Lecture 7

Physics of Vision, part 1

Science of vision

- Light is invisible, but stimulates the vision of other objects

- Ancient scientists - Optics – science of vision
- Claudius-Galen (130-200 AD)– described the anatomy of human eye for the first time, described light as a part of vision – “light of eye”
- Later Arabian scientist Ibn Alhayth Alhazen (11^{th} century AD) –

  “Light is an entity emitted by luminous objects”

- Modern view: Light is a flow of energy of dual nature - both electromagnetic waves and a stream of particles (photons)
- The name “Light” is used for visible spectrum of electromagnetic radiation

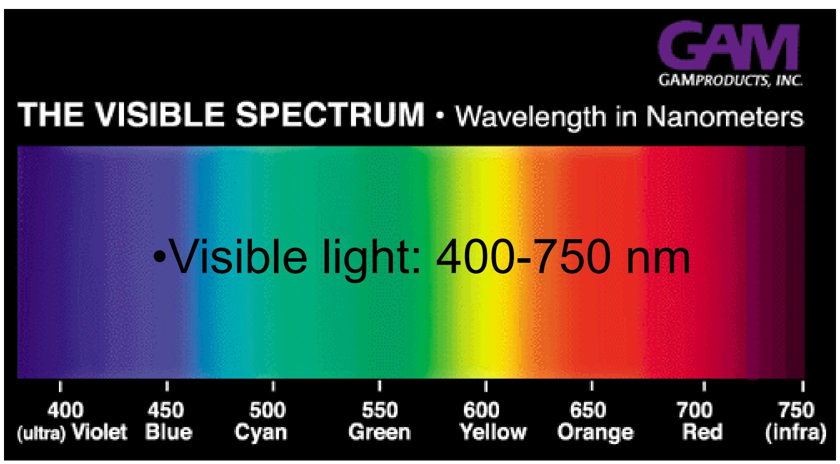
- Physics of vision :
- 1. light is emitted by objects (nature of light)
- 2. light strikes our eyes, vision is excited (interaction of light with matter and physiology of eye)

Wave nature of light

- Light is a wave:
- Bends around obstacles– diffraction
- Combines with like waves to reinforce or weaken each other – interference
- Characterized by speed, wavelength and frequency :

In vacuum: $$c = \lambda \nu$$

- Bending when entering to another medium - refraction



•Visible light: 400-750 nm

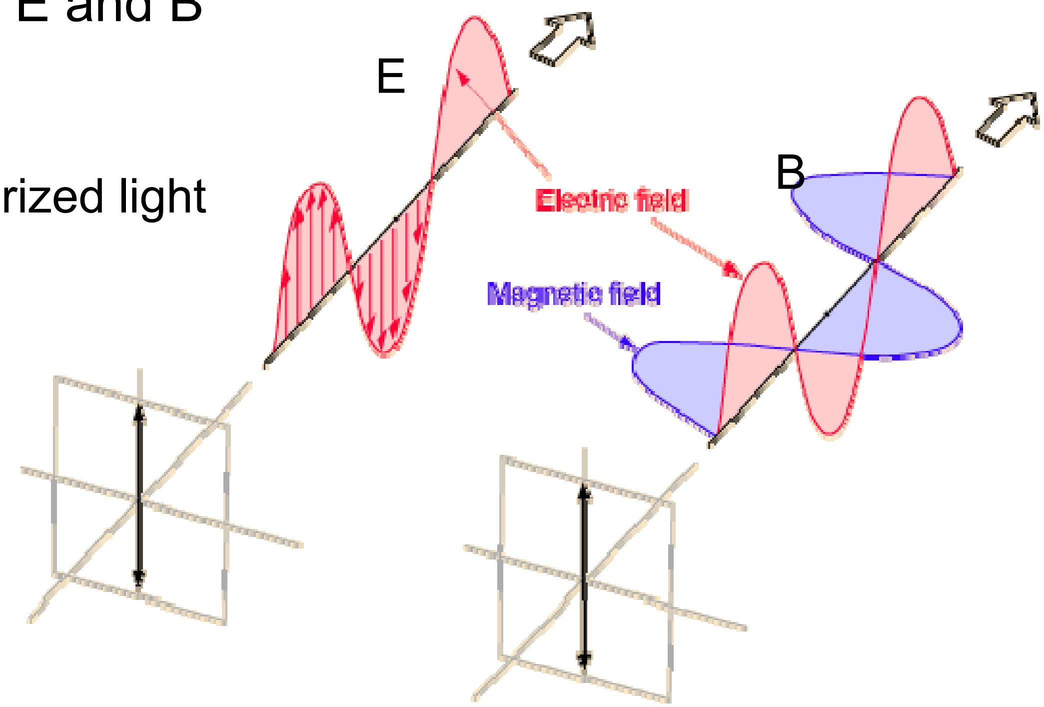
eye is sensitive to both wavelength and intensity

Intensity - amount of energy per unit area per unit time

Polarization

- Light is electromagnetic waves – varying electric and magnetic components, E and B

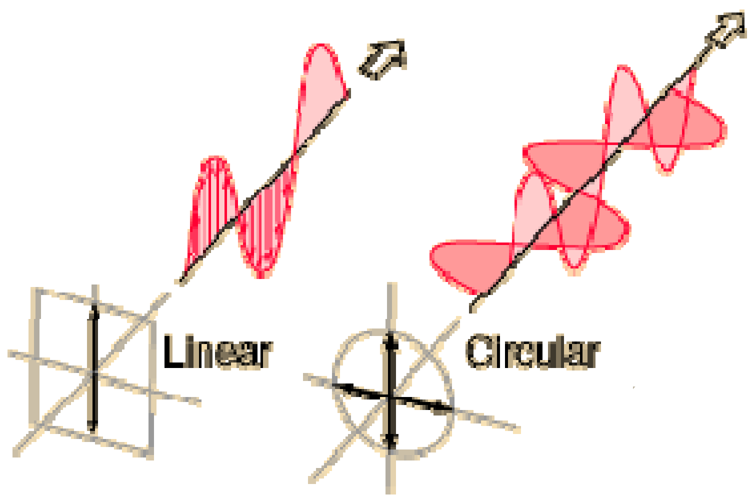
linear polarized light



- but natural light is generally non-polarized, all planes of propagation being equally probable.

