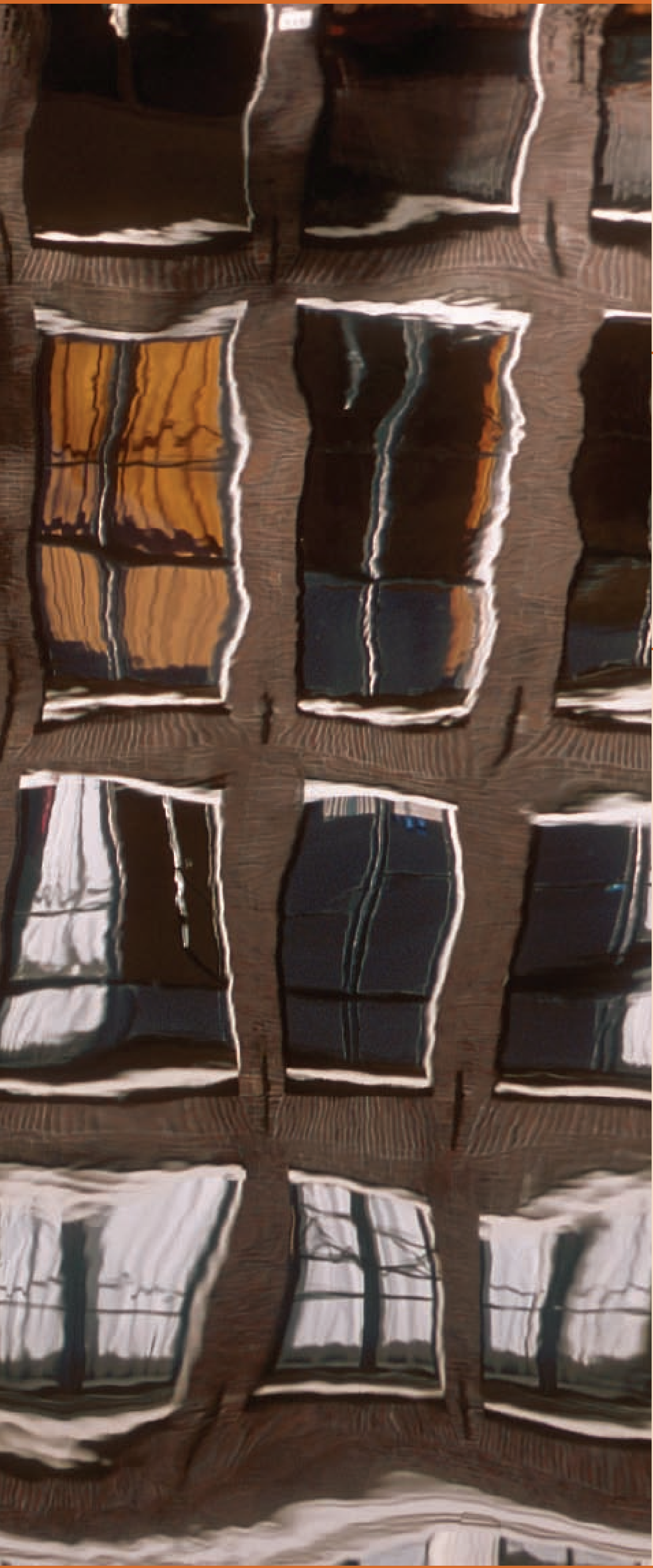
11 Ray diagrams model the behaviour of light in mirrors and lenses.

Buildings reflected in an Amsterdam canal



Skills You Will Use

In this chapter, you will:

- investigate the laws of reflection using plane and curved mirrors
- predict characteristics of images formed by mirrors and test those predictions
- investigate the refraction of light
- use ray diagrams and equations to predict position and characteristics of images formed by lenses
- calculate the velocity of light as it refracts through different media

Concepts You Will Learn

In this chapter, you will:

- describe images formed by mirrors and lenses
- explain partial and total reflection and refraction
- identify the factors that affect refraction as light passes from one medium to another

Why It Is Important

Our understanding of light as a ray that travels in a straight line has led to the invention of mirrors and lenses that perform a variety of functions. Learning about light will help you understand, select, and use optical devices and vision aids.

Before Reading

Thinking Literacy

Reading Diagrams

Diagrams provide a lot of information, often in a small format. You may have to read diagrams differently from word text. Skim this chapter, and preview the diagrams. How are they similar to and different from each other? What are some important features that may help you to understand diagrams?

Key Terms

• angle of incidence • angle of reflection • angle of refraction • concave • convex • focal length • focal point • magnification • mirage • normal refraction • virtual image

11.1 Mirrors

Here is a summary of what you will learn in this section:

- The angle of incidence equals the angle of reflection.
- Plane mirrors produce a virtual image that is upright and located as far behind the mirror as the reflected object is in front of it.
- Concave mirrors produce an enlarged, upright, virtual image if the object is closer to the mirror than the focal point.
- Concave mirrors produce an inverted, real image if the object is farther away from the mirror than the focal point.
- Convex mirrors produce an upright, virtual image that is smaller than the object.

Figure 11.1 The stainless steel mirror above Viganella is controlled by computer to follow the path of the Sun.

Figure 11.2 The construction of the mirror

Brightening a Winter's Day

Summer in the Italian village of Viganella high in the Italian Alps is peaceful, warm, and above all — sunny. But winter is another story. As the hours of daylight shrink each autumn and the Sun spends less and less time above the horizon each passing day, Viganella loses its direct view of the Sun. Viganella is located at the bottom of a steep valley, and every winter the mountains block out the Sun's rays from November 11 to February 2. During this time, the village is completely in the mountain's shadow.

But thanks to the science of optics, that situation has now changed. In 2006, a large flat mirror was placed at the top of one of the nearby mountains and directed at the village square (Figure 11.1). Airlifted into position with a helicopter at a total cost of about \$170 000, the 5 m × 8 m rectangular sheet of stainless steel is perched high above Viganella (Figure 11.2).

The mirror is controlled by computer so that as the Sun moves across the sky each winter day, the mirror always reflects into the village. Residents and tourists need not fear that the mirror will set them aflame or fry them into crisps, even on a hot summer's day. There is no magnifying-glass effect in which sunlight is focussed to a point. The mirror is flat, so that the Sun's rays are reflected without being concentrated.

Our understanding of how to control light for applications such as the mirror in Viganella is based on the orderly way that light reflects. The science of how light reflects and bends is called **geometric optics**.

D12 *Quick Lab*

Mirror Images

Purpose

To observe and count the number of reflections you can see in two plane mirrors

Materials & Equipment

- 2 plane mirrors
- tape
- felt pen
- protractor
- paper clip

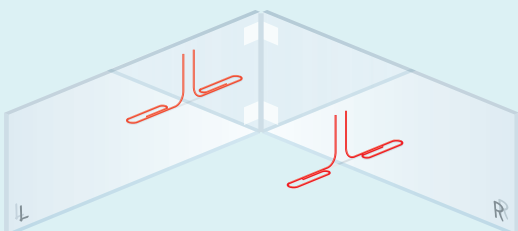


Figure 11.3 Handle glass mirrors carefully.

Procedure

1. Place two mirrors together so that their reflective surfaces face each other. Attach the tape so that the mirrors can open into a "V" shape (Figure 11.3).
2. Use the felt pen to label the mirrors as R for right and L for left.
3. Using a protractor, set the mirrors on a sheet of white paper open to an angle of 72°.
4. Bend a paper clip so that it will stand up, and place it in front of the right mirror.
5. Look into the mirrors, and count the number of images of the paper clip that you can see in each of the mirrors. Record your results.
6. Increase the angle between the mirrors to 90°. Observe and record the number of images of the paper clip you see in each mirror.
7. Open the mirrors even wider, to 120°. Observe and record the number of images of the paper clip you see in each mirror.

Question

8. What is the relationship between the angle of separation of the two mirrors and the number of reflections that you see?

During Reading — Thinking Literacy

Diagrams Require Special Reading Techniques

You cannot always read diagrams the way you read words, left to right and top to bottom. Look at the whole diagram first. Then, read the caption, and look again at the diagram. Let your eye follow the flow of the diagram. Are there arrows? Are there labels? What do they tell you? After examining the diagram, make notes about what you learned from it.

The Law of Reflection

Smooth, shiny surfaces like calm water, mirrors, glass, and even polished metal allow you to see an image. The smoother the surface is, the better the image will be. An **image** is a reproduction of an object produced by an optical device like a mirror. An **optical device** is any technology that uses light.

Light rays bounce off a mirror in a similar way to how a hockey puck bounces off the boards of an ice rink. To understand how light behaves when it reflects off a mirror, it helps to look at the reflection of a single ray of light in a ray diagram (Figure 11.4).

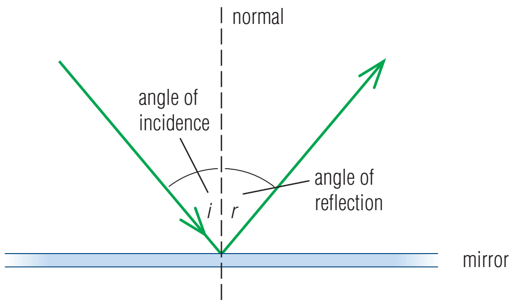


Figure 11.4 If the angle of incidence equals 45°, then the angle of reflection is also 45°.

WORDS MATTER

The word normal comes from the Latin word *norma*, meaning a carpenter's square.

The dashed line drawn perpendicular to the mirror at the point of reflection represents an imaginary line called the **normal**. The incoming ray is called the **incident ray**. The angle between the incident ray and the normal is called the **angle of incidence**, labelled *i*. The angle between the reflected ray and the normal is called the **angle of reflection**, labelled *r*. The relationship of these two angles is one of the most important properties of light, called the **law of reflection**:

> When light reflects off a surface, the angle of incidence is always equal to the angle of reflection.

Although the law of reflection may appear very simple, it is also very useful. For example, the law of reflection is used to design reflective tail lights for bicycles. A tail light is designed to reflect light from the headlights of the car behind it. This helps to make the bicycle more visible to the driver of the car. The ray diagram in Figure 11.5 shows how two mirrors arranged at an angle of 90° can use two reflections to send reflected rays back in the same direction as the incident rays, no matter where the incident rays come from. In each reflection, the angle of incidence equals the angle of reflection.

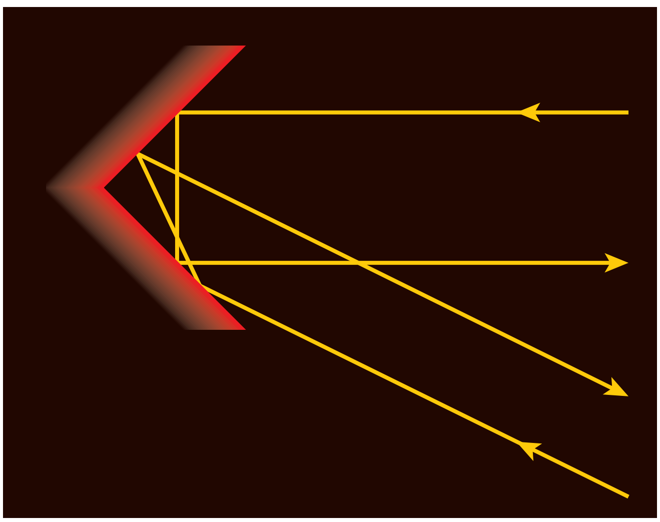


Figure 11.5 The mirrors in a bicycle tail light reflect headlight beams back to the driver of the car that sent them.

Using the Law of Reflection

The law of reflection can be written using mathematical symbols. The Greek letter theta, θ, is commonly used as the symbol for an angle. Subscripts are used to identify the angle. If the angle of incidence is θ_i and the angle of reflection is written as θ_r, then the law of reflection is:

$$\theta_i = \theta_r$$

The angle of incidence and the angle of reflection are always measured from the normal and not from the surface of the object. This is because some surfaces are curved, making it difficult to measure an angle from the surface.

Suggested Activity •

D13 Quick Lab on page 428

Plane Mirrors

The law of reflection applies to light rays reflected from both flat mirrors and curved mirrors. Any mirror that has a flat reflective surface is called a **plane mirror**. When you look into a plane mirror, your image appears to be as far behind the mirror as you are in front of it. In fact, the mirror may appear to be a kind of glass window. However, it is not possible to catch this image on a piece of paper placed behind the mirror, since no light from the object reaches this point. Because the light rays are not coming from where your image appears to be, we say that your image in a plane mirror is a virtual image. A **virtual image** is any image formed by rays that do not actually pass through the location of the image (Figure 11.7 below).

Figure 11.6 Reverse printing will be read normally when viewed in a mirror.

Image Orientation in a Plane Mirror

When you look in a mirror, your left hand appears to be a right hand. If you hold a textbook up to a mirror, you will notice that the text appears to be reversed. Sometimes, emergency vehicles are labelled in reverse printing so their signs can be read in a car's rear-view mirror, as in Figure 11.6.

The ray diagram in Figure 11.7 shows why this happens. To understand how the image forms, we draw a few rays from various points on the girl's face, and reflect them into her eyes. There is only one rule — the rays must follow the law of reflection. Once we have done this, we have shown the actual path of the light rays.

What does the girl see? To find out, we can extend the reflected rays back in a straight line behind the mirror to form the virtual image. So when the girl looks in the mirror, the image of her right eye is directly in front of her right eye in the virtual image. If she lifted her left arm, the arm in the virtual image would lift directly in front of it. The virtual image is an exact reflection of the real object.

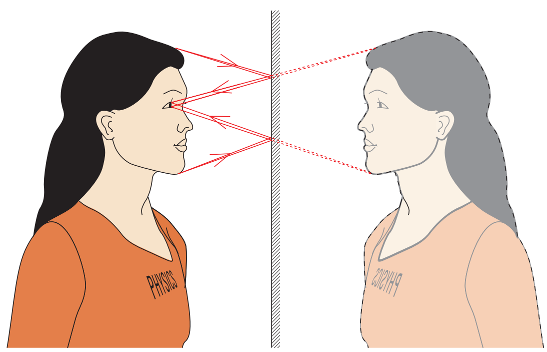


Figure 11.7 A ray diagram shows how a virtual image forms in a plane mirror.

Suggested Activity •
D16 Problem-Solving Activity on page 432

Learning Checkpoint

1. What is the difference between a reflected ray and an incident ray?
2. (a) What does the law of reflection state in words?
   (b) Write the law of reflection using mathematical symbols.
3. What is a plane mirror?
4. What is a virtual image?

Curved Mirrors

The strange image you see in a funhouse mirror is produced by a mirror that has flat, outward-curved, and inward-curved sections in it as shown in Figure 11.8. While they may be fun to look at, mirrors with multiple curves have no real practical uses. However, mirrors with a single curvature find many uses in our homes and optical devices. Two types of curved mirrors are concave (converging) and convex (diverging).

Figure 11.8 A reflection produced by a mirror with several curves

Curved Mirror Terminology

Like plane mirrors, curved mirrors obey the law of reflection. However, when parallel light rays strike a curved surface, each ray of light will reflect at a slightly different position. All of these rays eventually meet at a common point. The point where light rays meet, or appear to meet, is called the **focal point**, F (Figure 11.9).

The middle point of a curved mirror is called the **vertex**. The principal axis is an imaginary line drawn through the vertex, perpendicular to the surface of the curved mirror. The distance between the vertex and the object is represented by d_o. The distance between the vertex and the image is d_i. The height of the object is h_o, and the height of the image is h_i.

The **focal length**, f, is the distance from the vertex to the focal point of a curved mirror. If the object is farther away from the mirror than the focal point, the reflected rays form a real image. A **real image** is an image formed by light rays that converge at the location of the image. If you place a piece of paper at the spot where a real image forms, a focussed image would appear on the paper or screen. If the screen were moved slightly, the image would appear blurred because the reflected rays would not be converging at the screen's new location.

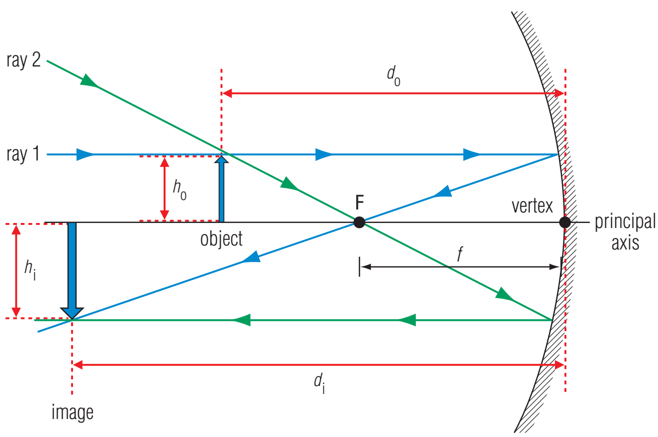


Figure 11.9 A ray diagram for a converging mirror

Concave Mirrors

A **concave mirror**, also called a **converging mirror**, has a surface that curves inward like a bowl (Figure 11.10). The image formed by a concave mirror depends on how far the object is from the focal point of the mirror. If the object is far away from the focal point, the reflected rays form an inverted image as shown in Table 11.1. The closer the object gets to the focal point, the larger the image becomes. If the object is between the focal point and the mirror, like the bird in Figure 11.11, the image becomes upright and enlarged. When the object is exactly at the focal point, all rays that leave the object reverse direction at the mirror and are reflected away from the mirror parallel to each other. In this case, no image is formed.

