ANCIENT AND CLASSIC WORLS

Until the 5-th Century

OPTICS

Collected and edited by Prof. Zvi Kam,

Weizmann Institute, Israel

VISION

Vision in the classical era:

Fire and light were considered one of the elements from which all materials are built.

The Greek philosophers perceive vision, similar to touching by hands, as a result of rays emitted from the eye, and reflected back by the seen object.

Polished gold mirror, used by the Pharaohs

300 BC Epicurus - describes light ray tracks in the eye, that emits the rays, and senses the reflected rays from an object.
The Greeks realized that sunlight is required for vision, and that moonlight is the reflected sunlight, yet they insisted to combine sunlight with rays emitted from the eye. They explained colors by mixture of sunlight with the rays emitted from the eye.

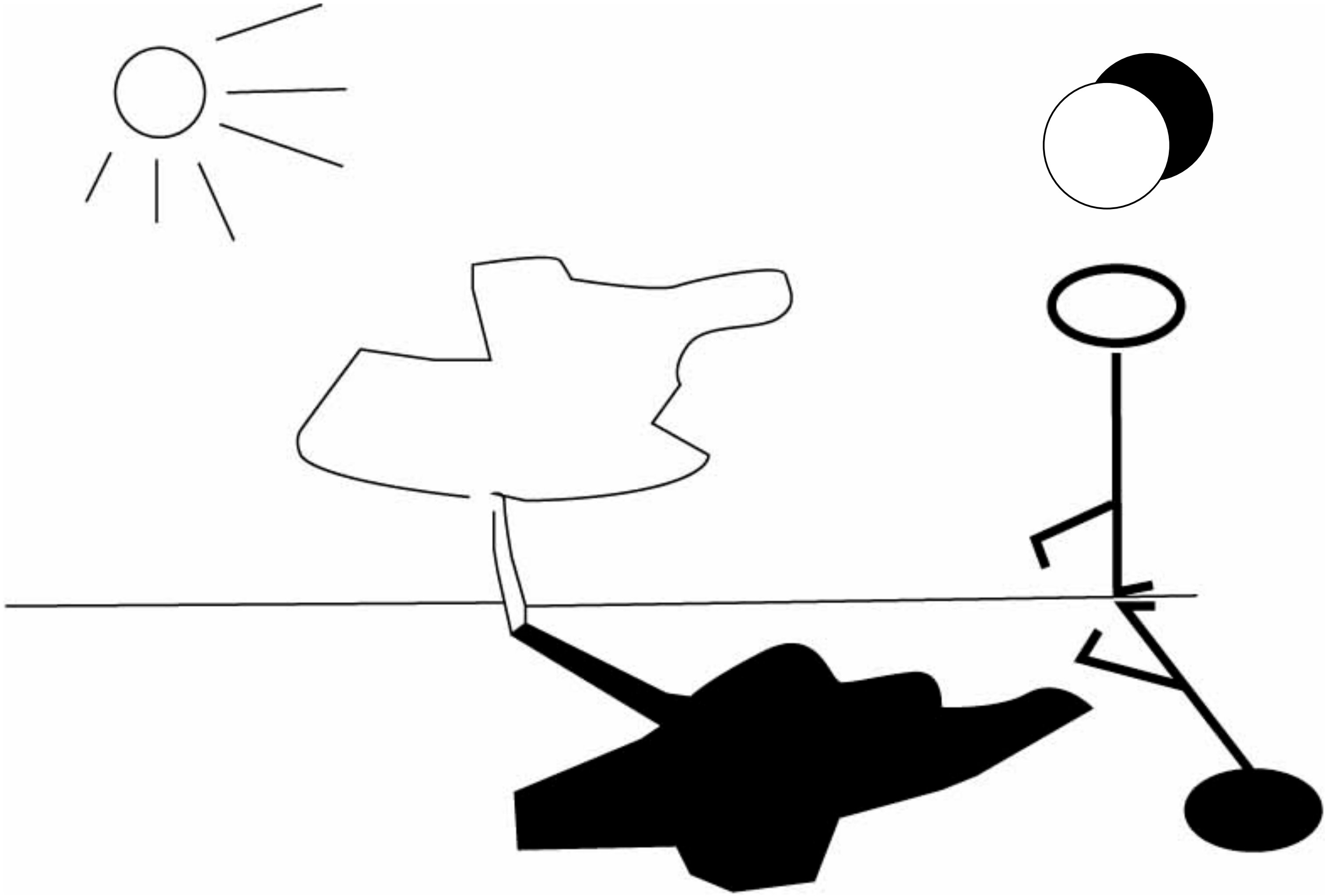
Aristo – realized that rays from the eye would not reach far away stars, thus explained vision by the medium between the eyes and the seen object. Colors were due to interaction with this medium: e.g. fog makes the sun look red.

Euclid – the famous geometrician, plotted rays as straight lines. He described angular magnification, and connected visible size to distance. He also realized that larger acceptance angle of vision when one comes nearer provide better resolution of details.
But Euclid draws a single ray from every point on the object and the eye, which implies he did not really understand focusing of multiple rays from a point on the object, to a point on the image, the basis of Geometrical Optics.

Archimedes – describes reflective optics of mirrors (and used it to deflect sunlight from polished shields to burn the Romans sails).

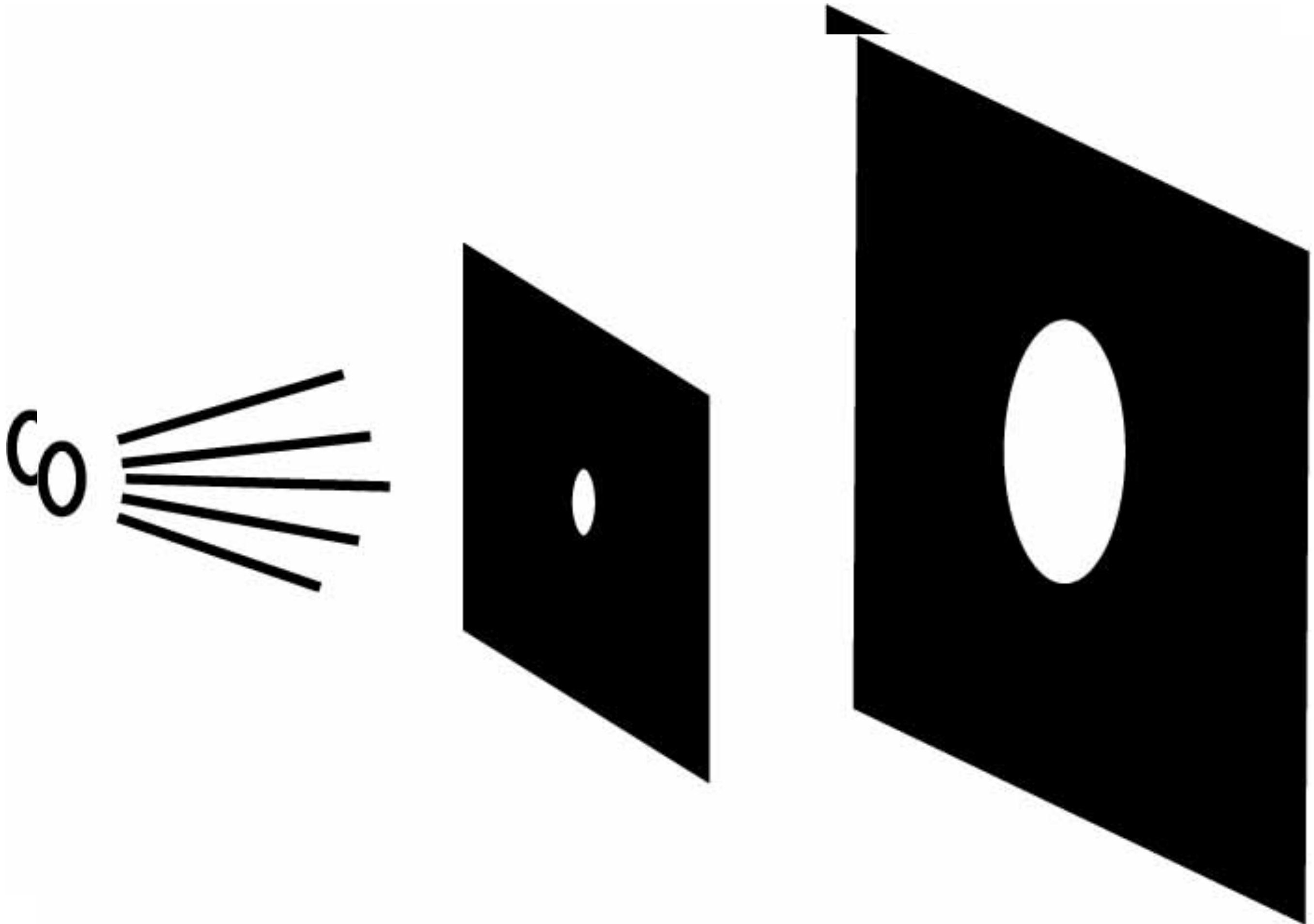
Diocles – in Alexandria, composed a book: “mirrors”.

GEOMETRICAL OPTICS



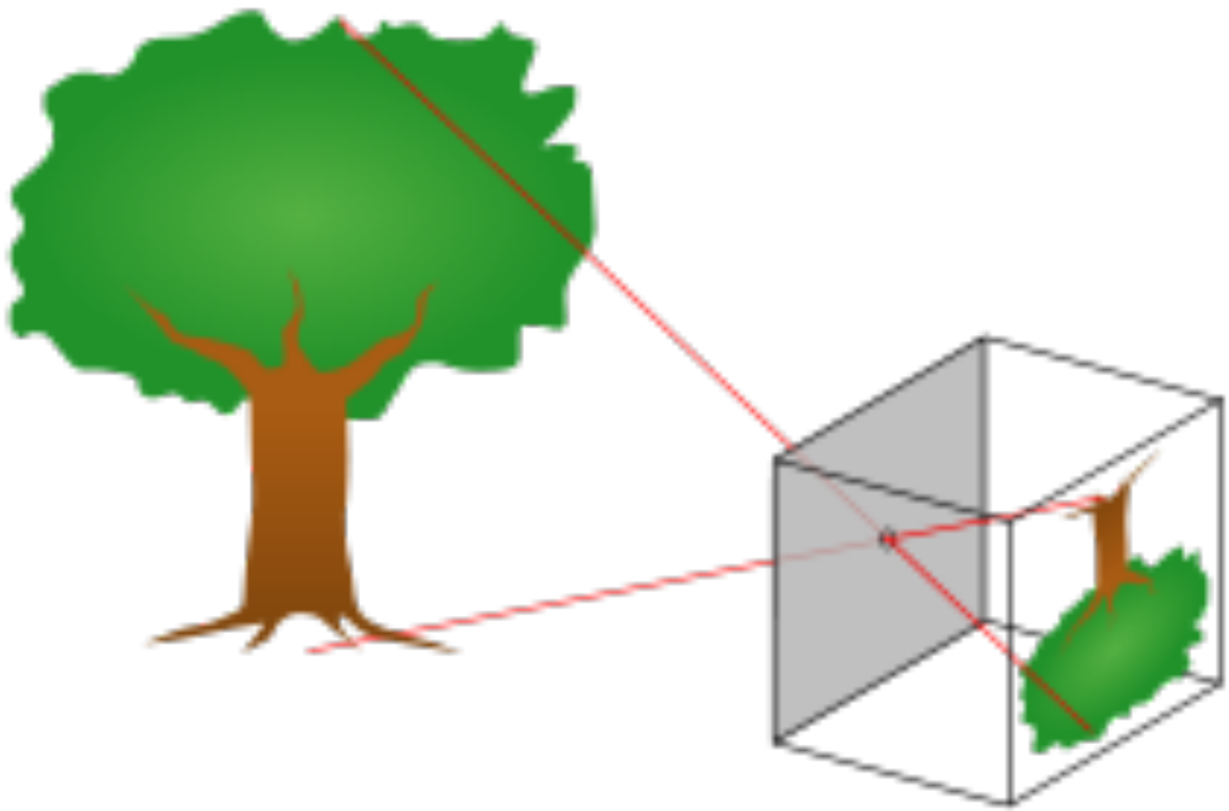
Simple demonstrations that light rays propagate in straight lines: Shadows, Phases of the moon, Sun and moon eclipse, Cannot see behind the corner.

GEOMETRICAL OPTICS



The projected image of a circular hole is also a circle.
Is it a sharp circle? What determines the degree of edge sharpness?
Try to measure the blurry edge width for projections with various size holes.
Can you create sharper projections? (Hint: smaller light source)

PINHOLE CAMERA (Camera Obscura)



Build a camera from a box with a hole and thin white paper on the opposite face of the box. What do you gain, and what is lost when the hole is larger or smaller.
Hint: Sharpness vs. Brightness.

Description of light rays **refraction** was only made after the Phoenicians learned to produce clear glass bottles. When filled with water they focused sunlight, and created enlarged or shrunk images of a scene behind it, depending on distances of the seen objects and the eye.
Uses of glass for optics (lenses) started only during late middle ages with eyeglasses (brought from China). The polishing of lenses for eyeglasses brought with it construction of telescopes and microscopes.

The next slide from “Chemistry” chapter is brought here as a reminder.

GLASS

1400 BC Phoenicians create glass bottles by blowing (Painting from upper Nile valley). Previous to blowing, small bottles were molded around sand, that was poured out after cooling. They spread all over the Mediterranean to hold volatile perfumes.

The chemistry of glass production:

Burnt seed ashes are rich in Sodium Carbonate (Na_2CO_3). When combined with sand silica (SiO_2) they make glass: $Na_2CO_3 + 2SiO_2 + CaO \rightarrow Na_2SiO_3 + CaSiO_3 + CO_2$

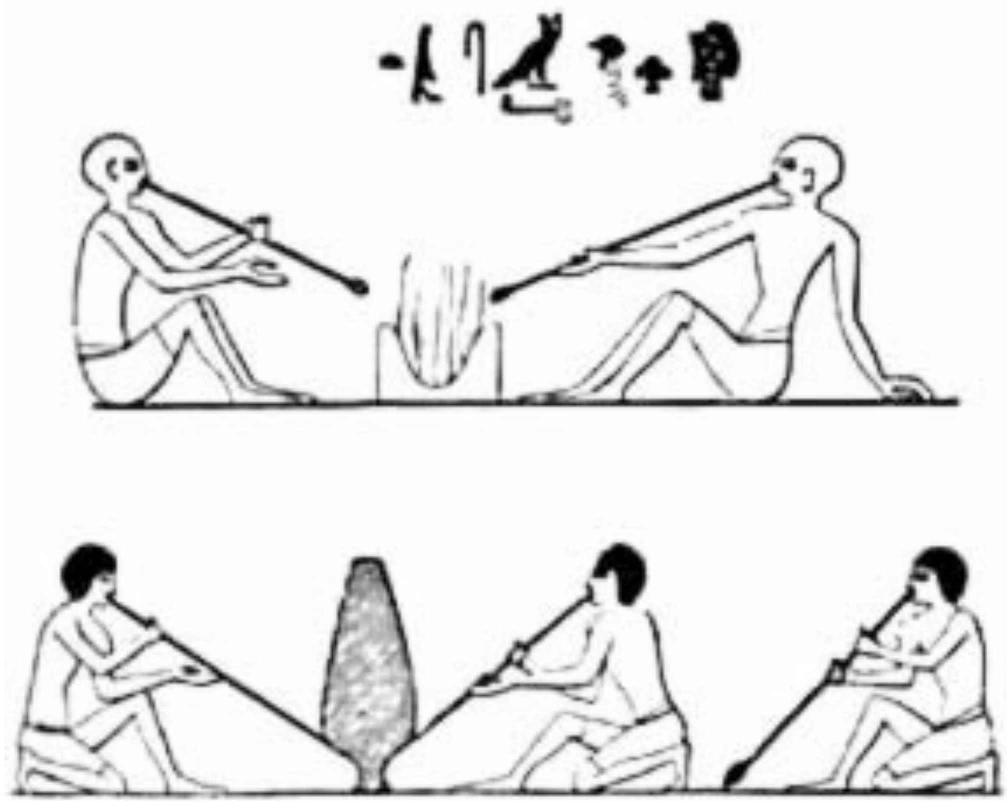
The story tells that camp fires left behind glass clumps igniting glass industry development. Pure silica melts at 2000°C, but with Sodium Carbonate the melting temperature is reduced to 1000°C.

Na_2CO_3 was also collected from dried lake beds in Egypt, and used for preservation of Mummies.

Adding burnt lime (CaO) to the glass make it less soluble by water.

