# CHAPTER 26 | *THE REFRACTION OF LIGHT: LENSES AND OPTICAL INSTRUMENTS*

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5. ***REASONING*** Since the light will travel in glass at a constant speed $v$, the time it takes to pass perpendicularly through the glass is given by $t = d/v$, where $d$ is the thickness of the glass. The speed $v$ is related to the vacuum value $c$ by Equation 26.1: $n = c/v$.

***SOLUTION*** Substituting for $v$ from Equation 26.1 and substituting values, we obtain

$$t = \frac{d}{v} = \frac{nd}{c} = \frac{(1.5)\left(4.0\times10^{-3}\text{ m}\right)}{3.00\times10^{8}\text{ m/s}} = \boxed{2.0\times10^{-11}\text{ s}}$$

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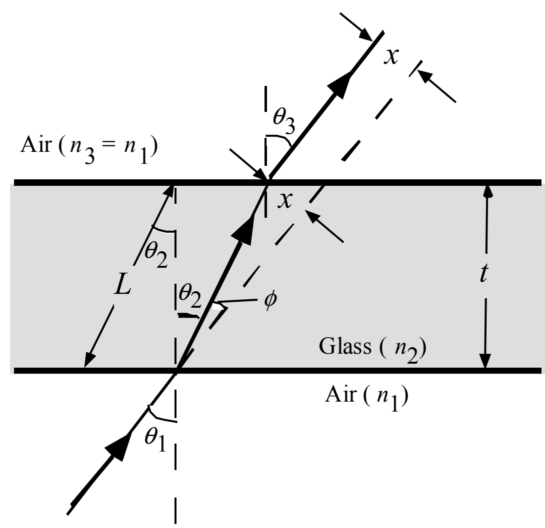
17. The drawing at the right shows the geometry of the situation using the same notation as that in Figure 26.7. In addition to the text's notation, let $t$ represent the thickness of the pane, let $L$ represent the length of the ray in the pane, let $x$ (shown twice in the figure) equal the displacement of the ray, and let the difference in angles $\theta_1 - \theta_2$ be given by $\phi$.




We wish to find the amount $x$ by which the emergent ray is displaced relative to the incident ray. This can be done by applying Snell's law at each interface, and then making use of the geometric and trigonometric relations in the drawing.

***SOLUTION*** If we apply Snell's law (see Equation 26.2) to the bottom interface we obtain $n_1 \sin\theta_1 = n_2 \sin\theta_2$. Similarly, if we apply Snell's law at the top interface where the ray emerges, we have $n_2 \sin\theta_2 = n_3 \sin\theta_3 = n_1 \sin\theta_3$. Comparing this with Snell's law at the bottom face, we see that $n_1 \sin\theta_1 = n_1 \sin\theta_3$, from which we can conclude that $\theta_3 = \theta_1$. Therefore, the emerging ray is parallel to the incident ray.

From the geometry of the ray and thickness of the pane, we see that $L\cos\theta_2 = t$, from which it follows that $L = t/\cos\theta_2$. Furthermore, we see that $x = L\sin\phi = L\sin\left(\theta_1 - \theta_2\right)$. Substituting for $L$, we find

$$x = L\ \sin(\theta_1 - \theta_2) = \frac{t\ \sin(\theta_1 - \theta_2)}{\cos\ \theta_2}$$

Before we can use this expression to determine a numerical value for $x$, we must find the value of $\theta_2$. Solving the expression for Snell's law at the bottom interface for $\theta_2$, we have

$$\sin\theta_2 = \frac{n_1\ \sin\theta_1}{n_2} = \frac{(1.000)\ (\sin 30.0°)}{1.52} = 0.329 \qquad \text{or} \qquad \theta_2 = \sin^{-1}\ 0.329 = 19.2°$$

Therefore, the amount by which the emergent ray is displaced relative to the incident ray is

$$x = \frac{t\ \sin(\theta_1 - \theta_2)}{\cos\ \theta_2} = \frac{(6.00\text{ mm})\sin(30.0° - 19.2°)}{\cos 19.2°} = \boxed{1.19\text{ mm}}$$

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31. ***REASONING*** Brewster's law (Equation 26.5: $\tan\theta_B = n_2/n_1$) relates the angle of incidence $\theta_B$ at which the reflected ray is completely polarized parallel to the surface to the indices of refraction $n_1$ and $n_2$ of the two media forming the interface. We can use Brewster's law for light incident from above to find the ratio of the refractive indices $n_2/n_1$. This ratio can then be used to find the Brewster angle for light incident from below on the same interface.

***SOLUTION*** The index of refraction for the medium in which the incident ray occurs is designated by $n_1$. For the light striking from above $n_2/n_1 = \tan\theta_B = \tan 65.0° = 2.14$. The same equation can be used when the light strikes from below if the indices of refraction are interchanged

$$\theta_B = \tan^{-1}\left(\frac{n_1}{n_2}\right) = \tan^{-1}\left(\frac{1}{n_2/n_1}\right) = \tan^{-1}\left(\frac{1}{2.14}\right) = \boxed{25.0°}$$

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111. ***REASONING*** The optical arrangement is similar to that in Figure 26.26. We begin with the thin-lens equation, [Equation 26.6: $(1/d_o) + (1/d_i) = (1/f)$]. Since the distance between the moon and the camera is so large, the object distance $d_o$ is essentially infinite, and $1/d_o = 1/\infty = 0$. Therefore the thin-lens equation becomes $1/d_i = 1/f$ or $d_i = f$. The diameter of the moon's imagine on the slide film is equal to the image height $h_i$, as given by the magnification equation (Equation 26.7: $h_i/h_o = -d_i/d_o$).
When the slide is projected onto a screen, the situation is similar to that in Figure 26.27. In this case, the thin-lens and magnification equations can be used in their usual forms.

***SOLUTION***
a. Solving the magnification equation for $h_i$ gives

$$h_i = -h_o \frac{d_i}{d_o} = (-3.48 \times 10^6 \text{ m})\left(\frac{50.0 \times 10^{-3} \text{ m}}{3.85 \times 10^8 \text{ m}}\right) = -4.52 \times 10^{-4} \text{ m}$$

The diameter of the moon's image on the slide film is, therefore, $\boxed{4.52 \times 10^{-4} \text{ m}}$.

b. From the magnification equation, $h_i = -h_o\left(d_i / d_o\right)$. We need to find the ratio $d_i / d_o$. Beginning with the thin-lens equation, we have

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \quad \text{or} \quad \frac{1}{d_o} = \frac{1}{f} - \frac{1}{d_i} \quad \text{which leads to} \quad \frac{d_i}{d_o} = \frac{d_i}{f} - \frac{d_i}{d_i} = \frac{d_i}{f} - 1$$

Therefore,

$$h_i = -h_o\left(\frac{d_i}{f} - 1\right) = -(4.52 \times 10^{-4} \text{ m})\left(\frac{15.0 \text{ m}}{110.0 \times 10^{-3} \text{ m}} - 1\right) = -6.12 \times 10^{-2} \text{ m}$$

The diameter of the image on the screen is $\boxed{6.12 \times 10^{-2} \text{ m}}$.

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