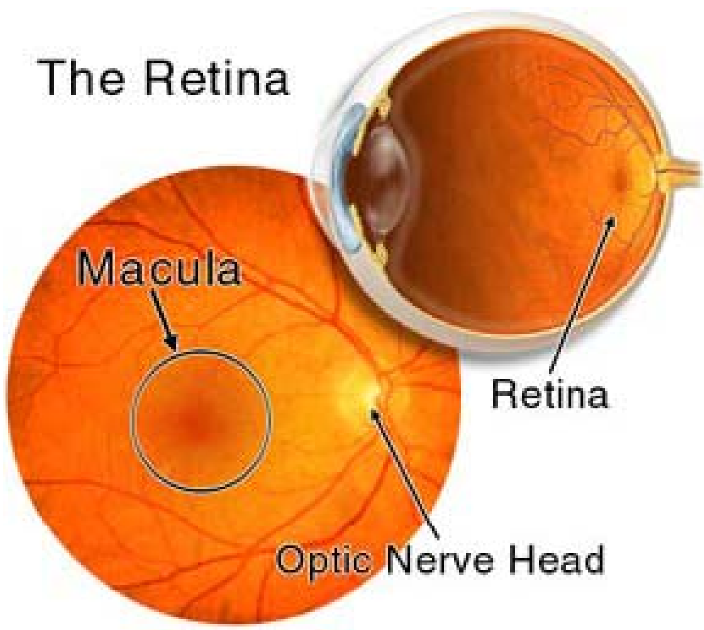
Lecture 8

Physics of Vision-part 2

L-7 Review how eye works, accommodation:

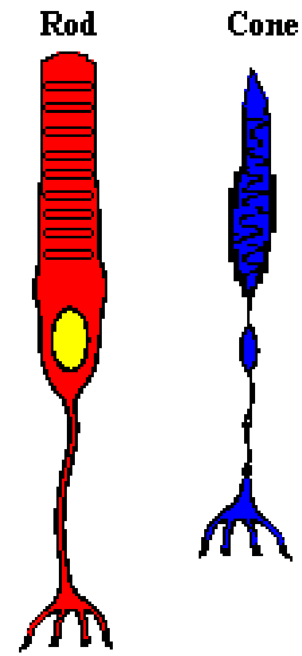
http://www.youtube.com/watch?v=EF5CnemVJQM&feature=related

Retina and photoreceptors



Photoreceptors capture light and convert it into electrical impulses. These impulses travel along the optic nerve to the brain where they are turned into images.

Photoreceptors in the retina: rods and cones.



The retina is a multi-layered sensory tissue that lines the back of the eye. It contains millions of photoreceptors

6 million cones - in macula, responsible for central vision. Cones best function - bright light - color. They are most densely packed within the fovea, the very center portion of the macula.

125 million rods, in peripheral retina - function best in dim lighting, responsible for peripheral and night vision.

Blind spot

- Cones are concentrated in fovea
- Rods are distributed around
- The area around optical nerve does not have any receptors- it is called blind spot
- Therefore any image that falls on this region will NOT be seen. It is in this region that the optic nerves come together and exit the eye on their way to the brain.

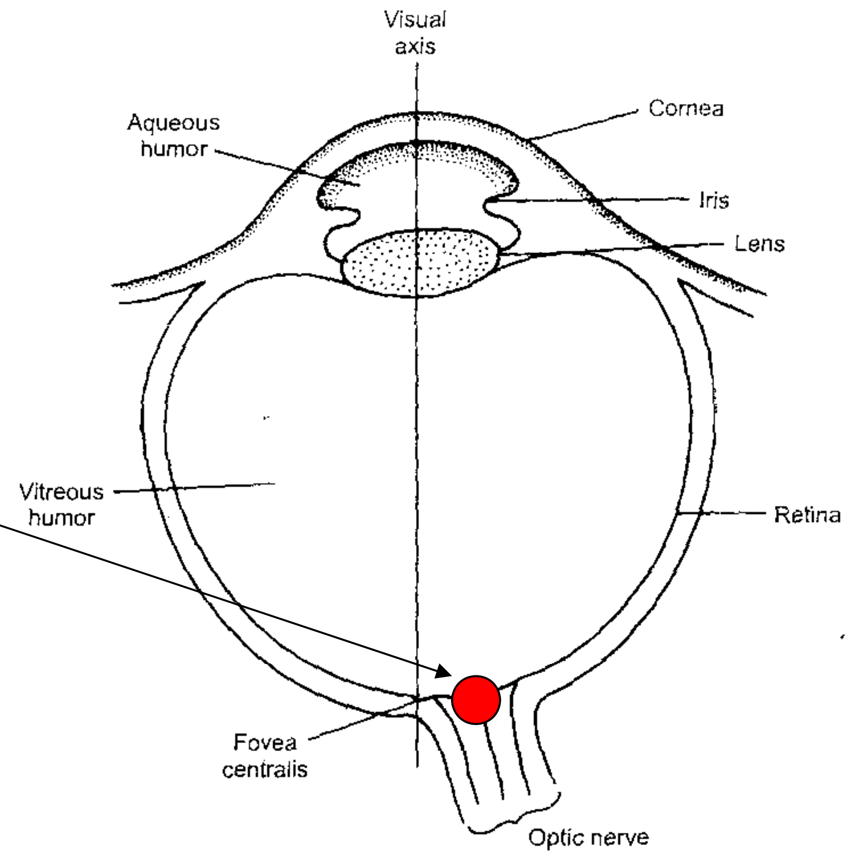
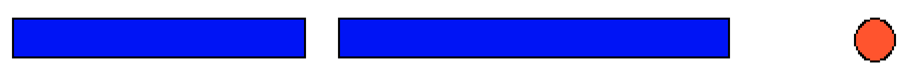


Fig. 5.1 The human eye.

