PURDUE UNIVERSITY DEPARTMENT OF PHYSICS

Physics 22100

General Physics II

Electricity, Magnetism, Optics and Modern Physics

Lecture 13 – Chapter 22.1-2

Propagation and Reflection of Light

Spring 2019 Semester

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Homework set discussion

Historical Context

- Optics is arguably the oldest discipline in physics
- https://en.wikipedia.org/wiki/History_of_optics
- The European scientific establishment (1600's) debated whether light was a wave phenomena or a stream of particles
  - Arguments for and against either viewpoint
  - Not satisfactorily resolved until the introduction of Quantum Mechanics in the early 20th century
- A theory of light first needs to describe the obvious:
  - Reflection (mirrors)
  - Refraction (lenses)

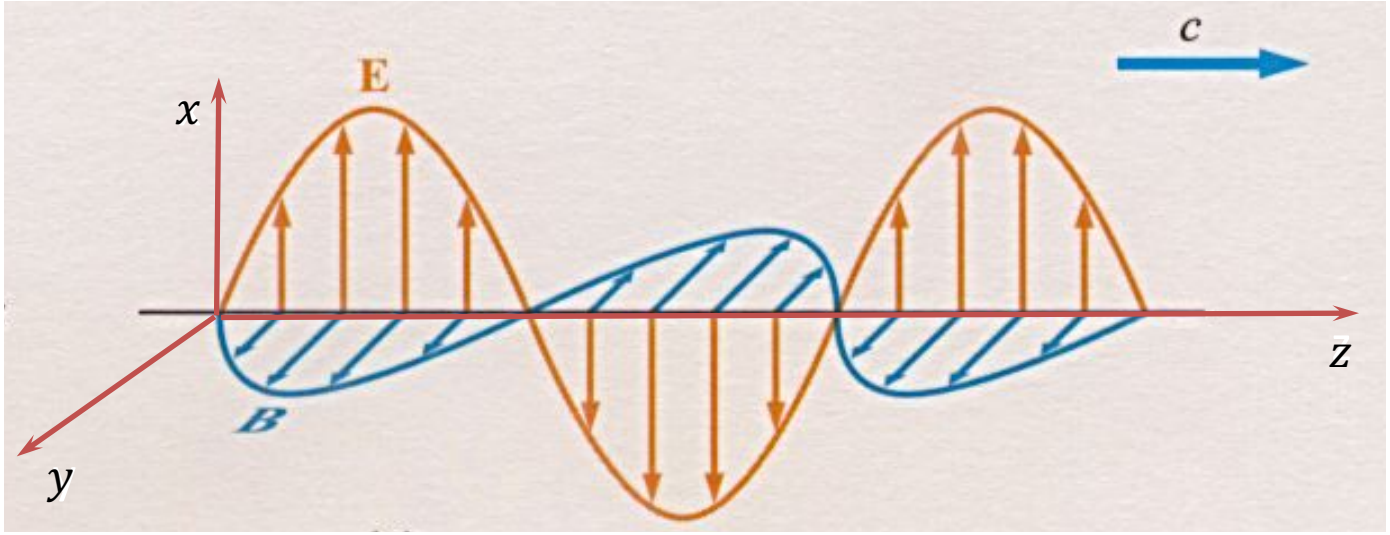
Connection With Electricity and Magnetism

- Faraday's law:

$$\mathcal{E} = -\frac{\Delta \Phi_B}{\Delta t}$$

- The changing magnetic field creates an electric field (which produces the EMF)
- It turns out that likewise, a changing electric field produces a magnetic field.
- This process can continue indefinitely…
- Light is an oscillating electric-magnetic field propagating through free space.
- Speed of light is $c = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$ in terms of electric and magnetic constants.

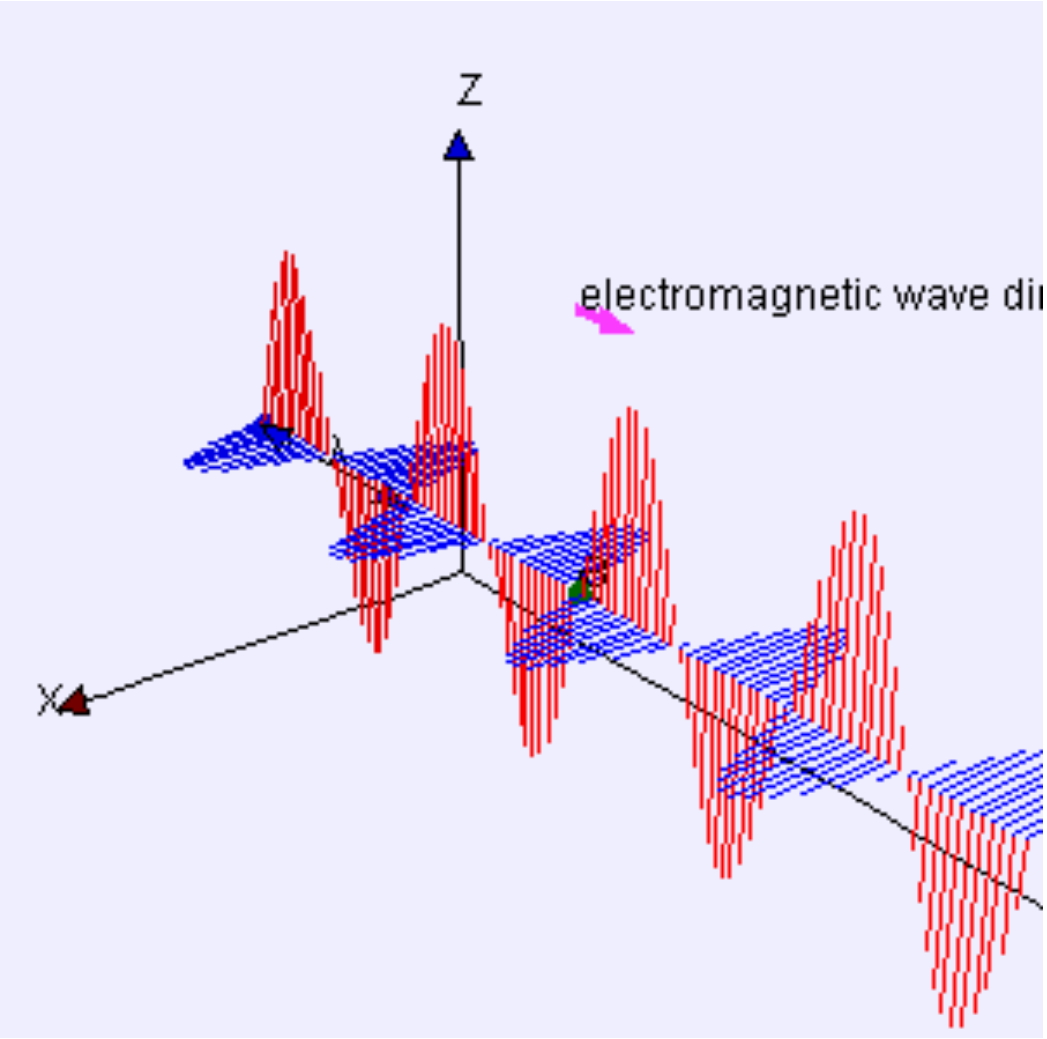
Electromagnetic Waves



- $\vec{E}$, $\vec{B}$ and $\vec{v}$ are mutually perpendicular.
- In general, the direction is

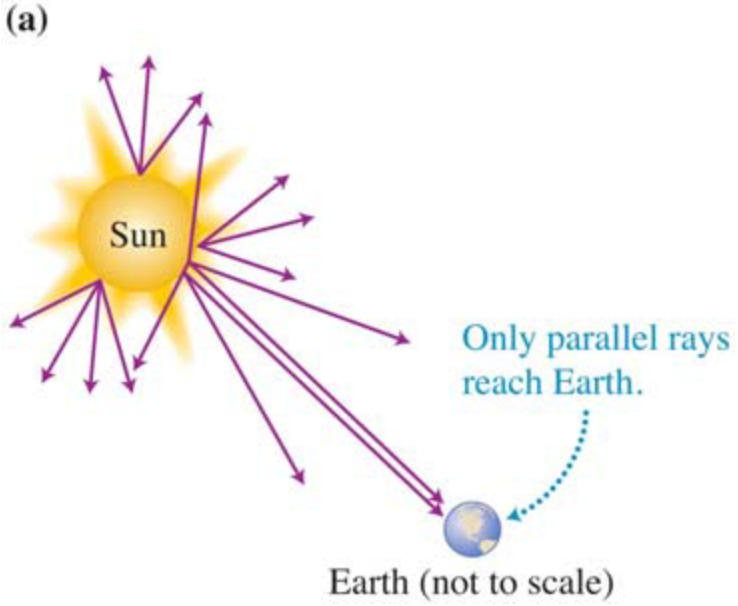
$$\hat{s} = \hat{E} \times \hat{B}$$

Electromagnetic Waves



Ray Diagrams

- For practical purposes (for now) light travels in straight lines, *away* from a source.
- So we draw a light ray as an arrow pointing away from the source
- Diagrams that have rays in them are called ray diagrams.



