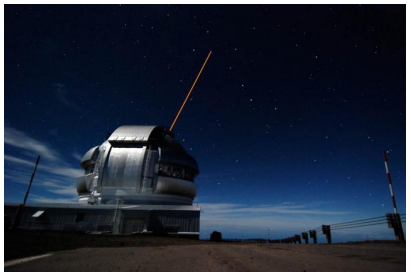
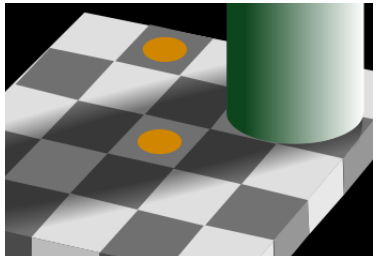
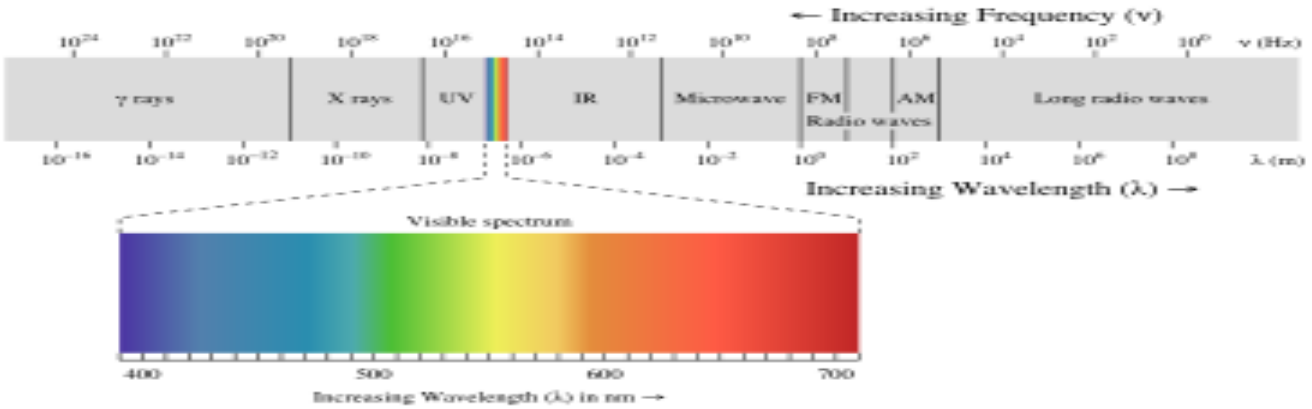
Physics 1230: Light and Color



- Prof. Leo Radzihovsky (lecturer)
- Gamow Tower F623 303-492-5436
- radzihov@colorado.edu
- office hours: T, Th 3-4pm

Susanna Todaro (TA/grader)
Help Room, Duane Physics
susanna.todaro@colorado.edu
M, W 3-4pm

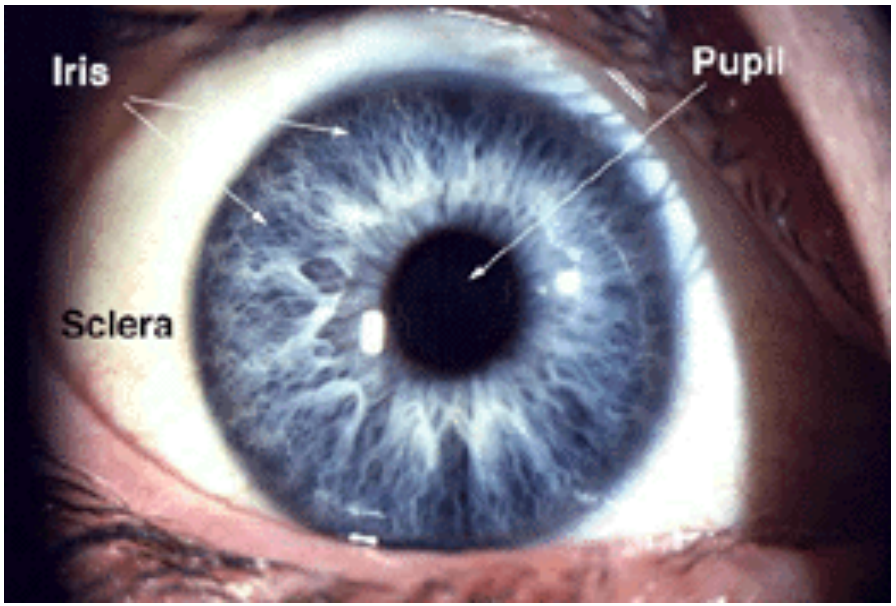
http://www.colorado.edu/physics/phys1230/

Lecture 9

The eye

Announcements:

- lectures 8 is posted on the class website
- midterm 2 on Tuesday, April 15
- homework 7 is posted on D2L
  - due Thursday, April 3 in homework box in Help Room
  - solutions will be posted on D2L
- reading for this week is:
  - Ch. 4, 5 in SL

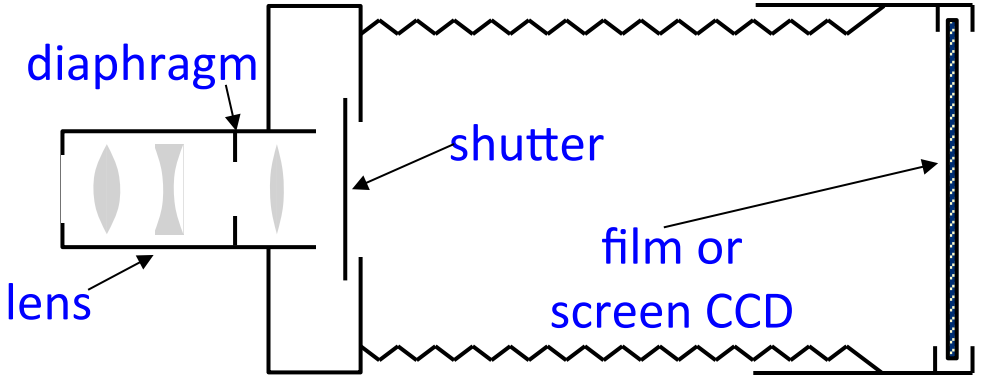


Recall

Last time

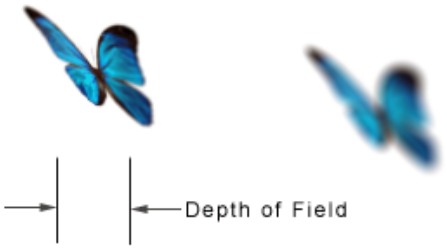
recall lecture 8: Cameras and photography

- camera's essential parts:



- different types of lenses:

- f-stop = f/D

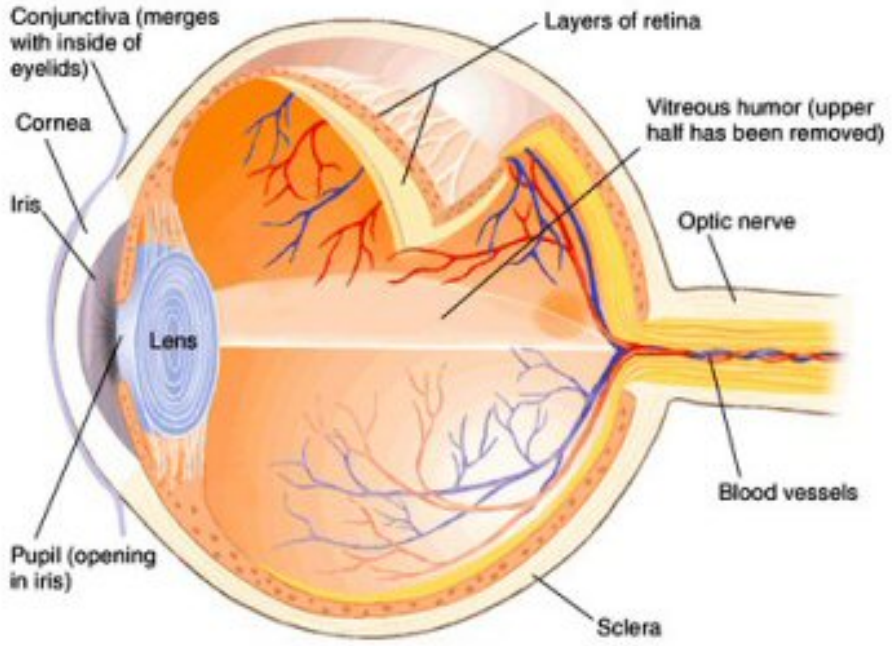


- depth of field/focus
- aperture

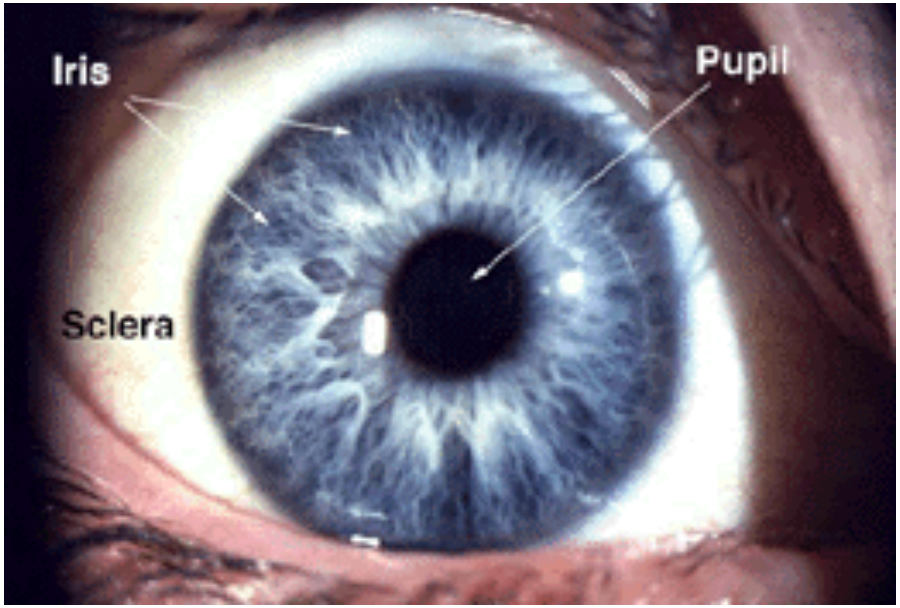
- shutter speed

Today

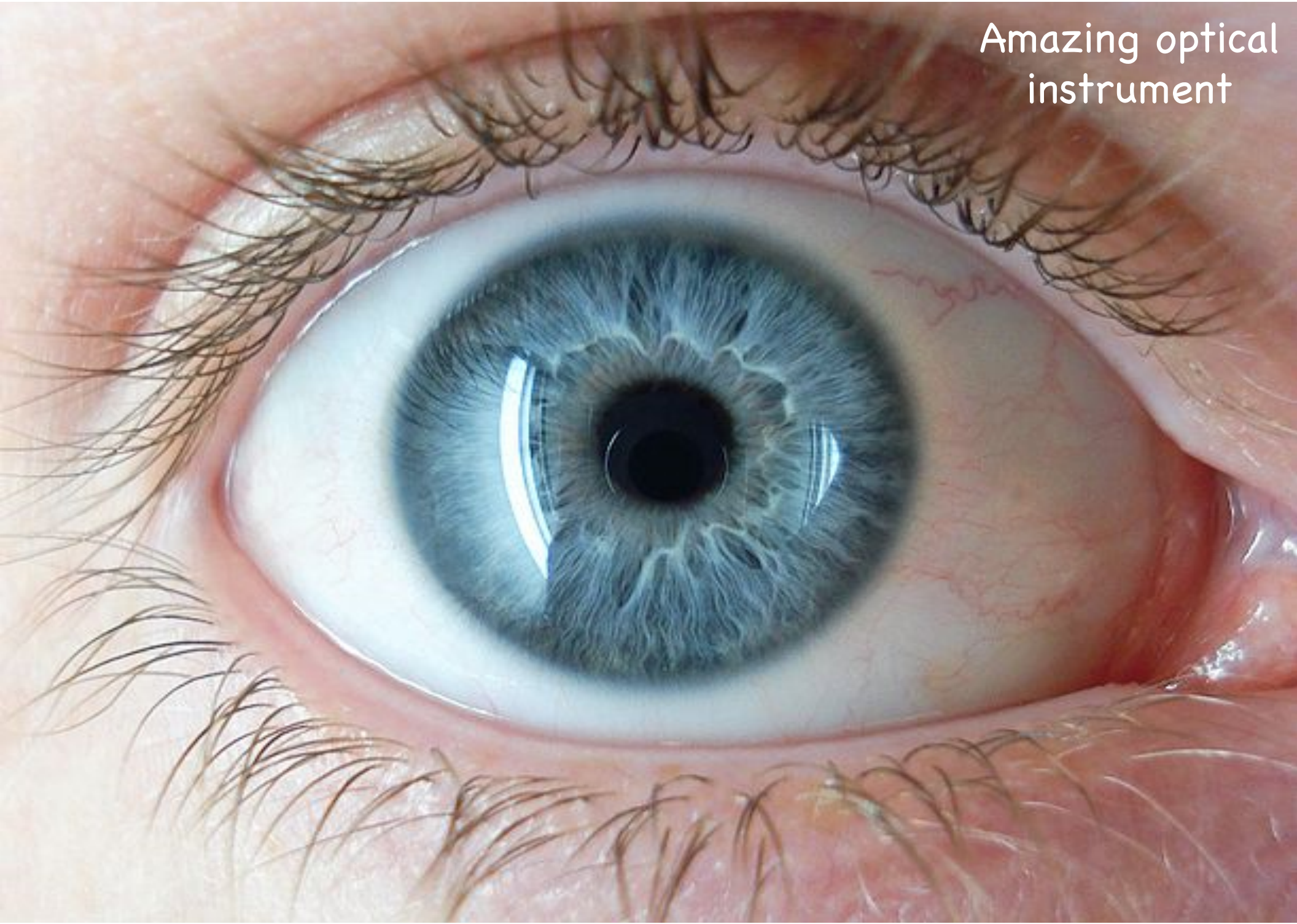
The eye



- cornea and lens: focusing system
- iris and pupil: diaphragm, controls f-number
- retina rods and cones: image formation
- persistence response: speed
- light sensitivity:



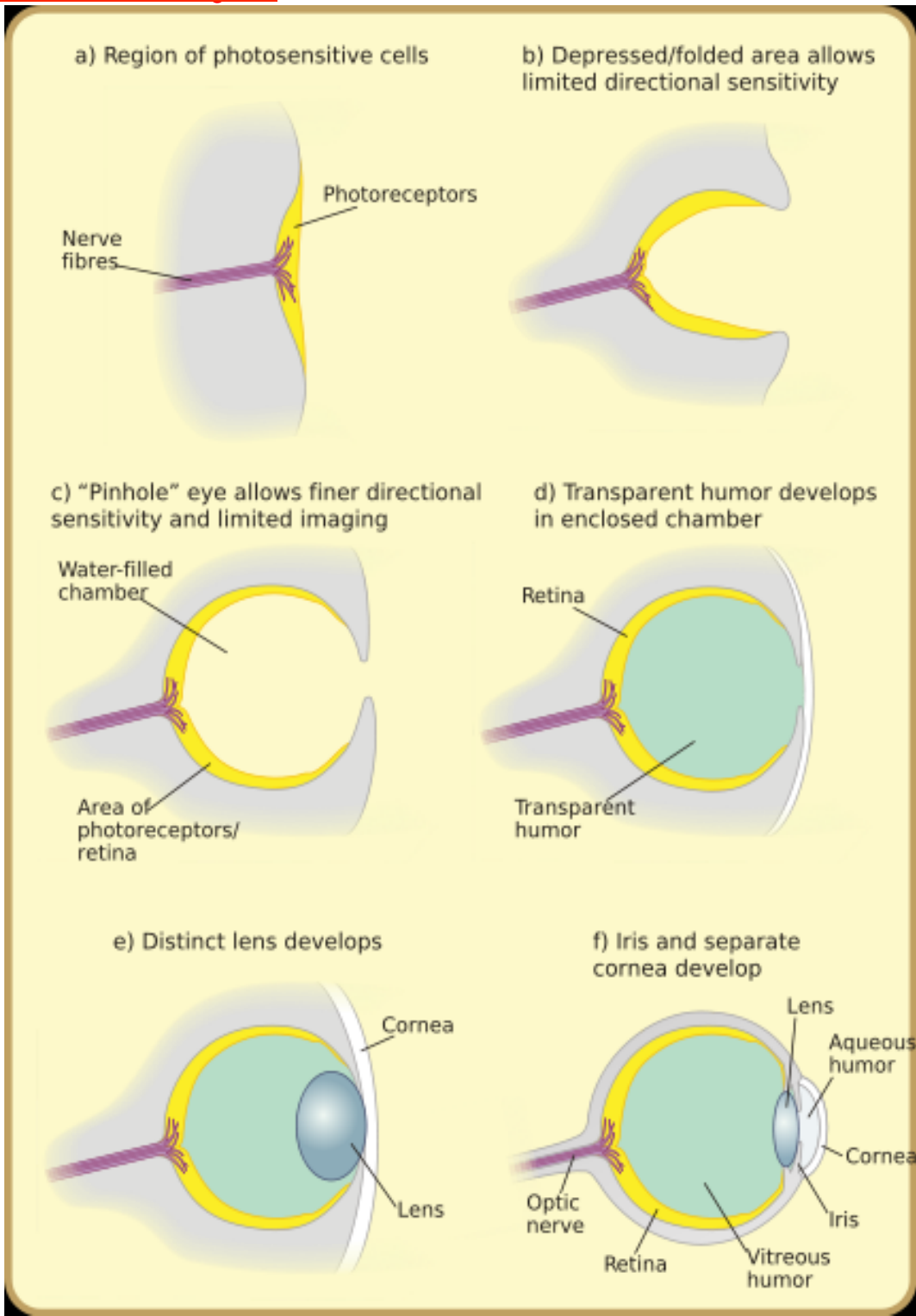
The Eye



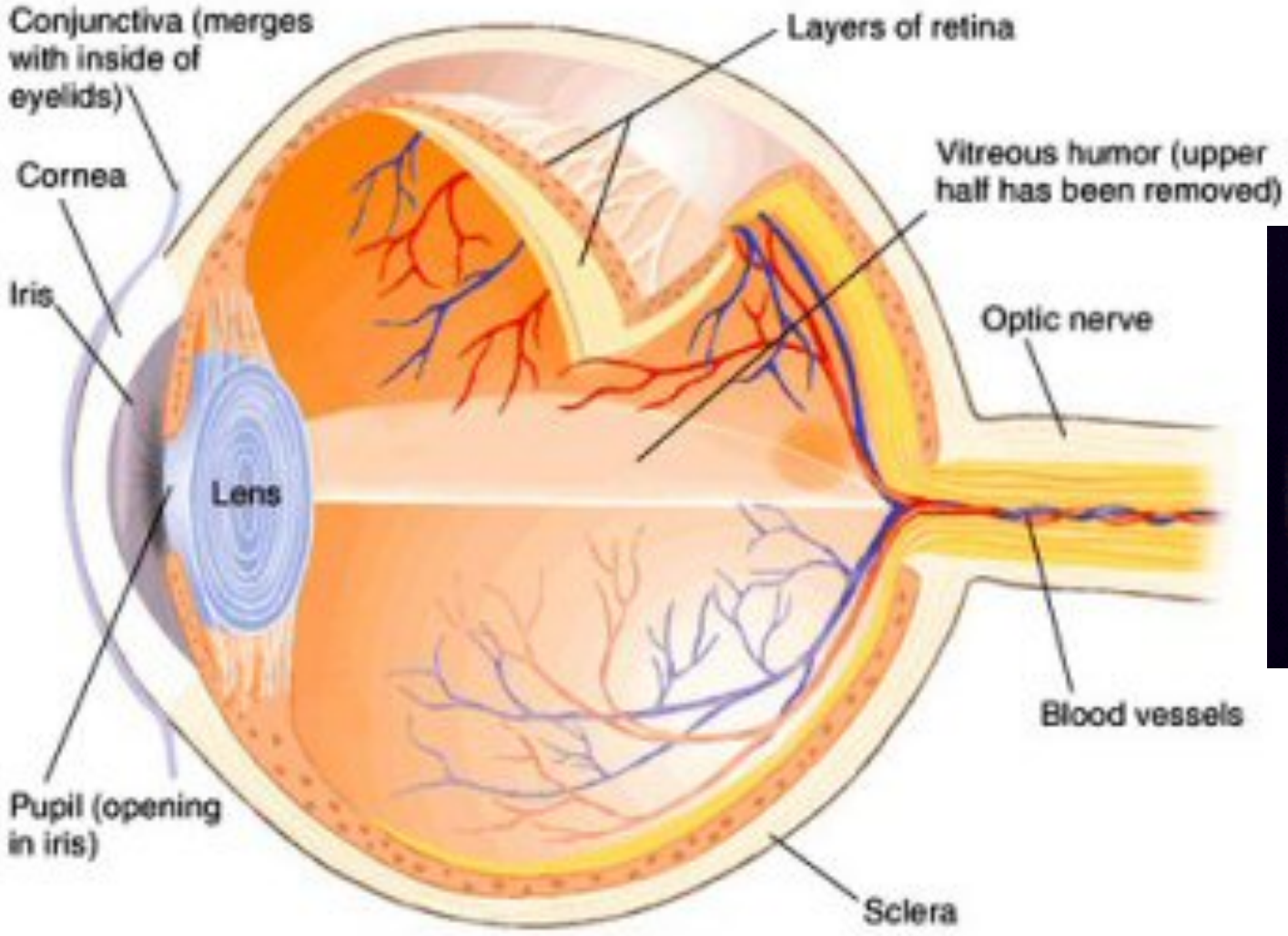
Evolution of the eye

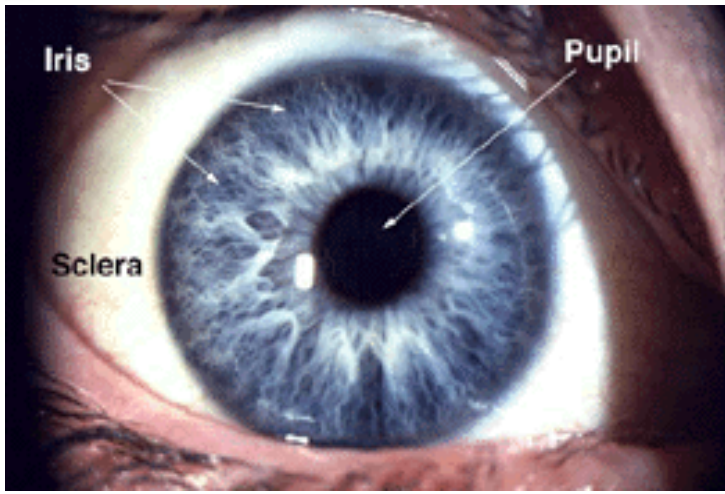
All these visual system still exist in various creatures

(Wikipedia)