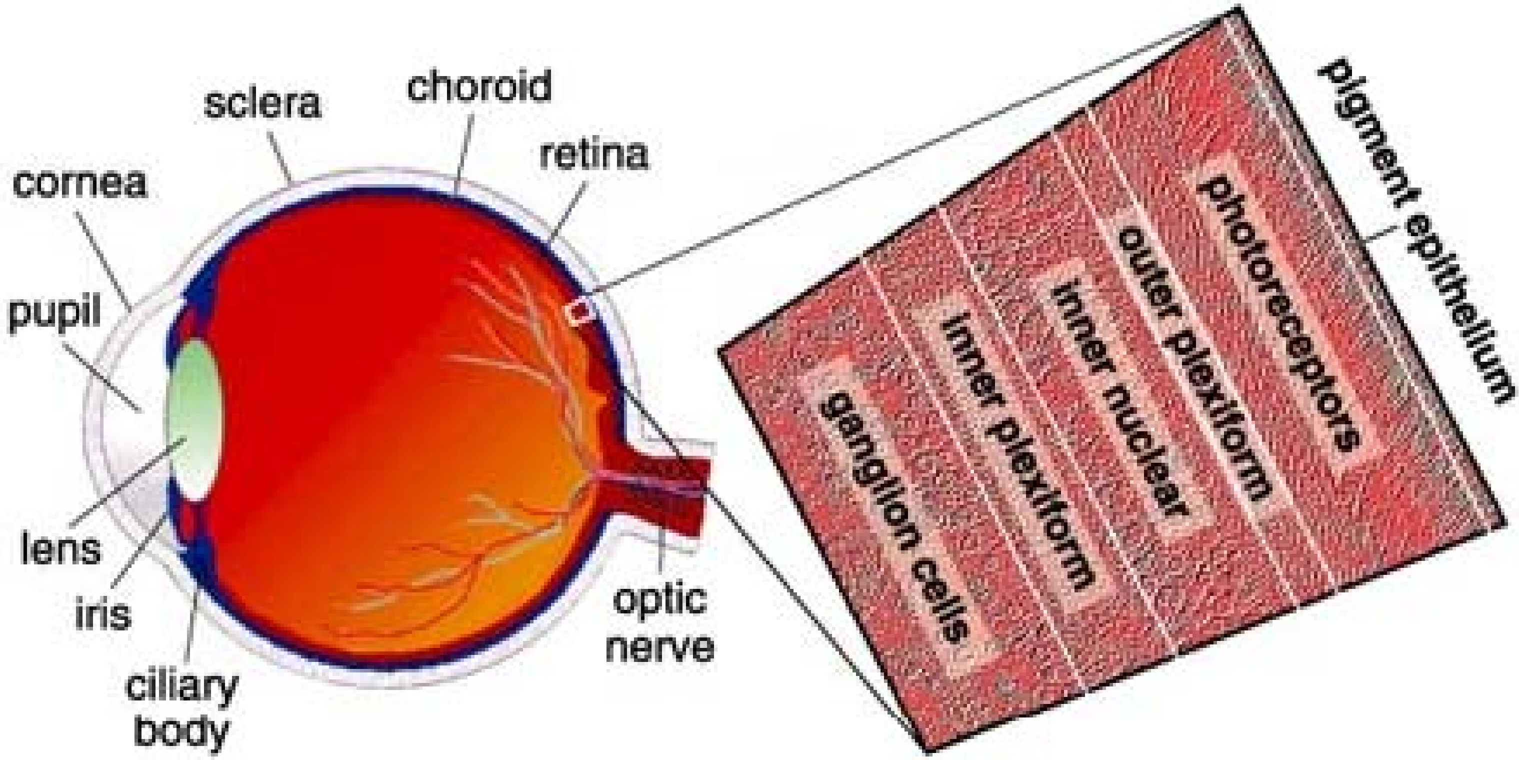
- To demonstrate the blind spot, look at the image below or draw it on a piece of paper:

- Hold the image (or place your head from the computer monitor) about 20 inches away. Close your left eye, with your right eye, look at the dot. Slowly bring the image (or move your head) closer while looking at the dot. At a certain distance, the + will disappear from sight...this is when the + falls on the blind spot of your retina. Reverse the process. Close your right eye and look at the + with your left eye. Move the image slowly closer to you and the dot should disappear.

- Another example: For this image, close your right eye. With your left eye, look at the red circle. Slowly move your head closer to the image. At a certain distance, the blue line will not look broken!!

