11.2 Partial Refraction and Total Internal Reflection

Key Terms
partial reflection and refraction
critical angle
total internal reflection

If you have never been diving, you might be surprised by what a diver can and cannot see when looking up toward the surface of the water. The photograph in **Figure 11.9** was taken underwater from a diver's perspective. As you can see, only the objects in an area directly above you are clearly visible. The water at the sides is dark, even though the day appears to be clear and bright.

You can analyze **Figure 11.9** based on what you have learned about the refraction of light. To be able to see an object above the water while you are underwater, you know that light must travel from the object to your eyes. The objects outside the area directly above you are not visible because no light from these objects is penetrating the surface of the water. Light is energy so it cannot disappear. If it is not penetrating the water, where is it going? You could find some clues by reviewing **Figure 10.12** on page 411. In **Figure 10.12**, light is reflected from the surface of the water. When light rays reach a boundary between two media, such as air and water, some light is always reflected and some is often refracted. In this section, you will learn about the conditions in which more refraction than reflection occurs and the conditions in which only reflection occurs.

Figure 11.9 When underwater and looking up, you can only see objects in an area directly above you.

Partial Reflection and Refraction

Figure 11.10 While looking out of a window, you can often see the reflection of objects inside the room as well as objects that are outside of the window.

Sometimes, when you look out a window, you see what is outside as well as your own reflection, as shown in **Figure 11.10**. In the photograph, light is obviously coming through the window because you can see objects that are outside. But light is also reflecting off the window because you can see your own reflection. In addition, someone standing outside could see you through the window. As mentioned earlier, some light reflects and some light refracts at a surface between two media that have different indices of refraction, as shown in **Figure 11.11**. This phenomenon is called **partial reflection and refraction**. The amount of reflection compared with the amount of refraction depends on the angle of incidence as well as the relative indices of refraction of the two media.

partial reflection and refraction a phenomenon in which some of the light that is travelling from one medium into another is reflected and some is refracted at the boundary between the media

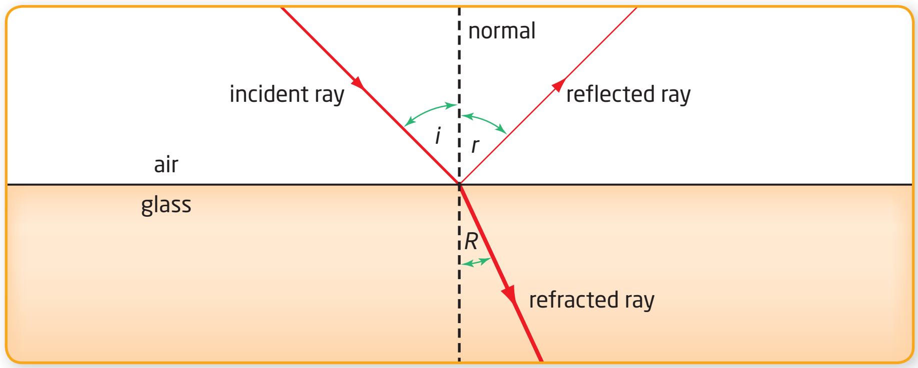


Figure 11.11 Both refraction and reflection occur, but not equally. The amount of each depends on the angle. In this case, more light is refracted than reflected, as indicated by the thickness of the rays.

Consider, first, light travelling from air into water. If the angle of incidence is nearly zero—that is, the light is travelling directly toward the water—most of the light penetrates the surface and very little is reflected. As the angle of incidence increases, more light is reflected at the surface and less light penetrates the surface and is refracted.

You have probably seen evidence of this phenomenon. **Figure 11.12A** shows water with the Sun overhead. You see very little reflection of sunlight because most of the light is penetrating the surface of the water. In **Figure 11.12B**, however, the Sun is close to the horizon, shining light on the water at a large angle of incidence. You can see that much of the light is reflected from the surface of the water.

Figure 11.12 **A** The sunlight is shining on the water, but you do not see any reflection because the Sun is almost directly overhead. **B** When the Sun reflects off the water (for example, at sunset), the reflection of the light can be almost blinding.

