



Chapter One

Light

CHAPTER OUTLINE

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1.5 Dispersion and Prisms

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Isaac Newton,
English physicist and
mathematician
(1642–1727)

Isaac Newton was one of the most brilliant scientists in history. Before the age of 30, he formulated the basic concepts and laws of mechanics, discovered the law of universal gravitation, and invented the mathematical methods of calculus. As a consequence of his theories, Newton was able to explain the motions of the planets, the ebb and flow of the tides, and many special features of the motions of the Moon and the Earth. He also interpreted many fundamental observations concerning the nature of light. His contributions to physical theories dominated scientific thought for two centuries and remain important today.
(Giraudon/Art Resource)

1.1 The Nature of Light

Before the beginning of the nineteenth century, light was considered to be a stream of particles that either was emitted by the object being viewed or emanated from the eyes of the viewer. Newton, the chief architect of the particle theory of light, held that particles were emitted from a light source and that these particles stimulated the sense of sight upon entering the eye. Using this idea, he was able to explain reflection and refraction.

Most scientists accepted Newton's particle theory. During his lifetime, however, another theory was proposed—one that argued that light might be some sort of wave motion. In 1678, the Dutch physicist and astronomer Christian Huygens showed that a wave theory of light could also explain reflection and refraction.

In 1801, Thomas Young (1773–1829) provided the first clear demonstration of the wave nature of light. Young showed that, under appropriate conditions, light rays interfere with each other. Such behavior could not be explained at that time by a particle theory because there was no conceivable way in which two or more particles could come together and cancel one another. Additional developments during the nineteenth century led to the general acceptance of the wave theory of light, the most important resulting from the work of Maxwell, who in 1873 asserted that light was a form of high-frequency electromagnetic wave. As discussed Hertz provided experimental confirmation of Maxwell's theory in 1887 by producing and detecting electromagnetic waves.

Although the wave model and the classical theory of electricity and magnetism were able to explain most known properties of light, they could not explain some subsequent experiments. The most striking of

these is the photoelectric effect, also discovered by Hertz: when light strikes a metal surface, electrons are sometimes ejected from the surface. As one example of the difficulties that arose, experiments showed that the kinetic energy of an ejected electron is independent of the light intensity. This finding contradicted the wave theory, which held that a more intense beam of light should add more energy to the electron. An explanation of the photoelectric effect was proposed by Einstein in 1905 in a theory that used the concept of quantization developed by Max Planck (1858–1947) in 1900. The quantization model assumes that the energy of a light wave is present in particles called photons; hence, the energy is said to be quantized. According to Einstein’s theory, the energy of a photon is proportional to the frequency of the electromagnetic wave:

$$E=h\nu \quad \dots\dots\dots(1)$$

where the constant of proportionality $h =6.63 \times 10^{-34}$ J.s is Planck’s constant.

In view of these developments, light must be regarded as having a dual nature: **Light exhibits the characteristics of a wave in some situations and the characteristics of a particle in other situations.** Light is light, to be sure. However, the question “Is light a wave or a particle?” is inappropriate. Sometimes light acts like a wave, and at other times it acts like a particle.

1.2 Properties of light

Reflection, refraction, dispersion and velocity are the important properties of light. We briefly discuss about them here.

1.2.1 Reflection of light

when light travelling in a medium encounters a boundary leading to a second medium, part of the incident light is returned to the first medium from which it came. This phenomenon is called reflection. Reflection of light from a smooth surface is called regular or specular reflection see figure 1a. If the reflecting surface is rough, as shown in Figure 1b, the surface reflects the rays not as a parallel set but in various directions. Reflection from any rough surface is known as diffuse reflection. A surface behaves as a smooth surface as long as the surface variations are much smaller than the wavelength of the incident light.

the difference between diffuse and specular reflection is a matter of surface roughness. In the study of optics, the term reflection is used to mean specular reflection.