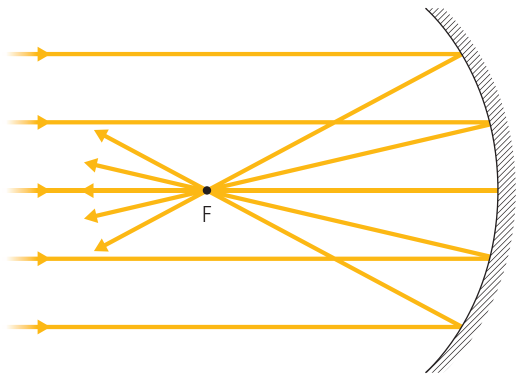


Figure 11.10 Parallel light rays approaching a concave mirror.

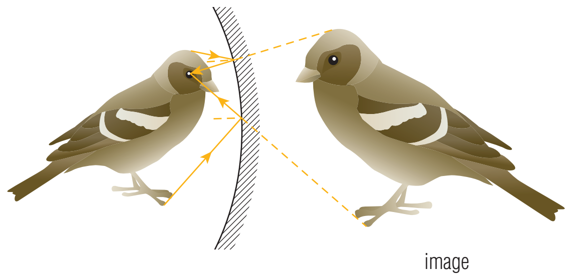
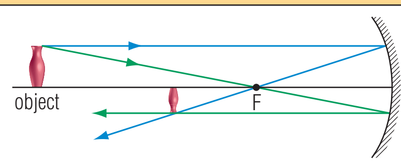
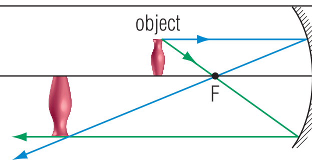
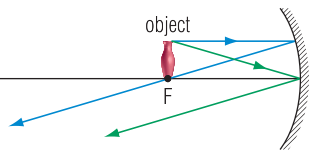
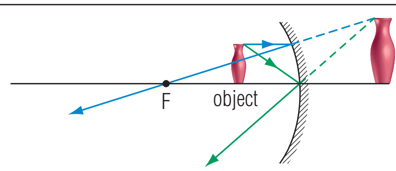


Figure 11.11 A virtual image produced by a converging mirror. The bird is between the focal point and the mirror so the virtual image is larger than the real bird.

Table 11.1 Ray Diagrams for Concave Mirrors

Distance of Object from Mirror, d_o	Type of Image Formed	How the Image Is Viewed	Ray Diagram
Object is more than two focal lengths.	Smaller than object, inverted, real	The mirror can project an image on a screen placed in front of the mirror.	
Object is between one and two focal lengths.	Larger than object, inverted, real	The mirror can project an image on a screen placed in front of the mirror.	
Object is at focal point.	No image is formed.	No image is formed.	
Object is between mirror and focal point.	Larger than object, upright, virtual	Viewer looks into the mirror to see the image.	

Drawing a Concave Mirror Ray Diagram

When you draw ray diagrams, you can sketch in the object or use an upright arrow to represent the object, as shown in Figure 11.12. Show real rays as solid lines. Use dashed lines to present virtual rays, which are rays that only appear to exist behind the mirror. Follow the steps in Figure 11.12 to draw a ray diagram of a concave mirror.

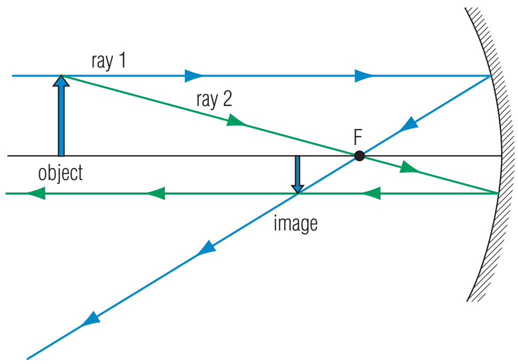


Figure 11.12 Concave mirror ray diagram

1. The first ray of a concave mirror ray diagram travels from a point on the object parallel to the principal axis (ray 1). Any ray that is parallel to the principal axis will reflect through the focal point on a converging mirror.
2. The second ray travels from a point on the object toward the focal point (ray 2). Any ray that passes through the focal point on a converging mirror will be reflected back parallel to the principal axis.
3. Draw the real image where the rays intersect.

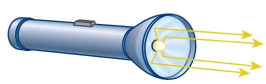
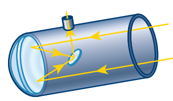
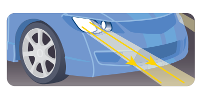
Some Uses for Concave Mirrors

Concave mirrors are specially designed to collect light and bring it to a single point. This is why concave mirrors are used in telescopes to collect light rays from a great distance and bring them together.

Can concave mirrors be used to send out beams of light rays as well? Imagine that a bright light were placed at the focal point of a concave mirror and allowed to shine into the mirror in Figure 11.10 on the previous page. By reversing the direction of the arrows in the ray diagram, you can see that the light rays would leave the mirror as parallel rays. That is why you will find concave mirrors in flashlights, car headlights, dental examination lights, and other applications (Table 11.2).

Figure 11.13 The concave mirror for the Hubble telescope is being prepared for launch into space.

Table 11.2 Some Uses of Concave Mirrors

Device	Use of Concave Mirror
Flashlight 	To produce a parallel beam
Telescope 	To collect light from a distant source and focus it for viewing
Cosmetic mirror 	To produce an enlarged image
Headlights of a car 	To produce a parallel beam of light that can be directed down (low beam) or straight ahead (high beam)

Solar Ovens

A **solar oven**, also called a solar cooker, is a device that uses light from the Sun as its energy source. A solar oven transforms sunlight directly into heat that can be used for cooking or boiling water (Figures 11.14 and 11.15). By making use of solar energy, precious resources can be saved. For example, trees are scarce in the Himalayas and using solar energy instead of wood for heat helps preserve forests.

A solar oven uses several strategies for producing heat, such as using a concave mirror to concentrate the Sun's rays, converting light to heat through absorption if the interior of the oven is a dark colour, and using a clear cover so that the Sun's rays can enter but very little heat can leave. The most efficient ovens create an insulated space where the food is cooked.

Figure 11.14 A man examines a solar oven that is heating water in Ladakh, high in the Himalayan Mountains.

Figure 11.15 This solar oven is located on a city rooftop.

Calculating Magnification

Concave mirrors have a number of uses including magnification. **Magnification** is the measure of how much larger or smaller an image is compared with the object itself. The magnification of an image, as compared with the object, may be the same size, enlarged, or diminished (smaller). Magnification is expressed as a ratio of the height of the image to the height of the object.

$$\text{magnification} = \frac{\text{image height}}{\text{object height}} \quad \text{or} \quad M = \frac{h_i}{h_o}$$

Magnification can also be determined by taking the ratio of the distance from the image to the mirror and the distance from the object to the mirror.

Suggested Activity •
D15 Inquiry Activity on page 430

$$\text{magnification} = \frac{\text{image distance}}{\text{object distance}} \quad \text{or} \quad M = \frac{d_i}{d_o}$$

These are very general definitions of magnification. You can use either formula to determine magnification. Be sure to use the same units for both heights or both distances in the calculation. However, no units are required in the answer since the units cancel out during the calculation. If the image is bigger than the object, then the magnification will be greater than 1. If the image is smaller than the object, the magnification will be less than 1.

Practice Problems

1. A microscope produces an image that is 1.00×10^{-4} m high from an object that is 4.00×10^{-7} m high. What is the magnification of the microscope?

2. A concave mirror produces an image on a wall that is 30.0 cm high from an object that is 6.5 cm high. What is the magnification of the mirror?

3. A pinhole camera produces a 2.34×10^{-2} m image of a building that is actually 50.0 m high. What is the magnification of the camera?

Example Problem 11.1

A microscope produces an image that is 5.50×10^{-4} m high from an object that is 2.00×10^{-6} m high. What is the magnification of this microscope?

Given
Object height $h_o = 2.00 \times 10^{-6}$ m
Image height $h_i = 5.50 \times 10^{-4}$ m

Required
Magnification $M = ?$

Analysis and Solution
The correct equation is $M = \dfrac{h_i}{h_o}$

Substitute the values and their units, and solve the problem.

$$M = \frac{h_i}{h_o}$$

$$M = \frac{5.5 \times 10^{-4}\ \text{m}}{2.00 \times 10^{-6}\ \text{m}}$$

$$= 275$$

Paraphrase
The magnification of the microscope is 275 times.

Practice Problems

1. An object is placed 75 cm from a concave mirror. A real image is produced 50 cm away. What is the magnification?

2. A person standing 3.00 m from a glass window sees her virtual image 3.00 m on the other side. What is the magnification of the window?

3. A camera creates a real image of a tree 40 m away. The image is formed 3.0 cm behind the lens. Find the magnification.

Example Problem 11.2

A candle is placed 22 cm from a concave mirror. A virtual image is produced 53 cm from the mirror. What is the magnification?

Given
Object distance $d_o = 22$ cm
Image distance $d_i = 53$ cm

Required
Magnification $M = ?$

Analysis and Solution
The correct equation is $M = \dfrac{d_i}{d_o}$

Substitute the values and their units, and solve the problem.

$$M = \frac{d_i}{d_o}$$

$$M = \frac{53\ \text{cm}}{22\ \text{cm}}$$

$$= 2.4$$

Paraphrase
The magnification of the mirror is 2.4 times.

Example Problem 11.3

An electron microscope magnifies a virus that is 3.50×10^{-7} m. If the magnification is 3.70×10^{5}, how big will the image be?

Given

Object height $h_o = 3.50 \times 10^{-7}$ m
Magnification $M = 3.70 \times 10^{5}$

Required

Image height h_i = ?

Analysis and Solution

The correct equation is $M = \frac{h_i}{h_o}$

Rearrange it to solve for the variable needed: $h_i = Mh_o$

Substitute the values and their units, and solve the problem.

$$h_i = Mh_o$$
$$h_i = (3.70 \times 10^{5})(3.50 \times 10^{-7}\ \text{m})$$
$$= 0.130\ \text{m}$$

Paraphrase

The size of the image is 0.130 m or 13.0 cm.

Practice Problems

1. A slide projector has a magnification of 50. How wide will the projected image be if the slide is 2.8 cm wide?
2. A concave mirror creates a virtual image of a candle flame that is 10 cm high. If the magnification of the mirror is 12.5, what is the height of the candle flame?
3. A magnifying glass will magnify 6 times. If the magnifying glass is held over a page and magnifies a letter that is 2 mm tall, how big is the image?

Example Problem 11.4

A concave mirror creates a real, inverted image 16.0 cm from its surface. If the image is 4.00 times larger, how far away is the object?

Given

Image distance d_i = 16.0 cm
Magnification M = 4.00

Required

Object distance d_o = ?

Analysis and Solution

The correct equation is $M = \frac{d_i}{d_o}$

Rearrange it to solve for the variable needed: $d_o = \frac{d_i}{M}$

Substitute the values and their units, and solve the problem.

$$d_o = \frac{d_i}{M}$$
$$d_o = \frac{16.0\ \text{cm}}{4.00}$$
$$= 4.00\ \text{cm}$$

Paraphrase

The object is 4.00 cm from the mirror.

Practice Problems

1. An insect is magnified 12 times by a concave mirror. If the image is real, inverted, and 6 cm from the mirror, how far away is the insect?
2. A lens produces a real image that is 23 times bigger than the object. If the object is 14 cm away, how far away is the image?
3. A human hair is placed 3 mm from a powerful microscope lens that has a magnification of 40 times. How far from the lens will the image be formed?

Convex Mirrors

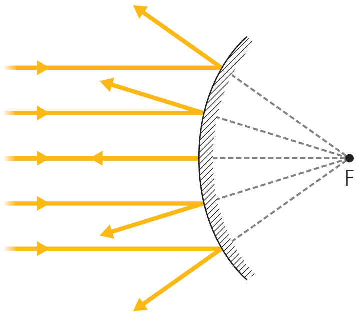


Figure 11.16 Parallel light rays approaching a convex mirror

A mirror with a surface curved outward is a **convex mirror**, also called a **diverging mirror** (Figure 11.16). Instead of collecting light rays, a convex mirror spreads out the rays. A convex mirror produces a virtual image that is upright and smaller than the object (Figure 11.17). The image is a virtual image because although the reflected rays appear to be originating from behind the mirror, if a screen were placed there, the incident light rays would not reach it. The rays would be blocked by the mirror.

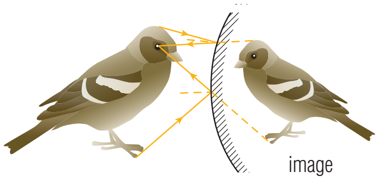
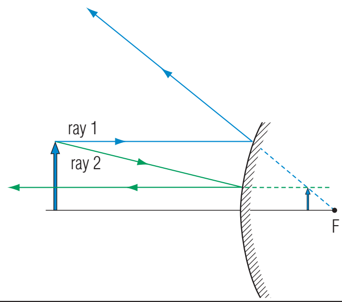


Figure 11.17 A virtual image produced by a diverging mirror is smaller than the object.

Table 11.3 Ray Diagram for Convex Mirror

Distance of Object from Mirror, d_o	Type of Image Formed	How the Image Is Viewed	Ray Diagram
All distances in front of the mirror	Smaller than object, upright, virtual	Behind the mirror between the vertex and the focal point	

Drawing a Convex Mirror Ray Diagram

You can follow the steps in Figure 11.18 to draw a ray diagram of a convex mirror.

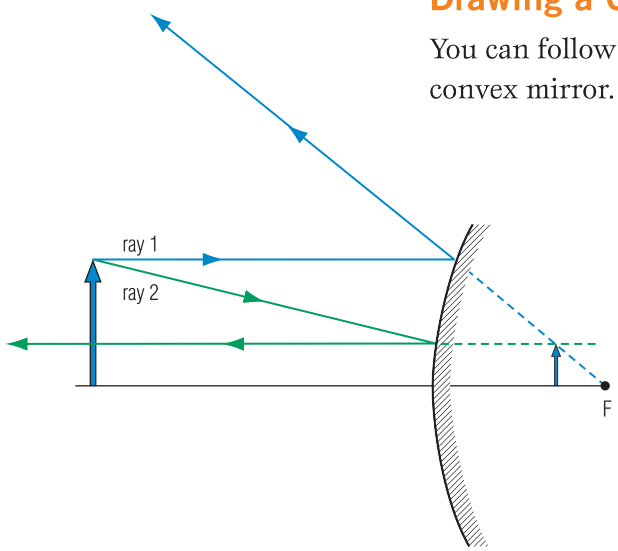


Figure 11.18 Convex mirror ray diagram

1. The first ray of a convex mirror ray diagram travels from a point on the object parallel to the principal axis (ray 1). Any ray that is parallel to the principal axis will appear to have originated from the focal point on a diverging mirror.
2. The second ray travels from a point on the object toward the focal point (ray 2). Any ray that is directed at the focal point on a diverging mirror will be reflected back parallel to the principal axis.
3. Draw the virtual image where the rays appear to intersect.

Uses for Convex Mirrors

If you were to compare a convex mirror with a plane mirror of the same size, you would discover that more objects can be seen in the convex mirror. For this reason, convex mirrors are often used as security mirrors in stores (Figure 11.19). A convex mirror allows you to view a large region of the store from one location. For the same reason, convex mirrors are used in vehicles as side-view mirrors and rear-view mirrors. However, if you look in a convex mirror, it appears as if the image is originating from a smaller point behind the mirror. Because of these smaller images, convex mirrors on cars often have a warning such as the one shown in Figure 11.20 that objects in the mirror are closer than they appear.

You may have noticed convex mirrors used in some automatic teller machines and computers (Figure 11.21). A convex mirror allows the machine users to see what is happening behind them while they are facing the machine screen. Many camera phones include a convex mirror so that you can accurately aim the camera to take a self-portrait.

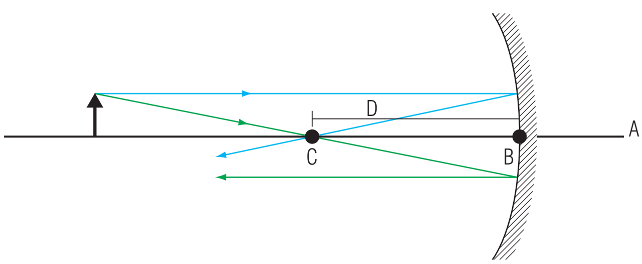
Figure 11.19 A store security mirror

Figure 11.20 A side-view mirror

Figure 11.21 A security mirror on an automatic teller machine

Learning Checkpoint

1. What is a real image?
2. What is a virtual image?
3. Name the features of the ray diagram identified as A, B, C, and D.



4. Draw a ray diagram where the object is between one and two focal lengths from a concave mirror with a focal length of 5 cm.
5. Draw a ray diagram where the object is more than two focal lengths from a concave mirror with a focal length of 5 cm.

*Take It **Further***

The first astronaut to walk on the Moon, Neil Armstrong, put a special mirror on the Moon's surface that was able to reflect light directly back in the direction from which it came. Scientists from Earth shine laser light at this mirror. Find out how this mirror works and what has been learned from pointing a laser from Earth at the mirror. Begin your research at ***ScienceSource***.

D13 *Quick Lab*

Plane Mirror Reflection

The reflective surface of the mirror may be at the back of the mirror or at the front of the mirror depending where the reflective coating was applied to the glass or plastic you are using.