Due to various common minerals, glass is naturally deeply colored: Blue-copper oxide, Brown and Green-Iron, Deep Blue or Black-Nickel, Deep Green- Chromium. Colored glass beads were used for necklaces.

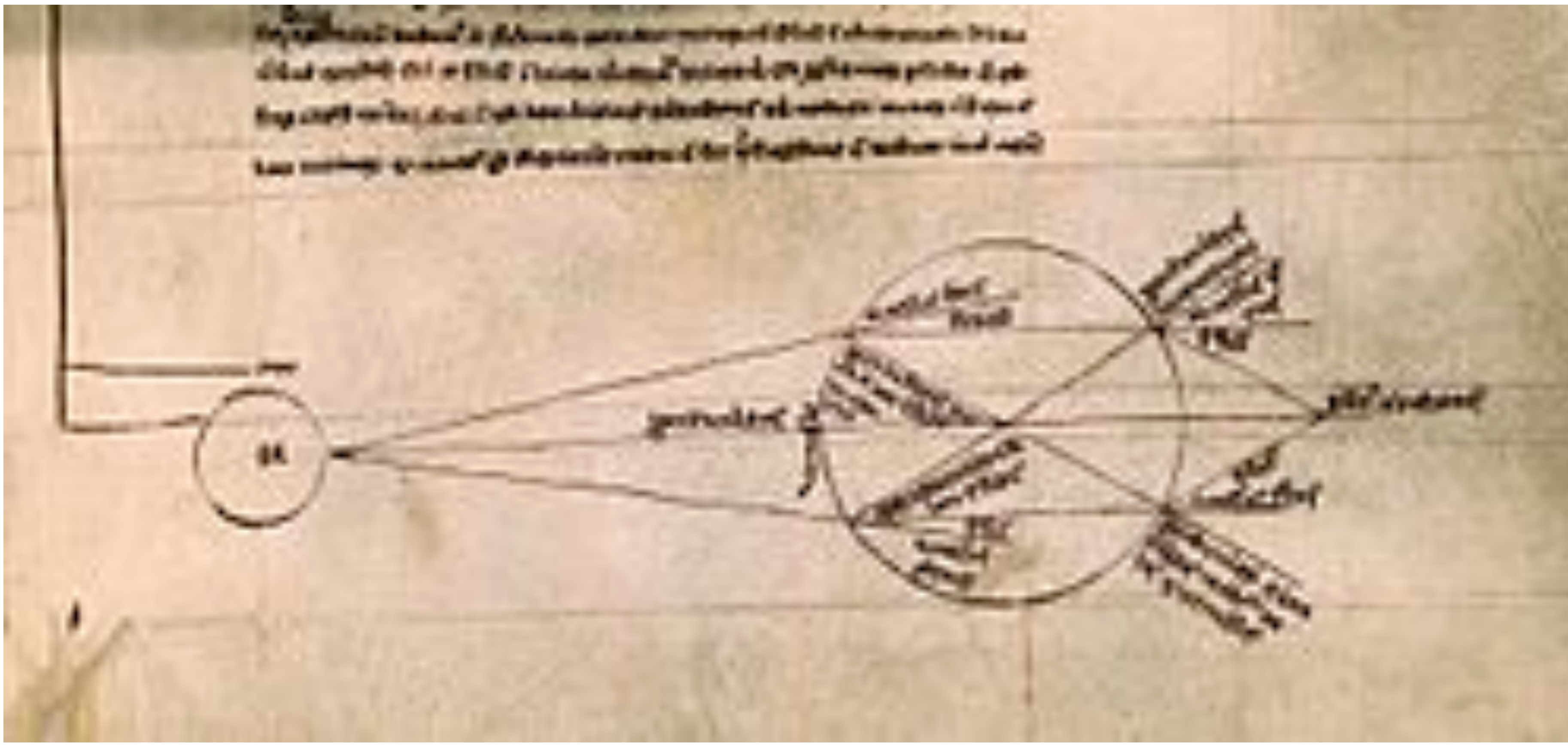
During Roman times: Addition of K_2O produces clearer glasses.



165-85 BC Claudius Ptolemy

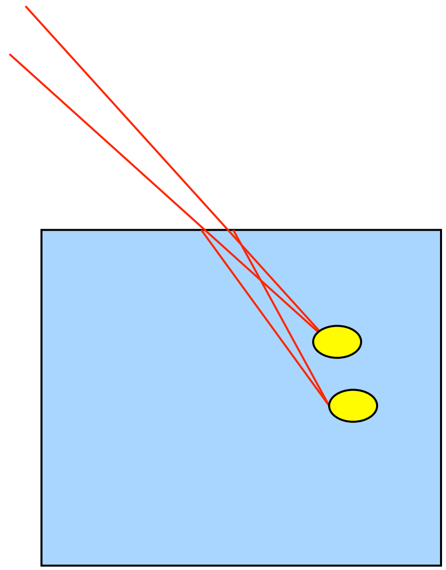
Claudius Ptolemy lived in Alexandria. He describes qualitatively refraction of light rays in various transparent media: water, oils and glass. However, he failed to understand that meeting of rays emitted from one point of the object creates the image.

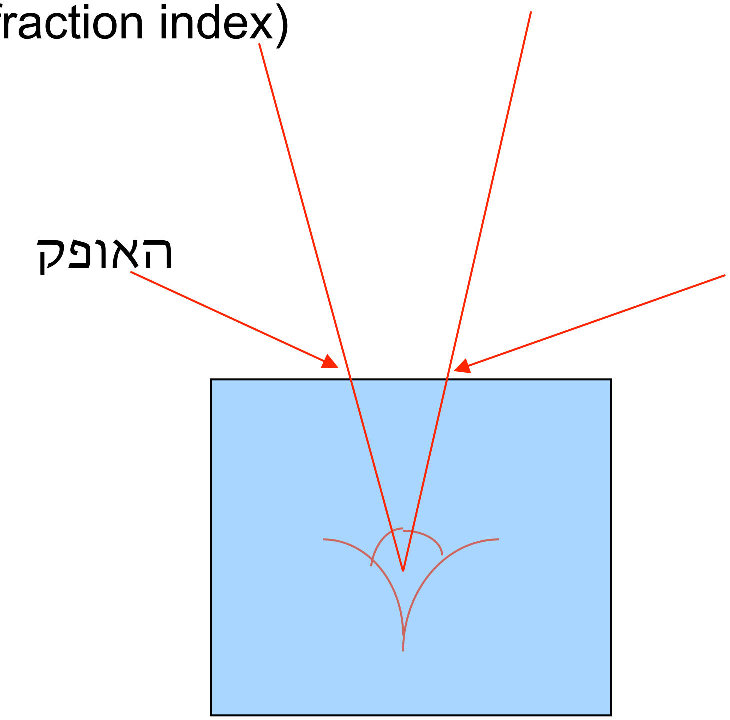
Below is one of Ptolemy's optical diagrams:



REFRACTION OF LIGHT

Rays move closer to the direction vertical to the interface surface when passing from low to high density medium (higher refraction index)

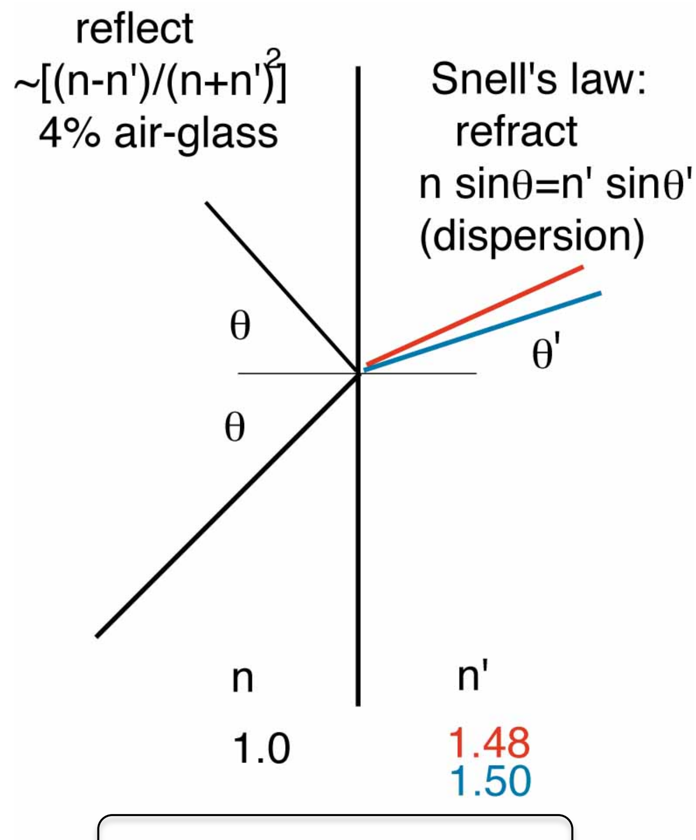




Straw in the cup looks broken
A coin in the fountain looks higher than its real depth
Looking up the sky from under the water, the horizon looks as a 50^{o} cone and not 90^{o}. (e.g. National Geographic underwater movies)

SNELL LAW OF REFRACTION

Quantitative description of refraction angles:

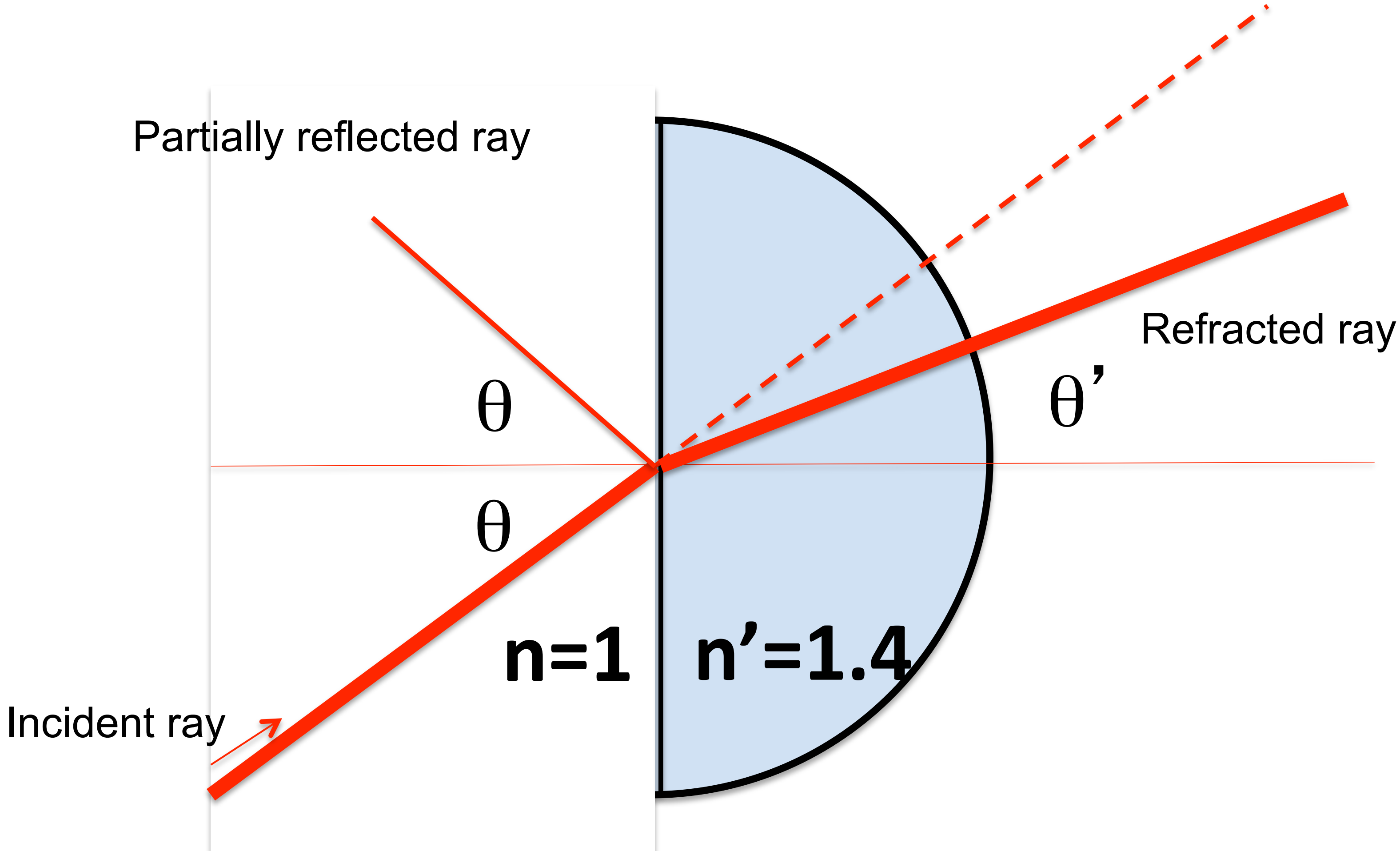


$$n \sin\theta = n' \sin\theta'$$

Refraction index, n, is defined as n=1 for air (actually vacuum), n=1.333 for water, and n~1.43 for common glasses. Modern eyeglasses are prepared from polymers with n=1.6, making thinner, lighter eyeglasses.

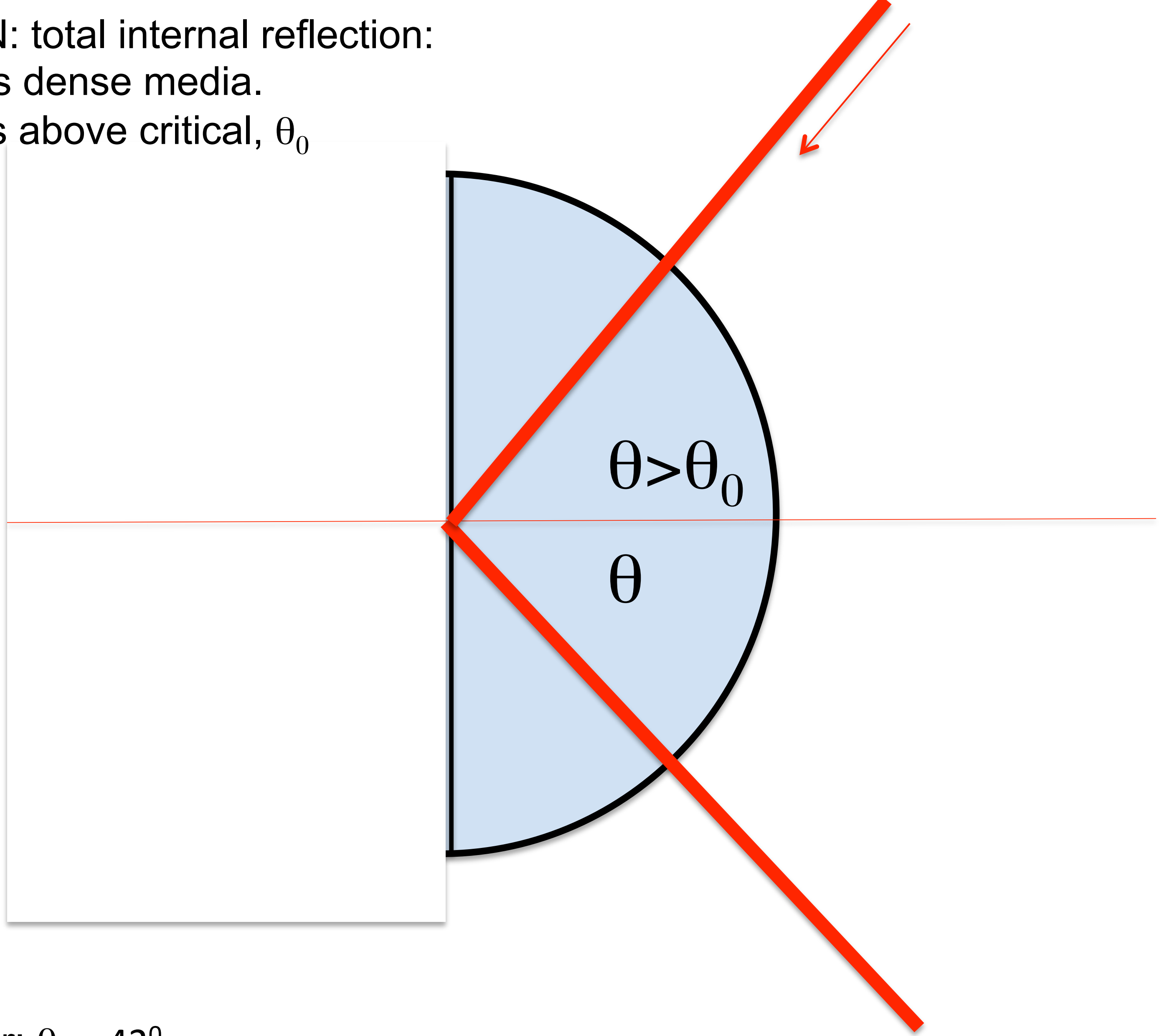
We shall later study the optics of lenses.