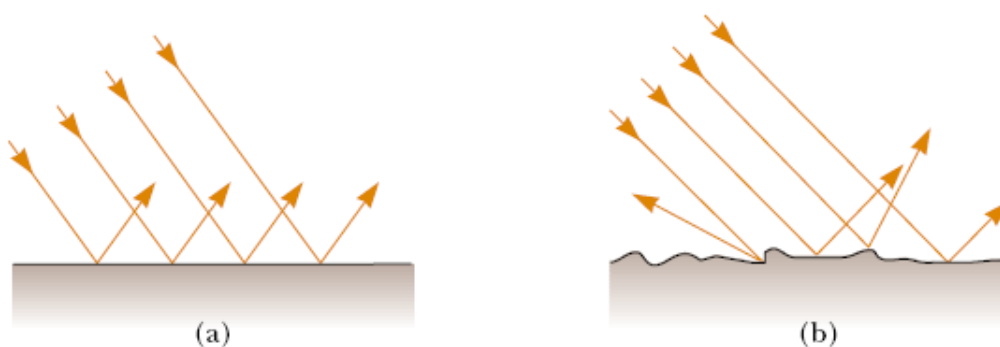


Figure 1: Schematic representation of (a) specular reflection, where the reflected rays are all parallel to each other, and (b) diffuse reflection, where the reflected rays travel in random directions.

➤ Laws of reflection

First law: The incident ray, the reflected ray and the normal at the of point incidence are in the same plane. This plane is called plane of incidence.

Second law: The angle of reflection equals the angle of incidence.

$$\theta_1 = \theta'_1 \quad \dots\dots\dots(2)$$

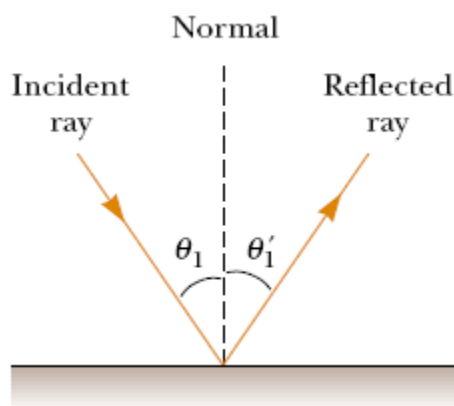


Figure 2: According to the law of reflection, $\theta_1 = \theta'_1$. The incident ray, the reflected ray, and the normal all lie in the same plane.

1.2.2 Refraction of light

When a ray of light traveling through a transparent medium encounters a boundary leading into another transparent medium, as shown in **Figure 3**, part of the energy is reflected and part enters the second medium. The ray that enters the second medium is bent at the boundary and is said to be **refracted**.

➤ Laws of refraction

First law: The incident ray, the refracted ray and the normal at the of point incidence lie in the same plane. This plane is called plane of incidence.

Second law: The ratio of the sine of the angle of incidence to the sine of the angle of refraction for any two given media is constant.

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1} = \text{constant} \quad \dots\dots\dots(3)$$

where v_1 is the speed of light in the first medium and v_2 is the speed of light in the second medium.

The **angle of refraction** in **Figure 3**, depends on the properties of the two media and on the angle of incidence.

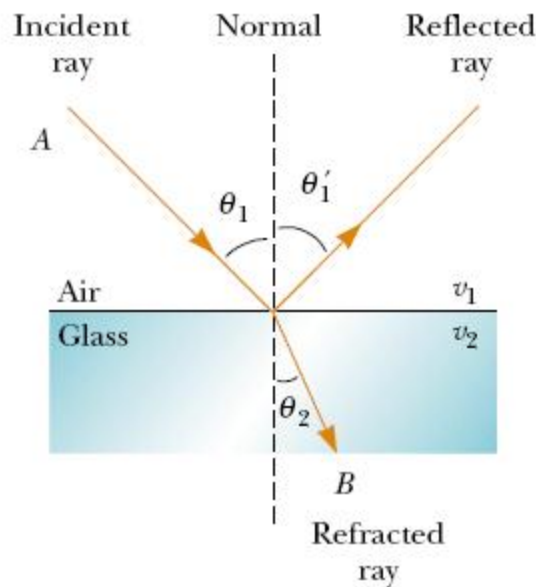


Figure 3: A ray obliquely incident on an air–glass interface. The refracted ray is bent toward the normal because $v_2 < v_1$. All rays and the normal lie in the same plane.

From Equation 3, we can infer that when light moves from a material in which its speed is high to a material in which its speed is lower, as shown in Figure 4a, the angle of refraction θ_2 is less than the angle of incidence θ_1 , and the ray is bent **toward** the normal. If the ray moves from a material in which light moves slowly to a material in which

it moves more rapidly, as illustrated in Figure 4b, θ_2 is greater than θ_1 , and the ray is bent *away* from the normal.

