

# GEOMETRIC OPTICS

MIKLÓS KELLERMAYER

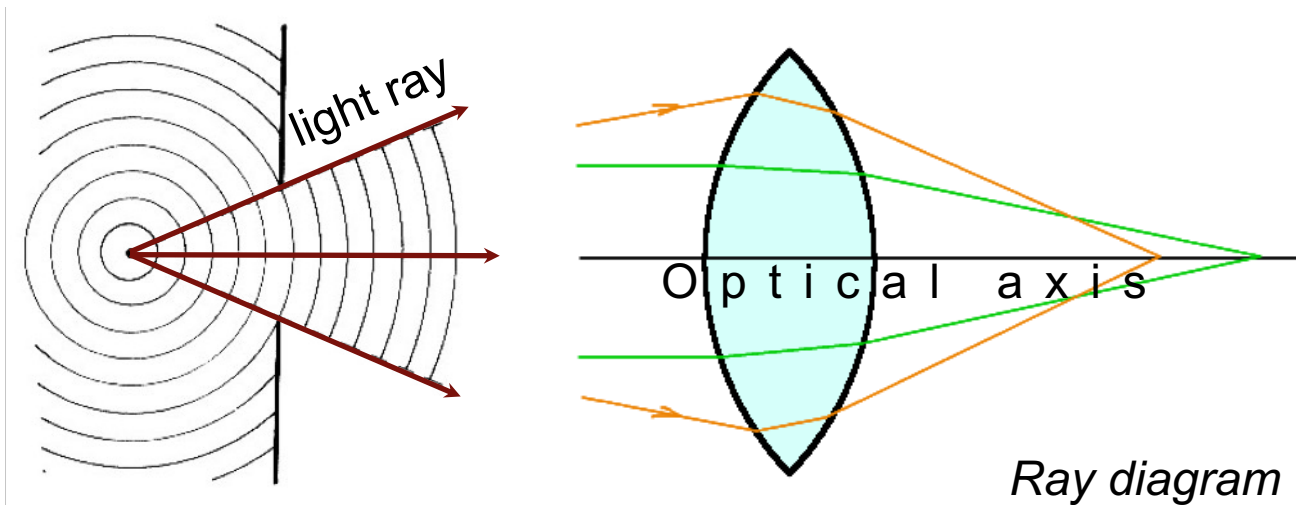
# Geometric optics

- 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”).



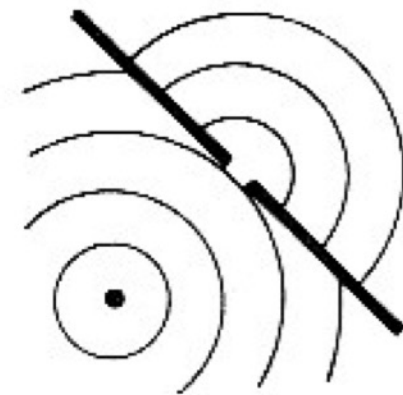
- Optical (light) ray (“light beam”): abstraction, mathematical line.
- Arrows represent the direction of energy propagation.
- Optical axis: line connecting the midpoint of optical components (e.g., lenses).
- Principle of reversibility: the direction of energy propagation (arrows) may be reversed.

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

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

(by comparison:  
wave optics - next week)

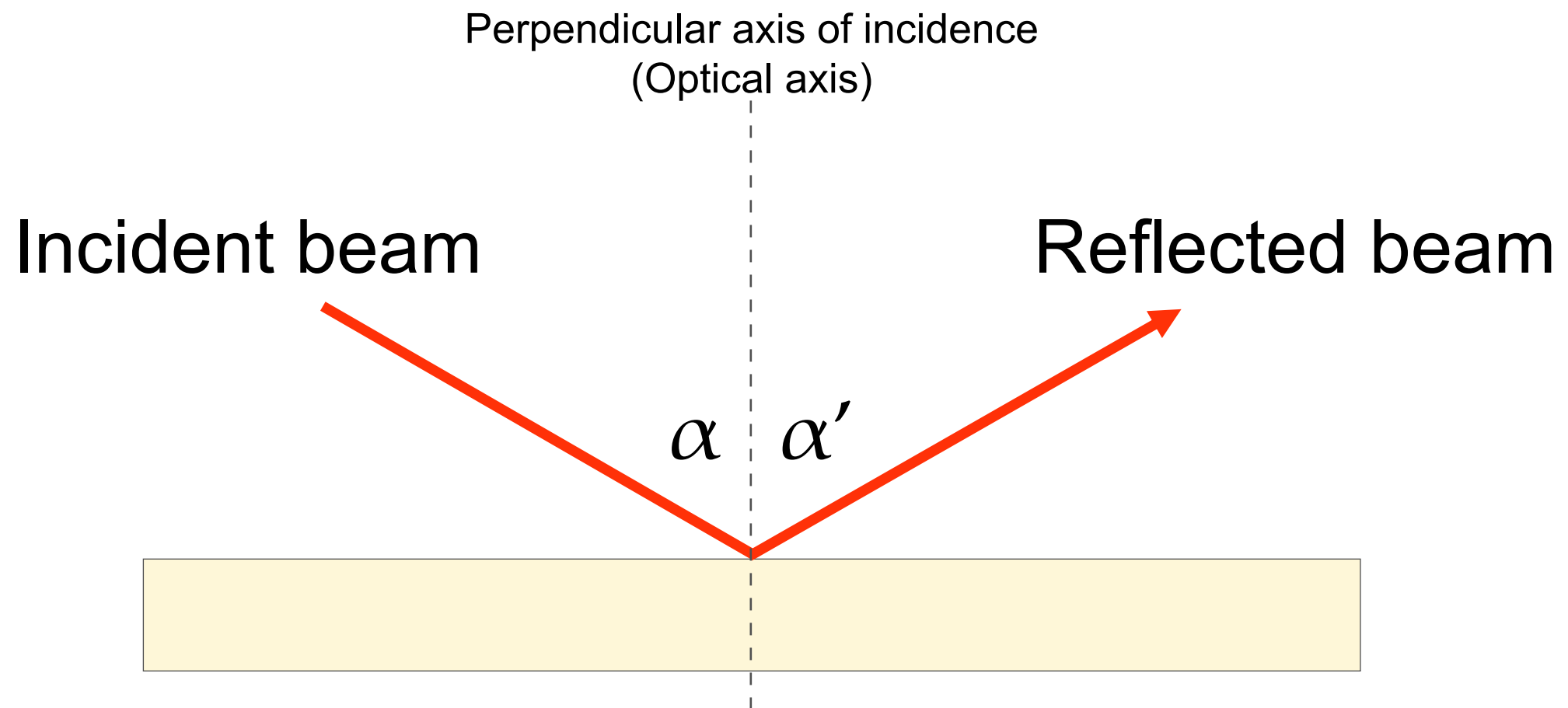
If light propagates through a slit comparable or smaller than its wavelength, then its wave properties must be taken into account.