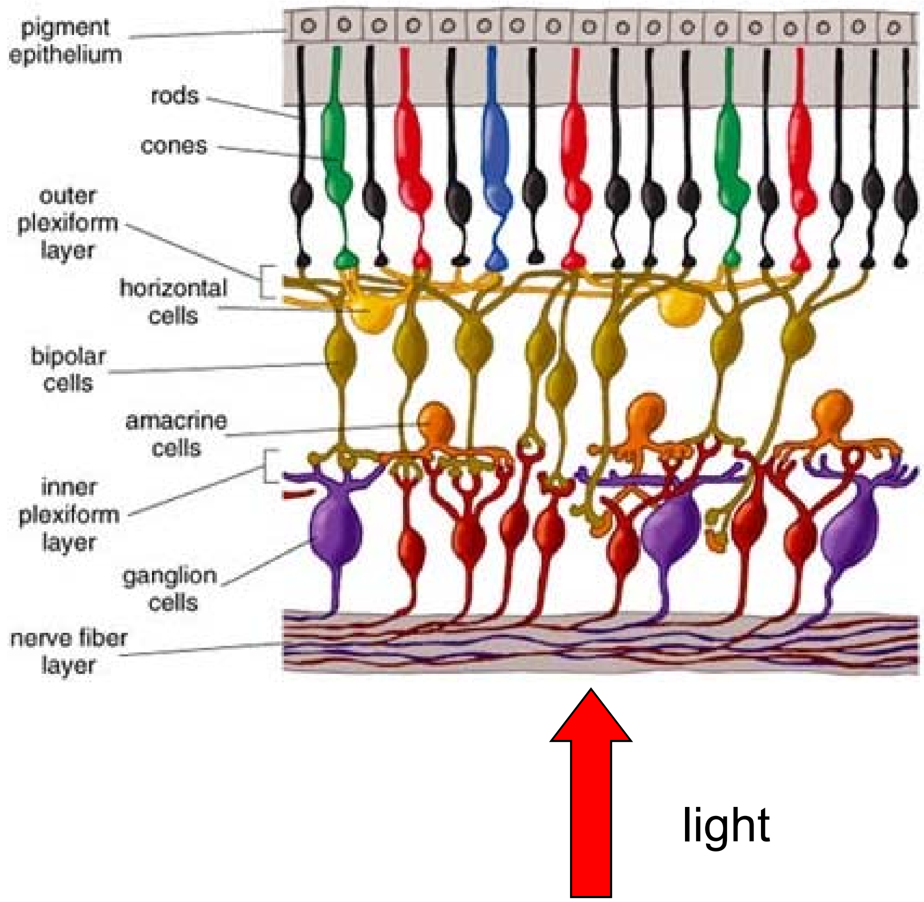


Structure of eye retina



fovea 0.1 mm thick

Retina 0.2 mm



- Cells in the retina are arrayed in discrete layers.
- The photoreceptors are close to the pigment epithelium, pointing away from the light source.
- pigment epithelium – dark cells, absorb light
- The bodies of horizontal cells, bipolar cells, amacrine cells, ganglion cells are almost transparent but not uniformly transparent
- Light has to come through thick layer of cells to reach the photoreceptors
- This degrades image

- Eye is "poorly designed device, which functions brilliantly"

Hallett – book

Rods and cones: http://www.youtube.com/watch?v=Lcv8g-0VdMI&feature=related

photoreceptors

- Contain pigments – “photon–sensitive molecules”, which are excited and initiate a chain of molecular reactions to amplify the input signal (million times amplification)

- Photoreceptors respond only to light stimulus with certain energy

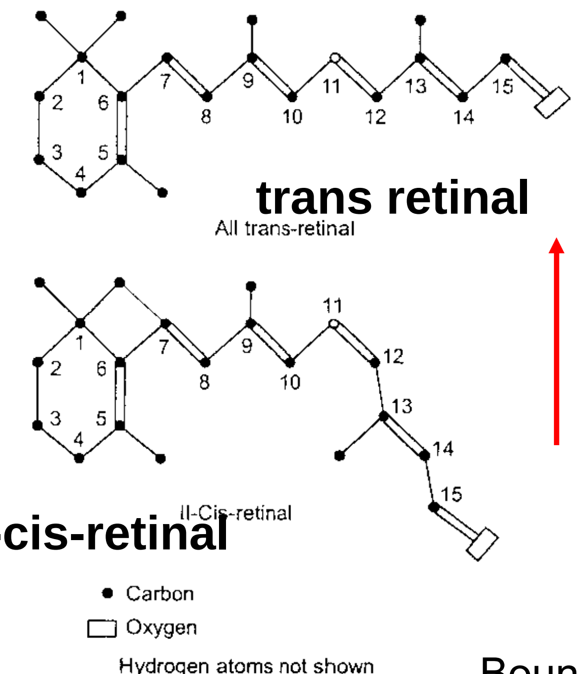
- Min energy to excite pigment molecules $4x10^{-19}$ J ~ wave length 600 nm,
- longer wavelength (infra-red) are not visible.
- UV light is absorbed by the transparent tissues of eye before it reaches the retina

Photochemistry of receptor cells

- Light sensitive pigment in rods – Rhodopsin- trans-membrane protein, light sensitive part – retinal:

When light enters the eye, it comes in contact with photosensitive rhodopsin (mixture of **scotopsin** and **11-cis-retinal**)

when exposed to light **11-cis-retinal** changes to **trans retinal** (a few trillionths of a second), and unbinds from scotopsin



