Geometric optics

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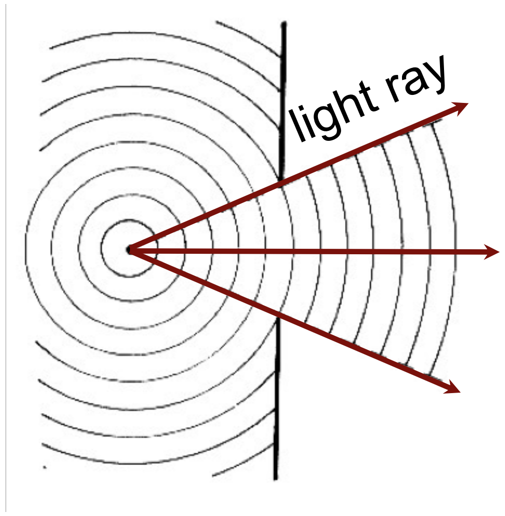
Geometric optics

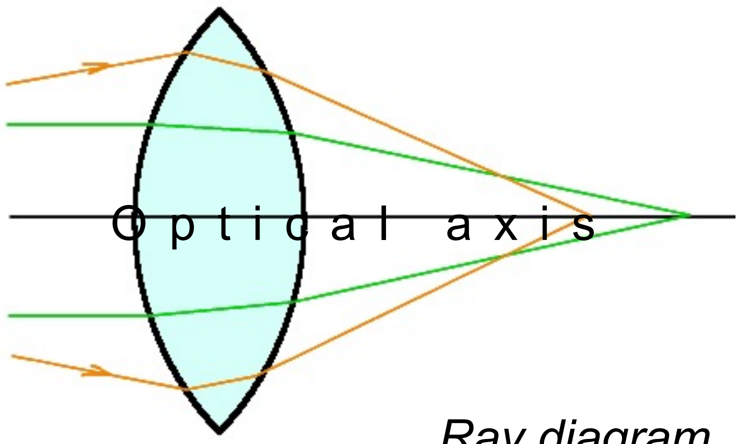
- Reflection, refraction, refractometry
- Total internal reflection, endoscopy
- Refraction on curved surfaces, optical imaging, lens equation
- Light microscope
- Optics of the human eye
- Manipulating objects with refraction

Geometric optics

Geometric optics

If light propagates through a slit much larger than its wavelength, then the spreading of the wavefront (phase) may be simplified into a line (“light ray”).

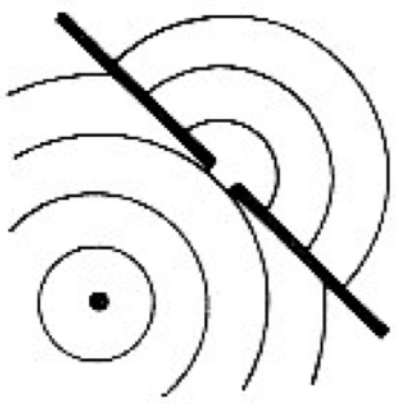




Ray diagram

(by comparison: wave optics - next week)

If light propagates through a slit comparable or smaller than its wavelength, then its wave properties must be taken into account.

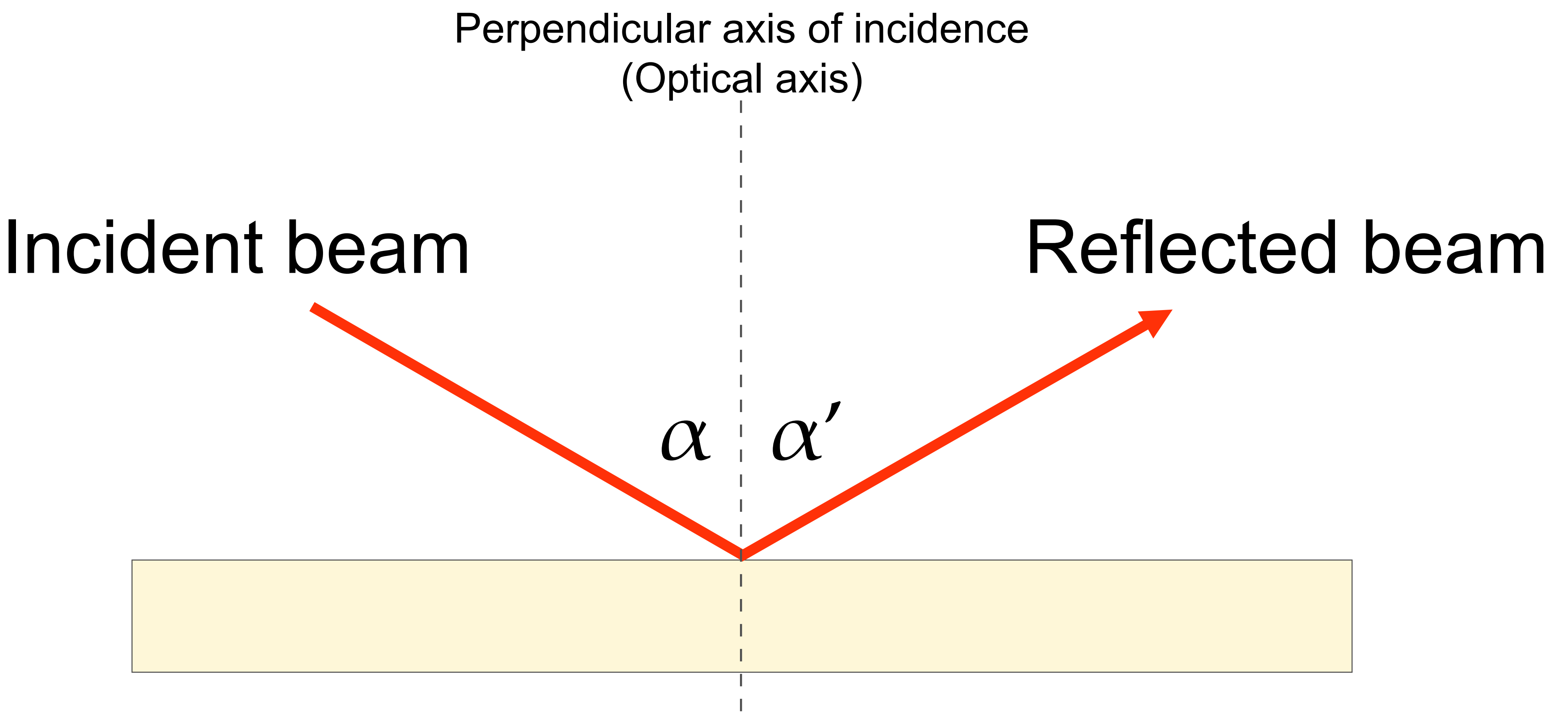


- Optical (light) ray (“light beam”): abstraction, mathematical line.
- Arrows represent the direction of energy propagation.
- Optical axis: line connecting the midpoint of optical components (e.g., lenses).
- Principle of reversibility: the direction of energy propagation (arrows) may be reversed.

Speed of propagation of light in ***vacuum***: $c=2{,}99792458 \times 10^8\ \mathrm{ms^{-1}}$
In optically denser media the speed of propagation is reduced (c_1).
This may be expressed with the ***absolute refractive index*** (n_1):

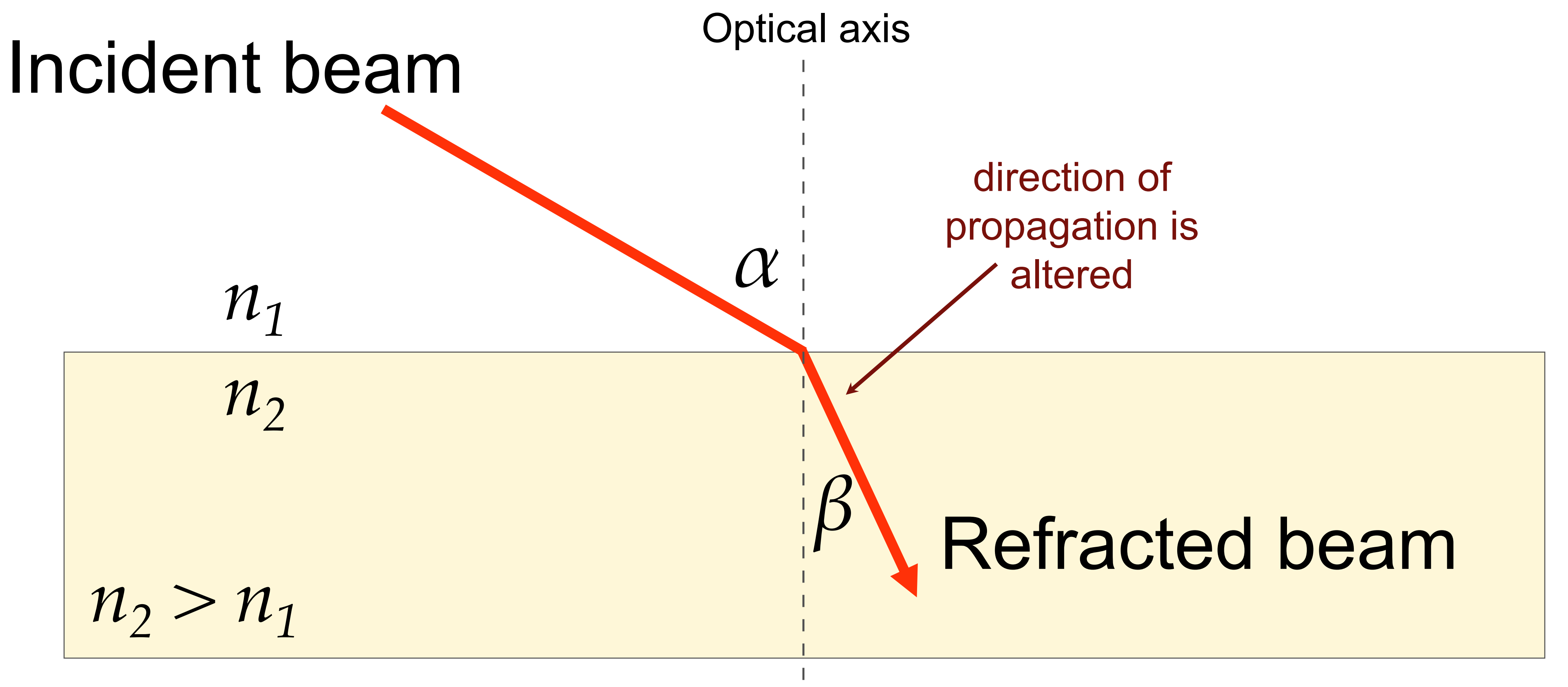
$$n_1 = \frac{c}{c_1}$$

Reflection



- α = angle of incidence; α' = angle of reflection.
- Incident beam, reflected beam and optical axis are in the same plane.
- Incident and reflected angles are identical ($\alpha = \alpha'$).

