Wave optics. Huygens–Fresnel-principle. Resolving power. Light polarization. Color mixing, color vision.

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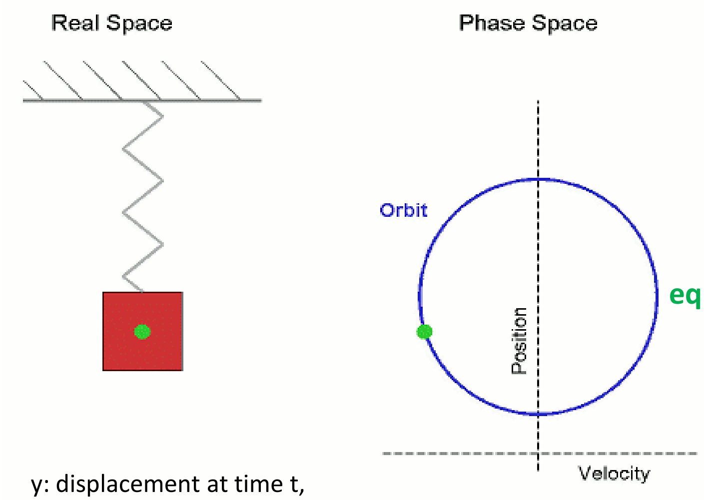
The origin and types of waves

Wave: oscillation that propagates through space

Source of the wave: oscillation

- special case: **harmonic oscillation:**
  If the restoring force acting on a system displaced from its equilibrium position is proportional to the displacement.
  e.g. mass suspended on a spring



+ displacement

equilibrium position

- displacement

displacement(time) function:

$$y = A \cdot sin(\omega t + \varphi_0)$$

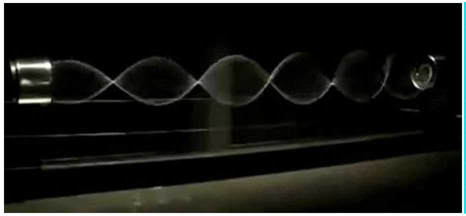
y: displacement at time t,
A: maximal displacement (amplitude),
ω: angular velocity,
ϕ_0: initial phase angle.

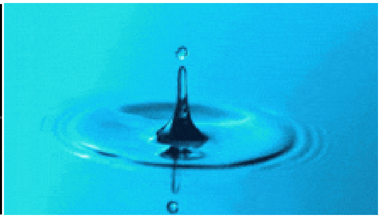
According to source:

- **mechanical**: elastic deformation propagating through elastic medium (e.g. sound),
- **electromagnetic**: electric disturbance propagating through space or vacuum (e.g. light).

According to propagation dimension:

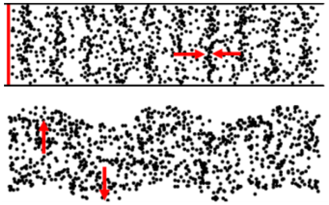
- **one-dimensional** (e.g. rope or string),
- **surface** waves (e.g. wave on water surface),
- **spatial** waves (e.g. sound).





According to relative direction of oscillation and propagation:

- **longitudinal** (e.g. sound propagation in gases or liquids),
- **transverse** (e.g. light).



Light as a wave

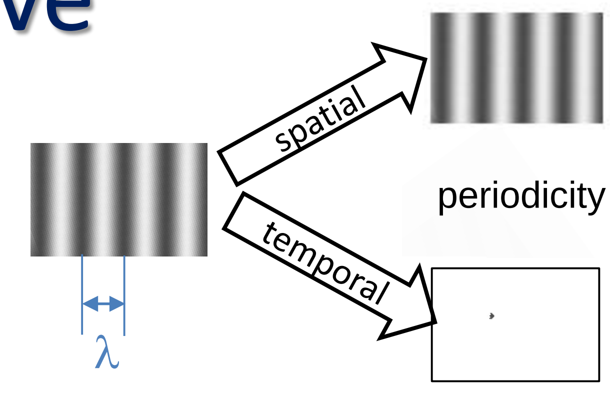
Important parameters of light as a wave:

- period (T),
- frequency (f),
- wavelength (λ),
- velocity (c):

$$f = \frac{1}{T}$$

λ: Lambda

$$c = \lambda \cdot f$$



Wavelength: the smallest distance between two points of a wave that are in the same phase

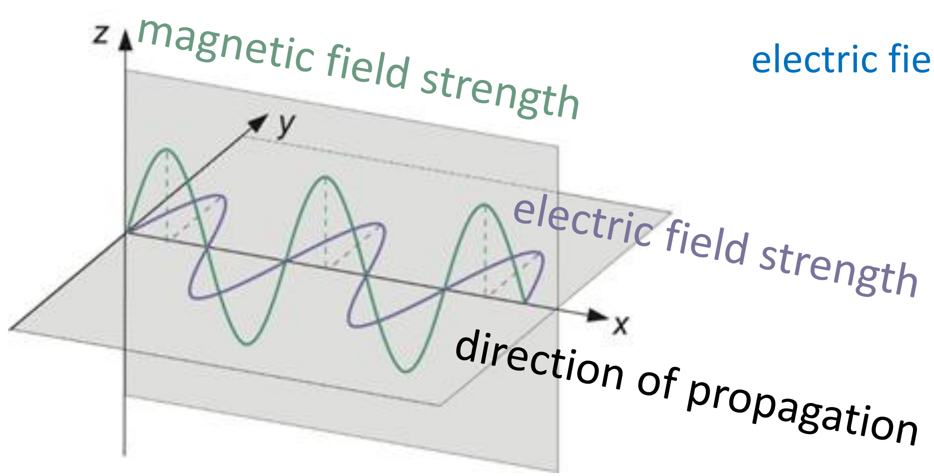
Speed of propagation of light in vacuum:

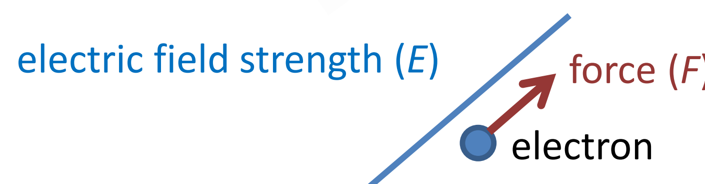
$$c = 3 \cdot 10^8 \ \frac{\text{m}}{\text{s}} \qquad c = 2{,}99792458 \cdot 10^8 \ \frac{m}{s}$$

Interaction between light and matter: (Maxwell)

Light as a wave:

- transverse
- electromagnetic



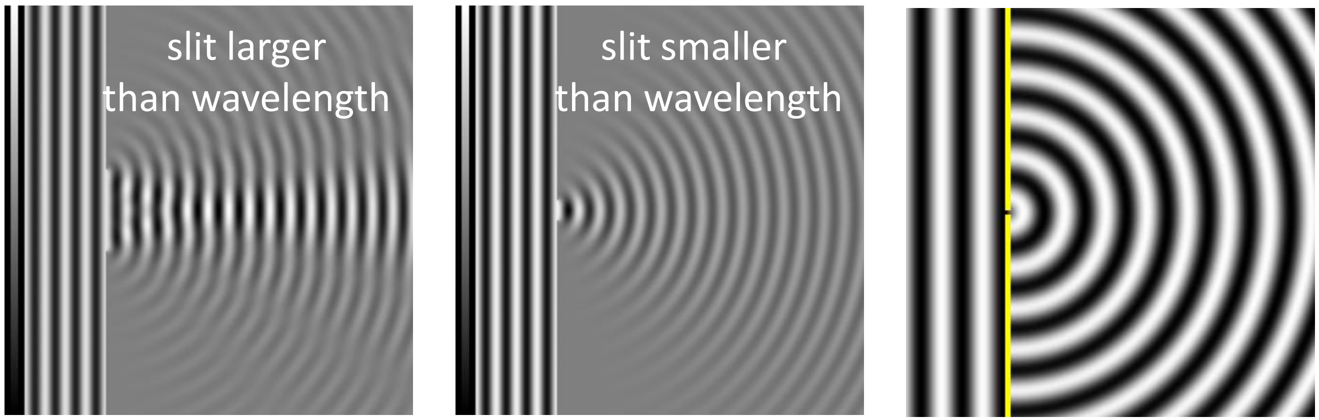


$F = e \cdot E$

Because of this interaction, light propagates slower in all materials than in vacuum.

The Huygens' principle

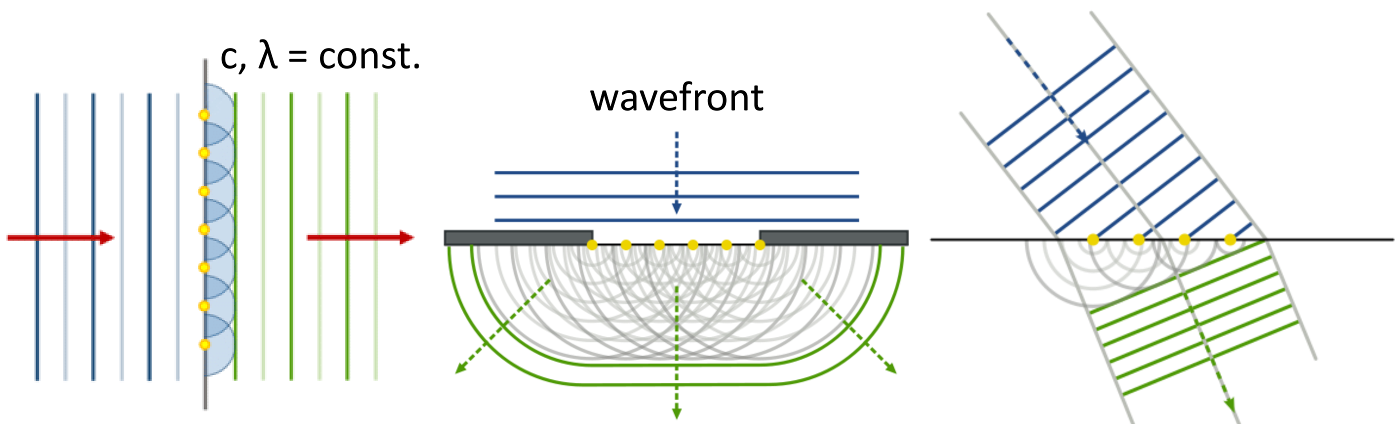
If light propagates through a slit comparable or smaller than its wavelength, then its wave properties must be taken into account. Some phenomena cannot be explained with geometric optics!



Huygens-Fresnel principle: **Each point on a primary wavefront serves as the source of spherical secondary wavelets. The primary wavefront at some later time is the envelope of these wavelets.**


Christiaan Huygens (1629-1695)

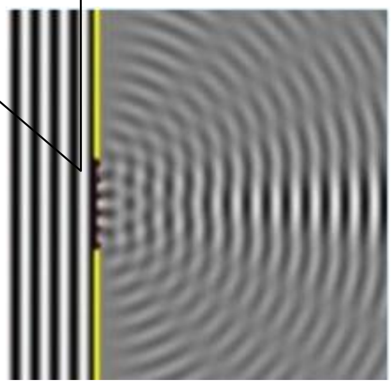

Augustin-Jean Fresne (1788–1827)

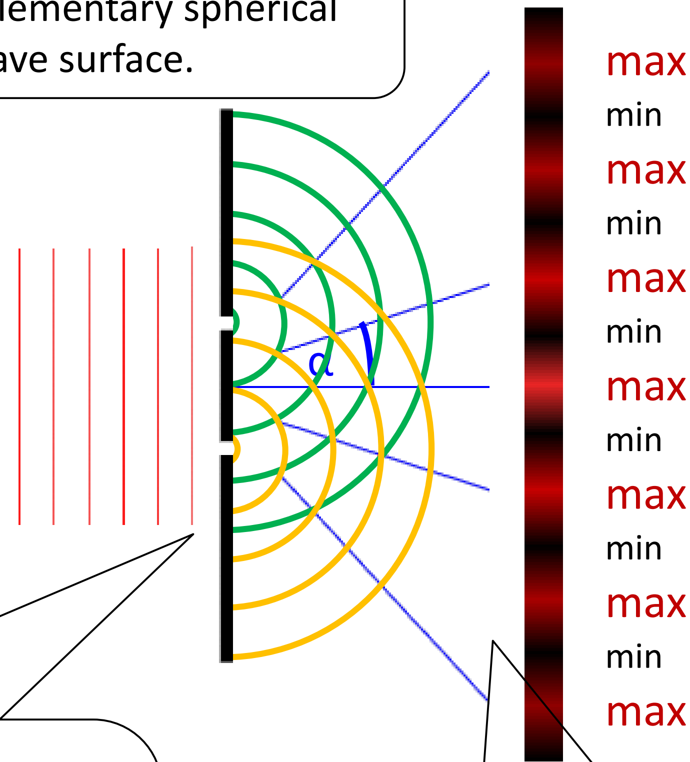


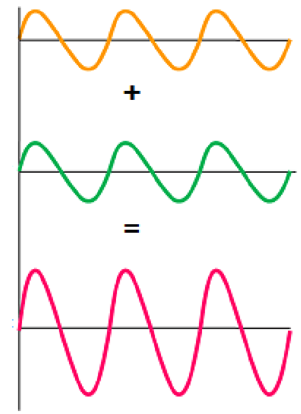
The wave appears in the "shaded" areas, too.

