Reflection and Refraction Phenomena

Chapter II - Geometrical Optics

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Chapter Overview

Light at Interfaces

Fundamental Concept:

- Light propagates rectilinearly in homogeneous media
- Its direction changes at interfaces between different media
- Two phenomena occur: reflection and refraction

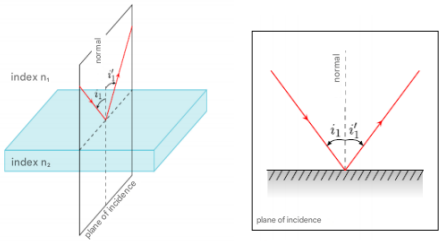

Figure: Light ray at an interface

Key Question

What happens when light encounters a boundary between two different optical media?

What is Reflection?

Definition

Reflection is the optical phenomenon in which light changes direction at an interface while remaining in the same medium.

Plane Mirror:

- Flat reflecting surface
- Simplest optical system
- Ideal for understanding basic principles

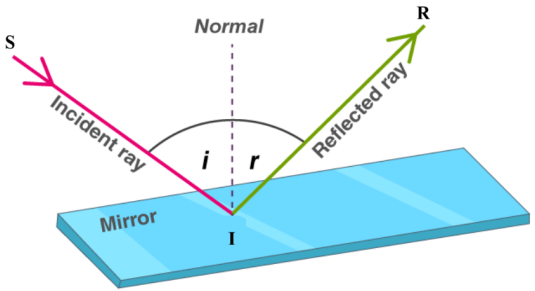

Figure: Reflection from a plane mirror

Laws of Reflection

First Law of Reflection

The incident ray, reflected ray, and normal to the surface all lie in the **same plane** (the plane of incidence).

Second Law of Reflection

The angle of incidence equals the angle of reflection:

$$\boxed{i = r}$$

The reflected ray is symmetric with respect to the normal.

Special Case

A ray incident normally ($i = 0$) is reflected back along its incident path.

Image Formation by Plane Mirror

Properties:

- Image point A' is symmetric to object point A
- Located at the same distance behind the mirror as the object is in front
- Reflected rays appear to diverge from A'
- Image is virtual (cannot be projected onto a screen)

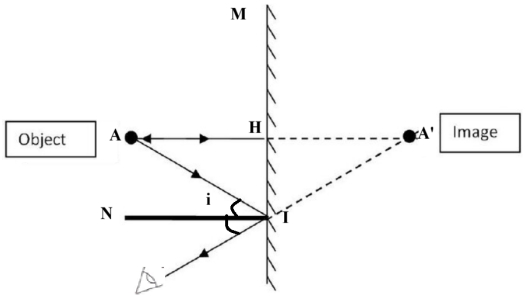

Figure: Image formation by plane mirror

Key Result

For a plane mirror:
Real object → Virtual image
Virtual object → Real image

Rigorous and Approximate Stigmatism

Rigorous Stigmatism

- All rays from A converge to a single point A'
- Perfect image formation

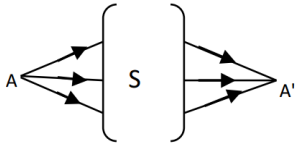

Figure: Rigorous stigmatism: all rays from point A converge exactly to the image point A'.

Approximate Stigmatism

- Rays converge to a small region around A'
- Requires Gauss conditions
- Satisfied by paraxial rays (small angles)

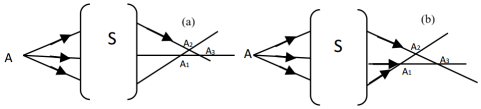

Figure: Approximate stigmatism. (a) Rays do not converge to a single point. (b) Under paraxial (Gauss) conditions, rays converge in a small region around the image point A'.

