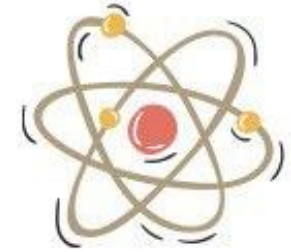


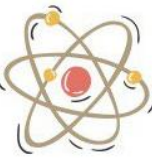
EOT – Term 1 – Part 2

Grade 11 Advanced

Inspire



SIMPLE PHYSICS
With Ms. Hoda



1	Describe the ray model of light, giving examples.	Figure 2	4
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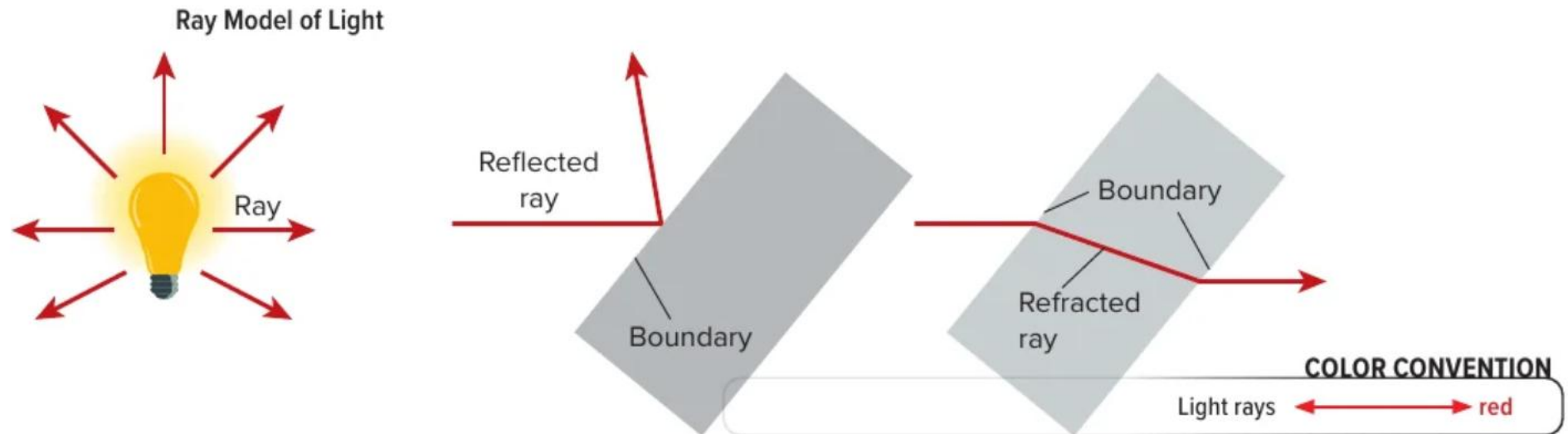
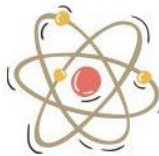


Figure 2 Light's straight-line path is demonstrated by the ray model. Light rays change direction when they are reflected or refracted by matter. In either case, light rays continue in a straight path.



2	Identify the speed of light in vacuum and light year.	Student Textbook	11 9-5
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The Speed of Light

Arguments that light must travel at a finite speed have existed for more than 2400 years. By the seventeenth century, several scientists had performed experiments that supported the view that light travels at a finite speed, but that this speed is much faster than the speed of sound.

Actually measuring the speed of light was not an easy task in the seventeenth century. As you know from studying motion, if you can measure the time light takes to travel a certain distance, you can calculate the speed of light. However, the time that it takes light to travel between objects on Earth is much shorter than a human's reaction time. How could a seventeenth-century scientist solve this problem?

Clues from Io Danish astronomer Ole Roemer was the first to measure the time it took for light to travel between two points with any success. Between 1668 and 1674, Roemer made 70 measurements of the 1.8-day orbital period of Io, one of Jupiter's moons. He recorded the times when Io emerged from Jupiter's shadow, as shown in **Figure 10**. He made his measurements as part of a project to improve maps by calculating the longitude of locations on Earth. This is an early example of the needs of technology driving scientific advances.

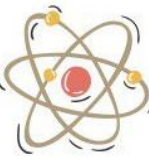
After making many measurements, Roemer was able to predict when the next eclipse of Io would occur. He compared his predictions with the actual measured times and found that Io's observed orbital period increased on average by about 13 s per orbit when Earth was moving away from Jupiter and decreased on average by about 13 s per orbit when Earth was approaching Jupiter. Roemer believed that Jupiter's moons were just as regular in their orbits as Earth's moon; thus, he wondered what might cause this discrepancy in the measurement of Io's orbital period. He considered another variable within the system, the movement and position of Earth relative to Jupiter.

Measuring the speed of light Roemer concluded that as Earth moved away from Jupiter, the light from each new appearance of Io took longer to reach Earth because it traveled farther. As Earth moved toward Jupiter, Io's orbital period seemed to decrease. During the 182.5 days it took for Earth to travel from position 1 to position 3, shown in **Figure 10**, there were (182.5 days) $(1 \text{ Io eclipse}/1.8 \text{ days}) = 1.0 \times 10^2$ Io eclipses. Thus, for light to travel the diameter of Earth's orbit, he calculated that it takes $(1.0 \times 10^2 \text{ eclipses})(13 \text{ s/eclipse}) = 1.3 \times 10^3 \text{ s}$, or 22 min.

Using the presently known value of the diameter of Earth's orbit ($2.93 \times 10^{11} \text{ m}$), Roemer's value of 22 min gives a value for the speed of light of $2.9 \times 10^{11} \text{ m}/((22 \text{ min})(60 \text{ s/min})) = 2.2 \times 10^8 \text{ m/s}$. Today, the speed of light is known to be closer to $3.0 \times 10^8 \text{ m/s}$, so light takes 16.5 min, not 22 min, to cross Earth's orbit. Nevertheless, Roemer had successfully proved that light travels at a finite speed.

Michelson's measurements Although many measurements of the speed of light have been made, the most notable were performed by American physicist Albert A. Michelson. Between 1880 and the 1920s, he developed Earth-based techniques to measure the speed of light. In 1926 Michelson measured the time required for light to make a round trip between two California mountains 35 km apart. Michelson's best result was $(2.99796 \pm 0.00004) \times 10^8 \text{ m/s}$. For this work, he became the first American to receive a Nobel Prize in science.

The speed of light in a vacuum has its own special symbol, c . The International Committee on Weights and Measurements has measured and defined the speed of light in a vacuum to be $c = 299,792,458 \text{ m/s}$. For many calculations, the value $c = 3.00 \times 10^8 \text{ m/s}$ is precise enough. At this speed, light travels $9.46 \times 10^{12} \text{ km}$ in a year. This distance is called a light-year.



Diffraction and the Wave Model

In 1665 Italian scientist Francesco Maria Grimaldi observed that the edges of shadows are not perfectly sharp. He introduced a narrow beam of light into a dark room and held a rod in front of the light such that it cast a shadow on a white surface. The shadow cast by the rod was wider than the shadow should have been if light traveled in a straight line past the edges of the rod. Grimaldi also noted that the shadow was bordered by colored bands. He determined that both of these observations could be explained if light bent slightly. He called the bending of light as it passes the edge of a barrier **diffraction**.

Huygens' principle In 1678 Dutch scientist Christiaan Huygens used a wave model to explain diffraction. According to Huygens' principle, all the points of a wavefront of light can be thought of as new sources of smaller waves.

These smaller waves, or wavelets, expand in every direction and are in step with one another. A flat, or plane, wavefront of light consists of an infinite number of point sources in a line. **Figure 12** illustrates Huygen's principle.

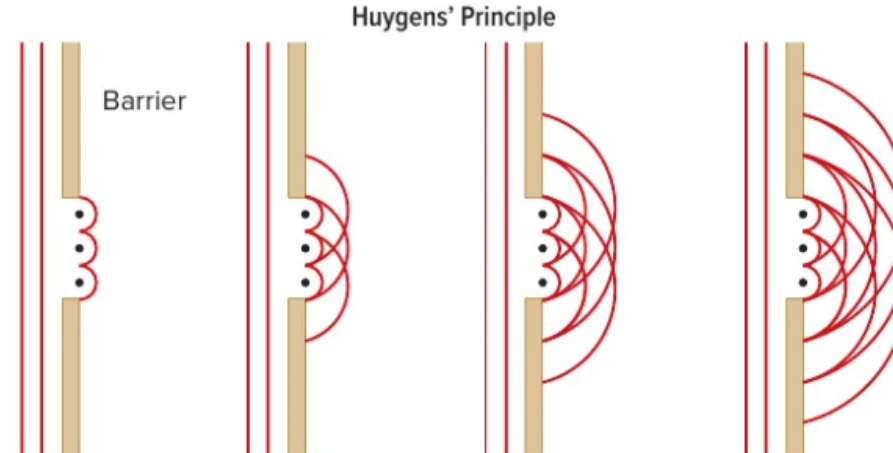
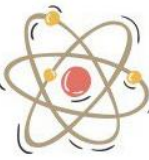


Figure 12 Huygens' wavelets combine to form a straight wavefront, except at the edges of the wave. The wavelets spread out in a circular manner when a barrier creates an edge.