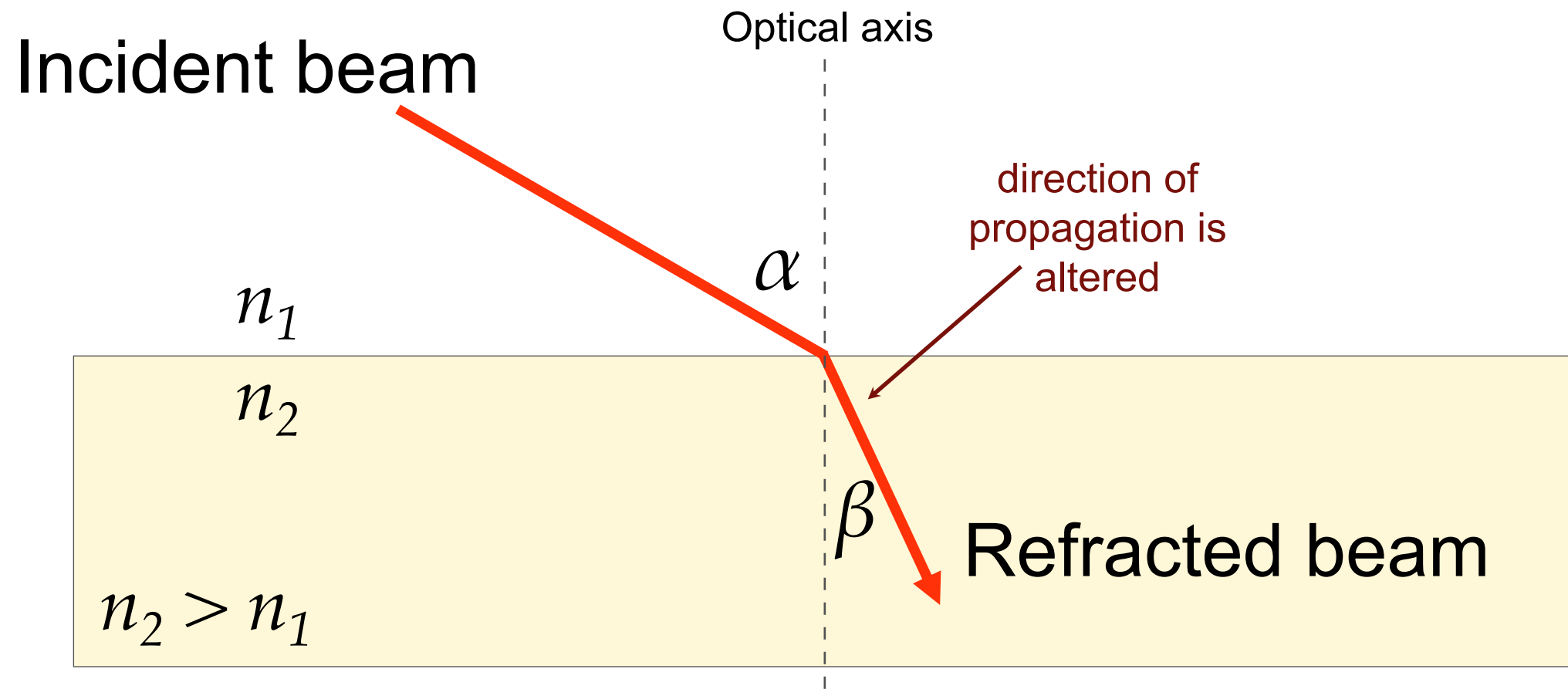
# Reflection

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

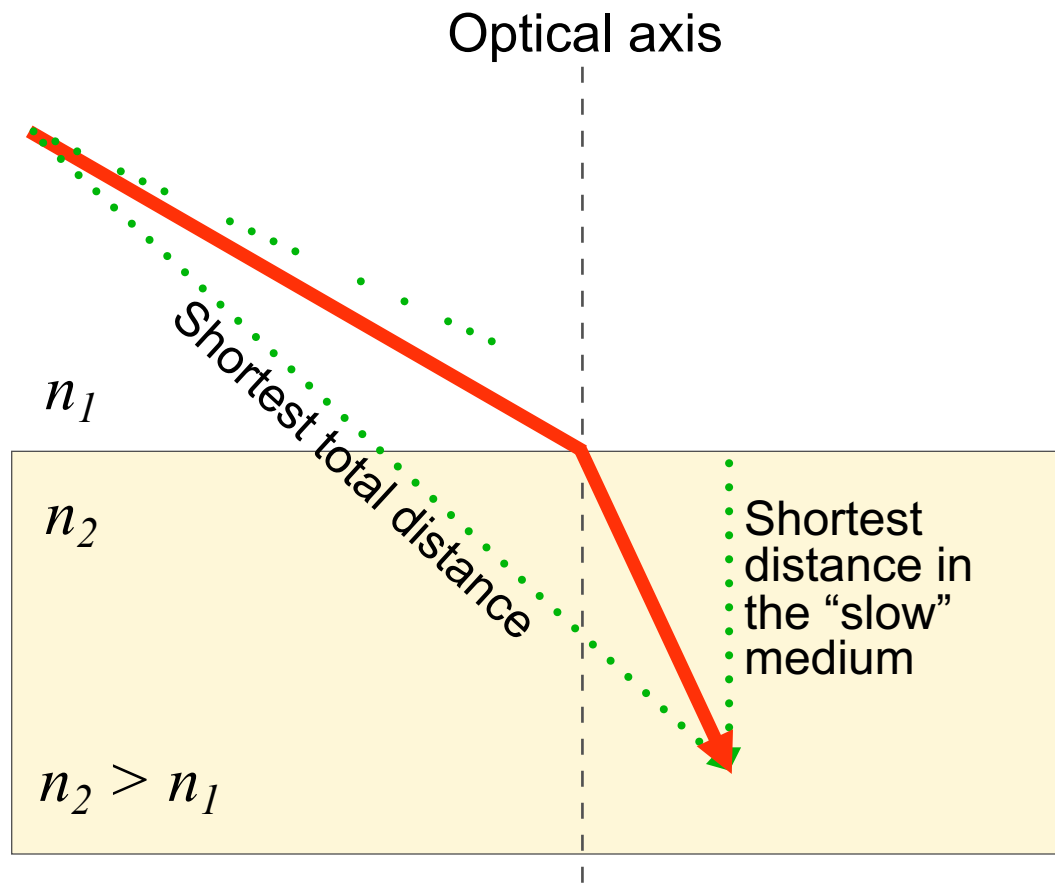
# Refraction



- $\alpha$  = angle of incidence;  $\beta$  = angle of refraction.
- Incident and refracted beams and axis of incidence are in the same plane.
- Snell's law:

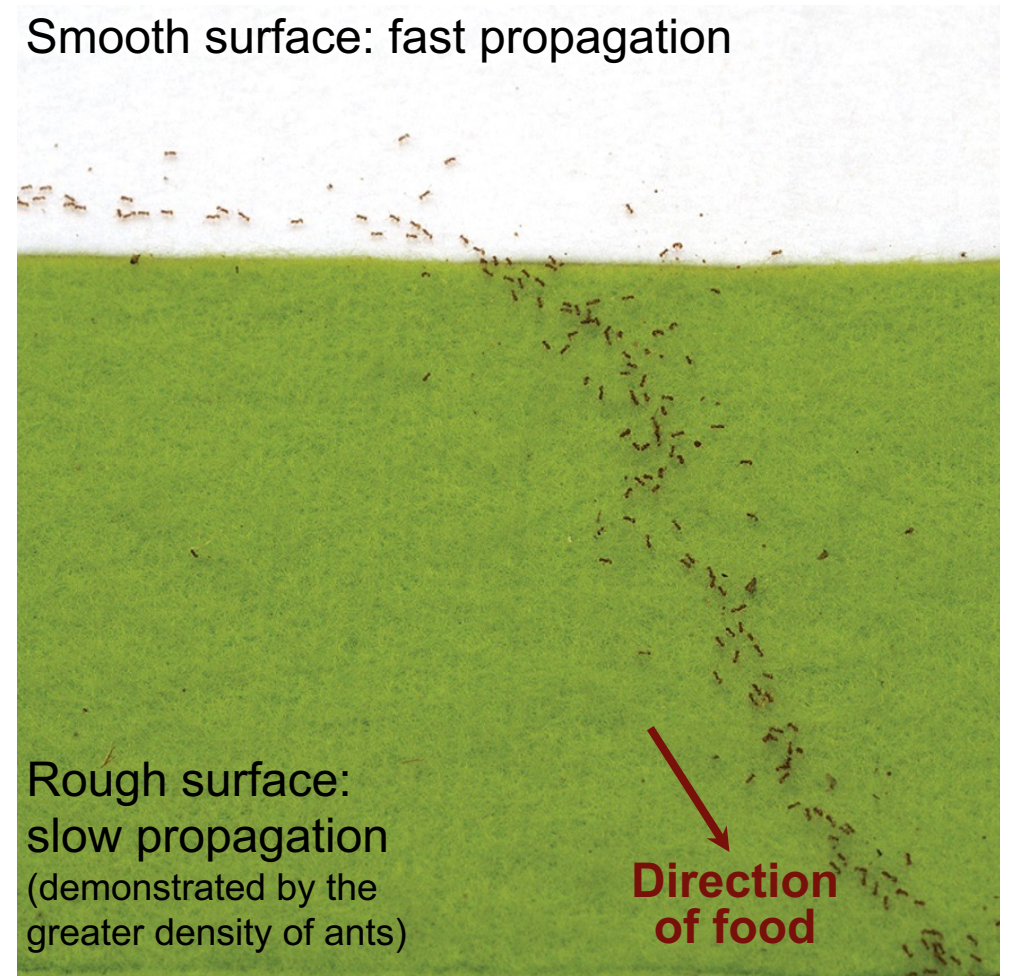
$$\frac{\sin \alpha}{\sin \beta} = \frac{c_1}{c_2} = \frac{n_2}{n_1}$$

# 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!

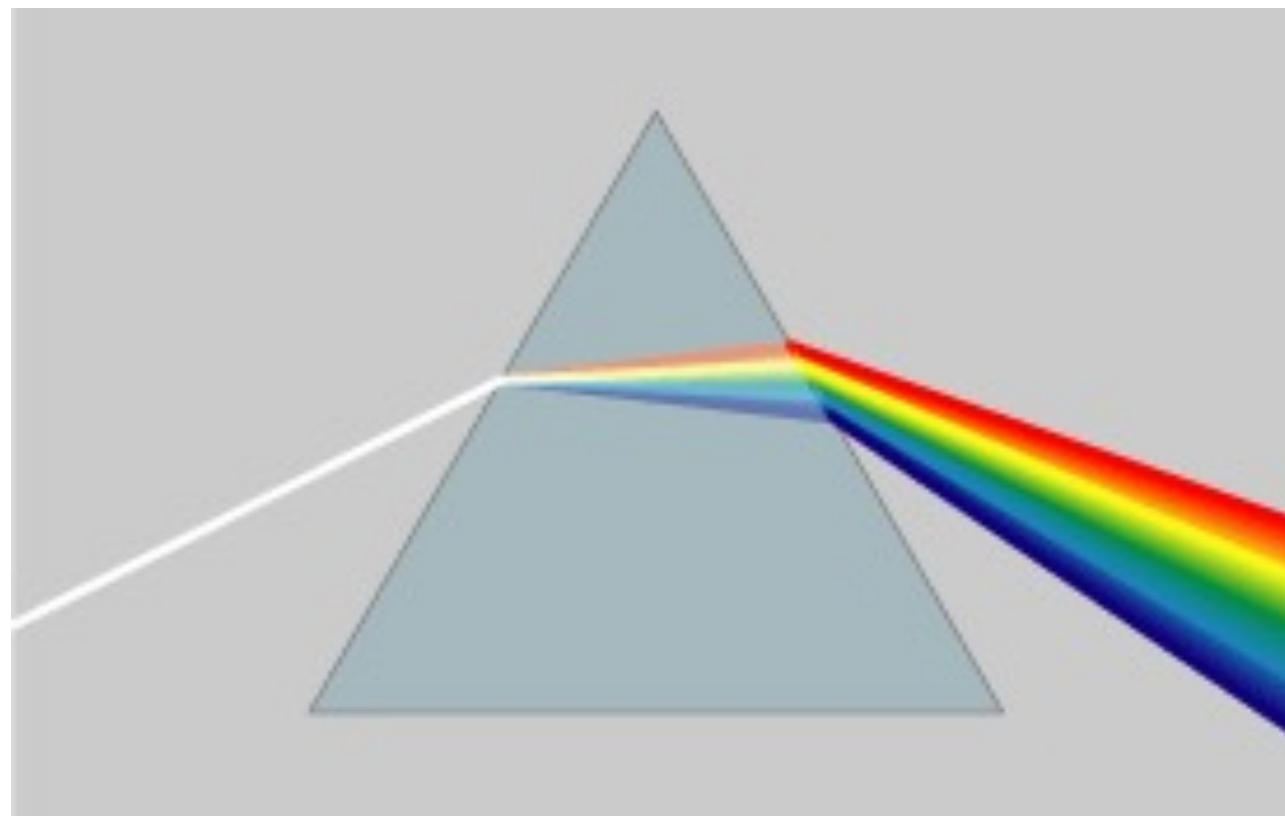


Path “selection” by ants (*Wasmannia auropunctata*) at the boundary of media with different “resistances”.

