Refraction

Unit: Light & Optics

MA Curriculum Frameworks (2016): N/A

AP® Physics 2 Learning Objectives: 6.E.1.1, 6.E.2.1, 6.E.3.1, 6.E.3.2, 6.E.3.3

Mastery Objective(s): (Students will be able to…)

- Explain how and why refraction happens.
- Solve problems using Snell's Law.

Success Criteria:

- Explanation accounts for the size, location and orientation of the image.
- Calculations are correct with correct algebra and trigonometry.

Language Objectives:

- Explain why we see the image of an object through a magnifying glass but not the object in its actual location.

Tier 2 Vocabulary: light, reflection, virtual image, real image, lens, focus

Labs, Activities & Demonstrations:

- laser through clear plastic
- laser through bent plastic (total internal reflection)
- laser through falling stream of water (with 1 drop milk)
- Pyrex stirring rod in vegetable oil (same index of refraction)
- penny in cup of water

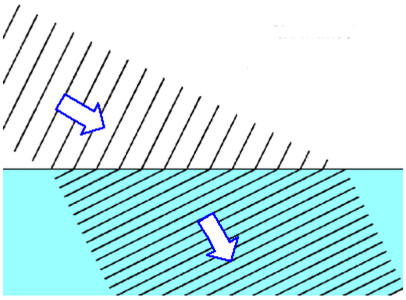
Notes:

refraction: a change in the velocity and direction of a wave as it passes from one medium to another. The change in direction occurs because the wave travels at different velocities in the different media.

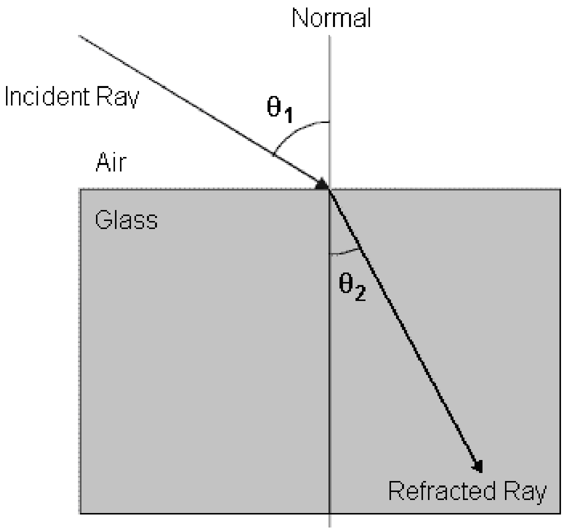
index of refraction: a number that relates the velocity of light in a medium to the velocity of light in a vacuum.

Use this space for summary and/or additional notes:

When light crosses from one medium to another, the difference in velocity of the waves causes the wave to bend. For example, in the picture below, the waves are moving faster in the upper medium. As they enter the lower medium, they slow down. Because the part of the wave that enters the medium soonest slows down first, the angle of the wave changes as it crosses the boundary.



When the waves slow down, they are bent toward the normal (perpendicular), as in the following diagram:



Use this space for summary and/or additional notes:

The index of refraction of a medium is the velocity of light in a vacuum divided by the velocity of light in the medium:

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

Thus the larger the index of refraction, the more the medium slows down light as it passes through.

The index of refraction for some substances is given below.

Substance	Index of Refraction	Substance	Index of Refraction
vacuum	1.00000	quartz	1.46
air (0°C and 1 atm)	1.00029	glass (typical)	1.52
water (20°C)	1.333	NaCl (salt) crystals	1.54
acetone	1.357	polystyrene (#6 plastic)	1.55
ethyl alcohol	1.362	diamond	2.42

These values are for yellow light with a wavelength of 589 nm.

