Biophysics of vision

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Learning Objectives

- Basic properties of light
- Anatomy of eye
- Optical properties of eye
- Retina – biological detector of the light
- Colour vision

Basic properties of light

Visible electromagnetic radiation:

λ = 380 – 760 nm

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

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

Visible light – (VIS): only a small percentage

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 bending is called refraction.

$n = c/v$ [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

Refraction of light (Snell's Law)

$$\frac{\sin\alpha}{\sin\beta} = \frac{n_2}{n_1} = \frac{v_1}{v_2}$$

α – angle of incidence
β – angle of refraction
(Angles are measured away from the normal!)
n_1, n_2 – indices of refraction
$n_1 > n_2$ – light refraction away the normal occurs
$n_1 < n_2$ – light refraction toward the normal occurs

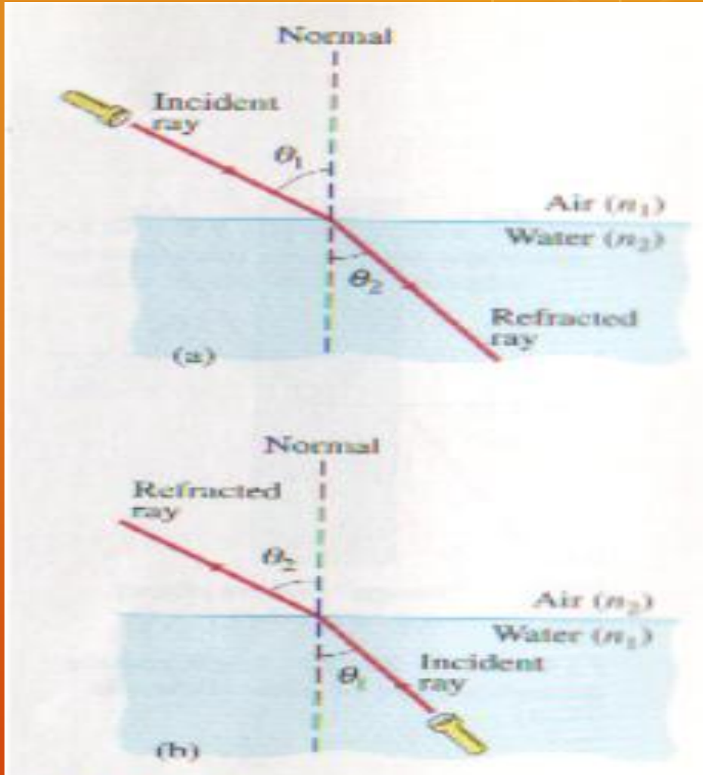


FIGURE 23–17 Refraction. Snell's law (law of refraction)

$\theta 1$ = angle of incidence; $\theta 2$ = angle of refraction

If speed of light is less in the new medium, it bends toward normal

$n1 \sin \theta 1 = n2 \sin \theta 2$

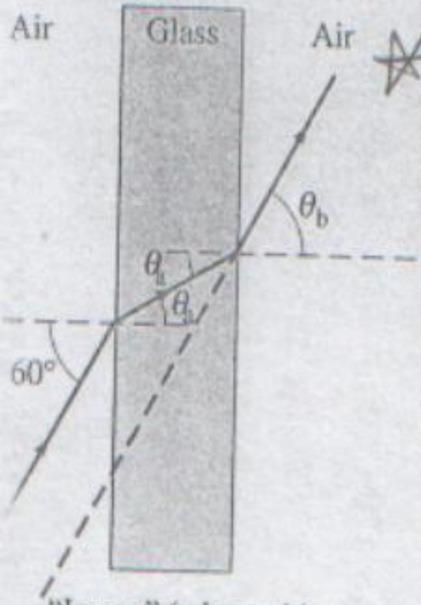
Incident and refracted rays lie in the same plane

If $n2 > n1$; then, $\theta 2 < \theta 1$

If the index of second medium is less, it bends away from the normal

At a particular incident angle, refraction angle will be 90° : total internal reflection will be 90° : total internal reflection

...nt. This is what we saw in Fig. 23–17.



...RE 23-20 Light passing ...h a piece of glass (Example

EXAMPLE 23–5 Light strikes a flat piece of glass at an incident angle of 60°, as shown in Fig. 23–20. If the index of refraction of the glass is 1.50, (*a*) what is the angle of refraction θ_a in the glass; (*b*) what is the angle θ_b at which the ray emerges from the glass?

SOLUTION (*a*) We assume the incident ray is in air, so $n_1 = 1.00$ and $n_2 = 1.50$. Then, from Eq. 23–5 we have

$$\sin\theta_a = \frac{1.00}{1.50}\sin 60° = 0.577,$$

so $\theta_a = 35.2°$.

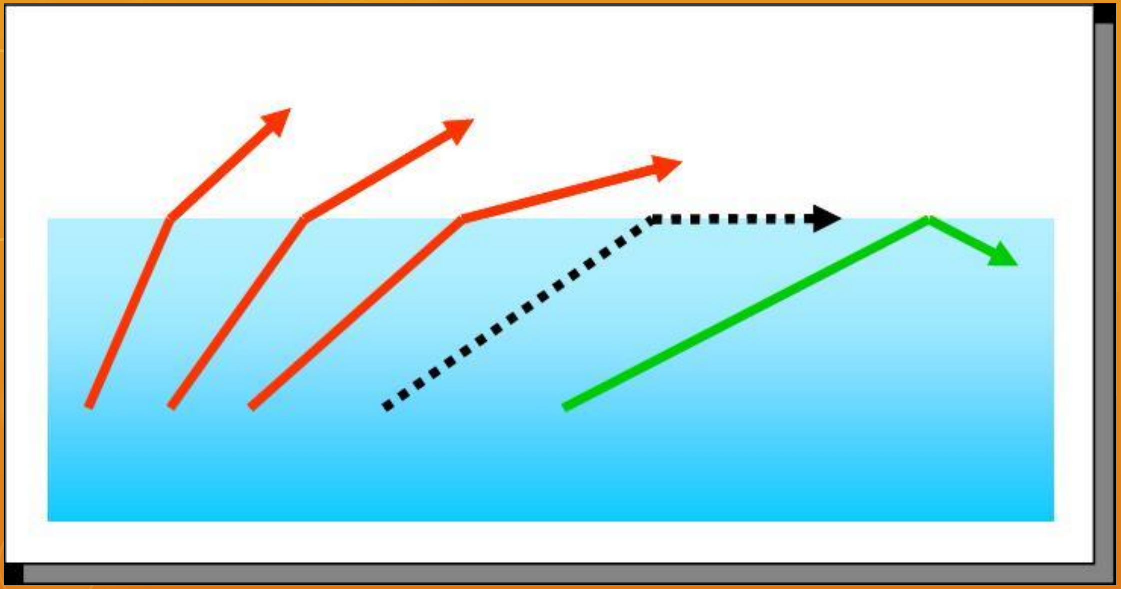
(*b*) Since the faces of the glass are parallel, the incident angle in this case is just θ_a, so $\sin\theta_a = 0.577$. This time $n_1 = 1.50$ and $n_2 = 1.00$. Thus, θ_b $(=\theta_2)$ is

$$\sin\theta_b = \frac{1.50}{1.00}\sin\theta_a = -0.866,$$

and $\theta_b = 60.0°$. The direction of the beam is thus unchanged by passing through a plane piece of glass. It should be clear that this is true for any angle of incidence. The ray is displaced slightly to one side, however. You can observe this by looking through a piece of glass (near its edge) at some object and then moving your head to the side so that you see the object directly.

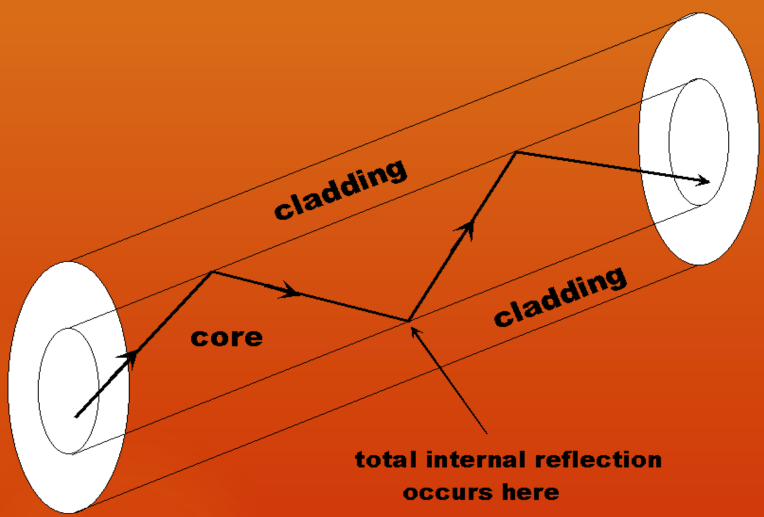
Total Internal Reflection

- Light passes to the medium with less refraction index and bends away from normal
- At particular angle , it skims the surface
- Critical angle : $\theta_c = n_2 / n_1$ (sin 90)
- If incident angle is greater than critical angle: all of the light is reflected. This effect is called "total internal reflection"



- Fiber Optics: Glass and plastic fibers as thin as a few micrometers in diameter
- Such a bundle of tiny fibers is called a light pipe
- A patient’s stomach can be examined by inserting a light pipe

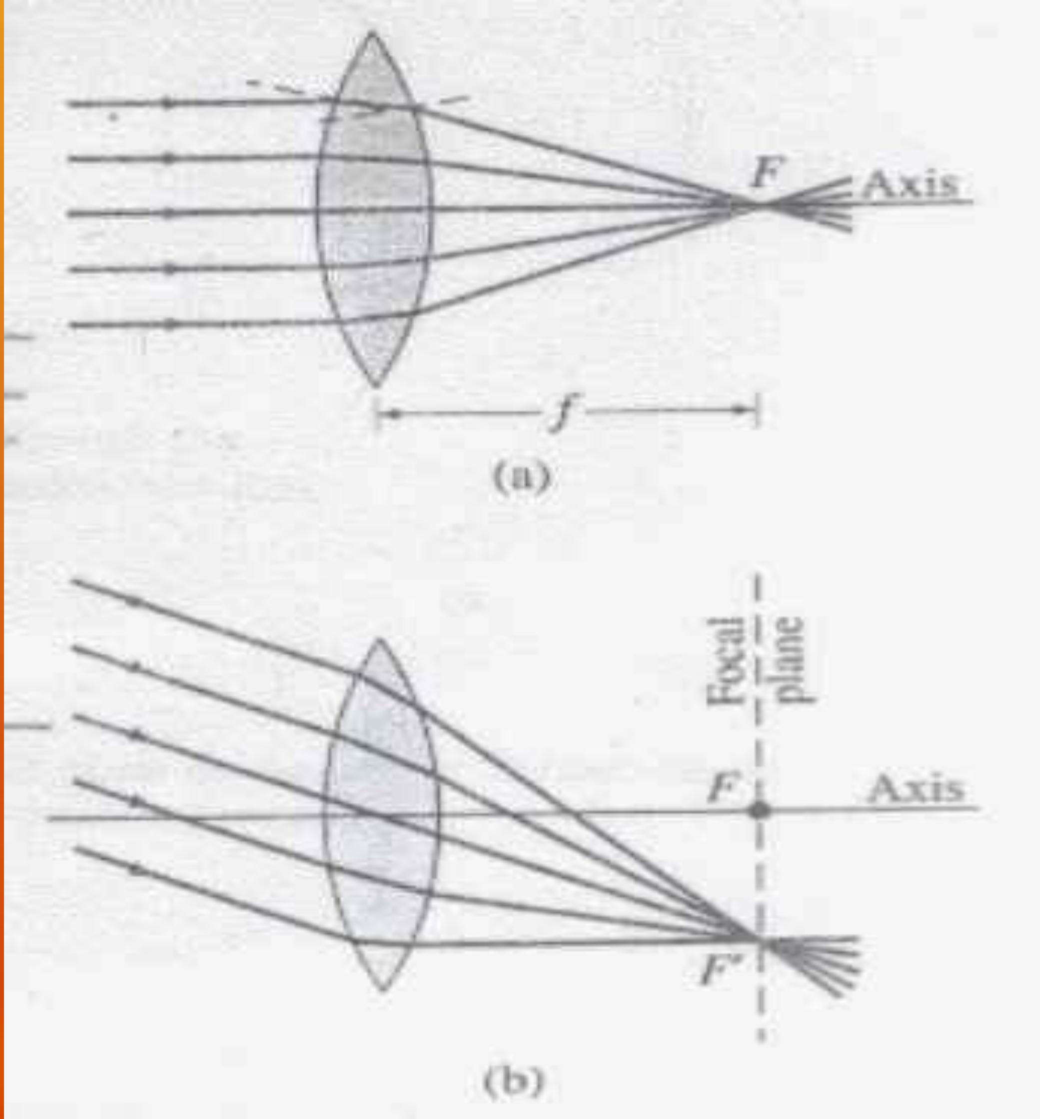
- **Fiber Optics**
- A fiber optic consists of a glass, plastic or silica core surrounded by an outer covering with a lower index of refraction than the core.
- Fiber optics transmit light via total internal reflection. The light inside of the fiber optic completely reflects off of the cover and back into the core. The light then travels down the fiber by bouncing off until it reaches the end of the fiber. The benefit of an optical fiber is that it can bend and travel fairly long distances without losing energy or distorting the light.