# Dispersion

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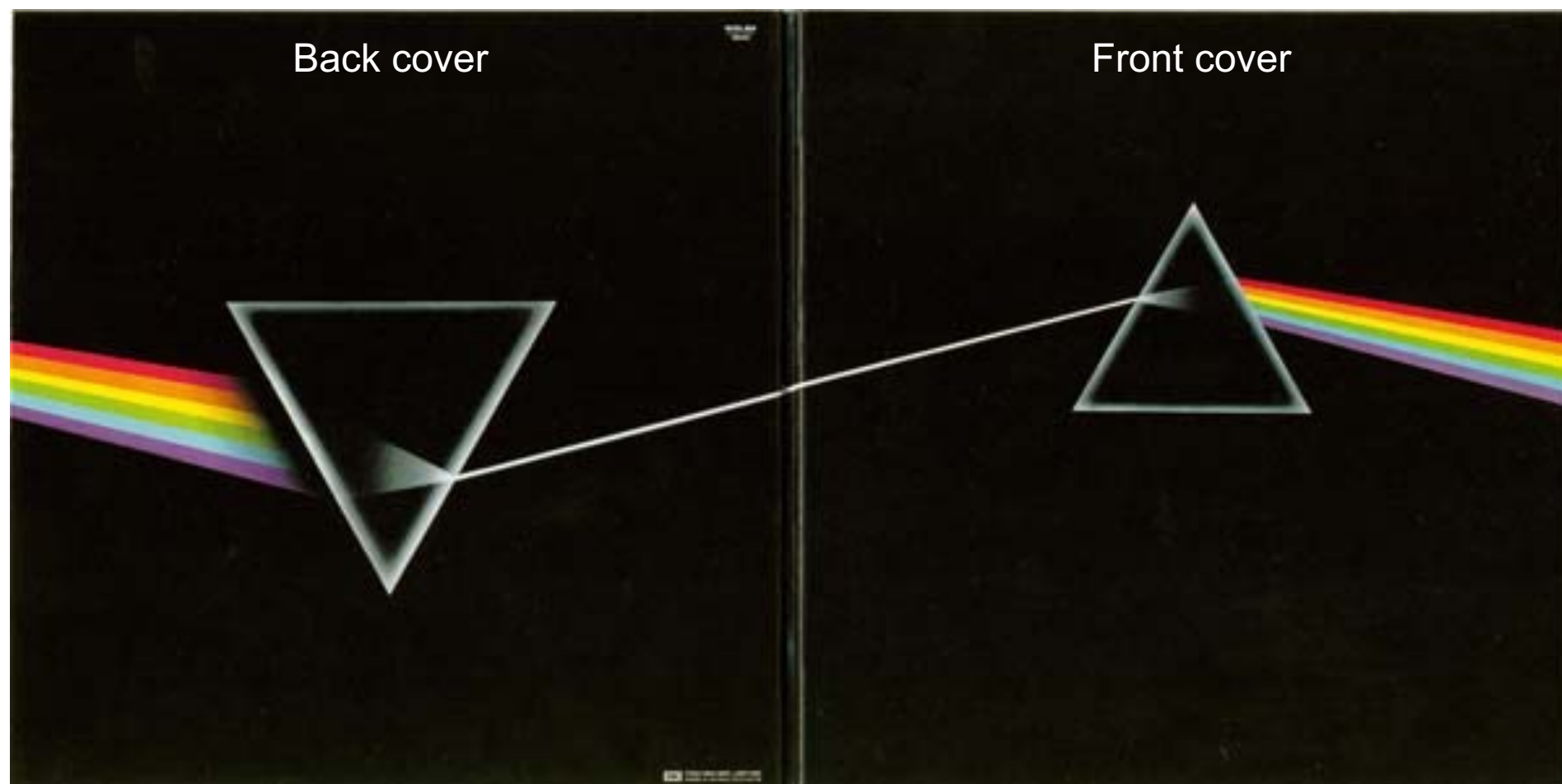
Index of refraction depends on frequency!



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

# Dispersion appears in interesting places...

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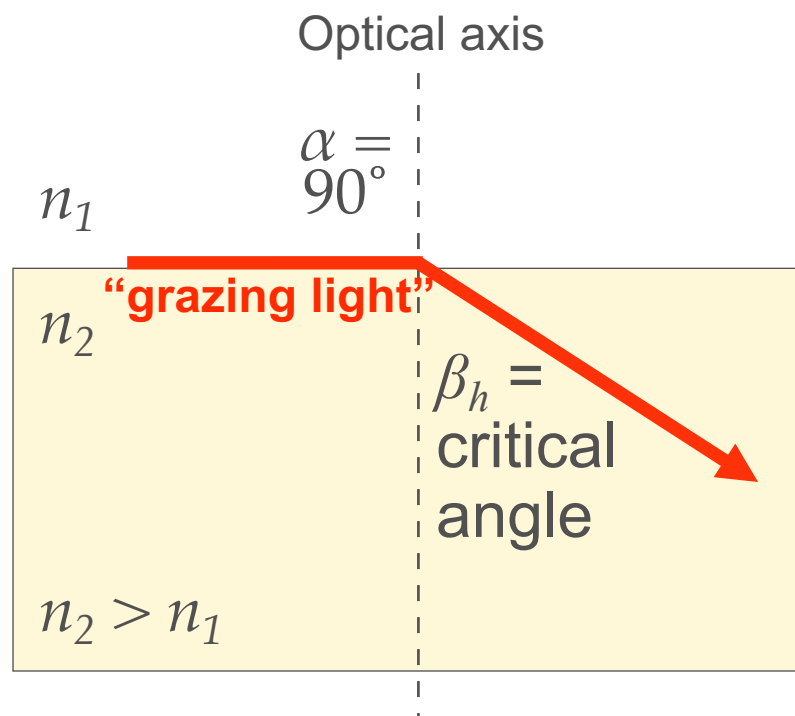


Pink Floyd: The Dark Side of the Moon



# Analytical application of refraction: Refractometry

## Boundary condition of refraction



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

$$n_1 = n_2 \sin \beta_h$$

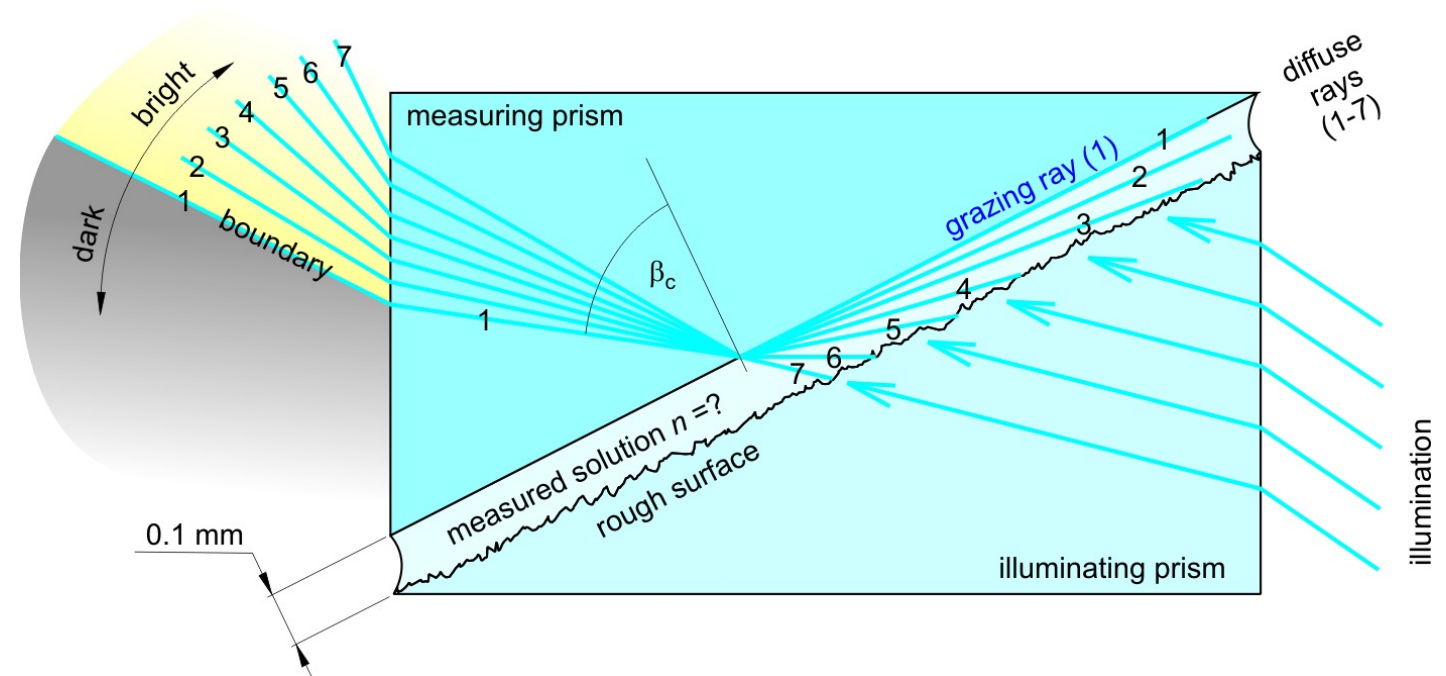
Thus, in case we know  $n_2$ , by measuring  $\beta_h$  the refractive index of the incident medium ( $n_1$ ) may be obtained.