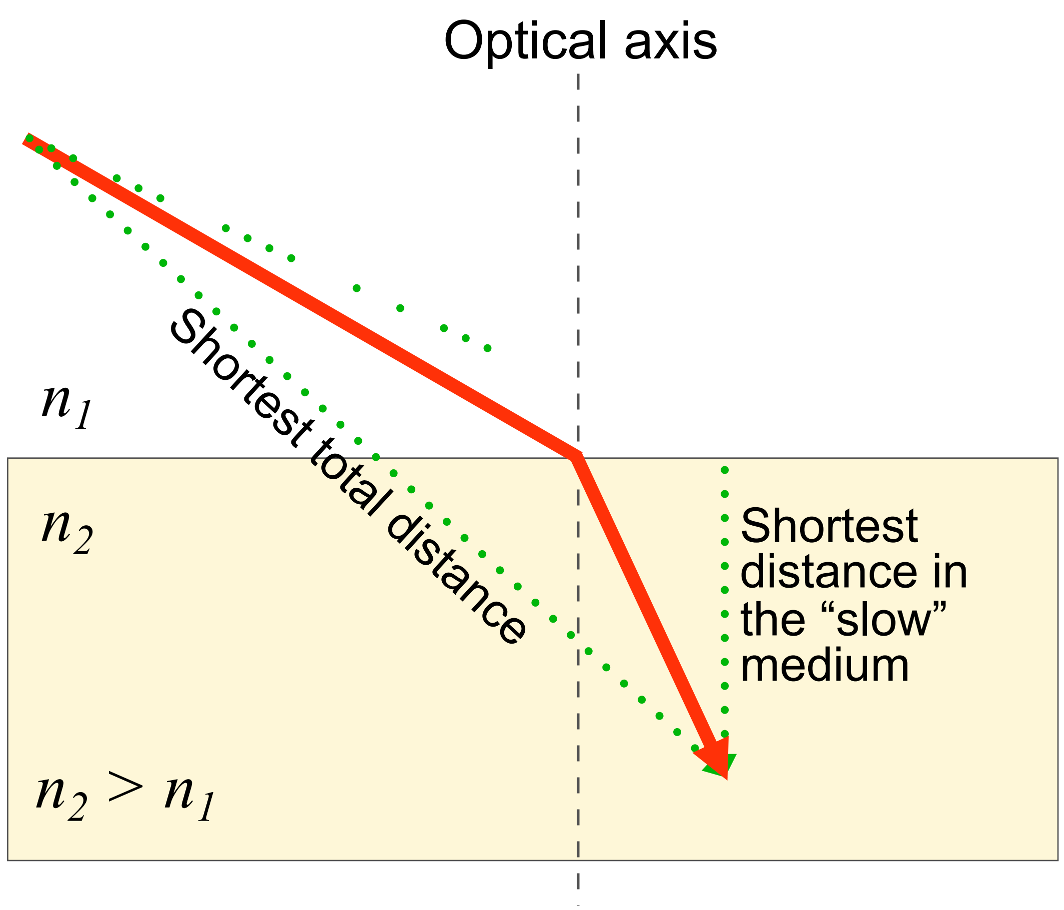
Refraction



- α = angle of incidence; β = angle of refraction.
- Incident and refracted beams and axis of incidence are in the same plane.
- Snell's law:

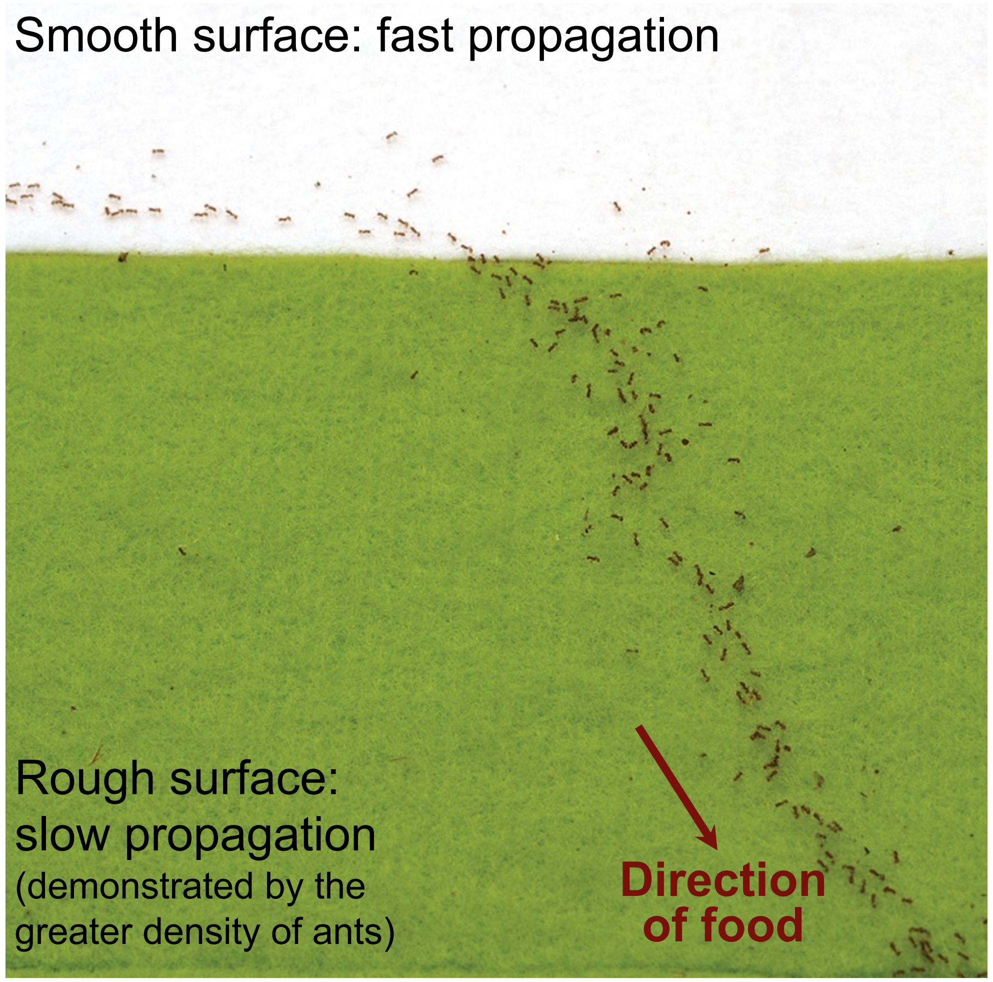
$$\frac{\sin\alpha}{\sin\beta} = \frac{c_1}{c_2} = \frac{n_2}{n_1}$$

Explanation of refraction:
Fermat's principle of least times



Light "chooses" the path that can be covered in the least time (i.e., fastest).

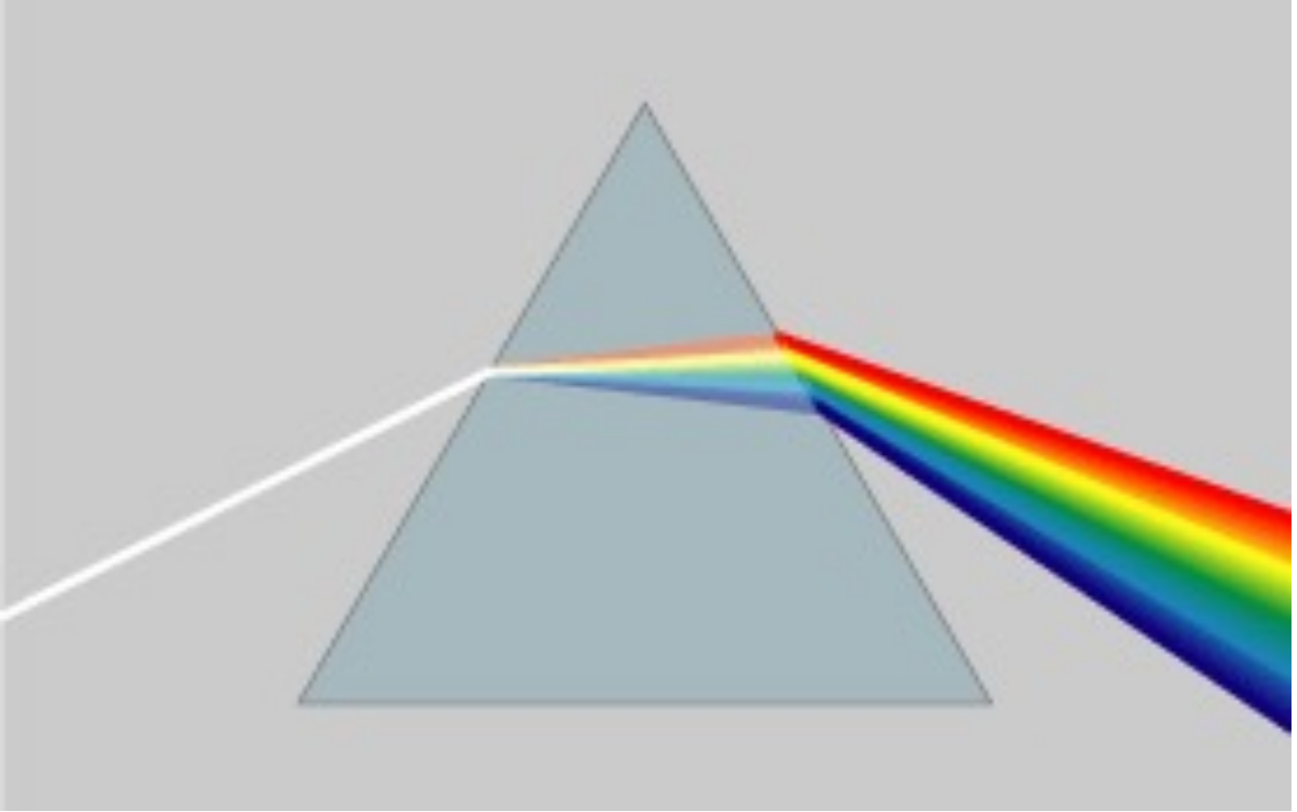
Fermat's principle is at work in other places, too!



Path "selection" by ants (*Wasmannia auropunctata*) at the boundary of media with different "resistances".

