SECTION 8

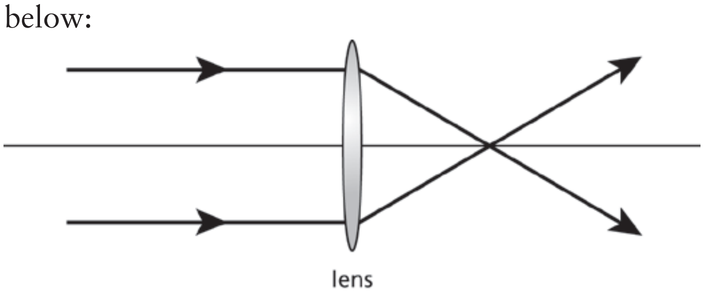
Refraction of Light

Section Overview

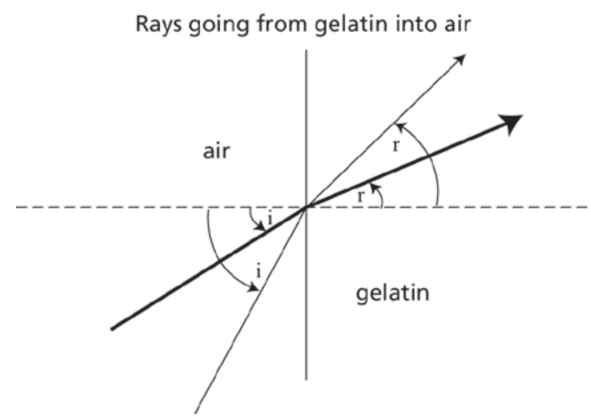
In this section, students investigate refraction. By shining a beam of light into a rectangular block of acrylic, they trace the path of light beams as they enter and leave the block at various angles. Students then measure the angles of incidence, reflection, and refraction and record the results in a table. They graph their results to predict the angle of refraction for an angle of incidence that is 45 degrees. They replace the acrylic block with a prism and mark the path of the incident and refracted rays measured to the normal. Students note that when the incident angle exceeds the critical angle, the prism acts as a mirror. They swivel the incident beam at various angles to observe the critical angle of refraction.

Background Information

Refraction (bending of light as it goes from one medium to another) is the basis of the operation of prisms and lenses. Light rays bend as they enter and leave the slab of acrylic, as shown in the drawing below:



The angles of incidence (θ_i) and refraction (θ_r), both measured with respect to the normal at the point of incidence, specify the path of the light as it moves from one substance into another, as shown in the following diagram:



The law of refraction (Snell's law) provides a relationship among the angle of incidence, the angle of refraction, and the index of refraction, a property of two materials that form the interface. The index of refraction, n, of a particular material is related to the speed of light in that material; therefore,

$$n = \frac{\text{speed of light in vacuum}}{\text{speed of light in the material}}$$

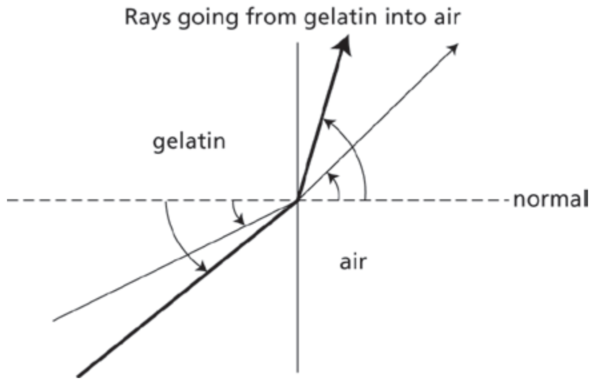
However, it is difficult to measure the speed of light in materials directly; so the index of refraction is simply defined as a property of the material which determines the amount of bending of light rays entering that material. It is important to note that the amount of bending depends on both the index of refraction of the material in which the incident ray is traveling and the index of refraction of the material into which the refracted ray propagates. The law of refraction (Snell's law) is expressed mathematically in the following equation:

$$n_i \sin \theta_i = n_r \sin \theta_r$$

For air, $n = 1.0003$, which can be set equal to 1 for most practical purposes. For acrylic, $n = 1.497$, which can be set equal to 1.5 for practical purposes. Going from air into acrylic, light bends toward the normal. Consequently, the ratio $\sin \theta_i / \sin \theta_r$

is greater than one (except for the special case of $\theta_i = 0°$). Going from acrylic into air, light bends away from the normal. The angle of refraction is greater than the angle of incidence. Therefore, it can be generally stated that in going from a low index of refraction material to a high index of refraction material, a light ray bends toward the normal. In going from a high index of refraction material to a low index of refraction material, the light ray bends away from the normal.

The critical angle occurs as light leaves the medium with the higher index of refraction and enters a medium with a lower index of refraction (in this investigation, moving from acrylic into air). Look at the diagram below.



The diagram shows how the angle of refraction changes as the angle of incidence, in the acrylic, increases from zero.

Eventually the angle of refraction reaches 90°. The corresponding angle of incidence is called the critical angle. What happens when the angle of incidence exceeds the critical angle? The light cannot be refracted, because the angle of refraction would be greater than 90°. It turns out that all the light is reflected back into the medium with the higher index of refraction. This effect is called total internal reflection. Although there appears to be an abrupt change at the critical angle, internal reflection begins considerably before the angle of incidence reaches the critical angle. When the angle of incidence is equal to or greater than the critical angle, there is total reflection. Likewise, the intensity of the refracted beam diminishes progressively as the critical angle is approached, and this effect can make the critical angle challenging to measure.

Total internal reflection is the basis of the operation of the light pipe or optical fiber. A light beam enters a small diameter, flexible glass or plastic rod. When the beam hits the wall of the fiber, total internal reflection occurs and the beam reflects entirely within the fiber. In this way, light signals can carry information through a system of bundled glass fibers called fiber optic cables.

CHAPTER 5

Crucial Physics

- When light rays travel from one medium to another, they (in general) change direction. This process is called refraction.
- When traveling from a medium with a low index of refraction to a medium with a higher index of refraction, the angle of incidence will be larger than the angle of refraction (within the larger index of refraction material). If the two indices of refraction happen to be the same, the light ray will not change direction.
- If a light ray is traveling in a medium with a higher index of refraction toward an interface with a medium with a lower index of refraction, the ray will be totally reflected at the interface if the angle of incidence exceeds the so-called critical angle.
- The higher the index of refraction of a material, the slower light travels in that medium.
- (*Active Physics Plus*) The law of refraction (Snell's law) can be expressed as
  $n_i \sin \theta_i = n_r \sin \theta_r$
  where n_i is the index of refraction for the incident ray and θ_i is the angle of incidence; n_r is the index of refraction for the refracted ray; and θ_r is the angle of refraction.

Learning Outcomes	Location in the Section	Evidence of Understanding
Observe refraction.	***Investigate*** Steps 1-3	Students look at a pencil through an acrylic box and observe how the acrylic box and a prism bend a light beam.
Measure angles of incidence and refraction.	***Investigate*** Step 4	Students measure the angles of incidence and refraction of the laser beam for oblique angles on an acrylic block.
Measure the critical angle.	***Investigate*** Step 8	Students observe the critical angle and measure the angle of reflection at this angle.
Observe total internal reflection.	***Investigate*** Step 9	Students swivel the incident beam at various angles to see where the refracted beam at the bottom of the prism begins to disappear.

NOTES

Section 8 Materials, Preparation, and Safety

Materials and Equipment

PLAN A		
Materials and Equipment	**Group (4 students)**	**Class**
Ruler, metric, in./cm	1 per group	
Clear glass rod 4"- 8"	1 per group	
Laser pointer - class 2	1 per group	
Plastic rod holder	1 per group	
Acrylic block	1 per group	
Right angle prism	1 per group	
Graph paper, pkg 50		1 per class
Paper*	1 per group	

*Additional items needed not supplied

Time Requirement

- Allow one and one-half periods or 65 minutes for students to complete the *Investigate* part of this section.

Teacher Preparation

- Assemble the required material.
- Darken the room as much as possible so students can see the light path of the laser easily. Using additional curtains, if available, to darken the room is helpful.
- Complete the *Investigate* prior to students in order to be familiar with the correct orientations of the prism and acrylic block to show the expected exit beam for the laser. Pay particular attention to how the refracted beam exits the prism as the angle of incidence approaches the critical angle.
- Have students set up their equipment at right angles to one another to minimize the effect of a neighboring light source on their equipment.
- If possible, prepare an acrylic tube to show total internal reflection. A bendable, soft plastic tube filled with clear gelatin is an acceptable substitute.

Safety Requirements

- Review safety requirements for lasers from *Section 6*.
- Acrylic transparent blocks and lenses should be used, if possible, rather than plastic or glass.
- If glass prisms or blocks are used, students must be careful not to drop the prisms. If a glass prism or block breaks, clean up all broken glass immediately and remove the pieces, being careful to avoid handling the broken glass.

Materials and Equipment

PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Ruler, metric, in./cm		1 per class
Clear glass rod 4″- 8″	1 per group	
Laser pointer - class 2	1 per group	
Plastic rod holder	1 per group	
Acrylic block	1 per group	
Right angle prism	1 per group	
Graph paper, pkg 50		1 per class
Paper*	1 per group	

*Additional items needed not supplied

Time Requirement

- Allow one and one-half periods or 65 minutes for students to complete the *Investigate* part of this section.

