Geometrical Optics

Introduction to Optical Systems

Dr. Lias Syham

Laboratory of Quantum Electronics (LEQ)
Faculty of Physics
University of Science and Technology Houari Boumediene

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Course Overview

What is Geometrical Optics?

Definition:

- Study of light propagation using light rays
- Valid when $\lambda \ll$ system dimensions
- Simplified model for optical phenomena

Key Assumption:

Light energy propagates along well-defined paths called **light rays**

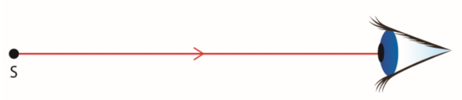


Figure: Light propagation

Validity of Geometrical Optics

✓ **Applicable When:**

- Wavelength λ very small compared to system size
- Example: visible light ($\lambda \sim 500$ nm) with lenses (cm scale)
- Ratio: $\lambda/D \sim 10^{-5}$

× **Not Applicable:**

- Diffraction phenomena
- Interference effects
- Wave nature of light
- Requires wave optics

Important

Geometrical optics provides an excellent approximation for most practical optical systems!

Light Sources

Primary Sources

Emit their own light

- The Sun
- Candle flames
- Filament of a lamp
- Stars

Secondary Sources

Reflect/scatter light

- The Moon
- Planets
- Walls, furniture
- Most things we see

Classification of Optical Media

Structure Classification

Homogeneous/Inhomogeneous
Uniformity of properties in space
Isotropic/Anisotropic

Transparency Classification

Transparent: Complete transmission
Translucent: Partial scattering
Opaque: No transmission

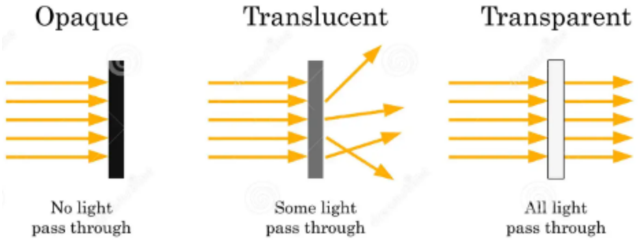


Figure: Types of optical media

Definition

A **light beam** is a collection of light rays bounded by two extreme rays

Three Types:

1. Divergent: rays spread apart
2. Convergent: rays come together
3. Parallel: rays remain parallel

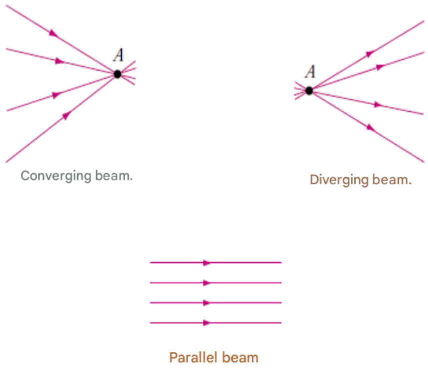


Figure: Classification of light beams

Speed of Light

In Vacuum

$$c = 3.0 \times 10^8 \text{ m/s}$$

Universal constant

In a Medium

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

where n = refractive index

Refractive Index:

$$n = \frac{c}{v} \geq 1$$

Medium	n
Vacuum	1.0000
Air	1.0003
Water	1.33
Glass	1.52
Diamond	2.42

Refractive Index and Dispersion

Wavelength Dependence:

$$n = n(\lambda)$$

- Refractive index varies with wavelength
- This phenomenon is called dispersion
- Responsible for prism effects
- Different colors travel at different speeds

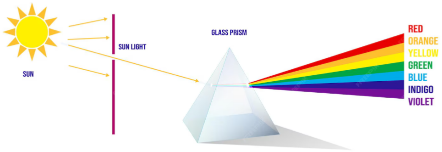


Figure: Dispersion effect

Example

White light through a prism separates into its component colors (rainbow effect)

What is an Optical System?

Definition

An **optical system** is an arrangement of transparent media separated by plane or spherical surfaces.