Purpose

To investigate the law of reflection using a plane mirror

Materials & Equipment

- ruler
- paper
- protractor
- plane mirror
- ray box or light source that can be made into a single 1-mm wide slit source

CAUTION: Do not shine bright light into anyone's eyes. Incandescent light sources can become very hot. Do not touch the bulbs or block air flow around the light bulbs.

Procedure

1. Use the ruler to draw a straight vertical line in the middle of a piece of paper. Use the protractor to create a perpendicular normal at the approximate centre of the first line.
2. Place the mirror upright along the vertical line. Hold the mirror in place. The normal should be perpendicular to the surface of the mirror.
3. Shine a ray of light at an acute angle to the normal so that it reflects where the normal meets the reflecting surface. Use the ruler to trace the incident ray between the light source and the mirror. Then, trace the reflected ray that reflects from the mirror.
4. Label the incident ray as i_1. Label the reflected ray as r_1 (Figure 11.22).
5. Repeat step 2 two more times with different angles. Be sure to label the successive incident and reflected rays as i_2, r_2 and i_3, r_3.
6. Measure and record the angle between each light ray and normal.

Questions

7. Compare the results of the angles of incidence and reflection. Describe how they are related.
8. (a) Are your results exactly the same as the law of reflection? Explain.

   (b) What aspects of your experimental method could make your results different from the law of reflection?

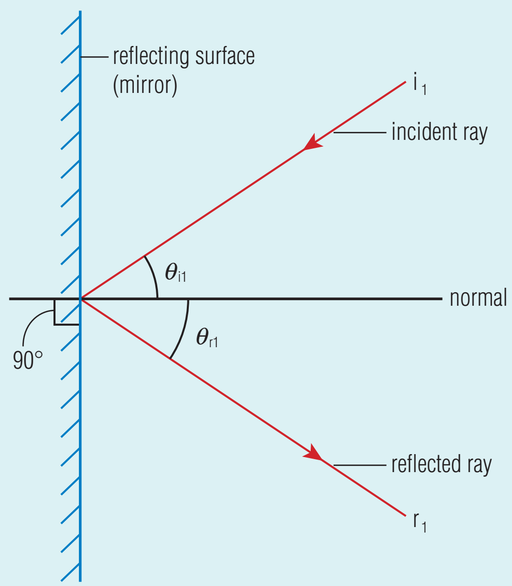


Figure 11.22 A sample drawing

D14 *Skill Builder Activity*

Drawing Ray Diagrams for Concave and Convex Mirrors

Concave Mirrors

1. Copy Figure 11.23(a) into your notebook.

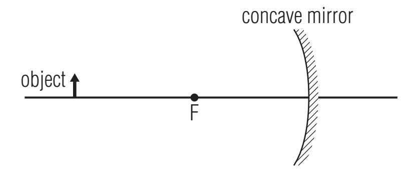


Figure 11.23(a) Draw the object and the mirror.

2. To determine where the image of the tip of the arrow will be, draw two rays. Draw the first ray parallel to the principal axis until it strikes the mirror and reflects through the focal point (Figure 11.23(b)).

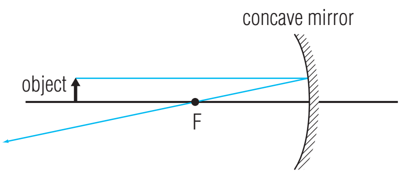


Figure 11.23(b) Draw the first ray.

3. Draw the second ray through the focal point until it strikes the mirror and reflects parallel to the principal axis (Figure 11.23(c)).

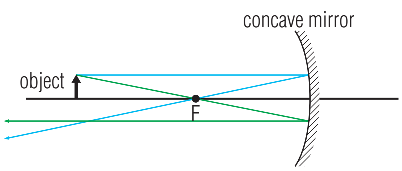


Figure 11.23(c) Draw the second ray.

4. These two rays intersect at only one location. This is where the image of the tip of the arrow is. Draw the inverted image (Figure 11.23(d)).

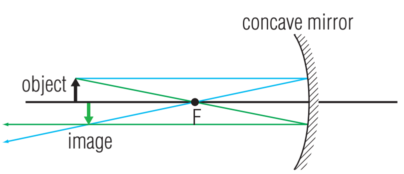


Figure 11.23(d) Draw the inverted real image.

5. Repeat the process for other parts of the object.

Convex Mirrors

1. Copy Figure 11.24(a) into your notebook.

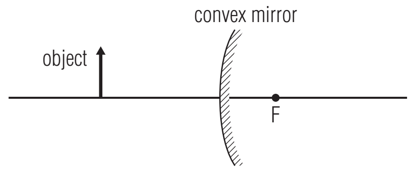


Figure 11.24(a) Draw the object and mirror.

2. Draw the first ray parallel to the principal axis until it strikes the mirror, where it reflects away in a line that appears to come from the focal point. Draw a dashed line from the point on the mirror where the ray strikes through the focal point (Figure 11.24(b)).

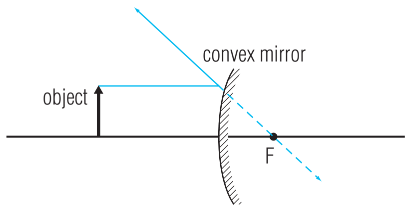


Figure 11.24(b) Draw the first ray.

3. Draw the second ray toward the mirror heading for the focal point until it strikes the mirror and reflects back parallel to the principal axis. Draw a dashed line through the mirror parallel to the principal axis until it intersects the first dashed line (Figure 11.24(c)).

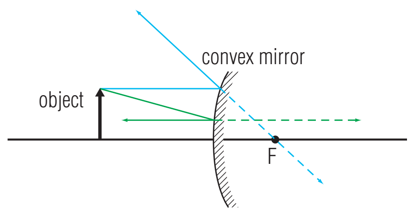


Figure 11.24(c) Draw the second ray.

4. The intersection of both dashed lines represents the virtual image of the tip of the arrow. The image for a convex mirror is always virtual, upright, and smaller.

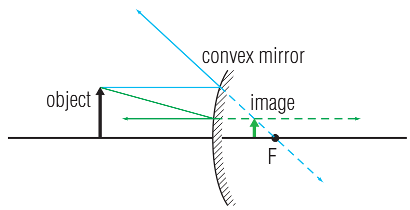


Figure 11.24(d) Draw the upright, virtual image.

DI Key Activity

D15 Inquiry Activity

Skills References 2, 8

SKILLS YOU WILL USE

- Gathering, organizing, and recording relevant data from inquiries
- Processing and synthesizing data

Concave Mirrors

Question

How does the distance of the object from a concave mirror affect the size and orientation of the image?

Materials & Equipment

- 2 optical benches
- good quality concave mirror with a predetermined focal length
- light source, such as candle or light bulb
- metre stick with millimetres marked
- screen

CAUTION Light Bulb: Do not shine bright light into anyone's eyes. Incandescent light sources can become very hot. Do not touch the bulbs or block air flow around the light bulbs.
Candle: Tie back long hair, secure loose clothing, and avoid sudden movement when using candles. Make sure the candle is in a secure holder. Be careful not to get the screen too close to the flame. Be careful when moving the candle so you are not burned by a drop of melted wax. Dispose of all matches in an appropriate location.

Procedure

1. Copy Table 11.4 into your notes. Record the focal length of your concave mirror as supplied by your teacher in the table title.
2. Set up the first optical bench with the concave mirror at one end and the light source at the other end. The concave mirror should be angled slightly away from the light.
3. Light the candle, or turn on the light bulb. Darken the room. Align a second optical bench with a screen so that the reflected image of the light strikes the screen, as shown in the diagram. It does not need to be in focus yet. The optical benches are now aligned and should not be moved (Figure 11.25 on the next page).

Table 11.4 Concave Mirror Focal Length: _______

Distance of Candle from Mirror	Object Distance d_o (cm)	Image Distance d_i (cm)	Orientation (upright or inverted)	Object Height h_o (cm)	Image Height h_i (cm)	Magnification
3 times the focal length						
2 times the focal length						
1.5 times the focal length						
Focal length						
0.5 of the focal length						

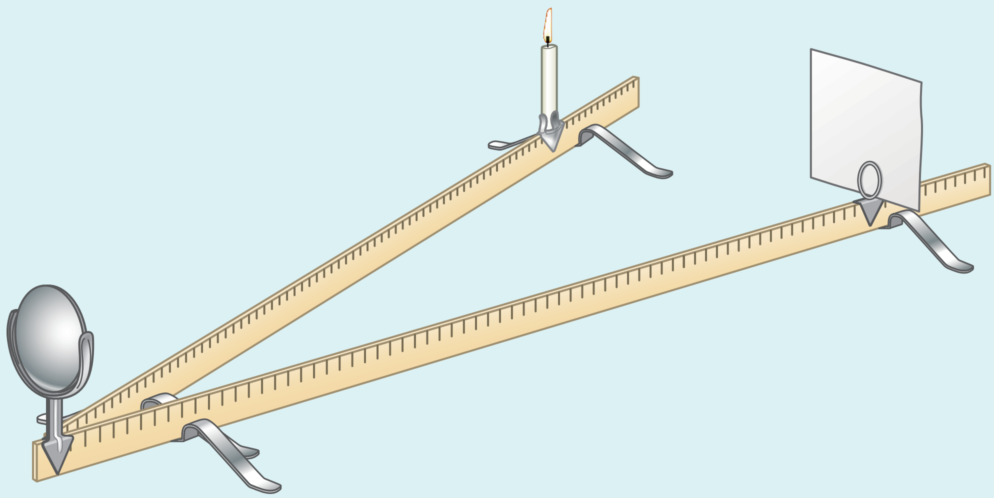


Figure 11.25 Step 3

4. Move the candle to the distance indicated in the first row of the table in the "Distance of Candle from Mirror" column. Write this actual distance into the table in the "Object Distance d_o" column that is beside it.

5. Slowly move the screen along the length of the bench until the image of the candle flame comes into focus. Measure the distance from the mirror to the screen. Record this distance as the image distance, d_i in the table. Record the orientation of the flame in the table.

6. Very carefully measure the size of the actual flame or bulb and the height of the image of the light. Record these values in your chart.

7. Repeat steps 4 to 6 for the next distance indicated in the table, until all rows of the table are complete.

Analyzing and Interpreting

8. How do you explain the results obtained when the object was placed at 0.5 of the focal length from the mirror?

Skill Practice

9. Complete the magnification column of the table. Show one of your calculations.

Forming Conclusions

10. Using the completed table, form a conclusion about:

(a) the magnification of the image based on the object's distance from the mirror

(b) the orientation of the image based on the object's distance from the mirror

D16 *Problem-Solving Activity*

Skills References 3, 6

SKILLS YOU WILL USE
- Identifying sources of error
- Expressing results accurately and precisely

Laser Light Security System

Recognize a Need

The local museum is displaying a number of priceless artifacts in two adjoining rooms that are connected by an open door (Figure 11.26). Security is provided by a laser light and light sensor combination.

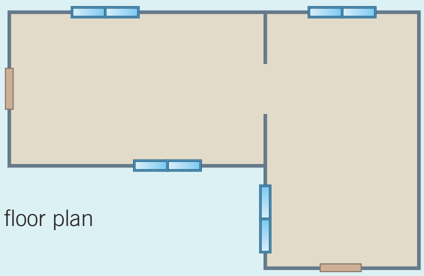


Figure 11.26 A floor plan of the museum

Problem

How can you set up a security system using the laser and the light sensor?

Materials & Equipment

- 2 empty shoe boxes
- tape
- piece of paper 60 cm × 60 cm and 2 cm × 2 cm
- protractor
- ruler
- selection of small plane mirrors
- modelling clay
- Class 1 or 2 laser

CAUTION: Do not shine the laser light in anyone's eyes.

Criteria for Success

- The laser light must enter one of the rooms from whichever direction you choose, through a small opening in the side of the room. It must bounce off all the windows and the outside doors. Finally, it must hit a 2 cm × 2 cm piece of paper attached to the wall of the last room that represents the alarm sensor.

Brainstorm Ideas

1. Brainstorm how to arrange plane mirrors within the rooms (shoe boxes) so that the light ray from the laser will bounce off every window and the two outside doors and hit the paper alarm sensor.

Make a Drawing/Build a Model

2. Firmly tape the two shoe boxes together in the orientation shown in Figure 11.26. Place the shoe boxes on a large piece of white paper and trace their outlines. Remove the boxes and draw the location of the windows and doors on the paper.
3. Plan the location of the mirrors based on the position of the doors and windows. Use a protractor and ruler to draw in the mirrors at the proper location and angle so the light ray will bounce off all the windows, the two outside doors, and finally the white paper sensor in the last room.
4. Use the ruler to draw a line on the paper that shows the path of the light ray as it moves through the rooms.
5. Build a 3D model of the rooms using the shoe boxes. Attach plane mirrors to the walls in the proper positions to represent the windows and the two outside doors.
6. Position the alarm sensor in your model.

Test and Evaluate

7. Have your teacher use a laser to test the effectiveness of your alarm system. Make adjustments to the mirrors as needed.

Skill Practice

8. How accurate did you have to be in placing your mirrors so the beam reflected properly?
9. What strategies did you use to ensure accurate placement?
10. How could you improve your solution?

Communicate

11. How well did the drawing of the mirrors and their angles correspond to what actually happened?

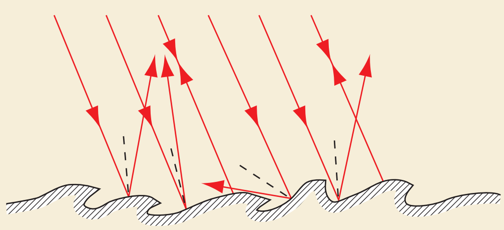
11.1 CHECK and REFLECT

Key Concept Review

1. Describe the law of reflection as a relationship between the angle of incidence, the angle of reflection, and the normal.
2. Describe the kinds of images that can be formed by plane mirrors.
3. (a) What type of mirror produces only diverging rays?
   (b) What type of mirror can produce both converging and diverging rays?
4. Describe what kind of mirror you would use if you needed to view a large, spread-out area in a small mirror.
5. Compare the shapes of convex and concave mirrors. How are they similar, and how do they differ?
6. What kind of images do convex mirrors form?
7. What are three uses for convex mirrors?
8. A lighted object is placed at the focal point of a concave mirror. Describe the light rays reflecting off the mirror.
9. Describe how the positions of a mirror, incident ray, reflected ray, and normal are related.
10. How does your image in a mirror compare with looking directly at yourself?
11. A bacterium has a length of 5.5×10^{-6} m but seen through a powerful microscope appears to be 1.2×10^{-3} m. What is the magnification of the microscope?
12. A virtual image is produced by a convex mirror that is 1.60 cm from the mirror. If the magnification is 0.20, how far from the mirror is the object?

Connect Your Understanding

13. Use a ray diagram with five rays to show how a car headlight uses a concave mirror to direct light.
14. Draw the following ray diagram: three rays, travelling generally left to right, converge 10 cm away from a concave mirror and are reflected away from the mirror as parallel rays.
15. Draw a ray diagram to determine the position of an image formed by a concave mirror that has a focal length of 3.0 cm and a 2.0 cm object positioned 6.0 cm from the mirror.
16. If you can see someone in a mirror, can that person see you? Explain why or why not. Use a ray diagram if necessary.
17. Draw a view from above of an arrangement of mirrors that would allow you to see the back of your head. Mark the angles of incidence and reflection on your diagram.
18. Does diffuse reflection, shown below, follow the law of reflection? Explain why it does or does not.



Question 18

Reflection

19. (a) Describe one idea you found easy to learn in this section.
    (b) Why do you think it was easy to learn?
    (c) Describe one idea you found difficult to understand in this section.
    (d) What did you do to help yourself understand it?

For more questions, go to ***ScienceSource***.

11.2 The Refraction of Light

Here is a summary of what you will learn in this section:

- Refraction is the bending of light as it passes between media that have different refractive indices.
- Refraction occurs due to the change in the speed of light in different media.
- The index of refraction of a medium is the ratio of the speed of light in a vacuum compared to the speed of light in the medium.
- As light passes at an angle from a less dense medium into a more dense medium, the light ray bends toward the normal.
- Snell's law relates the indices of refraction of a medium to the angle of incidence and reflection.

