Physics 30 Lesson 8 Refraction of Light

Refer to Pearson pages 666 to 674.

# Reflection and refraction of light

At any interface between two different mediums, some light will be reflected and some will be refracted, except in certain cases which we will soon discover. When problem solving for refraction, we usually ignore the reflected ray.

Glass prism

# Index of refraction

The fastest that light can travel is in a vacuum (c = 3.00 x 108 m/s). In other substances, the speed of light is always slower. The *index of refraction* is a ratio of the speed of light in vacuum with the speed of light in the medium:



Some common indices of refraction are:

Substance Index of refraction (n)

Notice that the index of refraction (n) is always greater than or equal to 1 and that it has no units.

vacuum 1.0000

air 1.0003

water 1.33

ethyl alcohol 1.36

quartz (fused) 1.46

glycerine 1.47

Lucite or Plexiglas 1.51

glass (crown) 1.52

sodium chloride 1.53

glass (crystal) 1.54

ruby 1.54

glass (flint) 1.65

zircon 1.92

diamond 2.42

The index of refraction for crown glass was measured to be 1.52. What is the speed of light in crown glass?



# Law of Refraction (Snell's Law)

*Refraction* is the change in *speed*, *wavelength* and *direction* of light caused by a change in medium. For example, when light passes from air into water, the speed decreases, the wavelength decreases, and the light ray bends in toward the normal.

normal

1 - angle of incidence

n1 , v1 , 1

Incident ray

i

2 - angle of refraction

n2 , v2 , 2

Refracted ray

r

In 1621, Willebrord Snell, a Dutch mathematician, determined the relationship between the angles, wavelengths and speeds of refracted waves. These relationships are referred to as **Snell’s law** or the **Law of Refraction**. We will now derive Snell’s law. The diagram represents a wave travelling from a fast medium into a slow medium.

90o angle

From the incident triangle we get 

1

1

1

1

1, v1, f

common hypotenuse

2

2

2, v2, f

From the refraction triangle we get 

2

2

90o angle

Dividing the equations we get 

We have 

Using the universal wave equation  we can derive another relationship:



For light we also have another relationship that we can include. Since 

 and  then 

Snell’s Law (i.e. **The Law of Refraction**) is:



and we can use any pairing that we desire.

If light has an angle of incidence of 30o when travelling from air into water, what is the angle of refraction?



30o

air

water

If light has an angle of incidence of 30o when travelling from water into air, what is the angle of refraction?



30o

water

air

If light has an angle of incidence of 30o and an angle of refraction of 26o when travelling from water into substance X, what is the index of refraction for X?



30o

water

X

26o

If the speed of light in air is 3.00 x 108 m/s, what is the speed of light in glass



(nglass = 1.50)?



If light has a wavelength of 750 nm in air, what is the wavelength of light in diamond

(ndiamond = 2.42)?



# Special problems

emerging ray

air

air

70o

70o

38o

38o

plate glass window pane

original ray extended

A. Parallel sides

When light passes through a medium with parallel sides, the original angle of incidence always equals the final angle of refraction. The internal angles are also the same. Note that the original ray is parallel with the emerging ray.

B. Triangular prisms

A classic problem is when light refracts through a triangular prism. Since the sides are not parallel, the internal angles of refraction and incidence will not be the same.

If light enters an equilateral glass prism (n = 1.50) with an angle of incidence of 45o, what is the angle of refraction as the beam emerges from the prism?

Note that an equilateral triangle has three 60o angles.

sin 1 = 1.00 sin 45o 1 = 28.12o

1.50

1

4

2

3

5

2 = 90o - 1 = 90o - 28.12o = 61.88o

3 = 180o - (60o + 2 ) = 180o - 121.88o = 58.12o

4 = 90o - 3 = 90o - 58.12o = 31.88o

sin 5 = 1.50 sin 31.88o

1.00

5 **= 52.4o**

# Total internal reflection

Refer to Pearson pages 672 to 674.

Low n

High n

i

r

When a light ray passes from a more optically dense medium (high n, low v) to a less optically dense medium (low n, high v), the angle of refraction (r) is greater than the angle of incidence (i).

Low n

High n

i

r

As the angle of incidence is increased, the angle of refraction becomes larger until finally r approaches 90o.