4	Describe that the color of light is related to its wavelength and frequency. Describe white light as a combination of the spectrum of colors, each having a different wavelength. Describe primary, secondary, and complementary colors of light and the effects of corresponding combinations.	Figure 14	13
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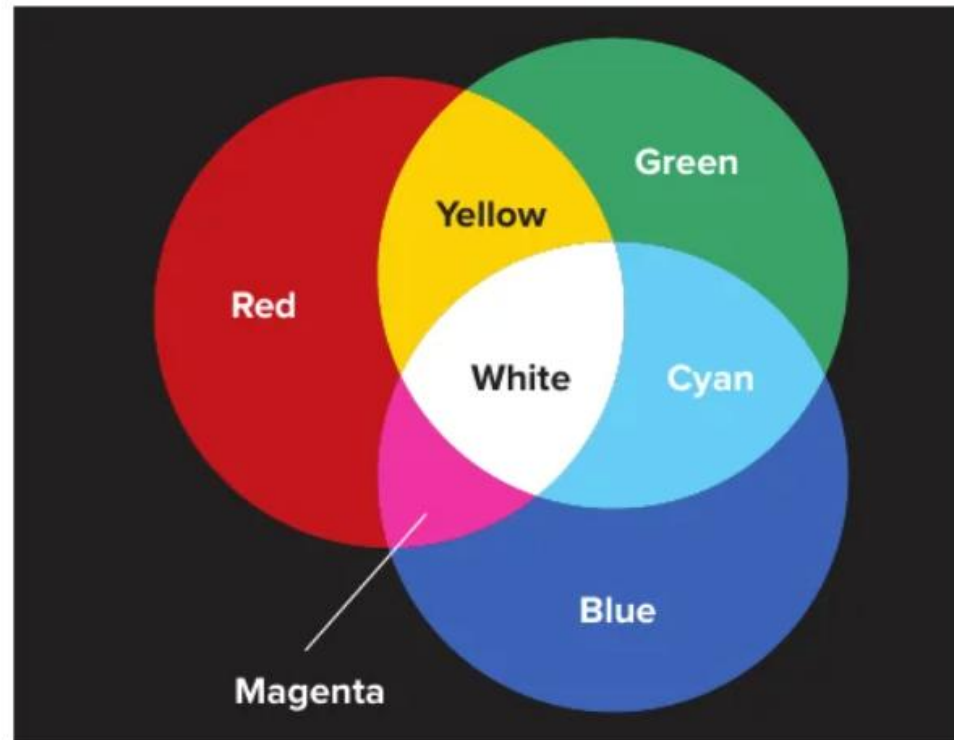
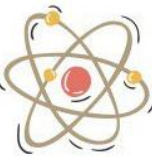


Figure 14 Red, green, and blue light, the primary colors, combine in pairs to produce yellow, cyan, or magenta light. The region where these three colors overlap on the screen appears white.



5	Describe primary and secondary pigments and the effects of mixing pigments or dyes.	Student Textbook	15
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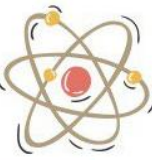
Pigments The difference between a dye and a pigment is that pigments usually are made of crushed minerals rather than plant or insect extracts. For example, hematite produces a red pigment, and blue pigment can be obtained from azurite. Pigment particles can be seen with a microscope. A pigment that absorbs only one primary color and reflects two from white light is called a **primary pigment**. Yellow pigment absorbs blue light and reflects red and green light. Yellow, cyan, and magenta are the colors of primary pigments.

A pigment that absorbs two primary colors and reflects one color is called a **secondary pigment**. The colors of secondary pigments are red (which absorbs green and blue light), green (which absorbs red and blue light), and blue (which absorbs red and green light). Note that the primary pigment colors are these secondary colors of light. In the same way, the secondary pigment colors are light's primary colors.

The primary and secondary pigments are shown in **Figure 16**. When the primary pigments yellow and cyan are mixed, the yellow absorbs blue light and the cyan absorbs red light. **Figure 16** shows yellow and cyan combining to make green pigment. When yellow pigment is mixed with the secondary pigment blue, which absorbs green and red light, all the primary colors are absorbed, and the result is black. Yellow and blue are complementary pigments. Cyan and red, as well as magenta and green, are also complementary pigments.



Figure 16 Magenta, cyan, and yellow are the primary pigments. Secondary pigments, red, green, and blue, are produced from mixing the primary pigments in pairs.



6	Describe the polarization of light by reflection. State and explain Malus's law. Apply Malus's law to light filtered by polarizer and analyzer filters.	Student Textbook	16 & 17
		PHYSICS Challenge	18

Polarization by Filtering

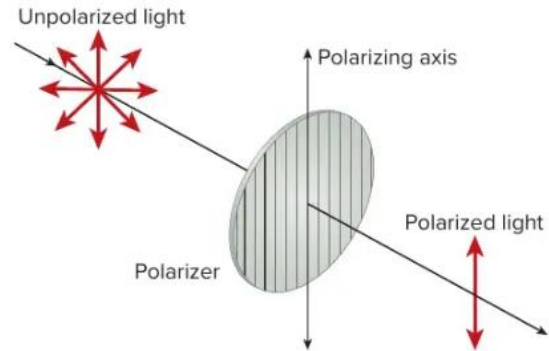


Figure 18 Nonpolarized light rays vibrate randomly in every direction perpendicular to the direction they travel. A polarizing medium blocks light that is not parallel to the polarizing axis.

Polarization of Light

Have you ever looked at light reflected off a road through polarizing sunglasses? If you rotate the glasses, the road first appears to be dark, then light, and then dark again. Light from a lamp, however, changes very little as the glasses are rotated. Why is there a difference? Normal lamp-light is not polarized. However, the light that is coming from the road is reflected and has become polarized. **Polarization** is the production of light with a specific pattern of oscillation.

Recall that light behaves as a transverse wave. For waves on a rope, the oscillating medium is the rope. For light waves, the oscillating medium is the electric field. When this electric field oscillates in random directions, the light is nonpolarized. How can you filter nonpolarized light so that whatever passes through the filter is polarized light?



Get It?

Draw a diagram, with text explanations, showing nonpolarized light.

Polarization by filtering The lines in the polarizer in **Figure 18** represent a polarizing axis. The light with the portion of the electric field that oscillates parallel to these lines passes through. The light with the portion of the electric field that oscillates perpendicular to these lines is absorbed. If a polarizer is placed in a beam of nonpolarized light, only the components of the waves in the same direction as the polarizing axis can pass through. As a result, half of the total light passes through, reducing the intensity of the light by half.

Polarization by reflection When you look through a polarizing filter at the light reflected by a sheet of glass and rotate the filter, you will see the light brighten and dim. The light is partially polarized parallel to the plane of the glass when it is reflected. Polarized reflected light causes glare. Polarizing sunglasses reduce glare from the polarized light reflected off roads. Photographers can use polarizing filters over camera lenses to block reflected light. This result is shown in **Figure 19**.

Malus's law Suppose you produce polarized light with a polarizing filter. What would happen if you place a second polarizing filter in the path of the polarized light? If the polarizing axis of the second filter is parallel to that of the first, the light will pass through. If the polarizing axis of the second filter is perpendicular to that of the first, no light will pass through, as shown in **Figure 20**.

If the light intensity after the first polarizing filter is I_1 and the intensity after the second filter is I_2 , how can you control I_2 ? I_2 depends only on I_1 and the angle between the axes of the filters, θ . If θ is 0° , I_2 equals I_1 ; if θ is 90° , all of the light is blocked, resulting in I_2 being 0. This indicates that the intensity might depend on the cosine of θ . The actual relationship is that of a cosine squared. The law that explains the reduction of light intensity as light passes through a second polarizing filter is **Malus's law**.

