Chapter 8: Light

Unit Overview

Light is one of the most fascinating forms of energy in nature and technology. It allows us to see the world, transmits data across continents, and powers many engineering systems.

This chapter explores the dual nature of light, its fundamental laws, and the technologies that harness its behaviour. Understanding light is crucial for engineers working in materials science, telecommunications, photonics, and renewable energy.

8.1 The Nature of Light and Its Electromagnetic Properties

Definition: Light is electromagnetic radiation that is visible to the human eye. In physics, it is treated under the **Wave-Particle Duality** model;

It consists of oscillating electric and magnetic fields that travel through space at the speed of light.

1. **Wave Model:** Light propagates as oscillating electric (E) and magnetic (B) fields perpendicular to each other and the direction of propagation. This model is essential for understanding interference and diffraction.
2. **Particle Model:** Light consists of discrete packets of energy called **photons**. This model explains how light interacts with matter at the atomic level, which is critical in materials science.

Key Constants and Equations:

To solve engineering problems, students must master these relationships;

Speed of Light (c): The universal speed limit in a vacuum.

$$c \approx 3.00 \times 10^{8} m/s$$

Photon Energy (E): The energy of a photon is directly proportional to its frequency (f). $E = hf = \frac{hc}{\lambda}$

Where h is Plank's constant $(6.626 \times 10^{-34} J \cdot s)$

Index of Refraction (n): A measure of how much light slows down in a medium. $n = \frac{c}{v}$

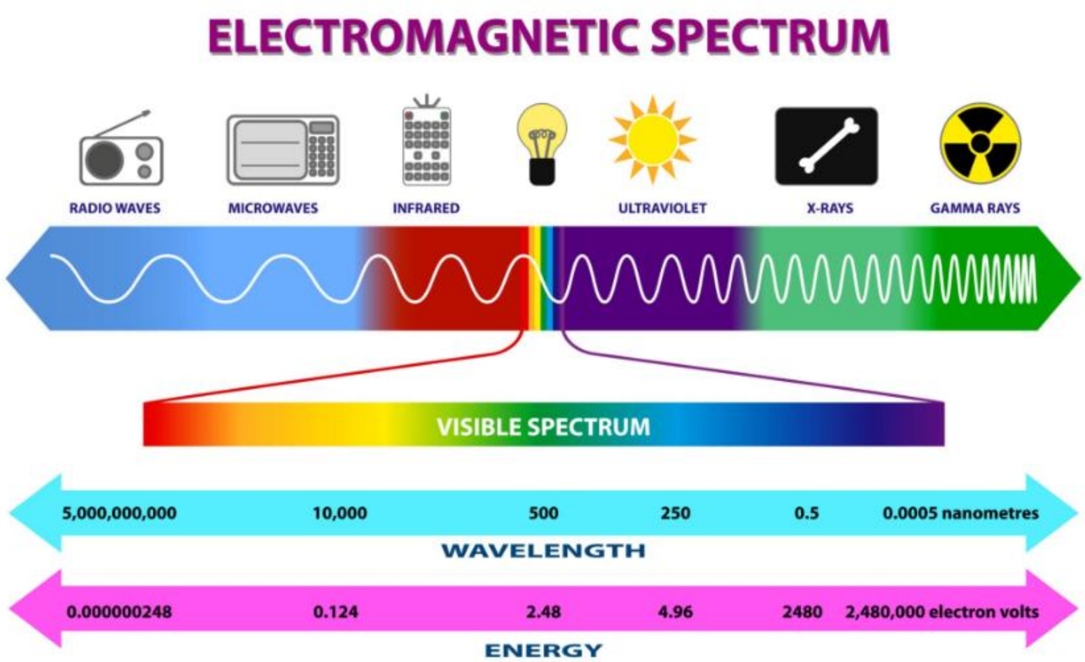

Figure 8.1: Electromagnetic Spectrum

Geometric Optics (Ray Optics)

This branch treats light as rays traveling in straight lines. It is valid when the wavelength of light is much smaller than the obstacles it interacts with ($\lambda \ll D$).

Wave optics explains light behaviour in terms of interference, diffraction, and polarization phenomena that arise from the wave nature of light.

