



**Fluids, Thermodynamics, Waves, & Optics**  
**Optics**  
**Lab 7**  
**Refraction**

Lana Sheridan

De Anza College

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# Overview

- Purpose
- Part 3.1: Refraction
- Part 3.2: Total internal reflection
- Part 3.3: Refracting surfaces
- Part 4.4: Light as a wave and dispersion

## Purpose of the Lab

To explore basic ray optics including the refraction of beams of light.

You will use the Bending Light PhET simulation to explore the behavior of light as it moves from one medium to another. You will use simulated prisms to observe total internal reflection, refraction at a curved surface, and dispersion.

# Theory: Reflection

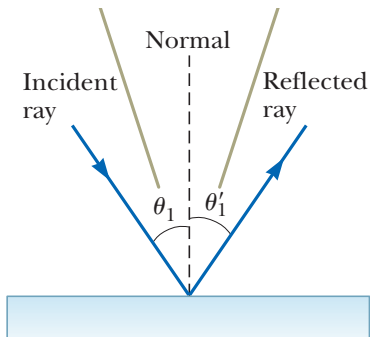
Specular (mirror-like) reflection:

Courtesy of Henry Leap and Jim Lehman



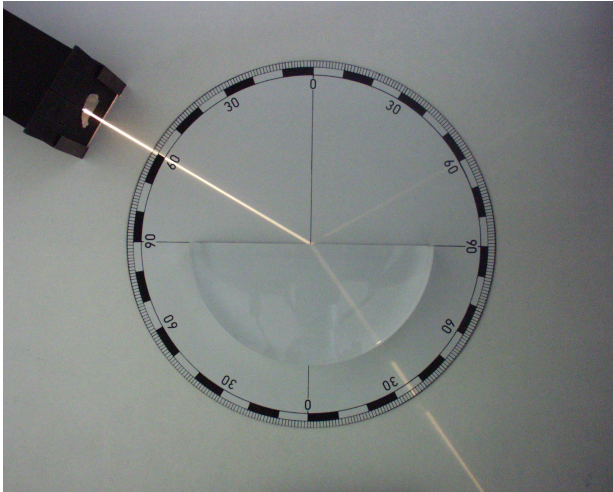
# Law of Reflection

$$\theta_i = \theta_{\text{refl}}$$



# Refraction

When light rays pass from one medium into another, they are often observed to bend.



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<sup>1</sup>Image from Wikipedia, by Zátanyi Sándor.

# Refraction

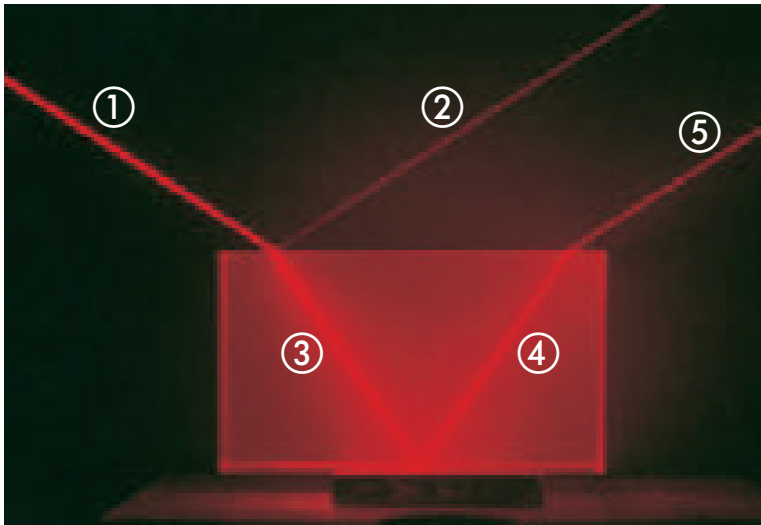
When light rays pass from one medium into another, they are often observed to bend.



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# Refraction

Courtesy of Henry Leap and Jim Lehman





# Refractive Index

Light *at a particular frequency* moves at different speeds in different media.

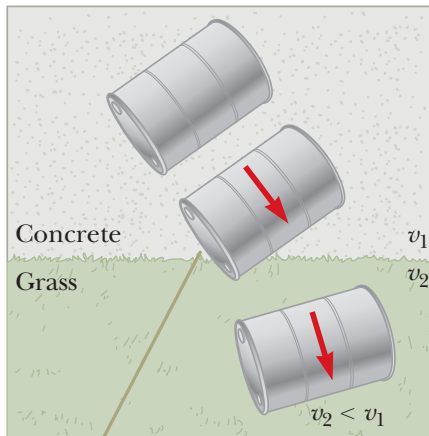
**Refractive index of a medium,  $n$**

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

where  $v = \frac{\omega}{k}$  is the phase velocity of light with angular frequency  $\omega$  in that medium.