Structure of the eye

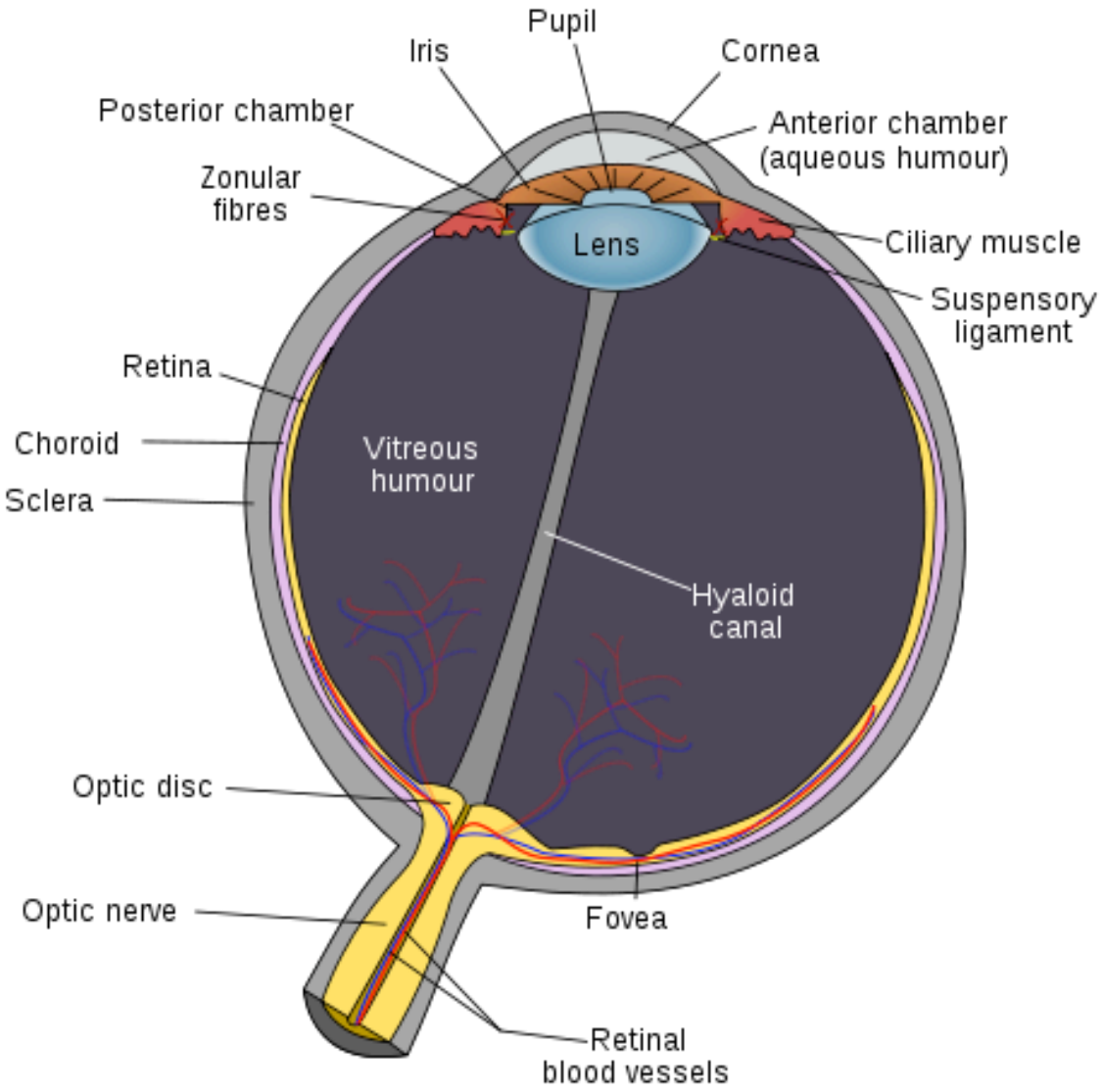


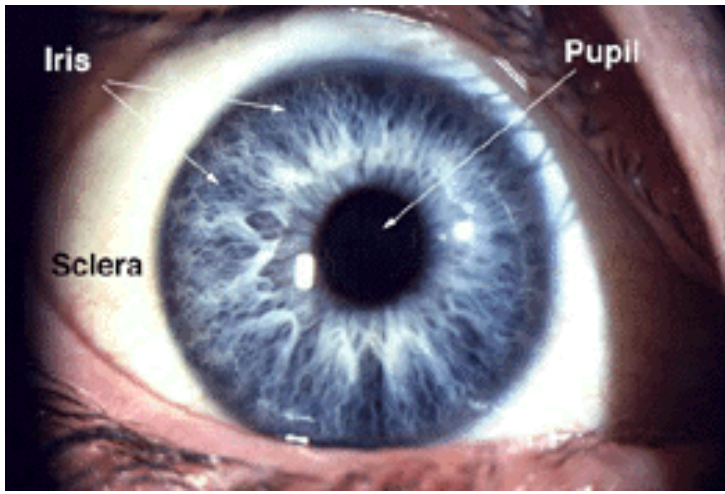


parts that are seen

- iris and pupil: diaphragm of the camera
- cornea and lens: lens-like to focus image
- retina: image recording, CCD sensor or film

Structure of the eye





parts that are seen

- iris and pupil: diaphragm of the camera
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Eye – camera analogy

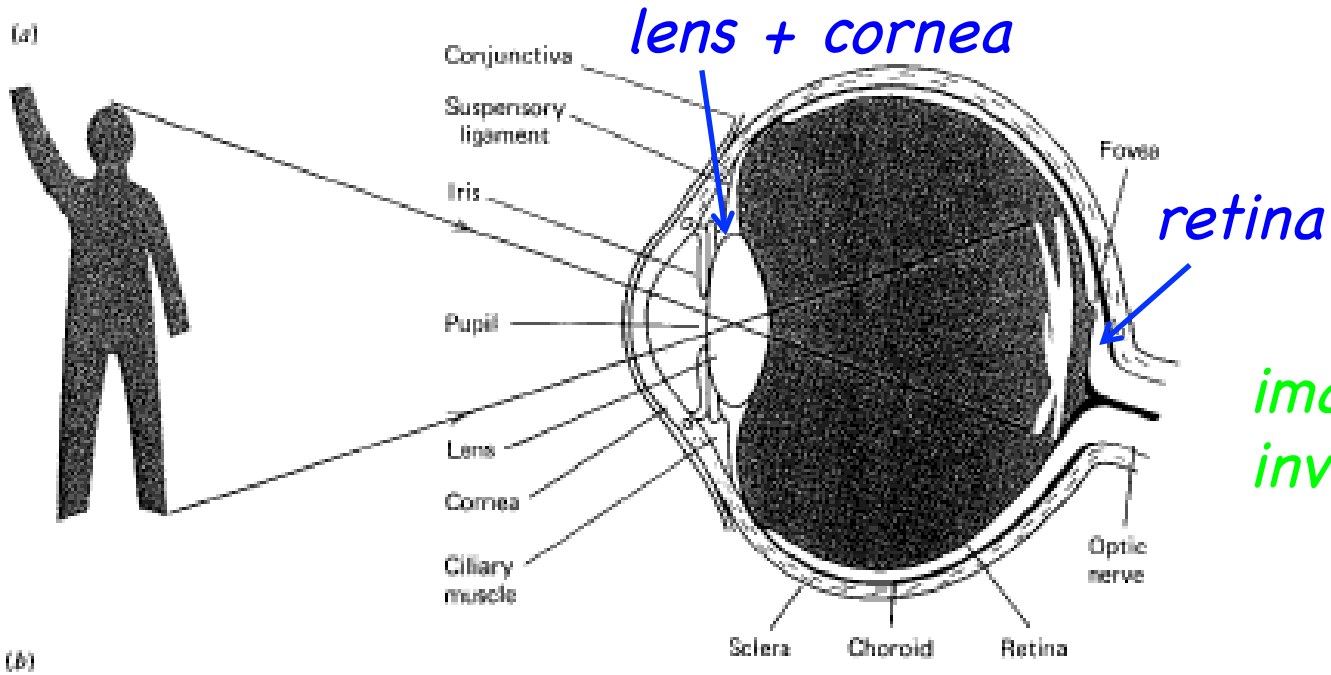
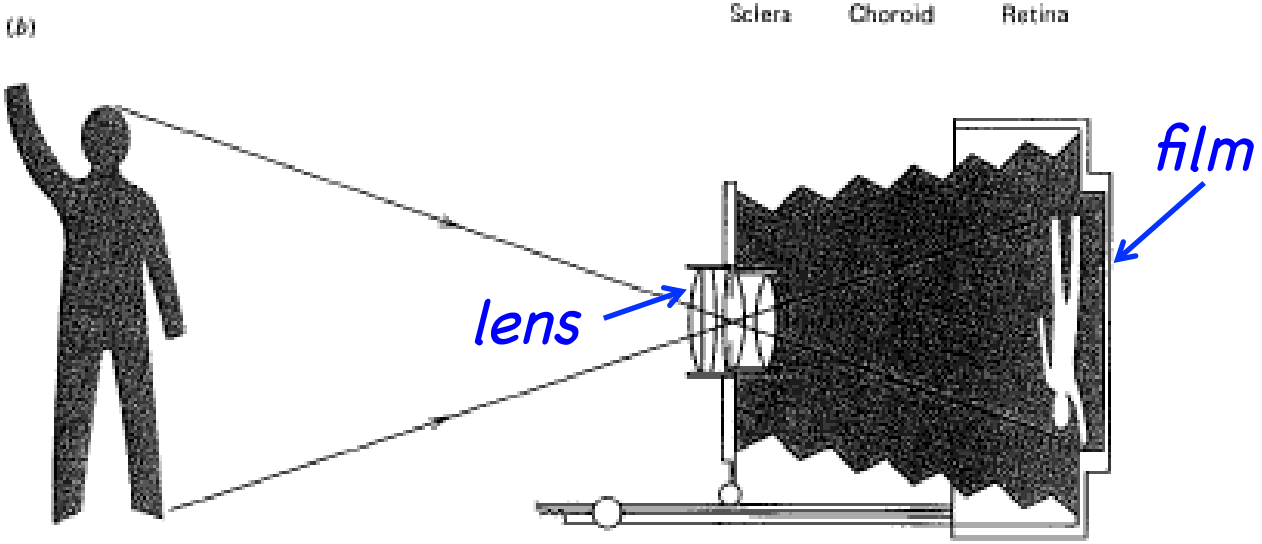
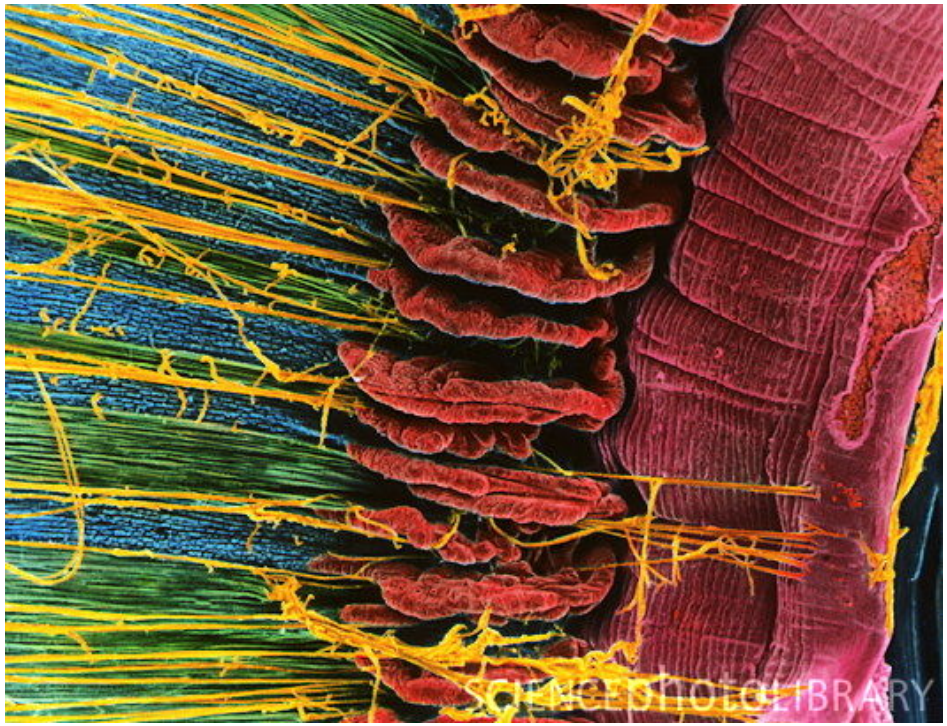