Malus's Law

The intensity of light coming out of a second polarizing filter is equal to the intensity of polarized light coming out of a first polarizing filter multiplied by the cosine, squared, of the angle between the polarizing axes of the two filters.

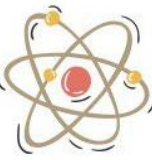
$$I_2 = I_1 \cos^2 \theta$$



Figure 19 Glare is light that has been polarized by reflection. Photographers use polarizing filters to reduce glare.



Figure 20 Polarizing filters with their axes parallel will allow the light with the same orientation to pass. With the polarizing axes at a 45° angle, the filters allow some light to pass. If the axes of the filters are perpendicular, the second filter will block the light that has passed through the first filter.



6

Describe the polarization of light by reflection.
State and explain Malus's law.
Apply Malus's law to light filtered by polarizer and analyzer filters.

Student Textbook

16 & 17

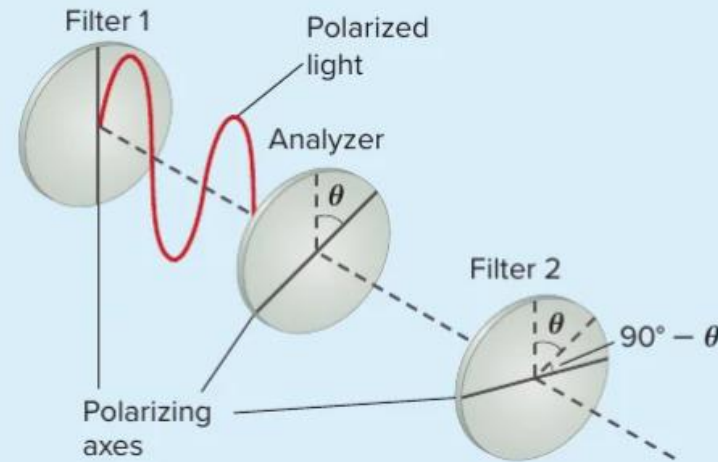
PHYSICS Challenge

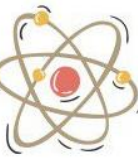
18

PHYSICS Challenge

You place an analyzer filter between the two cross-polarized filters, such that its polarizing axis is not parallel to either of the two filters, as shown in the figure to the right.

1. You observe that some light passes through filter 2, though no light passed through filter 2 before you inserted the analyzer filter. Why does this happen?
2. The analyzer filter is placed at an angle of θ relative to the polarizing axis of filter 1. Derive an equation for the intensity of light coming out of filter 2 compared to the intensity of light coming out of filter 1.





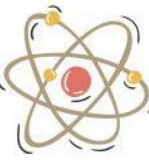
7	Relate the speed of light to its wavelength and frequency.	Student Textbook	18
		PRACTICE Problems 16	20

Speed, Wavelength, and Frequency of Light

As you have learned, the source of a wave determines that wave's frequency (f), and the medium and the frequency together determine the wavelength (λ) of a wave. Because light has wave properties, the same mathematical models used to describe waves in general can be used to describe light. For light of a given frequency traveling through a vacuum, wavelength is a function of the speed of light (c), which can be written as $\lambda_o = c/f$. The development of the laser in the 1960s provided new ways to measure the speed of light. The frequency of light can be measured with extreme precision using lasers and the time standard of atomic clocks. Measurements of wavelengths of light, however, are much less precise.

All colors of light travel at c in a vacuum, though the wavelengths are different. Since $\lambda_o = c/f$, once the frequency of a light wave in a vacuum is measured, the wavelength can be determined.

Relative motion and light What happens if a light source travels toward you or you move toward the source? You have learned that the frequency of a sound heard by a listener changes if either the source or the listener of the sound is moving. The same is true for light. However, when you consider the velocities of a sound source and the observer, you are really considering each one's velocity relative to the medium through which the sound travels. This is not the case for light.



8	Define the Doppler Effect. Explain the doppler's effect of light. Relate frequency change ($f_{\text{obs}} - f$) and doppler shift ($\lambda_{\text{obs}} - \lambda$) to actual frequency and wavelength using mathematical equations. Apply mathematical equations to calculate unknown physical quantities (wavelengths, frequencies, or speeds) when light waves are doppler shifted based on the relative speed of the observer and the light source. Describe that the doppler shift could be positive or negative based on the direction of the relative velocity of the source and the observer.	Student Textbook	19
		PRACTICE Problems 17 & 18	20

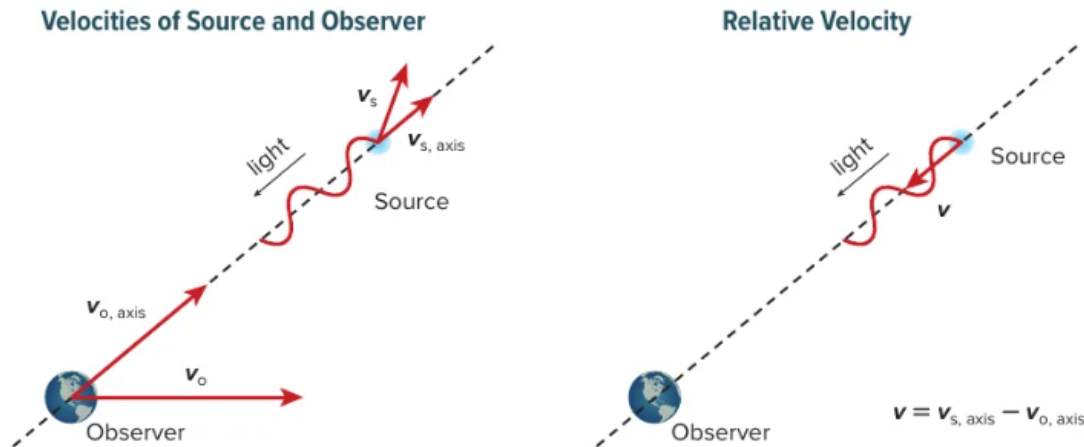


Figure 21 The Doppler effect describes how light frequency changes if an observer and a light source are moving toward or away from each other.

Doppler effect for light problems can be simplified by considering axial relative speeds that are much less than the speed of light ($v \ll c$). This simplification is used to develop the equation for the observed light frequency (f_{obs}), shown below.

Observed Light Frequency

The observed frequency of light from a source is equal to the actual frequency of the light generated by the source, times the quantity 1 plus the relative speed along the axis, divided by the speed of light, between the source and the observer if they are moving toward each other, or 1 minus the relative speed, divided by the speed of light, if they are moving away from each other.

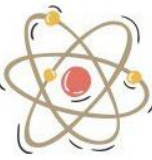
$$F_{\text{obs}} = f \left(1 \pm \frac{v}{c} \right)$$

Applications Most applications of the Doppler effect for light are in astronomy, where phenomena are discussed more in terms of wavelength. Using the relationship $\lambda = c/f$ and the $v \ll c$ simplification, the following equation describes the Doppler shift ($\Delta\lambda$), the difference between the observed and the actual wavelengths.

Doppler Shift

The difference between the observed wavelength of light and the actual wavelength of light generated by a source is equal to the actual wavelength of light generated by the source, times the relative speed of the source and observer, divided by the speed of light.

$$(\lambda_{\text{obs}} - \lambda) = \Delta\lambda = \pm \left(\frac{v}{c} \right) \lambda$$

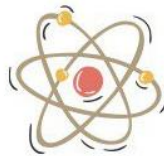


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		PRACTICE Problems 17 & 18	20

17. A hydrogen atom in a galaxy moving with a speed of 6.55×10^6 m/s away from Earth emits light with a frequency of 6.16×10^{14} Hz. What frequency of light from that hydrogen atom would be observed by an astronomer on Earth?

18. A hydrogen atom in a galaxy moving with a speed of 6.55×10^6 m/s away from Earth emits light with a wavelength of 486 nm. What wavelength would be observed on Earth from that hydrogen atom?

9	Describe the law of reflection. Apply the law of reflection in drawing ray diagrams and solving numerical problems.	Student Textbook	28 & 29
		Figure 3	29



Reflected Images

When you look at the surface of a body of water, you don't always see a clear reflection as in **Figure 1**. Sometimes, the wind causes ripples in the water, or passing boats produce waves. Disturbances on the water's surface prevent the light from reflecting in a manner such that a clear image is visible.