Teacher Preparation

- Assemble the required material.
- Darken the room as much as possible so students can see the light path of the laser easily. Use additional curtains, if available, to darken the room.
- Complete the *Investigate* prior to students in order to be familiar with the correct orientations of the prism and acrylic block to show the expected exit beam for the laser. Pay particular attention to how the refracted beam exits the prism as the angle of incidence approaches the critical angle.
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- Acrylic transparent blocks and lenses should be used, if possible, rather than plastic or glass.
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Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

Learning Issue	Reference	Augmentation and Accommodations
Understanding academic vocabulary	***Investigate*** Steps 2 and 5	**Augmentation** • Students are familiar with the word horizontal but may not remember its meaning. Ask for a volunteer to define "horizontal." Then ask students to provide examples of things in the classroom that are horizontal.
Differentiating all of the lines drawn on a ray diagram	***Investigate*** Steps 4 and 5 ***Physics to Go*** Questions 2, 3, 4, and 7	**Augmentation** • Students with fine motor, visual-spatial, or focus issues may struggle to differentiate all of the lines and angles drawn on their ray diagrams. Ask students to label the surface of the block, the normal, the incident ray, the refracted ray, the angle of incidence, and the angle of refraction. Then quickly check in to make sure that students have a diagram that is labeled correctly before they begin making measurements and drawing conclusions. • Students could also be strategically grouped to check each other's work. • Making each line a different color may help students visually differentiate the lines.
Recording data in an organized way	***Investigate*** Step 4	**Augmentation** • Students with organization and attention issues may struggle to keep track of their measurements if they do not create the table first. Ask students to create the table before they begin measuring the angles.
Making measurements with a protractor	***Investigate*** Steps 4 and 5 ***Physics Essential Questions***	**Augmentation** • Model how to use a protractor on an overhead projector or draw a large-scale model on the board. • Provide opportunities for practice with angles that have already been measured. When students are proficient at measuring these angles, ask them to measure the angles they have drawn for this *Investigate*. **Accommodation** • Use close proximity or hand-over-hand (physically guided) techniques to assist students in measuring angles with a protractor.
Drawing graphs	***Investigate*** Step 5	**Augmentation** • Make sure students know the difference between the x-axis and y-axis. • Many students do not recognize the patterns in numbers that make it possible to set up the scale for each axis. Use the board or an overhead to model the process for setting up the axes scales. **Accommodation** • Give students a graph with both the x-axis and the y-axis labeled and scaled, and then ask students to graph their data. • Some students may need one-on-one or small-group assistance to graph the data.
Drawing conclusions and making generalizations from data	***Investigate*** ***Physics Essential Questions*** ***Physics to Go*** Questions 1-7	**Augmentation** • Students are required to draw ray diagrams, measure angles, graph the data, and compare the data to make predictions in this *Investigate*. • Students who are sequential learners are able to follow steps to arrive at a conclusion and learn something new as long as they accurately complete each step. Check in with students to make sure that their diagrams, measurements, and graphs are accurate. • Students who are visual spatial learners struggle to follow step-by-step directions to arrive at a conclusion. These students benefit from seeing the big picture first and then applying new learning to the bigger concept. It may benefit these students to read the *Physics Talk* first and then complete the *Investigate*. **Accommodation** • Provide direct instruction to teach the properties of refraction, and then ask students to complete the *Investigate* to support their learning.

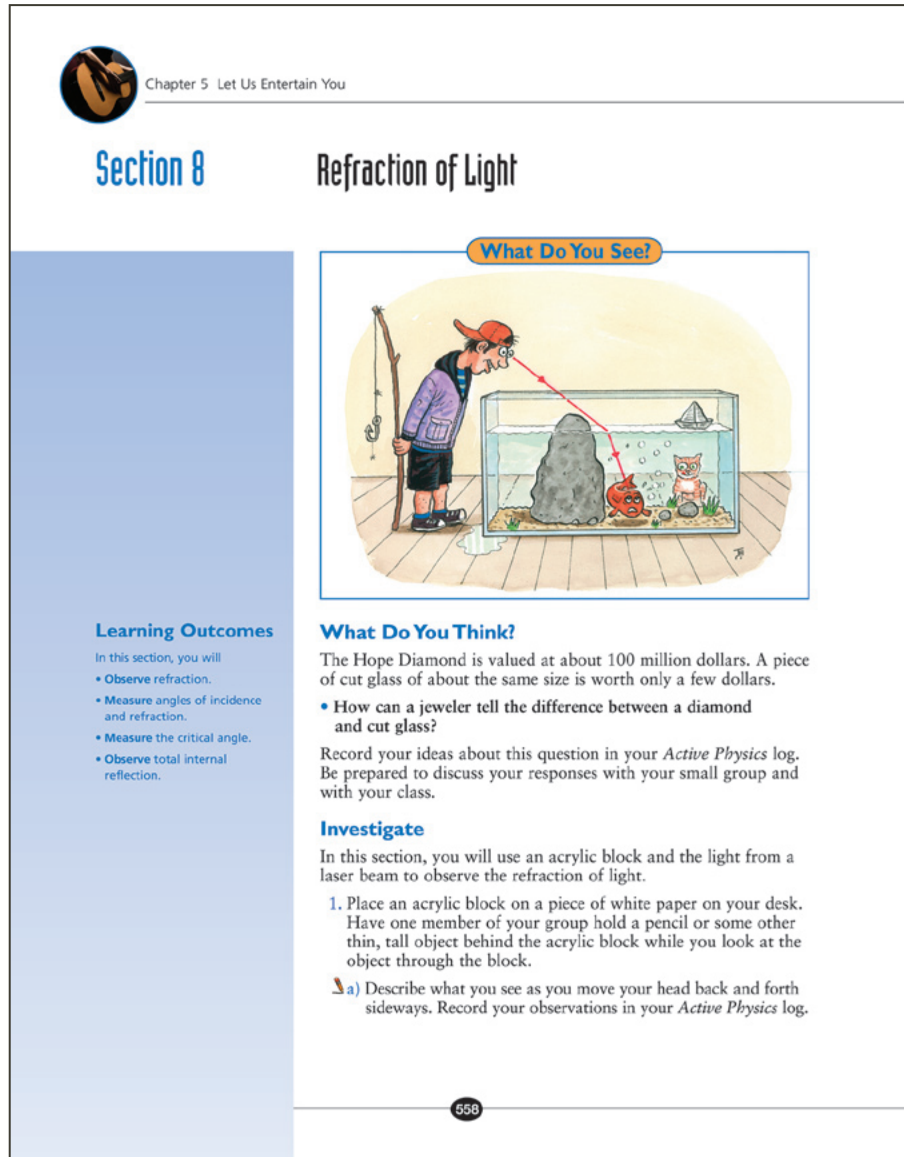
Learning Issue	Reference	Augmentation and Accommodations
Understanding the mathematical concepts introduced in Snell's law	***Physics Talk*** ***Active Physics Plus***	**Augmentation** • Students may not have the mathematical background knowledge to understand the sine of an angle without significant instruction. Focus on the concept instead of the mathematical relationship for some students. • Ask students to draw diagrams that represent the information in the last three paragraphs of the *Physics Talk*. Students can then present their drawings to the class to check their understanding. This *Investigate* can be differentiated by asking students to apply the sine of the angles and the index of refraction to their drawings for a challenge.

Strategies for Students with Limited English-Language Proficiency

Learning Issue	Reference	Augmentation
Vocabulary comprehension	***Investigate*** Steps 2 and 7	Be sure students are aware that "beam" and "ray" are used as synonyms, or words that mean the same thing. The incident ray is the same as the incident beam, for example.
Comprehension	***Investigate*** Step 4	Students have investigated the behavior of light when it bounces off a surface through which it cannot pass. Now they are investigating what happens when light passes through an object. Before they can determine the angle of refraction, they need to know that "refraction" means the apparent bending of light when it passes through an object.
Vocabulary comprehension Understanding concepts Research skills	***Investigate*** Step 8	Total internal reflection can be a difficult concept to grasp. Be sure students understand that it happens only when the incident ray (the light from the light source) hits the surface through which it passes exactly perpendicularly to the normal. If the incident ray hits the surface at any other angle, there will be some external reflection. If time allows, think about asking ELL students to research applications of total internal reflection and give a brief oral presentation on this useful phenomenon.
Vocabulary comprehension Understanding concepts	***Investigate*** Step 9	Draw a triangular prism showing total internal reflection on the board. Show the incident ray and the emerging ray. Ask an ELL student to volunteer to mark the critical angle of refraction on your drawing, so you can check understanding and answer any questions.
Comprehension Understanding concepts	***Physics Talk*** Snell's law (The law of refraction)	Now that students have worked with refraction, hold a brief class discussion to determine whether students have figured out that light refracts when it moves from one medium, or material, to another. Collaborate with students' math teachers to determine what level of comprehension students have obtained in trigonometry, specifically angles and sines of angles. Ask ELL students to put the equation for the index of refraction into their own words. Also, be sure students understand that the index of refraction is a characteristic of materials, so different materials have different indexes of refraction. A high index of refraction means that light exhibits lots of bending; a low index of refraction means less bending. Students should understand that the index of refraction is also a ratio of the speed of light in a vacuum to the speed of light in the material. Have ELL students paraphrase the law of refraction, also called Snell's law, into their own words. The information in this section is complicated, and is tied to many difficult terms. Hold a final, comprehensive class discussion to verify students' understanding of how Snell's law, the critical angle, and total internal reflection are related.

SECTION 8

Teaching Suggestions and Sample Answers


Chapter 5 Let Us Entertain You

Section 8 Refraction of Light

What Do You See?

Learning Outcomes

In this section, you will

- **Observe** refraction.
- **Measure** angles of incidence and refraction.
- **Measure** the critical angle.
- **Observe** total internal reflection.

What Do You Think?

The Hope Diamond is valued at about 100 million dollars. A piece of cut glass of about the same size is worth only a few dollars.

- **How can a jeweler tell the difference between a diamond and cut glass?**

Record your ideas about this question in your *Active Physics* log. Be prepared to discuss your responses with your small group and with your class.

Investigate

In this section, you will use an acrylic block and the light from a laser beam to observe the refraction of light.