For light traveling from one medium into another, the ratio of the speeds of light is related inversely to the ratio of the indices of refraction, as described by Snell's Law (named for the Dutch astronomer Willebrord Snellius):

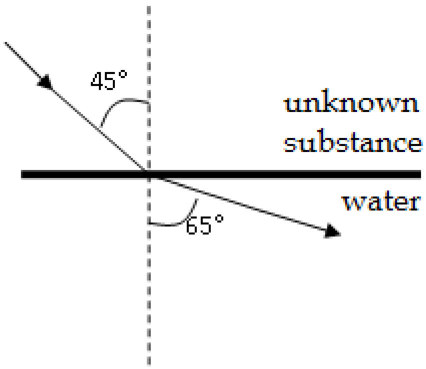
$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

The more familiar presentation of Snell's Law is:

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

Sample Problem:

Q: Incident light coming from an unknown substance strikes water at an angle of 45°. The light refracted by the water at an angle of 65°, as shown in the diagram at the right. What is the index of refraction of the unknown substance?



A: Applying Snell's Law:

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

$$n_1 \sin(45°) = (1.33)\sin(65°)$$

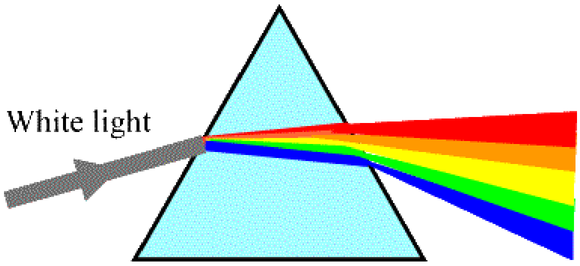
$$n_1 = \frac{(1.33)\sin 65°}{\sin 45°} = \frac{(1.33)(0.906)}{0.707} = 1.70$$

Use this space for summary and/or additional notes:

Prisms

The index of refraction of a medium varies with the wavelength of light passing through it. The index of refraction is greater for shorter wavelengths (toward the violet end of the spectrum) and less (closer to 1) for longer wavelengths (toward the red end of the spectrum.

prism: an object that refracts light



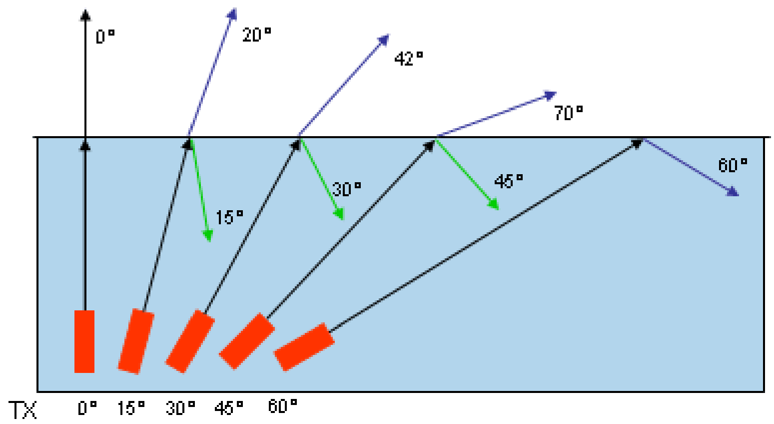
If light passes through a prism (from air into the prism and back out) and the two interfaces are not parallel, the different indices of refraction for the different wavelengths will cause the light to spread out.

When light is bent by a prism, the ratio of indices of refraction is the inverse of the ratio of wavelengths. Thus we can expand Snell's Law as follows:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$

Total Internal Reflection

If a light wave is traveling from a slower medium to a faster one and the angle is so steep that the refracted angle would be 90° or greater, the boundary acts as a mirror and the light ray reflects off of it. This phenomenon is called *total internal reflection*:

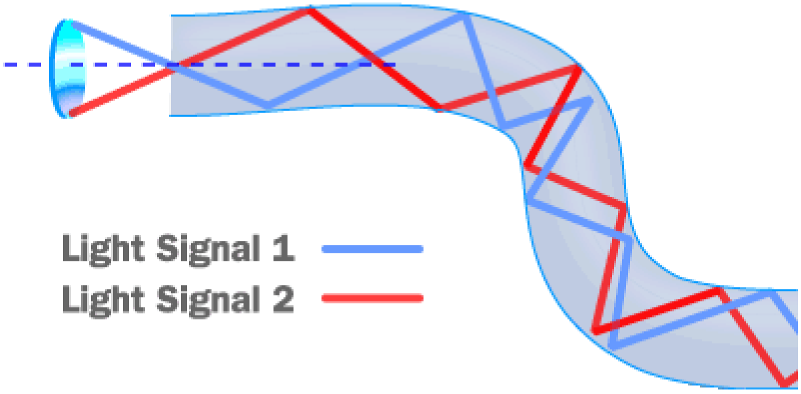


critical angle (θ_c): the angle beyond which total internal reflection occurs.