Types of Surfaces:

- Reflecting: mirrors
- Refracting: lenses
- Can be plane or spherical

Purpose:

Control light propagation to form images

Examples:

- Plane/spherical mirrors
- Thin/thick lenses
- Magnifying glass
- Microscope
- Telescope
- Human eye
- Camera

Optical Axis

Definition

For a **centered** optical system, the **optical axis** is the axis of symmetry that defines the reference direction.

Properties:

- Line of symmetry
- Reference for all measurements
- Used in ray diagrams

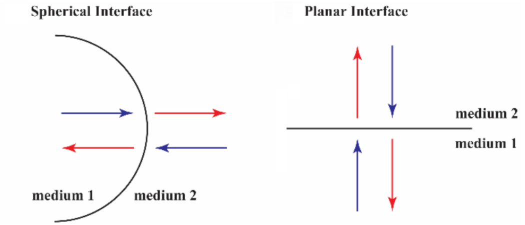


Figure: Optical interfaces with axis

Definition

An **optical interface** is a surface separating two media with different refractive indices.

Two Main Types:

1. **Plane interface**: flat surface
2. **Spherical interface**: curved surface (part of sphere)

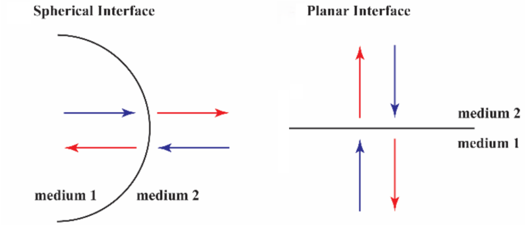
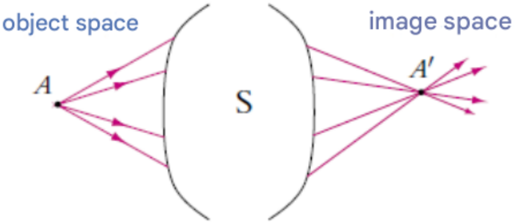


Figure: Plane (right) and spherical (left) interfaces

Object Point and Image Point

Definition

- A **point object** is given by the intersection of the rays which enter the optical system.
- A **point image** is given by the intersection of the rays which come out of the optical system.



Real Object (R.O.)

Definition

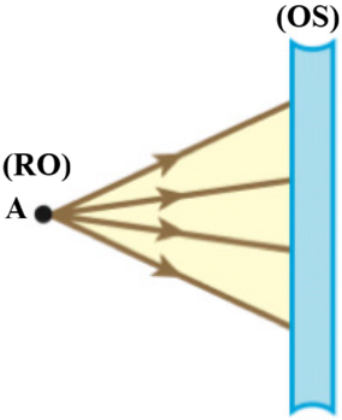
The incoming beam is divergent

Characteristics:

- Light rays spread out from point A
- A is a physical source of light
- Rays physically emanate from the object point

Key Point

A real object is the actual source of light entering the optical system



Virtual Object (V.O.)

Definition

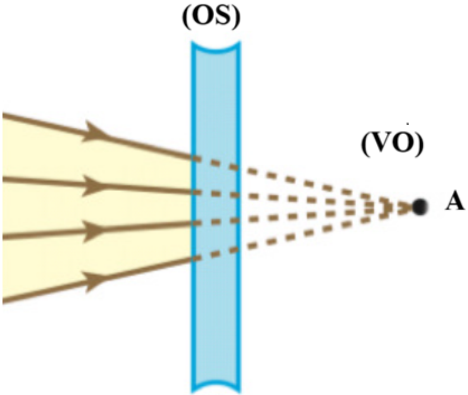
The incoming beam is convergent

Characteristics:

- Extensions of incoming rays converge to A
- Less common than real objects

Key Point

A virtual object is created when a convergent beam is intercepted before it can focus



Real Image (R.I.)