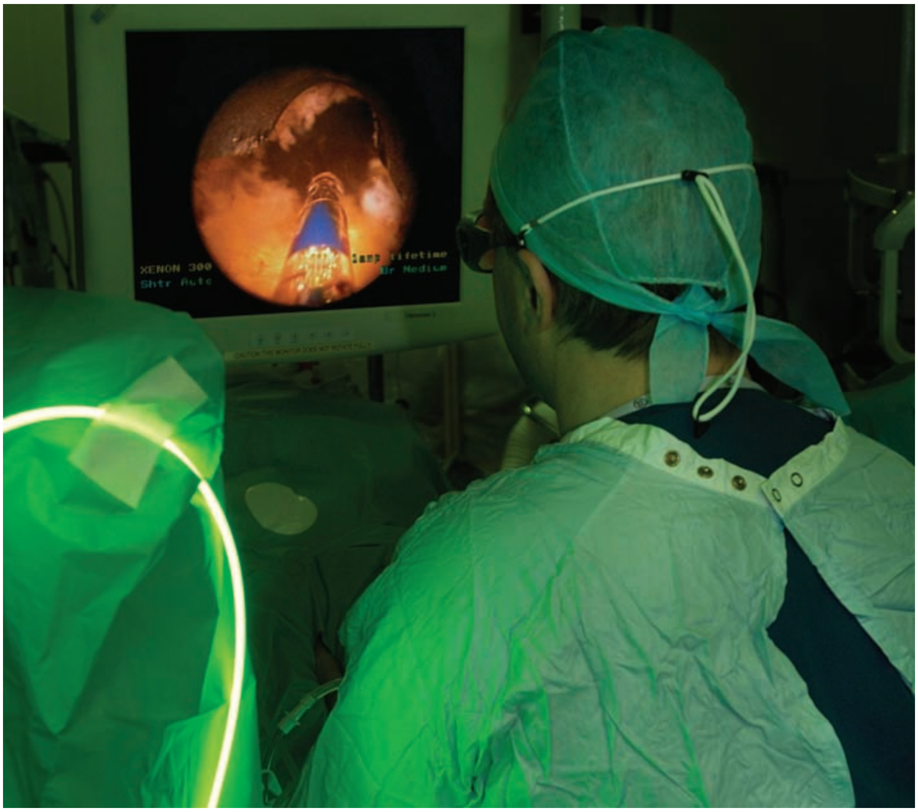


Figure 11.27 Laser light is transmitted along optical fibres for use in surgery.

Fibre Optics

One of the most important properties of light is that it tends to travel in straight lines. If you need light to bend around a corner or to shine into a difficult-to-reach place, you might want to use optical fibres. An **optical fibre** is a thin, transparent glass tube that can transmit light even around corners (Figure 11.27). This is because the light in a fibre optics tube cannot escape until it reaches the end of the tube.

How does an optical fibre conduct a light ray around a corner? Imagine a long, curved tunnel whose walls, floor, and ceiling are lined with mirrors. If you were to shine a laser beam into the tunnel, the beam of light would change direction each time it reflected from a mirror and would make it all the way to the end of the tunnel. This is exactly what happens on the inside of the optical fibre. The light ray reflects off the inside of the walls of the glass fibre. When the thin glass fibre bends around a corner, the light ray goes around the corner through a series of reflections.

We use fibre optics systems to transmit telephone and Internet communications. A single optical fibre can be as thin as a human hair, yet transmit thousands of different signals at the same time (Figure 11.28). This is because each signal is sent at a different wavelength through the same cable. Just as two flashlight beams can cross each other and then continue on their way unaffected, thousands of light beams can pass through the same cable. A typical optical fibre cable can be made from thousands of optical fibres tightly packed together.

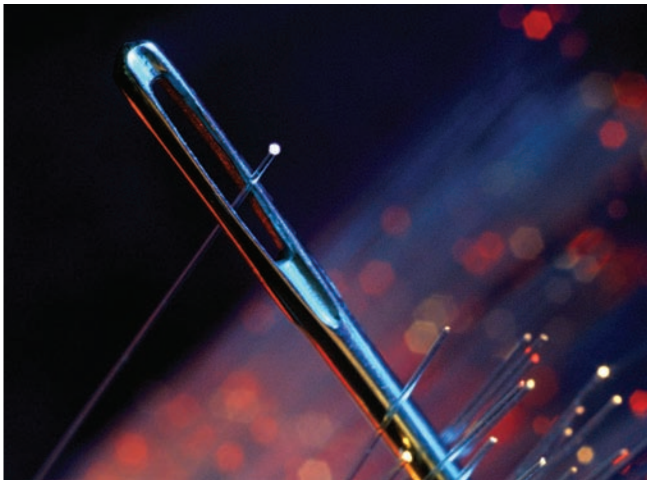


Figure 11.28 A single optical fibre can fit through the eye of a needle.

D17 *Quick Lab*

Observing Refraction

Purpose

To observe whether the bending of light affects the way we see certain objects

Materials & Equipment

- glass of water
- pencil
- jar lid with opaque rim
- coin

Procedure

1. Insert a pencil into the glass of water. Observe the glass from the side at various angles. Record your observations using labelled diagrams.
2. Place a jar lid with an opaque rim on a desk and put a coin in the middle.
3. Keep watching the coin while you lower the height of your head until the coin just disappears from view behind the rim of the lid (Figure 11.29).
4. Keeping your head at the same level, pour water into the lid, on top of the coin. Observe. Record your observations using labelled diagrams.

Figure 11.29 Step 3

Questions

5. Describe the path of light from the water to the air.
6. Draw a ray diagram of the light rays from the coin to your eye:

   (a) in step 3

   (b) in step 4
7. Compare your drawings in question 6 with those done by classmates.

   (a) How are your drawings similar?

   (b) How are your drawings different?

Figure 11.30 The spoon appears to be broken because light rays change direction as they move from air into water and from water into air.

Refraction

Although light travels in straight lines, it bends when it passes from one medium into another, such as from air into water. A **medium** (plural: media) is a material that is being used or is undergoing a process. The bending of light rays as they pass between two different media is called **refraction**. Refraction causes some very interesting visual effects. For example, the handle of the spoon in Figure 11.30 appears to be broken at the level of the top of the water. When light from the spoon passes from the water into the air, the light rays are bent. Refraction is more than just an optical curiosity. It is used in designing and building camera lenses, eyeglasses, and telescopes.

Refraction is due to changes in the speed of light. For example, as light moves from air into water, its speed decreases. Different media slow down light by different amounts. The more that light slows down, the more the light is refracted.

You may have stood beside a pool or lake and seen something on the bottom that you wanted to pick up. Yet, when you dove in, the object was not where it appeared to be. This is because the light rays changed direction at the surface of water as they passed between the water and the air. Figure 11.31 shows light rays moving from water into air and refracting as they leave the water. When we view the refracted light rays, we assume they have travelled in a straight line. If you trace the light rays that reach the eyes back in a straight line, you will find that they do not lead to the chest. Instead, the light from the chest in deep water appears to be coming from shallower water.

During Reading Thinking Literacy

Purpose of an Illustration

State the topic and purpose for the illustrations on these and the following pages in this section. Find words in the caption that also occur in the text. Write a statement about how the illustration helps you to understand a concept or idea.

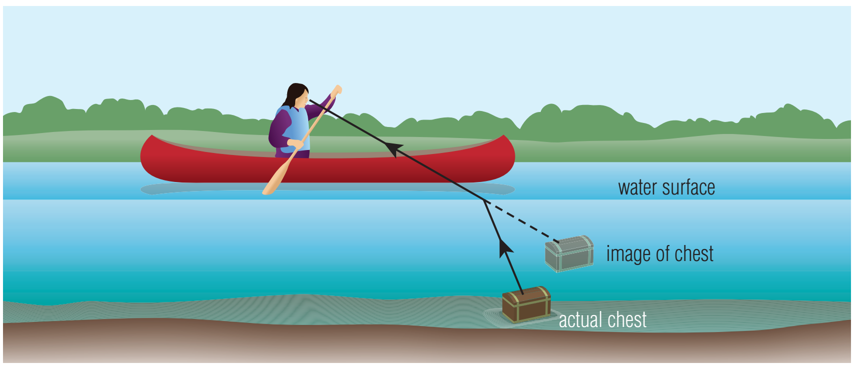


Figure 11.31 The underwater chest appears to be higher than it really is.

The Speed of Light

In the vacuum of space, where there are very few particles, light travels at almost 300 million m/s or 3.0×10^8 m/s. Moving at this speed, light could travel seven times around the Earth in one second. However, just like a student trying to move from class to class when the hallways are full, it is impossible for light to move at top speed when particles get in the way.

A ray of light is electromagnetic radiation, which is transmitted in waves. The particles in a medium slow down the passage of the waves, which results in light travelling more slowly through a block of glass, for example, than it travels through a vacuum.

The effects of changes in the speed of light can be seen in Figure 11.32. The light ray strikes the Plexiglas at an angle. As the light enters the Plexiglas, it slows down and refracts (a). When the light leaves the Plexiglas and enters the air, it speeds up and refracts again (b). Notice that light does not refract inside the block. Light refracts only at the boundary when it is entering or leaving a medium. This photograph also shows that refraction is a reversible process, in that the angle of refraction entering the block is exactly reversed as the light leaves the block. The light ray immediately speeds up again as it leaves the block.

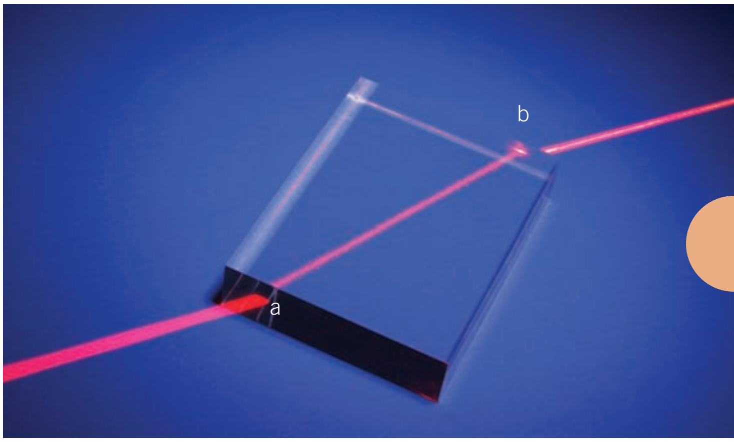


Figure 11.32 Light refracts as it enters and then leaves this block of Plexiglas.

The Index of Refraction

The amount by which a transparent medium decreases the speed of light is indicated by a number called the **index of refraction**, also called the refractive index. The larger the refractive index, the more the medium decreases the speed of light.

Light travels fastest in a vacuum. The refractive index of the speed of light in a vacuum is assigned a value of 1.00. A value of 1.00 can also be used for air, since the fourth decimal place does not affect calculations based on Table 11.5. Since water, glass, diamond, and other media all slow down light, they have higher values than air.

The refractive index of a medium, n, is determined by comparing the speed of light in the medium, v, with the speed of light in a vacuum, c. This leads to the following definition:

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

$$\text{or} \quad n = \frac{c}{v}$$

Since units cancel, a refractive index value does not have any units.

Table 11.5 Index of Refraction for Selected Media

Media	Index of Refraction
vacuum	1.00 (exactly)
air	1.0003
carbon dioxide gas	1.0005
water	1.33
alcohol	1.36
Pyrex glass	1.47
Plexiglas	1.49
table salt	1.51
flint glass	1.61
sapphire	1.77
cubic zirconia	2.16
diamond	2.42
gallium phosphide	3.50

Practice Problems

1. The speed of light in leaded glass is 1.66×10^8. What is the index of refraction of this type of glass?
2. The speed of light in quartz is 2.10×10^8 m/s. What is the index of refraction of quartz?
3. The speed of light through a material is 1.24×10^8 m/s. What material is it? (Hint: Refer to Table 11.5 on page 437.)

Example Problem 11.5

The speed of light in a sample of glass is 1.91×10^8 m/s. The speed of light in a vacuum is 3.00×10^8 m/s. What is the refractive index of this glass?

Given
Speed of light in glass $= 1.91 \times 10^8$ m/s
Speed of light in vacuum $= 3.00 \times 10^8$ m/s

Required
Refractive index $n = ?$

Analysis and Solution
The correct equation is $n = \frac{c}{v}$

Substitute the values and their units, and solve the problem.

$$n = \frac{c}{v}$$
$$= \frac{3.00 \times 10^8 \text{ m/s}}{1.91 \times 10^8 \text{ m/s}}$$
$$= 1.57$$

Paraphrase
The refractive index is 1.57.

Practice Problems

Use Table 11.5 on page 437 to answer the following questions.

1. What is the speed of light through alcohol?
2. What is the speed of light through gallium phosphide?
3. What is the speed of light through sapphire?

Example Problem 11.6

What is the speed of light in water given that water has a refractive index of 1.33?

Given
Refractive index of water $n = 1.33$
Speed of light in vacuum $c = 3.00 \times 10^8$ m/s

Required
Speed of light in water $v = ?$

Analysis and Solution
The correct equation is $n = \frac{c}{v}$
Rearrange it to solve for the variable needed: $v = \frac{c}{n}$

Substitute the values and their units, and solve the problem.

$$v = \frac{c}{n}$$
$$= \frac{3.00 \times 10^8 \text{ m/s}}{1.33}$$
$$= 2.26 \times 10^8 \text{ m/s}$$

Paraphrase
The speed of light in water is 2.26×10^8 m/s.

How Light Refracts

You can picture the beam of light as the leading edge of a wave, as shown in Figure 11.33. At first, all the waves are parallel. Then, the light waves are compressed as they enter the water and slow down. If the light strikes the surface of the water at an angle, that part of the light beam that enters first will slow down first. Notice in the diagram that this changes the direction of the waves and also the direction of the ray of light. It is like a line of skaters changing direction because the skaters at one end slow down on rough ice (Figure 11.34).

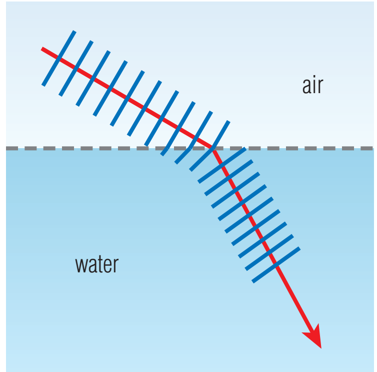


Figure 11.33 Light can be represented as a series of waves that compress and change direction as they enter water on an angle.

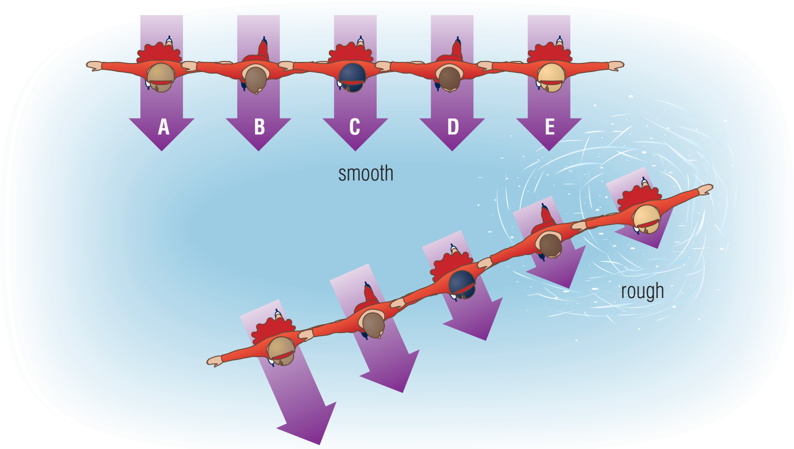


Figure 11.34 Skater E slows down, making the entire row of skaters turn.

Suggested Activity •

D18 Inquiry Activity on page 444

The angles of the refracted light rays are usually measured from the normal, drawn at 90° to the surface where the light ray crosses between the two media. When light travels from air, with a low refractive index, into water, with a higher refractive index, it bends toward the normal. When light travels from a denser (higher refractive index) medium into a less optically dense (lower refractive index) medium, it bends away from the normal.

The angle of incidence, θ_i, and the angle of refraction, θ_R, are measured from the normal. Figure 11.35 shows the angle of incidence, θ_i, and the angle of refraction, θ_R, as light refracts moving from (a) air to glass, and from (b) glass to air.

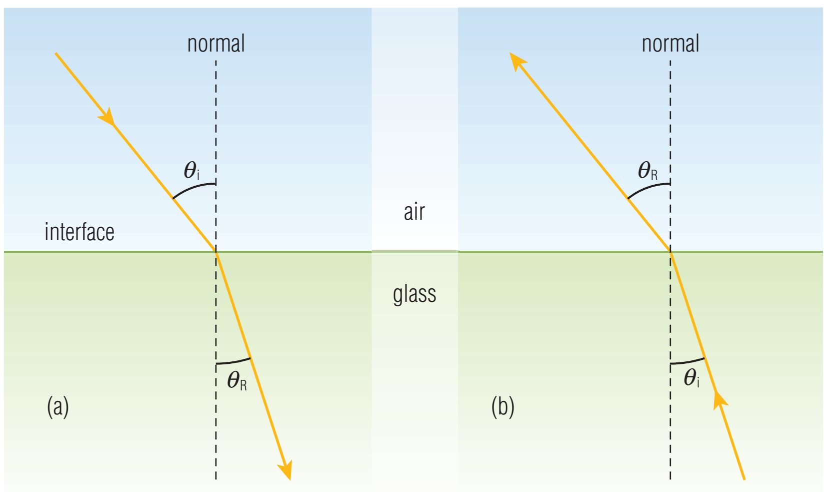


Figure 11.35 Light moves (a) from air to glass and (b) from glass to air.

Figure 11.36 This diamond is colourless but, due to dispersion, it acts as a prism to split white light up into its individual colours.

Dispersion

A special kind of refraction occurs in both a diamond and raindrops. A diamond can appear completely colourless and yet glitter in all colours of the rainbow because the amount of refraction is different for each colour. Since white light contains many colours, a single beam of white light can enter a diamond and be split into a whole rainbow of colours, as shown in Figure 11.36. This kind of refraction is called dispersion. **Dispersion** is the refraction of white light into separate wavelengths, or colours.

The most common type of dispersion is in the formation of a rainbow. When sunlight passes through a raindrop, some light is reflected. Some light is refracted twice, once on entering the raindrop and once on leaving. Both refractions cause the separation of the white sunlight into the colours of the rainbow (Figure 11.37).

