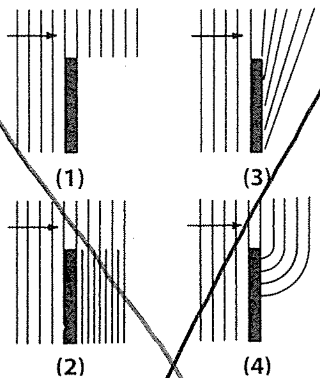
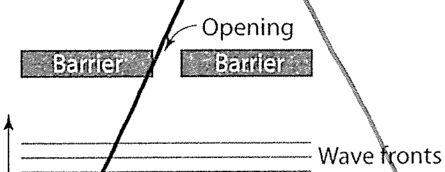
69. A wave spreads into the region behind a barrier. What is this phenomenon called?

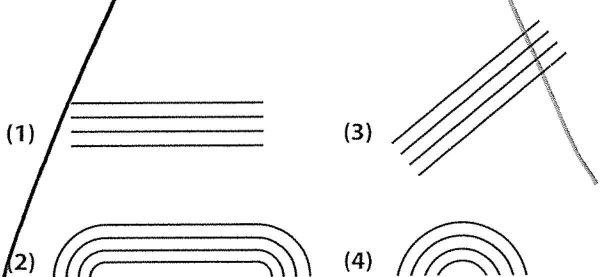
70. Which diagram best illustrates diffraction of waves incident on a barrier?



71. The diagram that follows represents straight wave fronts approaching a narrow opening in a barrier.



Which diagram best represents the shape of the waves after passing through the opening?



Light

The human eye can perceive only an extremely small fraction of the electromagnetic spectrum. That portion of the spectrum, which allows us to see, is called light and covers the range of wavelengths from approximately 3.90×10^{-7} to 7.81×10^{-7} meter. (The electromagnetic spectrum will be discussed in detail later in this topic.) Obviously, these wavelengths are too small to measure with a ruler as you might measure the wavelength of a transverse wave on a rope or a water wave in a shallow tank.

Speed of Light

Measurements of the speed of light to more than two or three significant figures could not be made until about 100 years ago. To three significant figures, the speed of light in a vacuum or air is 3.00×10^8 meters per second. Measurements of the speed of light are now recorded to nine significant figures. This more accurate data reveals that the speed of light in air is slightly less than it is in a vacuum. The speed of light in a vacuum is represented by the symbol *c*, an important physical constant.

The speed of light in a vacuum is the upper limit for the speed of any material body. No object can travel faster than *c*. The speed of light in a material medium is always less than *c*. The equation $v = f\lambda$ applies to light waves. Therefore, $c = f\lambda$, where f is the frequency of a light wave and λ is its wavelength in a vacuum.

Ray Diagrams

Because it is not possible to see individual wave fronts in a light wave, a ray is used to indicate the direction of wave travel. A **ray** is a straight line that is drawn at right angles to a wave front and points in the direction of wave travel. Ray diagrams show only the direction of wave travel, not the actual waves. An **incident ray** is a ray that originates in a medium and is incident on a boundary or an interface of that medium with another medium. A **reflected ray** is a ray that has rebounded from a boundary or interface. A **refracted ray** is a ray that results from an incident ray entering a second medium obliquely. Figure 5-13 on the following page shows these rays as well as the wave fronts whose motion they represent.

Incident, reflected, and refracted rays form corresponding angles measured from a line called the normal. The **normal** is a line drawn perpendicular to the barrier or to the interface between two media at the point where the incident ray strikes. In ray diagrams, all the rays and the normal lie in a single plane.

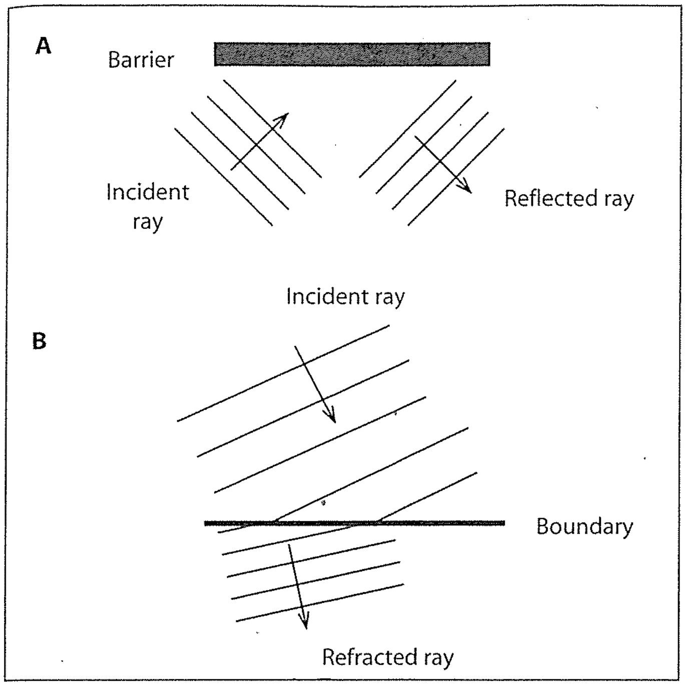


Figure 5-13. Reflected and refracted rays: (A) shows the direction of a reflected wave front at a barrier. **(B)** shows how a wave front changes at a boundary between two media.

Reflection of Light

The **angle of incidence,** θ_i, is the angle between the incident ray and the normal to the surface at the point where the ray strikes the surface. The ray rebounds from the surface at the **angle of reflection,** θ_r, which is the angle between the reflected ray and the normal to the surface at the point of reflection. The **law of reflection** states that the angle of incidence is equal to the angle of reflection.

$$\theta_i = \theta_r$$

Figure 5-14 illustrates the law of reflection. This law is valid for all types of waves including light, water, and sound waves. The reflection of sound waves is called an echo.

Parallel light rays incident on a smooth plane surface are reflected parallel to each other because all the normals to the surface are parallel. See Figure 15-5A. However, when a beam of parallel light rays strikes an irregular surface, the reflected rays are scattered in all directions. The surface irregularities produce nonparallel normals. Each individual ray obeys the laws of reflection and produces the effect shown in Figure 5-15B.