DEMONSTRATION: Measurement of incident and refracted angles by half sphere using a laser source directed to the center, taking advantage of the lack of refraction upon exit from the sphere.



The partial reflection always happens, and the part reflected is larger at higher incident angles. Today lenses (as most optics) are "coated" with multiple thin films of metallic compounds in order to reduce reflection. We shall study this phenomena in 20th century optics.

DEMONSTRATION: total internal reflection:
From dense to less dense media.
Happens for angles above critical, θ_0

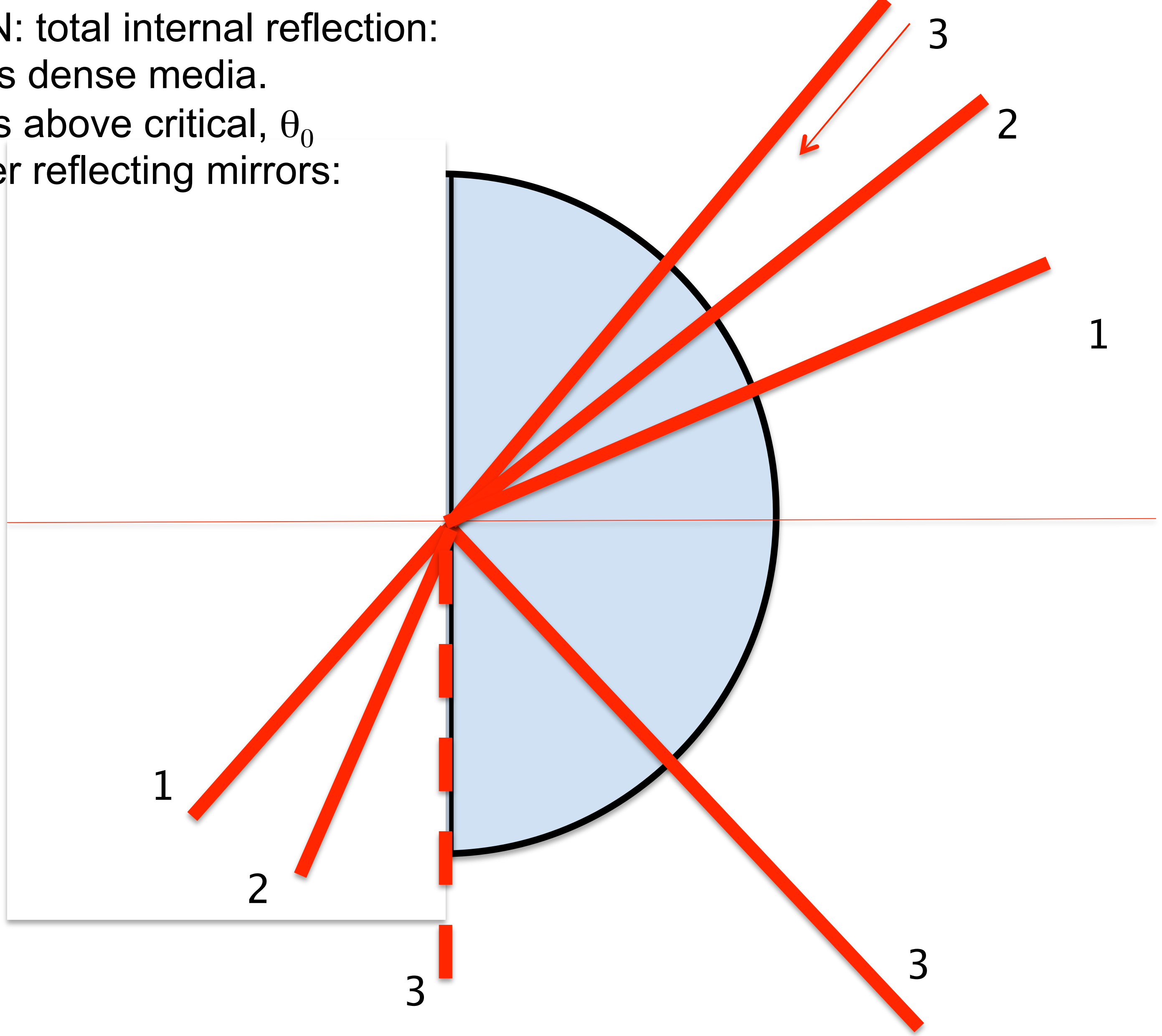


$\theta_0' = 90^0$
in Snell's law:

$\sin\theta_0 = n'/n$

e.g. Glass to air: $\theta_0 = 42^0$

DEMONSTRATION: total internal reflection:
From dense to less dense media.
Happens for angles above critical, θ_0
The advantage over reflecting mirrors:
100% reflection.



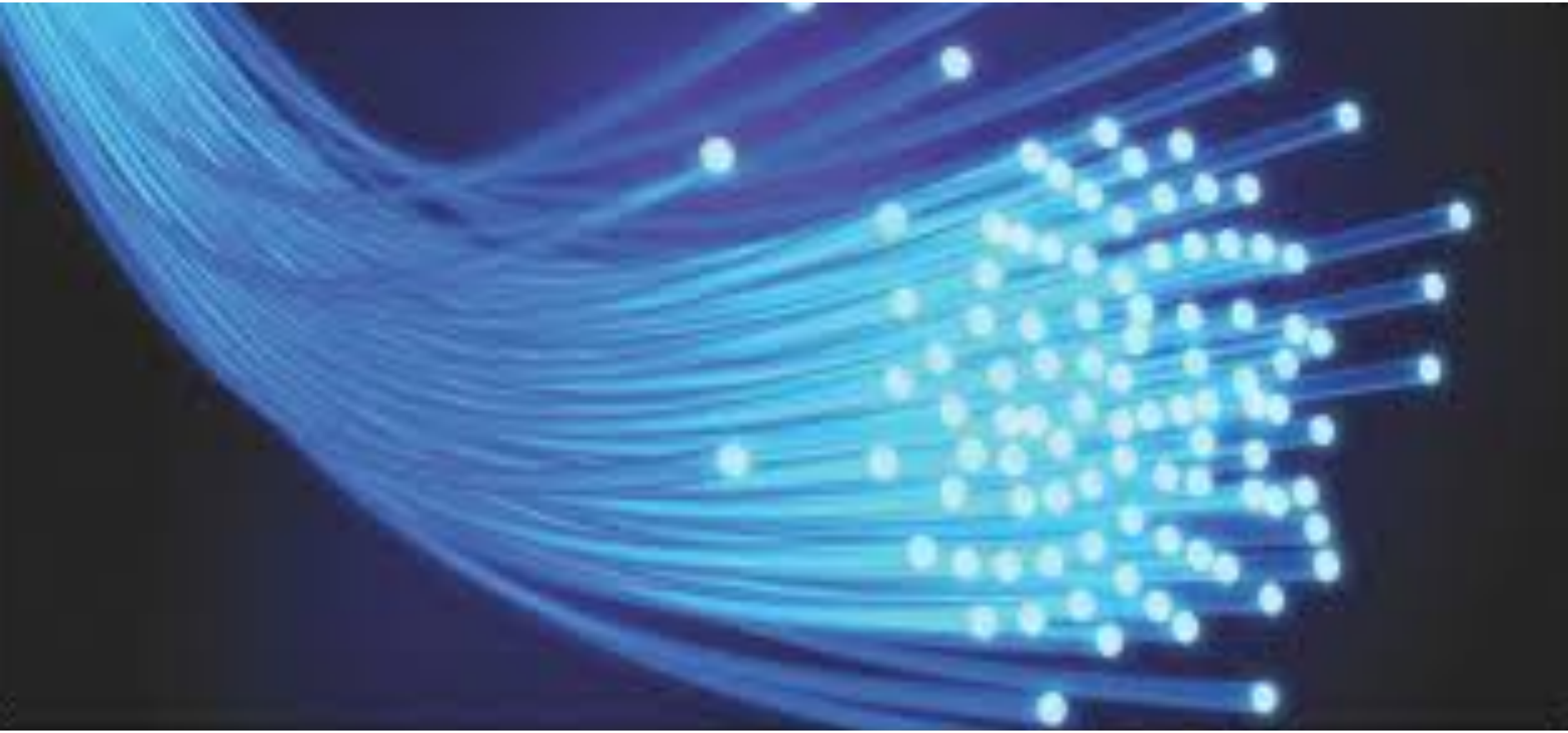
Substituting
$\theta_0' = 90^0$
in Snell's law:

$\sin\theta_0 = n'/n$

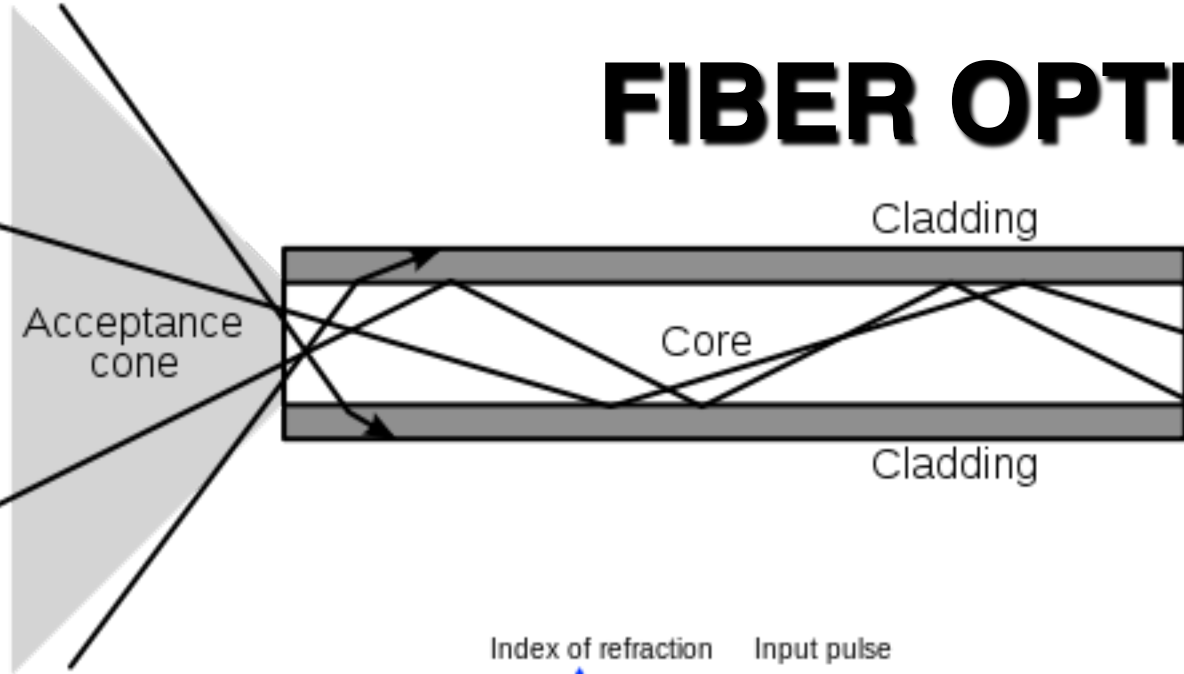
e.g. Glass to air: $\theta_0 = 42^0$

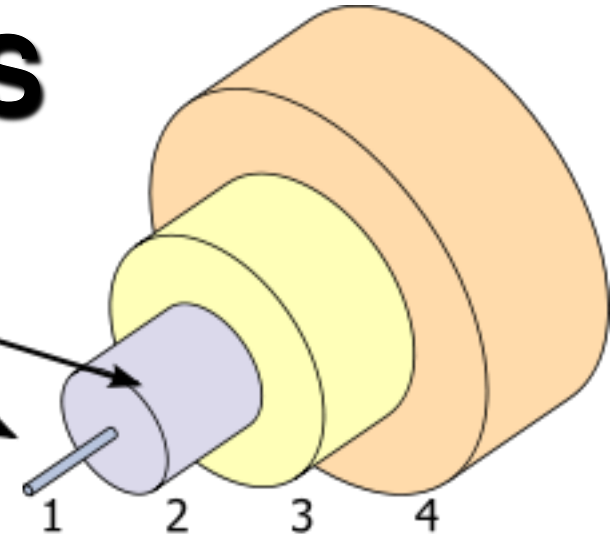
Where is internal reflection applied today?

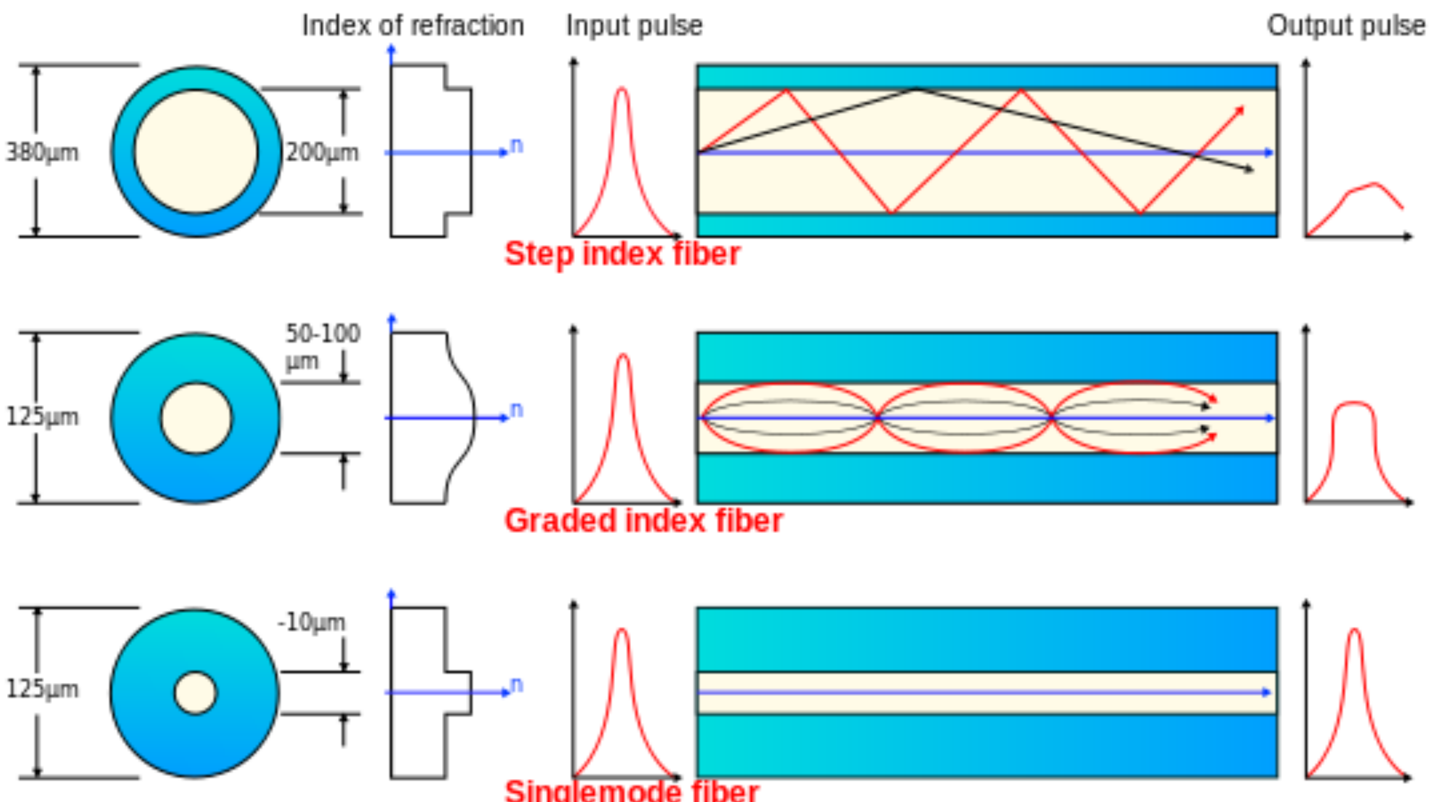
FIBER OPTICS: light led along the fiber by internal reflections, see next slide.