1. Place an acrylic block on a piece of white paper on your desk. Have one member of your group hold a pencil or some other thin, tall object behind the acrylic block while you look at the object through the block.

a) Describe what you see as you move your head back and forth sideways. Record your observations in your *Active Physics* log.

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What Do You See?

Students will come up with many suggestions for this *What Do You See?* illustration. Most of them will probably comment on the arrow leading to the fish. You could prompt them to notice that the arrow changes direction when it reaches the water. Emphasize to students that they should return to this visual to reassess the significance of this illustration, once they have progressed further in this section. Remind them that this stage is meant to stimulate their interest. Acknowledge all answers.

What Do You Think?

This *What Do You Think?* question is designed for students

Students' Prior Conceptions

The reference frames for how incident rays and reflected rays of light behave form the foundation for examining how refracted rays of light behave. By engaging students in what happens as light approaches the acrylic block, travels inside the block and exits from the block, this section builds the foundation for understanding refraction and total internal reflection. Students should ask why they should be interested in this, as they extend their knowledge to how critical angle and refraction affect light transmission in everyday situations, and how they can apply what they observe in this section to an interesting and entertaining show at the end of the chapter. Tie-ins with modern communication tools and fiber optics may enhance student learning.

1. **Students believe that the speed of light is the same in all media.** Scientists believe that light particles interact with other particles and this "communication" slows down the passage of light in materials. Based on scientific facts, students extend their ideas about interactions of matter to light acting as a particle and recognize that the speed of light through optically more dense or optically less dense materials is affected by the interactive communications between molecules and light particles. Students can recognize the result as the slowing down or speeding up of light as it passes from one material to another. They can then infer refraction, the bending of light away from or toward a normal drawn at the interface of two materials where the light refracts, as a result of this change in speed.

2. **Different kinds of electromagnetic radiation travels at different speeds in a vacuum.** To address this misconception, which is also related to the previous misconception in this

to think about surfaces that produce different effects when they reflect light. You may want to ask them what they know about diamonds. If possible, demonstrate the sparkle of a diamond vs. cut glass. A discussion which captures their curiosity will serve to generate interest in the *Investigate*. Encourage students to record their answers as they will need them later on for reflection and review.

What Do You Think?

A Physicist's Response

A jeweler with a trained eye can identify a diamond with a careful look. A diamond reflects more light than cut glass, because of the diamond's greater index of refraction. The diamond also has a range of color not found in glass and also particular small imperfections. Despite these visual differences, many jewelers rely on an electrical device that applies a small amount of heat to an unknown stone and identifies a diamond from the resulting temperature change.

Investigate

1.a)

Students should see a disjointed image of the pencil when moving their heads. When they move their heads side to side, the bottom part of the pencil seen through the acrylic block will appear to move from one side of the pencil in air to the other side.

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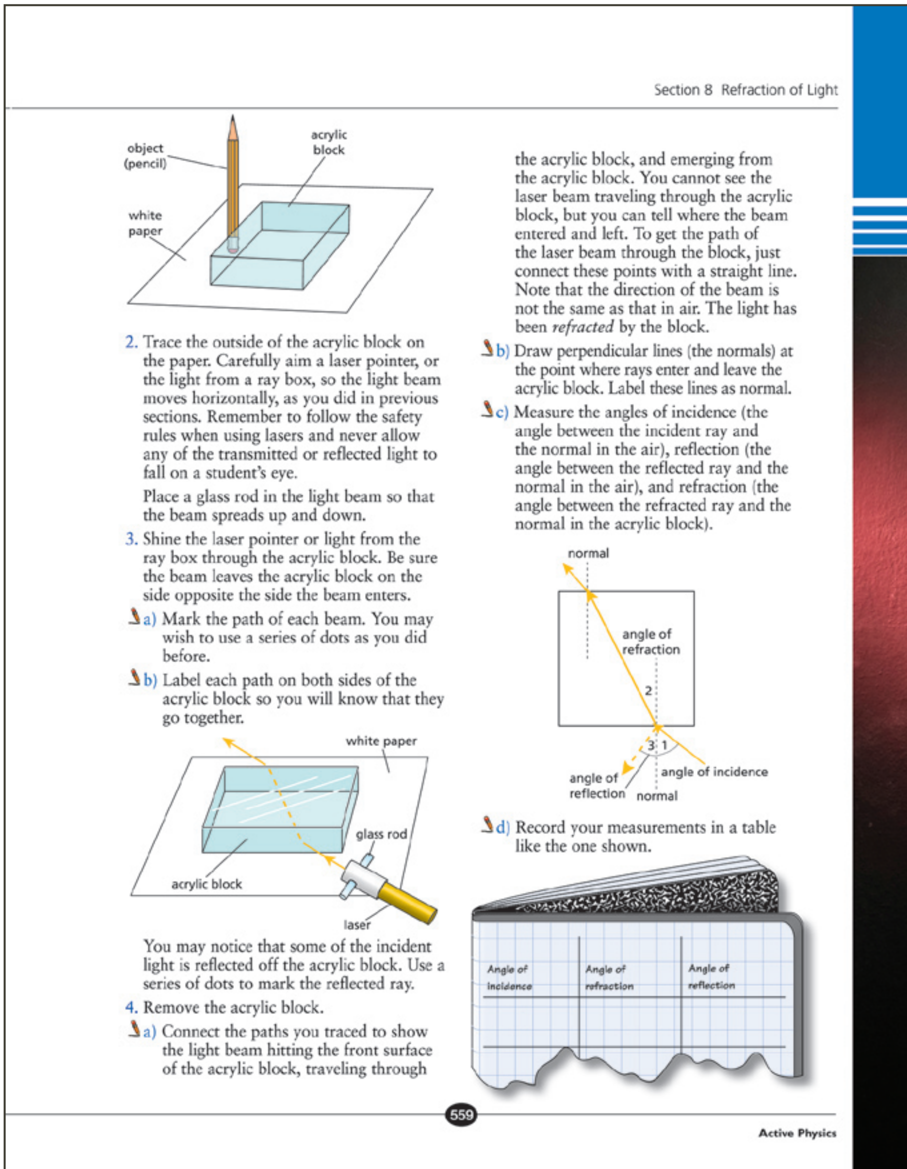
section, you need to emphasize that light consists of different energies, all found within the electromagnetic spectrum. Each of these has the same fundamental characteristic of traveling at the speed of light in a vacuum. Point out that the speed of light may be different for different frequency radiations in certain media, which for light results in a rainbow.

3. **Light bends toward the normal as it passes into the air from another medium.** This naïve conception is addressed through examination of the patterns of light passing from an optically more dense material to an optically less dense material. Experience, observations, collection of data, and model building assists students to contrast this prior conception with what they see and should believe. Both a mathematical description and the drawing of the observed light rays develop student understanding.

NOTES



2. Trace the outside of the acrylic block on the paper. Carefully aim a laser pointer, or the light from a ray box, so the light beam moves horizontally, as you did in previous sections. Remember to follow the safety rules when using lasers and never allow any of the transmitted or reflected light to fall on a student's eye.

Place a glass rod in the light beam so that the beam spreads up and down.

3. Shine the laser pointer or light from the ray box through the acrylic block. Be sure the beam leaves the acrylic block on the side opposite the side the beam enters.

a) Mark the path of each beam. You may wish to use a series of dots as you did before.

b) Label each path on both sides of the acrylic block so you will know that they go together.

You may notice that some of the incident light is reflected off the acrylic block. Use a series of dots to mark the reflected ray.

4. Remove the acrylic block.

a) Connect the paths you traced to show the light beam hitting the front surface of the acrylic block, traveling through the acrylic block, and emerging from the acrylic block. You cannot see the laser beam traveling through the acrylic block, but you can tell where the beam entered and left. To get the path of the laser beam through the block, just connect these points with a straight line. Note that the direction of the beam is not the same as that in air. The light has been *refracted* by the block.

b) Draw perpendicular lines (the normals) at the point where rays enter and leave the acrylic block. Label these lines as normal.

c) Measure the angles of incidence (the angle between the incident ray and the normal in the air), reflection (the angle between the reflected ray and the normal in the air), and refraction (the angle between the refracted ray and the normal in the acrylic block).

d) Record your measurements in a table like the one shown.

2.

Students set up the *Investigate*.

3.a)

Students will not be able to mark the path of the beam inside the block. They should find the path inside the block by connecting the points where the light enters and leaves the front and rear surfaces.

3.b)

Students should label the light ray that strikes the first surface, the refracted ray in the block, and the emerging ray at the rear surface.

5-8a **Blackline Master**

4.a)

Students should connect the dots with a ruler, tracing each ray up to the surface of the block, where the light ray changes direction.

4.b)

Students should add normals, so that their diagram looks similar to the one below *Step 4.c)* in the *Student Edition*.

4.c)

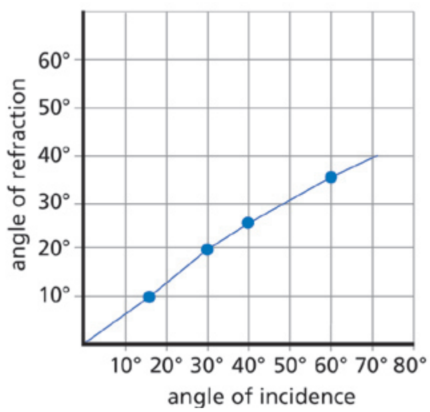
The angles of incidence, reflection, and refraction noted in the diagram should be measured as carefully as possible.

4.d)

Students should construct a data table to record the data for this and subsequent steps.

5.a)

Students construct the graph. Initially the graph may appear to be a straight line, but do not ask students to draw a line at this time. The graph should look similar to the following.



5.b)

Students should predict an angle of refraction of around 28°.