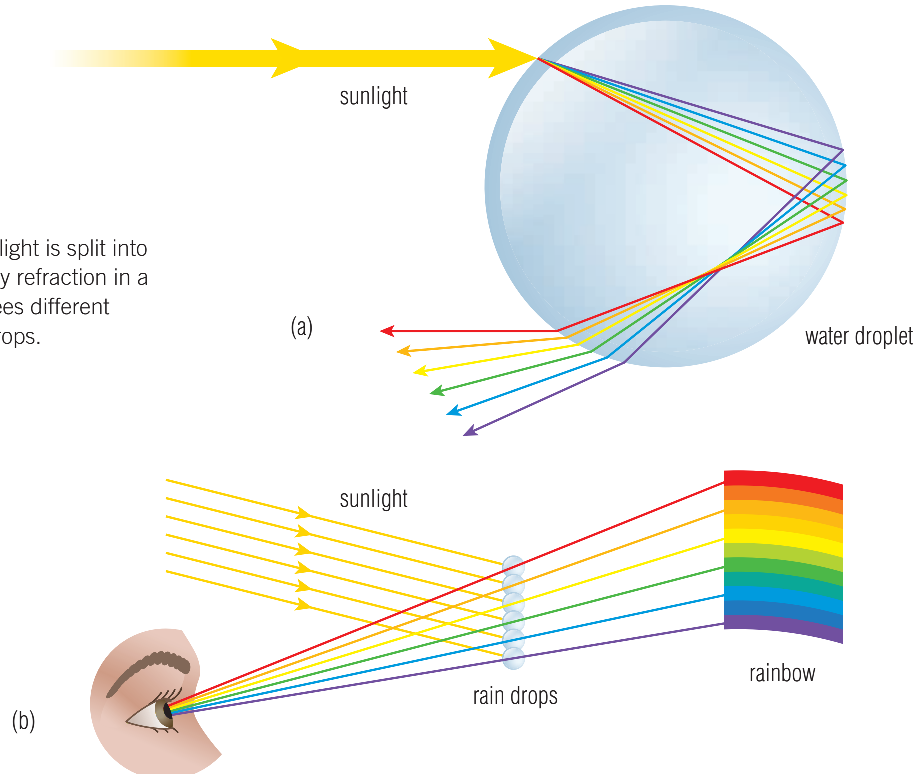


Figure 11.37 (a) White sunlight is split into the colours of the rainbow by refraction in a raindrop. (b) An observer sees different colours from different raindrops.

Learning Checkpoint

1. What is refraction?
2. Define "index of refraction."
3. What refracts light more, a sapphire or a diamond?
4. What direction does light bend when it travels from a denser medium to a less dense medium?
5. How is refraction related to dispersion?

Snell's Law

The phenomenon of refraction had been observed for centuries, but it was not until 1621 that its cause was stated mathematically. Willebrord Snell (1591–1626) was a Dutch astronomer and mathematician who is credited with identifying the exact relationship between the angle of incidence and the angle of refraction.

Snell's law is a formula that uses values for the index of refraction to calculate the new angle that a ray will take as a beam of light strikes the interface between two media (Figure 11.38). If you call the indices of refraction of the two media n_1 and n_2 and call the angles of incidence and the angle of refraction θ_1 and θ_2, then the formula for Snell's law is:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

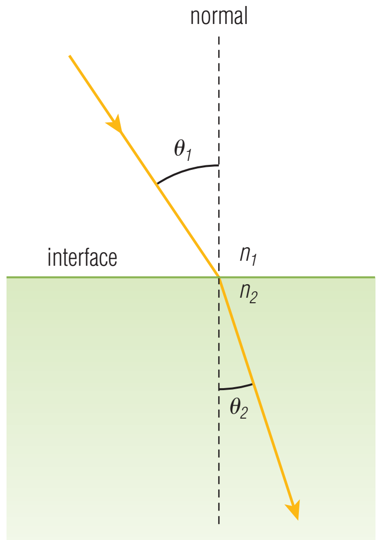


Figure 11.38 Snell's law relates the indices of refraction with the angle of incidence and the angle of refraction.

Example Problem 11.7

When light passes from air into water at an angle of 60° from the normal, what is the angle of refraction?

Given
Index of refraction of air $n_1 = 1.00$
Index of refraction of water $n_2 = 1.33$
Angle of incidence $\theta_1 = 60°$

Required
Angle of refraction $= \theta_2$

Analysis and Solution
The correct equation is $n_1 \sin\theta_1 = n_2 \sin\theta_2$

Manipulate it to solve for the variable needed $\sin\theta_2 = \dfrac{n_1 \sin\theta_1}{n_2}$
Identify air as medium 1 and water as medium 2.
Substitute the values and their units, and solve the problem.

$$\begin{aligned}\sin\theta_2 &= \frac{n_1 \sin\theta_1}{n_2}\\ &= \frac{1.00 \times \sin(60°)}{1.33}\\ &= \frac{1.00 \times 0.8660}{1.33}\\ &= 0.6511\end{aligned}$$

Therefore, $\theta_2 = 40.62°$

Paraphrase
The angle of refraction is 41°.

Practice Problems

1. When light passes from air into water at an angle of 30° from the normal, what is the angle of refraction?
2. When light passes from water into diamond at an angle of 45° from the normal, what is the angle of refraction?
3. The refractive index of the lens in a human eye is 1.41. If a ray of light goes from the air into the lens at an angle of 55.0°, what is the angle of refraction?

Suggested Activity •
D19 Inquiry Activity on page 445

Practice Problems

1. A ray of light approaches a jar of honey at an angle of 30.0°. If the angle of refraction is 19.5°, what is the refractive index of honey?
2. A block of amber is placed in water, and a laser beam travels from the water through the amber. The angle of incidence is 35° while the angle of refraction is 24°. What is the index of refraction of amber?
3. A red laser beam travels from flint glass into lemon oil. The angle of incidence is 40.0° and the angle of refraction is 44.4°. What is the refractive index of lemon oil?

Example Problem 11.8

In an experiment, a block of cubic zirconia is placed in water. A laser beam is passed from the water through the cubic zirconia. The angle of incidence is 50°, and the angle of refraction is 27°. What is the index of refraction of cubic zirconia?

Given
From Table 11.5, the index of refraction of water is 1.33.
Angle of incidence $\theta_1 = 50°$
Angle of refraction $\theta_2 = 27°$

Required
Index of refraction $= n_2$

Analysis and Solution
The correct equation is $n_1 \sin\theta_1 = n_2 \sin\theta_2$

Rearrange it to solve for the variable needed $n_2 = \dfrac{n_1 \sin\theta_1}{\sin\theta_2}$

Substitute the values and their units, and solve the problem.

$$\begin{aligned} n_2 &= \frac{n_1 \sin\theta_1}{\sin\theta_2} \\ &= \frac{1.33 \times \sin(50°)}{\sin(27°)} \\ &= \frac{1.33 \times 0.7660}{0.4540} \\ &= 2.244 \end{aligned}$$

Paraphrase
The index of refraction of cubic zirconia is 2.2.

Total Internal Reflection

Sometimes, such as in the case of fibre optics, light does not pass from one medium to another but stays within the medium as shown in Figure 11.39. In **total internal reflection**, light reflects completely off the inside wall of a denser medium (higher index of refraction) rather than passing through the wall into a less dense medium (lower index of refraction).

This same effect can happen in water as a ray of light reaches the surface between the water and the air. Recall that when light passes from a denser material, such as water, into a less dense medium, such as air, the light refracts away from the normal. As the angle of incidence increases, the angle of refraction increases.

Figure 11.39 Light rays reflect from the inside of a fibre optics tube.

At a certain angle, called the critical angle, the refracted ray of light follows a path exactly along the surface of the water. Even though the light refracts, it does not leave the water. In a way, the light is "trapped" inside the water (Figure 11.40).

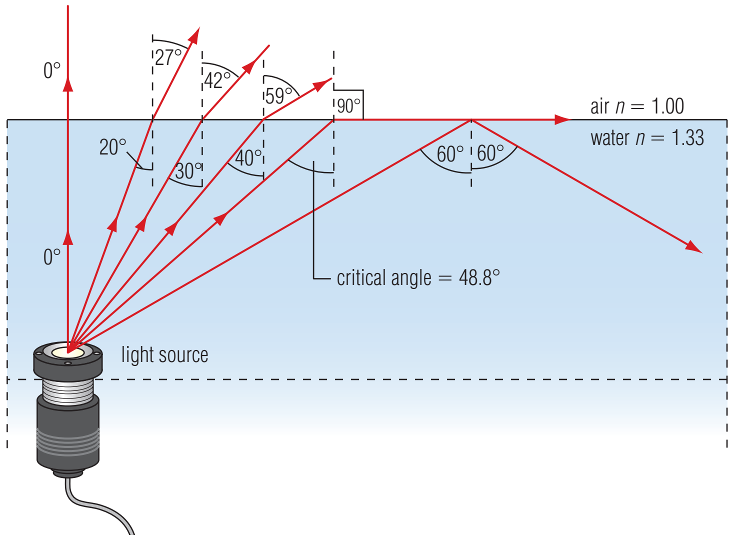


Figure 11.40 When the angle of incidence is greater than the critical angle, total internal reflection occurs.

Take It Further

Refractive index has many uses, including identifying gemstones. It can also be used to find the concentration of solutions. Find out about these and other uses of the refractive index. Begin your research at ***ScienceSource***.

What if the angle of the incident ray is increased even farther? The light ray is no longer refracted. Instead, it is completely reflected back inside the water. In an optical fibre, light is passed into the end of the fibre at an angle greater than the critical angle. Because the fibre is made of glass, which has a higher index of refraction than the surrounding medium, the light ray is completely reflected inside the fibre.

Suggested Activity •

D20 Design a Lab on page 446

Mirages

Both total internal reflection and refraction play a role in forming a mirage (Figure 11.41). A **mirage** is an image of a distant object produced as light refracts through air of different densities (Figure 11.42). Since the light rays pass through layers of air with progressively lower indices of refraction, eventually the light is totally internally reflected.

Figure 11.41 What looks like a puddle of water from the distance is actually an image of the sky that is produced as light from the sky is bent near the surface of the road up into the eyes of the observer.

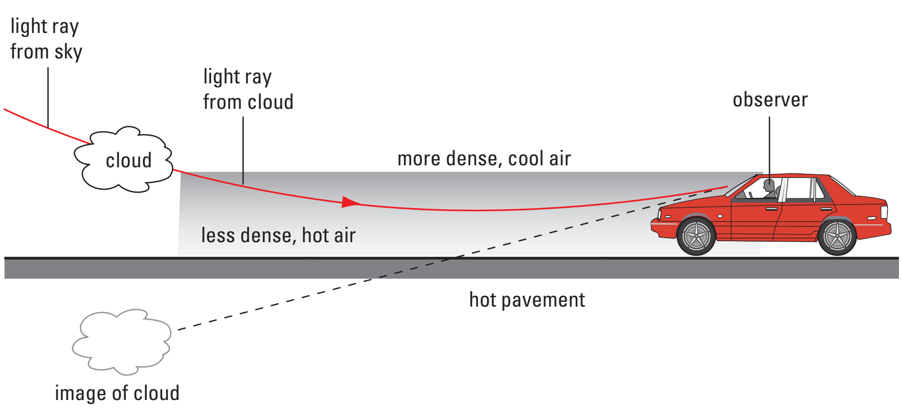


Figure 11.42 Light from an object in the sky is refracted due to the difference in density of the air above the pavement compared with the air higher up.

D18 *Inquiry Activity*

Skills References 2, 8

SKILLS YOU WILL USE
- Interpreting data/information to identify patterns or relationships
- Identifying sources of error

Refraction Measurement and Patterns

Question

What is the refractive index of tap water?

Materials & Equipment

- adhesive tape
- 360° protractor
- an aquarium or transparent container with flat vertical sides
- water
- ray box with single slit
- scientific calculator

CAUTION: Do not shine bright light into anyone's eyes. Incandescent light sources can become very hot. Do not touch the bulbs or block air flow around the light bulbs.

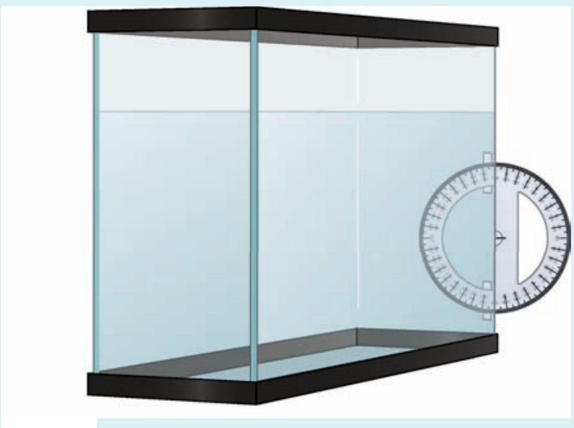


Figure 11.43 Step 3

Procedure

1. Make a table with the following headings. Give your table a title.

θ_1	θ_2	$\sin\theta_1$	$\sin\theta_2$

2. Tape the protractor to the container near the bottom so that the line from 0° to 180° is aligned vertically with the container's edge. Half the protractor should be flush with the side of the container, and the other half should be in air.
3. Fill the container with water so that the protractor is completely below the water line (Figure 11.43). The 90° angle is the normal for the incoming ray. The 270° angle is the normal for the water.
4. Hold the ray box so that the beam of light traces a path across the face of the protractor and enters the water. Begin with the angle 5° above the normal. This should be the 95° angle on the protractor. Record the refracted angle of the beam in water. Remember to measure magnitude of this angle from the 270° mark on the protractor.
5. Repeat step 4 for increments of 5° up to 50°.
6. Calculate $\sin\theta_1$ and $\sin\theta_2$ for each measured value of θ_1.
7. Draw a scatter plot of $\sin\theta_2$ against $\sin\theta_1$.

Analyzing and Interpreting

8. Is there a pattern in the data? Explain.
9. (a) Find the slope of the line.
   (b) Using Snell's law as a guide, determine what the slope represents.
   (Hint: what does $\frac{\sin\theta_1}{\sin\theta_2}$ equal?)
10. Assume the index of refraction of air is 1. Use the slope of the line to determine the index of refraction of water.

Skill Practice

11. The closer the points are to a straight line, the better your measurement skills. What does your graph suggest about the quality of your data collection skills?
12. Why should a scatter plot of θ_2 against θ_1 not be completely straight?

Forming Conclusions

13. Look up the index of refraction of water in Table 11.5 on page 437. How close was your value to this value? Explain any difference.

D19 *Inquiry Activity* **Skills References 2, 8**

SKILLS YOU WILL USE
- Observing and recording observations
- Identifying sources of error

Index of Refraction

Question

What is the index of refraction of various transparent solid media?

Materials & Equipment

- paper
- glass, Perspex, or similar acrylic, various other transparent media
- ray box with single slit
- ruler
- protractor
- scientific calculator

CAUTION: Do not shine bright light into anyone's eyes. Incandescent light sources can become very hot. Do not touch the bulbs or block air flow around the light bulbs.

Procedure

1. Copy the following table into your notebook. Give your table a title.

Medium	Angle of Incidence	Angle of Refraction	Index of Refraction	Speed of Light

2. Place a sheet of paper flat on a table. Draw a vertical line through the middle of the sheet, from the top to the bottom. You will place the edge of the transparent object on this line.
3. Choose three transparent media. Place one of the transparent objects flat on the paper on the right side of the line you drew, so that one edge of it is aligned with the line.
4. Place the ray box on the left side of the paper. Shine the single ray so that it strikes the transparent object at an angle to the surface. Draw a dot on the paper where the light ray leaves the ray box. Draw a second dot where the light ray strikes the transparent object. Draw a third dot where the ray exits the transparent object.
5. Remove the transparent object and draw a line that connects the first and second dots. This is the incident ray. Then draw another line that connects the second and third dots. This is the incident ray. Draw a horizontal normal line at the second dot. This line should be perpendicular to the vertical line you drew in step 2.
6. Use the protractor to measure the angle of incidence (between the normal and the incident ray) and the angle of refraction (between the normal and the refracted ray).
7. Use Snell's law to calculate the index of refraction of the medium. (See page 442 for an example calculation. Note that the index of refraction of air is 1.0003.)
8. Calculate and record the speed of light in each medium.
9. Repeat steps 2 through 8 for the remaining two materials.

Analyzing and Interpreting

10. How does the index of refraction relate to the amount of refraction the ray experiences?

Skill Practice

11. Show the calculations you did to determine the index of refraction in each transparent medium you used.
12. Compare the values you calculated for the refractive index of the media with the known values provided by your teacher. Explain any discrepancy in the two sets of values.

Forming Conclusions

13. (a) In which of the media is the speed of light the slowest? Why do you think so?
    (b) Is there a way to tell which medium has the slowest speed of light by just looking at the material? Explain.
14. What conclusions can you draw about the speed of light in the three different media and about transparent media in general?

D20 *Design a Lab* Skills References 2, 8

SKILLS YOU WILL USE
- Formulating questions
- Controlling variables

Transmitting Light Rays through Liquids

Question

What happens to a ray of light as it is transmitted through different liquids?