Reflection

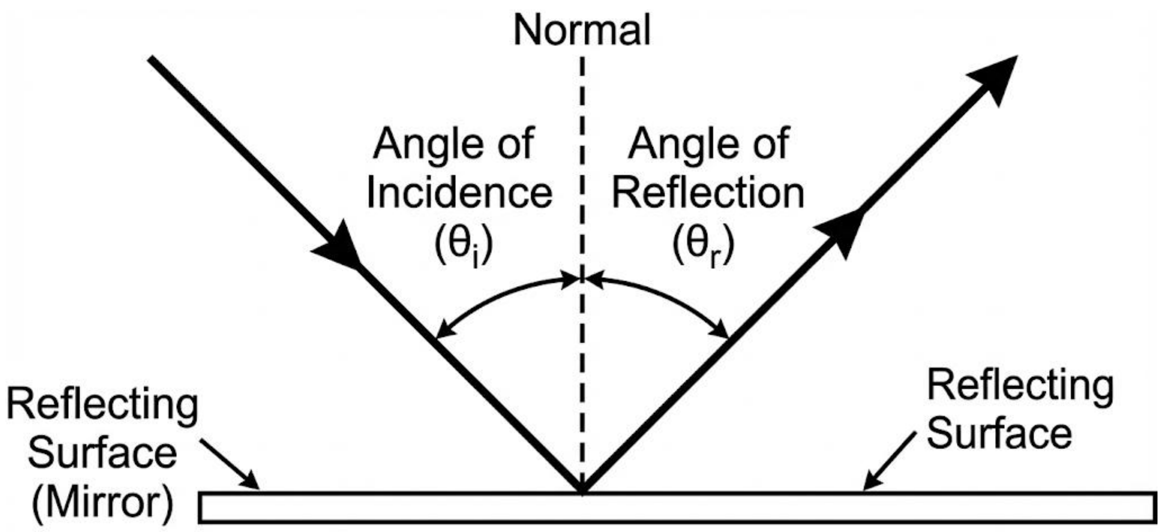

Figure 8.2 image of incident and reflected ray on a surface

Reflection occurs when light bounces off a surface. The angle of incidence equals the angle of reflection. Applications include mirrors, periscopes, and solar concentrators.

Law of Reflection: The angle of incidence equals the angle of reflection ($\theta_i = \theta_r$). Both rays and the normal lie in the same plane.

Specular Reflection

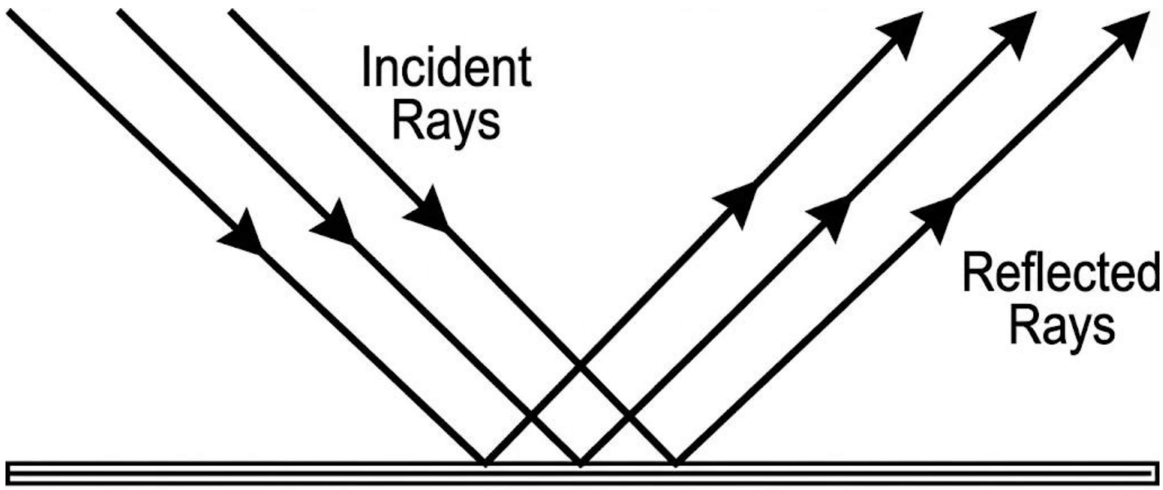

Figure 8.3 Specular reflection

Reflection off a smooth surface (e.g., mirror). This occurs when light reflects from a perfectly smooth surface at a definite, predictable angle. This type of reflection is responsible for the sharp images we see in mirrors and the polished surfaces of engineering materials.

Key Principles:

- **Ray Alignment**: Parallel incident rays remain parallel after reflecting from the surface.
- **Law of Reflection**: For every ray in the beam, the angle of incidence is exactly equal to the angle of reflection.
- **Virtual Image Formation**: Because the rays do not scatter, our brains can trace them back to a point behind the mirror, creating a clear "virtual" image.

