AP Physics-B **Geometric Optics**

Introduction: A great deal of evidence suggests that light travels in straight lines. A source of light – like the sun – casts distinct shadows. We can hear sound from around the side of a wall or building, but we cannot see around it. The beam of a flashlight appears to be a straight line. Indeed, we infer the positions of objects in our environment by assuming that light moves from the object to our eyes in straight-line paths. Our whole orientation to the physical world is based on this assumption.

This reasonable assumption has led to a model for light known as the ray model. The straight-line paths that light follows are called rays. When we see an object, we are aware that it occupies some space and that light reaches our eyes from each point on the object.

Although the ray model of light does not deal with the actual nature of light (wave or particle), it has been very successful in dealing with many aspects of light, such as reflection, refraction and the formation of images by mirrors and lenses. Because these explanations involve straight-line rays and analysis using geometry, this subject is referred to as geometric optics.

This unit is divided into two parts. The first part deals with reflection and mirrors. The second part deals with refraction and lenses. Lenses such as eyeglasses and magnifying glasses are based on refraction. We will look at the way in which different lenses transmit light so that we might better understand how they can be put to practical use. Some optical instruments, like the microscope, make use of both mirrors and lenses.

Reflection:

When a light ray is incident upon a surface, the angle of incidence is equal to the angle of reflection. Both of these angles are measured from a normal (perpendicular) to the surface at the point of incidence. The incident ray, the reflected ray, and the normal all lie in the same plane.

Light reflected from an uneven surface is scattered in different directions. This scattering is known as diffuse reflection. If rays of light fall on a very smooth surface, the rays are arranged in the same order after they leave a smooth surface as they were before they approached the surface. This is regular reflection. Mirrored surfaces are based on regular reflection.

Objects are placed in front of mirrors. Because of regular reflection, mirrors produce images. The images produced can be real or virtual. Light only appears to be coming from a virtual image - where as - the light actually diverges from points of the real image.

The image in a plane mirror is the same size as the object. It is as far behind the mirror as the object is in front of the mirror. The image is virtual, upright and reversed from left to right.

The image obtained in a concave mirror depends upon the location of the object relative to the mirror. When the object is outside the focal length, the image is real and inverted. When the object is between the focal point and the mirror, the image will be virtual, larger in size than the object and upright.

Convex mirrors always produce virtual images.

Performance Objectives: Upon completion of the readings and activities of this unit and when asked to respond either orally or on a written test, you will:

- ✓ Recognize that light travels in straight lines.
- ✓ State the law of reflection.
- ✓ Distinguish between regular and diffuse reflection.
- ✓ Use the law of reflection to locate images formed by plane and curved mirrors.
- ✓ Describe the five properties of images formed by plane mirrors.
- ✓ Define the terms: Center of Curvature, Radius of Curvature, Focal Point, Focal Distance, Optical Axis, Vertex, Object, Virtual Image and Real Image. Be able to label these parts of a ray diagram.
- ✓ Use ray diagrams to locate images formed by concave and convex mirrors.
- ✓ Define spherical aberration and discuss how to avoid it.
- ✓ Distinguish between real and virtual images.
- ✓ Explain the formation of real images by concave mirrors. Diagram the location of such images. Calculate the location of images using the mirror equation.

- ✓ Explain and demonstrate by diagram how convex mirrors form virtual images. Calculate the location of such images using the mirror equation.
- ✓ Use the mirror equation to solve mirror problems.

Textbook Reference: Hecht Physics: Chapter 24

Exercises and Problems:

1.) A ray of light strikes a mirror at an angle of 53° with the normal. a.) What is the angle of reflection? b.) What is the angle between the incident ray and the reflected ray? *53° 106°*

2.) A ray of light incident upon a mirror makes an angle of 36° with the mirror. What is the angle between the incident ray and the reflected ray? *108°*

Plane Mirrors:

3.) Pegleg Pete wants to shoot his assailant by ricocheting a bullet off of a mirrored metal plate. To do so, should he simply aim at the mirrored image of his assailant? Explain. *Yes*

4.) Suppose that you walk one meter per second toward a mirror. How fast do you and your image approach each other? *2 m/s*

5.) Why is the lettering on the front some emergency vehicles written backwards?

6.) Why is it difficult to see the roadway in front of you when driving on a rainy night?

7.) Why does reflected light from the sun or moon appear as a column in the body of water shown? How would it appear if the water surface were perfectly smooth?

8.) When you look at yourself in the mirror and wave your right hand, your beautiful image waves the left hand. Why then don't the feet of your image wiggle when you shake your head?

9.) What must be the minimum length of a plane mirror in order for you to see a full view of yourself?

