Optics
The Speed of Light
Ray Optics

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Last time

- nature of light
- speed of light

Overview

- speed of light
- ray optics
- reflection
- refraction

Measurements of the Speed of Light

Since light propagates so quickly it is difficult to measure its speed in practice.

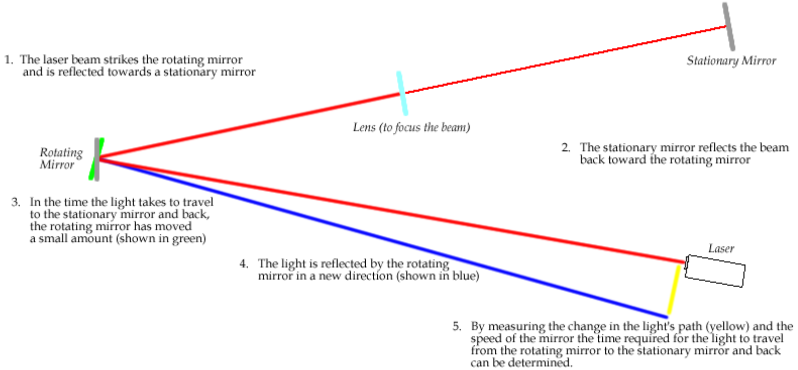
Galileo and others tried to measure it with procedures that relied on human reactions.

Human reactions are way too slow! This error dominates the data.

Many clever alternative methods were developed.

Foucault's Method

Foucault used a rotating mirror, to send light from a source to a stationary mirror and back again.

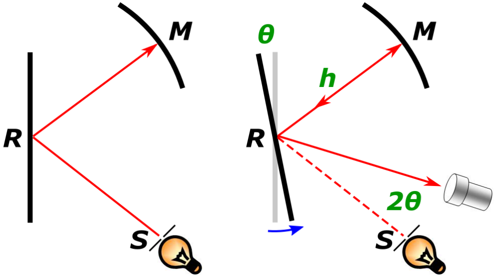


(Foucault did not use a laser, obviously.)

[1] Figure from Wikipedia, by user Rhodesl.

Foucault's Method

The angle formed between the source and the returning light beam allowed him to figure out how much the mirror had rotated (therefore how much time had passed) while the light traveled from R to M and back.



Foucault could only separate the mirrors by a distance of 20m, due to limitations on his mirrors and lenses.

[1]Figure from Wikipedia, by user Stigmatella aurantiaca.

Michelson's Refinement

Albert Michelson adapted Foucault's apparatus to increase path length of the light to 22 miles!

He used two observatories on adjacent mountains.

In spite of a forest fire and an earthquake, he got the value of

$$299,796 \pm 4 \text{ km/s}$$

This is only 4 km/s faster that the current accepted value.

He later worked on the famous Michelson-Morley experiment which showed that light needs no medium.

Medium in Optics

medium (for mechanical waves)

a material substance that carries waves. The constituent particles are temporarily displaced as the wave passes, but they return to their original position.

We will also use the word "medium" in optics, but we mean something slightly different:

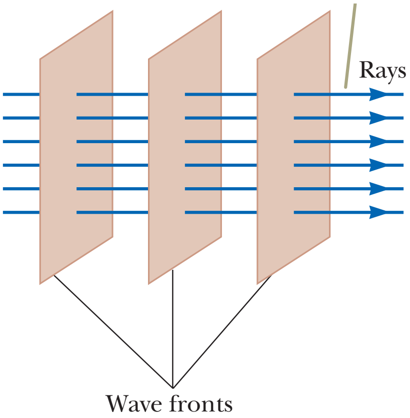
medium (in the case of light)

a material substance that light travels through. The electric field in light can interact with constituent charged particles in the substance.

Light can travel without a medium, so the medium does not "carry" light, it just interacts with the light.

Ray Optics

To study the behavior of light, we represent light as **rays** pointed in the direction of the light's travel.

