Chapter 21: Reflection and Refraction

- Can you make something become invisible?
- How do you build a periscope?
- How does fiber optics work?

Make sure you know how to:
1. Use a protractor to measure angles.
2. Draw a wave front.
3. Apply Huygens principle.

CO: Imagine a magic trick. A “magician” in front of your eyes breaks a glass vile with a hammer and places the broken glass pieces in a beaker full of oil that has nothing but oil in it. Then she says “abracadabra” and places her hand in the beaker and takes out an intact vile. Would you believe that the magic words made the broken pieces combine in the vile again, as the magician wants you to believe? You probably would not. Maybe the magician hid another vile in the oil prior to the experiment and just picked it out at the right time? But how could the magician hide an unbroken vile in transparent oil through which you can see? In this chapter you will learn how to do this trick!

Lead: So far we have studied mechanical, thermal and electro-magnetic phenomena. These phenomena seem different on the surface, but can be understood using physical quantities such as acceleration, force and electric charge and fundamental principles such as momentum, energy, and charge conservation. We also found that many tools that we invented in mechanics, such as motion and force diagrams and momentum and energy bar charts, help us understand and build microscopic models of processes involving fluids, gases and electrically charged objects. One phenomenon we have not investigated so far is LIGHT. Is light different from everything we studied before or can we use the principles and tools we mastered before to understand its nature and apply these ideas for useful purposes? This chapter and the rest of the book will help you see the connections between the nature of light and many physical phenomena already familiar to us and the ones that are awaiting our attention.

21.1. Sources and propagation of light, shadows

Light is a big part of everyday life but we rarely question how it works. A long time ago people thought that humans saw by using special invisible rays emitted by their own eyes. Their eyes emitted these rays, which then reached an object and wrapped around it to collect
information about it. The rays then returned to the person’s eyes with this information. According to this model, we can see in total darkness. That idea can be easily checked if you sit for a while in a completely closed room with no lights or windows. It is difficult to find a room like this so if you try this experiment on your own make sure that the room is “light-sealed”. You will find that if the room is totally isolated from the outside, then no matter how long you wait you see nothing. This experiment rejects the ancient model. There must be some other explanation for how we see things. Consider the experiments in the Observational Experiment Table 21.1.

**Observational Experiment Table 21.1** How do we see objects?

<table>
<thead>
<tr>
<th>Observational experiment</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) In a dark room shine a laser pointer so you see a spot of light on the wall. You do not see light going from the laser pointer to the wall. If you place your hand (like a screen) along the straight line connecting the laser to the bright spot on the wall – the bright spot disappears. If you place your hand along a straight line connecting the spot on the wall and your eye, you do not see the spot.</td>
<td>The light has to travel to the wall along a straight line. When the light reaches the wall, it somehow bounces to your eyes so that you see the bright spot on the wall).</td>
</tr>
<tr>
<td>(b) Repeat experiment (a). This time sprinkle chalk dust along a line from the laser pointer to the wall. You now see the path of the light from the laser to the wall. The path is a straight line</td>
<td>Evidently, you see the path because light reflects off the tiny pieces of chalk dust into your eyes.</td>
</tr>
</tbody>
</table>

**Pattern**

We can see surfaces of objects (even the tiny ones) illuminated by light by not light itself. The path of light is a straight line – from the source of light to the object and from the object to our eyes.

From the pattern in the table above we can conclude that light from a light source propagates in a straight line until it hits an obstacle from which it reflects. Some of the reflected light reaches your eyes and some goes in other directions, as others see the same spot on the wall. Summarizing the findings, three things are needed for us to see something: we need a source of light, an object from which the light bounces off and our eyes, which record light entering them.

Experiments in the table above indicate that light travels from a source in a straight line to an object in its path. We can indicate this path with a straight line and arrow showing the direction of travel. This line with an arrow can be a simple model of the process of light transmission – *a ray of light*. A light ray is not a real thing—just a way for us to represent the direction it travels. Light rays seem real when we see light traveling in a dusty room (light coming into the window of the church in Fig. 21.1a) or passing between trees in a forest after it rains (Fig. 21.1b). But we don’t see the rays of light; instead we see objects along the light’s path that intercept and reflect the light.
Light emitted by and reflected from object

We constructed a ray model to help describe light propagation. Can we use the ray model to investigate the behavior of light coming from more common objects such as light bulbs or the Sun?

We represented the light from a laser traveling toward a wall by a single ray. Representing light beam from a laser with just one ray is a model or a simplification. If this model accurately described light propagation, the spot on the wall would be tiny and the same size independently of the distance between the laser and the wall. But if you have laser pointer you can easily discover that the spot on the wall increases in size as you move the laser away from the wall. However, this increase is not very dramatic. Thus we will continue to use the model of a single ray (or several parallel rays) when we deal with laser pointers.

Notice that after the laser light hits the wall any observer in the room can see the small bright spot on the wall. It looks like the bright spot sends light that needs to be represented by multiple rays. These observations lead us to two different models to describe the light leaving an extended light source:

1) An extended light source consists of multiple points emitting light. Similar to the laser, each point of an extended light source sends out light that can be represented by one ray (Fig. 21.2a).

2) An extended light source consists of multiple points emitting light. Similar to the chalk dust in the laser beam’s path or a spot on the wall, each point on a light source emits light represented by multiple rays traveling in many different directions (Fig. 21.2b).

To decide which model represents the real phenomena better, we use the two competing ideas to make predictions about the outcome of three new experiments in Testing Experiment Table 21.2. All of the experiments should be conducted in a dark room.
Testing Experiment Table 21.2 How many rays does each point on a light source emit?

<table>
<thead>
<tr>
<th>Testing experiment</th>
<th>Predictions</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment 1:</strong> Turn on a light bulb and place a pencil close to the wall between the bulb and the wall.</td>
<td>Using the one-ray idea, we predict a dark shadow behind the pencil where the rays do not reach the wall.</td>
<td>We see a dark sharp shadow on the wall.</td>
</tr>
<tr>
<td></td>
<td>Using the multiple-ray idea, we predict a dark shadow behind the pencil where the rays do not reach the wall.</td>
<td></td>
</tr>
<tr>
<td><strong>Experiment 2:</strong> Turn on a light bulb and place a pencil closer to the bulb between the bulb and the wall.</td>
<td>Using the one-ray idea, we predict the same outcome as in the above experiment 1.</td>
<td>We see a fuzzy light shadow (not as dark as in experiment 1).</td>
</tr>
<tr>
<td></td>
<td>Using the multiple-ray idea, we predict a light shadow with a fuzzy shaded region in the middle.</td>
<td></td>
</tr>
<tr>
<td><strong>Experiment 3:</strong> Cover the bulb with aluminum foil and poke a hole in the foil in the middle front of the bulb. Turn the bulb on.</td>
<td>Using the one ray idea, we predict that will see only a spot on the wall directly in front of the hole.</td>
<td>We observe that the walls are dimly lit.</td>
</tr>
<tr>
<td></td>
<td>Using the multiple-ray idea, we predict that the wall will be dimly lit.</td>
<td></td>
</tr>
</tbody>
</table>

**Conclusion**

Experiment 1: Both models give predictions that matched the outcomes of this experiment. Neither can be rejected.

Experiments 2 and 3: The predictions based on one-ray model did not match the outcomes of the experiments, thus the model can be discarded; the predictions based on multiple-ray model matched the outcomes of both experiments thus the model has not been disproved.

The testing experiments above helped us discard the one-ray model. It also gives us an opportunity to observe a new phenomenon. In the second experiment we found that some of the light was blocked by the pencil and some light reached the wall behind the pencil. There was a real dark shadow anywhere on the wall, what we observed is called a *semi-shadow*. To distinguish a shadow from a semi-shadow we can say that a shadow is a space where no light rays from a source reaches it; a semi-shadow is the place where some rays reach and some do not—a fuzzy shadow.

**Tip!** In the experiment 3 we had a small shining hole in the cover of the bulb emitting light. We found that it sent light in all directions. Thus even a “single point” source of light cannot be
modeled as sending one ray. The only source of light that can be modeled with a single ray is a laser pointer.

You probably noticed that the shadows of our bodies on a sunny day are very sharp – never semi-shadows. Why? The Sun is so far from Earth that the only light from the Sun that reaches Earth can be seen as just one ray or a collection of parallel rays (Fig. 21.3).

![Figure 21.3 Sharp shadow produced by sunlight](image)

**Camera obscura (pinhole camera)**

A pinhole camera (camera obscura) consists of a box with a small hole in one wall and film inside the camera on the opposite wall. Before the invention of modern cameras that use lenses pinhole cameras were used to make photographs. How can the small hole through which light enters the camera help produce a picture?

**Conceptual Exercise 21.1 Camera obscura** Use the multi-ray model to predict what you will see in the following experiment. You place a lit candle several meters from the wall in an otherwise dark room. Between the candle and the wall (closer to the candle) you place a piece of stiff paper (or cardboard) with a small hole in it (Fig. 21.4a).

