Which of the rays refracts only once? Explain. Use a ray diagram in your answer.

Applying Inquiry Skills

6. Design an experiment to determine a relationship between the index of refraction of salt water and the concentration of a salt solution. Express the relationship in the form of a graph.

9.6 Total Internal Reflection

When light travels from one medium to another in which its speed changes, some of the light is reflected and some is refracted. When the light originates in the optically denser medium, for example from glass to air, the amount of reflection can be greater than the amount of refraction.

As the angle of incidence increases, the intensity of a reflected ray becomes progressively stronger and the intensity of a refracted ray progressively weaker. As the angle of incidence increases, the angle of refraction increases, eventually reaching a maximum of 90°. Beyond this point, there is no refracted ray at all, and all the incident light is reflected at the boundary, back into the optically denser medium (**Figure 1**). This phenomenon is called **total internal reflection**. It can occur only when light rays travel in the optically denser medium toward a medium in which the speed of the light increases, that is, when the angle of refraction is greater than the angle of incidence.

total internal reflection: the reflection of light in an optically denser medium; it occurs when the angle of incidence in the more dense medium is equal to or greater than a certain critical angle

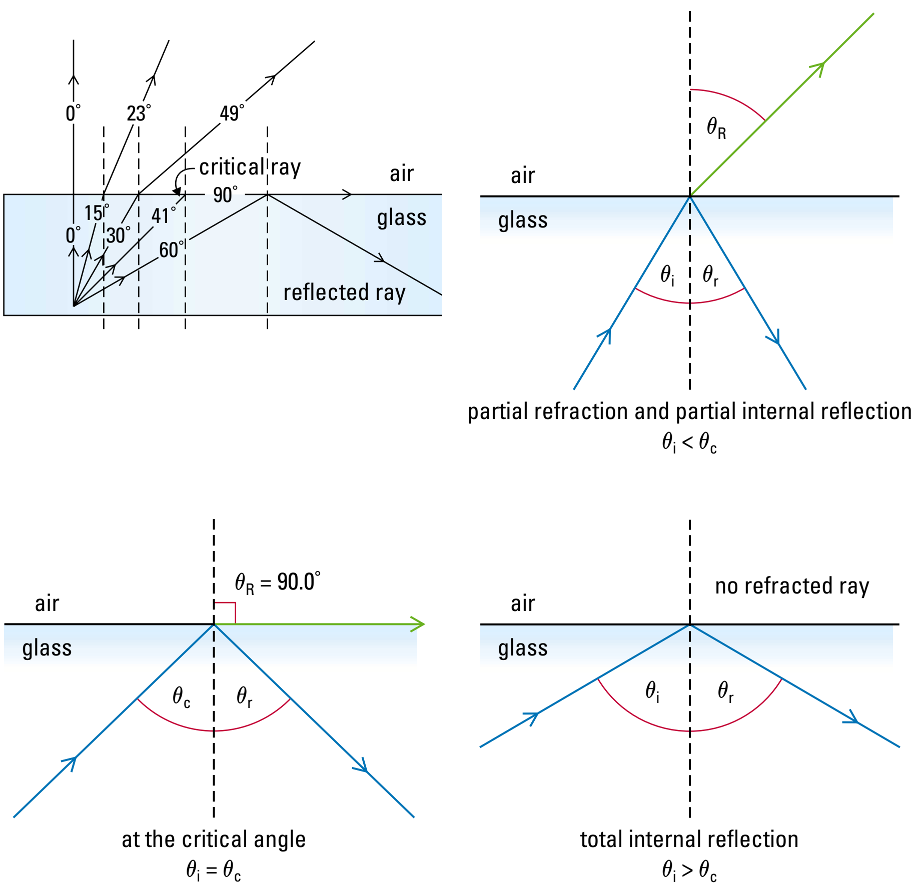

Figure 1
What happens when light rays pass from glass into air?

When the angle of refraction is 90°, the incident ray forms a unique angle of incidence called the "critical angle of incidence," or simply the **critical angle** (θ_c). Unless a second material is mentioned, always assume that the material under study is in air. The following sample problem illustrates how to determine the critical angle.

critical angle: (θ_c) the angle in an optically denser medium at which total internal reflection occurs; at this angle the angle of refraction in the less dense medium is 90°

Sample Problem 1

What is the critical angle in water? Include a diagram in your solution.