image upside down,
inverted left/right



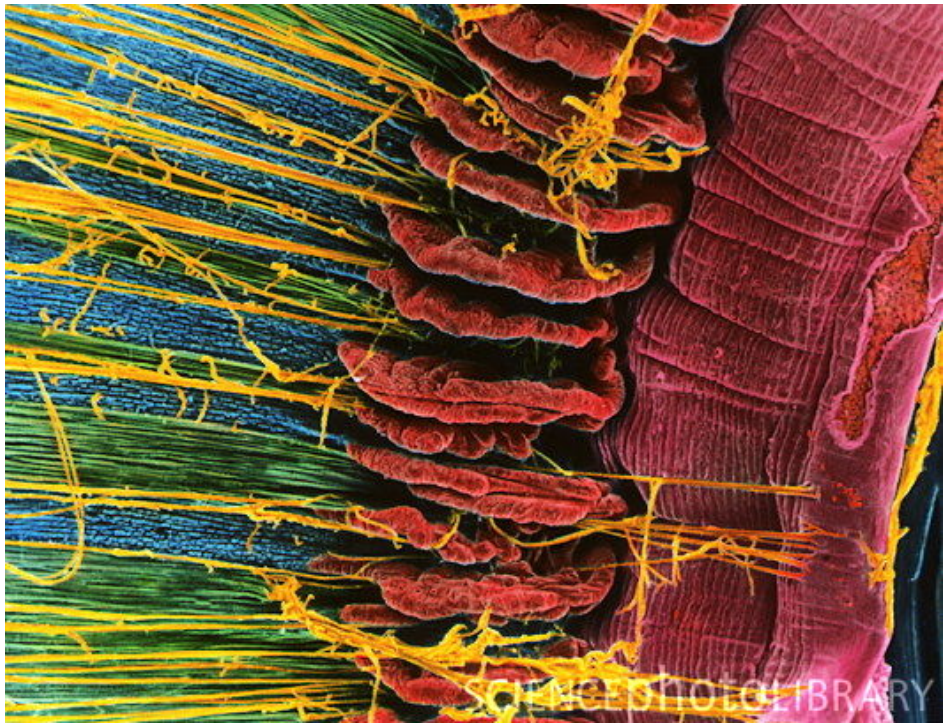
Structure of the eye: *iris*

- The iris is similar to the diaphragm in a camera
- Your iris *widens* in dim light (night) and *narrows* in bright light (day)
- The f-number of your eye varies from f/2 (large opening: short DOF) to f/8 (small opening: long DOF)
- Compare this to the range of an average camera lens, which may have f-numbers from f/2.8 to f/22



Structure of the eye: *iris*

- With a range of only f/2 – f/8, your iris can only reduce the light coming into your eye by a factor of 16 ($4^2 = 16$)
- The range of intensities that your eye can respond to is a factor of 10^{13}
- The main function of the iris is *not* to control the intensity of light coming into your eye
- Main functions of iris
  - *reduce aberrations, sharpen image*
  - *increase depth of field*



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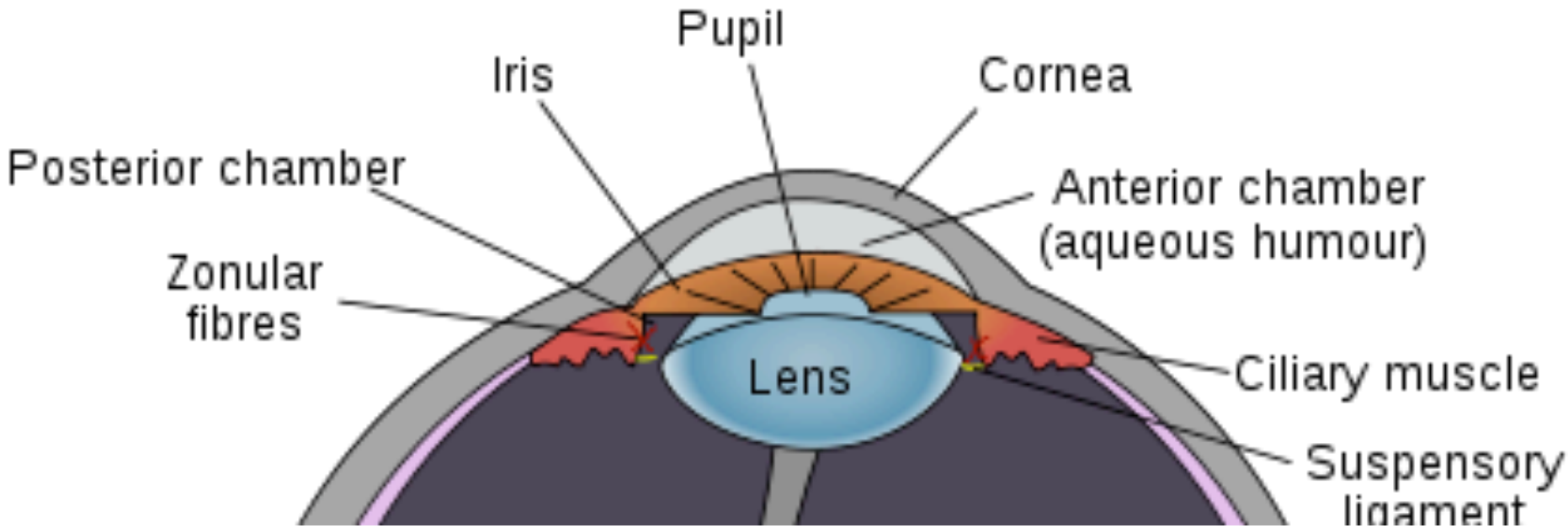
Structure of the eye: *cornea and lens*

- There are *two lenses* in your eye, the *cornea* and the eyelens
- The cornea, the front surface of the eye, does most of the focusing in your eye, most optical power, shorter fixed focal length
- The eyelens provides adjustable fine-tuning of the focus