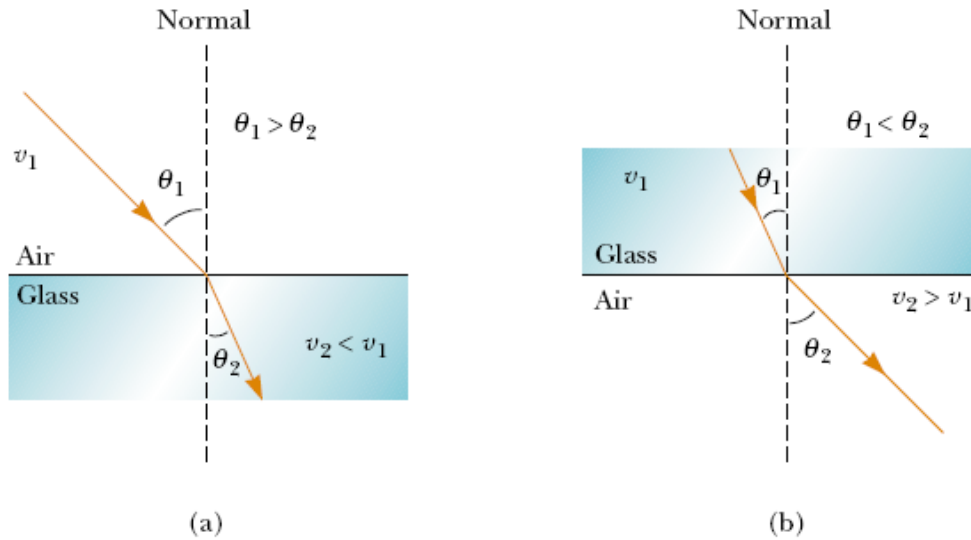


Figure 4: (a) When the light beam moves from air into glass, the light slows down on entering the glass and its path is bent toward the normal. (b) When the beam moves from glass into air, the light speeds up on entering the air and its path is bent away from the normal.

1.3 Index of Refraction

The refraction index of a medium is **defined** as the ratio of velocity of light in a vacuum to the velocity of light in the medium index. Refraction index defined as above is called as absolute refraction index. Thus,

$$n = \frac{c}{v} \dots\dots\dots(4)$$

From this definition, we see that the index of refraction is a dimensionless number greater than unity because v is always less than c . Furthermore, n is equal to unity for vacuum.

As light travels from one medium to another, its frequency does not change but its wavelength does.

$$v_1 = f\lambda_1 \quad \text{and} \quad v_2 = f\lambda_2 \quad \dots\dots\dots(5)$$

Because $v_1 \neq v_2$, it follows that $\lambda_1 \neq \lambda_2$.

We can obtain a relationship between index of refraction and wavelength by dividing the first Equation 5 by the second and then using Equation 4:

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1} \quad \dots\dots\dots(6)$$

This gives

$$n_1\lambda_1 = n_2\lambda_2$$

If medium 1 is vacuum, or for all practical purposes air, then $n_1 = 1$. Hence, it follows from Equation 6 that the index of refraction of any medium can be expressed as the ratio

$$n = \frac{\lambda}{\lambda_n} \quad \dots\dots\dots(7)$$

where λ is the wavelength of light in vacuum and λ_n is the wavelength of light in the medium whose index of refraction is n .

We are now in a position to express Equation 3 in an alternative form. If we replace the v_2/v_1 term in Equation 3 with n_1/n_2 from Equation 6, we obtain

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad \dots\dots\dots(8)$$

The experimental discovery of this relationship is usually credited to Willebrord Snell(1591–1627) and is therefore known as **Snell's law of refraction**.

Example: A beam of light of wavelength 550 nm traveling in air is incident on a slab of transparent material. The incident beam makes an angle of 40.0° with the normal, and the refracted beam makes an angle of 26.0° with the normal. Find the index of refraction of the material.

Solution:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

$$n_2 = \frac{n_1 \sin \theta_1}{\sin \theta_2} = (1.00) \frac{\sin 40.0^\circ}{\sin 26.0^\circ} = \frac{0.643}{0.438} = 1.47$$

1.4 Optical path

The shortest distance, L between two point A and B is called the geometric path. The length of geometric path is independent of the medium that surround the path AB. When a light ray travels from the point A to point B, it travels with the velocity (c) if the medium is air and with lesser velocity v if the medium is other than air. Therefore, the light ray takes more time to go from A to B located in a medium.