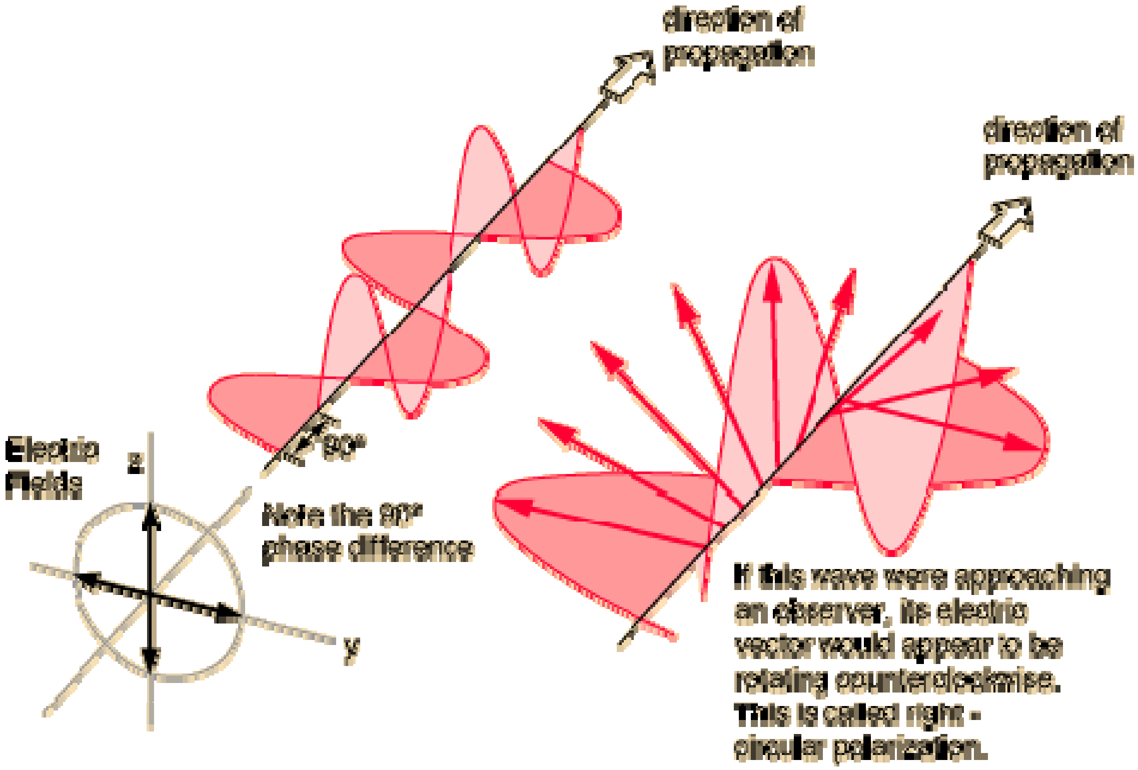
Polarization

- Light is considered linearly polarized – when E oscillates in one plane in space
- If light is composed of two plane waves of equal amplitude by differing in phase by 90°, then the light is said to be circularly polarized.



Eye is sensitive to intensity, wavelength, polarization,

Right circularly polarized light



Particle nature of light

- Light is a wave – continuous flow of energy,
- Light is a stream of particles –discrete bundles of energy – photons

- Planck proposed that the radiant energy could exist only in discrete quanta which are proportional to the frequency
- each photon has energy E:

$$E = h\nu = \frac{hc}{\lambda}$$

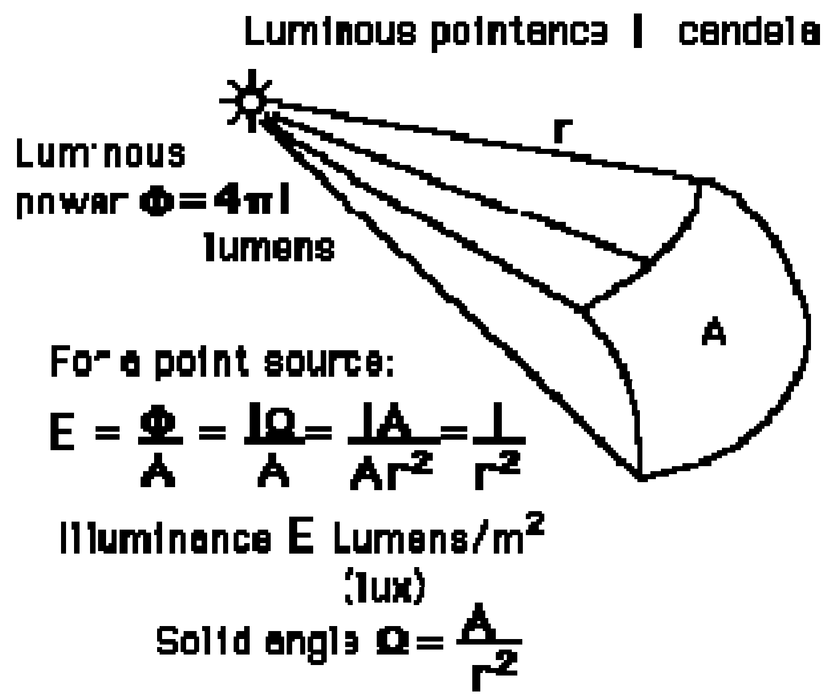
- h – Planck's constant, h = 6.63 x 10^{-34} Joule·sec

- The emission and adsorption of light by atoms and molecules occur by individual photons.

