Unit 6
Electromagnetic Waves and Geometrical Optics

Introduction

Light is a type of electromagnetic wave that enables us to see and interact with the world around us. The study of light and how it interacts with different materials is known as optics. Geometrical optics, a branch of this field, focuses on the behavior of light as it travels through various materials, considering factors like shape and the angles at which light hits surfaces. Understanding these principles allows us to design and use optical instruments such as mirrors, lenses, telescopes, microscopes, and prisms.

Key Concepts in Electromagnetic (EM) Waves

Electromagnetic Waves (EM Waves):
EM waves consist of oscillating electric and magnetic fields that propagate through space at the speed of light. Unlike mechanical waves, which require a medium to travel through, EM waves can travel through a vacuum (empty space). These waves transfer energy without the need for matter to carry that energy from one place to another.

Propagation of EM Waves:
EM waves are generated by charged particles, like electrons, that move back and forth. As they vibrate, they create oscillating electric and magnetic fields, which are perpendicular to each other and to the direction of wave propagation. This means EM waves are transverse waves.

Frequency and Wavelength:
The frequency of an EM wave is the number of times its electric and magnetic fields vibrate per second. The wavelength is the distance between two consecutive crests (high points) or troughs (low points) of the wave. These properties vary across the different types of EM waves, leading to a wide range of applications and effects.

The Electromagnetic Spectrum

The electromagnetic spectrum encompasses all types of EM waves, categorized by their wavelengths and frequencies:

1. **Radio Waves:**
   - **Wavelength:** Longest in the EM spectrum, from 1 meter to thousands of meters.
   - **Frequency:** Lowest, from 500 kHz to about 1000 MHz.
   - **Uses:** Communications (e.g., radio, television), radar.
   - **Dangers:** Large doses may cause health issues like cancer.
2. **Microwaves:**
   - **Wavelength:** A few centimeters.
   - **Frequency:** Higher than radio waves.
   - **Uses:** Cooking (microwave ovens), mobile phones, radar.
   - **Dangers:** Prolonged exposure can cause cataracts and brain effects.
3. **Infrared Waves:**
   - **Wavelength:** Just below visible light.
   - **Uses:** Remote controls, night vision, heat detection.
   - **Dangers:** Excessive exposure can cause burns.
4. **Visible Light:**
   - **Wavelength:** 400 to 700 nm.
   - **Uses:** Vision, photography, illumination.
   - **Dangers:** Intense light can damage the eyes, especially from sources like the Sun.
5. **Ultraviolet (UV) Rays:**
   - **Wavelength:** Shorter than visible light, around 400 nm to 0.6 nm.
   - **Uses:** Sterilization, sun tanning, detecting forgery.
   - **Dangers:** Can cause skin cancer, eye damage, and sunburn.
6. **X-rays:**
   - **Wavelength:** Very short, high frequency.
   - **Uses:** Medical imaging, security scanning.
   - **Dangers:** Can cause cell damage and cancer.
7. **Gamma Rays:**
   - **Wavelength:** Shortest, with the highest frequency.
   - **Uses:** Cancer treatment, sterilization of medical equipment.
   - **Dangers:** Highly penetrating, can cause severe cell damage and cancer.

The electromagnetic spectrum consists of a wide range of EM waves, each with unique properties and applications. Understanding these waves allows us to harness their benefits in various fields, but it is also crucial to be aware of their potential dangers.

Light as a Wave

Key Concepts:

- Light is an electromagnetic (EM) wave.
- It can travel through a vacuum and various materials like air, water, and glass.
- Light travels at different speeds depending on the medium.

Propagation of Light

Light, as an electromagnetic wave, can travel in a vacuum (like space) as well as through different materials such as air, water, and glass. Unlike water waves or sound waves, light does not require a medium to propagate, which is why we can see light from distant celestial bodies like the moon or stars.

Illustration: Imagine dropping a rock into a pond. Just as the ripples spread out on the water's surface, light waves spread out in all directions from a source like a light bulb. However, while the ripples only spread on the water's surface, light spreads in all directions through the space around it.

