

# Chapter 8 LIGHT

## 8.1 Introduction

In the previous chapters, we looked at waves and sound. Recall that waves are essentially disturbances that propagate through a medium and are divided into two main types: mechanical waves and electromagnetic waves. We discussed mechanical waves, examined their structure and how they propagate, behave and interact with each other. In this chapter, we will shift our focus a bit and take a look at electromagnetic waves.

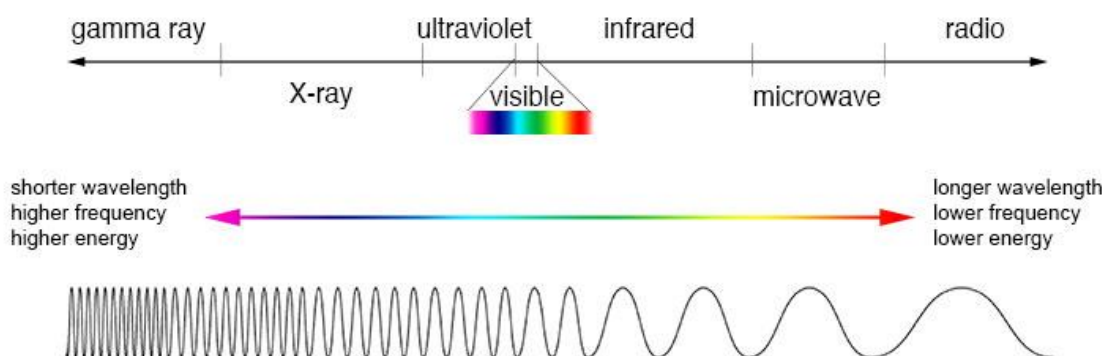
We know that all waves share some basic characteristics such as amplitude, wavelength, frequency, and speed. However, there is a primary difference between mechanical waves and electromagnetic waves which is the manner in which they propagate. Unlike mechanical waves that require a physical medium through which to propagate, electromagnetic waves do not and therefore can travel through a vacuum. Of the multiple electromagnetic waves encountered, the most common and frequently encountered type of electromagnetic waves is light.

Light is best described as a form of energy and is the foundation of the field of optics. For millennia, light has captivated human curiosity, dating from the ancient philosophers Empedocles (484 – 424 BC) and Aristotle (384 – 322 BC), through the age of enlightenment and contemporary time, several notable scientists including Isaac Newton (1643 – 1727), Max Planck (1858 – 1947) and Albert Einstein (1879 – 1955), countless hours have been spent contemplating its mystery. In this chapter, we will explore the nature of light and traverse the historical landscape from the musings of ancient philosophers to the groundbreaking insights of the scientific revolution. We will discuss the remarkable duality of light, where it behaves as both a wave and a particle, interference and diffraction patterns and its diverse uses and practical applications. We will begin our discovery of light by looking at its wide range of frequencies and energies.

## 8.2 The Electromagnetic Spectrum

Before discussing light as a concept, we will begin by examining the wide range of electromagnetic radiation known as the **electromagnetic spectrum**. The electromagnetic spectrum is a comprehensive framework of electromagnetic radiation. It is essentially *a vast, continuous range of electromagnetic waves that encompasses a broad array of frequencies and energies*. The electromagnetic spectrum includes wavelengths that are both visible and invisible to the human eye. It includes several distinct regions based on individual wavelength or frequency. From the long, low energy and frequencies which includes infrared, microwave, and radio waves, to the visible light that we can see, and ultimately to the short, higher energy and frequency regions (ultraviolet, X-rays, and gamma rays). Each portion of this spectrum serves unique purposes and

is used in various applications such as telecommunications, remote sensing, medical imaging and astronomy.



The Electromagnetic Spectrum (*adapted from* NASA's Imagine the Universe)

## Reflection, Refraction, Dispersion of Light

Light waves travel in straight lines called **rays**. Light rays do not require a medium for transmission and can pass through empty space for example sunlight that travels through a vacuum from the Sun to the Earth. In this section, we will examine what occurs when light encounters or interacts with an object or substance. When a ray of light encounters an object, like any other wave, the ray can be reflected, refracted or absorbed. The behavior of light when it encounters an object in its path is governed by two laws. As we examine these laws, we will come to appreciate the predictability and consistency of light's behavior.