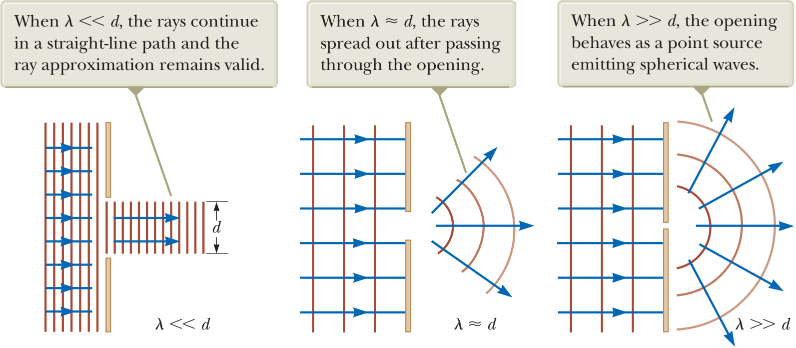


The wavefronts are perpendicular to the rays.

Ray Optics

In ray optics, we assume that light travels in a **straight line** as long as it is in a constant, uniform medium. It can only change direction on reflection, or when it changes medium.

This is not always true, however:



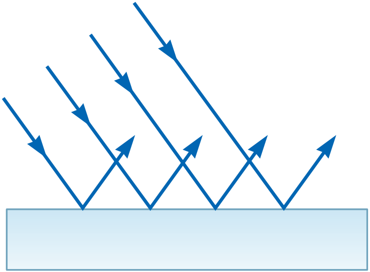
We use ray optics when we can ignore diffraction and interference effects.

Reflection

Just as pulses on strings can be reflected from a fixed or free end of the string, light can be reflected from a surface when there is a sudden change of medium.

When the surface is smooth, we see specular (mirror-like) reflection. If the incoming rays are parallel, so are the reflected rays.

Specular reflection:



[1]Figure from Serway & Jewett, page 1062.

Reflection

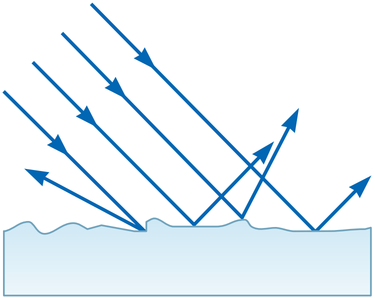
Specular (mirror-like) reflection:

Courtesy of Henry Leap and Jim Lehman

Reflection

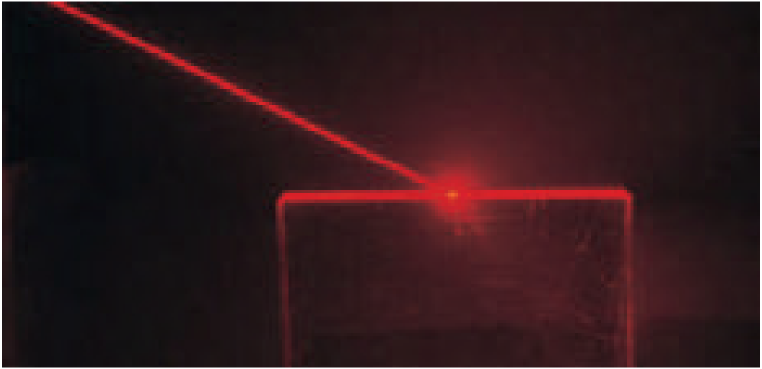
When the surface is rough, we see diffuse reflection. Even when the incoming rays are parallel, the reflected rays are not.

Diffuse reflection:



Reflection

Diffuse reflection:



Courtesy of Henry Leap and Jim Lehman

Why does reflection of light happen?

Incident light is composed of oscillating electromagnetic fields.

This causes oscillating polarizations of individual atoms or molecules (the distribution of their electron clouds change).

The atoms or molecules act like tiny dipole antennas that re-emit electromagnetic waves.

These re-emited waves are the reflected rays.

Metals make particularly good mirrors because the electrons in a metal are free to flow: they form better antennas.

Law of Reflection

In this course (and in the textbook) "reflection" will refer to specular reflection.

For (specular) reflection, the angle made by the incident (incoming) ray with respect to the normal to the surface is equal to the angle made by the reflected ray with the normal:

$$\theta_i = \theta_r$$

Law of Reflection

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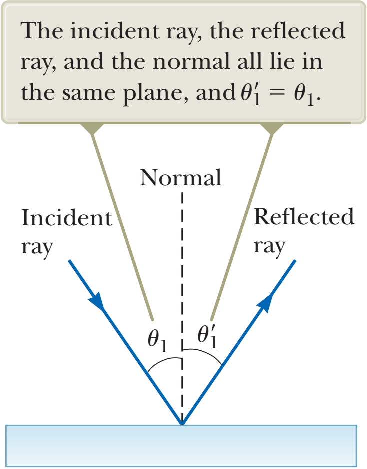

Law of Reflection Question

Quick Quiz 35.1[1] In the movies, you sometimes see an actor looking in a mirror and you can see his face in the mirror. It can be said with certainty that during the filming of such a scene, the actor sees in the mirror:

(A) his face
(B) your face
(C) the director's face
(D) the movie camera

Boris Karloff as Frankenstein's monster.