Free of scotopsin

trans retinal

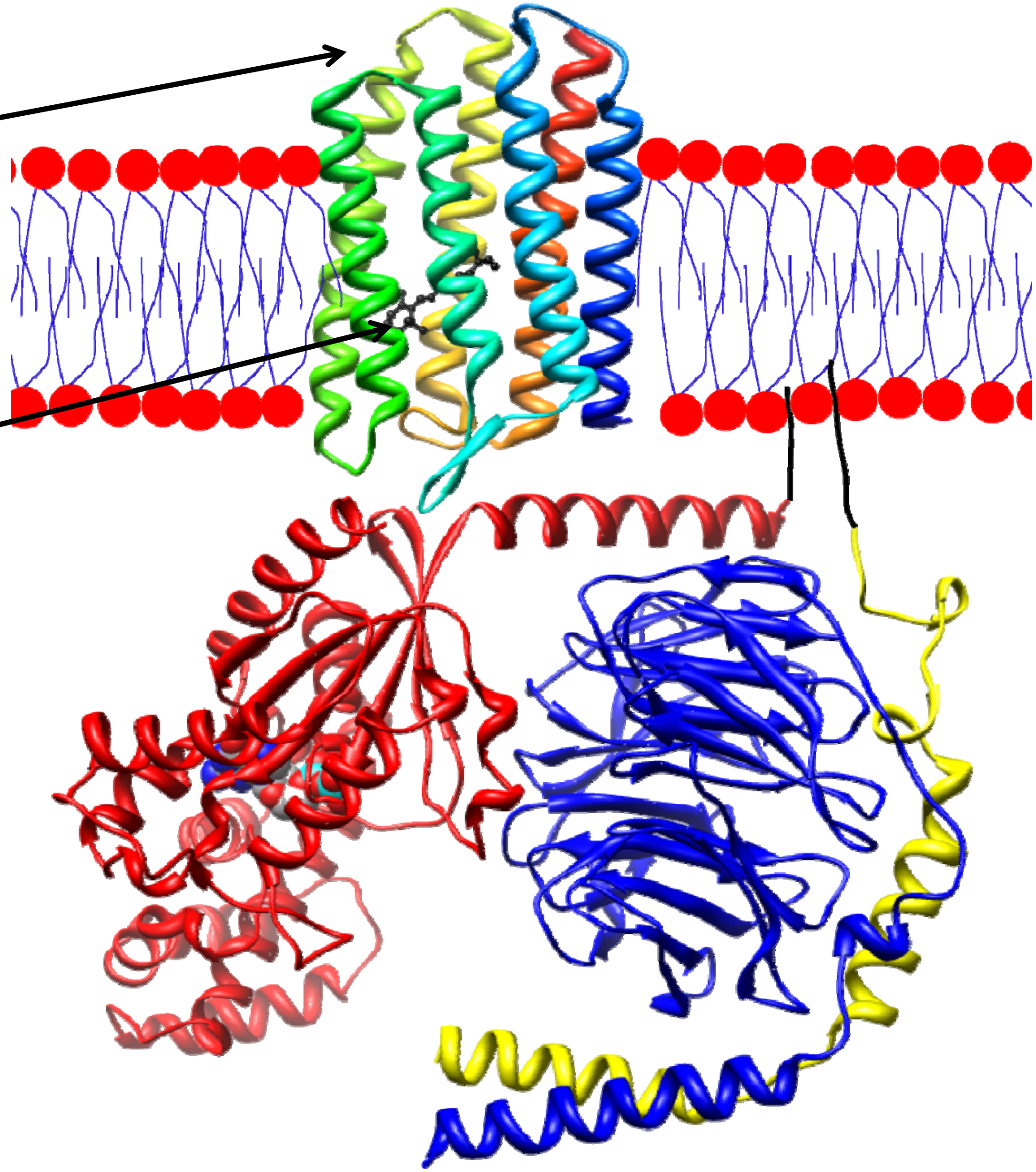
light

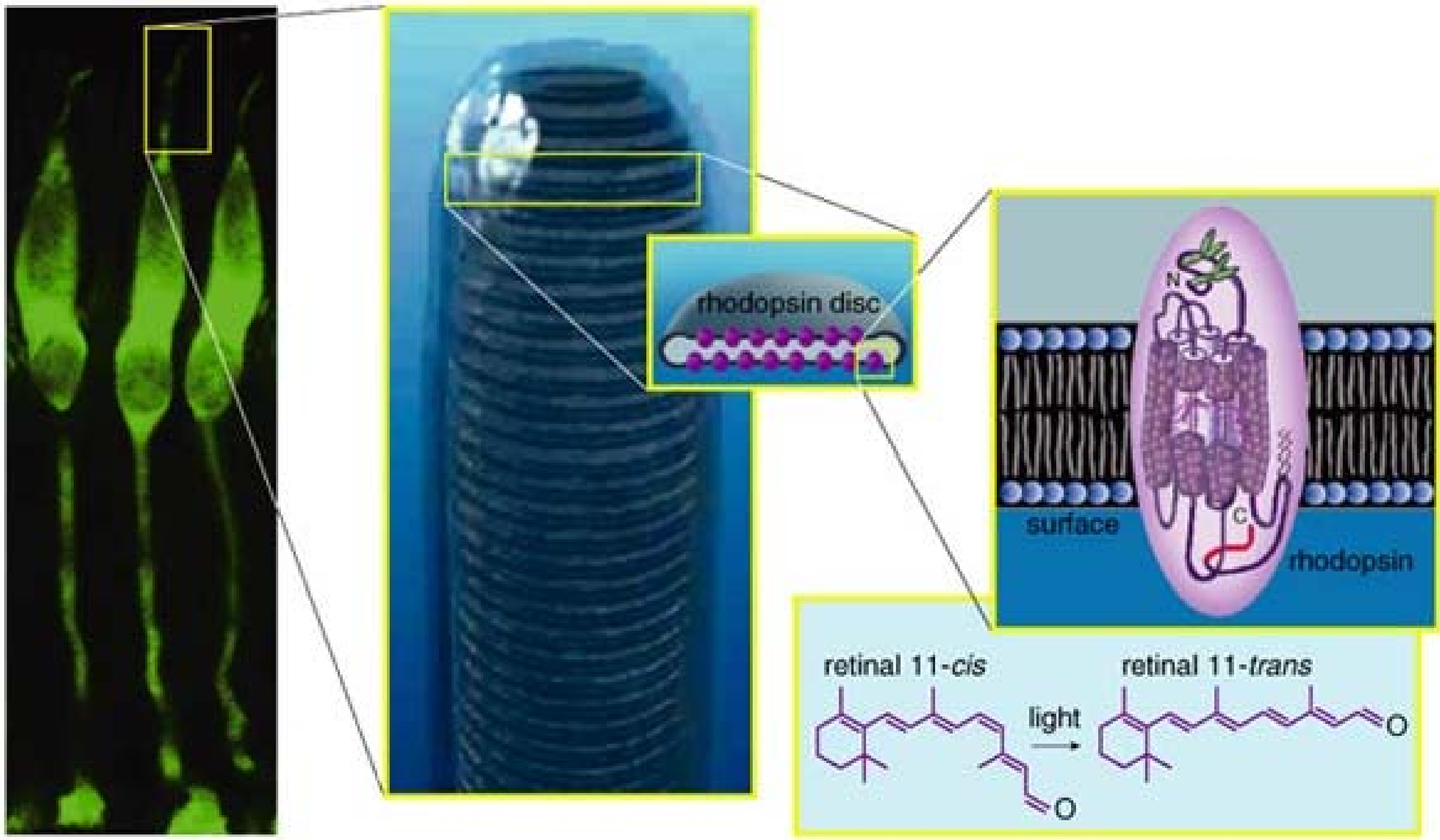
11-cis-retinal

Bound to scotopsin

Rhodopsin and retinal structure

Type 2 rhodopsin (rainbow colored) embedded in a lipid bilayer (heads red and tails blue) with transducin below it. There is a bound **retinal** (black) in the rhodopsin. The N-terminus of rhodopsin is red and the C-terminus blue. Anchoring of transducin to the membrane has been drawn in black.





