Has a core that has a **gradually decreasing** refractive index
- Pulse broadening
  - The length of a pulse is widened so it may overlap with the next pulse
  - Distorts the information in the final pulse
- Pulse absorption
  - Energy is absorbed by the fibre
  - Amplitude is reduced so information can be lost

- Solution
  - Use more transparent core
  - Use pulse repeaters to regenerate the pulse before significant pulse broadening has taken place
- Material / spectral dispersion
  - Happens if white light is used instead of monochromatic light
  - Light waves interact with the material
  - Red light has the longest wavelength it travels the fastest in the materials
  - Violet light has the shortest wavelength it travels the slowest in the materials
  - Causes pulse broadening
  - Solution
    - Use monochromatic light
- Modal / multipath dispersion
  - Light waves entered at **different angles of incidence** so they are spread out
  - They travel different distances as they take different paths and arrive at the other end at different times
  - Causes pulse broadening
  - Solution
    - Use a narrower core (monomode fibre)
    - Use a cladding with its refractive index as close to the core as possible (larger critical angle → less refraction)
- Applications of optical fibres
  - Endoscopes
  - Transmission of data for communications
- Producing coherent image
  - An incoherent bundle cannot be used to form an image because the ends of the individual fibres are arranged randomly so the image is incorrect
  - In a coherent bundle, the fibres have the same spatial position at each end of the bundle.
  - The light emitted from the end of the bundle is an **exact copy** of the incident light and **a single image** can be reproduced and analysed
  - Coherent bundles are expensive to manufacture so incoherent bundles are used for illumination
- Advantages of optical fibres
  - Less loss of strength
  - No interference
  - Greater bandwidth for more information per second
  - Increased security