Thin Lenses

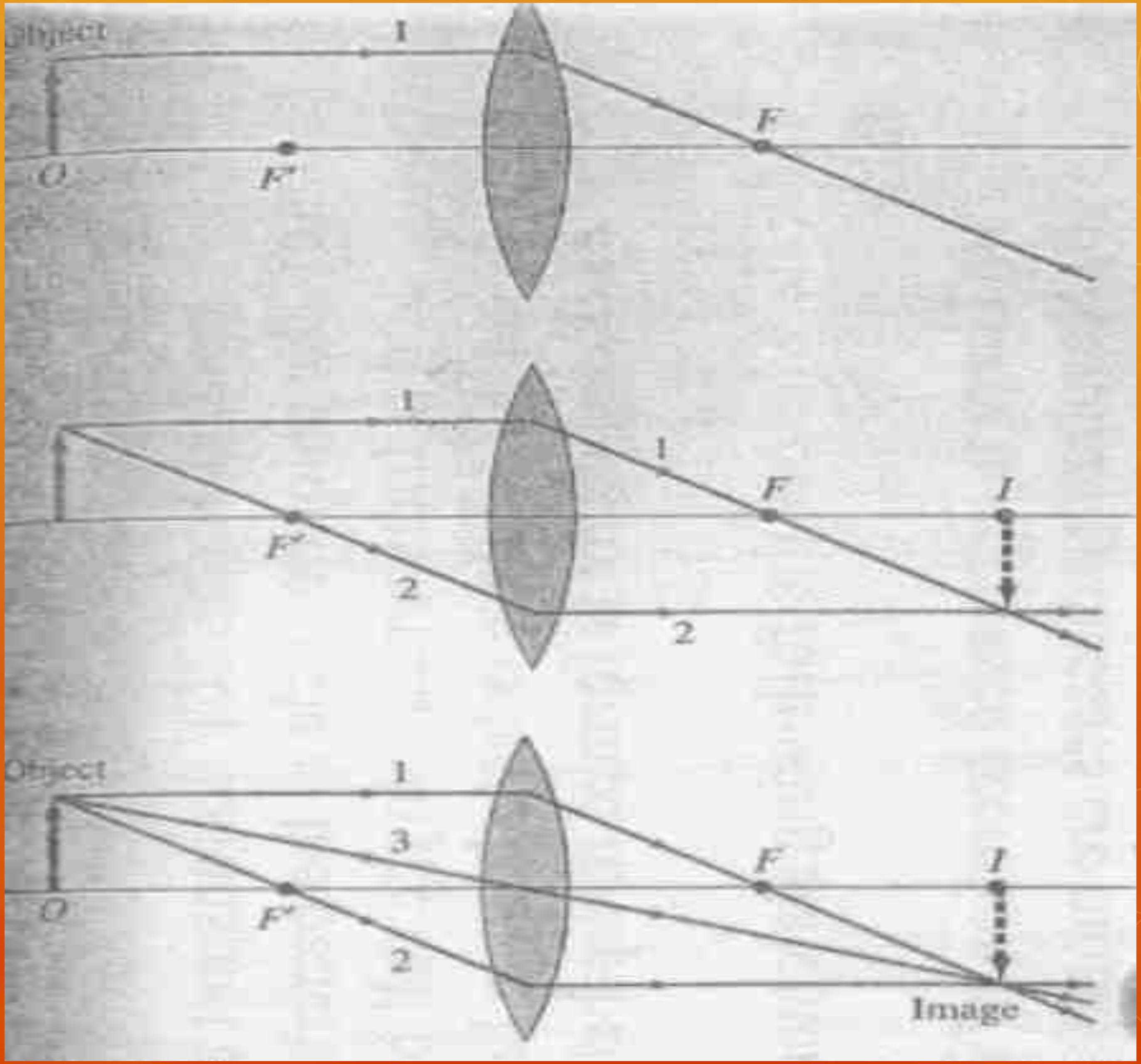
- A thin lense is usually circular, and its two faces are portions of a sphere
- Two faces can be concave, convex or plane
- Axis of a lens is the straight line through its center
- If rays parallel, they will be focused at focal point, F (assume diameter of lens << than the radius of curvature)

Properties of the image



- Focal point is the image point for an object at infinity
- Focal length is the same for both sides, even if the curvatures are different
- If parallel rays fall on a lens at angle, they will be focused in a new point, F', which is in the same plane with focal point, F. (focal plane)
- Any lens that is thicker in the center than at edges is called converging lens.

- Lenses that are thinner at the center are called diverging lenses, because they make parallel light diverge.
- Optometrists and opthalmologists use reciprocal of the focal length to specify strength of a lens:
- Power = $1 / f$
- Unit for lens power is diopter. 1 D = 1 m^{-1}. For ex. a 20 cm focal length lens has a power of 1/0.20 m = 5 D



Object
1
F
O
F'
1
1
F
I
F'
2
2
Object
1
3
F
I
O
F'
2
Image

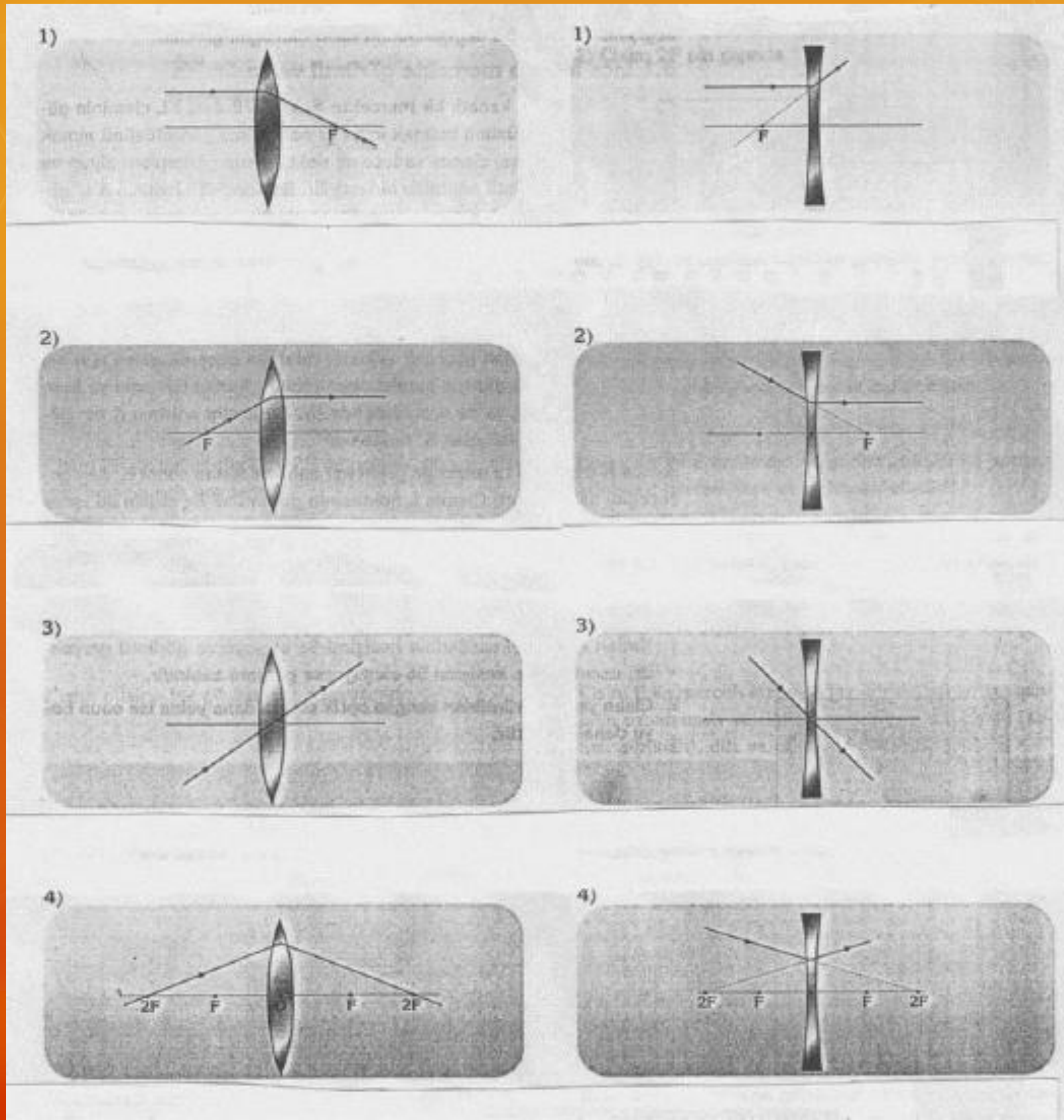
- d_o :object distance ; d_i : image distance
- h_o : height of the object ; h_i : height of the image
- h_i / h_o = d_i - f / f *
- h_i / h_o = d_i / d_o **
- $$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$ lens equation for a converging lens

- The focal length is positive for converging and negative for diverging lenses
- The object distance is positive if it is on the side of the lens from which light is coming.
- Image distance is negative if it is on the same side from where the light is coming
- Object and image heights, h_o and h_i are positive for points above the axis, and are negative if they are below the axis

- Lens equation for a diverging lens:
- $(1/d_0) - (1/d_i) = -(1/f)$
- The lateral magnification , m , of a lens is defined as the ratio of:
- image height = $\frac{h_i}{h_o}$
- object height
- $M = h_i / h_o = -d_i / d_o$
- Power of a converging lens is positive, power of a diverging lens is negative

What is (a) the position, and (b) the size, of the image of a large 7.6 cm high flower placed 1 m from a 50 mm focal length camera lens?

- (a) the camera lens is converging, with f=50 mm= 5 cm; and d_0 = 100 cm; then:
- $(1/d_i) = (1/f) - (1/d_o) = 100/19 = 5.26$ cm behind the lens
- image is 2.6 mm farther than an object at infinity
- (b) $m = -d_i / d_o = -5.26/100 = -0.0526$
- $h_i = m\, h_o = (-0.0526)\,(7.6) = -0.4$ cm. The image is 4 mm high and is inverted



1)
F
1)
F
2)
F
2)
F
3)
3)
4)
2F
F
O
F
2F
4)
2F
F
F
2F

Common principles of optical imaging

Real image (can be projected): convergence of rays

Virtual image (cannot be projected): divergence of ray

Principal axis – optical axis of centred system of optical boundaries

Principal focus is a point where rays parallel to the principal axis

intersect after refraction by the lens or reflection by the curved mirror - front (object) focus and back (image) focus

Focal distance (length) f [m] is the distance of focus from the centre of the lens or the mirror

The **radii of curvature** are positive (negative) when the respective lens

or mirror surfaces are convex (concave).