The larger the refractive index,  $n$ , the slower the speed in that medium.

# Refraction

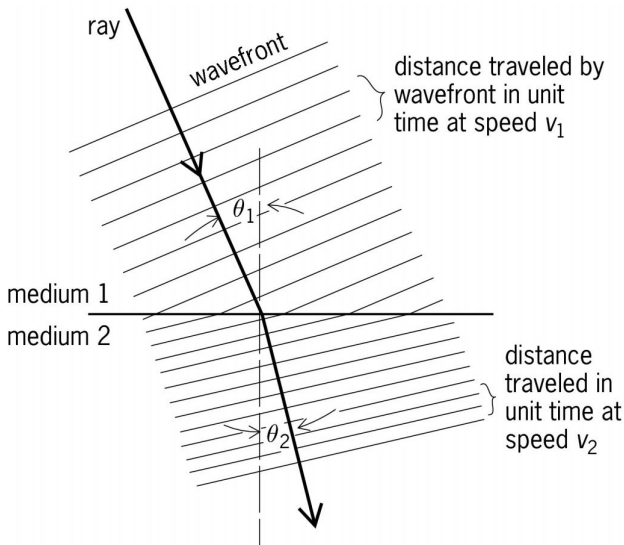


This end slows first; as a result, the barrel turns.

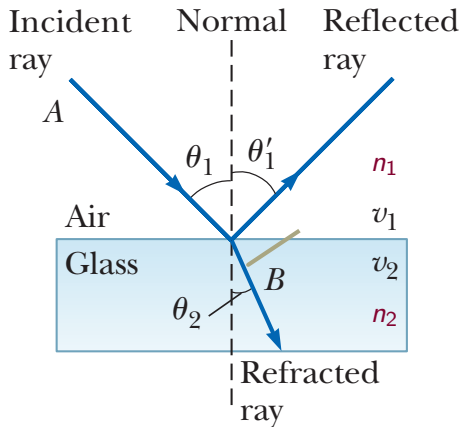
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<sup>1</sup>Serway & Jewett, 9th ed, page 1066.

# Refraction



# Refraction: Snell's Law

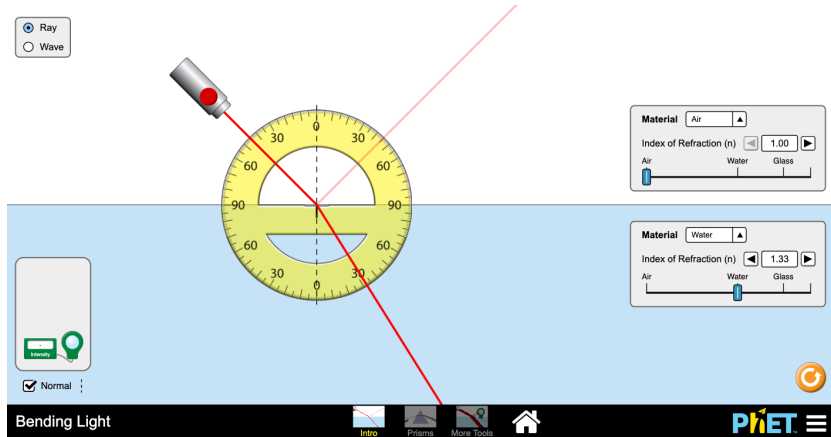


**Snell's Law:**

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

<sup>1</sup>Willebrord Snell discovered this law experimentally.

# Intro: Refraction Setup



The interface for the "Intro: Refraction Setup" simulation. It features a central circular protractor with a yellow face and black markings, divided into two semi-circles. A red laser ray originates from a grey cylindrical source at the top left, passes through the center of the protractor, and refracts into a blue rectangular region representing water. A dashed vertical line serves as the normal. A pink ray is also shown passing through the center of the protractor. On the left, a control panel includes a radio button for "Ray" (selected) and "Wave", a light source icon with a green "Intensity" slider, and a checked "Normal" checkbox. On the right, two material selection panels are present. The top panel is for the incident medium (Air) with an index of refraction of 1.00. The bottom panel is for the refracting medium (Water) with an index of refraction of 1.33. Both panels include a material dropdown, an index of refraction input field, and a slider. A circular orange button with a refresh icon is located in the bottom right corner. The bottom of the interface has a black navigation bar with icons for "Intro", "Prisms", "More Tools", and a home button, along with the "PhET" logo.