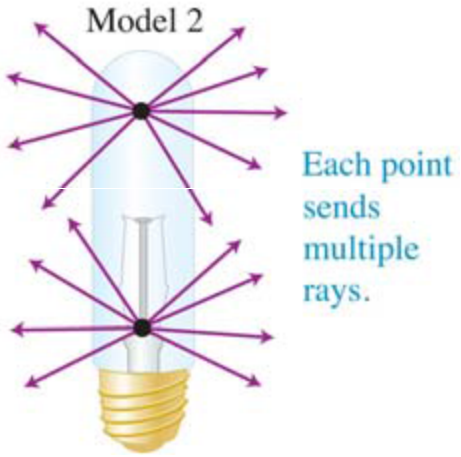
Ray Diagrams

Each point on an extended light source emits rays in many different directions

This can be represented by many different rays diverging from that point.

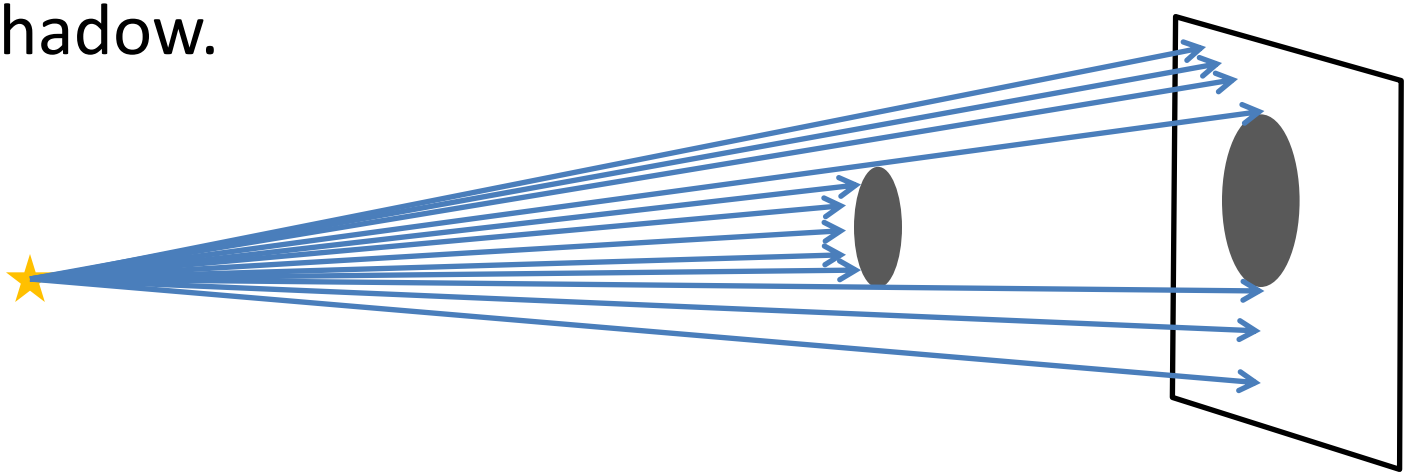
The rays propagate in straight lines until they encounter an interface to another type of material.

This defines the ray model of light.



Shadows

- Light will be blocked by an opaque object and form a shadow.

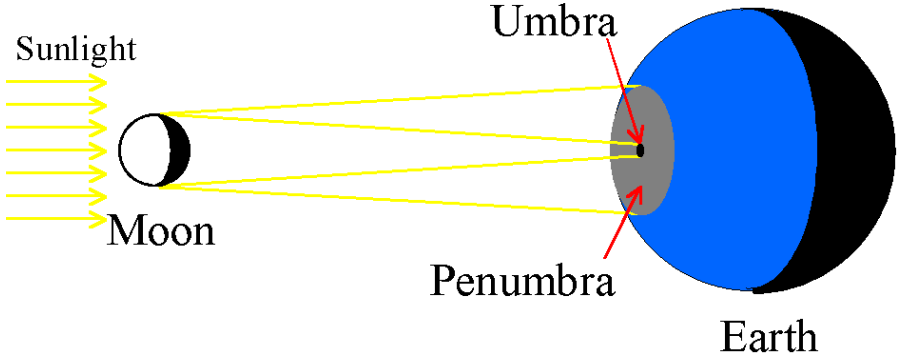


- A shadow (in case you didn't already know) is a dark area behind an object where no light reaches.
- The Latin word for shadow is *umbra*.
- A dim region that is reached by a little bit of light is called a *penumbra*.

Umbra and Penumbra

- Point light sources produce *umbras.*
- Multiple point sources or extended light sources produce *penumbras*.

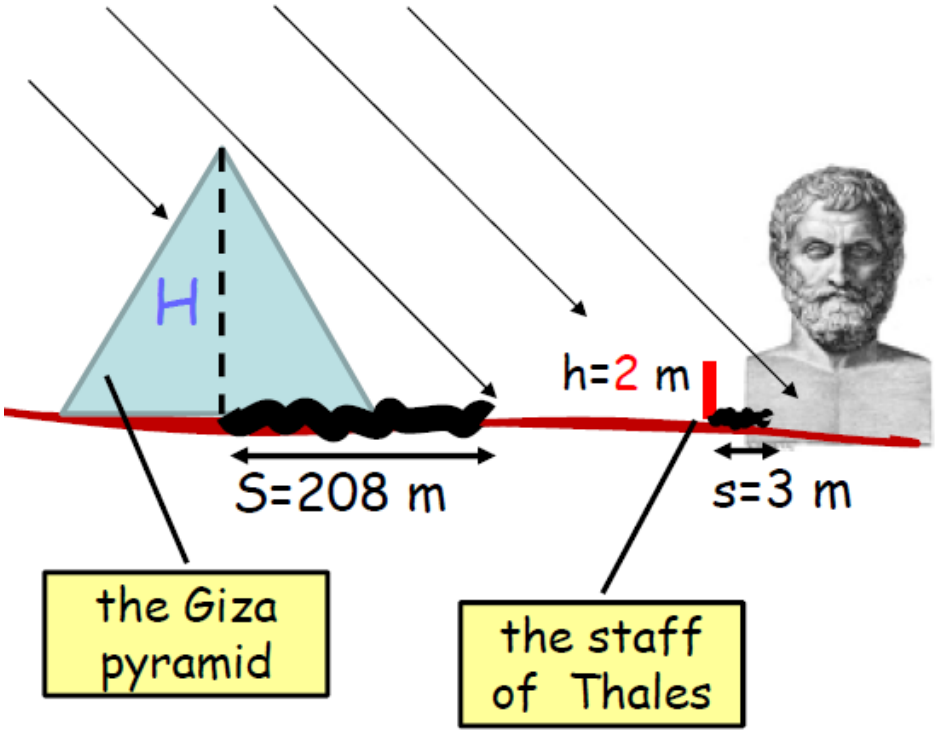
Example: fine art



Example: solar eclipse

Example

In ~2600 B.C., the Egyptians constructed the Great Pyramid of Giza. History records that ~2000 years after completion, in the 6th century B.C., Thales measured the height H of the Great Pyramid. How did he do it? And what value did he obtain for H?