Gauss Conditions

Gauss Conditions

An optical system exhibits **approximate stigmatism** when all rays:

- Remain close to the optical axis
- Make small angles with the axis
- Are termed **paraxial rays**

Significance:

- Most practical systems satisfy these conditions
- Enable simplified calculations
- Yield acceptable image quality

From this point forward:

- We assume Gauss conditions hold
- Focus on paraxial optics
- Simplified yet accurate approximations

Object and Image Space

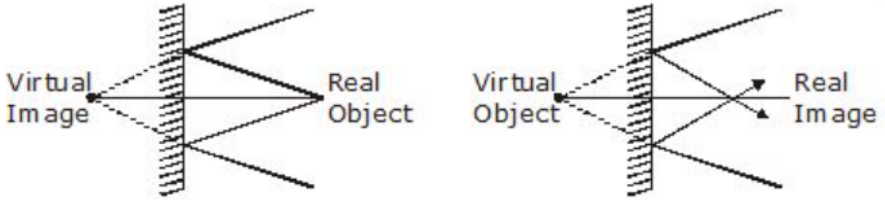

Figure: Object space and image space for a plane mirror - symmetric configuration

Symmetry Property

For a plane mirror, object space and image space are **symmetric** with respect to the mirror plane, with equal distances on opposite sides.

The Deviation

Definition:

- The deviation D is defined as the angle between the extension of the incident ray and the emergent ray from the system.

Case of a Flat Mirror

$$D = \pi - (i_1 + i_2)$$
$$= 180 - 2i_1$$

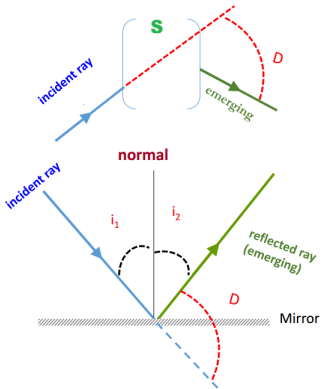

Figure: Deviation D of a light ray by a plane mirror: angle between the incident ray extension and the reflected (emergent) ray.

Two Parallel Plane Mirrors

Configuration:

- Two mirrors facing each other
- Separated by distance d
- Angle $\alpha = 0$

Result:

An infinite number of images are formed by successive reflections

Properties:

- Images are aligned perpendicular to the mirrors
- Equally spaced at intervals of $2d$

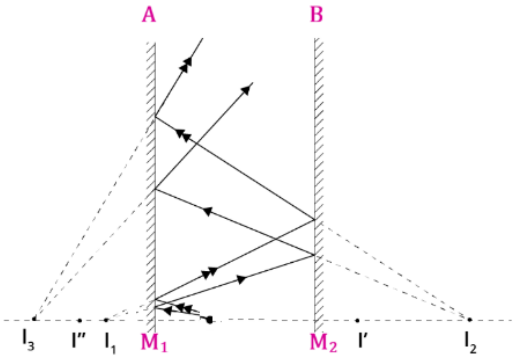

Figure: Multiple images in parallel mirrors

Two Inclined Plane Mirrors

Configuration:

- Mirrors at angle α
- Multiple reflections occur
- Number of images depends on α

Number of Images

$$N = \begin{cases} \frac{360}{\alpha} - 1, & \text{if } \frac{360}{\alpha} \text{ is an integer} \\ \left\lfloor \frac{360}{\alpha} \right\rfloor, & \text{otherwise} \end{cases}$$

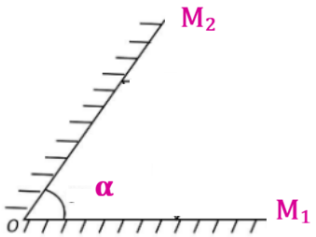

Figure: Inclined mirrors at angle α

Example

$\alpha = 60$: $N = 6 - 1 = 5$ images
$\alpha = 90$: $N = 4 - 1 = 3$ images

Rotation of a Plane Mirror

Fundamental Principle

When a plane mirror rotates through angle α, the reflected ray rotates through $\boxed{2\alpha}$

Explanation:

- Mirror rotation causes the normal to rotate by α
- Angle of incidence changes by α
- Angle of reflection also changes by α
- Total angular deviation: $\alpha + \alpha = 2\alpha$

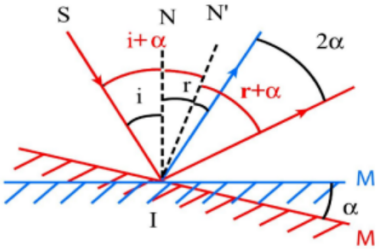

Figure: Effect of mirror rotation

What is Refraction?