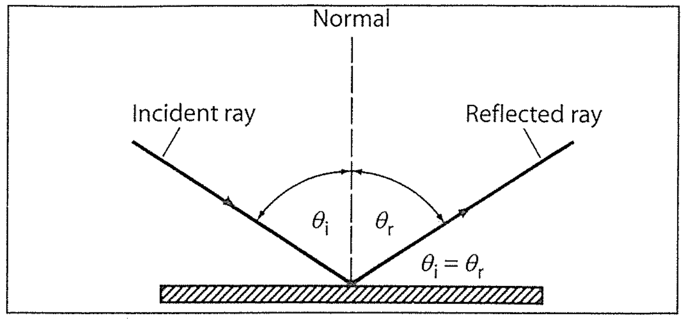


Figure 5-14. The law of reflection: The angle of incidence equals the angle of reflection.

IMAGES FORMED BY REFLECTIONS FROM A PLANE MIRROR The law of reflection is the basis for the formation of an image by a plane mirror. If several light rays originating from the same point are reflected from a plane mirror, the reflected rays appear to come from a single point on the other side of the mirror forming a virtual image. A virtual image is a point from which light rays appear to diverge without actually doing so. In Figure 5-16A on the next page, point P_i is the virtual image of point P_o. The virtual image is formed where light rays originating from P_o appear to intersect for the observer. The rays of light reaching the observer's eye actually come from the object P_o and are reflected by the mirror so as to appear to come from the image P_i. The virtual image cannot be projected on a screen. A geometric proof shows that the distance of the virtual image P_i from the mirror is equal to the distance of the object P_o from the mirror.

The image of an object in front of a plane mirror can be constructed as shown in Figure 5-16B. The image point corresponding to any given point on the object can be located by tracing the path of any two rays originating from the given point on the object. One ray can be the ray perpendicular to the mirror.

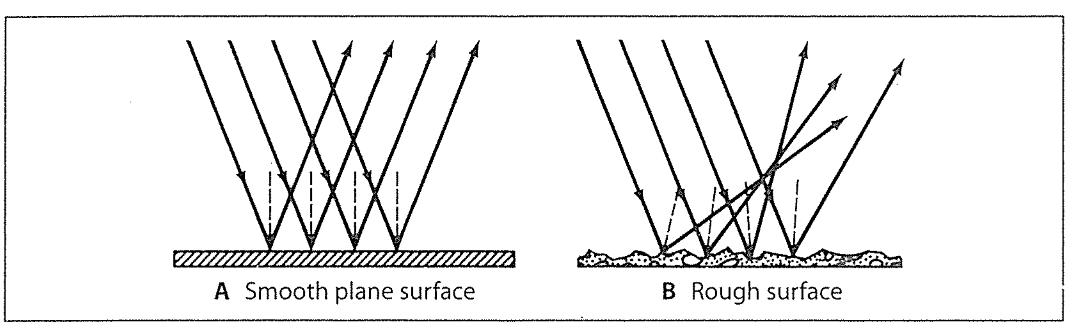


Figure 5-15. Reflection from a smooth plane surface and a rough surface: (A) Regular reflection; all normals are parallel. **(B)** Scattered or diffuse reflection; the normals are not parallel.

The second ray can be drawn at any other angle to the mirror. By means of geometry, it can be shown that the image is the same distance behind the mirror as the object is in front of it, and the image and the object are also the same size. Although the image formed by a vertical mirror is erect with respect to the object, it is reversed from left to right. For example, the top of the image of a printed page is the top of the page, but the print reads backward.

The minimum size of a vertical, plane mirror for viewing the entire body is one-half the viewer's height, as illustrated in Figure 5-17. By the law of reflection, the angle of incidence of a light ray is equal to the angle of reflection. Looking straight ahead into a plane mirror positioned in front of you and perpendicular to the floor, you see your eyes. If you look halfway down the mirror, you see your toes. If you raise your eyes and look at the mirror at a distance halfway between your eyes and the top of your head, you see the top of your head. Thus, the minimum size of a plane mirror for viewing the entire body is one-half the viewer's height.

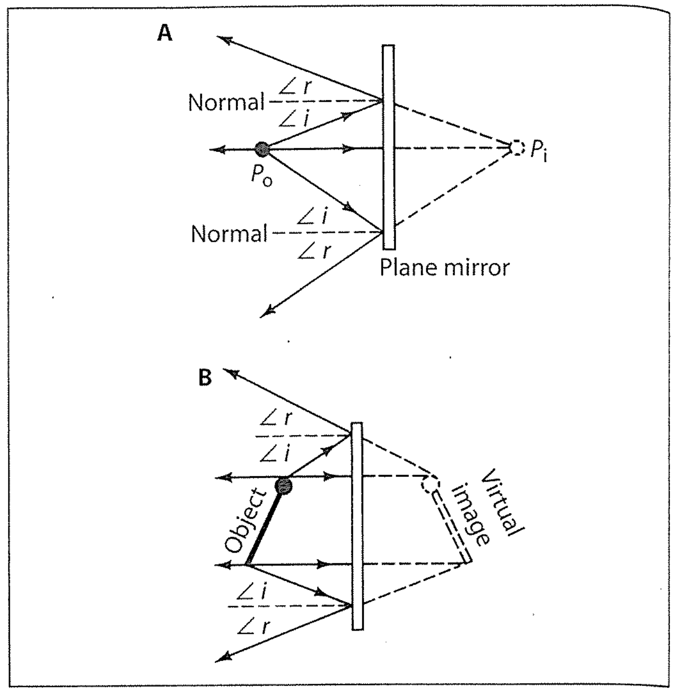


Figure 5-16. Image formation by a plane mirror: (A) All rays from a point source are reflected as though coming from an image point P_i, as far behind the mirror as P_o is in front of it. **(B)** Any two reflected rays that originate from a point on an object are sufficient to locate the virtual image of that point by extending the reflected rays until they intersect behind the mirror.

Refraction of Light

Waves travel at different speeds in different media, so when a wave travels from one medium to another, the speed of the wave changes. If the wave is incident on the interface between two media at an angle other than 90°, the direction of wave travel changes in the new medium. That means that both the speed and the direction of a wave usually change as the wave enters a new medium obliquely. The change in direction of a wave due to a change in speed at the boundary between two different media is called **refraction.** If the wave fronts of an incident wave are parallel to the interface, the angle of incidence is 0° and the wave may change speed upon entering the new medium, but the direction of the wave does not change.

The amount of refraction of a ray depends upon the properties of the two media at the interface and is measured by the angle of refraction. The **angle of refraction** is the angle between a ray emerging from the interface of two media and the normal to that interface at the point where the ray emerges.

