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 in air from approximately 4×10^{-7} to 7×10^{-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 formula $v = f\lambda$ 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 strikes 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 of different optical density obliquely. Figure 5-13 shows these rays as well as the wave fronts whose motion they represent.

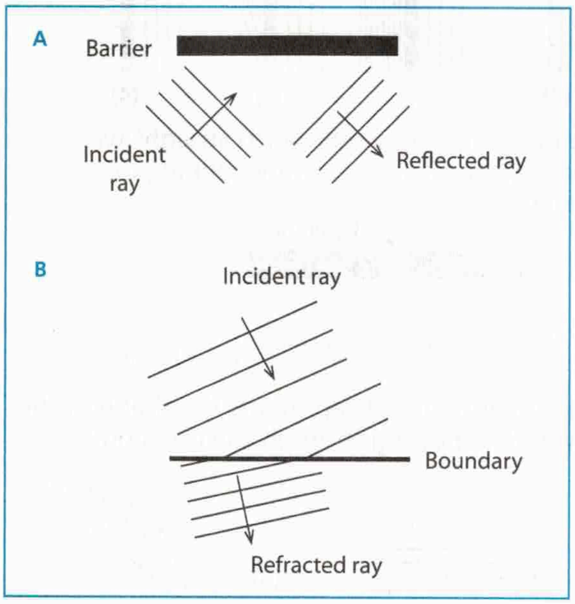


Figure 5-13. Reflected and refracted rays: **(A)** shows the direction of a reflected wave front at a barrier. **(B)** shows how a wave front changes at a boundary between air and a denser medium.

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.

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, 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.

R

$$\theta_i = \theta_r$$

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.

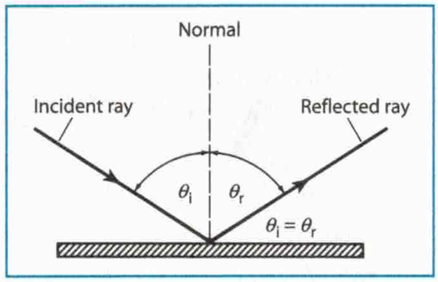


Figure 5-14. The law of reflection: The angle of incidence equals the angle of reflection.

Refraction of Light

Waves travel at different speeds in different media, so when a wave travels from one medium to another medium of different optical density, 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 travel. Figure 5-15 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.

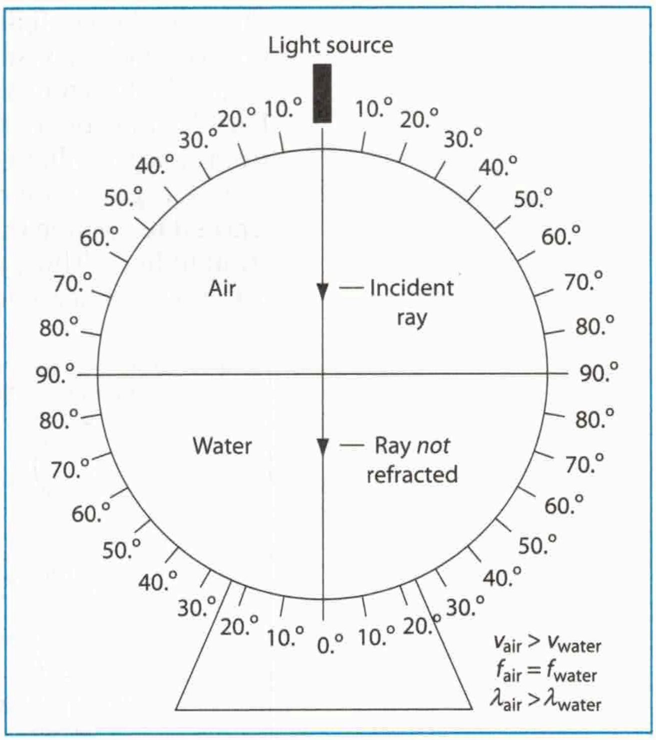


Figure 5-15. Refraction of light: A light ray passes from a less optically dense medium, air, into a more optically dense medium, water, at an angle of incidence of 0°.

