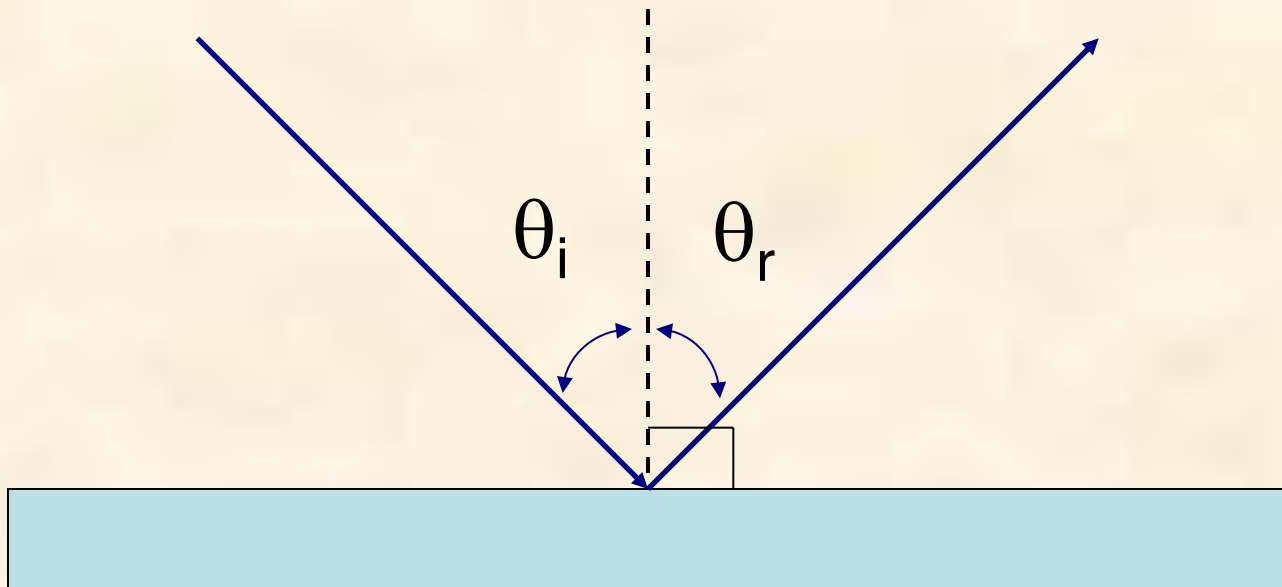


Law of Reflection

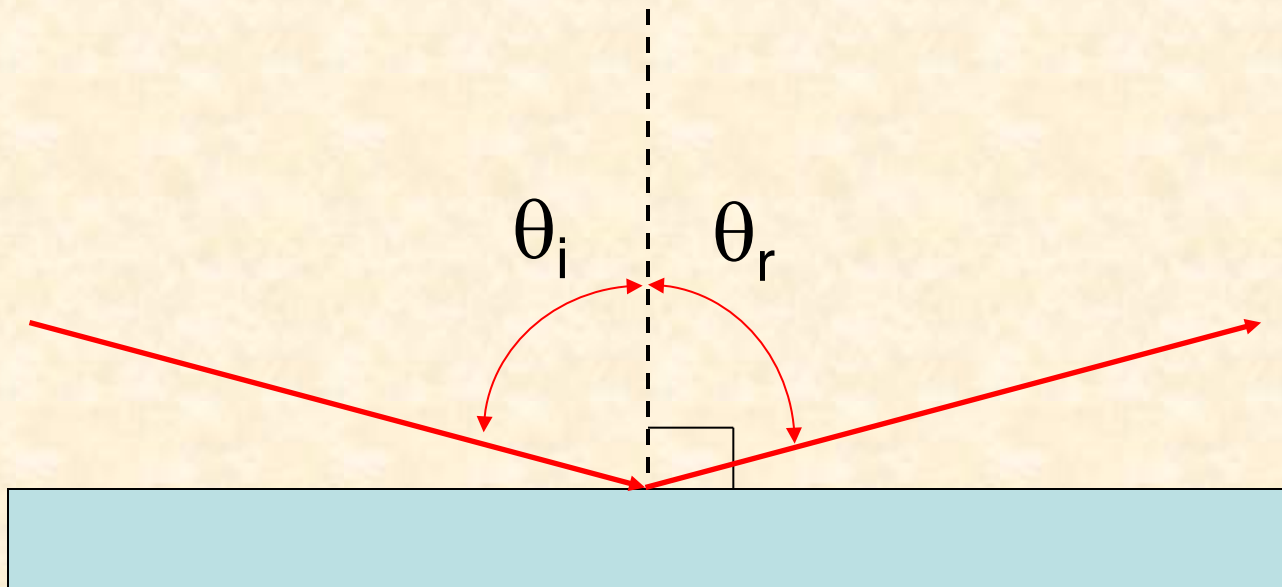
- Angle of incidence = angle of reflection



$$\theta_i = \theta_r$$

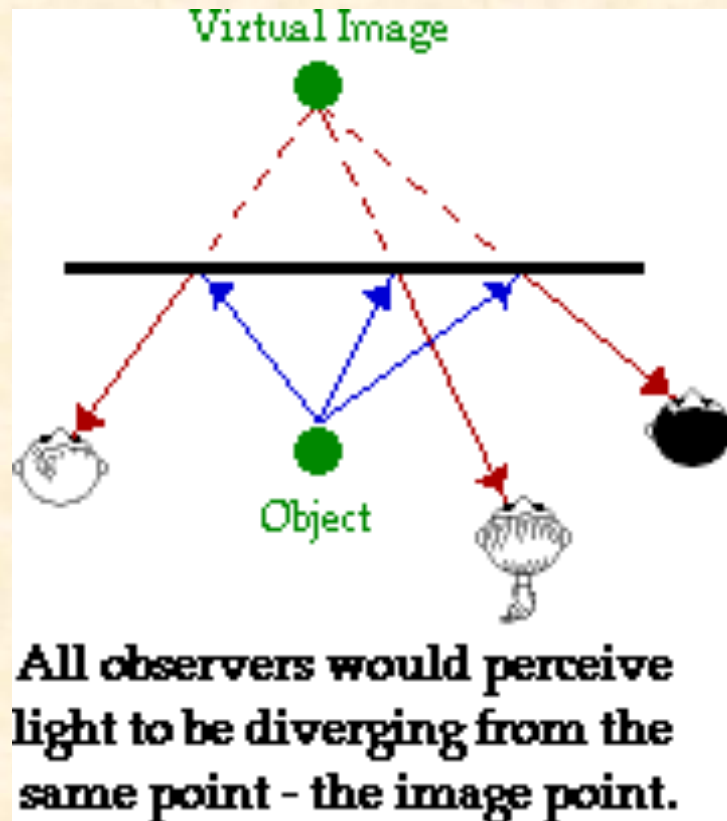
Law of Reflection

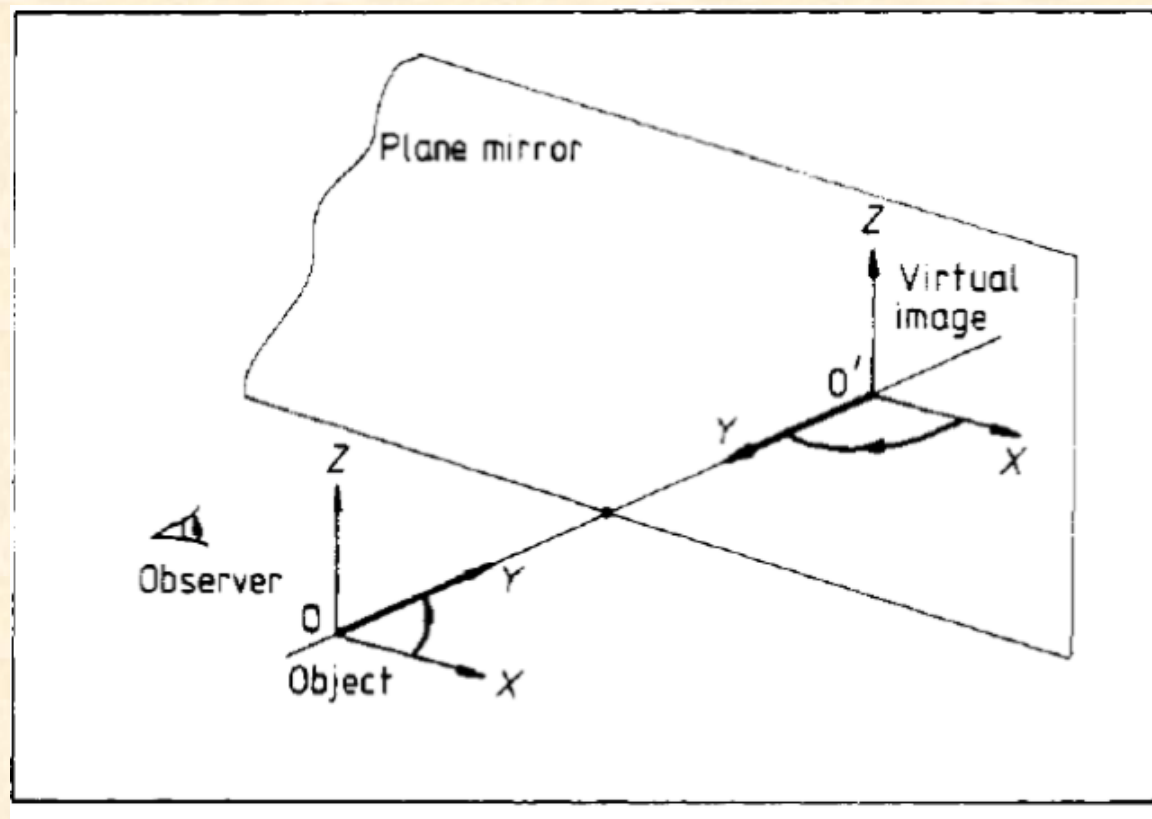
- Angle of incidence = angle of reflection



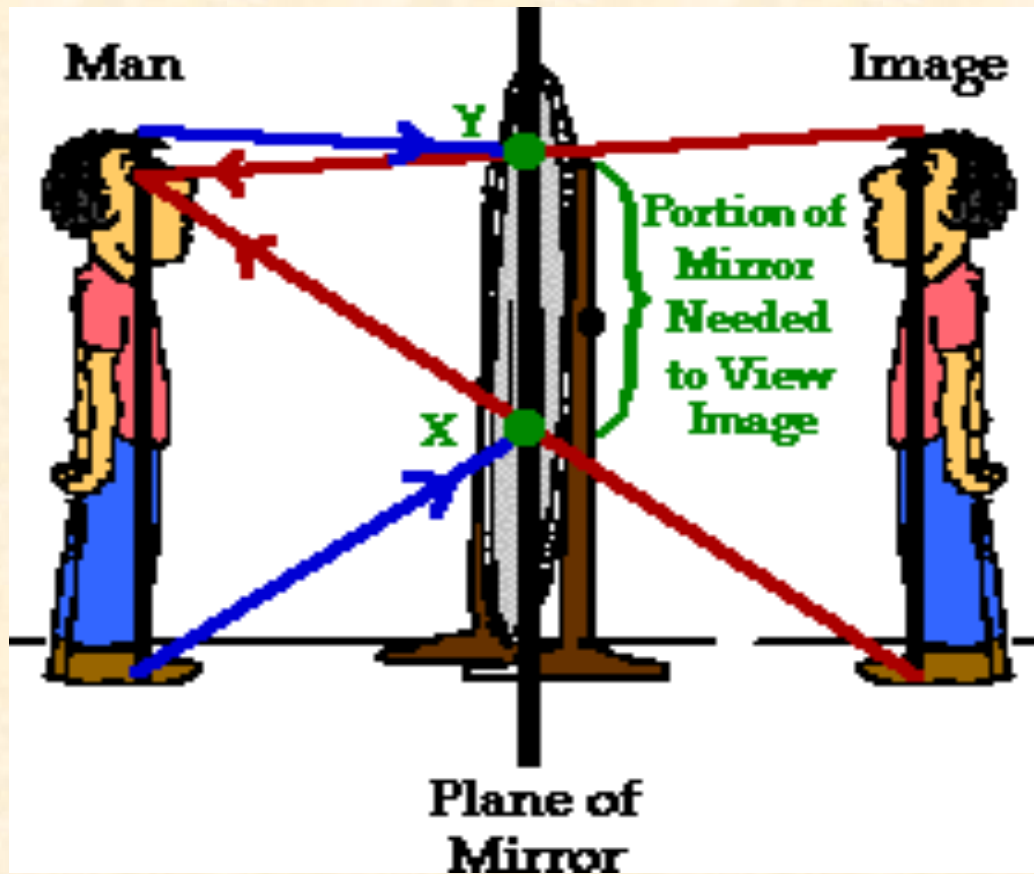
$$\theta_i = \theta_r$$

Your mind uses the direction of the rays to decide where the object is...





Full Length Mirror

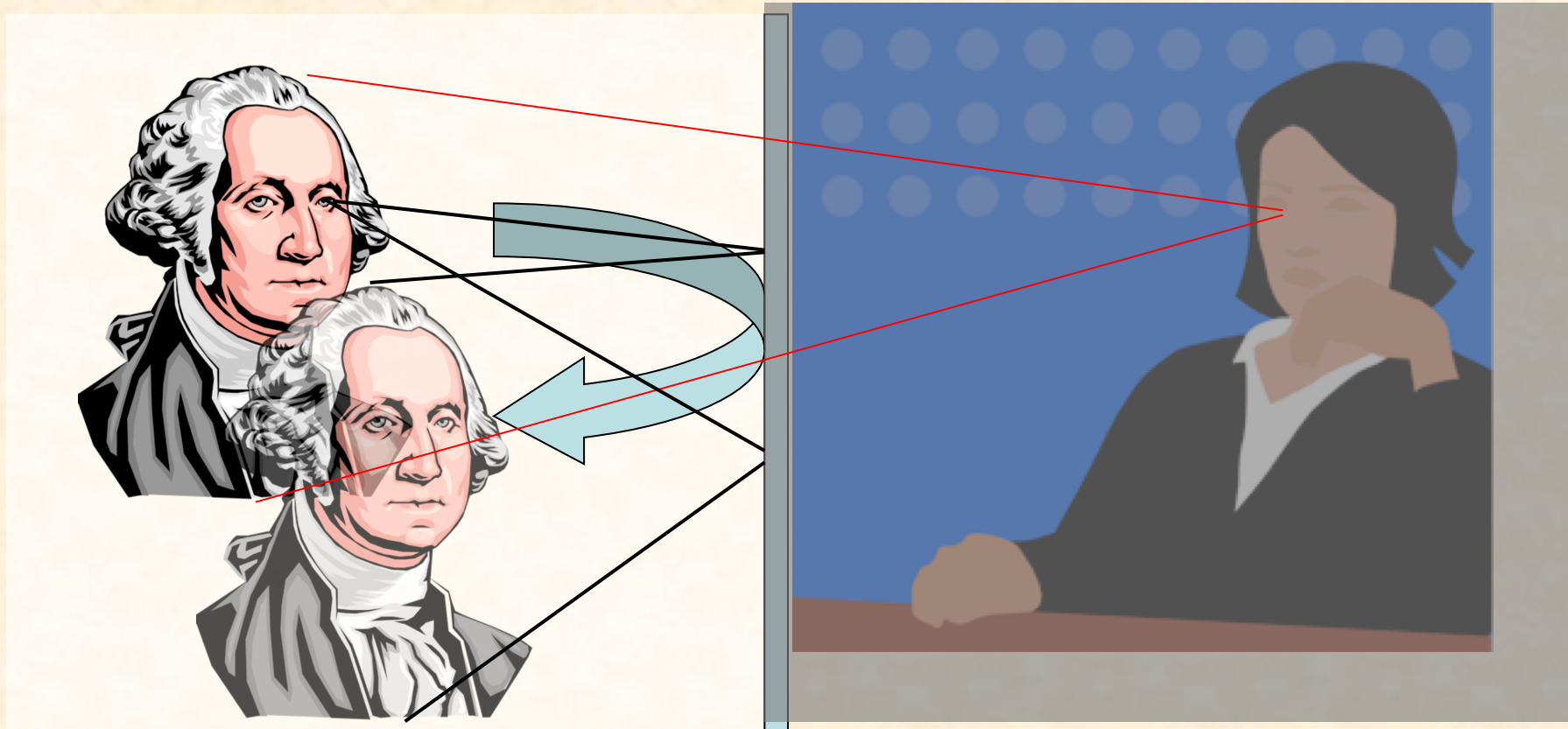


“One-way” mirrors

Half-silvered mirror

(reflects 50%, transmits 50%)

Could also be 90% reflecting and 10% transmission



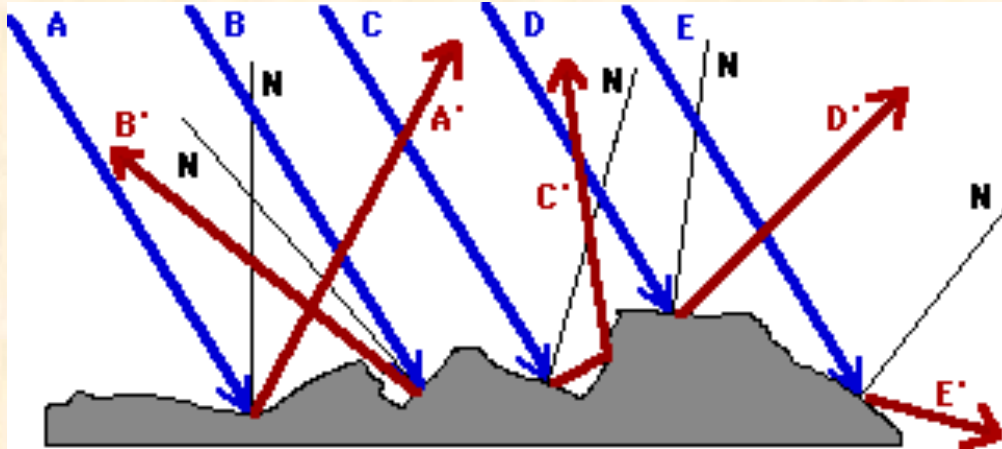
Test of Nerve?