Speed of Light

The speed at which light travels in a vacuum is constant, known as the speed of light, symbolized as **c**. This speed is approximately: $c=3.00\times10^8$ m/s

This means light travels at about 300,000 kilometers per second. For example, light from the Sun, which is about 150 million kilometers away, takes only about 8.5 minutes to reach Earth. However, when light travels through a medium (like glass or water), it slows down due to interactions with the atoms and molecules in the material.

Key Concept:

- In a vacuum, the speed of light is always **3.00×10^8 m/s**.
- The relationship between the speed of light (c), its frequency (f), and wavelength (λ) is given by: $c=f\times\lambda$

As the frequency of an electromagnetic wave increases, its wavelength decreases.

Example Calculations:

1. **Finding Frequency of Red Light (λ = 700 nm):** $f=\frac{c}{\lambda}=\frac{3\times10^8\ m/s}{700\times10^{-9}\ \mathrm{m}}=4.29\times10^{14}$ Hz
2. **Finding Wavelength of a Radio Wave (f = 103.4 MHz):** $\lambda=\frac{c}{\mathrm{f}}=\frac{3\times10^8 m/s}{103.4\times10^6\ \mathrm{Hz}}=2.9$ m

Light Rays and Beams

Light travels in straight lines called rays, and these rays can be represented by straight lines with arrowheads showing the direction of light. A group of rays forms a beam. A ray diagram can be used to show how light travels from an object to our eyes, allowing us to see the object.

key concept:

- Light travels in all directions from its source in straight lines.
- Light rays are a tool to represent the path light travels, not physical entities.
- Light can travel through empty space (a vacuum) and through materials.
- The speed of light in a vacuum is **3.00×10^8 m/s**.

Laws of Reflection & Refraction

Reflection of Light

Reflection occurs when light strikes a surface and bounces back. The incoming light ray is called the *incident ray*, and the light ray that bounces back is the *reflected ray*. These rays make angles with an imaginary line called the *normal*, which is perpendicular to the surface.

Laws of Reflection:

1. The angle of incidence (θi) is equal to the angle of reflection (θr). This means that the angle between the incident ray and the normal is the same as the angle between the reflected ray and the normal.
2. The incident ray, the normal, and the reflected ray all lie in the same plane.

Types of Reflection:

- **Specular Reflection**: Occurs on smooth, shiny surfaces like mirrors, where the reflected rays are parallel.
- **Diffuse Reflection**: Occurs on rough surfaces where reflected rays scatter in different directions.

Refraction of Light

When light passes from one medium to another, like from air to water, it changes direction. This bending of light is called *refraction*. The speed of light varies in different media, causing the light to bend.

Laws of Refraction:

1. The incident ray, the refracted ray, and the normal at the point of incidence all lie in the same plane.
2. The ratio of the sine of the angle of incidence ($\theta 1$) to the sine of the angle of refraction ($\theta 2$) is a constant. This law is known as Snell's Law and is expressed as:

$$\frac{\sin \theta 1}{\sin \theta 2} = \text{constant}$$

This constant is called the *refractive index*, which varies depending on the medium.

Refractive Index: The refractive index measures how much light slows down when passing through a medium. It is the ratio of the speed of light in a vacuum to the speed of light in the medium.

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

Where *c* is the speed of light in a vacuum, and *v* is the speed of light in the medium.

Total Internal Reflection: When light moves from a denser medium (like water) to a less dense medium (like air), and the angle of incidence exceeds a certain value called the *critical angle*, the light does not pass through the boundary but is entirely reflected back into the denser medium. This phenomenon is known as *total internal reflection*.

Exercise 6.7

1. **Why does a pencil appear bent when partially submerged in water?**
   - This is due to refraction. The light rays from the pencil bend as they pass from water to air, making the pencil appear displaced.
2. **Calculate the angle of refraction for a light ray passing from water (refractive index = 1.33) to air with an angle of incidence of 35°.**
   - Use Snell's Law to solve this problem: $\sin\theta 2 = \frac{\sin \theta 1 \times n1}{n2}$.

These principles are fundamental in understanding how light interacts with various materials and have numerous practical applications in optics, such as in lenses, glasses, and even in nature.

Mirrors and Lenses

Introduction

In this section, you will learn about mirrors and lenses, and how they form images. By understanding the laws of reflection and refraction, you'll be able to explain how these optical devices work and perform calculations related to them.