### Reflection

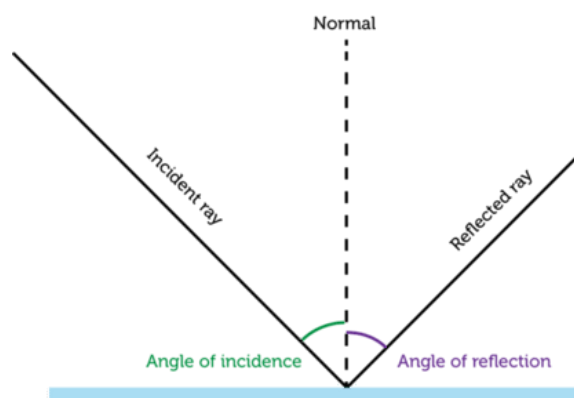
The first law we will discuss is the **law of reflection**. How light behaves when it interacts with a reflective surface is governed by the law of reflection. When a ray of light encounters a smooth reflective surface, it bounces off the surface in a very distinct and consistent manner which follows the law of reflection. According to the law of reflection, the **angle of incidence,  $\theta_i$**  which is the angle between the normal<sup>1</sup> and the incoming or incident ray of light is equal to the **angle of reflection,  $\theta_r$** , which is the angle between the normal and the reflected ray.

In simpler terms, when light strikes a reflective surface, it bounces off in a manner such that the angle at which it approaches the surface is identical to the angle at which it departs. This law holds true for all types of waves, not just light, and plays a pivotal role in understanding and predicting

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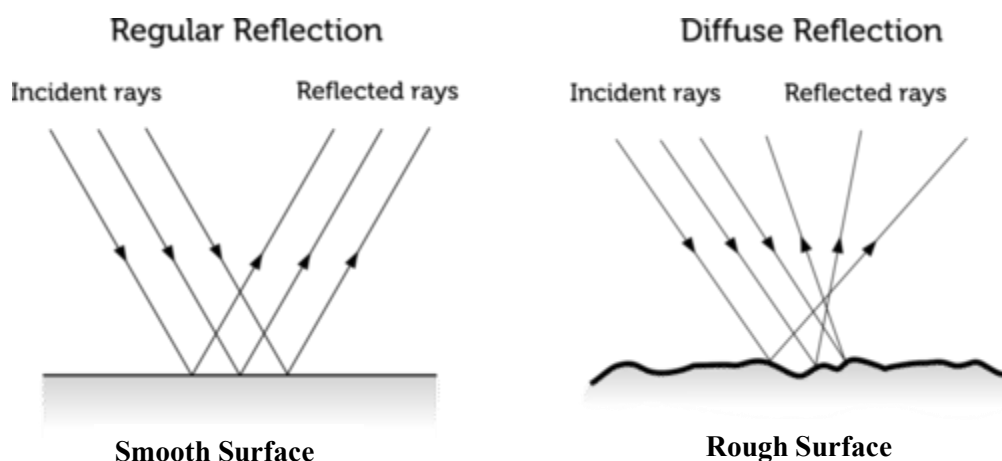
<sup>1</sup> the line perpendicular to the surface

the behavior of reflected light in various optical systems. The law of reflection is not only a cornerstone of geometric optics, it is useful for designing optical instruments and encountered in everyday uses such as the reflective surfaces in mirrors.



**Reflection** (credit: AuYeung, C. (2023) CK -12 Foundation)

Whenever light encounters a rough or irregular but reflective surface, the reflected rays bounce off the surface but the response differs. Because the surface is not smooth, in spite of the fact that the incident rays striking the surface are still parallel, the roughness of the surface results in a reflected light scattering or being reflected in various directions. This is known as **diffuse reflection** and occurs whenever we look at a sheet of paper or an article of clothing.



