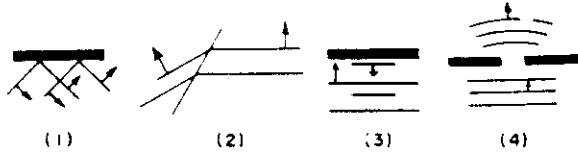
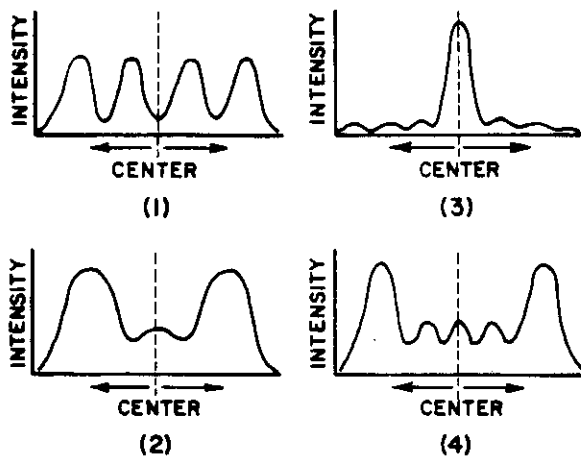


19. Which characterizes a polarized wave? (1) transverse and vibrating in one plane (2) transverse and vibrating in all directions (3) circular and vibrating at random (4) longitudinal and vibrating at random
20. Whether or not a wave is longitudinal or transverse may be determined by its ability to be (1) diffracted (2) reflected (3) polarized (4) refracted
21. Which diagram best illustrates the diffraction of waves?

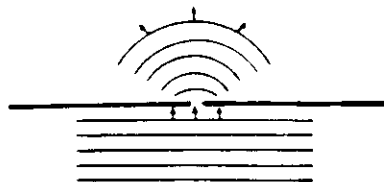


Base your answer to question 22 on the following information. Monochromatic light passes through a single narrow slit forming a diffraction pattern on a screen.

22. Which graph best represents the light intensity of the single-slit diffraction pattern for monochromatic light?



23. Which wave phenomenon is represented by the diagram? (1) Doppler effect (2) dispersion (3) diffraction (4) refraction



24. A wave spreads into the region behind a barrier. This phenomenon is called (1) diffraction (2) reflection (3) refraction (4) interference

THE BEHAVIOR OF LIGHT

Reflection

The Law of Reflection. Light that is reflected off a surface obeys the *Law of Reflection: the angle of incidence is equal to the angle of reflection*.

Wave Phenomena

Reflection. The **angle of incidence**, θ_i , is defined as the angle between the incident ray and a line normal (perpendicular) to the surface (Figure 4-12). The **angle of reflection**, θ_r , is defined as the angle between the normal and the reflected ray. The Law of Reflection says that $\theta_i = \theta_r$. If a ray of light strikes a surface at an angle of 40° from the normal, it will be reflected at an angle of 40° from the normal on the opposite side. The incident ray, the reflected ray, and the normal all lie in the same plane.

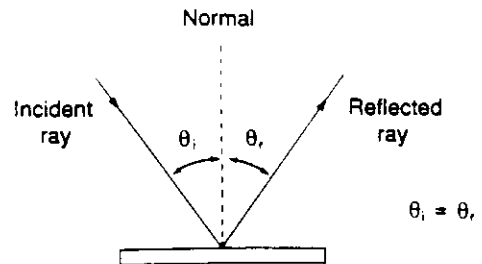


Figure 4-12. The Law of Reflection.

Regular Reflection. In real life a light source typically emits a multitude of rays in different directions. The law of reflection applies to every individual pencil-thin ray of light that strikes a surface (Figure 4-13). If the surface is smooth, all the reflected rays can be extended to one point behind the surface as illustrated in Figure 4-13. To an eye intercepting a batch of these reflected rays, they all appear to emanate from that point. The point looks like the source of light. We say that the eye sees an image of the source behind the surface at that point.

