Propagation and interactions of light

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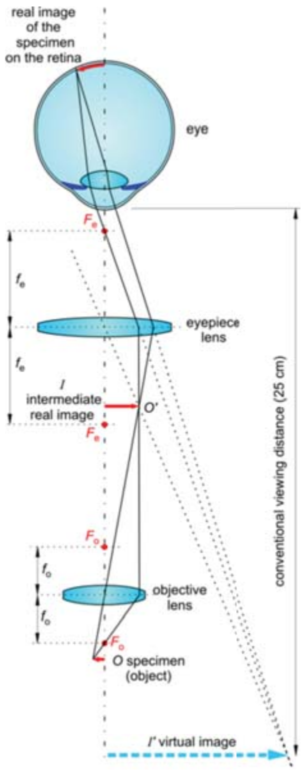
Propagation and interactions of light

- Applications of refraction
- Detectable parameters of the light wave
- Phase of the light wave, phase contrast microscopy
- Polarization, anisotropy, polarimetry
- Optics of the human eye
- Accomodation
- Refraction problems of the eye
- Resolution of the human eye
- Color coding, color vision

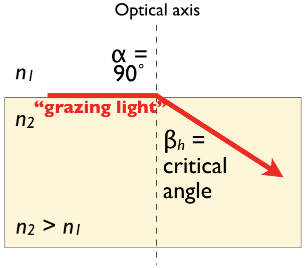
Refraction is used to form image in the light microscope

- 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



Analytical application of refraction: Refractometry

Boundary condition of refraction



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

$$n_1 = n_2 \sin \beta_h$$

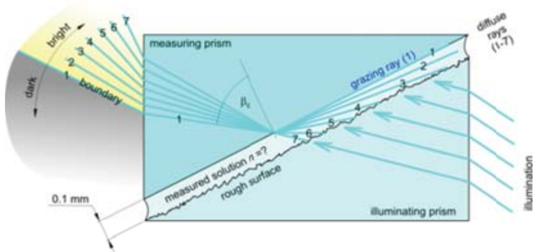
Thus, if we know n_2, by measuring $β_h$ the refractive index of the incident medium (n_1) may be obtained.

Refractometry

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

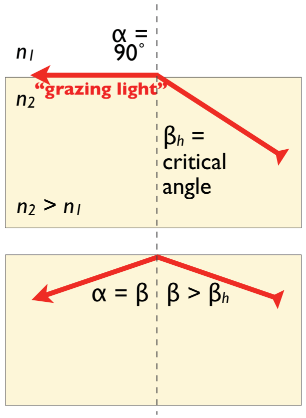
$$n_1 = n_0 + k \cdot c$$

n_0 = refractive index of solvent, k = constant

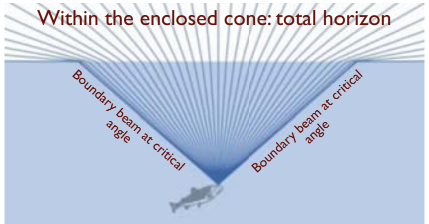


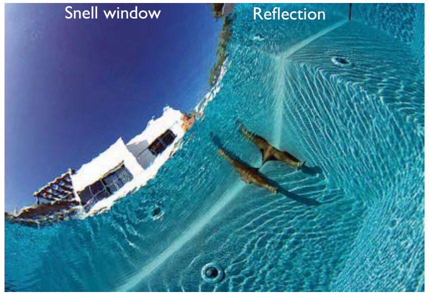
Conditions of applicability:
- Liquid sample
- Sample is transparent
- Refractive index of sample is smaller than that of the measuring prism.

Total internal reflection (TIR)



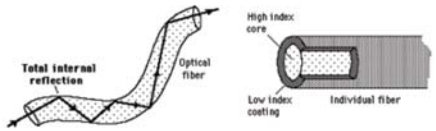
Total reflection within the optical medium of greater refractive index ("total ***internal*** reflection", TIR)



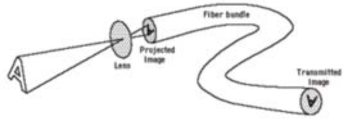


Biomedical Application of TIR: optical fibers

Single-mode fiber



Multi-mode fiber



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

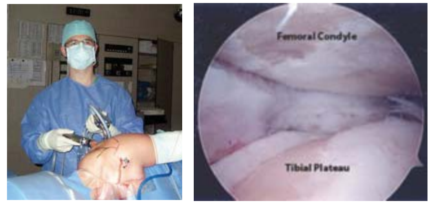
Endoscopy

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

During refraction the momentum of the photon changes

Einstein: mass-energy equivalence	Planck: law of radiation	Maxwell: speed of light
$E = mc^2$	$E = hf$	$c = \lambda f$