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Use this space for summary and/or additional notes:

Total internal reflection is how optical fibers (long strands of optically pure glass with a high index of refraction) are used to transmit information over long distances, using pulses of light.



Total internal reflection is also the principle behind speech teleprompters:

The speaker stands behind a clear piece of glass. The image of the speech is projected onto the glass. The text is visible to the speaker, but not to the audience.

Use this space for summary and/or additional notes:

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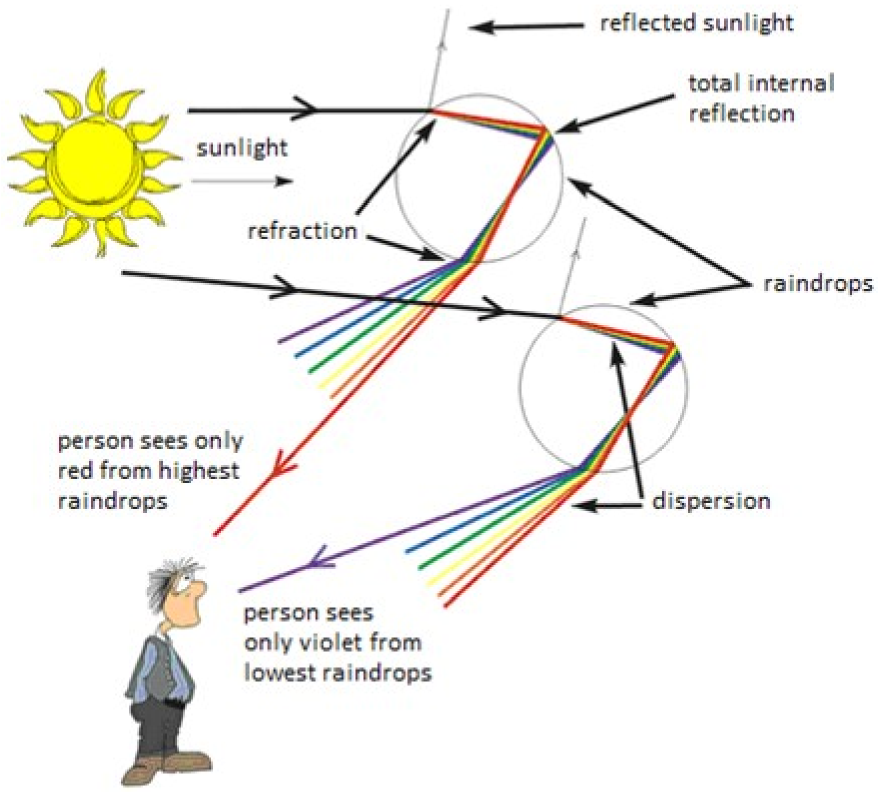
Rainbows

A rainbow occurs from a combination of refraction, total internal reflection, and a second refraction, with raindrops acting as the prisms.

When this process occurs, different wavelengths of are refracted at different angles. Because colors near the red end of the spectrum have a lower index of refraction, the critical angle is shallower for these wavelengths, and they are reflected at a shallower angle than colors closer to the violet end of the spectrum.

The overall change in the direction of the light after this combination of refraction–reflection–refraction (including both refractions as well as the reflection) ranges from approximately 40° for violet light to approximately 42° for red light. This difference is what produces the spread of colors in a rainbow, and is why red is always on the outside of the rainbow and violet is always on the inside.