Interference of waves

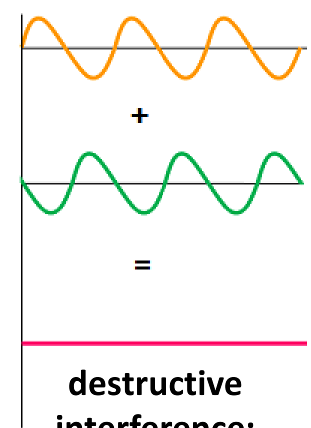
Huygens-Fresnel principle:
The wavefront propagates in such a way that elementary spherical waves emanate from every point on a given wave surface.







constructive interference:
amplification (waves in phase)

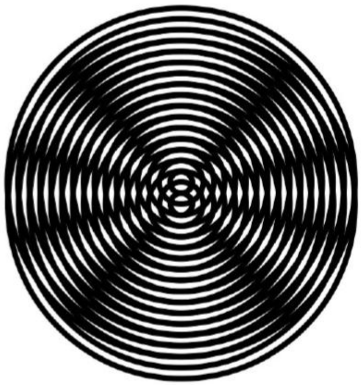


destructive interference:
cancellation ($\Delta\phi$=half wavelength)

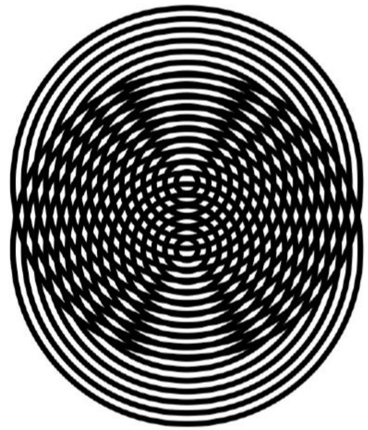
Thomas Young: double slit experiment:
A plane wave passing through a double slit creates a characteristic interference pattern on the screen located further away. In the case of a monochromatic and coherent light source, this pattern consists of alternating **bright (maxima)** and **dark stripes (minima)**.

Interference:
a new wave pattern resulting from the superposition of two or more waves.

Diffraction of waves



small d ~ large distance between maxima



large d ~ small distance between

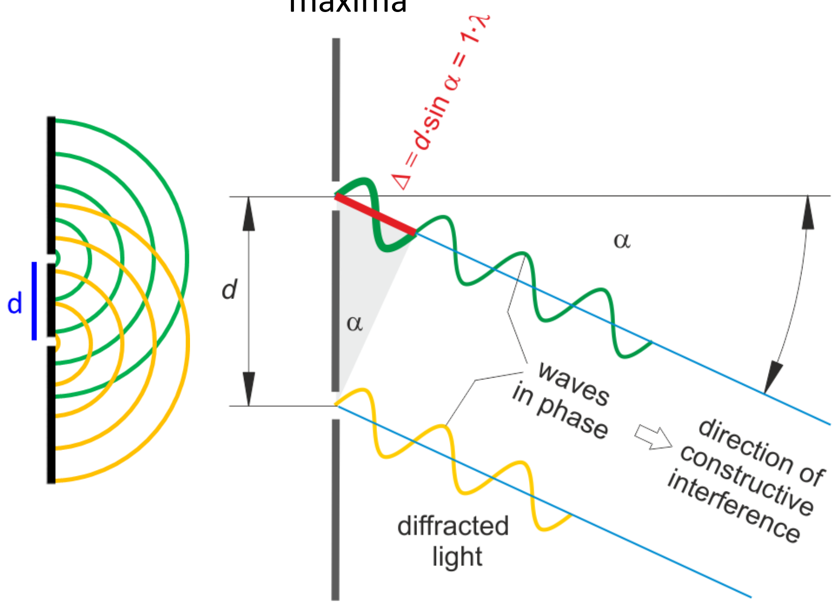
$$d \cdot \sin\alpha = k \cdot \lambda$$

where k = 0,1,2,3, ...

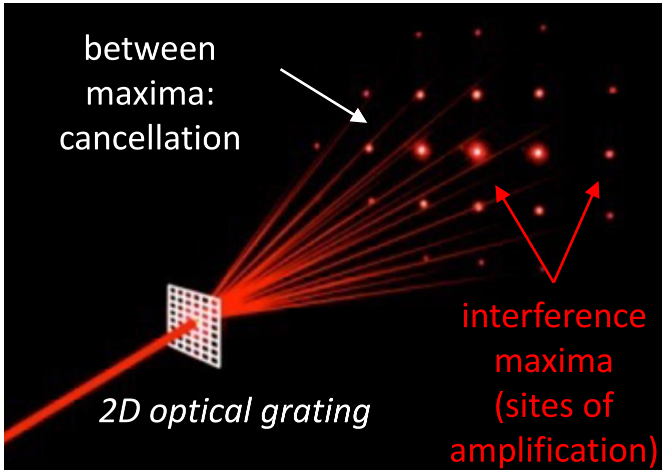
d: grating period
α: diffraction angle
λ: wavelength