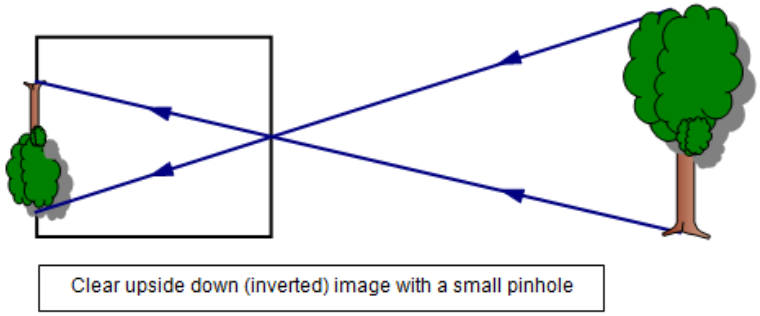
$$\frac{h}{H} = \frac{s}{S}$$

$$\frac{2\,m}{H} = \frac{3\,m}{208\,m}$$

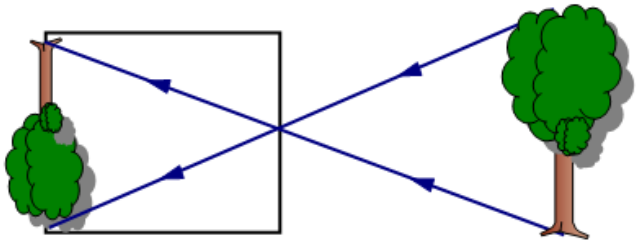
$$H = \frac{2}{3}(208\,m) \approx 139\,m$$

Pinhole Camera

- A light-tight box with a small hole in it allows a (relatively) sharp image to be formed.
- This is called a "*pinhole camera*" or more artistically, a "*camera obscura*".
- The image can expose a photographic plate



Clear upside down (inverted) image with a small pinhole

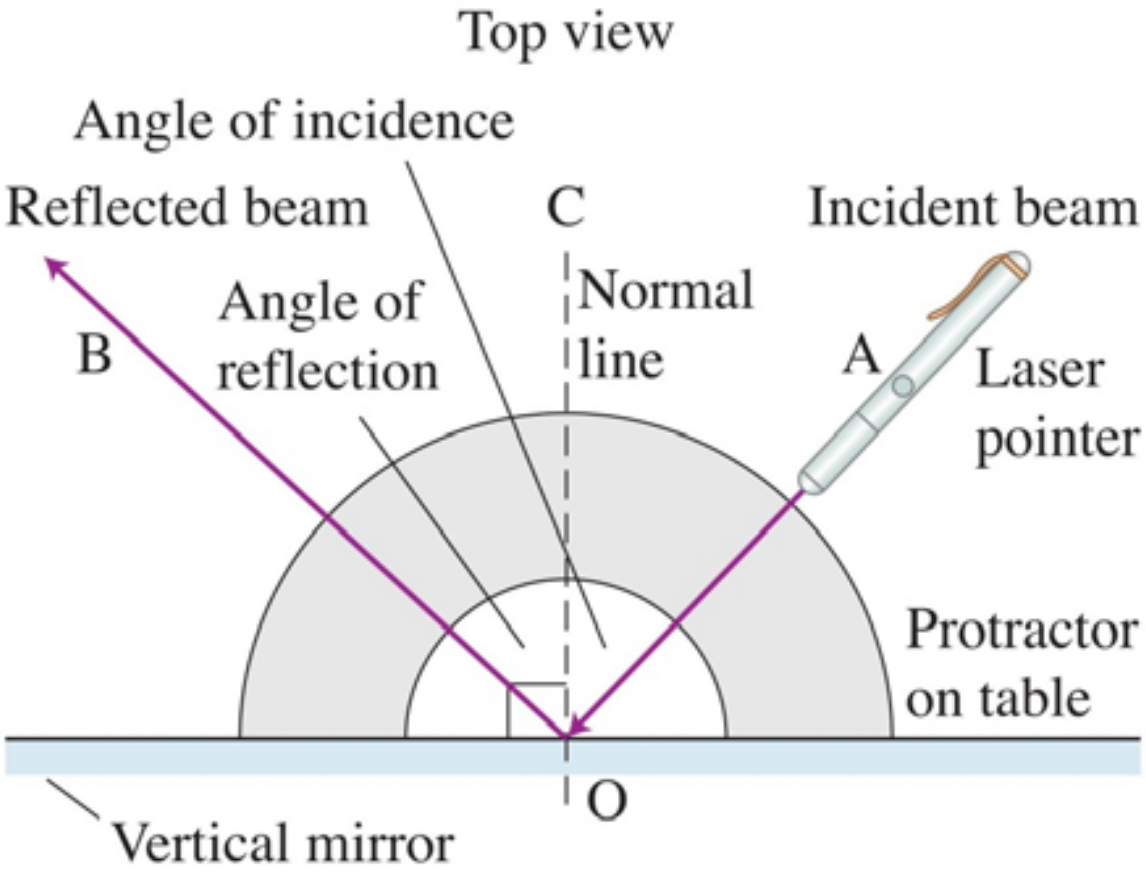


Camera closer to the object – a larger image

Cool art although it's upside down.

Reflection of Light

- When viewed from above, light from a laser pointer reflects off a vertical mirror:



Definitions

- **Incident light**: *the light striking the mirror.*
- **Normal line**: *a line perpendicular to the surface of the mirror at the point where the light hits it.*
- **Angle of incidence**: *angle between the incident beam and the normal line.*
- **Angle of reflection**: *angle between the reflected beam and the normal line.*

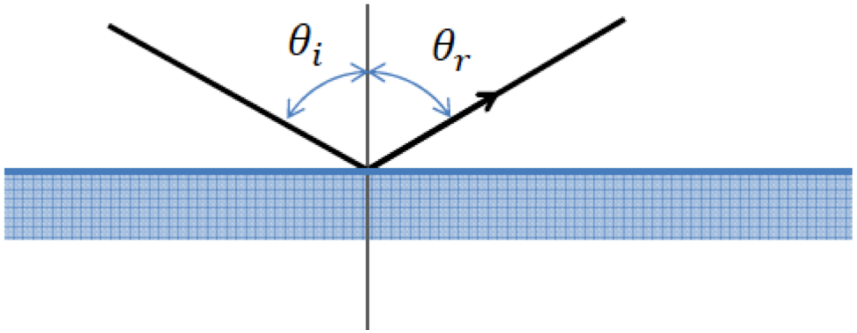
TIP The angle of incidence and the angle of reflection are always the angles that the light beams form with the normal line and not the angles that they form with the surface of the mirror.

The Law of Reflection

Law of reflection When a narrow beam of light, represented by one ray, shines on a smooth surface such as a mirror, the angle between the incident ray and the normal line perpendicular to the surface equals the angle between the reflected ray and the normal line (the angle of reflection equals the angle of incidence). The incident beam, reflected beam, and the normal line are in the same plane.

(21.1)

$$\theta_{incidence} = \theta_{reflection}$$



Many optical manipulations can be performed using just mirrors

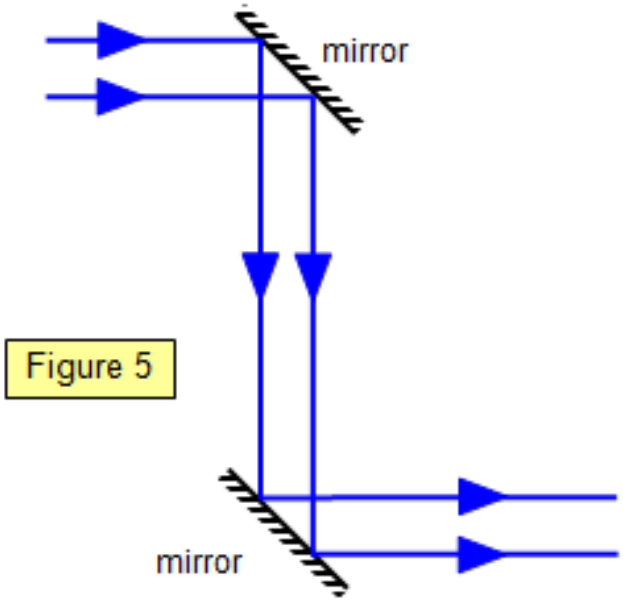


Figure 5

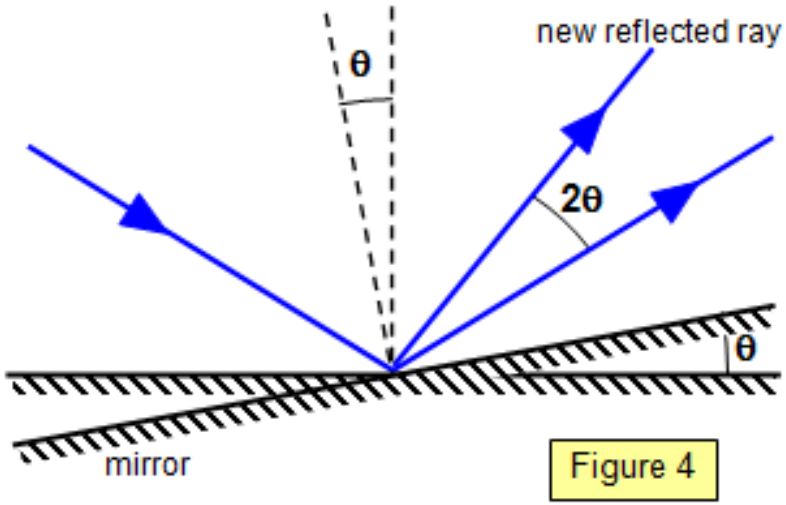
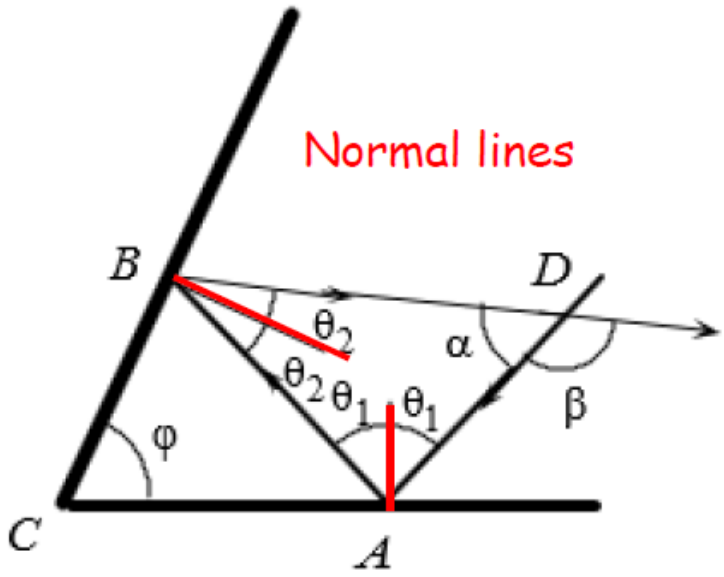


Figure 4

Most of the complications come from working out the geometry.