Low n

High n

c

r = 90o

At the angle of incidence called the **critical angle** (c) the angle of refraction = 90o.

At angles beyond the critical angle, refraction can no longer occur – the result is **total internal reflection** which obeys the law of reflection. In other words, at angles beyond the critical angle the boundary between the media acts as a mirror surface.

Low n

(high speed)

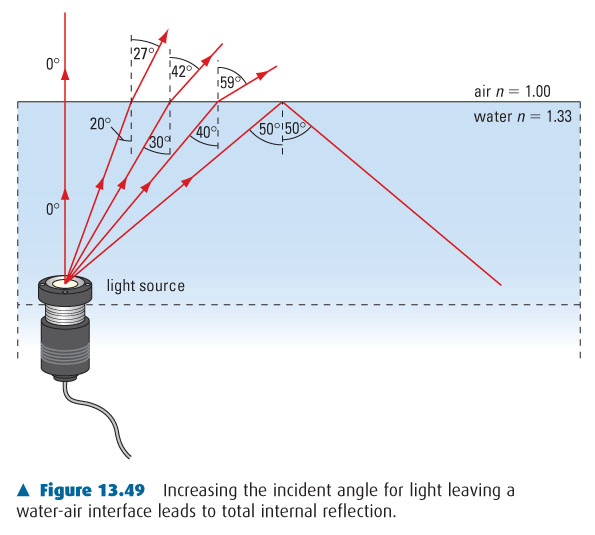
High n

(low speed)

Total internally reflected light ray

i

r = i



The properties of internal reflection are used in fibre optic technologies and in optical instruments like cameras, microscopes, binoculars, etc.

Note that **total internal reflection occurs only when light travels from low to high speed media**. It does not occur when light travels from high to low speed media.

What is the critical angle for a water and air interface?



For the critical angle 2 = 90o:



If light makes an angle of incidence of 60o when travelling from diamond into water, what is the angle of refraction produced?

Note that this error result does not indicate that you have made a mistake in calculation. The result means that no refraction is possible resulting in **total internal reflection**.



# Practice problems

1. A ray of light has an angle of incidence of 24o from air into water. What is the angle of refraction? (Refer to the table of refractive indices at the beginning of this lesson.) (17.8o)

2. A light ray is travelling from crown glass into air. The angle of incidence is 20o. What is the angle of refraction? (31.3o)

3. The angle of refraction in air is 60o . Find the angle of refraction in the water.

(nplastic= 1.52) (40.6o)

air

plastic

water

4. For the following prism (n = 1.50) find the indicated angle if the angle of incidence is 40o. (38.7o)

?

50o

5. To successfully spear a fish, you must aim below the apparent position of the fish. Explain.

6. What is the critical angle when light emerges from glass (n = 1.50) into air? (41.8o)

7. The critical angle between glass and water is 56.2o. What is the index of refraction for the glass? (1.60)

8. The angle of refraction in water is 60o . If nplastic= 1.62 trace the ray path through the system below.

water

plastic

air

# Hand-in assignment

1. The speed of light in a certain plastic is 2.0 x 108 m/s. What is the refractive index of the plastic? (1.5)

2. The index of refraction of crown glass for violet light is 1.53. and for red light 1.52. Assuming that the velocity of light in a vacuum is 3.00 x 108 m/s, what are the speeds of violet light and red light in crown glass? (1.96 x 108 m/s, 1.97 x 108 m/s)

3. A beam of light strikes the surface of water with an incident angle of 60o. Some of the light reflects off the water and some refracts into the water. If water has an index of refraction of 1.33, determine the angles of reflection and refraction. (60o, 41o)

4. A wave travelling from air to glass n = 1.52) has an angle of incidence of 30o. What is the angle of refraction? (19o)

5. If the angle of incidence is 20o and the angle of refraction is 10o, what is the index of refraction of the material if the wave started in air? (1.97)

6. What is the wavelength of light in water if the wavelength in air is 570 nm? (429 nm)

7. A ray of light enters from air to water and then into glass as shown in the diagram. Find the angle of refraction in glass. (nwater= 1.33, nglass= 1.50) (33o)

35o air

water

glass

8. Light strikes the 70o glass prism (n = 1.51) with an angle of incidence of 50.0o. Calculate the angle that the light leaves the prism. (73.9o)

70o

?

