SZEGEDI TUDOMÁNYEGYETEM
UNIVERSITAS SCIENTIARUM SZEGEDIENSIS

Medical Physics I.

Biophysics of the senses: vision

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Szeged, December 3, 2015.

Basic properties of light

Visible electromagnetic radiation:

λ = 380 – 760 nm

shorter wavelength – **Ultraviolet light (UV)**

longer wavelength – **Infrared light (IR)**

Visible light – (VIS)

Medium in which the light propagates is called **optical medium.**

In homogeneous media, light propagates in straight lines perpendicular to wave fronts, this lines are called **light rays.**

Speed (velocity) **of light** (in vacuum)

$c = 299\,792\,458\ ms^{-1}$ approx. $= 300\,000\,000\ ms^{-1}$

Polychromatic and Monochromatic Light, Coherence

- **Polychromatic or white light**

  consists of light of a variety of wavelengths.
- **Monochromatic light**

  consists of light of a single wavelength

According to phase character light can be

- **Coherent -** Coherent light are light waves "in phase“ one another, i.e. they have the same phase in the same distance from the source. Light produced by lasers is coherent light.
- **Incoherent -** Incoherent light are light waves that are not "in phase“ one another.

  Light from light bulbs or the sun is incoherent light.

Reflection and refraction of light

Reflection - Law of reflection: The angle of reflection α' equals to the angle of incidence α. The ray reflected travels in the plane of incidence.

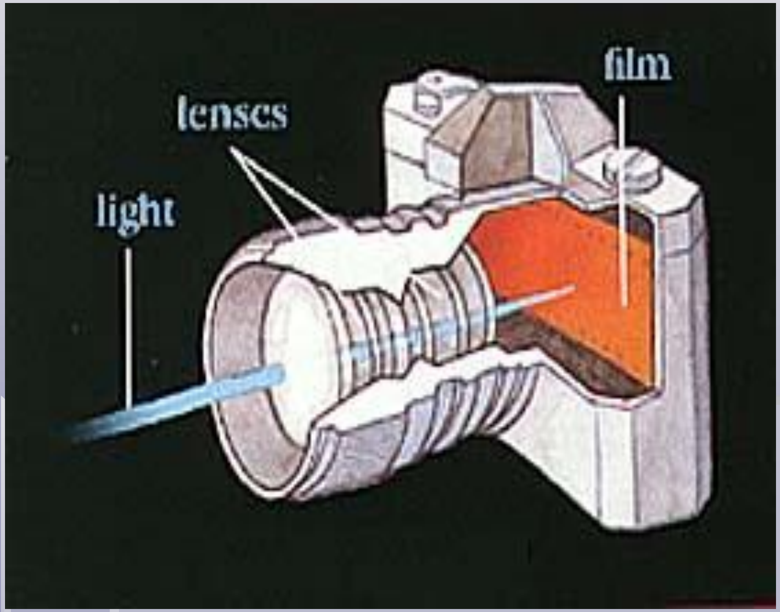
Refraction: When light passes from one medium into another, the beam changes direction at the boundary between the two media. This property of optical media is characterised by **index of refraction**

$$n = c/v \text{ [dimensionless]}$$

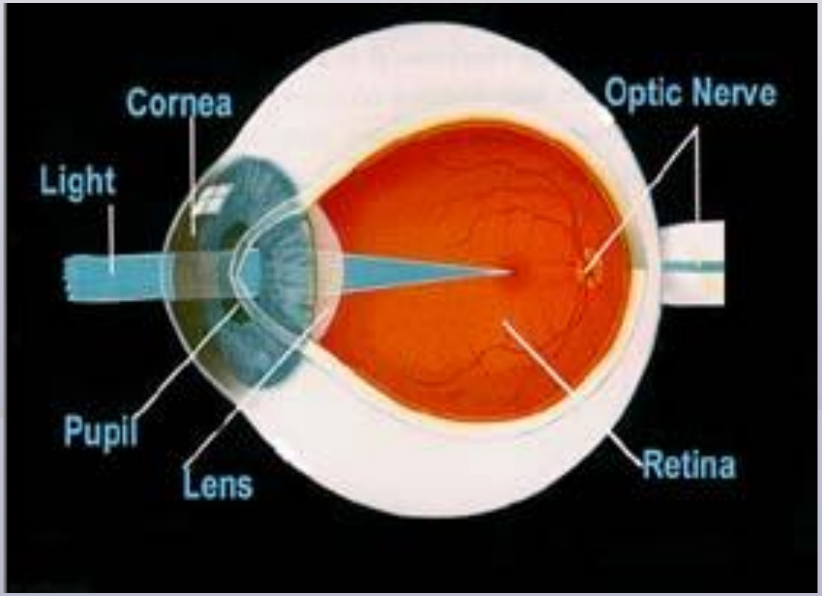
n – index of refraction of respective medium
c – speed of light in vacuum
v – speed of light in the respective medium
index of refraction of vacuum is 1

How Does The Human Eye Work?

The individual components of the eye work in a manner similar to a camera. Each part plays a vital role in providing clear vision.



The Camera



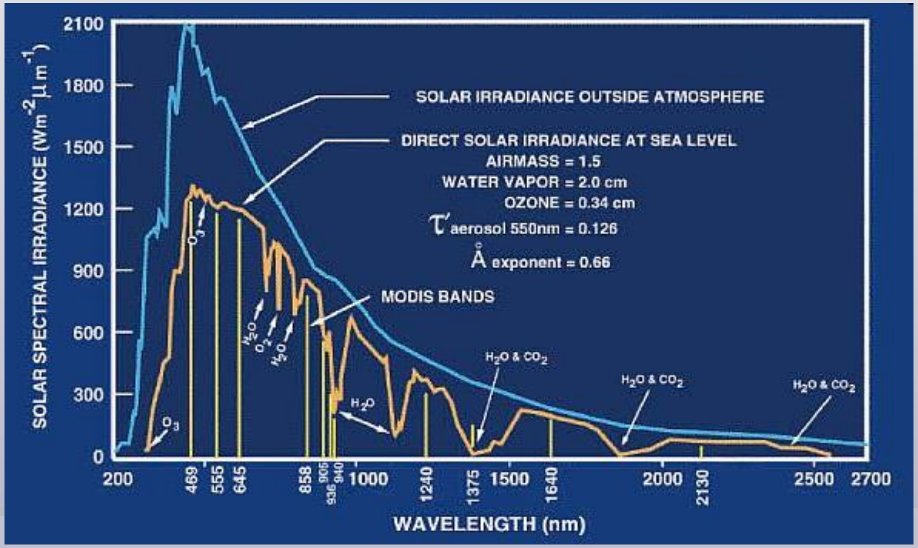
The Human Eye

Visual analyser consists of three parts:

- **Eye –** the best investigated part from the biophysical point of view
- **Optic tracts –** channel which consists of nervous cells, through this channel the information registered and processed by the eye are given to the cerebrum
- **Visual centre** – the area of the cerebral cortex where is outwards picture perceived

Aspects Determining the Visual Spectrum

- Solar emmission spectrum
  - Sun temp, atomic composition
- Atmospheric transmission
  - Scattering, absorption by greenhouse gases
- Absorption by optical elements
  - Macula lutea (yellow spot)
    - Contains the fovea
    - Protective yellow pigments xanthophyll and carotenoids
      - Short wavelength filter
- Visual pigments
  - Retinal + Opsins



http://en.wikipedia.org/wiki/File:MODIS_ATM_solar_irradiance.jpg

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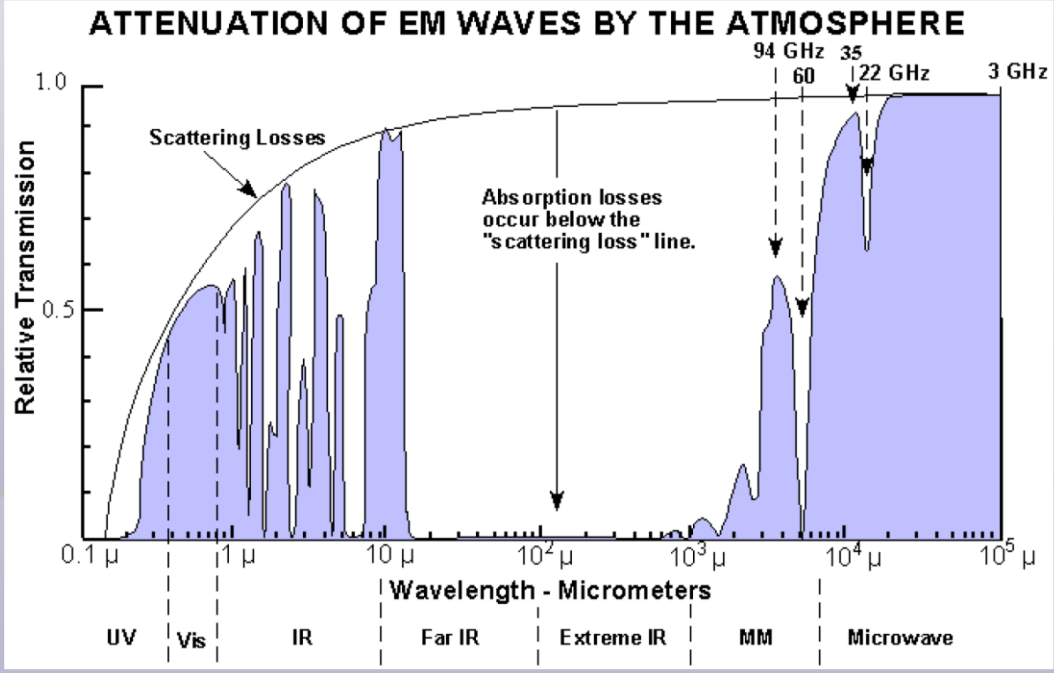
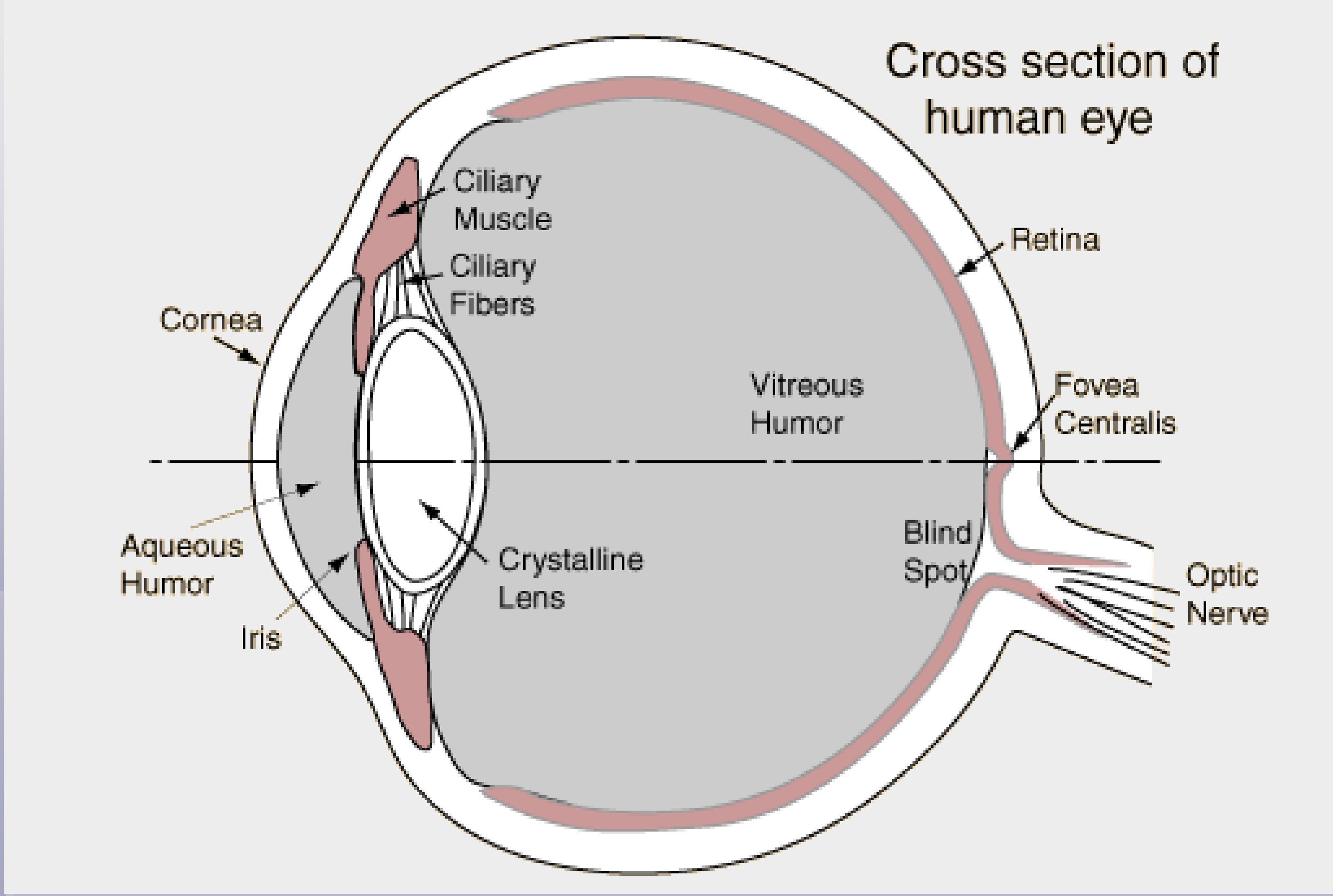