## Refractometry

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

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

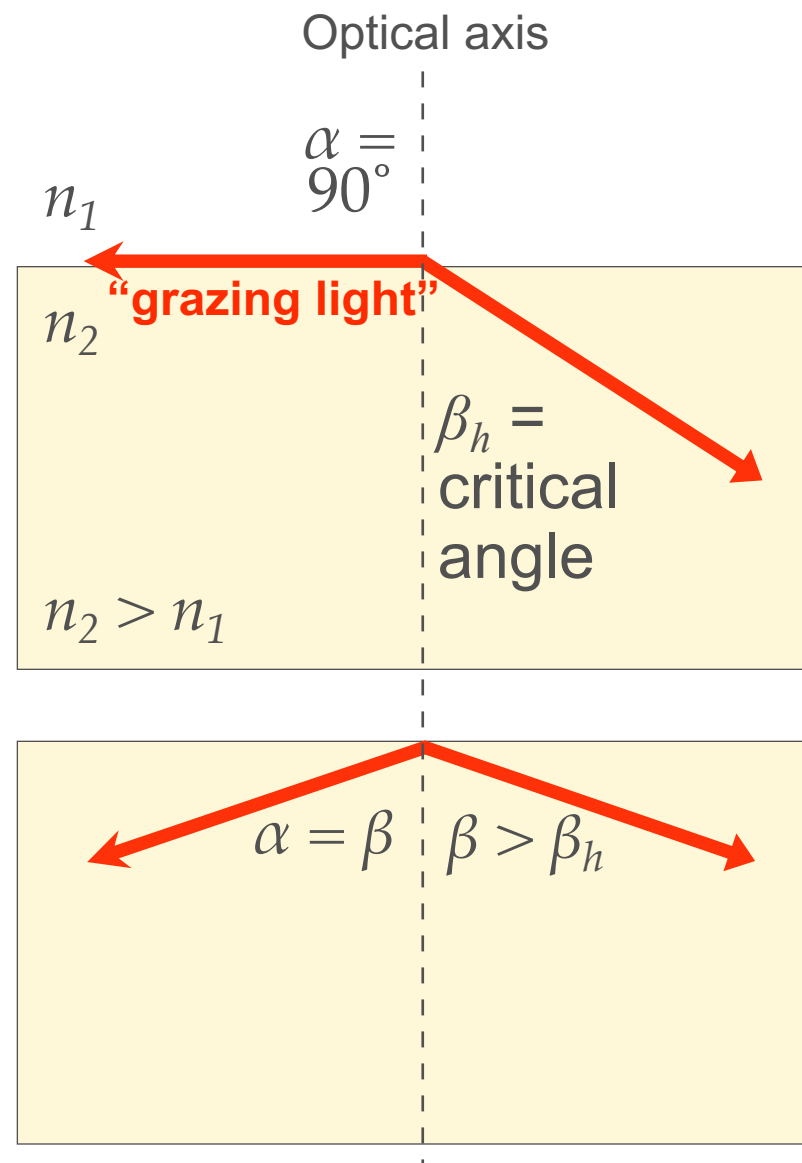
$n_0$  = refractive index of solvent,  $k$  = constant



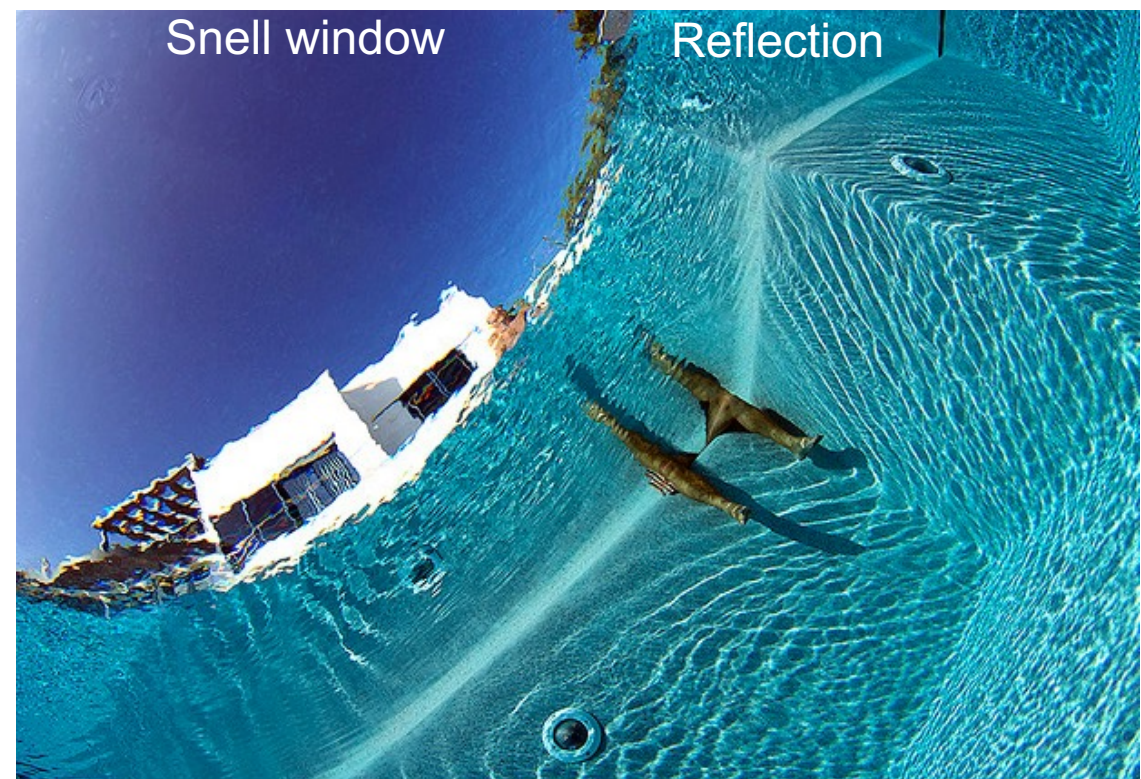
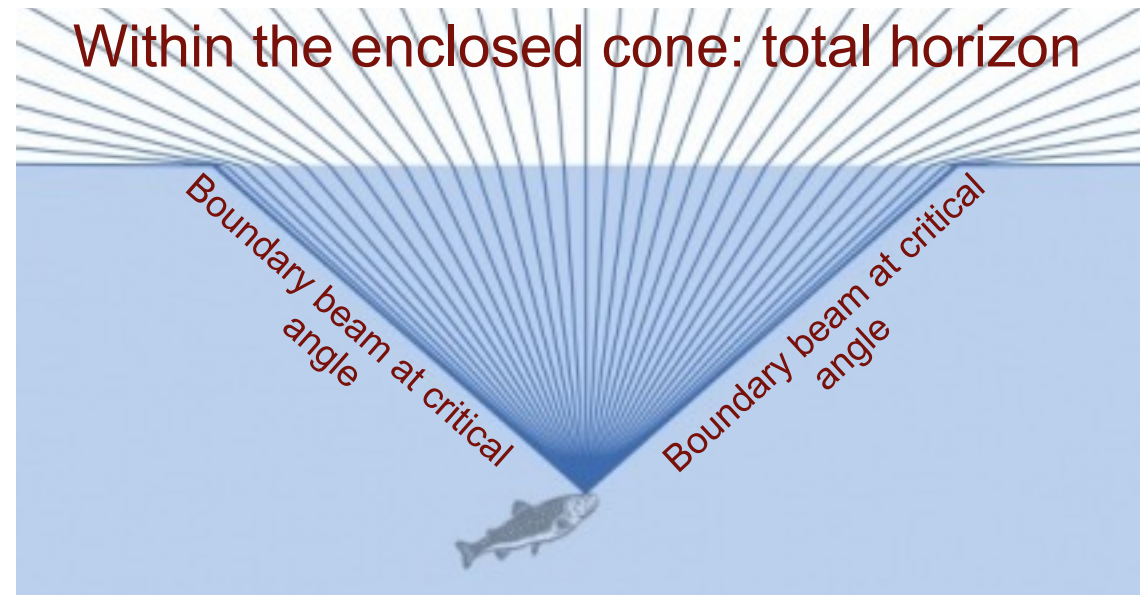
### Conditions of applicability:

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

# Total internal reflection



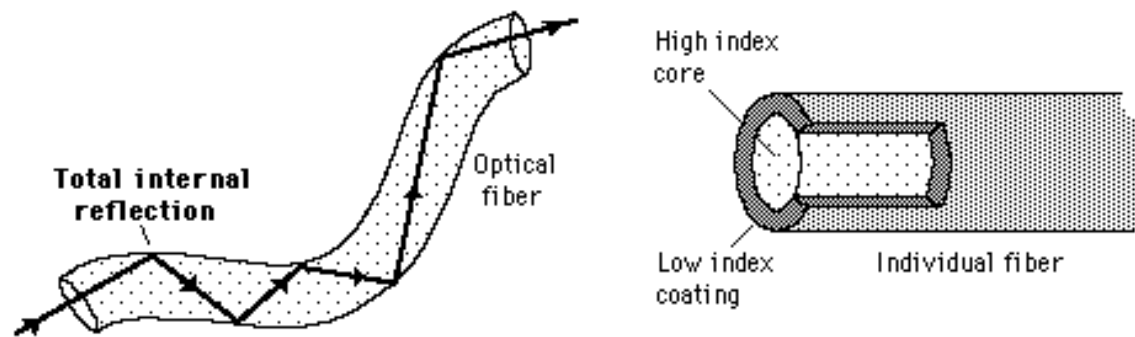
Total reflection within the optical medium of greater refractive index (“total *internal* reflection”, TIR)