**Regular Reflection vs Diffuse Reflection** (Credit: Sheng, J (2023), CK-12 Foundation)

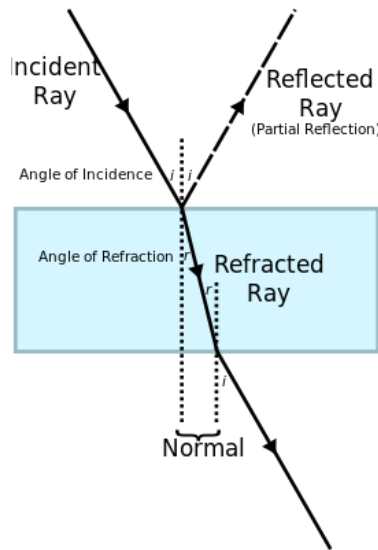
## Refraction

The **law of refraction** or **Snell's Law**, in honor of Dutch astronomer and mathematician Willebrord Snel van Royen (1580–1626), describes what occurs when a ray of light encounters and passes through different transparent media. As discussed above, when light encounters a reflective surface, it reflects or bounces off the surface in straight lines. By contrast, when light encounters and passes through a transparent medium, the light ray does not reflect, instead it bends and changes direction. This is why a body of clear water appears shallower than it actually is and an object, such as a spoon or straw, appears bent when placed in a glass of clear liquid such as water.



**Refraction of Drinking Straw** (Credit: © CK-12 Foundation 2023)

Light rays bend or refract when they pass through transparent media. This happens because the speed at which the light travels depends on the individual wavelength of the media. So, the speed at which a wave travels changes at the boundary of the two substances or where the individual substances water. As the light wave passes from one medium, for example air and water in the example above, the object appears bent.



Refraction (*credit: Wikipedia*© 2023)

How much the ray bends depends on the properties of the medium under consideration. The **optical density** of an object determines how quickly a light ray is transmitted through a transparent object or substance.

Accordingly, the incident ray of light will bend toward the normal if the light ray passes from a medium with a lower optical density to one with higher optical density. And the ray will bend towards the normal if a ray of light passes from a medium with a higher optical density to one that is less optically dense or has a lower optical density.

The optical density essentially measures how the speed of a light rays differs between materials. This determines the relative speed of light in a vacuum and to how quickly light travels through the medium and is known as the **refractive index**. The refractive index is denoted by the letter ***n*** is calculated as the ratio of the angle of incidence ( $\theta_1$ ) and the angle of refraction ( $\theta_2$ ) and has no units.

$$\text{Refractive Index} = \frac{\text{speed of light in a vacuum}}{\text{speed of light in the medium}}$$

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

Material	Refractive Index (n)
Water	1.33

Ice	1.31
Sodium Chloride	1.54
Vegetable Oil	1.47
Alcohol	1.36
Glass	1.52
Sapphire	1.76
Diamond	2.42
Ruby	1.7
Emerald	1.58
Cubic Zirconia	2.15

**Refractive Indices of Selected Substances**

### Sample problem:

How fast will a ray of light travel through a pure diamond?

$$n = 2.42$$

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

$$v_m = ?$$

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

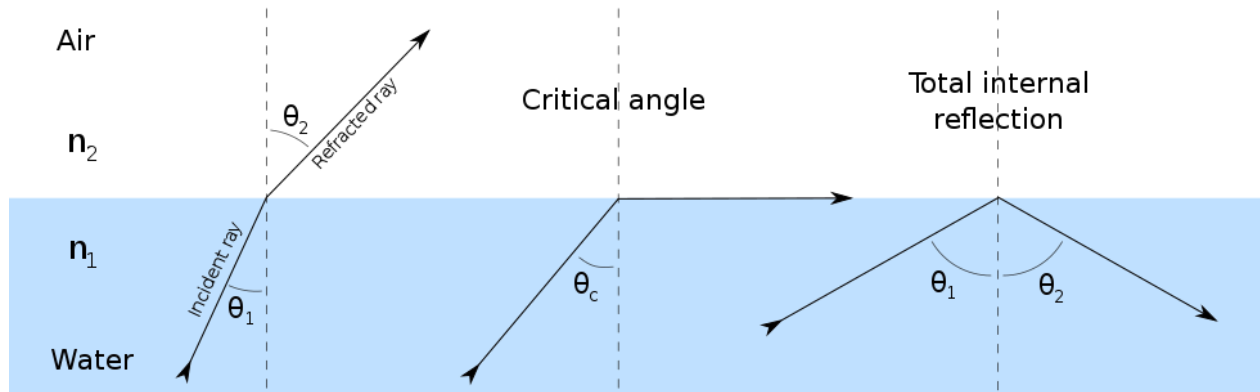
$$v_m = \frac{c}{n} = \frac{3.00 \times 10^8 \text{ m/s}}{2.42} = 1.24 \times 10^8 \text{ m/s}$$

### Total Internal Reflection

When light encounters an interface between two materials, and the angle of incidence exceeds a critical value, the entire reflection of light occurs within the first material. When light travels from a more optically dense medium to a less dense medium, the angle of incidence begins to increase. As the angle of incidence approaches a certain threshold, called the **critical angle**, the angle of refraction approaches  $90^\circ$ , at which the refracted ray becomes parallel to the boundary surface. If the angle of incidence increases beyond the critical angle, the conditions of refraction can no longer be satisfied, so there is no refracted ray, and the partial reflection becomes total. For visible light, the critical angle is about  $49^\circ$  for incidence from water to air, and about  $42^\circ$  for incidence from common glass to air.