Definition

Refraction is the change in direction of light as it crosses an interface between two transparent media with different refractive indices.

Snell's Law of Refraction

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

where:

- n_1, n_2 = refractive indices of media 1 and 2
- i = angle of incidence
- r = angle of refraction

First Law

The incident ray, refracted ray, and normal all lie in the same plane.

Case 1: From Less refractive to More refractive Medium ($n_2 > n_1$)

Condition:

$$n_2 > n_1 \quad \Rightarrow \quad r < i$$

Behavior:

- Refracted ray bends toward the normal
- Angle of refraction is smaller than angle of incidence
- Examples: Air $\rightarrow$ Water, Air $\rightarrow$ Glass

Important

- Refraction occurs at all angles
- No critical angle exists
- Total internal reflection cannot occur

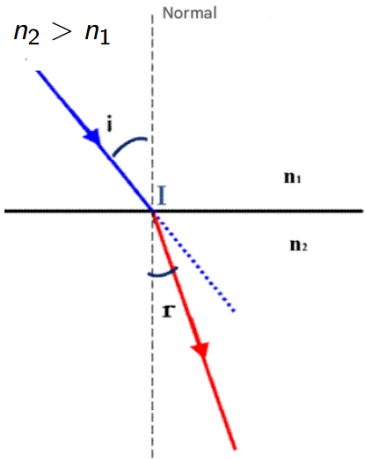

Figure: Ray bends toward the normal

Case 2: From More refractive to Less refractive Medium ($n_2 < n_1$)

Condition:

$$n_2 < n_1 \quad \Rightarrow \quad r > i$$

Behavior:

- Refracted ray bends away from the normal
- Angle of refraction is larger than angle of incidence
- Examples: Water $\rightarrow$ Air, Glass $\rightarrow$ Air

Critical Feature

- A critical angle exists
- Total internal reflection is possible
- Occurs only when $n_2 < n_1$

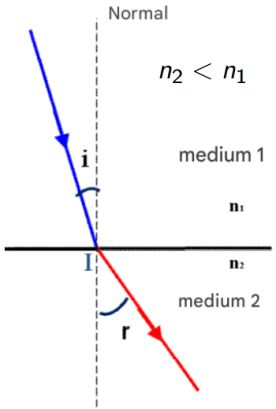

Figure: Ray bends away from the normal

Critical Angle and Total Internal Reflection

Definition

The **critical angle** i_c is the angle of incidence for which the refracted ray propagates along the interface ($r = 90°$):

$$\boxed{\sin i_c = \frac{n_2}{n_1}}, \qquad n_2 < n_1$$

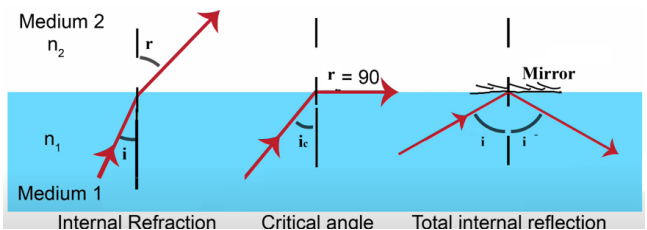

Figure: Left: $i < i_c$ (refraction occurs). Center: $i = i_c$ (critical case). Right: $i > i_c$ (total internal reflection)