An artist has created a usable public toilet in a glass cube to challenge the curiosity - and bravery - of people passing London's Tate Britain gallery





Diffuse Reflections



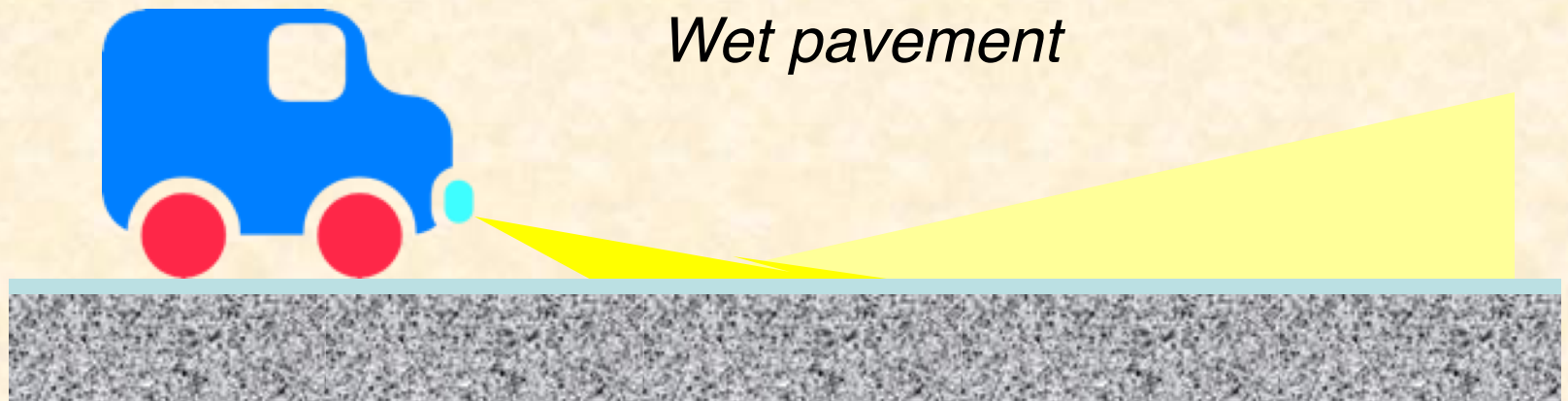
- Examples -
 - Paper
 - Movie theater screen
 - Dry pavement

Why do your headlights appear less bright to you on the road on a rainy night?

1. The rain absorbs & scatters the light
2. The light reflects off the wet road away from you
3. The light reflects in all directions from the wet road

Specular vs. Diffuse

- Specular obeys law of reflection
- Diffuse does not (except microscopically)



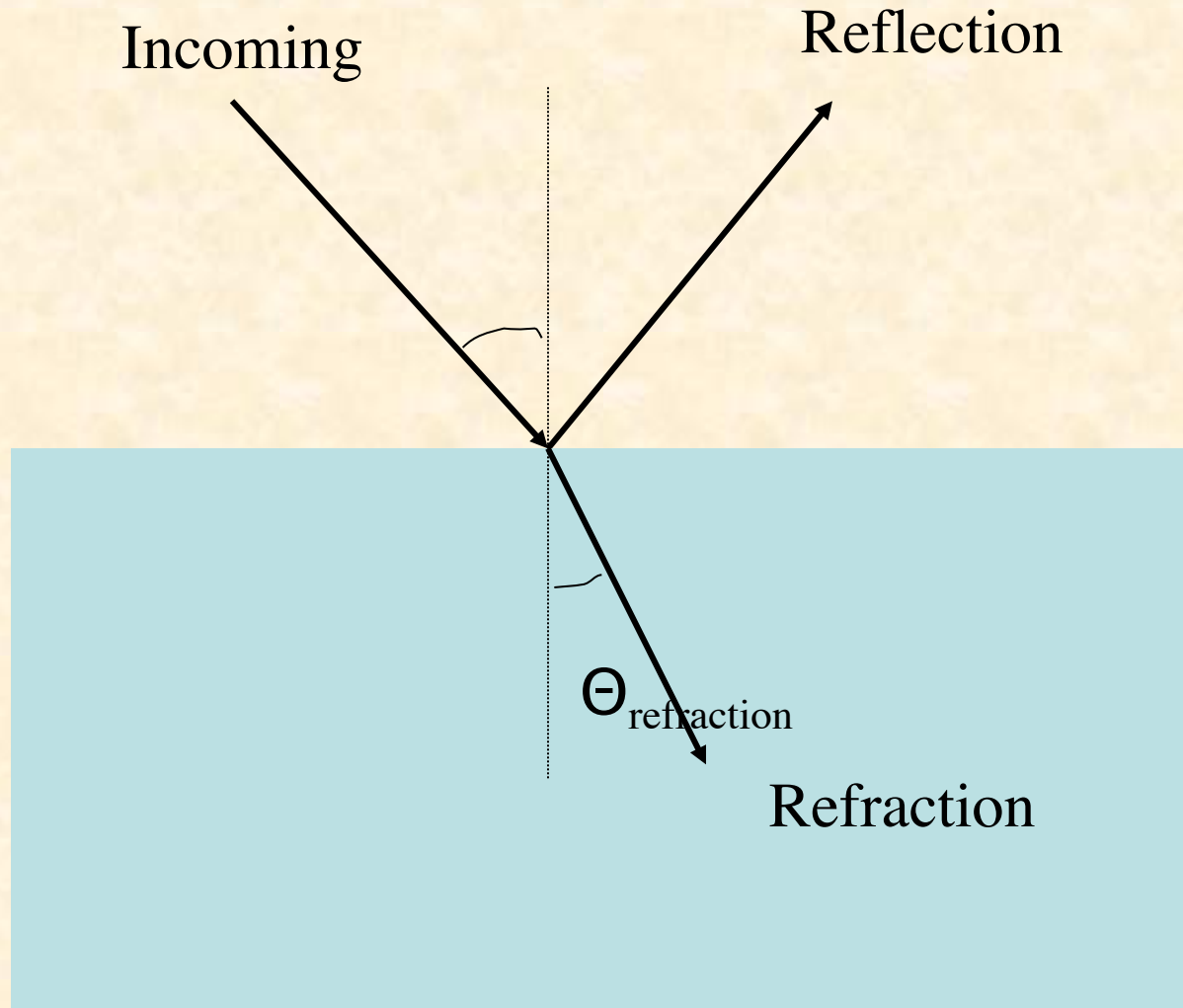
Wet Roads



Refraction

- Recall: when a wave enters a medium where the speed changes, some is **reflected**
- The angle of the transmitted portion is changed - this is **refraction**

Refraction



Index of refraction

- Index of the refraction, n , is defined as

$$n = c/v \quad \text{V: velocity of light in medium}$$

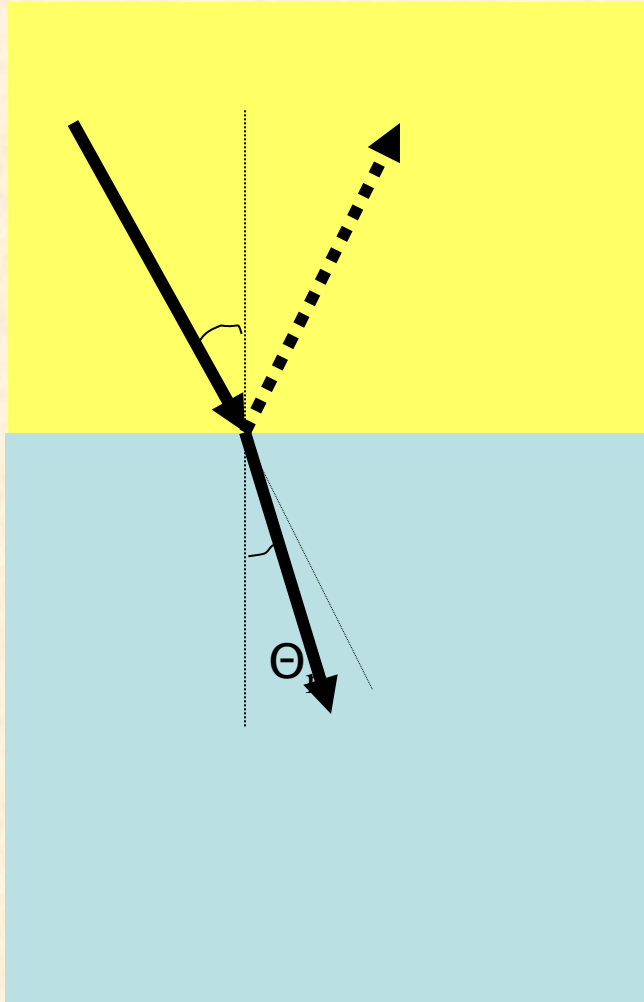
- Examples

– Vacuum	$n = 1$
– Air	$n = 1.0003$
– Water	$n = 1.33$
– Glass	$n = 1.5$
– Diamond	$n = 2.4$

Law of refraction

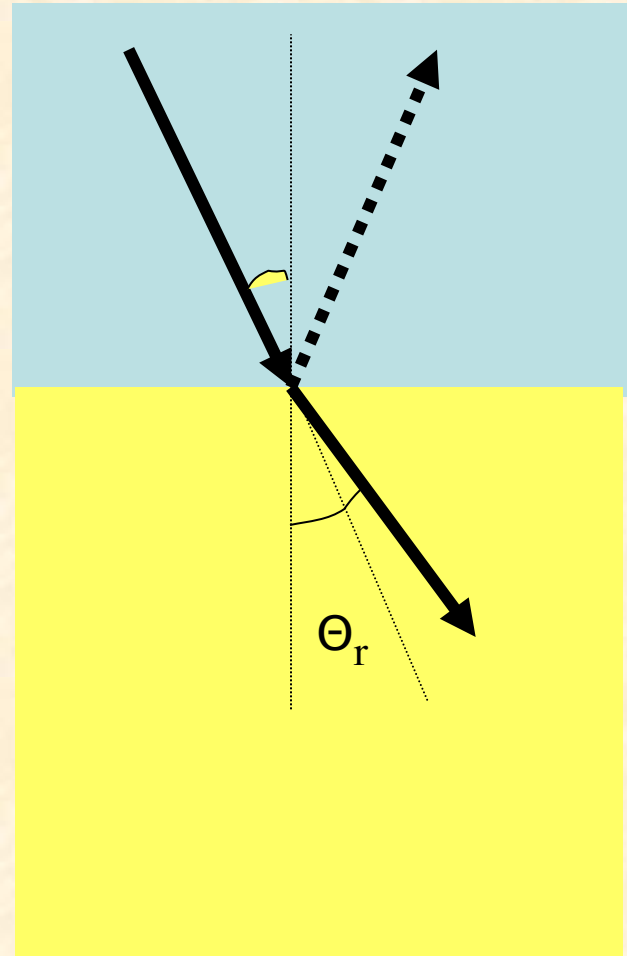
- When light goes from a medium with smaller index of refraction to a medium with larger index of refraction, it bends toward the normal.
- When light goes from a medium with larger index of refraction to a medium with smaller index of refraction, it bends away from the normal.

Air



Water

Water



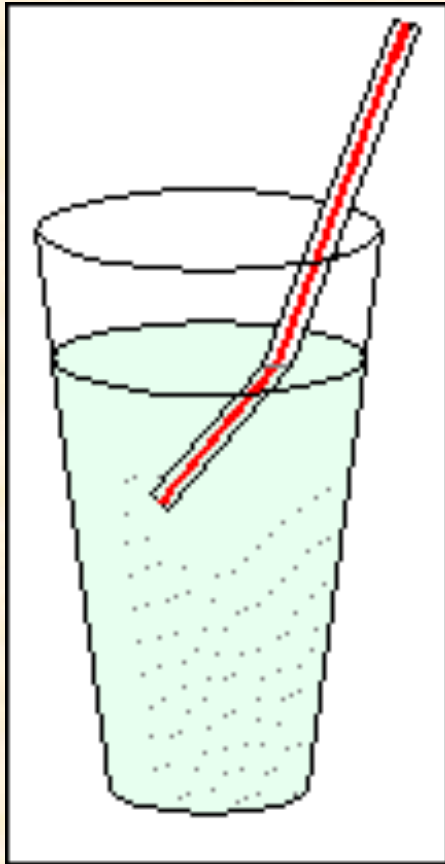
Air

Snell's Law

$$n_i \sin \theta_i = n_f \sin \theta_f$$

- From air to water, $\theta_{\text{air}} = 30^\circ$ then $\theta_{\text{water}} = 22^\circ$
- From water to air, if $\theta_{\text{water}} = 22^\circ$, then $\theta_{\text{air}} = 30^\circ$,
or if $\theta_{\text{water}} = 30^\circ$ then $\theta_{\text{air}} = 42^\circ$

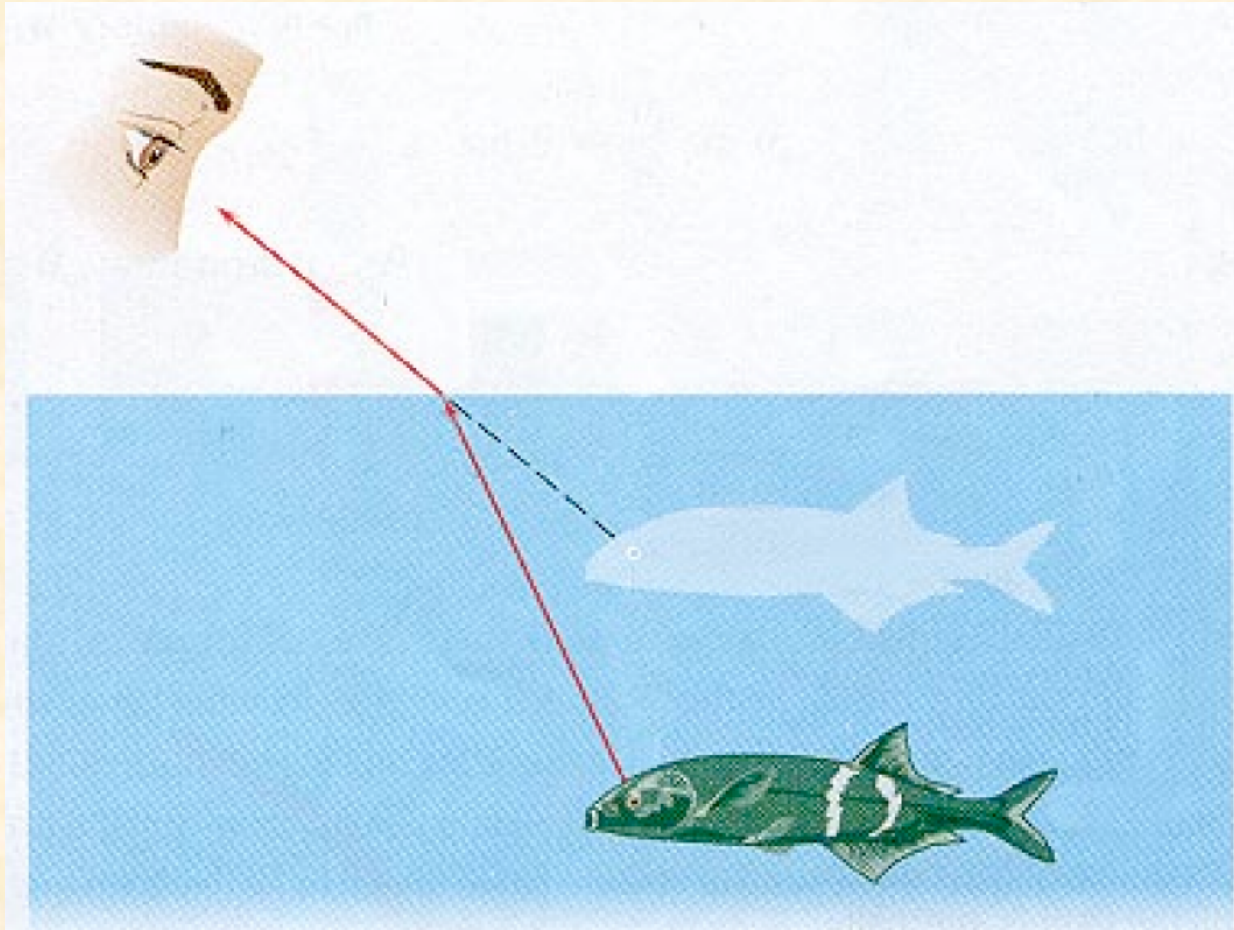
Straw illusion:



A straight straw
appears to have
bent in water
due to refraction.



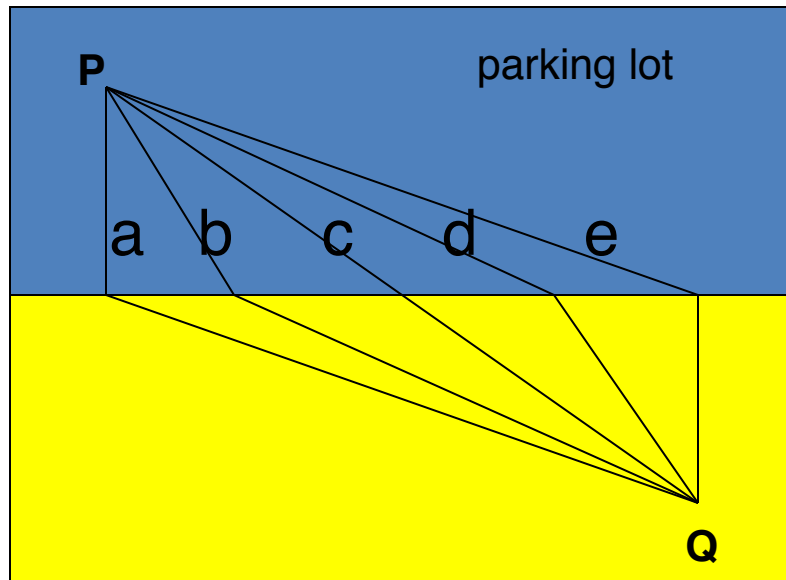
Spear fishing



Spear-fishing is made more difficult by the bending of light. To spear the fish in the figure, one must aim at a spot in front of the fish

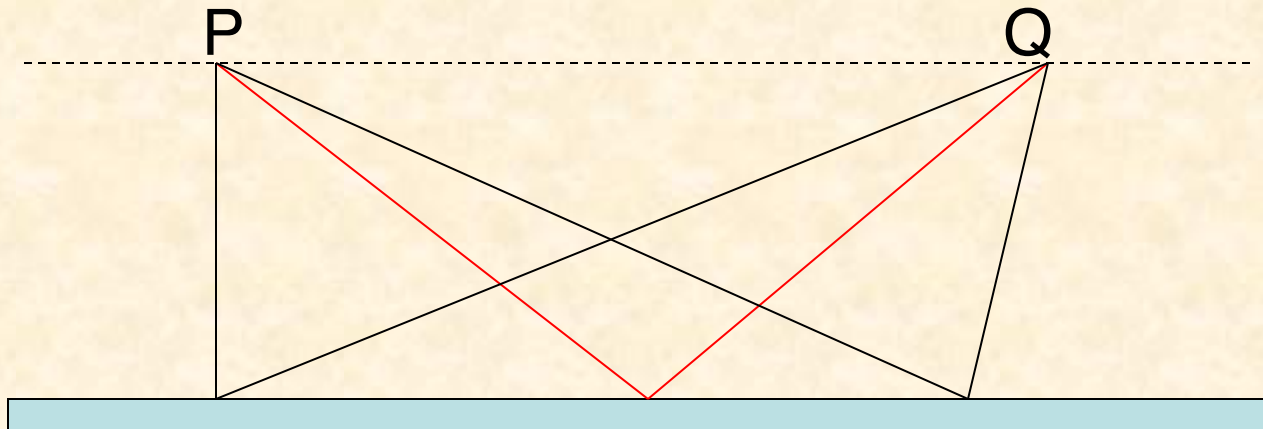
A group of sprinters gather at point P on a parking lot bordering a beach. They must run across the parking lot to a point Q on the beach as quickly as possible.