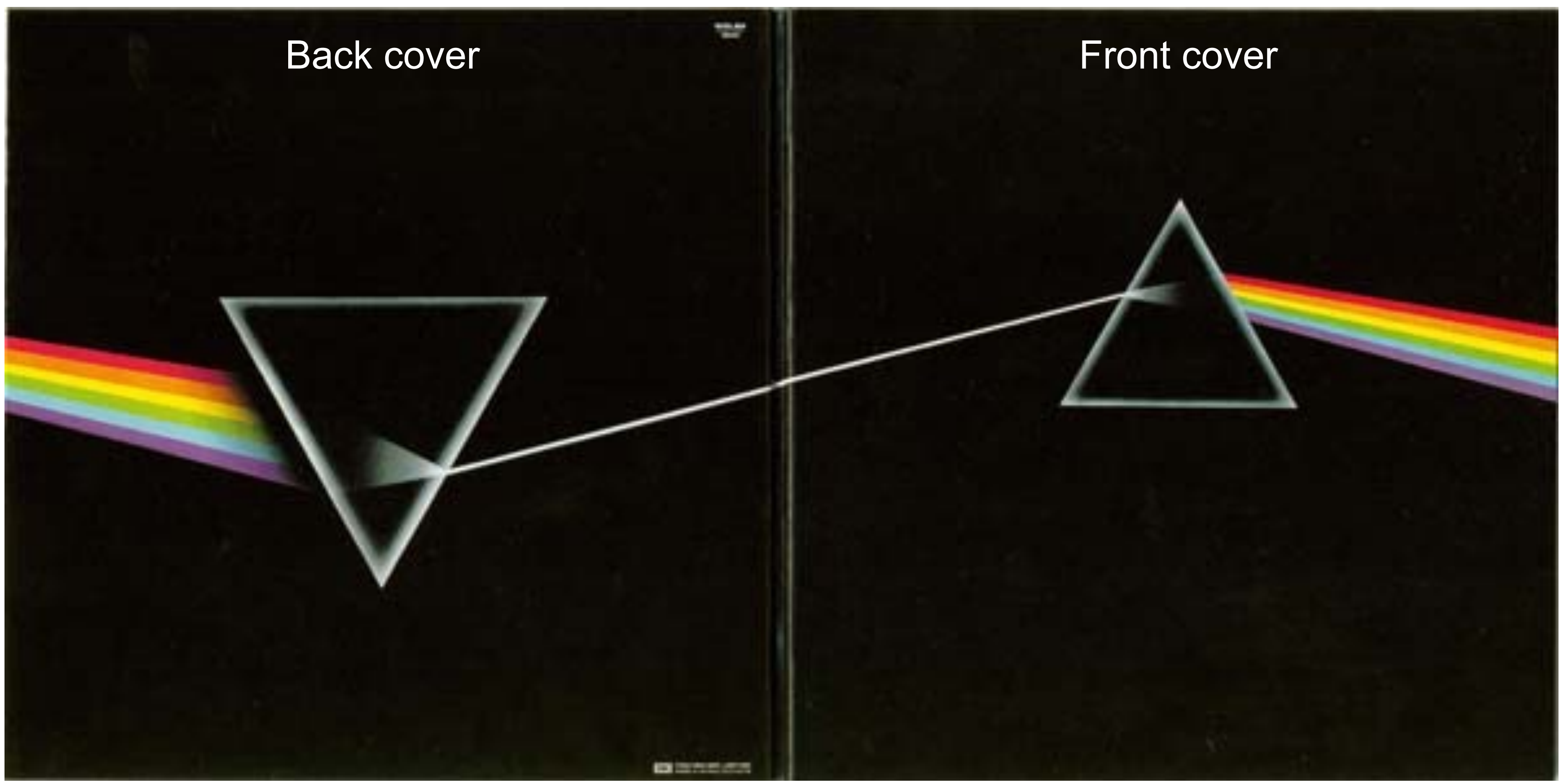
Dispersion

Index of refraction depends on frequency!



- The greater the frequency of light - the greater the refractive index.
- A prism decomposes white light according to wavelength (physical color).

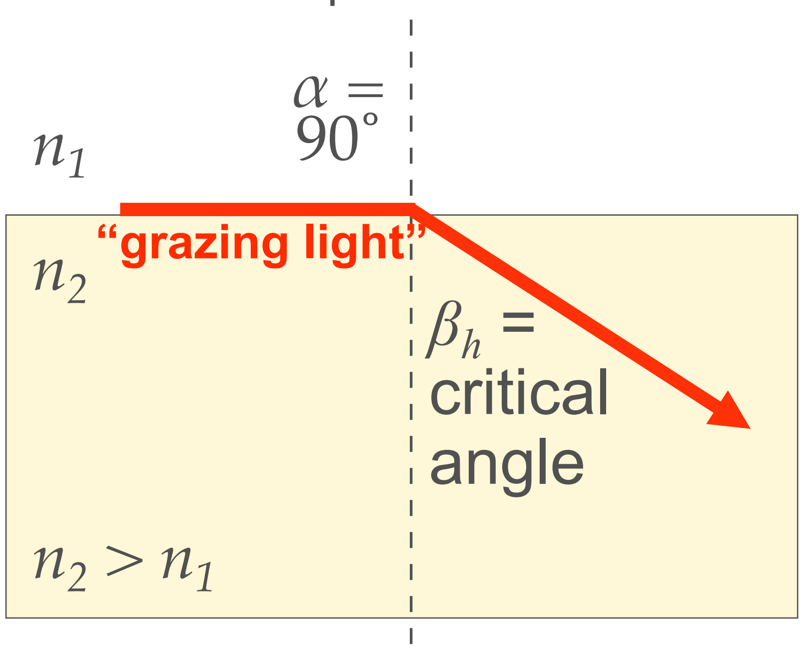
Dispersion appears in interesting places…



Pink Floyd: The Dark Side of the Moon

Analytical application of refraction: Refractometry

Boundary condition of refraction



Since $\sin(90°) = 1$, according to Snell's law:

$$n_1 = n_2 \sin \beta_h$$

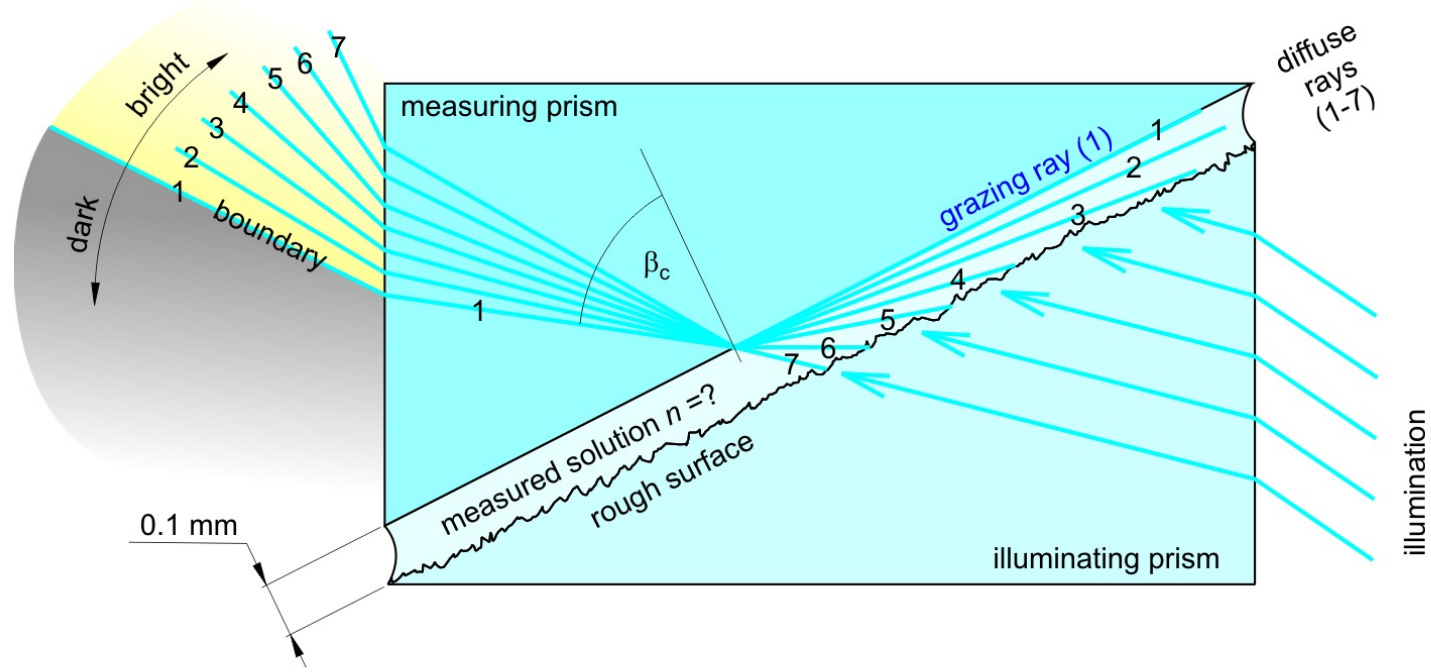
Thus, in case we know n_2, by measuring β_h the refractive index of the incident medium (n_1) may be obtained.

Refractometry

Refractive index of dilute solutions (n_1) depends on solute concentration (c):

$$n_1 = n_0 + k \cdot c$$

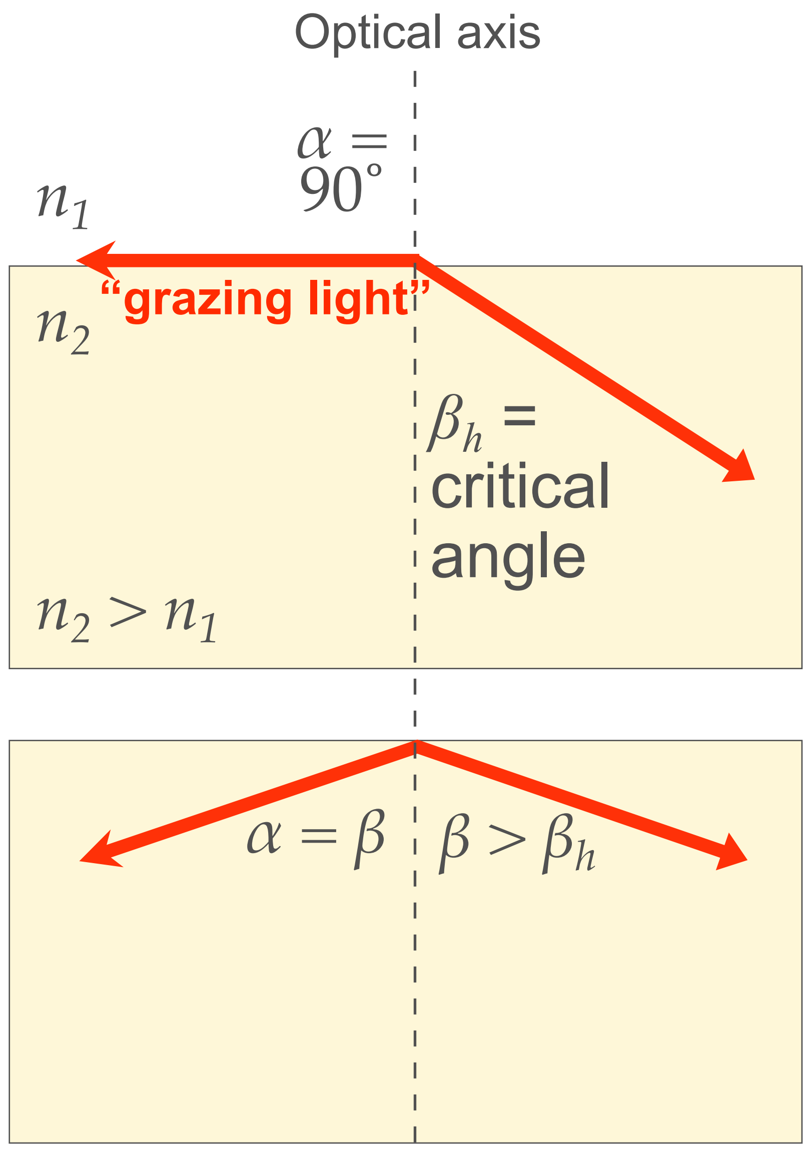
n_0 = refractive index of solvent, k = constant