5.c)

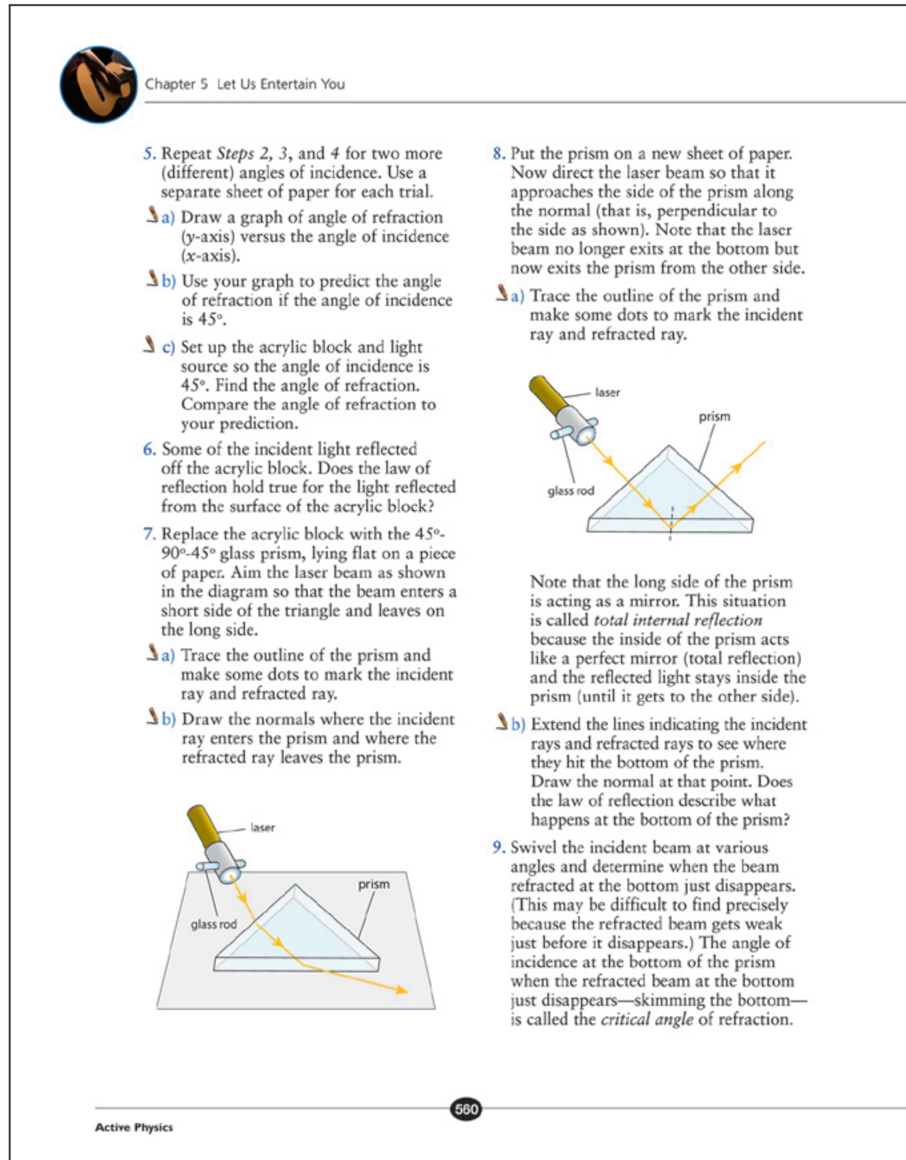
Students should measure an angle of refraction close to 28° if done carefully.

6.

Students will have to mark the incident and reflected beam from the front surface of the acrylic block to measure the angles of incidence and reflection. The law of reflection should hold with the angles being equal to each other within a few degrees.

7.a)

Students trace the outline of the prism and mark the incident and refracted angles. Students should shine the laser at an incident angle of approximately 40 degrees to the surface, as shown in the diagram after *Step 7.b)* for best results.



Chapter 5 Let Us Entertain You

5. Repeat *Steps 2, 3,* and *4* for two more (different) angles of incidence. Use a separate sheet of paper for each trial.

a) Draw a graph of angle of refraction (*y*-axis) versus the angle of incidence (*x*-axis).

b) Use your graph to predict the angle of refraction if the angle of incidence is 45°.

c) Set up the acrylic block and light source so the angle of incidence is 45°. Find the angle of refraction. Compare the angle of refraction to your prediction.

6. Some of the incident light reflected off the acrylic block. Does the law of reflection hold true for the light reflected from the surface of the acrylic block?

7. Replace the acrylic block with the 45°-90°-45° glass prism, lying flat on a piece of paper. Aim the laser beam as shown in the diagram so that the beam enters a short side of the triangle and leaves on the long side.

a) Trace the outline of the prism and make some dots to mark the incident ray and refracted ray.

b) Draw the normals where the incident ray enters the prism and where the refracted ray leaves the prism.

8. Put the prism on a new sheet of paper. Now direct the laser beam so that it approaches the side of the prism along the normal (that is, perpendicular to the side as shown). Note that the laser beam no longer exits at the bottom but now exits the prism from the other side.

a) Trace the outline of the prism and make some dots to mark the incident ray and refracted ray.

Note that the long side of the prism is acting as a mirror. This situation is called *total internal reflection* because the inside of the prism acts like a perfect mirror (total reflection) and the reflected light stays inside the prism (until it gets to the other side).

b) Extend the lines indicating the incident rays and refracted rays to see where they hit the bottom of the prism. Draw the normal at that point. Does the law of reflection describe what happens at the bottom of the prism?

9. Swivel the incident beam at various angles and determine when the beam refracted at the bottom just disappears. (This may be difficult to find precisely because the refracted beam gets weak just before it disappears.) The angle of incidence at the bottom of the prism when the refracted beam at the bottom just disappears—skimming the bottom—is called the *critical angle* of refraction.

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7.b)

Students should draw the normal lines and measure the angles of incidence and refraction for the laser beam striking the glass prism.

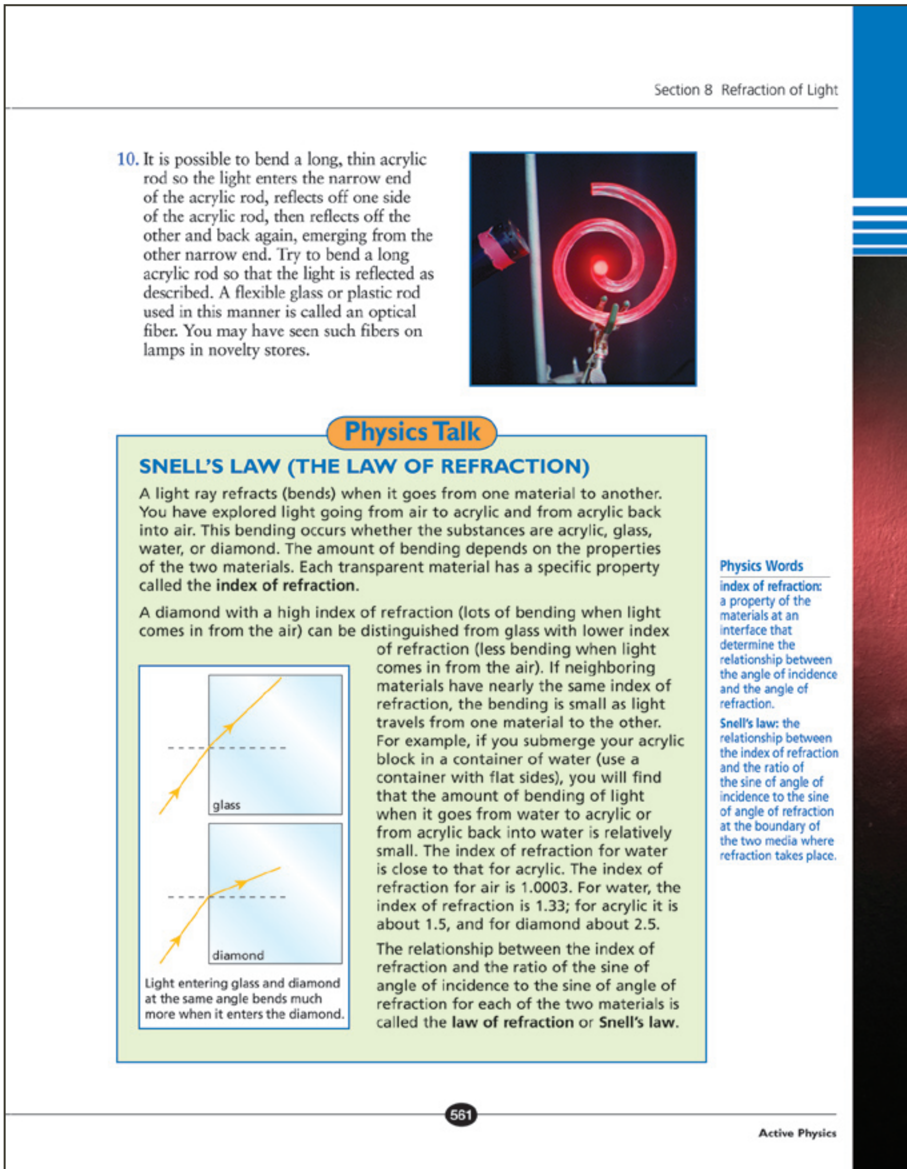
8.a)

Students trace the outline of the prism on the sheet of paper and set up an angle of incidence that is perpendicular to the face of the prism as shown in the diagram in *Step 8.a)*.

For a 45-90-45 prism, the angle of incidence at the bottom interface will be 45° if the incident ray is along the perpendicular to the side shown in the diagram. An angle of 45° is larger than the critical angle for a glass (or acrylic)-air interface. There should be total internal reflection.