[1] Serway & Jewett, page 1062.

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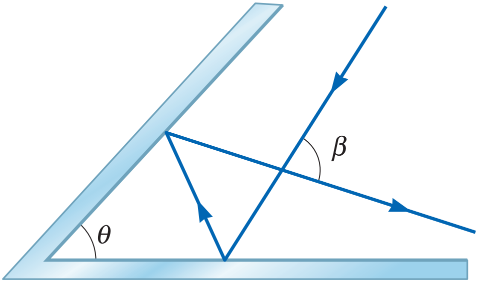
Example, Prob 18, page 1081

The reflecting surfaces of two intersecting flat mirrors are at an angle θ ($0^\circ \leqslant \theta \leqslant 90^\circ$) as shown. For a light ray that strikes the horizontal mirror, show that the emerging ray will intersect the incident ray at an angle $\beta = 180^\circ - 2\theta$.



[1] Compare this problem to example 35.2 in Serway & Jewett.

Retroreflectors

Notice that it doesn't matter at what angle the light strikes the mirror.

Retroreflectors

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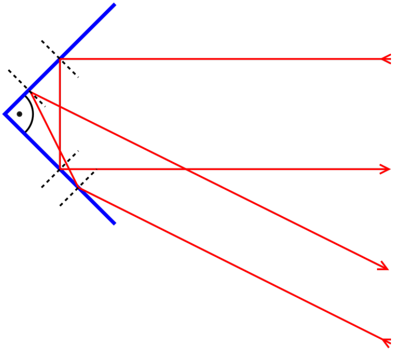
When $\theta = 90^\circ$, $\beta = 0^\circ$.

The reflected light travels back parallel to the incident light, no matter which way the light comes from.



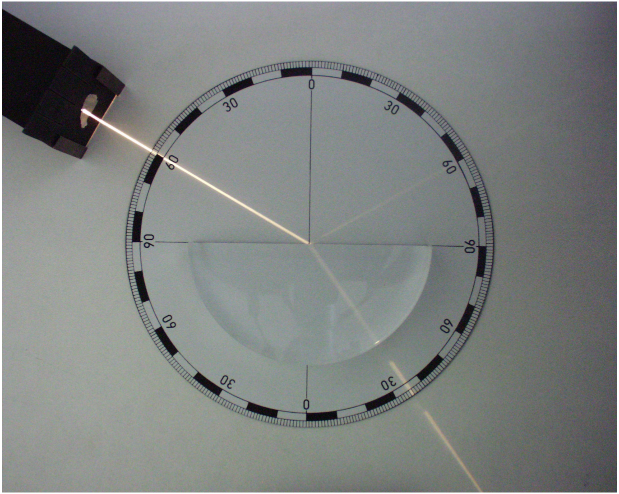
Retroreflectors

A device with mirrors placed like this is called a *retroreflector*.

© Cengage Learning/George Semple

Refraction

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



[1] Image from Wikipedia, by Zátonyi Sándor.