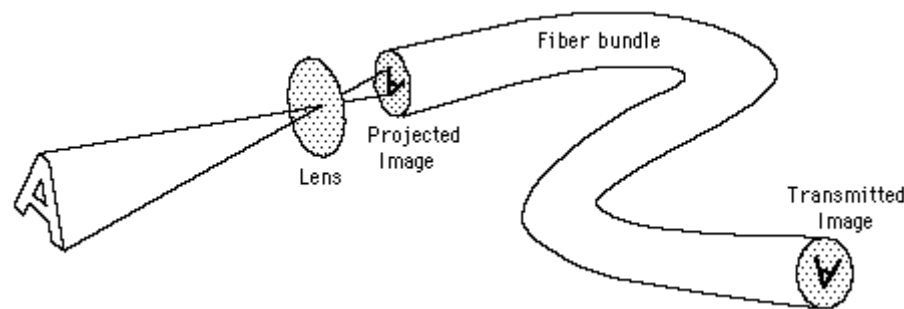


# Biomedical Application of TIR: optical fibers

Single fiber



Highly ordered fiber bundle



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

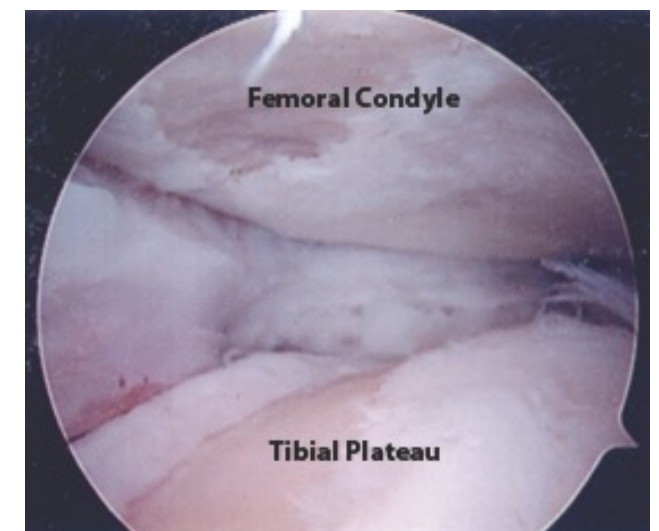
## Endoscopy

### OBJECTIVES

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

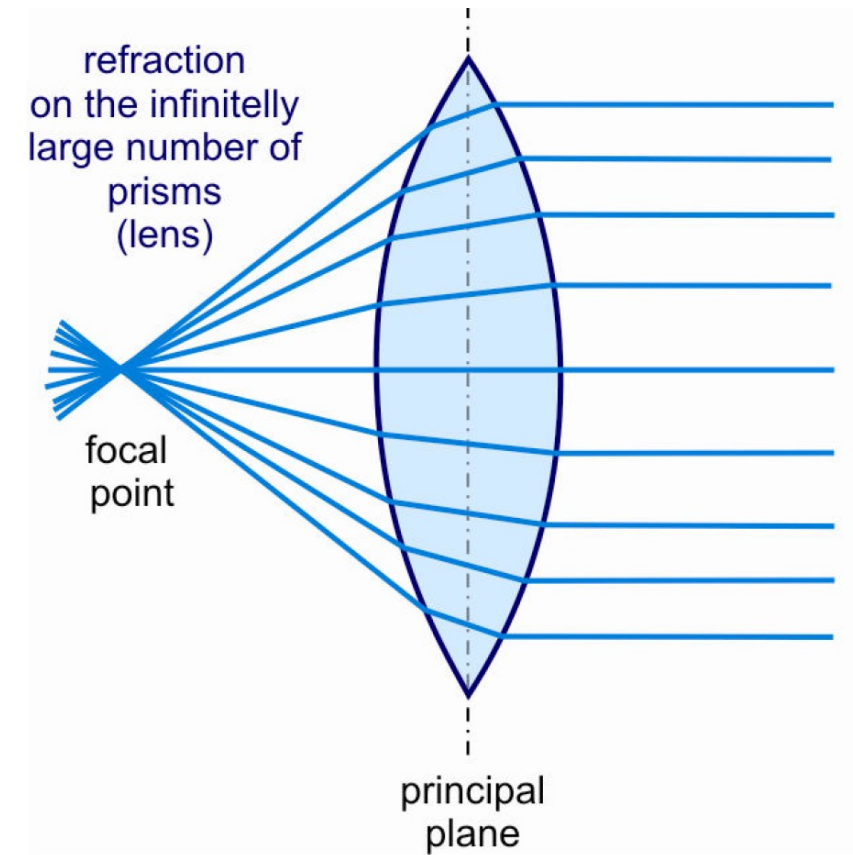
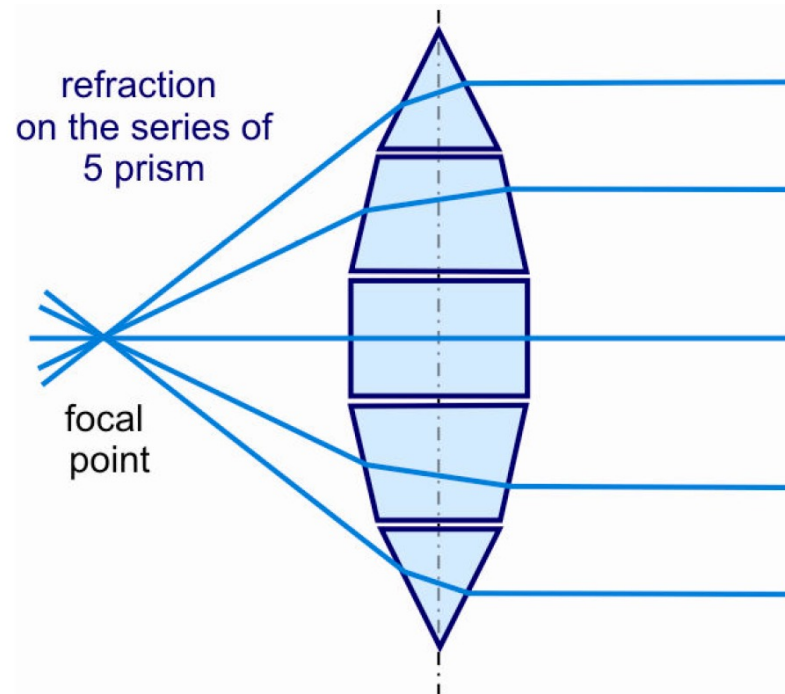
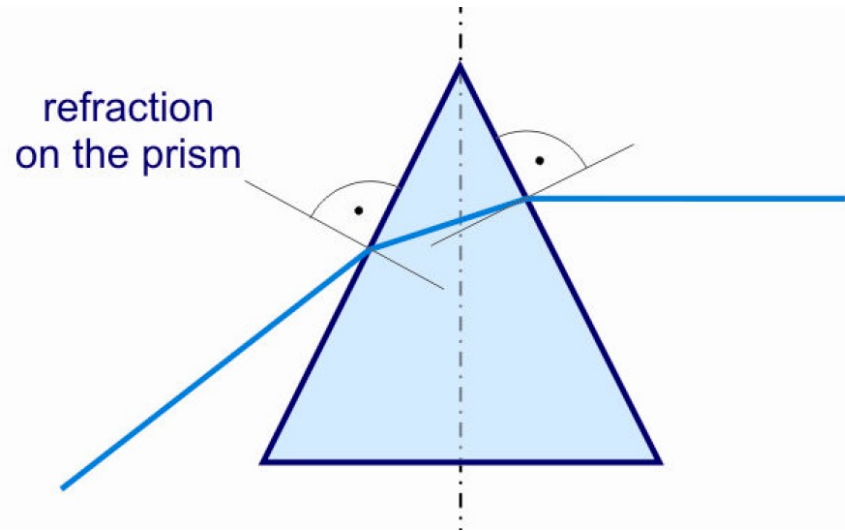
### TYPES

*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)



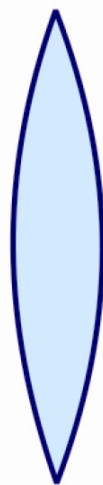
Arthroscopic surgery

# Refraction on curved surface



Types of lenses:

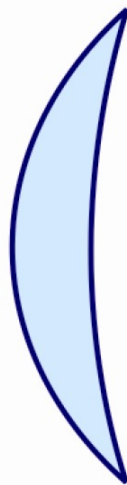
bi-convex



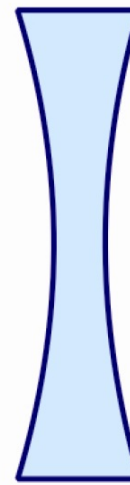
planar convex



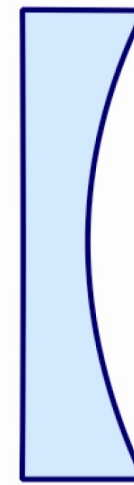
meniscus convex



bi-concave



planar concave



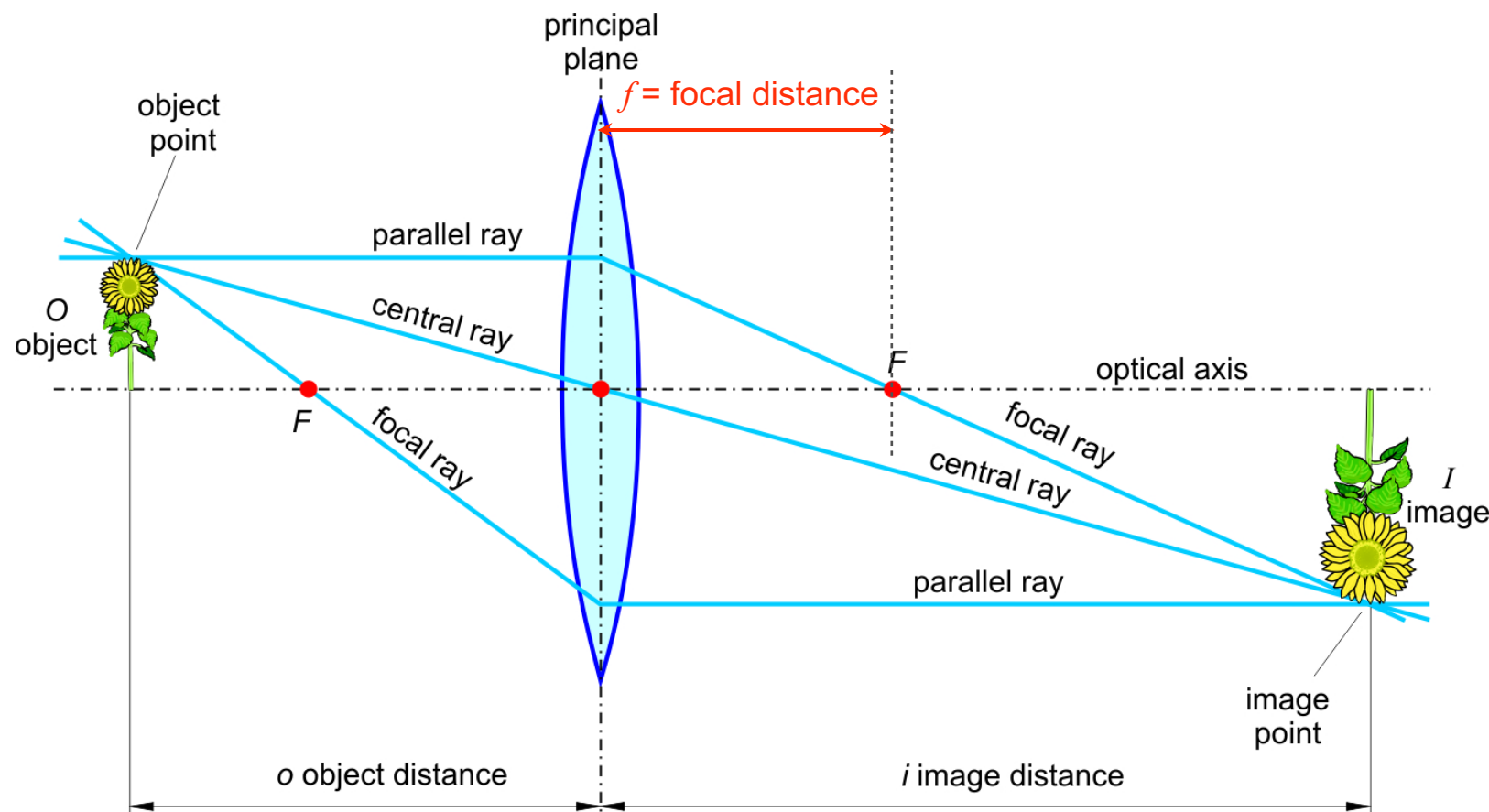
meniscus concave





# 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,  $\text{m}^{-1}$ )

Optical power of refractile surface

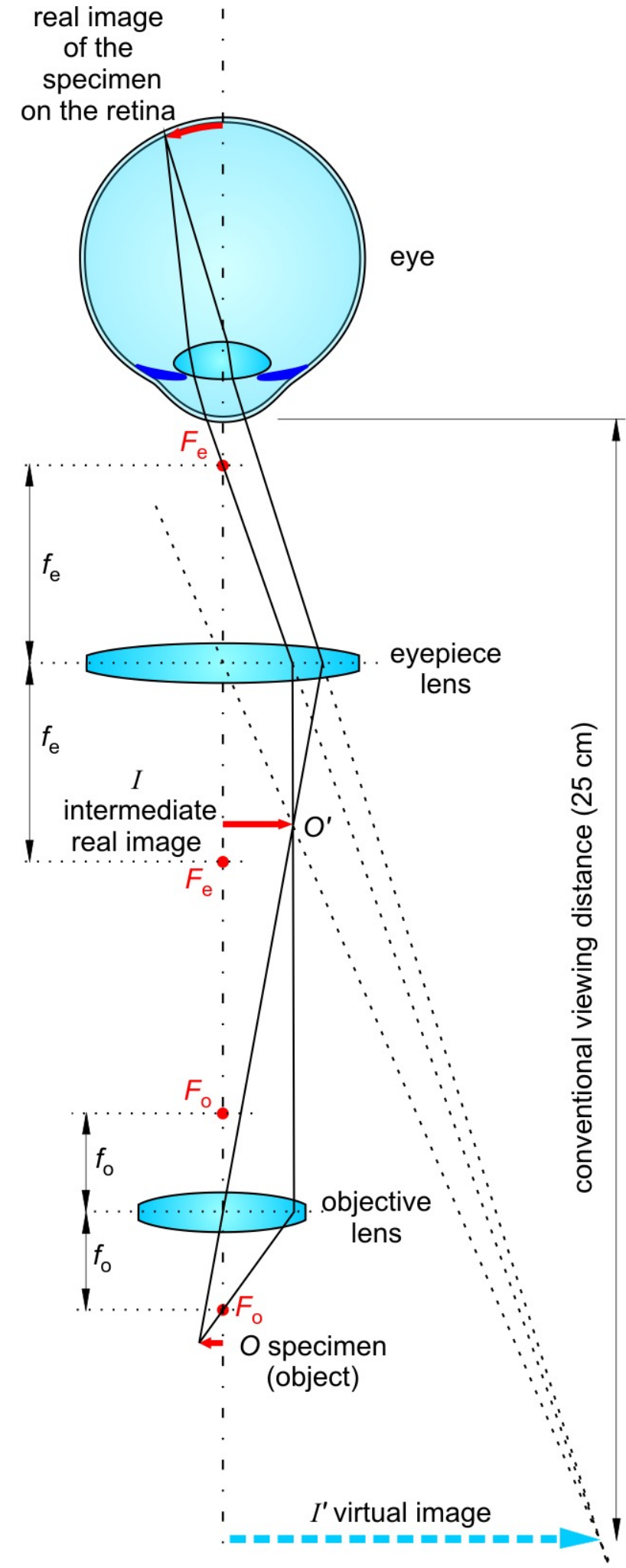
$$D = \frac{n - n'}{r}$$

$n - n'$  = difference between the refractive indices of optical media

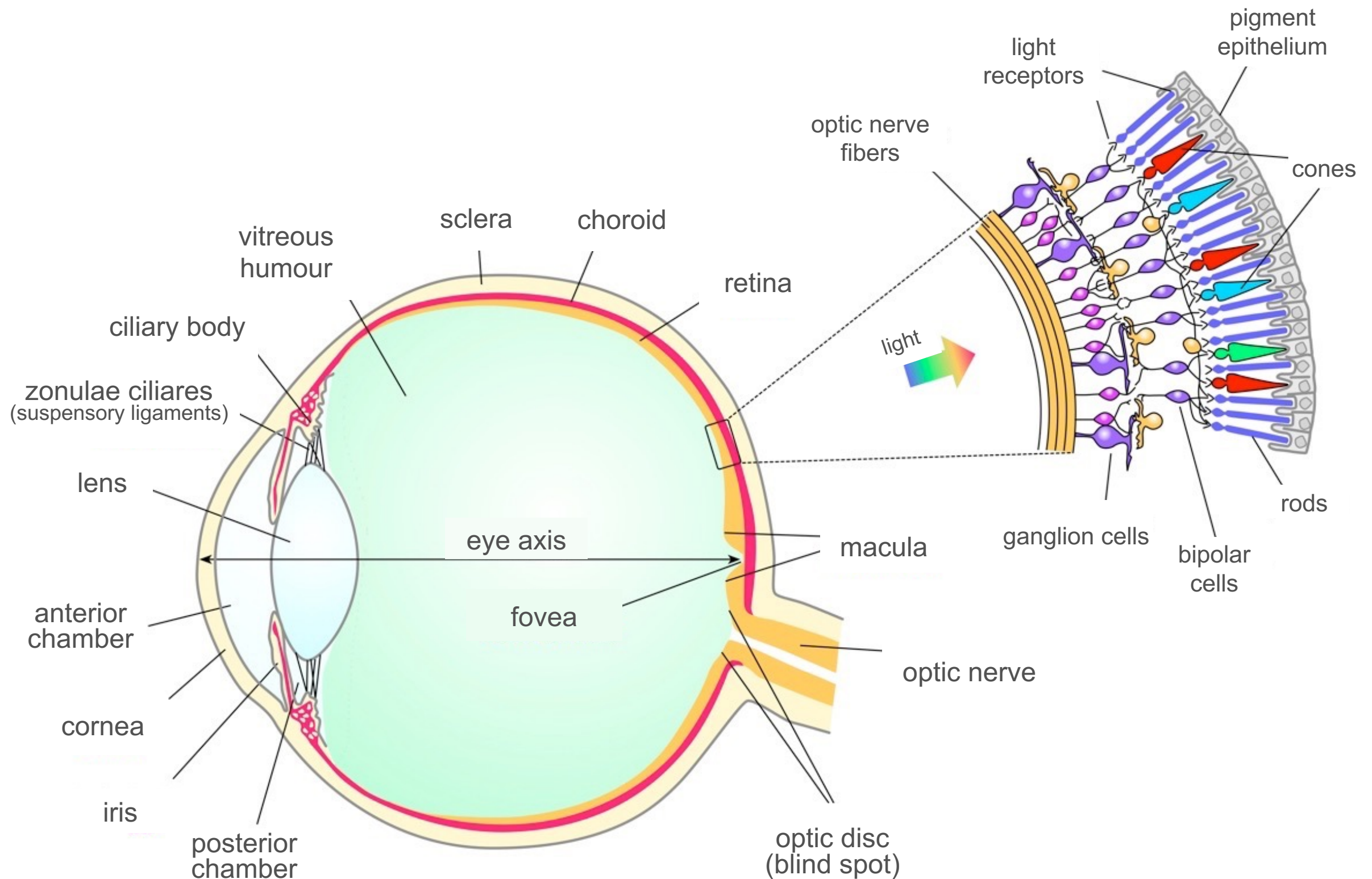
$r$  = radius of curvature of refractile surface