Dioptric power (strength of the lens): reciprocal value of focal length

$\phi = D = S = 1/f \quad [m^{-1} = dpt = D$ (dioptre)]

Converging lenses: f and ϕ are positive

Diverging lenses: f and ϕ are negative

The Lens-Maker's Equation:

- **The position, orientation, and size of an image formed by a lens**
- **are determined by two things:**
- **the focal length of the lens and**
- **the position of the original object.**

- **Now the focal length of a lens is determined by two**
- **things itself:**
- **the radius of curvature of the lens and**
- **the index of refraction of the material of which the lens is made.**

Lens equation

The rays parallel to the principal axis are refracted into the back focus (in converging lens), or so that they seem to be emitted from the front focus (in diverging lens). The direction of rays passing through the centre of the lens remains uninfluenced. Lens equation (equation of image, imaging equation):

$$\frac{1}{f} = \frac{1}{a} + \frac{1}{b}$$

a **– object distance [m]**

b **– image distance [m]**

Sign convention:

a is positive in front of the lens, negative behind the lens;

b is negative in front of the lens (the image is virtual), positive behind the lens (the image is real)

Lens–maker's equation

$$\frac{1}{f}=\left(\frac{n_2}{n_1}-1\right)\cdot\left(\frac{1}{r_1}+\frac{1}{r_2}\right)$$

Here focal length is related to radii of curvature and index of refraction.

!!! f DOES NOT DEPEND ON heights

So position of f does not depend on where the reays strike on lens

!!!!Equation is symmetrical in r_1 and r_2

F - focal distance (length) [m]

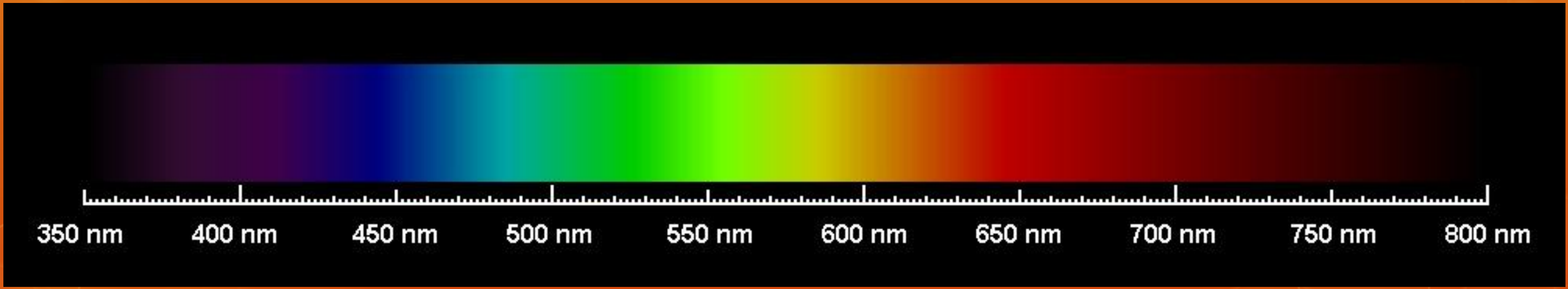
n_2 - index of refraction of the lens

n_1 - index of refraction of the medium

r_1, r_2 - radii of curvature of the lens

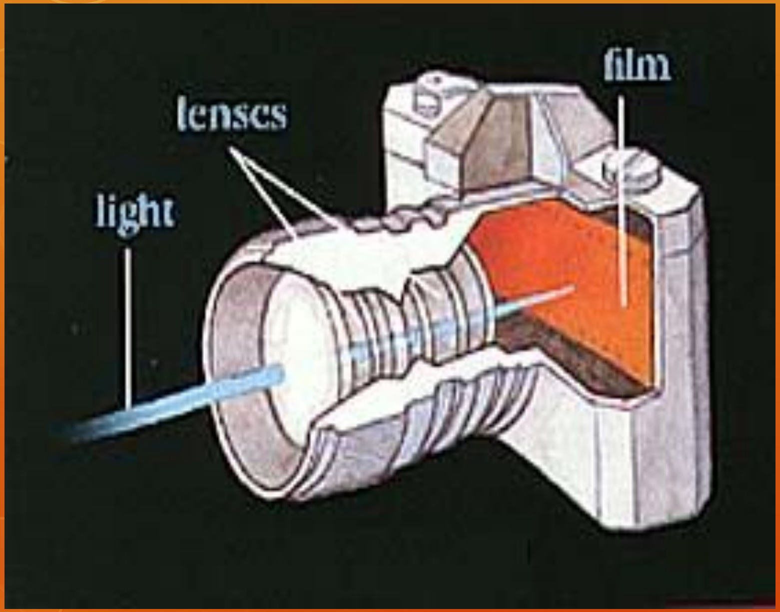
Visible spectrum

The human eye can detect light from about 380 nm (violet) to about 760 nm (red). Our visual system perceives this range of light wavelength as a smoothly varying rainbow of colours. We call this range **visible spectrum**. The following illustration shows approximately how it is experienced.

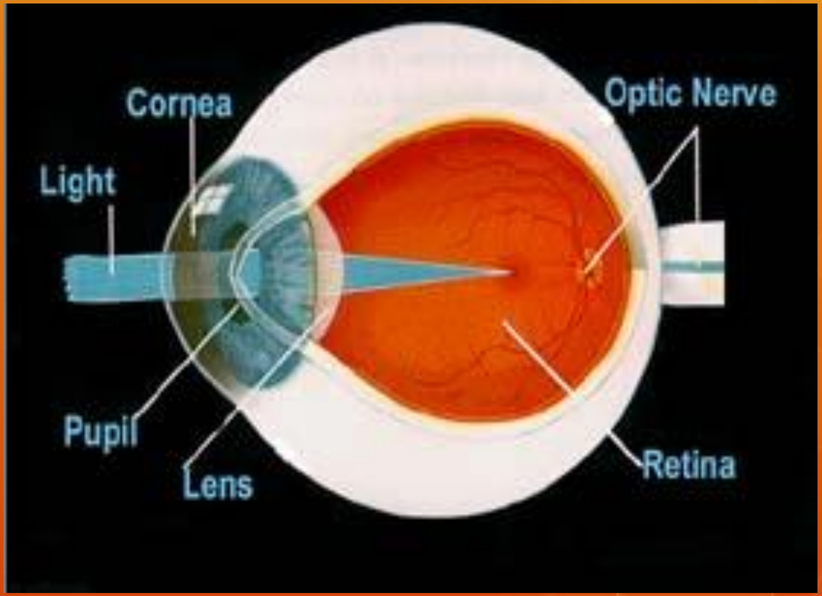


How Does The Human Eye Work?

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

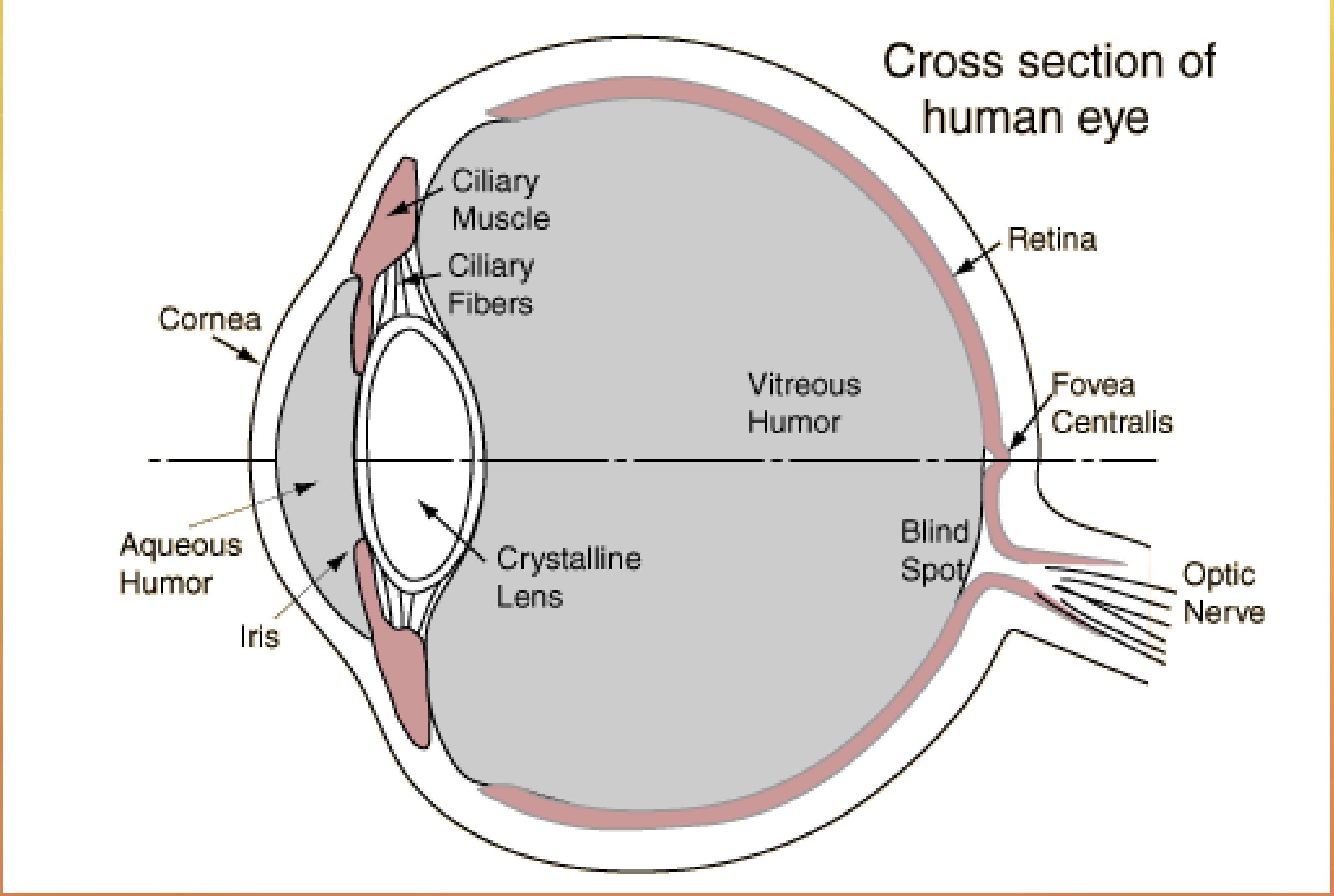
Visual analyser consists of three parts:

- **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 picture is perceived

Anatomy of the eyeball



Anatomy of the eyeball

The tough, outermost layer of the eye is called the **sclera**. It maintains the shape of the eye.

The front about sixth of this layer is clear and is called the **cornea**. All light must first pass through the cornea when it enters the eye. Attached to the sclera are the six_muscles that move the eye, called the **extraocular muscles**.

The **chorioid** (or uveal tract) is the second layer of the eye. It contains the blood vessels that supply blood to structures of the eye. The front part of the chorioid contains two structures:

- The **ciliary body** - the ciliary body is a muscular area that is attached to the lens. It contracts and relaxes to control the curvature of the lens for focusing.

Anatomy of the eyeball

The **iris** - the iris is the coloured part of the eye. The colour of the iris is determined by the colour of the connective tissue and pigment cells. Less pigment makes the eyes blue; more pigment makes the eyes brown. The iris is an adjustable diaphragm around an opening called the **pupil**.

Inside the eyeball there are two fluid-filled sections separated by the lens. The larger, back section contains a clear, gel-like material called **vitreous humour**

The smaller, front section contains a clear, watery material called **aqueous humour**

The aqueous humour is divided into two sections called the anterior chamber (in front of the iris) and the posterior chamber (behind the iris).