Which path from P to Q wins? You should consider the relative speeds of the sprinters on the hard surface of the parking lot and on loose sand.

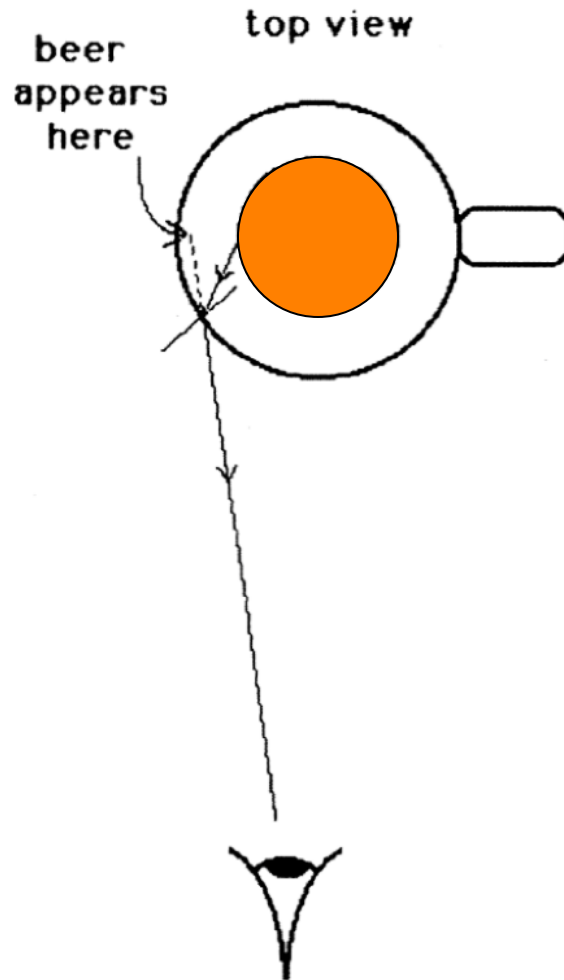


Fermat's Principle

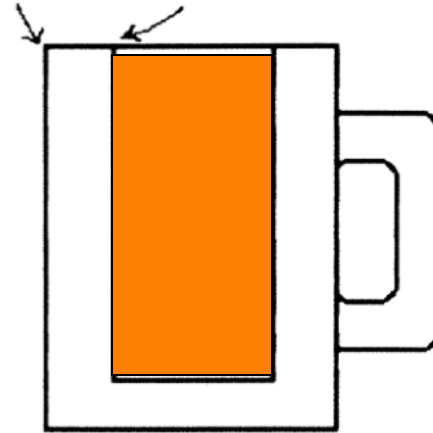
Light travels in the path that takes the least amount of time.



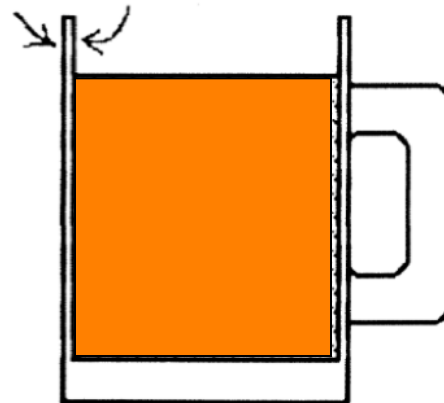
Beer Mug



actual thickness

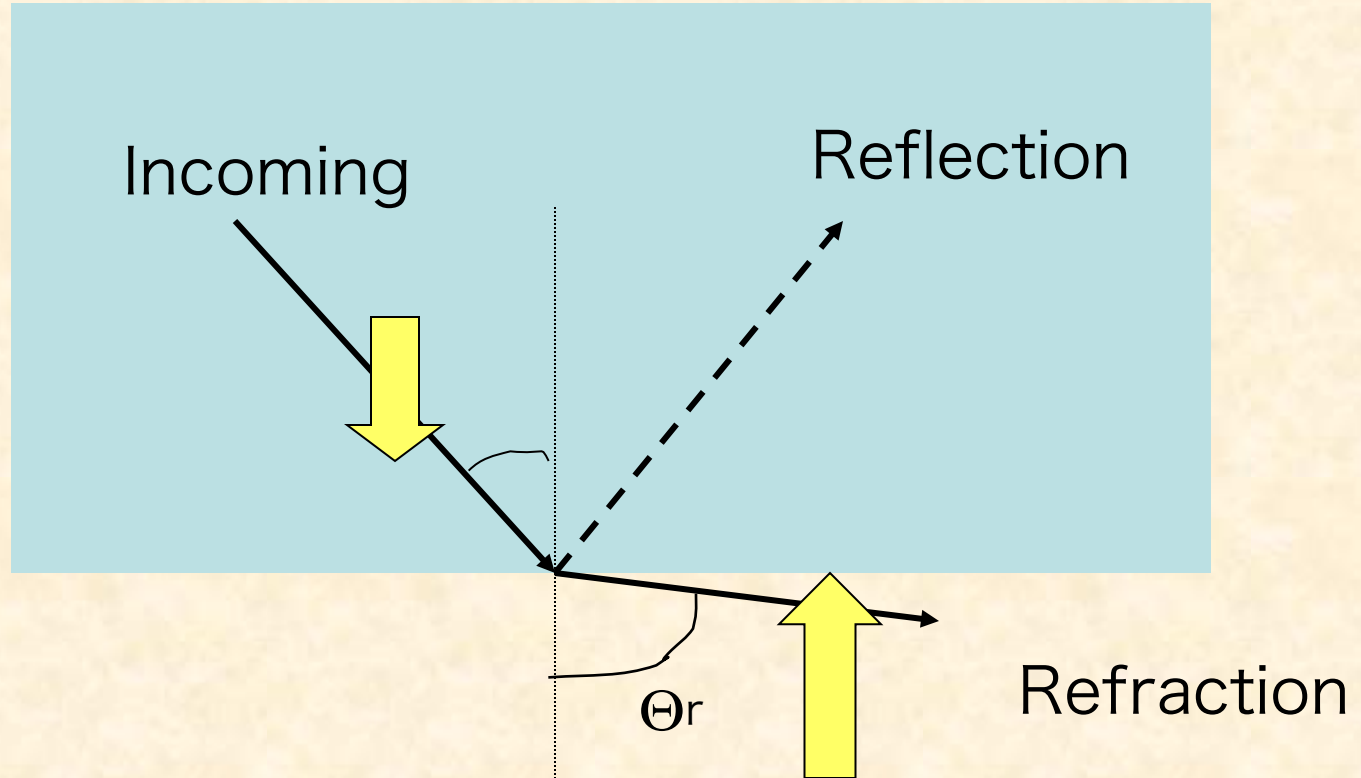


apparent thickness



Total Internal Reflection

- Remember that when the light goes from a dense (**large n**) to a less dense medium (**small n**), the angle of transmission is larger....
- From water to air, if the incident angle is $\sim 50^\circ$, the transmitted angle $\sim 90^\circ$. **If the incident angle is larger, there is NO transmission at all!**



<http://www.lon-capa.org/~mmp/kap25/Snell/app.htm>

<http://www.phy.ntnu.edu.tw/java/light/flashLight.html>

Critical Angle

- The incident angle at which the total internal reflection just occurs is called the **critical angle**.
 - From glass to air, 42°
 - From water to air, 50°
 - From diamond to air, 24.5°

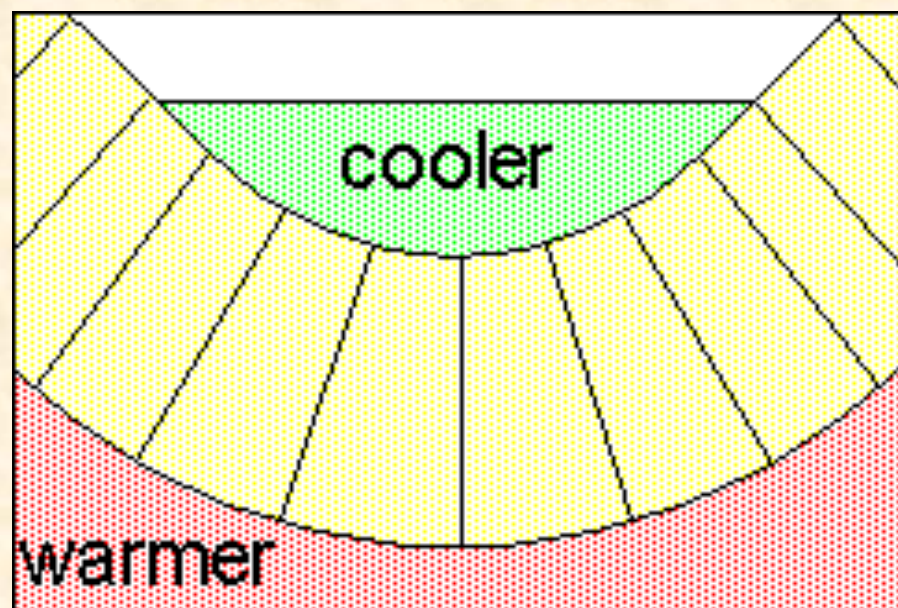
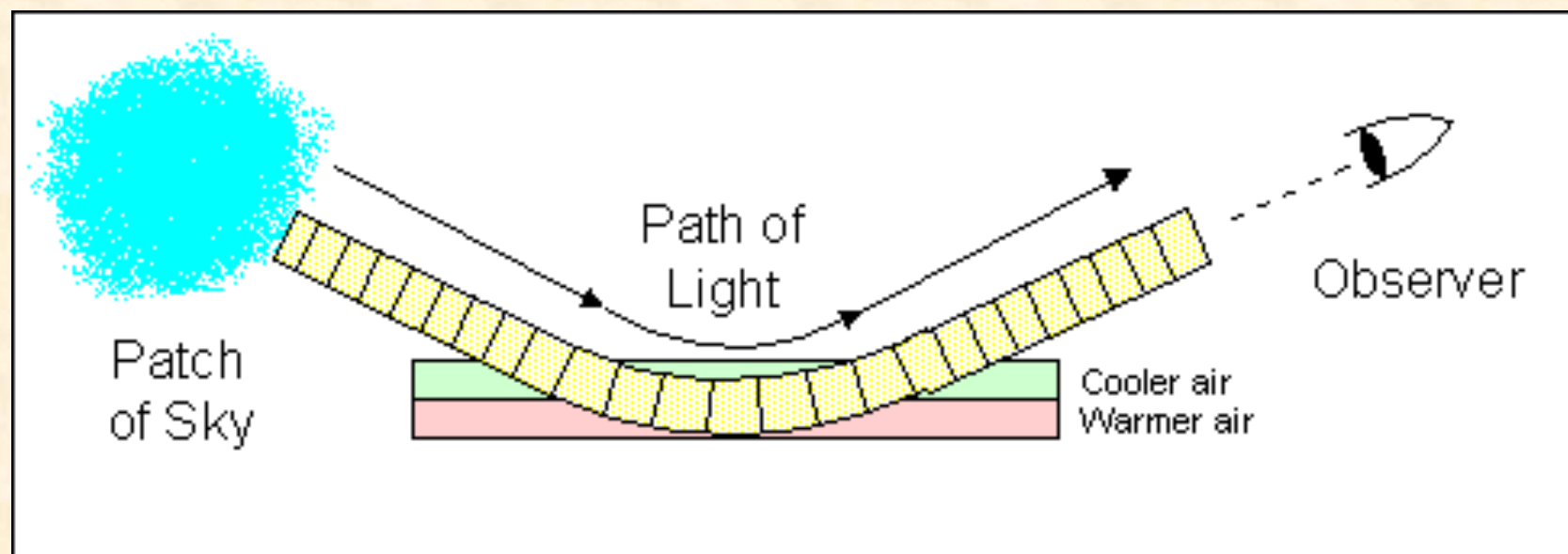
Fiber Optics

- Use thin, flexible glass or plastic fibers as light pipes
- If the light hits the surface at an angle larger than the critical angle, it is totally internally reflected: **No loss of light!**
Thus the light can be used to transmit information through the optical fibers.

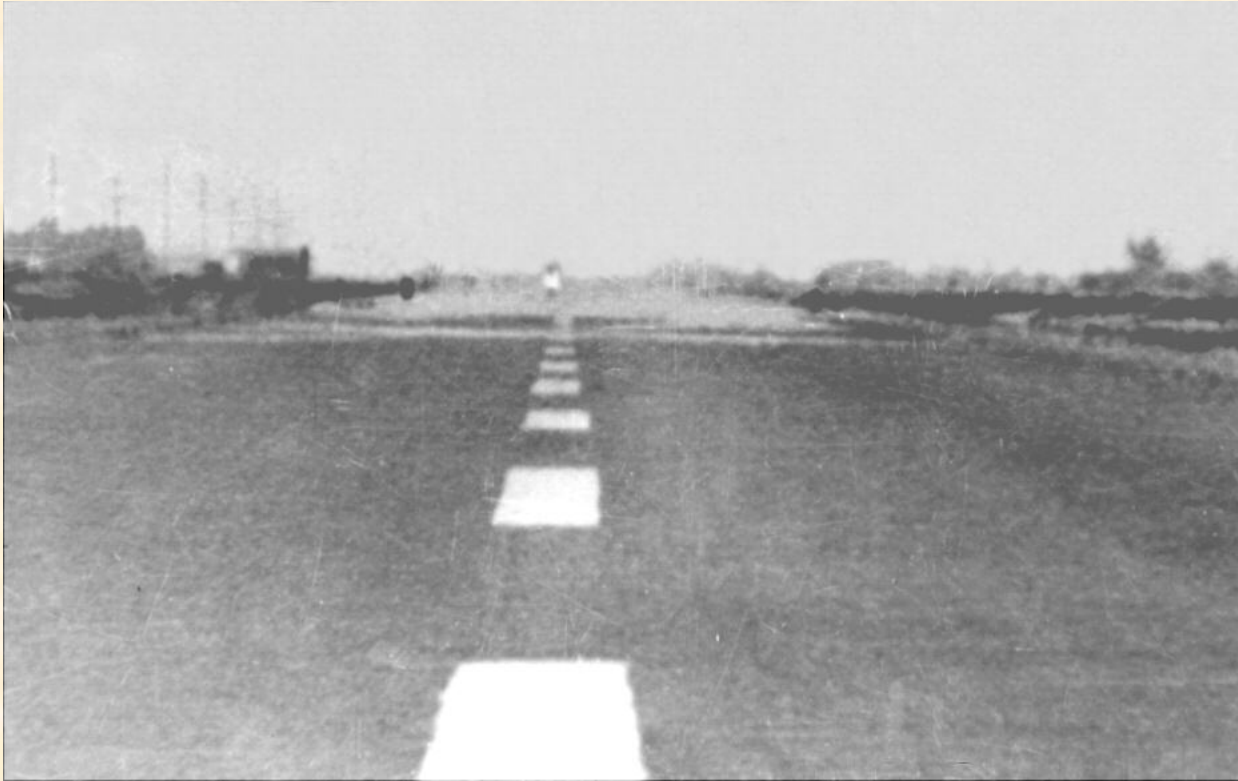
What is a mirage?



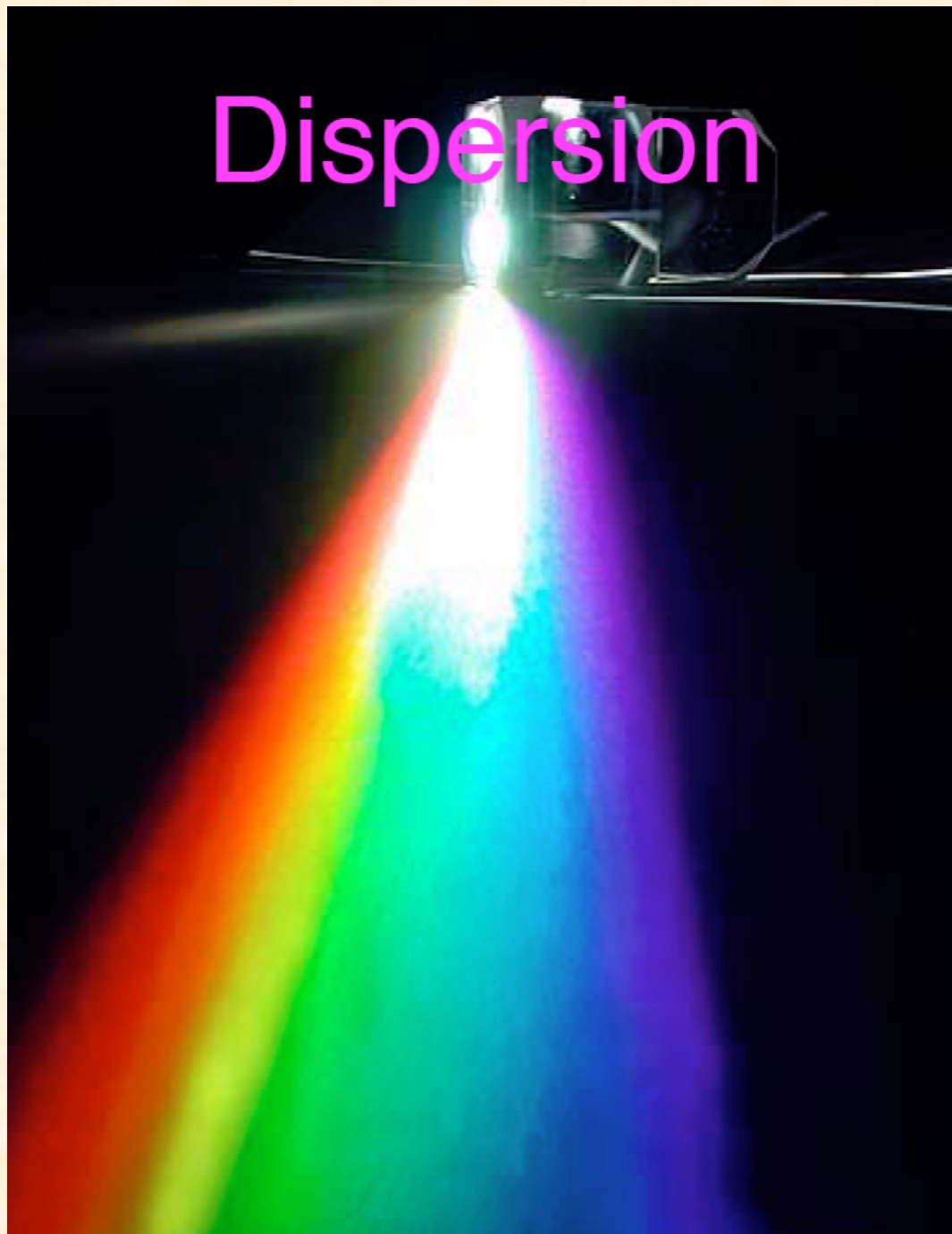
- The index of refraction of the air is not quite equal to 1, and **it changes with temperature**.
- A continuous change of the index of refraction makes a light bend from its original direction.
- A hot, dark asphalt road can cause the light to bend, producing a mirage.



