Refraction of light

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1 The physical phenomenon

Refraction is a physical phenomenon that occurs every time a wave, such as light or sound, travels from one medium (substance) to another in which its speed of propagation is different. The visible effect is a change in the direction of the propagating wave from the first to the second medium.

If the *incident ray* hits the interface (boundary) between the two media forming a 90° angle, then nothing happens and the ray continues its propagation in the same direction normal to the interface. If the incident ray does not hit normally the interface between the two media, then a change in the direction of wave propagation occurs causing strange effects such as the apparent bending of an object that is partially submerged in water (see figure 1) or the mirages observed on a hot, sandy desert.

Figure 1: An everyday experience of refraction

For centuries, man had noticed this rather odd, but obvious fact. Light is refracted when it leaves water, giving rise to the illusion that objects in water appear to be both distorted and closer than they really are.

As early as the first century (A.D.), the ancient Greek astronomer and geographer Ptolemy attempted to mathematically explain the amount of bending (or refraction) that occurred, but his proposed law was later determined to be unreliable. During the 1600s, the Dutch mathematician Willebrord Snell succeeded in developing a law that defined a value related to the ratio of the incident and refracted angles, which has subsequently been termed the *bending power* or *refractive index* of a substance. In effect, the more a substance is able to bend or refract light, the larger its refractive index value is said to be. The pencil in water appears to be bent because light rays coming from the pencil are abruptly bent at the air-water interface before reaching our eyes. To his disappointment, Snell never discovered the reason for this refraction effect.

In 1678, another Dutch scientist, Christiaan Huygens devised a mathematical relationship to explain Snell's observations and proposed that the refractive index of a material is related to the speed at which light travels through the substance. Huygens determined that the ratio relating the angles of light paths in two materials having differing refractive indices should be equal to the ratio of the velocity that light travels when passing through each material. Thus, he postulated, light would travel more slowly through materials having a greater refractive index. Stated another way, the velocity of light through a material is inversely proportional to its refractive index. Although this point has since been verified experimentally, it was not immediately obvious to a majority of seventeenth and eighteenth century investigators who lacked a reliable means to measure the velocity of light. To these scientists, light appeared to travel at the same speed, regardless of the material through which it passed. It was over 150 years after Huygens passed away that the speed of light was measured with enough accuracy

to prove his theories correct.

Expanding on the previous ideas, the *absolute refractive index n* of a transparent substance or material is defined as *the relative speed at which light moves through the material with respect to its speed in a vacuum*. Mathematically its definition is

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

where c is the speed of light in a vacuum, and v is the velocity of light in the material.

Material	Refractive Index
Air	1.0003
Water	1.333
Glycerin	1.473
Immersion Oil	1.515
Glass (Crown – convex lens)	1.520
Glass (Flint – concave lens)	1.656
Zircon	1.920
Diamond	2.417
Lead Sulfide (galena)	3.910

Table 1: List of refractive indices for common materials

Obviously, the absolute index of refraction of a vacuum is 1.0, whereas the absolute index of refraction of all other transparent materials exceeds the value of 1.0 because light attains its maximum speed in a vacuum (which is devoid of any material). For most practical purposes, the refractive index of air (1.0003) is so close to that of a vacuum that it can be employed to calculate refractive indices of unknown materials. The measured refractive indices of several common transparent materials are reported in table 1. Materials with higher refractive indices slow the speed of light to a greater degree than those with lower refractive indices. In effect, these materials are said to be more refractive, and they exhibit a larger angle of refraction for incoming light rays passing through an air interface

2 Laws of refraction

With reference to figure 2, we define

- the *incident ray* as the ray approaching the interface between the two media;

- the *point of incidence* as the point where the incident ray strikes the interface;

- the *refracted ray* as the ray leaving the boundary through the second medium;

- the *normal* as the construction line drawn perpendicular to the boundary at the point of incidence;

- the *angle of incidence* $\hat{i}$ as the angle between the incident ray and the normal;

- the *angle of refraction* $\hat{r}$ as the angle between the normal and the refracted ray.
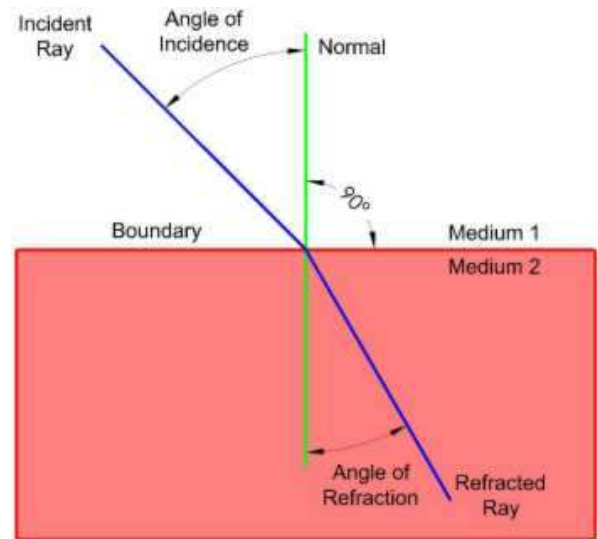