![Figure 21.4 (a)Pinhole camera (camera obscura)](image)

**Sketch and Translate** We already have a sketch of the situation in Fig. 21.4a. The candle flame is the extended source of light. We need to predict the shape of the candlelight on the wall. **Simplify and Diagram** Assume that each point of the candle flame sends rays in all directions. Simplify the candle flame by showing multiple light rays emitted from only the top and the bottom of the flame. Most of these rays hit the paper and do not reach the wall (Fig. 21.4b). However ray 1 from the bottom of the flame passes through the hole and reaches the wall. Ray 2 from the top of the flame reaches the wall below where ray 1 arrived. We predict that we will see
an upside-down image of the flame on the wall. Amazingly, if you perform the experiment (you should try the experiment), you see the candle flame upside down on the wall!

![Figure 21.4(b)](image)

**Try It Yourself:** Use the ray diagram to predict what you will see if: (a) you move the candle closer to the hole; (b) move it farther from the hole; and (c) keep the candle and the stiff paper fixed relative to each other but move them together away from the wall.

**Answer:** (a) The upside down image of the candle on the wall gets bigger; (b) The image gets smaller; (c) As you move them farther from the wall, the image gets bigger.

Conceptual exercise 21.1 explains how the pinhole camera could be used to take pictures. The first photocamera was just a box with a hole on one side and a photographic plate or film on the inside of the box on the other side. To photograph a person, you shined intense light on the person for a long time. A small amount of light that reflected off the person passed through the hole and formed an inverted image of the person on the film. In Fig. 21.5, the outside world is projected through a pinhole onto the wall above the tables and chairs in a meeting room.

![Figure 21.5 Pinhole view of outside world on wall](image)

**Example 21.2 Height of a tall pole holding a streetlight** On a sunny day, a streetlight pole casts a 9.6-m long shadow on the ground. You have a meter stick which when held vertical, casts a 0.40 m shadow. How can you use this information to determine the height of the pole?

**Sketch and Translate** The situation is sketched in Fig. 21.6a. The sketch cannot show how far away the Sun is. On the scale of the picture, we represent Sun’s rays as parallel rays incident on...
the earth’s surface. The meter stick and the pole block the Sun’s rays. The shadow of the stick is 0.40 m and of the pole is 9.6 m.

![Figure 21.6(a)](image)

**Simplify and Diagram** We assume that Sun light comes in parallel rays for both streetlight and the meter stick. The shadows, the rays, and the objects form similar triangles (Fig. 21.6b).

![Figure 21.6(b)](image)

**Represent Mathematically** Using similar triangles, we have:

\[
\frac{l_{\text{shadow of ruler}}}{h_{\text{ruler}}} = \frac{L_{\text{shadow of pole}}}{H_{\text{pole}}}
\]

**Solve and Evaluate** Now, rearrange this equation to determine the height of the pole \(H_{\text{pole}}\):

\[
H_{\text{pole}} = \frac{h_{\text{ruler}}L_{\text{shadow of pole}}}{l_{\text{shadow of ruler}}} = \frac{(1.0 \text{ m})(9.6 \text{ m})}{(0.40 \text{ m})} = 24 \text{ m}.
\]

The unit is correct and the magnitude is reasonable.

**Try It Yourself:** How would the above change when the Sun was lower in the sky and the shadow of the pole was 19.2 m?

**Answer:** The stick would then cast a 0.80-m shadow. The pole height would still be 24 m.

**What did we learn?**

So far we have found that we can model light sources as consisting of many point sources of light. Each point source emits light in all directions. That light propagates along a straight line, which we represent as rays. If an object (large or small) intercepts the light ray or rays, the light can reflect off the object into our eyes. We see an object because of light reflected from the object.
Tip! A laser pointer is a very special source of light that emits almost of its rays in one direction only. This is the result of the mechanism through which laser emits light – you will learn more about the mechanism in Chapter 26.

Review Question 21.1
Why doesn’t the Sun cast semi shadows of objects?

21.2. Reflection of light

We see objects because of light reflected from them. Let’s consider this reflected light more carefully using the equipment shown in the top view in Fig. 21.7. Light from a laser pointer shines on a small vertical mirror whose bottom edge rests on a sheet of paper. Before reaching the mirror the beam passes over a protractor lying on the paper and pressed against the mirror. A narrow reflected laser light beam moves off as shown. The protractor allows us to indicate the directions of the incident light and the reflected light beams. The results are recorded in Table 21.3. Notice line OC in the figure – it is perpendicular to the surface of the mirror at the point where the incident light hits the mirror. Such line is called a normal line (recall that in mathematics and physics “normal” means perpendicular).

![Figure 21.7 Light reflection from mirror](image)

Table 21.3 Angles indicating relative directions of incident and reflected light beams from a mirror.

<table>
<thead>
<tr>
<th>Angle $AOB$ between the incident and reflected beams</th>
<th>Angle between the incident beam $AO$ and the normal line $CO$</th>
<th>Angle between the reflected beam $BO$ and the normal line $CO$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ$</td>
<td>$0^\circ$</td>
<td>$0^\circ$</td>
</tr>
<tr>
<td>$40^\circ$</td>
<td>$20^\circ$</td>
<td>$20^\circ$</td>
</tr>
<tr>
<td>$60^\circ$</td>
<td>$30^\circ$</td>
<td>$30^\circ$</td>
</tr>
<tr>
<td>$90^\circ$</td>
<td>$45^\circ$</td>
<td>$45^\circ$</td>
</tr>
<tr>
<td>$120^\circ$</td>
<td>$60^\circ$</td>
<td>$60^\circ$</td>
</tr>
<tr>
<td>$160^\circ$</td>
<td>$80^\circ$</td>
<td>$80^\circ$</td>
</tr>
</tbody>
</table>

The angles between the incident and the reflected light beams (column one) are always twice the angles between the incident light ray and the normal line and between the reflected light ray and the normal line (columns two and three). The angles in columns two and three equal each other. Mathematically:
Angle between incident beam AO & normal line CO  
= Angle between reflected beam BO & normal line CO

Traditionally, physicists use the incident and reflected angles relative to the normal line CO rather than relative to the mirror. Let’s use this result to predict the outcome of a new experiment in Conceptual Exercise 21.3.

Tip! The angle between incident beam AO & normal line CO is sometimes called the angle of incidence and the angle between reflected beam BO & normal line CO is called the angle of reflection

Conceptual Exercise 21.3 Testing the proposed reflection pattern  Two vertical mirrors rest on a table with their faces making an angle greater than 90° (see the sketch in Fig. 21.8). Place a target on the table in front of mirror 2. Use the relation between the angle of incidence and the angle of reflection just devised to predict how to aim a laser beam to hit mirror 1 so that light reflected from mirror 1 then shines on mirror 2 and reflects so that it finally passes directly over the target.

Figure 21.8

Sketch and Translate The situation is already sketched in Fig. 21.8. There are multiple laser orientations and places for the beam to hit mirror 1 so the light eventually passes over the target. However, you would most likely have to use many trials to work forward from the laser pointer to the two mirrors so that the beam actually hits the target. Instead, we can do it in one try by drawing the beam backwards from the target to mirror 2 and then to mirror 1 and finally to an appropriate location and orientation for the laser pointer.

Simplify and Diagram We draw top view ray diagrams to represent the process in steps in Fig. 21.9 going backwards from the target to the mirrors and then to the laser pointer. (a) A top view drawing of a ray representing the laser beam that hits mirror 2 and then the target is shown in Fig. 21.9a (it is one of many possible rays). Note that the orientation of the normal line in the figure and the equal angles of incidence and reflection. (b) The beam incident on mirror 2, the laser beam had to first reflect from mirror 1. A top view drawing of a ray representing that light is drawn in Fig. 21.9b. Note that the incident and reflected angles relative to mirror 1 are equal. (c) We can now direct the laser beam along the mirror 1 incident ray and it should hit the target (Fig. 21.9c). If you do the experiment, you see that the ray indeed hits the target! This supports the reflection rule devised earlier.
Try It Yourself: Suppose the mirrors make $90^\circ$ angles relative to each other. Show that the ray reflected from the second mirror is parallel but in the opposite direction to the ray incident on the first mirror.

*Answer:* See Fig. 21.10.

We can now formulate a relation that is called the law of reflection.

**Law of reflection** When a narrow beam of light, represented by one ray, shines on a smooth surface such as a mirror, the angle between the incident ray and the normal line perpendicular to the surface equals the angle between the reflected ray and the normal line (the angle of incidence equals the angle of reflection).

$$\theta_\text{incidence} = \theta_\text{reflection} \quad (21.1)$$

**Diffuse reflection**

The law of reflection contradicts some of our earlier observations. Remember the experiment when we shined a laser beam on a wall and observed a bright spot on the wall? In that experiment the location of the observer was not specified. If a light beam always reflects at a particular angle determined by the angle of incidence, then how do we see laser light reflected off a wall independently of the location of our eyes? The light should go along only one line from the...
spot and unless a person is located on that line, she/he should not see the light spot on the wall. But many people in the room see it. Does it mean that the law of reflection is wrong?