http://en.wikipedia.org/wiki/File:Atmosph%C3%A4rische_Absorption.png

Anatomy of the eyeball

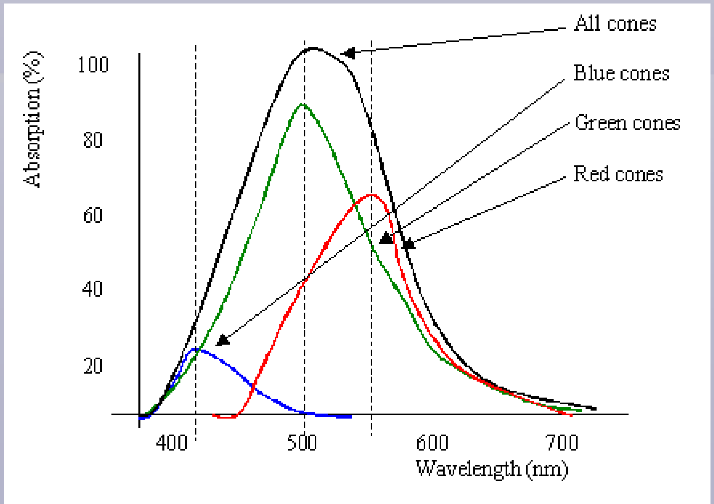


The pupil

- Dim light: iris dilates to allow light in
  - rods operative (see in black & white)

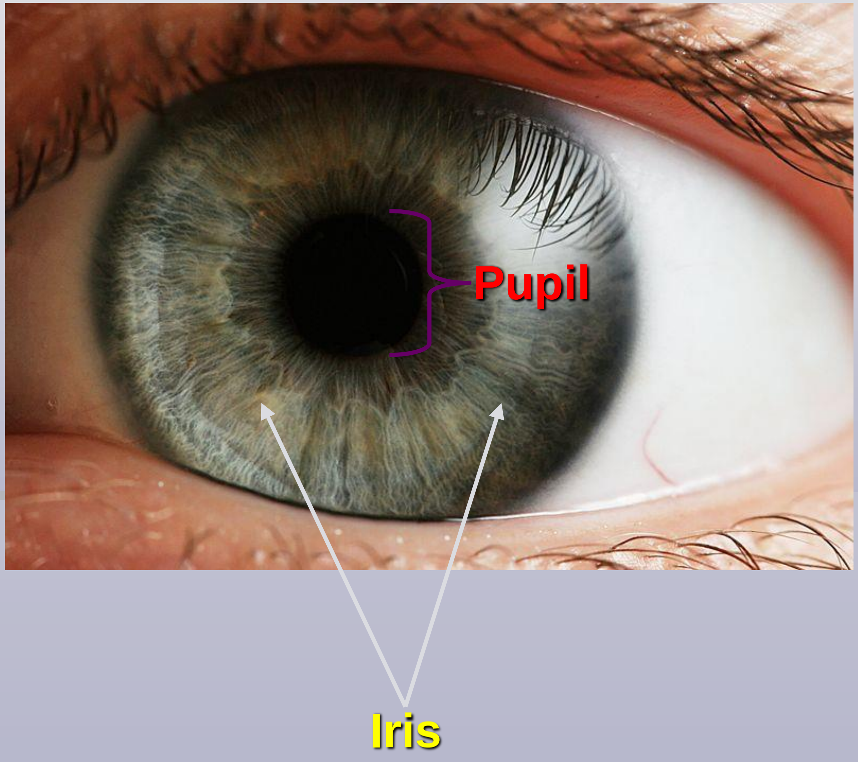
- Bright light: iris contract to avoid light flooding
  - cones are sensitive to either red, green & blue light

- Colour seen depends on proportion in which each type of cone is stimulated

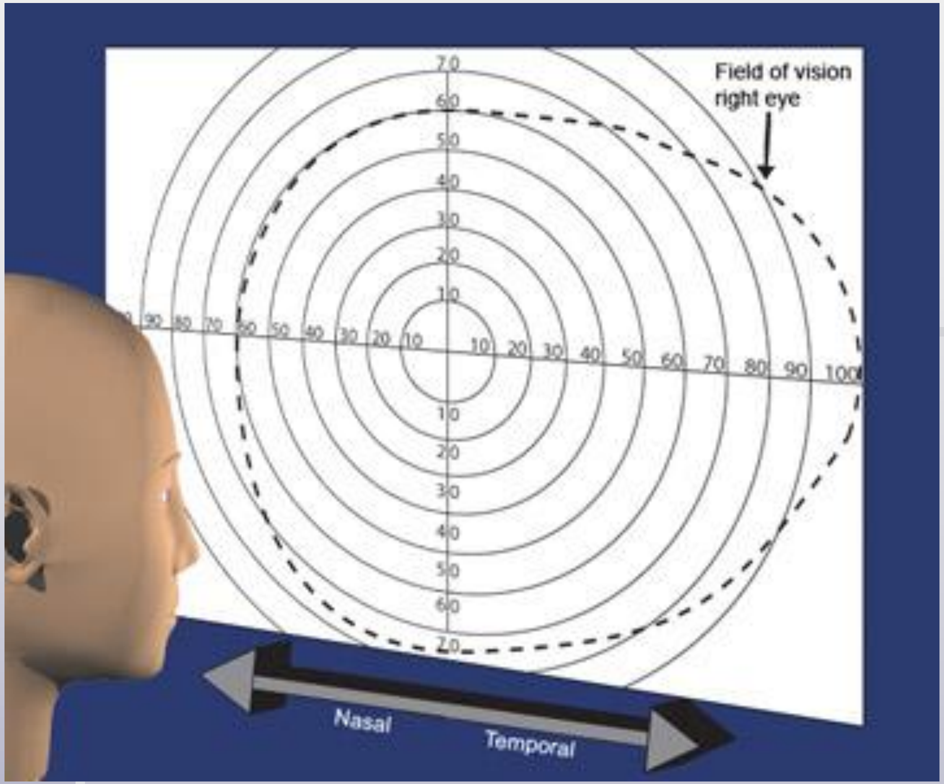


The Pupil is an Aperture

- **Pupil**
  - Opening in the center of the eyeball
  - Bounded by the **Iris**
    - The iris controls the size of the pupil
  - Opening through which light enters the eye



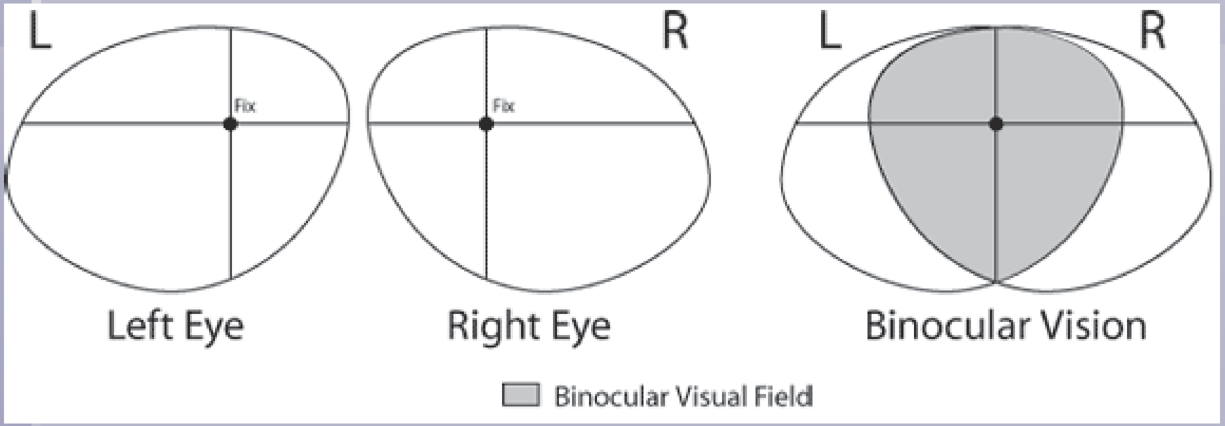
Petr Novák, Wikipedia
http://en.wikipedia.org/wiki/Image:Eye_iris.jpg



Why to check visual field?

