Refraction

Unit: Light & Optics

NGSS Standards/MA Curriculum Frameworks (2016): N/A

AP® Physics 2 Learning Objectives/Essential Knowledge (2024): 13.3.A, 13.3.A.1, 13.3.A.2, 13.3.A.3, 13.3.A.4, 13.3.A.4.i, 13.3.A.4.ii, 13.3.A.4.iii, 13.3.A.5, 13.3.A.5.i, 13.3.A.5.ii, 13.3.A.5.iii, 14.9.A, 14.9.A.1, 14.9.A.2, 14.9.A.2.i, 14.9.A.2.ii, 14.9.A.3, 14.9.A.4, 14.9.A.4.i, 14.9.A.4.ii, 14.9.A.5, 14.9.A.5.i, 14.9.A.5.ii, 14.9.A.5.iii

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:

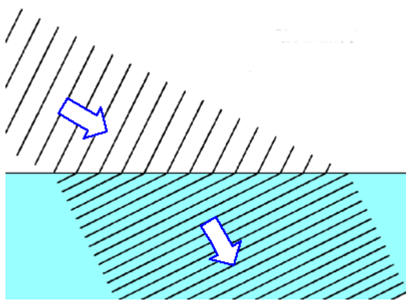
- laser through clear plastic
- laser through bent plastic (total internal reflection)
- laser through falling stream of water (with 1 drop milk)
- Pyrex stirring rod in vegetable oil (same index of refraction)
- penny in cup of water

Notes:

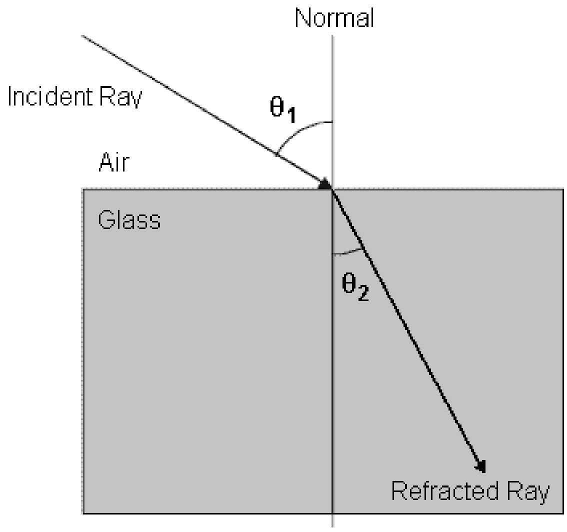
<u>refraction</u>: a change in the velocity and direction of a wave as it passes from one medium to another. The change in direction occurs because the wave travels at different velocities in the different media.

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

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:



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):

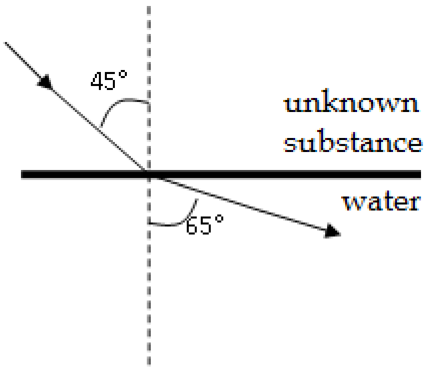
$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

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?



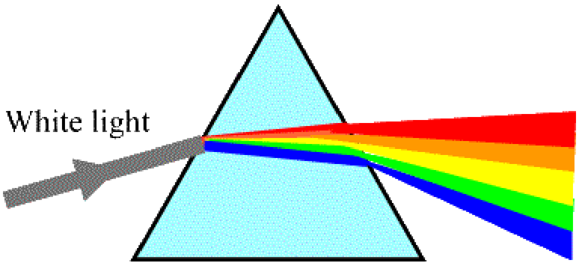
A: Applying Snell's Law:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$
$$n_1 \sin(45°) = (1.33)\sin(65°)$$
$$n_1 = \frac{(1.33)\sin 65°}{\sin 45°} = \frac{(1.33)(0.906)}{0.707} = 1.70$$

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:

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

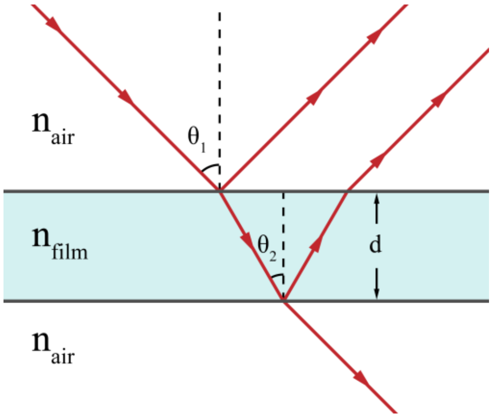
Thin-Film Interference

Thin-film interference occurs when light strikes a thin film of liquid. Some of the light is reflected off the film, and some is refracted through the film and reflected off the interface between the film and the surface on the other side of it.