Speed of Light and Refraction

When a light ray in air is incident on an interface with water at an angle of incidence of 0°, the ray of light slows down upon entering the more optically dense water, but does not change its direction of

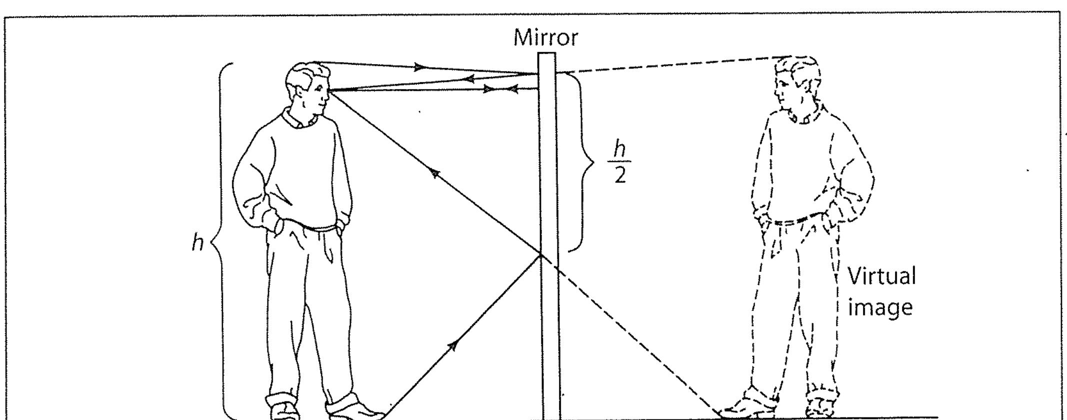
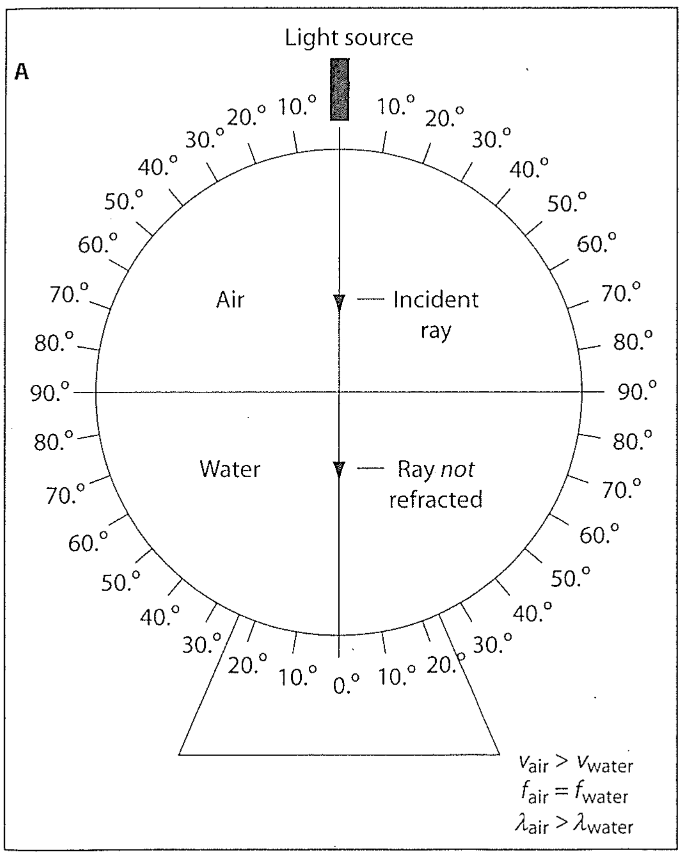


Figure 5-17. Your image in a vertical mirror: The symbol *h* represents your height. The portions of the mirror above and below the length marked $\frac{h}{2}$ are unnecessary for seeing your full image.

travel. Figure 5-18A shows an incident ray approaching the interface between air and water along the normal. The ray is not refracted as it travels from air into water. The ray travels more slowly in water than in air but its frequency remains the same. The speed of a wave is proportional to its wavelength when frequency is constant, so its wavelength in water is shorter than its wavelength in air.

The situation is different when a light ray passes obliquely from a less dense medium such as air into a more dense medium such as water. In this case, the ray is refracted towards the normal, as shown in Figure 5-18B. Upon entering the denser medium, the ray's frequency does not change, but its wavelength decreases as its speed decreases. If the path of the ray is from a more dense medium, such as water, into a less dense medium, such as air, the ray is refracted away from the normal, as shown in Figure 5-18C. Upon entering the less dense medium, the ray's frequency does not change, but its wavelength increases as its speed increases.