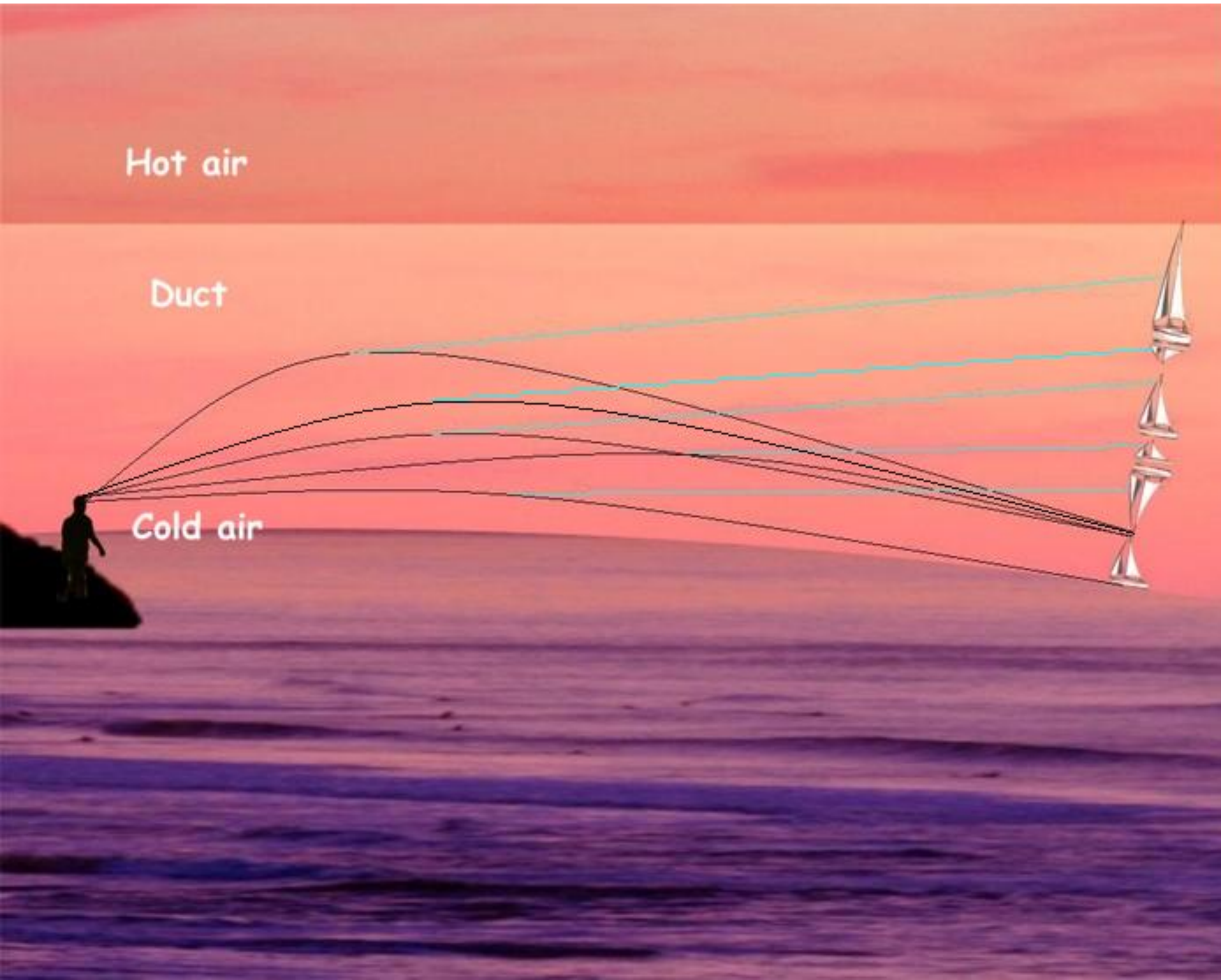
FIBER OPTICS

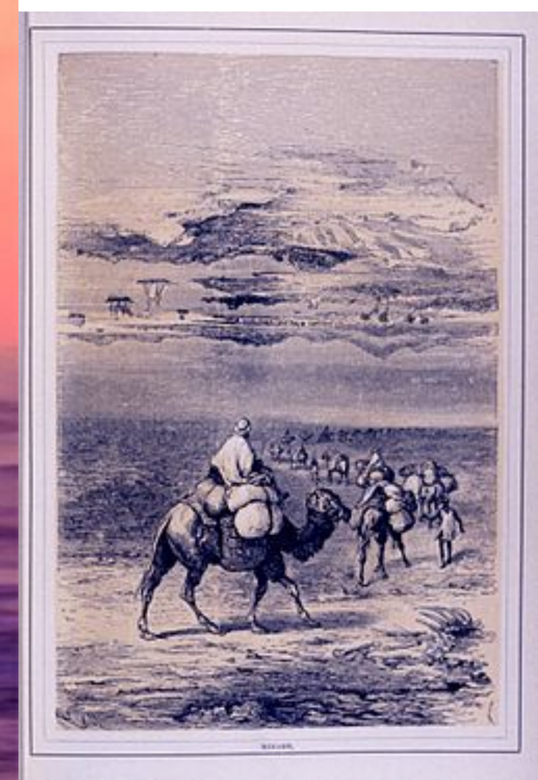






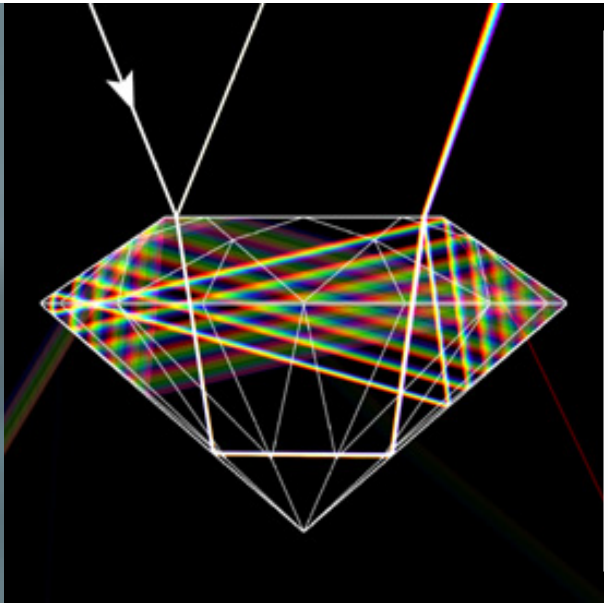
Fata Morgana (Mirage):
is also seen by the viewer due to internal reflection
by the interface between cold and hot air.

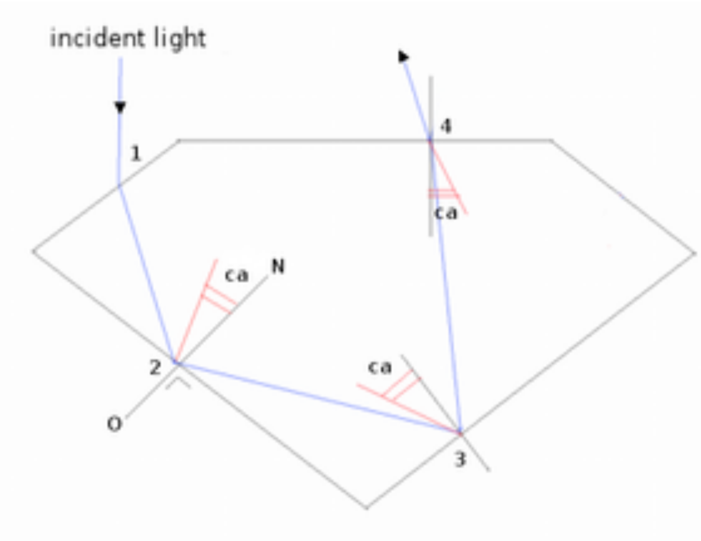


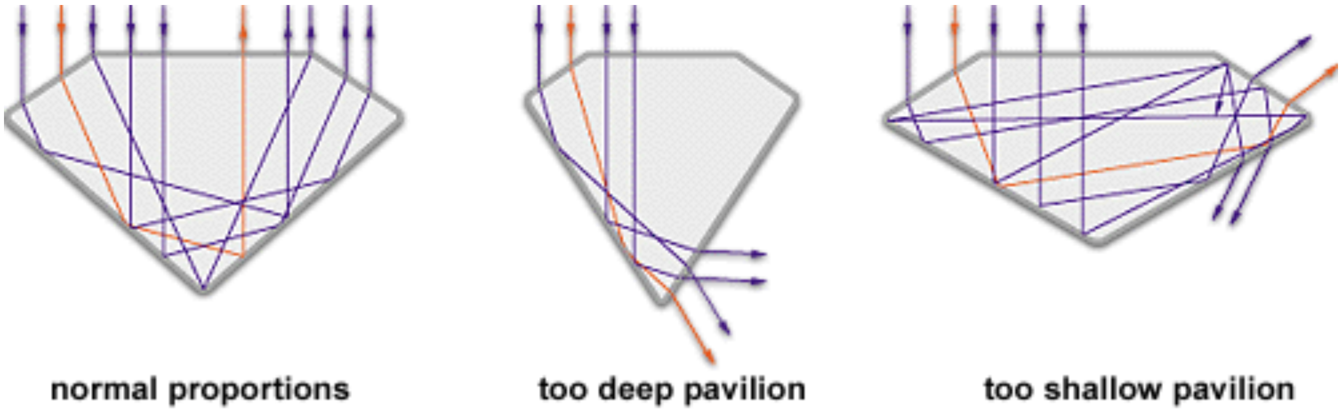


DIAMONDS

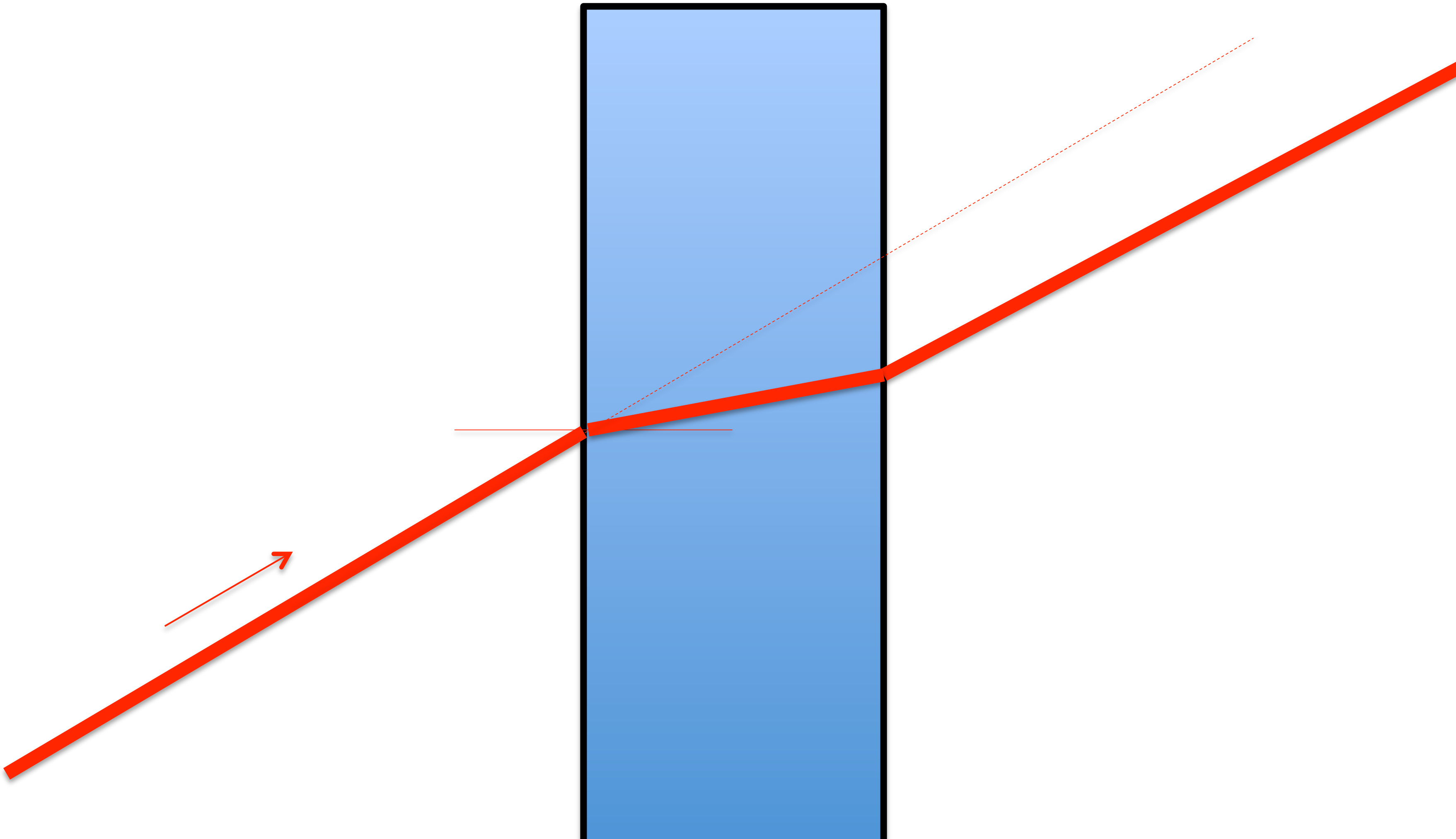
Due to their high refractive index, n=2.4 light goes through multiple internal reflections and refractions with color-dependent angles