Wet Road Mirage

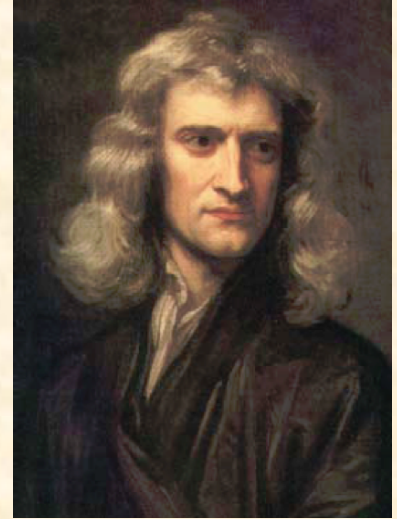


Dispersion



Newton's Discovery

- Newton (at the age of 23) reached the revolutionary conclusion that white light is not a simple, homogenous entity, as natural philosophers since Aristotle had believed.
- When he passed a thin beam of sunlight through a glass prism, he noted the oblong spectrum of colors: red, yellow, green, blue, violet— that formed on the wall opposite.



Sir Isaac Newton, age 47

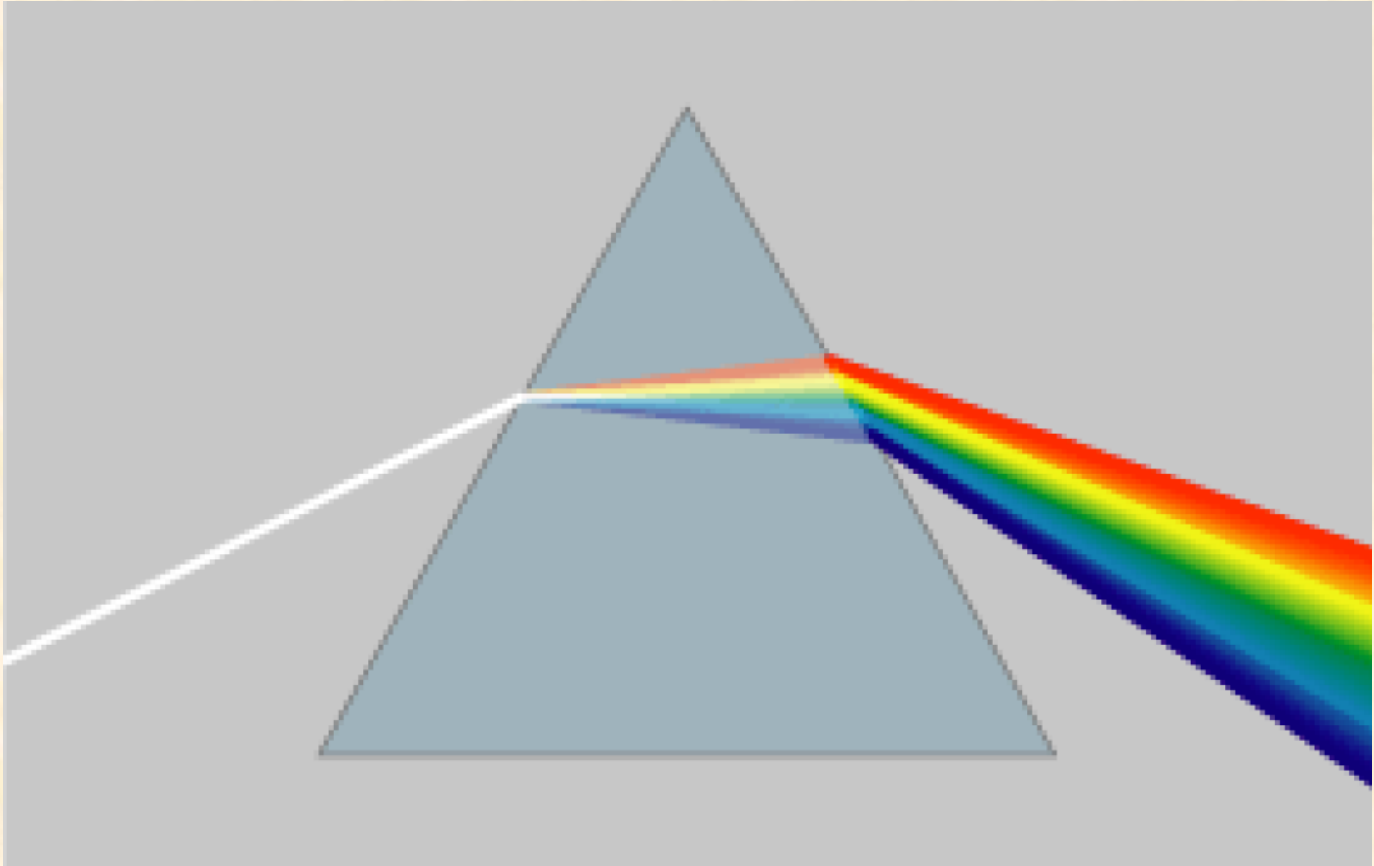
Dispersion

- The index of refraction is frequency-dependent.

		water	glass	diamond
Red	$\lambda=656$ nm	1.331	1.571	2.410
Yellow	$\lambda=589$ nm	1.333	1.575	2.418
Blue	$\lambda=434$ nm	1.340	1.594	2.450

- Snell's Law $\Rightarrow$ different colors refract by different angles

Dispersing Prism

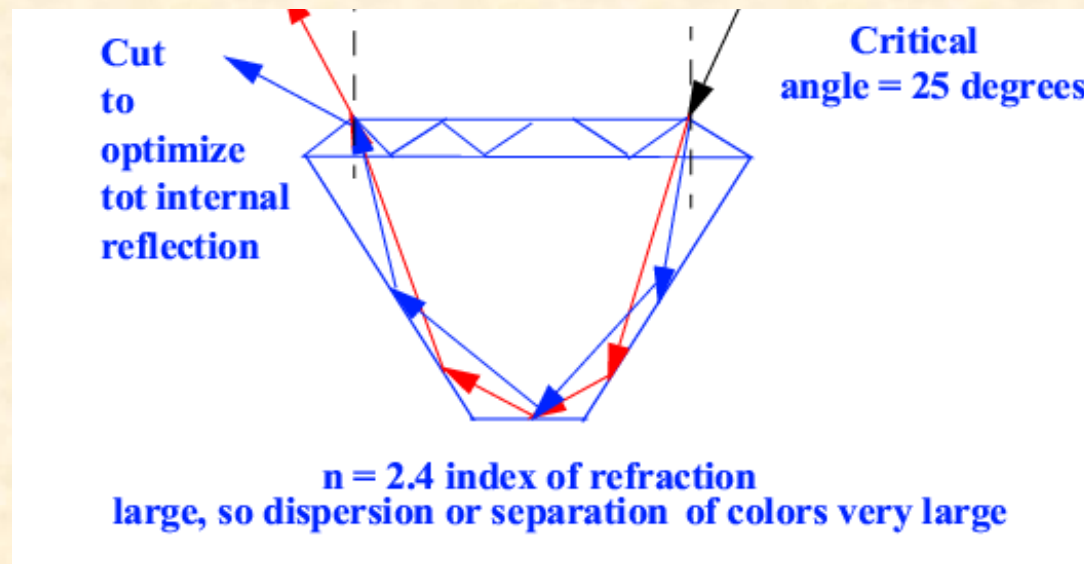
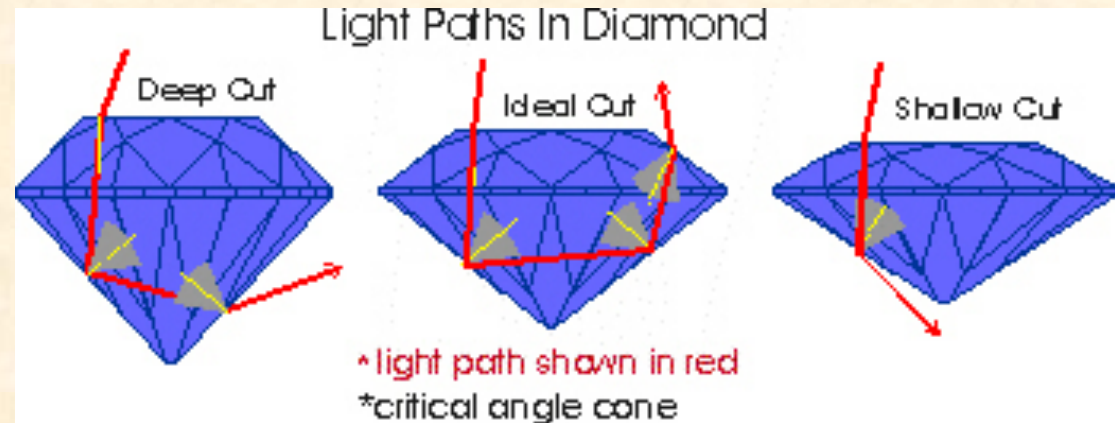


Since $n_{\text{blue}} > n_{\text{red}}$, blue is bent to greater angle

Optical properties of diamond

- Diamonds has a large index of refraction ($n=2.4$) and a small critical angle 24.5° .
- The diamond surfaces are cut so that most of light entering a diamond is eventually reflected back out the front $\Rightarrow$ **brilliance!**
 - if you look from the back, the diamond is black.

The right cut

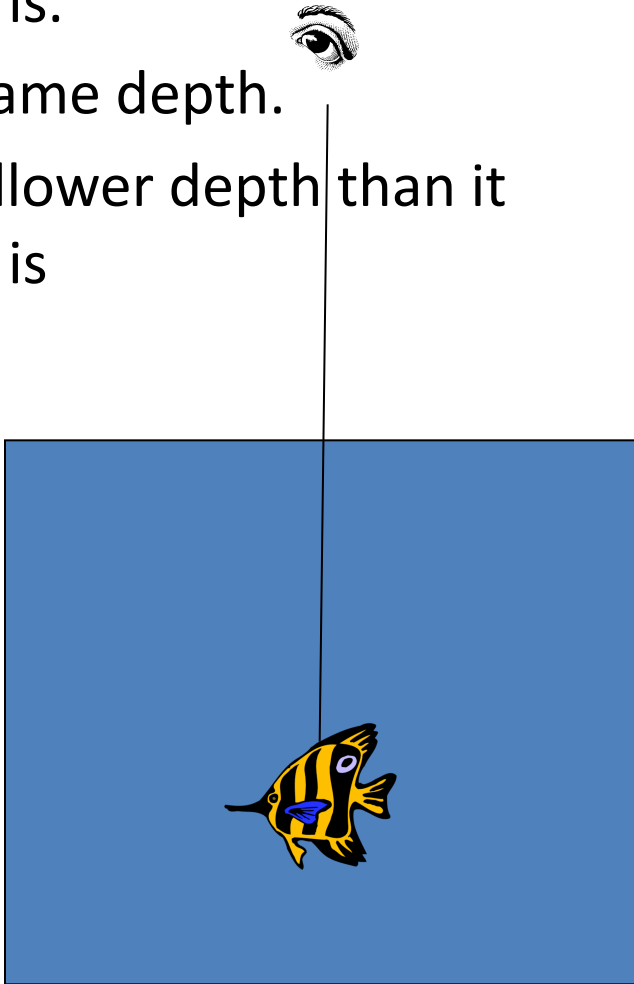


Geometrical Optics

How mirrors and lenses work...

A fish swims below the surface. An observer looking at the fish from straight above, sees the fish at:

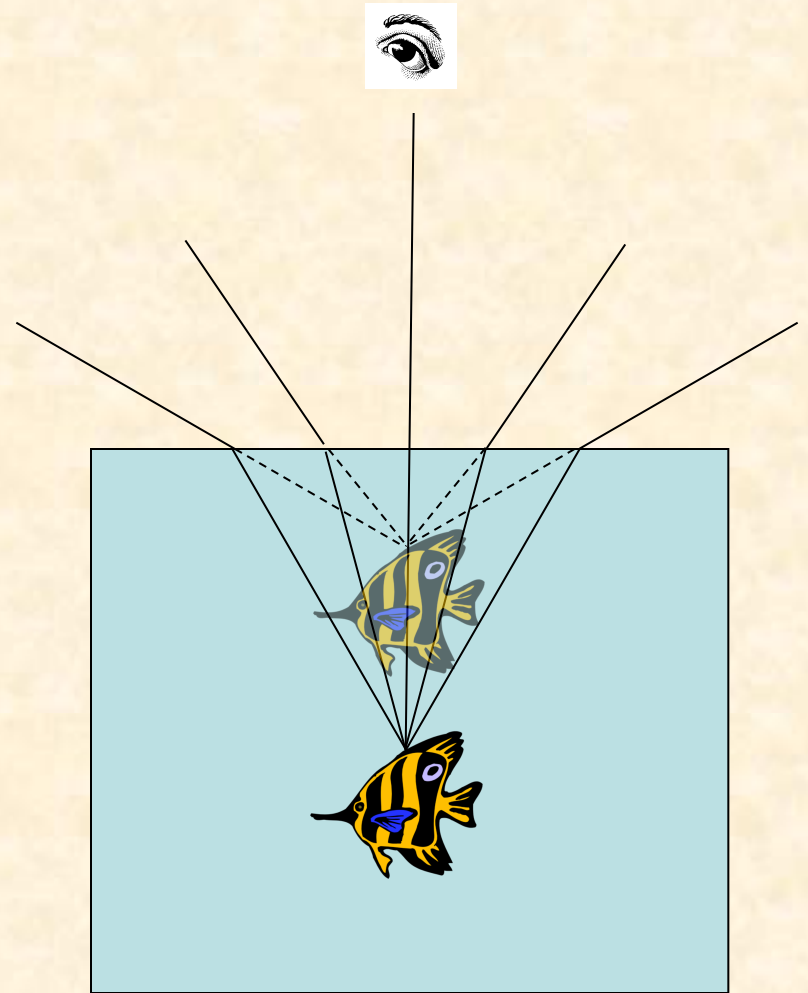
- A. A greater depth than it really is.
- B. The same depth.
- C. A shallower depth than it really is



Clicker Question

A fish swims below the surface.
An observer looking at the fish
from straight above, sees the fish
at:

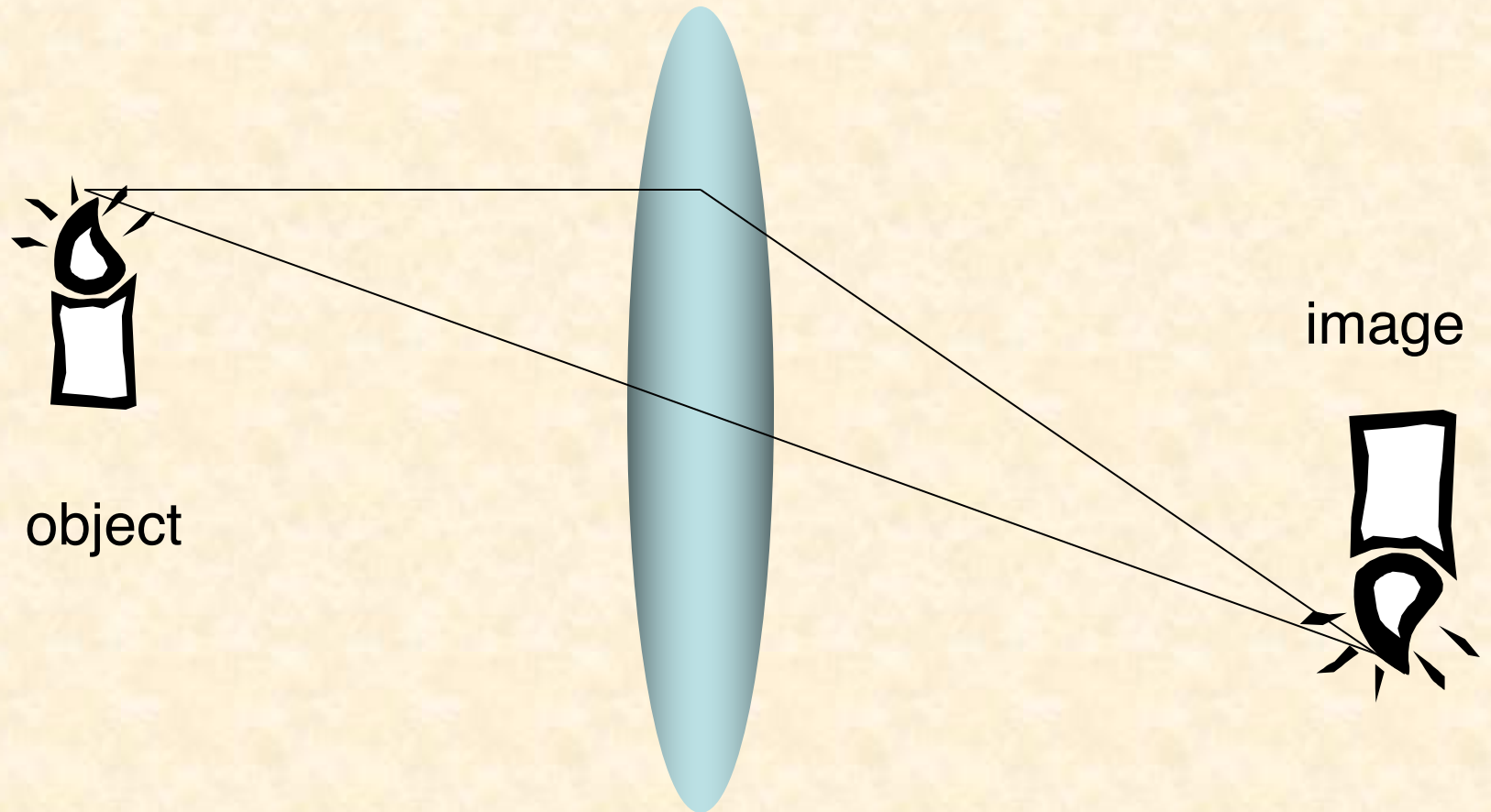
C) A shallower depth than it
really is.