Activity 11-2

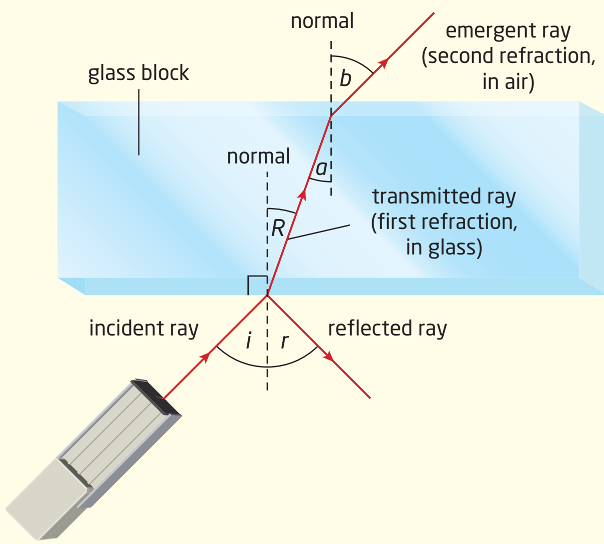
Investigating Properties of Light

In this activity, you will answer the following questions. How does the angle of incidence of a ray striking a glass surface compare with

(a) the angle of reflection at the surface,

(b) the angle of refraction at the surface, and

(c) the angle of refraction when the ray emerges into air again?



Materials

- glass block
- sheet of paper
- ray box (single slit)
- pencil
- ruler
- protractor

Procedure

1. In your notebook, make a table like the one below to record your observations. Give your table a title.
2. Place the glass block in the centre of the sheet of paper. Carefully draw an outline of the block.
3. Place a single slit in the ray box. Shine the light toward the longest side of the block as shown in the diagram on the left.
4. Make small pencil marks on the incident, reflected, and emergent rays.
5. Remove the block, and use a ruler to connect the dots with a solid line to show the path of the light ray. The light ray should change direction at the outline of the block.
6. Draw a normal at the point where the incident ray enters the block. Draw a second normal where the emergent ray leaves the block. Measure the angles of incidence (*i*), reflection (*r*), and refraction (*R*), as well as the angles labelled *a* and *b* in the diagram.

Questions

1. Explain how the reflection you observed in this activity (a) is the same as and (b) is different from the reflection of light at the surface of a plane mirror.
2. In previous activities and investigations, you have not considered a refracted light ray that enters and then continues on through and out the other side of the same medium. Explain how the refracted ray as it enters the medium (a) is the same as and (b) is different from the ray as it leaves.

Incident Ray	Reflected Ray	Transmitted Ray		Emergent Ray
		First Refraction, in Glass		Second Refraction, in Air
$\angle i$	$\angle r$	$\angle R$	$\angle a$	$\angle b$

Reflection and Refraction in a Rearview Mirror

The rearview mirror in most cars has a lever that allows the driver to choose how much light from behind the car will reach his or her eyes. During the day, the driver wants to clearly see the traffic that is behind the car. At night, however, the driver does not want to be blinded by headlights.

How a Rearview Mirror Works

As shown in **Figure 11.13A**, rearview mirrors are wedge-shaped and silvered on the back. A lever can quickly flip a rearview mirror from daytime to nighttime positions. Light coming from behind the car hits the mirror at a very small angle of incidence. As a result, most of the light is refracted and reaches the silvered back of the mirror, where it is reflected.

Daytime Setting of a Rearview Mirror

In the daytime, the mirror is positioned as shown in **Figure 11.13B**. The light that has reflected off the back of the mirror is directed to the driver's eyes. Thus, in the daytime, the driver has a clear view of the traffic behind the car. If the mirror was left in this position at night, however, any headlights behind the car would shine brightly in the driver's eyes, making it very difficult for the driver to see.

Nighttime Setting of a Rearview Mirror

Figure 11.13C shows how a driver can flip a rearview mirror to the night setting. At this angle, most of the light penetrates the mirror glass and is refracted as before. However, in this case, only a small amount of reflected light is directed toward the driver's eyes. This allows the driver to see the headlights, but at a low intensity. Most of the light penetrates the mirror, refracts, hits the silvered back of the mirror, and is reflected away from the driver's eyes. Such mirrors are designed so that the angles of incidence, reflection, and refraction direct the right amount of light toward the driver's eyes for both daytime and nighttime.