Figure 2: Definition of normal, incident ray and refracted ray

The laws of refraction state that

1. **The incident ray, the normal, and the refracted ray are coplanar**;

2. **The ratio of sines of the angles of incidence and refraction is equal to the ratio of refractive indices of the second and first medium**, i.e.

$$\frac{\sin \hat{i}}{\sin \hat{r}} = \frac{n_r}{n_i} \qquad \text{Snell's Law,}$$

where n_r is the absolute refractive index of the medium in which the refracted ray travels (second material), and n_i is the absolute refractive index of the medium in which the incident ray travels (first material).

Snell's Law describes the relationship between the angles of the two light waves and the indices of refraction of the two materials. When a light wave passes from a less refractive medium (such as air) to a more refractive medium (such as water), the velocity of the wave decreases. Conversely, when light passes from a more refractive medium (water) to a less refractive medium (air), the velocity of the wave increases. The angle of incidence in the first medium, with respect to the normal, and the angle of refraction in the second medium (also with respect to the normal), will differ in proportion to the difference in indices of refraction between the two substances. If a light wave passes from a medium of lower refractive index to one of higher refractive index, it is bent toward the normal. However, if the wave travels from a medium of higher refractive index to a medium of lower refractive index, it is bent away from the normal.

Rearranged to in a different form, Snell's Law demonstrates that the ratio of the sines of the incident and refracted angles is equal to a constant which is the ratio of the light velocities (or indices of refraction) in the two media. In fact

$$\frac{\sin \hat{i}}{\sin \hat{r}} = \frac{n_r}{n_i} = \frac{\frac{c}{v_r}}{\frac{c}{v_i}} = \frac{v_i}{v_r}.$$

The ratio n_r/n_i is termed the *relative index of refraction for those two substances*.
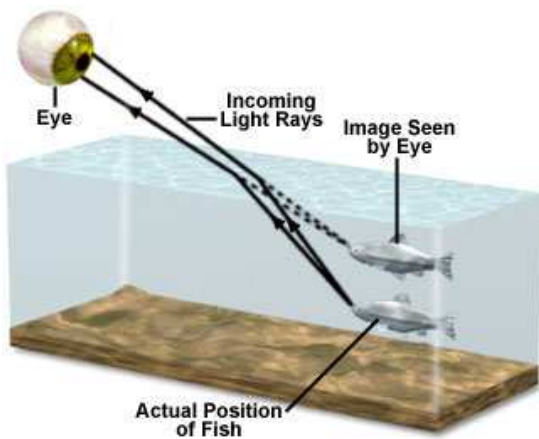
Figure 3: The virtual image seen by the observer seems to be less deep than what it really is

A number of phenomena that result from light refraction are often observed in everyday life. A part from the "broken pencil" of figure 1, one of the most common is experienced by nearly everyone who has tried to reach for and touch something submerged in water. An object seen in the water will usually appear to be at a different depth than it actually is, due to the refraction of light rays as they travel from the water into the air, as shown in figure 3. The eyes and brain trace the light rays back into the water as though they had not refracted, but traveled from the object in a straight line, creating a virtual image of the object that appears at a shallower depth.

3 Visible light wavelength dispersion

Although reference is usually made to a standard and fixed refractive index for a substance, careful measurements indicate that the index of refraction for a particular material varies with the frequency (and wavelength) of radiation, or the color of visible light. In other words, a substance has many refractive indices that may differ either marginally, or to a significant degree, as the color or wavelength of light is changed. This variation occurs for nearly all transparent media and has been termed *dispersion*. The degree of dispersion exhibited by a specific material is dependent upon how much the refractive index changes with wavelength. For any substance, as the wavelength of light increases, the refractive index (or the bending of light) decreases. In other words, blue light, which comprises the shortest wavelength region in visible light, is refracted at significantly greater angles than is red light, which has the longest wavelengths. It is the dispersion of light by ordinary glass that is responsible for the familiar splitting of light into its component colors by a prism.

In the late seventeenth century, Sir Isaac Newton performed a series of experiments that led to his discovery of the visible light spectrum, and demonstrated that white light is composed of an ordered array of colors starting with blue at one end and progressing through green, yellow, and orange, finally ending with red at the other end. Working in a darkened room, Newton placed a glass prism in front of a narrow beam of sunlight emerging through a hole drilled into a window shutter. When the sunlight passed through the prism, an ordered spectrum of color was projected onto a screen placed behind the prism.
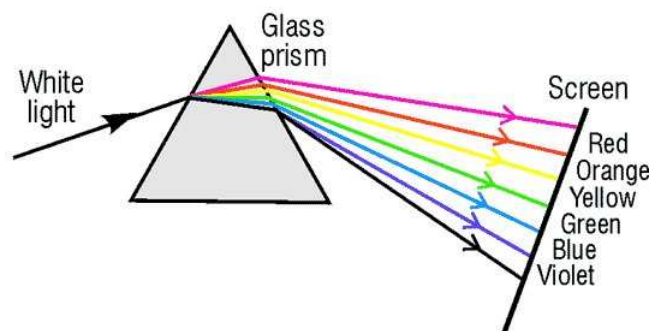