Engineering Relevance:

- **Surface Metrology**: Engineers measure the ratio of specular to diffuse reflection to determine the roughness of a material on a microscopic scale.
- **Optoelectronics**: Specular reflection is utilized in the design of high-precision mirrors for laser systems and solar concentrators.
- **Glare Management**: In the design of screens (laptops and phones), engineers often add "anti-glare" coatings to convert annoying specular reflection into diffuse reflection, making the screen easier to read in bright light.

Diffuse Reflection

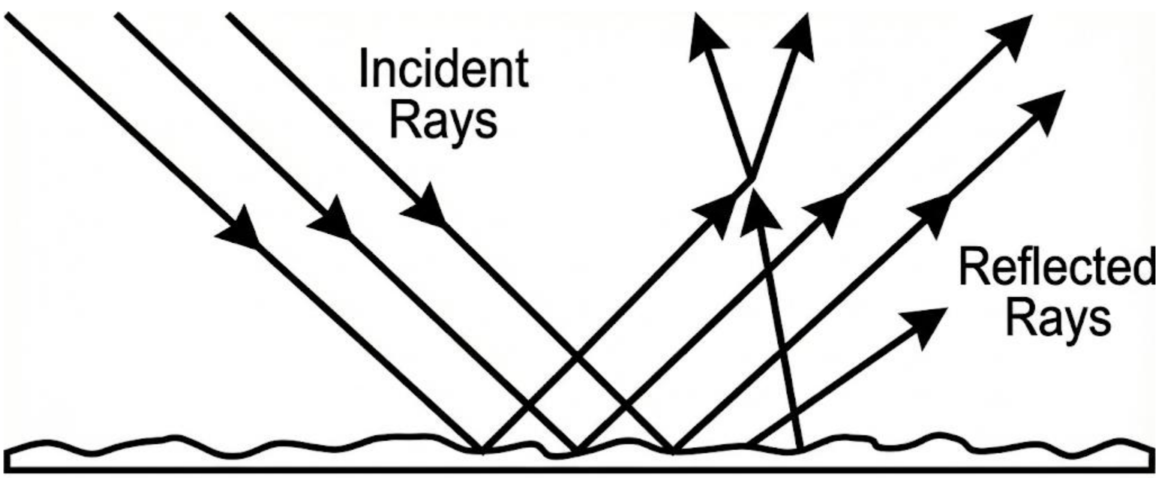

Figure 8.4: Diffuse reflection

Diffuse reflection occurs when light hits a "rough" or irregular surface and scatters in many different directions. While the law of reflection still applies to every individual ray at the microscopic point of contact, the varying orientation of the surface causes the reflected rays to diverge.

Key Principles:

- **Ray Scattering**: Incident parallel rays are reflected at many different angles, preventing the formation of a clear virtual image.
- **Microscopic Roughness**: A surface is considered "rough" for diffuse reflection if its irregularities are larger than the wavelength of the incident light.
- **Visibility**: Diffuse reflection is why we can see non-luminous objects (like paper, wood, or unpolished metal) from any angle.

Engineering Relevance:

- **Material Selection**: Engineers choose matte or "diffuse" finishes for architectural interiors or dashboard materials to prevent blinding glare for occupants and drivers.
- **Safety Engineering**: High-visibility clothing and road signs are designed to maximise diffuse (or retro-reflective) scattering so they are visible to drivers from various perspectives.
- **Optical Inspection**: In quality control, a shift from specular to diffuse reflection on a production line can indicate that a component has not been polished to the required tolerance or that a tool is wearing out.

Refraction, Snell's Law, and Fermat's Principle

Refraction is the bending of light as it passes from one medium to another with a different optical density. The bending of light as it passes from one medium to another due to a change in speed.

Fermat's Principle of Least Time

To understand why light follows a specific path, we look to **Fermat's Principle**, which states:

"The path taken by a ray between two points is the path that can be traversed in the least time."

While light always travels in a straight line within a single uniform medium, it chooses a bent path when crossing into a new medium (like air to water) to minimise the total travel time. To minimize total travel time, light chooses a path that allows it to spend **more distance in the faster medium (air)** and **less distance in the slower medium (water)**. This physical requirement is what causes the light to bend toward the normal, a phenomenon we mathematically describe using Snell's Law.

The degree of bending is given by Snell's Law: $n_1 \cdot sin\theta_1 = n_2 \cdot sin\theta_2$.

If $n_2 > n_1$**(e.g., air to water):** Light bends **towards** the normal.