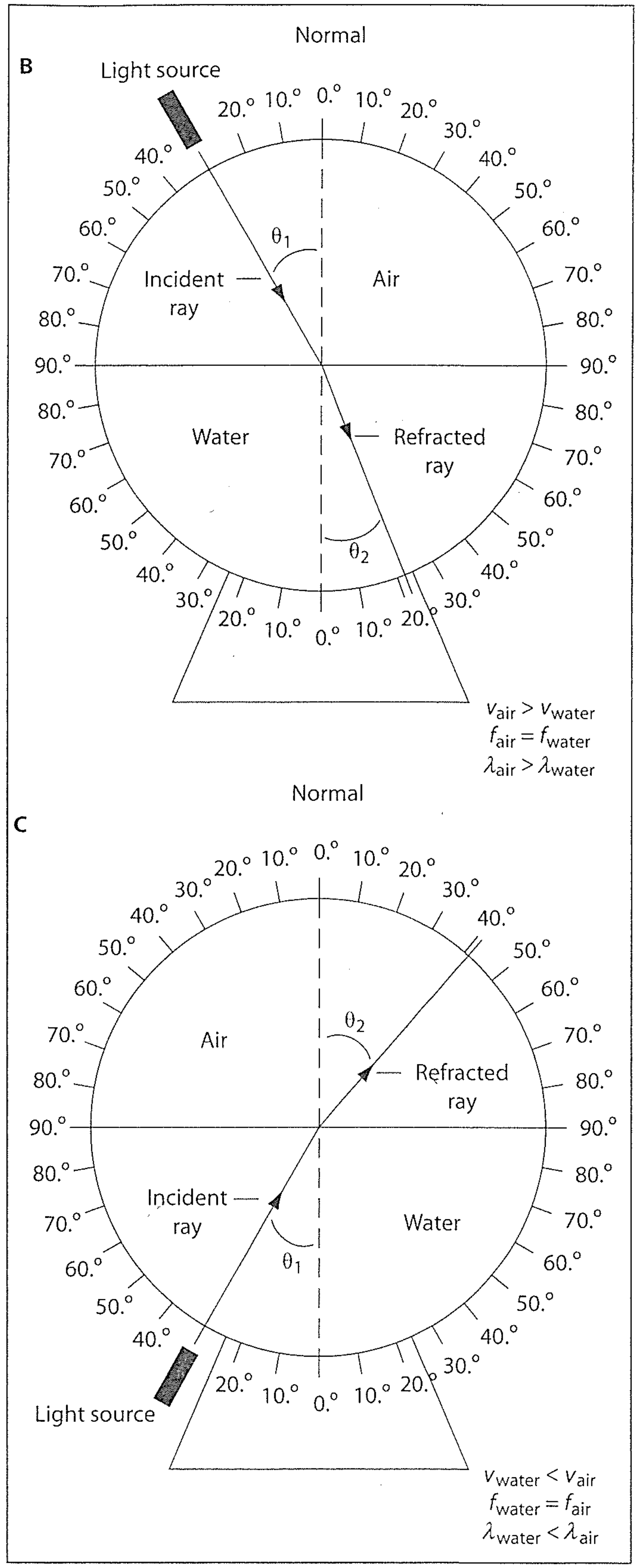


Figure 5-18. Refraction of light: (A) A light ray passes from a less dense medium, air, into a more dense medium, water, at an angle of incidence of 0°. **(B)** A light ray passes obliquely from a less dense medium, air, into a more dense medium, water, at an angle of incidence of 30°. The ray is refracted toward the normal. **(C)** A light ray passes obliquely from a more dense medium, water, into a less dense medium, air, at an angle of incidence of 30°. The ray is refracted away from the normal.

The refraction of light explains many everyday phenomena such as mirages and the visibility of the sun after it has actually disappeared below the horizon, as illustrated in Figure 5-19. Because the density of Earth's atmosphere increases gradually as Earth's surface is approached from space, sunlight entering the atmosphere obliquely, as it does at sunset, is gradually refracted to produce a curved path. Your brain has learned to assume that light entering your eyes has been traveling in straight lines. Thus, at sunset you "see" the sun higher in the sky than it actually is. When you "see" the sun on the horizon, it has already set.

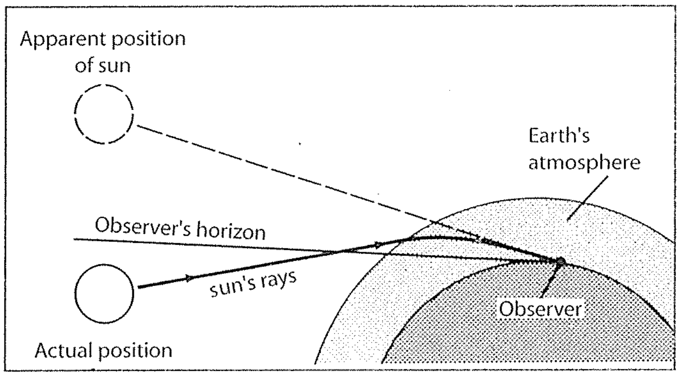


Figure 5-19. Curvature of the sun's rays by refraction in Earth's atmosphere

Another example of refraction is the apparent bending of a straw placed in a glass of water. The submerged portion of the straw appears to be closer to the surface than it actually is. Light from the submerged tip of the straw is bent away from the normal upon entering the less-dense air, as shown in Figure 5-20. To an observer, who interprets what is seen as light traveling in a straight line, the submerged tip of the straw seems closer to the surface than it actually is.

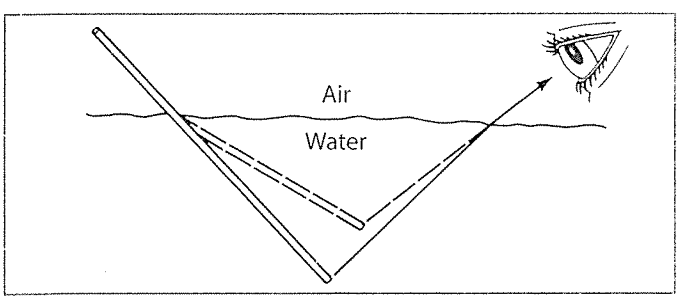


Figure 5-20. Refraction of light: Light rays from the tip of the straw are bent away from the normal as they emerge from the water. The effect is to make the straw appear to bend at the surface of the water.

Absolute Index of Refraction

The **absolute index of refraction,** n, is the ratio of the speed of light in a vacuum, c, to the speed of light in a material medium, v.

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

The absolute index of refraction has no units because both c and v are measured in the same units. The greater the value of n, the more optically dense the medium and the slower light travels in the medium. The absolute indices of refraction for a variety of materials are listed in the *Reference Tables for Physical Setting/Physics*.

Solving the equation for c yields $c = nv$. Thus, the following equations apply for two different media.

$$n_1v_1 = n_2v_2 \quad \text{or} \quad \frac{n_2}{n_1} = \frac{v_1}{v_2}$$

Also, the following equations apply for any two media.

$$v_1 = f\lambda_1 \text{ and } v_2 = f\lambda_2$$

Note that the frequency of the wave does not change as the wave enters a new medium. Thus, the relationship between the speeds and wavelengths of the wave in the two media is this.

$$\frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$$

These relationships can be combined as follows.

$$\frac{n_2}{n_1} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$$

Snell's Law

The mathematical relationship that governs the refraction of light as it passes obliquely from one medium to another of different optical density is called **Snell's law.**

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

Angles θ_1 and θ_2 are the angles of incidence and refraction respectively, and n_1 and n_2 are the absolute indices of refraction of the incident and refractive media, respectively.

Snell's law can be rearranged in this way.

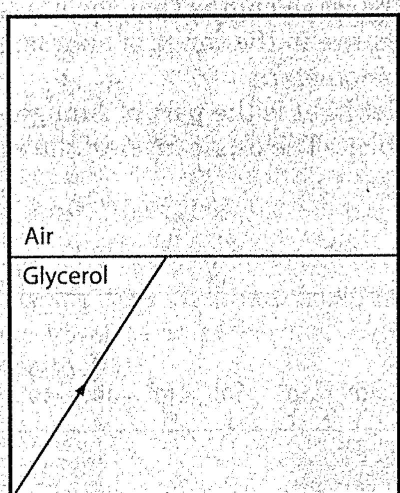
$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

The ratio n_2/n_1 is called the relative index of refraction for the two media.

SAMPLE PROBLEM

The diagram represents a ray of monochromatic light, having a frequency of 5.09×10^{14} hertz, as it is about to emerge from liquid glycerol into air. The index of refraction of glycerol, n_1, is 1.47. The index of refraction of air, n_2, is 1.00.