8.b)

Students should lift the prism off the paper. After the incident


Section 8 Refraction of Light

10. It is possible to bend a long, thin acrylic rod so the light enters the narrow end of the acrylic rod, reflects off one side of the acrylic rod, then reflects off the other and back again, emerging from the other narrow end. Try to bend a long acrylic rod so that the light is reflected as described. A flexible glass or plastic rod used in this manner is called an optical fiber. You may have seen such fibers on lamps in novelty stores.

Physics Talk

SNELL'S LAW (THE LAW OF REFRACTION)

A light ray refracts (bends) when it goes from one material to another. You have explored light going from air to acrylic and from acrylic back into air. This bending occurs whether the substances are acrylic, glass, water, or diamond. The amount of bending depends on the properties of the two materials. Each transparent material has a specific property called the **index of refraction**.

A diamond with a high index of refraction (lots of bending when light comes in from the air) can be distinguished from glass with lower index of refraction (less bending when light comes in from the air). If neighboring materials have nearly the same index of refraction, the bending is small as light travels from one material to the other. For example, if you submerge your acrylic block in a container of water (use a container with flat sides), you will find that the amount of bending of light when it goes from water to acrylic or from acrylic back into water is relatively small. The index of refraction for water is close to that for acrylic. The index of refraction for air is 1.0003. For water, the index of refraction is 1.33; for acrylic it is about 1.5, and for diamond about 2.5.

Light entering glass and diamond at the same angle bends much more when it enters the diamond.

The relationship between the index of refraction and the ratio of the sine of angle of incidence to the sine of angle of refraction for each of the two materials is called the **law of refraction** or **Snell's law**.

Physics Words

index of refraction: a property of the materials at an interface that determine the relationship between the angle of incidence and the angle of refraction.

Snell's law: the relationship between the index of refraction and the ratio of the sine of angle of incidence to the sine of angle of refraction at the boundary of the two media where refraction takes place.

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Active Physics

and reflected rays are extended back to the bottom surface of the prism, a normal should be drawn at this surface to measure the incident and reflected angles.

The angle of incidence should equal to the angle of reflection within a few degrees, verifying the law of reflection for this surface.

9.

Note that as the critical angle is approached, the refracted intensity diminishes and the reflected intensity grows. Students should measure and mark the angle of incidence at the second surface that gives an angle of refraction of 90°.

10.

This is a model of an optical fiber. When the light hits the walls, there is total internal reflection and the light is trapped inside the fiber. You see the path of the light beam because a small amount of light is reflected (or scattered) from bubbles and small imperfections in the gelatin. If you are using the laser to test this, remove the glass rod from the beam.

Physics Talk

The *Physics Talk* discusses the refraction of light. Students learn that light bends while passing through a transparent material, and the amount of bending is related to a quantity known as the index of refraction. Each material has a specific index of refraction. The diagrams in the *Student Edition* show how the relative bending of light depends upon the material's index of refraction. Snell's law of refraction states that the larger the difference between the speed of light in the two materials, the larger the difference between the angle of incidence and refraction.

Based on the values for the angles of refraction, consider asking students to indicate which material would have a higher index of refraction. Encourage them to write down the definitions of *Physics Words* and explain each definition with a diagram. Ask questions to determine if they understand the concept of a critical angle. Have students write and ponder the definitions they learn. Ask them to record any questions they might have. Discuss their comprehension of the *Physics Talk*. Getting them into small groups before they come together in a whole-class discussion would help them probe their understanding of new terms in greater depth.

Students should be able to connect the significance of the critical angle to total internal reflection. Ask them if they understand the index of refraction in terms of the speed of light in a vacuum and why such a relationship is significant.

5-8b Blackline Master

Checking Up

1.

Light rays bend when they travel from one substance to another because each substance has a different property that is responsible for how much a light will bend in that substance.

2.

The angle of refraction of a diamond would be measured in the same manner as measuring the index of refraction of the acrylic block, by measuring the angle of incidence and the angle of refraction and taking the ratio of the two numbers.

3.

The relationship between the angle of incidence, the angle of refraction, and the index of refraction for each of the two materials is called the law of refraction or Snell's law.

Snell's law states that as light enters a substance such as acrylic (high index of refraction) from air (low index of refraction), the light bends toward the normal. When light leaves a substance such as acrylic (high index of refraction) and enters the air (low index of refraction), it bends away from the normal. The larger the difference in the index of refraction for the two materials, the larger the difference between the angle of incidence and the angle of refraction.

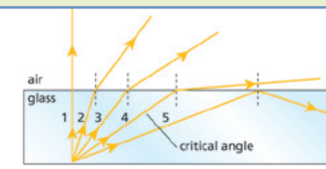
If the light is entering material such as air (with a low index of refraction) from a substance with a higher index of refraction, the angle in that substance may be such that the angle of refraction is 90°. In this special case, the angle in the substance is called the **critical angle**. If the angle in the substance is greater than this critical angle, then the light does not enter the air but reflects back into the substance as if the surface were a perfect mirror. This is the basis for optical fibers in which laser light reflects off the inner walls of glass or plastic and travels down the fiber, regardless of the bend in the fiber.

You noticed in the investigation at every air-glass interface, some of the light was reflected and some of the light was refracted. The exception to this was the light's angle of incidence was greater than the critical angle. In this case, all of the light was reflected back into the glass. The result is **total internal reflection**.

Physics Words

critical angle: the angle of incidence, for a light ray passing from one medium to another, that has an angle of refraction of 90°.

total internal reflection: a phenomenon in which the refracting medium acts like a perfect mirror and the reflected light stays inside the medium.

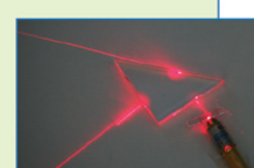


In the diagram, rays 1-3 leave the glass and bend away from the normal as they enter the air. Ray 4 leaves the glass and bends away from the normal such that its angle of refraction is 90°. The angle of incidence is defined as the critical angle. Ray 5 has an angle of incidence greater than the critical angle. It reflects back into the glass. The angle of incidence is equal to the angle of reflection.

It turns out that the index of refraction is also related to the speed with which light travels in vacuum and also to the average speed with which light travels through the material. The relationship is expressed as

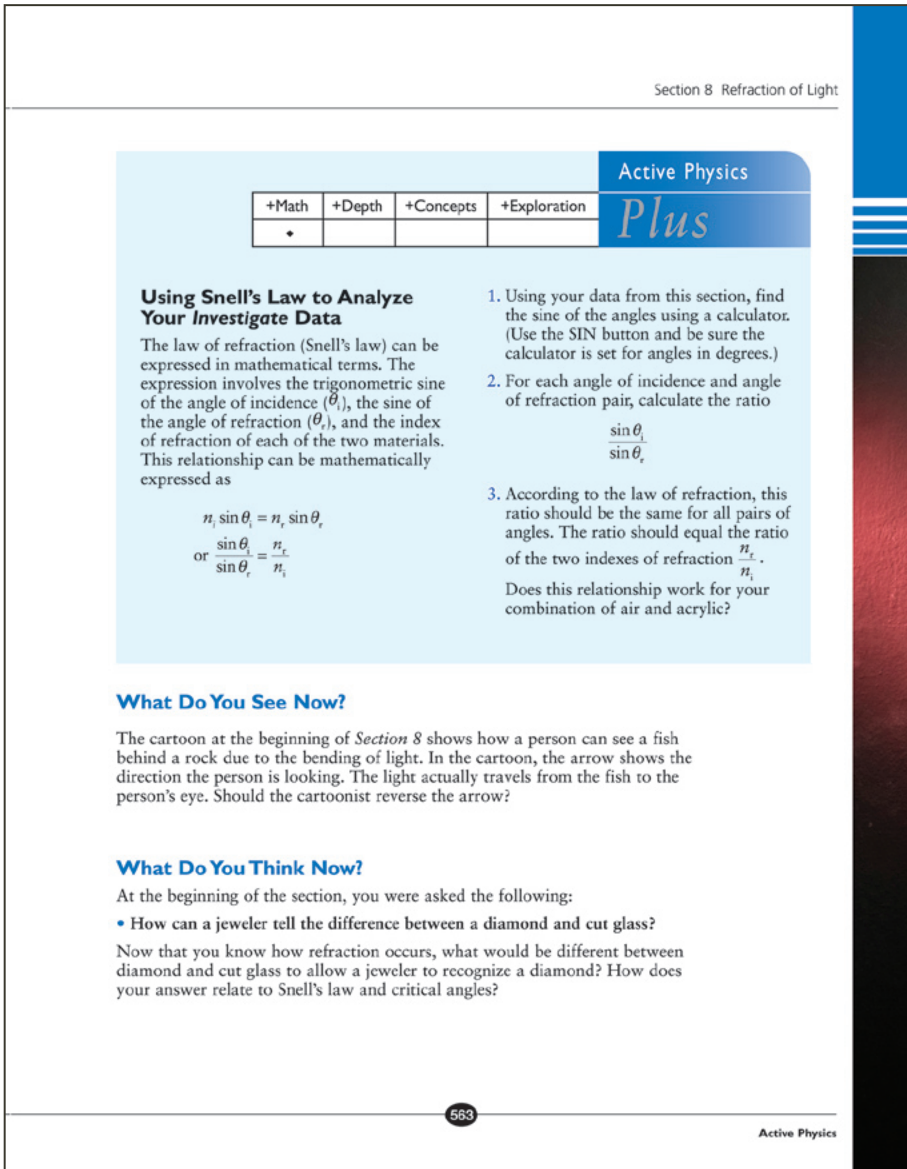
$$\text{index of refraction} = \frac{\text{speed of light in vacuum}}{\text{speed of light in the material}}$$

The speed of light in a vacuum is 2.99×10^8 m/s, a very high speed! In fact, it is the fastest speed that anything can attain.



Checking Up

1. Why do light rays bend when they travel from one substance to another?
2. Explain how you can measure a diamond's index of refraction.
3. Explain Snell's law.