If $n_2 < n_1$ **((e.g., glass to air):** Light bends **away** from the normal

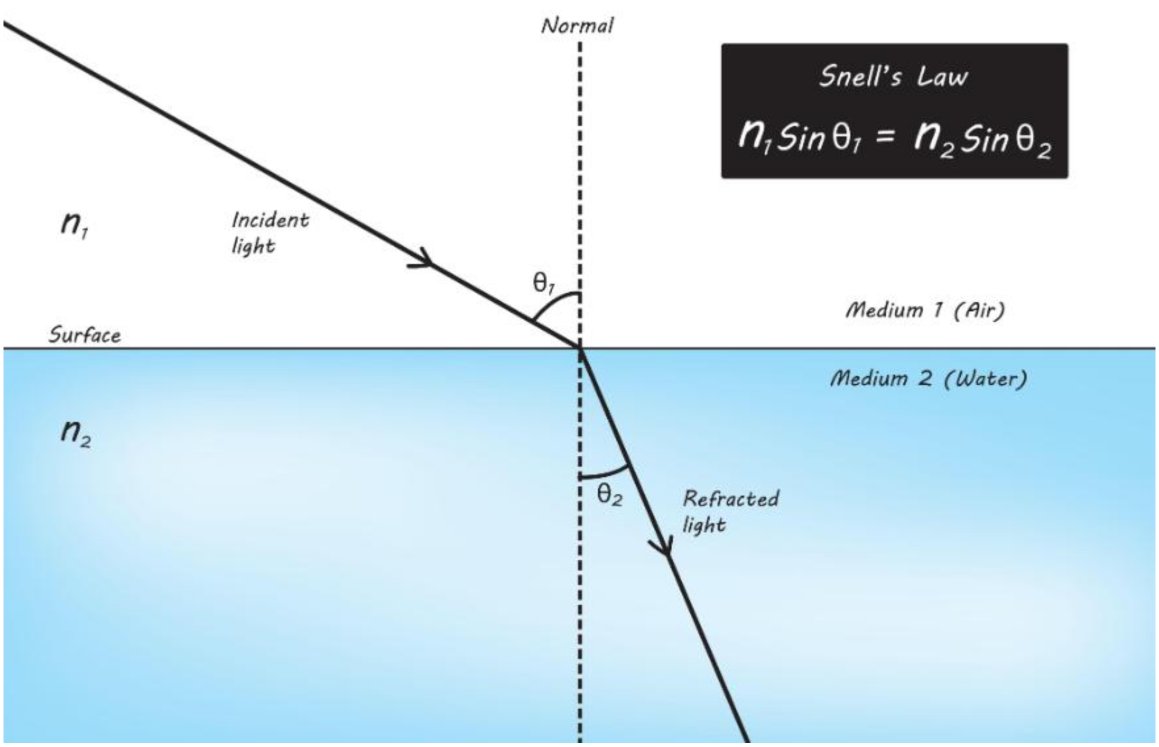

Figure 8.5: Refraction

Total Internal Reflection (TIR)

If light travels from a denser medium to a rarer medium ($n_1 > n_2$) at an angle greater than the **Critical Angle (θ_c)**, no light escapes; all is reflected back.

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

Application: Fiber optics. They form the backbone of modern communication systems, enabling high-speed internet and medical imaging (endoscopy). This is the principle behind high-speed internet. The light signal is "trapped" inside the glass core by reflecting off the cladding.

Example: Snell's Law and Critical Angle

A fiber optic cable has a core with a refractive index of 1.55 and a cladding with a refractive index of 1.45. Calculate the critical angle θ_c for total internal reflection.

Solution:

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

Calculation: $sin\theta_c = \frac{1.45}{1.55} \approx 0.935$

$$\theta_c = (0.935) \approx 69.3°$$

Conclusion: Any light hitting the boundary at an angle greater than $69.3°$ will be trapped in the core.

Interference

When two or more light waves overlap, they interfere with each other. If the crests of one wave coincide with the crests of another, they produce constructive interference (brighter light). If the crest coincides with the trough, destructive interference occurs (dimmer or no light). Applications include thin-film coatings, anti-reflective lenses, and holography.

Diffraction

Diffraction occurs when light bends around obstacles or passes through narrow openings. This effect becomes significant when the obstacle size is comparable to the wavelength of light. Diffraction is exploited in optical instruments such as spectrometers and diffraction gratings to separate light into its component wavelengths.