d: structure **matter**

λ: wavelength **light**

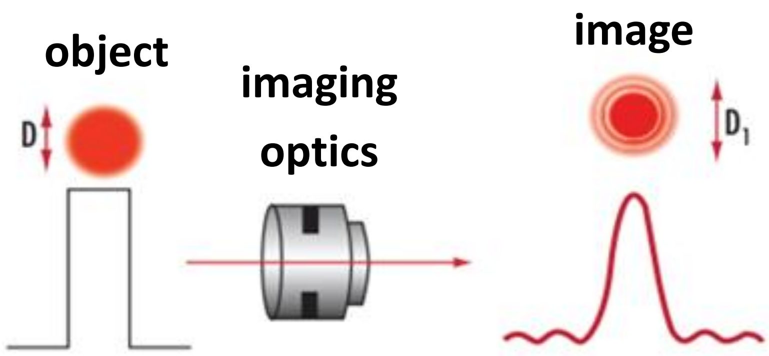


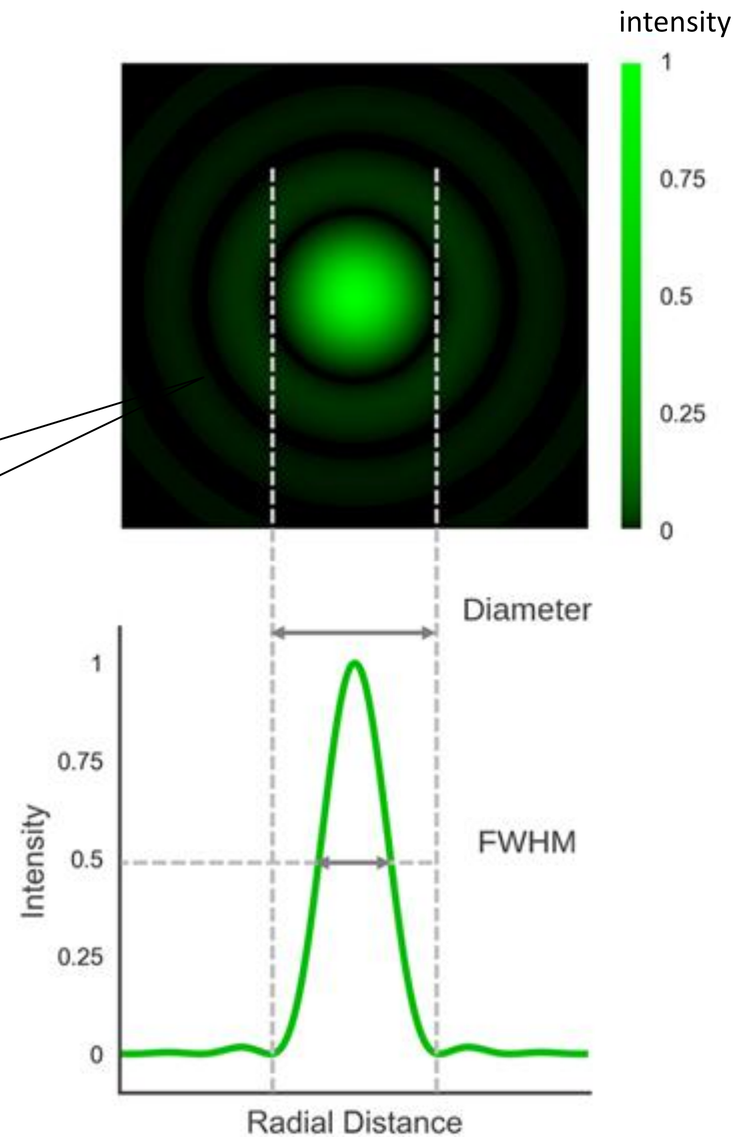
see: Microscopy II. practical exercise



Medical application: structure analysis
- light microscope
- X-ray diffraction

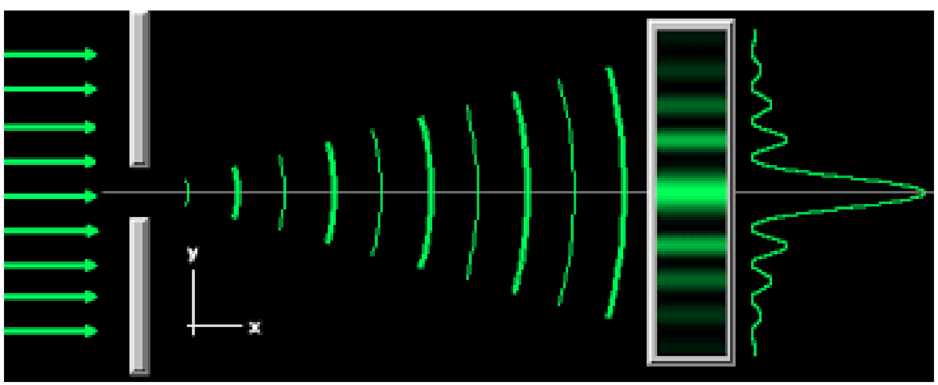
Optical imaging with light waves





Airy-disk:
central maximum, surrounded by concentric rings of decreasing intensity

Formation of Airy-disks:



Limit of resolution, resolving power

Rayleigh-limit, Abbe's formula

$$d = 0{,}61 \cdot \frac{\lambda}{n \cdot \sin(\alpha)}$$

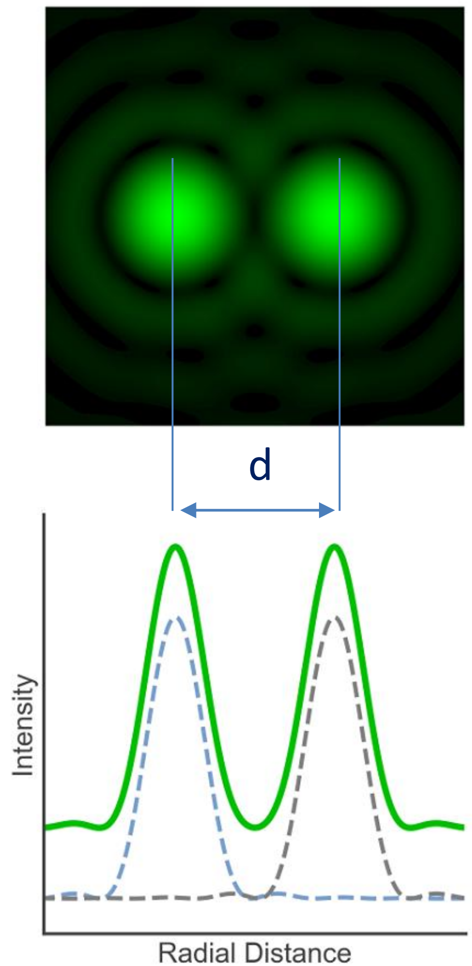
d: limit of resolution

α: diffraction angle (half-aperture angle of the objective lens)