Active Physics *Plus*

+Math	+Depth	+Concepts	+Exploration
•			

Using Snell's Law to Analyze Your *Investigate* Data

The law of refraction (Snell's law) can be expressed in mathematical terms. The expression involves the trigonometric sine of the angle of incidence (θ_i), the sine of the angle of refraction (θ_r), and the index of refraction of each of the two materials. This relationship can be mathematically expressed as

$$n_i \sin\theta_i = n_r \sin\theta_r$$

or $$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_r}{n_i}$$

1. Using your data from this section, find the sine of the angles using a calculator. (Use the SIN button and be sure the calculator is set for angles in degrees.)
2. For each angle of incidence and angle of refraction pair, calculate the ratio
$$\frac{\sin\theta_i}{\sin\theta_r}$$
3. According to the law of refraction, this ratio should be the same for all pairs of angles. The ratio should equal the ratio of the two indexes of refraction $\frac{n_r}{n_i}$.
Does this relationship work for your combination of air and acrylic?

What Do You See Now?

The cartoon at the beginning of *Section 8* shows how a person can see a fish behind a rock due to the bending of light. In the cartoon, the arrow shows the direction the person is looking. The light actually travels from the fish to the person's eye. Should the cartoonist reverse the arrow?

What Do You Think Now?

At the beginning of the section, you were asked the following:

- **How can a jeweler tell the difference between a diamond and cut glass?**

Now that you know how refraction occurs, what would be different between diamond and cut glass to allow a jeweler to recognize a diamond? How does your answer relate to Snell's law and critical angles?

Active Physics Plus

1.

Students should note that different calculators use different notations to find the sine of an angle. For a graphing calculator, students push the buttons in the order indicated by the expression—first "sin" and then the angle. For non-graphical calculators students first push the angle button, then the "sin" button. For both cases, make certain that the calculator is set to degrees, not radians.

2.

An example of the data might be an angle of incidence of 45° and an angle of refraction of 29°. The expression then becomes

$$\frac{\sin\ \theta_i}{\sin\ \theta_r} = \frac{\sin 45°}{\sin 29°} = \frac{0.707}{0.485} = 1.458.$$

3.

Depending upon how carefully students measured the angles, the values for an acrylic-air interface should cluster around 1.5.

What Do You See Now?

Yes! The arrow should be reversed since light reflects off the fish, travels through the water to the surface, and then bends away from the normal, and up to the human eye. The ancient Greeks used to believe that light was emitted from the eye, which allowed you to see the things you looked at, but science has since disproved this idea.

No! If the arrow was reversed, the physics would be correct, but the viewer would think that the fish was looking at the man. Yes or no? How do you reconcile the correct physics with the way in which people interpret pictures?

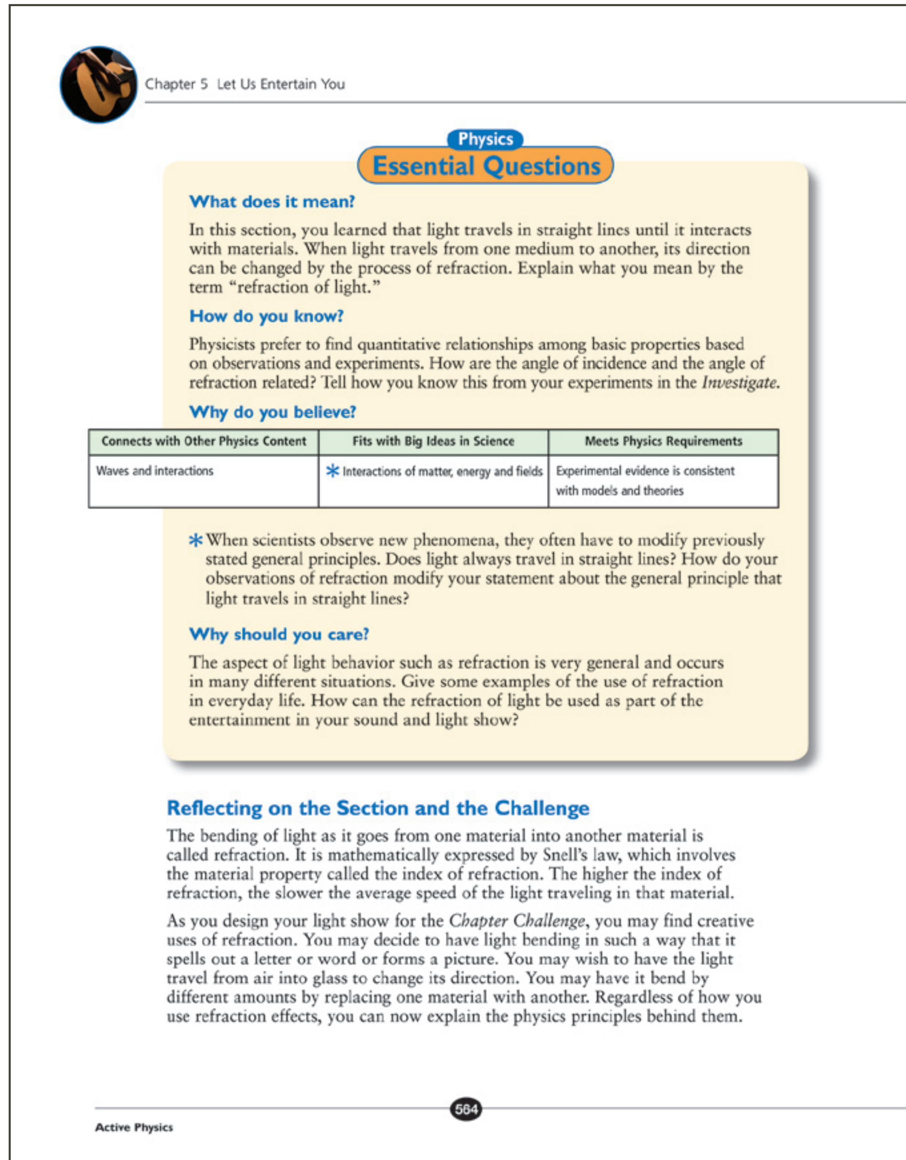
What Do You Think Now?

Students should look up information on the index of refraction of a diamond and compare it to the index of refraction of glass. Point out to them that the considerably higher index of refraction of diamond explains the higher "brilliance" of the diamond (more internal reflection sending light rays toward your eyes). This is the time for them to revise and update their answers.

CHAPTER 5

Reflecting on the Section and the Challenge

Students should be able to connect the physics principles they have learned in this section to their *Chapter Challenge*. Develop a discussion that focuses on refraction and have students list the main concepts they have learned in this section. You might want to highlight the creative aspects of using refraction techniques for the light effects that students can use in their show. Point out to them how light changes direction. Consider asking them to write a paragraph on the importance of refraction.



Chapter 5 Let Us Entertain You

Physics **Essential Questions**

What does it mean?

In this section, you learned that light travels in straight lines until it interacts with materials. When light travels from one medium to another, its direction can be changed by the process of refraction. Explain what you mean by the term "refraction of light."

How do you know?

Physicists prefer to find quantitative relationships among basic properties based on observations and experiments. How are the angle of incidence and the angle of refraction related? Tell how you know this from your experiments in the *Investigate*.

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Waves and interactions	* Interactions of matter, energy and fields	Experimental evidence is consistent with models and theories

* When scientists observe new phenomena, they often have to modify previously stated general principles. Does light always travel in straight lines? How do your observations of refraction modify your statement about the general principle that light travels in straight lines?

Why should you care?

The aspect of light behavior such as refraction is very general and occurs in many different situations. Give some examples of the use of refraction in everyday life. How can the refraction of light be used as part of the entertainment in your sound and light show?

Reflecting on the Section and the Challenge

The bending of light as it goes from one material into another material is called refraction. It is mathematically expressed by Snell's law, which involves the material property called the index of refraction. The higher the index of refraction, the slower the average speed of the light traveling in that material.

As you design your light show for the *Chapter Challenge*, you may find creative uses of refraction. You may decide to have light bending in such a way that it spells out a letter or word or forms a picture. You may wish to have the light travel from air into glass to change its direction. You may have it bend by different amounts by replacing one material with another. Regardless of how you use refraction effects, you can now explain the physics principles behind them.

Active Physics 564

Physics Essential Questions

What does it mean?

When light travels from one transparent medium to another (for example, air to glass) at an angle greater than 0°, the light changes direction. This bending of light is called refraction of the light.

How do you know?