Design and Conduct Your Investigation

1. This activity involves investigating what happens to light when it travels through different liquids. You will need to develop a clear inquiry question, propose a hypothesis, identify variables or related factors, create a process for gathering data, and recognize where your results may end up. First, brainstorm all the questions you have about the behaviour of light in liquids. Choose one question that you would like to investigate further.
2. Narrow your question so it is something you can actually investigate. Ask yourself "What do I want to know? How could I find out? What do I think the answer might be?" Phrase your question as a cause-and-effect question, such as "How does (your choice of an independent variable) affect (your choice of a dependent variable)?"
3. Once you have phrased your question, write a hypothesis. Your hypothesis makes a prediction that your experiment will test. Your hypothesis should indicate the relationship between the independent and dependent variables.
4. Plan your experiment to test your hypothesis.
   - Make sure your experiment is a fair test by determining which variables you will need to control and which variable you will change.
   - Identify what tools, equipment, and material you need (Figure 11.44).
   - Carefully consider any safety issues involved in performing your experiment. Record any safety precautions you will take.
5. Write up the step-by-step procedure you will follow to perform your experiment. Record your procedure clearly so that others could follow it to perform the same experiment.
6. Decide how you will record your results clearly. Prepare any charts, tables, graphs, or sketches you will need.
7. Obtain your teacher's approval of your plan, and then perform your experiment. Use your scientific and technical skills to follow your procedure. Be sure to gather and record both qualitative and quantitative observations in your lab notes.
8. After you have completed your experiment, clean up and put away your equipment and materials.
9. Analyze your data. You may find it helpful to create a visual representation, such as a graph, or to make calculations in order to identify patterns or trends in the data. Ask yourself "What is the meaning of the data I collected? How else can I interpret the data?"
10. Use your completed analysis of your data to draw conclusions that support or refute your hypothesis. Address any errors you noted as you performed your experiment, and indicate their effect on the observed results.
11. Write a summary statement that answers the question you posed. Remember to use your data and observations to support your answer.
12. Communicate your results clearly using the correct terminology, symbols, conventions, SI units, and number of significant figures.

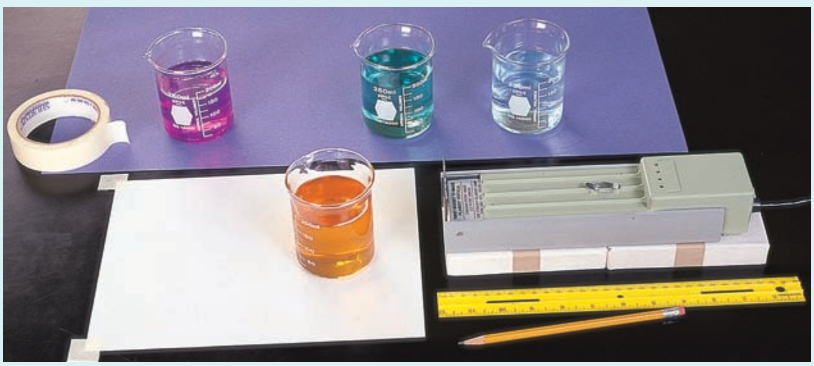
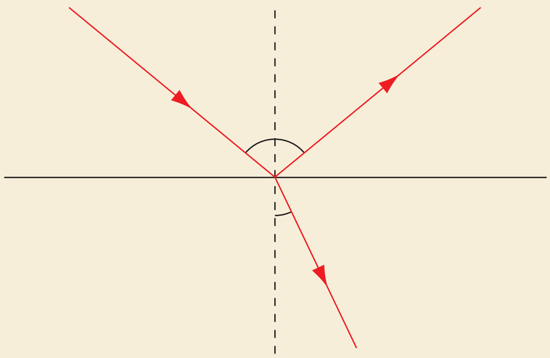


Figure 11.44 These are some materials and equipment you might consider using.

11.2 CHECK and REFLECT

Key Concept Review

1. When is light travelling at its fastest?
2. What is dispersion?
3. Under what conditions can you slow down light and then speed it up again?
4. Describe how light changes its direction when moving from one medium to another.
5. Copy the following diagram into your notebook. Label all the lines and angles.



Question 5

6. What property of a medium is given by its index of refraction?
7. Through which medium does light pass more quickly, one with a refractive index of 2.0 or one with a refractive index of 3.0?
8. (a) What is total internal reflection?
   (b) When does it occur?
9. (a) What is the formula for Snell's law?
   (b) Explain how you would calculate the changing speed of light using Snell's law.
10. Describe how Snell's law can be used to describe the bending of light toward and away from the normal.

Connect Your Understanding

11. Determine the refractive index of a medium if the speed of light slows to 1.2×10^8 m/s.
12. Jade has a refractive index of 1.61. If light approaches the gem at an angle of 80.0°, what is the angle of refraction?
13. A student is given a clear material to identify. She shines a laser at the surface of the material at an angle of 25.0°. The angle of the refracted ray is 16.7°. What material is it?
14. Calculate the index of refraction of a material if the angle of incidence is 60° and the angle of refraction is 50°.
15. A light ray passes from a vacuum into a substance where its speed is 2.26×10^8 m/s. What is the substance?
16. A super-dense material called a "Bose-Einstein condensate" has a refractive index of 1.76×10^7. What is the speed of light in this material?
17. How do reflection and refraction affect light similarly?
18. How do reflection and refraction affect light differently?
19. Why is it not possible to have an index of refraction less than 1.0?

Reflection

20. (a) What do you think is the most interesting information you learned in this section?
    (b) How does this information connect with what you already knew about the subject?
21. What scientific terms do you understand better now than you did before you read this section?

For more questions, go to ***ScienceSource***.

11.3 Lenses

Here is a summary of what you will learn in this section:

- Lenses refract light in useful ways to form images.
- Concave lenses, which cause light to diverge, are used in multi-lens systems to help produce images.
- Convex lenses cause light to converge and can be used in magnifying glasses or to project images on a screen.
- When the object is farther away from a convex lens than the focal point, the image is real and inverted.
- When the object is closer to the lens than the focal point, the image is virtual and upright.

Figure 11.45 Police officers using night vision goggles while patrolling along the St. Lawrence River

Seeing in the Dark

Imagine taking to the skies in a helicopter over the forests of northern Ontario. It is the middle of the night, and all you see out the window is total blackness. Your task is to fly to a remote forest location and rescue a team of firefighters needing emergency evacuation. Or picture yourself on night patrol watching along the shores of the St. Lawrence River (Figure 11.45). Would you be ready for such a mission?

In addition to excellent training, it helps to have good equipment, including radar, radio, lights, and night vision goggles (Figure 11.46). Modern night vision goggles are so sensitive that the tiny amounts of starlight reflecting off forests can be amplified to levels visible to pilots and rescue staff to give a clear view of the countryside. With these ultra-sensitive devices, you can literally fly and search by starlight.

Figure 11.46 Night vision goggles

Night vision goggles use lenses to focus light onto a device called an image intensifier. Inside the intensifier, the light energy releases a stream of particles. These particles then hit a phosphor-coated screen. The phosphors glow when the particles strike them. The person wearing the goggles sees a glowing green image (Figure 11.47).

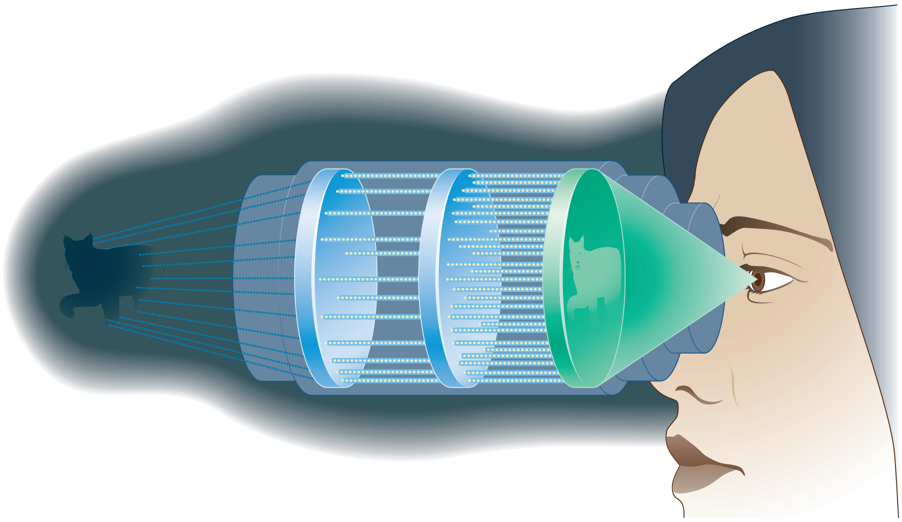


Figure 11.47 The image intensifier of night goggles amplifies the particles before they hit the screen. The image appears as shades of green.

D21 *Quick Lab*

Observing Lenses

Purpose

To observe how concave and convex lenses affect light

Materials & Equipment

- convex lens (bulges out)
- concave lens (middle is thinner than the edges)
- light source, such as a candle
- screen, such as a piece of paper
- candle holder, such as sand and a metal tray

CAUTION: If an open flame is used, it must be secured so that it cannot fall over. Keep all combustible materials away from open flames. Tie back long hair before using an open flame.

Procedure

1. Look though each lens at the printed text in this student book. Record your observations.
2. Look through both lenses at some printed text. Record your observations.
3. Try to use each of the lenses to project a candle flame or light onto a screen or piece of paper. Record your observations.

Questions

4. Which single lens would be most useful as a magnifying glass?
5. How should the convex and concave lenses be arranged to make a distant object appear closer?
6. What arrangement of lenses is most effective in projecting the image of a light source onto a piece of paper?

WORDS MATTER

The word "lens" is derived from the Latin word *lenticula*, which means lentil. A lens is in the shape of a lentil like those shown here.

Types of Lenses

If you have ever used a microscope, telescope, binoculars, or a camera, you have worked with one or more lenses (Figure 11.48). A **lens** is a curved transparent material that is smooth and regularly shaped so that when light strikes it, the light refracts in a predictable and useful way.

Most lenses are made of transparent glass or very hard plastic. These materials have several useful properties. For example, they are strong and hard. They can also be shaped and polished. By shaping both sides of the lens, it is possible to make light rays diverge or converge as they pass through the lens. The most important aspect of lenses is that the light rays that refract through them can be used to magnify images or to project images onto a screen. Relative to the object, the image produced by a thin lens can be real or virtual, inverted or upright, larger or smaller.

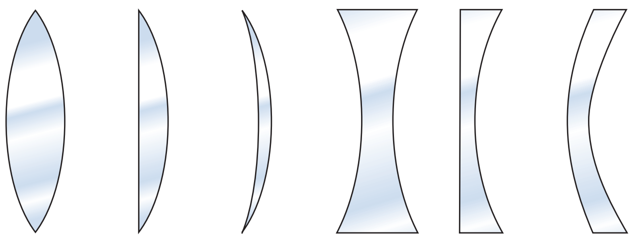


Figure 11.49 Lenses can be grouped into two types, converging and diverging, depending on how they refract the light that enters them.

Lens Terminology

Figure 11.50 illustrates some of the terms associated with both converging and diverging lenses:

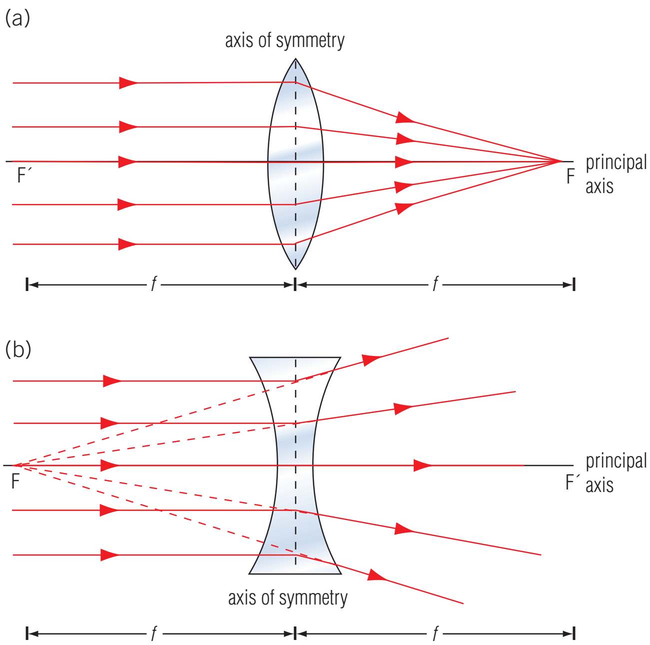


Figure 11.50 (a) Converging lens and (b) diverging lens

- The principal axis is an imaginary line drawn through the optical centre perpendicular to both surfaces.
- The **axis of symmetry** is an imaginary vertical line drawn through the optical centre of a lens.
- Both kinds of lenses have two principal focuses. The focal point where the light either comes to a focus or appears to diverge from a focus is given the symbol F, while that on the opposite side of the lens is represented by F′.
- The focal length, *f*, is the distance from the axis of symmetry to the principal focus measured along the principal axis. Since light behaves the same way travelling in either direction through a lens, both types of thin lenses have two equal focal lengths.

Concave Lenses

A **diverging lens** is sometimes called a **concave lens** because it is thinner in the centre than at the edges. As parallel light rays pass through a concave lens, they are refracted away from the principal axis. This means the light rays diverge and they will never meet on the other side of the lens (Figure 11.51). The image formed is always upright and smaller than the object (Figure 11.52 and Table 11.6).

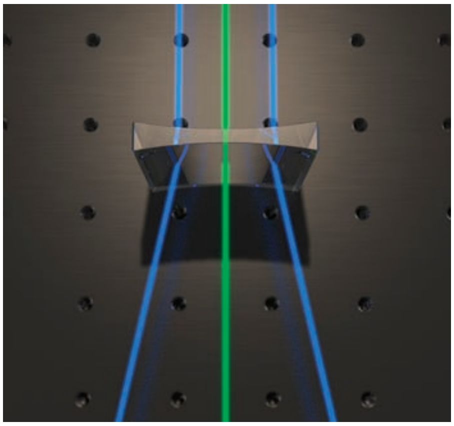


Figure 11.51 A concave lens causes light rays to diverge.

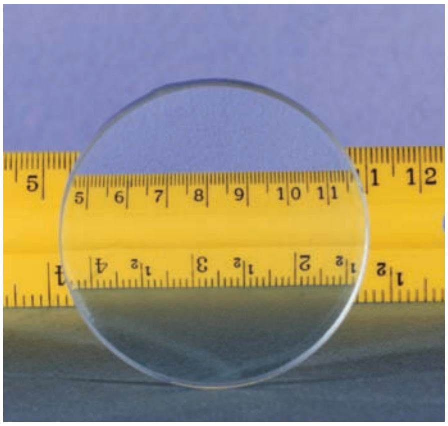
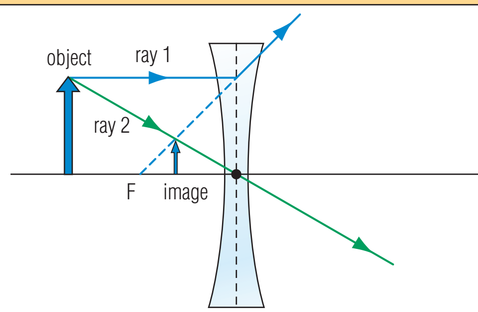


Figure 11.52 A diverging lens forms an upright, smaller image.

Table 11.6 Images Formed by Concave Lenses

Distance of Object from Lens	Type of Image Formed	How the Image Is Used	Ray Diagram
All distances	Smaller, upright	Some types of eyeglasses and telescopes make use of the diverging properties of concave lenses. These lenses are often used in combination with converging lenses.	

Drawing a Ray Diagram for a Lens

A ray diagram is a useful tool for predicting and understanding how images form as a result of light rays emerging from a lens. The index of refraction of a lens is greater than the index of refraction of air. This means that when a light ray passes from air into the lens, the light ray bends, or refracts, away from the lens surface and toward the normal. When the light passes out of the lens at an angle, the light rays refract again, this time bending away from the normal. In other words, light rays undergo two refractions, the first on entering the lens and the second on leaving the lens (Figure 11.53).

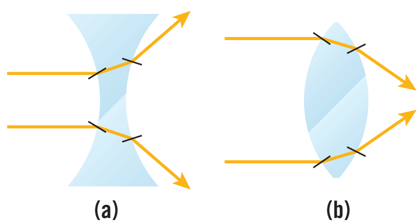


Figure 11.53 (a) Concave lens (b) and convex lens

In your ray diagrams in this unit, assume you are working with a thin lens. A **thin lens** is a lens that has a thickness that is slight compared to its focal length. An example of a thin lens is an eyeglass lens. You can simplify drawing a ray diagram of a thin lens without affecting its accuracy by assuming that all the refraction takes place at the axis of symmetry.

Drawing a Concave Lens Ray Diagram

Ray diagrams for lenses are similar to ray diagrams for curved mirrors. You need to use two rays to predict image location. You can follow the steps in Figure 11.54 to draw a ray diagram of a concave lens.

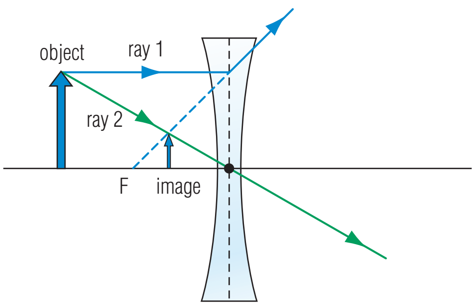


Figure 11.54 Concave lens ray diagram

1. The first ray of a concave lens ray diagram travels from the tip of the object parallel to the principal axis (ray 1). When it emerges from the lens, it appears to come from the principal focus.
2. The second ray travels from the tip of the object through the optical centre of the lens and is not refracted (ray 2).
3. Draw the virtual image where the rays appear to intersect.