- Photoreceptive cells in the eye– are excited by a photon with appropriate E, a chain of molecular reactions transmits signal to brain
- Photoreceptive cell is sensitive to a single photon

Light intensity

- **Intensity =Power Per Unit Solid Angle**
- I -intensity = the power (flux) per unit solid angle (sometimes called luminous pointance).
- For visible light, Light Intensity is expressed in
- lumens per steradian = candela.
- If the intensity (I = dΦ/dω) of a source is the same in all directions, the source is isotropic.



Geometrical optics. Refraction

Refraction is the bending of a wave when it enters a medium where it's speed is different.

The amount of bending depends on the refractive index n of the medium (in respect to vacuum)

$$n = \frac{c}{v_m}$$

c-speed in vacuum

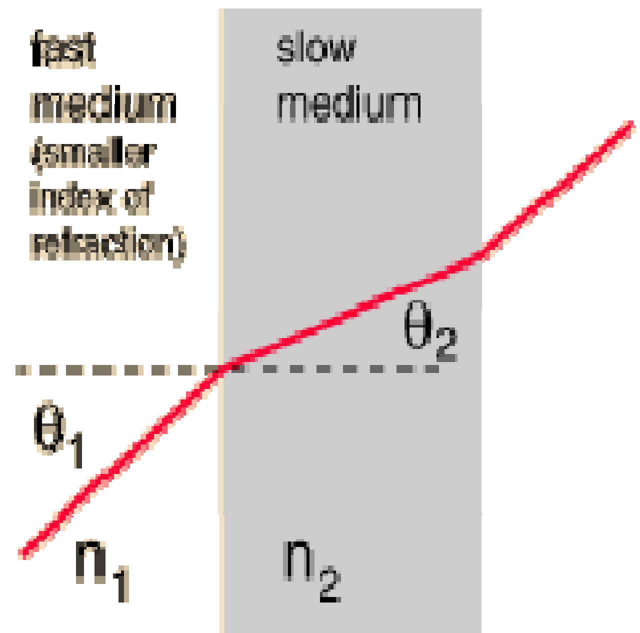
v-speed in medium

Geometrical optics. Refraction

Snell’s law – lights enters from one medium to another:

Snell's Law

$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$$



Refractive indices in medium 1 and 2

Geometrical optics. Refraction

$$n = \frac{c}{v_m}$$

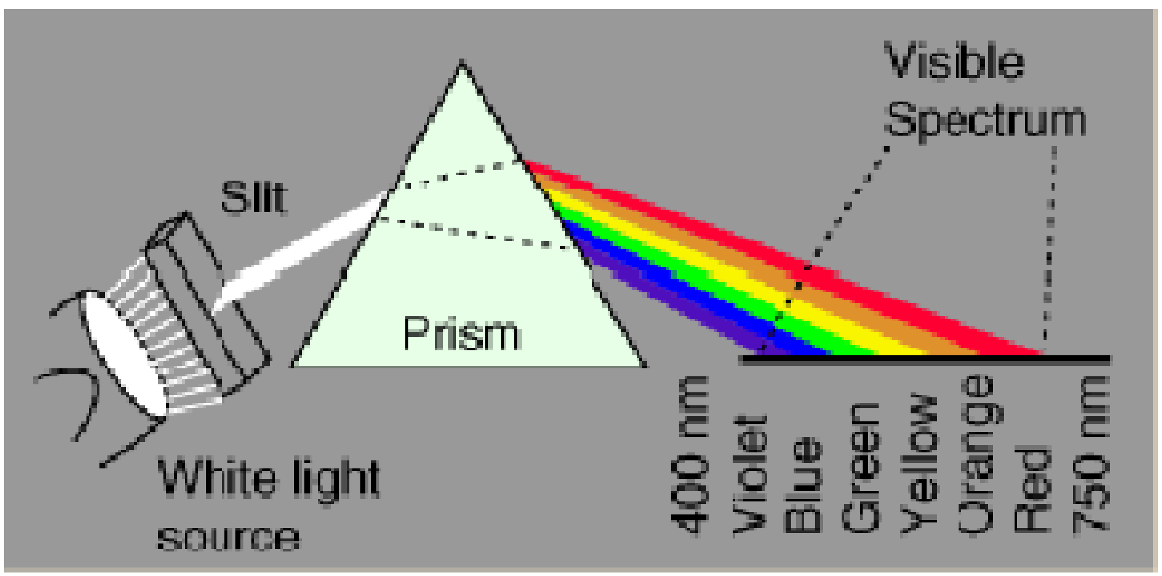
Speed in vacuum

Speed in medium

$$n = \frac{c}{v_m} = \frac{\lambda}{\lambda_m}$$

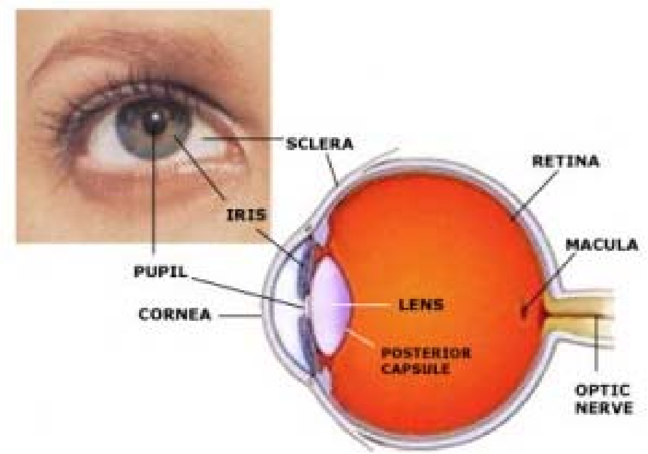
$$c = \lambda \nu$$

frequency



refraction of light depends on light wavelength

Human eye. Gradient – index lens.



In human eye lights travels through 4 media: cornea, aqueous humor, eye lens, vitreous humor. Refractive indices are similar in these parts, most bending at the air – cornea

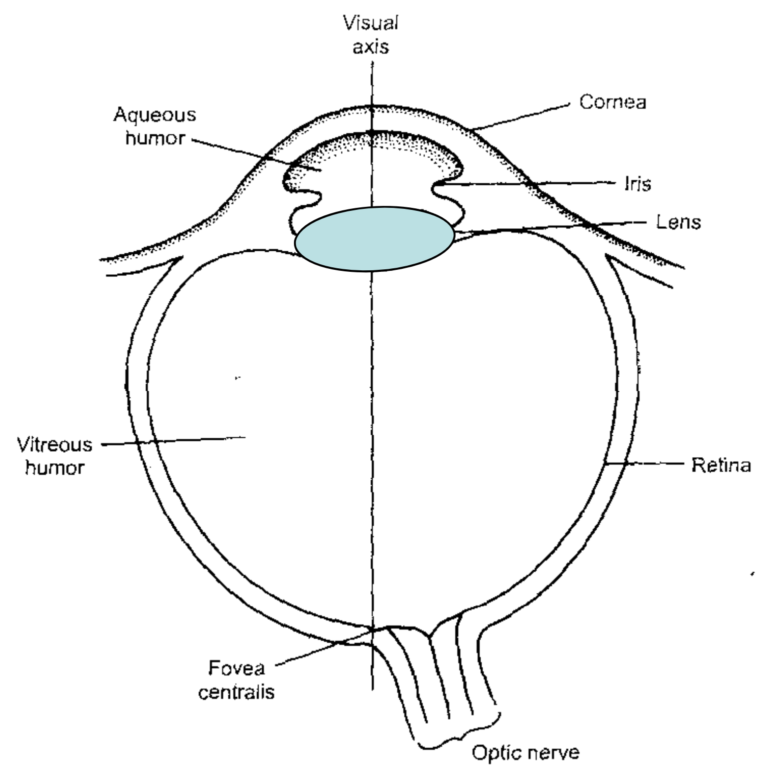
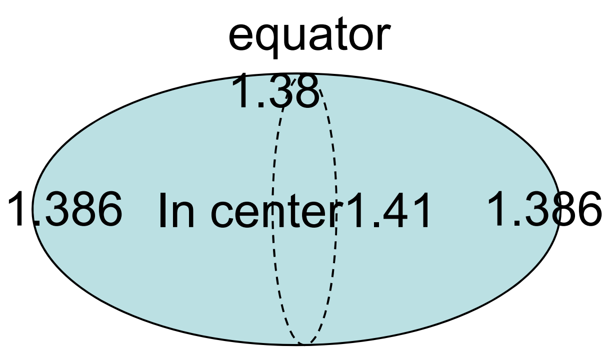


Fig. 5.1 *The human eye.*

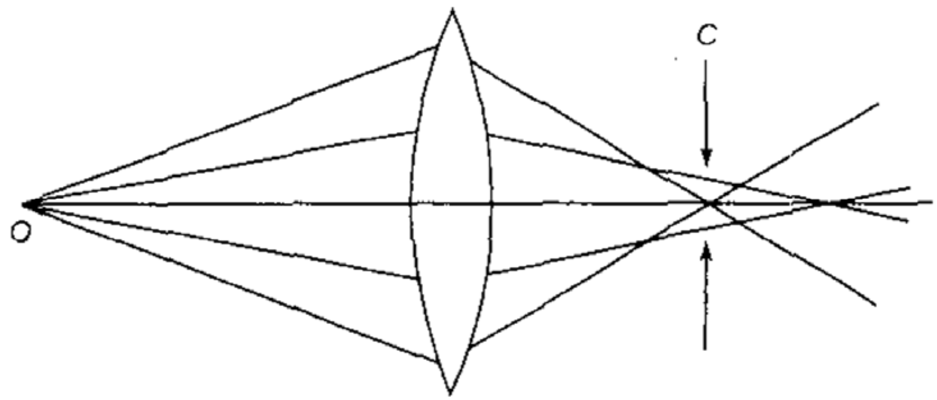
Refractive index of eye-lens is not the uniform in the eye lens:



Gradient-index lens (GRIN) lens, the average is taken as n=1.4

Spherical aberration

- In an ideal optical system, all rays of light from a point in the object plane would converge to the same point in the image plane, forming a clear image. The influences which cause different rays to converge to different points are called aberrations.
- For lenses made with spherical surfaces, rays which are at different distances from the optic axis fail to converge to the same point – spherical aberration.