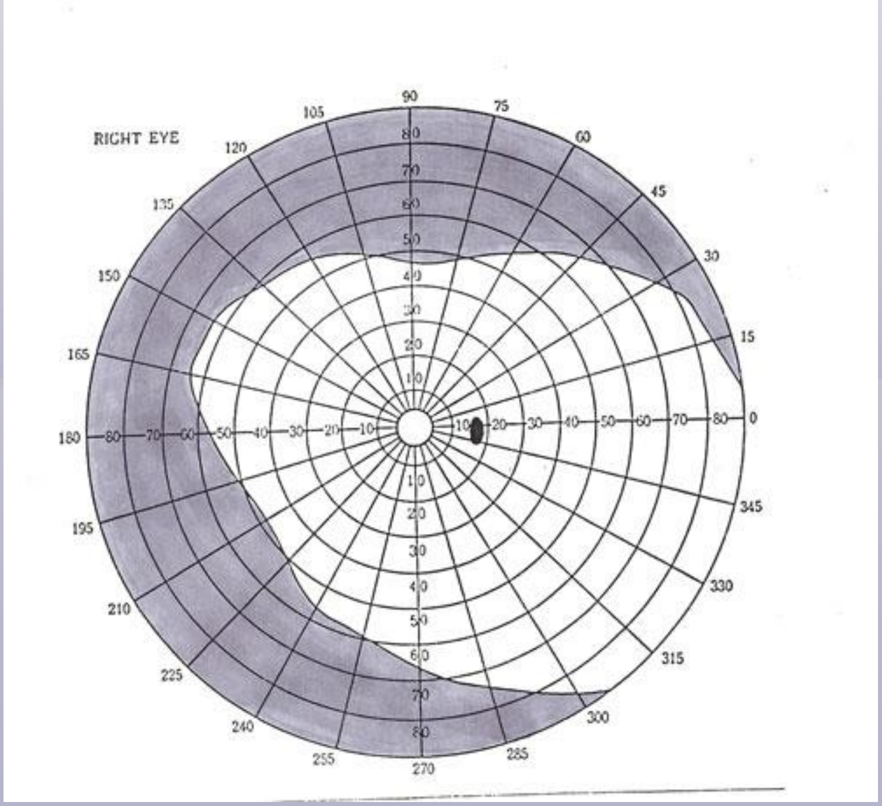
Glaucoma

neuroophthalmology



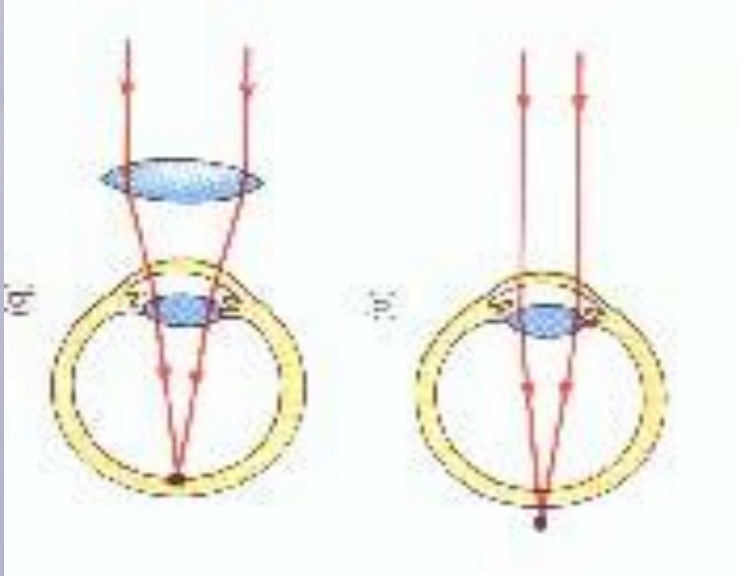
THE NORMAL VISUAL FIELD

- The field of vision is defined as the area that is perceived simultaneously by a fixating eye. The limits of the normal field of vision are 60° into the superior field, 75° into the inferior field, 110° temporally, and 60° nasally..



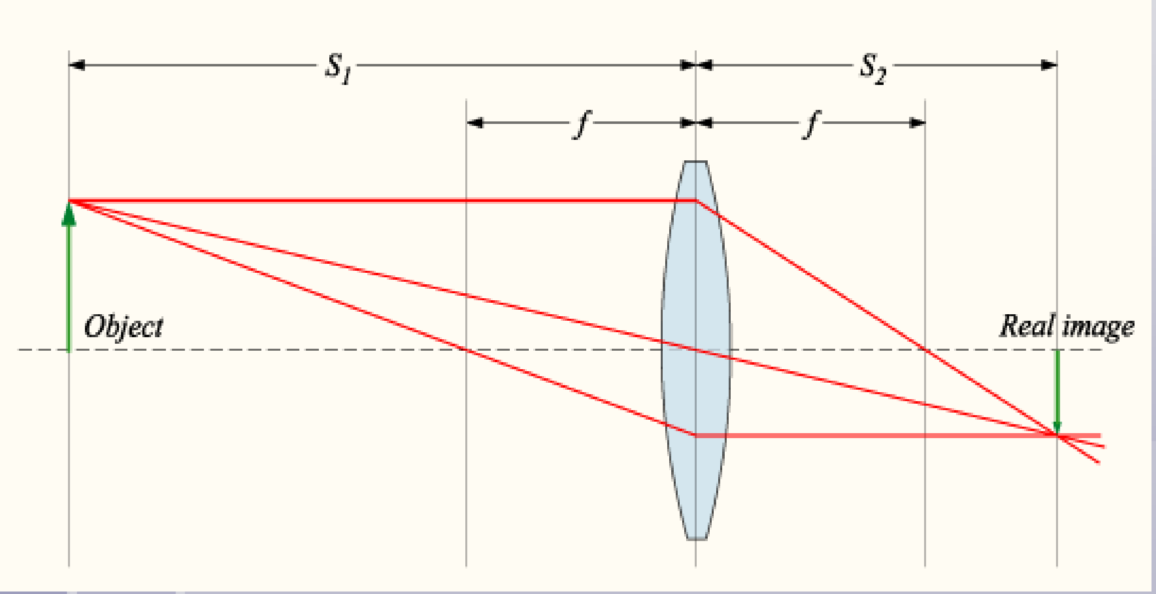
Lenses and focal points

- The cornea and lens of the eye act as two convex lenses. In order to understand illness and disorders of the eye, we must understand how lenses and focal points work.



Lenses and focal points

To find the focal point, distance of an image, or distance to the object you can use the thin lens equation.

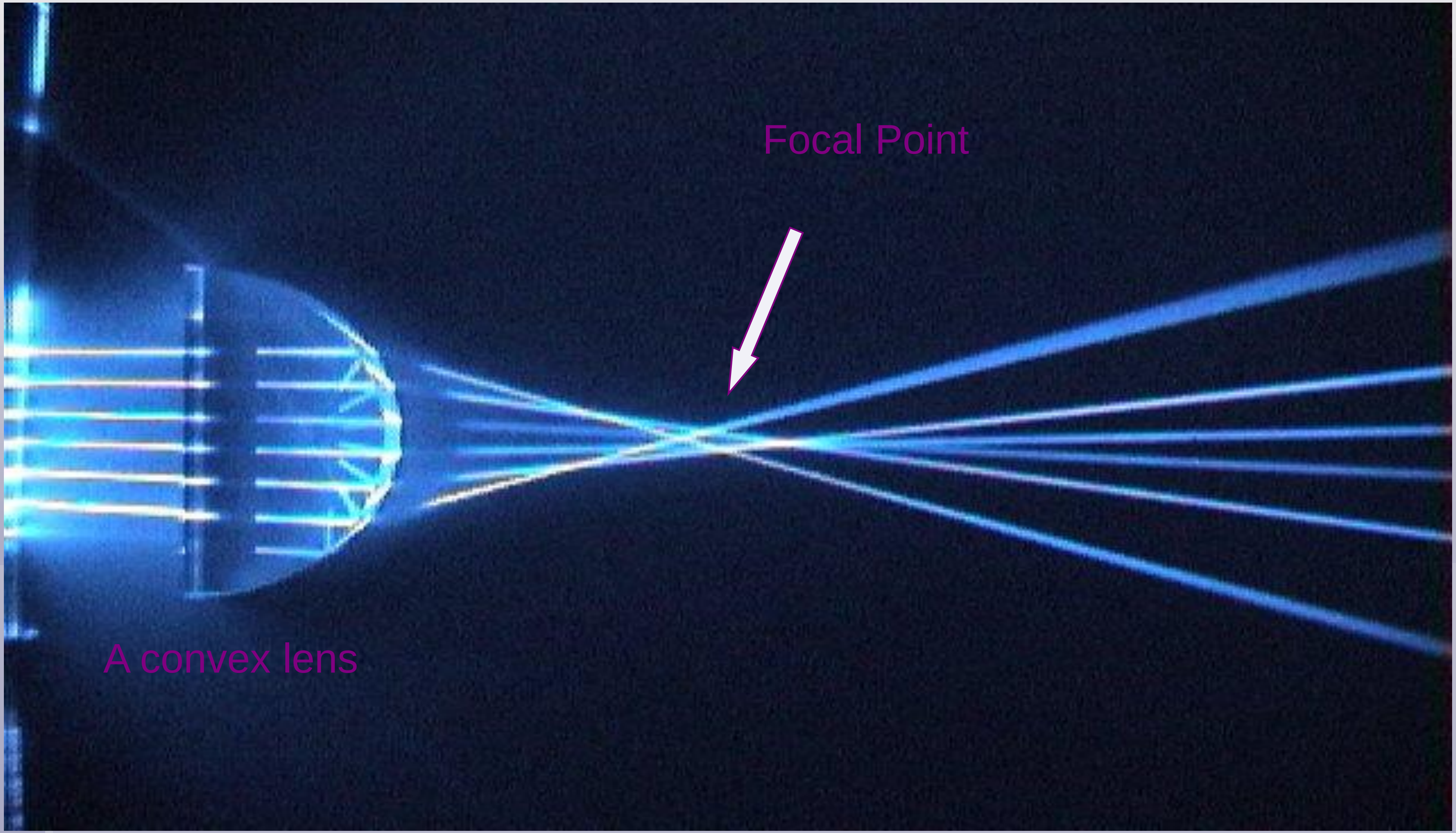


Light bounces off an object from a distance s1. This light passes through the lens to be focused on the other side. This image is real, inverted, and smaller, and is located at a distance of s2 from the lens.

$$\frac{1}{S_1} + \frac{1}{S_2} = \frac{1}{f}$$

The thin lens equation

Lenses and focal points

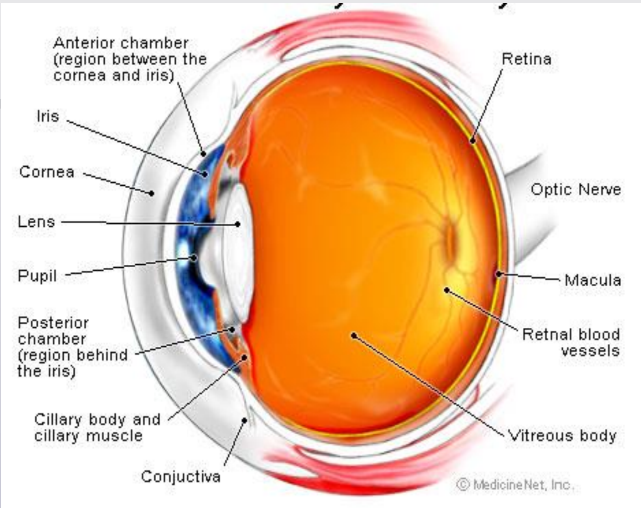


Lenses and focal points

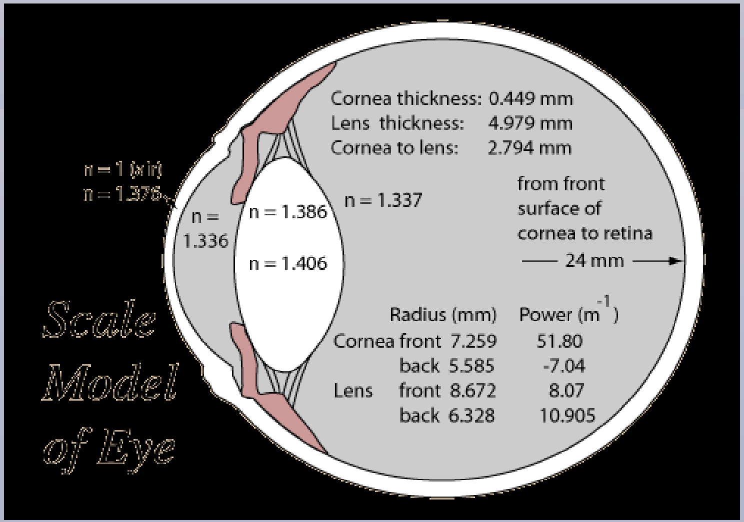
- Changing the distance to an object, or changing the focal length of a lens, will result in a different focal point.
- Changes of these kind in the eye are the causes of visual acuity loss.