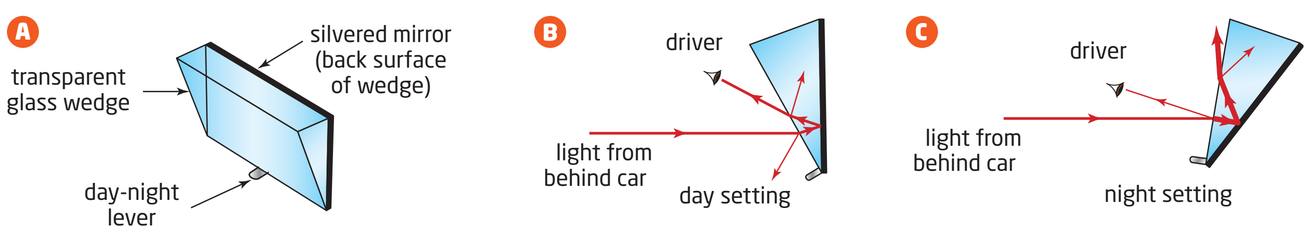


Figure 11.13 **A** A rearview mirror reflects light to the driver's eyes. **B** With the daytime setting, most of the light goes to the driver's eyes. **C** With the nighttime setting, just a small amount of the incoming light goes to the driver's eyes.

Large Angles of Incidence

Now that you understand partial reflection and refraction, you can explain **Figure 11.9** on page 457. Imagine that you are scuba diving and are underwater looking up, as shown in **Figure 11.14**. The light coming from the area directly above you or at a small angle of incidence will penetrate the surface of the water, refract, and be visible to you. But as the angle of incidence of the light increases, more of the light will reflect off the water, and a smaller amount will refract and be visible to you. Nearly all the light that is coming in your direction from large angles of incidence will reflect from the surface and never reach you. Therefore, from below the surface of the water, it looks like light is coming through a hole.

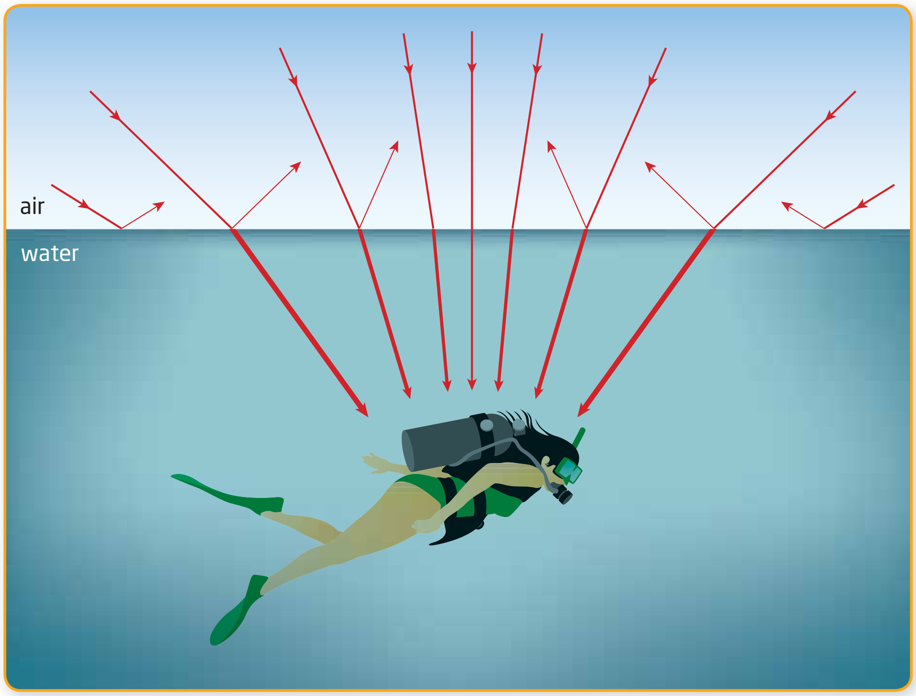


Figure 11.14 When you are underwater, you can only see the light that reaches you from an area directly above. The bottom of the water-air boundary and the sky above look dark because light that is coming from this direction is reflected away and you cannot see it.