Polarisation

Polarisation is the restriction of light vibrations to a single plane. Normally, light vibrates in multiple planes, but through filters or reflection, it can be polarised.

Unpolarised Light: The electric field vibrates in all directions perpendicular to propagation.

Linearly Polarised Light: The electric field vibrates in only one specific direction.

Malus's Law: Describes the intensity I of polarised light passing through an analyser: $I = I_0 cos^2\theta$.

Engineering Importance:

1. **Stress Analysis:** Polarised light helps engineers visualise internal stresses in transparent materials.
2. **Display Technology:** LCD screens use polarisation filters to control light for every pixel.
3. **Glare Reduction:** Polarised filters in sunglasses block horizontally polarized reflections from surfaces like water or roads.

Geometric Optics

Geometric optics describes light in terms of straight-line rays. It explains reflection, refraction, and image formation through mirrors and lenses.

c) Lens Theory

Lenses refract light to form images. Engineers use lenses to manipulate light for imaging and measurement. Convex lenses converge light rays to a focal point, while concave lenses diverge them. The lens formula relates object distance (u), image distance (v), and focal length (f) as $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$. This principle is used in cameras, magnifiers, and microscopes.

d) Everyday Technology: Camera Lenses and Optics

Modern smartphone cameras are practical examples of geometric optics. Each camera module contains a miniature lens system that focuses light onto a digital sensor (the image plane). The same physical principles of refraction and focal length apply, just at a compact scale.

• Focal Length (f): The distance between the lens and the image sensor when the subject is in focus. A smaller focal length gives a wider field of view (useful for selfies or landscapes), while a larger focal length provides zoom or magnification.
• Aperture (f-number): The adjustable opening through which light enters. It controls brightness and depth of field a wide aperture (e.g., f/1.8) lets in more light and blurs the background, while a narrow aperture (e.g., f/8) increases sharpness throughout the image.
• Lens Combination: Smartphones often use multiple lenses wide, ultra-wide, and telephoto to simulate optical zoom and create portrait effects by blending images through software.

This example shows how fundamental laws of reflection and refraction are used in optical engineering, leading to clear, high-resolution images on devices we use every day.

8.4 Optical Instruments

Optical instruments use lenses and mirrors to form images and magnify or analyse light. They are fundamental tools in both scientific research and industrial applications.

Thin Lenses

Convex (Converging) Lens: Focuses parallel rays to a focal point.

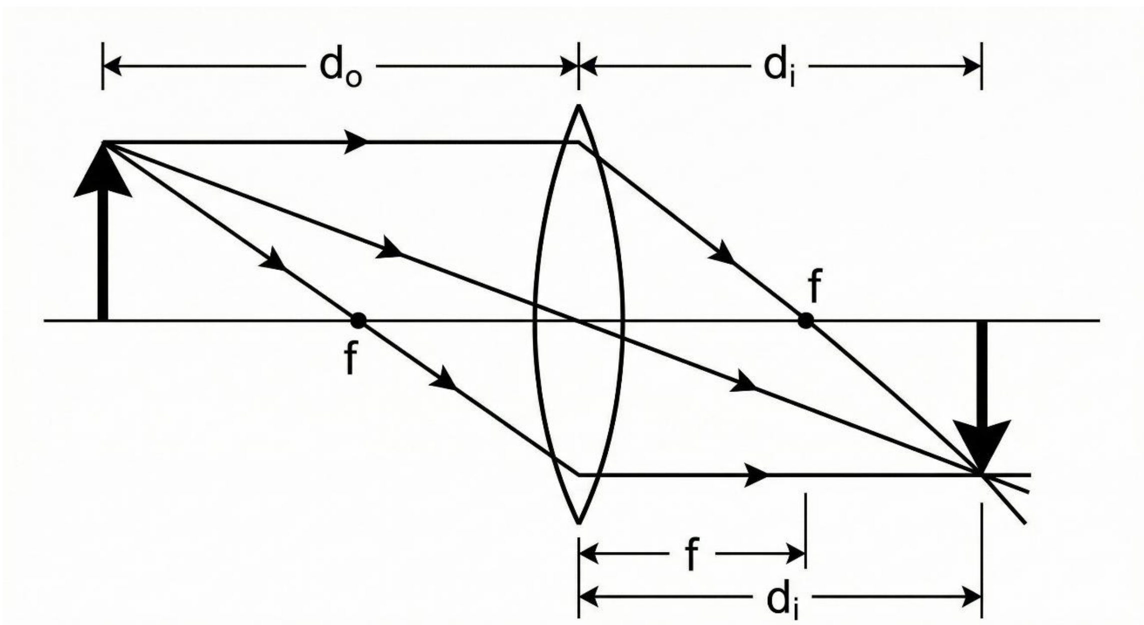

Figure 8.6: Converging Lens forming a real image

This diagram shows a converging lens forming a **real, inverted, and diminished** image. This occurs when the object is placed outside $2f$ (twice the focal length) from the lens.