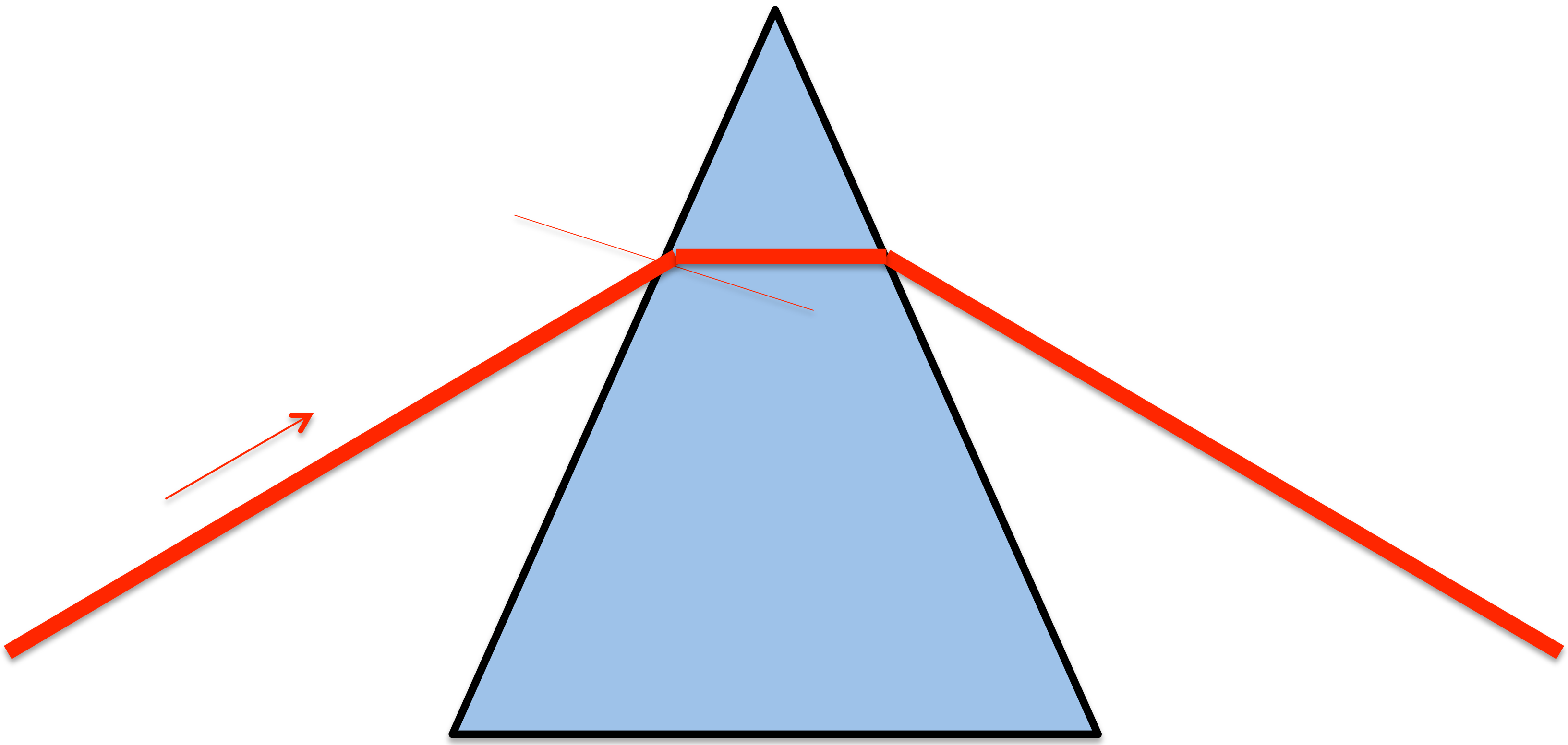


Glass window



Double refraction – ray exits at the same angle, but shifted

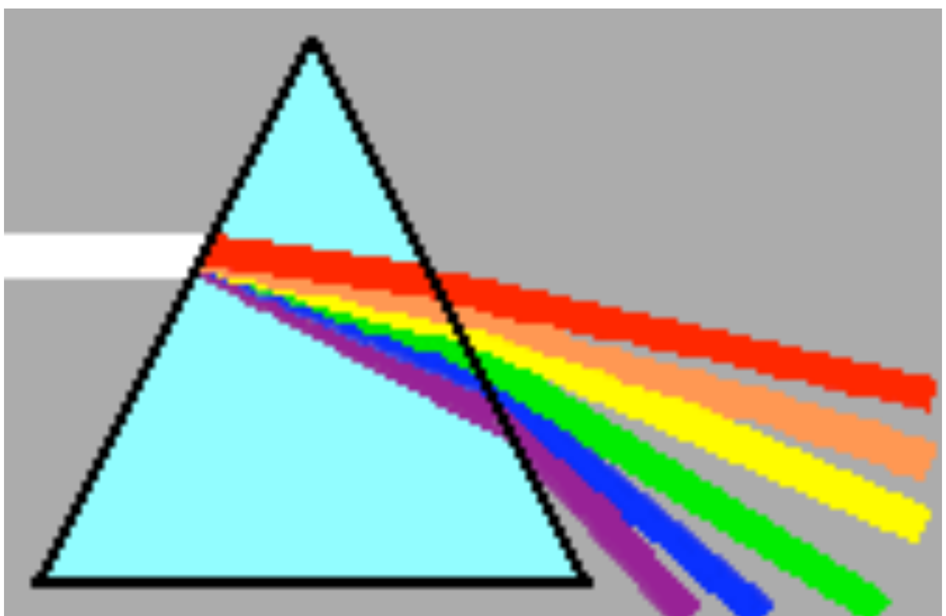
PRISM

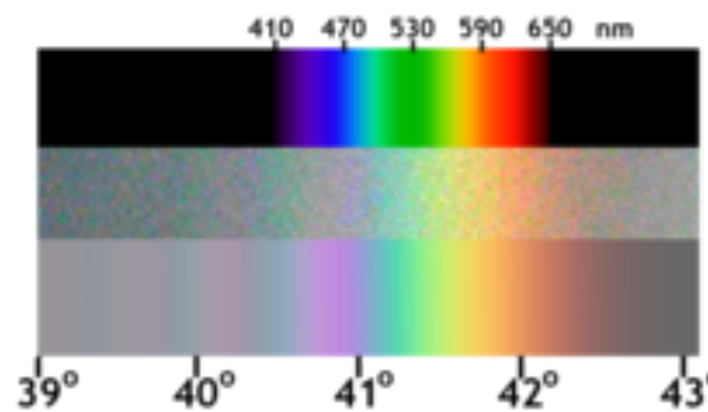


Double refraction, but ray exits at an angle

DISPERSION

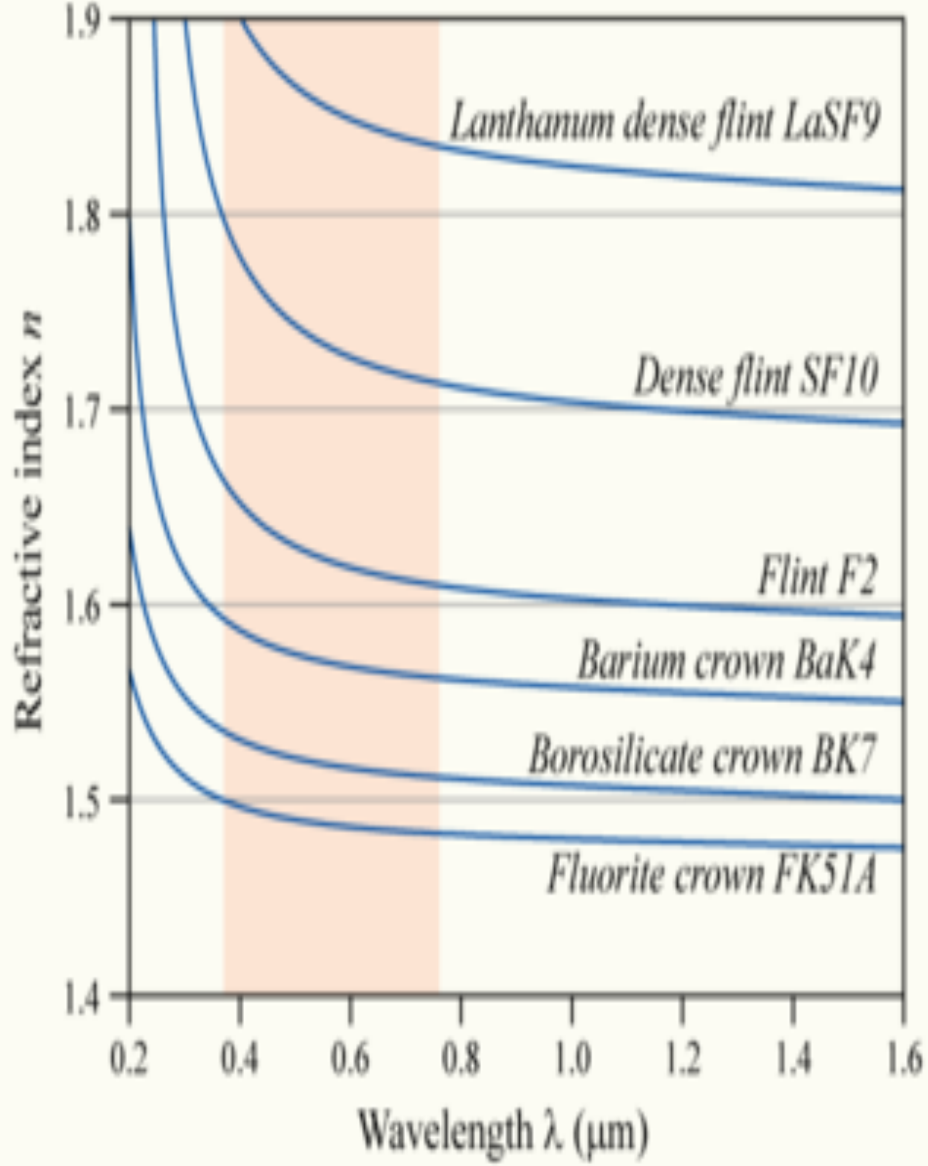
The refractive index depends on the light color (wavelength). By double refraction in a prism light colors separate.
The effect was first viewed in rainbows and in color dispersion by quartz crystals, but explanations were erroneous. Newton was first to describe color dispersion in a prism correctly.
For water $n_{0.4\mu m}=1.339$ $n_{0.6\mu m}=1.332$ For incident ray angle of 30° the difference between violet and red is less than 1°:
$Arcsin(sin(30)/1.332)=22.05^0$ $Arcsin(sin(30)/1.339)=22.93^0$



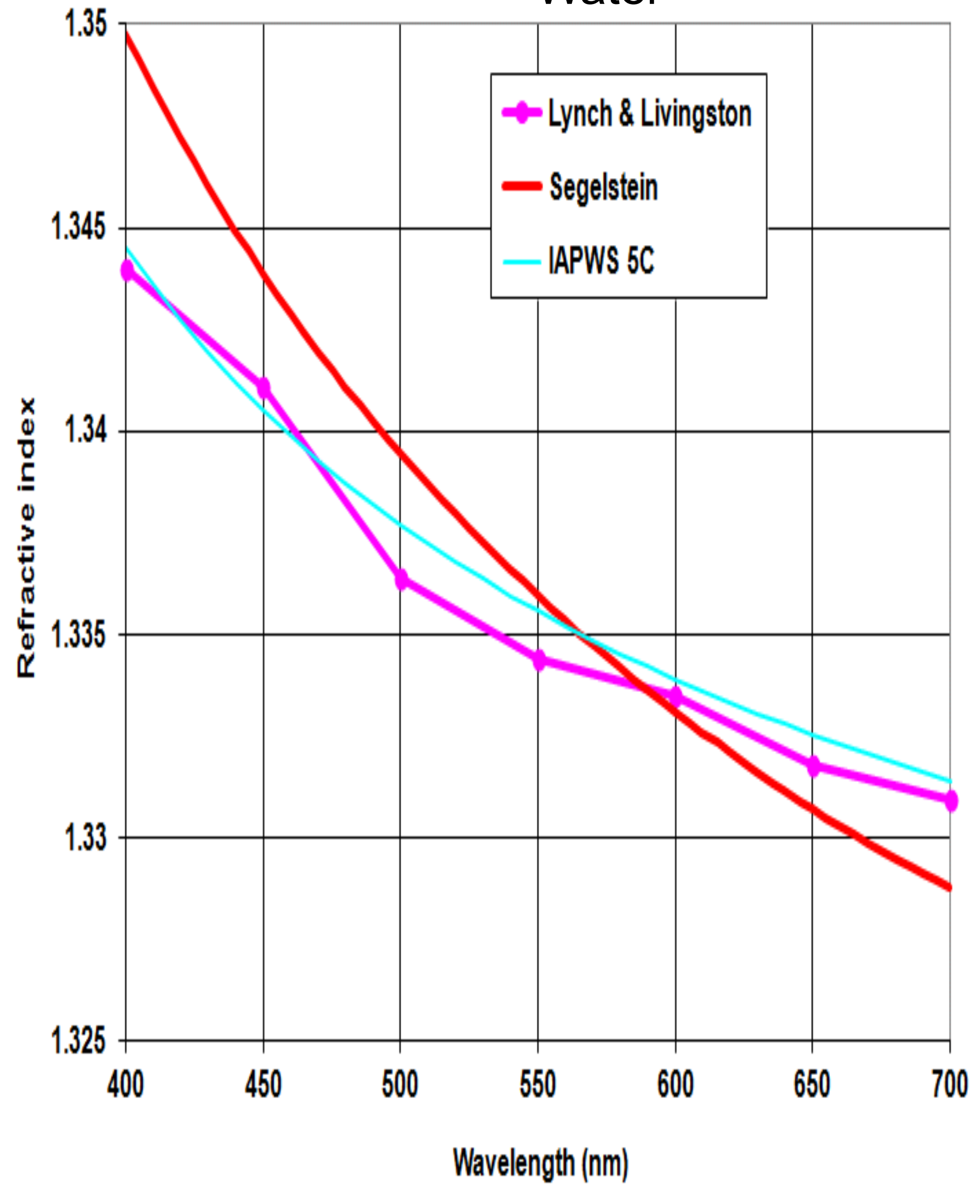


Refractive index in most materials increase towards the violet

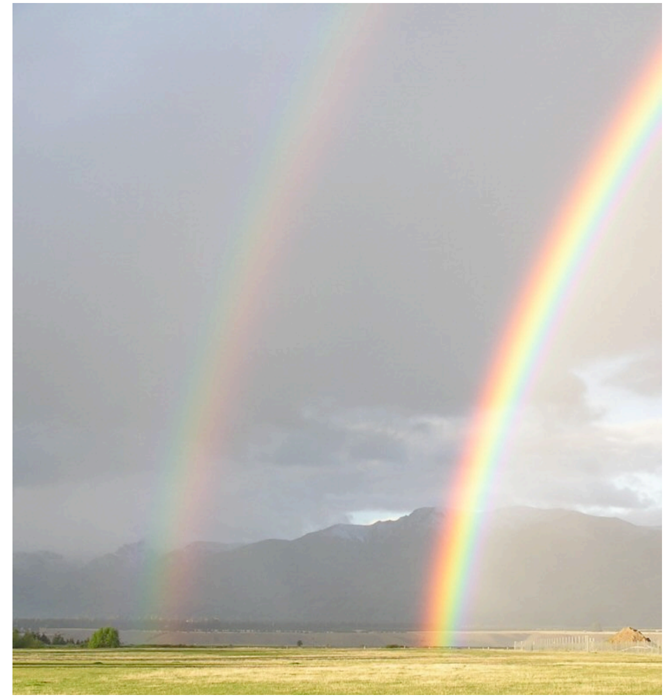
Glass



Water



THE RAINBOW

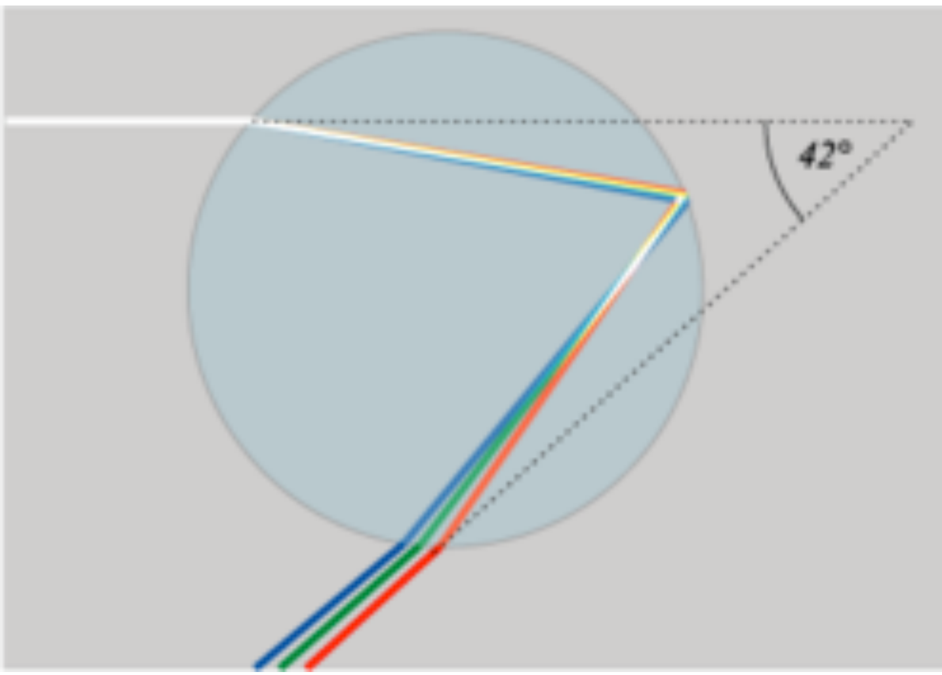


Resulted from dispersive refraction and internal reflection in rain drops
The arc is in angle of 42^{o} with respect to the sun, in opposite direction.
Its width is 2^{o}, twice the dispersion angle between red and violet.
The secondary rainbow is weaker in intensity, and color order is inverted, see following slides.

Rainbows fascinated humans from antiquity, and the history of models proposed to explain its formation spans 3000 years.

384-322 BC Aristo – The first we know who explained rainbow formation.
65 AC Seneca - Devoted a book to rainbows. His observations: rainbows appear in opposite direction to the sun. Created by one of two options: 1. raindrops, and connected to dispersion of colors in glass particles. 2. Reflection from concave cloud formation, his preferred and wrong model.
1031-1095 Shen Kuo – connected rainbow colors to dispersion by water droplets.
965-1039 Alhazen (Ibn Haitam) &1198-1126 Averroes – Accepted this explanation.
980-1037 Avicenna (Ibn Sina) – noted that rainbows appear in tin fogs acting as screen for projecting the rainbow. Denied reflection from clouds.
1236-1311 Qutb al-Din Shirazi & his student Kamal al-Din-al-Faris – finally reached the correct explanation of internal total reflection inside rain drops. They developed a mathematical model, drew ray tracing (see their book) and experimented with glass balls.

1637 Rene Descartes – Expanded this model to explain the secondary rainbow from double internal reflections inside the rain drops.
Newton's dispersion in prisms completed the explanation for the rainbow color order, and its inversion in the secondary rainbow.
1820 Airy – explained the dependence of rainbow brightness on droplets size.
1908 Mie - developed a complete theory for light scattering by droplets.