Cone photoreceptors from a monkey are stained with a fluorescent green dye (*left*). When the outer segments of cones or rods are magnified further, stacked membrane disks are visible inside (*middle*). The disks are studded with thousands of rhodopsin complexes. Each rhodopsin consists of a membrane-traversing protein with a retinal molecule embedded in its core (*right*). When exposed to light, one of the bonds in the retinal molecule rotates, changing the shape of the protein (*lower right*).

Intensity sensitivity

- photochemistry in rods and cones :

- Excitation in rods involves
  scotopsin - scotopic vision
  resolves dark and light
- very sensitive – one photon 600 nm gets picked up by one molecule in one rod cell and activates the 100 % efficiency of the cell
- When sensitivity is high rhodopsin molecules decompose – bleach (purple to yellow)
- At near complete bleaching – rods are nonfunctional – vision by cones
- 120 million rods in each eye
- 10^{17} molecules of rhodopsin

- Excitation in cones involves
- photopsin - photopic vision
- Produce Image in colors
- Works better when light intensity is high
- 6.5 million of cones
- at the center of retina

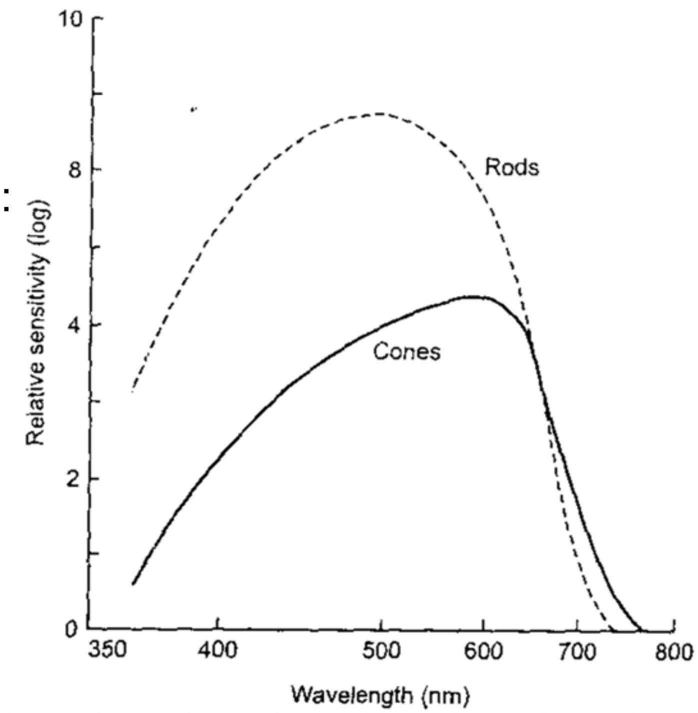
- when light intensity decreases cones adapt rapidly in 5 min, rods adapt to dark in 30-60 min

Spectral sensitivity

- Rhodopsin (rods) is sensitive:
- 380-650 nm wave length
- Max sensitivity at 505 (blue-green)

- Cones: red, green and blue, they contain pigments:
- **Erythrolab** 430-720 (max at 570 red)
- **Chlorolab** 400-630 (max at 535 green)
- **Cyanolab** 380-530 (max at 445 blue-violet)
- when activated in different proportions –
- combined produce different color sensation
- Not very sensitive – require bright light

$$I_R + I_G + I_B = I$$ - stimulations of different cones



- Stimulation of orange color is produced by combination - I_R=0.66, I_G=0.34, I_B=0
- Tri-color vision theory – Thomas Young, and later Helmholtz

- In light condition sensitivity of eye is max at 555nm (cones), in the dark at 505(rods), this shift of sensitivity – Purkinie shift

* Probability to activate receptor cell

- Mean number of photon striking the cell - μ
- Minimum number of photons required to activate the cell - n

- Probability that minimum number n of photos required to activate the cell reaches the cell is calculated using Poisson's distribution:

Considering that retina is evenly occupied by receptors, P is a probability that in random distribution, n photons will reach a receptor

$$P(n) = \frac{\mu^n}{n!} e^{-\mu}$$

- Response function R of the eye varies with illumination, Weber-Fechner relation:

$$R = a \cdot \log I$$

$$R = a \frac{I}{b + cI}$$

a, b, c - constants

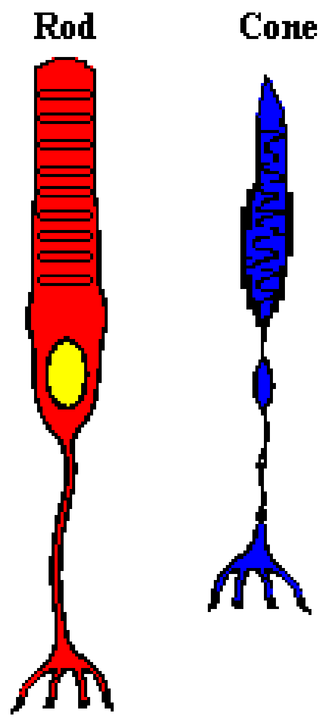
Photoreceptors and fiber optics

- Net impulse of light on eye defined by probability of absorption, which is
- defined by orientation form and size of photoreceptor

- Rods and cones are long and thin structures
- Photoreceptor molecules are packed inside
- in shape of long and thin cylinders