Images

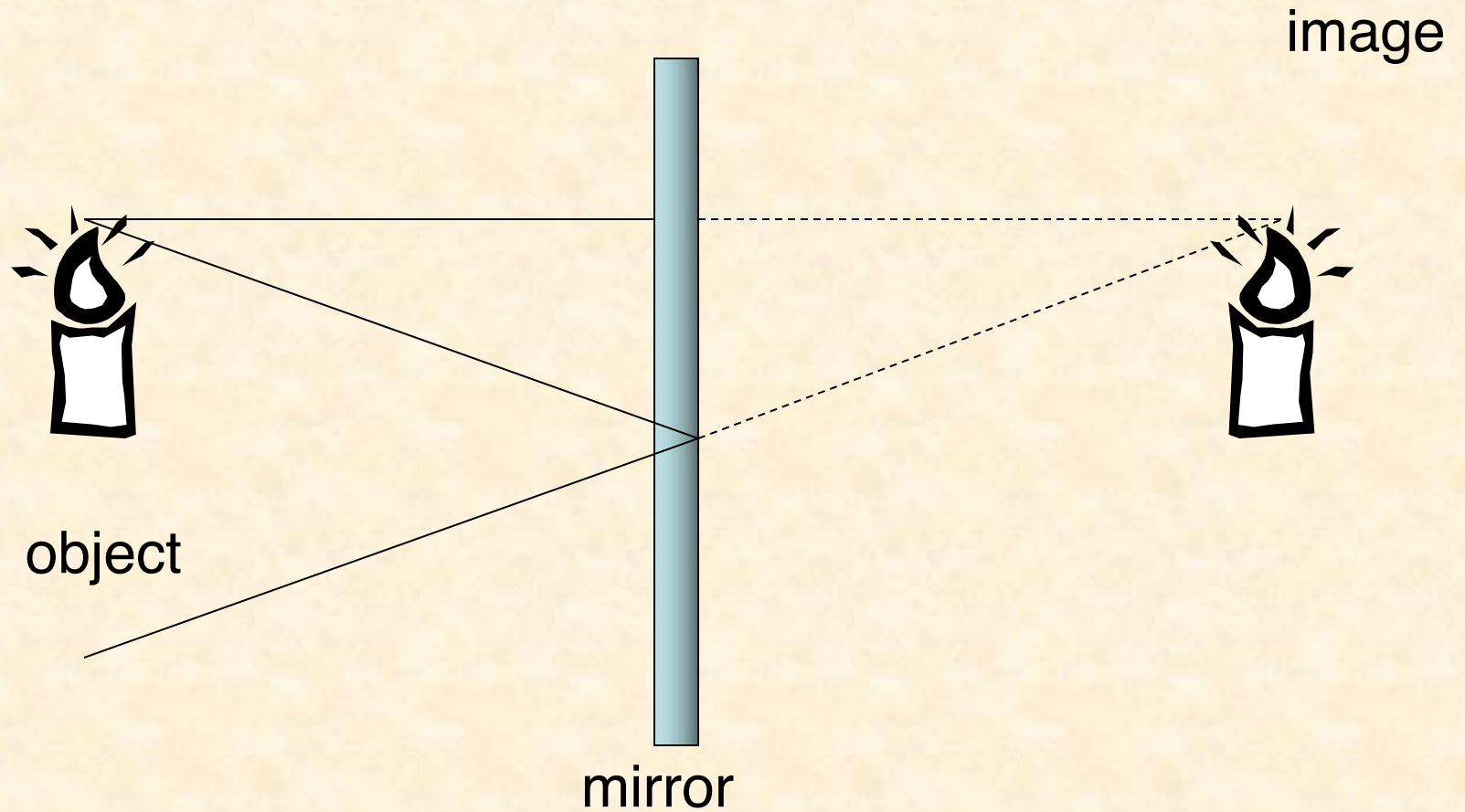
- **Real** Images
 - Image is formed by intersecting rays that came from source
- **Virtual** Images
 - Image is formed by rays that *appear* to intersect at the image

Real Image

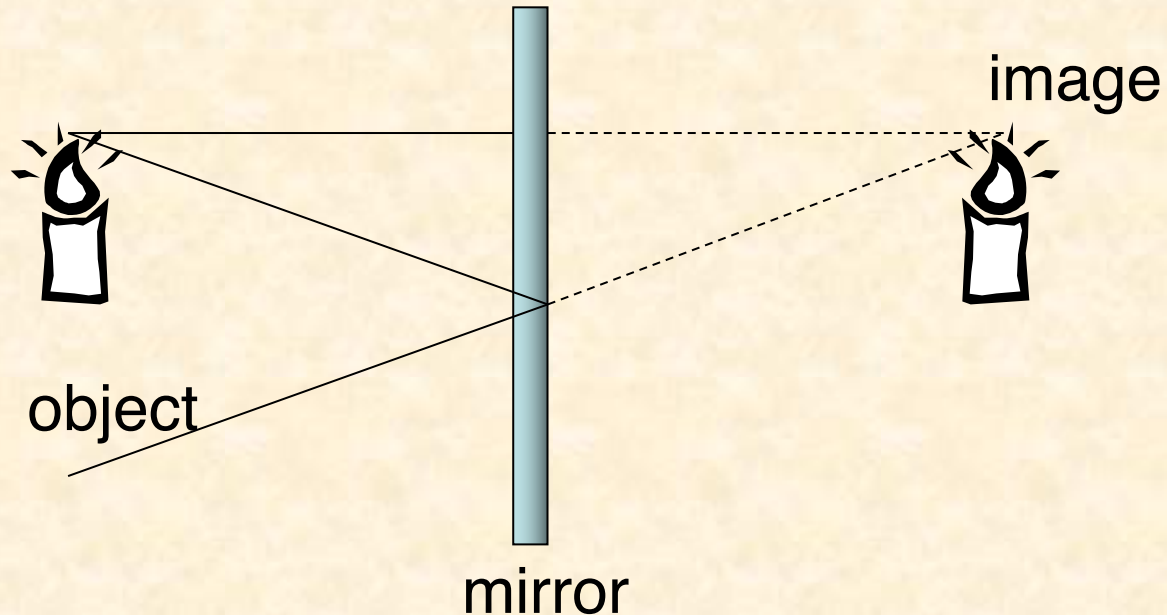


More on lenses later...

Virtual Image



Plane Mirror Image

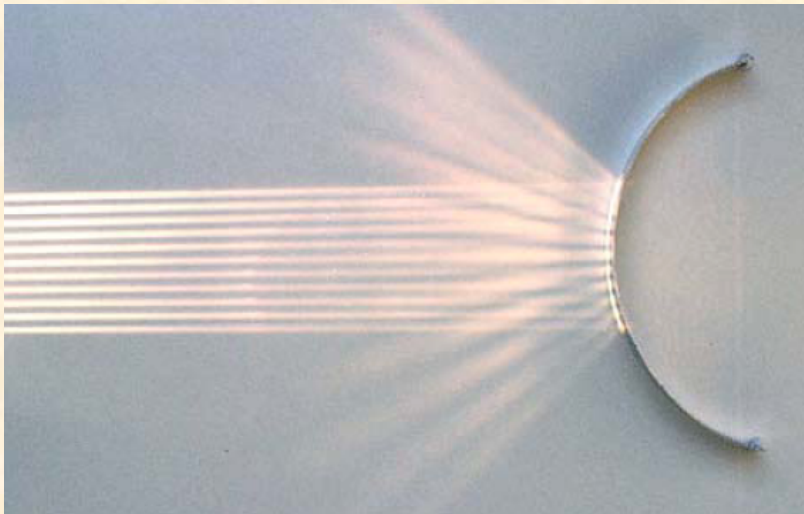


- virtual image
- upright (non-inverted)
- same size as object (magnification = 1)
- same distance from mirror as object

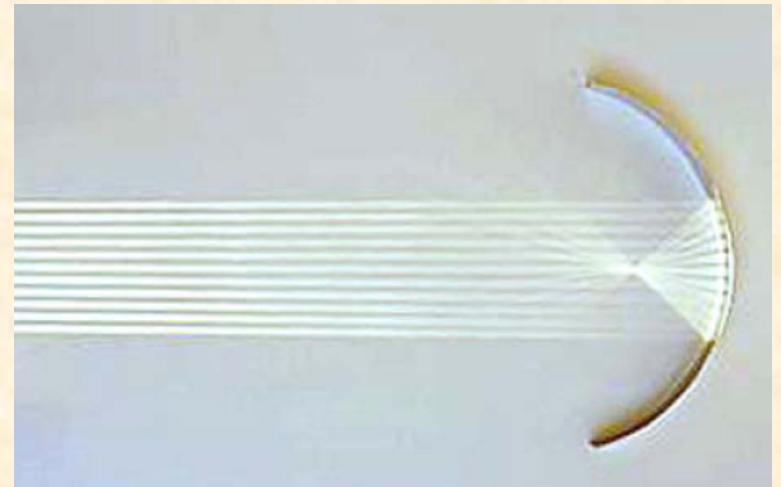
Spherical Mirrors

- reflector in the shape of part of a sphere

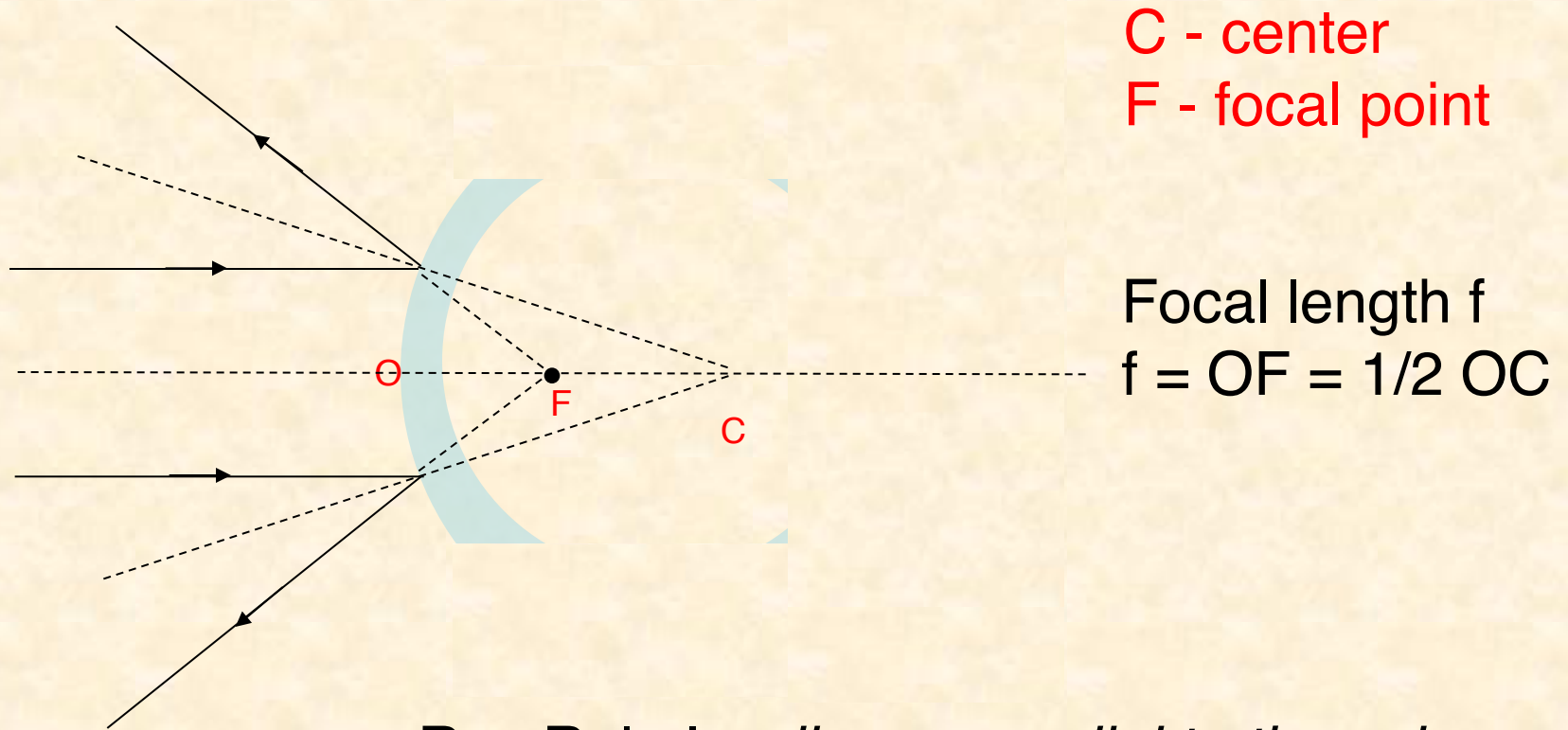
Convex



Concave

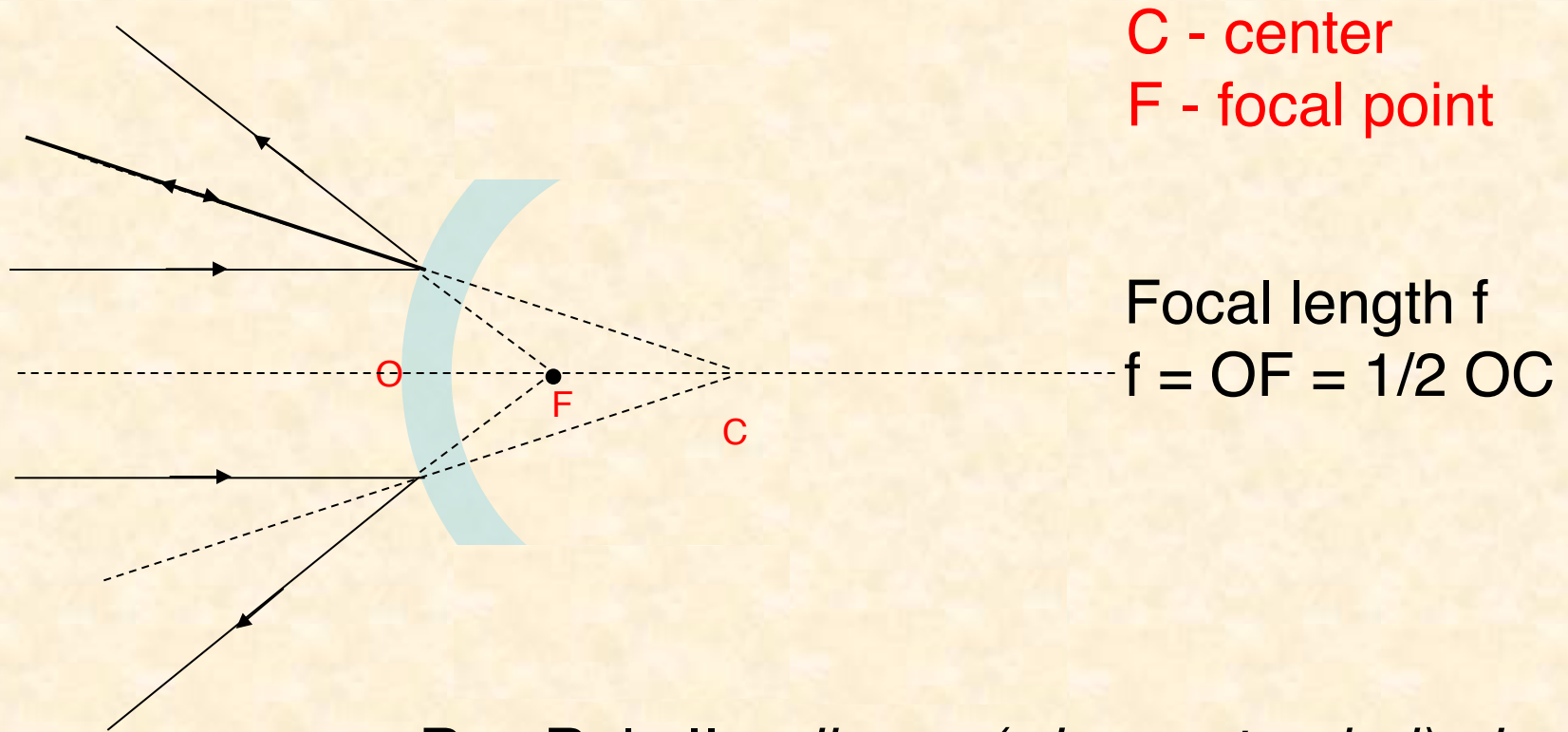


Convex mirror



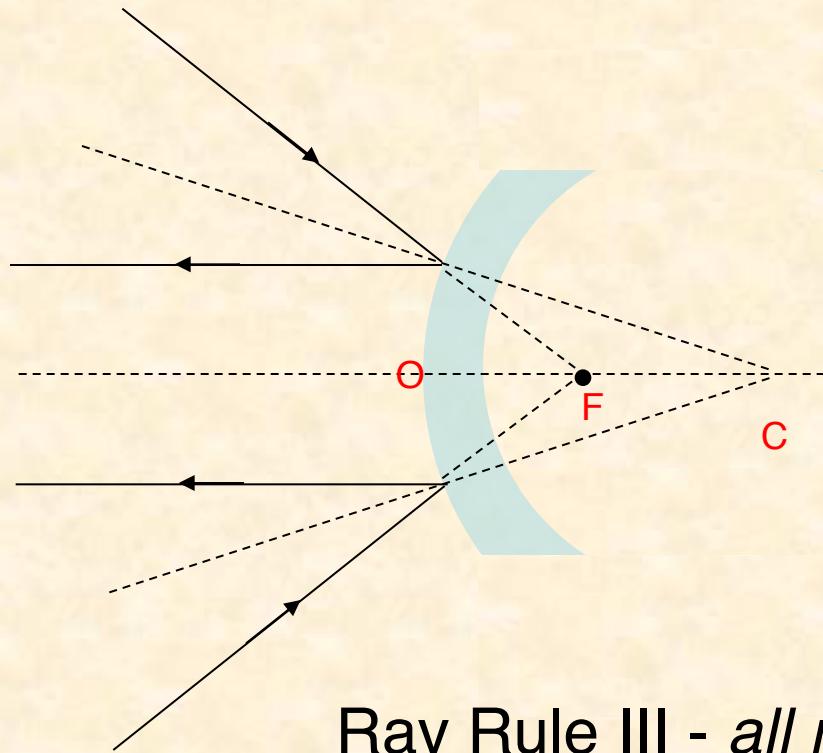
Ray Rule I - *all rays parallel to the axis are reflected so that they appear to be coming from the focal point **F**.*