Almost 4000 years ago, Egyptians understood that the type of reflection you see from a still pond requires a smooth surface. They used polished metal mirrors to view their images.

Artisans in sixteenth-century Venice created mirrors by coating the back of a flat piece of glass with a thin sheet of metal. Sharp, well-defined, reflected images were not possible until 1857, however, when Jean Foucault, a French scientist, developed a method of coating glass with silver.

Today, we don't only use mirrors to view our reflections. Mirrors are key components in lasers, telescopes, and other precise optical systems. We use ever-increasing precision to make modern mirrors. Today's mirrors are made by evaporating aluminum or silver onto highly polished glass. The same basic physics principles, however, govern reflection from the smooth surface of a pond, from a sixteenth-century mirror, and from a tiny mirror inside a laser.



Figure 1 Disturbances on the surface of a pond or lake produce distorted reflected image.

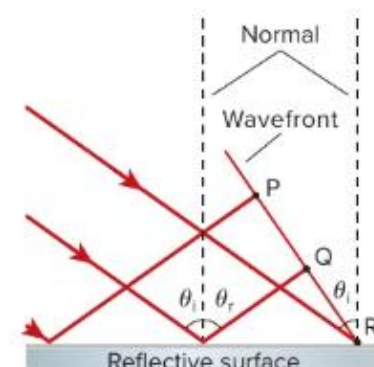
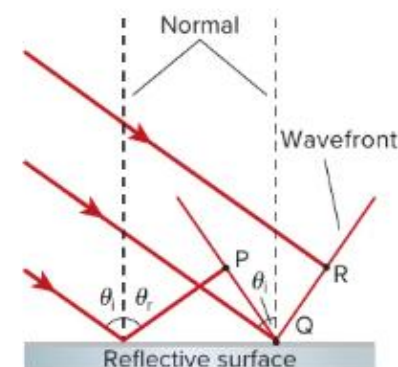
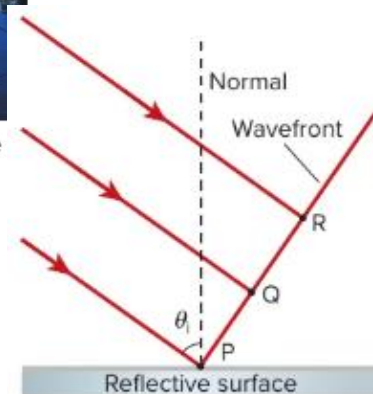
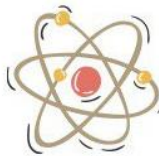


Figure 3 All parts of a wavefront reflect from a surface at the same angle. The angle of incidence equals the angle of reflection.



9	Describe the law of reflection. Apply the law of reflection in drawing ray diagrams and solving numerical problems.	Student Textbook	28 & 29
		Figure 3	29

The Law of Reflection

Figure 2 shows a light ray striking a reflecting surface. The normal is an imaginary line that is perpendicular to a surface at the location where light strikes the surface. The incident ray, the reflected ray, and the normal are in the same plane, which is perpendicular to the surface. Although light travels in three dimensions, the reflection of light is planar (two-dimensional). Planar relationships are known as the law of reflection.

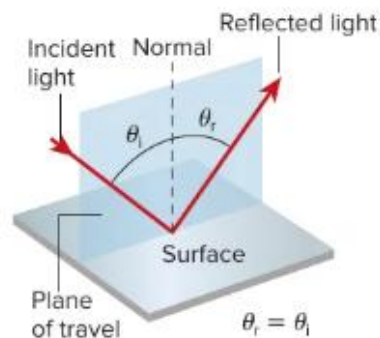


Figure 2 Reflecting light waves have an angle of reflection in the same plane as and equal to the angle of incidence.

Law of Reflection

The angle that a reflected ray makes as measured from the normal to a reflective surface equals the angle that the incident ray makes as measured from the same normal.

$$\theta_r = \theta_i$$

Wave model We can describe this law in terms of the wave model of light. **Figure 3** shows a wavefront of light approaching a surface. The wavefront is perpendicular to the light ray. As each point along the wavefront reaches the surface, it reflects off that surface. Because all points are traveling at the same speed, they all travel the same total distance in the same time. Thus, the wavefront as a whole leaves the surface at an angle equal to its incident angle. Note that the wavelength of the light does not affect this process. The surface reflects red, green, and blue light all in the same direction.

Smooth surfaces Consider the light rays shown on the left in **Figure 4** on the next page. All the rays reflect off the surface parallel to one another. This occurs only if the reflecting surface is not rough on the scale of the wavelength of the light. We consider such a surface to be

smooth. A smooth surface, such as a mirror, produces **specular reflection**, in which parallel light rays reflect in parallel.

Rough surfaces What happens when light strikes a sheet of paper? A sheet of paper might appear smooth, but on the scale of the wavelength of light, paper is actually quite rough. The right side of **Figure 4** shows light rays reflecting off a sheet of paper. All of the light rays are parallel before they strike the surface, but the reflected rays are not parallel, as shown. This scattering of light off a rough surface is called **diffuse reflection**.

The law of reflection applies to smooth and rough surfaces. For a rough surface, the angle that each incident ray makes with the normal equals the angle that its reflected ray makes with the normal. On a microscopic scale, however, the normals to the surface locations are not parallel.

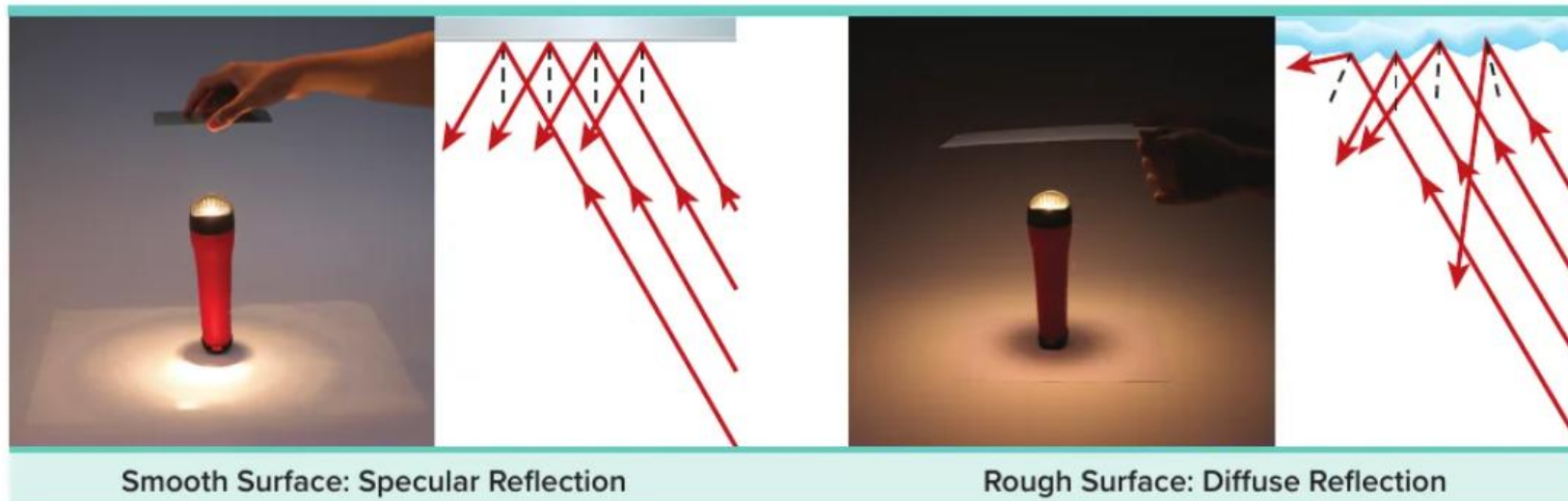
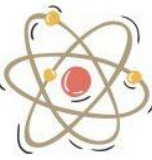
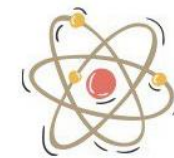


Figure 4 Notice that the image of the lightbulb in the flashlight is reflected on the table by the smooth mirror. The surface of the paper reflects a featureless area of light. Diffuse reflection enables you to read this page from various angles.



Properties of Plane-Mirror Images

Looking at yourself in a mirror, you can see that your image in the mirror appears to be the same distance behind the mirror as you are in front of the mirror. How could you test this? Place a ruler between you and the mirror. Where does the image touch the ruler? You see that your image is vertically oriented as you are, and it matches your size. This is where the expression *mirror image* originates.