**Ray Mode:** ☒ Ray ☐ Wave

**Material Selection (Top):**  
Material: Air  
Index of Refraction (n): 1.00  
Air | Water | Glass

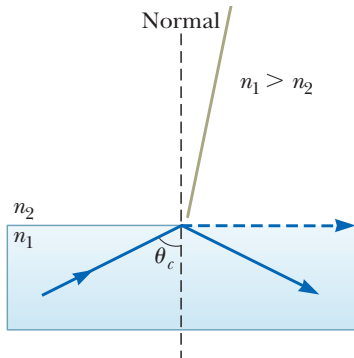
**Material Selection (Bottom):**  
Material: Water  
Index of Refraction (n): 1.33  
Air | Water | Glass

**Left Panel:**  
Intensity: [Slider]  
☒ Normal

**Bottom Navigation:**  
Intro | Prisms | More Tools | Home | PhET

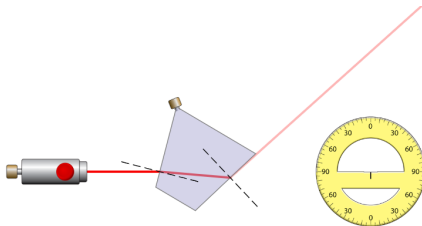
# Total Internal Reflection

The **critical angle**,  $\theta_c$ , is the maximum angle of incidence such that there could be a refracted ray. The ray would just skim along the surface between the media.



In this case, the angle of refraction  $\theta_2 = 90^\circ$ .

# Prisms: Total Internal Reflection Setup



Environment Air

Index of Refraction (n)

Air Water Glass

650 nm

A control panel for the simulation. It includes a dropdown menu for the environment (set to Air), a scale for the index of refraction (n) with markers for Air, Water, and Glass, and a spectral color bar with a red marker at 650 nm.

Objects Glass

Index of Refraction (n)

Air Water Glass

☐ Reflections

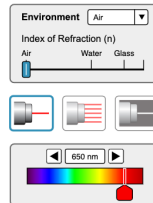
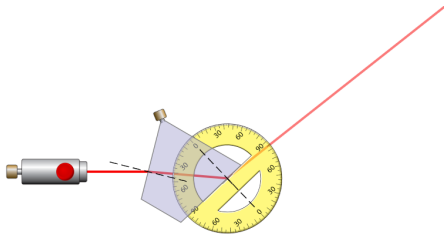
☒ Normal

☒ Protractor

A control panel for the simulation. It includes a row of icons for different prism shapes (triangle, trapezoid, square, circle, and semi-circle), a dropdown menu for the object (set to Glass), a scale for the index of refraction (n) with markers for Air, Water, and Glass, and checkboxes for Reflections, Normal, and Protractor.



# Prisms: Total Internal Reflection Setup





# Theory: Images Formed by Refraction

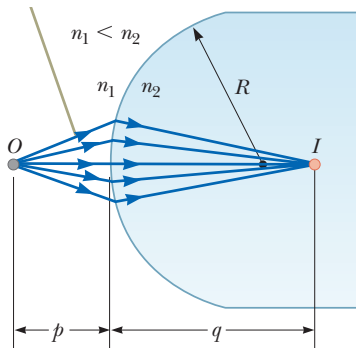
When light rays change media they are bent.



This also can form images.

# Images Formed by Refraction

We can find the location and size of the image formed by considering paraxial rays.



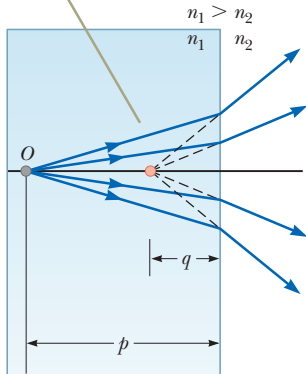
For paraxial rays:

$$\frac{n_1}{p} + \frac{n_2}{q} = \frac{n_2 - n_1}{R}$$

# Flat Refracting Surfaces

(Like a rectangular fish tank.)

The image is virtual and on the same side of the surface as the object.