Convex Lenses

A **converging lens** is also called a **convex lens** because it is thicker at the centre than at the edges. As parallel light rays travel through a convex lens, they are refracted toward the principal axis. This causes the rays to move toward each other. The light rays cross at the focal point of the lens. Converging lenses are often used as magnifying glasses (Figure 11.56).

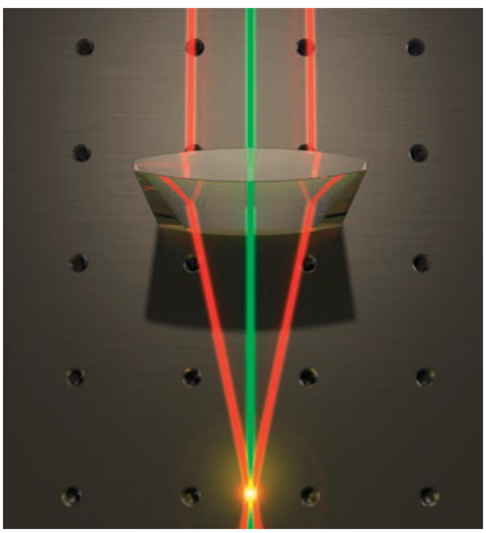


Figure 11.55 A convex lens causes light rays to converge.

Figure 11.56 A converging lens can be used as a magnifying glass.

Forming a Real Image

Convex lenses are useful because they can form a real image on a screen. For example, the light rays coming from one point on the flame in Figure 11.57 diverge and strike the lens at different places. However, the lens redirects all those rays so that they converge at a single point. The screen must be placed so that the light rays strike it exactly as they converge. This way, when the light rays reflect off the screen, they are coming from a single point, just like when they originally left a single point on the candle.

At the same time, the lens must also redirect all light rays that come from a point at the base of the candle and send them to a single point on the screen. The rays then reflect off the screen in all directions, just like when the light rays from the base of the candle left the candle. When the rays from every point on the candle are sent to the screen, a complete image is formed. You can compare the type of image formed at different distances as well as some of the uses of convex lenses in Table 11.7.

During Reading — Thinking Literacy

Comparing Graphics and Text

Read the paragraph on forming a real image, and then look at the graphics beneath the explanation. Which was easier to understand — the word text or the graphics? Would you be able to understand one feature without the support of the other, i.e., words without graphics or graphics without words? How did each graphic help you to understand the idea more fully?

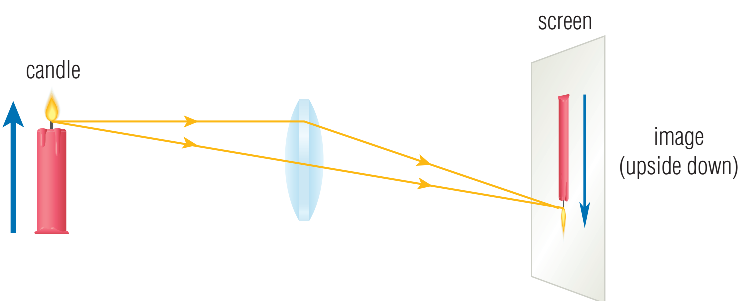
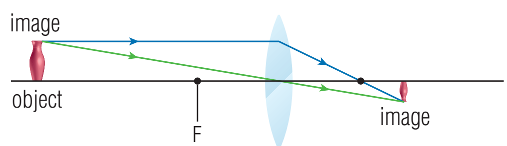
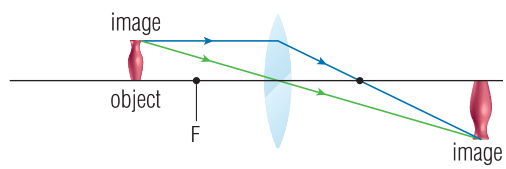
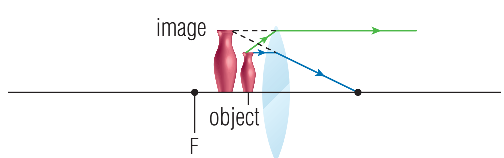


Figure 11.57 As you can see in this illustration, there is one drawback to convex lenses. The image is upside down!

Suggested Activity
D24 Quick Lab on page 459

Table 11.7 Images Formed by Convex Lenses

Distance of Object from Lens	Type of Image Formed	How Image Is Used	Ray Diagram
More than two focal lengths	Smaller, inverted, real	A camera uses this distance to make smaller images of an object.	
Between one and two focal lengths	Larger, inverted, real	Photographic enlargers, slide projectors, and movie projectors use this distance.	
Less than one focal length away	Larger, upright, virtual	Magnifying glasses and reading glasses make use of this distance.	

Drawing a Convex Lens Ray Diagram

You can follow the steps in Figure 11.58 to draw a ray diagram of a convex lens.

1. The first ray of a convex lens ray diagram travels from the tip of the object parallel to the principal axis (ray 1). When it emerges from the lens, it passes through the principal focus.
2. The second ray travels from the tip of the object through the optical centre of the lens and is not refracted (ray 2).
3. Draw the real image where the rays appear to intersect.

Suggested Activity
D25 Inquiry Activity on page 460

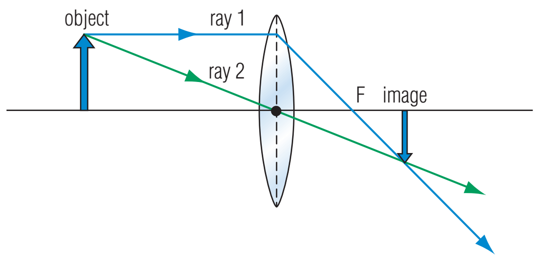


Figure 11.58 Convex lens ray diagram

Learning Checkpoint

1. Describe the difference in shape between a convex lens and a concave lens.
2. Which lens, convex or concave, can also be called a *diverging* lens?
3. Why do light rays bend twice when lenses are used?
4. Draw a ray diagram for a convex lens when the object is situated:
   (a) more than two focal lengths away from the lens
   (b) exactly two focal lengths from the lens

Thin Lens Equation

The distance of the object from the lens, d_o, the distance of the image from the lens, d_i, and the focal length of a lens, f, can all be related using the **thin lens equation**. Given any two of these quantities, you can use the thin lens equation to solve for the third:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

Keep in mind the following points when working with the thin lens equation (see also Table 11.8).

- A concave lens has a negative focal length and a negative distance to the image.
- A convex lens has a positive focal length and either a positive or negative distance to the image, depending where the object is placed.
- The image distance d_i is positive if the image is real and negative if the image is virtual.

Table 11.8 Images Formed by Convex Lenses

Lens Type	Focal Length	Distance to Object	Distance to Image
Convex	positive	positive	positive or negative depending on object location

Example Problem 11.9

A convex lens of a magnifying glass is held 2.00 cm above a page to magnify the print. If the image produced by the lens is 3.60 cm away and virtual, what is the focal length of the magnifying glass?

Given
Distance of the object from the lens, $d_o = 2.00$ cm
Distance of the virtual image from the lens, $d_i = -3.60$ cm

Required
Focal length of the lens, f

Analysis and Solution

The correct equation is $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$

Substitute the values and their units, and solve the problem.

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

$$\frac{1}{f} = \left(\frac{1}{2.00} + \frac{1}{-3.60}\right)\frac{1}{\text{cm}}$$

$$\frac{1}{f} = \frac{0.222}{\text{cm}}$$

Take the reciprocal of both sides.

$$f = 4.50 \text{ cm}$$

Paraphrase
The focal length is about 4.50 cm.

Take It Further

Large glass lenses can be extremely heavy. However, because refraction only occurs at the surface of a lens, the middle material can be removed, as long as the lens surface remains correctly curved. These lenses are called Fresnel lenses, and they are used in lighthouses and overhead projectors. Find out more about how Fresnel lenses are constructed and used. Begin your research at ***ScienceSource***.

Suggested Activity •
D26 Inquiry Activity on page 461

Practice Problems

1. A powerful magnifying glass produces a real image 4 mm from the convex lens. If the object was placed 28 mm away, what is the focal length of the lens?
2. Determine the focal length of a convex lens that produces a virtual image at a distance of 30 mm when the object is placed 15 mm away.
3. The objective lens of a microscope is convex. The light from a specimen 4.0 mm from the lens forms a real image 10.0 mm from the lens. What is the focal length of this lens?

Example Problem 11.10

A convex lens has a focal length of 60.0 cm. A candle is placed 50 cm from the lens. What type of image is formed, and how far is the image from the lens?

Given
Focal length of the convex lens, $f = 60$ cm
Distance of the object from the lens, $d_o = 50$ cm

Required
Distance of the image from the lens, d_i

Analysis and Solution
A convex lens has a positive focal length, so $f = 60.0$ cm

Use the thin lens formula: $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$

Rearrange the formula for $\frac{1}{d_i}$: $\frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o}$

Substitute the values and their units, and solve the problem.

$$\frac{1}{d_i} = \frac{1}{f} - \frac{1}{d_o}$$

$$\frac{1}{d_i} = \left(\frac{1}{60} - \frac{1}{50}\right)\frac{1}{\text{cm}}$$

$$\frac{1}{d_i} = \frac{-0.003333}{\text{cm}}$$

Take the reciprocal of both sides of the equation to eliminate the fractions.
$d_i = -300$ cm

Paraphrase
Since d_i is negative, the image is virtual and is located 300 cm from the lens.

Practice Problems

1. A convex lens has a focal length of 15 cm. An object is placed 20 cm from the lens. What type of image is formed? How far from the lens is the image?
2. A convex lens focusses the light from the image of a bacterium that is 0.02 cm from the lens. If the focal length of the lens is 0.03 cm, how far from the lens is the image?
3. A convex lens has a focal length of 5.0 cm. If a penny is placed at the focus, where is the image of the penny formed?

Example Problem 11.11

A camera with a 200-mm lens makes a real image of a bird on film. The film is located 201 mm behind the lens. Determine the distance from the lens to the bird.

Given
Focal length of lens, $f = 200$ mm
Image distance, $d_i = 201$ mm

Required
Object distance of the bird from the lens, d_o

Analysis and Solution

Use the thin lens formula: $\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$

Rearrange the formula for $\frac{1}{d_o}$: $\frac{1}{d_o} = \frac{1}{f} - \frac{1}{d_i}$

Substitute the values and their units, and solve the problem.

$$\frac{1}{d_o} = \frac{1}{f} - \frac{1}{d_i}$$

$$\frac{1}{d_o} = \left(\frac{1}{200} - \frac{1}{201}\right)\frac{1}{\text{mm}}$$

$$\frac{1}{d_o} = \frac{2.4876 \times 10^{-5}}{\text{mm}}$$

Take the reciprocal of both sides of the equation to eliminate the fractions.

$d_o = 4.02 \times 10^4$ mm

Paraphrase
The bird is about 40.2 m away from the camera lens.

Practice Problems

1. A convex lens with a focal length of 18 mm produces an image 25 mm from the lens. How far from the lens is the object?
2. Where is the object placed if a convex lens with a focal length of 7.00 cm produces a virtual image 3.00 cm from the lens?
3. An image of a candle is produced by a convex lens 14 cm away. If the focal length of the lens is 7.0 cm, how far from the lens is the candle placed?

D22 STSE Science, Technology, Society, and the Environment

Two-Way Mirrors

A two-way mirror is partly reflective and partly transparent. The reflective coating of a two-way mirror is not nearly as thick on a regular mirror so that some light gets reflected and some passes through. For the mirror to work properly, there must be a significant difference in the brightness of light on the two sides. The side where the observers are positioned must be dark so that no light goes through the mirror to the other room. The other side, where the person being observed is located, must be bright so that enough of the light is reflected and the person does not see through to the other side.

1. How might you be able to tell if you were looking at a two-way mirror, without looking at it from the other side?
2. Two-way mirrors are sometimes used in training hospitals so interns can watch operations being performed. Brainstorm other situations in which two-way mirrors would be useful.
3. What issues do you think arise from the use of two-way mirrors?

D23 *Skill Builder Activity*

Drawing Ray Diagrams for Convex Lenses

Convex (Converging) Lenses

1. Copy Figure 11.59(a) into your notebook To determine where the image of the top of the arrow will be, draw the first ray parallel to the principal axis until it strikes the lens and refracts through the focal point.

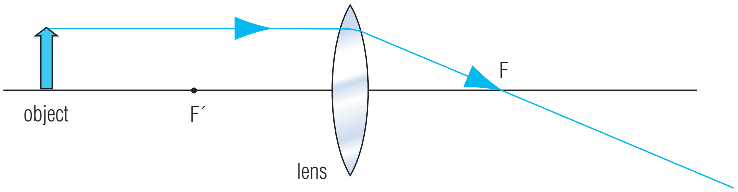


Figure 11.59(a) Draw the first ray.

2. Draw the second ray from the tip of the arrow through the optical centre of the lens (Figure 11.59(b)).

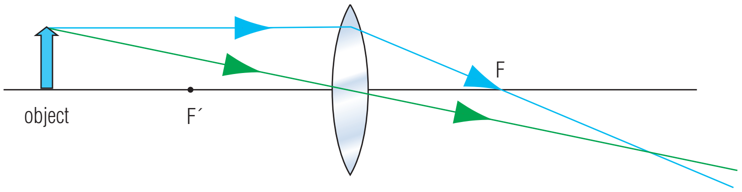


Figure 11.59(b) Draw the second ray.

3. Draw the real image where the rays appear to intersect. A real image is shown as a solid arrow (Figure 11.59(c)).

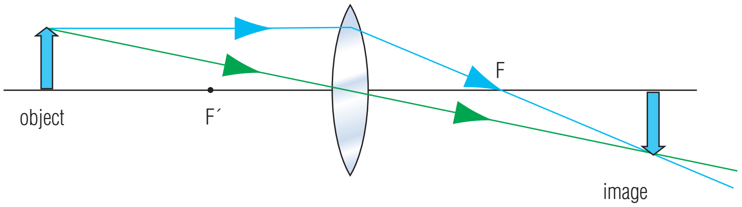


Figure 11.59(c) Draw the real image.

4. Optional: You can add a third ray to check your work. Draw the third ray travelling from the top of the arrow toward the secondary focus on the far side of the lens. When this ray emerges from the lens, it travels parallel to the principal axis (Figure 11.59(d)).

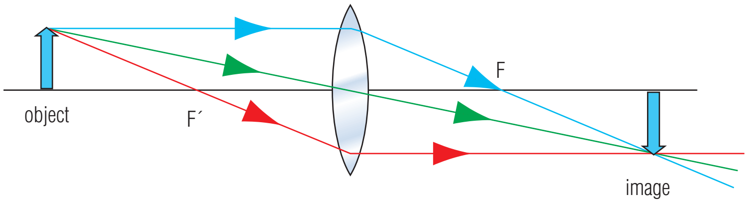


Figure 11.59(d) Optional: Draw a third ray to check your work.

D24 *Quick Lab*

Focal Length

Purpose

To find a good approximation of the focal length of any convex lens and see the relationship between the curvature of the lens and the focal length

Materials & Equipment

- ruler
- 279 × 432 mm blank paper
- several flat convex lenses of different focal lengths
- ray box with several parallel rays of light
- 216 × 279 mm blank paper

CAUTION: Do not shine bright light into anyone's eyes. Incandescent light sources can become very hot. Do not touch the bulbs or block air flow around the light bulbs.

Procedure

1. Copy the data table below into your notes. Give your table a title.

Lens	Focal Length (cm)	Radius (cm)
1.		
2.		
3.		
4.		

2. Use your ruler to draw a straight line lengthwise across the middle of the 279 × 432 mm paper. This line will act as the principal axis for each lens.
3. Near one end of the paper, draw a vertical line that intersects the first line at 90°. This line will act as the axis of symmetry for each lens.
4. Place the first convex lens on the principal axis aligned with the axis of symmetry as shown in Figure 11.60.

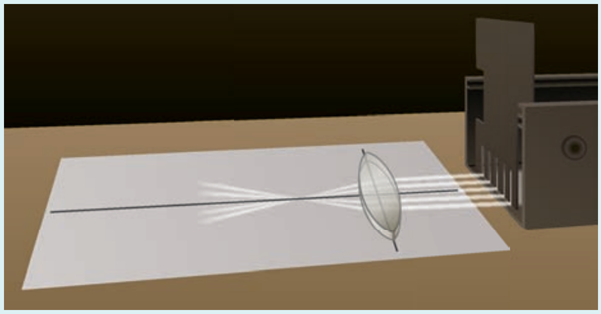


Figure 11.60 Step 4

5. Place the ray box off the paper so that the rays will shine parallel to the principal axis through the lens. An equal number of rays should be above and below the principal axis.
6. Look to see where the rays converge on the principal axis. If they converge above or below the axis, adjust the ray box a little to make them converge on the principal axis.
7. Place a dot at the location where the rays converge. This is the focus. Remove the lens, then measure the distance from the vertex, which is the intersection of the principal axis and the axis of symmetry, to the dot. Record this as the focal length.
8. Determine the radius of the lens by placing the lens on a sheet of 216 × 279 mm paper and tracing one side of the lens to create an arc. Reposition the lens so that the arc is extended until you have traced a full circle. Measure the radius of this circle, and record it in your table.
9. Repeat steps 4 to 8 for the remaining lenses.

