### Key Concepts

Chapter 10

Refraction

Snell's law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$

### Takeaways

Complex problems can be solved with a little bit of ingenuity. Snell's law is a simple concept and is likely to be one of the first steps in any problem dealing with the refraction of light. When light passes through multiple layers, the final angle can be determined merely by comparing the first and final media.

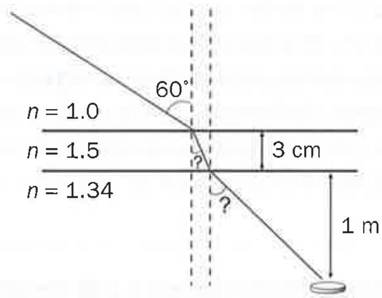
### Things to Watch Out For

Light reflects off of media boundaries, too. Because of this, the refracted ray of light is less intense than the incident ray. Different wavelengths also have slightly different indices of refraction—this difference is what causes dispersion.

## Snell's Law

A gold doubloon rests on a rock 1 m below the surface of the ocean. A glass-bottom boat passes over the area, and a passenger spots the coin at a 60° angle from the normal. If the glass layer is 3 cm thick, find the apparent depth of the coin. The indices of refraction are as follows: air, $n = 1$; glass, $n = 1.5$; salt water, $n = 1.34$.

**1) Sketch the situation.**




Light bends toward the normal when going from a medium with a lower refractive index to one with a higher refractive index.

***Remember:*** *Our sketch need not be to scale; we use it to approximate what is going on and to keep track of the important data.*

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**2) Apply Snell's law.**

Snell's law shows that light bends towards the normal (decreasing the angle) when it enters a medium with a higher refractive index. Here, we "plug-and-chug" through the formula to find the angles of light entry and exit for the two other substances.

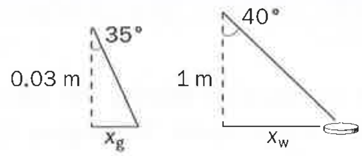
$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$
$$n_{air} \sin (\theta_a) = n_{glass} \sin (\theta_g)$$
$$(1) \sin 60° = (1.5) \sin (\theta_g)$$
$$\frac{(1) \sin 60°}{1.5} = \sin \theta_g \rightarrow \sin^{-1} 0.577 = \theta_g \approx 35°$$
$$n_{glass} \sin(\theta_g) = n_{water} \sin(\theta_w)$$
$$\frac{(1.5) \sin 35°}{1.34} = \sin \theta_w \rightarrow \sin^{-1} 0.642 = \theta_w \approx 40°$$

*OR*

To do this more quickly, realize that when light passes through multiple layers, the final angle can be determined merely by comparing the first and final media. The glass in this example alters the distance that the light travels in the $x$-direction but has no bearing on the final angle, because the light enters and exits the glass at the same angle.

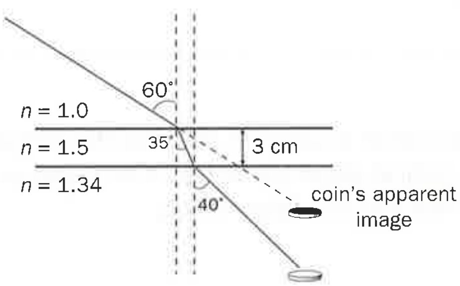
$$n_{air} \sin(\theta_a) = n_{water} \sin(\theta_w)$$
$$(1) \sin 60^\circ = (1.34) \sin(\theta_w)$$
$$\frac{[(1) \sin 60^\circ]}{1.34} = \sin \theta_w \rightarrow \sin^{-1} 0.646 = \theta_w \approx 40^\circ$$

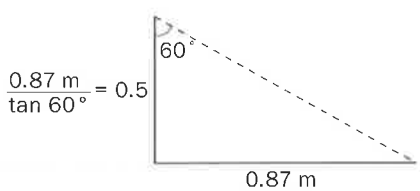
**3) Use trigonometry to determine how far the light goes.**




We know the thickness and depth of the glass and water, respectively, so we can use that information to determine how far the coin is from the ray of light the passenger sees. Light travels through a total of three media, but the distance of the observer from the glass doesn't actually matter. As long as he is looking 60° from the normal, he will see the coin. The trigonometry here is direct, using the relationship tan $\theta$ = opposite/adjacent or, in this case, $\frac{x}{y}$. The triangle in the glass, then, is $\tan 35^\circ = \frac{x_g}{0.03}$, and $x_g \approx 0.02$ m. The triangle in the water is solved the same way, and $x_w = 0.85$ m. The ray of light escapes the water and glass 0.87 meters from the coin.

**4) Find the object's image.**




When the passenger sees the coin, his brain interprets light as a straight line. In other words, his brain doesn't consider the bending of light due to the refractive indices, and he perceives the coin to be closer than it actually is. We previously determined the **X** component of the light ray to be 0.87 m. The observer sees the coin at a 60° angle from the normal, so set up a new triangle with this angle. We are trying to find the apparent depth of the coin—the **Y** component of this triangle. Solving $\tan 60^\circ = \frac{0.87}{y}$ gives us $y = 0.50$ m.

## Similar Questions

1) A firefighter shines her flashlight through a smoky room at a 45° angle to a window. What angle does the beam of light make with the pane of glass on the outside? The indices of refraction are as follows: air, $n = 1$; glass, $n = 1.5$; smoke, $n = 1.1$.
2) A piece of gallium phosphide is frozen in ice. A beam of light is directed downward through the ice-gallium phosphide boundary at a 25° angle from the normal. The light emerges from the gallium phosphide 12.25 mm away from where it would have, had the solid been pure ice. Find the thickness of the gallium phosphide layer. Gallium phosphide has the highest known optical density (3.5), and ice has the third lowest (1.31).
3) A jeweler is appraising the stone on a ring. He aims a beam of light 35° from the normal at a flat edge of the gem. What angle would he observe in the gem if the stone were diamond ($n = 2.4$)? What angle would he observe if the stone were zircon ($n = 1.9$)?