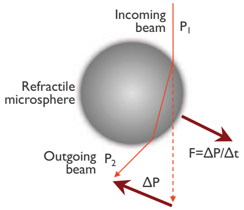
Louis-Victor-Pierre-Raymond, 7th duc **de Broglie** (1892-1987)

$$mc^2 = h \cdot \frac{c}{\lambda}$$

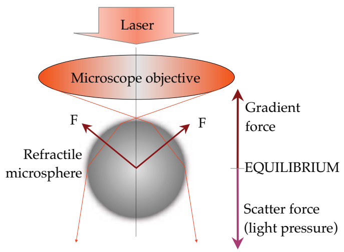
Momentum of the photon:

$$P = \frac{h}{\lambda}$$

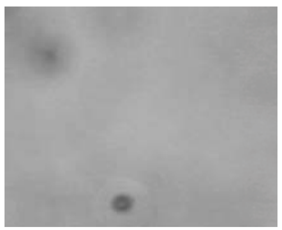
Refraction is accompanied by photonic momentum change (ΔP):



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

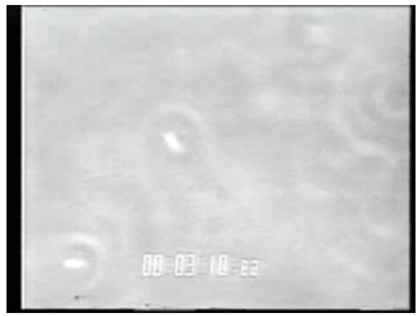


*In the **optical trap** a momentum change occurs between the photons and the trapped particle:*



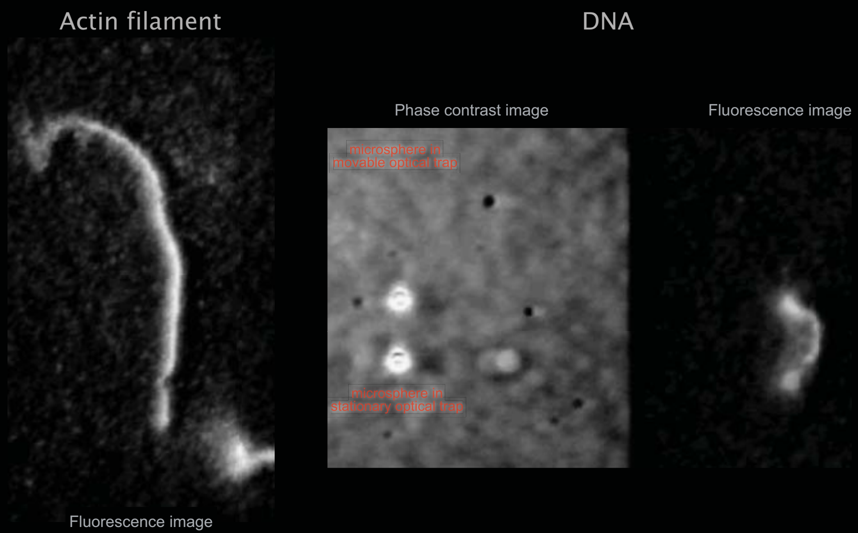
3 μm latex (polystyrene) microspheres in the optical trap