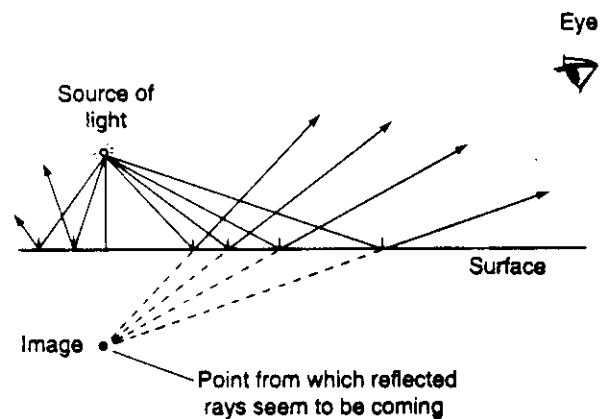


Figure 4-13. Regular reflection.

Diffuse Reflection. If the rays emitted by a light source encounter a rough, irregular surface, the reflected rays are scattered in different directions, as shown in Figure 4-14. The reflected rays do not seem to be emanating from any one point and no image appears.

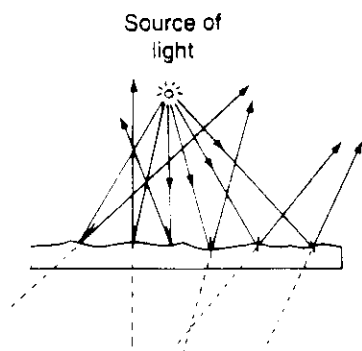


Figure 4-14. Diffuse reflection.

Refraction

The Law of Refraction. When light passes obliquely from one medium into another, it is **refracted**, or bent, at the boundary between the two media. The direction of this bending depends on the change in speed experienced by the light as it went from the first medium into the second medium. If the speed of light is slower in the second medium, as is the case when light passes from air into glass, the light bends toward the normal. In this case, the angle between the refracted ray and the normal (the **angle of refraction**) is smaller than the angle of incidence (Figure 4-15a). On the other hand, if the speed of light is greater in the second medium, as is the case when light passes from water to air, the light bends away from the normal. In this case, the angle of refraction is greater than the angle of incidence (Figure 4-15b). If light strikes a boundary between two media perpendicularly, that is, along the normal, no bending takes place and the light passes straight through.

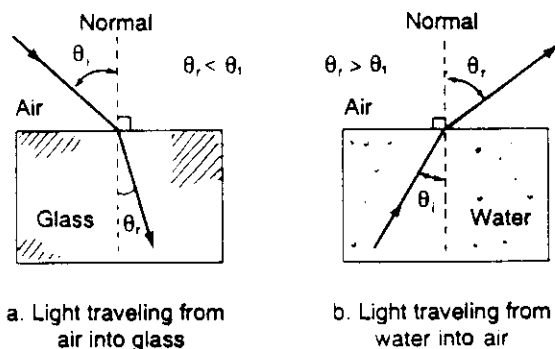


Figure 4-15. Laws of refraction.

The Absolute Index of Refraction. The amount of bending of light, whether toward or away from the normal, depends on the ratio of the speed of light in the first medium to that in the second medium.

The **absolute index of refraction**, n , of a medium is defined as the ratio of the speed of light

in vacuum (c) to the speed of light in the medium (v). This is expressed by the equation

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

Since the speed of light varies in different media, it follows that different substances have different absolute indices of refraction. The absolute index of refraction of vacuum is 1.00. Since light travels slower in all material media than it does through vacuum, all substances have absolute indices of refraction greater than 1.00. The absolute index of refraction of air is only slightly greater than 1.00, since the speed of light in air is only slightly less than in vacuum. A table of n values for several substances appear in an appendix to this book.

Sample Problem

The speed of yellow light in crown glass is 1.97×10^8 m/s. What is the absolute index of refraction of crown glass?

Solution:

$$\begin{aligned} n &= \frac{c}{v} \\ &= \frac{3.0 \times 10^8 \text{ m/s}}{1.97 \times 10^8 \text{ m/s}} = 1.52 \end{aligned}$$

Snell's Law. The angle of refraction for any given angle of incidence is found by using *Snell's Law*:

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

where θ_1 is the angle of incidence, θ_2 is the angle of refraction, n_1 is the absolute index of refraction of the first medium, and n_2 is the absolute index of refraction of the second medium.