The iris has two muscles:

The *m. dilator pupillae* makes the iris smaller and therefore the pupil larger, allowing more light into the eye;

the *m. sphincter pupillae* makes the iris larger and the pupil smaller, allowing less light into the eye.

Pupil size can change from 2 millimetres to 8 millimetres.

This means that by changing the size of the pupil, the eye can change the amount of light that enters it by 30 times.

The transparent ***crystalline lens*** of the eye is located immediately behind the *iris*. It is a clear, bi-convex structure about 10 mm in diameter. The lens is kept in flattened state by tension of fibres of suspensory ligament. The lens changes shape because it is attached to muscles in the ciliary body, which act against the tension of ligament. When this **ciliary muscle** is

- **relaxed**, its diameter increases and the **lens is flattened**.
- **contracted**, its diameter is reduced, and the **lens becomes more spherical** (which is its natural state).

These changes enable the eye to adjust its focus between far objects and near objects.

The crystalline lens is composed of 4 layers, from the surface to the center: capsule, subcapsular epithelium, cortex, nucleus

The lens system of the eye is composed of

- (1) the interface between air and the anterior surface of the cornea
- (2) the interface between posterior of the cornea and the aqueous humor
- (3) the interface between the aqueous humor and the anterior surface of the lens
- (4) the interface between the posterior surface of the lens and the vitrous humor

Divisions of Eye *n*

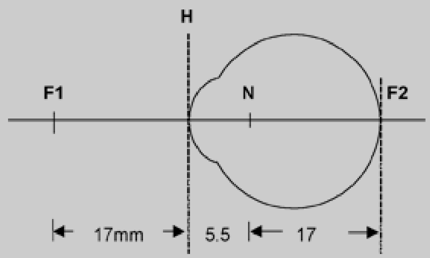
Cornea	***1.38***
Aqueous humor	***1.34***
Lens	***1.41***
Vitreous humor	***1.34***

- Refractive index is markedly different than air
- Surface is farther away from retina
- Curvature is great

- Refraction in the cornea and lens
- Most of the refraction: cornea which has a fixed focal length
- Crystalline lens is adjustable
- When ciliary muscles are relaxed, the lens is held in a strained position by ciliary fibers : focus on a distant object

Reduced Eye

In the real eye the cornea supplies 40 D and the lens 20 D of focusing power. In the simplified model they are combined as one focusing unit, located at H, with total focusing power (P) of 60 D. The index of refraction of the inside of the eye is taken as n′ = 1.33. Note total eye length in the reduced model is: 17mm + 5.5mm = 22.5mm.



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

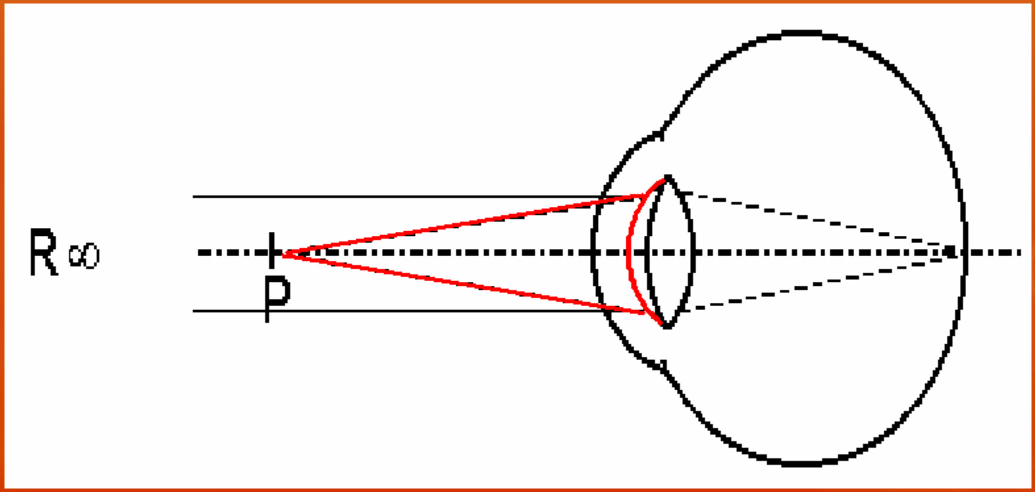
- Two lenses act together as a single lens
- Effective position of this single lens is about 2.2 cm from retina
- Then S = 45 diopters
- Effective focal length for distant object is also 2.2 cm
- Since the image distance is fixed, focal length must change

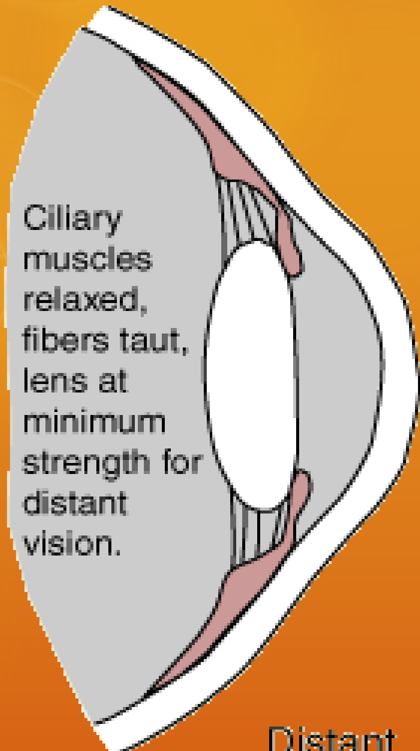
Accommodation

Accommodation is eye lens ability to change its dioptric power in dependence on distance of the observed object.

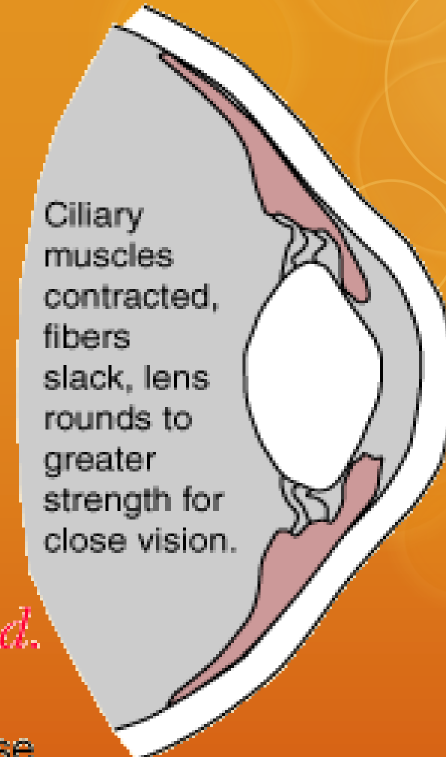
Accommodation – allowed by increasing curvature of outer lens wall (J.E.Purkyně)

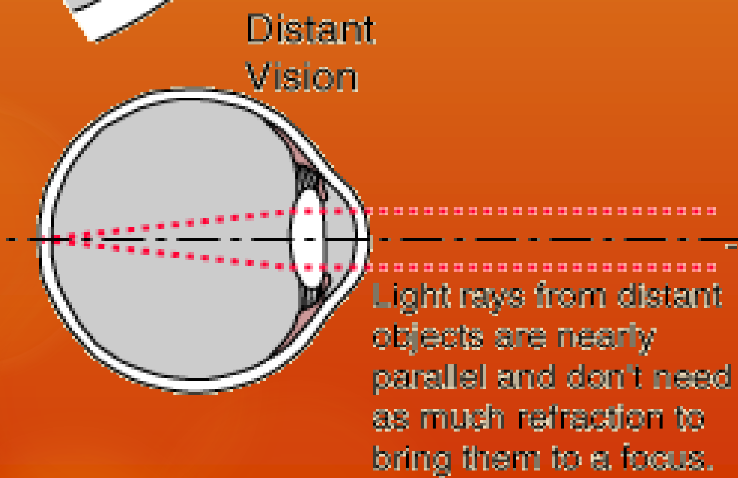
- **Far point** - *punctum remotum* (R) - farthest point of distinct vision without accommodation.
- **Near point** - *punctum proximum* (P) - nearest point of distinct vision with maximum accommodation.
- The **amplitude of accommodation** is defined as the difference of reciprocal values of the distances of the near a and far point, expressed in dioptres. In an emmetropic eye the reciprocal value of the far point equals to zero ($1/\infty = 0$), thus the amplitude of accommodation is given by the reciprocal value of the near point distance.

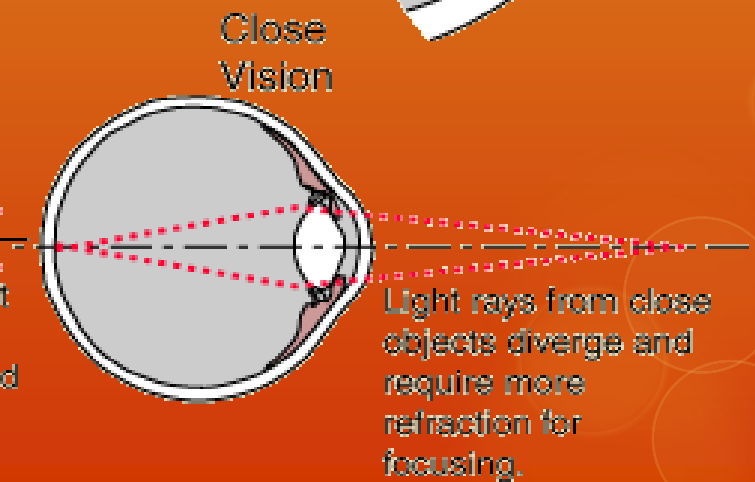




The eye accommodates for close vision by tightening the ciliary muscles, allowing the pliable crystalline lens to become more rounded.

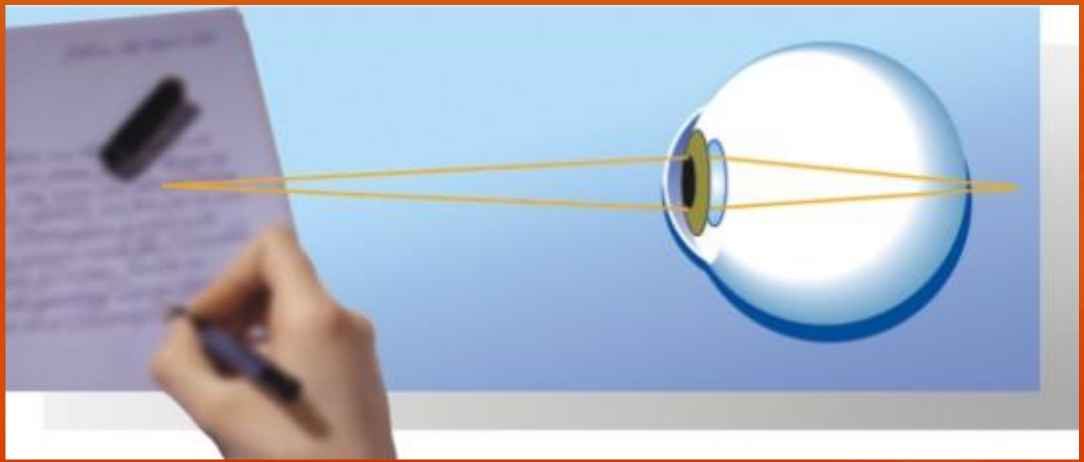






Presbyopia ("after 40" vision) Old–age sight

After age 40, and most noticeably after age 45, the human eye is affected by ***presbyopia***, which results in greater difficulty maintaining a clear focus at a near distance with an eye which sees clearly at a far away distance. This is due to a lessening of flexibility of the crystalline lens, as well as to a weakening of the ciliary muscles which control lens focusing, both attributable to the aging process.