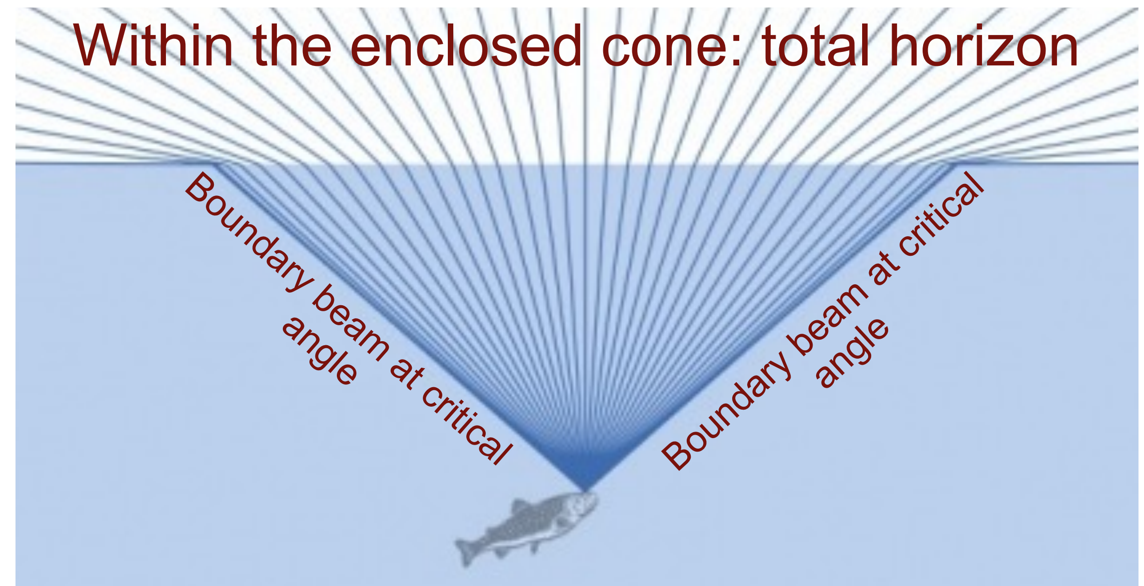
Conditions of applicability:

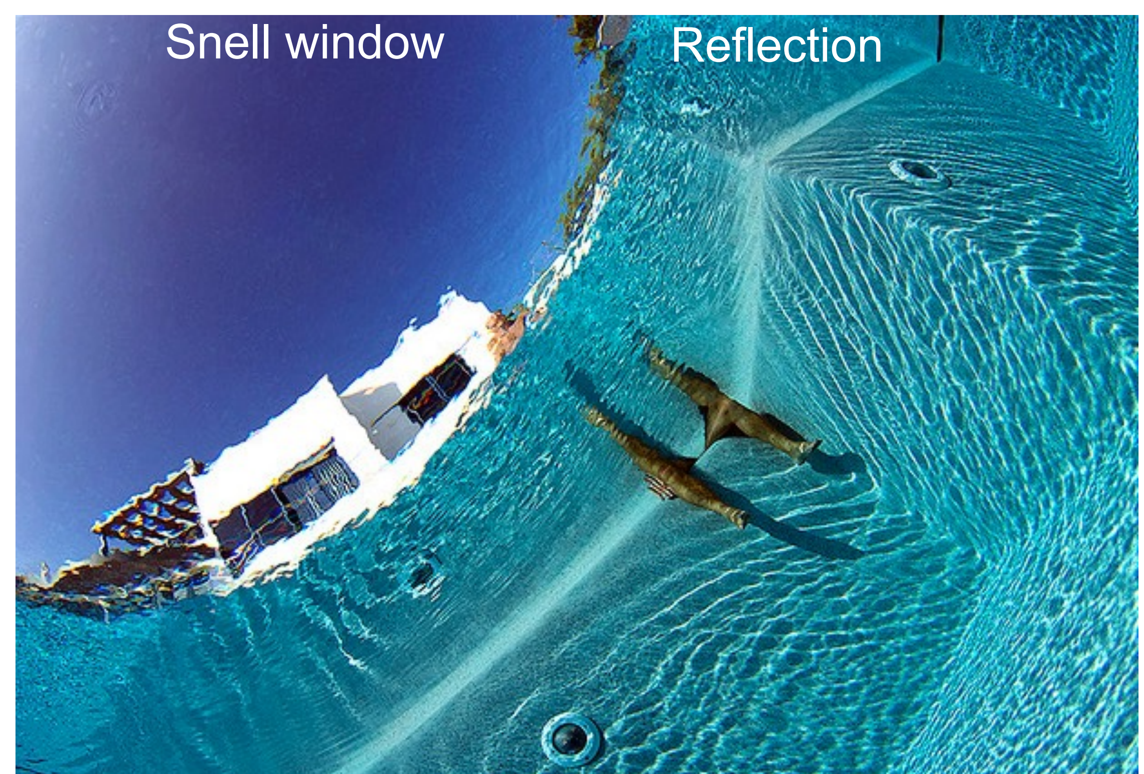
- Liquid sample
- Sample is transparent
- Refractive index of sample is smaller than that of the measuring prism.

Total internal reflection



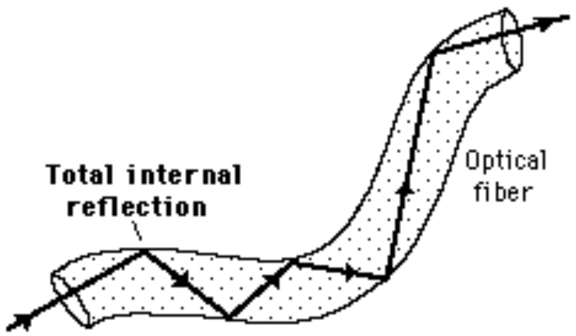
Total reflection within the optical medium of greater refractive index ("total ***internal*** reflection", TIR)

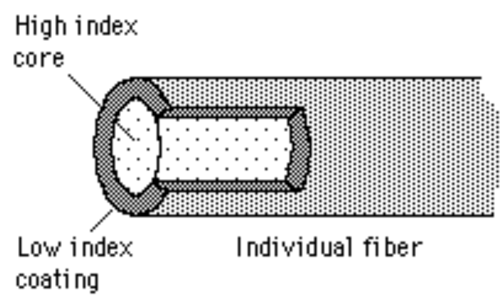




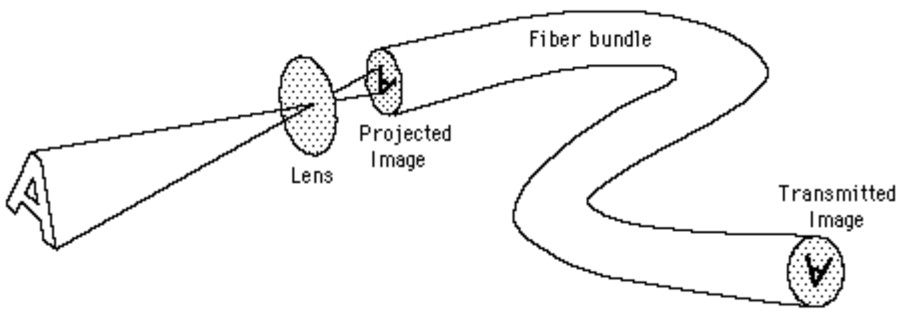
Biomedical Application of TIR: optical fibers

Single fiber





Highly ordered fiber bundle



If the arrangement of fibers is maintained within the bundle, then the image is faithfully transmitted.

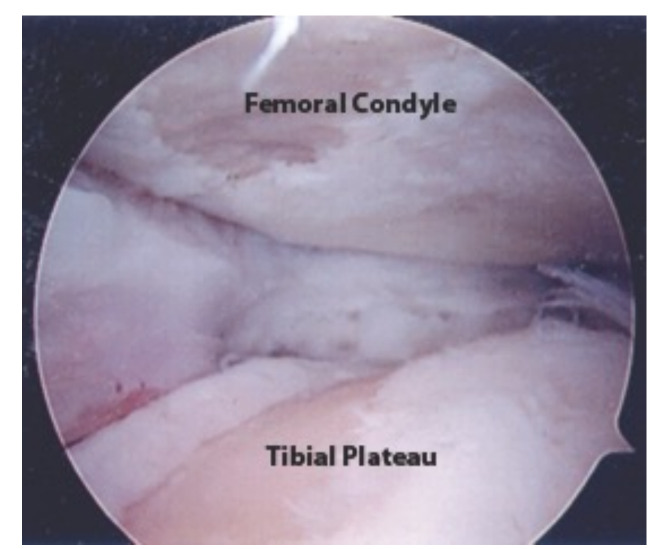
Endoscopy

OBJECTIVES

1. Diagnostics: visual inspection, biopsy, contrast agent delivery
2. Therapy: surgery, cauterization, removal of foreign objects