Convex mirror



Ray Rule II - *all rays (when extended) aimed at C are reflected back on themselves*

Convex mirror



C - center

F - focal point

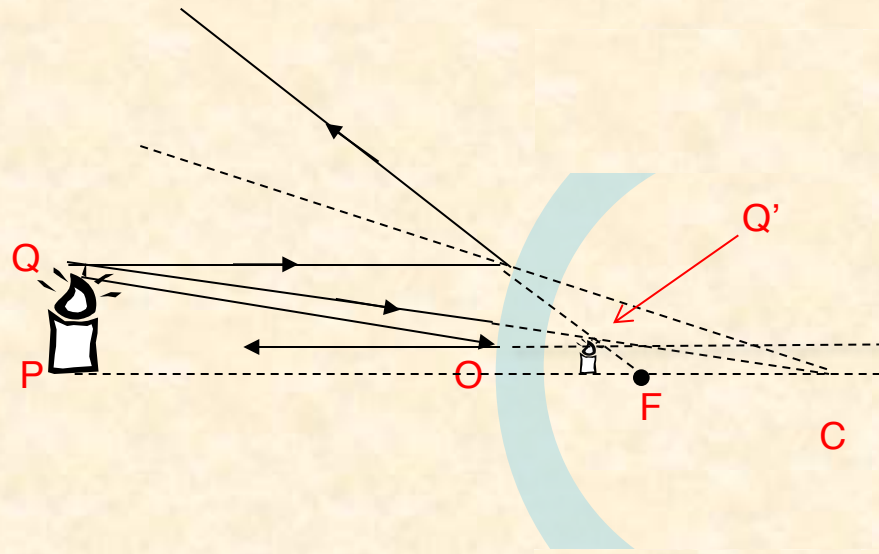
Focal length f

$$f = OF = \frac{1}{2} OC$$

Ray Rule III - all rays (when extended) aimed at F are reflected back parallel to the axis

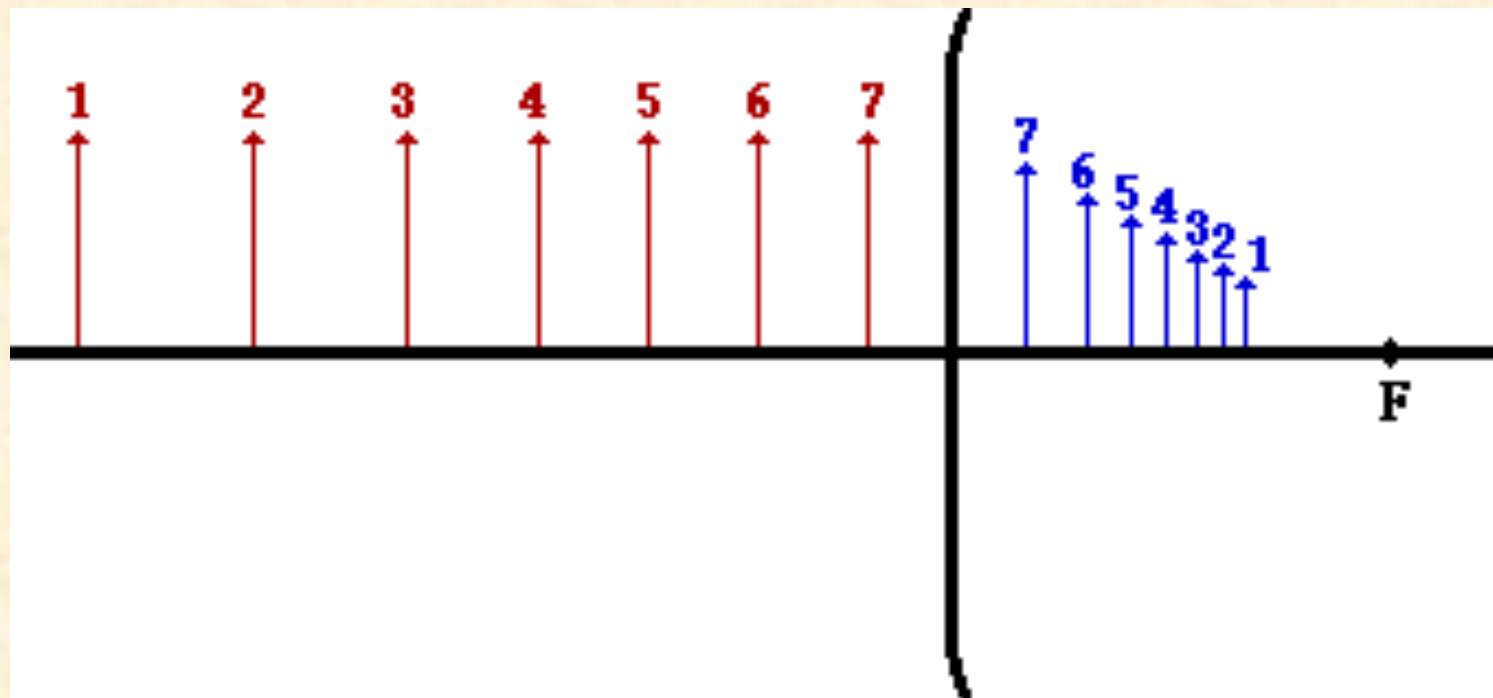
This is just Rule I reversed

Finding the image



- draw ray from object point Q towards C
- draw ray from Q parallel to axis; extend from mirror surface to F
- where the extended rays intersect is Q'

Image from a convex mirror



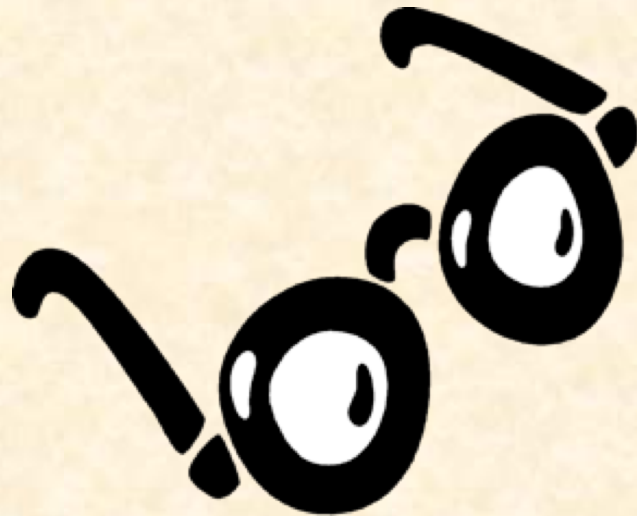
<http://www.microscopy.fsu.edu/primer/java/mirrors/convex.html>

Properties of the image

- It is a **virtual** image
- It is an upright (or **erect**) image.
- It is **closer** to the mirror than the real object
- The image is **smaller** than the real object.
- Applications: **store and car**
 - (allows to see wider angles)

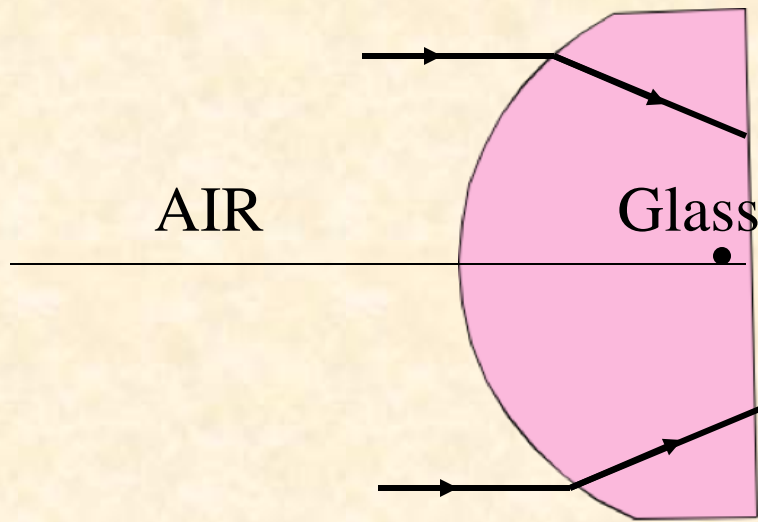


Lenses



Converging and Diverging Surfaces

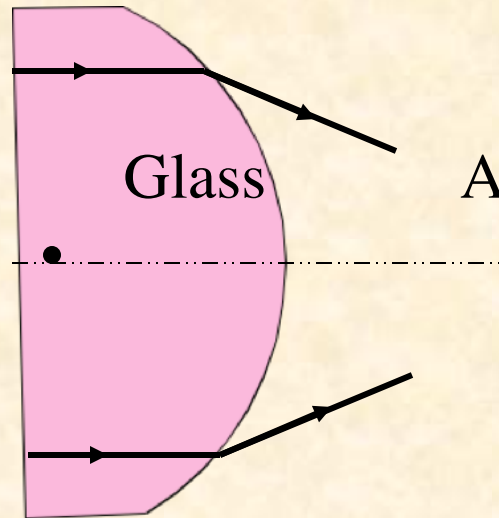
- If the surface is **convex**, it is a **converging surface** in the sense that the parallel rays bend toward each other after passing through the interface.
- If the surface is **concave**, it is a **diverging surface**.



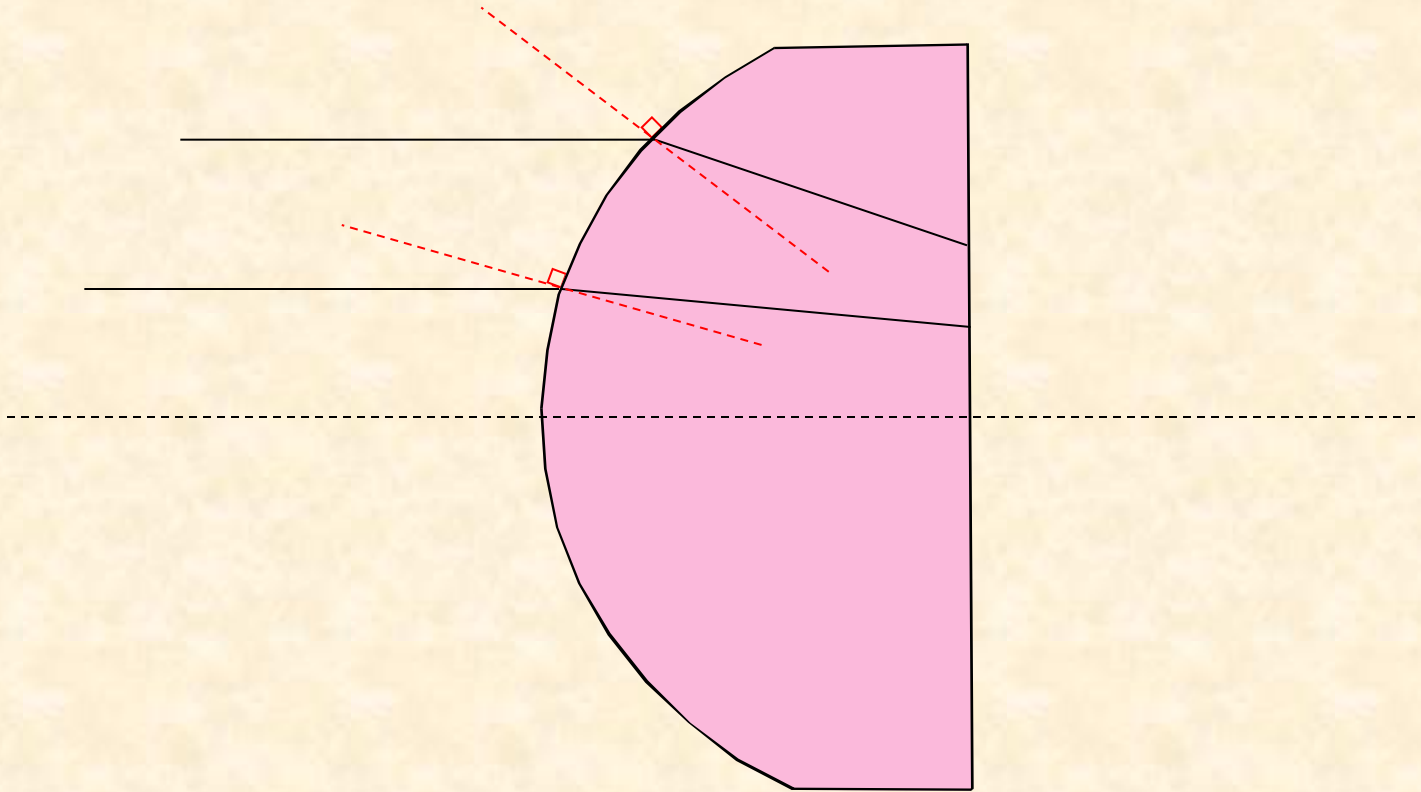
Converging
Surface

convex

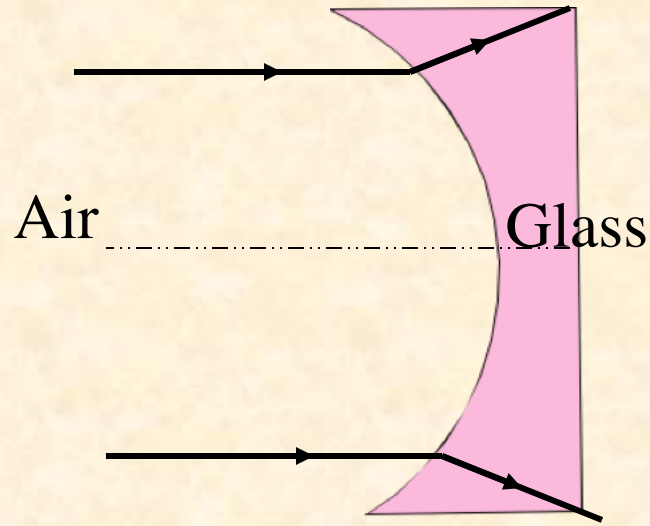
Converging
Surface



Snell's Law at work



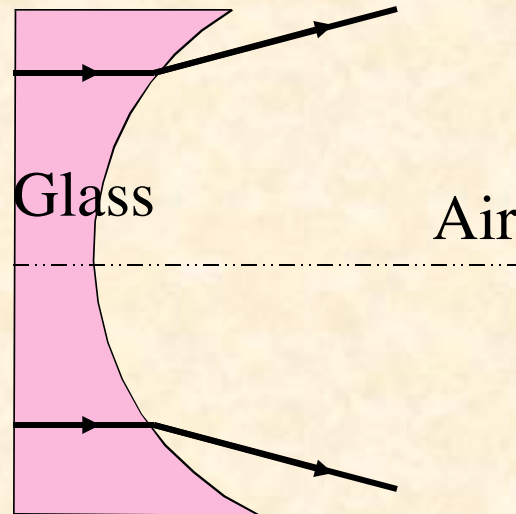
$$\sin \theta_r = (1/n_{\text{glass}}) \sin \theta_i$$



Diverging
Surface

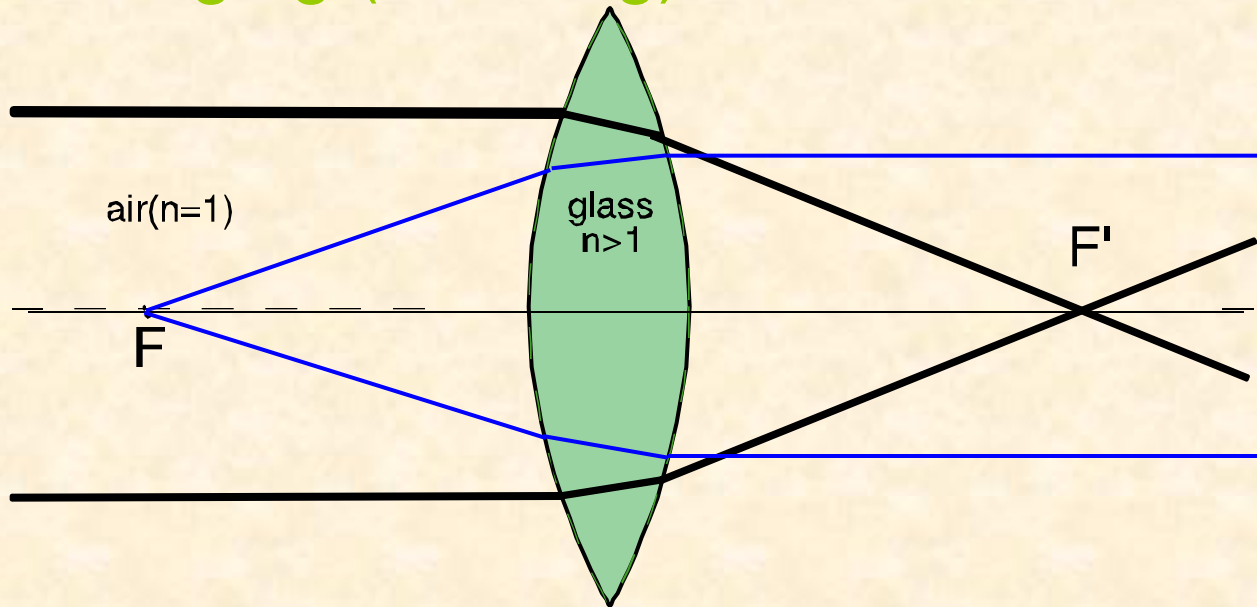
concave

Diverging
Surface



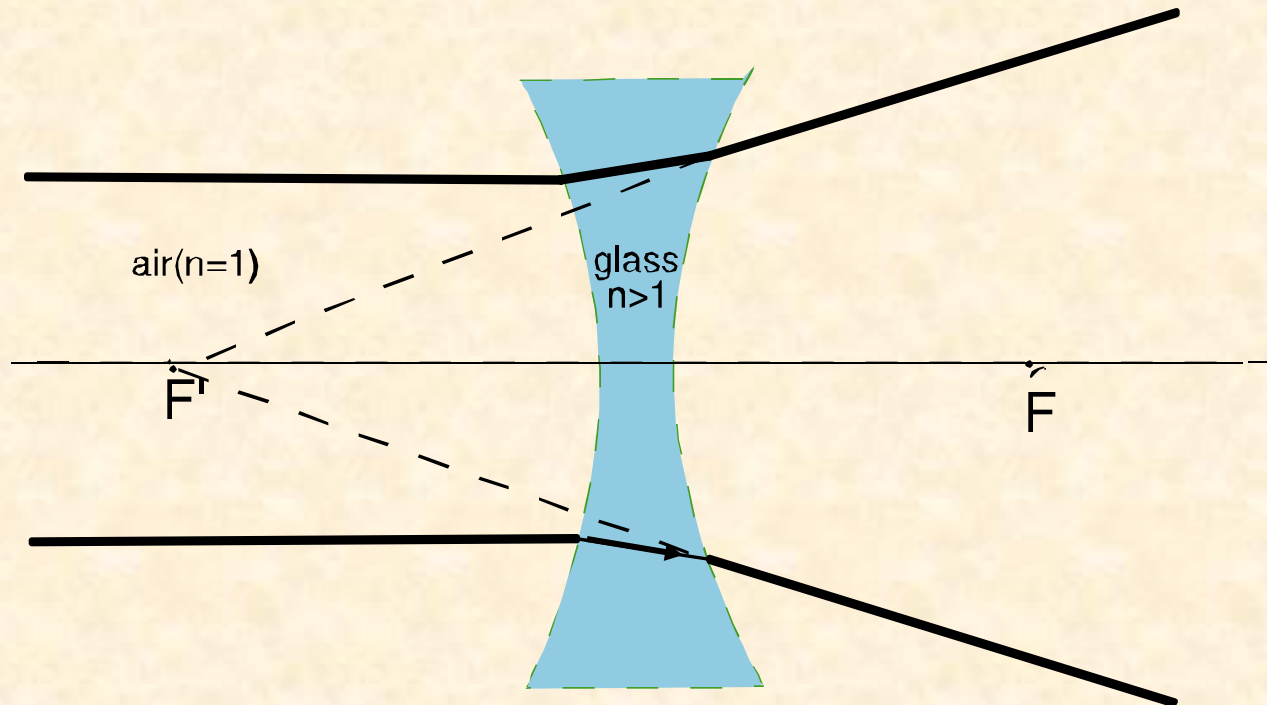
Converging Lens

Combining two converging surfaces, one gets **converging (focusing) lens**:



- The parallel rays converge at the **second focal point F'** .
- The **first focal point** is at the front. All rays originated at this point become parallel to the axis after the lens.