Retina – biological detector of the light

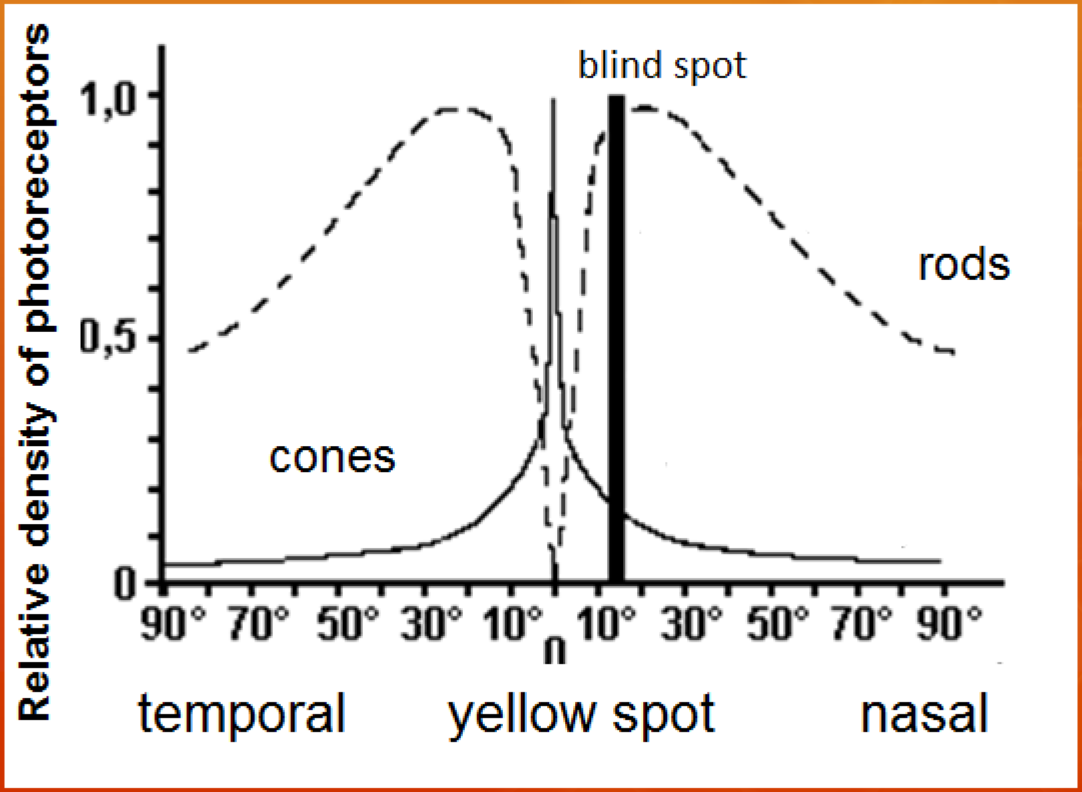
Retina - the light-sensing part of the eye.

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.

Blind spot

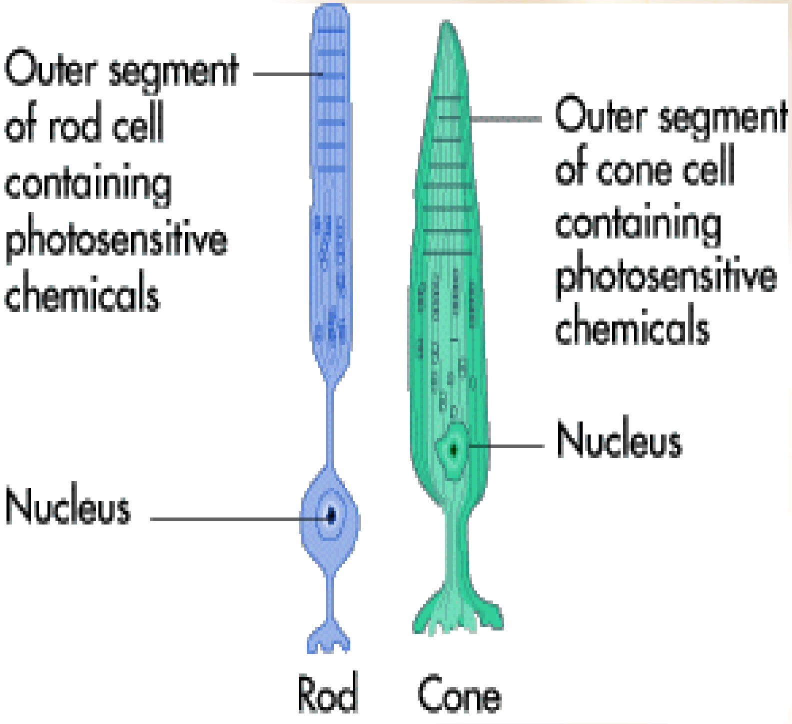
Density of cones decreases from the yellow spot to the periphery of retina. The rods have maximum density in a circle around the yellow spot (20° from this spot). The nerve fibres transmitting the stimulation of photoreceptors converge to a place positioned nasally from the yellow spot. This place with no photoreceptors is called **blind spot.**



Rods and cones

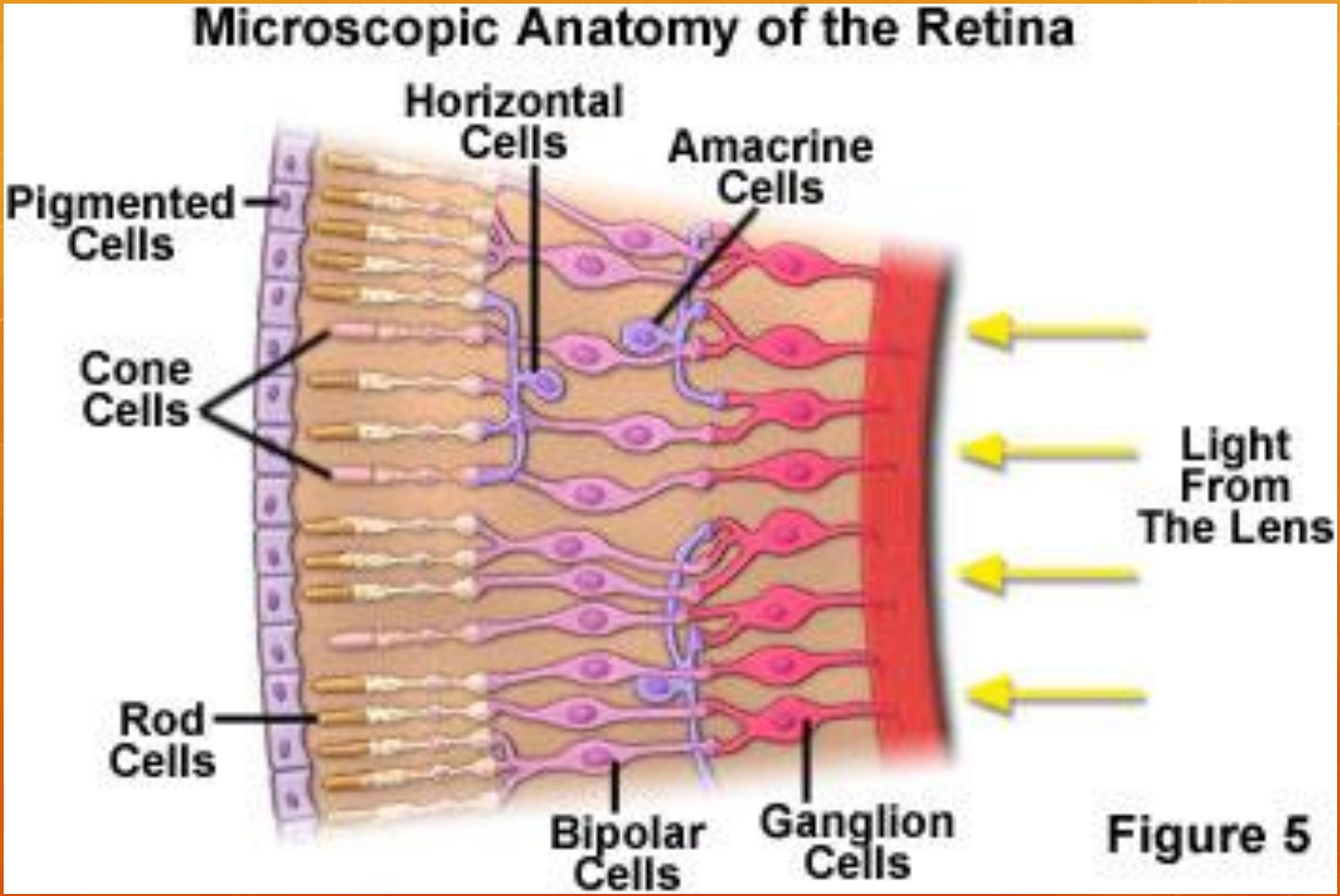
The outer segment of a rod or a cone contains the photosensitive chemicals. In rods, this chemical is called **rhodopsin.** In cones, these chemicals are called **colour pigments**.

The retina contains 100 million rods and 7 million cones.

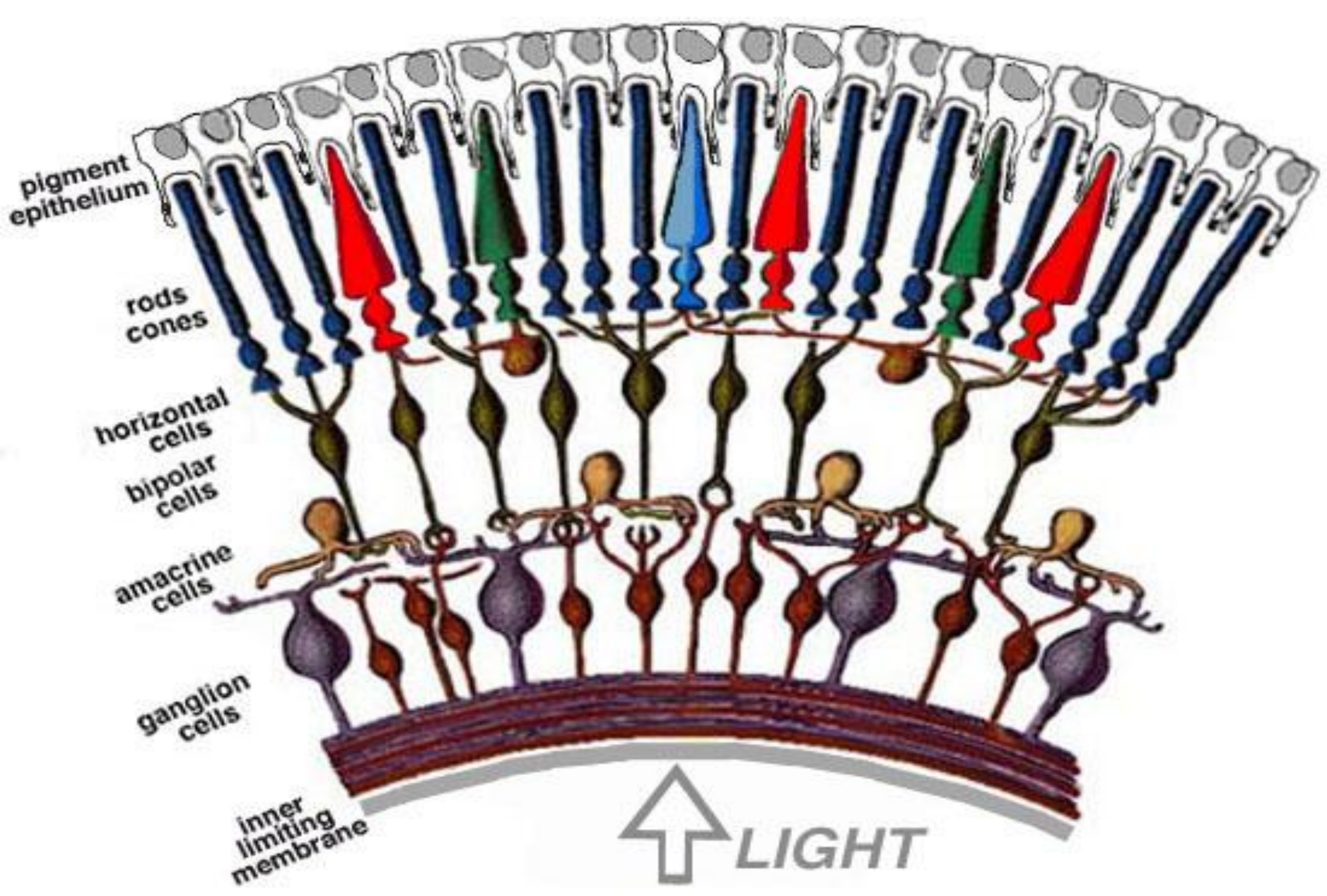


- If effective center is 2.0 cm apart from retina for a person, find the focal length and lens strength required to focus on objects at ∞, 50 meters, 1 meter, and 25 cm.
- (50, 50.02, 51, 54 D)