Mirrors

A mirror is a surface that reflects light to form images. The main types of mirrors are plane mirrors and spherical mirrors, which include concave and convex mirrors.

Plane Mirrors

- **Definition**: A plane mirror has a flat reflective surface.
- **Image Formation**: When an object is placed in front of a plane mirror, light rays bounce off the mirror, and an image is formed that appears to be behind the mirror.

  Key Properties of the Image in a Plane Mirror:

  1. The image is virtual (it cannot be projected onto a screen).
  2. The image is the same size as the object.
  3. The image is upright.
  4. The image is laterally inverted (left and right are swapped).
  5. The distance of the image behind the mirror is equal to the distance of the object in front of the mirror.

Spherical Mirrors

Spherical mirrors have curved surfaces and are of two types: concave and convex.

- **Concave Mirror**:
  - **Description**: This mirror curves inward, like the inside of a spoon.
  - **Image Formation**: The image formed by a concave mirror depends on the object's position relative to the mirror.
    - **If the object is far from the mirror**: The image is real, inverted, and smaller.
    - **If the object is close to the mirror**: The image is real, inverted, and larger.
    - **If the object is very close (between the focus and the mirror)**: The image is virtual, upright, and larger.

Uses: Concave mirrors are used in devices like flashlights, vehicle headlights, and shaving mirrors to focus light.

- **Convex Mirror**:
    - **Description**: This mirror curves outward, like the back of a spoon.
    - **Image Formation**: The image formed is always virtual, upright, and smaller than the object, regardless of the object's position.

  Uses: Convex mirrors are commonly used as rear-view mirrors in vehicles because they provide a wider field of view.

Lenses

Lenses are transparent objects that refract (bend) light to form images. They are primarily of two types: convex and concave lenses.

- **Convex Lens**:
    - **Description**: A convex lens is thicker at the center than at the edges. It converges light rays to a point.
    - **Image Formation**:
        - **If the object is far**: The image is real, inverted, and smaller.
        - **If the object is close**: The image is real, inverted, and larger.
        - **If the object is very close**: The image is virtual, upright, and larger.

  Uses: Convex lenses are used in magnifying glasses, cameras, and eyeglasses for farsightedness.

- **Concave Lens**:
    - **Description**: A concave lens is thinner at the center than at the edges. It diverges light rays.
    - **Image Formation**: The image is always virtual, upright, and smaller than the object.

  Uses: Concave lenses are used in eyeglasses for nearsightedness and in devices like peepholes in doors.

Key Concepts

- **Reflection**: The bouncing back of light rays when they hit a reflective surface.
- **Refraction**: The bending of light rays when they pass through a medium with a different density.

Mirror Formula and Magnification

In the study of spherical mirrors, we use specific terms to describe the positions of objects and images relative to the mirror:

- **Object Distance (u):** The distance from the object to the pole of the mirror.
- **Image Distance (v):** The distance from the image to the pole of the mirror.
- **Focal Length (f):** The distance from the principal focus to the pole of the mirror.

These three quantities are related by the **Mirror Formula**, given as:

$$\frac{1}{v}+\frac{1}{u}=\frac{1}{f}$$

This equation allows us to calculate the position of the image formed by a mirror when we know the object distance and the focal length.

Magnification

Magnification (m) tells us how much larger or smaller the image is compared to the object. It is defined as the ratio of the height of the image (h') to the height of the object (h):

$$m=\frac{h'}{h}$$

Magnification can also be expressed in terms of object distance (u) and image distance (v):

$$m=-\frac{v}{u}$$

- **Positive magnification** ($m > 0$) indicates that the image is upright and virtual.
- **Negative magnification** ($m < 0$) indicates that the image is inverted and real.

Sign Conventions for Spherical Mirrors

When using the mirror formula and calculating magnification, it's important to follow these sign conventions:

- **Object Distance (u):** Positive if the object is in front of the mirror (real object), negative if behind the mirror (virtual object).

- **Image Distance (v):** Positive if the image is in front of the mirror (real image), negative if behind the mirror (virtual image).
- **Focal Length (f):** Positive for a concave mirror, negative for a convex mirror.
- **Magnification (m):** Positive if the image is upright, negative if inverted.