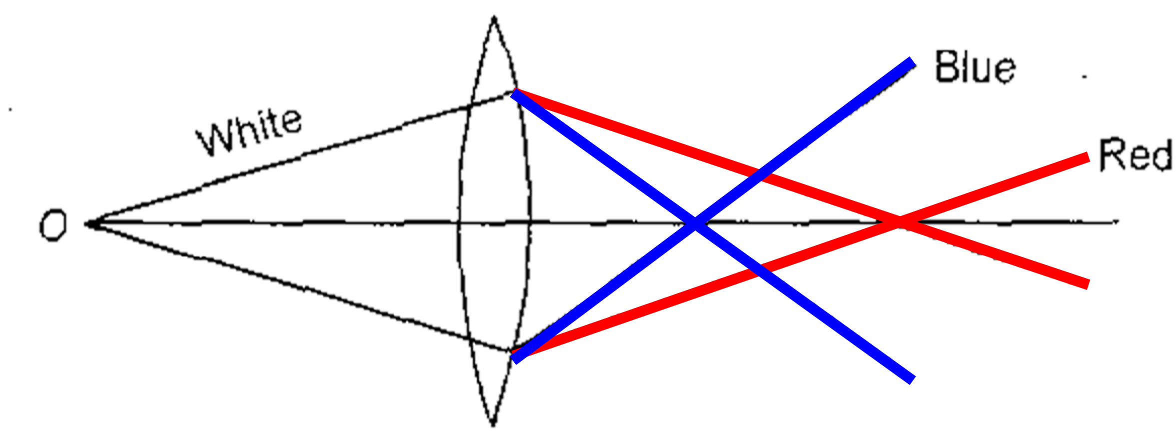
- **GRIN lens of eye corrects spherical aberration**
- Pupil is reduced at bright light - reduces the spherical aberration
- In the dark the pupil is large and does not reduce spherical aberration as well as at bright light

Chromatic aberration

- A refractive index of medium depends on wavelength, because light of different wavelengths travels with different speeds.
- Refractive index decreases with increase in wavelength – Cauchy's relation:

$$n = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^2} + \dots$$

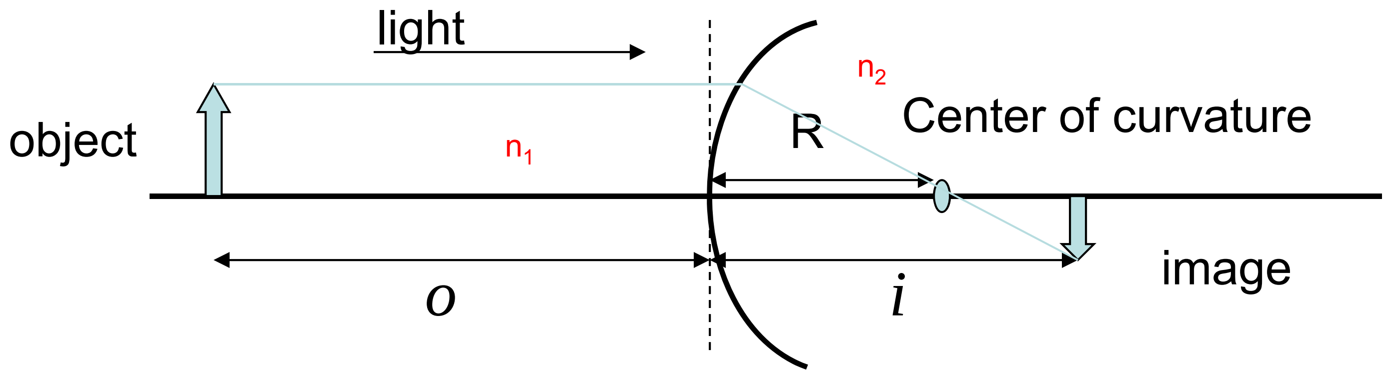
A, B, C – empirically determined constants for the medium



- Chromatic aberration is caused by different amount of bending for different colors. Because of this the lens will not focus different colors in exactly the same place :

Refractive power, surfaces

When light comes from one medium (refractive index n_1) to another medium (refractive index n_2) through the curved surface:



$$\frac{n_1}{o} + \frac{n_2}{i} = \frac{n_2 - n_1}{R}$$

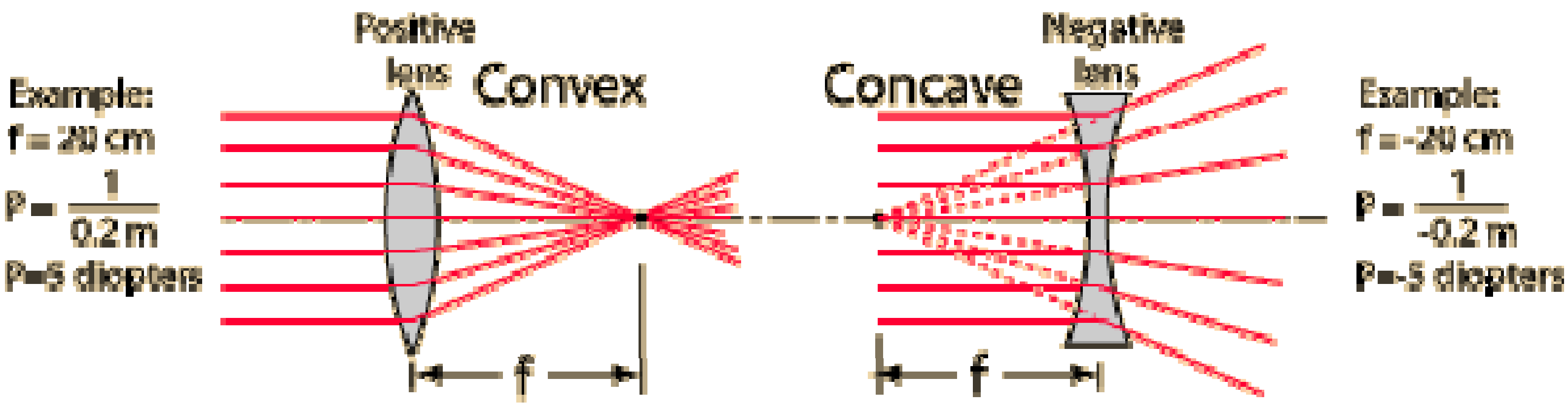
R- radius of curvature of a surface

$$P = \frac{n_2 - n_1}{R}$$

Refractive power P is positive for convex, negative for concave
the physical units for refractive power is 1/meter called dioptres.

Refractive power, lens

•Lens- is two surfaces enclosed a medium different from outside



$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f}$$

$$\frac{1}{\text{object distance}} + \frac{1}{\text{image distance}} = \frac{1}{\text{focal length}}$$

refractive power is the degree to which a surface or lens converges or diverges light

P is positive for convex, negative for concave

P=1/f, where f is a focal length of the lens,

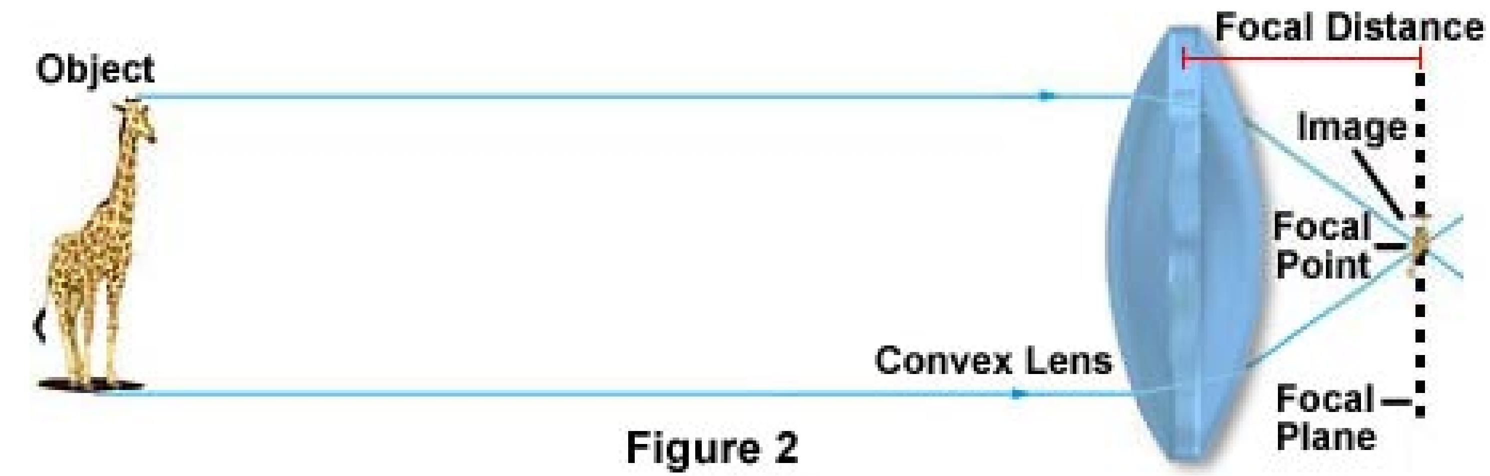


Figure 2

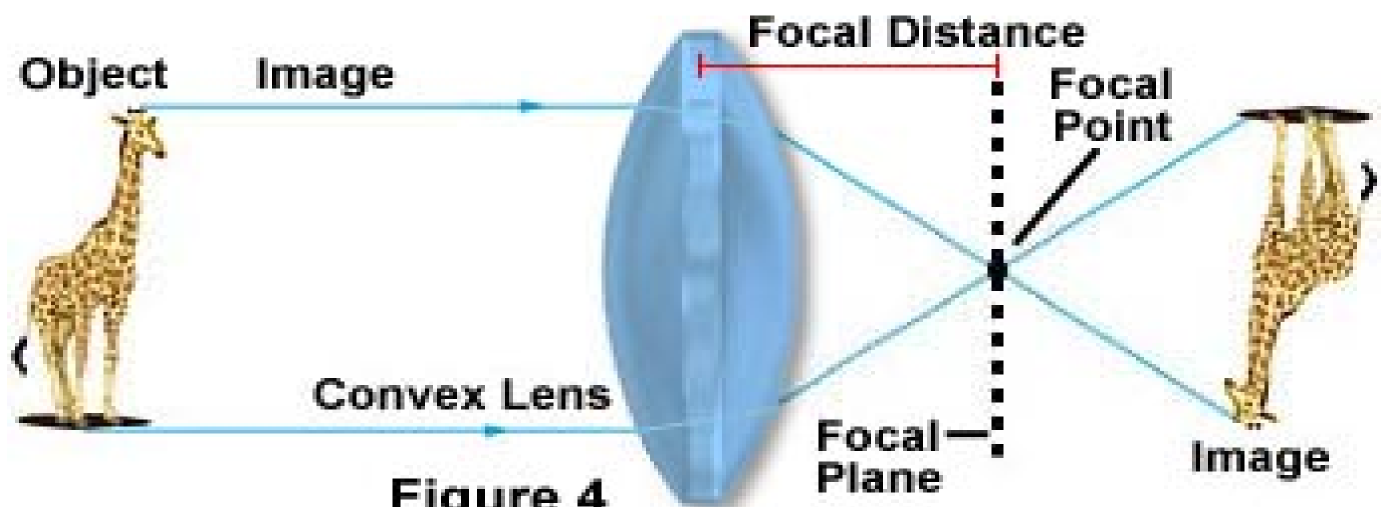


Figure 4

Light from an object that is very far away from the front of a convex lens will be brought to a focus at a fixed point behind the lens. This is known as the **focal point of the lens**