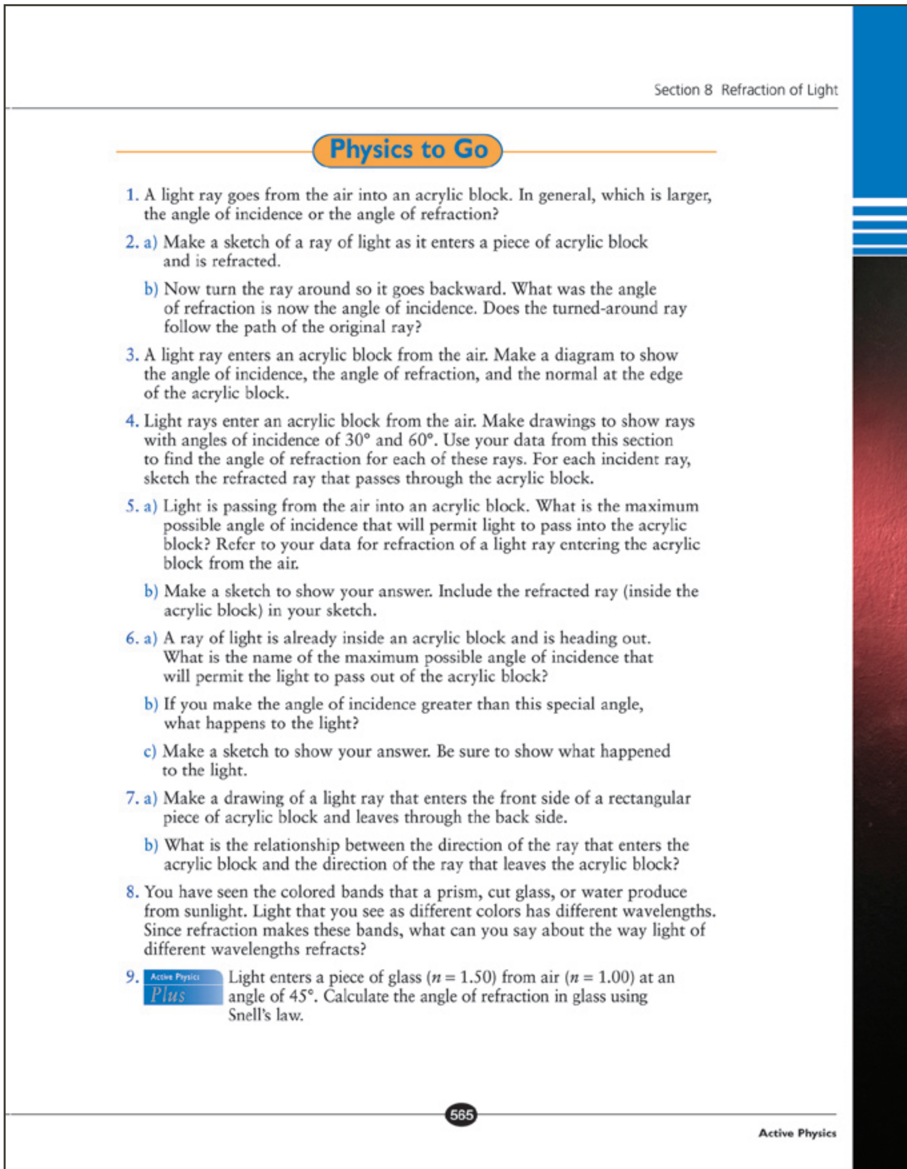
In the *Investigate, Step 5,* finding angles of refraction for different angles of incidence shows that as the angle of incidence increases, the angle of refraction also increases. This is not a linear relationship. The sine of the angle of incidence is directly proportional to the sine of the angle of refraction. Snell's law is the mathematical statement of that relationship.

Why do you believe?

Light travels in a straight line in one medium. When it enters another medium, it can refract (change direction) and then travel in a different straight line.

Why should you care?

When you see people in a swimming pool, they appear to have short legs because of the refraction of light. When you look at the depth of a pool or an aquarium, it appears less deep because of refraction. The background behind a barbecue appears distorted because of refraction of light through the heated air. In the light and sound show, the light can be shown to bend to produce interesting effects.



Physics to Go

1. A light ray goes from the air into an acrylic block. In general, which is larger, the angle of incidence or the angle of refraction?
2. a) Make a sketch of a ray of light as it enters a piece of acrylic block and is refracted.
   b) Now turn the ray around so it goes backward. What was the angle of refraction is now the angle of incidence. Does the turned-around ray follow the path of the original ray?
3. A light ray enters an acrylic block from the air. Make a diagram to show the angle of incidence, the angle of refraction, and the normal at the edge of the acrylic block.
4. Light rays enter an acrylic block from the air. Make drawings to show rays with angles of incidence of 30° and 60°. Use your data from this section to find the angle of refraction for each of these rays. For each incident ray, sketch the refracted ray that passes through the acrylic block.
5. a) Light is passing from the air into an acrylic block. What is the maximum possible angle of incidence that will permit light to pass into the acrylic block? Refer to your data for refraction of a light ray entering the acrylic block from the air.
   b) Make a sketch to show your answer. Include the refracted ray (inside the acrylic block) in your sketch.
6. a) A ray of light is already inside an acrylic block and is heading out. What is the name of the maximum possible angle of incidence that will permit the light to pass out of the acrylic block?
   b) If you make the angle of incidence greater than this special angle, what happens to the light?
   c) Make a sketch to show your answer. Be sure to show what happened to the light.
7. a) Make a drawing of a light ray that enters the front side of a rectangular piece of acrylic block and leaves through the back side.
   b) What is the relationship between the direction of the ray that enters the acrylic block and the direction of the ray that leaves the acrylic block?
8. You have seen the colored bands that a prism, cut glass, or water produce from sunlight. Light that you see as different colors has different wavelengths. Since refraction makes these bands, what can you say about the way light of different wavelengths refracts?
9. Active Physics Plus Light enters a piece of glass ($n = 1.50$) from air ($n = 1.00$) at an angle of 45°. Calculate the angle of refraction in glass using Snell's law.

Physics to Go

1.

The light is bent toward the normal, so the angle of incidence is larger (except when the angle of incidence is zero).

2.a)

Students' sketches should be similar to the sketch in the *Investigate, Step 3*.

2.b)

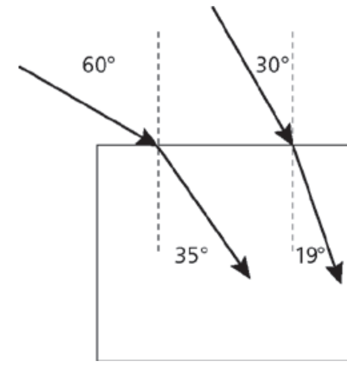
Yes. This is the principle of ray reversibility.

3.

Students' sketches should be similar to the sketch in the *Investigate, Step 4*.

4.

Students' diagrams should appear similar to the one above. The angles of refraction they list will depend upon the accuracy of their measurements from *Steps 4* and *5* of the *Investigate*.

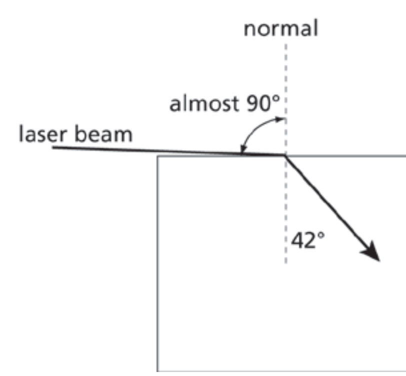


5.a)

The maximum angle of incidence is 90°. There is no critical angle for incidence. However, as the angle of incidence increases, more light is reflected off the surface and less is refracted into the block.

5.b)

The angle of incidence equals 90°. The angle of refraction equals 42°, the critical angle.



6.a)

The critical angle.

6.b)

All the light is reflected inside the block.

6.c)

The angle of reflection (inside the block) should equal the angle of incidence (inside the block).

CHAPTER 5

Students drawing should resemble the drawing in the *Investigate, Step 8*.

7.a)

Students' sketches should be similar to the sketch in the *Investigate Step 3.b)*.

7.b)

The incident ray striking the front surface of the block is parallel to the refracted ray exiting the back surface of the block if the front and back of the block are parallel. This can be demonstrated using geometry. By alternate interior angles, inside the acrylic block the angle of refraction at the front surface is equal to the angle of incidence at the rear of the block if the front and back are parallel. Because the light paths can be reversed, the angle of refraction in the air equals the angle of incidence in the air.

8.

The amount of refraction depends on the wavelength. Equivalently, the angle of refraction varies with the wavelength.

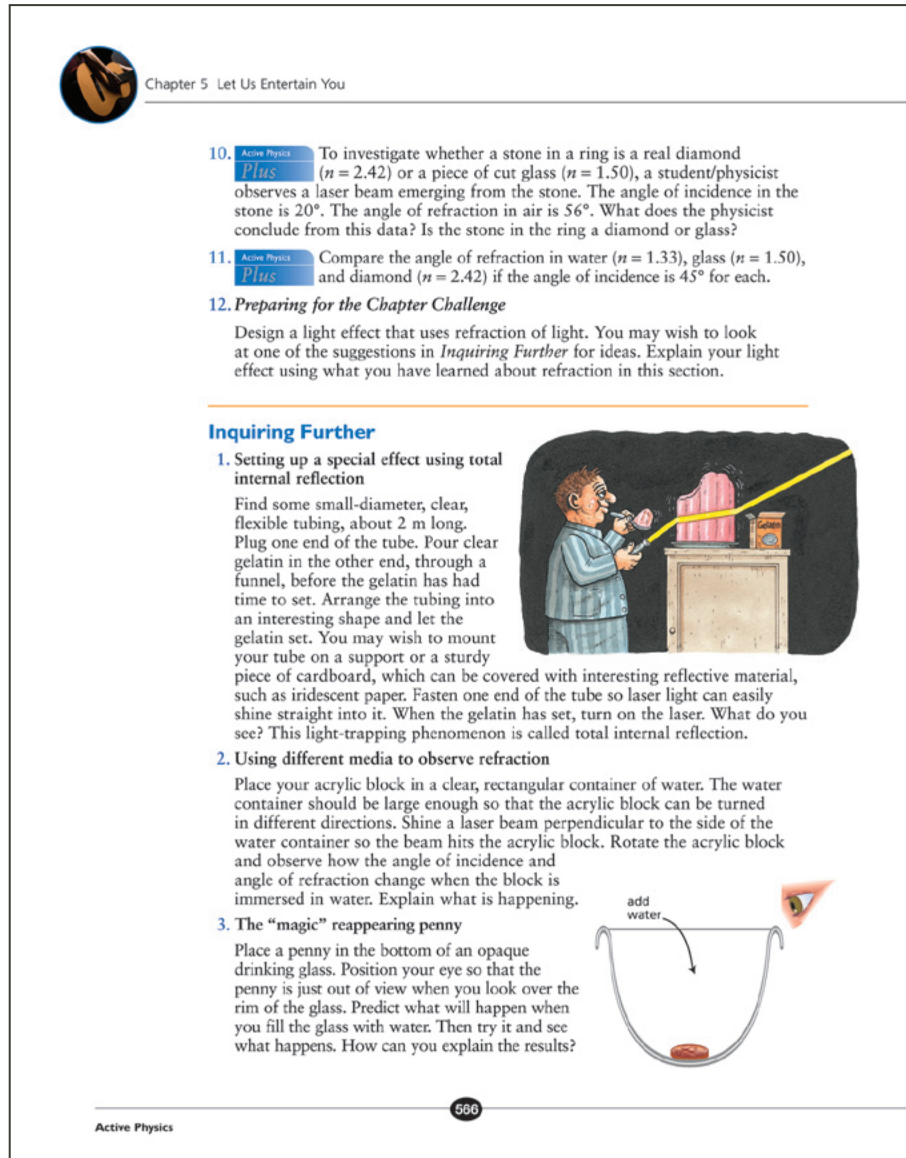
9. Active Physics *Plus*

Because $n_i \sin\theta_i = n_r \sin\theta_r$,
$1(\sin 45°) = 1.5 \sin\theta_r$;
therefore, $\theta_r = 28°$.