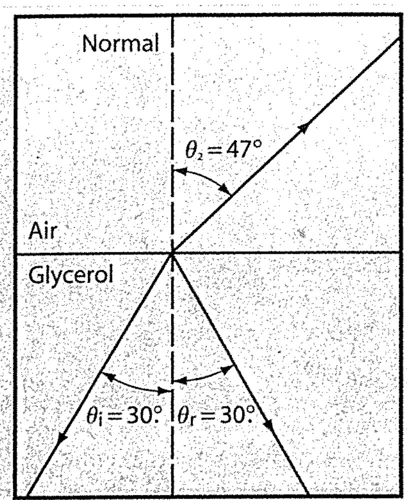
(a) On the diagram, label the angle of incidence θ_1. Determine its measure to the nearest degree.
(b) Determine the corresponding angle of refraction to the nearest degree.
(c) On the diagram, draw the refracted light ray, label the angle of refraction θ_2, and indicate its measure to the nearest degree.
(d) At a boundary between two media, some of the incident light is always reflected. On the diagram, draw the reflected ray, label the angle of reflection θ_r, and indicate its measure to the nearest degree.
(e) Determine the speed of light in glycerol.
(f) Determine the wavelength of the light in air in nanometers to the proper number of significant digits.
(g) What is the ratio of the speed of light in glycerol to the speed of light in air?



Solution: Identify the known and unknown values.

Known	*Unknown*
$f = 5.09 \times 10^{14}$ Hz	$\theta_1 = ?$ degrees
$n_1 = 1.47$	$\theta_2 = ?$ degrees
$n_2 = 1.00$	$\theta_r = ?$ degrees
	$v = ?$ m/s
	$\lambda = ?$ nm
	ratio $v_1/v_2 = ?$

(a) On the diagram, draw a normal to the surface at the point of incidence. The angle of incidence is measured from the normal.
See the diagram that follows. The angle of incidence is 30°.



(b) Use the equation $n_1 \sin \theta_1 = n_2 \sin \theta_2$. Note that the subscript 1 refers to the incident medium and the subscript 2 refers to the refractive medium. Solve the equation for $\sin \theta_2$.

$$\sin \theta_2 = \frac{n_1 \sin \theta_1}{n_2}$$

Substitute the known values and solve for θ_2.

$$\sin \theta_2 = \frac{(1.47)(\sin 30.°)}{1.00} = 0.735$$

$$\theta_2 = 47°$$

(c) The angle of refraction is in air and is measured from the normal using a protractor.

(d) The angle of incidence equal the angle of reflection. Thus, the angle of reflection is 30.°, and is measured from the normal.

(e) Solve the equation $n = c/v$ for v.

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

Substitute known values and solve for v.

$$v = \frac{3.00 \times 10^8 \text{ m/s}}{1.47} = 2.04 \times 10^8 \text{ m/s}$$

(f) Solve the equation $c = f\lambda$ for the wavelength, λ.

$$\lambda = \frac{c}{f}$$

Substitute the known values and solve.

$$\lambda = \frac{3.00 \times 10^8 \text{ m/s}}{5.09 \times 10^{14} \text{ Hz}}$$

$$\lambda = 5.89 \times 10^{-7} \text{ m}$$

$$\lambda = 589 \text{ nm}$$

(g) To find the ratio of the speed of light in air to the speed of light in glycerol, use the following relationship.

$$\frac{v_1}{v_2} = \frac{n_2}{n_1}$$

Substitute the known values and solve for $\frac{v_1}{v_2}$.

$$\frac{v_1}{v_2} = \frac{n_2}{n_1} = \frac{1.00}{1.47}$$

The Electromagnetic Spectrum

Light waves are **electromagnetic waves** which consist of periodically changing electric and magnetic fields and move through a vacuum at speed $c = 3.00 \times 10^8$ meters per second. All electromagnetic waves, regardless of their frequency and wavelength, are produced by accelerating charged particles. The **electromagnetic spectrum,** which is the complete range of frequencies and wavelengths of electromagnetic waves, is shown in Figure 5-21. Notice that visible light is only a small portion of the spectrum.

There are no sharp divisions between the various kinds of electromagnetic waves. They are classified according to the methods by which they are generated or received. For example, radio waves, used for communication systems, are produced by charges accelerating in a wire.

Microwaves are used in radar systems in air-traffic control, for transmitting long-distance telephone communications in outer space, and to cook food. The frequency of microwaves used in a microwave oven is the same as the natural rotational frequency of water molecules. Resonance is produced in water molecules contained in food and the resulting internal energy due to vibration heats the food.

Infrared waves appear as heat when absorbed by objects. Practical applications of the infrared portion of the electromagnetic spectrum include heat lamps used in physical therapy and infrared photography.

Visible light is approximately one percent of the electromagnetic spectrum. It is produced by the rearrangement of electrons in atoms and molecules. The wavelengths that the human eye can detect are in the range of approximately 400 to 700 nanometers.

Ultraviolet light is the part of sunlight that causes sunburns. The ozone layer of the atmos-