In this case  $R \rightarrow \infty$ .

$$\frac{n_1}{p} + \frac{n_2}{q} = 0$$

And so

$$q = -\frac{n_2}{n_1}p$$

## Flat Refracting Surfaces Example (Problem 30)

A cubical block of ice 50.0 cm on a side is placed over a speck of dust on a level floor. Find the location of the image of the speck as viewed from above. The index of refraction of ice is 1.309.

## Flat Refracting Surfaces Example (Problem 30)

A cubical block of ice 50.0 cm on a side is placed over a speck of dust on a level floor. Find the location of the image of the speck as viewed from above. The index of refraction of ice is 1.309.

$$\frac{n_1}{p} + \frac{n_2}{q} = \frac{n_2 - n_1}{R}, \quad R \rightarrow \infty$$

$$\Rightarrow q = -\frac{n_2}{n_1} p$$

## Flat Refracting Surfaces Example (Problem 30)

A cubical block of ice 50.0 cm on a side is placed over a speck of dust on a level floor. Find the location of the image of the speck as viewed from above. The index of refraction of ice is 1.309.

$$\frac{n_1}{p} + \frac{n_2}{q} = \frac{n_2 - n_1}{R}, \quad R \rightarrow \infty$$

$$\begin{aligned}\Rightarrow q &= -\frac{n_2}{n_1} p \\ &= -\frac{1}{1.309} (50.0 \text{ cm}) \\ &= \underline{38.2 \text{ cm}}\end{aligned}$$

# Sign Conventions for Refracting Surfaces!

$$\frac{n_1}{p} + \frac{n_2}{q} = \frac{n_2 - n_1}{R}$$

Variable	is Positive	is Negative
$p$	object in front of surface	[virtual object] <sup>1</sup>
$q$	image behind surface (real)	image in front of surface (virtual)
$h'$ (and $M$ )	image upright	image inverted
$R$	object faces convex surf. ( $C$ behind surface)	object faces concave surf. ( $C$ in front of surface)

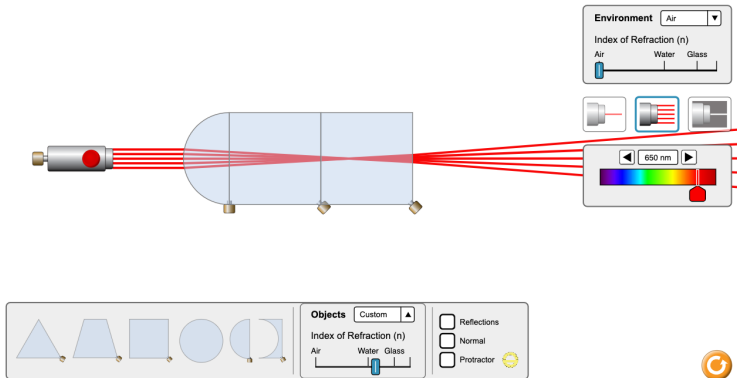
$C$  is the center of curvature.

$$M = \frac{h'}{h} = -\frac{n_1 q}{n_2 p}$$

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<sup>1</sup>Will be useful in derivations.

# Prisms: Refracting Surfaces Setup





# More Tools: Light as a wave

The simulation interface for "More Tools: Light as a wave" is shown. It features a central area where a light wave, represented by a red and black striped cylinder, is incident on a horizontal boundary between air (top) and water (bottom). A dashed vertical line indicates the normal. The wave refracts into the water, bending towards the normal. A red dot marks the point of incidence.

**Top Left Controls:**

- Mode: ☐ Ray, ☒ Wave
- Wavelength: 650 nm (with left and right arrows)
- Color spectrum bar with a red slider at the right end.

**Bottom Left Controls:**

- Protractor: A yellow circular scale from 0 to 90 degrees.
- Intensity: A green lightbulb icon.
- Speed: An orange icon with a question mark.
- Time: A blue icon with a clock.
- Checkboxes: ☒ Normal, ☐ Angles.
- Buttons: ☒ Normal, ☐ Slow Motion, a pause button (II), and a play button (▶).

**Right Side Material Controls:**

**Top Right:**

- Material: Custom (dropdown)
- Index of Refraction (n): 1.000 (with left and right arrows)
- Slider: Air | Water | Glass

**Bottom Right:**

- Material: Water (dropdown)
- Index of Refraction (n): 1.333 (with left and right arrows)
- Slider: Air | Water | Glass

**Bottom Bar:**

- Text: Bending Light
- Navigation icons: Intro, Prisms, More Tools (highlighted), Home.
- PhET logo and menu icon.