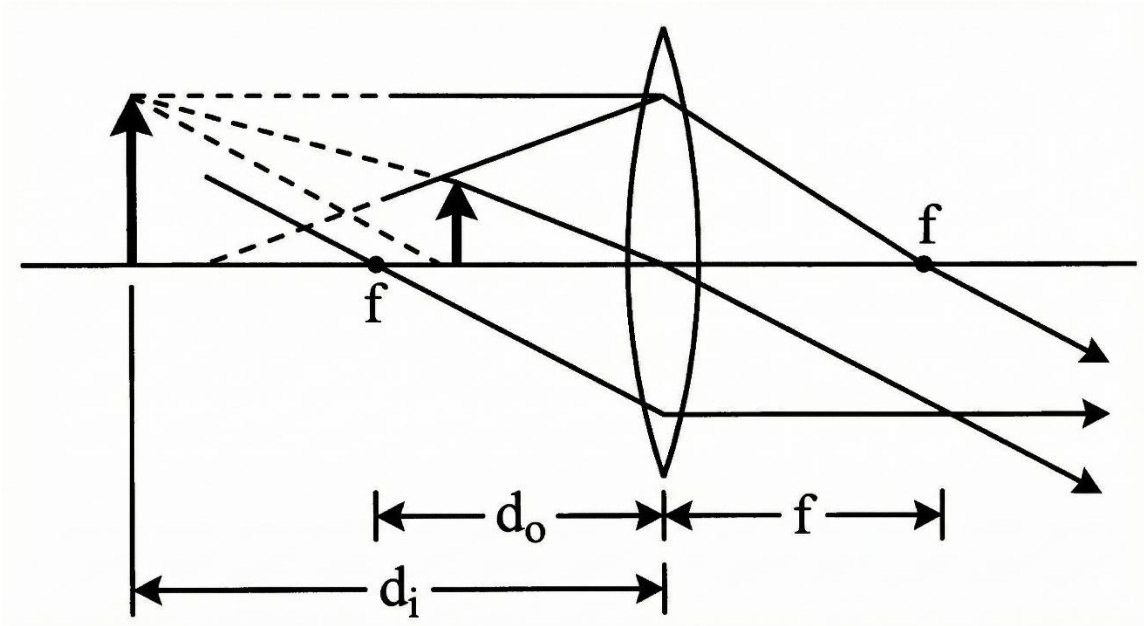

Figure 8.7: Converging lens forming a virtual image

The diagram shows a converging lens forming a **virtual, upright, and magnified** image. This occurs when the object is placed *inside* the focal point f of the lens, which is how a magnifying glass works.