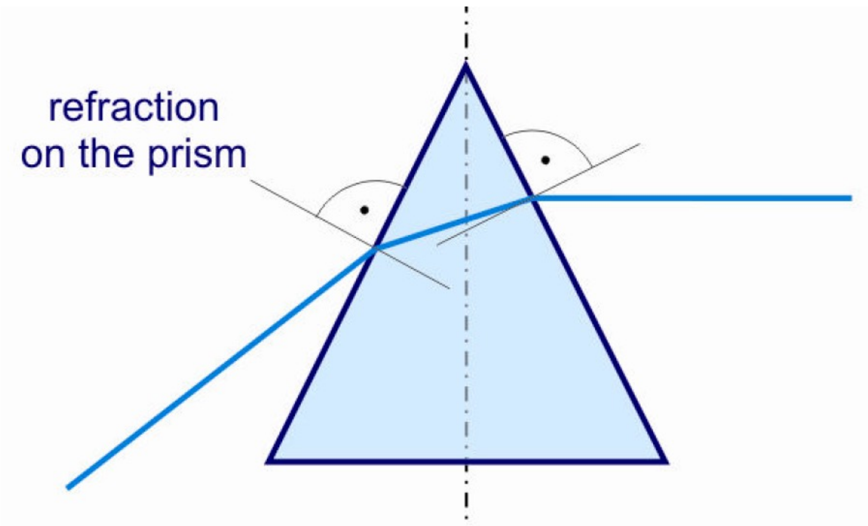
TYPES

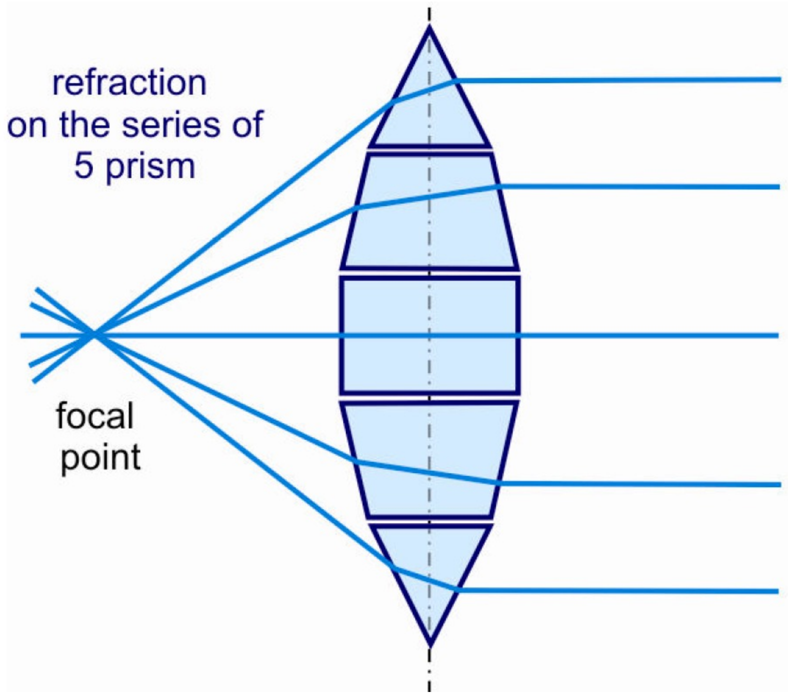
Arthroscopy (joints); *Bronchoscopy* (trachea and bronchi); *Colonoscopy* (colon); *Colposcopy* (agina and cervix); *Cystoscopy* (urinary bladder, urethra uterus, prostate via urethra); *ERCP* (endoscopic retrograde cholangio-pancreatography, delivery of X-ray contrast agent into biliary tract and pancreatic duct) ; *EGD* (Esophago-gastroduodenoscopy, upper GI tract); *Laparoscopy* (stomach, liver, female gonads via abdominal wall); *Laryngoscopy* (larynx); *Proctoscopy* (rectum, sigmoidal colon); *Thoracoscopy* (pleura, mediastinum and pericardium via chest wall)

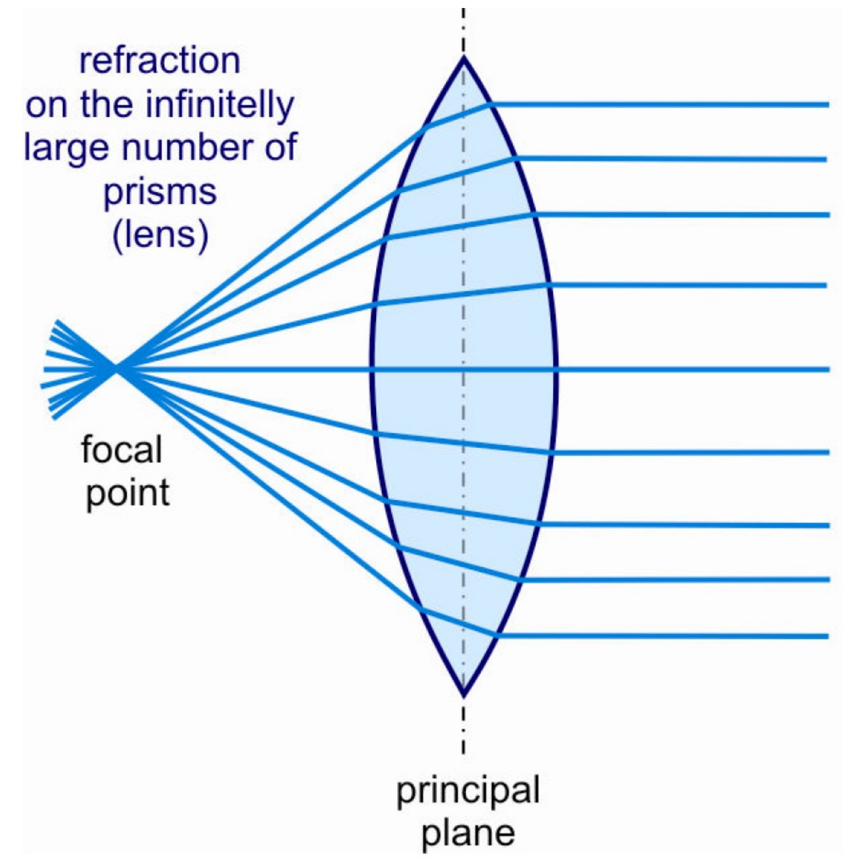


Arthroscopic surgery

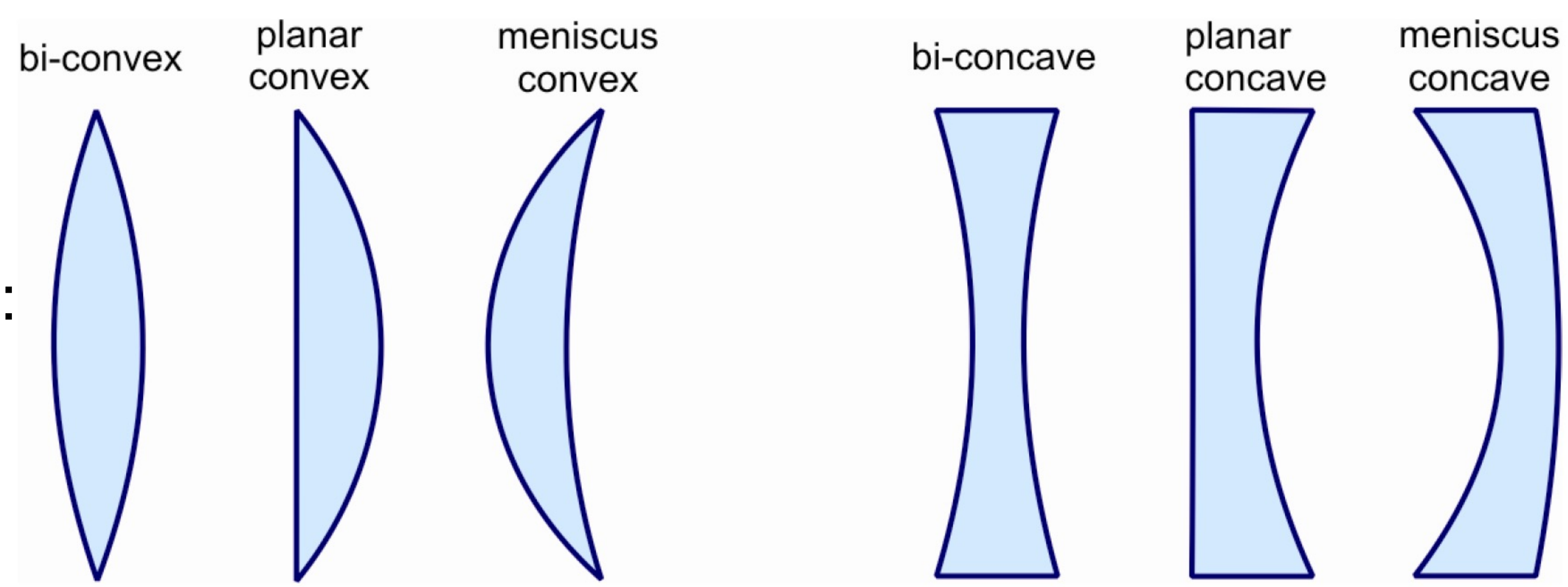
Refraction on curved surface





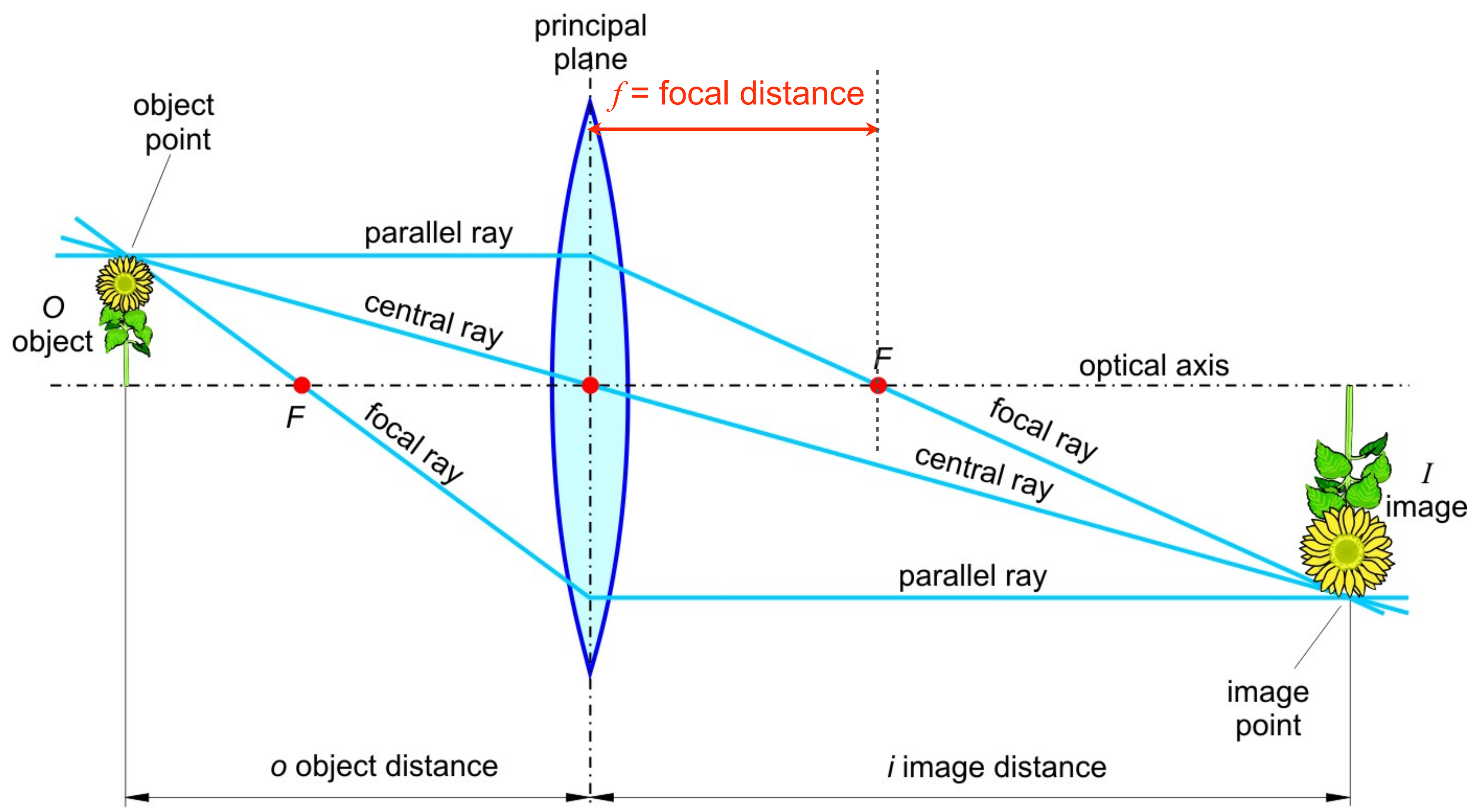


Types of lenses:



Optical imaging

Image formation may be achieved by using a curved refractile surface



- Real image: may be projected onto a surface
- Virtual image: may be mapped by using an accessory lens
- Magnification > 1, if the object is within $2f$ distance

Magnification

$$N = \frac{K}{T} = \frac{k}{t}$$

Lens equation

$$D = \frac{1}{f} = \frac{1}{t} + \frac{1}{k}$$

D=optical power (diopter, m^{-1})

Optical power of refractile surface

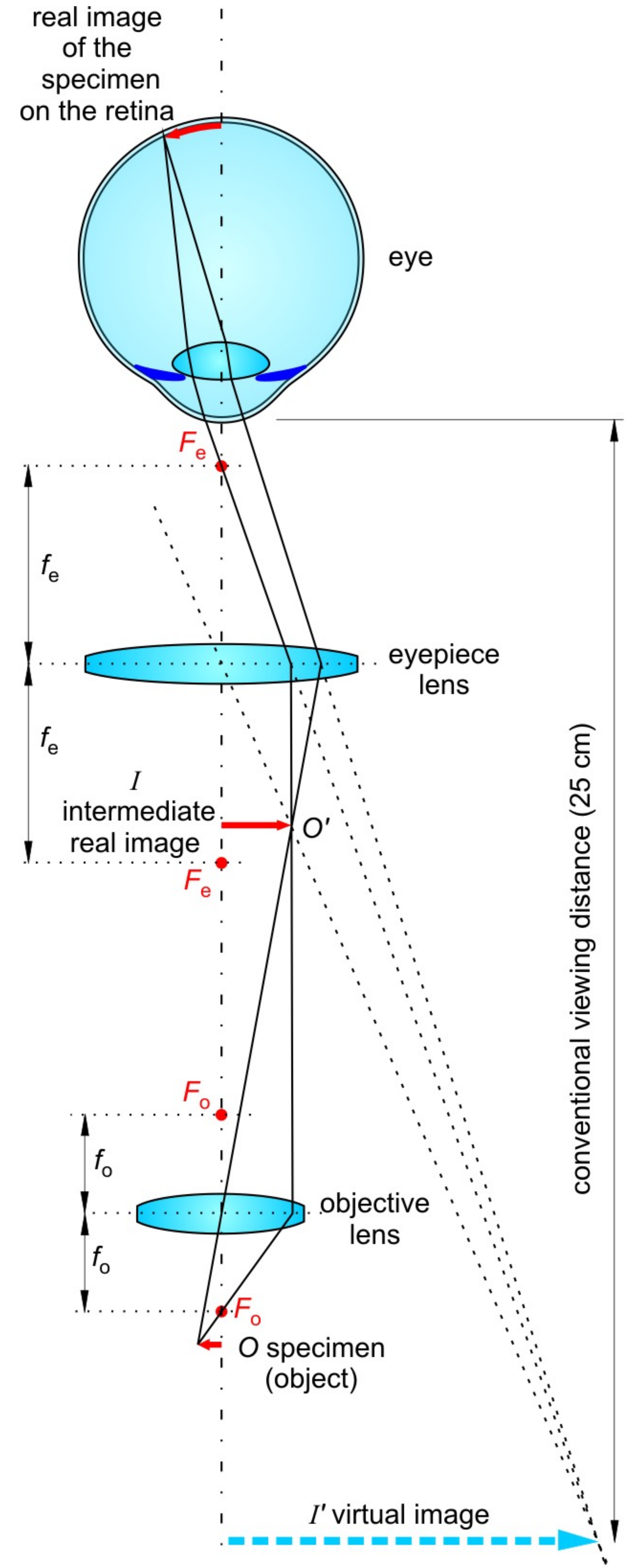
$$D = \frac{n - n'}{r}$$

n-n' = difference between the refractive indeces of optical media

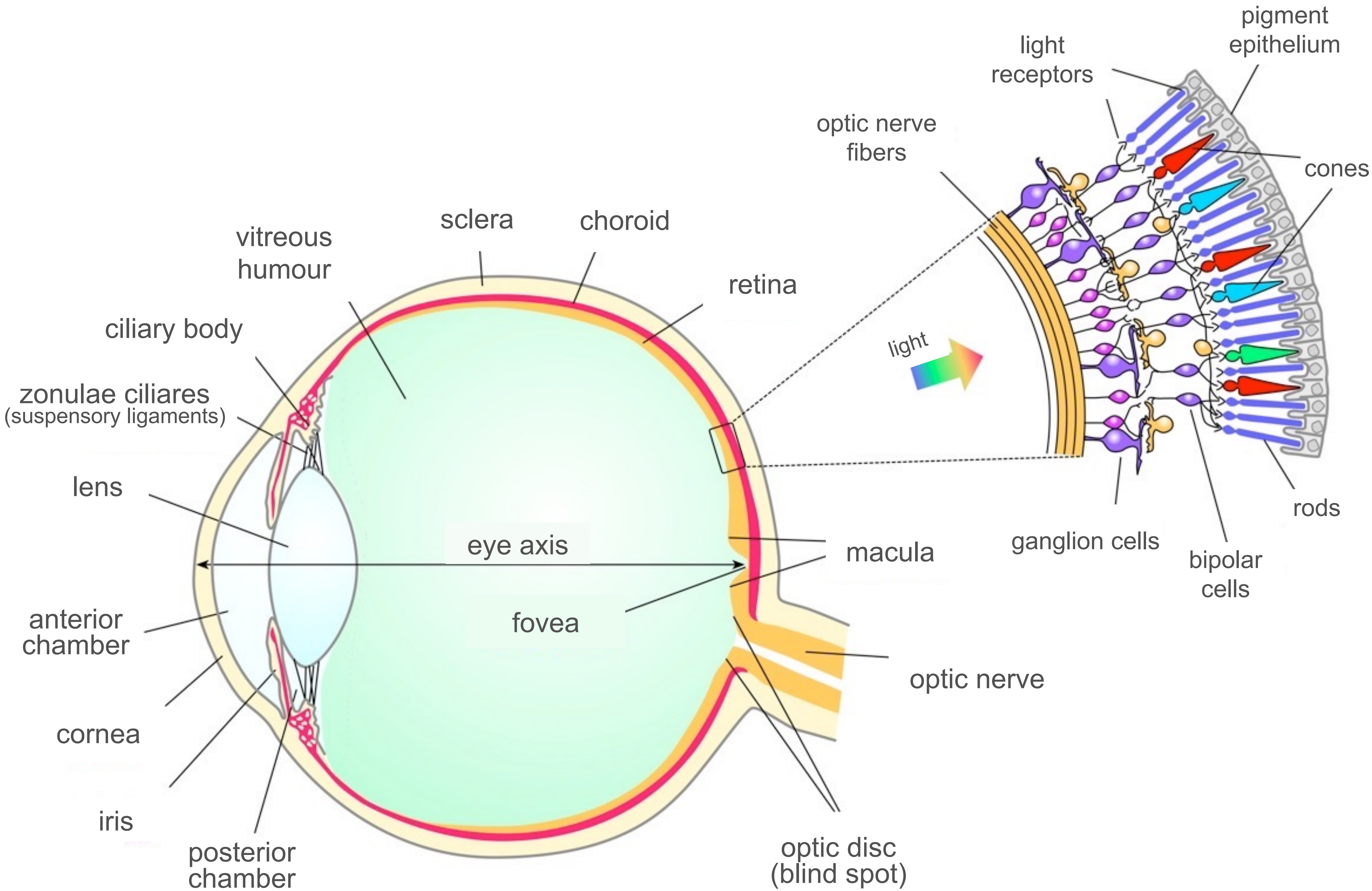
r = radius of curvature of refractile surface

Image formation in the compound microscope

- Magnified, up-side-down, virtual image
- Condition of the formation of projected image: an accessory lens (eye lens) needs to be positioned in the optical path.
- Projection screen: retina