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 5-16A. 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 5-16B. Upon entering the less dense medium,

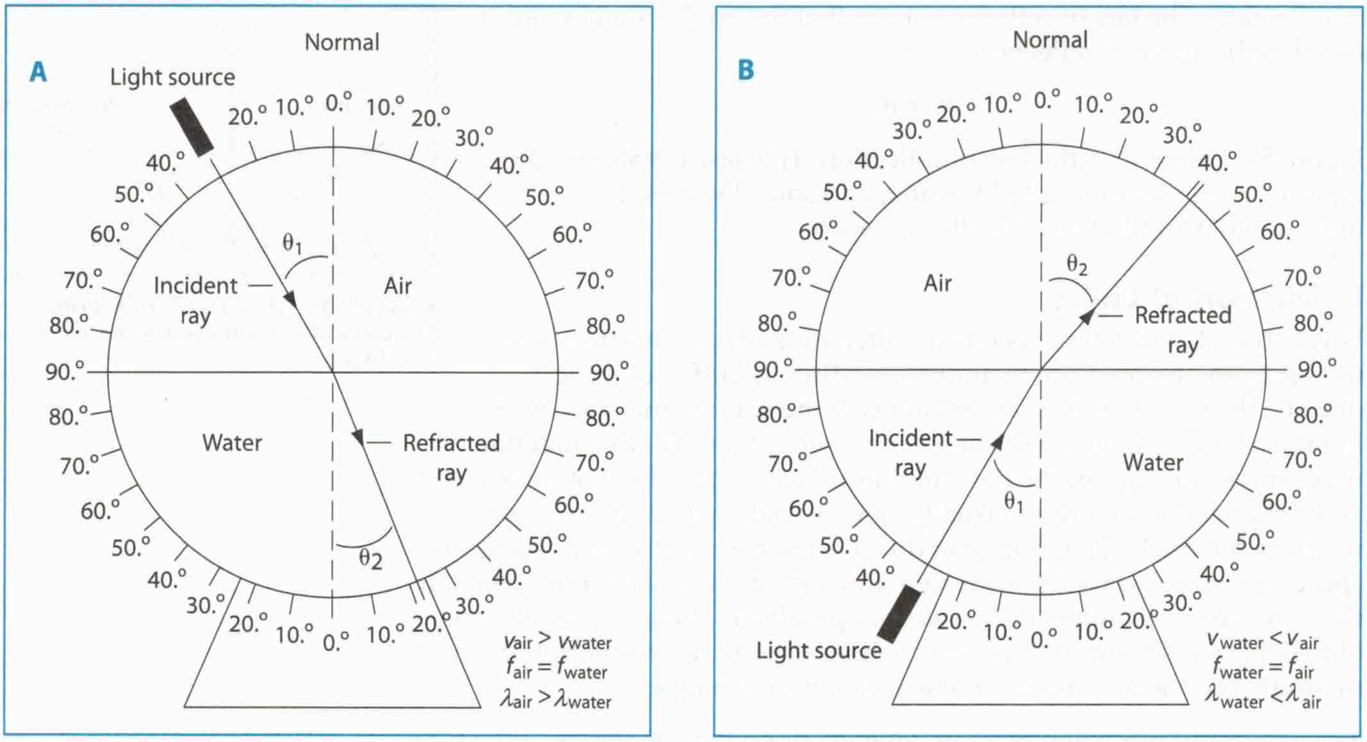


Figure 5-16. Additional examples of refraction of light: (A) A light ray passes obliquely from a less optically dense medium, air, into a more optically dense medium, water, at an angle of incidence of 30°. The ray is refracted toward the normal. (B) A light ray passes obliquely from a more optically dense medium, water, into a less optically dense medium, air, at an angle of incidence of 30°. The ray is refracted away from the normal.

the ray's frequency does not change, but its wavelength increases as its speed increases.

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 5-17. 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.

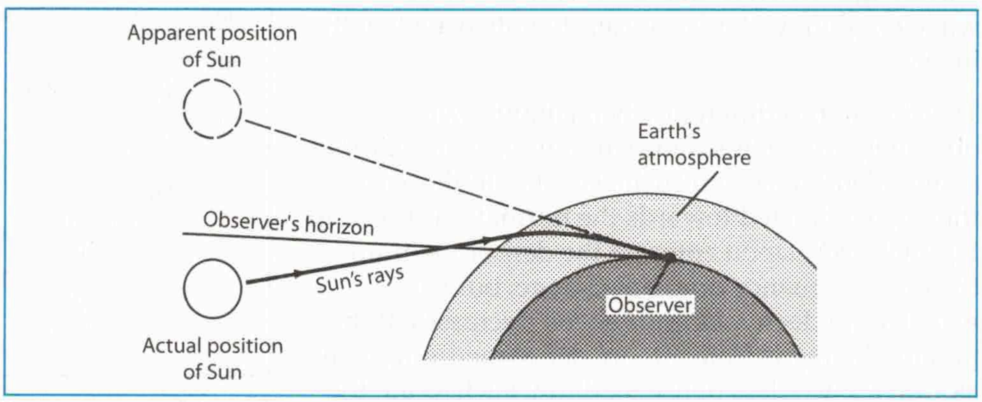


Figure 5-17. Curvature of the Sun's rays by refraction in Earth's atmosphere (not drawn to scale)

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 5-18. 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.