The Solution is Accomodation

- Accomodation
  - The ability of the eye to change its focal length (f)
  - Mediated by the lens and ciliary muscles

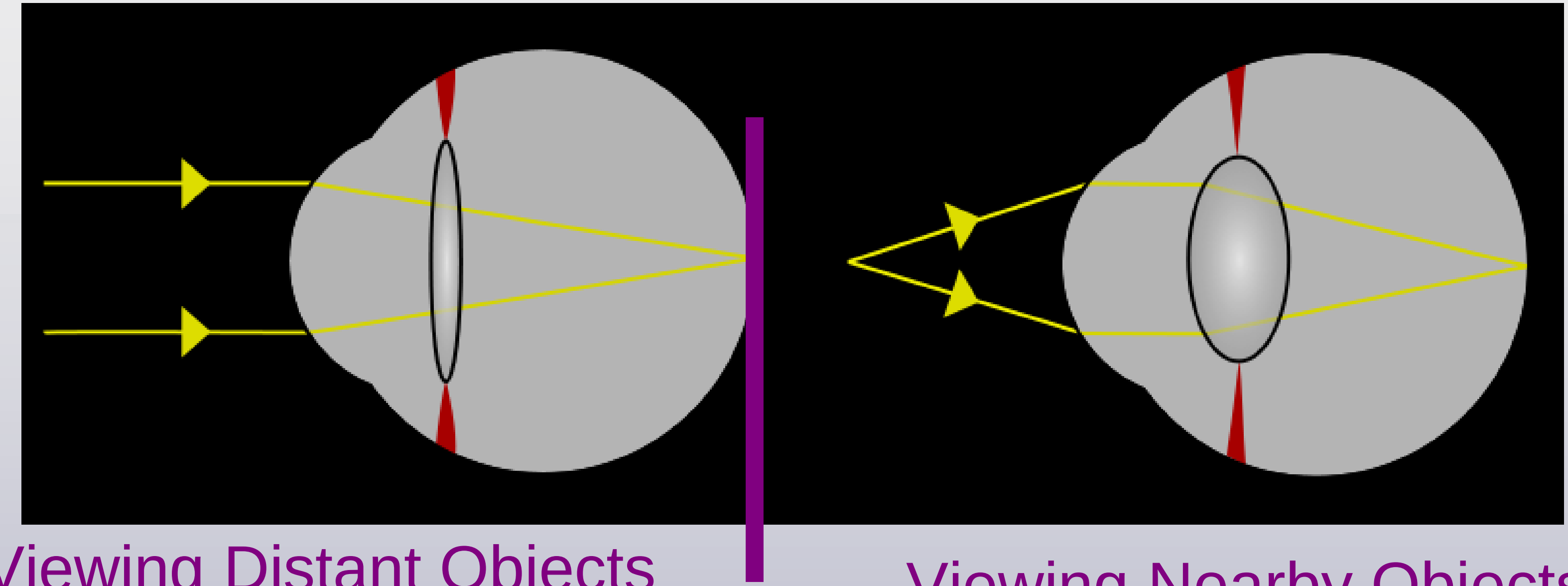


http://en.wikipedia.org/wiki/Eye



http://hyperphysics.phy-

Accomodation



<u>Viewing Distant Objects</u>

- Ciliary muscles relaxed
  - Lens assumes a flatter (skinnier) shape
  - Cornea is not pushed out = less curvature
- C-L system has a long focal length
  - Low refractive Power

<u>Viewing Nearby Objects</u>

- Ciliary muscles contract
  - Squeeze the lens into a more convex (fat) shape
  - Pushes cornea bulge out further = greater curvature
- C-L system has a short focal length
  - High refractive power

Erin Silversmith, AzaToth http://en.wikipedia.org/wiki/Image:Focus_in_an_eye.svg

Far Point

- Farthest point at which an object can be brought into focus by the eye
- Typically is infinity
- Decreases with age

Near Point

- Closest point at which an object can be brought into focus by the eye
  - Ideally ~25 cm
- Finger Experiment
- Limited by the curvature of the cornea and adjustable radii of the lens
  - Recedes with age (can lead to farsightedness)

The Power of Accomodation

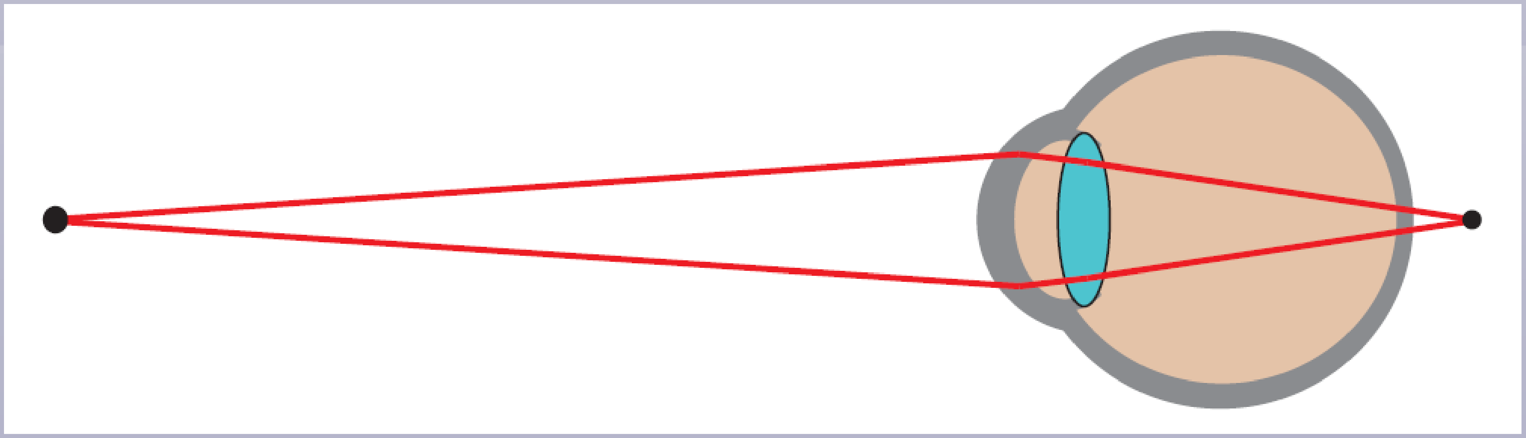
- What is the maximum change in focusing power due to accomodation for a typical eye?
- $P_{accomodation} = P_{far\ point} - P_{near\ point}$
- $P = 1/f$
- $1/f = 1/d_{object} + 1/d_{image}$
  - Assume image distance (lens to retina) = 2 cm
- $1/f_{far\ point} = 1/d_{object} + 1/d_{image}$
  - $P_{far\ point} = 1/\text{infinity} + 1/0.02 = 0 + 50 = 50$ D
- $1/f_{near\ point} = 1/d_{object} + 1/d_{image}$
  - $P_{near\ point} = 1/0.25 + 1/0.02 = 4 + 50 = 54$ D
- $P_{accomodation} = P_{far\ point} - P_{near\ point} = 50\text{ D} – 54\text{ D} = 4\text{ D}$

Visual Defects and Correction

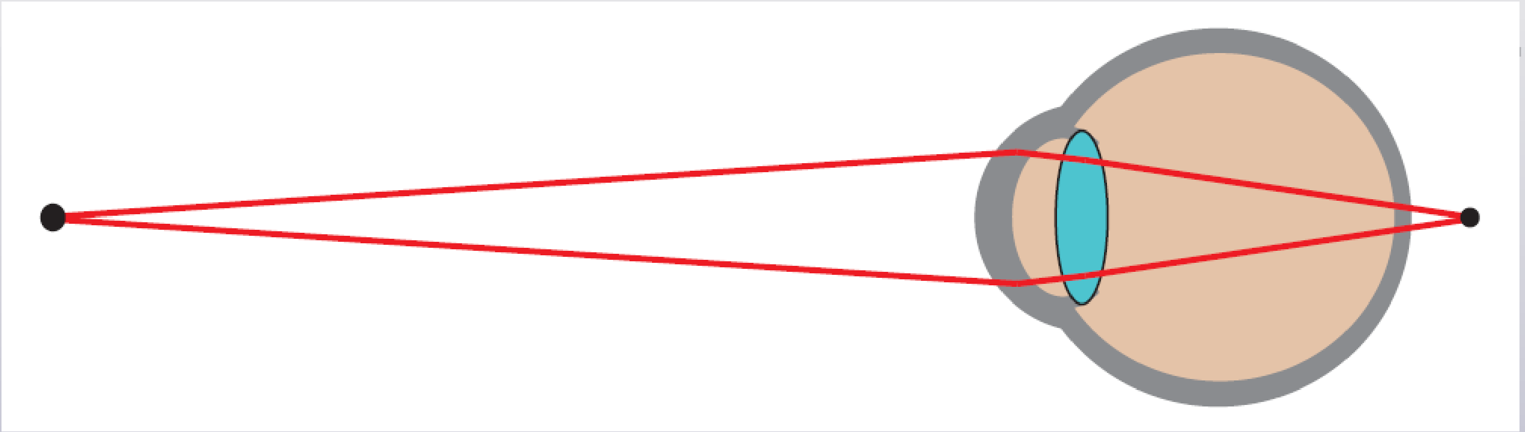
- Visual defects
  - When an eye cannot focus an object’s image on the retina
    - Image formed in front of or behind the retina
    - Results in blurred vision
  - Typical causes:
    - Abnormal length of the eyeball
    - Abnormal curvature of the cornea
    - Abnormal accommodation
- Correction
  - Glasses or Contact lenses

Hyperopia (Farsightedness)

- INABILITY of the eye to focus on NEARBY objects
- “Can see far” – no difficulty focusing on distant objects
- Images of nearby objects are formed at a location BEHIND the retina
- Near point is located farther away from the eye



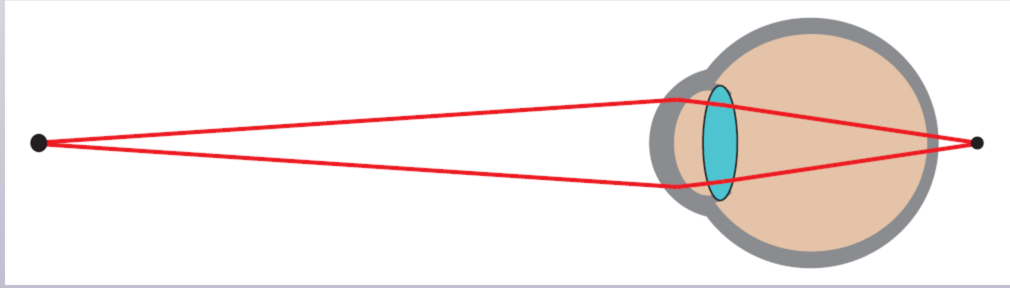
Hyperopia: Causes



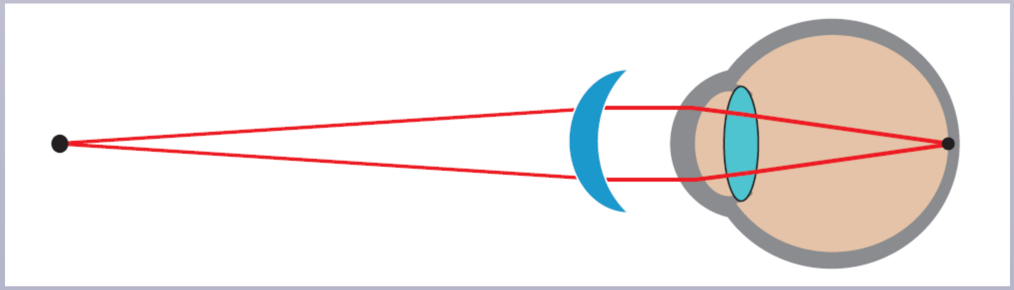
- Shortened eyeball (retina is closer than normal to the cornea lens system)
  - Axial hyperopia
- Cornea is too flat
  - Refractive hyperopia
- Lens can not assume a highly convex (fat) shape
  - Refractive hyperopia

Hyperopia: Correction

- Need to refocus the image on the retina
  - Decrease the focal length of the cornea-lens system

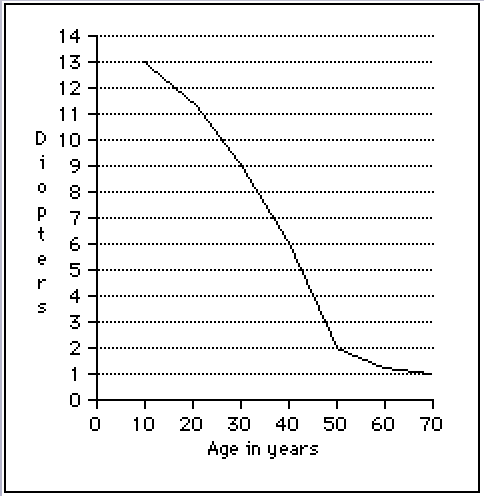


- Add a converging lens (positive power, +D)