EXAMPLE

Show that if two plane mirrors meet at an angle φ, a single ray reflected successively from both mirrors is deflected through an angle of 2φ from the incident beam, independent of the incident angle.



Assume φ < 90 ° and that only two reflections, one from each mirror, take place.

1. *From* ΔABC

$$\phi + \left(\frac{\pi}{2} - \theta_1\right) + \left(\frac{\pi}{2} - \theta_2\right) = \pi$$

$$\phi = \theta_1 + \theta_2$$

2. *From* ΔABD

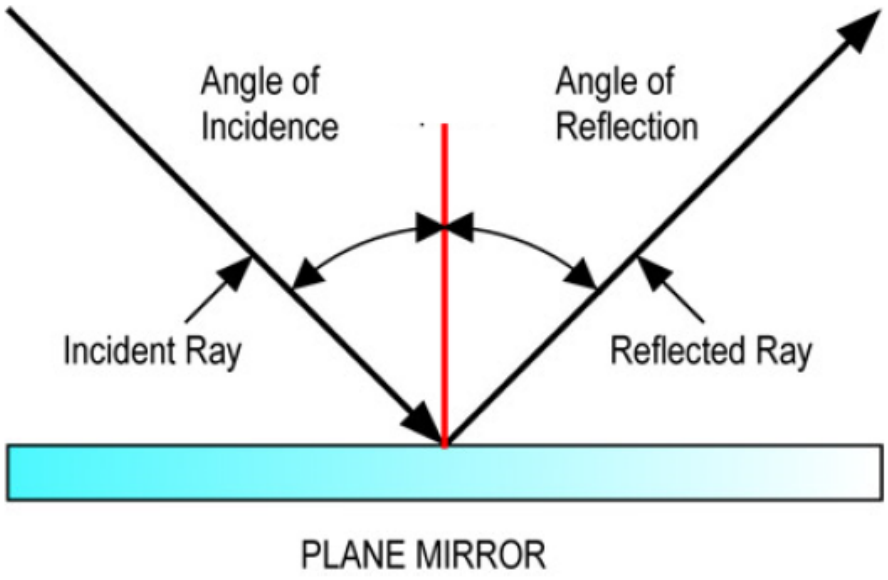
$$\alpha + 2\theta_1 + 2\theta_2 = \pi$$

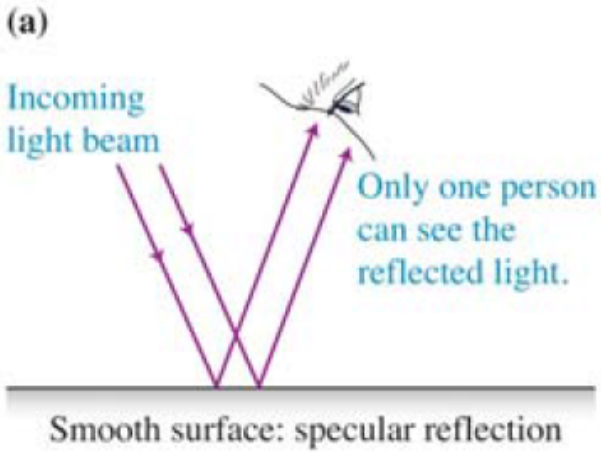
$$\alpha = \pi - 2\left(\theta_1 + \theta_2\right) = \pi - 2\phi$$

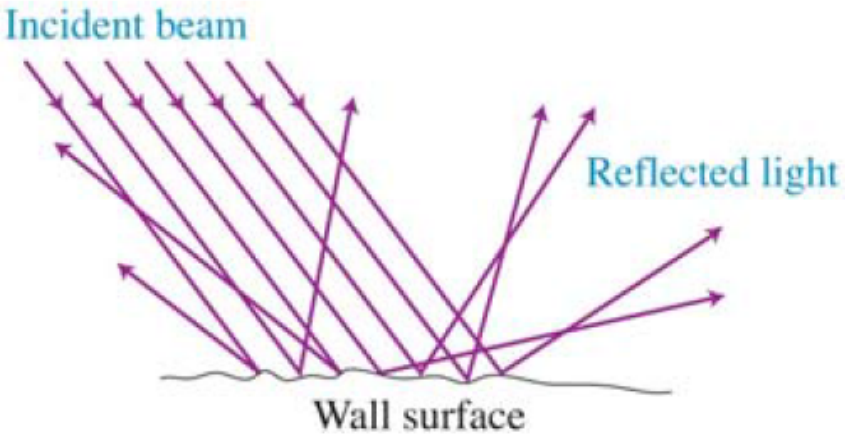
3. *At point D*

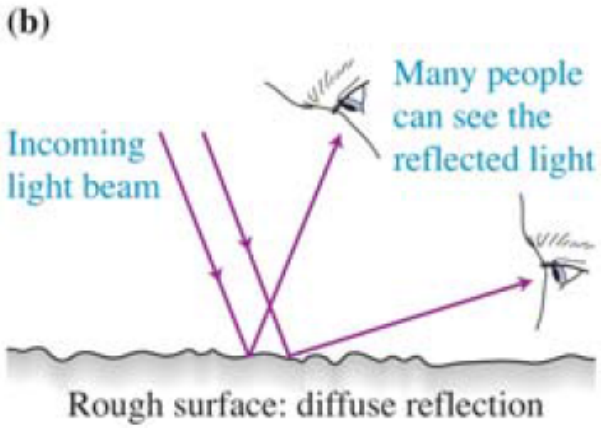
$$\beta = \pi - \alpha = \pi - \left(\pi - 2\phi\right) = 2\phi$$

Specular and diffuse reflection



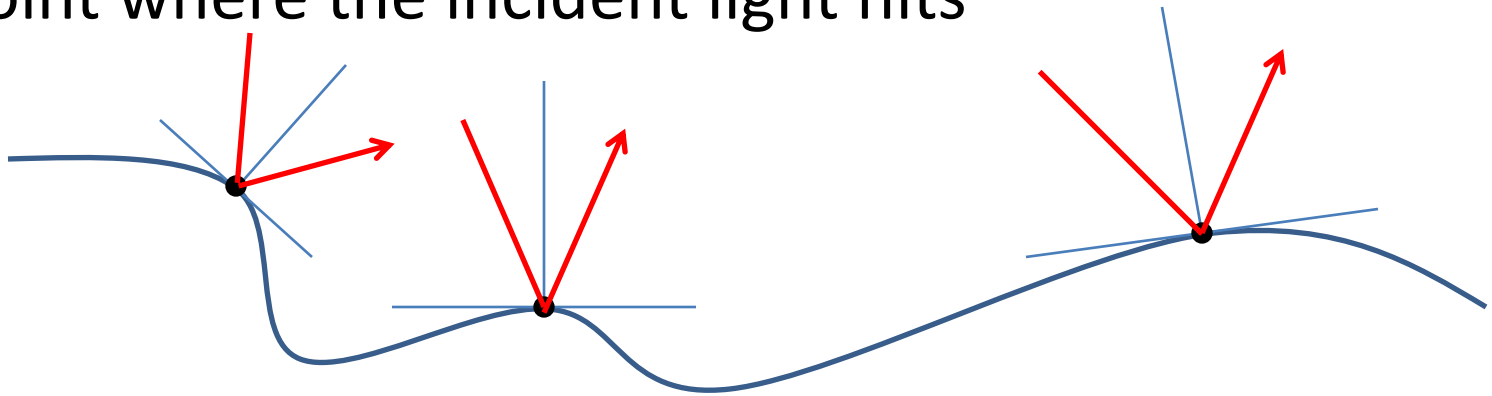






Reflection from curved surfaces

- Imagine a plane that is tangent to the surface at the point where the incident light hits



- In general, finding the tangent plane might not be easy
  - Computers are pretty good at parameterizing surfaces in terms of polynomials and then it's easy
  - Ray tracing programs do this
- We might only have to do it for a spherical surface which will be simple.