Diverging Lens



To an eye on the right-hand side, these diverging rays appear to be coming from the point F' : the **second focal point**.

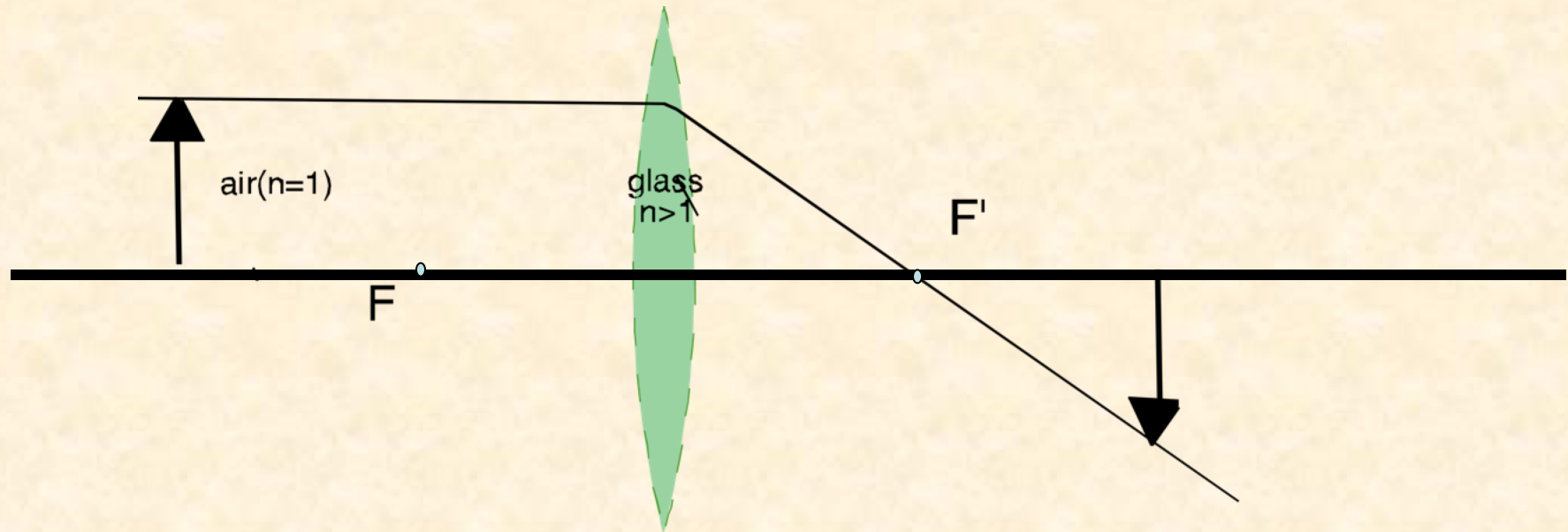
Thin Lenses

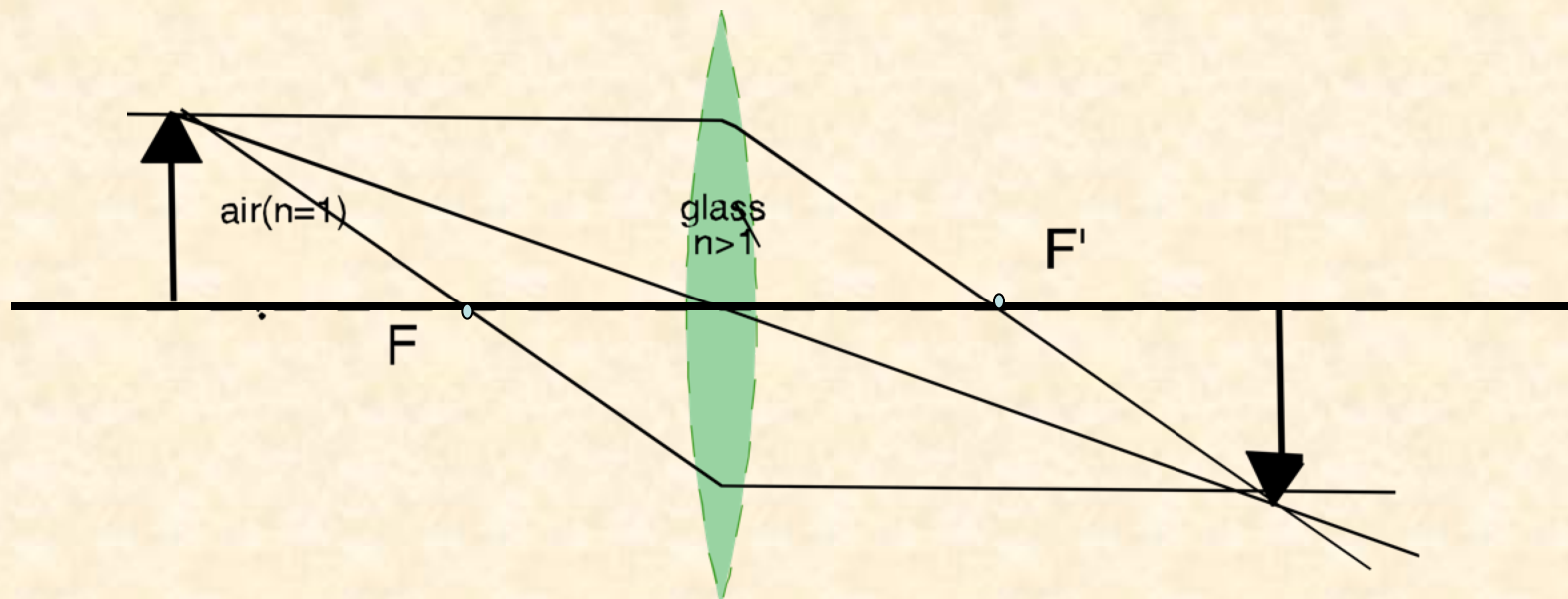
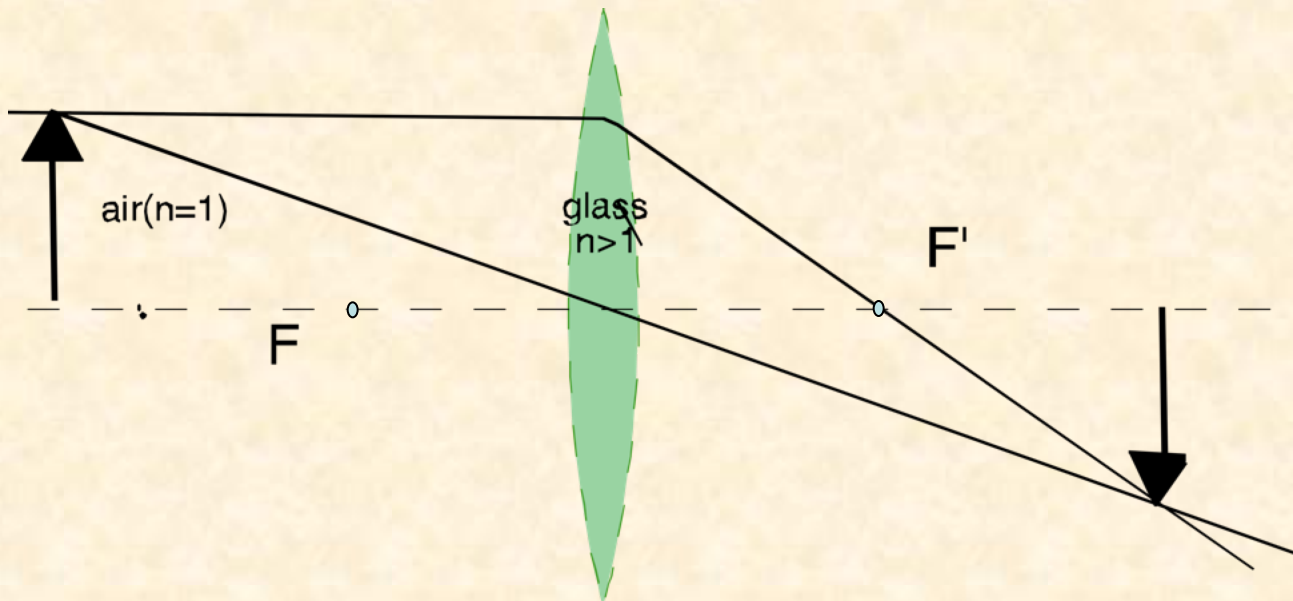
- Thin Lenses:
 - If the thickness of the lens is much less than the distance from the lens to each focal point.
- The distances from the lens to F and F' are the same (**focal length f** of the lens).
- f is taken as **positive** for converging lenses and **negative** for diverging lenses.
- All rays passing through the center of the lens do not refract (bend).

Three Rays Again

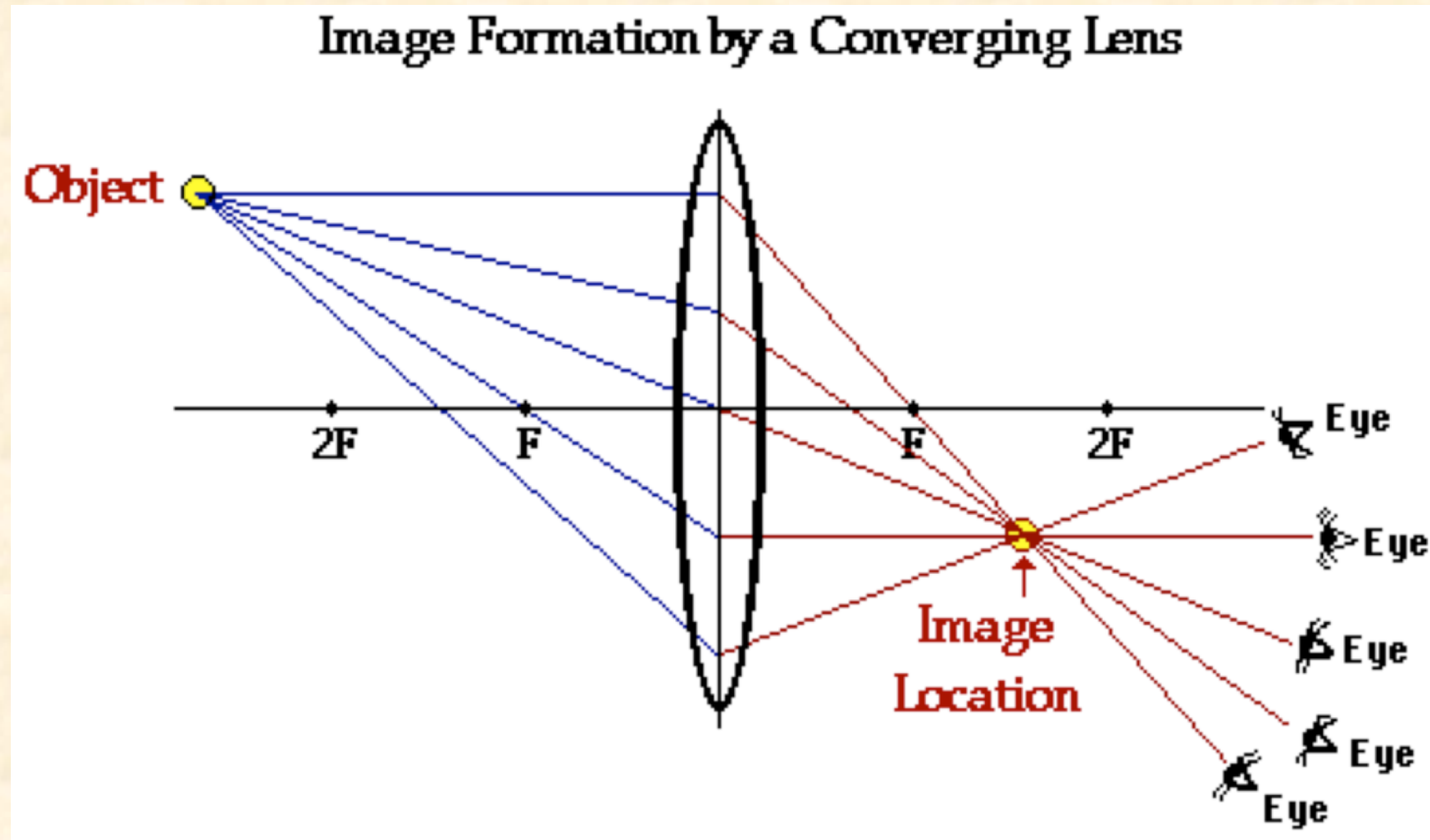
- A ray parallel to the axis is refracted through F' .
- A ray through the center of the lens continues un-deviated.
- A ray that (extended when necessary) passes through F is deflected parallel to the axis.
- *Any of the two rays are sufficient to locate the image point.*