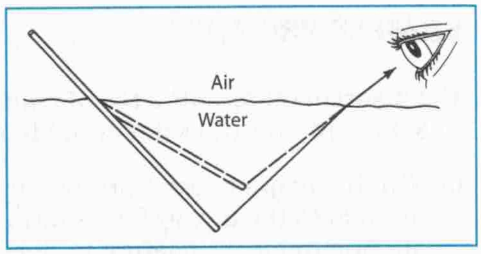


Figure 5-18. Refraction of light: Light rays from the tip of the straw are bent away from the normal as they emerge from the water. The effect is to make the straw appear to bend at the surface of the water.

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.

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

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.

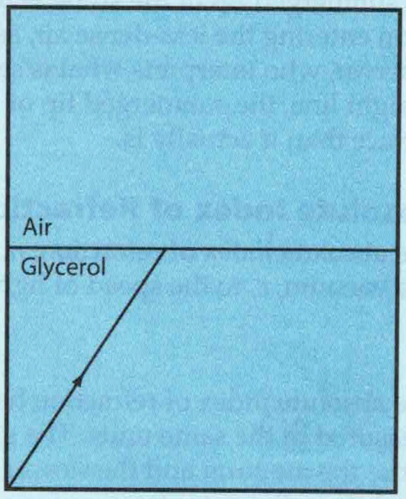
Snell's law can be rearranged in this way.

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

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 glycerol into air.

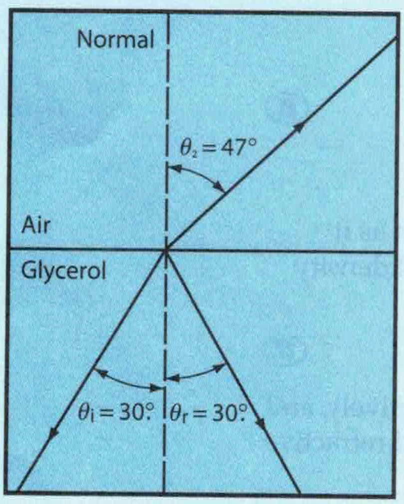


(a) On the diagram, use a protractor and a straight edge to draw a normal to the glycerol-air interface. Label the angle of incidence θ_1. Determine its measure to the nearest degree.
(b) Calculate the angle of refraction.
(c) On the diagram, draw the refracted light ray, label the angle of refraction 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, use a protractor and a straight edge to draw the reflected ray, label the angle of reflection θ_r, and indicate its measure to the nearest degree.
(e) Calculate the speed of the light in glycerol.
(f) Calculate the wavelength of the light in air in nanometers.
(g) Calculate the wavelength of the light in glycerol in nanometers.

SOLUTION: Identify the known and unknown values.

Known	Unknown
$f = 5.09 \times 10^{14}$ Hz	$\theta_1 = ?°$
$n_1 = 1.47$ (glycerol)	$\theta_2 = ?°$
$n_2 = 1.00$ (air)	$\theta_r = ?°$
$v_2 = c = 3.00 \times 10^8$ m/s	$v_1 = ?$ m/s (glycerol)
	$\lambda_2 = ?$ nm (air)
	$\lambda_1 = ?$ nm (glycerol)

(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 formula $n_1 \sin\theta_1 = n_2 \sin\theta_2$. 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.

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

$$\theta_2 = 47°$$

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

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

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

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

Substitute the known values and solve.

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

(f) Solve the formula $v = f\lambda$ for the wavelength, λ.

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

Substitute the known values and solve.

$$\lambda_2 = \frac{3.00 \times 10^8 \text{ m/s}}{5.09 \times 10^{14} \text{ Hz}}$$

$$\lambda_2 = 5.89 \times 10^{-7} \text{ m}$$

$$\lambda_2 = 589 \text{ nm}$$

(g) Write the formula relating absolute indices of refraction and wavelengths.