What do scientists do when new experimental data does not fit a model? Before rejecting the model, they carefully examine the experiment and any assumptions they made. In this case, there is a difference between a mirror and a wall. A mirror is considered very smooth. In addition, we assumed that the laser beam is very thin and can be represented by one light ray. What if the reflecting surface is bumpy and the actual laser beam is wider than the bumps on the surface (Fig. 21.11a)? As we see, the microscopic parts of the surface are oriented at different angles. The laser beam hits many of these bumps so that light is reflected in diverse directions. Observers at many different locations can see reflected light.

This phenomenon is called diffuse reflection as opposed to specular reflection by a smooth mirror. A familiar example of diffuse reflection is light reflected from a newspaper (Fig. 21.11b). The difference between specular and diffuse reflection is evident in glossy and matte paints. While both exhibit a combination of specular and diffuse reflection, glossy paints have a greater proportion of specular reflection and matte paints have a higher proportion of diffuse reflection. Highly polished surfaces, such as high quality mirrors, exhibit almost perfect specular reflection. If we put a little chalk powder on the surface of such a mirror and shine a laser beam on the chalk powder, we see a bright spot on the surface no matter where we stand.

![Figure 21.11 Diffuse reflection from bumpy surface](image)

**Conceptual Exercise 21.4 Dark windows on a sunny day** You probably noticed that on a sunny day, house windows with no blinds look almost black. Why?

*Sketch and Translate* The outsides of the houses do not look black because they reflect incident sunlight and some of it reaches your eyes (Fig. 21.12a). If the windows look black, then they do not reflect sunlight to your eyes. But light hits them just as it hits the outside walls of the house. Why don’t the windows reflect light to our eyes?

![Figure 21.12(a) Windows of house look dark](image)
Simplify and Diagram When light shines on the walls of the house, it reflects back diffusely at different angles and some of the light reaches your eyes—you see the wall. When light reaches the window, most of it passes into the room and reflects many times inside so that little comes back out (see the top view of room in Fig. 21.12b). A small amount reflects off the smooth window in specular reflection. If you are not in the one correct location to see that reflected light, you don’t see any light coming from the window—it appears dark. But if you are exactly in that one location, there is a glare from the widow.

Figure 21.12(b)

Try It Yourself: Why is the pupil of your eye black?

Answer: It is a hole in the eye similar to windows. Incident light enters the pupil and nothing is reflected back – the pupil looks black.

What is the nature of light?

So far the observable phenomena have helped us describe seeing, shadows, and light reflection. But what microscopic model concerning the nature of light explains “why” these observations occur? The first scientific model of light was based on Newtonian mechanics. Newton modeled light as a stream of very small, light particles moving at high speeds. They are affected by Earth’s gravitational pull and move like projectiles but as they move very quickly the deflection from straight lines is unnoticeable. Thus the particles fly in almost straight lines after being emitted by a light source. Does this model explain: (a) shadows and semi-shadows, and (b) the law of reflection.

To use this model to explain shadows, imagine an extended light source sending small particles (like shooting bullets) in all directions from each point. If we place an obstacle close to the light source, some bullets will still reach all parts of the screen producing a semi-shadow or no shadow (Fig. 21. 13a). If the obstacle is farther away, there will be a place on the screen where no bullets reach the screen thus producing a shadow (Fig. 21. 13b). The model works. We can explain the reflection of light if we imagine that the bullets are similar to billiard balls that reflect from the walls of the billiard table, or basketballs bouncing off a backboard. For the Newtonian model of light, the normal force exerted by a surface on light particle bullets can only change the component of velocity perpendicular to the wall; the component parallel to the wall stays the
same (Fig. 21.13c), consistent with the law of reflection. Since, this bullet particle model of light is consistent with the formation of shadows, semi-shadows, and the law of reflection, we will keep it for the time being.

![Bullet Model of Light](image)

**Figure 21.13** Newton’s bullet model of light

**Review Question 21.2**
How can we test the law of reflection?

### 22.3. Refraction and the law of refraction

We have been discussing the reflection of light from a surface. When at the shore of a lake, you see sunlight reflecting off the water’s surface. But you also see rocks and sea plants under the water surface. To see them, light must have entered the water, reflected off the rocks and plants, then returned to the water surface and left the surface to arrive at your eyes. If you ever tried to use a stick to touch something under water (a rock for example) you know that it is not easy – every time you carefully point at it and extend the stick – you miss. It looks like you always extend the stick farther away from you than is needed to touch the rock. Why is that?

To answer this question, we begin by using a laser beam to study light passing from air into and through a clear glass container filled with water. The container sits on a supporting ring so that its bottom is transparent to light. We shine a laser beam at different angles from above onto the top surface of the water and observe what happens (see Table 21.4).
Observational Experiment Table 21.4 Changing the path from air to water

<table>
<thead>
<tr>
<th>Observational experiment</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>When shining the laser straight down, we see red spots on the ceiling, on the floor, and on the bottom of the container.</td>
<td>Draw light rays to explain the appearance of the red spots. We do not draw rays from the spots to our eyes for simplicity.</td>
</tr>
<tr>
<td>When we shine the laser at an angle, all three spots move.</td>
<td></td>
</tr>
<tr>
<td>Increasing the spots shift even more.</td>
<td></td>
</tr>
</tbody>
</table>

Patterns
When light shines at the air-water boundary at the top surface, the incident light beam represented by ray 1:
- Partially reflects back (ray 2) at the same angle as the angle of incidence; and
- Partially passes into the second medium (ray 3) with bending at the interface (called refraction, a change in direction).

The same things happen to light beam represented by ray 3 when it reaches the bottom water-air interface:
- Partial reflection (ray 4) at the same angle as the angle of incidence; and
- Partial refraction from the water into the air below the container (ray 5) with bending at the interface.

Note that when the incident light represented by rays 1 and 3 is perpendicular to the boundary of the surfaces, it light reflects back along the same line (rays 2 and 4) and passes into the second medium without bending (ray 5). However if it is not perpendicular to the surface, the light bends and travels in a different direction than in the previous medium. If we replace the water with a transparent thick piece of glass, we observe a similar pattern. To develop a mathematical relationship between the angle of incidence and the angle of refraction (the bent light), try an experiment similar to that used when studying reflection (Fig. 21.14). Shine a laser beam in a vertical plane at a horizontal interface of air-water and air-glass and record angles of incidence and refraction using a protractor. You will find results similar to those reported in Table 21.5.

Figure 21.4 Experiment to measure refracted angle
Table 21.5 Angles of incidence and refraction between laser beams and the normal line

<table>
<thead>
<tr>
<th>Incident angle (ray in air) $\theta_{\text{air}}$</th>
<th>Refraction angle (air into water) $\theta_{\text{water}}$</th>
<th>Refraction angle (air into glass) $\theta_{\text{glass}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ$</td>
<td>$0^\circ$</td>
<td>$0^\circ$</td>
</tr>
<tr>
<td>$10^\circ$</td>
<td>$8^\circ$</td>
<td>$7^\circ$</td>
</tr>
<tr>
<td>$20^\circ$</td>
<td>$15^\circ$</td>
<td>$13^\circ$</td>
</tr>
<tr>
<td>$30^\circ$</td>
<td>$22^\circ$</td>
<td>$19^\circ$</td>
</tr>
<tr>
<td>$40^\circ$</td>
<td>$29^\circ$</td>
<td>$25^\circ$</td>
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<tr>
<td>$50^\circ$</td>
<td>$35^\circ$</td>
<td>$30^\circ$</td>
</tr>
<tr>
<td>$60^\circ$</td>
<td>$41^\circ$</td>
<td>$35^\circ$</td>
</tr>
</tbody>
</table>

Notice that as the angle of incidence increases, the angle of refraction also increases but not in a simple way.

In 1621 the Dutch scientist Willerbrord Snell (1591-1626) found a pattern. The ratio of the sine’s of the incident angle and the refracted angle for all angles remained the same for the air/water experiment and also for all angles for the air/glass experiment (but a different constant number)—see Table 21.6.

Table 21.6 Pattern found by Snell concerning sines of incident and refracted angles.

