Chapter 22

Reflection and Refraction of Light

ANSWERS TO MULTIPLE CHOICE QUESTIONS

1. The index of refraction of a material in which light has speed v is $n = c/v = c/\lambda f$. Thus,

$$\frac{n_{\text{liquid}}}{n_{\text{air}}} = \frac{c/(\lambda_{\text{liquid}} f)}{c/(\lambda_{\text{air}} f)} = \frac{\lambda_{\text{air}}}{\lambda_{\text{liquid}}} \quad \text{and} \quad n_{\text{liquid}} = \left(\frac{\lambda_{\text{air}}}{\lambda_{\text{liquid}}}\right) n_{\text{air}} = \left(\frac{495 \text{ nm}}{434 \text{ nm}}\right)(1.00) = 1.14$$

so the correct choice is (c).

2. The critical angle as light passes from medium 1 into medium 2 is $\theta_c = \sin^{-1}(n_2/n_1)$, so as light is incident on crown glass ($n_2 = 1.52$) from carbon disulfide ($n_1 = 1.63$),

$$\theta_c = \sin^{-1}\left(\frac{1.52}{1.63}\right) = 68.8°$$

and choice (b) is the correct response.

3. The energy of a photon is $E = hf = hc/\lambda$. Thus, if n 800-nm photons have the same energy as four 200-nm photons, it is necessary that

$$n(hc/800 \text{ nm}) = 4(hc/200 \text{ nm}) \quad \text{or} \quad n = 4(800 \text{ nm}/200 \text{ nm}) = 16$$

Therefore, the correct answer is (e).

4. Observe that the angle of refraction is greater than the angle of incidence as the light ray passes from medium 1 into medium 2. Thus, the speed of light increases as the light crosses the boundary between these materials. Since $n = c/v$, the index of refraction of medium 2 is less than that of medium 1, or $n_1 > n_2$. The correct choice is (d).

5. Total internal reflection will occur when light, in attempting to go from a medium with one index of refraction n_1 into a second medium where it travels faster than in the first medium (or where $n_2 < n_1$), strikes the surface at an angle of incidence greater than or equal to the critical angle. The correct choice is (b).

6. Water and air have different indices of refraction, with $n_{\text{water}} \approx 4n_{\text{air}}/3$. In passing from one of these media into the other, light will be refracted (deviated in direction) unless the angle of incidence is zero (in which case, the angle of refraction is also zero). Thus, rays B and D cannot be correct. In refraction, the incident ray and the refracted ray are never on the same side of the line normal to the surface at the point of contact, so ray A cannot be correct. Also in refraction, the ray makes a smaller angle with the normal in the medium having the highest index of refraction. Therefore, ray E cannot be correct, leaving only ray C as a likely path. Choice (c) is the correct answer.

7. When light is in water, the relationships between the values of its frequency, speed, and wavelength to the values of the same quantities in air are

$$f_{\text{water}} = f_{\text{air}}, \quad \lambda_{\text{water}} = \left(\frac{n_{\text{air}}}{n_{\text{water}}}\right)\lambda_{\text{air}} \approx \frac{3}{4}\lambda_{\text{air}}, \quad \text{and} \quad v_{\text{water}} = \left(\frac{n_{\text{air}}}{n_{\text{water}}}\right) v_{\text{air}} = \left(\frac{3}{4}\right) c$$

Therefore, only choice (b) is a completely true statement.

8. In a dispersive medium, the index of refraction is largest for the shortest wavelength. Thus, the violet light will be refracted (or bent) the most as it passes through a surface of the crown glass, making (a) the correct choice.

9. For any medium, other than vacuum, the index of refraction for red light is slightly lower than that for blue light. This means that when light goes from vacuum (or air) into glass, the red light deviates from its original direction less than does the blue light. Also, as the light reemerges from the glass into vacuum (or air), the red light again deviates less than the blue light. If the two surfaces of the glass are parallel to each other, the red and blue rays will emerge traveling parallel to each other but displaced laterally from one another. The sketch that best illustrates this process is C, so choice (c) is the best answer.

ANSWERS TO EVEN NUMBERED CONCEPTUAL QUESTIONS

2. (a) From Snell's law, $\sin\theta_2 = (n_1/n_2)\sin\theta_1$. Thus, if $n_2 < n_1$, then $\sin\theta_2 > \sin\theta_1$ and $\theta_2 > \theta_1$, so the ray refracts away from the normal.

(b) The index of refraction is defined as $n = c/v = c/\lambda f$. The wavelength may then be written as $\lambda = c/nf = (c/f)/n = \lambda_0/n$, where λ_0 is the wavelength of the light in vacuum. Thus, as the ray moves into a medium of lower index of refraction, the wavelength will increase.