Learning Check

1. The term *partial refraction* implies that only part of the light that hits a boundary between two media refracts. What happens to the rest of the light?
2. Explain how a rearview mirror works. Review **Figure 11.13** if necessary. In your explanation, include why many rearview mirrors have two settings.
3. If you were sitting on a riverbank, holding a fishing rod, a fish in the river would probably not be able to see you. Explain why.
4. Describe an example in your everyday life that demonstrates that both reflection and refraction occur at a boundary between two media with different indices of refraction.

Refraction: Water to Air

If you were standing in shallow water at the edge of a clear lake, as in **Figure 11.15**, you would be able to see stones on the bottom of the lake or fish swimming in the water that were very near you. As you look farther away, objects underwater are more difficult to see. At a great enough distance, you cannot see anything below the surface of the water. You know that the water is clear and that there is plenty of light. Why is it not possible to see objects underwater?

Figure 11.15 The water is clear, but you can see objects under the water only when they are close to you.

The Critical Angle

> **Suggested Investigation**
> Inquiry Investigation 11-D, Investigating Total Internal Reflection in Water, on page 480

For you to see an object underwater, light must hit the object, reflect off it, and travel to your eyes. **Figure 11.16A** shows two separate incident rays travelling toward the boundary between air and water, at relatively small angles of incidence. Because the incident rays are going from water to air, the refracted rays bend away from the normal. As you can see, as the angle of incidence increases, the angle of refraction increases more rapidly.

As the angle of incidence continues to increase, the angle of refraction will eventually reach 90°, as shown in **Figure 11.16B**. At this angle of incidence, the refracted ray lies along the boundary between the two media. No light passes into the second medium, which is air in this example. The angle of incidence that produces a refracted ray at an angle of 90° from the normal is called the **critical angle**, and is symbolized by $\angle c$.

> **critical angle** the angle of incidence that produces an angle of refraction of 90°

Total Internal Reflection

The size of the critical angle depends on the indices of refraction of the two media. When the angle of incidence is larger than the critical angle, the angle of refraction cannot get any larger because the refracted ray would no longer be in the second medium. So, at angles of incidence that are greater than the critical angle, no refraction occurs. All the light is reflected back into the first medium, as shown in **Figure 11.16C**. This phenomenon is called **total internal reflection**. Note that total internal reflection happens only when light travels from a medium in which its speed is lower to a medium in which its speed is higher.

> **total internal reflection** the phenomenon in which incident light is not refracted but is entirely reflected back from the boundary; occurs when light travels from a medium in which its speed is lower to a medium in which its speed is higher

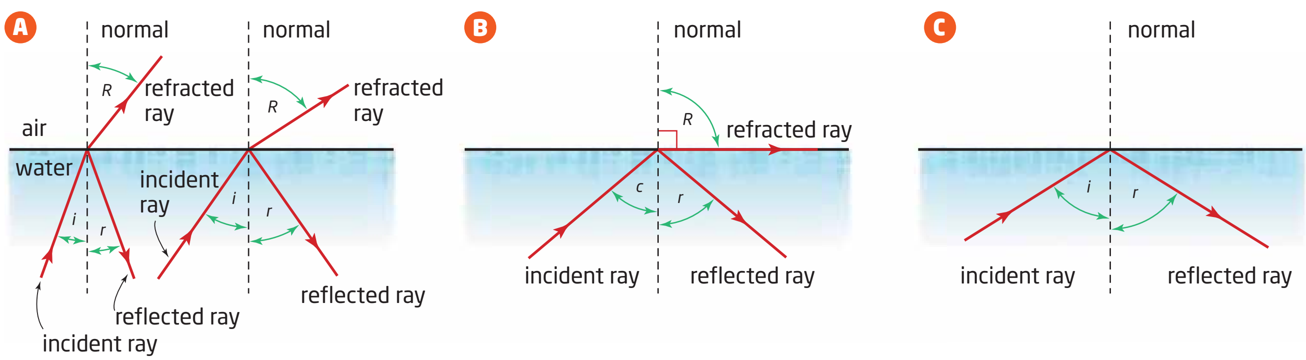


Figure 11.16 **A** When the angle of incidence is smaller than the critical angle, both refraction and reflection occur at the boundary between the two media. **B** When the angle of refraction reaches 90°, the refracted ray lies along the boundary between the two media. **C** When the angle of incidence is larger than the critical angle, all the light is reflected back into the first medium.