Snell's law can also be expressed in terms of the velocities of light in the two media, as follows:

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2}$$

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

Note that for any two substances, the ratio n_2/n_1 is equal to v_1/v_2 . This ratio is referred to as the **relative index of refraction** of the particular pair and order of media.

Sample Problem

A ray of light strikes crown glass at an angle of 30° from the normal. The absolute index of refraction of crown glass is 1.52, and the speed of light in the glass is 1.97×10^8 m/s. What is the angle of refraction?

Solution:

Method 1

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

$$(1.00)(\sin 30^\circ) = (1.52)(\sin \theta_2)$$

$$\sin \theta_2 = \frac{.50}{1.52} = .33$$

$$\theta_2 = 19^\circ$$

Method 2

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2}$$

$$\frac{\sin 30^\circ}{\sin \theta_2} = \frac{3.00 \times 10^8 \text{ m/s}}{1.97 \times 10^8 \text{ m/s}}$$

$$\frac{.50}{\sin \theta_2} = 1.52$$

$$\sin \theta_2 = .33$$

$$\theta_2 = 19^\circ$$

Critical Angle. When light crosses a boundary and its speed is greater in the second medium, the Law of Refraction states that it bends away from the normal. The angle of refraction is then greater than the angle of incidence. Therefore, at such boundaries, there exists an angle of incidence for which the corresponding angle of refraction is 90° . At this angle of incidence, called the **critical angle**, θ_c , the ray emerges parallel to the boundary (Figure 4-16). The value of θ_c depends on the absolute indices of refraction of the two media and is therefore different for different media. If the first medium is some material and the second is vacuum (or air), the value of θ_c is given by the formula

$$\sin \theta_c = \frac{1}{n}$$

where n is the absolute index of refraction of the first medium.

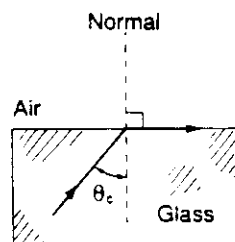


Figure 4-16. Critical angle.

Sample Problem

What is the critical angle when light passes from diamond to air? (The absolute index of refraction of diamond is 2.42.)

Solution:

$$\sin \theta_c = \frac{1}{n} = \frac{1}{2.42} = .41$$

$$\theta_c = 24^\circ$$

Critical angles do not exist when the speed of light is slower in the second medium. The light then bends toward the normal and away from the boundary.

Total Internal Reflection. The critical angle is the largest angle of incidence for which Snell's law works when light crosses a boundary where its speed is greater in the second medium. For all angles of incidence greater than the critical angle, no refraction occurs and the light does not enter the second medium. Instead, the rays are reflected back into the first medium, obeying the Law of Reflection (Figure 4-17). This phenomenon is known as **total internal reflection**.

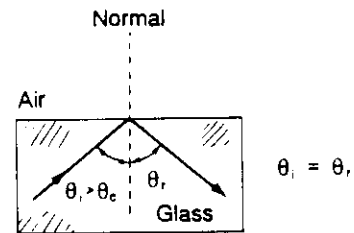


Figure 4-17. Total internal reflection.

For example, consider a ray of light that strikes perpendicularly into a $45^\circ\text{-}45^\circ\text{-}90^\circ$ glass prism (Figure 4-18). No refraction occurs at the first boundary (into the glass) since the light strikes that boundary perpendicularly. The light continues straight into the glass and approaches the opposite boundary, on the way out of the glass, with an angle of incidence of 45 degrees. This is larger than the critical angle of glass-to-air which is 42 degrees. The light does not leave the prism but is internally reflected. The angle of reflection is equal to the angle of incidence, and the light is reflected 45 degrees from, and on the other side of, the normal.

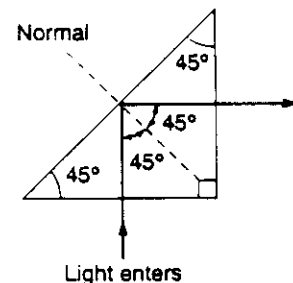


Figure 4-18. A ray of light strikes a $45^\circ\text{-}45^\circ\text{-}90^\circ$ prism perpendicularly.