Three Regimes of Light Behavior

$i < i_c$

Partial Refraction

- Light enters medium 2
- Partial reflection also occurs
- Normal behavior

$i = i_c$

Critical Angle

- Ray propagates along the interface
- $r = 90^\circ$
- Limiting case

$i > i_c$

Total Internal Reflection

- 100% reflection
- No refracted ray
- Utilized in fiber optics

Example Calculation

Glass ($n_1 = 1.5$) to air ($n_2 = 1.0$):

$$\sin i_c = \frac{1.0}{1.5} = 0.667 \quad \Rightarrow \quad i_c \approx 42^\circ$$

Applications of Total Internal Reflection

Optical Fibers:

- Light confined by TIR
- Propagates over long distances
- Telecommunications applications
- Internet infrastructure

Prisms:

- Superior to mirrors
- No absorption losses
- Used in binoculars and periscopes

Waveguides:

- Integrated photonics
- Optical circuits
- Optical sensors

Key Requirements

TIR occurs only when:

- $n_2 < n_1$
- $i > i_c$

No critical angle exists for $n_2 > n_1$

Field of View of a Mirror

Definition

The **field of view** is the region of space visible to an observer looking into a mirror.

Key Concepts:

- Determined by the mirror boundaries
- Depends on observer position
- Based on the principle of reversibility

Reversibility Principle

Point O' (image of the eye) acting as an object corresponds to image O (actual eye position)

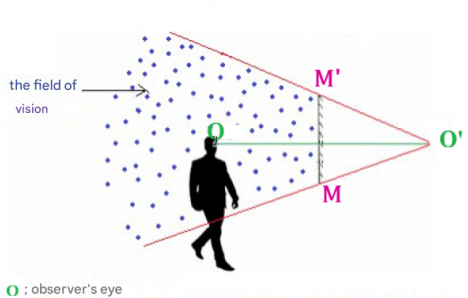

Figure: Field of view defined by rays at mirror edges

Key Takeaways - Reflection

1. Laws of Reflection

- $i = r$ (angle of incidence equals angle of reflection)
- Symmetric reflection with respect to the normal

2. Plane Mirror Properties

- Image is symmetric to object across the mirror plane
- Real object $\rightarrow$ Virtual image
- Equal distances from the mirror

3. Stigmatism

- Rigorous: all rays converge at a single point (ideal)
- Approximate: Gauss conditions (paraxial rays)
- Most practical systems exhibit approximate stigmatism

Key Takeaways - Multiple Mirrors

4. Parallel Mirrors

- Infinite images formed
- Equally spaced at intervals of $2d$
- Created by successive reflections

5. Inclined Mirrors

- Number of images: $N = \frac{360}{\alpha} - 1$ (when the quotient is an integer)
- Smaller angle $\rightarrow$ greater number of images

6. Mirror Rotation

- Mirror rotates by $\alpha \rightarrow$ reflected ray rotates by 2α
- Amplification effect
- Applied in galvanometers and scanning systems

Key Takeaways - Refraction

7. Snell's Law

- $n_1 \sin i = n_2 \sin r$
- Relates angles at the interface
- Fundamental law of refraction

8. Two Cases of Refraction

- $n_2 > n_1$: ray bends toward the normal, $r < i$
- $n_2 < n_1$: ray bends away from the normal, $r > i$

9. Critical Angle

- Exists only when $n_2 < n_1$
- $\sin i_c = n_2/n_1$
- Refracted ray propagates along the interface when $i = i_c$

Key Takeaways - Total Internal Reflection

10. Total Internal Reflection (TIR)

- Occurs when $n_2 < n_1$ and $i > i_c$
- 100% reflection, no refracted ray
- Evanescent field present in the second medium

12. Important Distinctions

- Real vs Virtual: actual rays vs backward extensions
- Reflection: same medium; Refraction: different media
- Critical angle exists only for more refractive $\rightarrow$ less refractive transitions