Solution

The diagram for this solution is shown in **Figure 2**.

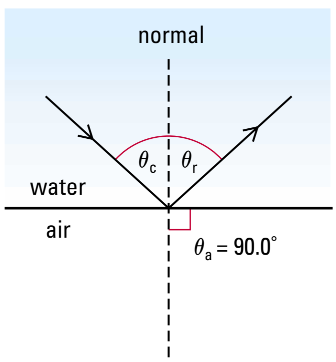

Figure 2
For Sample Problem 1

$n_w = 1.33$
$\theta_w = \theta_c$
$n_{air} = 1.00$ (Assume that the second medium is air.)
$\theta_{air} = 90.0°$

$$n_w \sin \theta_c = n_{air} \sin \theta_{air}$$
$$\sin \theta_c = \frac{n_{air} \sin \theta_{air}}{n_w}$$
$$\sin \theta_c = \frac{(1.00)(\sin 90.0^\circ)}{1.33}$$
$$\theta_c = \sin^{-1}(0.752)$$
$$\theta_c = 48.8^\circ$$

The critical angle in water is 48.8°.

Practice

Understanding Concepts

1. The critical angle in benzene is 41.8°. Which of the following angles of incidence of light rays in benzene would result in total internal reflection?
   (a) 35.1° (b) 50.5° (c) 42.0° (d) 3.0°
2. What is the critical angle for zircon?
3. The critical angle for glass is 41°. What is the index of refraction of the glass? What type of glass is it?
4. Light incident in water ($n_w = 1.33$) strikes a layer of ice ($n_i = 1.31$) that has formed on top of the water. What is the critical angle in the water?

Applying Inquiry Skills

5. You are given a sample of each of the four liquids mentioned in **Table 1**, section 9.4. Describe how you would apply the concept of internal reflection to experimentally determine the identity of each liquid.

Answers

2. 31.4°
3. 1.5 (likely crown glass)
4. 80.1°

Activity 9.6.1

Critical Angle

In this activity you will

(a) determine the critical angle in various materials surrounded by air
(b) study an application of total internal reflection

Materials

ray box with single-slit and double-slit windows
semicircular solid prism (made of glass or plastic)
semicircular plastic dish for water
2 triangular solid prisms having angles of 45° and 90°
polar graph paper (optional)

Procedure

1. Place the semicircular solid prism on a piece of paper and draw its outline. (If polar graph paper is available for this procedure, your teacher will explain its use.) Aim a single light ray ($\theta_i = 10°$) through the curved side of the prism directly toward the middle of the flat edge, as in **Figure 3(a)**. This will ensure that no refraction takes place at this curved surface. Trace the direction of the reflected and refracted rays.
2. Slowly increase the angle of incidence from 10° until the refracted ray in the air just disappears, as in **Figure 3(b)**. Mark the rays, remove the prism, and measure the critical angle, θ_c , for the solid prism.
3. Predict the critical angle θ_c for water ($n_w = 1.33$). Repeat steps 1 and 2 to verify your prediction, using water in a semicircular plastic dish.
4. Make a periscope from two 45° right-angle glass prisms as in **Figure 4**. To observe how light travels in a periscope, aim two rays along X and Y as shown. Draw a ray diagram of your results.

Analysis

(a) Account for any differences between the predicted critical angle for water and the measured critical angle.
(b) Assume that the prisms in **Figure 4** have an index of refraction of $n_g = 1.5$. Explain why light entering and leaving each triangular prism is not refracted and why light rays striking the hypotenuse side of the prism at an angle of 45° are totally internally reflected.
(c) Explain why the arrangement of triangular prisms is considered to be a periscope.