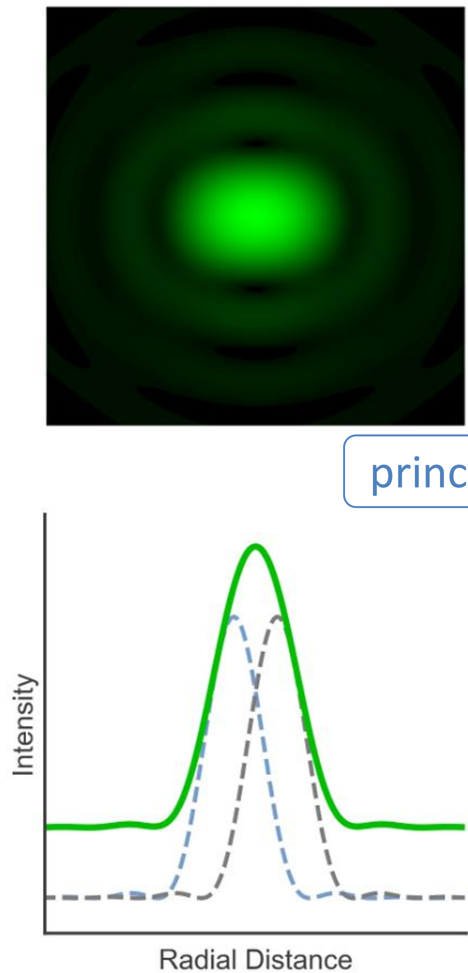
λ: wavelength

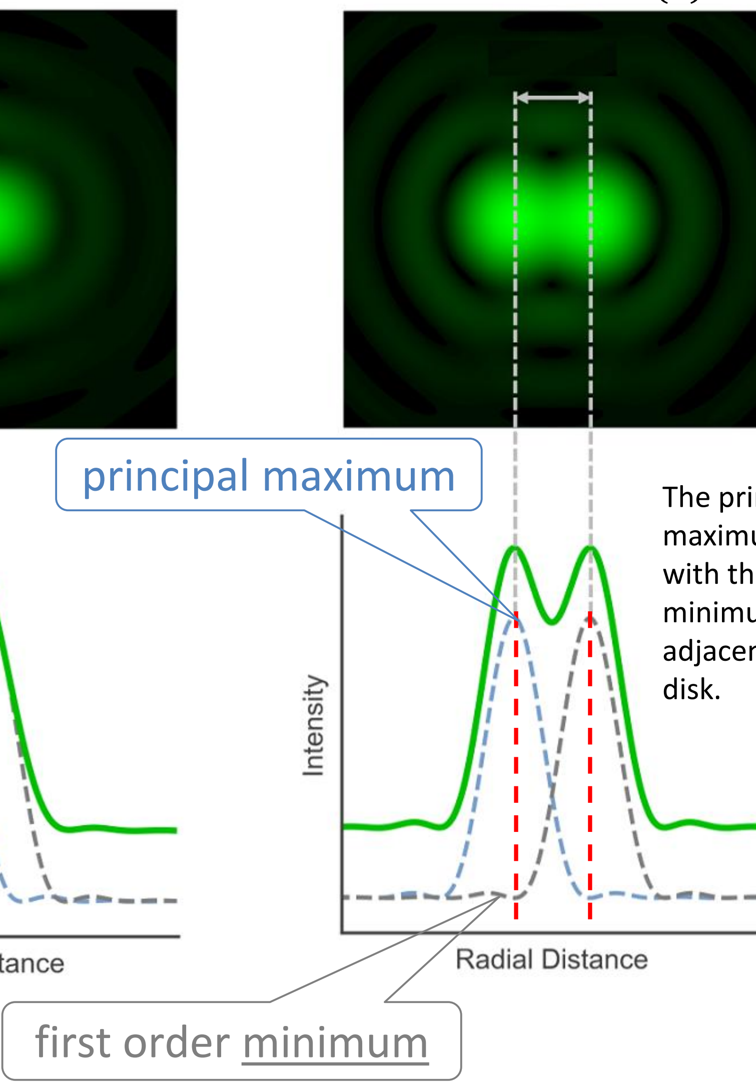
n: index of refraction of the medium

optically resolvable



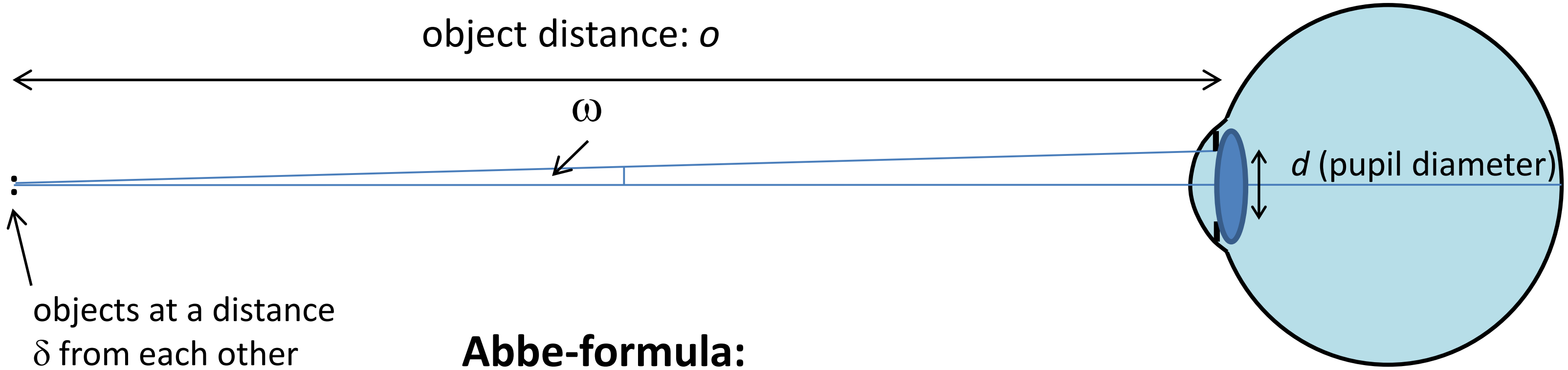
not resolvable





The principal maximum coincides with the first-order minimum of the adjacent deflection disk.

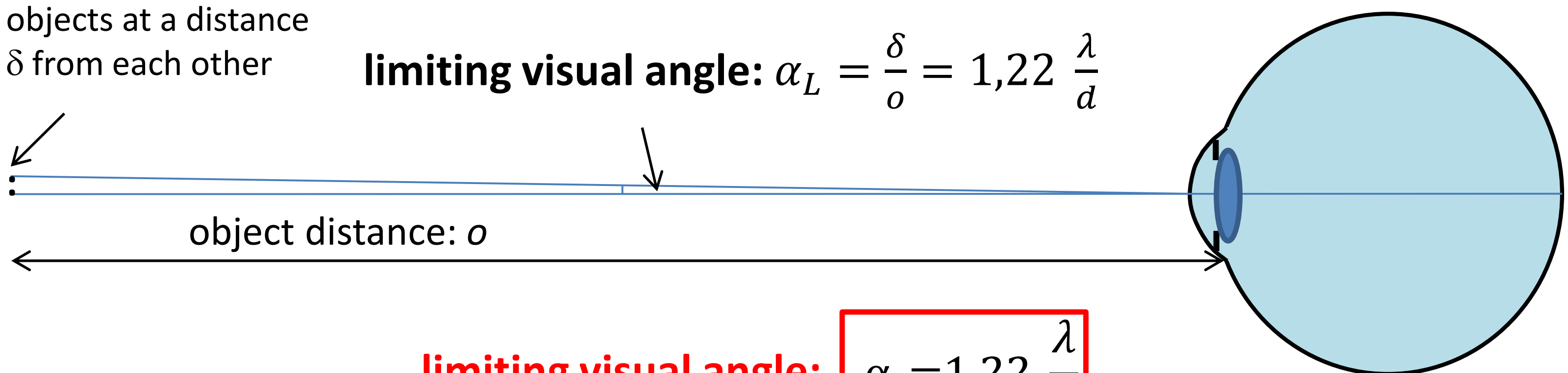
Limit of resolution of the eye I.



Abbe-formula:

$$\delta = 0{,}61\frac{\lambda}{\sin\omega} \approx 0{,}61\frac{\lambda}{\frac{d/2}{o}} = 1{,}22\frac{\lambda\cdot o}{d}$$

for small angles:
sin(x) = tan(x) = x (rad)

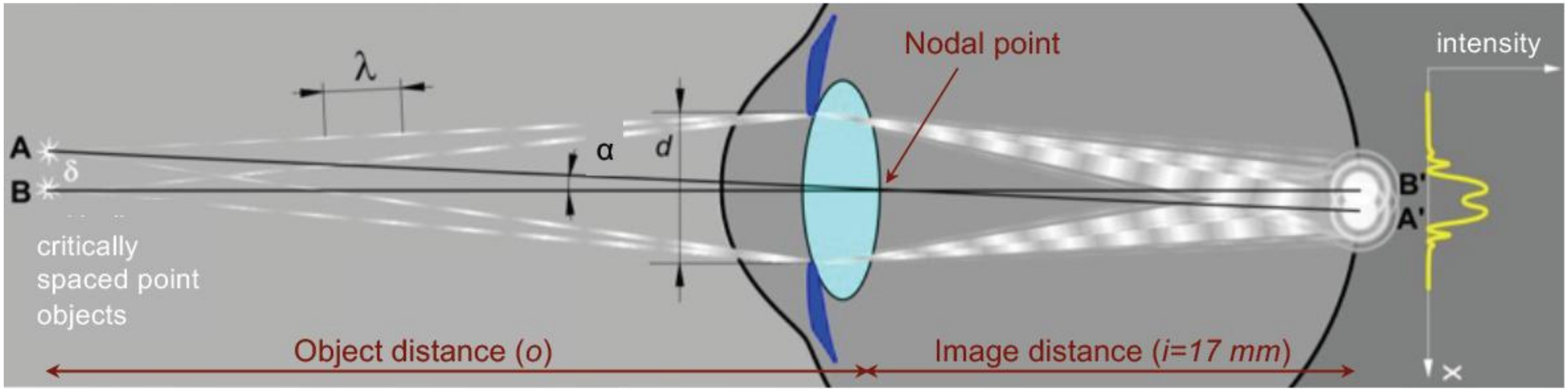


limiting visual angle: $\alpha_L = \frac{\delta}{o} = 1{,}22\,\frac{\lambda}{d}$

limiting visual angle: $\alpha_L = 1{,}22\,\frac{\lambda}{d}$

Limit of resolution of the eye II.