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

Solve the equation for λ_1.

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

Substitute the known values and solve.

$$\lambda_1 = \frac{(1.00)(589 \text{ nm})}{1.47} = 401 \text{ nm}$$

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 5-19. 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. Do not confuse electromagnetic radio waves with longitudinal sound waves.

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.

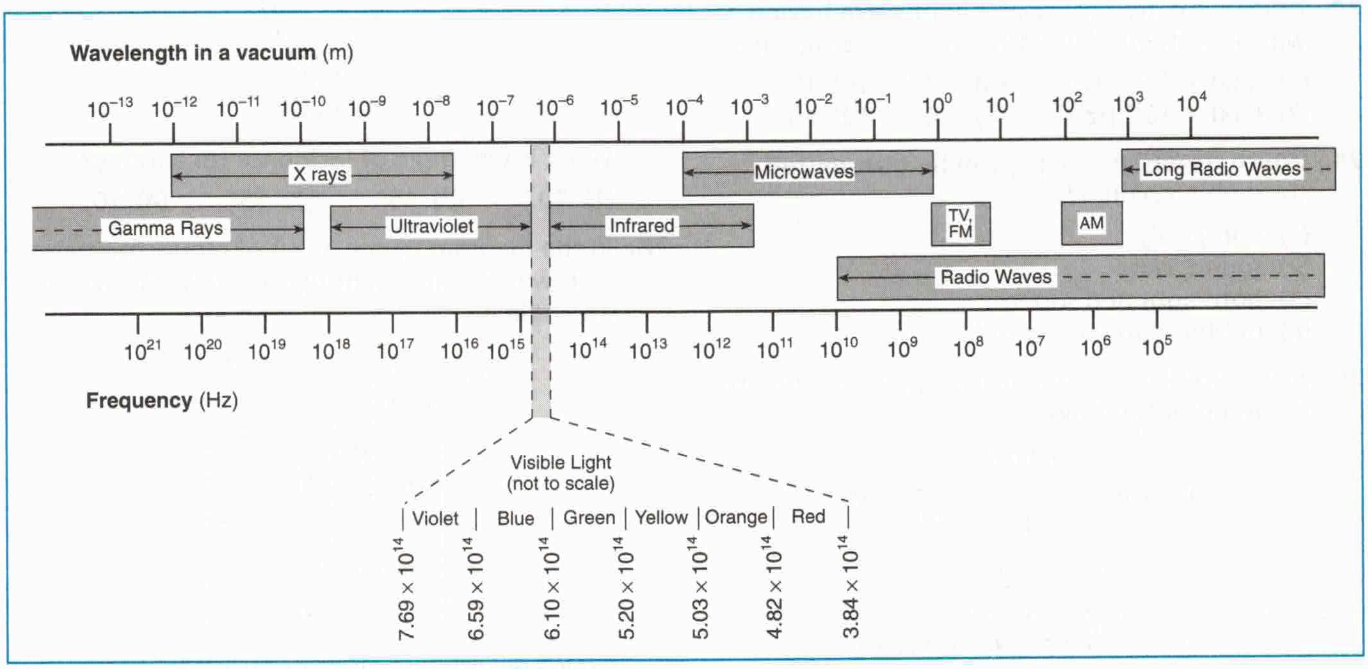


Figure 5-19. The electromagnetic spectrum Ⓡ

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 atmosphere 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. Calculate the wavelength in a vacuum of a light wave having a frequency of 5.3×10^{14} hertz. Express the wavelength in nanometers.

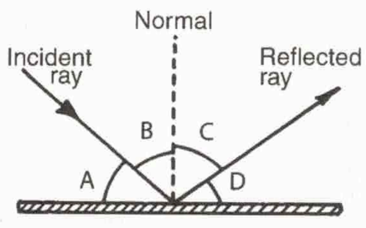
74. What is the frequency of a light wave having a wavelength of 5.00×10^{-7} meter in a vacuum?

(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. Which form(s) of energy can be transmitted through a vacuum?

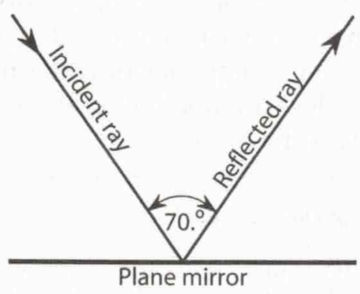
(1) light, only
(2) sound, only
(3) both light and sound
(4) neither light nor sound

76. A ray is reflected from a surface, as shown in the diagram that follows.



Which letter represents the angle of incidence?