Presbyopia

- "After – 40" vision
- Progressively diminished ability to focus on near objects as one ages
  - Similar to hyperopia, but different cause
  - Type of refractive hyperopia
- Cause = diminished power of accomodation due to natural process of aging
  - Reduced elasticity of the lens
  - Weakening of the ciliary muscles
  - Changes in lens curvature due to continued growth

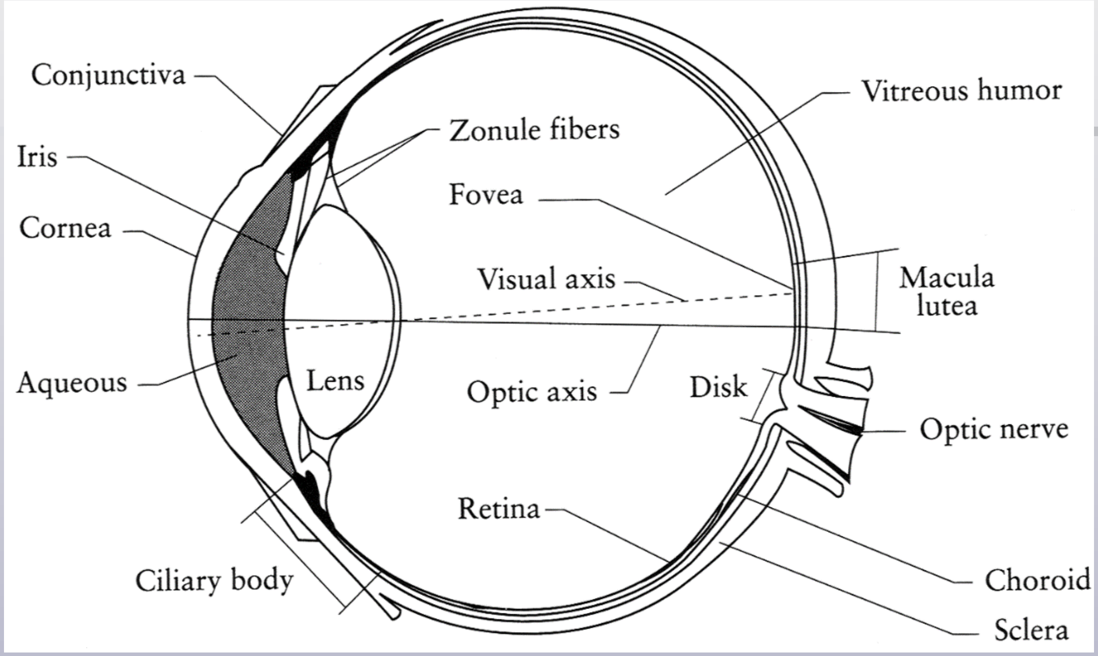


http://en.wikipedia.org/wiki/Image:Specrx-accom.png

Myopia (Nearsightedness)

- Inability of the eye to focus on DISTANT objects
- “Can see near” – no difficulty focusing on nearby objects
- Images of distant objects are formed in front of the retina
- Far point is closer than normal

The eye is a camera



- The human eye is a camera!
  - **Iris** - colored annulus with radial muscles
  - **Pupil** - the hole (aperture) whose size is controlled by the iris
  - What's the "film"?
    - – photoreceptor cells (rods and cones) in the **retina**

Gullstrand´s model of the eye – basic parameters

Allvar Gullstrand
1852 – 1930
Nobel Award – 1911
Swedish ophthalmologist

- **Refraction Index:**
  cornea................................ 1.376
  aqueous humour............... 1.336
  lens... ....1.413
  vitreous humour……………. 1.336

- **Dioptric power:**
  cornea .... 42.7 D
  lens – inside eye................ 21.7 D
  eye (whole)....................... 60.5 D

- **Radius of curvature:**
  cornea .... 7.8 mm
  lens – outer wall........ .... 10.0 mm
  lens – inner wall..................... -6.0 mm

- **Focus location:**
  (measured from top of the cornea):
  front (object) focus.................... -14.99 mm
  back (image) focus .... 23.90 mm
  retinae location......................... 23.90 mm

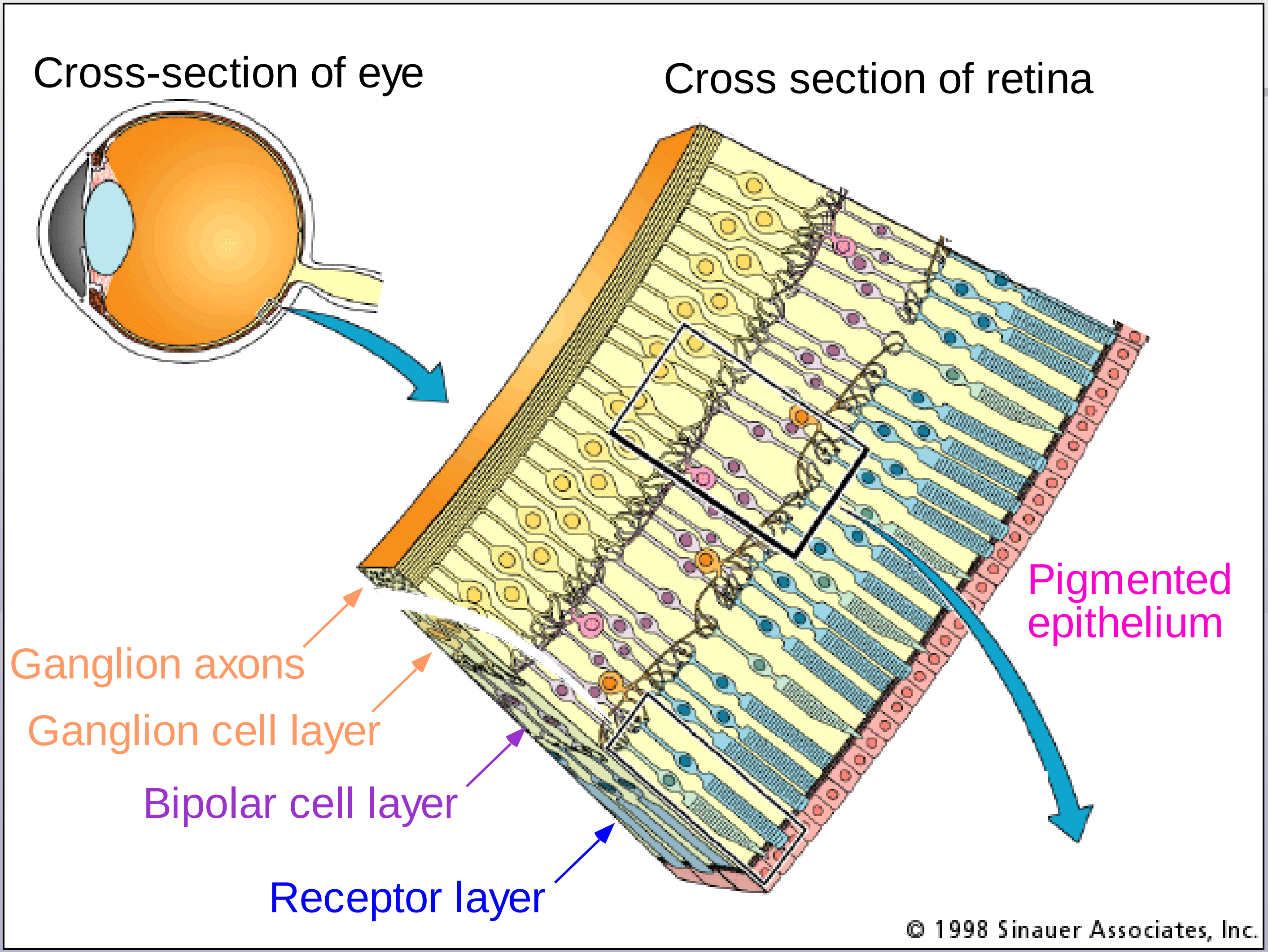
Retina – biological detector of the light

Retina - the light-sensing part of the eye.

It contains **rod cells**, responsible for vision in low light, and **cone cells**, responsible for colour vision and detail. When light contacts these two types of cells, a series of complex chemical reactions occurs. The light-activated rhodopsin creates electrical impulses in the optic nerve. Generally, the outer segment of rods are long and thin, whereas the outer segment of cones are more cone-shaped.

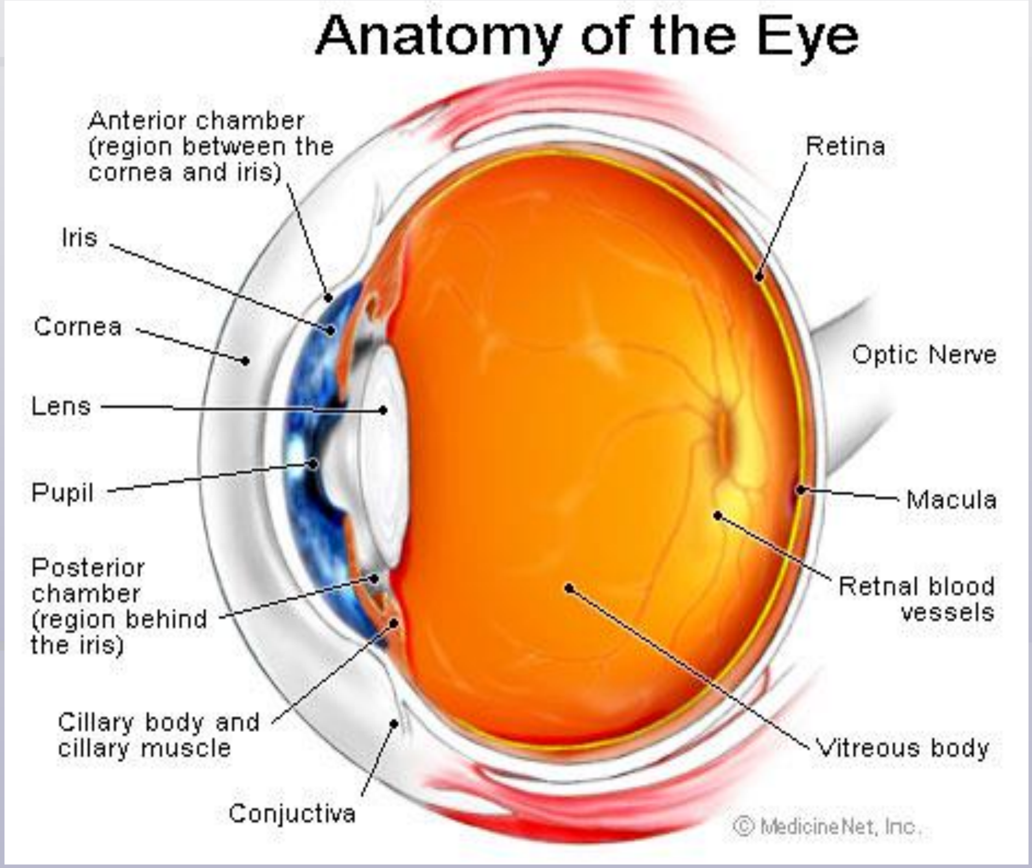
In the back of the eye, in the centre of the retina, is the **macula lutea (yellow spot).** In the centre of the macula is an area called the **fovea centralis.** This area contains only cones and is responsible for seeing fine detail clearly.

The Retina


Cross-section of eye
Cross section of retina
Pigmented epithelium
Ganglion axons
Ganglion cell layer
Bipolar cell layer
Receptor layer
© 1998 Sinauer Associates, Inc.