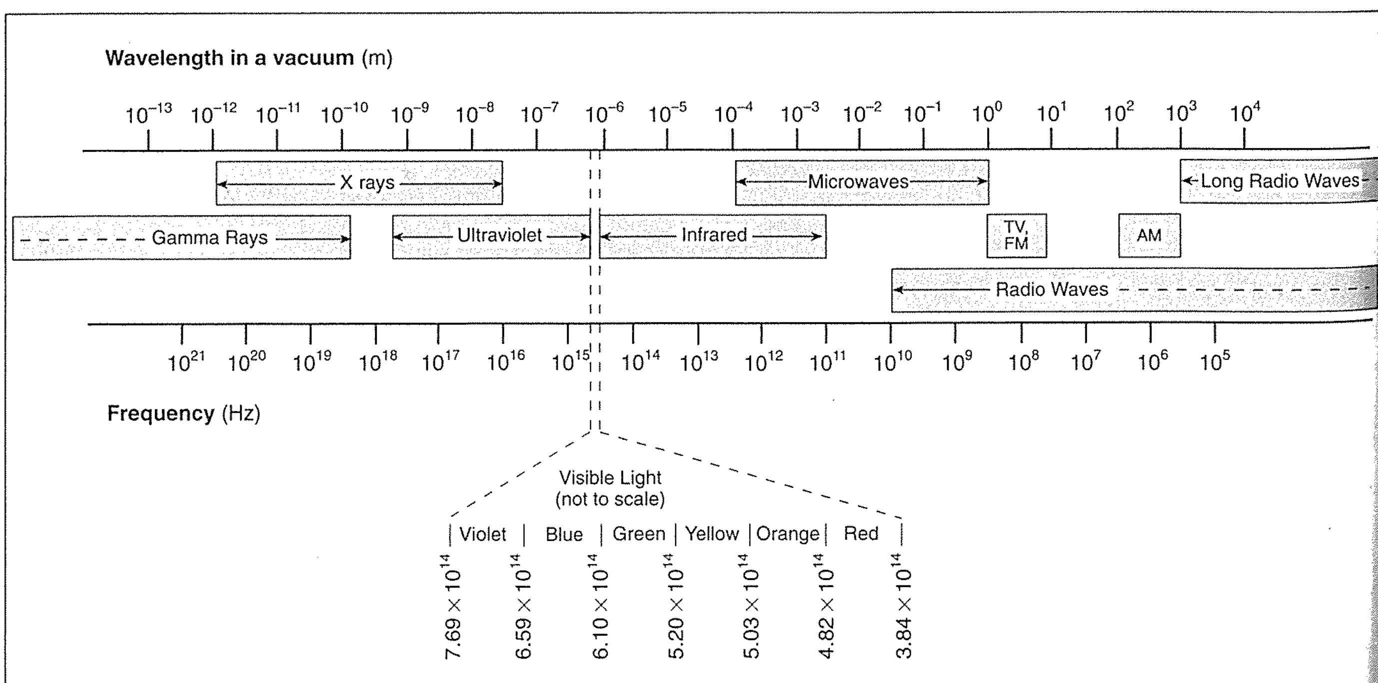


Figure 5-21. The electromagnetic spectrum

phere filters practically all of the high frequency components of ultraviolet radiation from the sun, but the inner atmosphere readily transmits the remaining lower frequency ultraviolet radiation. Some commercial skin lotions are designed to absorb ultraviolet rays to prevent them from affecting the skin.

X rays are used as diagnostic tools by physicians. Living tissues and organisms can be destroyed by X rays, so precautions should be taken to avoid overexposure.

Gamma rays are emitted by radioactive nuclei. This electromagnetic radiation is harmful to living tissues.

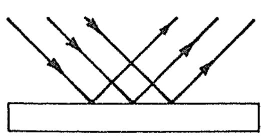
Review Questions

72. How long does it take light to travel a distance of 100. meters? (1) 3.00×10^{10} s (2) 3.00×10^{8} s (3) 3.33×10^{-7} s (4) 3.33×10^{7} s

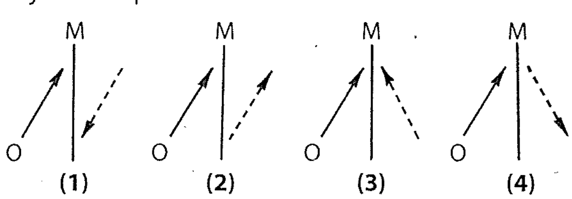
73. Determine the wavelength in a vacuum of a light wave having a frequency of 5.3×10^{14} hertz. Express your answer in nanometers to the proper number of significant digits.

74. What is the frequency of a light wave having a wavelength of 5.00×10^{-7} meter in a vacuum? (1) 6.00×10^{-14} Hz (2) 6.00×10^{14} Hz (3) 6.00×10^{15} Hz (4) 6.00×10^{16} Hz

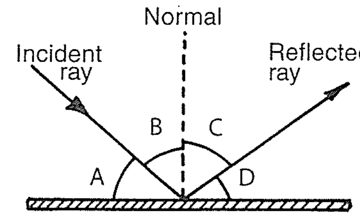
75. The following diagram shows parallel rays of light interacting with a barrier. Which phenomenon of light is illustrated?



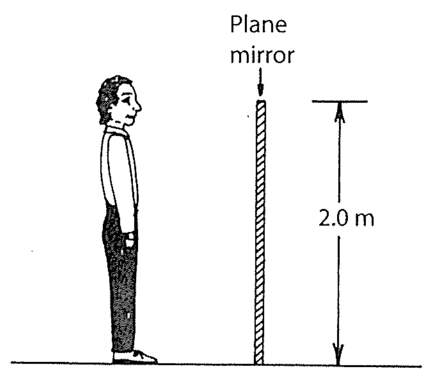
76. Which diagram best represents the reflection of object O in plane mirror M?



77. A ray is reflected from a surface, as shown in the diagram that follows. Which letter represents the angle of incidence?



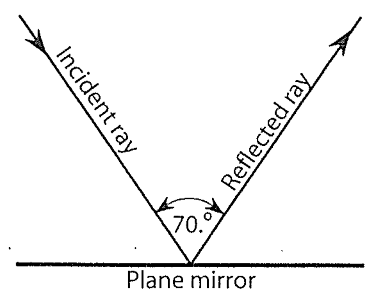
78. A tall person stands in front of a vertical plane mirror 2.0 meters high, as shown in the following diagram. A ray of light reflects off the mirror, allowing him to see his foot. Approximately how far up the mirror from the floor does this ray strike the mirror?



(1) 1.0 m (2) 2.0 m (3) 0.25 m (4) 0 m

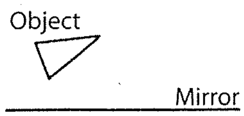
79. The image of an object is viewed in a plane mirror. What is the ratio of the object size to the image size? (1) 1:1 (2) 2:1 (3) 1:2 (4) 1:4

80. The following diagram represents a light ray being reflected from a plane mirror. The angle between the incident and reflected ray is 70.° What is the angle of incidence for this ray?



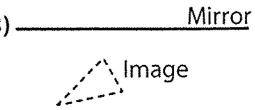
(1) 20.° (2) 35° (3) 55° (4) 70.°

81. An object is placed in front of a plane mirror as shown in the following diagram.

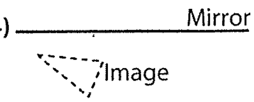


Which diagram best represents the image that is formed?