Dispersion. White light is **polychromatic**. It consists of waves of different colors and frequencies. In some media, called **dispersive media**,

waves of different frequency travel at different speeds. Since the amount of refraction at a boundary depends on the ratio of the speed of light in the first medium to that in the second medium, it follows that at some boundaries different colors undergo different amounts of bending and have different absolute indices of refraction. When white light passes obliquely into a dispersive medium, each of the different colors and frequencies in the mixture undergoes a different amount of bending. The net result is that the colors are separated, or **dispersed**, by the dispersive medium.

Both glass and water are dispersive media for light. A ray of white light passing through glass emerges not as a single ray of white, but as separate rays of red, orange, yellow, green, blue, and violet. The red is refracted the least while the violet is refracted the most (Figure 4-19).

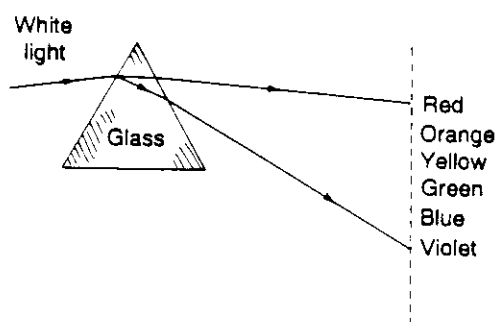


Figure 4-19. Dispersion.

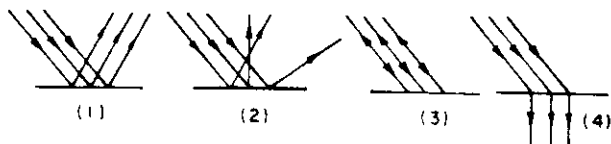
A **nondispersive medium** is one in which the speed of the wave does not depend on the frequency. A vacuum is nondispersive for light.

QUESTIONS

1. Which phenomenon of light is illustrated by the diagram below? (1) regular reflection (2) diffuse reflection (3) diffraction (4) refraction

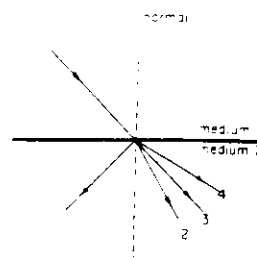


2. Which of the diagrams representing light rays reflecting from a surface illustrates diffuse reflection?

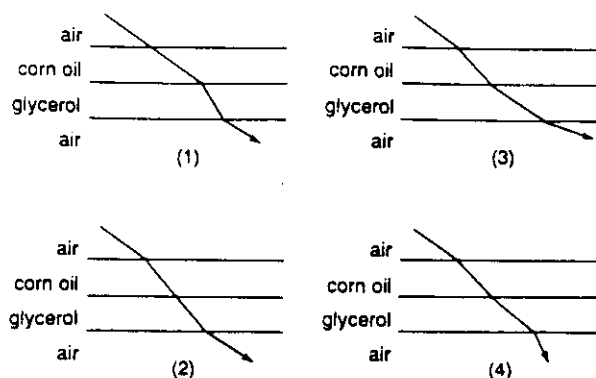


3. The change in the direction of a wave when it passes obliquely from one medium to another is called (1) diffraction (2) interference (3) refraction (4) superposition

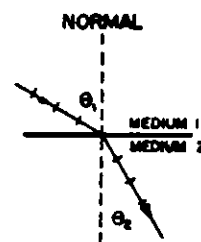
4. When a light ray passes from medium 1 to medium 2, its speed decreases. Which arrow best represents the path of the ray in medium 2? (1) 1 (2) 2 (3) 3 (4) 4



5. Which arrow best represents the path that a monochromatic ray of light will travel as it passes through air, corn oil, glycerol, and back to air?