From equation (3)

$$n = \frac{c}{v} = \frac{AB/t}{AB/T} = \frac{T}{t}$$

Where t and T are the time taken by the light ray in air and in a medium respectively.

$$T = nt \quad \dots\dots\dots(9)$$

The above relation means that a light ray takes n times more time to cover the distance AB a medium . To take into account the delay , we use another distance called the optical length. If a ray of light travels a distance L in a medium of refraction index n in a certain interval of time, then it would travel a greater distance Δ in air during same interval of time. Therefore,

$$\frac{\Delta}{L} = \frac{ct}{vt} = n$$

or

$$\Delta = nL \quad \dots\dots\dots(9)$$

i.e., optical path length =(Refraction index)(Geometric path length)

Thus, **the optical path length is defined as the product of refraction index and the geometric length.**

1.5 Dispersion and Prisms

An important property of the index of refraction n is that, for a given material, the index varies with the wavelength of the light passing through the material, as Figure 5 shows. This behavior is called **dispersion**. Because n is a function of wavelength, Snell's law of refraction indicates that light of different wavelengths is bent at different angles when incident on a refracting material.

the index of refraction generally decreases with increasing wavelength. This means that violet light bends more than red light does when passing into a refracting material. To understand the effects that dispersion can have on light, consider what happens when light strikes a

prism, as shown in Figure 6. A ray of single-wavelength light incident on the prism from the left emerges refracted from its original direction of travel by an angle δ , called the **angle of deviation**.

Now suppose that a beam of *white light* (a combination of all visible wavelengths) is incident on a prism, as illustrated in Figure 6. The rays that emerge spread out in a series of colors known as the visible spectrum. These colors, in order of decreasing wavelength, are red, orange, yellow, green, blue, and violet. Clearly, the angle of deviation δ depends on wavelength. Violet light deviates the most, red the least, and the remaining colors in the visible spectrum fall between these extremes. Newton showed that each color has a particular angle of deviation and that the colors can be recombined to form the original white light.

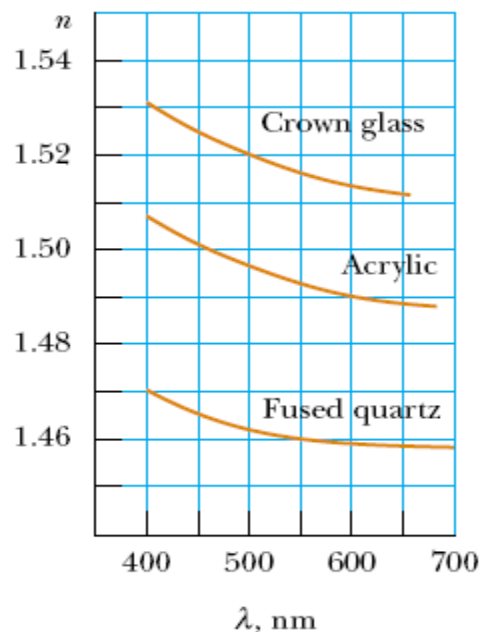


Figure 5: Variation of index of refraction with vacuum wavelength for three materials.

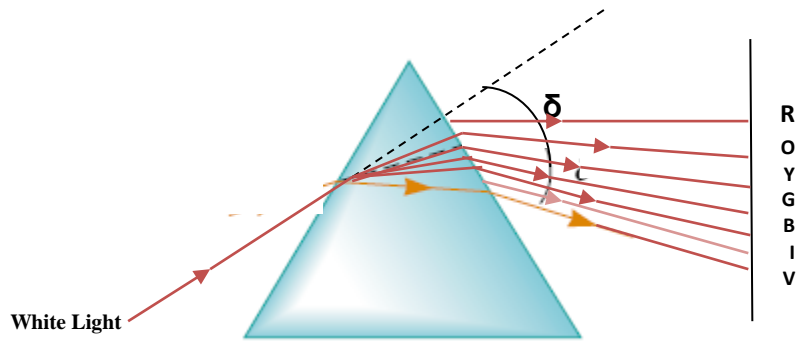


Figure 6: A prism refracts a single-wavelength light ray through an angle δ .