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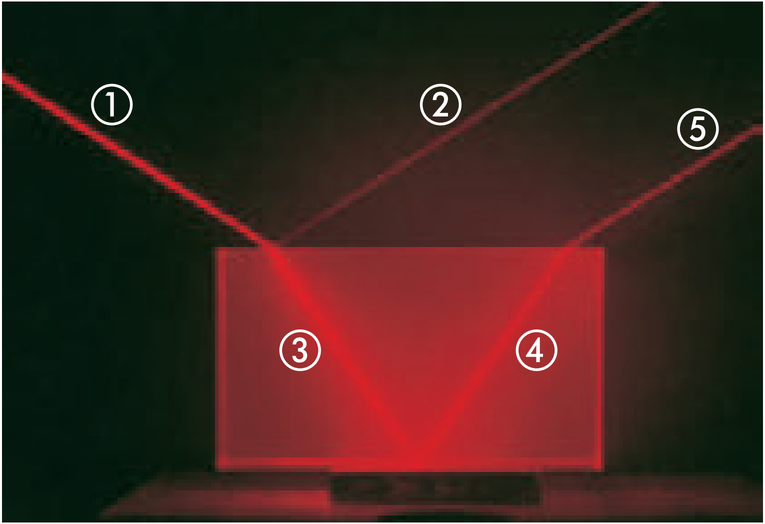
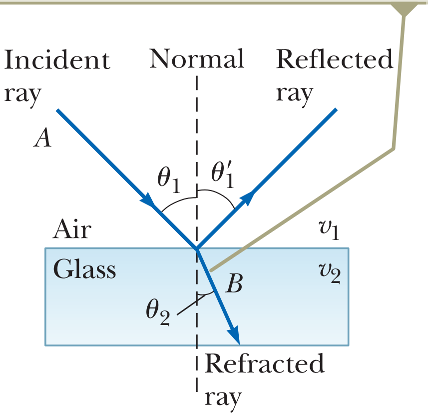


Courtesy of Henry Leap and Jim Lehman

Refraction

All rays and the normal lie in the same plane, and the refracted ray is bent toward the normal because $v_2 < v_1$.



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That is because the answer to the puzzle was already suspected.

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Foucault did the experiment in water (1850), and Fizeau (1851) went further investigating light moving water.

Both found visible light had a **slower speed** in water than in air. This agreed with the **wave model** of light.

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Both found visible light had a **slower speed** in water than in air. This agreed with the **wave model** of light.

However, Fizeau could not explain the magnitude of the speed change that occurred for light in moving water...

Refraction

If a wave enters a medium where it moves more slowly, what happens?

1. the frequency cannot change – the source still "updates" the medium about a new wave front every T seconds.

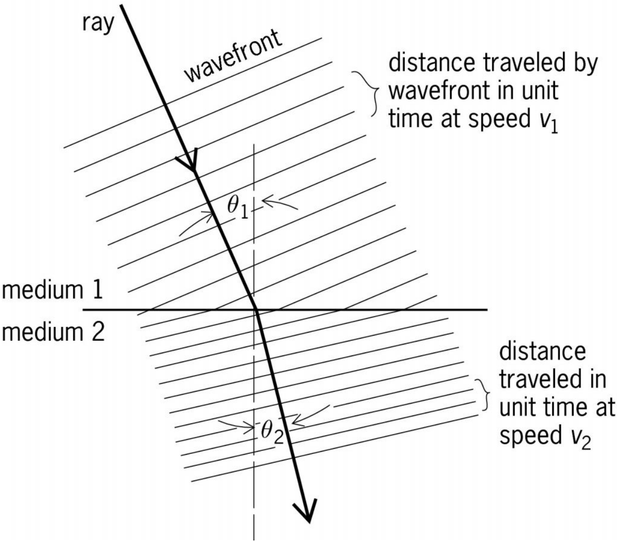
Refraction

If a wave enters a medium where it moves more slowly, what happens?

1. the frequency cannot change – the source still “updates” the medium about a new wave front every T seconds.
2. the wavelength changes ($v = f\lambda$)

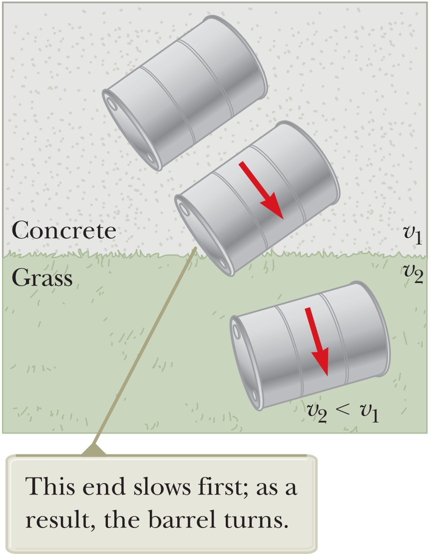
When the wavefronts slow, they bend.

Refraction



[1] McGraw-Hill Concise Encyclopedia of Physics. © 2002 by The McGraw-Hill Companies, Inc.