Refractive power of eye

- 4 refracting surfaces in human eye, refractive powers:
- Cornea 2 surfaces – convex, R=7.8

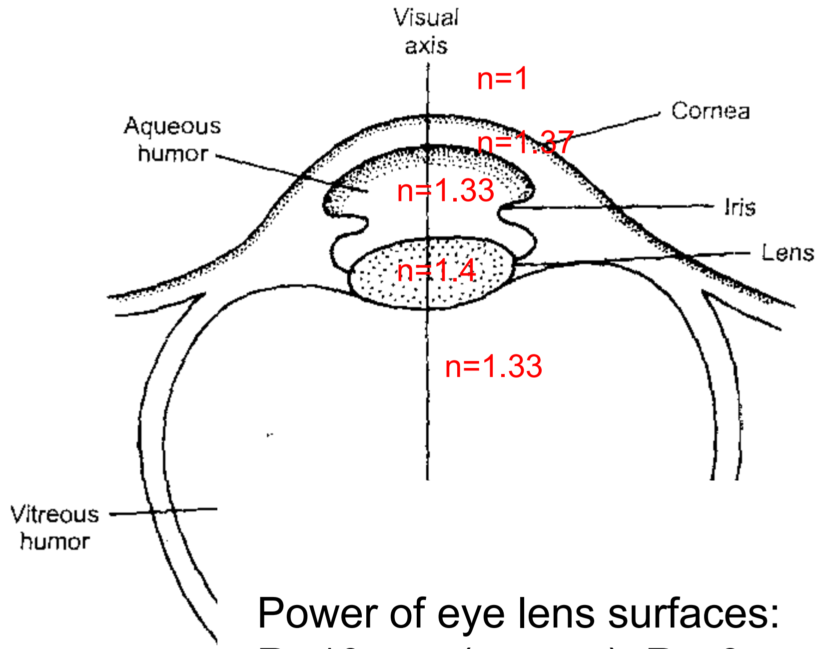
- Power of air-cornea:

$$P_1 = \frac{1.37 - 1}{7.8 \times 10^{-3}} \approx 47 m^{-1} \approx 47 Dioptres$$

- n cornea 1.37, n air =1

- Power of cornea-aqueous humor:
- n aq humor =1.33

$$P_2 = \frac{1.33 - 1.37}{7.8 \times 10^{-3}} \approx -5D$$



Power of eye lens surfaces:
R_1 10 mm (convex), R_2 -6mm (concave)
n lens (av) =1.4, n vitr humor =1.33

$$P_3 = \frac{1.40 - 1.33}{10 \times 10^{-3}} \approx +7D$$

$$P_4 = \frac{1.33 - 1.40}{-6 \times 10^{-3}} \approx +11D$$

- Lens- is two surfaces enclosed a medium different from outside
- Lens has 2 Radii of curvature

Gullstrand's equation

$$P = P_1 + P_2 - P_1 P_2 \frac{d}{n}$$

If lens is thin d=0

$$P = P_1 + P_2$$

d – distance between two surfaces, n-refractive index of lens, P_1 and P_2 power of two surfaces

The power of eye lens (thin lens approximation):

$$P_{eyelense} = P_3 + P_4 = +18D$$

- The power of cornea (thin lens approximation)

$$P_c = P_1 + P_2 = 47 - 5 = +42D$$

The power of eye total:

18+42=60D

Reduced eye model

- The model of eye where all refractive surfaces are replaced by one lens of total power 60D is called reduced eye model
- The equivalent lens is assumed to be in air, n=1.34
- When eye is focused at far point $o \to \infty$ the distance i of image from optical center of lens = f *(focal length)*

$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f}$$

$$\frac{1}{\text{object distance}} + \frac{1}{\text{image distance}} = \frac{1}{\text{focal length}}$$