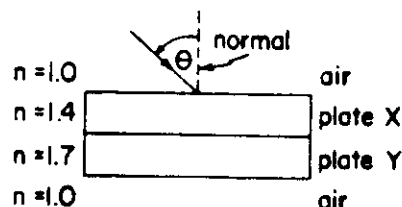


6. The diagram at the right represents a wave traveling from medium 1 to medium 2. The relative index of refraction may be determined by calculating the ratio of



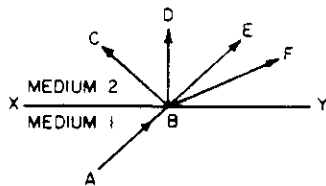
- (1) $\frac{\theta_1}{\theta_2}$ (2) $\frac{\sin \theta_2}{\sin \theta_1}$
 (3) $\frac{\sin \theta_1}{\sin \theta_2}$ (4) $\frac{n_1}{n_2}$

Base your answers to questions 7 through 10 on the following diagram which represents a ray of monochromatic light incident upon the surface of plate X. The values of n in the diagram represent absolute indices of refraction.



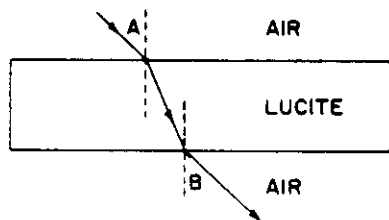
7. The speed of the light ray in plate X is approximately (1) 1.8×10^8 m/sec (2) 2.1×10^8 m/sec (3) 2.5×10^8 m/sec (4) 2.9×10^8 m/sec

8. What is the sine of the critical angle for the light ray at the boundary between plate Y and the air? (1) 1.0 (2) 0.83 (3) 0.71 (4) 0.59
9. Compared to angle θ , the angle of refraction of the light ray in plate X is (1) smaller (2) greater (3) the same
10. Compared to angle θ , the angle of refraction of the ray emerging from plate Y into the air will be (1) smaller (2) greater (3) the same
11. Which wave phenomenon could *not* be demonstrated with a single wave pulse? (1) a standing wave (2) diffraction (3) reflection (4) refraction
12. In the following diagram, ray AB is incident on surface XY at point B. If medium 2 has a lower index of refraction than medium 1, through which point will the ray most likely pass? (1) E (2) F (3) C (4) D



13. For a given angle of incidence, the greatest change in the direction of a light ray will be produced when the light ray passes obliquely from air into (1) Lucite (2) glycerol (3) alcohol (4) flint glass
14. When a wave enters a medium of higher refractive index, its velocity (1) decreases (2) increases (3) remains the same
15. A ray of light traveling through water strikes a water-air surface with an angle of incidence equal to the critical angle. What will be the angle of refraction? (1) 180° (2) 90° (3) 45° (4) 30°

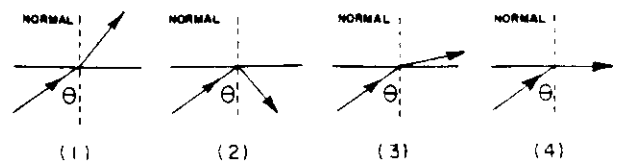
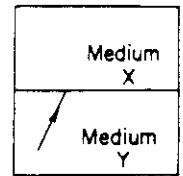
Base your answers to questions 16 through 20 on the following diagram which represents a ray of monochromatic violet light waves ($\lambda = 4.0 \times 10^{-7} \text{ m}$) passing from air through Lucite and then into air again.



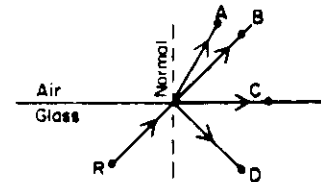
16. The frequency of these light waves in air, in hertz (cycles per second), is (1) 7.5×10^{14} (2) 1.3×10^{14} (3) 7.5×10^{-14} (4) 1.3×10^{-14}
17. The apparent wavelength of these light waves in Lucite is (1) $6.0 \times 10^{-7} \text{ m}$ (2) $2.7 \times 10^{-7} \text{ m}$ (3) $6.4 \times 10^{-7} \text{ m}$ (4) $4.0 \times 10^{-7} \text{ m}$
18. Compared to the speed of the violet light in air, the speed of the violet light in Lucite is (1) less (2) greater (3) the same
19. Compared to the frequency of waves of violet light in air, the frequency of waves of violet light in Lucite is (1) less (2) greater (3) the same