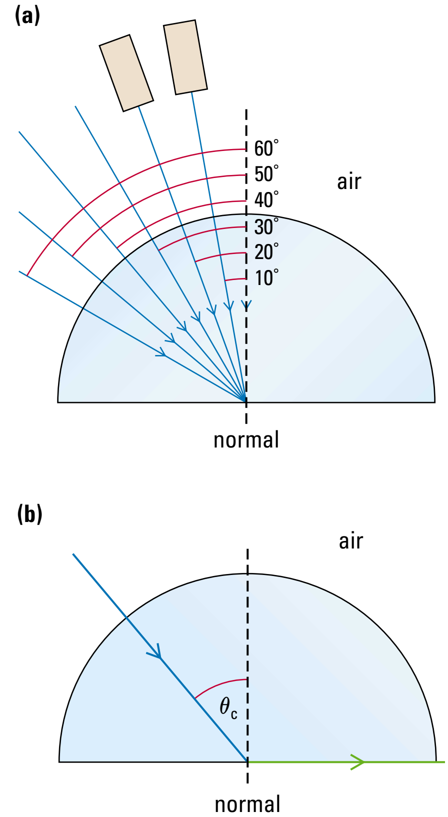

Figure 3
Determining the critical angle in a prism or water

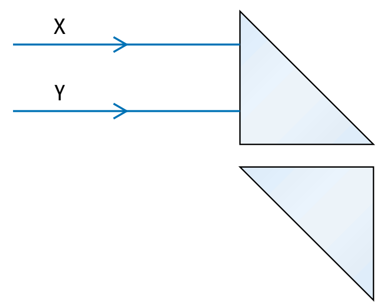

Figure 4
Why is this arrangement of prisms a periscope?

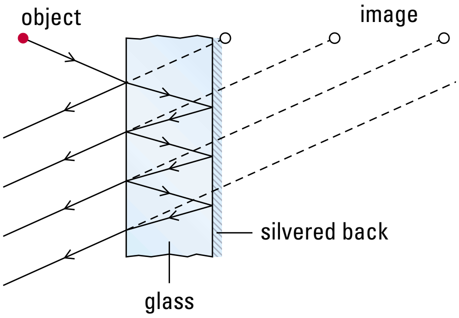

Figure 5
Rear surface mirrors cause multiple images and dispersion. Extra images are usually much weaker than the image formed by the silvered surface at the back; therefore, they go unnoticed.

Applications of Total Internal Reflection

Mirrors and Prisms

Only 90% of the light energy is reflected by most metallic reflectors, the other 10% being absorbed by the reflective material. Plane mirrors, made by silvering the back of the glass, can produce extra images due to reflection from the front surface of the glass and internal reflections in the glass (**Figure 5**). For this reason, the curved mirrors in telescopes are silvered on the front surface. Front surface mirrors, however, are easily damaged and require special handling, cleaning, and care.

To remedy some of the difficulties with front surface mirrors, total internal reflection prisms are used. They reflect nearly all the light energy and have non-tarnishing reflective surfaces. For example, total internal reflection prisms are used in combination with a series of lenses in binoculars (**Figure 6**).

In some cases, different types of prisms are used to change or rotate the attitude of images (**Figure 7**). A single 45° right-angle prism can be used to deflect an image 90° or 180°. Right-angle prisms are used in many laser applications.

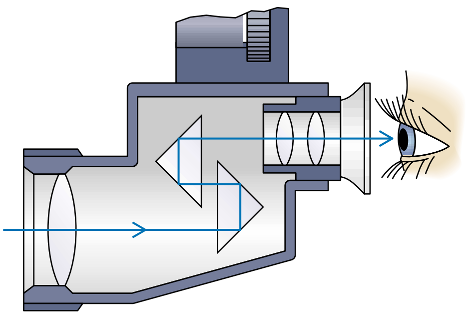

Figure 6
Using total internal reflection in binoculars

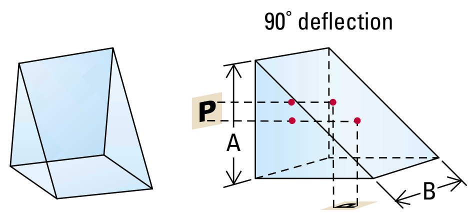

Figure 7

Sample Problem 2

An incident ray of light enters a 45°–90°–45° flint prism as shown in **Figure 8**. Trace the ray through the prism, indicating the angles of incidence, reflection, and refraction at each boundary until the light leaves the prism. Record your answers in an appropriate chart (see **Table 1**).