10.) Suppose that you want to take a photograph of yourself as you look at your image in a mirror 2.0 meters away. For what distance should the camera lens be focused? *4 meters*

11.) A student sitting in an optician's chair views a chart located 1.0 m behind his head by facing a mirror 2.5 m away from him. How far away from him does the chart appear to be? *6.0 meters*

12.) A man is 1.85 m tall and just sees his image in a vertical plane mirror 3.0 m away. His eyes are 10.0 cm from the top of his head. Determine the height and position of the mirror. *0.925 m 0.875 m above the floor*

13.) Two plane mirrors make an angle of 15° with each other. Graphically locate four images of a luminous point "A" placed between the two mirrors on the bisector of the angle they make.

Concave Mirrors:

14.) Draw a ray diagram to locate the image of an object placed in front of a concave mirror with a radius of curvature of 10.0 cm. The object is placed:

a.) 12.5 cm from the mirror. *8.3 cm*
b.) 10.0 cm from the mirror. *10.0 cm*
c.) 7.5 cm from the mirror. *15.0 cm*
d.) 5.0 cm from the mirror. *No Image*
e.) 3.0 cm from the mirror. *-7.5 cm*
f.) 1.5 cm from the mirror. *-2.1 cm*

15.) What is the radius of a concave reflecting surface that brings parallel light rays to a focus 13.7 cm in front of it? *27.4 cm*

16.) How far from a concave mirror (radius of curvature = 40.0 cm) must an object be placed if its image is to be at infinity? *20.0 cm*

Convex Mirrors:

17.) Draw a ray diagram to locate the image of an object placed in front of a convex mirror with a radius of curvature of -10.0 cm. The object is placed:
a.) 12.5 cm from the mirror. *-3.57 cm*
b.) 10.0 cm from the mirror. *-3.33 cm*
c.) 7.5 cm from the mirror. *-3.0 cm*
d.) 5.0 cm from the mirror. *-2.5 cm*
e.) 2.5 cm from the mirror. *-1.66 cm*

18.) A mirror used to watch for shoplifters in a department store has a focal length of -40.0 cm. A person stands in an aisle 6.0 m from the mirror. Locate the person's image. *37.5 cm behind the mirror*

19.) What is the focal length of a 30.0 cm diameter crystal ball whose surface reflects light? *-7.5 cm*

Solve the following using the mirror equation: $1/f = 1/d_o + 1/d_i$ Magnification (m) = $h_i/h_o = -d_i/d_o$

20.) An object 2.0 cm high is placed 25 cm from a concave mirror with a focal length of 10.0 cm. Where is the image located? How high is it? *16.7 cm* *1.33 cm*

21.) An object 1.6 cm high is 24 cm from a concave mirror whose radius of curvature is 16 cm. Locate the image. Is it real or virtual? What is its size? *12 cm* *0.80 cm*

22.) A fortune teller uses a polished sphere of 12.5 cm radius. If her eye is 20.0 cm from the sphere, where is the image of her eye? *-4.76 cm*

23.) A magnifying mirror produces an upright virtual image 2.5 times as high as an object 24 cm from it. Find the radius of curvature of the mirror. *80.0 cm*

24.) An object is placed 90.0 cm from a convex mirror with a focal length of 60.0 cm magnitude. Find the image distance and the ratio of the height of the image to the height of the object. *-36.0 cm* *2:5*

25.) An object 3.0 cm high is 30.0 cm from a concave mirror of 20.0 cm focal length. Find the image distance and image height. If the object is moved 5.0 cm closer to the mirror, how far does the image move?
d_i = 60 cm *h_i = 6 cm* *Image moves 40 cm*

26.) Where must an illuminated object be placed with reference to a concave mirror with a radius of curvature of 2.0 cm in order to have its image focused on a screen 6.0 meters from the mirror?

27.) An object 1.6 cm high is located 24 cm in front of a convex mirror with a radius of curvature of 16 cm. Locate the image. Is it real or virtual? Is it upright or inverted? What is its size? *-6.0 cm* *0.4 cm*

28.) A plane mirror lies face up, making an angle of 15° with the horizontal. A ray of light shines down vertically on the mirror. What is the angle of incidence? What will be the angle between the reflected ray and the horizontal? *15°* *60°*

AP Physics-B **Geometric Optics**

Refraction:

When light is incident on a transparent substance, part of the light is reflected from the surface and part is transmitted through the medium. If the angle of incidence is greater than zero, the ray changes direction at the boundary between the two media as it enters the transparent substance. This bending of the ray of light is called refraction.