9. Light is incident on an equilateral Lucite prism (n = 1.5) at an angle of 35o. Calculate the angle that the light leaves the prism. (66o)

?

10. Freddie the fish shines his flashlight upward from under water.

A. If Freddie shines his flashlight at an incident angle of 20o, at what angle does the light leave the water? (27o)

B. Beyond what critical angle will the light no longer be able to leave the water? (48.8o)

30o

water

n = 1.33

air

n = 1.00

glass

n = 1.50

11. From inside an aquarium a ray of light is directed at the glass so the angle of incidence, in water, is 30o. (a) Determine the angle of refraction when the ray emerges from the glass into the air. (b) If the angle of incidence in the water is 52o at what angle will the rays emerge from the glass? (42o, no ray emerges)

12. An underwater swimmer looks up toward the surface of the water on a line of sight that makes an angle of 25o with a normal to the surface of the water. What is the angle of incidence in air for the light rays that enter the swimmer's eyes? (34o)

13. You tape a penny to the inside bottom of a cup and move your eye away from the cup to just that point where you can no longer see the penny over the rim of the cup. If someone slowly adds water to the cup, the penny comes into view. Using diagrams and a word description, explain why. (Pennies and styrofoam cups are available. Seeing is believing! Try it!)

14. Hot air rises over a heated stove element. Explain why the wall behind the stove appears to shimmer.

15. The critical angle from rock salt into air is 40.5o. What is the index of refraction for rock salt. (1.54)

16. The critical angle for a certain liquid-air surface is 61o. What is the liquid's index of refraction? (1.14)

17. The refractive indices of diamond and crown glass are 5/2 and 3/2 respectively. What is the critical angle between diamond and glass? (37o)

18. A ray of light enters AC along the normal. Trace the subsequent ray path. (n = 1.50)

A

45o

C

B

19. A bright point source of light is placed at the bottom of a 20 cm deep pool of water, n = 1.33. What is the area of the circle of light which is seen at the surface of the water? What happened to the other light rays? (1634 cm2)

20. A student performs an experiment where she measures the angles of incidence and refraction for a particular type of glass. She obtains the following results:

|  |  |
| --- | --- |
| angle of incidence | angle of refraction |
| 0o  10o  20o  30o  40o  50o  60o | 0o  6o  12o  18o  23o  28o  32o |

Using an appropriate graphing technique, calculate the index of refraction for the glass.

**Activity 1 – Index of Refraction**

Procedure:

1. Working with one partner, place a piece of paper on the table and place the rectangular prism as shown in the diagram below. With a pencil, trace around the rectangular prism. Then draw a line that meets the rectangular prism at an angle of incidence of 50o.

Rectangular prism

8 x 11 paper

Top View

line

2. Place the laser pointer so that the light runs down the pencil line. Look for the emergent ray as it leaves the prism and draw a pencil line for the emergent ray.

3. Draw in the ray path through the prism.

4. At the point where light enters the prism draw in a normal to the prism surface. Using a protractor measure the angle of incidence and the angle of refraction at the interface.

5. Calculate the index of refraction for the rectangular prism.

**Activity 2 – Equilateral Triangle Prism**

Procedure:

1. Working with one partner, place a piece of paper on the table and arrange an equilateral triangle prism as shown in the diagram below. With a pencil, trace around the prism and draw a line as shown.

Equilateral prism

8 x 11 paper

Top View

line

2. Place the laser pointer so that the light runs down the pencil line. Look for the emergent ray as it leaves the prism and draw a pencil line for the emergent ray.

3. Draw all of the resulting ray paths including the rays through the prism and those reflected from and within the prism.

4. For each ray, explain how and why the ray is emerging where it is.

**Activity 3 – Equilateral Triangle Prism (Total Internal Reflection)**

Procedure:

1. Working with one partner, place a piece of paper on the table and arrange a equilateral triangle prism as shown in the diagram below. With a pencil, trace around the prism. Use a protractor to draw a line at 90o to the prism face. (Note: Make sure that you do not draw the line from the centre of the face of the triangular prism. The line should be offset from centre.)

Equilateral prism

8 x 11 paper

Top View

2. Point the laser pointer directly down the line. Draw a pencil line in for the emergent ray.

3. Draw in the ray path through the prism. Explain the resulting ray path.

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