Refraction

- Refraction is the change in direction of a light ray when it passes from one medium to another.

“bent” straws

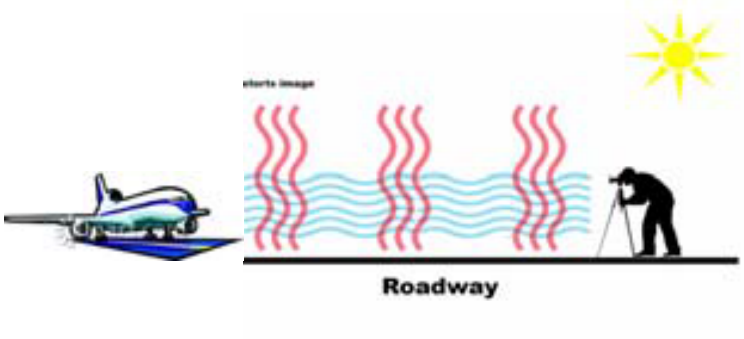
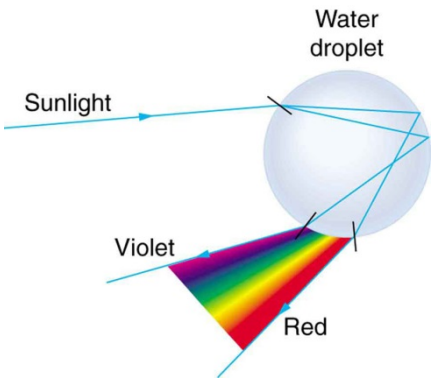


Image distortion



Rainbows

Refraction of Light

Angles of incidence and transmission are measured with respect to the normal line which is perpendicular to the interface.

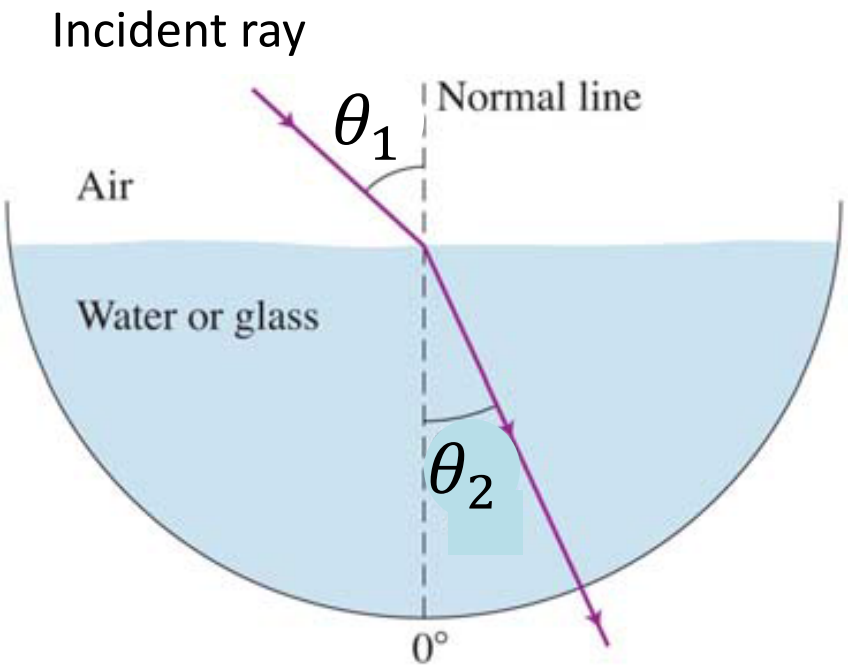


Table 21.6 Pattern found by Snell for ratio of the sines of the incident and refraction angles.

Air $\sin\theta_1$	Water $\sin\theta_2$	Glass $\sin\theta_2$	Air/water $(\sin\theta_1)/(\sin\theta_2)$	Air/glass $(\sin\theta_1)/(\sin\theta_2)$
0.000	0.000	0.000		
0.174	0.131	0.114	1.33	1.53
0.342	0.259	0.225	1.32	1.52
0.500	0.374	0.326	1.34	1.53
0.643	0.485	0.423	1.33	1.52
0.766	0.573	0.500	1.34	1.53
0.866	0.649	0.569	1.33	1.52

Index of refraction (n)

Experiment established a mathematical relationship between the angle of incidence and the angle of transmission that depends on the particular medium.

Index of Refraction

- The index of refraction is a property of a particular medium.
- Indices of refraction have been measured for many materials:

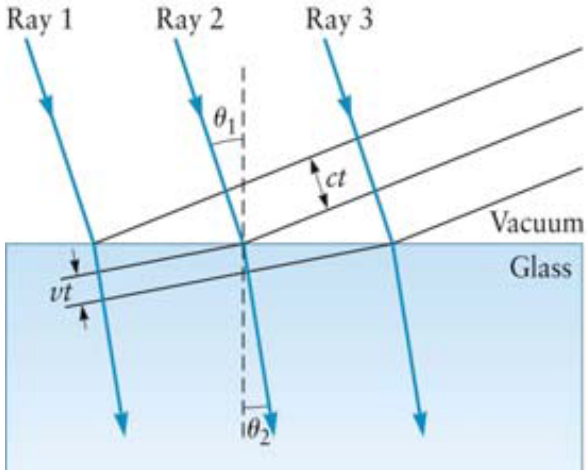
	Index of refraction
Air	1.0003
Water	1.33
Vegetable oil	1.47
Crown glass	1.51
Salt	1.54
Flint glass	1.61
Corundum (ruby, sapphire)	1.77*
Diamond	2.42
At 20° C, λ = 589 nm	*Approximate value

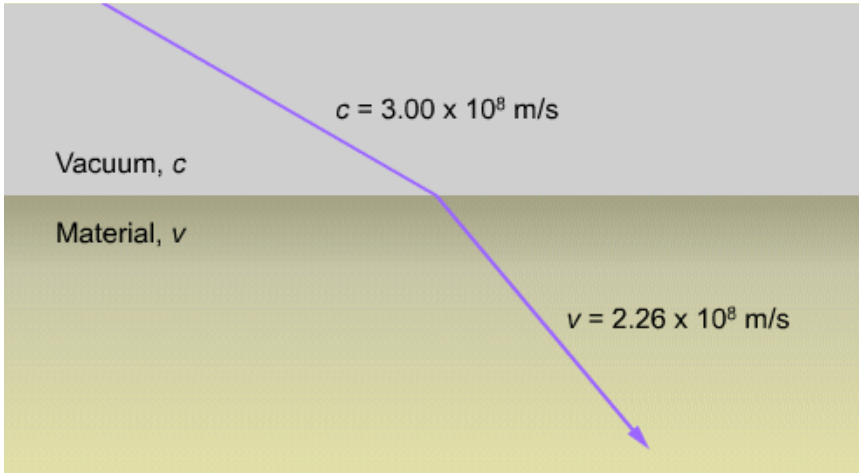
The index of refraction of vacuum is always n=1.

The index of refraction of any material is always n>1.

Origin of the Refractive Index

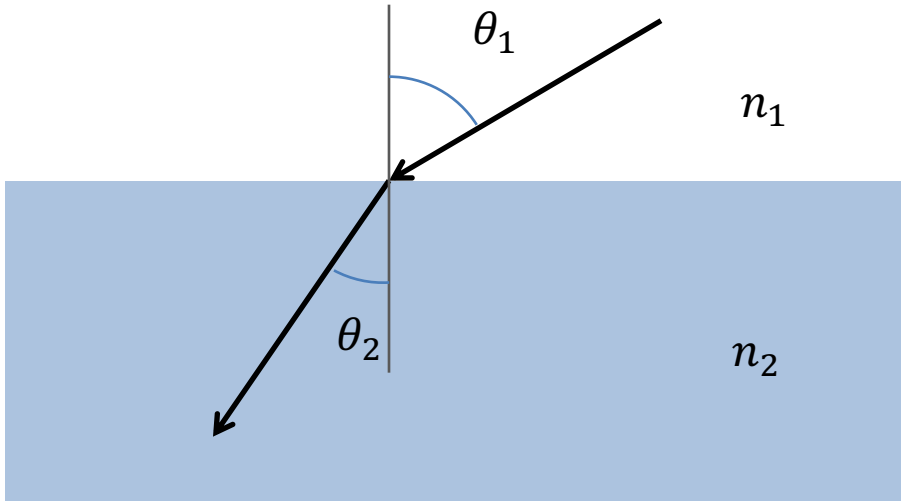
- Refraction is caused by the change in the speed at which light propagates in one material compared to the other.
- The index of refraction (n) is the ratio of the speed of light in vacuum (c) to the speed of light in the material (v).