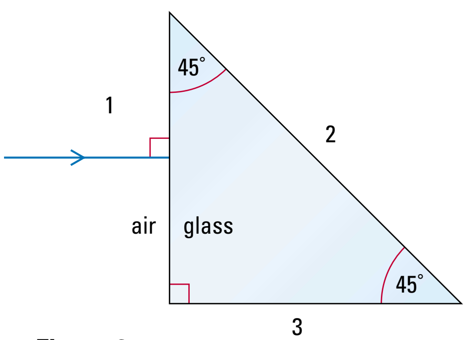

Figure 8
For Sample Problem 2

Solution

Table 1

Boundary	Angle of incidence	Angle of reflection	Angle of refraction
1	0°	0°	0°
2	45°	45°	no refraction
3	0°	0°	0°

Practice

Applying Inquiry Skills

6. An incident ray of light enters a crown glass prism as shown in **Figure 9**. Trace the ray through the prism, indicating the angles of incidence, reflection, and refraction at each boundary until the light leaves the prism. Take into account the possibility of partial reflection and refraction. Record your answers in an appropriate chart.

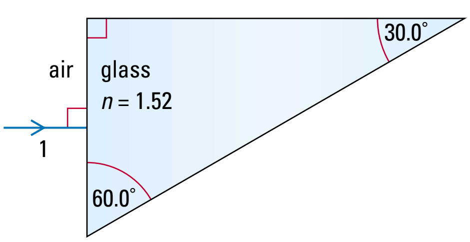

Figure 9
For question 6

Fibre Optics and Communication

Another important application of total internal reflection is communication by the transmission of light along fibre optic cables. The most basic optic fibre is a transparent glass or plastic rod.

In **Figure 10** you can see how ray 1 refracts out of the rod, but rays 2, 3, and 4 don't. They strike the internal surface of the rod at angles greater than the critical angle and so undergo total internal reflection.

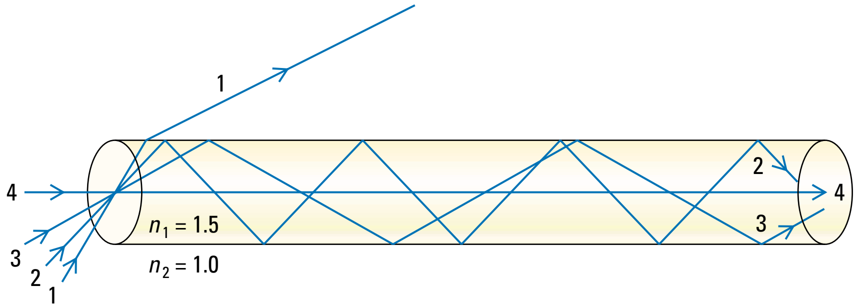

Figure 10
As long as light enters the rod close to the rod's axis, the light remains trapped in the rod by total internal reflection.

Even if the fibres are gently bent or twisted, the critical angle is not usually exceeded, and the light energy is "trapped" by reflecting every time it encounters an internal surface (**Figure 11**).

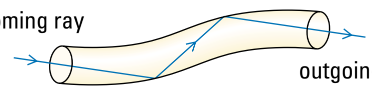

Figure 11
Light will follow a fibre even around bends and twists.

Fibre optic technology is gradually replacing the thousands of copper wires that connect telephone substations (**Figure 12**). Eventually optical fibres will be the backbone of the information superhighway, transmitting voice, video, and data to businesses, schools, hospitals, and homes.

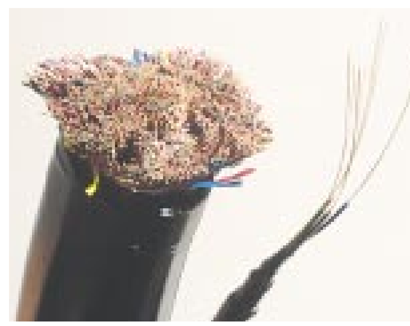

Figure 12
Laser light transmitted through thin glass fibres carries many more telephone calls at a time, with much less energy loss, than is possible with thick copper wire. Also, laser light is not affected by solar flares, lightning flashes, or other forms of electronic interference.