Gullstrand model

The eye is approximated as an centred optical system with ability of automatic focussing, however, this model does not consider certain differences in curvature of the front and back surface of cornea as well as the diferences of refraction indices of the core and periphery of the crystalline lens.



Rod and Cone Distribution

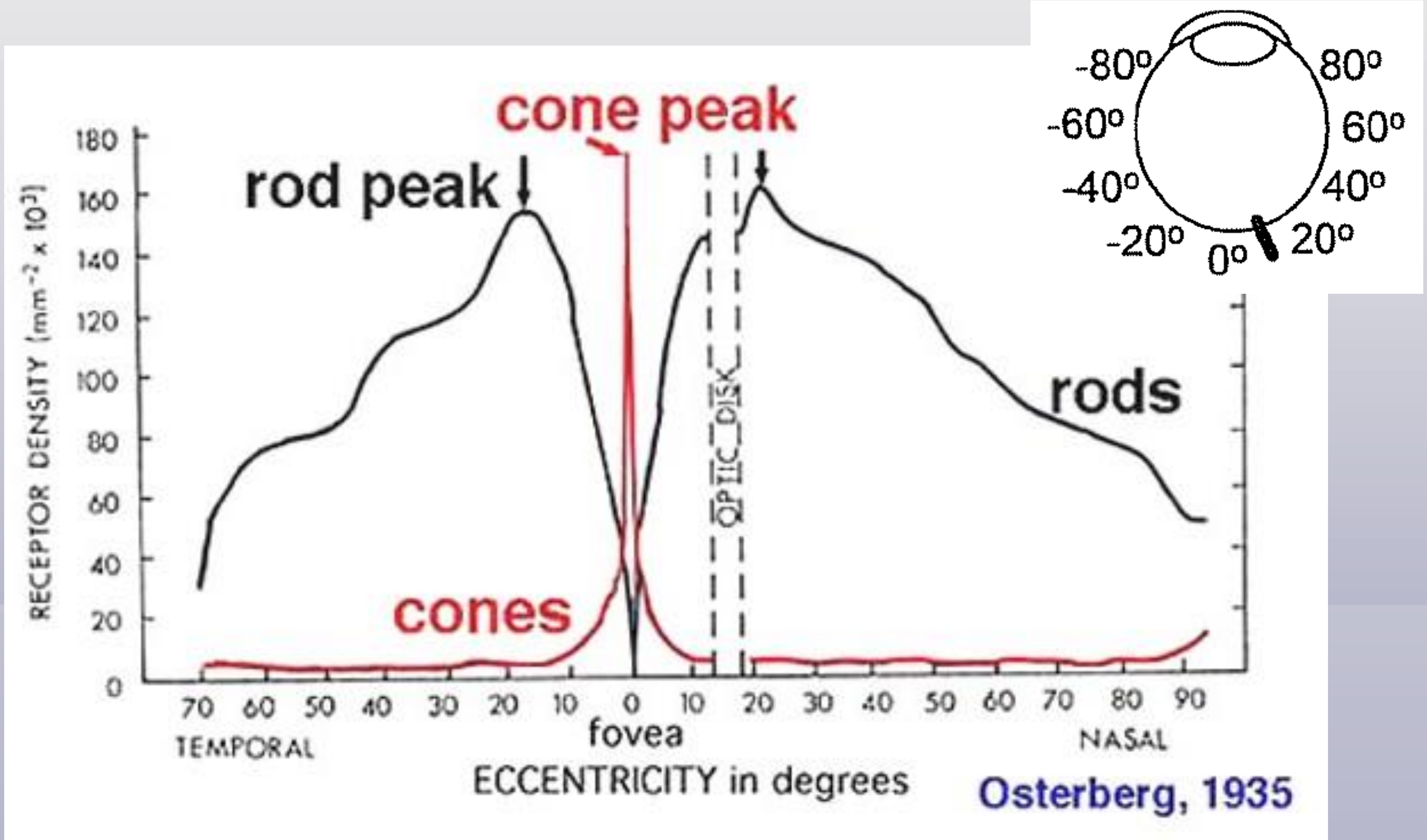
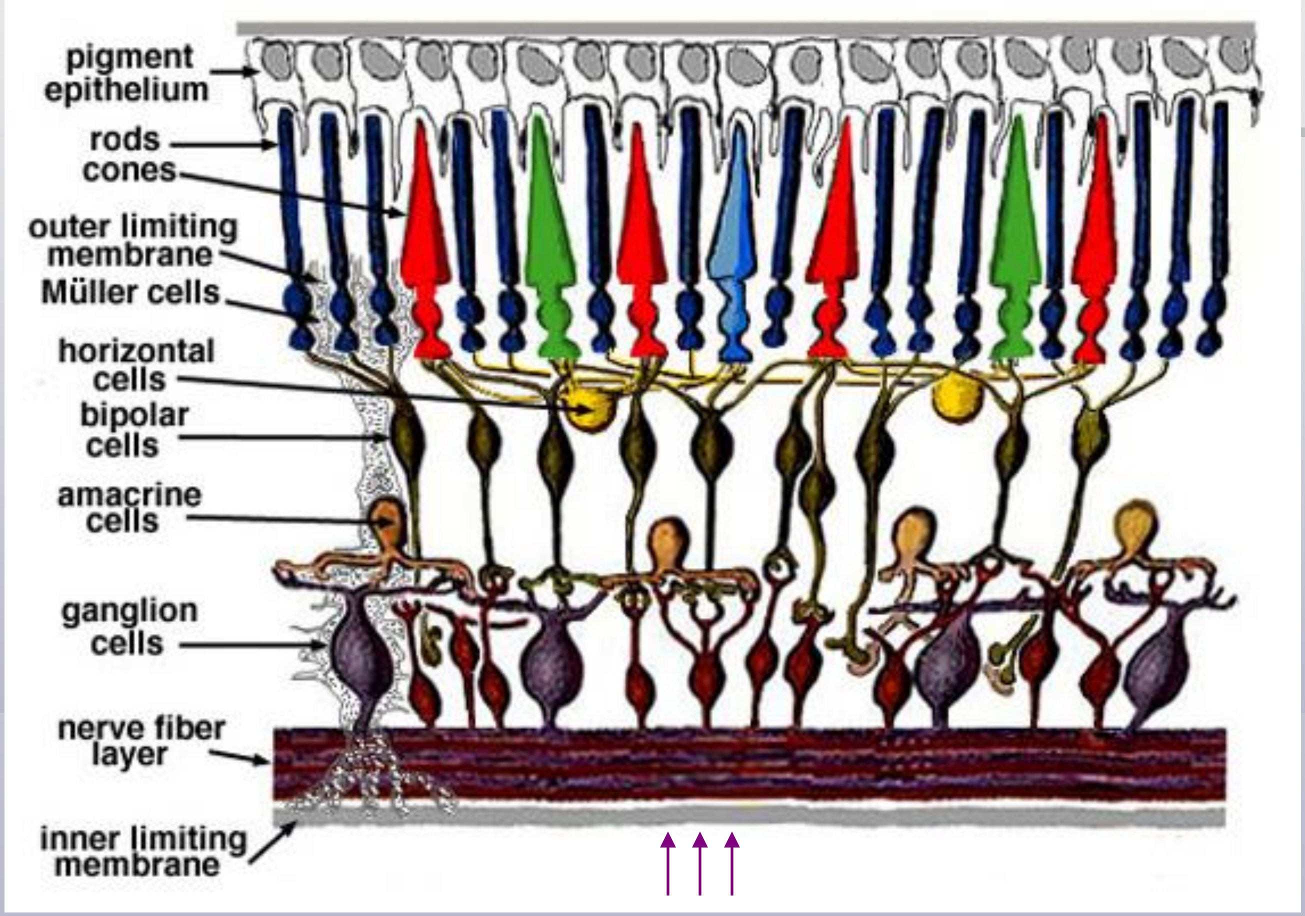


Fig. 20. Graph to show rod and cone densities along the horizontal meridian.

http://webvision.med.utah.edu/imageswv/Ostergr.jpeg

Retina up-close



Light

Visual Phototransduction

- Conversion of electromagnetic radiation into electrical signals
  - Absorption of electromagnetic radiation
  - Triggering of a signaling cascade
  - Change in electrical properties of the cell

Photoreceptor Functions

Rods

- Monochromatic vision
  - Single visual pigment
- Scotopic vision (low light conditions)
  - “Night” vision
  - High Sensitivity
    - Often respond to single photon
    - Slow response – stimuli added
- Peripheral vision
  - “Warning” vision
  - Wide distribution
    - Covers large visual angle
    - None in fovea

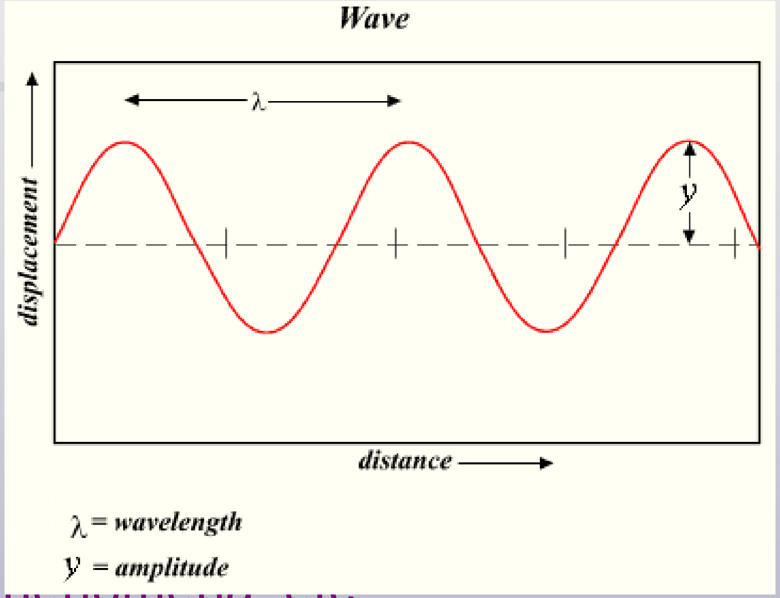
Cones

- Chromatic vision
  - 3 visual pigments
    - Trichromatic vision
- Photopic vision (high light conditions)
  - Low sensitivity
    - 1000x less than rods
  - Often misconstrued as “Color” vision
- Detail vision
  - Foveal location
  - High spatial acuity (resolution)
    - High density
    - Less “escaped light”
  - Fast response to stimuli

Quantum Mechanics

- Classical Mechanics
  - Description of large populations of particles
  - An approximation of quantum mechanics
- Quantum Mechanics
  - Arose from the inability to explain certain behaviors of electromagnetic radiation and electrons in atoms using classical mechanics
    - Newton, Planck, Einstein, Bohr, and others
  - Description of physical systems at the atomic level
    - Light
    - Electrons
    - Molecules

Properties of Light



- Wave model
  - Classical sinusoidal wave
    - Unique in that can travel through a vacuum
  - Describes reflection, refraction, diffraction, interference, and Doppler Effect phenomena, etc.
- Particle model
  - “photon”
  - Describes absorption and emission phenomena

Image from http://en.wikipedia.org/wiki/Image:Wave.png

Visual Pigments

- Photosensitive molecules mediating visual phototransduction
  - Chromophore
    - Chemical group that absorbs light
    - Retinal
  - Auxochrome
    - Chemical group that modifies a chromophore’s light absorption (tuning)
      - Wavelength
      - Intensity
    - Opsins
- Retinylidene proteins
  - Protein family that uses retinal as a chromophore