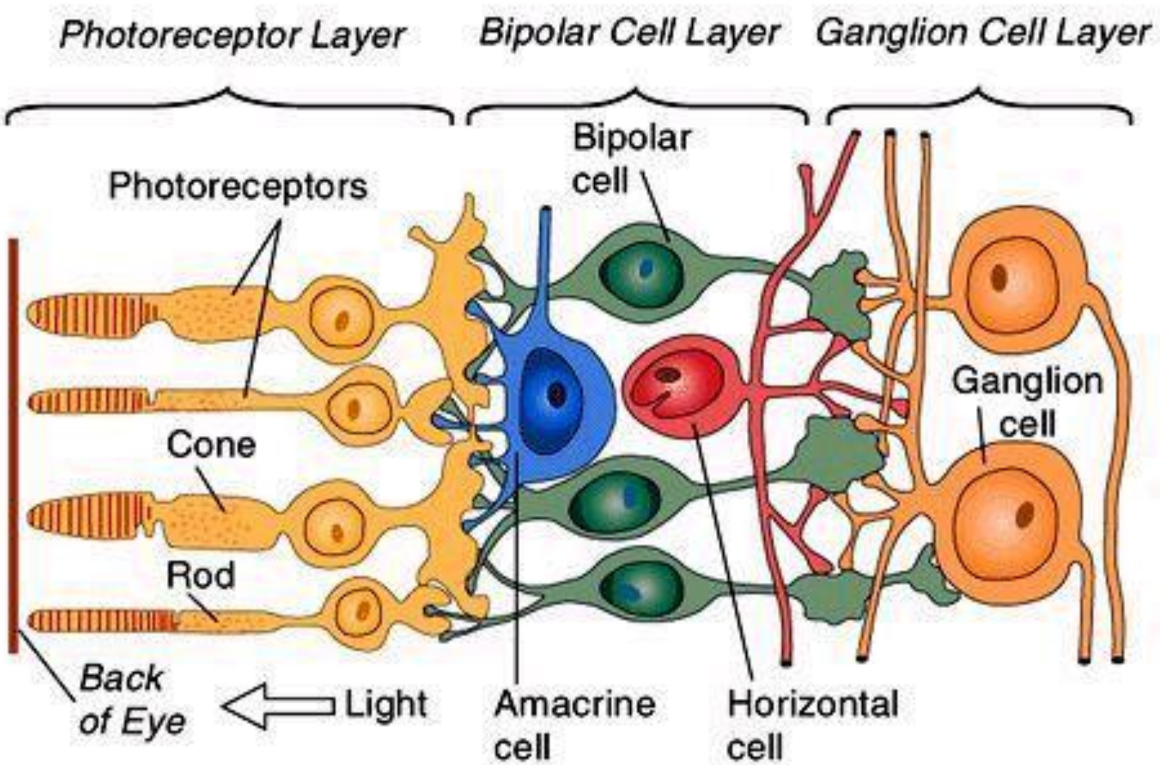
- !!The focal length of the lens system changes only about 6% to 8% in the entire range of focus of the eye.


Microscopic Anatomy of the Retina
Horizontal Cells
Amacrine Cells
Pigmented Cells
Cone Cells
Light From The Lens
Rod Cells
Bipolar Cells
Ganglion Cells
Figure 5

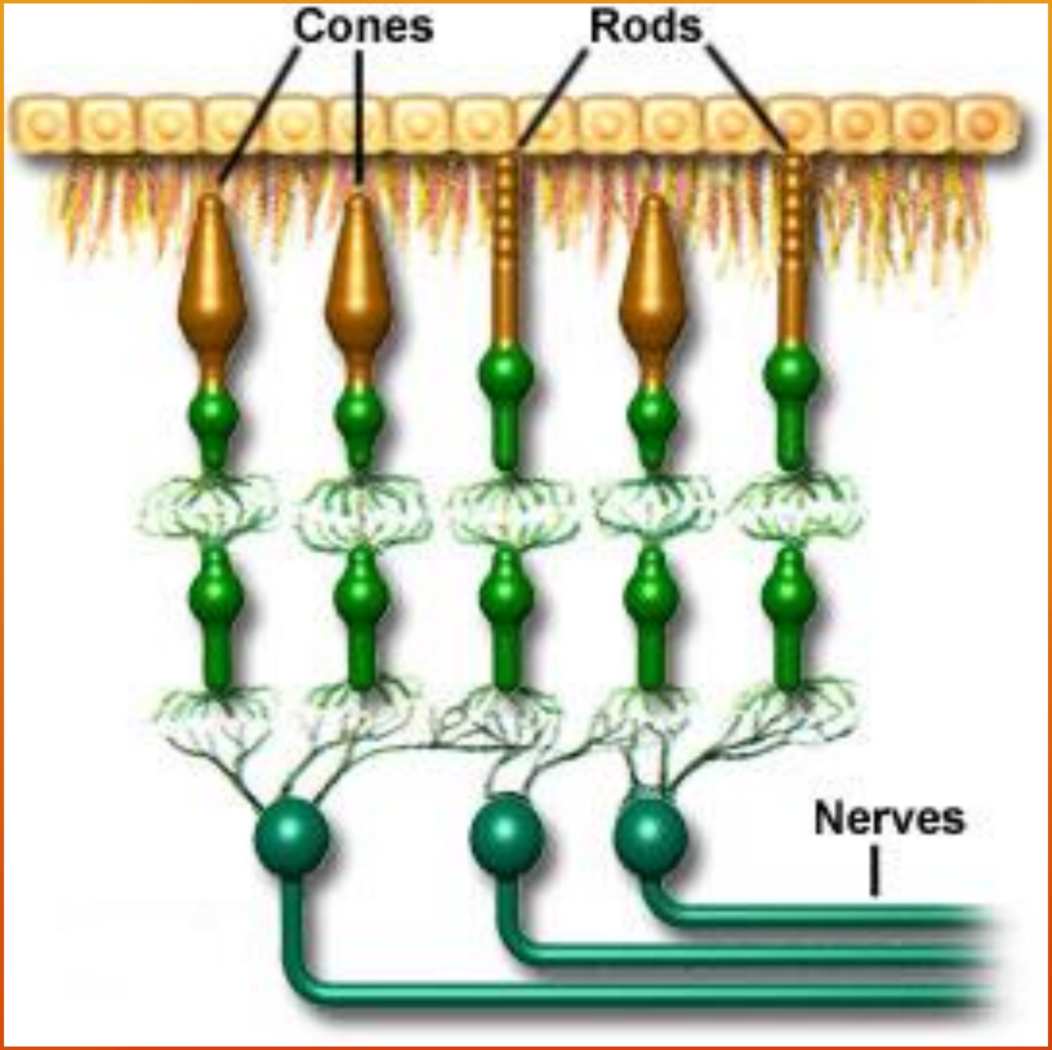
Structure of retina



► **Details of Retinal Circuitry**



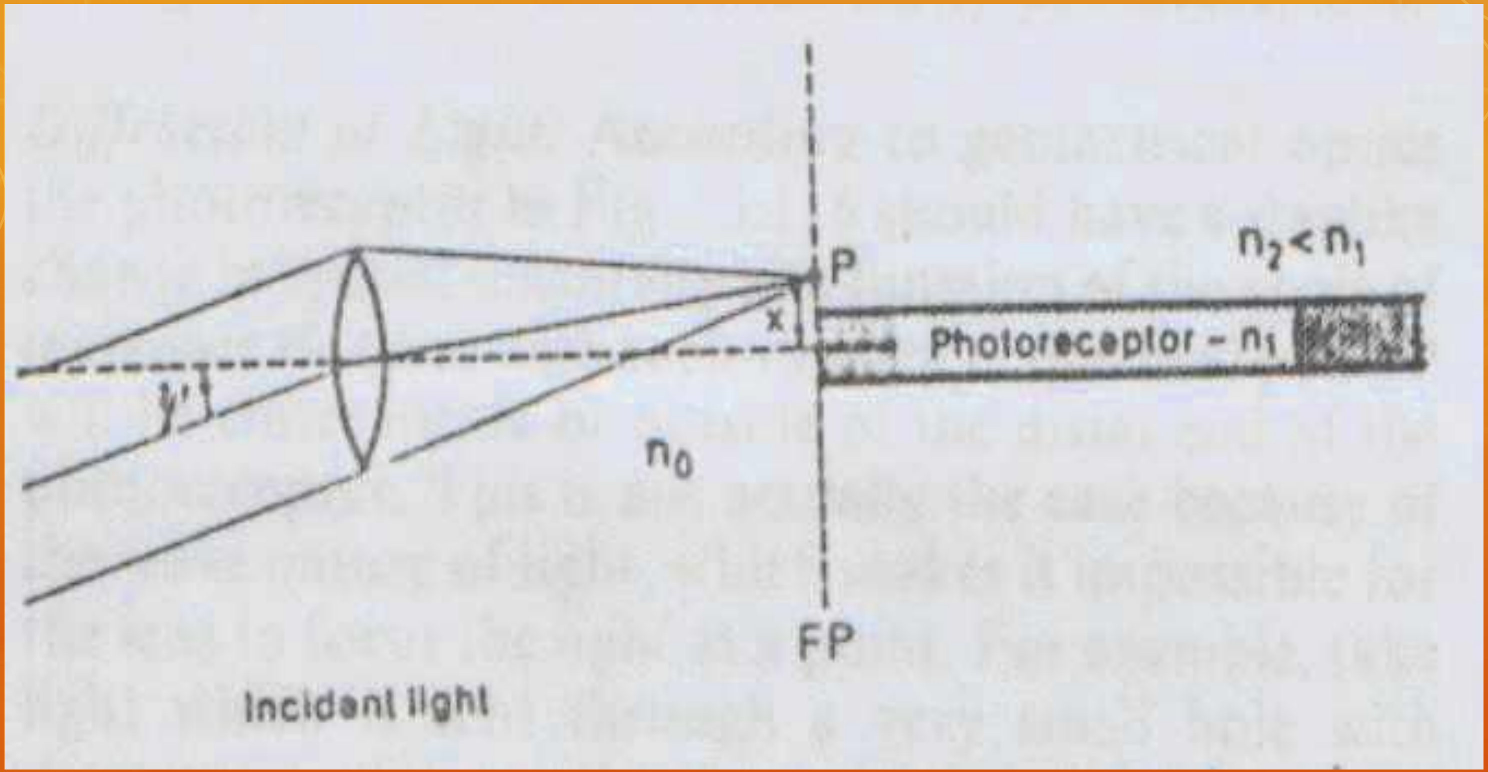
Source: Adapted from Dowling, J. E., and Boycott, B. B. *Proceedings of the Royal Society of London, B.*, 1966, *166*, 80–111