Activity 11-3

The Fountain of Light

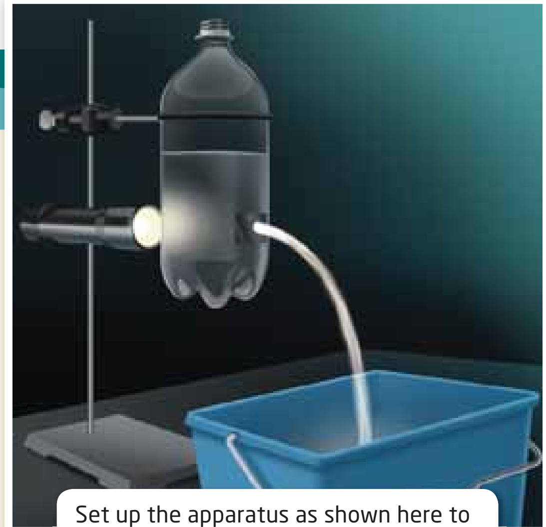
What is happening in the diagram on the right? In this activity, you will observe total internal reflection within a stream of water in a darkened room.

Materials

- clear plastic bottle (remove the label if necessary)
- duct tape (about 5 cm)
- thumbtack
- masking tape (about 3 cm)
- water
- bucket (or use a sink)
- flashlight
- scissors

Procedure

1. Place a short piece of duct tape on a part of the bottle that is clear on both sides, about 6 to 8 cm from the bottom of the bottle.
2. Use the thumbtack to make a small hole in the centre of the duct tape. Cover the hole with a small piece of masking tape.
3. Fill the bottle with water. Perform the rest of this activity over a bucket or sink.
4. Have your partner shine the light from a flashlight through the bottle from the side that is opposite the hole. Remove the masking tape, and observe the stream of water as it exits the hole, as well as the height of the water in the bottle as it nears the hole.



Set up the apparatus as shown here to see the light in the stream of water.

5. Look for the spot where total internal reflection suddenly occurs. Try to measure the critical angle.
6. Empty the water from the bottle. Use the point of the scissors to make the hole larger, and cover the hole with masking tape. Repeat steps 3 to 5.

Questions

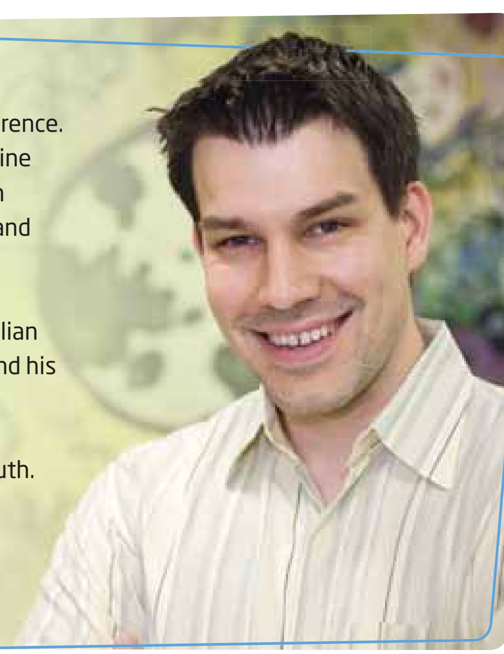
1. Total internal reflection occurs when light in water hits the water–air surface at an angle of incidence that is greater than 49°. Compare 49° with your measurement in step 5.
2. When did you observe the greater amount of total internal reflection: when the stream of water fell far from the bottle, or when the stream of water fell close to the bottle? Explain your observation using a diagram.

Making a Difference

Michael Furdyk uses Internet communications technology to make a difference. He is co-founder and director of technology for TakingITGlobal.org, an on-line community for youth interested in positive change. More than five million users from 200 countries have visited TakingITGlobal.org to learn about and engage in global issues, such as education and sustainable development.

Michael started his first computer business when he was 8. At 15, he formed a company called MyDesktop.com with Michael Hayman, an Australian friend. The website had more than 500 000 users monthly, and Michael and his friend eventually sold it. In 2000, Michael co-founded the non-profit TakingITGlobal.org with another friend, Jennifer Corriero.

Michael has advised many organizations on how to engage today's youth. He speaks at conferences around the world and was named one of Teen People's "20 teens that will change the world" in 2000.



How could you use the Internet and other communications technologies to make positive changes in your community?