Light travels at different speeds in different media. Optical density is a property of a medium that determines the speed of light in that medium. A more optically dense medium slows light more than a medium which is less optically dense.

The index of refraction (n) is the ratio of the speed of light in a vacuum to the speed of light in a transparent substance. The index of refraction for a substance can be considered a measure of the medium's optical density – the greater the optical density of the medium, the larger the index of refraction. When light travels from a medium of less optical density (small index of refraction) to a medium of greater optical density (large index of refraction), the ray is bent toward the normal. When light travels from a medium of greater optical density to a medium of less optical density, the ray is bent away from the normal.

The angle the incident ray makes with the normal at the point of incidence is called the angle of incidence. Likewise, the angle that the refracted ray makes with the normal is called the angle of refraction. These angles are not equal unless the angle of incidence is zero.

In 1621, a Dutch scientist (Willebrord Snell) discovered the relationship between the angle of incidence and the angle of refraction. We now call the law of refraction "Snell's Law" in his honor. Snell's Law can be written in equation form: $n_i \sin \Theta_i = n_r \sin \Theta_r$, where Θ_i is the angle of incidence and Θ_r is the angle of refraction, n_i in the index of refraction of the incident medium and n_r is the index of refraction in the refractive medium.

Listed below are some common indices of refraction. More extensive tables can be found in your textbook.

Indices of Refraction for Common Substances

Medium	**Index**	**Medium**	**Index**	**Medium**	**Index**
Vacuum	1.00000	Crown Glass	1.517	Polyethylene	1.520
Air	1.00029	Glycerol	1.475	Quartz	1.458
Alcohol	1.360	Diamond	2.420	Water	1.333
Calcite	1.486	Flint Glass	1.627	Water Vapor	1.00025

Performance Objectives: Upon completion of the readings and activities in this unit and when asked to respond either orally or on a written test, you will be able to:

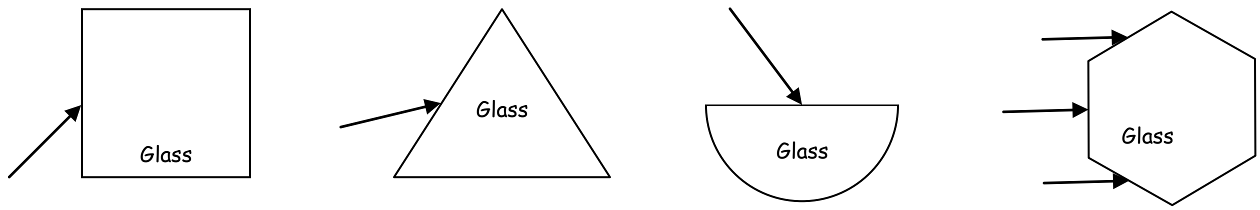
- ✓ Define Refraction. Use the index of refraction to determine optical density and predict the path of light through the medium.
- ✓ Relate the index of refraction to the speed of light. Solve problems using this information.
- ✓ State Snell's Law of refraction. Use Snell's Law to solve refraction problems.
- ✓ Describe examples of refraction occurring naturally in the environment.
- ✓ Describe and explain the phenomenon of total internal reflection and associated effects.
- ✓ Define the critical angle. Determine the critical angle of a substance from Snell's Law. Use the critical angle to predict the path of light through optical fibers.
- ✓ Explain the dispersion of light by a prism.
- ✓ Use ray diagrams to locate images formed by converging and diverging thin lenses.
- ✓ Use the lens equation to solve thin lens problems.
- ✓ State and use the lens maker equation to solve lens problems.
- ✓ Use ray diagrams to determine the location of an image formed by multiple lens-mirror arrangements in such optical instruments as the telescope and the microscope.

Textbook Reference: Hecht: Chapter 24

Exercises and Problems:

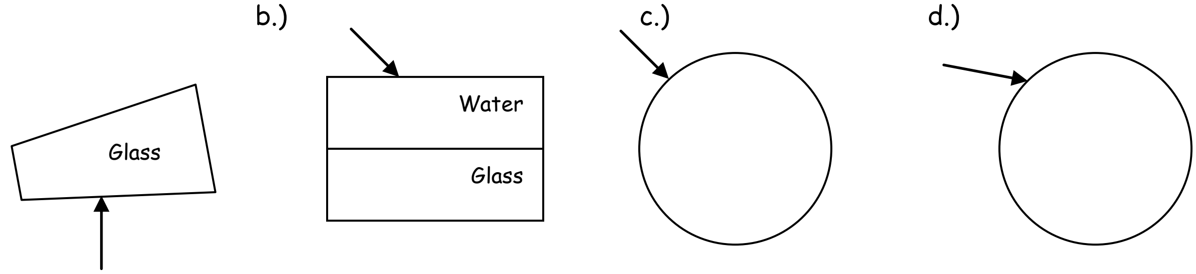
1.) Find the path of the incident light ray through and beyond the glass blocks in each case. The surrounding medium is air.

a,) b.) c.) d.)