<table>
<thead>
<tr>
<th>Air $\sin \theta_1$</th>
<th>Water $\sin \theta_2$</th>
<th>Glass $\sin \theta_2$</th>
<th>Air/Water $(\sin \theta_1)(\sin \theta_2)$</th>
<th>Air/Glass $(\sin \theta_1)(\sin \theta_2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>1.33</td>
<td>1.53</td>
</tr>
<tr>
<td>0.174</td>
<td>0.131</td>
<td>0.114</td>
<td>1.32</td>
<td>1.52</td>
</tr>
<tr>
<td>0.342</td>
<td>0.259</td>
<td>0.225</td>
<td>1.34</td>
<td>1.53</td>
</tr>
<tr>
<td>0.500</td>
<td>0.374</td>
<td>0.326</td>
<td>1.33</td>
<td>1.52</td>
</tr>
<tr>
<td>0.643</td>
<td>0.485</td>
<td>0.423</td>
<td>1.34</td>
<td>1.53</td>
</tr>
<tr>
<td>0.766</td>
<td>0.573</td>
<td>0.500</td>
<td>1.34</td>
<td>1.53</td>
</tr>
<tr>
<td>0.866</td>
<td>0.649</td>
<td>0.574</td>
<td>1.33</td>
<td>1.52</td>
</tr>
</tbody>
</table>

Notice that the ratio of the sines for air/water is about 1.3 and for air/glass is about 1.5. Based on observations such as shown in Table 21.6, Snell formulated a relationship between the angle of the incident ray $\theta_1$ and of the angle of the refracted ray $\theta_2$ when light travels from medium 1 to a different medium 2:

$$\frac{\sin \theta_1}{\sin \theta_2} = n_{1\to2} .$$  \hspace{1cm} (21.2)

where $n_{1\to2}$ is a number that depends on the types of matter in the two media.

Let’s try another experiment (we will use the data in the fourth row of Table 21.5). Send a beam of light in air down from above into water that is in a thick walled container of glass on the bottom. The angle between the incident ray traveling in air and the normal line to the surface air-water $\theta_1$ is $30^\circ$. When the light enters the water, it is refracted so that the angle between the ray in water and the same normal line $\theta_2$ is now $22^\circ$ (the same as observed in the fourth row, second column of Table 21.5). The light then moves from the water into the glass so that the beam in glass makes a $19^\circ$ angle $\theta_3$ relative to the normal line. This is exactly the final
orientation of the light if it went directly from the air into the glass (look at the fourth row, third column of Table 21.5). We can apply Snell’s rule [Eq. (21.2)] to this process:

\[
\frac{\sin \theta_1}{\sin \theta_2} \times \frac{\sin \theta_2}{\sin \theta_3} = n_{1 \to 2} \times n_{2 \to 3}.
\]

The \( \sin \theta_2 \) term cancels. Thus, we find that:

\[
\frac{\sin \theta_1}{\sin \theta_3} = n_{1 \to 2} \times n_{2 \to 3}.
\]

The left side of this equation does not involve the number 2 medium (water). Consequently, medium 2 should not affect the right side of the equation. What form can \( n_{1 \to 2} \) and \( n_{2 \to 3} \) take so that medium 2 is not involved in the product of those two \( n_{1 \to 2} \times n_{2 \to 3} \)? If \( n_{1 \to 2} \) is a ratio of two numbers \( n_{1 \to 2} = \frac{n_1}{n_2} \) and \( n_{2 \to 3} \) is a ratio of two numbers \( n_{2 \to 3} = \frac{n_2}{n_3} \), then:

\[
\frac{\sin \theta_1}{\sin \theta_3} = \frac{n_{1 \to 2} \times n_{2 \to 3}}{n_1 \times n_3} = \frac{n_1}{n_2} \times \frac{n_2}{n_3} = \frac{n_1}{n_3} = n_{1 \to 3}.
\]

Thus, it seems reasonable to characterize each medium in terms of a property that affects the transmission of light in that medium. We call this property the index of refraction \( n \) of the medium—an experimentally determined property sometimes called optical density. Snell’s law now becomes:

**Snell’s law** The experimentally determined index of refraction \( n_i \) of light in incident medium 1 times the sine of the angle \( \theta_i \) between a light ray in that medium and normal line equals the index of refraction \( n_2 \) of light in the refracted medium 2 times the sine of the angle \( \theta_2 \) between a light ray in that medium and the normal line:

\[
n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (21.3)
\]

If the refracted ray is closer to the normal than the incident ray, then medium 2 is called optically denser or having a higher index of refraction than medium 1.

If we arbitrarily define the index of refraction of air as 1.00, then the index of refraction of water is 1.33 and of glass used in Tables 21.5 and 6 is 1.53. Notice that glass refracted the light ray more toward the normal line than water did; the glass is optically denser than water. The refractive indices of several different materials are given in Table 21.7.

**Table 21.7** Refractive indices of yellow light in various substances.

<table>
<thead>
<tr>
<th>Material</th>
<th>Refractive index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum</td>
<td>1.00000</td>
</tr>
<tr>
<td>Air</td>
<td>1.00029</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>1.00045</td>
</tr>
</tbody>
</table>
Example 21.5 Concentration of glucose in blood

The refractive index of blood increases as the glucose concentration in the blood increases. Therefore, measuring the index of refraction of blood can help determine the glucose concentration. A semispherical container holds a small sample of blood (Fig. 21.15). A narrow laser beam enters perpendicular to the bottom-curved surface and into the sample. The light reaches the blood-air interface at a $40.0^\circ$ angle relative to the normal line. The light leaves the blood and passes through the air to a row of tiny light detectors at the top indicating that the light beam left the blood at a $61.7^\circ$ angle. Determine the refractive index of the blood.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Refractive Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water ($20^\circ$C)</td>
<td>1.3330</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>1.3617</td>
</tr>
<tr>
<td>Glucose solution (25%)</td>
<td>1.3723</td>
</tr>
<tr>
<td>Glucose solution (50%)</td>
<td>1.4200</td>
</tr>
<tr>
<td>Glucose solution (75%)</td>
<td>1.4774</td>
</tr>
<tr>
<td>Glass, light crown</td>
<td>1.517</td>
</tr>
<tr>
<td>Glass, light flint</td>
<td>1.579</td>
</tr>
<tr>
<td>Glass, heavy flint</td>
<td>1.647</td>
</tr>
<tr>
<td>Fluorite</td>
<td>1.434</td>
</tr>
<tr>
<td>Diamond</td>
<td>2.417</td>
</tr>
</tbody>
</table>

Sketch and Translate A sketch of the experiment is shown in Fig. 21.15. The goal is to use Snell’s law to determine the index of refraction of the blood (and indirectly, the glucose concentration in the blood).

Simplify and Diagram The diagram in Fig. 21.15 can be used as a ray diagram if we assume that the laser beam is narrow.

Represent Mathematically We know that the angle between the incident light ray and the normal line at the glucose-air interface is $\theta_{1\text{ glucose}} = 40.0^\circ$; the angle of the refracted light ray and the normal line in the air $\theta_{2\text{ air}} = 61.7^\circ$; and the index of refraction of the air $n_{2\text{ air}} = 1.00$. We can use Snell’s law to determine $n_{1\text{ glucose}} : n_{1\text{ glucose}} \sin \theta_{1\text{ glucose}} = n_{2\text{ air}} \sin \theta_{2\text{ air}}$.

Solve and Evaluate Dividing both sides of Snell’s law equation by $\sin \theta_{1\text{ glucose}}$ we have:
\[
n_{\text{glucose}} = \frac{n_{\text{air}} \sin \theta_{\text{air}}}{\sin \theta_{\text{glucose}}} = \frac{1.00 \cdot \sin 61.7^\circ}{\sin 40.0^\circ} = 1.37.
\]

This is greater than the index of refraction of water because of the presence of the blood. But, the number is reasonable, similar to the refractive index of water.

*Try It Yourself:* Suppose the refractive index was 1.43 instead of 1.37. What then is the refracted angle if the incident angle is still 40.0°?

*Answer:* 66.8°.

At the beginning of this section we discussed how difficult is to touch an object under water with a stick. Underwater objects are not where they appear to be for a person outside the water. Imagine that while in Rome you are admiring the famous *Fontana dei Quattro Fiumi* or the "*Fountain of the Four Rivers*" in the center of Piazza Navona. You think about retrieving a coin at the bottom of the fountain.

**Example 21.6 Retrieving a coin in a fountain** You see a coin at the bottom of the Fountain of Four Rivers. Light from the coin reaches your eye at an angle of 37° below the horizontal (the angle between your line of sight and the vertical normal line is 53°). Where is the coin?

*Sketch and Translate* Sketch the situation and label the known quantities and the unknowns (Fig. 21.16a). You see the coin because the sunlight reflecting from it enters your eye. The light traveling in the air after leaving the water makes a 37° relative to the horizontal and a 53° angle relative to the normal line with the air-water interface (the angle of refraction). For you the coin appears to be somewhere on this line (Fig. 21.16a). However, you know that light does not travel straight when it passes from water into air. Thus you need to find the angle of that light when under the water on the way from the coin to the water surface.