Changing the Direction of a Light Ray

A glass prism can change the direction of light by creating the conditions for total internal reflection. The critical angle between glass and air is less than 45°. Therefore, light hitting an inner surface at exactly 45° will be totally reflected inside the glass.

Figure 11.17A shows how a glass prism that is shaped like an isosceles right triangle can change the direction of a light ray by 90°. When light enters the prism perpendicular to one of the short sides of the prism, the angle of incidence is zero. Thus, there is no refraction at this surface. The light travels straight through the prism to the inside of the long side of the prism. At the long side of the prism, the angle of incidence is 45°, so the angle of reflection is also 45°. The total change in the direction of the ray is 90°. In comparison, when light enters the prism perpendicular to the long side of the prism, as shown in **Figure 11.17B**, it is reflected off both short sides, changing direction by 90° each time. The total change in direction is therefore 180°.

When light enters the long side at any angle, as shown in **Figures 11.17B** and **C**, the reflected light is reflected by 180°, or directly back in the direction that it came from. When the angle of incidence into the prism is not 0°, the light will be refracted. However, after the light has reflected off both inner short sides and then leaves the prism, it will refract at the same angle.

> **Study Toolkit**
>
> **Summarizing** It may be helpful to summarize the information in the first three paragraphs on this page in a table like the one on page 448.

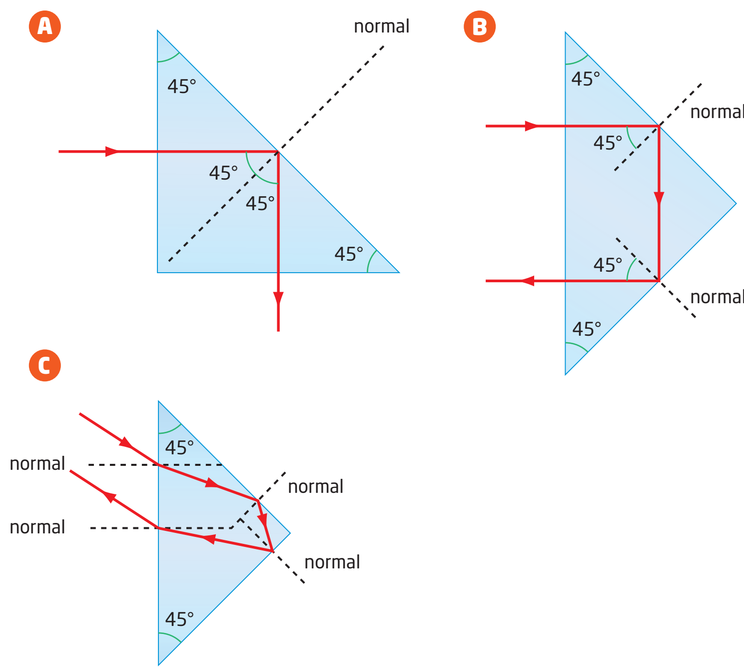


Figure 11.17 **A** The direction of light is changed 90°. **B** The direction of light is changed 180°. **C** Regardless of the angle of incidence at the long side of the prism shown, the refracted and reflected rays will go back in exactly the same direction from which they came.

Applications of Total Internal Reflection

Figure 11.18 shows how binoculars use total internal reflection. See how the path of light in the binoculars is lengthened and moved to the side. When you study lenses in Chapter 12, you will find out why the long path length is important.

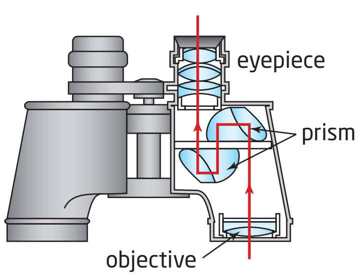


Figure 11.18 The direction of the light is reflected twice in binoculars to make the path of the light longer.

Retroreflectors

The ability to change the direction of light by 180° has some very useful applications. One of these applications is *retroreflectors*, which look like small plastic prisms. For example, the reflectors on the back of a bicycle are retroreflectors, as shown in **Figure 11.19A**. Regardless of the direction that light from headlights hits the reflectors, the light is always reflected directly back to the car so the driver can see the bicycle, as shown in part **B**.