Cones
Rods
Nerves

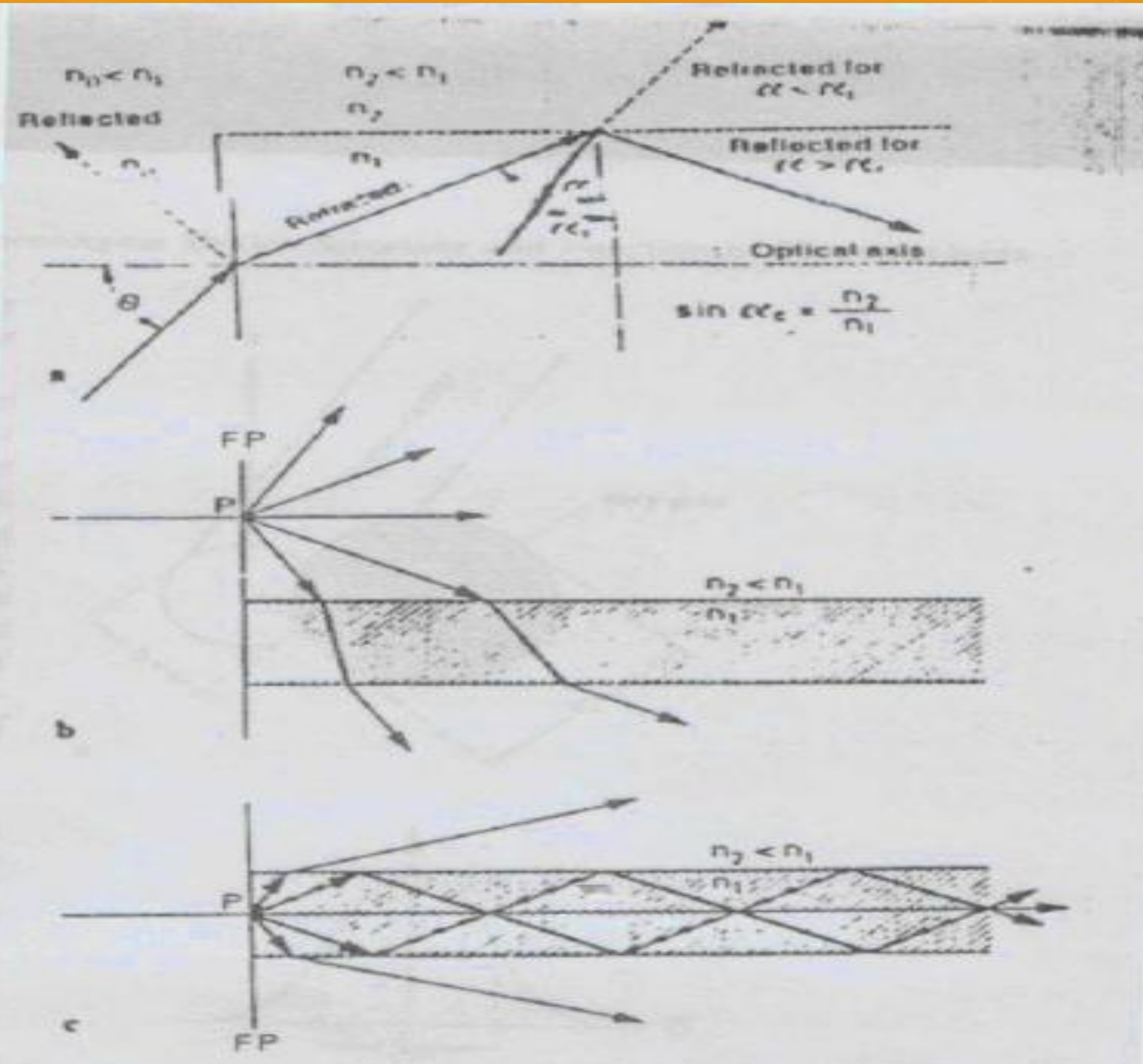
Photoreceptor Optics

- Duration of light stimulus
- direction of light
- wavelength

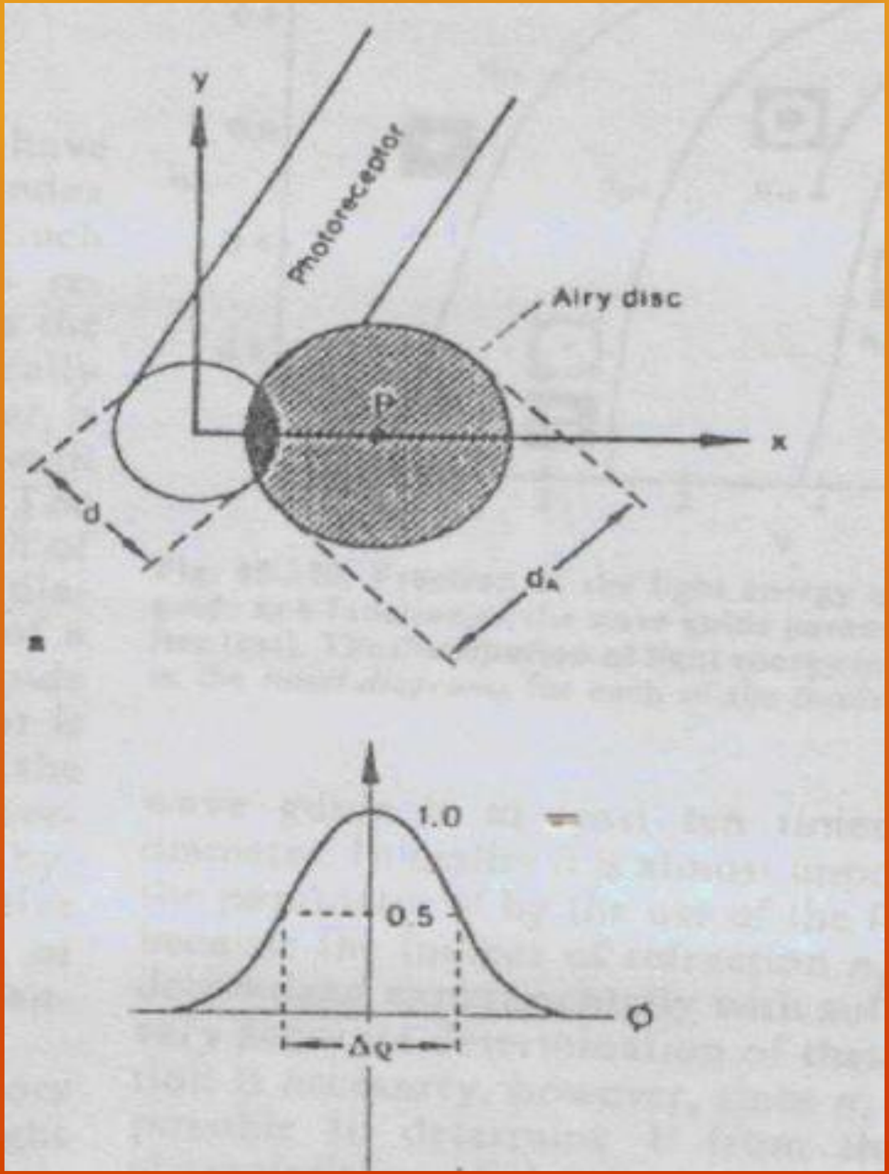
- Visual pigments
- Higher index of refraction
- Elongated structure
- Higher density $\rightarrow$higher resolution
- Layered system



P
$n_2 < n_1$
x
Photoreceptor – n_1
y'
n_0
FP
Incident light

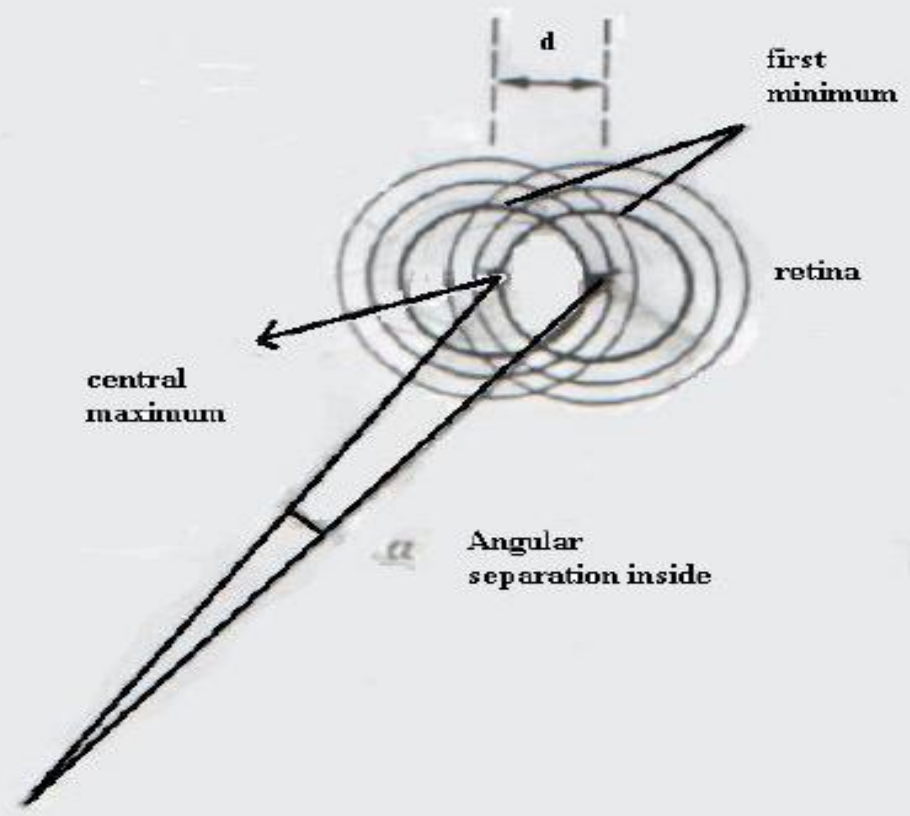


n0 < n1
n2 < n1
Refracted for α < αc
Reflected
n2
n1
Reflected for α > αc
Refracted
Optical axis
θ
sin αc = n2/n1
a
FP
P
n2 < n1
n1
b
n2 < n1
n1
P
c
FP


y
Photoreceptor
Airy disc
P
x
d
dA
1.0
0.5
Δφ
φ

Diameter of the diffraction disc(Airy Disc)

- **$d_A = 2.44 (\lambda / d_a)(f / n_o)$ for $d_A << f$**
  - d_a : diameter of the lens
  - d_A : diameter of the airy disk
  - f : focal length of the lens
  - n_0 : index between lens and the focal plane (retina)
  - For constant lens parameters (f, n_0) $d_A \propto \lambda / d_a$



Rayleigh resolution criterion

- If the minimum diameter of pupil is 1.5 mm and λ = 500 nm, angular separation:
- α = 1.22 (500×10^{-9}) = 3×10^{-4} radians.
- 1.33 (1.5×10^{-3})
- If it is open at maximum (8 mm), α = 7.6×10^{-5} radians. I.e., when pupilla is open, resolution is greater.
- This angular separation can be converted to linear separation, by multiplying it to corneal-retinal distance, which is the focal distance of the eye lens (0.025 m on average).
- α = dl / 0.025 m
- When pupil is open 1.5 mm, dl = 7.5 μm (at worst)
- When pupil is open 2.0 mm, dl = 5.8 μm
- When pupil is open 8.0 mm, dl = 1.9 μm (at best)

- The average cone separation in the fovea (where cones are very densely packed and eye's resolution is highest) is about 2 μm (diameter of cones). So, when pupil is 2 mm open, distance between two adjacent points is 5.8 μm which corresponds to 3 cones.
- This is necessary to create an effective visual response. Two active cones must be separated by a "cold" cone in order to create the sensation of an image point.
- Even this is very high resolution indeed. Generally we need at least 4 cones. In reality, eye can not discriminate objects closer than 5x10-4 radians, which corresponds to objects separated 1 cm at a distance of about 20 m.