Ray tracing for a thin convergent lens

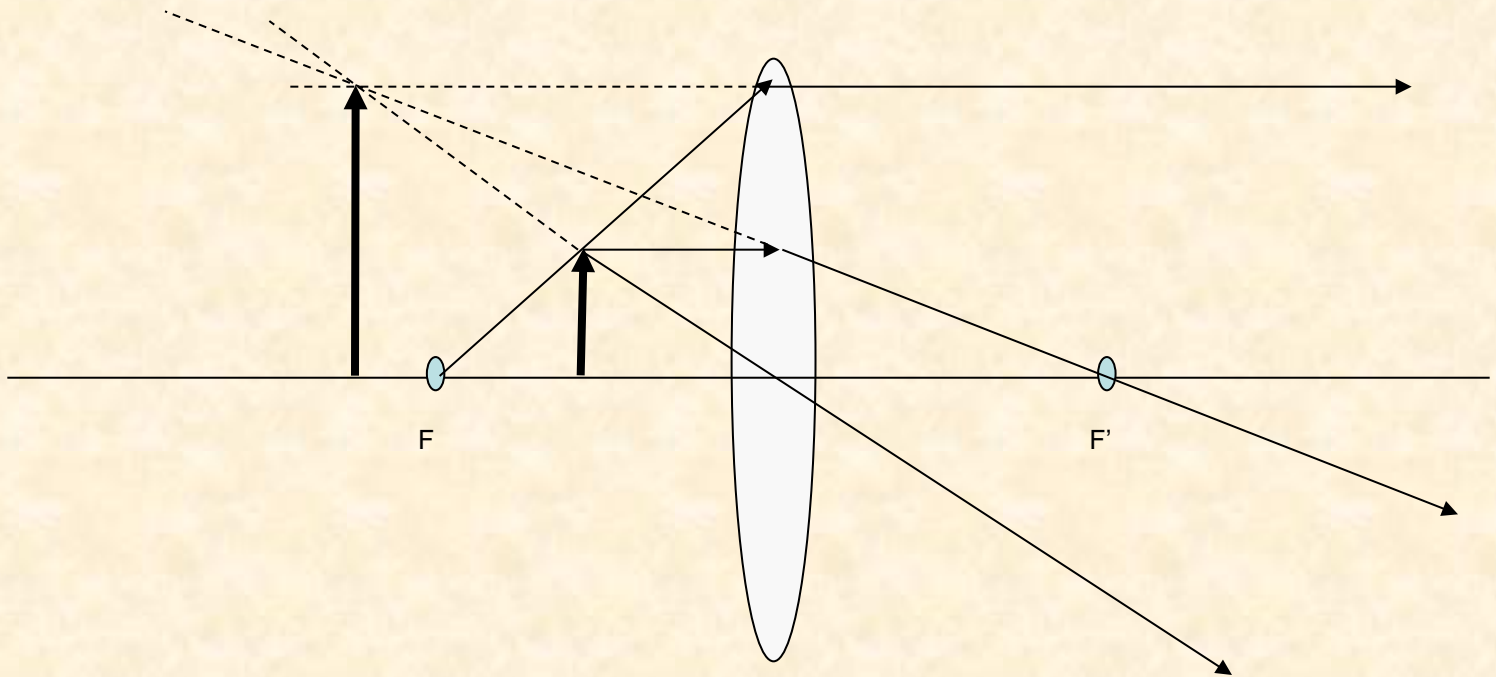




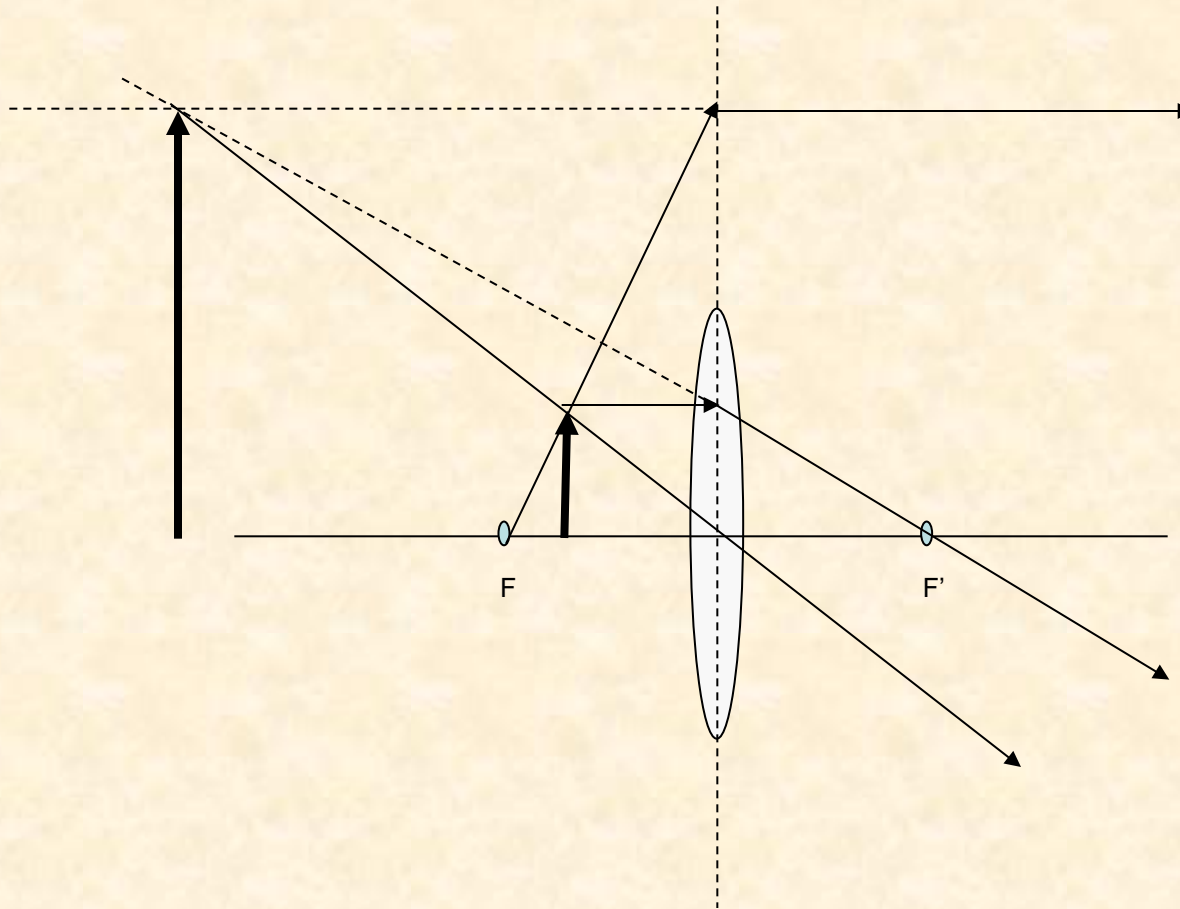
Real Image from a Lens



Virtual Image from a converging lens



Principal Rays don't really have to hit the lens



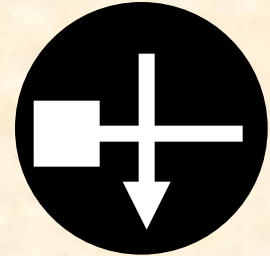
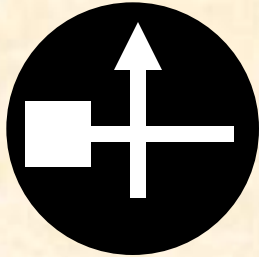
Java Applet

- <http://www.phys.hawaii.edu/~teb/optics/java/clens/>
- Very similar to the images of a concave mirror.

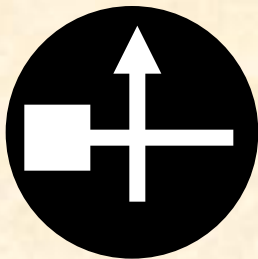
Properties of the image

- **If the object is outside the focal point**
 - It is **real**: the light rays do go through where the image is.
 - It is **inverted**.
 - If the object is outside of $2f$, the image is smaller; At $2f$, it has the same size; Inside $2f$ and up to f , it has a larger size.
- **Inside the focal point**
Virtual, vertical, and always bigger.

Question



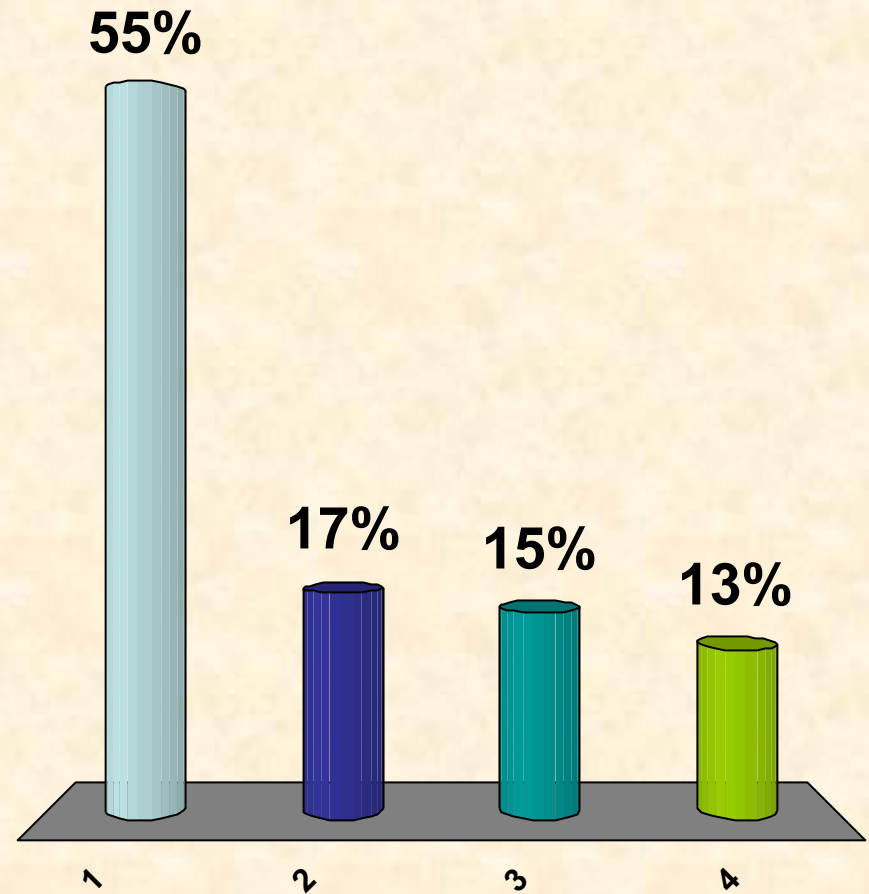
Two Lenses – same focal length – one lens is bigger in diameter than the other



?

Two Lenses – same focal length – one lens is bigger in diameter than the other

1. The image will be the same in both cases
2. The image will be bigger for the bigger lens
3. The image will be brighter for the bigger lens
4. The image will be bigger and brighter for the bigger lens



Two Lenses – same focal length – one lens is bigger in diameter than the other

1. The image will be the same in both cases
2. The image will be bigger for the bigger lens
3. The image will be brighter for the bigger lens
4. The image will be bigger and brighter for the bigger lens

Usage of a converging lens



- Camera
- Eye
- Magnifying glass
- Telescope
- Microscope
- Eyeglasses
- ...

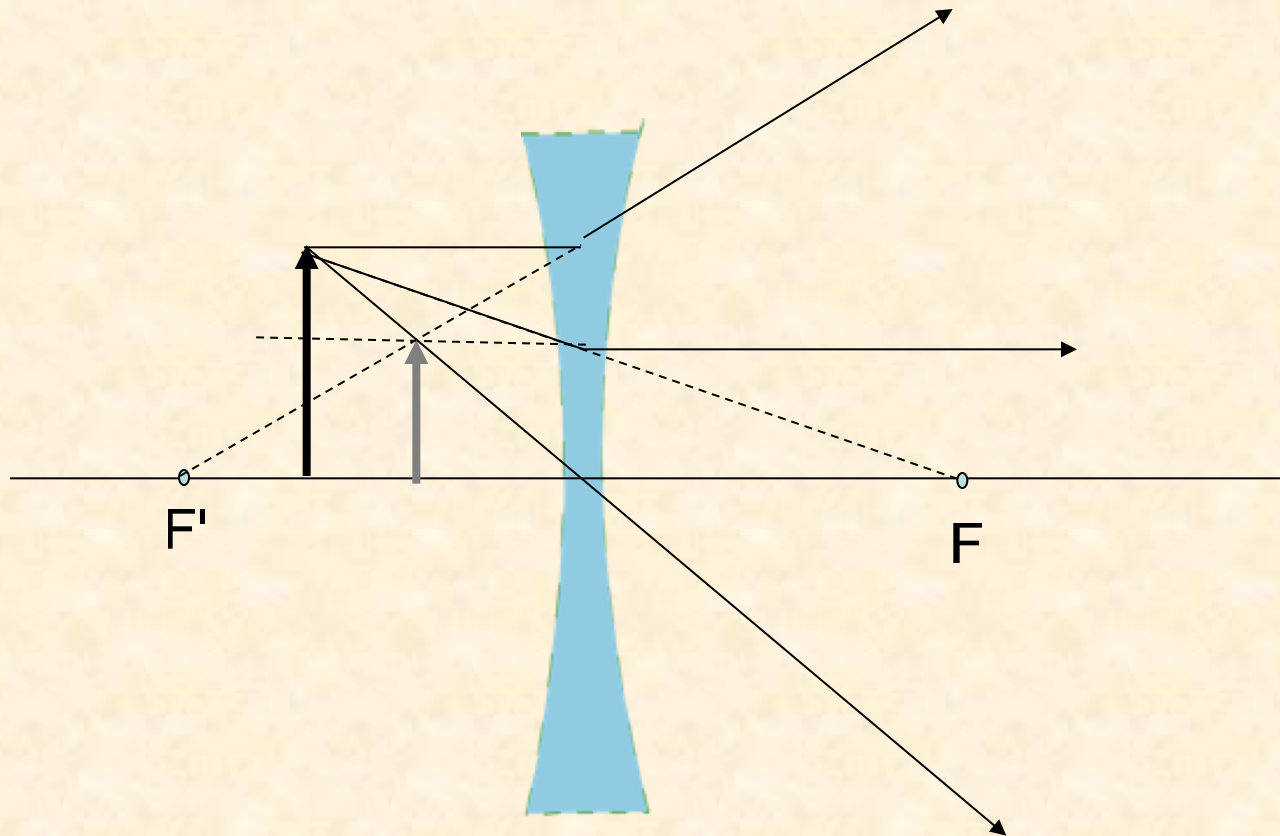


Parallel Rays

- If parallel rays fall on the lens, then the image can be determined by a ray going through the center of the lens and a second ray going through the first focal point of the lens.
- The image is always on the **focal plane.**

Divergent Lens

<http://www.phys.hawaii.edu/~teb/optics/java/dlens/>

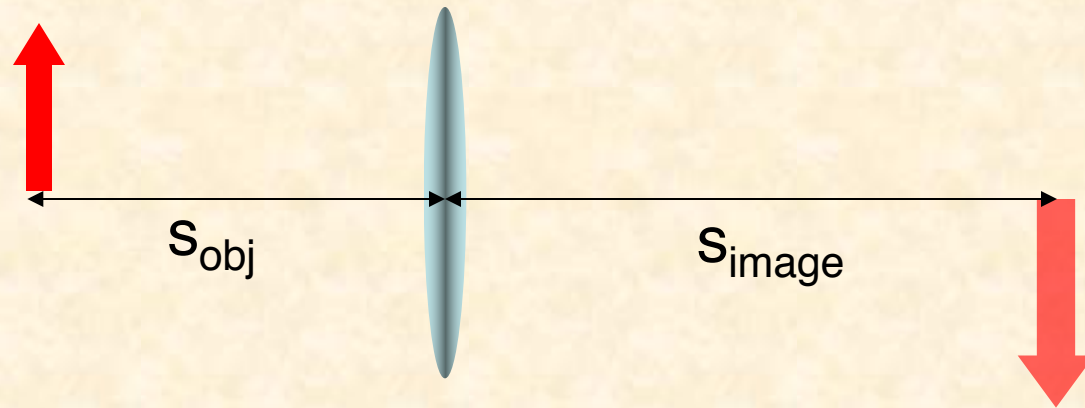


Features of the image

- It is a **virtual** image: the light rays do not go through the image.
- The image is always **smaller** than the object.
- The image is **erect**.

The Lens Formula

$$\frac{1}{s_{image}} + \frac{1}{s_{obj}} = \frac{1}{f}$$

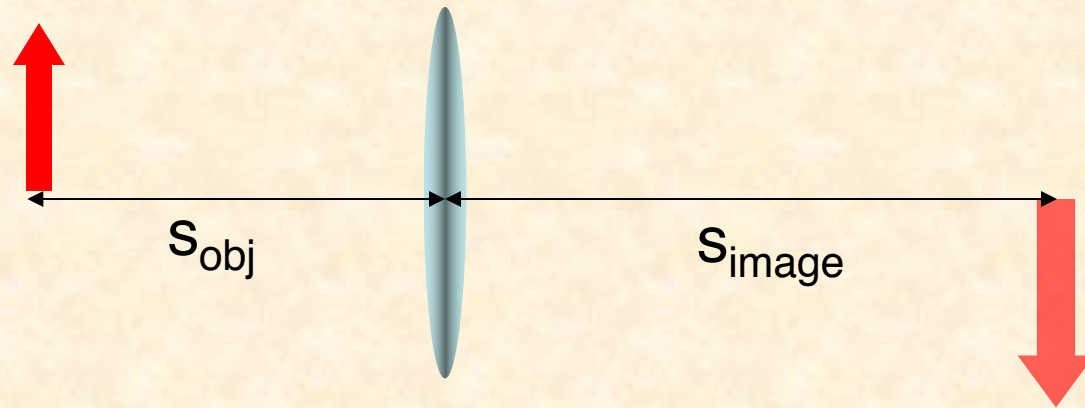


Converging lens $f > 0$; Diverging lens $f < 0$

$s_{obj} > 0$; if $s_{image} > 0$, real image; $s_{image} < 0$, virtual

The Lens Formula

$$\frac{1}{s_{image}} = \frac{1}{f} - \frac{1}{s_{obj}}$$



Converging lens $f > 0$; Diverging lens $f < 0$

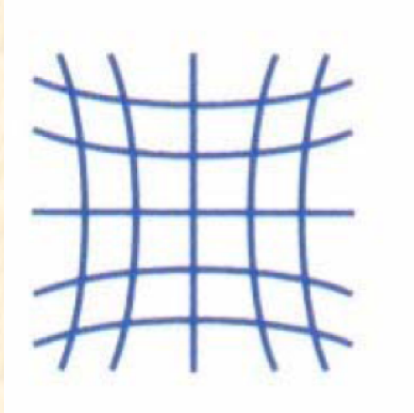
$s_{obj} > 0$; if $s_{image} > 0$, real image; $s_{image} < 0$, virtual

Power of a lens

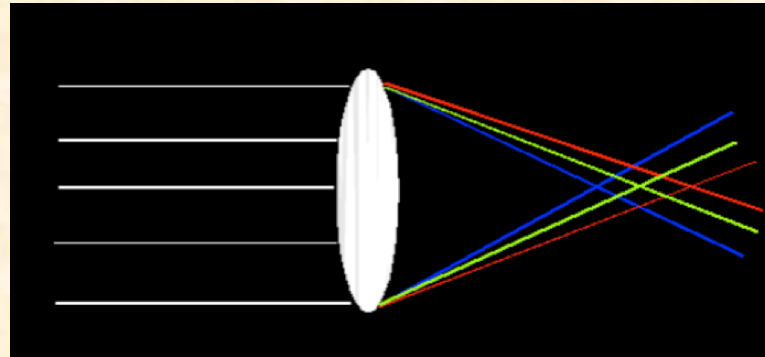
- The focal length determines the image of the object formed by a lens.
- **The power of the lens is defined as $1/f$.** It describes the extent that the lens bends the light rays. When f is in meters, the power is in **diopters**.
 - $f = 50\text{cm} = 0.5\text{m}$ $P = 1/0.5 \text{ D} = 2 \text{ D}$
 - For a diverging lens, both f and P are negative.

Example - prescription : $-2.5\text{D} \Rightarrow -40 \text{ cm}$ (diverging lens)

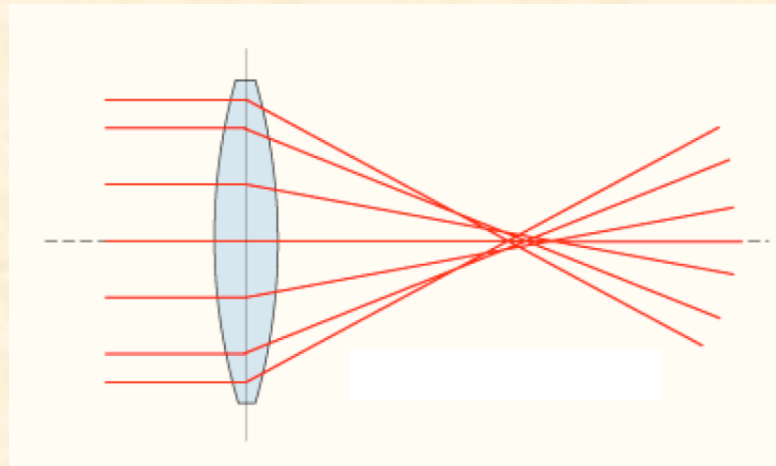
Aberrations



Pincushion
distortion



Chromatic
aberration



Spherical
aberration

- If the thin lenses are so close that they touch each other, they form a combination that behaves just like another thin lens.
- The power of the combined thin lens is equal to the sum of the powers for the separate lenses.

$$1/f = 1/f_1 + 1/f_2 \text{ in meters}$$

$$\text{or } D = D_1 + D_2$$