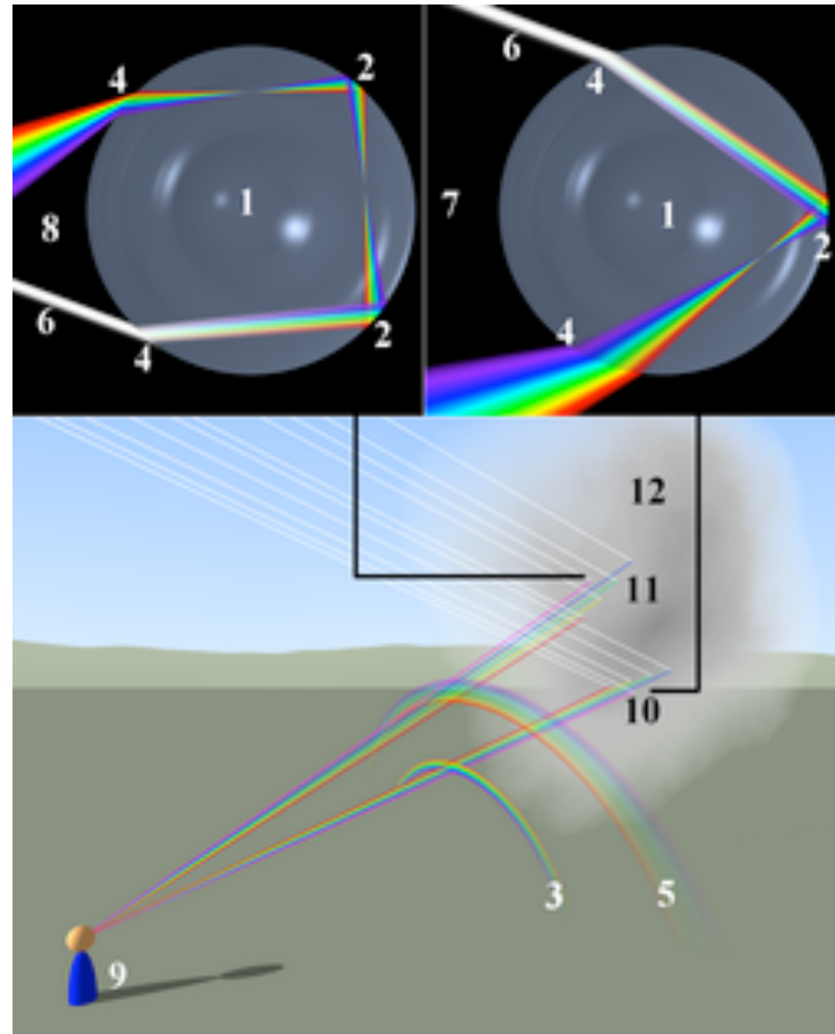
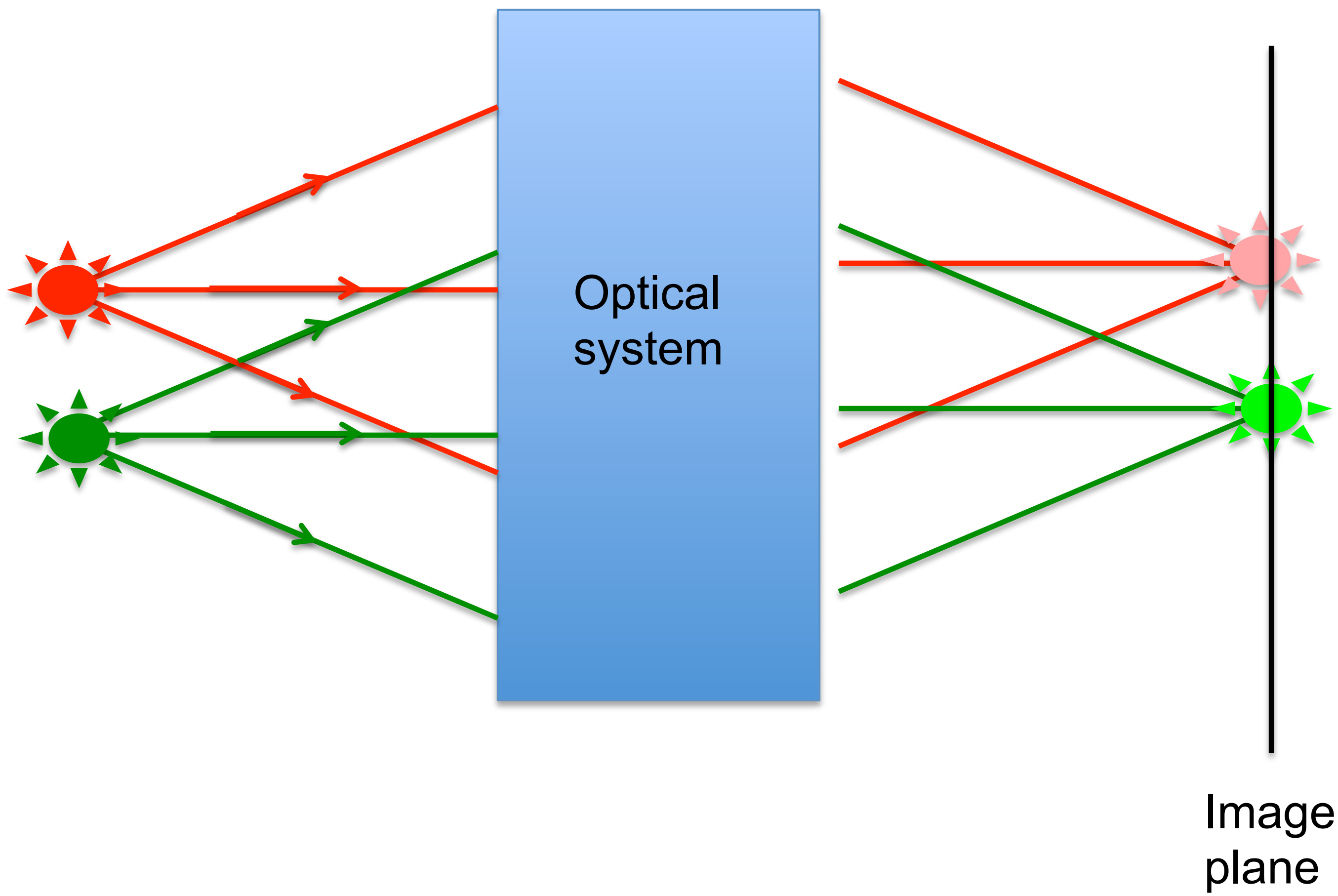


IMAGE FORMATION

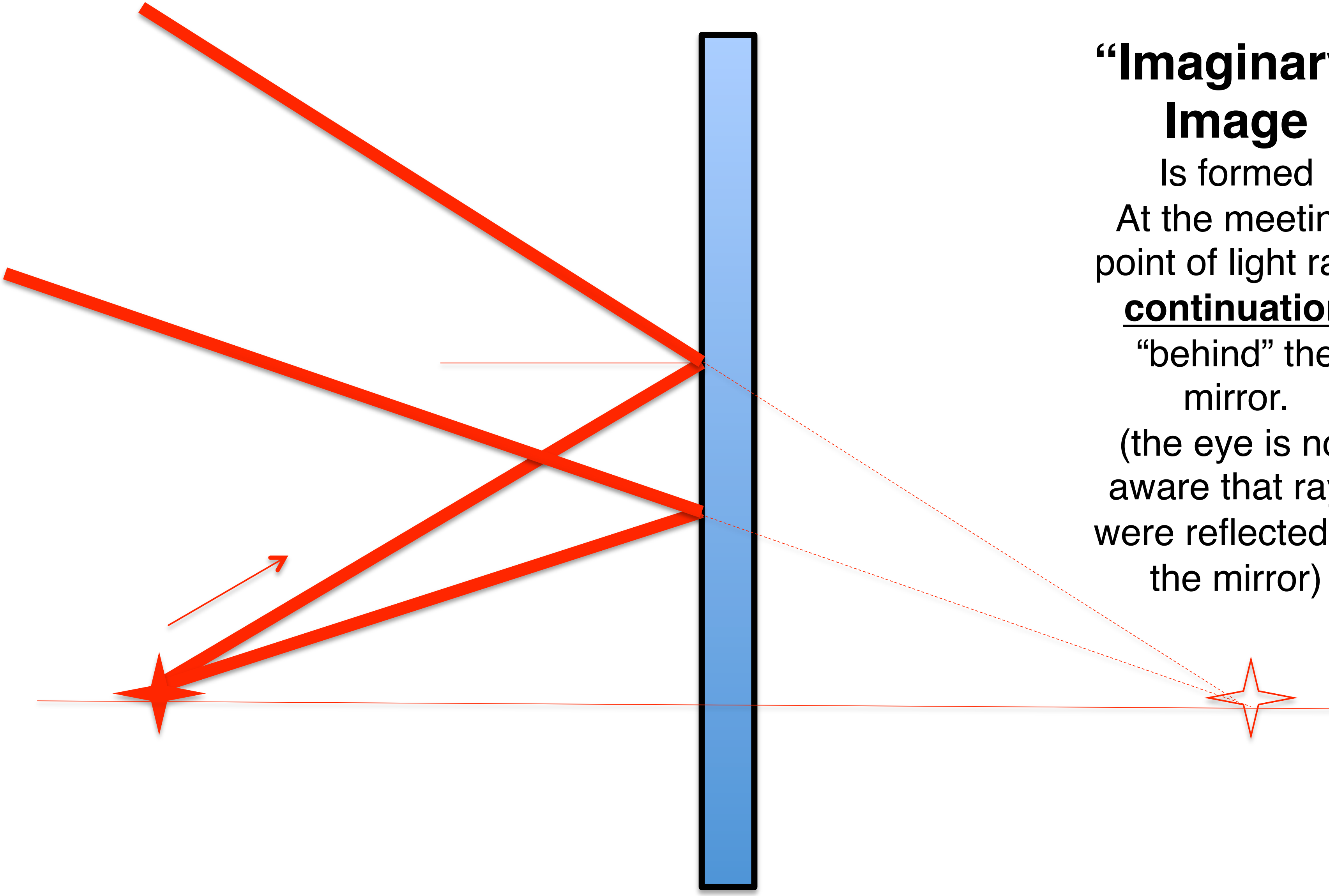
Mirrors and lenses

THE IMAGE IN OPTICAL SYSTEMS

Image is formed at the site of intersection of all rays emerging from one point on the source. At all other sites rays from all points form blurred distribution of light intensities.



PLANAR MIRROR



“Imaginary” Image

Is formed
At the meeting point of light rays **continuation** “behind” the mirror.
(the eye is not aware that rays were reflected by the mirror)

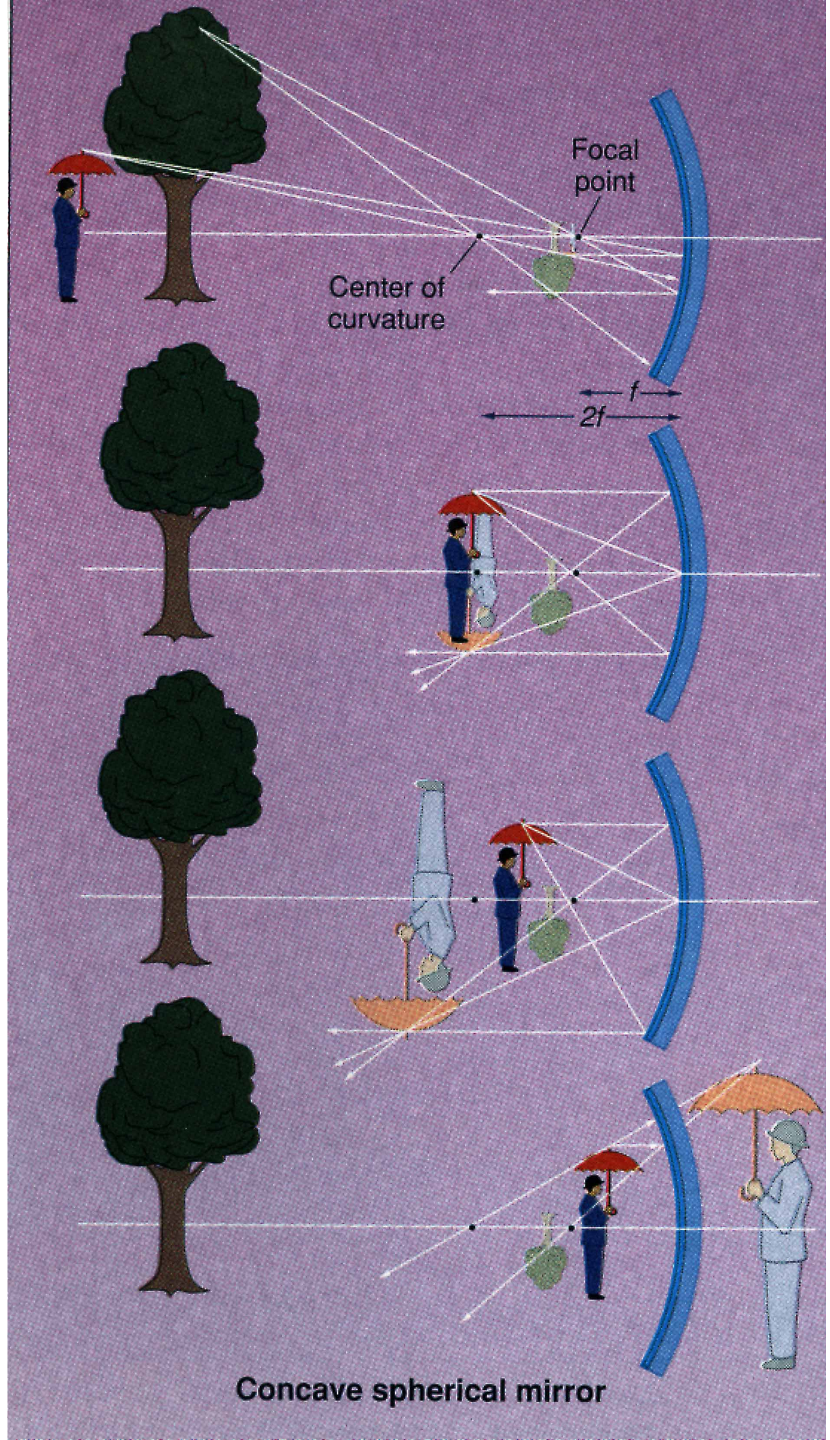
Concave Mirror

For distant objects –
Real image.

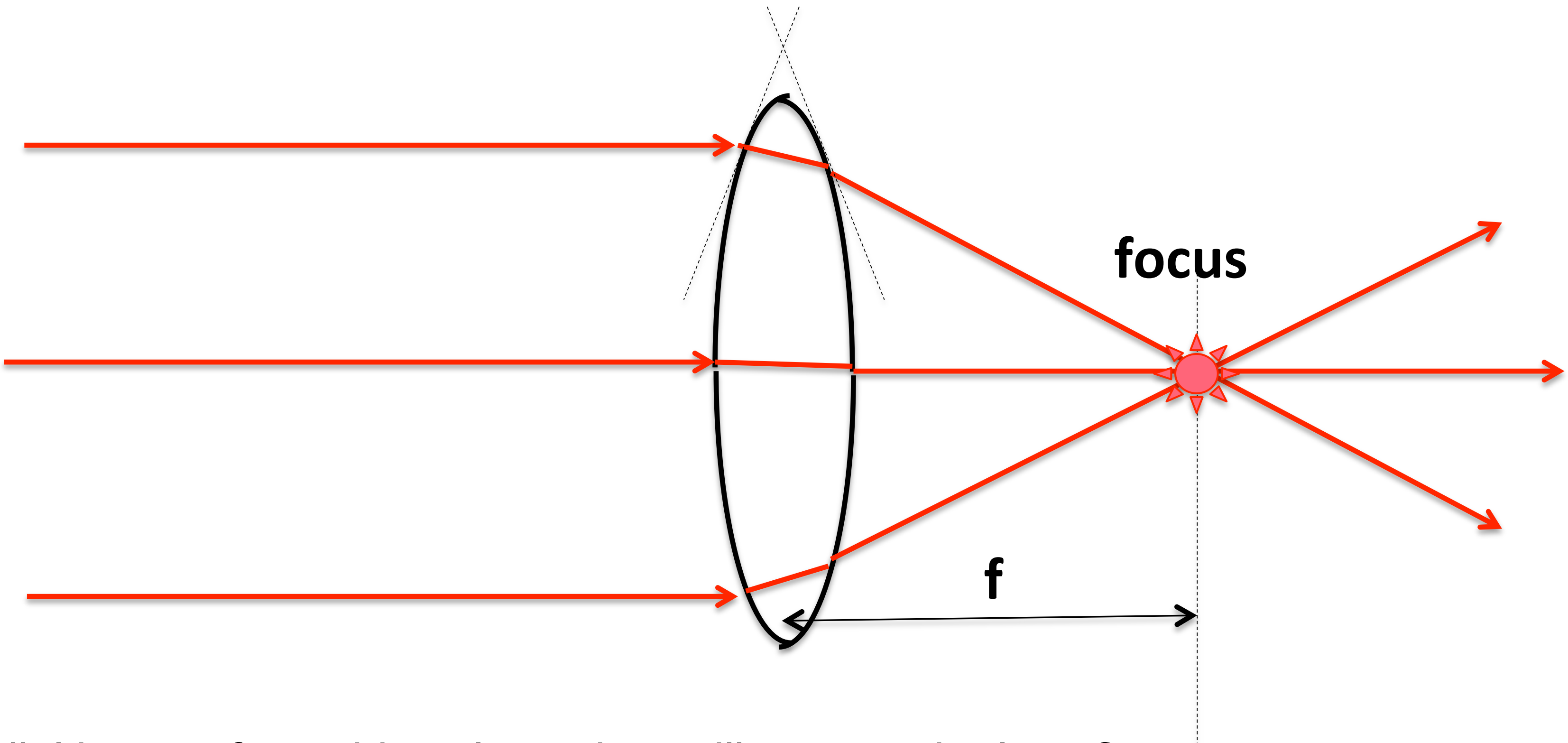
For close by objects –
Enlarged imaginary image
“behind” the mirror.
(e.g. shaving mirror)

Note: something happens
on the way from far to near:
The real image grows and migrates in front of the mirror from near to far, then “returns” as an imaginary image from far behind the mirror.