Wave Phenomena

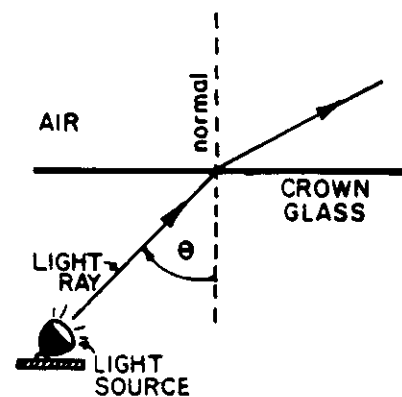
20. Compared to angle A, angle B is (1) smaller (2) larger (3) the same
21. The speed of light in corn oil is the same as the speed of light in (1) diamond (2) flint glass (3) air (4) glycerol
22. If the speed of light in a medium is 2.0×10^8 meters per second, the index of refraction for the medium is (1) 1.0 (2) 2.0 (3) 1.5 (4) 0.67
23. The diagram at the right shows a light ray incident on the boundary between two media. Total internal reflection may occur when the index of refraction of medium Y is (1) less than the index of refraction of X (2) greater than the index of refraction of X (3) equal to the index of refraction of X
24. In which diagram is angle θ a critical angle?



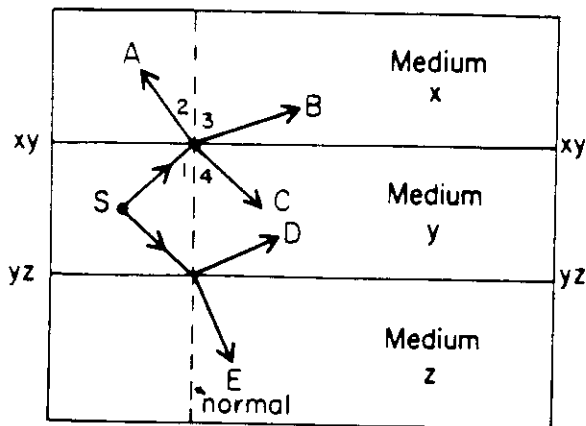
25. The following diagram shows a ray of light (R) incident upon a surface at an angle greater than the critical angle. Through which point is the ray most likely to pass? (1) A (2) B (3) C (4) D



26. The following diagram represents a light ray traveling from crown glass into air. The position of the light source is changed to vary the angle θ . As θ approaches the critical angle, the angle of refraction approaches (1) 0° (2) 41° (3) 90° (4) 55°

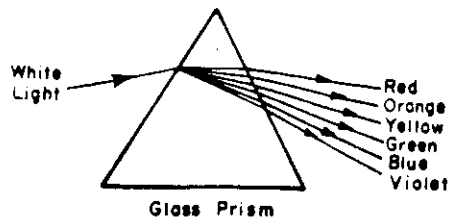


Base your answers to questions 28 through 32 on the following diagram. The diagram shows two light rays originating from source S in medium y. The dashed line represents a normal to each surface.



27. Which light ray would *not* be produced in this situation? (1) A (2) B (3) C (4) E
28. A reflected light ray is ray (1) A (2) B (3) C (4) E
29. Which two angles must be equal? (1) 1 and 2 (2) 2 and 3 (3) 3 and 4 (4) 1 and 4
30. Light originating from source S could produce total internal reflection at (1) surface yz , only (2) surface xy , only (3) neither surface xy nor yz
31. Compared to the speed of light in medium x , the speed of light in medium z is (1) less (2) greater (3) the same

32. Which phrase best describes the phenomenon illustrated by the following diagram? (1) scattering and diffraction (2) reflection and interference (3) transmission and Doppler effect (4) refraction and dispersion



33. The separating of polychromatic light into its component frequencies as it passes through a prism is called (1) interference (2) diffraction (3) diffusion (4) dispersion
34. A medium in which waves of different frequencies travel at different speeds and may be separated is called (1) a dispersive medium (2) a nondispersive medium (3) an inelastic medium (4) a coherent medium
35. Compared to the speed of light in a vacuum, the speed of light in a dispersive medium is (1) less (2) greater (3) the same