# 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



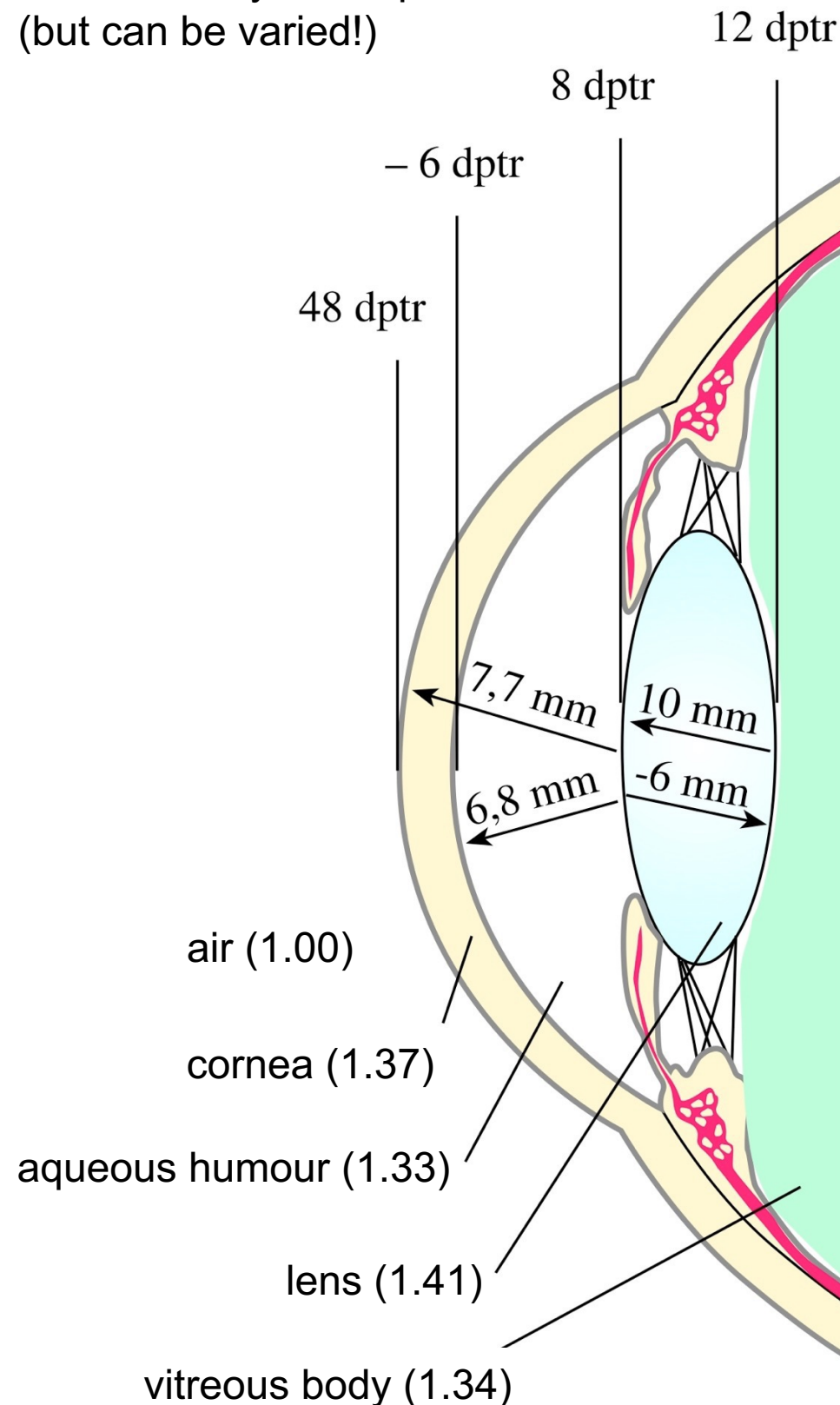
# Optics of the human eye



*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 ( $\text{W}/\text{m}^2$ )  
 $d$ =pupil diameter

Power depends on pupil diameter:

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

$d_{\max}=8 \text{ mm}$   
 $d_{\min}=2 \text{ mm}$

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  $r$ )!

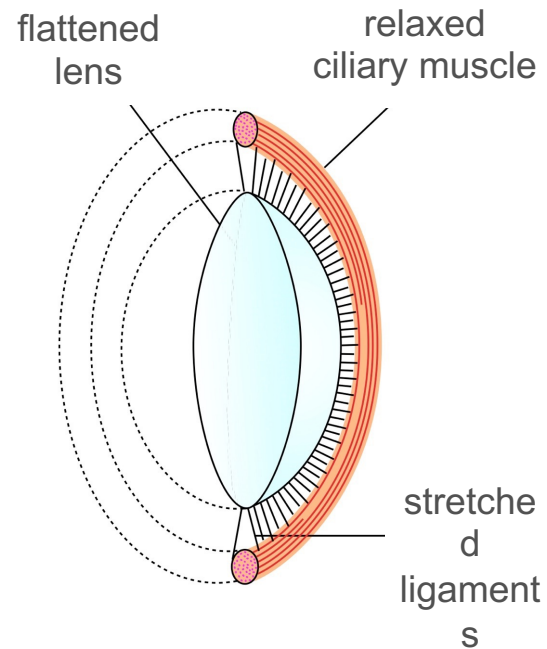


# Accommodation and refraction problems

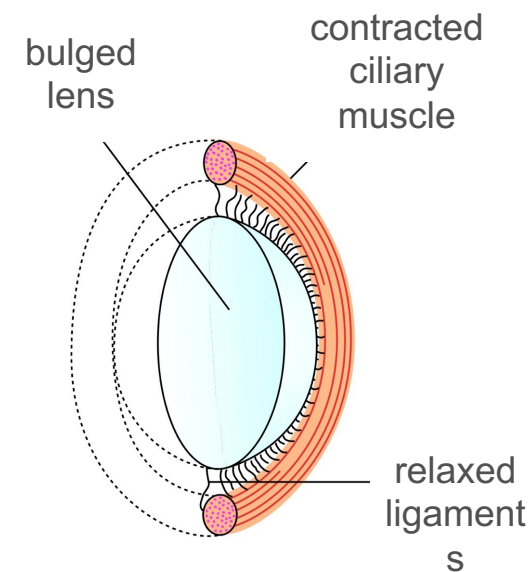
## Accommodation:

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

Farsight



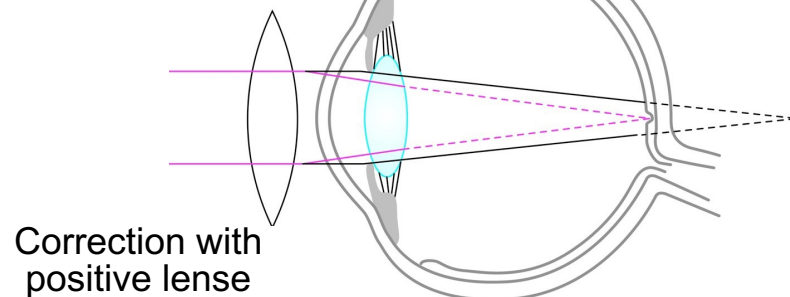
Nearsight



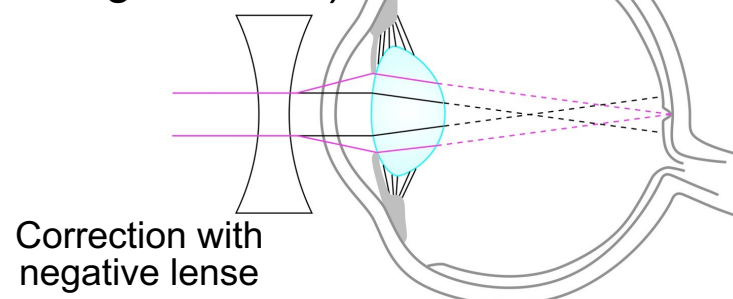
## Presbyopia:

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

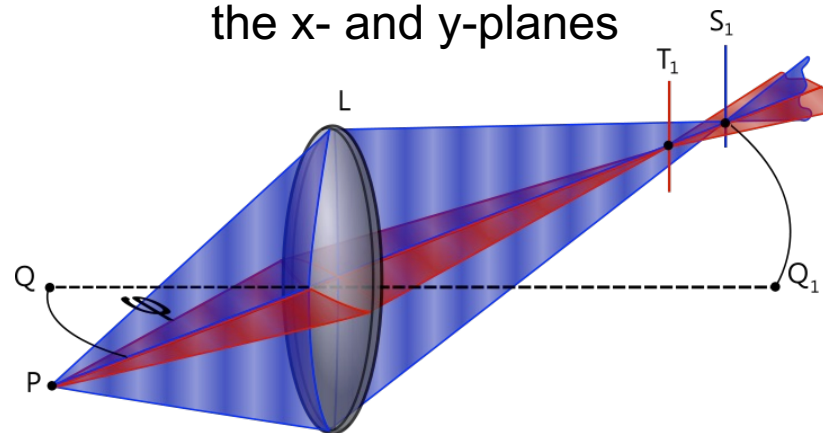
Hypermetropia  
(farsightedness)



Myopia  
(nearsightedness)

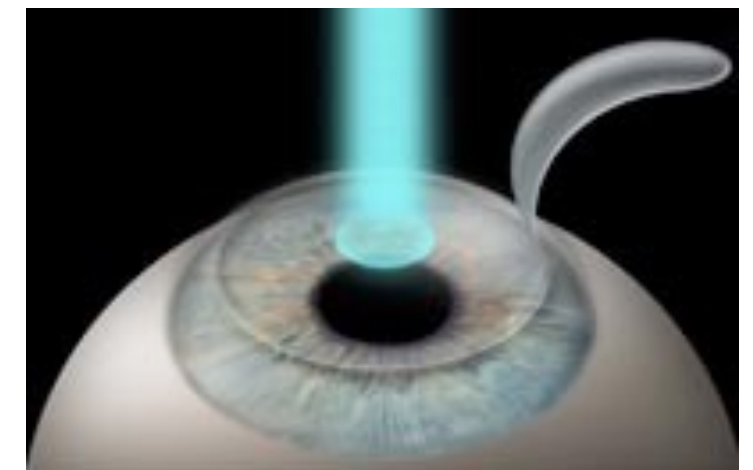


Astigmatism:  
focal distance is different in  
the x- and y-planes



Correction with  
cylindrical lens

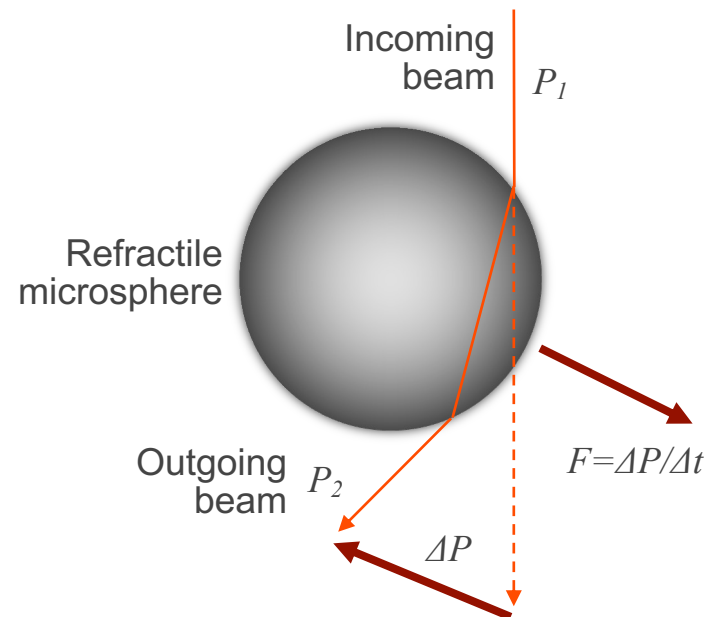
Permanent correction of refractive  
problem: LASIK (Laser Assisted In  
Situ Keratomileusis)