*Figure 21.16(a) Observe coin in fountain*

*Simplify and Diagram* Assume that just one ray represents the light from the coin to your eye (Fig. 21.16b). It changes direction when it goes from the water to the air.
Represent Mathematically
We want to determine the incident angle of the light ray and the normal line in the water when it reaches the water-air interface so that after refraction, the ray moves toward your eyes at a 37° angle below the horizontal or at a 53° angle relative to a line perpendicular to the water-air interface. We use Snell’s law to find the angle between the light ray moving in the water toward the surface (and eventually to your eye) and the normal line:

\[ \frac{n_1 \sin \theta_1}{n_2 \sin \theta_2} = 1.00 \sin 53^\circ = 0.600. \]

Solve and Evaluate
Noting that \( n_{\text{water}} = 1.33 \), \( n_{\text{air}} = 1.00 \), and \( \theta_{\text{air}} = 53^\circ \), we then find \( \theta_{\text{water}} \) by dividing both sides of the Snells’ equation by \( n_{\text{water}} \):

\[ \sin \theta_{\text{water}} = \frac{n_{\text{air}} \sin \theta_{\text{air}}}{n_{\text{water}}} = \frac{1.00 \sin 53^\circ}{1.33} = 0.600. \]

Since \( \sin 37^\circ = 0.600 \), the light ray in the water makes a 37° angle relative to the normal line at the water-air interface. The special ray that makes it to your eye is shown in Fig. 21.16b. Thus when you look from the air at the coin under water, the coin appears farther from you according to your line of sight that it actually is. That is why the objects in water appear farther away from you than they really are. The solution to this example explains the experience described at the beginning of the section.

Try It Yourself: Suppose you shined a laser light into the water at an incident angle of 37° relative to the horizontal or 53° relative to the normal line to the surface. Determine the angle of the light in the water relative to the normal line.

Answer: 37°.

Tip! There are several important things to remember when you draw ray diagrams:
(a) Most objects do not emit light; they reflect light shining on them. For simplicity we draw them as light-emitting objects. They are really sources of reflected light.
(b) Each point of an object emits an infinite number of rays in all directions. Choose convenient ones to describe the situation.
(c) No rays come out of our eyes when we see a shining point. When you draw a diagram think of what rays will reach the eyes of the observer.

**Restoring a broken glass**

Now imagine, that we place a piece of glass in water, instead of a coin. Will you be able to see it? If you remember, we see things that reflect incident light. The index of refraction of glass is different from that of water. When light traveling in water hits the glass, it refracts at water-glass boundary; and it also reflects some light back to the eyes of an observer, thus making the glass visible. Although the refraction indices of water and of glass are close, you still see a piece of glass in a cup of water. Now, imagine that you have a liquid, whose refractive index is exactly equal to that of glass. A good example of such liquid is Wesson vegetable oil. Light traveling through this oil will not reflect off the piece of glass submerged in it, as there will be no “optical” boundary between the two. Light will just continue traveling in straight lines as if glass were not there. A piece of glass becomes invisible in Wesson vegetable oil!

Now you can go back and reread the chapter opening – the magician’s trick is pure physics. She just hid another unbroken vial in the oil and picked it up after she dumped the broken pieces into the oil. If you decide to repeat the experiment, make sure you are very careful – do not cut yourself, and also remember to fill the unbroken vial with oil before you put it in the water; otherwise it will be full of air and the air will make it visible!

From this experiment we can say that in order for us to see things, they should either radiate light like light bulbs, candles, or fire, or reflect light like planets, or all objects on Earth. Reflection occurs only if the optical density of the reflecting object is different from that of air (if the object is in air). We do not see air because air and a vacuum have almost identical optical densities. At the same time if the optical density of air increases, we can see it; for example we can see wet air in the form of steam and clouds. We can even explain why thunderstorm clouds are so dark. They consist of many big water droplets, the spaces between the droplets are similar to the house windows. Light does not reflect off them.

**Review Question 21.3**

Why is the expression “light travels in a straight line” not accurate?

### 21.4 Total reflection

In two of our examples in the last section, light traveled from an optically denser medium into an optically less dense medium, for example from water to air. In such cases the light bent away from the normal line when entering the less dense medium. This behavior has some very important applications in the transmission of light by optical fibers.

Consider the situation represented by a ray diagram in Fig. 21.17a. You perform a series of experiments in which an incident ray under water hits a water-air interface at an increasingly
larger angle relative to the normal line. As the incident angle gets bigger, the refracted angle between the ray and the normal line in the air gets even bigger. At the so-called critical angle of incidence $\theta_c$ (Fig. 21.17c), the refracted angle is $90^\circ$. The refracted ray moves along the water-air interface. At angles larger then $\theta_c$, the light is totally reflected back into the water-air interface (Fig. 21.17d).

Figure 21.17 Total internal reflection

This behavior occurs for any situation in which the light moves from an optically denser medium 1 of refractive index $n_1$ to an optically less dense medium 2 of refractive index $n_2$, where $n_1 > n_2$. We use Snell’s law to determine the critical angle: $n_1 \sin \theta_1 = n_2 \sin \theta_2$ where $\theta_1 = \theta_c$ and $\theta_2 = 90^\circ$. Remember that $\sin 90^\circ = 1$.

$$n_1 \sin \theta_c = n_2 \sin 90^\circ = n_2 \cdot 1$$

$$\sin \theta_c = \frac{n_2 \cdot 1}{n_1} = \frac{n_2}{n_1}.$$  

If the incident angle $\theta_1$ is slightly greater than $\theta_c$, there is no solution to Snell’s law as $\sin \theta_2$ would be greater than 1.00—but the maximum value of sine is 1.00. For $\theta_1 > \theta_c$, all of the light is reflected back into the water. Remember that this applies for $n_1 > n_2$. This phenomenon is called total internal reflection.

**Total internal reflection** When light travels from an optically denser medium 1 of refractive index $n_1$ into an optically less dense medium 2 of refractive index $n_2$ ($n_1 > n_2$), the refracted light beam in medium 2 bends away from the normal line. If the incident angle in medium 1 $\theta_1$ is greater than a critical angle $\theta_c$, all of the light is reflected back into the denser medium at the interface. The critical angle is determined using Snell’s law:

$$\sin \theta_c = \frac{n_2}{n_1}.$$  

(21.4)
Refractometry

Refractive index is a fundamental physical property of a substance, and is often used to identify an unknown substance, confirm its purity, or measure its concentration. A refractometer is an instrument used to measure refractive index. Refractometers are used for medical, pharmaceutical, industrial fluid, petrochemical, plastic, food, and beverage industry applications. For example, refractometers are used to measure alcohol content in distilled liquors, beer, and wine; the concentration of frozen concentrate in lemonade and of soluble solids in fruits and fruit products; the concentration of sugar in fruits, fruit products, and in raw and refined syrups; to determine the soluble salt content in soils; to measure the inhibitors for deicing airplanes; and to determine the nonvolatile matter (total solids) in floor polishes. Veterinarians use portable refractometers such as shown in Fig. 21.18 to measure the total serum protein in blood and urine; it is also used to detect drug tampering in racehorses. Many refractometers work based on the ideas of total internal reflection—see the next example.

Figure 21.18

Example 21.7 Another method to measure glucose concentration in blood Light travels in a narrow beam through a high refractive index hemispherical block of glass (Fig. 21.19a). A thin layer of blood is pressed between it and another hemispherical block on top. The glucose concentration in the blood can be determined through the refractive index of the blood. For this problem we assume that the blood refractive index is 1.360 and the glass refractive index is 1.600. What pattern of light reaching tiny light detectors on the top curved surface of the top hemispherical block will you observe as you move the light source clockwise around the edge of the curved surface of the bottom block? Be specific.

Figure 21.19(a) Detecting blood glucose by measuring critical angle

Sketch and Translate We already have a sketch of the apparatus (Fig. 21.19a). Our goal is to predict what happens to the refracted beam if we vary the angle of incidence.
Simplify and Diagram Assume that the light source is always oriented perpendicular to the curved surface on the bottom and points toward the same point on the bottom glass-blood interface. Next draw a ray diagram for four rays (Fig. 21.19b).

![Ray Diagram](image)

**Figure 21.19(b)**

Ray 1 bends away from the normal line at the first glass-blood interface. It is partially reflected and partially refracted into the blood. On the top surface of the blood, it bends back toward the normal line as it moves into the hemispherical glass block above (part of it is reflected at the second interface—not shown). Ray 2 has a greater incident angle with the first glass-blood interface and also bends away from the normal line as it enters the blood. It is partially transmitted into the blood and partially reflected (we do not draw the reflected ray). On the top surface of the blood it bends back toward the normal line as it moves into the hemispherical glass block above—to the right of Ray 1. Ray 3 has a greater incident angle and is refracted at 90° in the blood. Hence, the incident angle is the critical angle. Ray 4 has an even greater incident angle than the critical angle and is totally reflected back into the lower hemispherical block.

The detectors on the top surface stop detecting light from the place where the light traveling at a critical angle reaches the interface and clockwise from that angle. Thus, you can detect the critical angle by the place where the light stops arriving at the top block.

Represent Mathematically We can use Eq. (21.4) to determine the critical angle:

\[
\sin \theta_c = \frac{n_2}{n_1}.
\]

Solve and Evaluate Using the above with the lower glass index of refraction \( n_1 = 1.600 \) and the blood index of refraction \( n_2 = 1.360 \), we find that:

\[
\sin \theta_c = \frac{n_2}{n_1} = \frac{1.360}{1.600} = 0.850.
\]

A 58.2° angle has a sine equal to 0.850. Normally, we would measure the critical angle and use it to determine the index of refraction of the blood. The blood index increases with increasing glucose concentration. Consequently, the index indicates the glucose concentration.