10. Active Physics *Plus*

Because $n_i \sin\theta_i = n_r \sin\theta_r$,
$1(\sin 56°) = n_r \sin 20°$;
therefore, $n_r = 2.42$.

The stone is a diamond.



Chapter 5 Let Us Entertain You

10. Active Physics *Plus* To investigate whether a stone in a ring is a real diamond ($n = 2.42$) or a piece of cut glass ($n = 1.50$), a student/physicist observes a laser beam emerging from the stone. The angle of incidence in the stone is 20°. The angle of refraction in air is 56°. What does the physicist conclude from this data? Is the stone in the ring a diamond or glass?

11. Active Physics *Plus* Compare the angle of refraction in water ($n = 1.33$), glass ($n = 1.50$), and diamond ($n = 2.42$) if the angle of incidence is 45° for each.

12. *Preparing for the Chapter Challenge*

Design a light effect that uses refraction of light. You may wish to look at one of the suggestions in *Inquiring Further* for ideas. Explain your light effect using what you have learned about refraction in this section.

Inquiring Further

1. **Setting up a special effect using total internal reflection**

Find some small-diameter, clear, flexible tubing, about 2 m long. Plug one end of the tube. Pour clear gelatin in the other end, through a funnel, before the gelatin has had time to set. Arrange the tubing into an interesting shape and let the gelatin set. You may wish to mount your tube on a support or a sturdy piece of cardboard, which can be covered with interesting reflective material, such as iridescent paper. Fasten one end of the tube so laser light can easily shine straight into it. When the gelatin has set, turn on the laser. What do you see? This light-trapping phenomenon is called total internal reflection.

2. **Using different media to observe refraction**

Place your acrylic block in a clear, rectangular container of water. The water container should be large enough so that the acrylic block can be turned in different directions. Shine a laser beam perpendicular to the side of the water container so the beam hits the acrylic block. Rotate the acrylic block and observe how the angle of incidence and angle of refraction change when the block is immersed in water. Explain what is happening.

3. **The "magic" reappearing penny**

Place a penny in the bottom of an opaque drinking glass. Position your eye so that the penny is just out of view when you look over the rim of the glass. Predict what will happen when you fill the glass with water. Then try it and see what happens. How can you explain the results?

add water

566

Active Physics

11. Active Physics *Plus*

Using $n_i \sin\theta_i = n_r \sin\theta_r$
for water, $1(\sin 45°) = 1.33 \sin\theta_r$;
therefore, $\theta_r = 32°$.

Using $n_i \sin\theta_i = n_r \sin\theta_r$
for glass, $1(\sin 45°) = 1.5 \sin\theta_r$;
therefore, $\theta_r = 28°$.

Using $n_i \sin\theta_i = n_r \sin\theta_r$
for diamond,
$1(\sin 45°) = 2.42 \sin\theta_r$;
therefore, $\theta_r = 17°$.

12.

Preparing for the Chapter Challenge

Students should design a light effect that uses refraction of light. They should explain their light effect using what they know about refraction.

Inquiring Further

1. Setting up a special effect using total internal reflection

The laser beam will pass through the gelatin and tubing. Whenever it reaches the surface between the gelatin and the tubing, total internal reflection occurs. This is an example of an optical fiber.

2. Using different media to observe refraction

For the acrylic block in water, the index of refraction acrylic (about 1.5) is close to that of water (about 1.33). Therefore, as the ray goes from water to acrylic and vice versa, there will be much less bending of a light ray than in the case of air-acrylic. The important point is that the amount of bending depends on both indices of refraction— that of the medium in which the incident ray is traveling and of the medium in which the refracted ray is traveling.

3. The "magic" reappearing penny

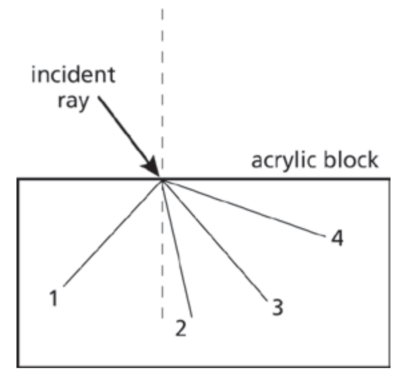
When the light rays leave the water, they bend away from the normal (the vertical). If you find the ray from the water that enters your eye, extend this ray backward to find where you will see the coin.

NOTES

SECTION 8 QUIZ

5-8c Blackline Master

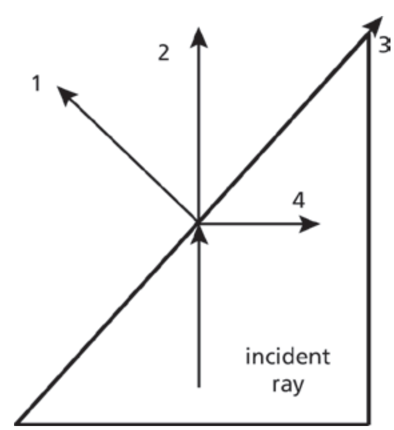
1. The diagram at the right shows a beam of light in air striking an acrylic block. As the beam enters the block it will travel along path



a) 1. b) 2.

c) 3. d) 4.

2. A light ray is traveling in a glass right-angle prism as shown in the diagram at the right. If the beam of light in the prism strikes the surface at an angle greater than the critical angle, the light beam will travel along path



a) 1. b) 2.

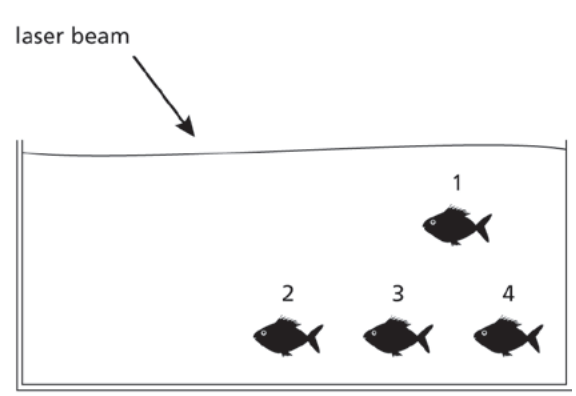
c) 3. d) 4.

3. A student measures the speed of light in a material and finds that a light beam travels at the speed of 2×10^8 m/s there. If the speed of light in a vacuum is 3×10^8 m/s, what is the index of refraction of this material?

a) 1×10^8. b) 2×10^8.

c) 1.5. c) 6.

4. A student shines a laser into a fish tank as shown in the following diagram. On which of the fish in the diagram would the laser beam shine?



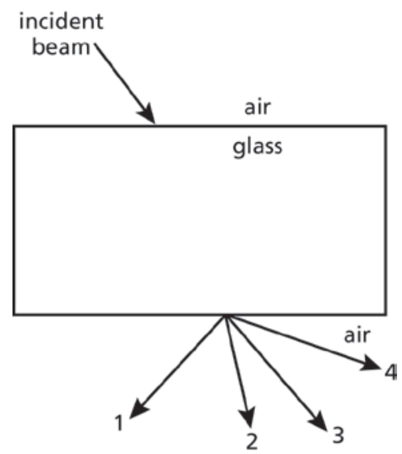
a) 1.

b) 2.

c) 3.

d) 4.

5. The diagram at the right shows a beam of light traveling in air and striking a glass block. Which light ray correctly shows the path of the light as it leaves the glass block and goes back into air?



a) 1.   b) 2.

c) 3.   d) 4.

SECTION 8 QUIZ ANSWERS

1 b) When light goes from a material with a lesser index of refraction (air) to a greater index of refraction (acrylic), the light beam slows down and bends toward the perpendicular. The light beam can never cross the normal, as in choice *a)*, and is not bending toward the perpendicular, as in choices *c)* and *d)*.

2 d) When a light beam strikes a surface at an angle greater than the critical angle, it will undergo total internal reflection. Only path 4 shows a reflected beam. Path 3 is the direction the refracted beam would take if it struck exactly at the critical angle.

3 c) The index of refraction of a material can be calculated from $n = c/v$ or $(3 \times 10^8 \text{ m/s})/(2 \times 10^8 \text{ m / s}) = 1.5$.

4 b) When light goes from a material of lesser index of refraction (air) to a greater index of refraction (water), the light beam slows down and bends toward the perpendicular. Only the fish in position 2 could be struck by a beam that bends toward the perpendicular from its present position.

5 c) When a light beam passes through a transparent material with 2 parallel faces, the beam emerges parallel to the incident beam. Only path 3 shows a parallel beam. Path 1 would require a reflection, and there is no surface to reflect from (the normal is not a surface). Path 2 can only be taken when a beam strikes the surface at an angle of incidence that is zero degrees.