Even cells can be captured with the optical trap



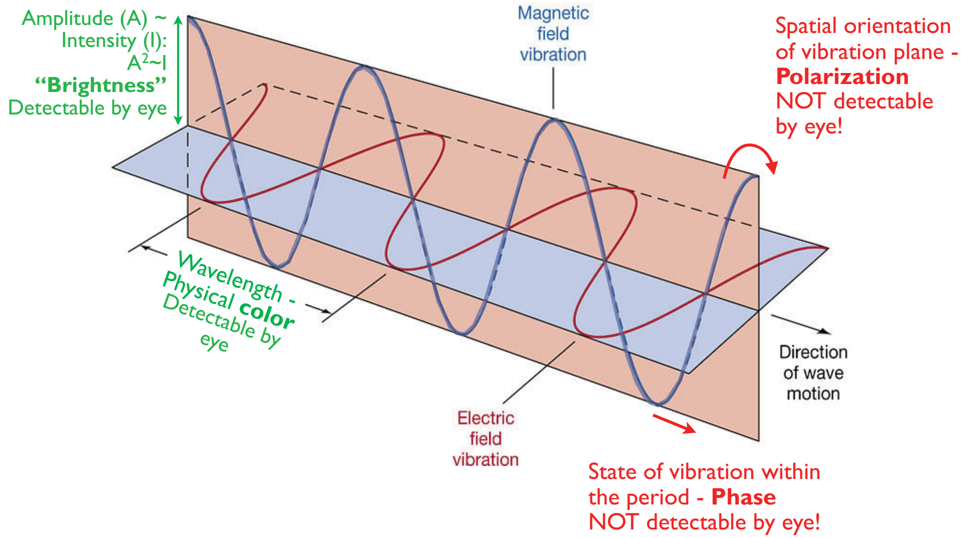
Trapping of bacterial cells

Tying a knot on a molecular filament by using optical trap



Arai et al. Nature 399, 446, 1999.

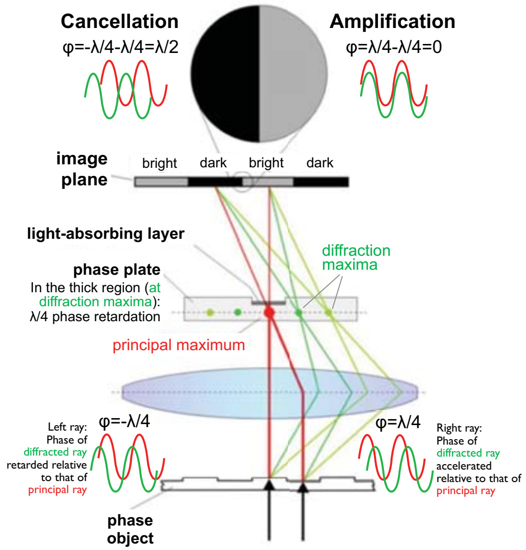
Detectable parameters of the light wave



Phase, phase contrast microscopy

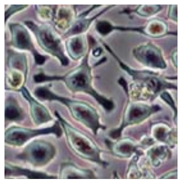
Frits Zernike (1888-1966) Nobel-prize

- **Phase**: shows the state of vibration within the entire period (2π).
- Expressed with the **phase angle** (φ).
- Phase difference between waves: **phase shift** (retardation or acceleration)



Live (unstained) cells

Bright-field microscopic image

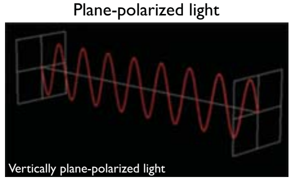


Phase-contrast microscopic image

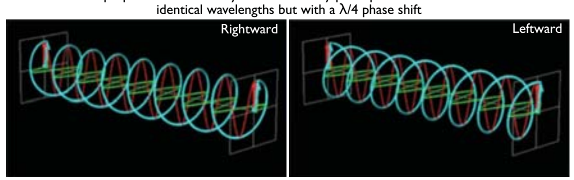
Polarized light and its interactions

Direction of the vibration (electric or magnetic field) has preferred orientation

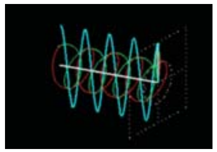
Plane-polarized light



Circularly polarized light:
Superposition of vertically and horizontally plane-polarized waves with identical wavelengths but with a λ/4 phase shift

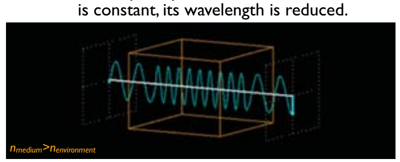


Superposition of a right- and leftward circularly polarized wave results in plane-polarized light.

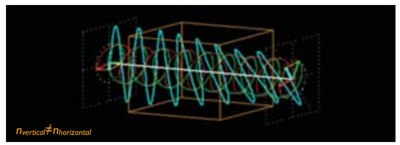


Orientation of polarization plane depends on the relative phase of the two circularly polarized waves

Light decelerates in optically dense medium; because its frequency is constant, its wavelength is reduced.



In an anisotropic* medium a phase shift occurs between the circularly polarized components: the polarization plane of the emerging wave rotates.

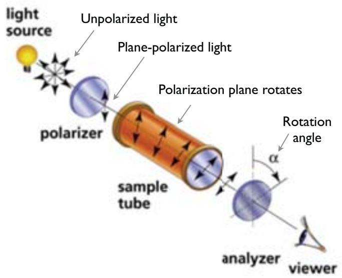


**Anisotropy (birefringence)*: refractive index (~light speed) is orientation dependent (i.e., in different directions within the sample, light propagates with different speeds).