At the critical angle, the light wave is completely reflected back into the higher refractive index medium, with none of it transmitted into the lower refractive index medium. Total internal reflection is a crucial concept in various optical applications, such as fiber optics and prisms, where

controlling the reflection and transmission of light is essential. The phenomenon finds applications in telecommunications, medical imaging, and other technologies and extremely designing optical systems for efficient light propagation and manipulation.



Refraction, Critical Angle and Total Internal Reflection between Air ( $n_1$ ) and Water ( $n_2$ )

(Credit: Wikipedia 2023©)

## Dispersion of Light

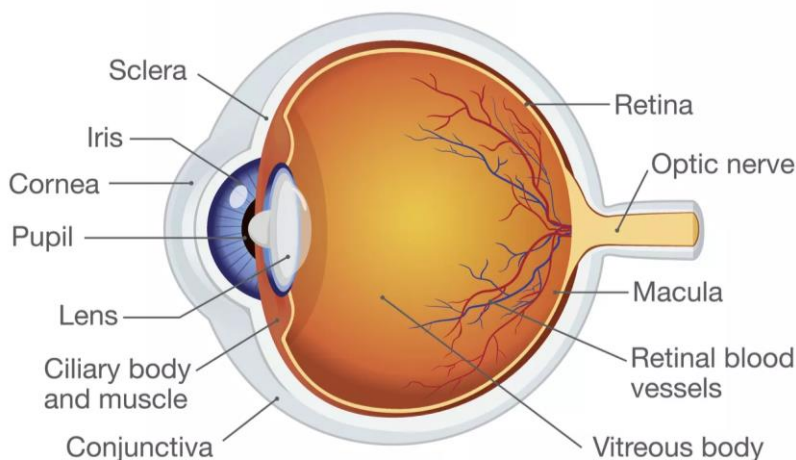
The process of dispersion can be observed in a prism, which is a triangular piece of glass or other transparent material. When white light passes through a prism, it is bent or refracted twice—once when entering the prism and once when leaving. However, different colors of light are refracted by different amounts due to their varying wavelengths. As a result, the colors spread out and form a spectrum, with red light being refracted the least and violet light being refracted the most. The order of colors in the spectrum, from longer to shorter wavelengths, is typically red, orange, yellow, green, blue, indigo, and violet, forming the acronym ROYGBIV.

Dispersion is not limited to prisms; it also occurs in raindrops, creating rainbows, and in lenses, affecting the quality of images produced by optical instruments. The dispersion of light is governed by the principles of refraction and the varying refractive indices of different colors in a medium. It is very important in photography.

## How We See

The human eye is a complex organ that plays a crucial role in vision. The eye operates as a sophisticated optical system that facilitates the remarkable process of vision. It does this by

employing intricate mechanisms which allows light to enter and assists in transmitting visual information to be decoded by the brain.



The Human Eye (*adapted from Helmenstine 2019, ThoughtCo®*)

The eye is comprised of several easily visible parts including the **cornea**, the transparent front surface of the eye; the **pupil**, the black circular opening in the center of the eye and the **iris**, the colored part of the eye. The three parts function in tandem to regulate the amount of light that enters the eye. The quantity of light that enters the eye is controlled by the iris which uses ambient light conditions to adjust the size of the pupil and the pupil which regulates amount of light that actually enters the eye. The light enters the eye through the cornea whose role is to help to focus the incoming light. The focused light then passes through the lens, which further adjusts its focus and the light is directed to the **retina** at the back of the eye.

The retina contains a series of specialized cells called photoreceptors known as **rods** and **cones**. The rods are responsible for vision in low light conditions, while cones are responsible for color vision and detail in well-lit conditions. When light hits the photoreceptor cells, it triggers a chemical reaction that converts light into electrical signals. The electrical signals generated by the photoreceptor cells are transmitted through the optic nerve to the brain.