Try It Yourself: For a different sample of blood, you stop detecting light from a 59.2° angle and larger. What is the refractive index of this new blood supply?
Tip! Note that the normal line is not necessarily a vertical line; the normal line is perpendicular to the interface between the two materials at the place where the light strikes it.

Review Question 21.4
Why did we study total internal reflection after the section on refraction of light and not after the reflection section?

21.5 Explanation of the law of refraction: two models of light
The history of the development of ideas concerning the nature of light is long and interesting, and continues to evolve even today. Rene Descartes’ theory of refraction was published in 1637 in his book Optics. Newton used some of Descartes’ ideas for a particle model of light that was popular in the 17th and 18th centuries. In Section 21.2, we found that this particle model was consistent with observations concerning light reflection and shadows. Is the model of light particles also consistent with observations concerning light refraction?

Particle model of light
Descartes rejected light as being made of something material and thought light traveled at infinite speed. But he knew of Snell’s work and that light bent toward the normal line if it moved from air to water or glass. So he developed a model adjusting his views to explain this phenomenon. According to his model, light traveled in air with a velocity $v$. When it reached the interface with water or glass, the light got a “hit” from the interface (like a racket hitting a tennis ball) that increased its speed perpendicular to the interface. The speed parallel to the interface did not change. Hence the velocity now had an increased component perpendicular to the interface and the same component parallel (Fig. 21.20). The new velocity was bent toward the interface. This was consistent with Snell’s law but was inconsistent with Descartes’ earlier idea that light traveled at infinite speed. Such inconsistencies are typical of early efforts in science to develop models to explain observed phenomena. Newton took Descartes’ model and extended it by suggesting that light was material and consisted of particles whose velocity perpendicular to an interface changed as the light particles moved between two media due to the attractive forces exerted by a more optically dense media as light approaches the interface.
This Newtonian explanation leads us to a testable prediction – the speed of light in media such as water or glass should be greater than in the air. Based on this model, we predict the following:

*If* the particle model of light is correct *and* we measure the speed of light in these media, *then* the speed in water or glass should be higher than the speed in the air.

This reasoning led physicists to try experiments to determine the speed of light in different media. One of the first to attempt this measurement was Galileo in early 1600's. He tried to measure the time interval for a beam of light to travel a certain distance. He and his assistant climbed two hills that were several miles apart (Fig. 21.21). They carried lanterns whose shutters could be opened and closed quickly letting light out. The idea was that Galileo would open his shutter and let light out. The assistant would open his lantern the moment he saw the light. The time lag between Galileo opening the shutter and seeing the return beam was supposed to help calculate the speed of light. And Galileo did calculate it. Then they increased the distance between the lanterns and repeated the experiment – but the time did not increase. It remained the same and after several experiments, Galileo realized that he was measuring the time it took to open the shutters – the speed of light was too high to measure this way.

**Figure 21.21**

In fact, astronomical distances were required for anyone to notice the effects of the speed of light. The first actual measurements that could be used to calculate light speed was by Danish astronomer Ole Roemer in 1676. He observed the eclipses of the moons of Jupiter through a telescope and recorded the times when the moons moved behind Jupiter. Analyzing his observations taken during several years, he noticed that there was a small difference Δt in the time from one eclipse to the next when the Earth was nearest Jupiter and when farthest from Jupiter. He reasoned that the time difference between the eclipses was due to the different distances that light needed to travel to Earth ($\Delta t = \frac{\Delta l}{v_{\text{light}}}; \frac{2R_{\text{Earth's orbit}}}{v_{\text{light}}}$), as depicted in Fig. 21.22.

Using Roemer’s data for Δt and knowing $R_{\text{Earth's orbit}}$, H. Huygens calculated the speed of light as $2 \times 10^8$ m/s, reasonably close to the modern value of $2.998 \times 10^8$ m/s.

If the particle model of light is correct, then the speed of light in water or glass should be even higher. Unfortunately at that time there was no way to measure the speed of light in these
media. In addition, some scientists started developing a conflicting model of light. Instead of thinking of light as a stream of particles, they used waves as a new analogy. The person who started this rebellious movement was Huygens. He reasoned that not only particles reflect off obstacles, but waves do too. So, perhaps light could be modeled as a wave. In order to understand his reasoning, we need to review his ideas for wave propagation.

Wave model of light

Huygen’s wave propagation ideas involved disturbances of a medium caused by each point on a wave front that was moving in the medium. Imagine that you have a wave with a wave front moving parallel to the page toward its top (see Fig. 21.23). Choose six dots on this wave front to help understand how the wave front propagates. From each dot draw a wavelet originating on the old wave front. The wave front and wavelets are drawn as shown in Fig. 21.23. Each dot represents the source of a wavelet produced by the wave disturbance passing that point. According to Huygens principle (Chapter 20), each small wavelet disturbance produces its own semicircular disturbance that moves up the page in the direction the wave is traveling. Now, note places where the net disturbance from the six wavelets is two or more times bigger than the disturbance caused by any one wavelet—places where the wavelets add together to form bigger waves. These places are part of the new crest of the wave. A line on the sketch indicates the location of the new wave crest that was formerly at the position of the dots. We also draw an arrow indicating the direction the wave is traveling – the ray. The ray is perpendicular to the wave crest.

Waves often travel at a different speed in one place than in a neighboring region. For example, water waves travel slower in shallow water than in deeper water. Sound travels slower
in cold air than in warm. Huygen’s principle helps us understand what happens to the direction of the wave propagation when its speed changes. Imagine the same wave front moving toward the top of the page only now the speed of the wave is greater on the right side than on the left side. What happens to the wave front?

In the sketch in Fig. 21.24, the six dots are part of wave crest again moving toward the top of the page. However, in this case the wave travels slower on the left side than on the right side. Thus, the wavelets originating from the left side have smaller radii than those farther to the right. New wave crests form at places where the wavelets add together to form a bigger wave disturbance than that caused by a single wavelet. An arrow (a ray) indicates approximately the wave’s path as it moves up the page. We see that the wave front bends toward the region where it moves slower and away from the faster moving region. We conclude that speed difference in different regions causes the wave to change direction.

**Figure 21.24** Wave bends if speed less on one side

**Wave model and refraction**

Can Huygens principle explain light refraction? Imagine a light wave moving in one medium and reaching an interface with a second medium, like going from air to water. Using the wave model of light, we can now draw wave fronts when light travels from medium 1 into medium 2 at an arbitrary non-zero incident angle relative to the normal line (Fig. 21.25a). Assume first that the wave travels slower in medium 2 than in medium 1. During a certain time interval, the wavelet that earlier departed from the right edge of the wave front is just reaching the boundary between medium 1 and medium 2. The wavelet that departed from the lower left edge of the wave front at the same time travels less distance in medium 2 as it is moving slower. The wavelets leaving the middle of the wave front travel part of the time in faster medium 1 and part of the time in slower medium 2. We see that the wave front bends toward the normal. What if a light wave travels from a slower to a faster medium as in Fig 21.25b? Using similar reasoning as in Fig. 21.25a, we see that the light bends away from the normal. The first prediction – bending towards the normal - based on the wave model and the assumption that light travels slower in water than in the air matches the actual observations for light. The second prediction – bending away from the normal - based on the wave model and the assumption that light travels faster in water than in the air does not match the observations. Thus if we accept that the wave model describes the observed behavior of light, we need to conclude that light travels slower in water than in air.

According to the wave model of light, the speed of light should be lower in water than in
the air. The particle model predicted the opposite. Which model is more accurate? An obvious way to answer this question is to measure the speed of light in water. But this experiment is difficult. Thus, we are left with two models of light that both explain the reflection and refraction of light but lead to different predictions about its speed in water. This is a dilemma that existed in physics for a long time. What do scientists do when they have two conflicting models for the same phenomenon? They use either one depending on how helpful it is for a particular situation and wait for new evidence to help them discard one the models, or sometimes both!

![Figure 21.25 Bending of wave at interface (Huygens)](image)

**Tip!** In the wave model the ray becomes the direction in which the wave travels, or a line perpendicular to wave fronts.

**Review Question 21.5**
What is the difference between two models of light and what predictions do they give for the speed of light in water?

### 21.6 Problem-solving strategies for analyzing reflective and refractive processes

Here we will practice solving more problems using a problem solving strategy similar to that used in previous chapters. The strategy is illustrated on a problem involving mosquitofish.

**Are Mosquitofish good or bad?**

Mosquitofish fish feed on aquatic larval and mosquito pupae. Mature females reach maximum lengths of 7 cm (2.5 inches), while males reach only 4 cm (1.5 inches).

![Mosquito fish supposedly protect us from mosquitoes](image)

They have been imported into many waters to help control mosquito growth. They are remarkably hardy, surviving in waters of very low oxygen content, high salinities (twice that of

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Etkina/Gentile/Van Heuvelen *Process Physics* 1/e, Chapter 21

21-28
seawater), and high temperatures. They may now be the most widespread freshwater fish in the world. Their introduction into local waters to control mosquito growth is now considered a mistake as local fish species already provide maximal mosquito control and the mosquitofish is highly damaging to local fish populations. Estimates of their breeding potential indicates an incredible ability to multiply and dominate new habitats into which they have been introduced. They are common targets of kingfisher birds flying above a lake.