Rhodopsin

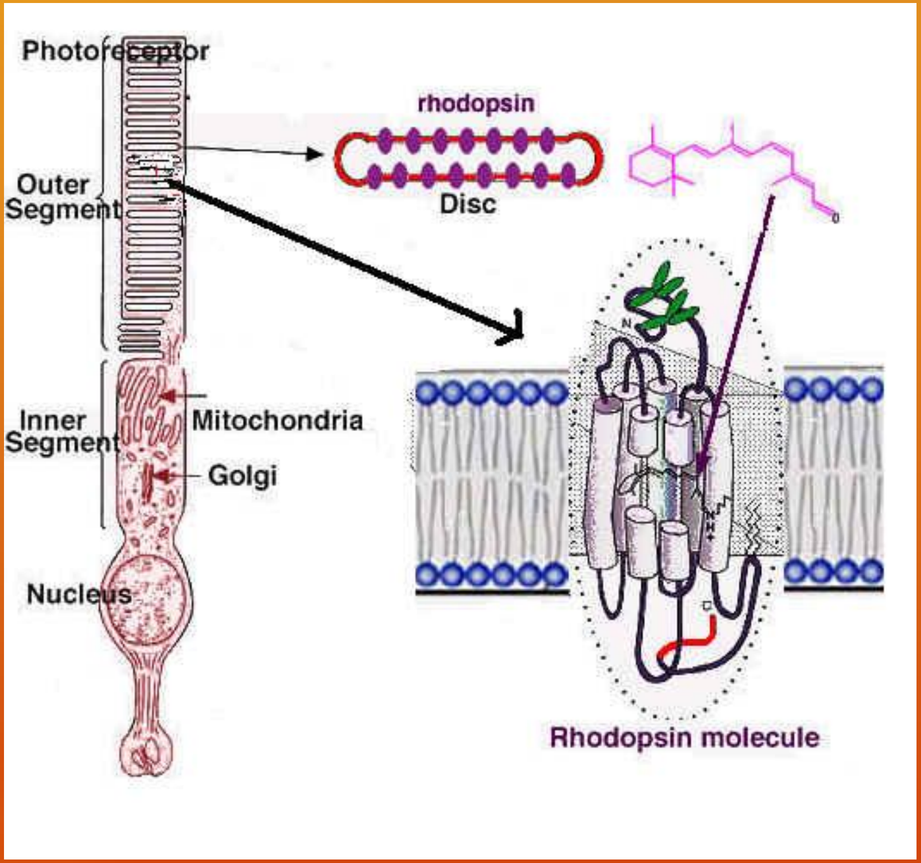
Rhodopsin is a complex of a protein consisted of **opsin** and **11-cis-retinal** (derived from **vitamin A)** (⇒ lack of vitamin A causes vision problems).

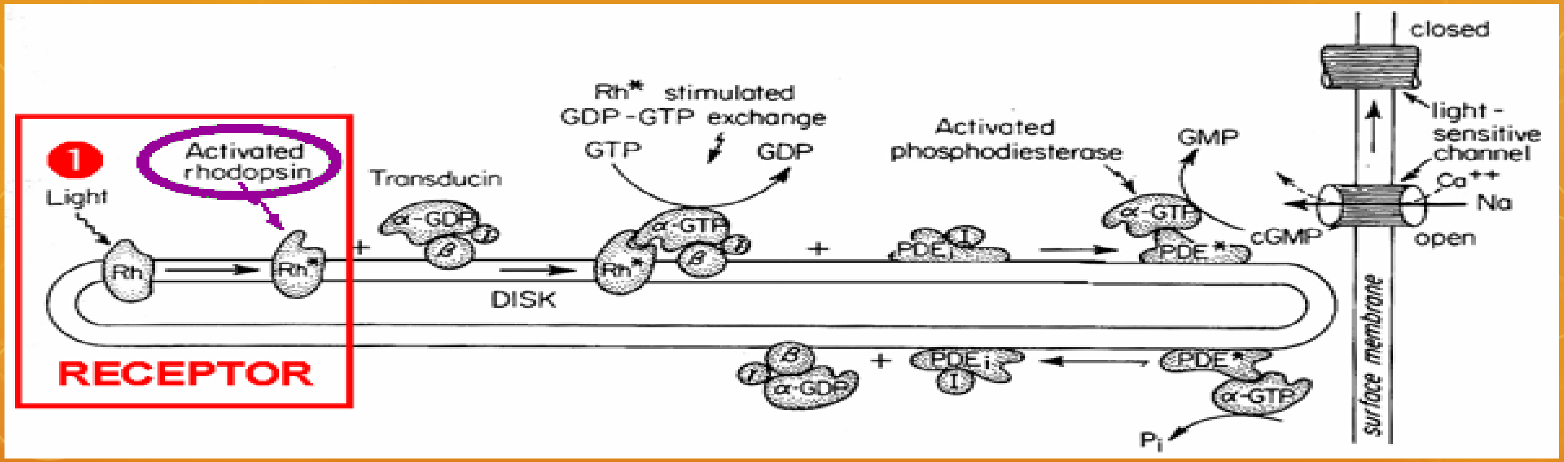
Rhodopsin decomposes when it is exposed to light because light causes a physical change in the 11-cis-retinal, changing it to **all-trans retinal**.

This first reaction takes only a few *trillionths of a second.* The 11-cis-retinal is an angulated molecule, while all-trans retinal is a straight molecule. This makes the chemical unstable.

Rhodopsin breaks down into several intermediate compounds, but eventually (in less than a second) forms **metarhodopsin II** (activated rhodopsin).

Biochemistry of rhodopsin:





1) activation of the receptor protein in rods (rhodopsin)
1 photon → 1 rhodopsin
2) the activated receptor protein stimulates the G-protein transducin : GTP is converted to GDP in the process
1 rhodopsin →100 transducins/s
3) In turn, activated transducin activates the effector protein phosphodiesterase PDE converts cGMP to GMP
1 transducin → 100 PDE/s
4) Falling concentrations of cGMP cause the transduction channels to CLOSE, DECREASING a Na^{+} current
1 PDE → 1000 GMP/s

Colour Vision

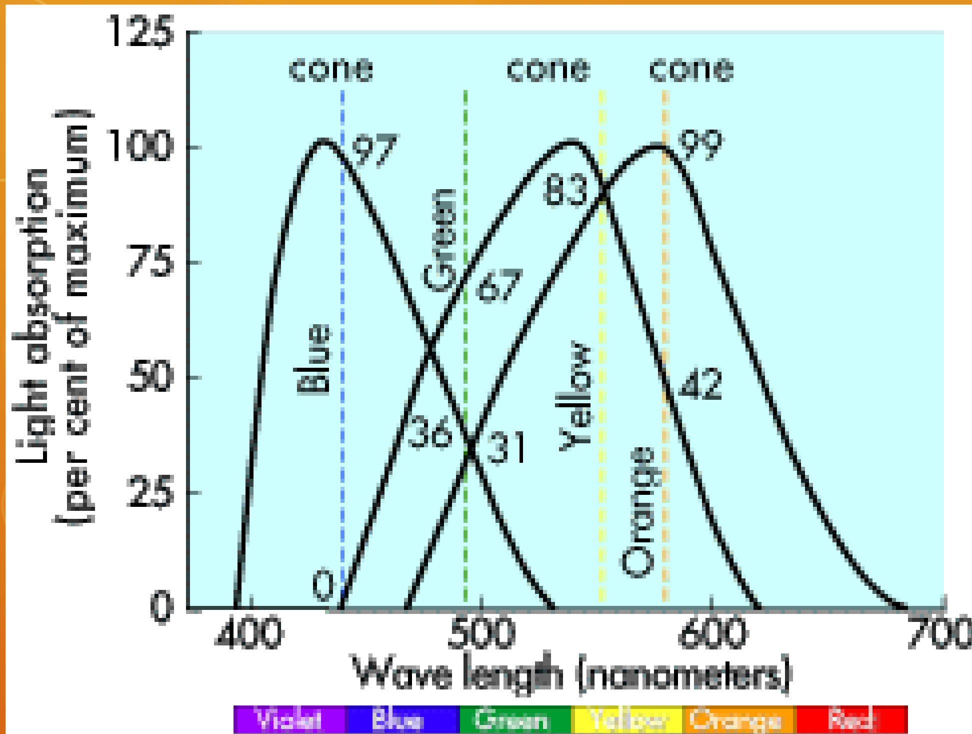
The colour-responsive chemicals in the cones are called **cone pigments** and are very similar to the chemicals in the rods.

There are three kinds of colour-sensitive pigments:

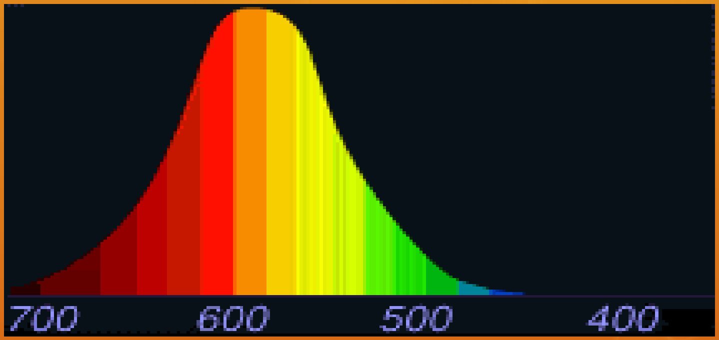
- **Red-sensitive pigment**
- **Green-sensitive pigment**
- **Blue-sensitive pigment**

Each cone cell has one of these pigments so that it is sensitive to that colour. The human eye can sense almost any gradation of colour when red, green and blue are mixed (originally Young-Helmholtz trichromatic theory).

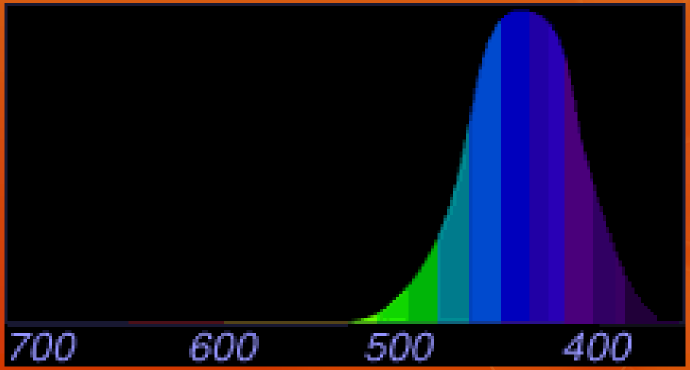
Colour Vision – spectral sensitivity



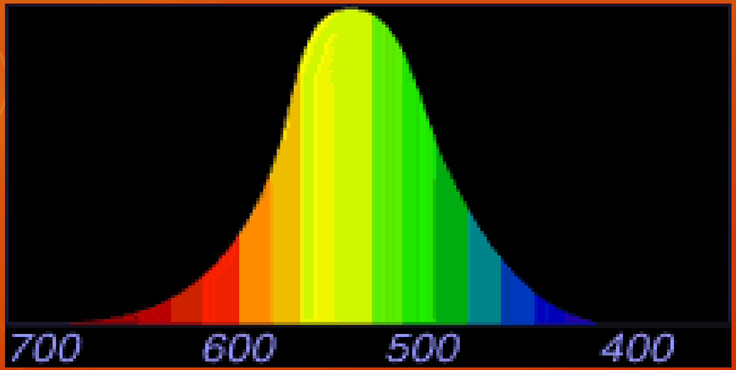
“Red-sensitive” or “L” cones



“Blue-sensitive” or “S” cones



“Green-sensitive” or “M” cones



Limits of vision

- **visual acuity:** given by angle of 1min. of arc (tested by Snellen's charts)
- **sensitivity (intensity) limit:** 2 – 3 photons in several ms
- **frequency:** 5 - 60 Hz depending on brightness
- **wavelength limit about:** 380 – 760 nm
- **limit of stereoscopic vision:** stereoscopic parallax difference smaller than 20 seconds of arc