Movies - http://www.enzim.hu/~szia/cddemo/demo0.htm

Applications of polarization

Polarimetry



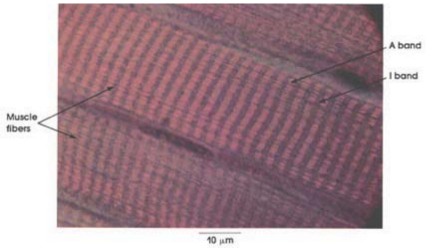
Rotation angle depends on the concentration (c) of the optically active* material:

$$\alpha = [\alpha]_D^{20} \cdot c \cdot l$$

[α] = specific angle of rotation ("20": room temperature; "D": emission spectral line of Na λ=589 nm)
l = length of sample tube

Polarization microscopy

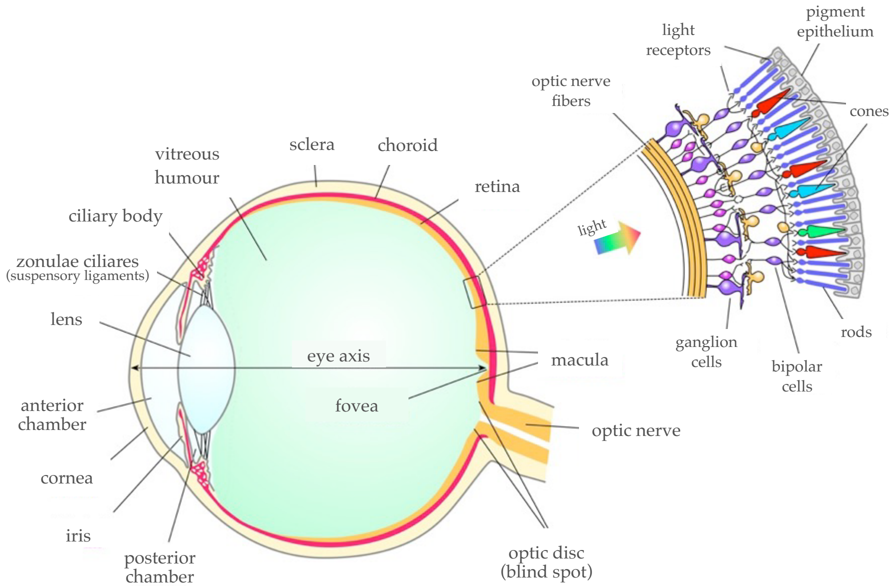
Cross-striated skeletal muscle in the polarization microscope



- A-band: anisotropic (birefringent) region (contains myosin helically ordered myosin molecules)
- I-band: isotropic region

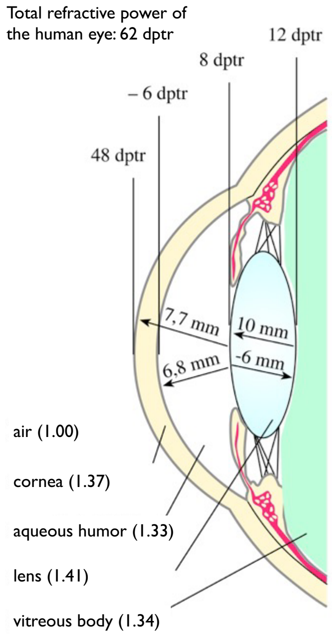
*Optically active material: contains *chiral* (mirror-symmetric) molecules tat rotate the plane of polarization.

Optics of the human eye



Horizontal section of the human eye

Optics of the human eye



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):

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

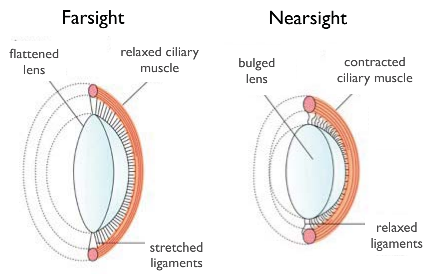
n-n' = refractive index difference of bounding media (air, cornea, etc.)
r = radius of curvature of refractive surface

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

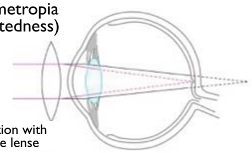
Accomodation:

- 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.



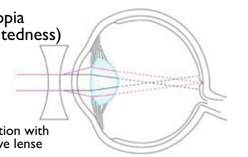
Presbyopia:
- Accomodation power decreases.
- Manifests with age (>45 years).
- Nearsight worsens.