The point where the image is at infinity is called the mirror focus. For the reciprocal case: object at infinity the image is at the focus with diminishing size.

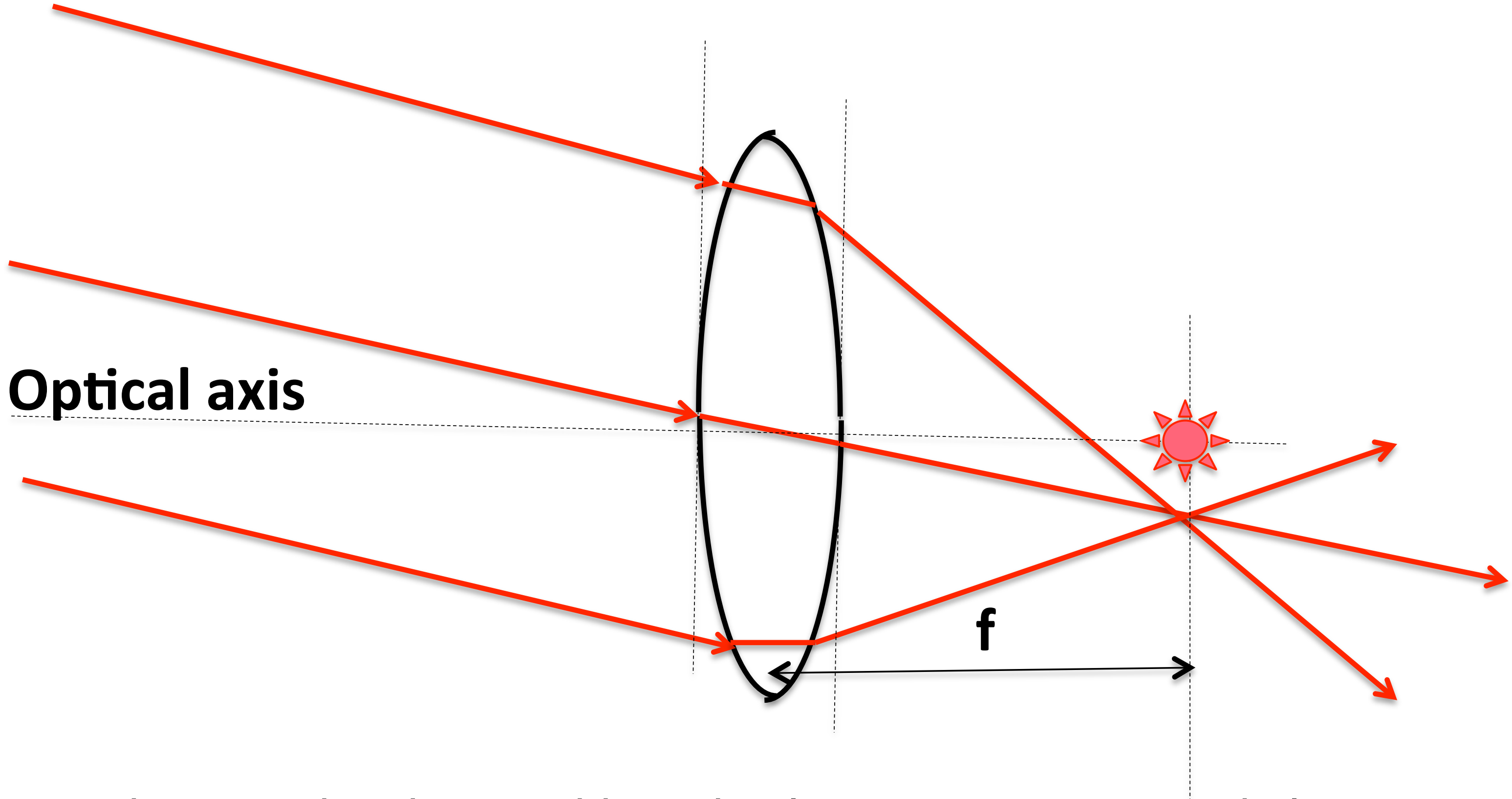


LIGHT REFRACTION BY A LENS



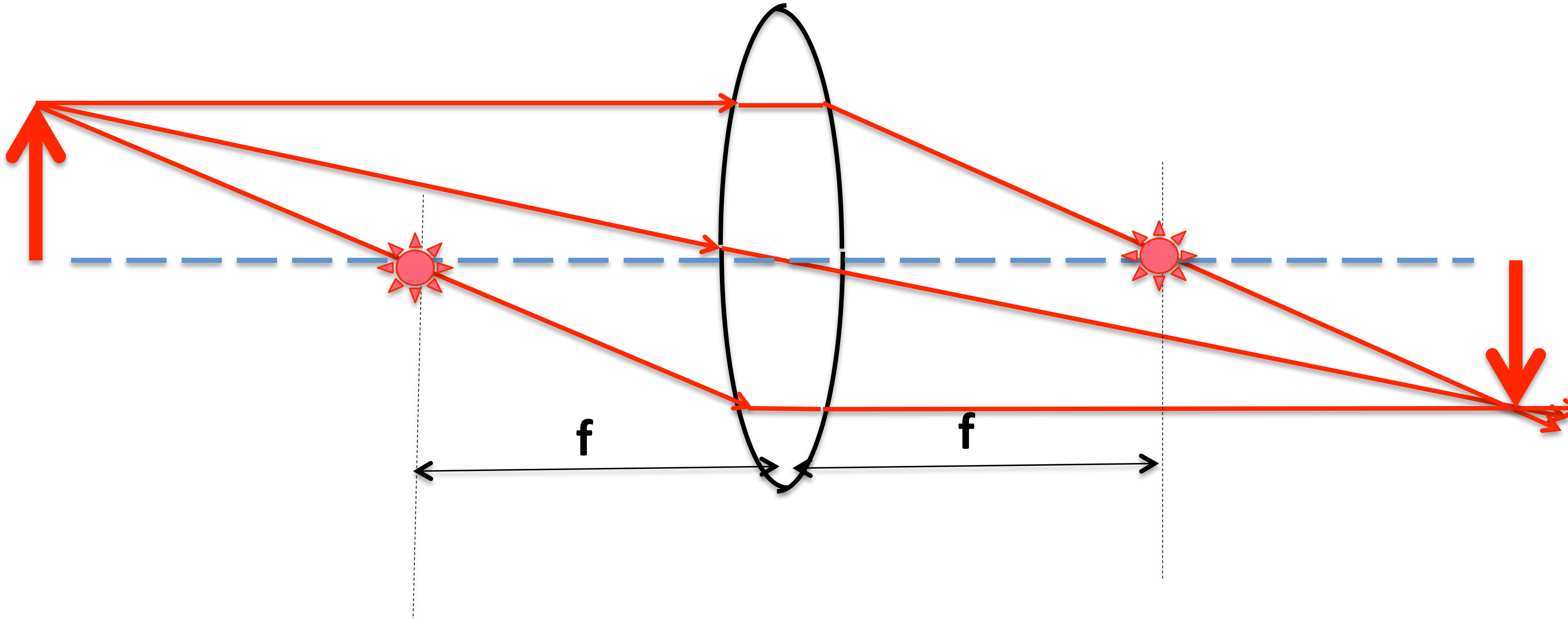
If parallel beam of rays hits a lens, they will meet at the lens **focus**.
Spherical lenses (front and back spherical surfaces) refract more rays that hit the lens father from its center (since the “prism” tangential to the lens has larger opening angle). They quite precisely cause all rays to meet at a point. The approximation becomes worse for lenses with high surface curvatures and rays with large angles with respect to the “optical axis”.
Optical axis is a line through the center of the lens and perpendicular to its surfaces.

LIGHT REFRACTION BY A LENS



The geometric approximation provide a simple mean to trace rays in lenses.
Rays that hit the lens center continue without refraction (negligible deflection for thin lenses), similar to rays path through a window.
Parallel rays with an angle to the optical axis meet on the **Focal Plane** at a point off the optical axis.

Geometrical ray tracing approximation

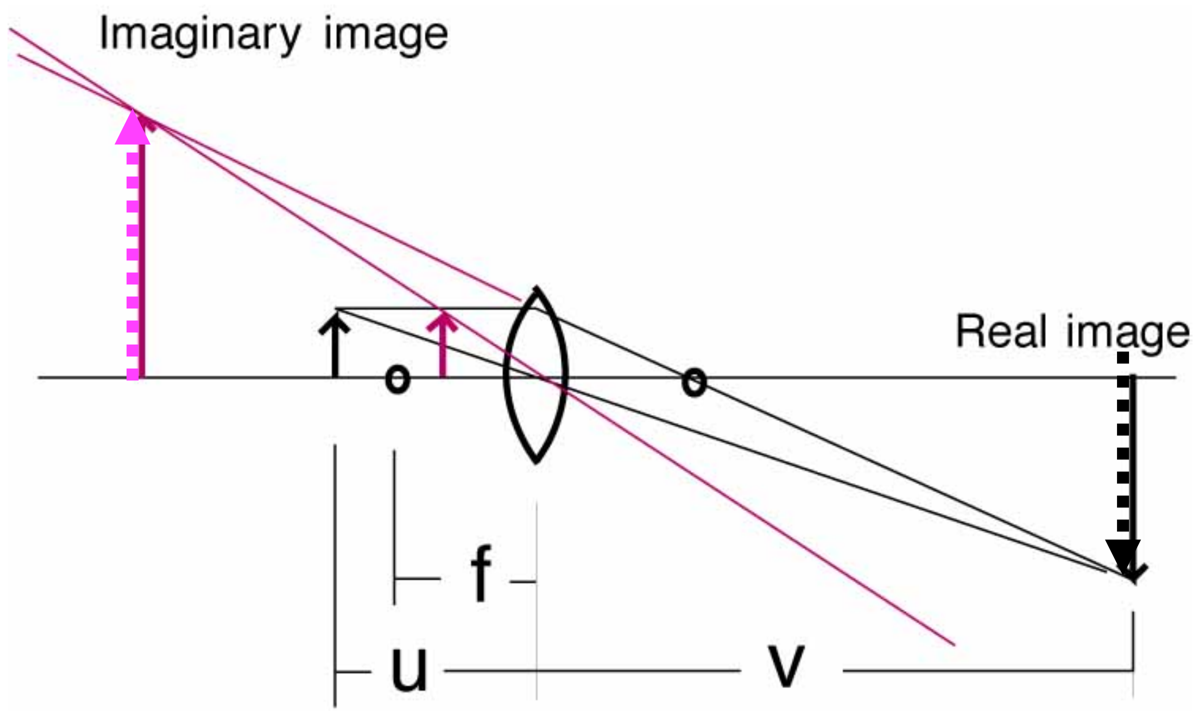


Three rays are easy to draw:

1. Ray passing through the lens center continue without refraction.
2. Ray impinging in parallel to the optical axis exits the lens and pass through the focus (called "**front focus**").
3. Ray the pass the "**back focus**" on its way to the lens exit in parallel to the optical axis.

IMAGE FORMATION BY LENSES

Find the image from the top of the arrows using two of the three “special” rays



$$1/u + 1/v = 1/f$$ Lens makers formula

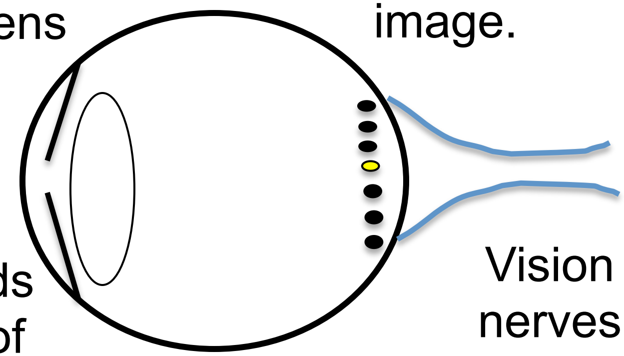
$$\text{or: } (u-f)*(v-f) = f^2$$ Newton’s formula

Show that the two equations are identical.

THE EYE

The eye lens
Focus near or far
objects by
contracting the
lens

The
retina is
at the
position
of the
image.

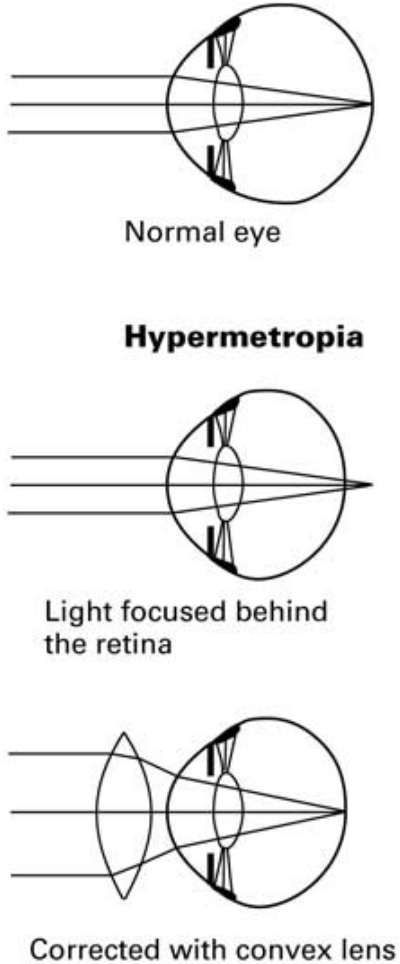


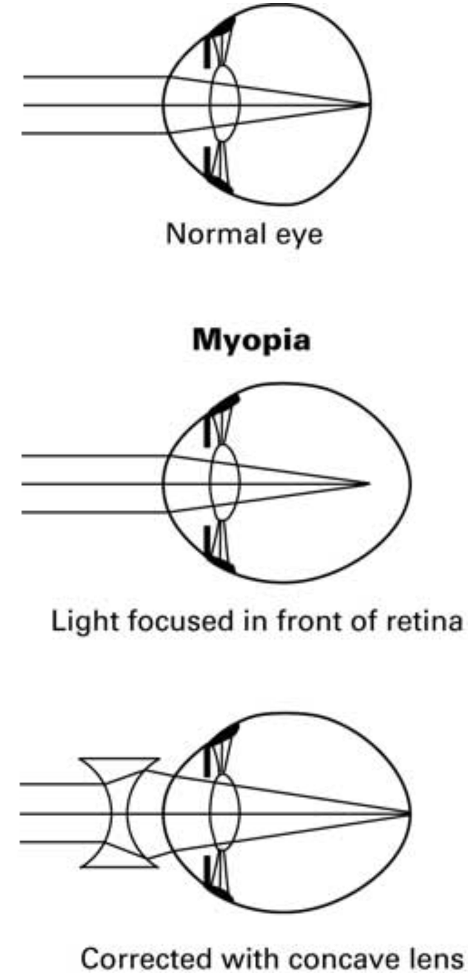
Vision
nerves
lead to
the
brain

Pupil shrinks and expands
modulating the amount of
light entering the eye

Normal eye lenses focus from far objects (no strain)
to near objects with maximum adaptation at 250mm distance