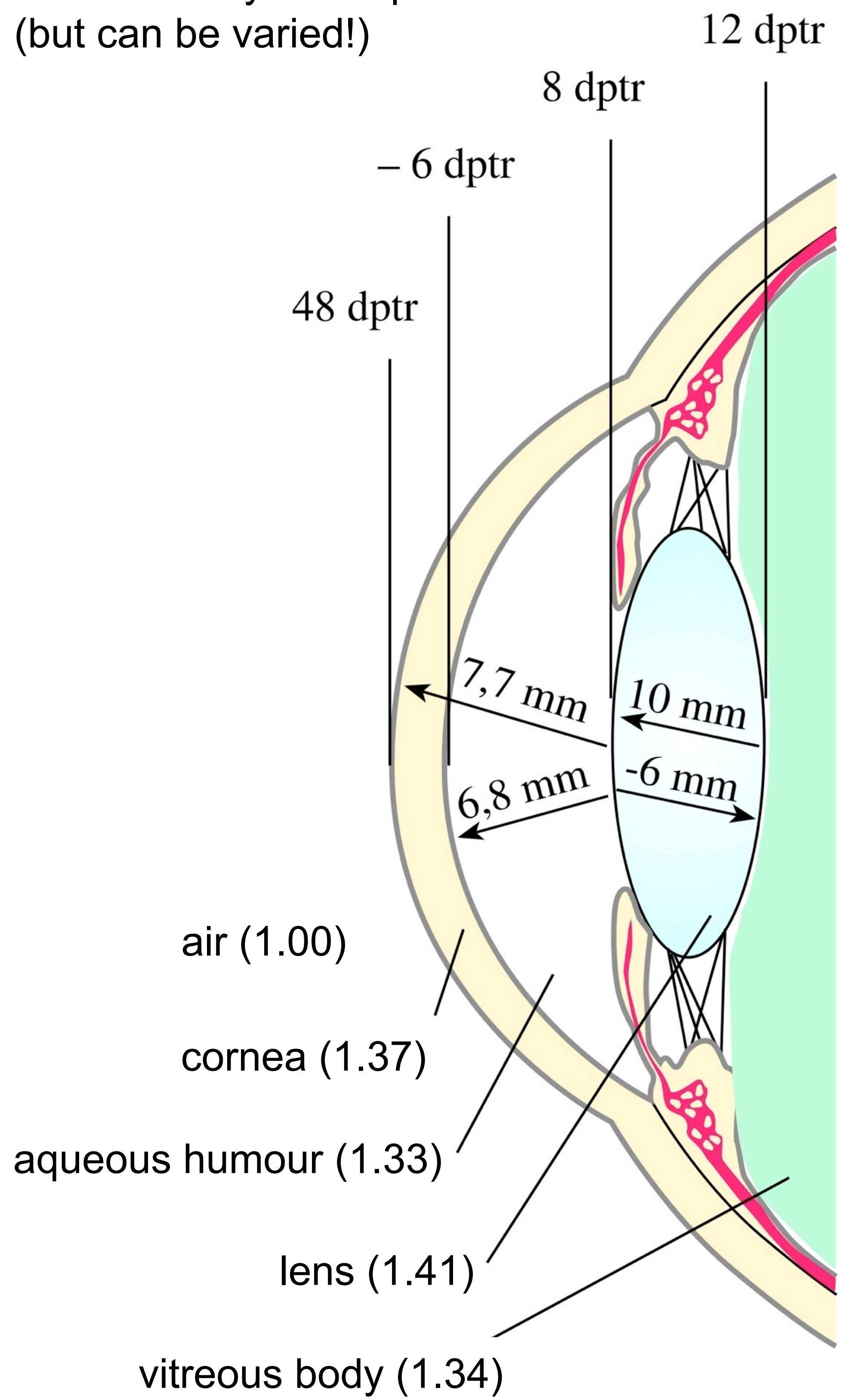
Optics of the human eye



Horizontal section of the human eye

Optics of the human eye

Total refractive power of the human eye: 62 dptr (but can be varied!)



Optical power entering the eye (P):

$$P = J\pi\left(\frac{d}{2}\right)^2$$

J=intensity (W/m^2)
d=pupil diameter

Power depends on pupil diameter:

$$\frac{P_{\max}}{P_{\min}} = \left(\frac{d_{\max}}{d_{\min}}\right)^2 = 16$$

d_{max}=8 mm
d_{min}=2 mm

Refractive power of surfaces (D, dptr):

$$D = \frac{n - n'}{r}$$

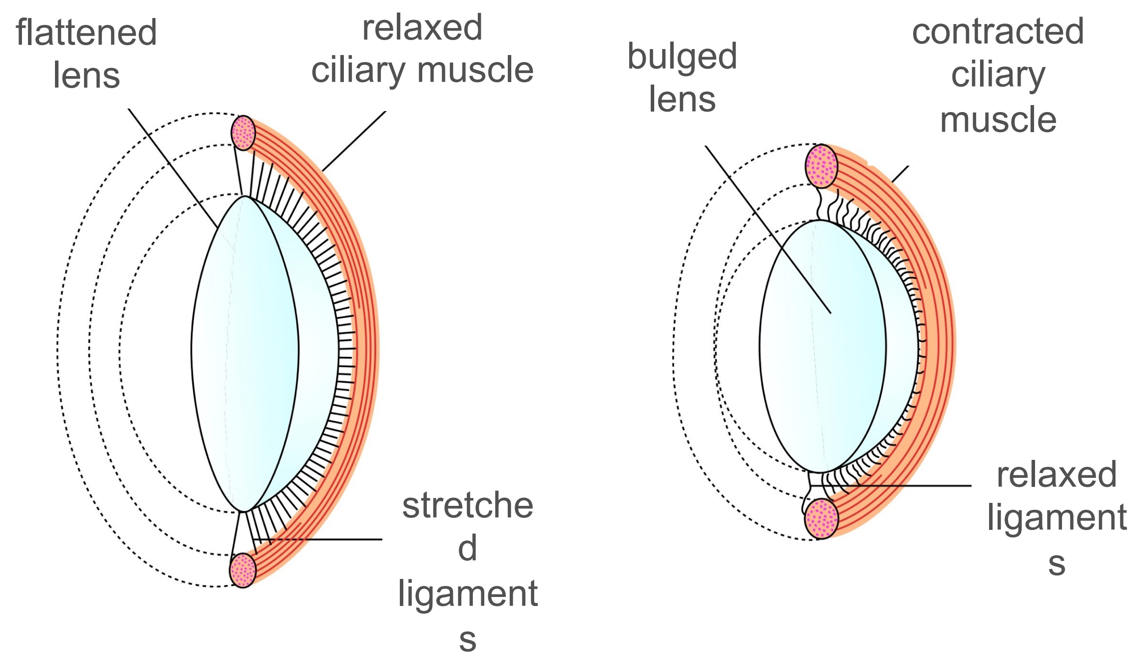
n-n' = refractive index difference of bounding media (air, cornea, etc.)
r = radius of curvature of refractive surface

N.B.:
1) n-n' is greatest at the air-cornea surface.
2) There are two possible mechanisms for controlling refractive power (variation of n' or r)!

Accomodation and refraction problems

Accomodation:

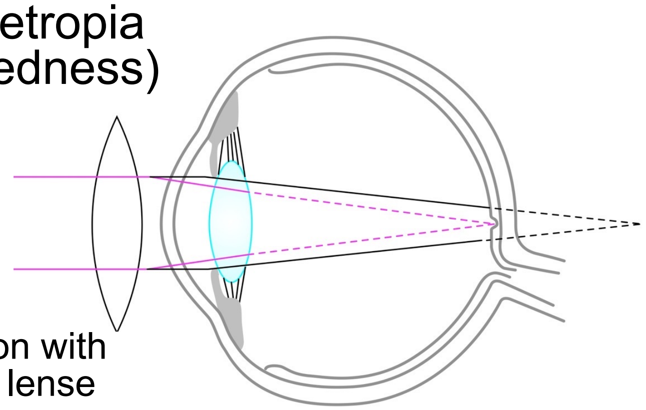
- Adaptation of the eye's refractive power to the object distance.
- Mechanism: radius of curvature of the lens is modified.
- Accomodation power: difference, in diopter, between the far and near points of the eye.



Presbyopia:

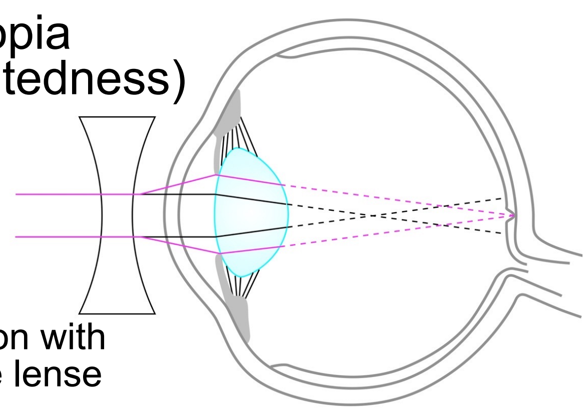
- Accomodation power decreases.
- Manifests with age (>45 years).
- Nearsight worsens.

Hypermetropia (farsightedness)



Correction with positive lense

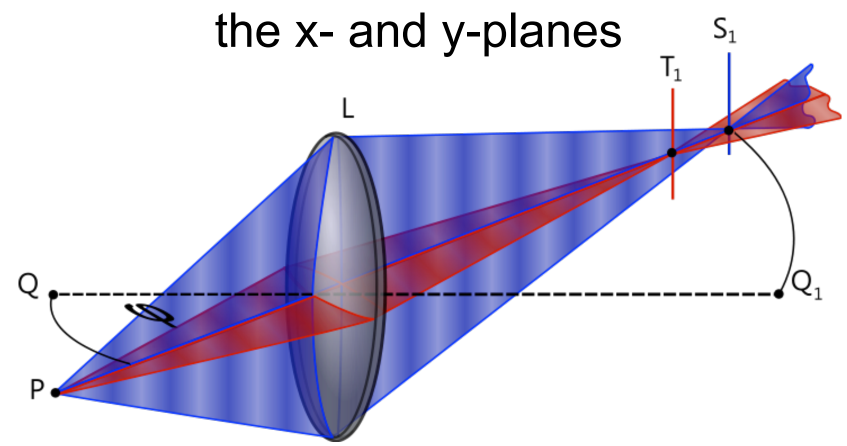
Myopia (nearsightedness)



Correction with negative lense

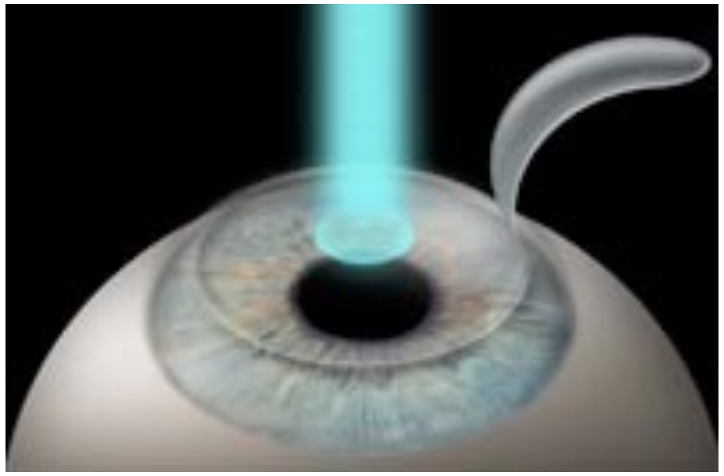
Astigmatism:

focal distance is different in the x- and y-planes



Correction with cylindrical lens

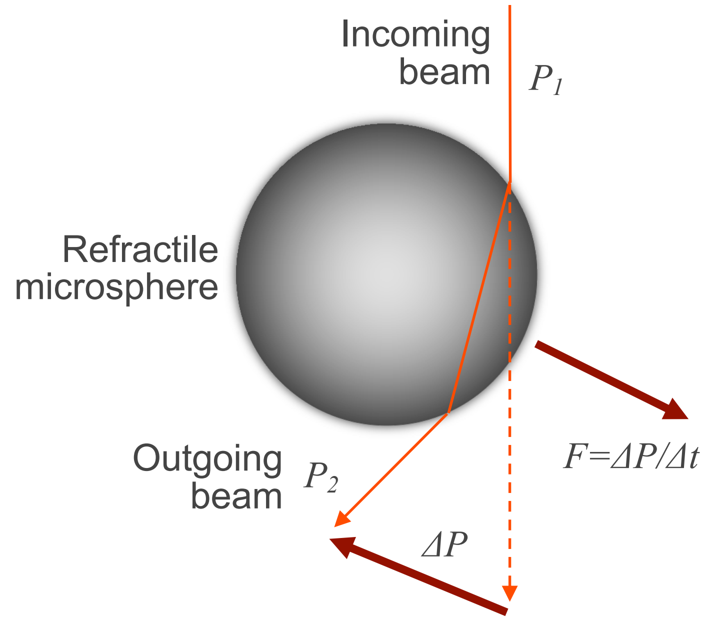
Permament correction of refractive problem: LASIK (Laser Assisted In Situ Keratomileusis)