2.) …more of the same! The surrounding medium is still air!

a.) b.) c.) d.)



3.) Light initially in air is incident upon a piece of crown glass at an angle of 45°. What is the angle of refraction to the nearest degree? *28°*

4.) A ray of light traveling through air is incident upon a sheet of flint glass at an angle of 30°. What is the angle of refraction? *17.9°*

5.) A ray of light traveling through air is incident upon a diamond at 45°. a.) What is the angle of refraction? b.) Compare your answer to that for problem 3…does glass or diamond bend light more? *17°*

6.) A ray of light passes from water into air at an angle of 22°. Find the angle of refraction to the nearest degree. *30°*

7.) A ray o light travels from air into a liquid. The ray is incident upon the liquid at an angle of 30°. The angle of refraction is 19.8°. a.) What is the index of refraction for the liquid? b.) What might the liquid be? *1.476*

8.) Light travels from crown glass into air. The angle of refraction in air is 60°. What is the angle of incidence in glass? *34.8°*

9.) Light travels from crown glass into water. The angle of incidence in crown glass is 40°. What is the angle of refraction in water? *47°*

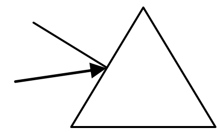
10.) A ray of light is incident at an angle of 45° on one surface of a 10.0 cm crown glass cube. At what angle with the normal does the ray emerge from the other side of the cube? *45°*

11.) By what perpendicular distance is the emergent ray of problem 10 shifted from its original path? *3.3 cm*

12.) A diver shines a flashlight upward from beneath the water at a 30° angle to the vertical. At what angle does the light leave the water? *42°*

13.) An aquarium filled with water has flat glass sides whose index of refraction is 1.50. A beam of light from outside the aquarium strikes the glass at a 37° angle to the normal. What is the angle of the light ray when it enters the glass and then the water? What would it be if the ray entered the water directly? *24° 27° 27°*

14.) Light is incident on an equilateral crown glass prism at an angle of 45° to one face. Calculate the angle at which light emerges from the opposite face. *55°*



Total Internal Reflection and the Critical Angle:

When light travels from a more optically dense medium to a less optically dense medium, it bends away from the normal. As the angle of incidence increases, the angle of refraction also increases, eventually reaching a maximum of 90°. Beyond this point, refraction ceases and all of the incident light is reflected internally. This phenomenon is called total internal reflection.

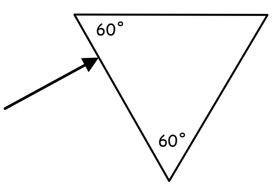
When the angle of refraction is 90°, the incident ray forms an angle of incidence that has a unique value for each medium to medium interface. This unique angle of incidence is called the "critical angle of incidence," or simply the critical angle. Substituting 90° for the angle of refraction in Snell's Law and solving for the sine of the angle of incidence we get: $\sin \Theta_c = n_r/n_i$ (where Θ_c is the critical angle).

15.) What is the critical angle in flint glass when light passes from flint glass into air? *38.4°*

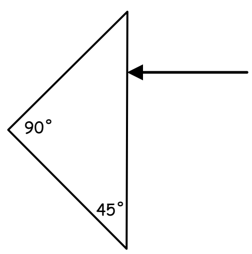
16.) What is the critical angle for light passing from crown glass into air? *42°*

17.) In each of the diagrams below, a ray of light is incident upon the surface of a crown glass prism. Extend each ray to show how it travels through the prism and beyond. The surrounding medium is air. Don't forget critical angle possibilities…

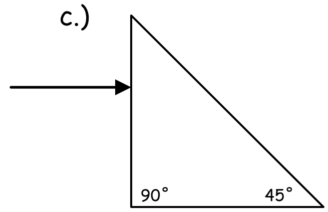
a.)



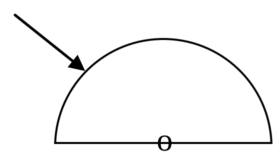
b.)



c.)



d.)