**Example 21.8 Hiding mosquito fish** A mosquito fish hides at the bottom of a shallow 0.40-m deep part of a lake from a kingfisher flying above (Kingfishers see fish from the air and then dive and grab them). A leaf blown into the lake is floating above the mosquito fish. How big should the leaf be so the kingfisher cannot see the prey from any location?

<table>
<thead>
<tr>
<th>Sketch and Translate</th>
<th>Simplify and Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Sketch the described situation or process.</td>
<td>- Consider the fish as a shining point particle and the leaf as circular.</td>
</tr>
<tr>
<td>- Indicate all the known quantities and the unknowns.</td>
<td>- Draw a ray diagram. is the critical angle. For incident angles greater than , there is no refracted ray—all light is totally reflected.</td>
</tr>
<tr>
<td>- Indicate as best you can a solution for the problem.</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Represent Mathematically</th>
<th>Solve and Evaluate</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Use the sketch and ray diagram to help construct a mathematical description using the law of reflection or Snell's law for refraction or the application of Snell's law for total reflection.</td>
<td>- We find that . The angle whose sin is 0.75 equals $48.8^\circ$.</td>
</tr>
<tr>
<td>- Use Eq. (21.4) sin $\theta = \frac{n_1}{n_2}$, where $n_1 = 1.33$ (the refractive index of water) and $n_2 = 1.00$ (the refractive index of air).</td>
<td></td>
</tr>
<tr>
<td>- Knowing the angle we can determine the radius of the leaf: $R = h \tan \theta$.</td>
<td></td>
</tr>
</tbody>
</table>

- We find that $\sin \theta = 1.00 / 1.33 = 0.75$. The angle whose sin is 0.75 equals $48.8^\circ$.
Try It Yourself: If the leaf radius is 0.20 m, how far below the leaf would the mosquito fish have to be so that it could not be seen by the kingfisher bird?

*Answer:* 0.18 m.

**Periscope**

In the last example we used all problem-solving steps. However, in many cases you can solve a problem without complex mathematics – just with the help of a ray diagram. A periscope is an example. Johann Gutenberg, famous for his development of printed books, also invented in the 1430s and marketed a periscope to help pilgrims see over the heads of the crowd at religious festivals in Aachen, Germany, an important political center for about 800 years since the times of Charlemagne in 792. Periscopes had military applications later when Simon Lake developed them for submarines at the beginning of the 20th century. Soldiers in World War I used periscopes attached to rifles to see out of trenches.

**Conceptual Exercise 21.9 Build a periscope**

A simple periscope has a tube with two mirrors positioned parallel to each other at a certain angle relative to the vertical direction. Determine that angle.

*Sketch and Translate* Imagine an observer at a lower elevation than the object she wants to see. The mirrors inside a tube provide light and images to the observer. Think about the arrangement of the mirrors that will allow incident light traveling horizontally to reach the eye of the observer.

*Simplify and Diagram* If we draw a ray diagram with two mirrors parallel to each other at an arbitrary angle, horizontal light striking the first mirror gets reflected into the wall of the tube and does not reach the second mirror (Fig. 21.26a). For horizontal incident light to reach the second mirror, it must go vertically through the tube. If the mirror is positioned at a 45° angle relative to the vertical, the reflected light (according to the law of reflection) will be 90° relative to the incident light or vertically down (Fig. 21.26b). At the lower mirror, also oriented at 45° relative to the vertical, the light is reflected horizontally to the eye.

![Figure 21.26 Periscope](image)
Try It Yourself: Suppose you wish to see around the corner of the pentagon—an eight-sided building. How should you arrange a mirror or mirrors?

Answer: One mirror oriented at a $22.5^\circ$ angle relative to your side of the building will do.

Equation Jeopardy

In addition to drawing sketches and ray diagrams to help write mathematical descriptions of the process, it is important to be able to interpret the mathematical descriptions of processes, i.e. to use them to imagine a situation and to draw a ray diagram to represent it. We get practice doing that with equation jeopardy problems.

Example 21.10 What’s the problem? The equation below describes a physical process. Invent a problem for which the equation might provide a solution.

$$1.60 \sin 30^\circ = 1.33 \sin \theta_2.$$ 

The problem-solving procedure is reversed.

Solve and Evaluate Solve for the unknown quantity:

$$\sin \theta_2 = \frac{1.60 \sin 30^\circ}{1.33} = 0.60,$$

or $\theta_2 = 37^\circ$.

Represent Mathematically The equation appears to be an application of Snell’s law.

Simplify and Diagram Light in a medium with refractive index 1.60 (something like glass) is moving into a second medium with refractive index 1.33 (probably water). The incident angle is $\theta_1 = 30^\circ$ (Fig. 21.27a). The light bends away from the normal since the refractive index decreased.

![Figure 21.27(a)](image)

Sketch and Translate This might be a narrow beam of light moving up from the thick glass bottom of an aquarium into the water inside (Fig. 21.27b).

![Figure 21.27(b)](image)
Try it yourself: Describe a process consistent with the equation $1.60 \sin 48^\circ = n_2 \sin 90^\circ$.

Answer: Light in a glass-like material of refractive index 1.60 is incident on a different medium with refractive index 1.19. The light is refracted $90^\circ$. Thus, the critical angle is $48^\circ$.

Review Question 21.6
What is the angle of total internal reflection for light going from water into glass of refractive index 1.56?

21.7 Putting it all together: fiber optics, prisms, mirages, and the color of the sky

There are many applications of reflection, refraction, and total reflection in everyday life and in technology, such as: the color of the sky, the reflection of the sky off of a highway on a hot summer day (mirages), the appearance of a straw in a glass of water, mirrors used from grooming, and the huge fiber optics industry used in medicine and high speed communications systems. We will consider some of these applications in this section.

Fiber optics

You have probably heard about fiber optics used to view inside the human body when doing knee, carpel tunnel, and other operations and when used for high-speed communication lines for information transfer by light. How does it work? Suppose light travels inside a glass rod of refractive index $n_1 = 1.56$ surrounded by air of refractive index $n_2 = 1.00$. The critical angle for the glass-air interface according to Eq. (21.4) is:

$$\sin \theta_c = \frac{n_2}{n_1} = \frac{1.00}{1.56} = 0.64, \text{ or } \theta_c = 40^\circ.$$

If the incident angle of light in the glass is greater than this critical angle, all light is reflected at the glass-air interface. What happens if the glass is a long rod?

Conceptual Exercise 21.11 Trapping light in a tube Imagine that you have a long glass block of refractive index 1.56 surrounded by air (Fig. 21.28a). Light moving inside the block hits the top horizontal surfaces at a $41^\circ$ angle. What happens next?

![Figure 21.28(a) Fiber optic light pipe](image-url)
Sketch and Translate: The situation is already sketched in Fig. 21.28a. We found above that $\theta_c = 40^\circ$. The given $41^\circ$ angle is slightly greater than the critical angle for total internal reflection.

Simplify and Diagram: Assume that the top and bottom surfaces of the block are parallel to each other. The light hitting the top of the glass at a $41^\circ$ angle is totally reflected and moves down and to the right and hits the bottom surface at a $41^\circ$ angle where it is again totally reflected. The light then moves up and to the right—the process repeats itself (Fig. 21.28b).

Try it yourself: What happens if the light hits the top surface at $45^\circ$? At $38^\circ$?

Answer: For $45^\circ$ incidence, total reflection occurs (it occurs for all light incident at $40^\circ$ or more). For $38^\circ$ incidence, some light leaks out of the top and bottom at each incidence and such a beam would soon leave the pipe (it occurs for all light incident at less than $40^\circ$).

Now imagine instead of a glass block, the light moves inside a long glass cylinder hitting the top inside surface at an angle of $41^\circ$ or more. The light is totally reflected. The reflected light moves toward the bottom surface of the glass and strikes it at an incident angle of $41^\circ$. The light is once again totally reflected. The light continues to move along the cylinder bouncing from one side to the other, each bounce resulting in total reflection. If the cylinder is very thin, it is called a fiber. If the fiber is gently bent, light continues to reflect totally from the surfaces. The fiber is a light pipe carrying light along the fiber much the way water flows along a pipe. No light is lost from the sides.