The brain then interprets these electrical signals as visual information, creating the perception of an image. It also integrates visual information from both eyes to provide depth perception and provide us with a three-dimensional view of the world. The eyes and the brain work together to process visual information, allowing us to perceive the world around us.

## Lenses

Lenses operate on the principles of refraction, which is the bending of light as it passes through a medium with a different refractive index. A lens is a transparent optical element with curved surfaces designed to focus or diverge light. When parallel rays of light pass through a lens, the rays converge or diverge at a point on the opposite side of the lens. This point is called the **focal point**. The distance between the lens and the focal point is the **focal length**. The focal length is the distance from the center of the lens to the imaging point (focal plane) where the light for the image is collected. It is a measure of how strongly the system converges or diverges light. A positive focal length indicates that a system converges light, while a negative focal length indicates that the system diverges light. A system with a shorter focal length bends the rays more sharply, bringing them to a focus in a shorter distance or diverging them more quickly.

There are two main types of lenses: convex or converging lenses and concave or diverging lenses. A **convex lens** is thicker in the center than at the edges. When parallel rays of light pass through a convex lens, the rays converge at a point on the opposite side of the lens. The shorter the focal length of the lens, more pronounced convergence since the rays bend more sharply which bring the image into better focus.

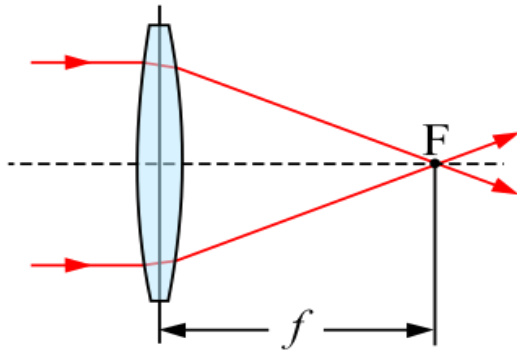
A **concave lens** is thinner in the center than at the edges. When parallel rays of light pass through a concave lens, they appear to diverge from a virtual focal point behind the lens. The image formed by a concave lens is always virtual, upright, and diminished.

In both types of lenses, the bending of light is governed by Snell's Law, which relates the angle of incidence and the angle of refraction. The shape of the lens and the refractive index of the material determine how much the light is bent.

In both convex and concave lenses, the bending of light is governed by Snell's Law, which relates the angle of incidence and the angle of refraction. The shape of the lens and the refractive index of the material determine how much the light is bent. There are numerous applications for lenses including:

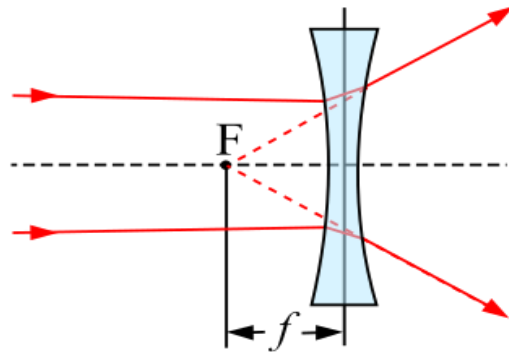
1. Cameras – cameras contain converging lenses which focus light onto the camera sensor to form an image.
2. Eyeglasses - Convex and concave lenses are used to correct vision by adjusting the focal point of incoming light.
  - a. In nearsightedness, the distance between the eye's lens and retina is too long. Concave lenses are used to correct vision by shorten the distance which reduces the refraction of light and lengthens the focal length so that the image is formed on the retina.

- b. In farsightedness, the distance between the eye's lens and retina is too short. In this case convex lenses are used to lengthen the distance by increasing the angle of refraction which reduces the focal length and causes the rays to bend more sharply and bring closer images into focus.
- 3. Microscopes and Telescopes – use lenses to magnify and focus light to observe small or distant objects.
- 4. Projectors and Magnifying Glasses - use lenses to project images or magnify small objects.