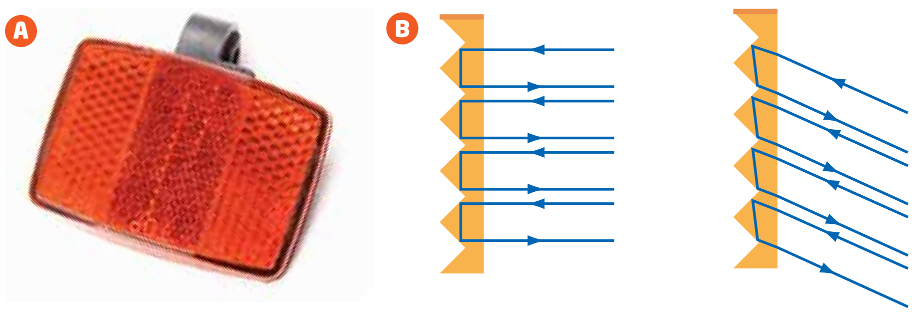


Figure 11.19 **A** Look closely at this bicycle reflector. You will see small circles or hexagons. **B** Each circle or hexagon is a cut in the plastic. It functions like a prism to reflect light directly back in the direction it came from.

Optical Fibres

Fibre optics has revolutionized all forms of communication, including the Internet. Optical fibres are made from a glass core, which is surrounded by an optical cladding. A *cladding* is a covering, much like a sleeve but completely closed. In this case, the fibre core is made of one type of glass, and the cladding is made of another type of glass. The material that makes up the cladding must have a lower index of refraction than the core to facilitate total internal reflection. See **Figure 11.20A**. When light enters the end of the fibre in a direction that is almost parallel to the axis of the fibre, it hits the boundary between the core and cladding at an angle that is larger than the critical angle, as shown in **Figure 11.20B**. Even when the fibre is bent, the light is totally internally reflected along the entire fibre until it reaches the other end.

Individual fibres are somewhat fragile. Therefore, they are coated for strength and protection. Groups of fibres are then bundled together into a cable, as shown in **Figure 11.20C**. Depending on their use, the cables can be as short as a metre or as long as several kilometres.

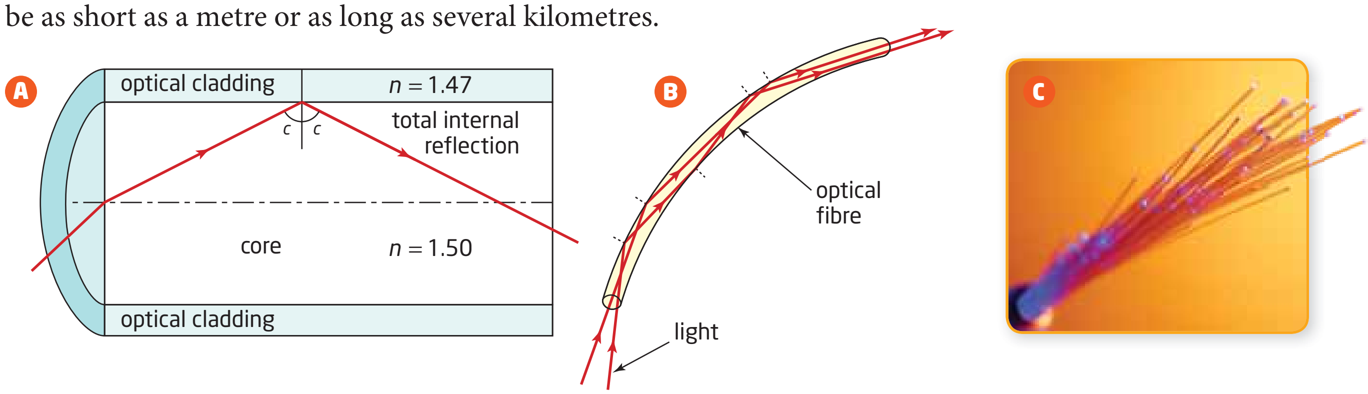


Figure 11.20 **A** Total internal reflection will occur each time the light hits the boundary between the core and cladding in an optical fibre, regardless of the amount of bending of the fibre. **B** The light is totally internally reflected along the optical fibre until it reaches the other end. **C** A fibre optics cable can carry hundreds of telephone conversations, cable television signals, or data.

Figure 11.21 The small optical fibres can carry as much information as the large copper cable on the right.