You have likely seen thin-film interference, which you observe as the colors on the surface of a soap bubble or an oil slick.

Thin-film interference in a soap bubble.
Used with permission.

The following diagram shows what happens when light strikes the bubble:

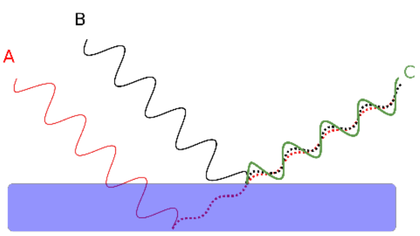


Light passing through the air strikes a soap bubble of thickness *d* at an incident angle of θ_1.

Some of the light is reflected at the same angle. The rest of the light is refracted through the bubble at angle θ_2 (as described by Snell's Law). Some of that refracted light is reflected off the interface between the soap bubble and the air inside it, also at angle θ_2.

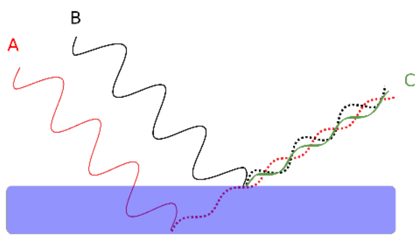
The light is then refracted back into the air outside the bubble, parallel to the original ray (angle θ_1).

Different wavelengths of light refracted through the bubble might interfere either constructively or destructively with the light reflected off the surface:



constructive interference

$$2n_{film}d\cos(\theta_2) = (m - \tfrac{1}{2})\lambda$$



destructive interference

$$2n_{film}d\cos(\theta_2) = m\lambda$$

where:

- $n_{film} =$ index of refraction of film
- $d =$ thickness of film
- $\theta_2 =$ angle of incidence of light ray at bottom of film interface
- $m =$ any integer
- $\lambda =$ wavelength of light

(You need only a qualitative understanding of thin-film interference for the AP® exam; you will not need to use these equations or perform calculations.)

Because those different wavelengths of light are different colors, that means some *colors* will interfere constructively, whereas other *colors* will interfere destructively, producing the patterns seen on the surface of the bubble.

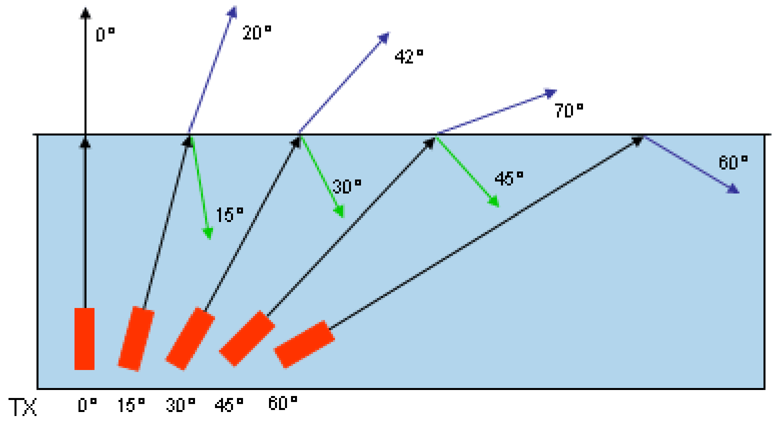
Because the index of refraction of the soap bubble is greater than the index of refraction of air that the light is coming from, the reflected light at the outside of the soap bubble is phase-shifted 180°. The index of refraction of the air inside the bubble is less than the index of refraction of the soap bubble that the light is coming from, so the light reflecting off the inside of the soap bubble is not phase-shifted. This is why $(m - \tfrac{1}{2})\lambda$ in the above equations results in *constructive* interference and $m\lambda$ results in *destructive* interference, instead of the other way around.