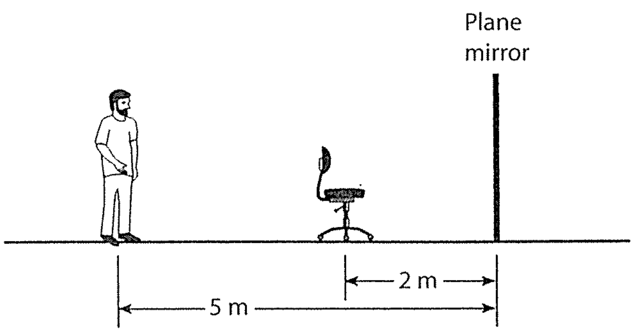
(1) 

(3) 

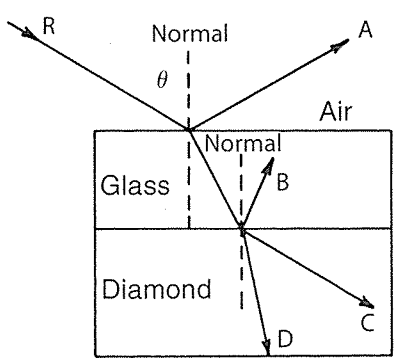
(2) 

(4) 

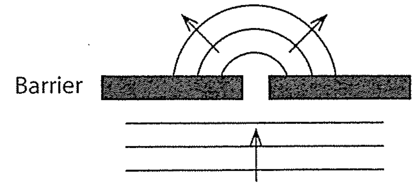
82. In the following diagram, a person is standing 5 meters from a plane mirror. The chair in front of the person is located 2 meters from the mirror. What is the distance between the person and the image he observes of the chair?



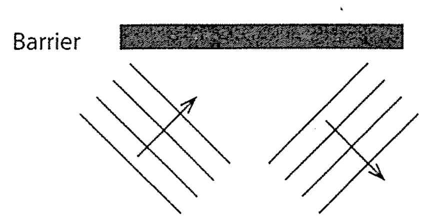
83. In the diagram that follows, ray R of monochromatic yellow light is incident upon a glass surface at an angle θ. Which resulting ray is *not* possible?



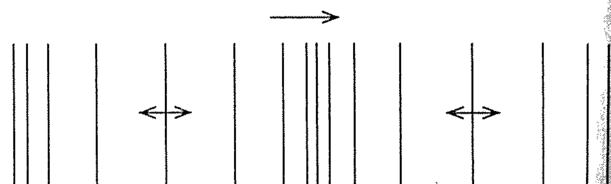
84. Which diagram best represents wave reflection?



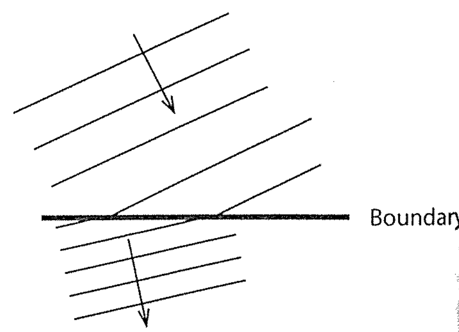
(1)



(2)



(3)



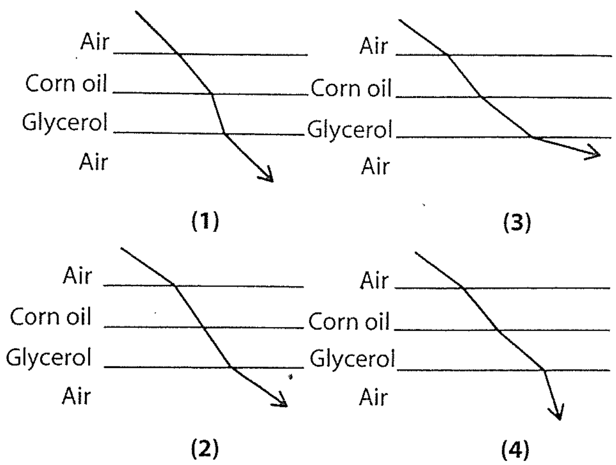
(4)

85. When a ray of light strikes a mirror perpendicular to its surface, what is the angle of reflection?

86. 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

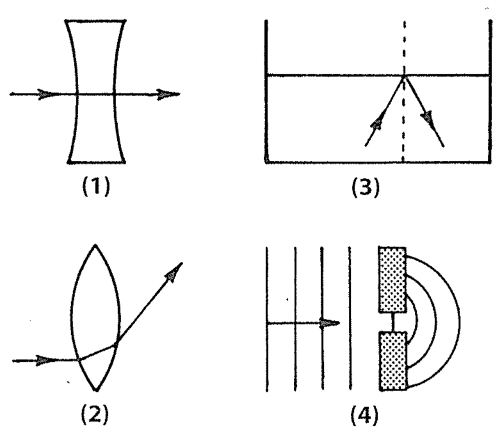
87. As a wave enters a new medium, there may be a change in the wave's (1) frequency (2) speed (3) period (4) phase

88. Which arrow best represents the path that a monochromatic ray of light travels as it passes through air, corn oil, glycerol and back into air?

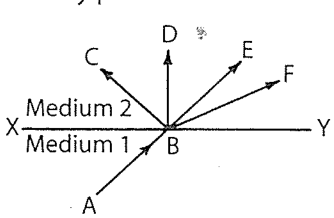


89. What occurs when light passes from water into flint glass? (1) Its speed decreases, its wavelength becomes shorter, and its frequency remains the same. (2) Its speed decreases, its wavelength becomes shorter, and its frequency increases. (3) Its speed increases, its wavelength becomes longer, and its frequency remains the same. (4) Its speed increases, its wavelength becomes longer, and its frequency decreases.

90. Which ray diagram best illustrates refraction?



91. 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?



92. A beam of monochromatic red light passes obliquely from air into water. Which characteristic of the light does *not* change? (1) direction (2) velocity (3) frequency (4) wavelength

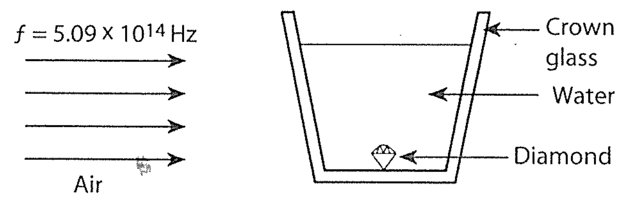
93. The speed of light in corn oil is the same as the speed of light in (1) diamond (2) flint glass (3) air (4) glycerol

94. If the speed of light in a medium is 2.00×10^8 meters per second, what is the absolute index of refraction for the medium?

95. In which medium is the wavelength of red light the shortest? (1) flint glass (2) crown glass (3) diamond (4) zircon

96. The frequency of a ray of light is 5.09×10^{14} hertz. What is the ratio of the speed of this ray in diamond to its speed in zircon?

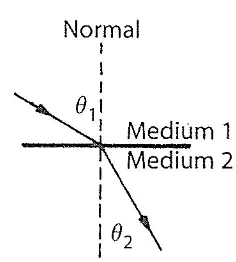
97. In the diagram that follows, monochromatic light having a frequency of 5.09×10^{14} hertz in air is about to travel through crown glass, water, and diamond. In which substance does the light travel at the slowest speed?