Absorption of Light

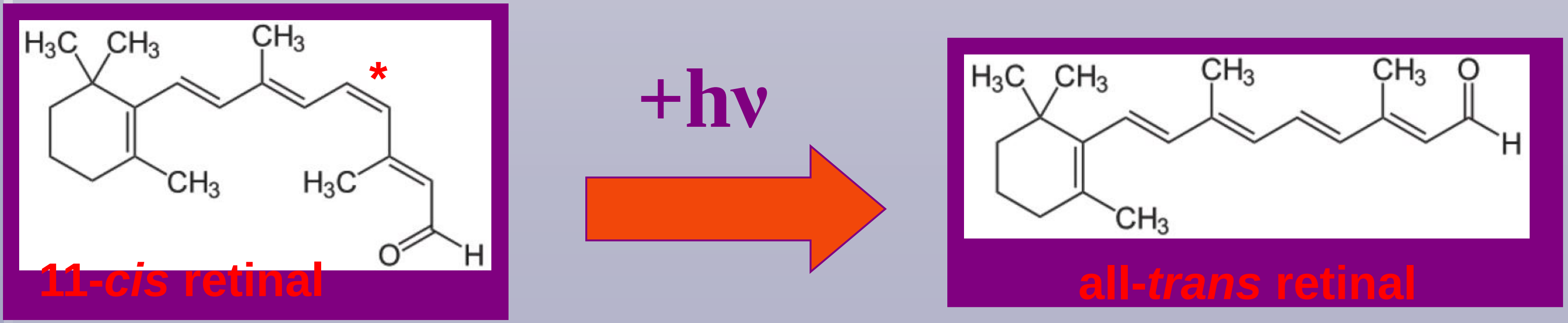
- Absorption of a photon transfers energy (E)
  - $E = h\nu = hc/\lambda$
    - h = Planck's constant = 6.626×10^{-34} J/s
    - c = speed of light = 3.0×10^{8} m/s
    - λ = wavelength
  - Excites the molecule to a higher energy state
- A molecule can only exist at discrete energy levels.
  - Absorption only occurs if energy of the photon equals the energy difference between the molecules energy levels.

Visual Phototransduction

- Retinal undergoes a photoisomerization
  - Single photon required
  - Converts 11-*cis* retinal to all-*trans* retinal
- Induces a conformational change in the opsin molecule
- Triggers an intracellular signal transduction cascade
- Closes ion channels
- Changes the electrical state of the cell

Visual Pigments: Chromophore

- Retinal
  - (aldehyde derivative of Vitamin A)
    - Aka retinaldehyde
  - Absorption in near ultraviolet (330-365 nm)
    - Induces photoisomerization
    - hν = energy required to promote retinal to an excited state
      - Rotation around the double bond more energetically favored



Visual Pigments: Auxochrome

- Opsin
  - Promote electron delocalization and charge perturbation
    - Lowers energy required to excite electrons in retinal
    - Shifts energy requirement into visual spectrum
  - G protein coupled transmembrane receptor
  - Covalently bonded to retinal
  - Links photon absorption to signal transduction cascade

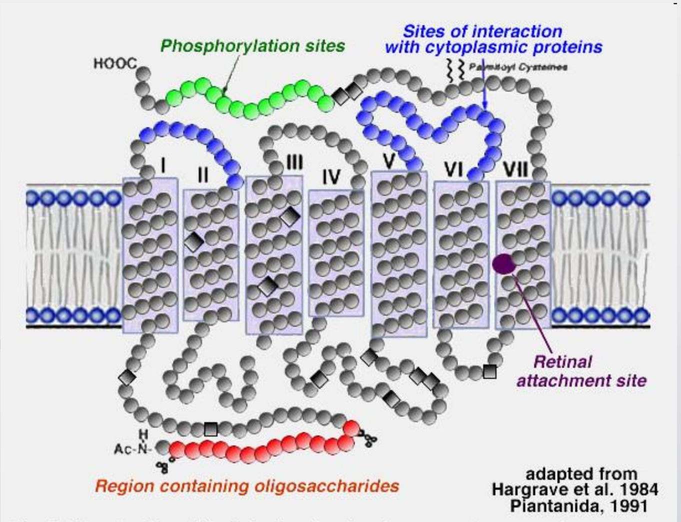
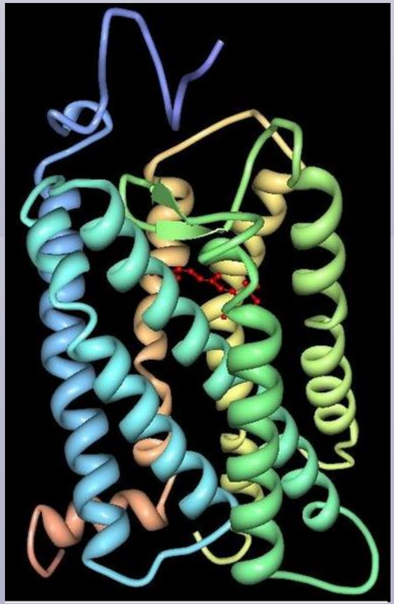


Fig. 9. Structural model of rhodopsin showing seven transmembrane components and the attachment site for retinal.

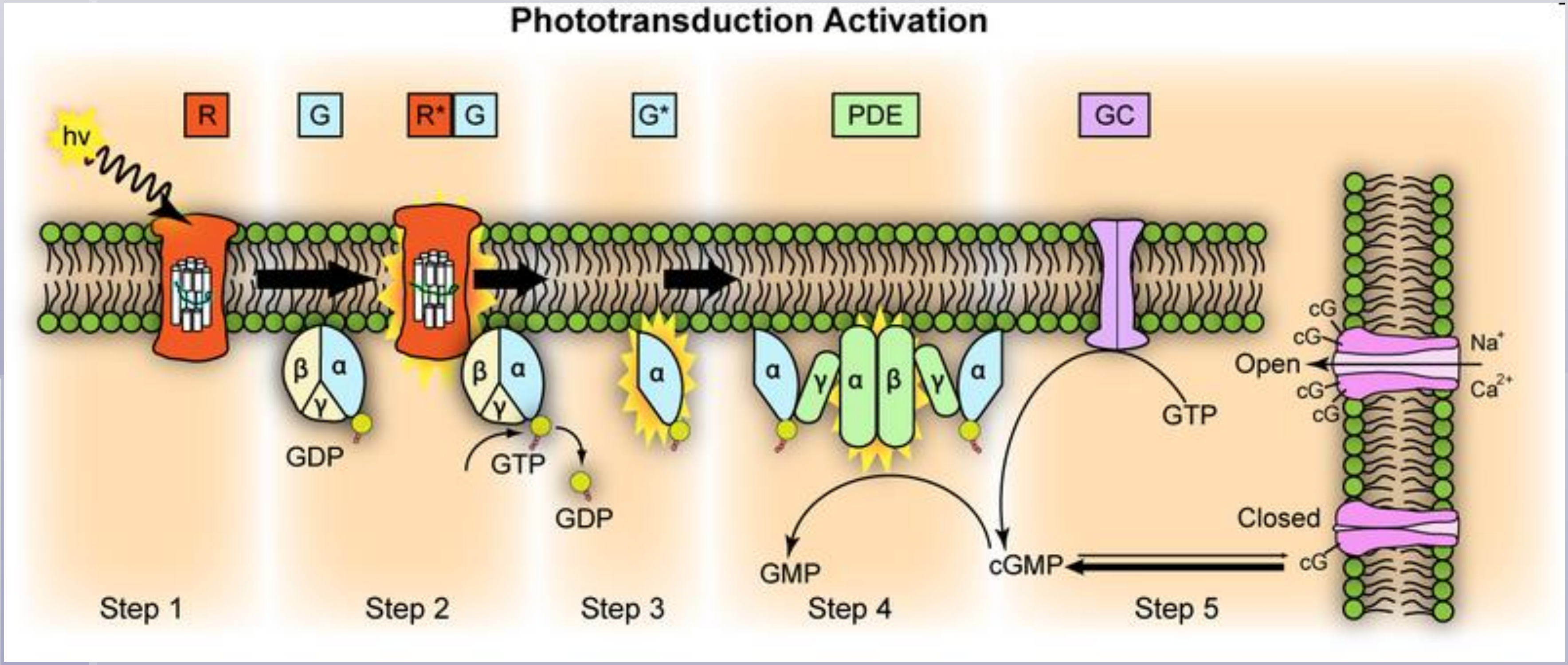
http://webvision.med.utah.edu/imageswv/rhodopH.jpeg