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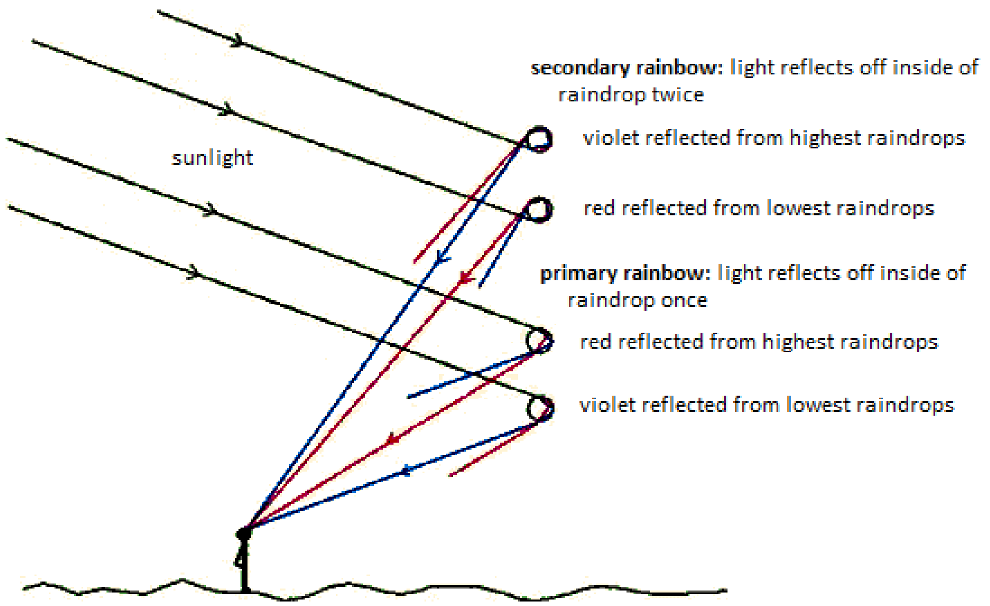
When internal reflection occurs twice on the inside of a raindrop, the result is a second rainbow.



The second rainbow appears above the first because the angle of light exiting the raindrop is greater—varying from 50° for red light to 52.5° for violet light. The second internal reflection reverses the colors, which is why violet is on the outside and red is on the inside in the second rainbow.

Use this space for summary and/or additional notes:

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This is a picture of a double rainbow in Lynn, Massachusetts. Note that the order of the colors in the second rainbow is reversed.

Note also that the sky is brighter inside the primary rainbow. There are two reasons for this. First, it's not actually true that each band is only one color of light. Because red light reflects at *all* angles greater than or equal to 40°, red light is therefore a component of all of the colors inside the red band of the rainbow. The same is true for each of the other colors; inside of the violet band, all wavelengths of visible light are present, and the result is white light. Outside of the red band, no visible light is refracted, which causes the sky outside the rainbow to appear darker.

Second, raindrops scatter light at all wavelengths, and light scattering is also a significant contributing factor to the brightness inside. (See the *Scattering* topic starting on page 528 for more information.)

You may also notice that because the second rainbow is reversed, the sky is slightly brighter outside of the second rainbow.

Use this space for summary and/or additional notes:

Homework Problems

You will need to look up indices of refraction in Table Q on page 587 of your Physics Reference Tables in order to answer these questions.

1. **(M)** A ray of light traveling from air into borosilicate glass strikes the surface at an angle of 30°. What will be the angle of refraction?

   Answer: 19.8°

2. **(S)** Light traveling through air encounters a second medium which slows the light to $2.7\times10^{8}\,\frac{\text{m}}{\text{s}}$. What is the index of refraction of the second medium?

   Answer: 1.11

3. **(M)** What is the velocity of light as it passes through a diamond?

   Answer: $1.24\times10^{8}\,\frac{\text{m}}{\text{s}}$

Use this space for summary and/or additional notes:

4. **(M)** A diver in a freshwater lake shines a flashlight toward the surface of the water. What is the minimum angle (from the vertical) that will cause beam of light to be reflected back into the water (total internal reflection)?

   Answer: 48.6°

5. **(S)** A graduated cylinder contains a layer of silicone oil floating on water. A laser beam is shone into the silicone oil from above (in air) at an angle of 25° from the vertical. What is the angle of the beam in the water?

   Answer: 18.5°

6. **(S)** A second graduated cylinder contains only a layer of water. The same laser beam is shone into the water from above (in air) at the same angle of 25° from the vertical. What is the angle of the beam in the water?

   Answer: 18.5°

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