(not drawn to scale)

98. For a given angle of incidence, the greatest change in the direction of a light ray is produced when the light ray passes obliquely from air into (1) Lucite (2) glycerol (3) fused quartz (4) crown glass

99. The following diagram represents a wave traveling from medium 1 to medium 2.

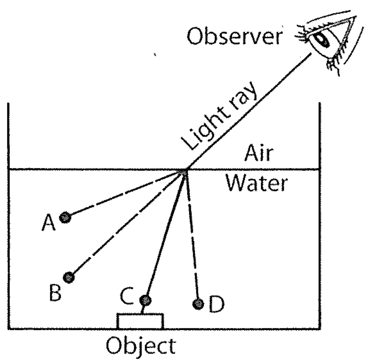


The relative index of refraction may be determined by calculating the ratio of (1) $\frac{\theta_1}{\theta_2}$ (2) $\frac{\sin\theta_2}{\sin\theta_1}$ (3) $\frac{\sin\theta_1}{\sin\theta_2}$ (4) $\frac{n_1}{n_2}$

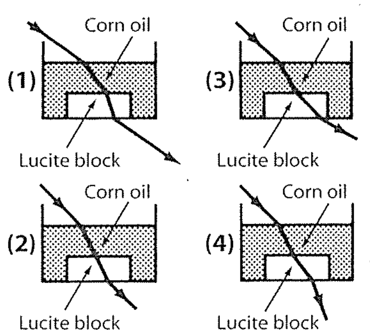
100. A ray of light in air is incident on a block of Lucite at an angle of 60.° from the normal. The angle of refraction of this ray in Lucite is closest to (1) 35° (2) 45° (3) 60.° (4) 75°

101. A beam of monochromatic yellow light passes from air into a tank of salt water. As more salt is dissolved in the water, the index of refraction of the liquid increases and the speed of the light in the liquid (1) decreases (2) increases (3) remains the same

102. In the following diagram, a person observes an object resting on the bottom of a tank of water. To the observer, the object appears to be at which point?



103. Which diagram shows the path that a monochromatic ray of light will travel as it passes through air, corn oil, Lucite, and back into air?



104. Which electromagnetic radiation has the shortest wavelength? (1) infrared (2) radio (3) gamma (4) ultraviolet

105. Which are *not* in the electromagnetic spectrum? (1) light waves (2) radio waves (3) sound waves (4) X rays

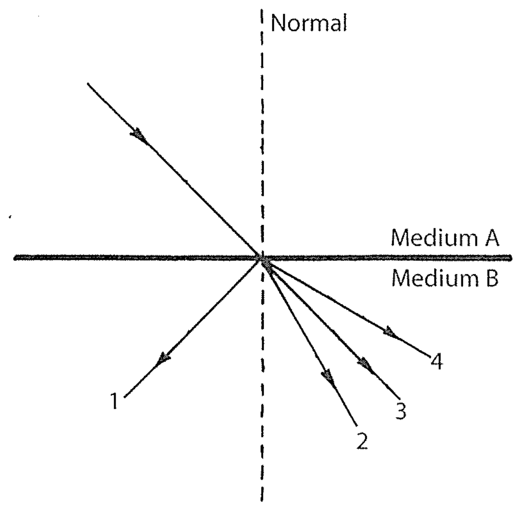
106. In a vacuum, all electromagnetic waves have the same (1) frequency (2) wavelength (3) speed (4) energy

107. A monochromatic beam of light with a frequency of 5.45×10^{14} hertz travels in a vacuum. What is the color of the light?

108. The wavelength of a typical AM radio wave is 3×10^{3} meters. Determine the order of magnitude of its frequency.

Base your answers to questions 109 through 112 on the information and diagram that follow.

When a ray of monochromatic light passes from medium A to medium B, its speed decreases.



109. Which arrow best represents the path of the ray in medium B?

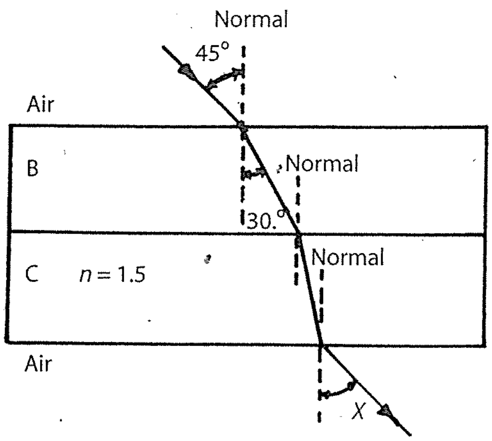
110. Compared to the frequency of the light in medium A, the frequency of the light in medium B is (1) lower (2) higher (3) the same

111. Compared to the wavelength of the light in medium A, the wavelength of the light in medium B is (1) shorter (2) longer (3) the same

112. According to information listed in the *Reference Tables for Physical Setting/Physics,* what could be the identity of substance B if medium A is corn oil?

Base your answers to questions 113 through 116 on the information and diagram that follow.

A ray of light having a frequency of 5.09×10^{14} hertz moves from air through substance B, through substance C, and back into air. The surfaces of substances B and C are parallel.



113. Determine the index of refraction of substance B.

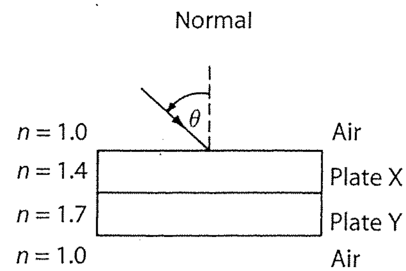
114. Determine the speed of light in substance C.

115. If the angle of incidence of the light ray in air is increased, the angle of refraction in substance B will (1) decrease (2) increase (3) remain the same

116. The measure of angle X is (1) less than 45° (2) greater than 45° (3) equal to 45°

Base your answers to questions 117 through 120 on the information and diagram that follow.

A ray of monochromatic light traveling in air and having a frequency of 5.09×10^{14} hertz is incident upon the surface of plate X. The values of n in the diagram represent absolute indices of refraction.



117. What is the relative index of refraction of the light going from plate X to plate Y? (1) $\frac{1.0}{1.7}$ (2) $\frac{1.0}{1.4}$ (3) $\frac{1.7}{1.4}$ (4) $\frac{1.4}{1.7}$

118. Determine the speed of the light ray in plate X.

119. Compared to angle θ, the angle of refraction of the light ray in plate X is (1) smaller (2) greater (3) the same

120. Compared to angle θ, the angle of refraction of the ray emerging from plate Y into air is (1) smaller (2) greater (3) the same