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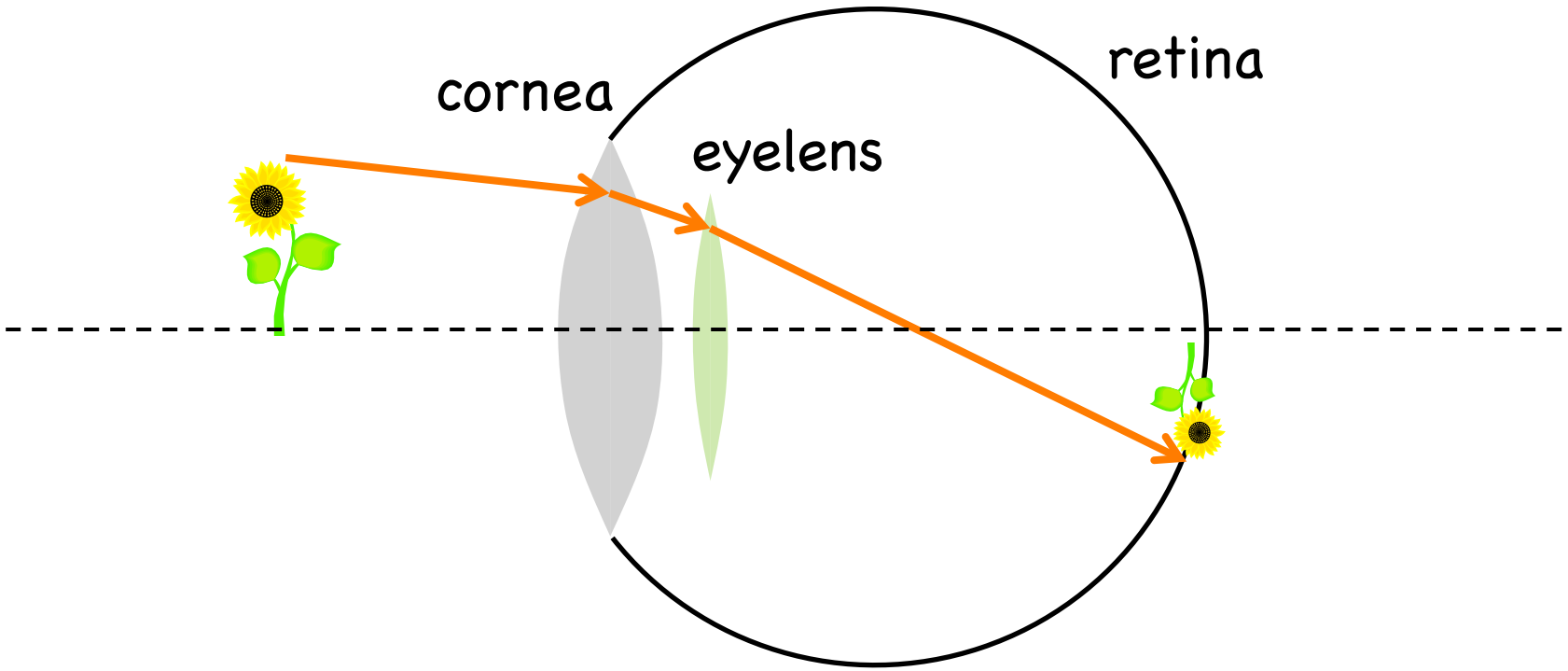
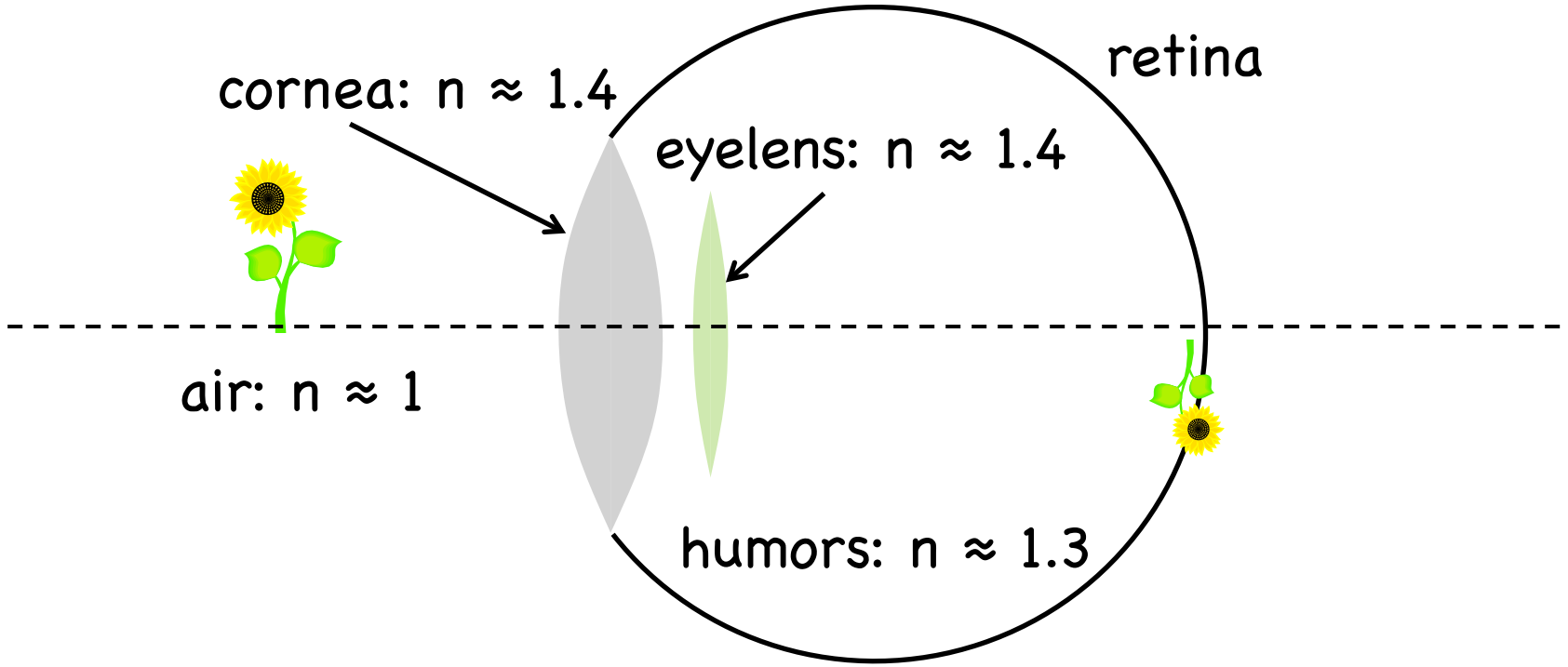


Structure of the eye: *cornea and lens*

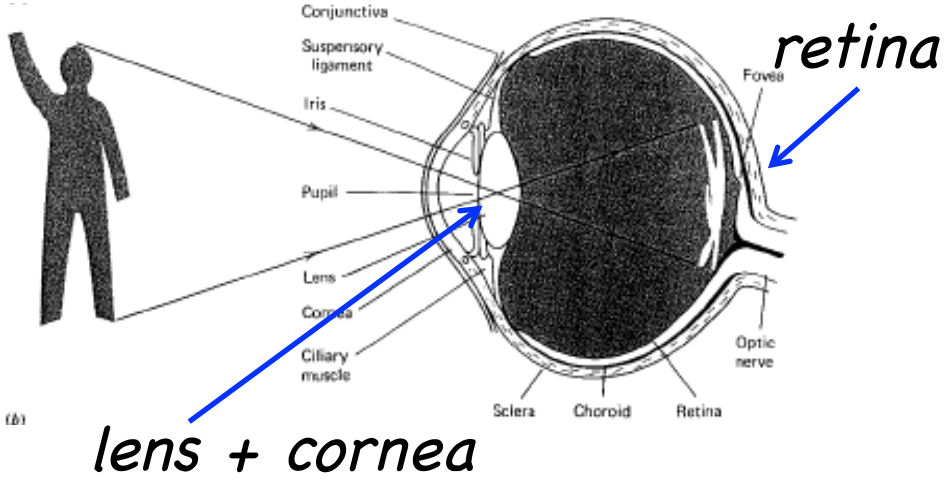
- Cornea-air surface has a larger change in the index of refraction, so light bends more -> larger power
- The power of the cornea is ≈ 43 diopters (f = 2.3cm)
- The eyelens is surrounded by the humors, which have a very similar index of refraction as the lens itself