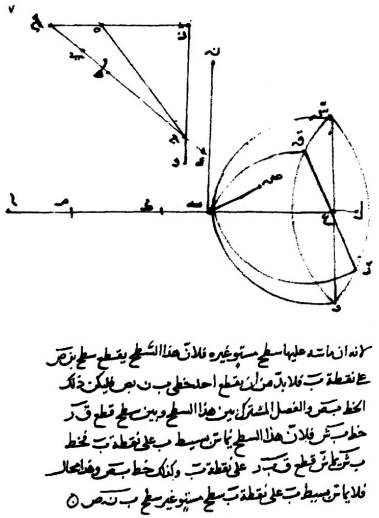
$$n = \frac{c}{v} = \frac{3.00\times10^8\ m/s}{2.26\times10^8\ m/s} = 1.33$$

Snell's Law (1621)*



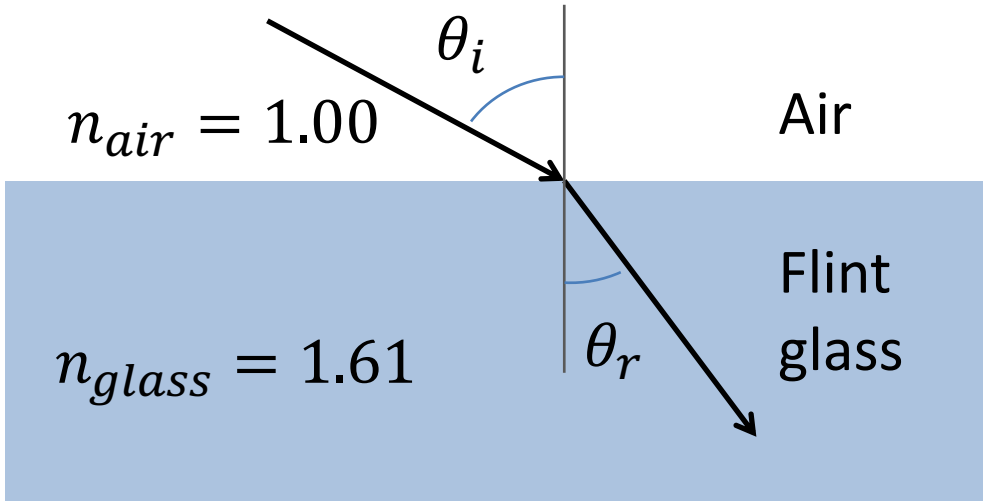
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

We use the convention where light propagates from medium 1 into medium 2.



* First reported by Ibn Sahl, Baghdad – 984 AD.

Examples



$$n_1 \sin(\theta_i) = n_2 \sin(\theta_r)$$

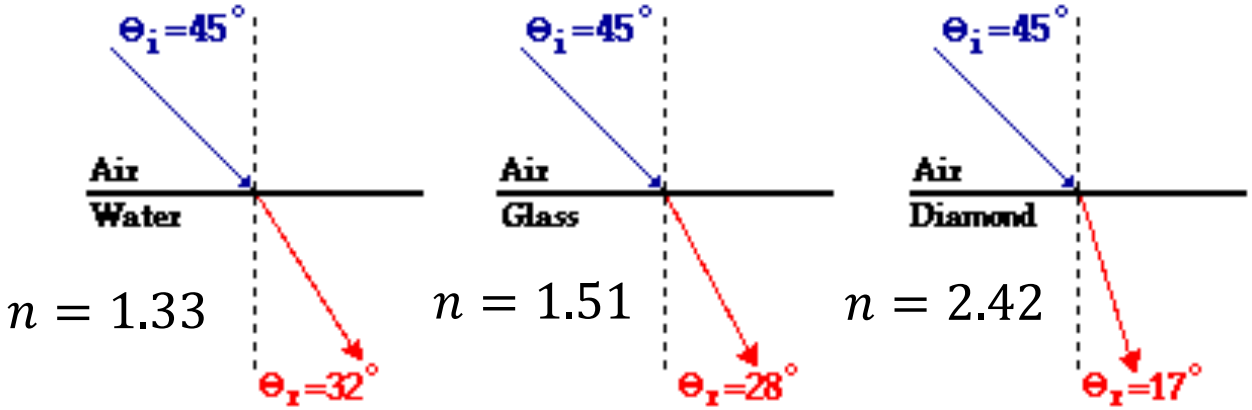
$$\sin(\theta_r) = \frac{n_1}{n_2} \sin(\theta_i)$$