Fibers that carry light have become important tools in technology. The communications industry developed laser communications systems in which telephone conversations and other forms of information are transmitted by light traveling along flexible glass fibers. These glass fibers are also used to make ornamental lamps consisting of a large number of flexible fibers that carry light upward along the fibers from a light source at the base (Fig. 21.29). Another application of fiber optics is for inexpensive solar telescopes; if you point a fiber at the Sun, you can then transmit the Sun’s light to any device for analysis.
Fiber optics used in medicine

Fiber optic devices are used to view places that are normally inaccessible to our eyes, such as the inside of car radiators or the inside of a person's knee. In these devices, a thin bundle of tiny glass fibers transmit a view of the inaccessible region at one end of the bundle to a person's eye looking at the other end of the bundle or to a television monitor that enlarges that image. If a lens is placed at the entrance end of the bundle, a larger field of view can be transmitted along the rods. A picture taken inside the knee joint is shown in Fig. 21.30a. An outer group of fibers carries light into the joint to illuminate it; an inner group carries an image of the illuminated surfaces of the joint to the viewer. A tool can be used to clean cartilage or repair tendons (Fig. 21.30b). Only a small slit is needed in the skin to insert the fibers and tool. Often this is done as an outpatient. Fiber optics is used in dentistry, dermatology, general surgery, ophthalmology, orthopedic surgery, and in other parts of the medical profession.

Figure 21.30 Fiber optics for looking inside body

Prisms

Many years ago Isaac Newton observed an interesting phenomenon. He was in a room with shutters closing the windows on a sunny day. A thin beam of light was coming into a room through a tiny hole in one of the shutters. This beam accidentally hit a prism sitting on a desk and to Newton’s surprise he saw a colored band of light on the opposite wall. The experimental set up was similar to that in Fig. 21.31a. Newton noticed that the band of light on the wall was much wider than the original beam and that violet light was on the bottom while red was on top. Could the prism create these colors? He performed several experiments to test whether the prism actually did it. He inverted the prism and noticed the same effect but with a violet light on top of the band of light and red on the bottom. He put an identical prism after the first one, but upside down (Fig. 21.31b) and the colored band disappeared – the spot on the wall was white and small. He concluded that the prism did not create the colors; it somehow could separate the different colors out of white light and then recombine them back into white light.
Newton used his observations to suggest that different colors are always inside a white beam of light and that the different colors of light had different refractive indexes – the refractive index should be greater for violet light and smaller for red. This model explained the separation of colors very nicely. It also explained how the second prism could turn a colored beam of light into a white one. If we measure the angles of refraction of light of different colors, we find that the refractive indexes vary (see Table 21.8).

Since the critical angle for total internal reflection from a glass-air interface is less than 45°, glass prisms with 45° and 90° angles are used in many optical instruments such as telescopes and binoculars to totally reflect light through 90° or 180° angles. Examples of the reflecting ability of prisms are shown in Fig. 22.32. The reflective ability of prisms is preferred over mirrors for several reasons. First, prisms reflect almost 100 percent of the light incident on the prism, whereas mirrors reflect somewhat less than 100 percent. Second, mirrors tarnish and lose their reflective ability with age, whereas prisms retain their reflective ability. Finally, prisms can invert an image, that is, make it appear upside down (Fig. 21.32b and c). This inversion may seem like a disadvantage. However, as you will learn later, the lenses in optical devices such as telescopes and binoculars cause an object viewed through the telescope to appear inverted. In binoculars, a form of telescope, prisms are placed in the light path so that the inverted image of the telescope lenses is re-inverted and appears right side up.

Mirages

One of the interesting consequences of the refraction of light is the formation of mirages. On a hot day there may be a layer of very hot air just above the ground. This hot air is less dense than cooler air farther above the surface. The index of refraction of cold air farther above the
ground is greater than that of hot near the ground. This leads to the bending of light rays coming from different objects to our eyes (Fig. 21.33a). Some of the light originally slanting downward is refracted or bent upward through the hot air and into our eyes; the light never hits the ground. The refracted light from a distant tree (Fig. 21.33b) appears to come from the surface in front of the tree, like the reflection of light off a pond of water. A mirage is caused not by a loss of mental facility on a hot, dry desert, but by refracted light that appears to be reflected light from the smooth surface of a pond in front of an object (really light from the sky). Occasionally, a motorist observes what appears to be a wet spot on a distant part of a hot highway. This is just light that originates in the sky and travels toward the highway. Before reaching the pavement, it bends or refracts up into your eye due to the hot air above the road. You see light from the sky that curves down toward the highway but misses.

![Figure 21.33 Mirage](image)

**Color of the sky**

The sky blue; yet, the Sun that makes it bright, is of bright yellow color. Yellow is the color that we would see if looking directly at the Sun (you should never do it without special protective glasses). The fact that we see blue sky when we do not look directly at the Sun is surprising for two reasons: (a) the color of the sky is different from the Sun; (b) light is coming from the sky where there is no source of light. We solve the second problem by assuming that the atmospheric air becomes a source of light because it reflects the sunlight. We can solve the first problem by using Newton’s idea that the Sun sends light of all colors. Molecules in the atmosphere reflect this light (Fig. 21.34). We can hypothesize that Earth’s atmosphere reflects blue light better than other colors of light. These other colors just pass through the atmosphere but are not reflected into our eyes. If this is due to the physical and chemical structure of the atmosphere, then an atmosphere made of different chemical elements should have a different color. The atmospheres of Mars and Venus have different chemical elements than Earth and different temperatures. And they are, in fact, of different colors even though they are illuminated by the same Sun.
If our atmosphere reflected all colors the same way, we would see the sky as white – this is in fact what we see when the sky is covered with clouds. The clouds are made of water droplets that reflect light differently from the cloudless sky. Also red light is reflected less by the atmosphere. Consequently, the Sun looks redder at sunrise and at sunset when we look more directly at the sunlight (Fig. 21.34).

**What don’t we know?**

Although we learned a great deal about light, there are still questions that we have not answered. We do not know why different media bend light differently. We still do not know whether light propagates faster or slower in water and other media than in the air. We do not know how objects radiate light. Why are some stars white and some red? We also did not decide which model of light is better – the particle model or the wave model. We will attempt to answer these questions in Chapters 23-26. In Chapter 22 we will learn how the properties of light rays that we studied in this chapter are used for practical purposes in optical instruments that use mirrors and lenses to help us see things better.
## Summary

<table>
<thead>
<tr>
<th>Words</th>
<th>Sketches and/or diagrams</th>
<th>Mathematical</th>
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<tbody>
<tr>
<td><strong>Light sources</strong> Light bulbs, candles, and the Sun are examples of sources of light that are often very hot. Light from such sources illuminates other objects, which reflect the light. We see these other objects because the reflected light reaches our eyes. Each tiny point on the reflecting object is the source of reflected light moving outward in all directions and is represented by rays (arrows) pointing away from each point on the object in many directions.</td>
<td><img src="image" alt="Light sources diagram" /></td>
<td><img src="image" alt="Law of reflection" /> [ \theta_{\text{incident}} = \theta_{\text{reflected}} ]</td>
</tr>
<tr>
<td><strong>Law of reflection (specular)</strong> When a light beam strikes a smooth surface such as a mirror, the angle between the incident ray and the normal line perpendicular to the surface equals the angle between the reflected ray and the normal line (the angle of incidence equals the angle of reflection).</td>
<td><img src="image" alt="Law of reflection" /></td>
<td><img src="image" alt="Law of reflection" /> [ \theta_{\text{incident}} = \theta_{\text{reflected}} ]</td>
</tr>
<tr>
<td><strong>Diffuse reflection</strong> If light is incident on an irregular surface (like a newspaper) with bumps and indentations, the incident light is reflected in many different directions.</td>
<td><img src="image" alt="Diffuse reflection" /></td>
<td><img src="image" alt="Diffuse reflection" /></td>
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<tr>
<td><strong>Refraction and index of refraction</strong> The direction of travel of light changes as it moves from one medium to another; the light is said to refract (bend) as it moves between the media. The optical nature of a medium is characterized by its refractive indices ( n ) (e.g., 1.00 for air, 1.33 for water, and about 1.6 for glass).</td>
<td><img src="image" alt="Refraction and index of refraction" /></td>
<td><img src="image" alt="Snell's law" /> [ n_1 \sin \theta_1 = n_2 \sin \theta_2 ]</td>
</tr>
<tr>
<td><strong>Snell’s law</strong> The refractive index ( n_1 ) of light in incident medium 1 times the sin of the angle ( \theta_1 ) of light in that medium equals the refractive index ( n_2 ) of light in medium 2 times the sin of the angle ( \theta_2 ) of light in that medium.</td>
<td><img src="image" alt="Snell's law" /></td>
<td><img src="image" alt="Total internal reflection" /> [ \sin \theta_c = \frac{n_2}{n_1} ]</td>
</tr>
<tr>
<td><strong>Total internal reflection</strong> If light tries to move from an optically denser medium 1 of refractive index ( n_1 ) into an optically less dense medium 2 of refractive index ( n_2 ) (( n_1 &gt; n_2 )), the refracted light in medium 2 bends away from the normal line. If the incident angle in medium 1 ( \theta_1 ) is greater than a critical angle ( \theta_c ), all of the light is reflected back into the denser medium.</td>
<td><img src="image" alt="Total internal reflection" /></td>
<td><img src="image" alt="Total internal reflection" /> [ \sin \theta_c = \frac{n_2}{n_1} ]</td>
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