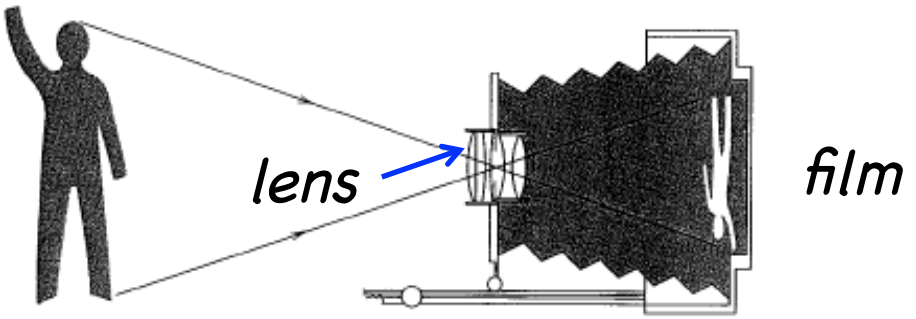
Focusing

- The *eyelens* is a *fixed, unchanging* distance, x_i from the retina at the back of the eyeball, where the image is created, as the distance to the object, x_o changes. Focus via *changing the focal length, f, by changing shape*

$$\frac{1}{x_o} + \frac{1}{x_i} = \frac{1}{f}$$



- A *camera* is focused by *changing* the distance, x_i from the lens to the image at the back of the film or CCD as the distance to the object, x_o changes



Eye focusing

- The *eyelens* is a *fixed, unchanging* distance, x_i from the retina at the back of the eyeball, where the image is created, as the distance to the object, x_o changes. Focus via *changing the focal length, f, by changing shape*

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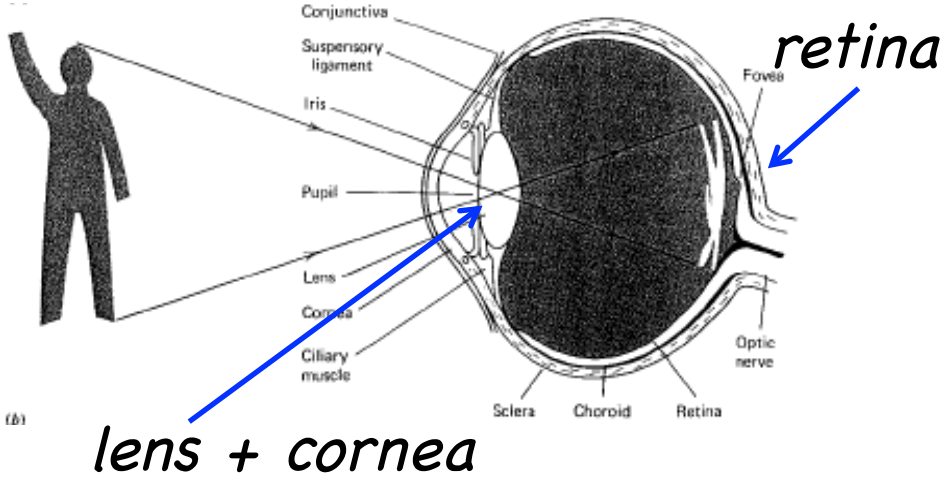
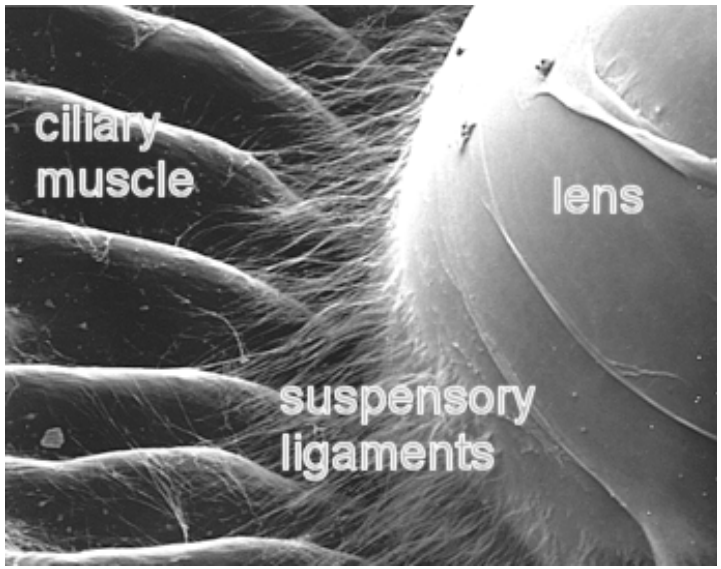
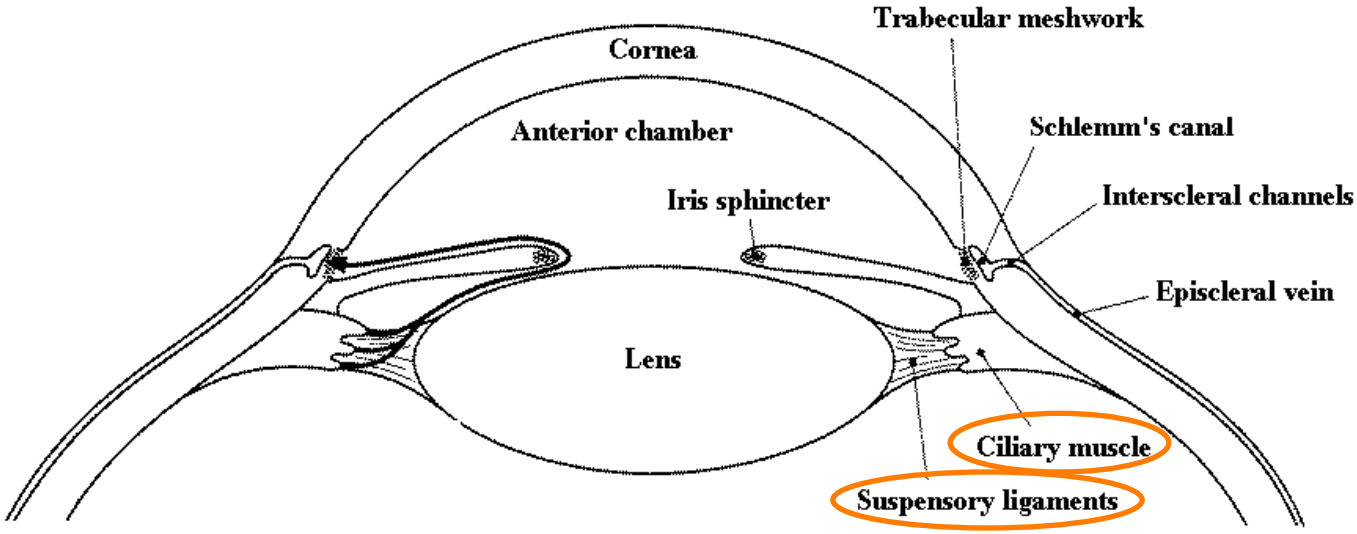