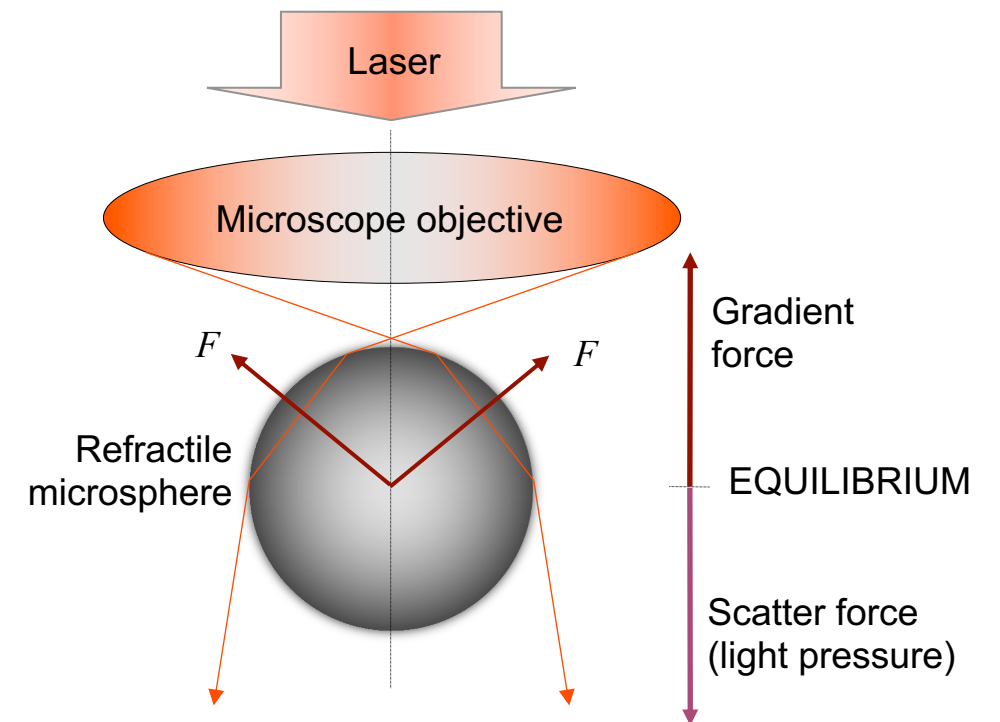
The radius of curvature of the cornea is  
changed (with laser surgery)

# Manipulating objects with refraction

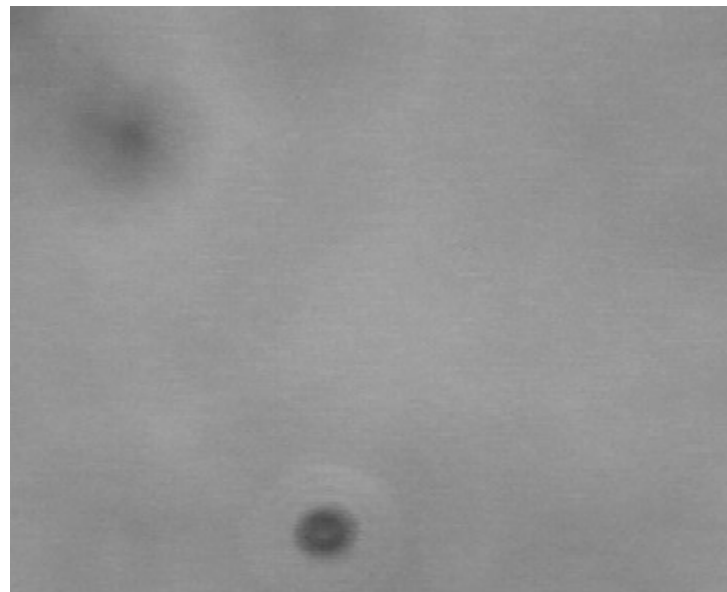
*Refraction is accompanied by photonic momentum change ( $\Delta P$ )  
(Theory later):*



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

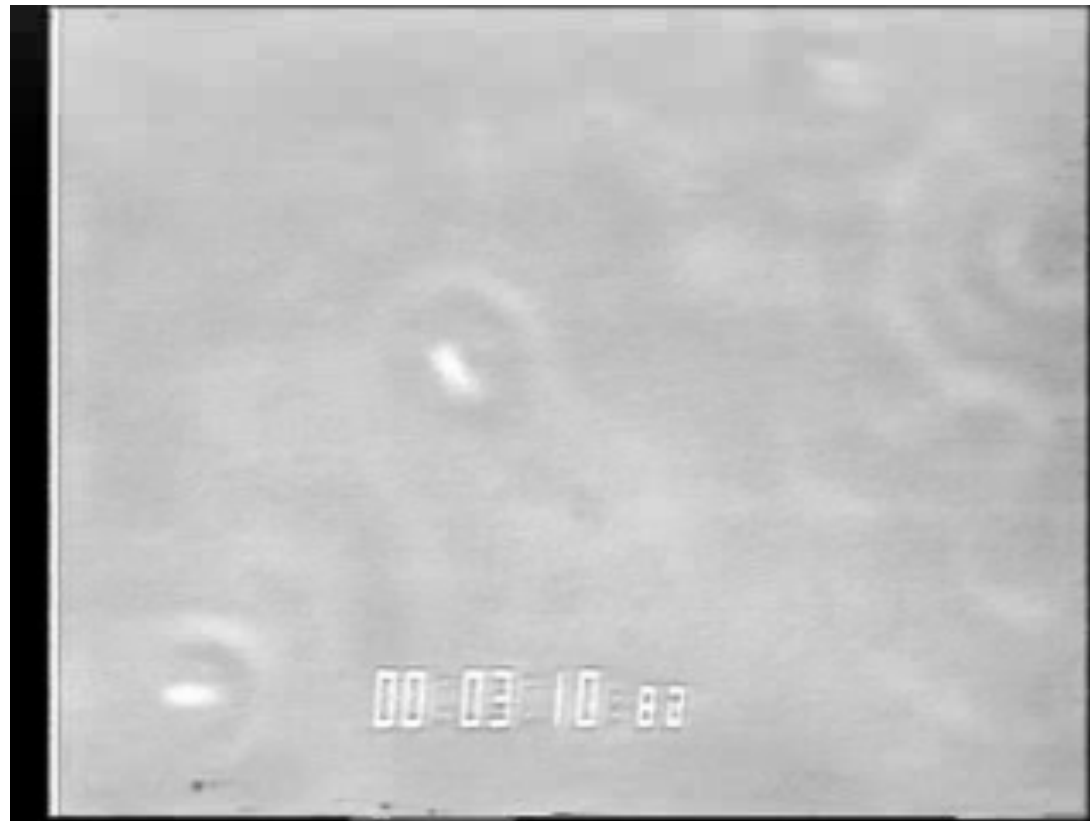


*In the **optical trap** a momentum change occurs between the photons and the trapped particle:*



3  $\mu\text{m}$  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

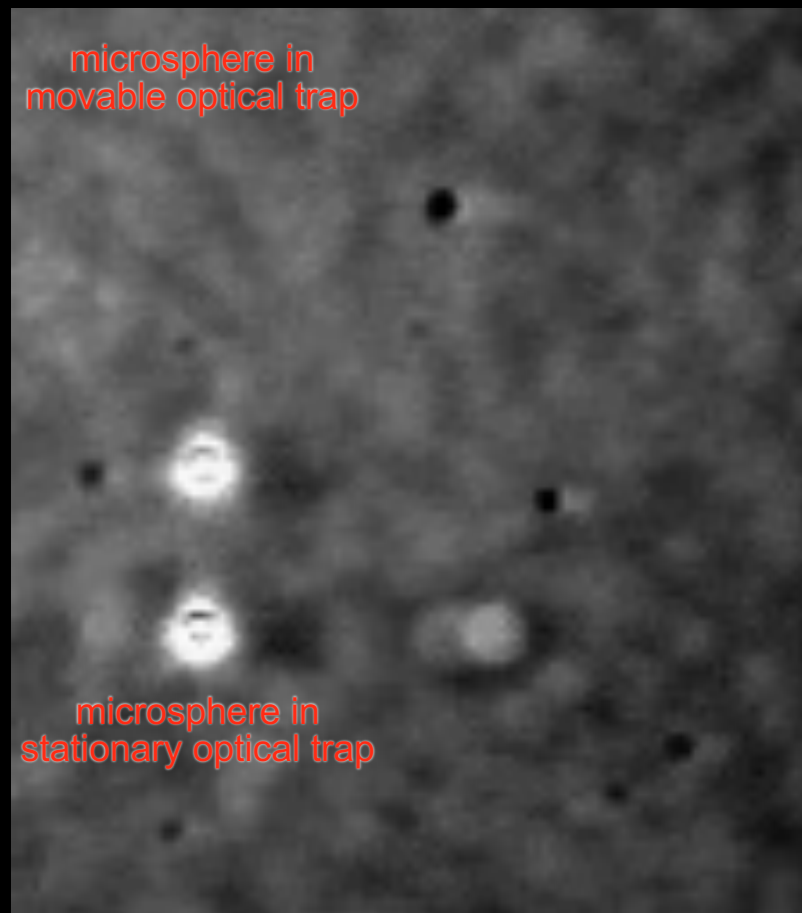
Actin filament



Fluorescence image

DNA

Phase contrast image



Fluorescence image





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