Definition

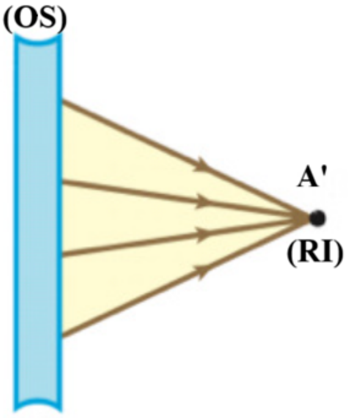
The outgoing beam is convergent

Characteristics:

- Rays physically meet at point A'
- Light energy is actually present at A'
- Point of actual convergence

Key Point

A real image can be captured because light physically converges at that point



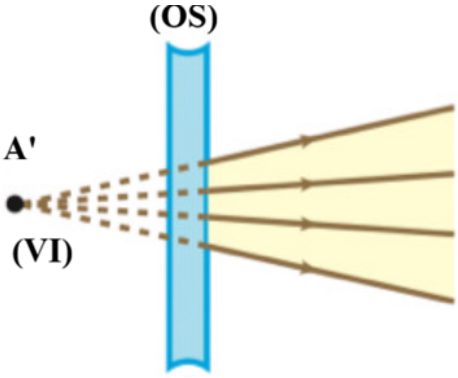
Virtual Image (V.I.)

Definition

The outgoing beam is divergent

Characteristics:

- Extensions of outgoing rays intersect at A'
- Rays appear to come from A'
- No actual light at the image point



Key Point

A virtual image cannot be projected because rays only appear to diverge from that point

Summary: Objects and Images

Concept	Incoming Beam	Outgoing Beam	Key Characteristic
Real Object	Divergent	—	Light comes from a physical source
Virtual Object	Convergent	—	Rays intercepted before they can focus
Real Image	—	Convergent	Rays physically meet; can be projected
Virtual Image	—	Divergent	Rays appear to come from a point; cannot be projected

Remember

- **Objects:** determined by the incoming beam
- **Images:** determined by the outgoing beam

Summary: Object and Image Nature

Type	Ray Behavior	Can Project?
Real Object	Rays diverge from point	—
Virtual Object	Ray extensions converge to point	—
Real Image	Rays converge to point	✓ Yes
Virtual Image	Ray extensions meet at point	× No

Key Point

The distinction between real and virtual depends on whether actual rays or only their **extensions** meet at a point.

Stigmatism

Definition

An optical system is **stigmatic** for a pair of points (A, A') if all rays from object point A converge to a single image point A' after passing through the system.

Stigmatic System:

- Perfect image formation
- All rays meet at one point
- Sharp, clear image
- Ideal case (rarely perfect)

Astigmatic System:

- Imperfect image formation
- Rays don't meet at one point
- Blurred image
- Common in practice

Stigmatism vs Astigmatism

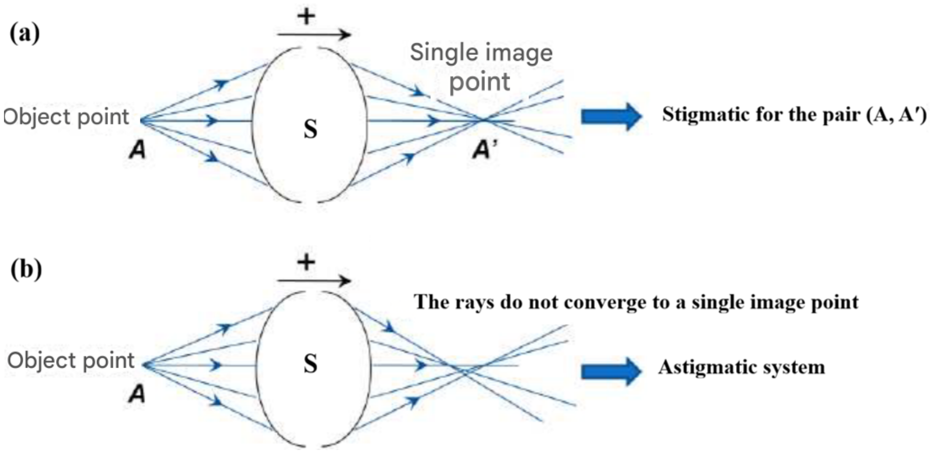


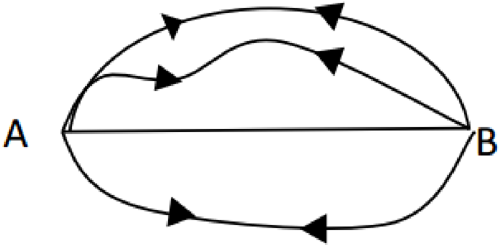
Figure: (a) Stigmatic system: all rays converge to single point A'. (b) Astigmatic system: rays scatter, no unique image point

Fermat's Principle

Light follows the path for which the optical travel time is **stationary** (usually minimum).