http://en.wikipedia.org/wiki/File:Rhodopsin_3D.jpeg

Visual Phototransduction

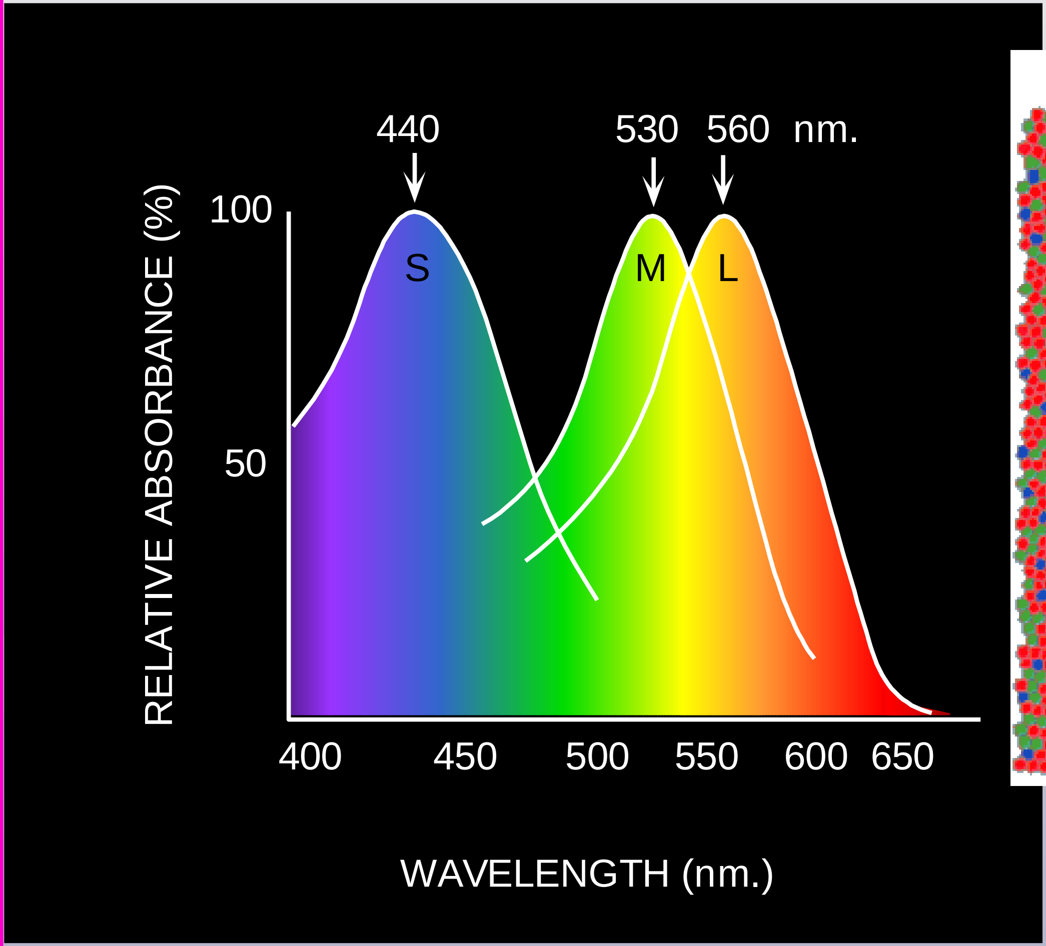
- Light $\rightarrow$ electrical signal

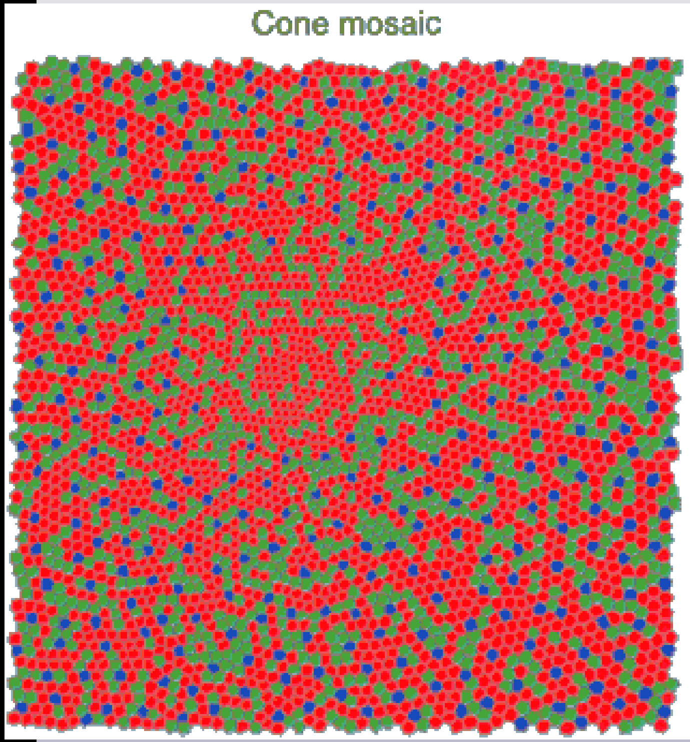


http://en.wikipedia.org/wiki/File:Phototransduction.png

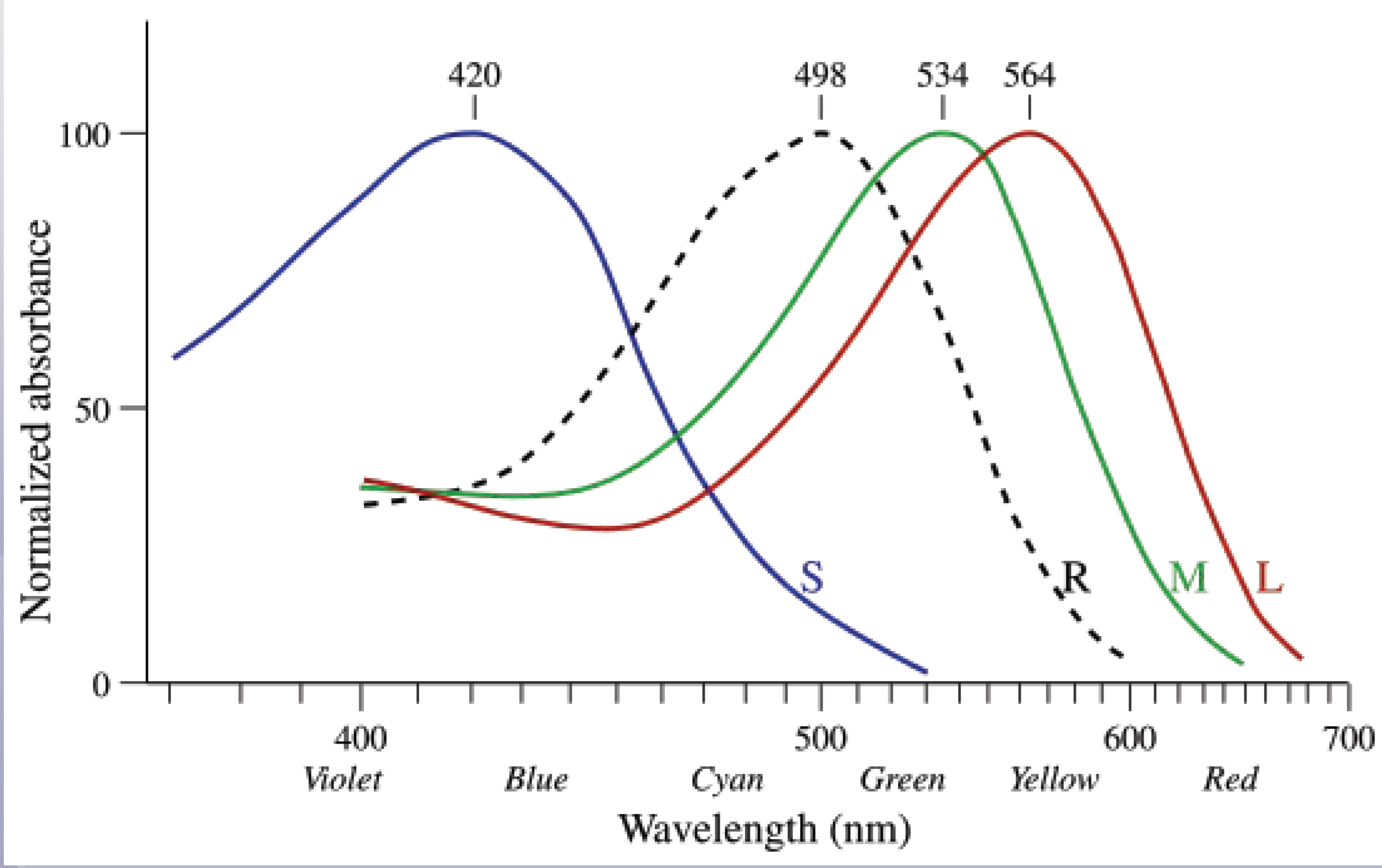
Physiology of Color Vision

Three kinds of cones:





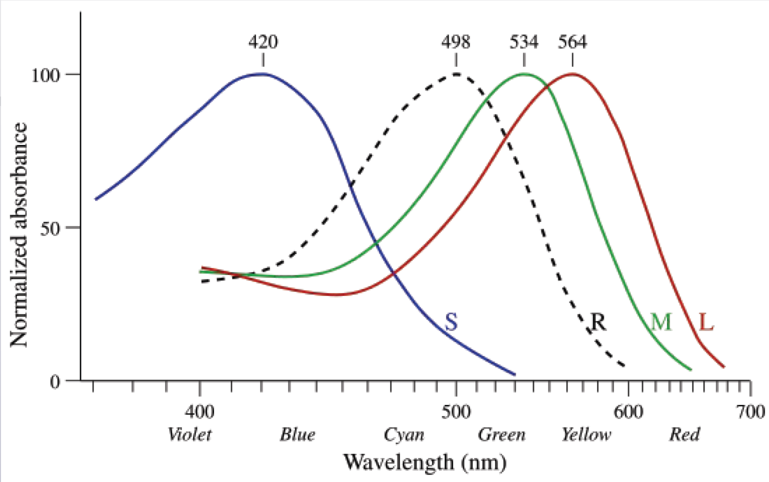
Photoreceptor Absorption Spectra



http://en.wikipedia.org/wiki/File:Cone-response.svg

4 Human Opsins

- Different absorbance maxima accomplished by differences in amino acid sequence
  - Slight differences in 3D conformation
- Red vs green
  - 98% identical
- Blue vs Rhodopsin
  - 40% identical
- Red or Green vs Blue or Rhodopsin
  - 40% identical



http://en.wikipedia.org/wiki/File:Cone-response.svg

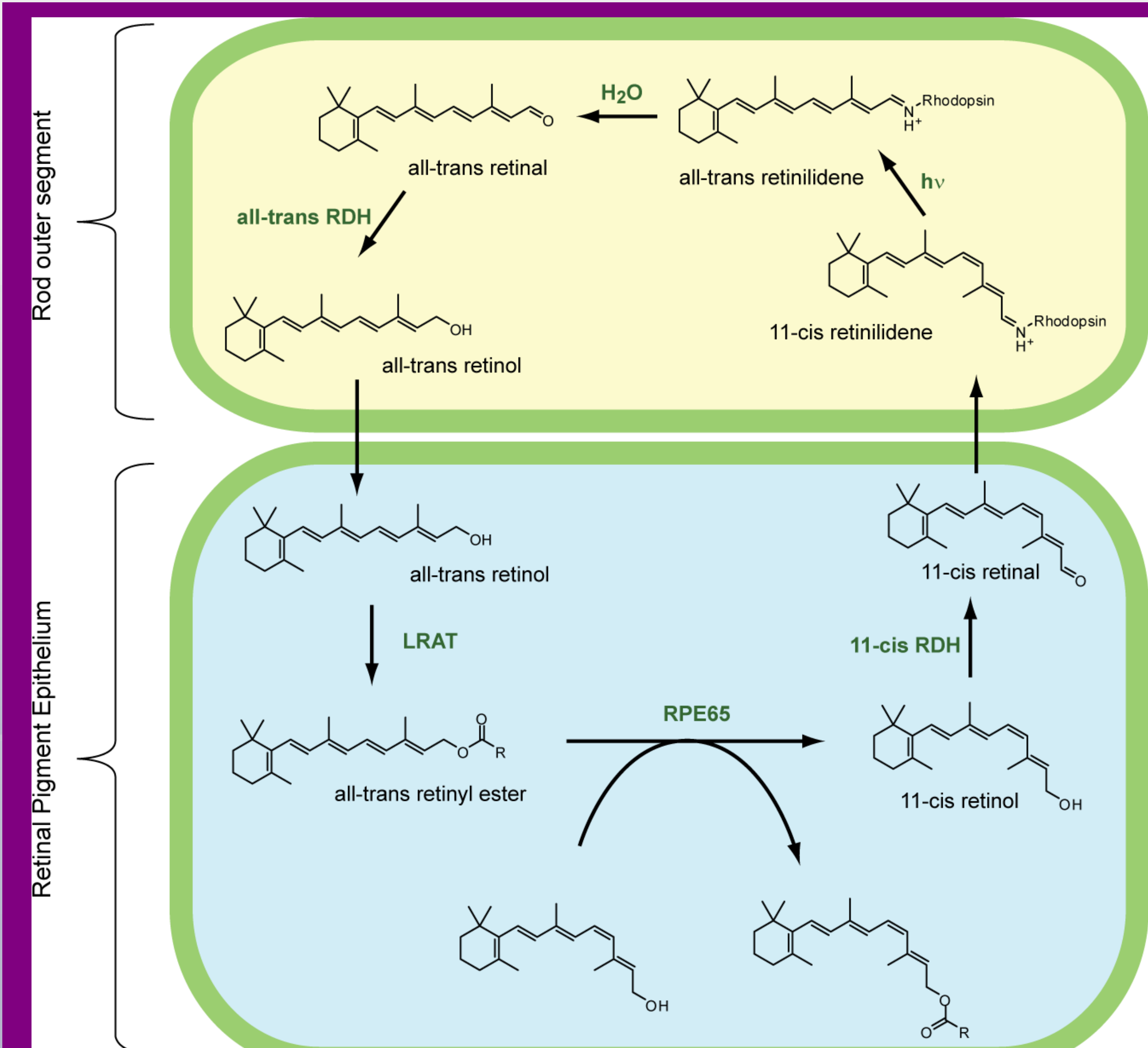
Amino acid variants in protein structure

Nathans, Cell Press, 1999

Vision Deficiencies

- Absence of visual pigment components
  - Retinal → complete vision deficiency
  - Opsins → color vision deficiency
    - Monochromacy
      - Lack 2 or all 3 cone pigments
    - Dichromacy
      - Lack one cone pigment
    - Anomalous trichromacy
      - Altered spectral sensitivity of one cone pigment
      - Most common

Replenishment of 11-*cis* retinal



http://en.wikipedia.org/wiki/File:Visual_cycle_v2.png

Aspects Determining Visual Acuity

- Density of photoreceptor cells (= pixel size)
- Connectivity of photoreceptor cells
  - Degree of convergence at ganglion cells
- Light levels
- Diffraction
  - Significant at small apertures (when pupil < 3 mm)
- Spherical aberration
  - Imperfect imaging by spherical surface
  - Significant at larger apertures
- Chromatic aberration
  - Different colors come into focus at different distances
- Optical scattering
  - Reduced by Retinal Pigment Epithelium
    - Absorbs excess photons