Image position and height The geometric model in **Figure 7** shows why the distances are the same. Two rays from point O at the tip of the candle strike the mirror at points P_1 and P_2 . The mirror reflects both rays according to the law of reflection.

We can extend the reflected rays behind the mirror as sight lines (the dashed lines in the figure). These sight lines converge at point I, which is the image of point O. Ray 1, which strikes the mirror at an angle of incidence of 0° , reflects back on itself, so the sight line is at 90° to the mirror, just as ray 1 is. Ray 2 also reflects at an angle with respect to the normal equal to the angle of incidence, so the sight line is at the same angle to the mirror as ray 2.

This geometric model reveals that line segments OP_1 and IP_1 are corresponding sides of two congruent triangles, $\triangle OP_1P_2$ and $\triangle IP_1P_2$. The object's position with respect to the mirror (x_o) has a magnitude equal to the length of $\overline{OP_1}$. The apparent position of the image with respect to the mirror, which is called the image position (x_i), has a magnitude equal to the length of $\overline{IP_1}$. If image position is negative, indicating that the image is virtual, the following is true.

Plane-Mirror Image Position

With a plane mirror, the image position is equal to the negative of the object position. The negative sign indicates that the image is behind the mirror (and therefore virtual).

$$x_i = -x_o$$

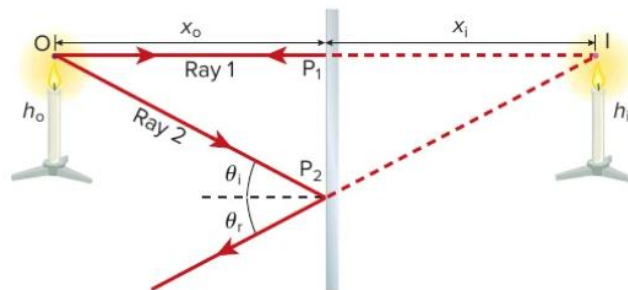


Figure 7 Reflected light rays from the candle (two rays are shown) strike the mirror. Some of those rays reach the viewer's eye. Sight lines (dashed lines) are drawn from where the rays reflect from the mirror to where they converge. The image is located where the sight lines converge.

Explain why $x_i = -x_o$.

You can draw more light rays from the object to the mirror to determine the size of the image. The sight lines of two rays originating from the bottom of the candle in **Figure 7** will converge at the bottom of the image. From the law of reflection and congruent-triangle geometry, we find the following is true of the object height (h_o) and image height (h_i) and any other dimension of the object and image.

Plane-Mirror Image Height

With a plane mirror, image height is equal to object height.

$$h_i = h_o$$

Image orientation A plane mirror produces an image with the same orientation as the object. If you

stand upright, a plane mirror produces an image of you standing upright. If you do a headstand, the mirror shows you doing a headstand. However, the mirror gives a front-to-back reversal. You are looking face-to-face at the image of yourself.

Follow the sight lines in **Figure 8**. The image is behind the mirror such that the boy appears to be facing himself. When the boy extends his right hand, it appears as though the left hand of the image is extended, but from the boy's perspective, the hand that is extended is on his right-hand side. This happens because a plane mirror does not really reverse left and right. The mirror in **Figure 8** only reverses the boy's image such that it is facing in the opposite direction as the boy, or, in other words, it produces a front-to-back reversal.

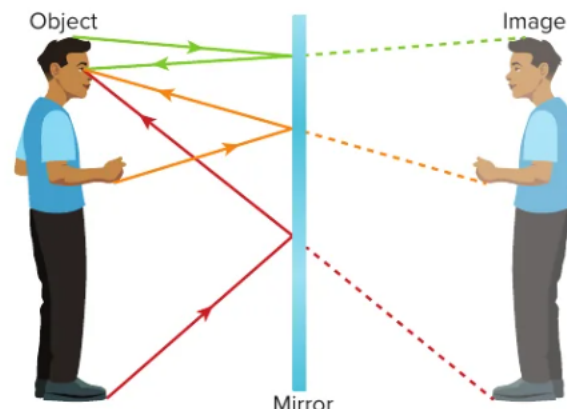
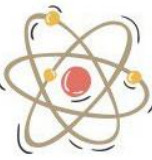


Figure 8 Viewed in a mirror, your height and distance from the mirror appear the same. There is, however, a difference. You are facing the opposite direction.

12	Represent mathematically the relation between image position and object position, as well as the image height and object height for a plane mirror.	Student Textbook	32 & 33
		Check Your Progress 8	33



8. **Image Properties** A dog looks at its image, as shown in **Figure 9**. What are the position, height, and type of image?

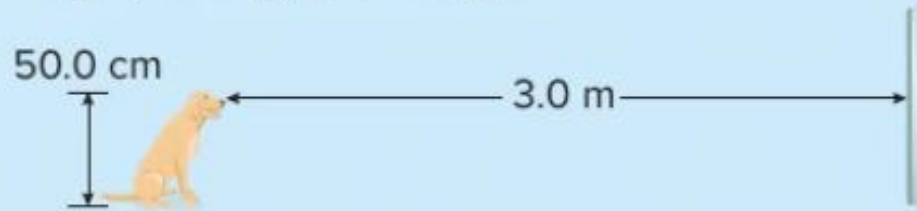
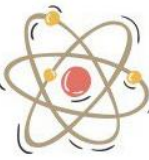


Figure 9



Properties of Curved Spherical Mirrors

Move a metal spoon toward and away from your face. Look at your image on both sides of the spoon. Your image may appear larger or smaller, or it may even be inverted. The properties of curved mirrors, such as a metal spoon, and the images that they form depend on the shape of the mirror and the object's position.

The way that a spherical mirror reflects light depends on its curve. **Figure 10** shows two spherical mirrors and some important points and distances for understanding how they form images. A spherical mirror is shaped as if it were a section of a hollow sphere. The mirror (M) has the same geometric center (C) as a sphere of radius r . The distance r is also called the radius of curvature.

The straight line that includes line segment CM is called the **principal axis**, or line perpendicular to the mirror's surface that divides the mirror in half.

Focal point Light rays from the Sun to Earth are almost parallel because the Sun is so far away. When you point the principal axis of a concave mirror toward the Sun, all the rays reflect through a point. You can locate this point by moving a sheet of paper toward and away from the mirror until the smallest and sharpest spot of sunlight is focused on the paper. This spot is the mirror's **focal point**, which is the point at which incident light rays that are parallel to the principal axis converge after reflecting from the mirror. This is point F.

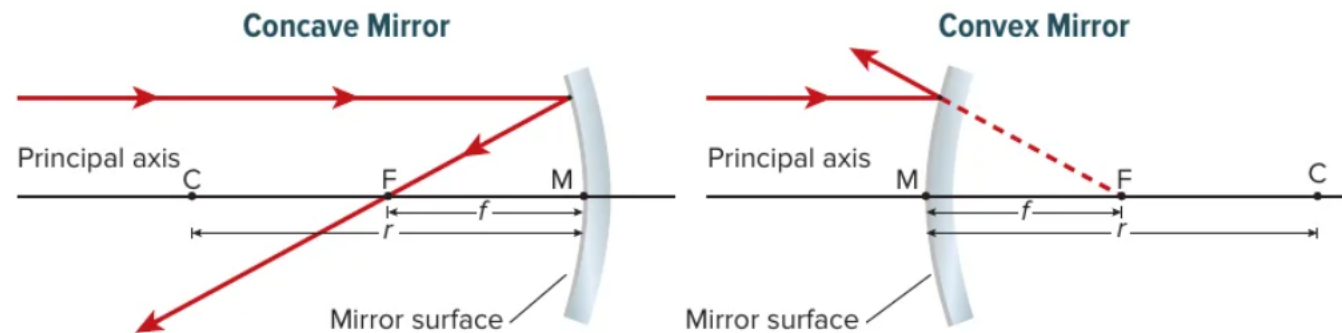
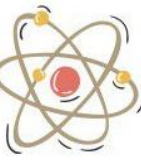


Figure 10 For concave and convex mirrors, the distance from M to F (the focal point) is half the distance from M to C.



13

Draw a ray diagram to find the image of an object located at a distance greater than twice the focal length of a concave mirror, and determine the properties of the formed image.