Implications:

- Explains rectilinear propagation
- Derives reflection law
- Derives refraction law
- Foundation of geometrical optics



Principle of Reversibility

Reversibility Principle

The path of light is reversible: if you reverse the direction, light follows the same geometric path.

Consequence:

- If A $\rightarrow$ A', then A' $\rightarrow$ A
- Direct consequence of Fermat
- Valid for transparent media
- Does not apply to absorbing media

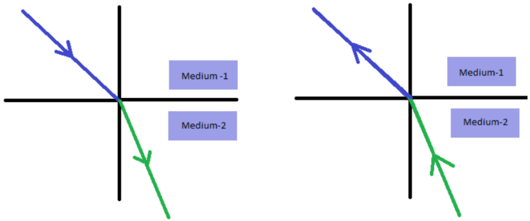


Figure: Reversibility of light path

Laws of Reflection and Refraction

Snell-Descartes Laws

When light encounters an interface between two media:

1. **Coplanar Rays:**
   - Incident ray
   - Normal to interface
   - Reflected/refracted ray
   - All in same plane

2. **Law of Reflection:**

$$\boxed{i = r}$$

3. **Law of Refraction:**

$$\boxed{n_1 \sin i = n_2 \sin r}$$

where:

- n_1, n_2 = refractive indices
- i = angle of incidence
- r = angle of refraction

Detailed study in Chapter II

Key Takeaways

1. Geometrical Optics Basics

- Light as rays: valid when $\lambda \ll$ system size
- Light travels in straight lines in homogeneous media

2. Fundamental Quantities

- Speed of light: $c = 3 \times 10^8$ m/s
- Refractive index: $n = c/v$
- Dispersion: $n = n(\lambda)$

3. Objects and Images

- Real: physical rays converge/diverge
- Virtual: ray extensions converge/diverge

Key Takeaways (continued)

4. Optical Systems

- Stigmatic: all rays from A converge to single A'
- Most systems approximately stigmatic (paraxial)

5. Fundamental Principles

- Fermat: light follows path of stationary time
- Reversibility: optical paths are bidirectional
- Snell-Descartes: $n_1 \sin i = n_2 \sin r$

Next Chapter

Detailed study of reflection and refraction phenomena

Quick Quiz - Test Your Knowledge!

1. **Geometrical optics is applicable when:**
   - A) The wavelength is comparable to system dimensions
   - B) The wavelength is much larger than system dimensions
   - C) The wavelength is much smaller than system dimensions
   - D) Light behaves purely as a wave

2. **The refractive index of a medium is defined by:**
   - A) $n = v/c$
   - B) $n = c/v$
   - C) $n = c \cdot v$
   - D) $n = \sqrt{c \cdot v}$

3. **A real image is formed when the emergent rays:**
   - A) Are parallel
   - B) Are divergent
   - C) Converge toward a point
   - D) Are totally reflected

Quick Quiz (continued)

4. **Fermat's principle states that light follows the path of:**
   A) Maximum optical length
   B) Minimum geometrical distance
   C) Stationary optical travel time
   D) Highest refractive index

5. **According to Snell-Descartes law for refraction:**
   A) $n_1 \cos i = n_2 \cos r$
   B) $n_1 \sin i = n_2 \sin r$
   C) $n_1 \cdot i = n_2 \cdot r$
   D) $i = r$ for all media

Think about your answers before moving to the next slide!

Quiz Solutions

Question 1:

Answer: C

Geometrical optics is valid when $\lambda \ll$ system dimensions

Question 2:

Answer: B

By definition: $n = c/v$

Question 3:

Answer: C

Real images form where rays physically converge

Question 4:

Answer: C

Fermat's principle: stationary optical time

Question 5:

Answer: B

Snell's law: $n_1 \sin i = n_2 \sin r$