$$= \frac{1.00}{1.61} \times \sin(35°)$$

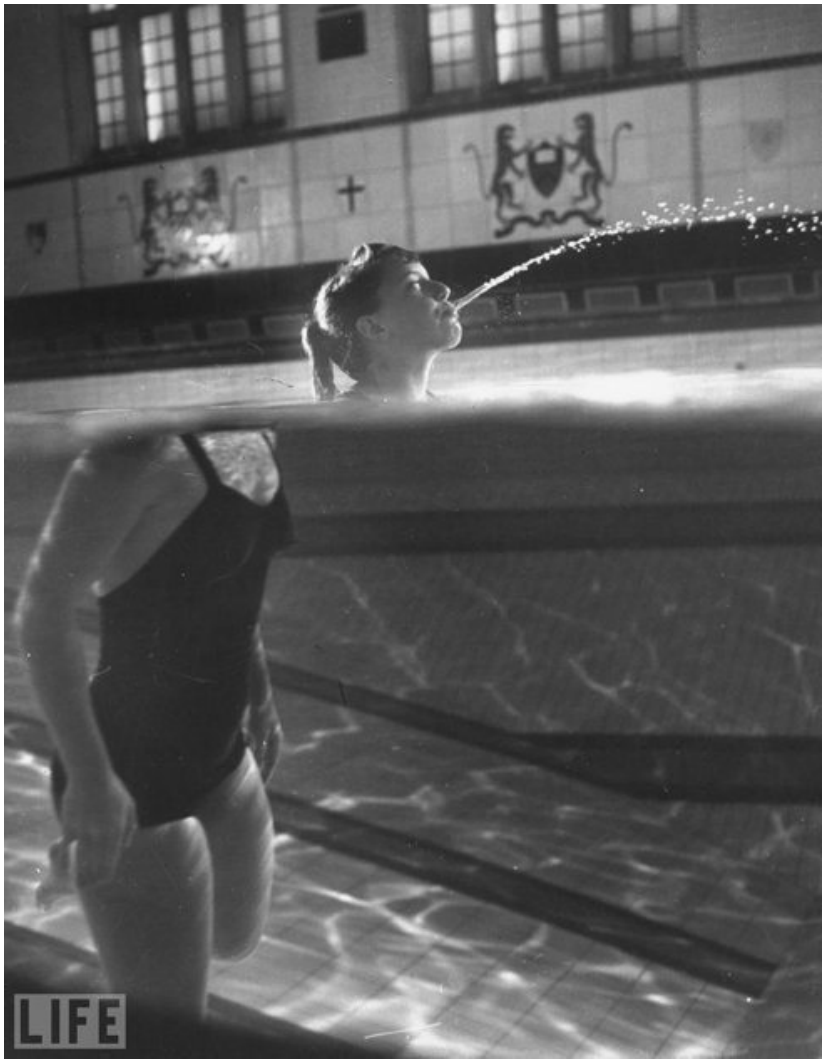
$$= 0.356$$

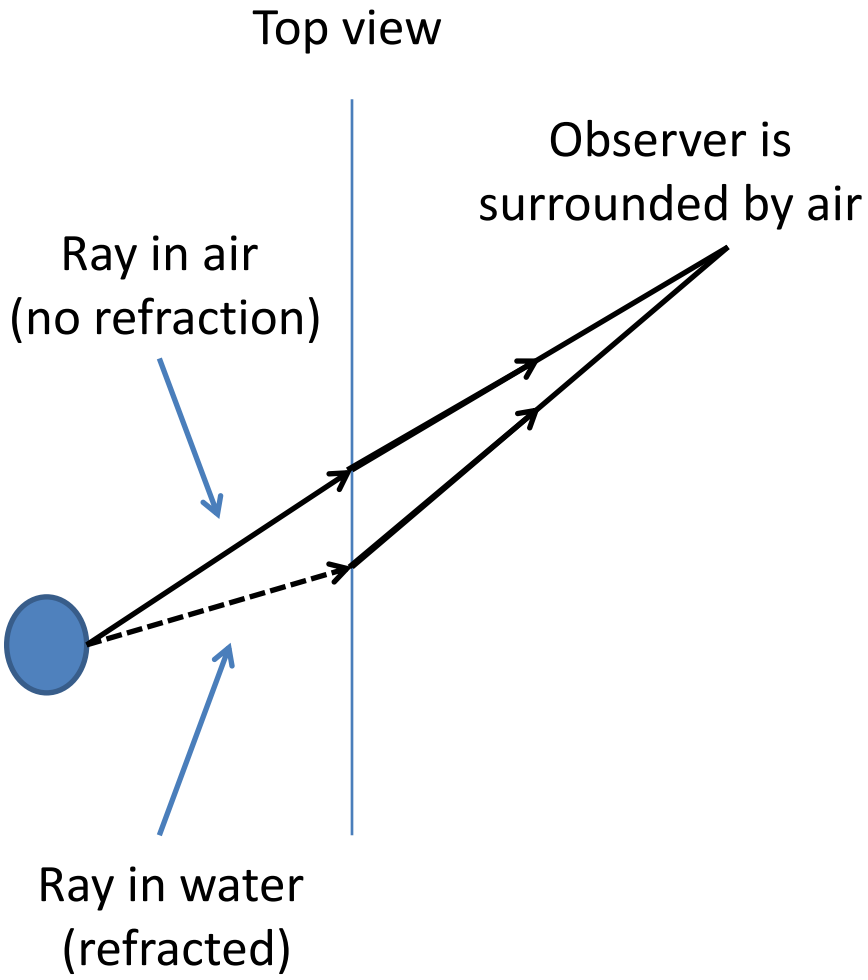
$$\theta_r = \sin^{-1}(0.356)$$

$$\theta_r = 20.9°$$

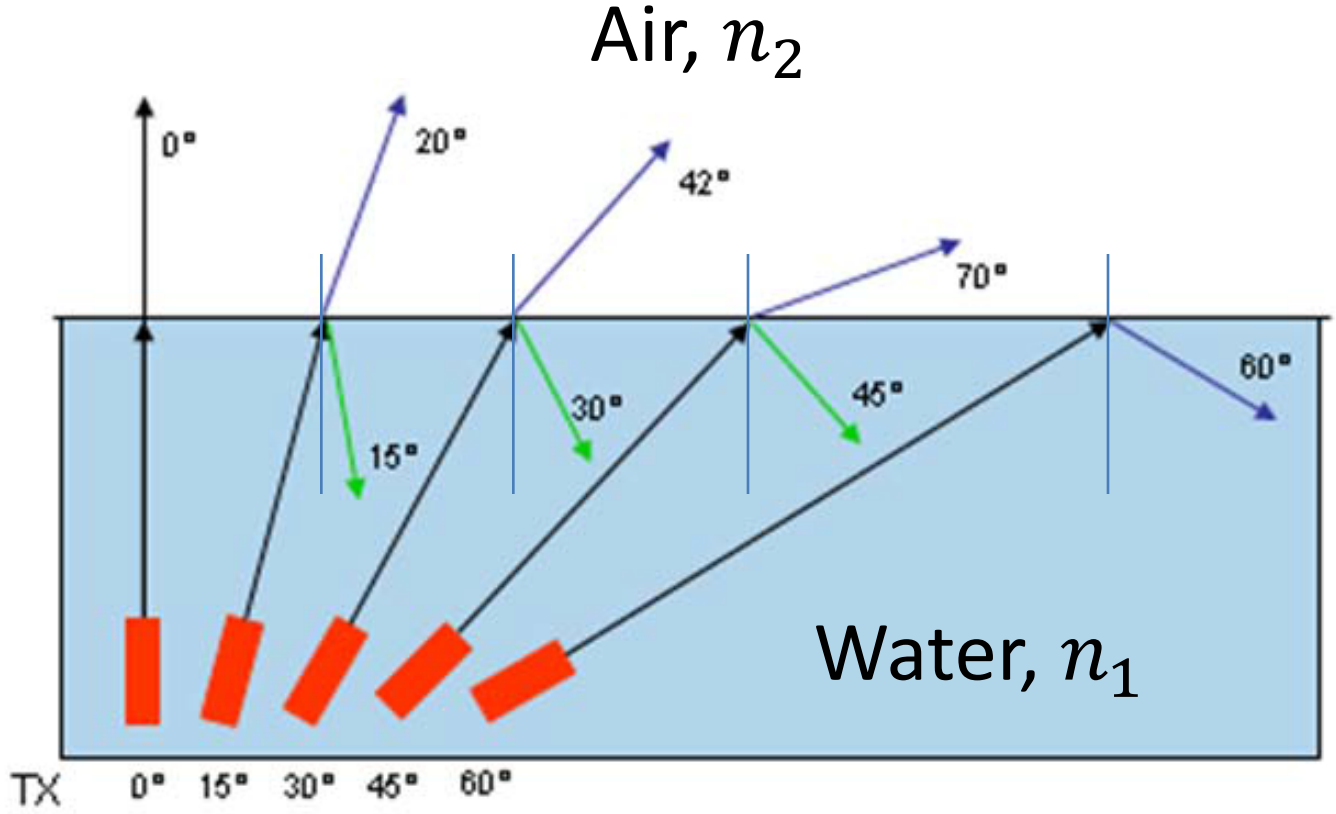


Example


LIFE


Top view
Observer is surrounded by air
Ray in air (no refraction)
Ray in water (refracted)

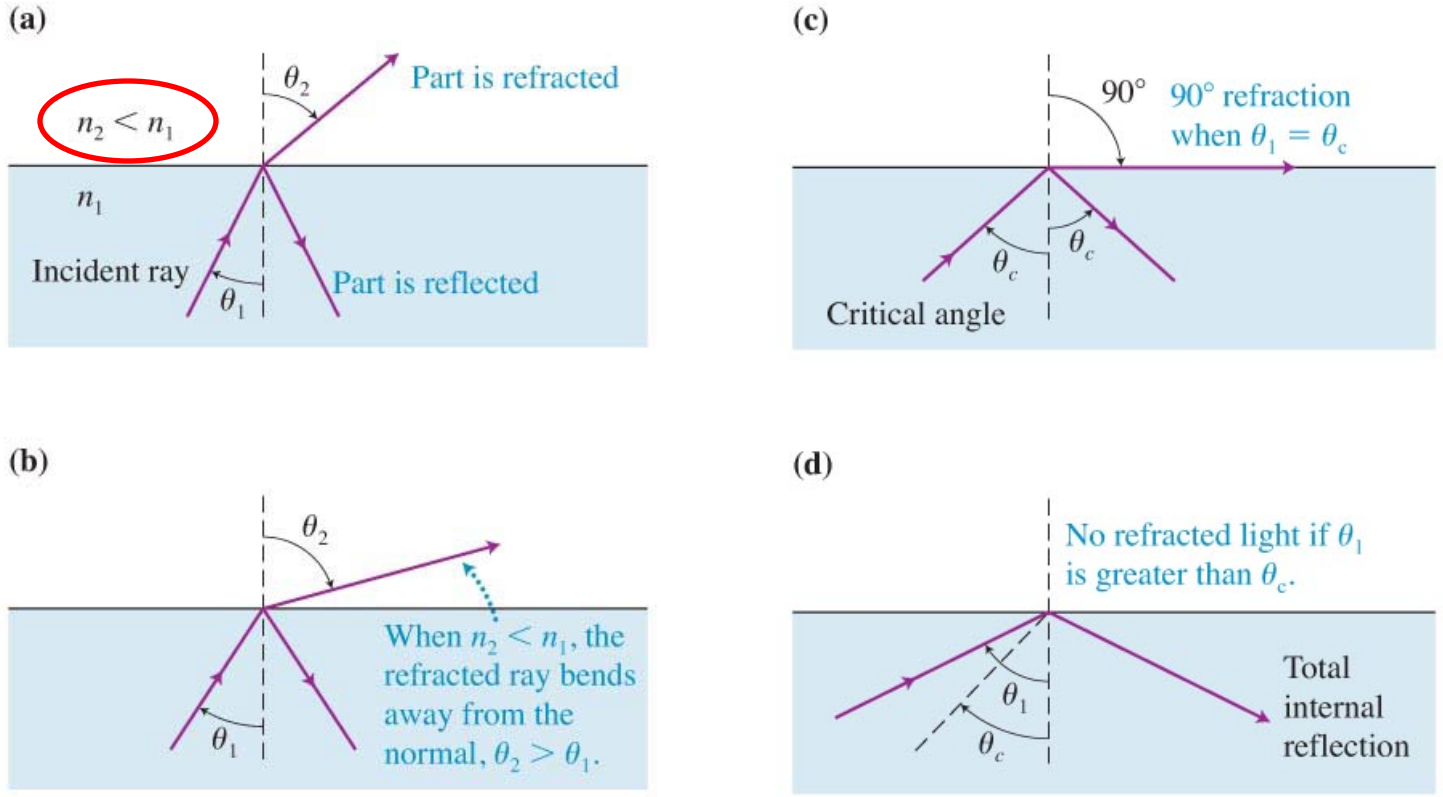
Total Internal Reflection



TIP Total internal reflection occurs only when light travels from a medium with a higher refractive index to a medium with a lower one.