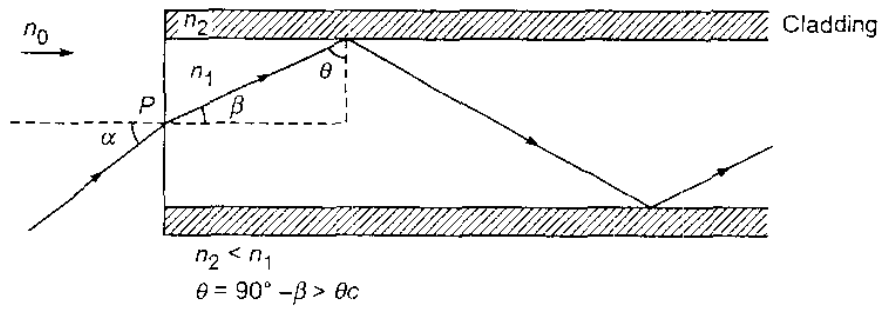
- light travels through these structure

- similar to propagation of light through optic fiber



Fiber optics

- Optic fiber or wave guide is a transparent core of refractive index n_1 surrounded by medium of lower index n_2 , ($n_2 < n_1$)
- Most of the light travels inside,
- trapped by total internal reflection and absorbs



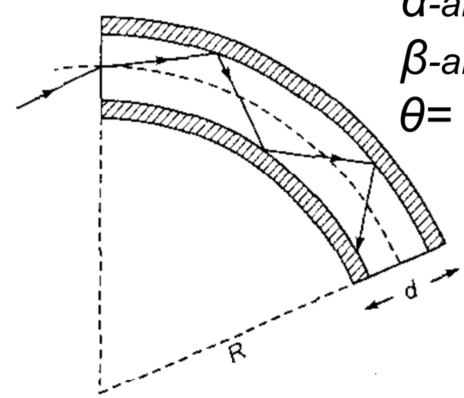
(a)

α-angle of incidence

β-angle of refraction

θ= 90°- β

$$\frac{\sin\alpha}{\sin\beta} = \frac{n_1}{n_0}$$



curved fiber,

(b) works when d < R

Total internal reflection requires θ>θ$_c$ $\longrightarrow$ $\sin\theta_c = \dfrac{n_2}{n_1}$

Limiting case *θ=θc*

$$\sin\theta_c = \sin(90^\circ - \beta) = \cos\beta = \frac{n_2}{n_1}$$

$$n_0 \sin\alpha_c = n_1 \sin\beta = \sqrt{\left(n_1^2 - n_2^2\right)}$$

critical angle of incidence

light with $\alpha < \alpha_c$ is trapped

- Photoreceptors work as optical fibers,
- n inside is higher than surrounding medium
- absorption of light depends on the length of photoreceptor waveguide
- diameter of photoreceptor cell determines probability of focusing light on cell, above critical d probability is high (600nm).
- in cones cross-section is not uniform – light penetrates to a certain length L and then escapes:
-

$$L = \frac{d}{\phi}\left(1 - \frac{\sin\alpha}{\sqrt{\left(n^2 - 1\right)}}\right)$$

$$n = \frac{n_1}{n_2}$$

refractive index of fiber with respect to medium

diameter/angle of cone - measure of length - determines absorption
Thus absorption depends on length of cones or rods

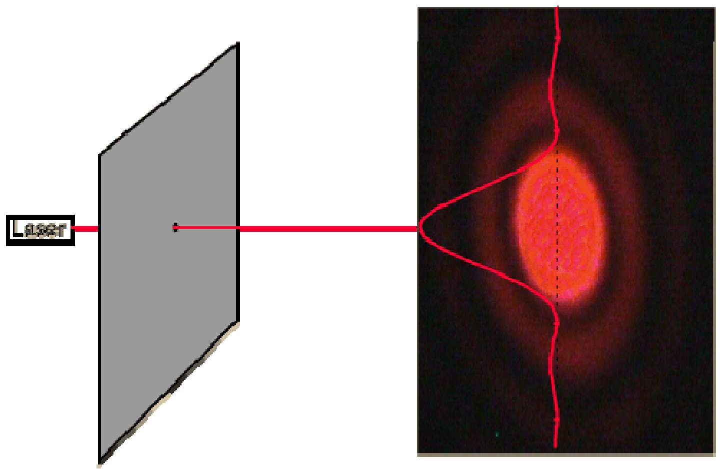
Resolving power of eye

- Resolving power of eye - ability of eye to distinguish distant point objects with small separation – visual acuity.
- It is defined by:

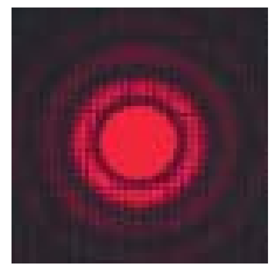
- 1. spatial distribution of receptors and their diameter
- resolution is better if photoreceptors are separated

- 2. focus by eye-lens
- 3. diffraction by the pupil – it is a small aperture, light diffracted by pupil is not focused by eye-lens, but spread

Diffraction



Diffraction is bending of light at the obstacles



Circular Aperture Diffraction

When light from a point source passes through a small circular aperture, it does not produce a bright dot as an image, but rather a diffuse circular disc known as Airy's disc surrounded by much fainter concentric circular rings.

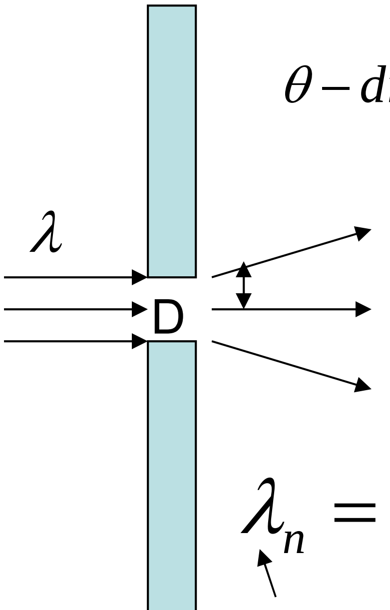
The eye and many optical instruments have circular apertures. If this smearing of the image of the point source is larger that that produced by the aberrations of the system, the imaging process is said to be diffraction-limited, -resolution is limited by diffraction.