Comprehensive Summary Table

Phenomenon	**Key Equation**	**Condition**
Reflection	$i = r$	Same medium
Refraction (general)	$n_1 \sin i = n_2 \sin r$	Different media
Less refractive medium $\rightarrow$ More refractive medium	$r < i$	$n_2 > n_1$
More refractive medium $\rightarrow$ Less refractive medium	$r > i$	$n_2 < n_1$
Critical Angle	$\sin i_c = n_2/n_1$	$n_2 < n_1$
Total Internal Reflection	No refraction	$i > i_c$, $n_2 < n_1$
Mirror Rotation	Ray rotates by 2α	Mirror rotates by α
Inclined Mirrors	$N = 360/\alpha - 1$	If $360/\alpha$ is an integer

Quick Quiz - Test Your Knowledge!

1. **According to the law of reflection:**
   A) The angle of incidence is always greater than the angle of reflection
   B) The angle of incidence equals the angle of reflection
   C) The incident and reflected rays are perpendicular
   D) The angle of reflection is always 90°

2. **A plane mirror forms what type of image of a real object?**
   A) Real and inverted
   B) Real and upright
   C) Virtual and inverted
   D) Virtual and upright

3. **When a plane mirror rotates by 15°, the reflected ray rotates by:**
   A) 7.5°
   B) 15°
   C) 30°
   D) 45°

Quick Quiz (continued)

4. **Snell's law of refraction is expressed as:**
   A) $n_1 \cos i = n_2 \cos r$
   B) $n_1 \sin i = n_2 \sin r$
   C) $n_1 / \sin i = n_2 / \sin r$
   D) $n_1 i = n_2 r$

5. **When light travels from water (n=1.33) to air (n=1.00), the refracted ray:**
   A) Bends toward the normal
   B) Bends away from the normal
   C) Continues without bending
   D) Is completely absorbed

6. **Total internal reflection can occur when:**
   A) Light propagates from any medium to any other medium
   B) Light propagates from a more refractive to a less refractive medium at angles greater than the critical angle
   C) Light propagates from a less refractive to a more refractive medium
   D) The angle of incidence is less than the critical angle

Quick Quiz (continued)

7. **The critical angle for total internal reflection exists when:**
   A) $n_1 = n_2$
   B) $n_2 < n_1$
   C) $n_2 > n_1$
   D) For any pair of media

8. **Two parallel plane mirrors create:**
   A) Exactly two images
   B) A finite number of images depending on the separation distance
   C) An infinite number of images
   D) No images

9. **For glass (n=1.5) to air (n=1.0), the critical angle is approximately:**
   A) 30°
   B) 42°
   C) 60°
   D) 90°

Quick Quiz (final question)

10. **Gauss conditions require that:**
    A) All rays must be perpendicular to the optical axis
    B) Rays must make large angles with the optical axis
    C) Rays must remain close to and make small angles with the optical axis
    D) The optical system must have no aberrations

Take your time and think carefully about each answer!

Quiz Solutions (1-6)

Question 1:

Answer: B

By the law of reflection: $i = r$

Question 2:

Answer: D

Plane mirror: real object $\rightarrow$ virtual, upright image

Question 3:

Answer: C

Mirror rotation $\alpha \rightarrow$ ray rotation $2\alpha = 30$

Question 4:

Answer: B

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

Question 5:

Answer: B

$n_1 > n_2 \rightarrow$ ray bends away from the normal

Question 6:

Answer: B

TIR: more refractive medium $\rightarrow$ less refractive medium, $i > i_c$

Quiz Solutions (7-10)

Question 7:

Answer: b

Critical angle exists only when $n_2 < n_1$

Question 8:

Answer: C

Parallel mirrors create an infinite number of images

Question 9:

Answer: B

$\sin i_c = 1.0/1.5 = 0.667$, therefore $i_c \approx 42$

Question 10:

Answer: C

Gauss conditions: paraxial rays (small angles, close to axis)

How many did you answer correctly?

8-10: Excellent! *6-7: Good!* *4-5: Review needed* *0-3: Further study required*

Thank You!

Questions?

Next: Chapter III - Prisms