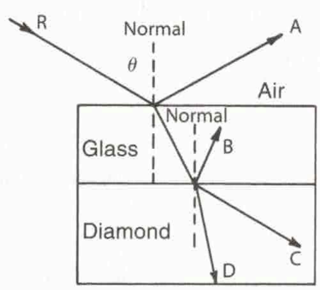
77. The diagram below represents a light ray being reflected from a plane mirror. The angle between the incident and reflected ray is 70°.



What is the angle of incidence for this ray?

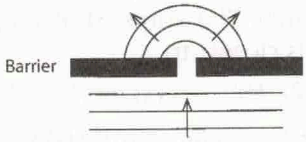
(1) 20.° (2) 35° (3) 55° (4) 70.°

78. In the diagram below, ray R of monochromatic yellow light is incident upon a glass surface at an angle θ.

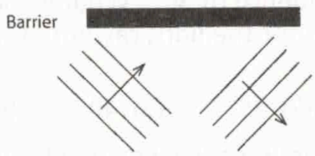


Which resulting ray is *not* possible?

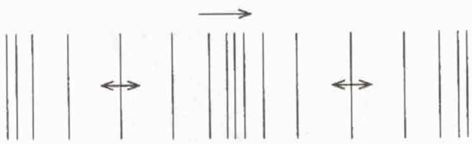
79. Which diagram best represents wave reflection?



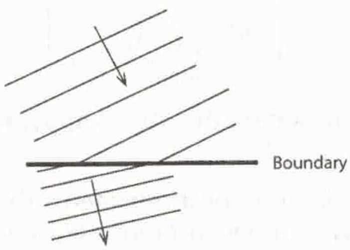
(1)



(2)



(3)



(4)

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

81. A ray of light passes from air into glass at an angle of incidence of 0°. Which statement best describes the speed and direction of the light ray as it passes into the glass?

(1) Only speed changes.
(2) Only direction changes.
(3) Both speed and direction change.
(4) Neither speed nor direction changes.

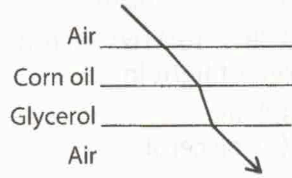
82. As a wave enters a new medium, there may be a change in the wave's

(1) frequency
(2) speed
(3) period
(4) phase

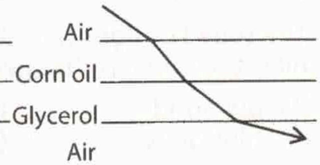
83. The speed of a ray of light traveling through a substance having an absolute index of refraction of 1.1 is

(1) 1.1×10^8 s
(2) 2.7×10^8 s
(3) 3.0×10^8 s
(4) 3.3×10^8 s

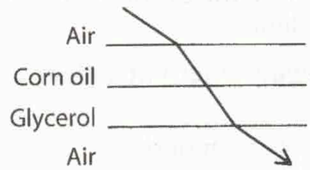
84. Which arrow best represents the path that a monochromatic ray of light ($f = 5.09 \times 10^{14}$ Hz) travels as it passes through air, corn oil, glycerol, and back into air?



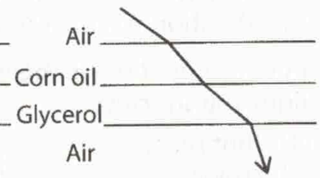
(1)



(3)



(2)

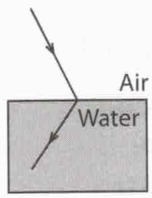


(4)

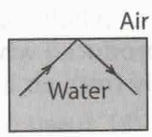
85. What happens to the speed, wavelength, and frequency of light when it passes from water into flint glass?

(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.

86. Which ray diagram best represents the phenomenon of refraction?



(1)



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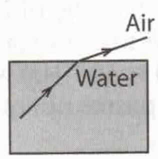
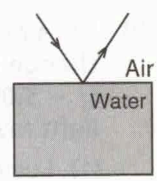
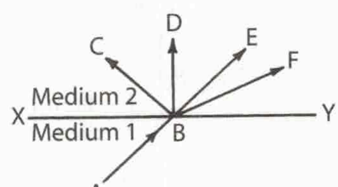


(3)



(4)

87. In the diagram below, 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?