$$i = f = \frac{1.34}{P_{lens}} = \frac{1.34}{60} m \approx 22.5mm$$

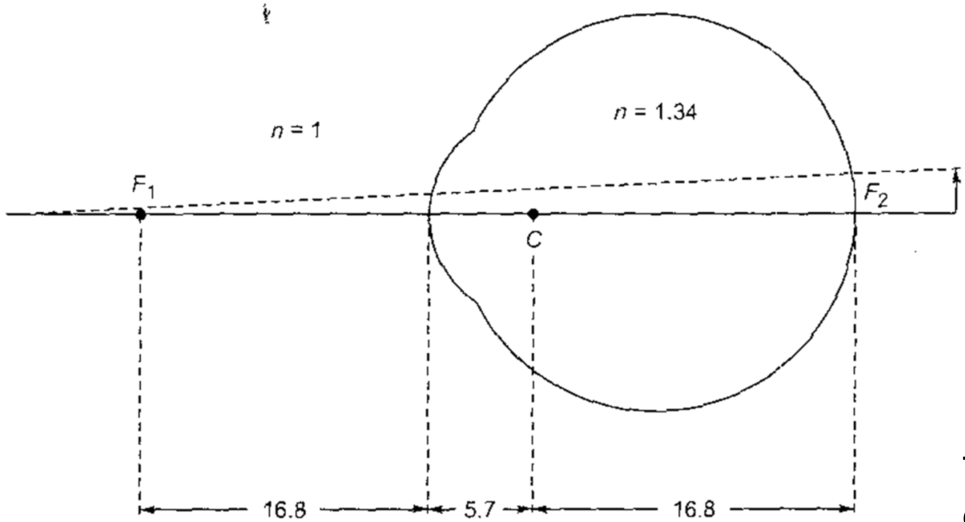
P=n/f, f=n/P

- *Optical center of the lens of reduced eye is 22.5mm away from retina*

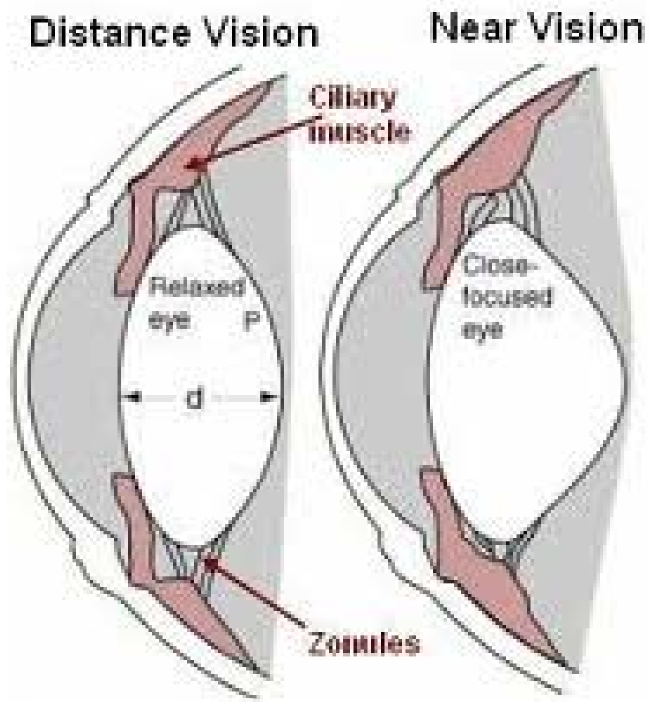
Accomodation

Accomodation is ability of eye to adjust its refractive power by automatic change of curvature of the eye-lens

Normal P=60D,
Max P =72 D due to accomodation



The reduced model of eye assumes
one refractive surface of R=5.7 mm, n inside 1.34,
focal length inside the eye 22.5 mm,
lens power 60D



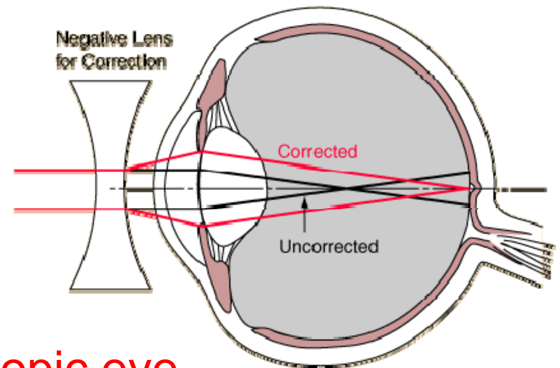
For near vision, the ciliary muscles contracts and the central lens thickness increases to increase its power.

The eye lens is held by strong fibers attached to ciliary muscles, when relaxed the eye-lens flattens – far point, tense – lens becomes more spherical – increases the power – focus at near point (min distance eye can see clearly 8 cm from eye)

[Review how eye works, accommodation: http://www.youtube.com/watch?v=EF5CnemVJQM&feature=related](http://www.youtube.com/watch?v=EF5CnemVJQM&feature=related)

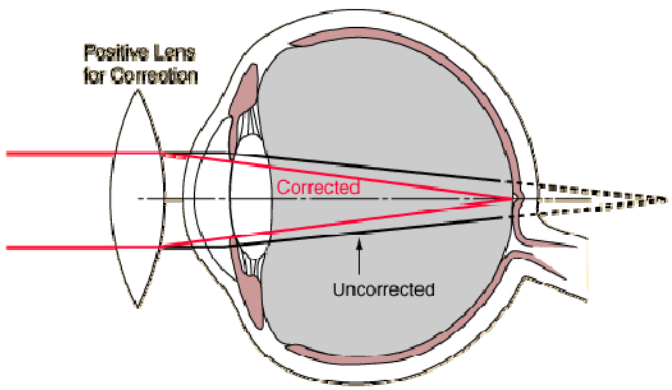
Refractive errors

normal eye in relaxed condition - the image of a distant object is focused on retina



myopic eye

•Myopic eye, light is focused in front of the retina (the focal length is too short).



hyperopic eye

•hyperopic eye, light is focused behind the retina (focal length is too long).

example

- Calculate accommodation of eye in Dioptres, if this accomodation corresponds to the change in radius of curvature in eye lens (-) 0.6 mm, (radius is reduced) use reduced eye model.

- The reduced model of eye assumes
- one refractive surface of R=5.7 mm,
- n_2 inside =1.34, n_1 outside =1 (we consider that it does not change)
- lens power 60D

$$P = \frac{n_2 - n_1}{R}$$

$$P_1 = 60D = 60m^{-1}$$

$$\frac{P_1}{P_2} = \frac{R_2}{R_1} = \frac{5.1}{5.7} = 0.9$$

Accomodation =7D

$$P_2 = P_1 / 0.9 = 60 / 0.9 = 67D$$