Figure 14

38

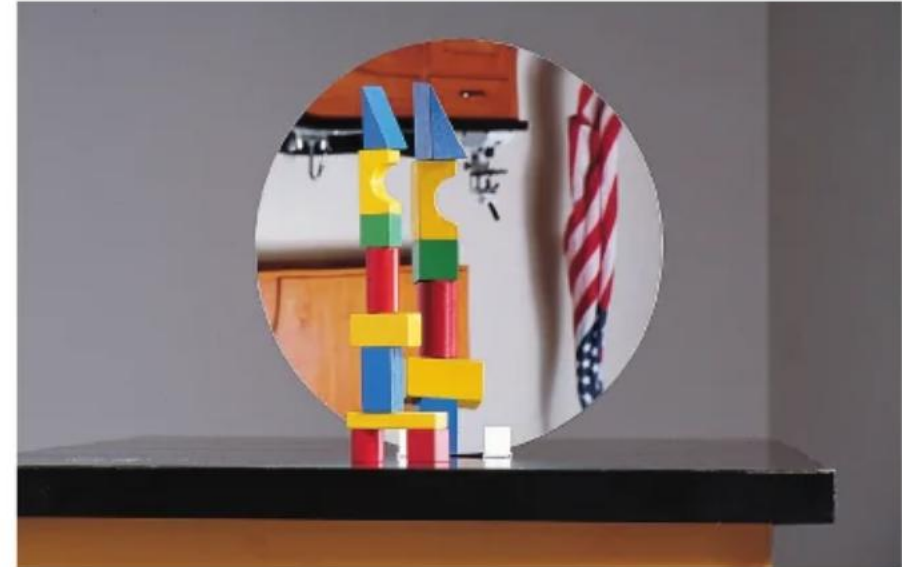
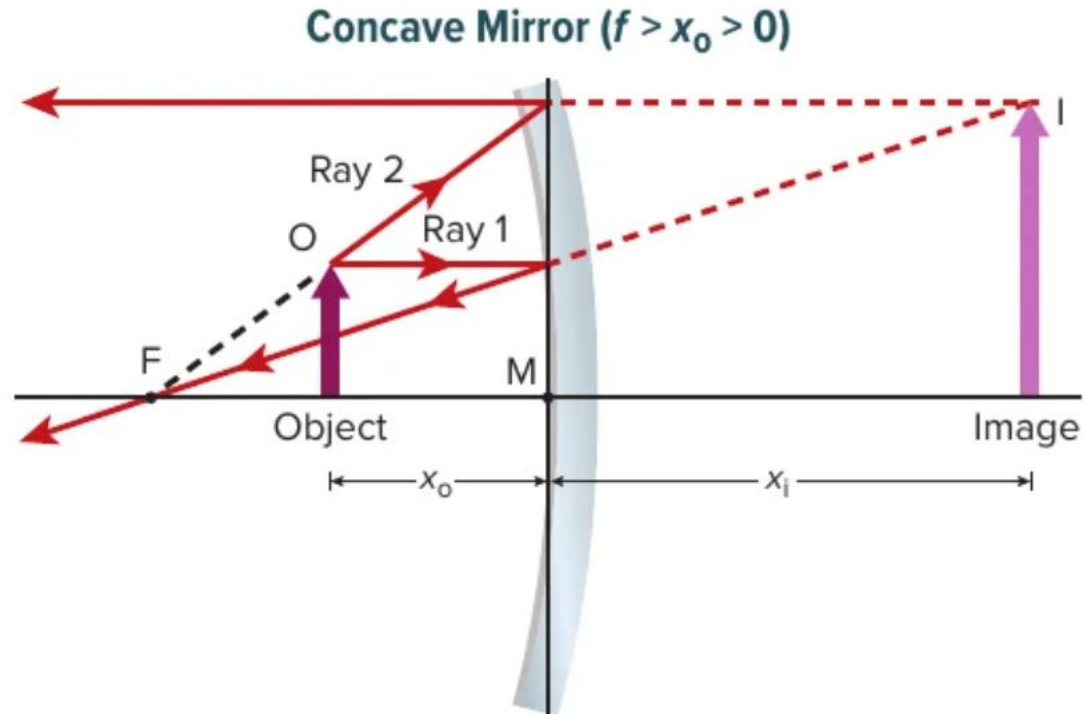


Figure 14 A virtual, upright, enlarged image is formed when an object, such as the block tower on the right, is placed between the focal point and the surface of a concave mirror.

Consider the cause of the appearance of the other images in the mirror.

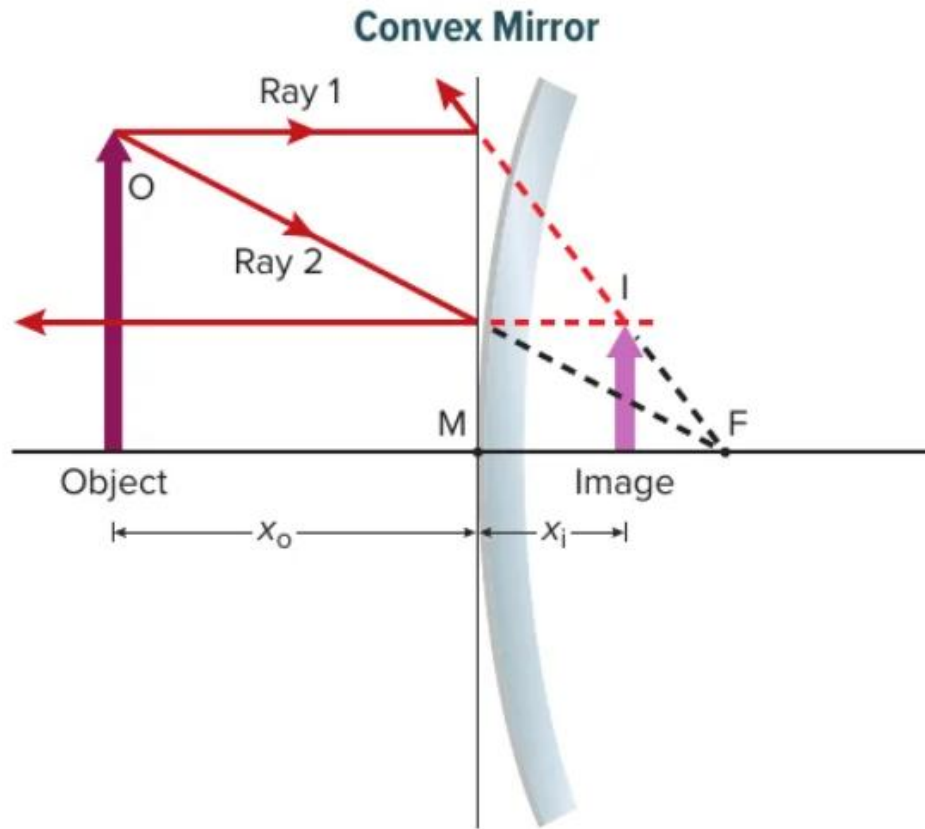
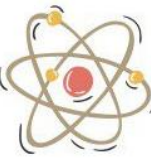
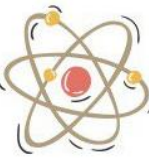


Figure 15 Convex mirrors form images that are virtual, upright, and smaller than the object.



Figure 16 Images from convex mirrors are smaller than the object. This increases the field of view and decreases the driver's blind spot.

Explain why a warning stating that objects in a convex side-view mirror are closer than they appear may be useful.



16	Calculate the refractive index of a medium using a suitable mathematical representation $(n = \frac{c}{v})$.	Student Textbook	47
		Check Your Progress 38	50

Using $\lambda = \frac{v}{f}$ and canceling the common factor f , because frequency stays constant, the equation can be rewritten:

$$\frac{\sin \theta_2}{\sin \theta_1} = \frac{v_2}{v_1}$$

Snell's law also can be written as a ratio of the sines of the angles of incidence and refraction.

$$\frac{\sin \theta_2}{\sin \theta_1} = \frac{n_1}{n_2}$$

Using the transitive property of equality, the previous two equations lead to the following equation:

$$\frac{n_1}{n_2} = \frac{v_2}{v_1}$$

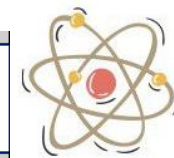
In a vacuum, $n = 1.00$ and $v = c$. If either medium is a vacuum, then the equation is simplified to an equation that relates the index of refraction to the speed of light in a medium.