Example Problem

Problem: A convex mirror with a radius of curvature of 3.00 m is used. A bus is located 5.00 m from the mirror. Find the position, nature, and size of the image.

Solution:

- Radius of curvature (R) = -3.00 m
- Object distance (u) = +5.00 m
- Focal length (f) = R/2 = -1.50 m

Using the mirror formula:

$$\frac{1}{\mathrm{v}}+\frac{1}{\mathrm{u}}=\frac{1}{\mathrm{f}}$$

$$\frac{1}{\mathrm{v}}=\frac{1}{1.50}-\ -\frac{1}{5.00}=\frac{-5.00-1.50}{7.50}=\frac{-7.50}{7.50}=-1.15\ \mathrm{m}$$

The image is formed 1.15 m behind the mirror.

Magnification:

$$\mathrm{m}=-\frac{v}{\mathrm{u}}=-\frac{-1.15\ m}{5.00\ \mathrm{m}}=+0.23$$

Conclusion: The image is virtual, upright, and smaller in size by a factor of 0.23.

Image Formation by Lenses

Lenses form images by refracting (bending) light. This process depends on the shape of the lens, which can be either convex or concave, and the position of the object relative to the lens.

Convex Lenses

A convex lens is thicker in the middle and thinner at the edges. It converges light rays that are parallel to its principal axis, bringing them to a focus at a single point.

Activity: Image Formation by a Convex Lens

1. **Setup**: Place a convex lens on a lens stand on a table. Draw five parallel lines on the table, spaced according to the lens's focal length. Label them as $2F_1$, F_1, F_2, and $2F_2$.
2. **Experiment**: Place a burning candle at various positions relative to the lens:
   - Far beyond $2F_1$
   - Just beyond $2F_1$
   - Between F_1
   - At F_1
   - Between F_1 and the lens's optical center (O)
3. **Observation**: For each position, observe and record the nature (real or virtual), position (location on the other side of the lens), and size (magnified, diminished, or same size) of the image formed.

Summary of Observations:

- **At Infinity**: The image is at the focus F_2, highly diminished, and real.
- **Beyond $2F_1$**: The image is between F_2 and $2F_2$, diminished, and real.
- **At $2F_2$**: The image is at $2F_2$, same size, and real.
- **Between F_1 and $2F_2$**: The image is beyond $2F_2$, enlarged, and real.
- **At F_1**: The image is at infinity, highly enlarged, and real.
- **Between F_1 and O**: The image is on the same side as the object, enlarged, and virtual.

Concave Lenses

A concave lens is thinner in the middle and thicker at the edges. It diverges light rays, making them appear to originate from a single point behind the lens.

Activity: Image Formation by a Concave Lens

1. **Setup**: Place a concave lens on a stand. Place a burning candle on one side.
2. **Experiment**: Look through the lens and observe the image. Move the candle to different positions and note how the image changes.
3. **Observation**: The image formed is always virtual, erect, and diminished, regardless of the object's position.

Summary of Observations:

- **At Infinity**: The image is at the focus F_1, highly diminished, and virtual.
- **Between Infinity and O**: The image is between F_1 and O, diminished, and virtual.

Lens Formula and Magnification

For both convex and concave lenses, the relationship between the object distance (uuu), image distance (v), and focal length (f) is given by the lens formula:

$$\frac{1}{f}=\frac{1}{v}+\frac{1}{u}$$

The magnification (mmm) produced by a lens is the ratio of the height of the image (h′h'h′) to the height of the object (hhh):

$$\text{m}=\frac{h'}{\text{h}}$$

This formula applies to all spherical lenses. The sign conventions used in these formulas are essential for solving related problems accurately.