Concave (Diverging) Lens

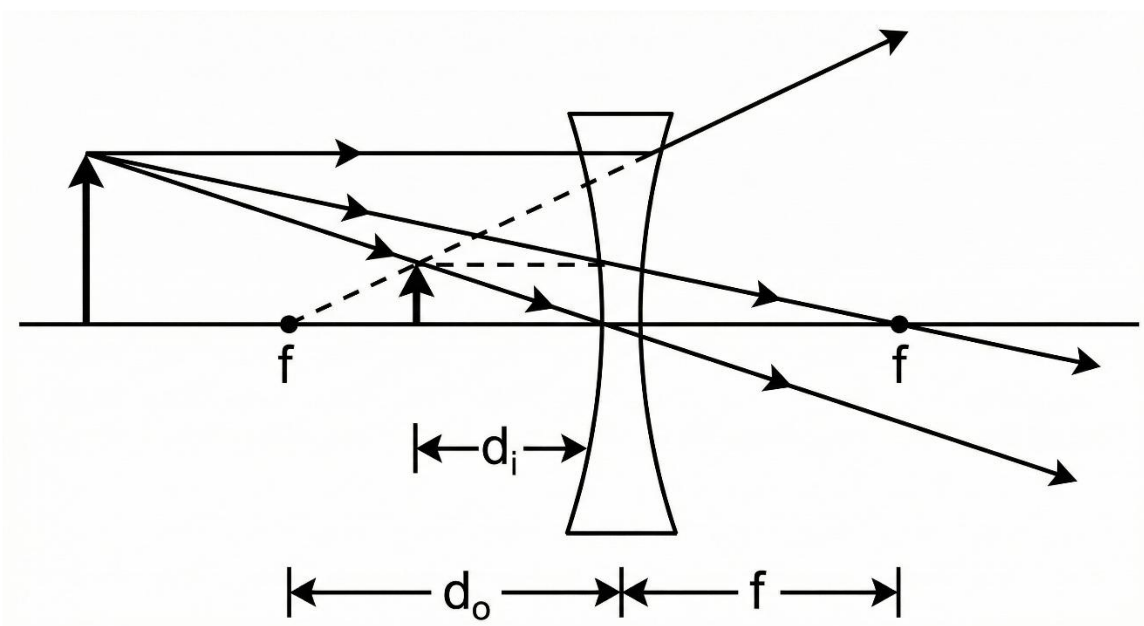

Figure 8.8: Diverging lens showing a virtual image

This diagram shows a diverging lens, which *always* forms a virtual, upright, and diminished image, regardless of where the object is placed. Spreads parallel rays out as if coming from a focal point.

The Thin Lens Equation: $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$

f: Focal length (positive for convex, negative for concave).

d_o: Object distance.

d_i: Image distance.

Magnification (M): $M = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$

If M is negative, the image is **inverted**.

Wave Optics (Physical Optics)

This branch treats light strictly as a wave and is necessary to explain phenomena like interference and diffraction.

Interference

The superposition of two coherent light waves (waves with a constant phase difference).

- **Young's Double Slit Experiment:** Demonstrates the wave nature of light.
  - **Constructive Interference (Bright Fringes):** Path difference is an integer number of wavelengths.

$$dsin\theta = m\lambda \quad (m = 0,1,2 \ldots.)$$

Destructive Interference (Dark Fringes): Path difference is a half-integer.

$$dsin\theta = (m + \frac{1}{2})\lambda$$

(d= slit separation, θ = angle to screen)

Application: Anti-reflective coatings on smartphone screens and camera lenses.

Diffraction

The bending of light around obstacles or through slits.

- **Single Slit Diffraction:** Light passing through a slit of width a creates a central bright spot with fading fringes. The condition for **dark minima** is:

$$a sin\theta = m\lambda$$

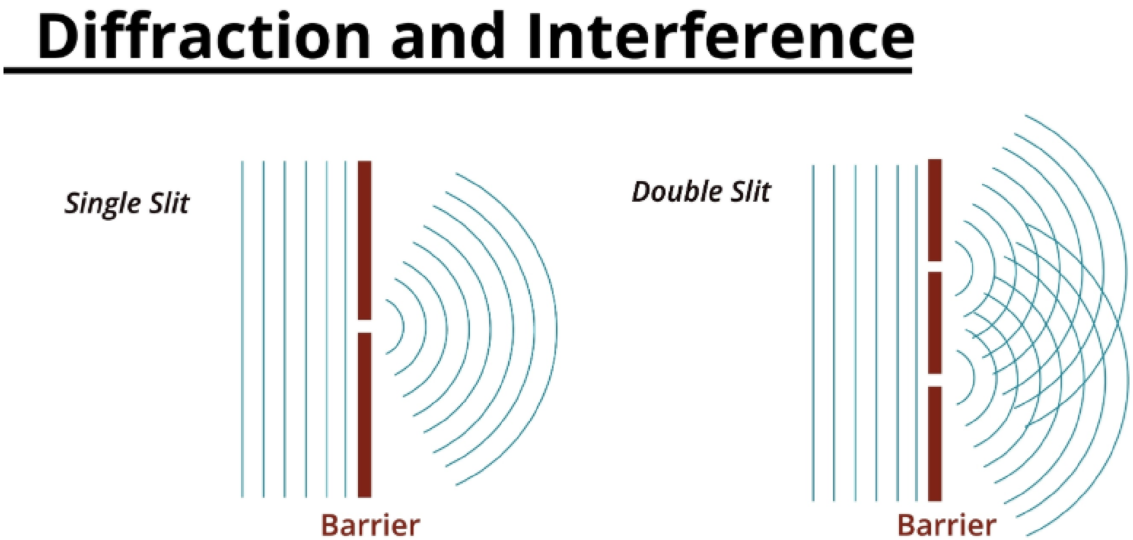

Figure 8.9: Diffraction and Interference

Polarization

Light is a transverse wave. Polarization refers to the orientation of the electric field oscillation.