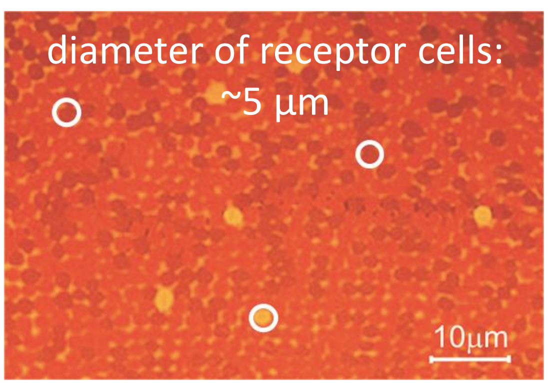
Diffraction limit of the human eye:



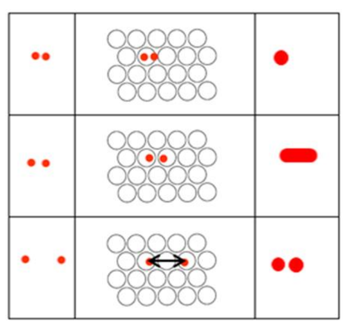
limiting visual angle: $\alpha_L = 1{,}22\ \frac{\lambda}{d}$

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

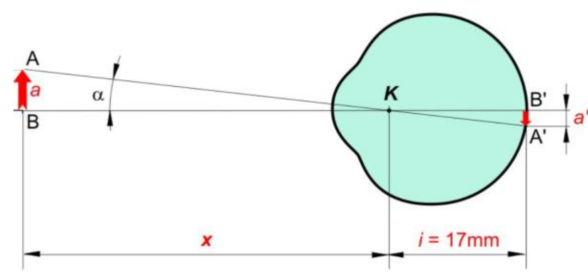
Biological limit of the resolution of the human eye: density of retinal photoreceptors.



object | image on receptors | sensed image



„reduced eye” model



Condition of resolution: at least one inactivated receptor cell falls in between two activated ones.

limiting visual angle: α=

visual acuity (VA):

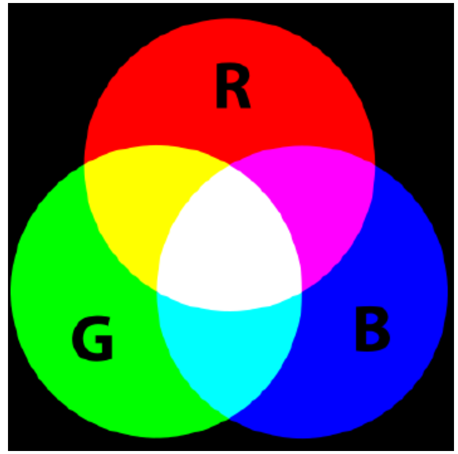
visus=1’/α (·100%)=

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.

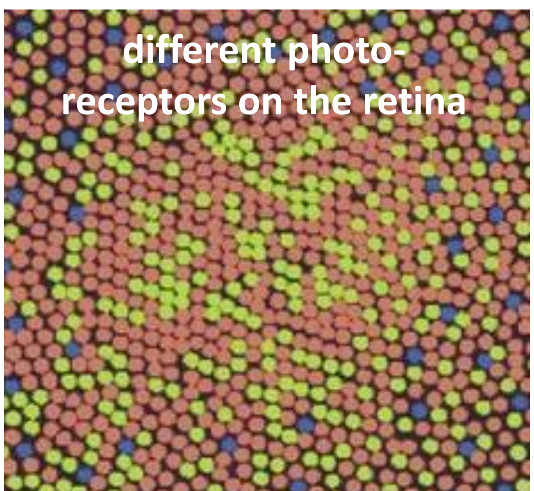
$$X = rR + gG + bB$$

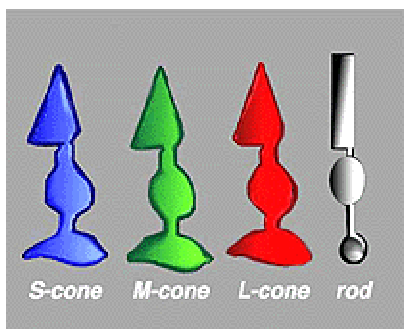


In the human eye:

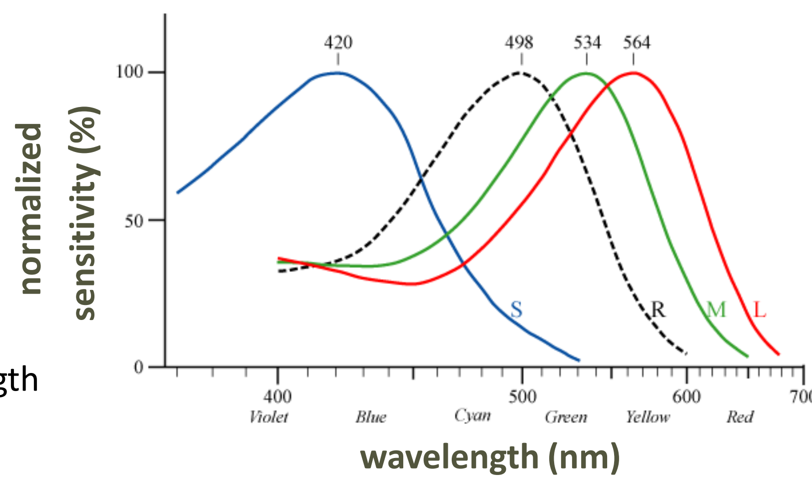
- 3 different color-sensitive photoreceptors (so-called cones).
- Each receptor absorbs in different regions of the visible light spectrum.
- Their ratio: R=64%, G=32%, B=2%.
- They perceive the intensity of light ($J \sim A^2$).