Hypermetropia (farsightedness)



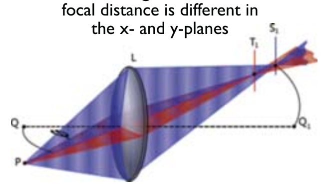
Correction with positive lense

Myopia (nearsightedness)



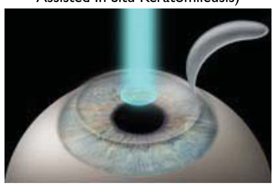
Correction with negative lense

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)

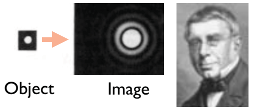


The radius of curvature of the cornea is changed (with laser surgery)

Resolution of the human eye I.

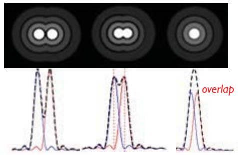
Diffraction limit

Because of diffraction: image of a point object is an Airy disk



Sir George Biddel Airy (1801-1892)

Rayleigh criterion: objects may be resolved if their corresponding Airy disks do not overlap



Lord Rayleigh (1842-1919)

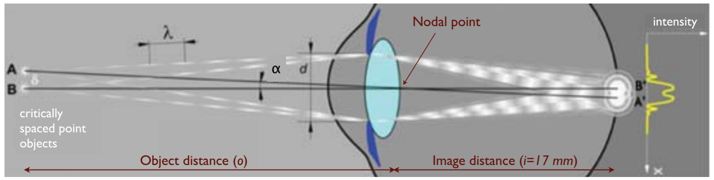
Smallest resolved distance has a limit (Abbe equation):

$$d = \frac{0.61\lambda}{n \sin\alpha}$$

λ = wavelength
n = refractive index of medium
α = angle between axis and outermost ray

Ernst Abbe (1840-1905)

Diffraction limit of the human eye



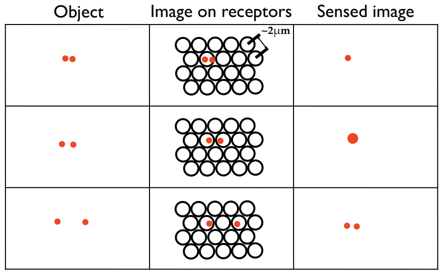
Reduced eye model

Limiting visual angle: $\alpha_H = 1.22\frac{\lambda}{d}$

Smallest angle of view at which two closely spaced objects may be resolved.
At average wavelength (550 nm) and pupil diameter (4 mm): **0.6'** (angular minutes)

Resolution of the human eye II.

Biological limit: receptor cell density



- Condition of resolution: at least one inactivated receptor cell falls in between two activated ones. The limiting angle of view under this condition is (α_B)≈ **0.8'**
- The diffraction and biological limits of the human eye are **comparable**!

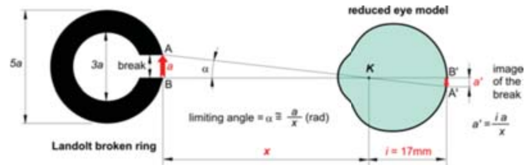
Visual Acuity ("visus", vision):

$$visual\_acuity = \frac{1'}{\alpha}100\%$$

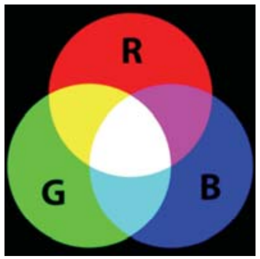
α = experimental (measured) visual angle

Average visual angle in healthy humans:
1' (= 100% vision)

Measurement of visual acuity



Color coding, color vision

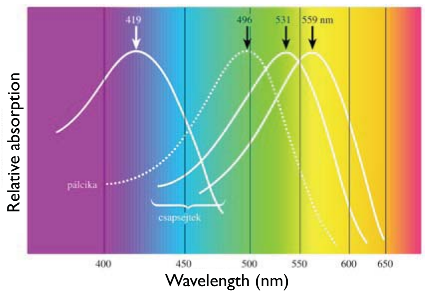


Additive color coding

Any color may be generated by mixing three basic colors (R=red, G=green, B=blue) with varying weighing factors.

$$X = rR + gG + bB$$

Absorption spectra of the human color-sensitive receptors (cones)



In the human eye:

- 3 different color-sensitive receptors.
- Each receptor absorbs in different regions of the visible spectrum (R=64%, G=32%, B=2%).