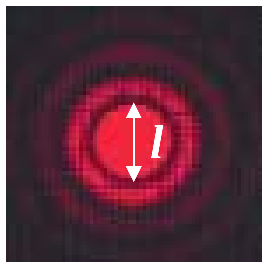
This limitation on the resolution of images is quantified in terms of the Rayleigh criterion so that the limiting resolution of a system can be calculated.

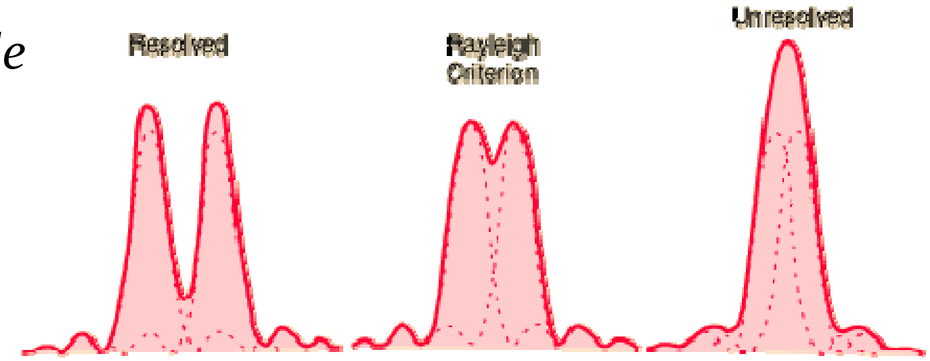
The Rayleigh Criterion

When the central maxima from two distinct objects fall separately on retina - the objects can be resolved, if they overlap – the objects are unresolved

$$\theta - diffraction\_angle$$







$$\lambda_n = \lambda / n$$

λ_n – in medium after diffraction

λ – in air before diffraction

$$\theta = 1.22 \frac{\lambda_n}{D}$$

2θ -angular width of central max

l - diameter of central bright spot

f - focal length of lens

D - diameter of aperture

n – refractive index of medium

diameter of central bright spot

$$l = f(2\theta) = 2.44 \frac{\lambda}{D} \cdot \frac{f}{n}$$

For reduced eye-lens model

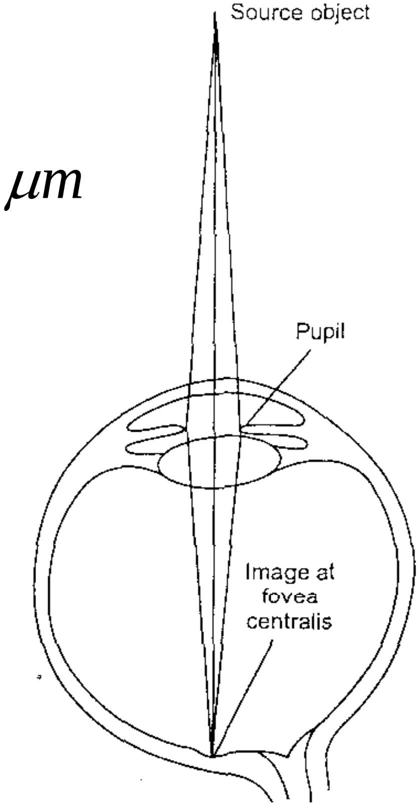
$$l = 2.44 \times \frac{22mm}{1.3 \times 4mm} \times 550nm \approx 5.7\mu m$$

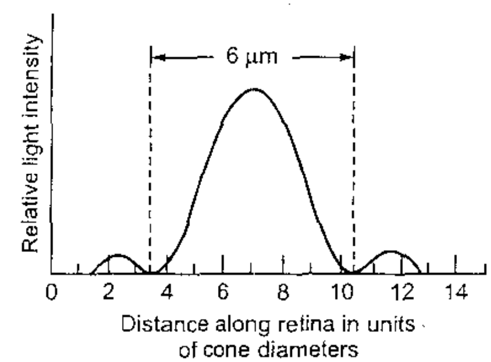
$f = 22mm$ - *focal length of eye-lens*

$n = 1.3$ - *refractive index of medium*

$D = 4mm$ - *diameter of pupil*

$\lambda = 550nm$ -*light absorbed by eye*





Diameters of rods and cones – 1-2 μm, there are many of them within the spot of central maximum. The more densely they are packed – the better resolution

Polarization and vision

- Some substances are optically anisotropic – their interaction with light depends on polarization

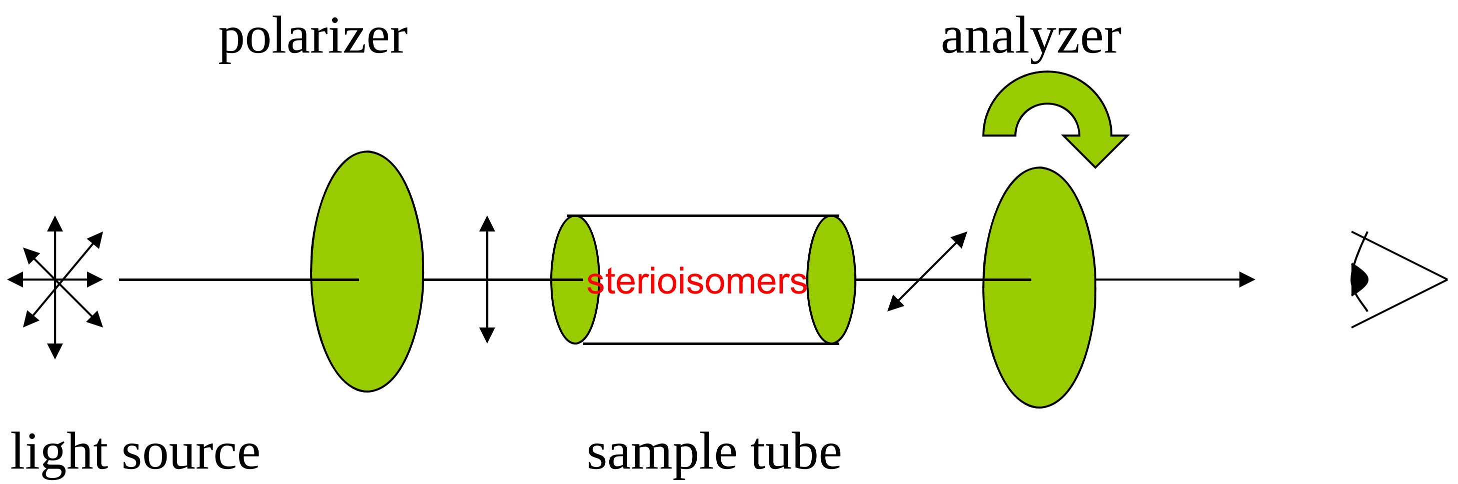
- if refractive index may be different depending on the polarization as it is observed in birefringent substances