The spectral sensitivity of the human eye:

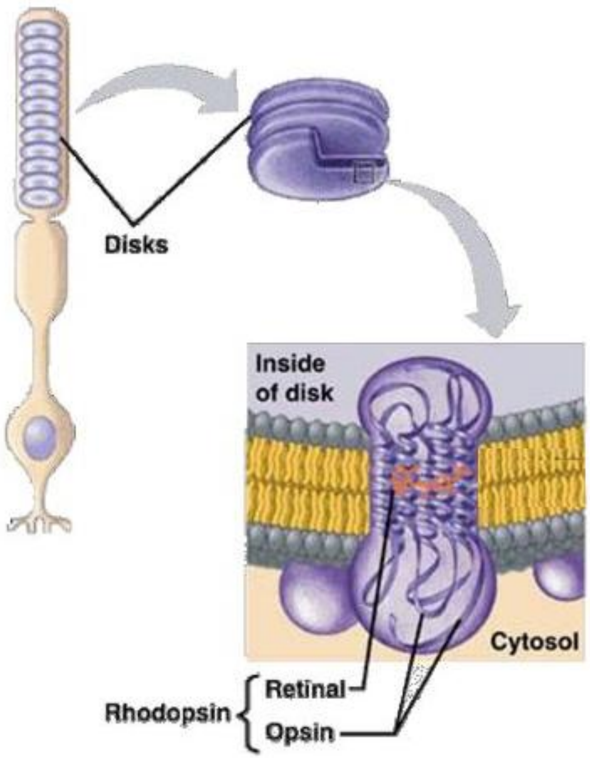




S: „short”
M: „middle”
L: „long”
} wavelength



Color blindness



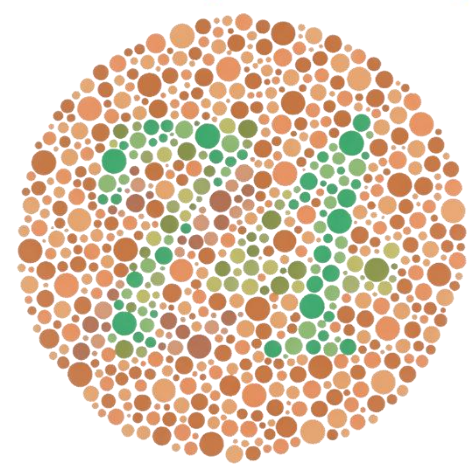
Possible causes of color blindness:

- **mutations of opsin protein**
- **changes in the structure and light absorption of rhodopsin**
- receptor cell dysfunction

normal color vision

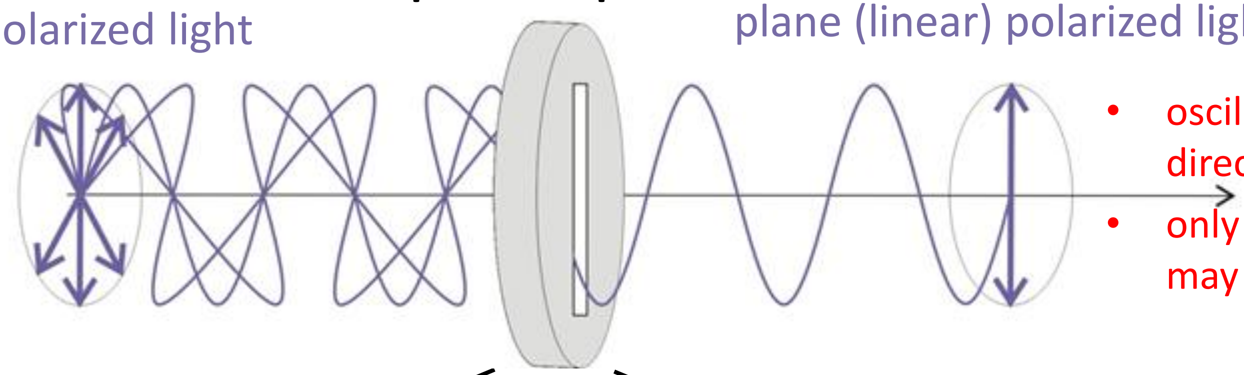
Light-sensing protein: rhodopsin

- **opsin**
- **retinal** (vitamin-A derivative)
- the cis/trans conformational change of retinal creates an ion current in the receptor cell



Ishihara test chart for screening for color blindness

Linear polarization of light

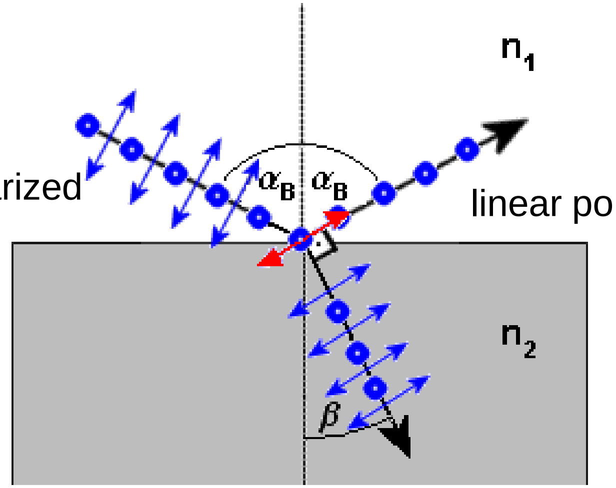


- oscillation in preferred direction
- only transverse waves may be polarized

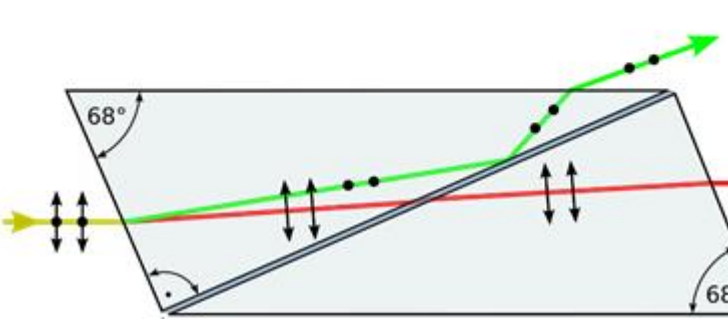
mirror (reflection)

polarizer filter (absorption)

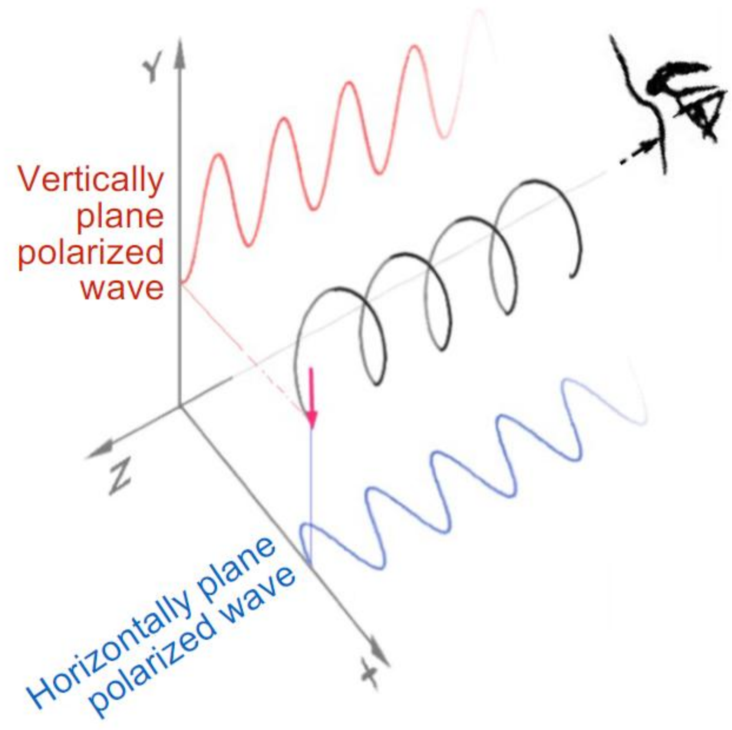
α_B = Brewster-angle: $tg(\alpha_B) = n_2/n_1$