- **Unpolarized Light:** Electric field vibrates in all directions.
- **Linearly Polarized Light:** Electric field vibrates in one specific direction.
- **Malus's Law:** Describes the intensity (I) of polarized light passing through an analyser.

$$I = I_o cos^2{}_{\theta}$$

Optical Instruments

a) Microscope

Microscopes use combinations of lenses to magnify tiny objects beyond the limits of human vision. They are used in biology, materials science, and nanotechnology to examine microstructures.

b) Telescope

Telescopes collect and magnify light from distant objects. Refracting telescopes use lenses, while reflecting telescopes use mirrors. Applications include astronomy, surveillance, and remote sensing.

c) Spectrometer

A spectrometer splits light into its component wavelengths to analyse materials or light sources. It is used in chemical analysis, quality control, and material characterisation.

8.5 Applications of Light in Engineering

a) Fibre Optics

Optical fibres transmit light signals through total internal reflection.

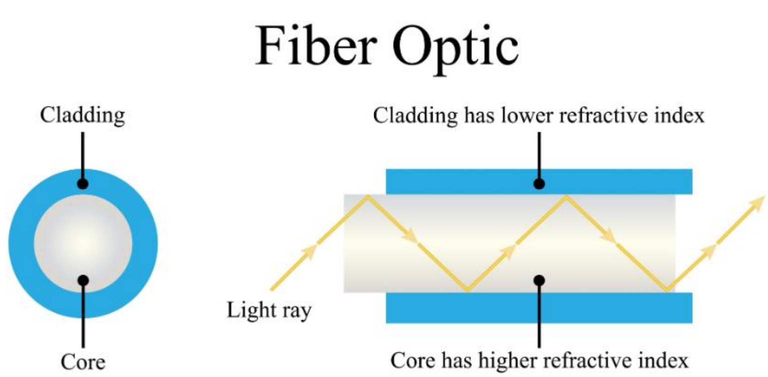

Figure 8.10: A diagram of a fibre optic cable

b) Laser Technology

Lasers produce coherent, monochromatic beams of light. Their precision makes them useful in cutting, welding, barcode scanning, and optical storage devices.

Case Study: Optical Characterisation in Materials Science

The Role of Spectroscopy in Ore Analysis

As an engineering intern, you may deal with the processing of gold ore. Identifying the composition of these materials quickly is vital.

The Technology: Spectrometers utilise the principles of **diffraction** and **refraction** to split light reflected from an ore sample into its component wavelengths. Every element has a “spectral fingerprint” specific wavelength of light it absorbs or emits.

Engineering Impact:

- **Quality Control:** By analysing the light spectrum, engineers can determine the concentration of minerals in a sample without destroying it.
- **Efficiency:** Automated optical sensors can sort "waste" rock from valuable ore on a conveyor belt in milliseconds using high-speed imaging.

Laboratory Practical: Determination of Refractive Index

Aim: To determine the refractive index of a rectangular glass block using Snell’s Law and to observe the phenomenon of lateral displacement.

Equipment

- Rectangular glass block
- Ray box / laser pointer
- Protractor, ruler, and drawing pins
- A4 drawing paper

Methodology

1. Place the glass block on the paper and trace its outline.
2. Draw a normal line perpendicular to the surface of the block.
3. Direct a light ray at an angle of incidence θ_1 of $20°$ and mark the entry and exit points.
4. Remove the block and draw the refracted ray inside the glass.
5. Measure the angle of refraction θ_2 using a protractor.
6. Repeat for angles $30°$, $40°$, $50°$, and $60°$

Data Analysis

- Plot a graph of θ_1 (y-axis) against θ_2 (x-axis).

Questions:

1. What does the gradient of the resulting straight line represent?
2. Calculate the speed of light within your specific glass block using $v = \frac{c}{n}$.

Exercise

1. Explain the difference between specular and diffuse reflection in the context of metal polishing.
2. A lens has a focal length of 15 cm. If an object is placed 30cm away,
   i) where is the image formed?
   ii) Is the image inverted?
3. How does the spectral fingerprint of a material help in the mining industry?
4. Explain why fiber optic cables use a cladding layer with a lower refractive index.
5. A concave mirror has a focal length of 20 cm. An object is placed 30 cm away from the mirror. Determine the position, the size and the nature of the image formed by the mirror. Also, draw a ray diagram to show the image formation.

6. An underwater scuba diver sees the Sun at an apparent angle of $45.0°$ above the horizontal. Calculate the actual elevation angle of the Sun above the horizontal.