- The ability to sense light polarization by substances is called dichroism.

- Examples of substances sensitive to polarization: rhodopsin, photoreceptors in insects, shell fish, crabs, lipid membrane

Optical activity – when a substance rotates the plane of plane-polarized light. (1815 by Biot)

arises when light interacts with **sterioisomers**



If plane of polarization rotates clockwise - the substance is dextro-rotatory
anti - clockwise - the substance is levo-rotatory

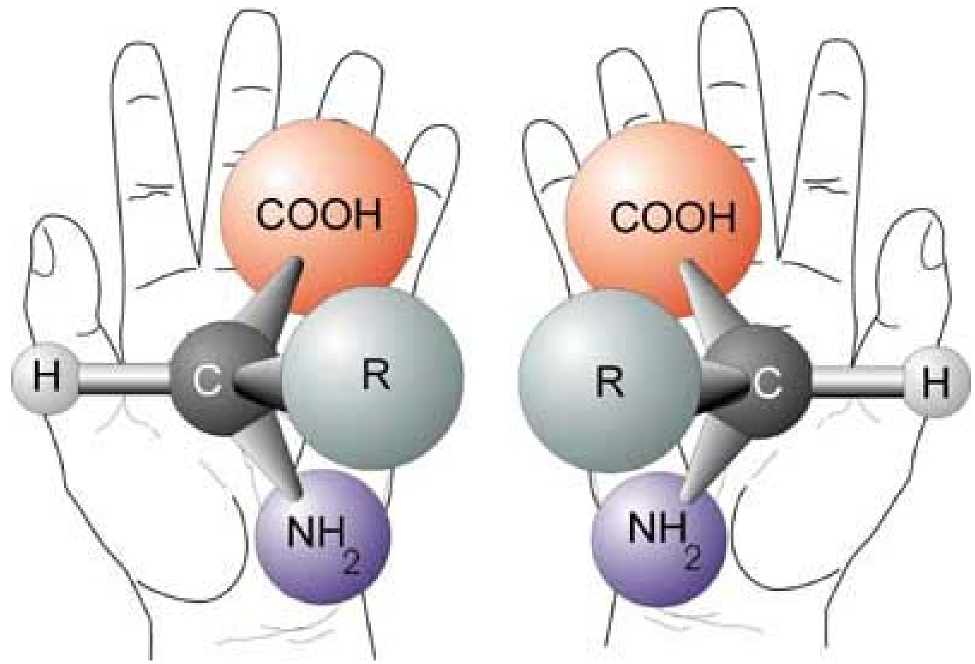
Dichroism- absorption depends on polarization of light and orientation of molecules in optically anisotropic medium

What are sterioisomers?

- Immanuel Kant, 1783,
- “The glove of one hand cannot be used on the other”

The substances which mirror image cannot be superimposed with real image

DNA (right-handed, left handed), sugars, proteins, Crystalline- quartz



(S) “sinister” LEFT

(R) “rectus” RIGHT

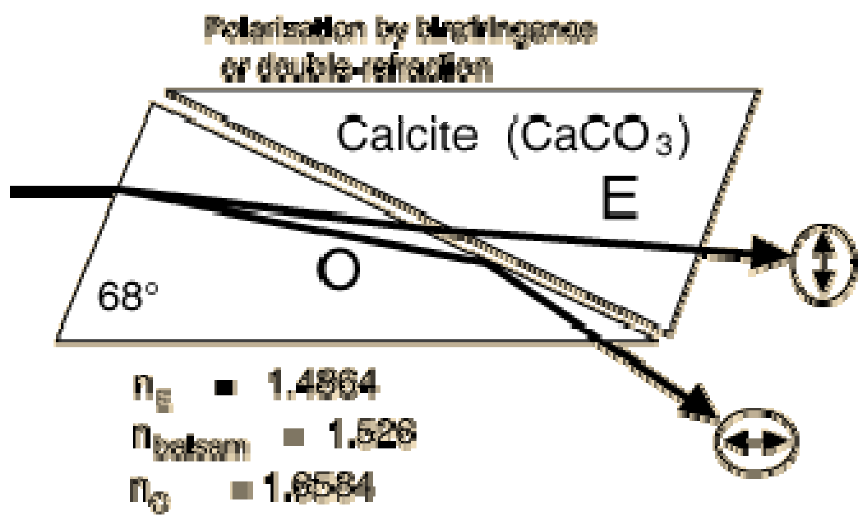
birefringence

Light polarized in perpendicular planes exhibits different refractive indices in some crystals, this property is called birefringence

In such optically anisotropic crystals molecules are oriented in preferential direction, ex. quartz ,

Such crystals absorb more light in one incident plane than another, so that light progressing through the material become more and more polarized as they proceed.

http://www.youtube.com/watch?v=y4pknNBvEeE



Polarization of light can be achieved with birefringence materials, which have a different index of refraction in different crystal planes. The Nicol prism is made up from two prisms of Calcite cemented with Canada balsam.