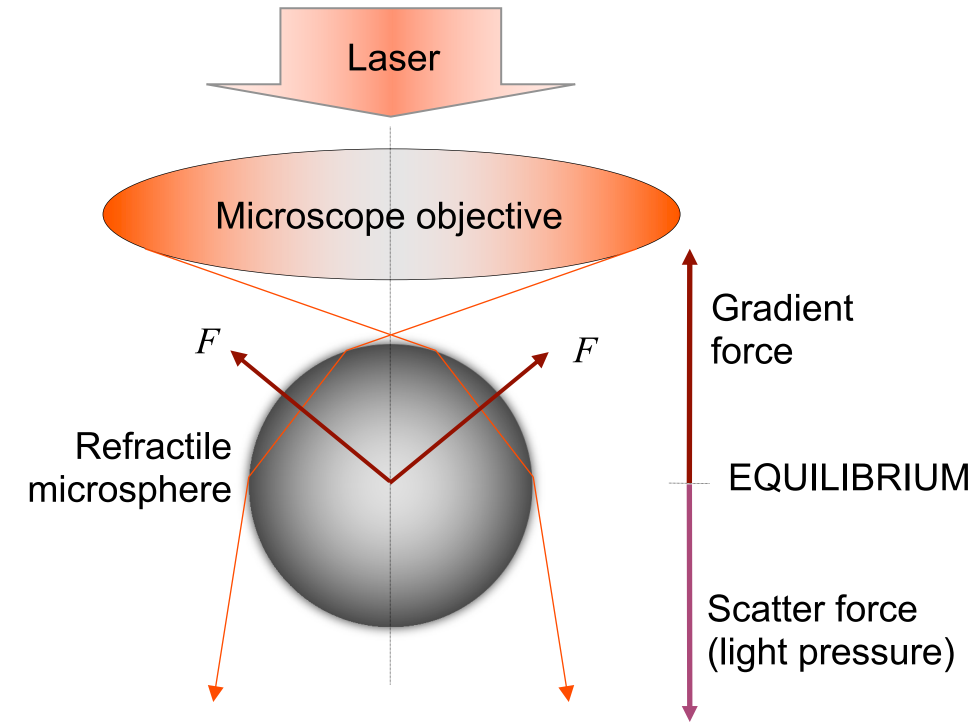
The radius of curvature of the cornea is changed (with laser surgery)

Manipulating objects with refraction

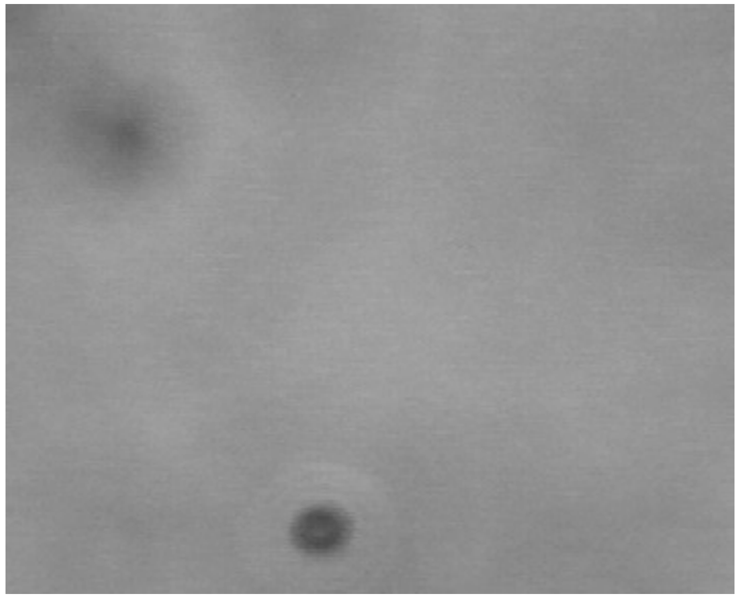
Refraction is accompanied by photonic momentum change (ΔP) (Theory later):



Refractile particles may be ***captured*** *with photonic forces:*

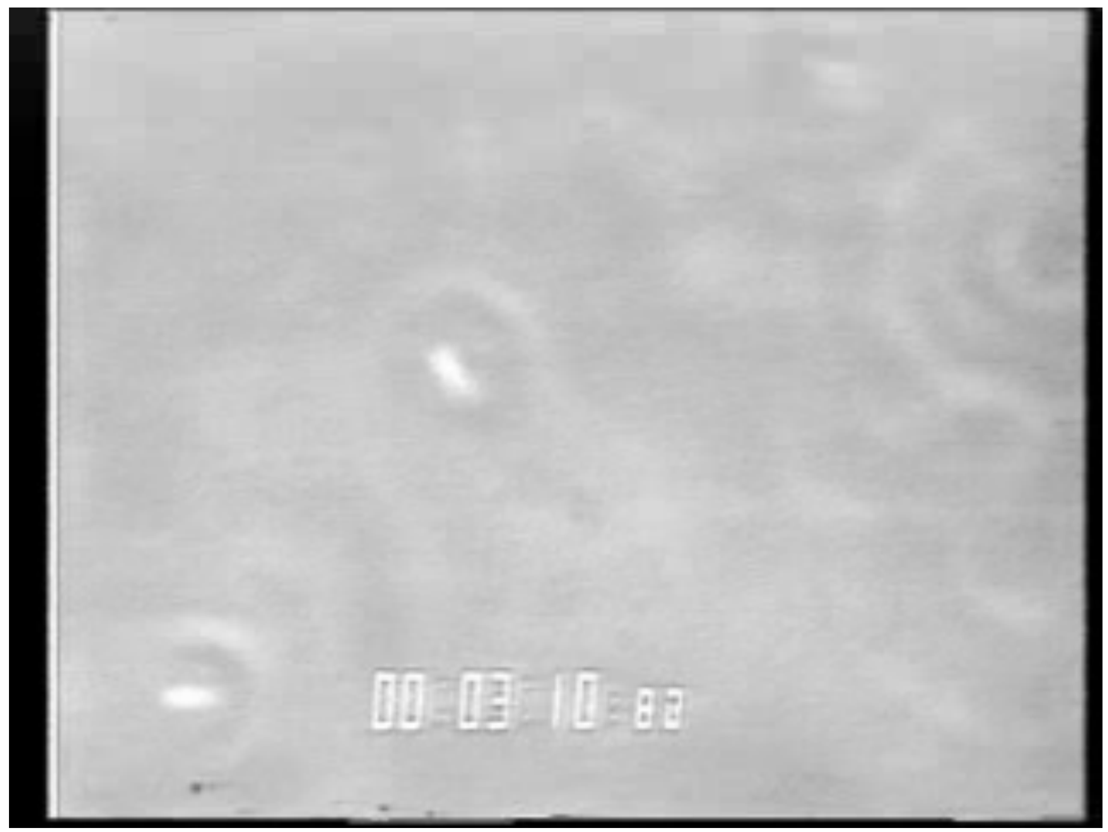


In the ***optical trap*** *a momentum change occurs between the photons and the trapped particle:*



3 μm latex (polystyrene) microspheres in the optical trap

Even cells can be captured with the optical trap



Trapping of bacterial cells

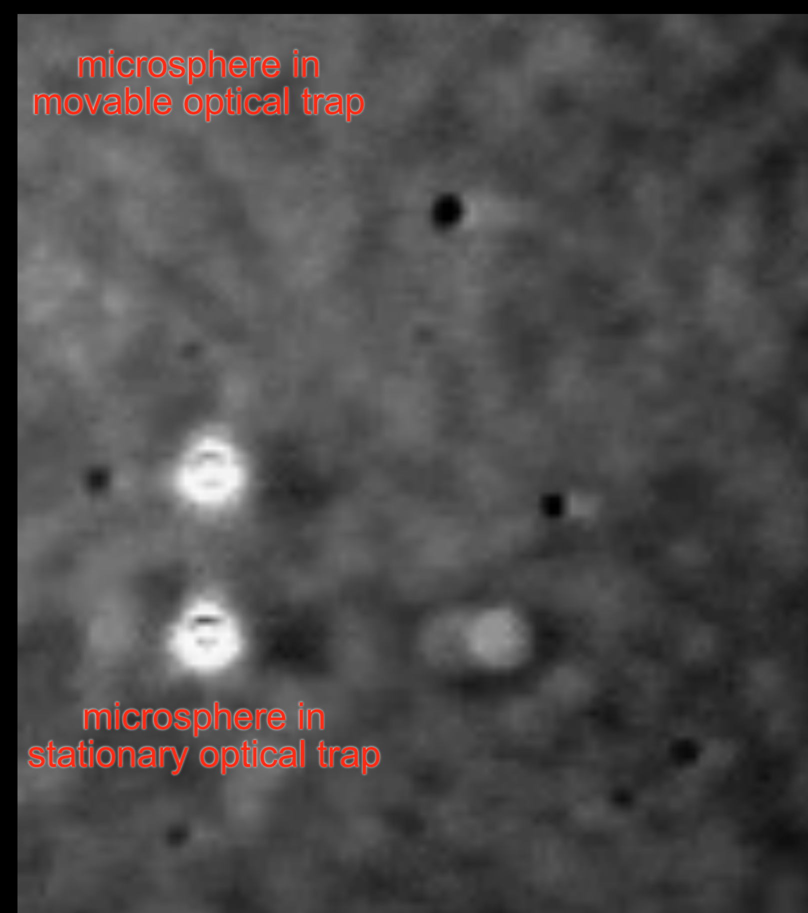
Tying a knot on a molecular filament by using optical trap

Actin filament

Fluorescence image

DNA

Phase contrast image



Fluorescence image

Arai et al. Nature 399, 446, 1999.

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