Refraction



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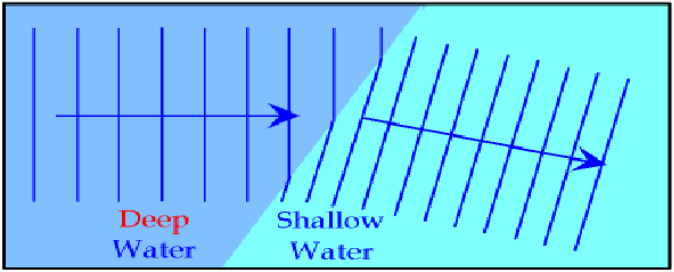
[1]Serway & Jewett, 9th ed, page 1066.

Refraction

The same thing happens when waves move into shallower water on a beach.



[1]http://astarmathsandphysics.com/o-level-physics-notes/297-refraction-of-waves.html

Refractive Index

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

Light interacts with the charges that constitute the medium, and the net effect is a wave that moves more slowly.

Refractive index of a medium, n

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

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

Materials with a higher n are said to be more **optically dense**.

Refractive Index

The index of refraction also relates to the ratio of the wavelength of light at a particular frequency in the medium, λ_n, to that same light's wavelength in a vacuum, λ.

$$n = \frac{c}{v} = \frac{f\lambda}{f\lambda_n}$$

so,

$$n = \frac{\lambda}{\lambda_n}$$

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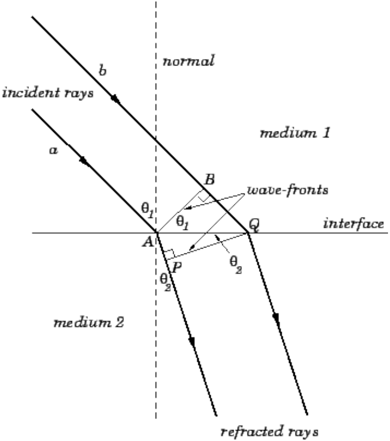
If the light passes from one medium with refractive index n_1 to another with index n_2:

$$\frac{n_1}{n_2} = \frac{\lambda_2}{\lambda_1}$$

Snell's Law: Angle relationship in Refraction

How do the refractive indices relate to the angles of incidence and refraction?



Let h be the hypotenuse of the two triangles.

$$h = \frac{\lambda_1}{\sin\theta_1} = \frac{\lambda_2}{\sin\theta_2}$$

[1]Figure by Richard Fitzpatrick, http://farside.ph.utexas.edu/teaching/

Snell's Law

$$\frac{\lambda_1}{\sin\theta_1} = \frac{\lambda_2}{\sin\theta_2}$$

Rearranging,

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

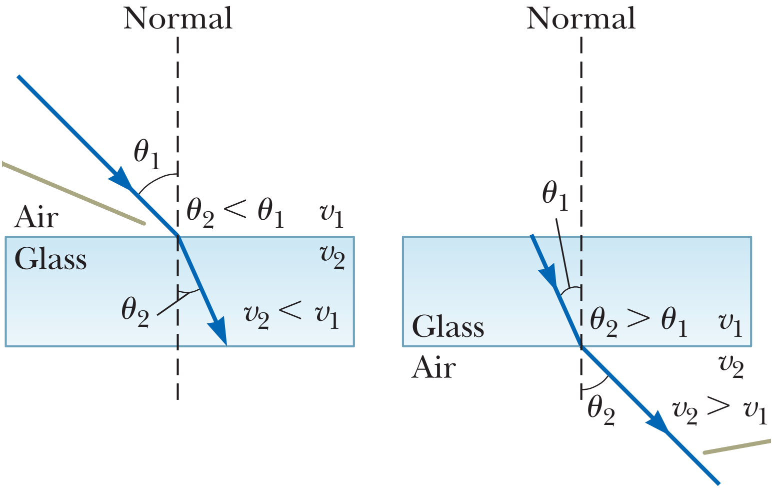
And rearranging again gives **Snell's Law**:

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

[1] Willebrord Snell discovered this law experimentally.

Snell's Law and Refraction

If $n_1 < n_2$ the ray bends towards the normal, if $n_1 > n_2$ the ray bends away from the normal.



Summary

- speed of light
- ray optics
- reflection
- refraction

Homework Serway & Jewett:

- Ch 35, onward from page 1077. OQs: 1, 8; CQs: 4, 15; Probs: 1, 3, 21