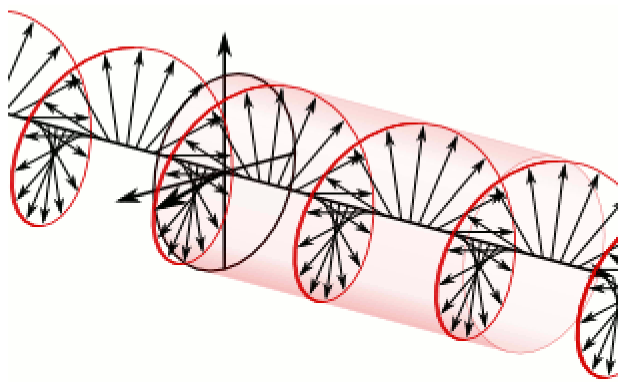


- birefringent crystals
- Nicol-prism
- polymers

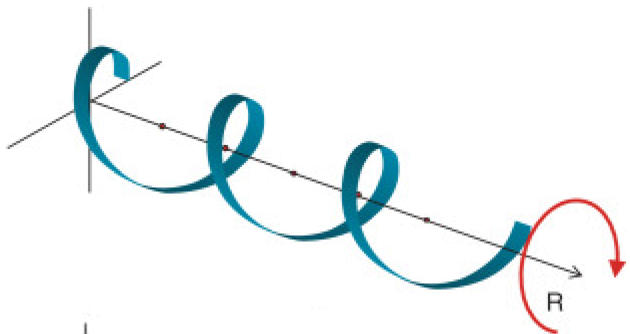


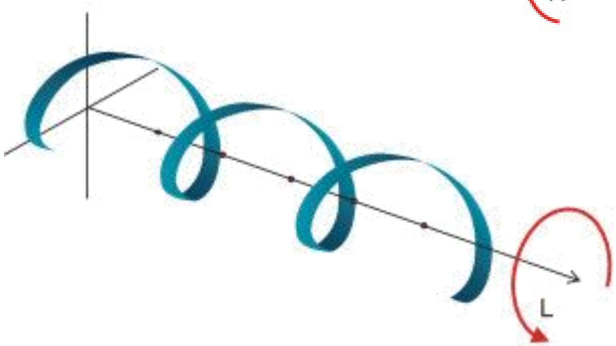
Circular polarization of light





- The electric field vector rotates in the frontal plane



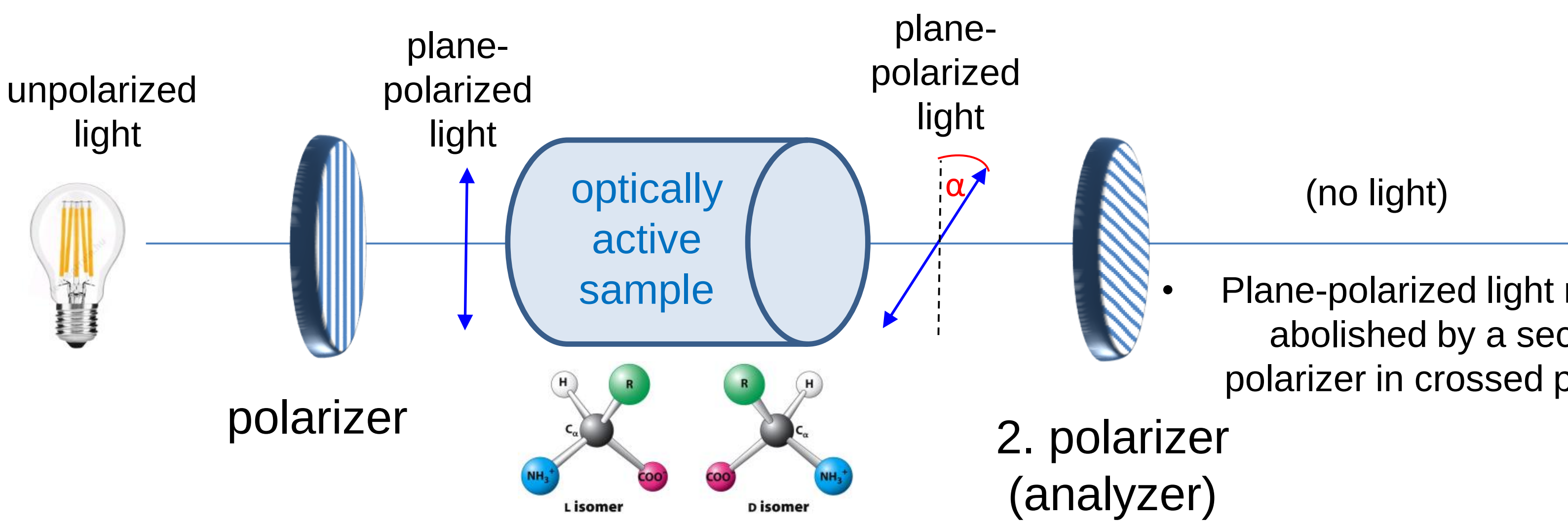


- **phase difference: +λ/4 or -λ/4**
- **Plane-polarized light: sum of right- and leftward rotating circularly polarized light**
- spatial orientation of vibration plane of light waves: NOT detectable by human eye
- state of vibration within the period (phase): NOT detectable by human eye

Polarized light in medicine

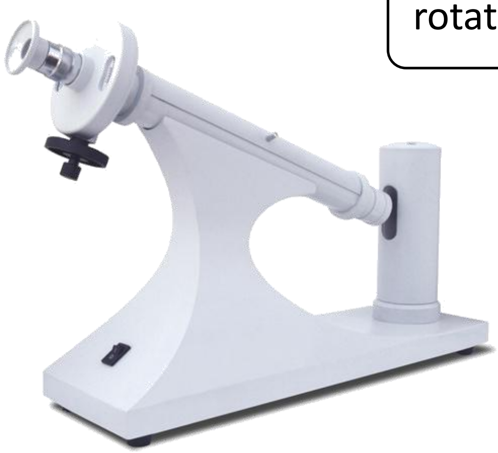
Application: **polarization microscopy** - birefringent materials in human tissues

polarimetry - measurement of concentration



- Plane-polarized light may be abolished by a second polarizer in crossed position

Biot law:



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

- α: rotation angle (°)
- c: concentration (g/cm^3)
- l: thickness of the sample (dm)
- $[\alpha]_D^{20}$: **specific rotation** ($°\cdot cm^3/(g\cdot dm)$) at 20°C and at the D-line of sodium lamp (589 nm)