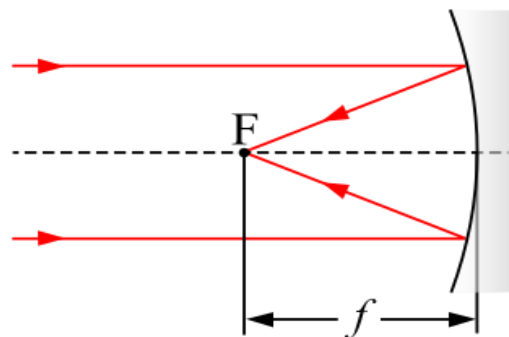
### Convex Lens

Focal Point (F)  
focal length ( $f$ )



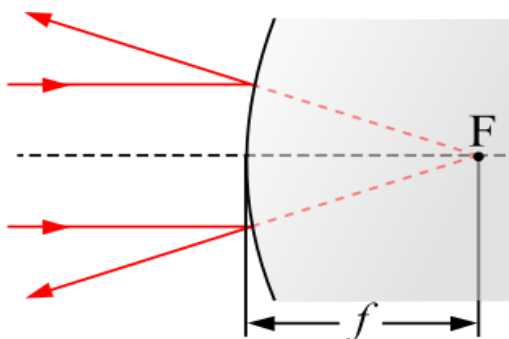
### Concave Lens

Focal Point (F)  
focal length ( $f$ )



### Convex Mirror

Focal Point (F)  
focal length ( $f$ )



### Concave Mirror

Focal Point (F)  
focal length ( $f$ )

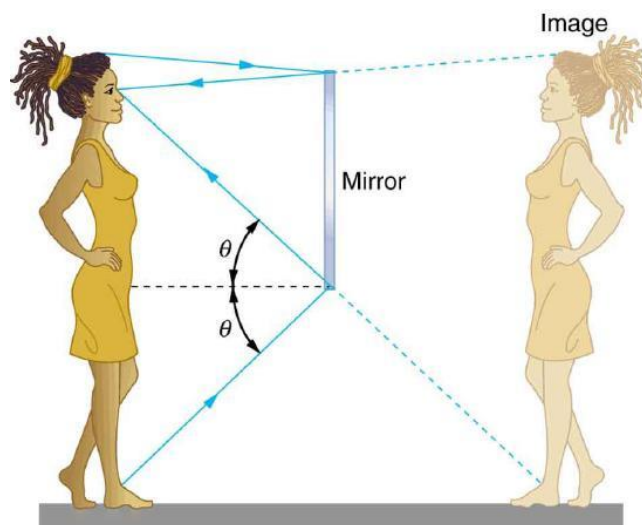
Concave and Convex Lenses with focal length and point.  
(credit Wikipedia 2023 ©)

## Image Formation

Real and virtual images are concepts in optics that describe the characteristics of images formed by optical systems such as lenses and mirrors. The key differences between real and virtual images are related to the behavior of light rays and the actual or apparent location of the image.

When actual light rays converge at a specific point on the opposite side of the lens or mirror a real image is formed. In real images, light rays from a single point on the object converge and actually intersect after passing through the lens. Real images are formed on the opposite side of the lens or mirror from the object and can be projected onto a screen or surface as the light rays physically converge to form the image. Depending on the optical system being used and the position of the object, a real image can be either upright or upside down.

By contrast, a virtual image is an upright image that is achieved where the rays seem to diverge. The rays appear to extend backwards and a virtual image is formed. Virtual images are produced by diverging lens or convex mirrors.



Virtual Image (Credit: College Physics 1 OpenStax, author///)

In sum, real images are what you experience when you look at a television or movie screen, whilst a virtual image is what you see when you look in a mirror.

## Colors and Light

Early in life, we are taught the color wheel, the three primary colors and the results of combining pigments. We learn that the primary colors in pigments (red, yellow and blue) could be combined to form almost any color and that combining these colors will result in the color black and white was the absence of color. As we study light waves, you will come to understand that the opposite is true when discussing light. In light, black is the absence of color and white the mixture of all the colors. Mixing light involves the combination of different colors of light to produce new colors. This process is based on the principles of additive color mixing, which is distinct from the subtractive color mixing observed in the mixing of pigments. Additive color mixing occurs when colored light is combined, and the resulting color is the sum of the individual colors.

The primary colors used in additive color mixing are red, green, and blue, commonly referred to as RGB. The combination of these colors in different intensities can produce a wide range of colors. The additive color model is commonly used in electronic displays, such as computer monitors, television screens, and LED displays.