1.6 Total Internal Reflection

An interesting effect called total internal reflection can occur when light is directed from a medium having a given index of refraction toward one having a lower index of refraction. Consider a light beam traveling in medium 1 and meeting the boundary between medium 1 and medium 2, where n_1 is greater than n_2 (Fig. 7a). Various possible directions of the beam are indicated by rays 1 through 5. The refracted rays are bent away from the normal because n_1 is greater than n_2 . At some particular angle of incidence θ_c , called the **critical angle**, the refracted light ray moves parallel to the boundary so that $\theta_2 = 90^\circ$ (Fig. 7b).

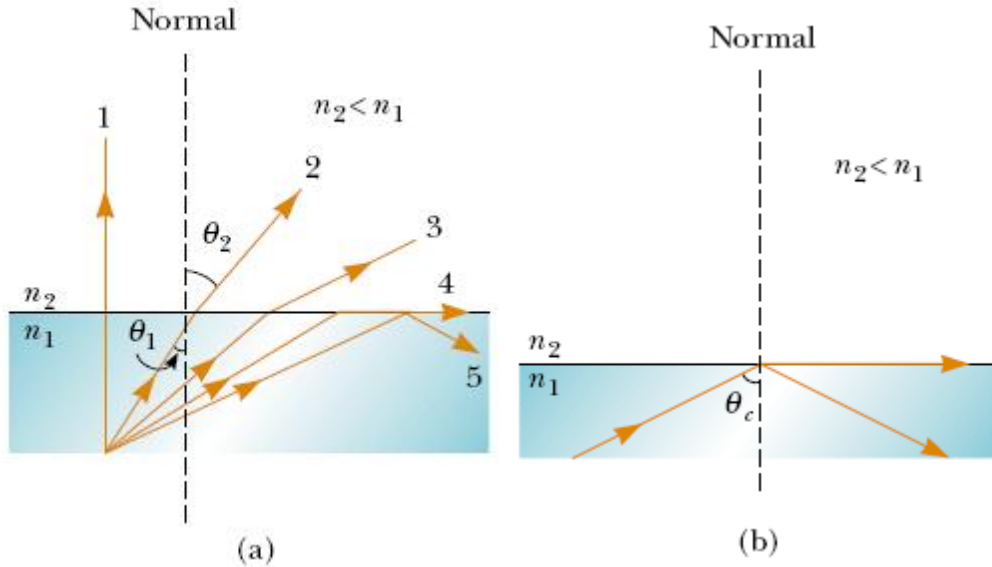


Figure 7: (a) Rays travel from a medium of index of refraction n_1 into a medium of index of refraction n_2 , where $n_2 < n_1$. As the angle of incidence θ_1 increases, the angle of refraction θ_2 increases until θ_2 is 90° (ray 4). For even larger angles of incidence, total internal reflection occurs (ray 5). (b) The angle of incidence producing an angle of refraction equal to 90° is the critical angle θ_c . At this angle of incidence, all of the energy of the incident light is reflected.

For angles of incidence greater than θ_c , the beam is entirely reflected at the boundary, as shown by ray 5 in Figure 7a. This ray is reflected at the boundary as it strikes the surface. This ray and all those like it obey the law of reflection; that is, for these rays, the angle of incidence equals the angle of reflection.

We can use Snell’s law of refraction to find the critical angle. When $\theta_1 = \theta_c$, $\theta_2 = 90^\circ$ and Equation 8 gives

$$n_1 \sin \theta_c = n_2 \sin 90^\circ = n_2$$

$$\sin \theta_c = \frac{n_2}{n_1} \quad (\text{for } n_1 > n_2) \quad \dots\dots\dots(10)$$

This equation can be used only when n_1 is greater than n_2 . That is, **total internal reflection occurs only when light is directed from a medium of a given index of refraction toward a medium of lower index of refraction.** If n_1 were less than n_2 , Equation 10 would give $\sin \theta_c > 1$; this is a meaningless result because the sine of an angle can never be greater than unity.

Example: Find the critical angle for an air–water boundary. (The index of refraction of water is 1.33.)

Solution:

$$\sin \theta_c = \frac{n_2}{n_1} = \frac{1}{1.33} = 0.75$$

$$\theta_c = \sin^{-1} 0.75 = 48.8^\circ$$

Question:

1. what is meant by reflection?
2. state and explain the law of reflection?
3. what do you mean by refraction of light?
4. hat is absolute refraction index of a medium?
5. what is Snell's law?
6. what is meant by optical path? How is it different from geometrical path length?