Index of Refraction

The index of refraction of a medium is equal to the speed of light in a vacuum divided by the speed of light in the medium.

$$n = \frac{c}{v}$$

38. Speed of Light What is the speed of light in chloroform ($n = 1.51$)?



Total Internal Reflection

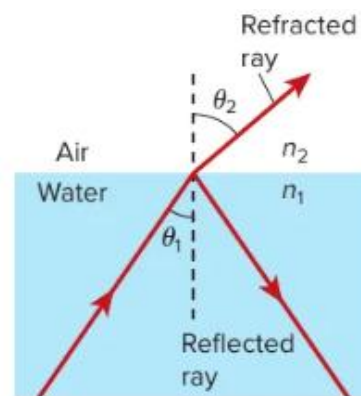
Recall that when light strikes a transparent boundary, some of the light is transmitted and some is reflected. As light travels from a medium of higher index of refraction to a medium of lower index of refraction, the angle of refraction is larger than the angle of incidence, as shown in **Figure 21**.

This leads to an interesting phenomenon. As the angle of incidence increases, the angle of refraction increases. At a certain angle of incidence known as the **critical angle** (θ_c), the refracted light ray lies along the boundary of the two mediums.

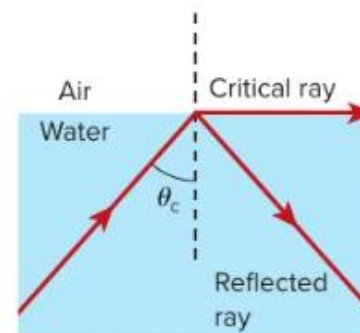
Total internal reflection occurs when light traveling from a region of a higher index of refraction to a region of a lower index of refraction strikes the boundary at an angle greater than θ_c such that all the light reflects back into the region of the higher index of refraction. This is shown in the third diagram of **Figure 21**. Using Snell's law and substituting $\theta_1 = \theta_c$, and $\sin \theta_2 = \sin 90.0^\circ = 1$:

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

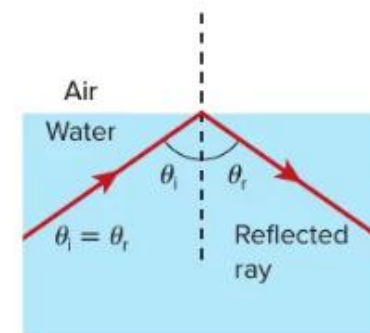
Total internal reflection causes some curious effects. Suppose you are looking up at the surface from under water in a pool. You might see an upside-down reflection of another nearby object that is also under water. You might see a reflection of the bottom of the pool itself. The surface of the water acts like a mirror, reflecting the image back into the water.



At an angle of incidence less than the critical angle, light is partially refracted and partially reflected.



A ray refracted along the boundary of the medium forms the critical angle.



An angle of incidence greater than the critical angle results in total internal reflection, which follows the law of reflection.

Figure 21 Refraction and reflection of light traveling between mediums depend on the angle of incidence θ_1 .

18	Explain some natural phenomena, such as the formation of mirage or rainbows or others, which involve optical phenomena like reflection, refraction, total internal reflection, or dispersion of light. Define dispersion and explain the dispersion of light through a prism.	Student Textbook	49 & 50
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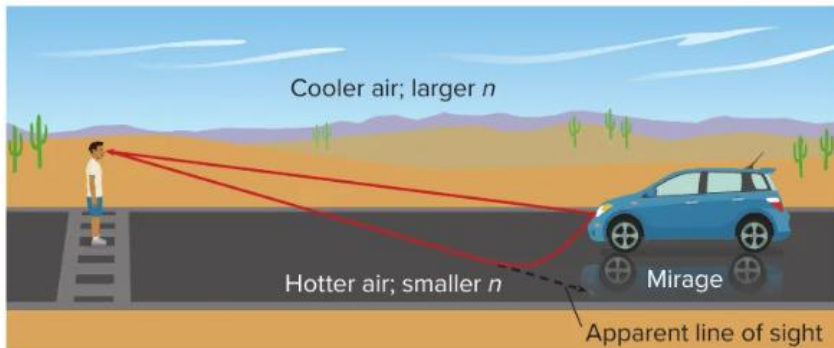
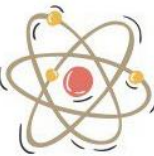


Figure 22 Light waves reflected from the vehicle on the road are refracted when the air near the surface of the road is hotter than the air above it.

Apply Are the light waves traveling faster near the surface of the road or near the top of the vehicle?

Mirages

On a hot summer day, you sometimes can see what appears to be the reflection of an oncoming vehicle in a pool of water as shown on the left in **Figure 22**. The pool, however, disappears as you approach it. This mirage is the result of the Sun heating the road. The speed of light and, therefore, the index of refraction, for a gaseous medium can change slightly with temperature. The hot road heats the air above it and produces a thermal layering of air, causing light traveling toward the road from the car to gradually bend upward. This makes the light appear to be coming from a reflection in a pool.

The diagram in **Figure 22** shows how this occurs. As light from a distant object travels downward toward the road, the index of refraction of the air decreases as the air gets hotter, but the temperature change is gradual. Recall that light wavefronts are comprised of Huygens' wavelets. In the case of a mirage, the Huygens' wavelets closer to the ground travel faster than those higher up, causing the wavefronts to gradually turn upward.

glass. This results in glass having a slightly higher index of refraction for violet light than it has for red light. This separation of white light into a spectrum of colors is called **dispersion**.

The speed of light in a medium is determined by interactions between the light and the atoms that make up the medium. The speed of light and the index of refraction for a solid or liquid medium vary for different wavelengths of light.

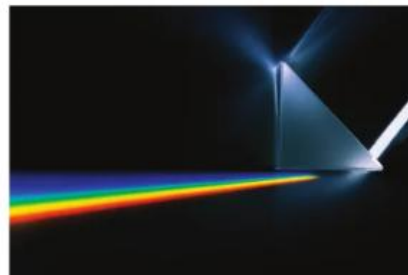


Figure 23 Dispersion through a prism occurs because the index of refraction varies with the wavelength of light.

Dispersion of Light

If you look carefully at the spectrum formed by light passing through the prism in **Figure 23**, you will notice that violet light is refracted more than red light. This occurs because the speed of violet light through glass is less than the speed of red light through glass. Violet light has a higher frequency than red light, which causes it to interact differently with the atoms of the

Although each droplet produces a complete spectrum, an observer positioned between the Sun and the rain will see only a certain wavelength of light from each droplet. The wavelength observed depends on the relative positions of the Sun, the droplet, and the observer, as shown in **Figure 24**.

Second-order rainbow Sometimes, you can see a faint second-order rainbow like the one shown in **Figure 25**. The second rainbow is outside of the first. It is also fainter and has the order of the colors reversed. Light rays that are reflected twice inside water droplets produce this effect.



Figure 25 Light reflected within raindrops can cause the appearance of a secondary rainbow.

Rainbows A rainbow is a spectrum formed when sunlight is dispersed by water droplets in the atmosphere. Sunlight that falls on a water droplet is refracted. Since each color has a different wavelength, it is refracted at a slightly different angle, as shown in **Figure 24** on the next page, resulting in dispersion. At the back surface of the droplet, some of the light undergoes internal reflection. On the way out of the droplet, the light once again is refracted and dispersed.

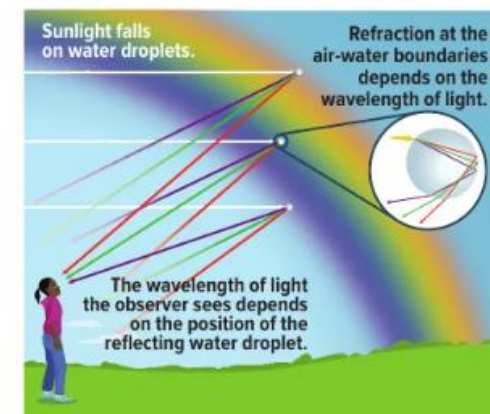
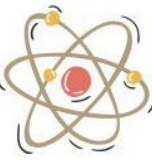


Figure 24 Light from the Sun is dispersed by water droplets to form rainbows. Because there are many droplets at various positions in the sky, a complete spectrum is visible.

Consider whether it is possible for a rainbow to be close enough to touch.



19	Explain defects in spherical lenses such as spherical aberration and chromatic aberration and how they can be corrected.	Student Textbook	56
		Figure 33	56



Figure 32 Spherical aberration from the camera lens blurs the edges of this image.