(c) The frequency at which wavefronts move away from a boundary equals the frequency with which they arrive at the boundary. That is, the frequency of the light stays the same as it moves between the two materials.

4. A mirage occurs when light changes direction as it moves between batches of air having different indices of refraction. The different indices of refraction occur because the air has different densities at different temperatures. Two images are seen: one from a direct path from the object to you, and the second arriving by rays originally heading toward Earth but refracted to your eye. On a hot day, the Sun makes the surface of asphalt hot, so the air is hot directly above it, becoming cooler as one moves higher into the sky. The "water" we see far in front of us is an image of the blue sky. Adding to the effect is the fact that the image shimmers as the air changes in temperature, giving the appearance of moving water.

8. The index of refraction of water is 1.333, quite different from that of air, which has an index of refraction of about 1. The boundary between the air and water is therefore easy to detect, because of the differing refraction effects above and below the boundary. (Try looking at a glass half full of water.) The index of refraction of liquid helium, however, happens to be much closer to that of air. Consequently, the refractive differences above and below the helium-air boundary are harder to see.

PROBLEM SOLUTIONS

22.5 The speed of light in a medium with index of refraction n is $v = c/n$, where c is its speed in vacuum.

(a) For water, $n = 1.333$, and $v = \dfrac{3.00\times10^8 \text{ m/s}}{1.333} = \boxed{2.25\times10^8 \text{ m/s}}$.

(b) For crown glass, $n = 1.52$, and $v = \dfrac{3.00\times10^8 \text{ m/s}}{1.52} = \boxed{1.97\times10^8 \text{ m/s}}$.

(c) For diamond, $n = 2.419$, and $v = \dfrac{3.00\times10^8 \text{ m/s}}{2.419} = \boxed{1.24\times10^8 \text{ m/s}}$.

22.7 From Snell's law, $n_2 \sin\theta_2 = n_1 \sin\theta_1$. Thus, when $\theta_1 = 45.0°$ and the first medium is air ($n_1 = 1.00$), we have $\sin\theta_2 = (1.00)\sin 45.0°/n_2$.

(a) For quartz, $n_2 = 1.458$, and $\theta_2 = \sin^{-1}\left(\dfrac{(1.00)\sin 45.0°}{1.458}\right) = \boxed{29.0°}$.

(b) For carbon disulfide, $n_2 = 1.628$, and $\theta_2 = \sin^{-1}\left(\dfrac{(1.00)\sin 45.0°}{1.628}\right) = \boxed{25.7°}$.

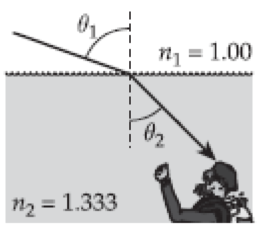
(c) For water, $n_2 = 1.333$, and $\theta_2 = \sin^{-1}\left(\dfrac{(1.00)\sin 45.0°}{1.333}\right) = \boxed{32.0°}$.

22.9 $n_1 \sin\theta_1 = n_2 \sin\theta_2$

$\sin\theta_1 = 1.333 \sin 45.0°$

$\theta_1 = \sin^{-1}(1.333 \sin 45.0°) = 70.5°$

Thus, the sun appears to be $\boxed{19.5° \text{ above the horizontal}}$.



22.15 The index of refraction of zircon is $n = 1.923$.

(a) $v = \dfrac{c}{n} = \dfrac{3.00\times10^8 \text{ m/s}}{1.923} = \boxed{1.56\times10^8 \text{ m/s}}$

(b) The wavelength in the zircon is $\lambda_n = \dfrac{\lambda_0}{n} = \dfrac{632.8 \text{ nm}}{1.923} = \boxed{329.1 \text{ nm}}$.

(c) The frequency is $f = \dfrac{v}{\lambda_n} = \dfrac{c}{\lambda_0} = \dfrac{3.00\times10^8 \text{ m/s}}{632.8\times10^{-9} \text{ m}} = \boxed{4.74\times10^{14} \text{ Hz}}$.

22.37 When light attempts to cross a boundary from one medium of refractive index n_1 into a new medium of refractive index $n_2 < n_1$, total internal reflection will occur if the angle of incidence exceeds the critical angle given by $\theta_c = \sin^{-1}(n_2/n_1)$.

(a) If $n_1 = 1.53$ and $n_2 = n_{air} = 1.00$, then $\theta_c = \sin^{-1}\left(\dfrac{1.00}{1.53}\right) = \boxed{40.8°}$.

(b) If $n_1 = 1.53$ and $n_2 = n_{water} = 1.333$, then $\theta_c = \sin^{-1}\left(\dfrac{1.333}{1.53}\right) = \boxed{60.6°}$.