Questions

10. Explain how you determined the radius of the lens once you drew the circle.
11. What is the relationship between curvature (radius) of the lens and focal length of the lens?
12. Explain how you would modify this lab to make it work for:

(a) concave lenses

(b) concave mirrors

D25 *Inquiry Activity*

Skills Reference 2

SKILLS YOU WILL USE

- Conducting inquiries safely
- Using appropriate formats to communicate results

Convex Lens Images

Question

How does the distance between an object and a convex lens affect image formation?

Materials & Equipment

- cardboard stand
- sheet of unlined white paper
- adhesive tape
- light bulb and socket
- battery and wires
- 2 convex lenses with different focal lengths
- modelling clay
- metre stick

CAUTION: Do not shine bright light into anyone's eyes. Incandescent light sources can become very hot. Do not touch the bulbs or block air flow around the light bulbs.

Procedure

1. Prepare a data table that will allow you to record the following values. Give your table a title.
   Distance (cm) from bulb to lens (d_o)
   Distance (cm) from the lens to the screen (d_i)
   Size of the glass part of the light bulb (h_o)
   Size of the image on the screen (h_i)
   Orientation of the image (inverted or upright)
2. Tape the paper onto the cardboard stand. This is your "screen."
3. Measure the height of the glass part of the bulb. Record this in your notebook as the object height.
4. Determine the focal length (f) of your lens as shown in Figure 11.61:
   - Using the modelling clay for support, place the lens in between the stand and the bulb.
   - Move the screen and bulb slowly inward, then outward, keeping the lens in the middle. At a certain distance, an inverted image of the same size as the actual bulb will come into focus on the screen.
   - Measure the distance between the bulb and lens. This measurement is equal to 2f. Divide the value by 2 to determine the focal length of your lens. Record this value for f in your notebook.

Figure 11.61 Finding the focal length of the lens

5. Record values in your data table for the following placements of the light bulb: 2.5f, 2f, 1.5f, and 0.5f. In each case, you will need to move the screen until the image comes into focus before recording your data. If at any time you cannot get an image on the screen, look at the bulb through the lens. If you see an image through the lens, estimate h_i, but do not record a value for d_i.
6. Repeat steps 3 to 5 with another convex lens of different focal length.

Analyzing and Interpreting

7. (a) Is the image formed by a convex lens always inverted?
   (b) If not, under what conditions is it upright?
8. (a) What happens to h_i as the bulb is moved toward the lens?
   (b) What happens to d_i?
9. What type of image is formed when the bulb is placed closer than one focal length?
10. How does focal length affect convex lens image formation?

Skill Practice

11. Draw ray diagrams to represent the images formed at the different bulb placements for both lenses.

Forming Conclusions

12. (a) Convex lenses are often used in computer projectors. Explain why an image changes size and must be refocussed when a projector is moved closer to or farther from the screen. Use the data you have collected in this activity.
    (b) Explain why different projectors might have convex lenses of different focal lengths.

SKILLS YOU WILL USE

- Interpreting data/information to identify patterns or relationships
- Identifying sources of error

D26 *Inquiry Activity* Skills References 2, 8

Identifying the Properties of Images

Question

How can you use ray diagrams to determine the properties of images formed by convex lenses?

Materials & Equipment

- 3 sheets of legal paper
- sharp pencil
- ruler
- calculator

Procedure

1. Make an observation table with the rows and columns shown at the bottom of this page. Name the table "Convex Lens Focal Length 4.0 cm."
2. Turn a piece of legal paper sideways. Use the ruler to draw a horizontal line across the middle of the paper. This is the principal axis of the lens.
3. At the midpoint of the principal axis, draw a perpendicular vertical line that is 5.0 cm above and below. This is the axis of symmetry of the lens. Label the axis "Convex Lens."
4. Measure 4.0 cm to the left of the vertex along the principal axis, and place a dot. This is the secondary focus, F', of the lens. Do the same thing on the other side of the lens for the primary focus, F. Label both focuses.
5. Place two more dots at twice the focal length, and label them $2f'$ and $2f$ accordingly.
6. Repeat steps 2 to 5 twice to create a total of three convex lens diagrams.
7. Using one of the convex lens diagrams, draw a vertical arrow at d_o as indicated in the "Convex Lens" table to the height h_o.
8. Complete the ray diagram to produce the image of the arrow at the appropriate place on the diagram. Label the object and the image.
9. Measure and record d_i and h_i. Then, finish the next two ray diagrams for convex lenses using the values in the next two rows of the table.

Analyzing and Interpreting

10. Write a general statement that relates the size, orientation, and type of image to the object for a convex lens when:

    (a) d_o is greater than $2f$

    (b) d_o is between $2f$ and f

    (c) d_o is less than f

Skill Practice

11. Use the data you collected to interpolate where the object would have to be placed so that the magnification of a convex lens would be exactly 1.
12. Calculate d_i and h_i using the thin lens and magnification equations for each set of data in the table. Compare these values to the ones you obtained using ray diagrams. Do they agree? If not, suggest reasons why the values are different.

Forming Conclusions

13. Describe how you can use ray diagrams to determine the properties of images formed by convex lenses.

Object Data		Image Characteristics				Image Data		Calculate	
d_o (cm)	h_o (cm)	Side of Lens	Real or Virtual	Size	Upright or Inverted	d_i (cm)	h_i (cm)	d_i	h_i
10.0	2.0								
6.0	2.0								
2.0	2.0								

11.3 CHECK and REFLECT

Key Concept Review

1. (a) What type of lens produces a real image?
   (b) What type of lens produces a virtual image?

2. A converging lens produces a real image 10 cm from the lens when the object is placed 30 cm from the lens.
   (a) What is the focal length of the lens?
   (b) What is the magnification of the lens?

3. An object is placed at each of the following distances from a converging lens. For each location, draw a ray diagram and state the properties and location of the image. (Hint: Choose a convenient value for f.)
   (a) $2.5\,f$
   (b) $1.5\,f$
   (c) $0.75\,f$

4. Suggest one use for each lens set-up in question 3.

5. What is one use for a diverging lens?

6. An object 1.2 cm high is placed 4.0 cm from a converging lens that has a focal length of 3.0 cm.
   (a) What is the location of the image?
   (b) What is the size of the image?

7. A converging lens is placed 12 cm from a wall chart. The focal length of the lens is 15 cm.
   (a) What is the location of the image?
   (b) What is the magnification?

8. A photographer uses his camera to view some deer in a field. If the image of the deer is produced 120.14 mm from a convex lens that has a focal length of 120 mm, how far away are the deer?

Question 8

Connect Your Understanding

9. At what distance from a convex lens must an object be placed so that the image is the same distance from the lens?

10. A student examines a ladybug using a magnifying glass with focal length of 5.0 cm. He holds the magnifying glass 3.5 cm above the ladybug. What is the magnification?

11. A photographer uses a telephoto lens to take a photograph of a 50-m high building that is 1000 m away. The image on the negative is 2.0 cm high. What is the focal length of the lens?

12. How can you find a good approximation of the focal length of an unknown concave lens by using an unknown convex lens as a starting point?

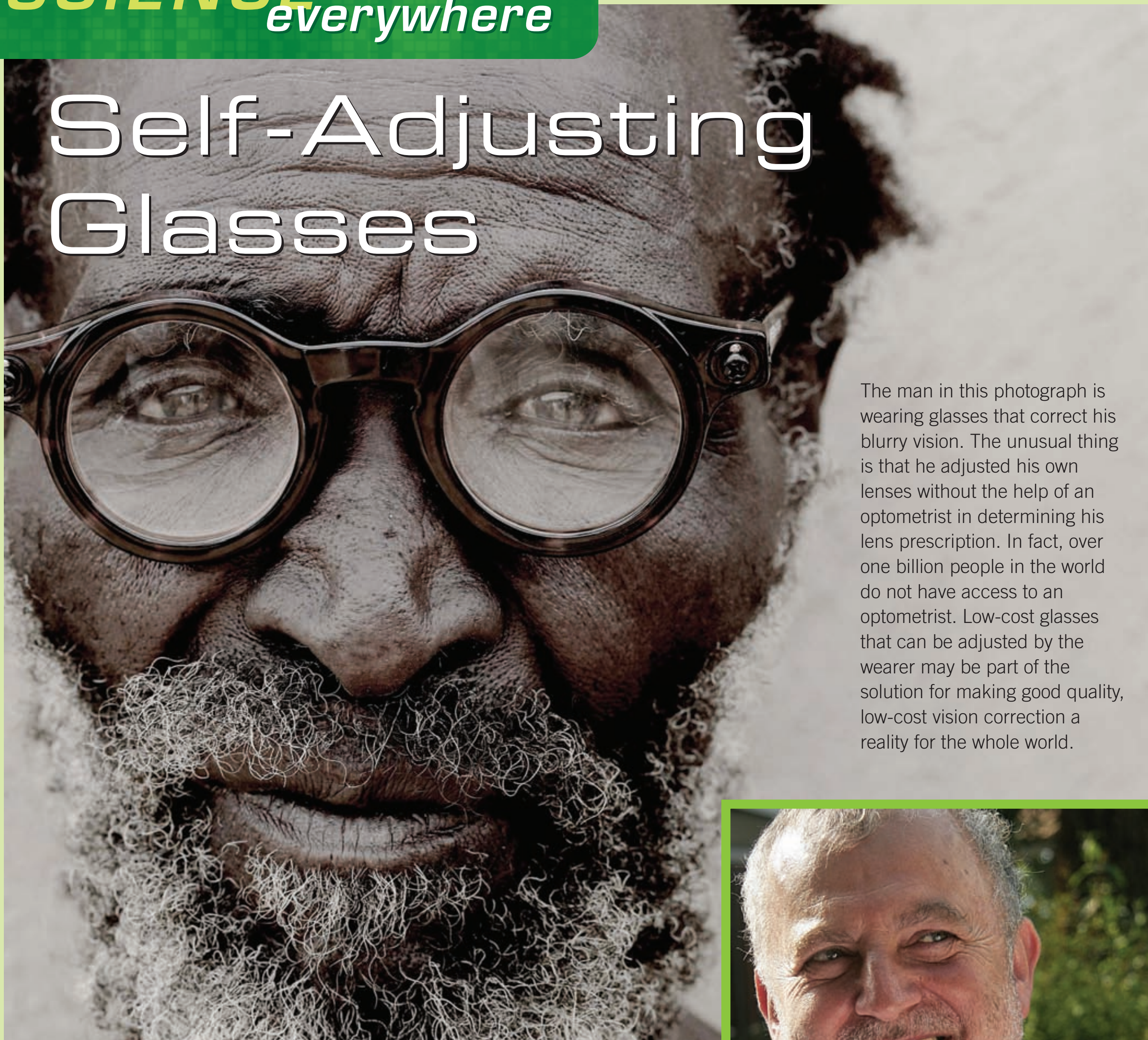
Reflection

13. Why do you think it is important to understand how light travels through lenses?

14. What analogy or model could you use to remember the differences between virtual and real images?

For more questions, go to *ScienceSource*.

Self-Adjusting Glasses



The man in this photograph is wearing glasses that correct his blurry vision. The unusual thing is that he adjusted his own lenses without the help of an optometrist in determining his lens prescription. In fact, over one billion people in the world do not have access to an optometrist. Low-cost glasses that can be adjusted by the wearer may be part of the solution for making good quality, low-cost vision correction a reality for the whole world.

This pair of self-adjusting glasses is constructed by sandwiching a fluid-filled sac inside a flexible plastic lens. More fluid means a thicker lens and a stronger correction in the glasses. To make an adjustment, the wearer uses a small syringe to add or remove the fluid, and a small screw to lock the amount of fluid in the lens. One design hurdle is finding a way to produce the glasses in bulk cheaply. Another difficulty is the bulky frame that is currently needed. Dr. Silver and others are working to overcome these difficulties.

The inventor of self-adjusting glasses is Joshua Silver, a professor at Oxford University in England. Dr. Silver wondered whether people could correct their own vision if they could manually adjust the focussing power of the lenses. This would be just like anyone focussing a camera or a pair of binoculars. By 2008, Dr. Silver had already seen 30 000 pairs of his self-adjusting glasses delivered to people in 15 developing countries. By 2020, he would like to see 100 000 pairs distributed annually at a cost of less than $2 per wearer.

11 CHAPTER REVIEW

ACHIEVEMENT CHART CATEGORIES

k Knowledge and understanding t Thinking and investigation
c Communication a Application

Key Concept Review

1. Describe how the law of reflection applies similarly to regular and diffuse reflection. k

2. Use a ray diagram to show why images produced by plane mirrors are considered to be virtual images. k

3. (a) Name three places where concave mirrors are useful. k
(b) Name three places where convex mirrors are useful. k

4. (a) What are the properties of images that a convex mirror can produce? k
(b) What are the properties of images that a concave mirror can produce? k

5. (a) What are the properties of images that a concave lens can produce? k
(b) What are the properties of images that a convex lens can produce? k

6. Explain why the speed of light can vary when it travels through transparent or translucent materials. t

7. Explain what happens to the direction of a light ray if it enters a medium with a lower refractive index. k

8. Explain why the incident and refracted angles are measured from the normal instead of the surface. k

9. What properties of light does Snell's law explain? k

10. Draw ray diagrams for a converging mirror and state the properties of the image formed for the following object positions: k
(a) $3.0\,f$ (b) $1.4\,f$ (c) $0.70\,f$

11. Draw ray diagrams for a diverging mirror and state the characteristics of the image at the following object positions: k
(a) $1.0\,f$ (b) $0.50\,f$

Connect Your Understanding

12. A convex lens is placed near an object. The height of the image is 3.8 mm, giving a magnification of 0.26.
(a) What is the height of the object? a
(b) Does the answer depend on whether the image is real or virtual? Explain. t

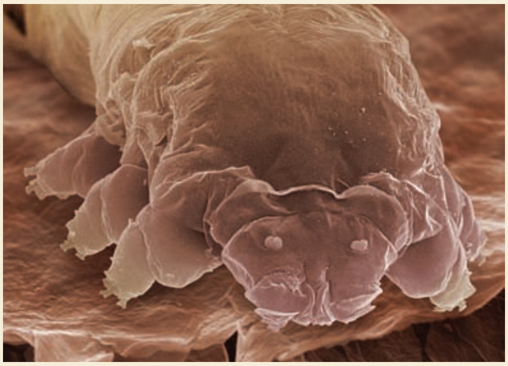
13. Describe the properties of a lens that determine its focal length. t

14. The image of a 30-cm-tall rose is captured by a camera with a 28-mm lens. The image forms 29 mm behind the lens.
(a) How far is the lens from the rose? a
(b) How high is the image? a

15. Light passes from a diamond into air. The angle of refraction as the light emerges from the diamond is 25°. What was the angle of incidence? a

16. A ray of light passes from the air into a sapphire at an incident angle of 15°. Calculate the angle of refraction. a

17. An eyelash mite measures 0.28 mm long. What is the magnification if a microscope produces a 56-mm image? a



Question 17

18. A student looks at the letters on a page through a convex lens. The student holds the lens so the image of the letters appears to be 12 cm from the lens. The focal length of the lens is 24 cm.
    (a) How far away from the page is the student holding the lens? a
    (b) What is the magnification of the lens? a

19. An object placed near a convex lens is magnified 14 times. The image formed is 6.0 cm high. What is the height of the object? a

20. A layer of oil floats on top of water. A ray of light in the oil approaches the surface of the water at an angle of 40°. It is refracted at an angle of 35.6°. What is the refractive index of the oil? a

21. A ray of light approaches the flat surface of a diamond at normal incidence 0.0°. What is the angle of refraction? a

22. A camper viewing the reflection of the full Moon in a smooth lake notices that the image is almost perfectly circular. What would happen to the image of the Moon if the water became rough? t

23. You look at an image in a reflecting surface. How can you tell if the image is real or virtual? a

24. Explain the conditions required for total internal reflection. a

25. A compound microscope uses a convex objective lens that magnifies the object 40.0 times. If the object is 0.20 mm high, how high is the image? a

26. Lenses and mirrors both create images by redirecting light. Make a chart to compare the differences and similarities in how lenses and mirrors create images. t

27. You have been given several pieces of clear, hard, rock-like material from a fraud investigation. The subject of the investigation is accused of trying to substitute cubic zirconia for diamond. Explain the steps you would follow to identify the material. t

28. (a) Suppose you were camping and forgot to bring matches for your campfire. Explain how you could start a fire with a converging piece of glass. a
    (b) Would a diverging piece of glass work equally well for this job? Explain why it would or would not. t

Reflection

29. What can you explain about light and the way it interacts with matter that you were not able to before this chapter? c

30. What are three concepts from this chapter that you are interested in learning more about in this class or in the future? c

After Reading

Thinking Literacy

Reflect and Evaluate

Interview a partner about the challenges of reading graphics. Why can graphics be difficult to read and understand? How can graphics support you in understanding concepts and ideas? Together, create a poster on the computer using a diagram or flowchart to alert readers to strategies for reading graphics.

Unit Task Link

Your Unit Task is to design and build a shade for a streetlight that reduces light pollution in the night sky. What kind of mirror or lens will you use to make most of the light shine downward? How will the design of your shade prevent light from shining upward? Sketch some possible designs you could use for your shade.