When red, green, and blue light are combined at full intensity, they create white light. This is in contrast to subtractive color mixing, where combining pigments results in darker colors. With regard to light, when the following colors are combined, the results are as follows:

Red + Green = Yellow

Red + Blue = Magenta

Green + Blue = Cyan

Colors can be adjusted by varying the intensity (brightness) of each primary color. For example, reducing the intensity of blue while keeping red and green at full intensity results in a yellowish color. Colors are often represented in terms of RGB values, where each color component is specified by an intensity value ranging from 0 to 255. For example, pure red may be represented as (255, 0, 0) in RGB. Adjusting the relative intensities of red, green, and blue is crucial for achieving accurate white balance in displays and imaging devices. Additive color mixing is widely used in electronic displays, LED lighting, stage lighting and digital imaging.

Color mixing is a versatile and efficient way to produce a broad spectrum of colors for visual communication and artistic expression. Understanding how to mix light is essential for creating appealing digital media, sound graphic design and impressive display technologies.

## Light and Technology

## Fiber Optics

Fiber optics has become an integral component of modern communication and information technology, offering high-speed and reliable data transmission capabilities for various applications. Fiber optics is a technology that involves the transmission of data, such as light signals, through thin, flexible, and transparent fibers made of glass or plastic. This technology, which relies on the principle of total internal reflection, allows the efficient and high-speed transmission of information over long distances.

Fiber optics uses a core (central part of the optical fiber through which light travels), an outer layer or clad with a lower refractive index that surrounds the core to enable total internal reflection and an additional protective layer or buffer to shield the fiber from external factors. Inside the cable, light signals are transmitted through the core of the fiber. Since, the refractive index of the core is higher than that of the cladding, when light encounters the core-cladding interface at an angle greater than the critical angle, total internal reflection occurs, preventing light from escaping the core. Fiber optics can be designed for a single path of light, allowing for higher data transmission rates over longer distances (single mode) or to support multiple paths of light, suitable for shorter distances and less stringent bandwidth requirements (multi-mode). Lasers or light-emitting diodes (LEDs) are commonly used as light sources for transmitting signals into the fiber.

Fiber optics is widely used in telecommunications for high-speed data transmission over long distances. Many broadband internet connections use fiber optics for faster and more reliable data transfer and in data centers and local area networks (LANs) for high-speed and secure data transmission.

Fiber optics are employed in cable TV networks for high-definition video transmission and in medical imaging devices such as endoscopes for flexible light transmission in the human body.

There are many advantages of using fiber optics such as a high bandwidth for transmitting large amounts of data quickly; less signal loss over long distances as compared to traditional copper cables and insusceptibility to electromagnetic interference, making them suitable for environments with high electrical noise. However, fiber optic cables require specialized installation and maintenance and the initial infrastructure costs for fiber optics are higher compared to traditional copper cabling.

## LCD

Liquid Crystal Display (LCD) technology is a widely used display technology that employs the unique properties of liquid crystals to produce images. LCDs are commonly used in computer monitors, television screens, smartphones, and other display devices. An LCD consists of several layers, including two layers of glass or other transparent materials. The inner surface of these layers is coated with a layer of liquid crystals, and the outer surfaces have transparent electrodes. Liquid crystals are organic compounds that have properties of both liquids and solids. They can flow like liquids but also maintain a certain degree of molecular order like

solids. In the absence of an electric field, the liquid crystals naturally align themselves in a specific direction.

The most common type of LCD technology is the Twisted Nematic (TN) configuration. In the resting state, the liquid crystals are twisted, and light passes through them without significant alteration. When an electric field is applied to a specific region of the liquid crystal layer by activating the electrodes, the molecules align themselves with the electric field. This realignment affects the polarization of light passing through the liquid crystal layer. Polarized light passes through the first layer of glass, the liquid crystal layer, and then the second layer of glass. The electric field-induced realignment of liquid crystals modifies the polarization of the light.

The LCD display typically employs color filters to generate red, green, and blue colors and a backlight is positioned behind the LCD panel to illuminate the pixels. Each pixel in an LCD display consists of subpixels, usually corresponding to the three primary colors (red, green, and blue). The combination of these subpixels, each independently controlled, produces a full spectrum of colors.

Brightness is controlled by adjusting the voltage applied to the liquid crystal layer to control the amount of light allowed to pass through each pixel. By varying the voltage, the alignment of liquid crystals change which regulated the amount of light that reaches the color filters. Advanced LCD technologies such as In-Plane Switching (IPS) have also been developed to reduce narrow viewing angles and improve color reproduction.