The Human Eye and Optical Instruments

The Human Eye

The human eye is a complex and vital organ that functions similarly to a camera. It allows us to perceive the world in all its colors and details. The eye works by focusing light onto the retina, a light-sensitive screen at the back of the eye. Here's a breakdown of how it operates:

1. **Cornea**: Light first enters the eye through the cornea, a transparent, dome-shaped membrane. The cornea is responsible for most of the eye's refraction, bending light rays so they can pass through the eye.
2. **Lens**: After passing through the cornea, light travels through the lens. The lens is flexible and can change its shape with the help of ciliary muscles. This ability to change shape, known as accommodation, allows the lens to focus on objects at various distances.
3. **Iris and Pupil**: Behind the cornea is the iris, a colored muscular diaphragm. The iris controls the size of the pupil, the opening that allows light to enter the eye. The pupil regulates the amount of light that reaches the retina.
4. **Retina**: The lens focuses light onto the retina, which is lined with light-sensitive cells. These cells convert light into electrical signals that are sent to the brain via the optic nerve. The brain then processes these signals into the images we see.

Power of Accommodation

The eye's ability to adjust its focus for objects at different distances is called accommodation. The lens becomes thinner to see distant objects and thicker to focus on nearby objects. This adjustment is crucial for clear vision. However, the eye's ability to accommodate can decrease with age, leading to vision problems.

Defects of Vision and Their Correction

There are three common vision defects:

1. **Myopia (Near-sightedness)**: People with myopia can see nearby objects clearly but struggle to see distant objects. This occurs when the eye focuses images in front of the retina. Myopia can be corrected with concave lenses that help focus the image on the retina.
2. **Hypermetropia (Far-sightedness)**: People with hypermetropia can see distant objects clearly but have difficulty with close objects. This happens when the image focuses behind the retina. Convex lenses are used to correct this defect.
3. **Presbyopia**: This condition is common with aging and involves difficulty focusing on close objects. It is caused by the weakening of the ciliary muscles and the reduced flexibility of the lens. Bifocal lenses or reading glasses can help correct presbyopia.

Optical Instruments

Optical instruments use lenses and mirrors to enhance vision or magnify images. Here are a few common ones:

1. **Simple Microscope**: Also known as a magnifying glass, it uses a single convex lens to enlarge the image of an object. The lens is held close to the object, producing an erect, magnified, and virtual image.
2. **Compound Microscope**: This microscope uses two lenses—the objective lens and the eyepiece lens. The objective lens produces an enlarged image inside the microscope, which is then further magnified by the eyepiece, allowing us to see much smaller details.
3. **Telescopes**: Telescopes are used to observe distant objects. There are two main types:
   - **Refracting Telescopes**: Use lenses to form an image. The objective lens collects light and focuses it into an image, which is then magnified by the eyepiece.

    - **Reflecting Telescopes**: Use mirrors instead of lenses to gather light. A concave mirror collects light and reflects it to a focal point, where a secondary mirror directs it to the eyepiece for magnification.

Each of these instruments leverages the principles of optics—reflection, refraction, and magnification—to help us observe and explore the world around us, from tiny cells to distant galaxies.

Primary Colors of Light and Human Vision

Primary Colors of Light

- The primary colors of light are **red**, **green**, and **blue**. These colors are fundamental because they can be combined in various ways to produce a wide range of colors.

How We See Colors

- Light enters the eye and reaches the retina, which is the light-sensitive layer at the back of the eye. The retina contains two types of photoreceptor cells:
    - **Cones**: These cells are sensitive to color and are responsible for detecting different wavelengths of light. There are three types of cone cells, each sensitive to one of the primary colors: red, green, or blue.
    - **Rods**: These cells are more sensitive to light intensity and are not involved in color vision.

Color Perception

- When light hits an object, it reflects some wavelengths and absorbs others. The reflected light enters the eye, where it stimulates the cone cells. The brain processes signals from these cones to interpret the color we see. For example, a red object reflects more red light and absorbs other colors.

Additive Color Mixing

- When red, green, and blue lights are mixed together in various intensities, they produce other colors. For instance:
    - **Red + Green = Yellow**
    - **Red + Blue = Magenta**
    - **Green + Blue = Cyan**
    - Combining all three primary colors in equal amounts produces **white light**.

Color Addition in Technology

- The principles of color addition are used in devices like color televisions, computer monitors, and projectors. These devices mix red, green, and blue light to create a full spectrum of colors.

Summary

- **Red, green, and blue** are the primary colors of light.
- The combination of these primary colors through additive color mixing produces a variety of colors.
- The human eye uses cone cells to detect these colors and the brain combines their signals to perceive a wide range of colors.