EYE GLASSES



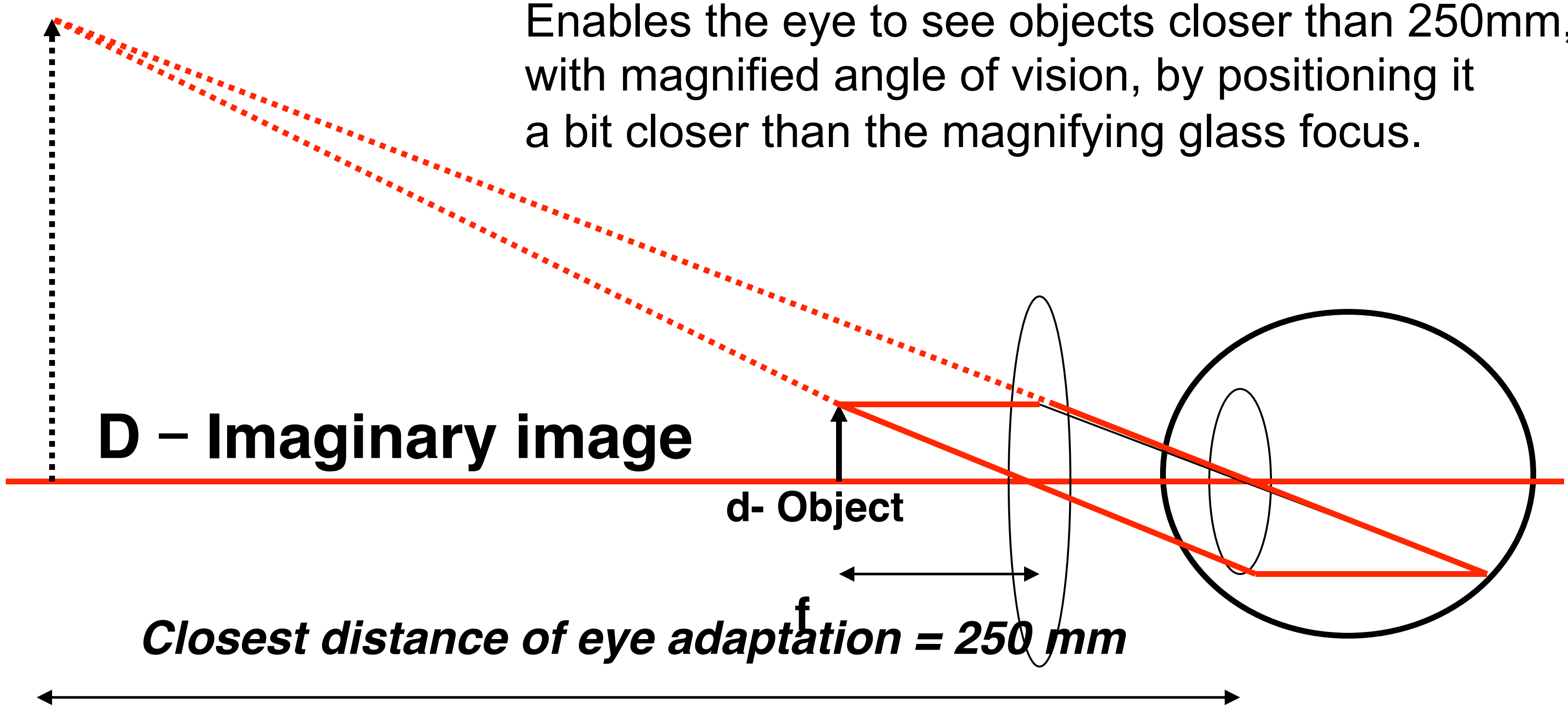


Far sighted eye –
The retina is too close, or the lens is too relaxed at minimal stress.
Corrected with positive (concave) glasses

Near sighted eye–
The retina is too far, or the lens is too strong when at minimal stress.
Corrected by negative (convex) glasses

MAGNIFYING GLASS

Enables the eye to see objects closer than 250mm,
with magnified angle of vision, by positioning it
a bit closer than the magnifying glass focus.



M= *D/d* ***Linear Magnification for object and image at finite distances.***

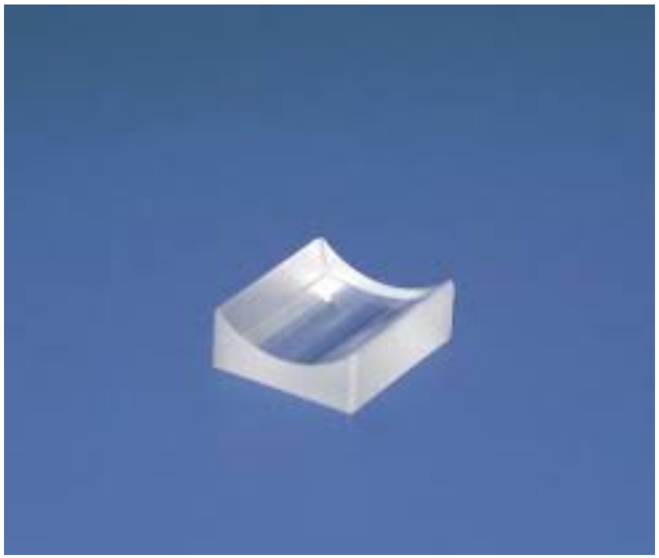
For object a bit closer than the focus, and image at 250mm:

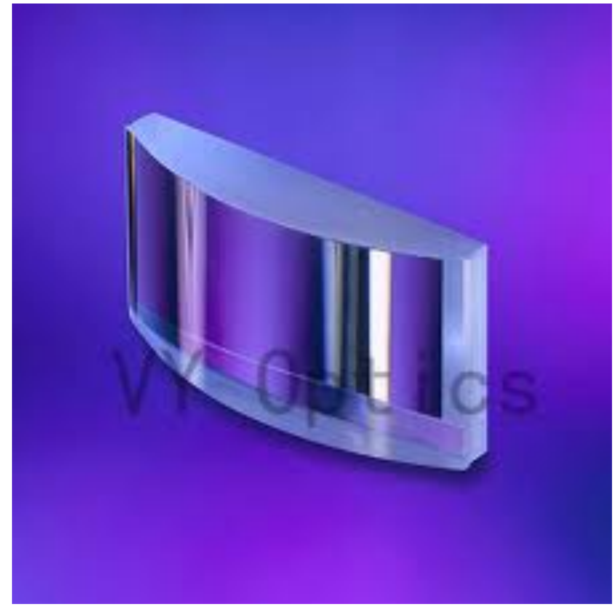
M=250/f (d~f, D=250)

For object at the focus, image at infinity: Angle of view magnification:

M=250/f+1 (d=f, D=∞)

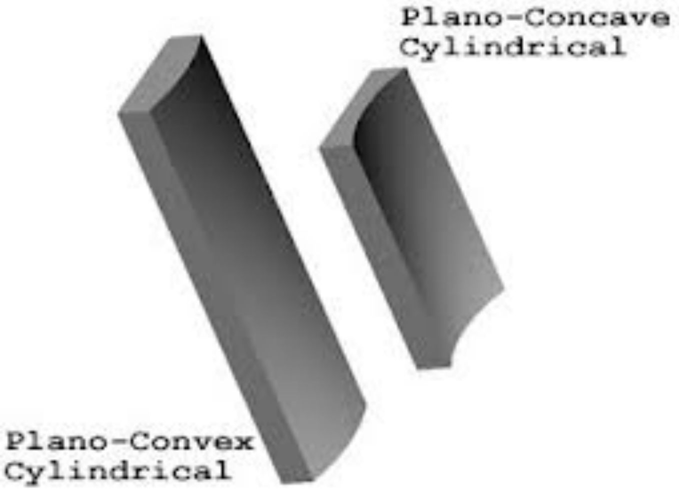
CYLINDRICAL LENSES

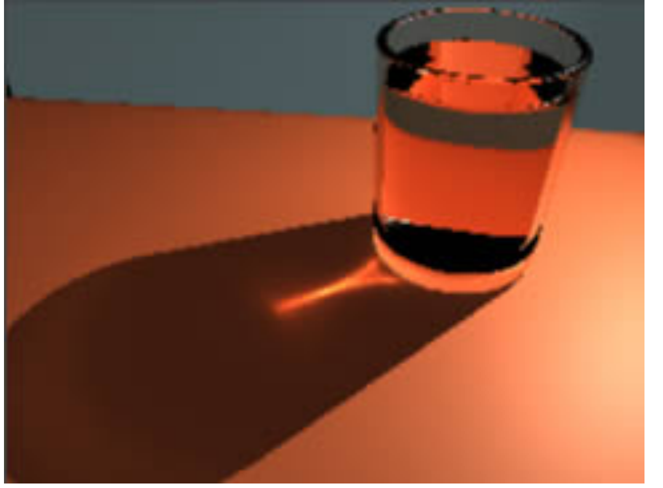




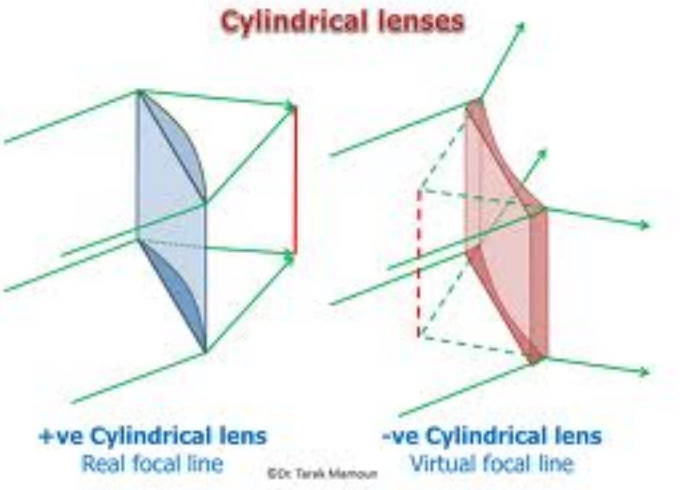
Has different focus for rays shifted horizontally and vertically from the optical axis rays

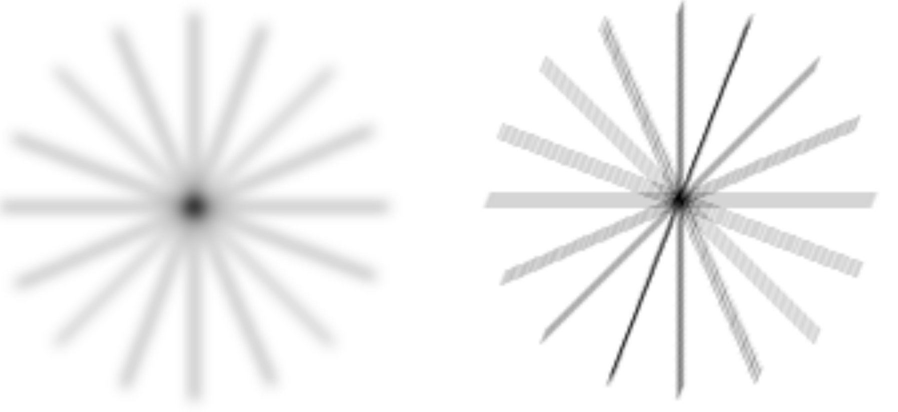
Why do some people need cylinder eye glasses ?



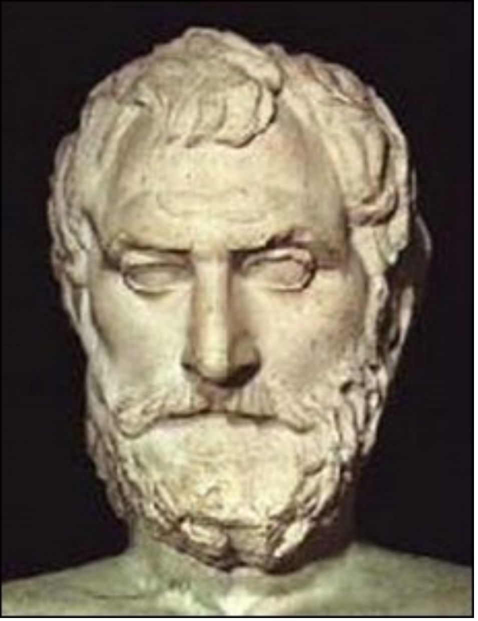


Note the focusing of the sun by a glass of water



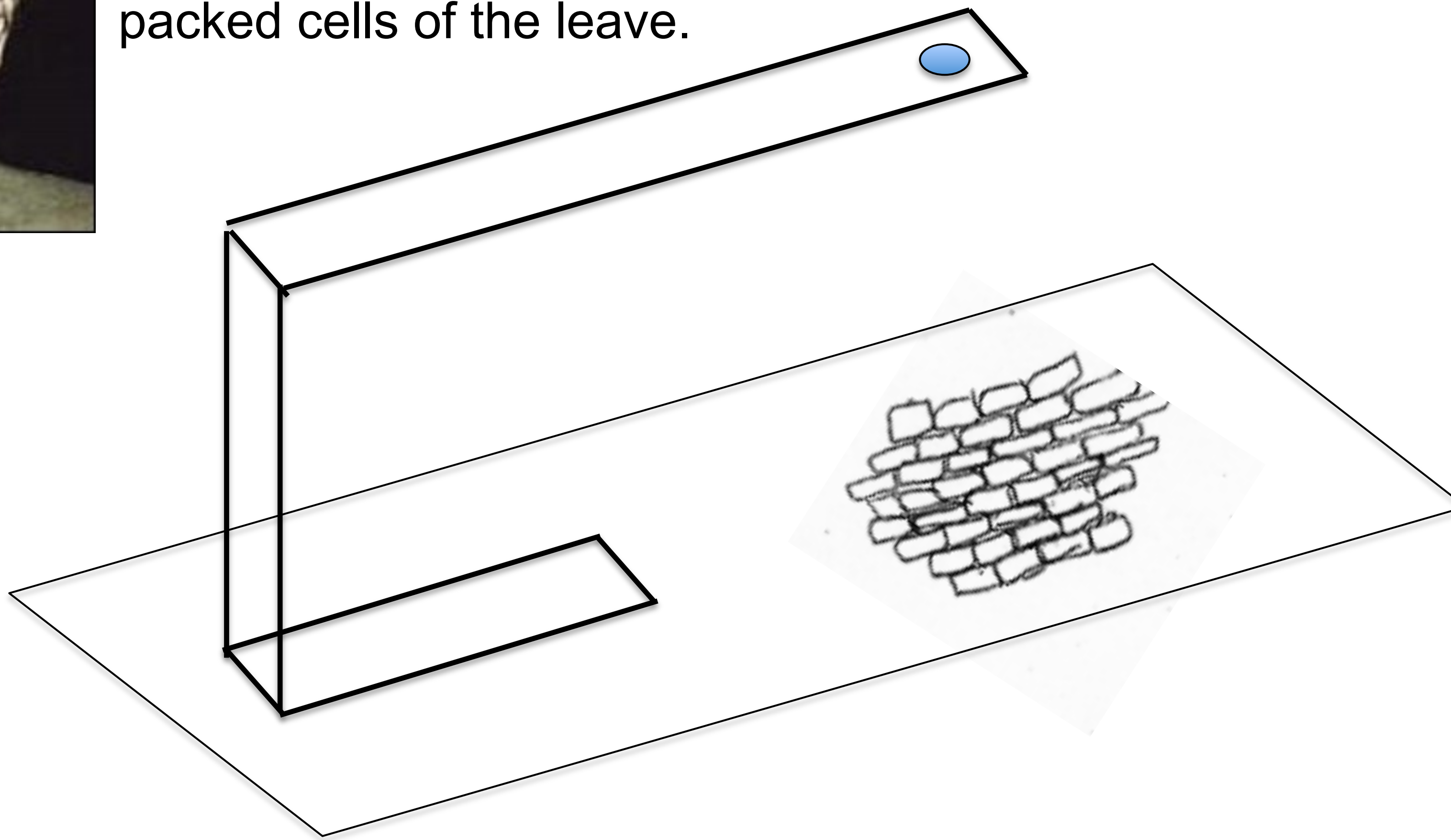


The vision seen by an eye in need of cylinder correction:
Left: short sighted eye – all lines are blurred.
Right: Eye with need of “cylinder” correction – vertical lines clear, horizontal line blurred



Thales of Miletus 620—546 BC

Is told to notice the magnifying effect of mill due droplets on leaves, when he saw leave aphids, and detected packed cells of the leave.



EXPERIMENT: You can easily build Thales microscope, drilling a small hole in a metal foil, smear oil around the hole, and hang a water droplet in it. Use thin onion shell and tilt the metal to bring the onion shell to focus.

SUMMARY:

Vision and light were a subject of research from antiquity. Mirrors were available in Egypt, and light reflections from the moon and from polished objects, as well as light scattered by fogs brought about various optical models. However, optical theories could be tested only after clear glasses were produced during the early Roman period.

Laws of light refraction were formulated by experiments in water and oil surfaces, and glass bottles in Alexandria. Glass bottles were found to focus sun light, but couldn’t form good images.

Rainbows fascinated scientists, but lack of optical theories created many wrong explanations. Only after color dispersion and internal reflection were understood correct models were proposed during the renaissance.

The import of eyeglasses from China towards the **end of middle-ages** created a market for glass polishers, and induced developing technologies for production of lenses not only to correct vision, but to enlarge small objects, and build multi-lens instruments such as telescopes and microscopes.