18.) What is the critical angle in water when light passes from water into air? *48.6°*

19.) When light passes from a medium to air, the critical angle is 40.5°. What is the index of refraction of the medium? *1.54*

20.) Find the critical angle for a carbon disulfide (n = 1.643) to water surface. Which direction must the light be going to have total internal reflection? *54°*

21.) Light strikes one side of an equilateral glass prism at an angle of incidence of 25°. The prism is made of flint glass. Find the angle that the light makes with the normal to the prism as it again emerges into the air. *25°*

Lens-Maker Equation: $1/f = (n_r - n_i)(1/R_1 - 1/R_2)$

The focal length of a lens depends on the index of refraction of the lens or refractive material, the index of refraction of the surrounding or incident material, and the radius of curvature of each side. The equation for calculating the focal length of the lens is written as shown. Choose a direction for light to travel through the lens. R_1 is the radius of curvature of the first side of the lens that the light encounters as it travels through the lens. R_2 is the radius of curvature of the second side. If the surface comes before the center of curvature, R is a positive number. If the center comes before the surface, R is negative.

22.) A double convex glass thin lens ($n = 1.52$) has both radii of curvature of magnitude 20.0 cm. Find the focal length of the lens. *19.2 cm*

23.) The following thin lenses are made of glass with an index of refraction of 1.5. Given the magnitudes of the radii of curvature, find the focal length in air for each:
a.) Double Convex: $R_1 = 10.0$ cm & $R_2 = 20.0$ cm. *13.3 cm*
b.) Plano-Convex: $R_1 \rightarrow \infty$ & $R_2 = 10.0$ cm. *20.0 cm*
c.) Double-Concave: $R_1 = 10.0$ cm & $R_2 = 20.0$ cm. *-10.0 cm*
d.) Plano-Concave: $R_1 \rightarrow \infty$ & $R_2 = 20.0$ cm. *-40.0 cm*

24.) Glass with an index of refraction of 1.6 is used to make a thin lens which has radii of equal magnitude. Find the radii of curvature if the focal length in air is to be a.) 5.0 cm b.) -5.0 cm. *6cm*

25.) The following thin lenses are made of glass of index of refraction 1.5. Find the focal length in air for each:
a.) $R_1 = 20.0$ cm & $R_2 = 10.0$ cm. b.) $R_1 = -10.0$ cm & $R_2 = 20.0$ cm. c.) $R_1 = -10.0$ cm & $R_2 = -20.0$ cm.
d.) $R_1 = 10.0$ cm & $R_2 = -20.0$ cm. *-40.0 cm* *-13.3 cm* *-40.0 cm* *13.3 cm*

Converging Lenses:
26.) Draw a ray diagram to locate the image of an object placed in front of a convex lens with a focal length of 5.0 cm. The object is placed: a.) 15.0 cm from the lens. b.) 10.0 cm from the lens. c.) 7.5 cm from the lens.
d.) 5.0 cm from the lens. e.) 2.5 cm from the lens. *7.5 cm* *10.0 cm* *15.0 cm* *No Image* *-5.0 cm*

27.) An object 1.5 cm high is 12 cm from a convex lens of 6.0 cm focal length. Find the position and height of the image. 12.0 cm *-1.5 cm*

28.) The focal length of a convex lens is 20.0 cm. A newspaper is 6.0 cm from the lens. Find the image distance.
-8.6 cm

Diverging Lenses:
29.) Draw a ray diagram to locate the image of an object placed in front of a concave lens with a focal length of -5.0 cm. The object is placed: a.) 10.0 cm from the lens. b.) 5.0 cm from the lens. c.) 2.5 cm from the lens.
-3.3 cm *-2.5 cm* *-1.6 cm*

Solve the following using either the lens equation or ray diagrams: $1/f = 1/d_i + 1/d_o$ $m = h_i/h_o = -d_i/d_o$
30.) An object 6.0 cm high is 24.0 cm to the left of a converging lens of focal length 8.0 cm. Where is the image? Is it real or virtual? Upright or Inverted? How large is it? *12 cm to the right* *3.0 cm*

31.) How far from a converging lens of focal length 30.0 cm must an object be placed if the image is to be real and three times larger than the object? *40.0 cm*

32.) Repeat problem 31 for the same converging lens – this time though, have the image be virtual and three times larger than the object. *20.0 cm*

33.) A positive lens of focal length 20.0 cm forms a real image 5 times as large as the object. How far apart are the object and the image? *144 cm*

34.) An object is placed 18.0 cm from the center of a converging lens of focal length 6.0 cm. a.) Draw a ray diagram to locate the image. b.) Is the image real or virtual? Explain your answer! c.) Using the lens equation, compute the distance of the image from the lens. d.) A second converging lens – also of focal length 6.0 cm – is placed 6.0 cm to the right of the original lens. Draw a ray diagram to locate the final image formed by this two-lens system.