A practical use of thin-film interference is antireflective coatings on lenses (such as eyeglasses). There are two requirements for these coatings to work:

- The thickness of the coatings is ¼ of the wavelength of the middle of the visible light spectrum, to create maximum destructive interference.
- The index of refraction of the coating is greater than the index of refraction of air, but less than the index of refraction of the surface of the glass that the coating is applied to.

Total Internal Reflection

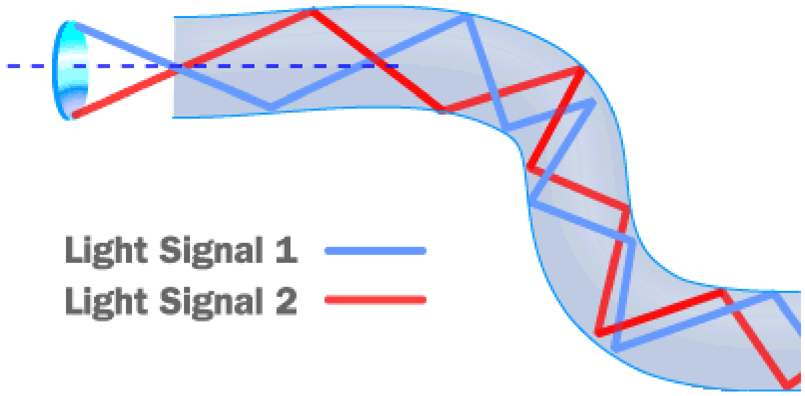
If a light wave is traveling from a slower medium to a faster one and the angle is so steep that the refracted angle would be 90° or greater, the boundary acts as a mirror and the light ray reflects off of it. This phenomenon is called *total internal reflection:*



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

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

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:

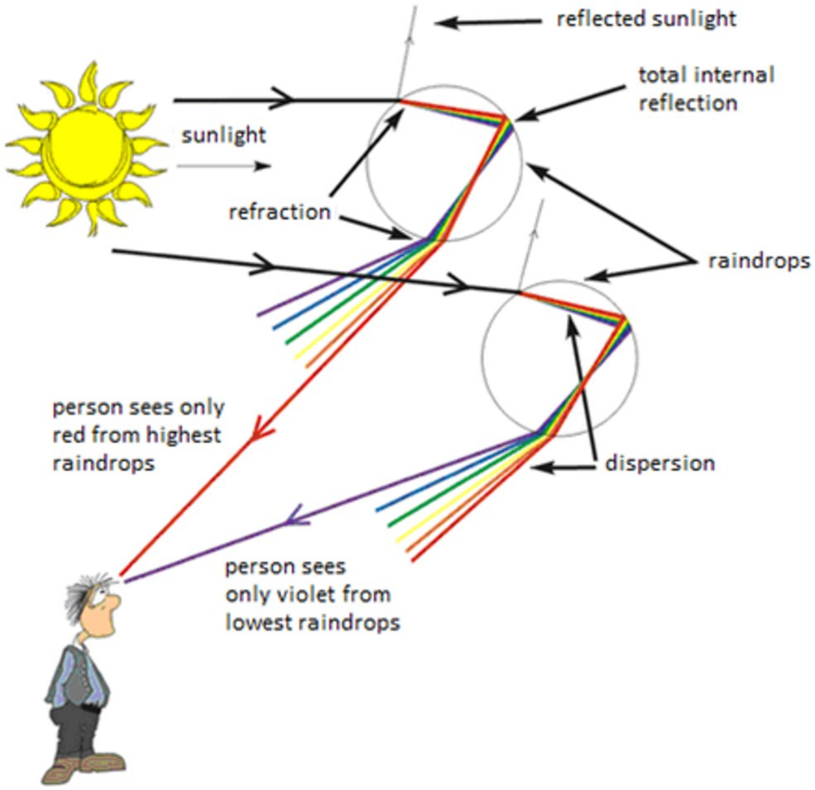
The speaker stands behind a clear piece of glass. The image of the speech is projected onto the glass. The text is visible to the speaker, but not to the audience.

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.



Because the light reflected and refracted through the raindrops must be viewed at angles of 40–42°, rainbows can be seen only when the sun is low in the sky (around sunrise or sunset). Otherwise, the rainbow would appear below the horizon.

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. Both internal reflections create a phase shift of 180°, reversing the colors (as with thin-film interference), which is why violet is on the outside of the second rainbow, and red is on the inside.

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.

The second reason is that 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 419 for more information.)

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

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

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°