Total Internal Reflection

- At the critical angle of incidence, the angle of refraction is 90° and the refracted ray would travel along the surface of the interface.



Prisms – Dispersion of Light

- The refractive index of most materials depends on the color of light (wavelength).
- In general, n is larger for violet light and smaller for red light.

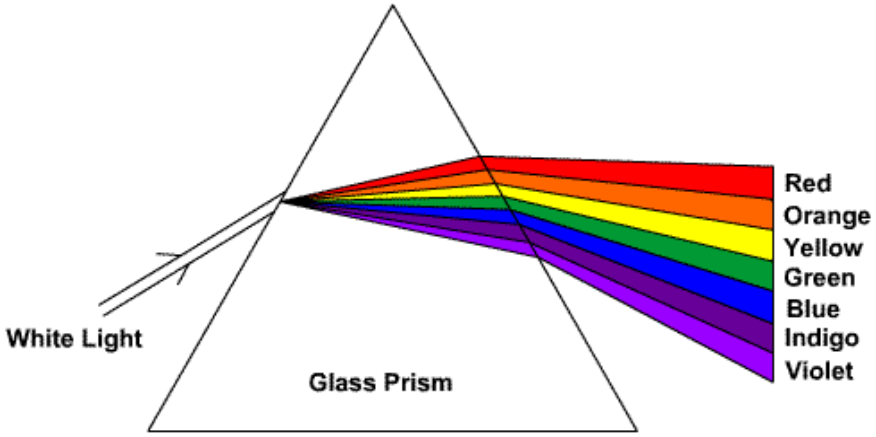
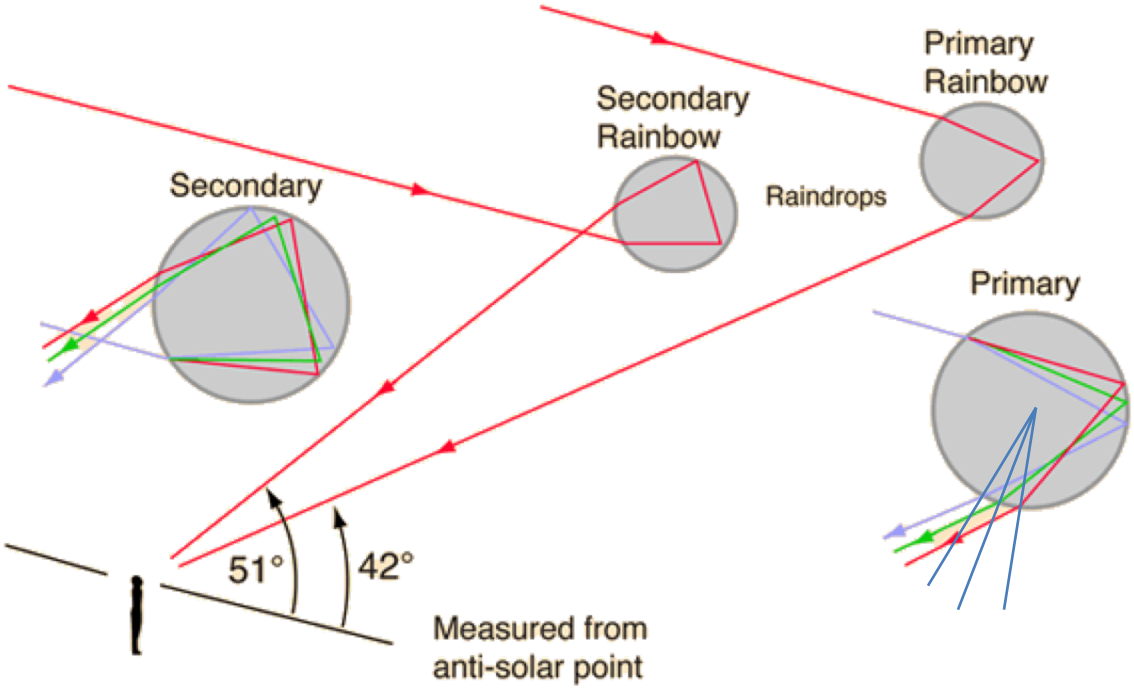


Table 21.8 Refractive indexes of glass for different colors.

Color of Light	n_{glass}
Red	1.613
Yellow	1.621
Green	1.628
Blue	1.636
Violet	1.661

$$n_1 \sin\theta_i = n_2(\lambda) \sin\theta_r$$

Rainbows



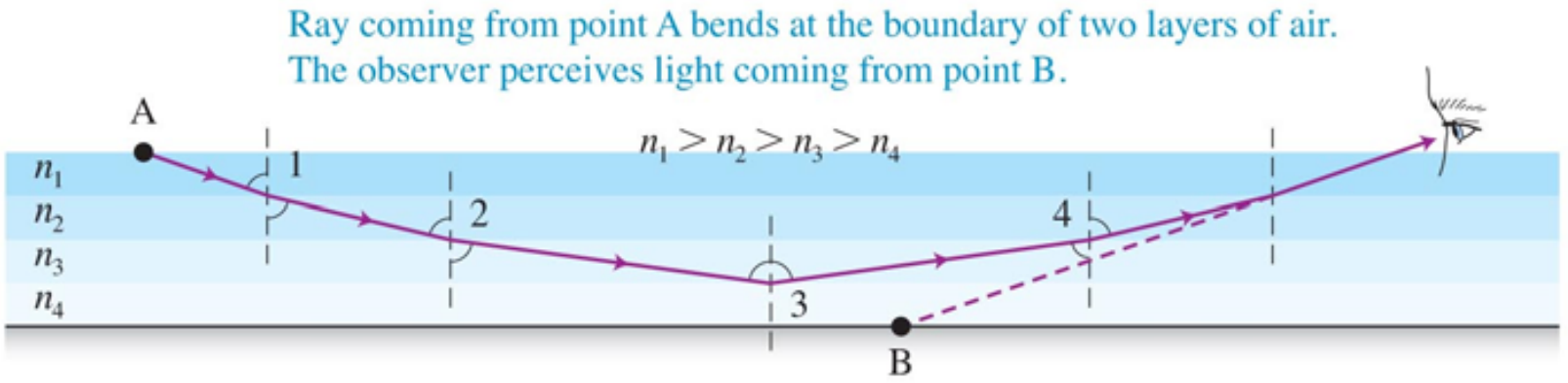
This explains why the colors are reversed on double-rainbows.

Mirages

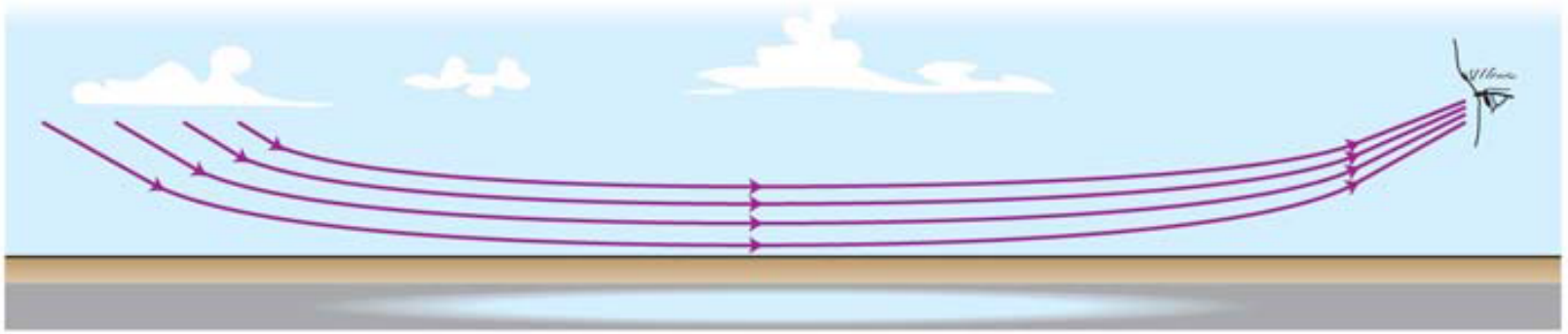
- On a hot day with little or no wind, the hot ground heats a layer of air just above the surface.
- Hot air is less dense and has a lower index of refraction than the cooler air above it.
- When light from the sky passes through air with a gradually changing index of refraction, its path gradually bends.

Mirages

(a)



(b)



Blue region is perceived as water, but is really formed by light from the sky.