Figure 4: Light dispersion, Newton's experiment

From this experiment, Newton concluded that white light is produced from a mixture of many colors, and that the prism spread or "dispersed" white light by refracting each color at a different angle so they could be easily separated (figure 4). Newton was unable to further subdivide the individual colors, which he attempted by passing a single color of dispersed light through a second prism. However, when he placed a second prism very close to the first, so that all of the dispersed colors entered the second prism, Newton found that the colors were recombined to produce white light again. This finding produced conclusive evidence that white light is composed of a spectrum of colors that can easily be separated and reunited.

The phenomenon of dispersion plays a critical role in a wide variety of common observations. Rainbows result when sunlight is refracted by raindrops falling through the atmosphere, producing a spectacular display of spectral color that closely mimics that demonstrated with a prism.

4 Critical angle and total internal reflection

Upon passing through a medium of higher refractive index into a medium of lower refractive index, the path taken by light waves is determined by the incident angle with respect to the boundary between the two media. If the incident angle increases past a specific value (dependent upon the refractive index of the two media), it reaches a point at which the angle is so large that no light is refracted into the medium of lower refractive index, as illustrated in figure 5.
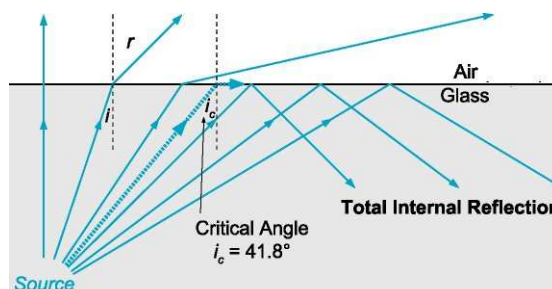

Figure 5: Critical angle and total internal reflection

The *critical angle* (or *limit angle*) is defined as the angle of incidence that causes a refracted angle equal to 90°. In other

words, as long as the angle of incidence is smaller than the critical angle, refraction occurs, whereas at the critical angle the refracted ray travels along the interface between the two media and refraction vanishes. For angles of incidence greater than the critical angle, light is *reflected* totally back into the higher refractive index medium. This phenomenon is termed *total internal reflection*. Very common applications based on total internal reflection are diamonds and optical fibers. The cut of the diamond favors total internal reflection. Most rays entering the top of the diamond will internally reflect until they reach the top face of the diamond where they exit. This gives diamonds their bright sparkle. An optical fiber is a glass "hair" which is so thin that once light enters one end, it can never strike the inside walls at less than the critical angle. Therefore, the light undergoes total internal reflection each time it strikes the wall and only when it reaches the other end is it allowed to exit the fiber. Optical fibers are used to carry telephone and computer communications because of several advantages:

1. They can carry much more information in a much smaller cable.

2. No interference from electromagnet fields results in "clear" connections.

3. No electrical resistance.

4. No hazard of electrocution if cable breaks.

Another everyday example of total internal reflection is the swimming pool. If the interface between air and water is rather flat (because there are no people in the water), a person staying underwater can look outside, owing to refraction, if and only if the incident angle is less than the critical angle. On the contrary, if the incident angle is larger than the critical one, the person staying underwater can see inside the pool thanks total internal reflection simply by looking at the free surface between air and water.

5 Conclusion

Optical devices ranging from microscopes and telescopes to cameras, charge-coupled devices (CCDs), video projectors, and even the human eye, rely in a fundamental way on the fact that light can be focused, refracted, and reflected. The refraction of light produces a wide variety of phenomena, including mirages, rainbows, and curious optical illusions such as making fish appear to be swimming in more shallow water than they really are. Refraction also causes a thick-walled beer mug to appear fuller than it really is, and deceives us into thinking the sun is setting several minutes later than it really does. Millions of people use the power of refraction to correct faulty vision with eyeglasses and contact lenses, which enable them to see the world more clearly. By understanding these properties of light, and how to control them, we are able to view details that are invisible to the unaided human eye, regardless of whether they are located on a microscope slide or in a distant galaxy.

6 Questions

1. When does refraction occur?

2. What illusion does water create when partially submerged objects are observed?

3. Who tried to explain the phenomenon of refraction?

4. What is the refractive index?

5. What did Christiaan Huygens determine about the relation between the refractive index and light?

6. Why was Huygens' theory difficult to prove at first?

7. Where does light reach its maximum speed?

8. What does the expression "to hit normally" mean?

9. What is Snell's Law about?

10. What conclusion did Newton draw after experimenting with prisms?

11. What works as a prism in a rainbow?

12. What is the critical angle?