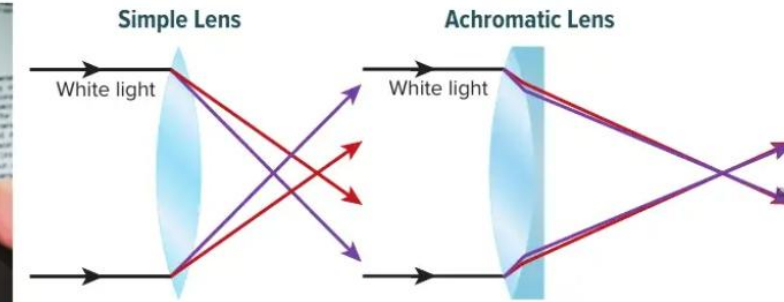


Figure 33 Simple lenses, such as the one shown in the photo on the left, exhibit a rainbow fringing effect called chromatic aberration. Achromatic lenses reduce chromatic aberration.

Explain why the index of refraction is important for achromatic lenses.

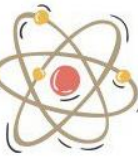
Defects of Spherical Lenses

Throughout this section, you have studied lenses that produce perfect images at specific positions. In reality, spherical lenses, just like spherical mirrors, have intrinsic defects that cause problems with the focus and color of images. Spherical lenses exhibit an aberration associated with their spherical design, just as mirrors do. In addition, the dispersion of light through a spherical lens causes an aberration that mirrors do not exhibit.

Spherical aberration The model you have used for drawing rays through spherical lenses suggests that all parallel rays focus at the same position. However, this is only an approximation. In reality, parallel rays that pass through the edges of a spherical lens focus at positions different from those of parallel rays that pass through the center. This inability of a spherical lens to focus all parallel rays to a single point is called spherical aberration. The effects are shown in **Figure 32**. In reality, most lenses have a slightly different shape to address this, but the spherical approximation works well enough for our purposes. In high-precision instruments, many lenses, often five or more, are used to form sharp, well-defined images.

Chromatic aberration Lenses have a second defect that mirrors do not have. Because the index of refraction of a medium depends on wavelength, different wavelengths of light are refracted at slightly different angles, as you can see on the right in **Figure 33**. Light that passes through a lens is slightly dispersed, especially near the edges, causing an effect called **chromatic aberration**. This is seen as an apparent ring of color around an object viewed through a lens, as shown on the left in **Figure 33**.

Chromatic aberration is always present when a single lens is used. However, this defect can be greatly reduced by an **achromatic lens**, which is a system of two or more lenses, such as a convex lens with a concave lens, that have different indices of refraction. A simple lens and an achromatic lens are shown in **Figure 33**. Both lenses disperse light, but the dispersion caused by the achromatic lens is less than the dispersion caused by the simple lens. The index of refraction of the achromatic lens is chosen so that the light will still converge at the desired location.



20	Describe the process by which your eye focuses light and forms an image. Define nearsightedness (Myopia) and farsightedness (Hyperopia). Describe the formation of image in case of nearsightedness and farsightedness and how defects in vision are corrected using concave and convex lenses.	Student Textbook	57 & 58
		Figure 35	58

Lenses in Eyes

The concepts that you have learned for the refraction of light through lenses apply to almost every optical device, including the eye. The eye is a remarkable optical device. As shown in **Figure 34**, the eye is a fluid-filled, almost spherical vessel. Light that is emitted from or reflected off an object travels into the eye through the cornea and pupil. The light then passes through the lens and focuses onto the retina, which is at the back of the eye. Specialized cells on the retina absorb this light and send information about the image along the optic nerve to the brain.

BIOLOGY Connection Because of its name, you might assume that the lens of an eye is responsible for focusing light onto the retina. In fact, light entering the eye is primarily focused by the cornea, because the air-cornea boundary has the greater difference in indices of refraction. The lens is responsible for the fine focus that allows you to clearly see both distant and nearby objects.



Get It?

Describe the roles of the cornea and the lens in your eye.

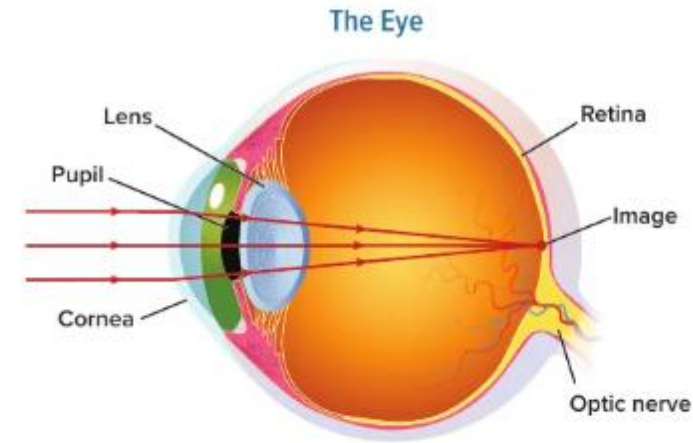
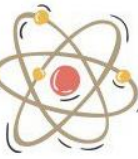


Figure 34 The cornea and the lens of your eye refract light that is reflected off every object you see.

Summarize why most of the refraction occurs at the air-cornea boundary rather than at the lens.

The eye lens uses a process called accommodation. Muscles surrounding the lens can contract or relax, thereby changing the shape of the lens. This, in turn, changes the focal length of the eye. For a healthy eye, when the muscles are relaxed, the image of distant objects is focused on the retina. When the muscles contract, the focal length is shortened, and this allows images of closer objects to be focused on the retina.

Nearsightedness The eyes of many people focus images either in front of the retina or behind it. External lenses, such as eyeglasses and contact lenses, adjust the focal length and move images to the retina. **Figure 35** on the next page shows the condition of **nearsightedness**, also called myopia.



20	Describe the process by which your eye focuses light and forms an image. Define nearsightedness (Myopia) and farsightedness (Hyperopia). Describe the formation of image in case of nearsightedness and farsightedness and how defects in vision are corrected using concave and convex lenses.	Student Textbook	57 & 58
		Figure 35	58

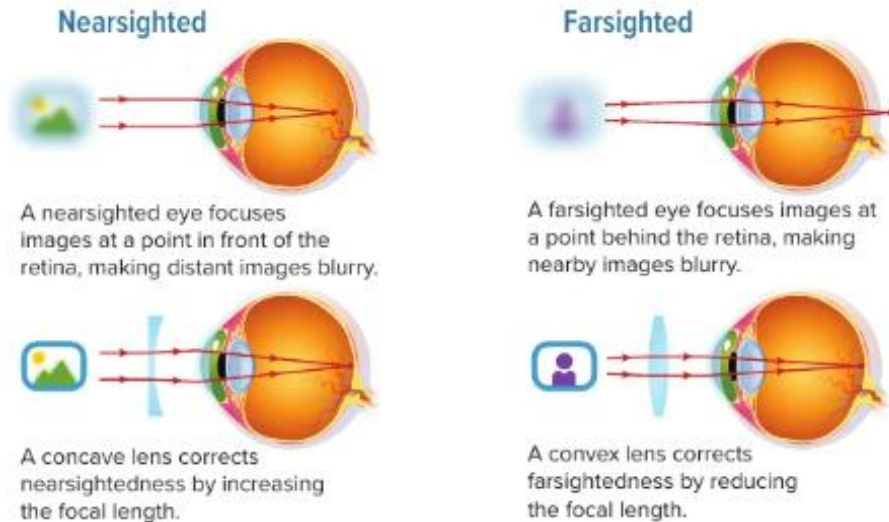


Figure 35 Objects at a distance are blurred for a nearsighted person. For a farsighted person, objects nearby are blurred.

Explain how bifocal lenses might be made.

With myopia, the focal length of the eye is too short to focus light on the retina. Images are formed in front of the retina. As shown in **Figure 35**, concave lenses correct this by diverging light, thereby increasing images' distances from the lens, and forming images on the retina.

Farsightedness You also can see in **Figure 35** that **farsightedness**, also called hyperopia, is the condition in which the focal length of the eye is too long. Images are therefore not formed on the retina.

A similar result is caused by the increasing rigidity of the lenses in the eyes of people who are more than about 45 years old. Their muscles cannot shorten the focal length enough to focus images of close objects on the retina.

For either condition, convex lenses produce virtual images farther from the eye than the associated objects, as shown in **Figure 35**. The images then become the objects for the eye lens and can be focused on the retina, thereby correcting the condition.

Real-World Physics



CONTACT LENSES produce the same results as eyeglasses. These small, thin lenses are placed directly on the corneas. A thin layer of tears between the cornea and lens keeps the lens in place. Most of the refraction occurs at the air-lens boundary, where the difference in indices of refraction is greatest.