SUMMARY Total Internal Reflection

- When the angle of incidence is equal to the critical angle, the angle of refraction is 90.0°.
- Use $\theta_c = 90.0°$ in the general mathematical relationship of Snell's law to determine the critical angle of the denser medium in the less optically dense medium.
- Light remains confined to fibre optic cables due to total internal reflection.

Section 9.6 Questions

Understanding Concepts

1. State two conditions necessary for total internal reflection.
2. The critical angle for a medium is 60.0°. What is the index of refraction of the medium?
3. A layer of olive oil ($n = 1.47$) floats on water. What is the critical angle for a ray directed from the oil to the water?
4. The glass cores used in fibre optics are surrounded by a thin, transparent film called a *cladding* (**Figure 13**).
   (a) Should the cladding have a lower or higher optical density than the fibres in the core? Explain your answer.
   (b) What do you think is the function of the cladding? (*Hint:* Hundreds of fibres are bundled together to form a fibre tube.)

(continued)

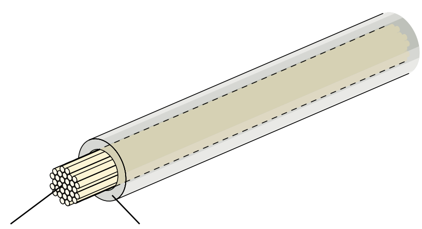

Figure 13
Individual glass fibres are surrounded by a transparent protective cladding.

5. In **Figure 10** of this section, ray 1 is incident on the inside surface of the glass fibre at an angle less than the critical angle.
   (a) What is the critical angle for this fibre if the index of refraction for the glass is 1.50?
   (b) With what maximum angle relative to the normal of the fibre's end can it strike the end of the fibre without later escaping?

Applying Inquiry Skills

6. Design an experiment to determine whether light will undergo total internal reflection within gases, for example, when travelling in carbon dioxide ($n = 1.000450$) toward air ($n = 1.000293$). What is the critical angle of light in carbon dioxide, according to Snell's law? How will this affect the design of your experiment?

Making Connections

7. Research which fields, other than communications, have been greatly affected by the use of fibre optics.

DID YOU KNOW ?

Medical Application of Total Internal Reflection

An endoscope is a device that transmits images using bundles of fibres. Endoscopes probe parts of the body that would otherwise require exploratory surgery.

9.7 Applications of Refraction

Geometric optics is a good model of light for explaining many natural optical phenomena. Recall that a point is perceived by the eye when a cone of diverging light enters the eye. The diverging light is traced backward and where the rays meet, an image of the object is perceived.

Atmospheric Refraction

For many purposes, we assume the index of refraction of air to be 1.000. Although variation of the index of refraction of air from this value is just a small fraction of a percent, it is this small fraction that causes many optical effects. The atmosphere's index of refraction varies, especially along vertical lines. Refractive effects such as mirages and shimmering are due to variations in the index of refraction caused by temperature variations.

Twinkling and Shimmering

Earth's atmosphere consists of flowing masses of air of varying density and temperature; therefore, the refractive index varies slightly from one region of the atmosphere to another. When light from a star enters the atmosphere it is refracted as it moves from one mass of air to another, and, since the variable masses of air are in motion, the star seems to twinkle.

Under conditions of constant pressure, warm air has a slightly lower index of refraction than cold air. When light passes through a stream of warm air, as it does above a hot stove or barbecue, it is refracted away from the normal. This refraction is not uniform because the warm air rises irregularly, in gusts. Light from objects seen through the warm air is distorted by irregular refraction, and the objects appear to shimmer. You can see the same effect over hot pavement in the summer or at an airport as jets go by.

DID YOU KNOW ?

Observing the Sky

Most large telescopes are located high on mountains where there is less of Earth's atmosphere between them and the stars, and where the air is more uniform in temperature. This minimizes distortions caused by atmospheric refraction. Astronomers find that cold winter nights are usually best for celestial observation since vertical temperature variations are minimized. Any atmospheric distortions are corrected using specialized software.