Fibre Optics in Telecommunications

Copper wire cables have been used in the past to carry information. But fibre optic cables are rapidly replacing them. There are three main ways that fibre optics cables are superior to copper wire cables:

- The signals are not affected by electrical storms, as they would be in copper wire cables.
- Fibre optics cables can carry many more signals over long distances, losing less energy than copper cables.
- Fibre optics cables are smaller and lighter than copper cables.

Figure 11.21 shows a fibre optics cable and a copper cable that carry the same amount of information.

Study Toolkit

Making Inferences Read the text under the heading "Fibre Optics in Telecommunications." What prior knowledge do you have about copper wire cables?

Fibre Optics in Medicine

The use of optical fibre bundles has transformed many surgical procedures. An instrument called an endoscope uses optical fibre bundles. The surgeon inserts the endoscope in a small incision. One bundle of optical fibres in the endoscope carries light into the area where the surgery is needed. Another bundle of optical fibres carries an image of the area back to a monitor. The surgeon watches the monitor while manipulating the instrument to complete the surgery. Before this technique was available, a large incision was necessary, making the recovery time several weeks long. Traditional surgery also increases the possibility of infection.

Doctors also use endoscopes to help diagnose problems in their patients. In **Figure 11.22**, the doctor has fed an endoscope down her patient's esophagus and can view the inside of the patient's stomach on a computer monitor. The doctor in the middle, holding the white instrument, is taking a tissue sample from the stomach. By being able to see the inside of the stomach and take a tissue sample, the doctor may be able to diagnose any problems, such as an ulcer or cancer.

Sense of *time*

Fibre optics are not a recent invention. Sponges, which are the oldest multicellular organisms, transmit light inside their bodies using silica structures. The silica structures are basically glass rods.

Figure 11.22 The doctor has inserted the flexible, fibre optic end of the endoscope down the patient's throat and is watching the image of the stomach on a monitor.

Section 11.2 Review

Section Summary

- When light strikes a boundary between two transparent media that have different indices of refraction, some light reflects off the boundary and some light refracts through the boundary. This phenomenon is called partial reflection and refraction.
- At a small angle of incidence, more light refracts than reflects. As the angle of incidence increases, more and more light reflects than refracts.
- When light travels from a medium with a higher index of refraction to a medium with a lower index of refraction, the angle of refraction is larger than the angle of incidence. Therefore, an angle of incidence that results in a 90° angle of refraction is eventually reached. This angle of incidence is called the critical angle.
- When the angle of incidence is larger than the critical angle, no refraction occurs. All the light is reflected from the boundary. This phenomenon is called total internal reflection.
- Total internal reflection has many practical applications, such as binoculars, retroreflectors, and optical fibres in telecommunications and in surgical instruments.

Review Questions

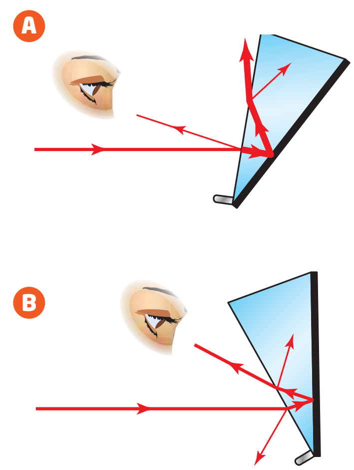
C **1.** Using diagrams, define the terms *critical angle* and *total internal reflection*.

K/U **2.** Under what conditions will nearly all the light that reaches a boundary between two different media be refracted?

K/U **3.** What two conditions must exist for total internal reflection to occur?

K/U **4.** Describe the structure of optical fibre cables.

A **5.** The diagrams on the right show rearview mirrors at two different settings. Which rearview mirror is set for daytime driving, and which is set for nighttime driving? Explain your reasoning. Review **Figure 11.13** if necessary.



Use these diagrams for question 5.

T/I **6.** Refer to **Figure 11.17**. If the light enters one of the short sides of the prism at an angle of incidence of 40°, will the light change direction by 90°? Explain your answer.

A **7.** Evaluate the impact of the development of optical fibres. Which type of application do you think has the greatest impact on our lives?

T/I **8.** Diamonds have a large index of refraction of 2.42, and they are cut with many facets. Based on what you know about refraction, explain why cut diamonds sparkle more than any other cut stones.


A facet on a diamond is a small, flat area.