LCDs offer bright and vibrant displays and are very energy-efficient because each pixel can be independently controlled. However, it does have some limitations such as limited viewing angles and slow response time in fast-moving scenes, but this has improved with advancements like higher refresh rates and response time reduction technologies.

LCD technology has evolved over the years, and it remains a dominant display technology due to its versatility, cost-effectiveness, and widespread adoption in various electronic devices.

Some of the advanced in displays technologies include OLED (Organic Light-Emitting Diode) and mOLED (Micro-OLED). Both OLED and mOLED are advanced display that use organic compounds to emit light. These technologies offer several advantages over traditional display technologies like LCD.

OLEDs are based on organic compounds that emit light when an electric current is applied.

Each pixel in an OLED display is made up of organic materials that emit red, green, or blue light when an electric current pass through them. OLED displays are "emissive," meaning that each pixel emits its own light, eliminating the need for a separate backlight. And they are extremely flexible and thin which allows for the creation of curved or flexible screens and the development of foldable and rollable displays.

OLEDs offer superior contrast ratios and unlike traditional displays, individual pixels can be turned off completely to achieve true black. They also have very fast response times, making them suitable for applications where fast motion and responsiveness are crucial.

OLED technology is used in various devices, including smartphones, TVs, smartwatches, and virtual reality headsets.

Micro-OLED or mOLED is a miniaturized version of OLED technology. These displays are significantly smaller and are often used in applications like electronic viewfinders, camera displays, and wearable devices. mOLED displays can achieve higher pixel densities compared to larger OLED displays, making them suitable for applications where a small form factor and high resolution are essential. They also exhibit improved energy efficiency and lower power consumption compared to larger OLED displays.

Micro-OLED displays are commonly used in VR headsets and other head-mounted displays due to their compact size, high pixel density, and fast response times. Micro-OLED displays can achieve vibrant colors and high brightness levels, contributing to a more immersive visual experience.

Both OLED and mOLED technologies have contributed to advancements in display technology. They offer enhanced visual experiences, flexibility and greater efficiency. OLED displays, in particular, have become prevalent in consumer electronics due to their ability to provide vibrant colors, deep blacks, and thin form factors. On the other hand, mOLED technology has found specialized applications in compact devices where high pixel density and small sizes are critical.

## Conclusion

In this chapter, we uncovered the myriad practical applications of reflection and refraction. From the design of optical instruments like telescopes and microscopes to the creation of lenses for cameras and eyeglasses, the principles elucidated in this chapter are instrumental. Furthermore, we explore the marvels of optical illusions, where the principles of reflection and refraction create captivating visual effects that have fascinated artists, scientists, and the general public alike.

We also looked at the ubiquitous presence of mirrors and lenses in everyday life, from simple magnifying glasses to the complexities of telescopes and cameras. In summary, the chapter offers a simplified yet powerful framework for understanding the behavior of light in optical systems. It equips us with the tools to appreciate the fundamental concepts of reflection, refraction, and image formation through lenses and mirrors, making it possible to comprehend the functioning of a wide array of optical instruments used in science, industry, and our daily lives that underlie the familiar experiences of mirrors and lenses while also illuminating their essential roles in modern optical technologies, from medical imaging to telecommunications.



## Problems

1. An incident ray of light makes an angle of 20 degrees with a flat surface. (a) What is the angle of incidence? (b) What is the angle of reflection?
2. Calculate the refractive index of a block of material  $\alpha$  if light travels through the block at a speed of  $4.52 \times 10^9$  m/s.
3. A light wave has a frequency of  $3.75 \times 10^{15}$  cycles a second. Calculate the wavelength of this wave.
4. How does the image you see when you look in a mirror differ from an image of you captured on video?
5. How do eye glasses correct vision problems?
6. Calculate how quickly light travels through cubic zirconia.
7. A light ray strikes a mirror surface at an angle of 35 degrees to normal. Calculate the angle of reflection.
8. How long would it take sunlight to reach planet X if this planet is  $9.50 \times 10^6$  meters away from the sun?
9. The speed of light through an unknown medium is  $3.75 \times 10^8$  m/s. What is the index of refraction of the medium?
10. What is total internal reflection? How does it occur?