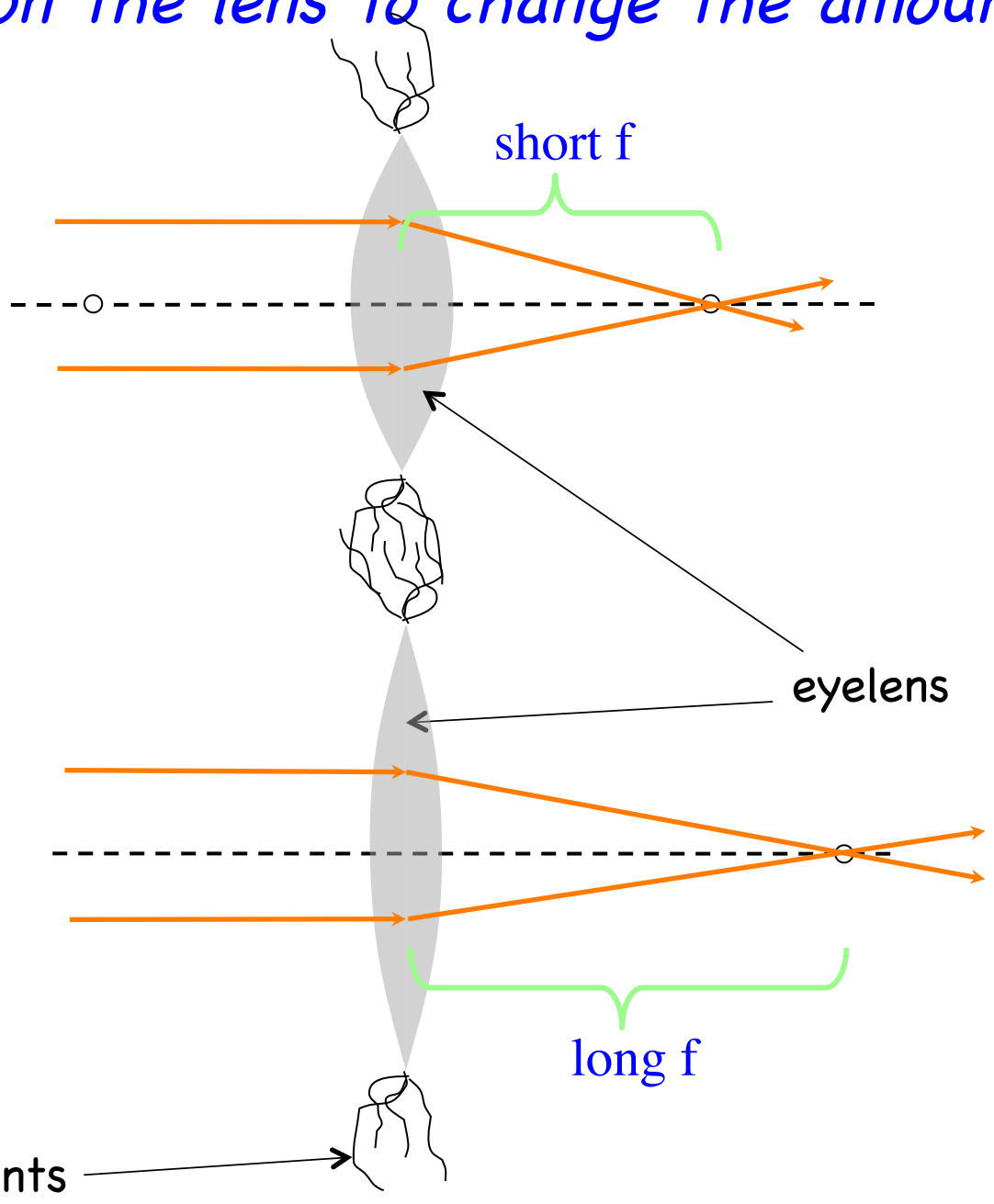


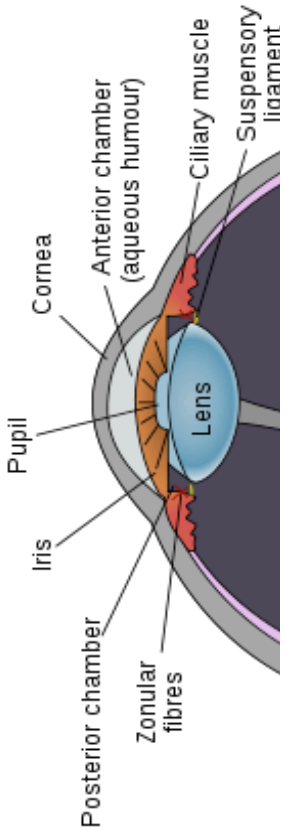
The eyelens: *accommodation*

$$\frac{1}{x_o} + \frac{1}{x_i} = \frac{1}{f}$$

- The *eyelens changes its focal length by changing shape. Ligaments pull on the lens to change the amount of bulge*

muscles contract, ligaments relax, more bulge, more bending power, shorter focal length



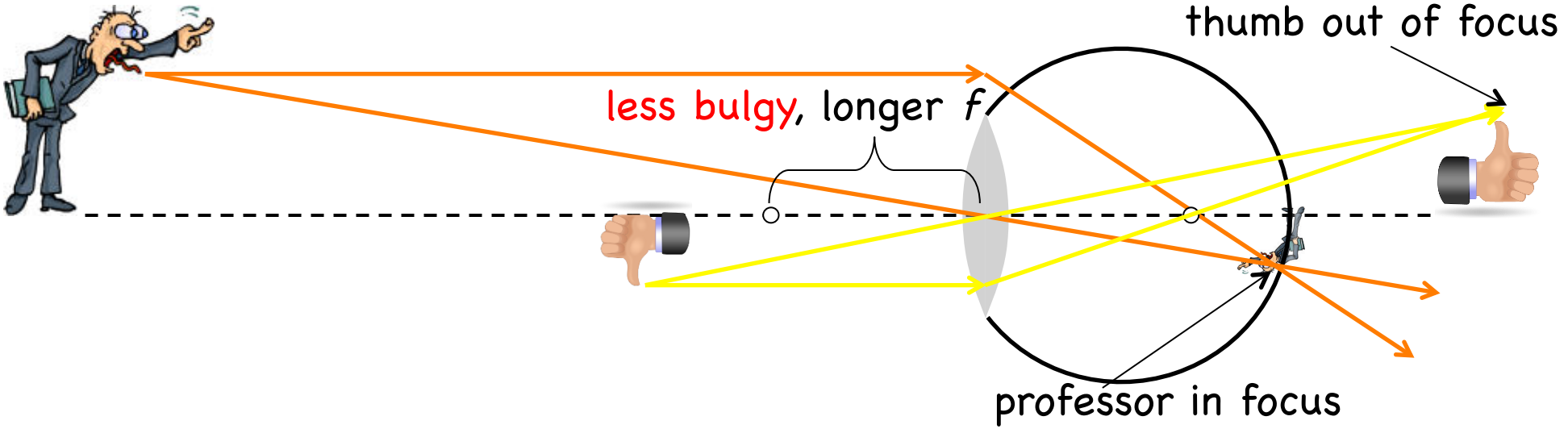


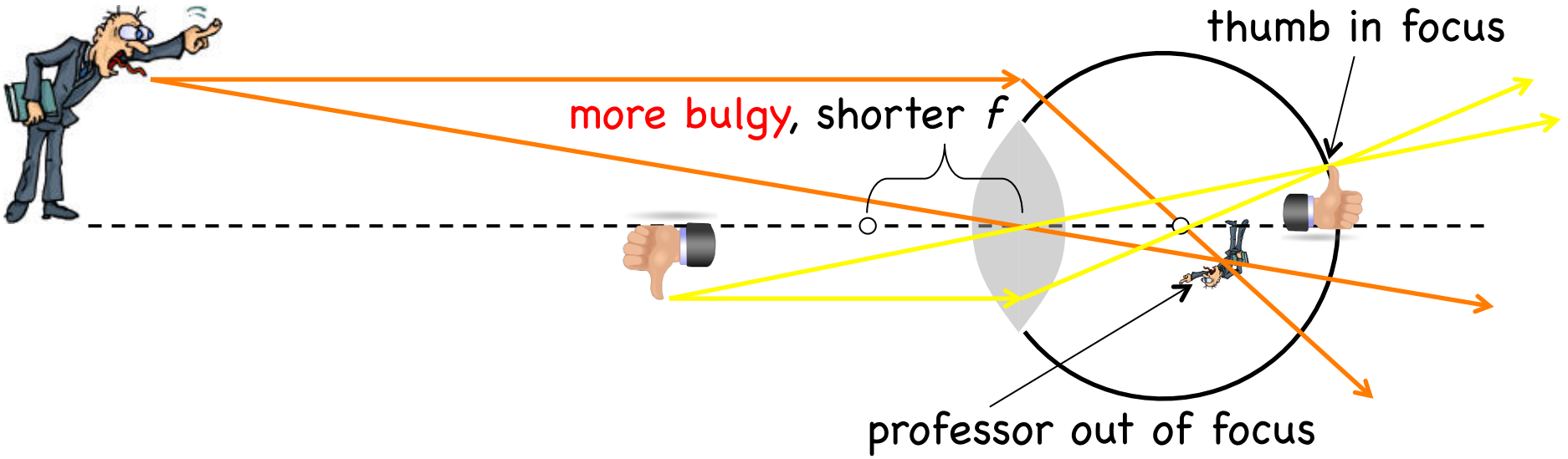
muscles relax, ligaments contract, less bulge, less bending power, longer focal length

The eyelens: *accommodation*

$$\frac{1}{x_o} + \frac{1}{x_i} = \frac{1}{f}$$

- *eyelens* has *small depth of field*, focusing by changing shape
  -> changing its focal length
- cannot see both me and your thumb in focus at same time



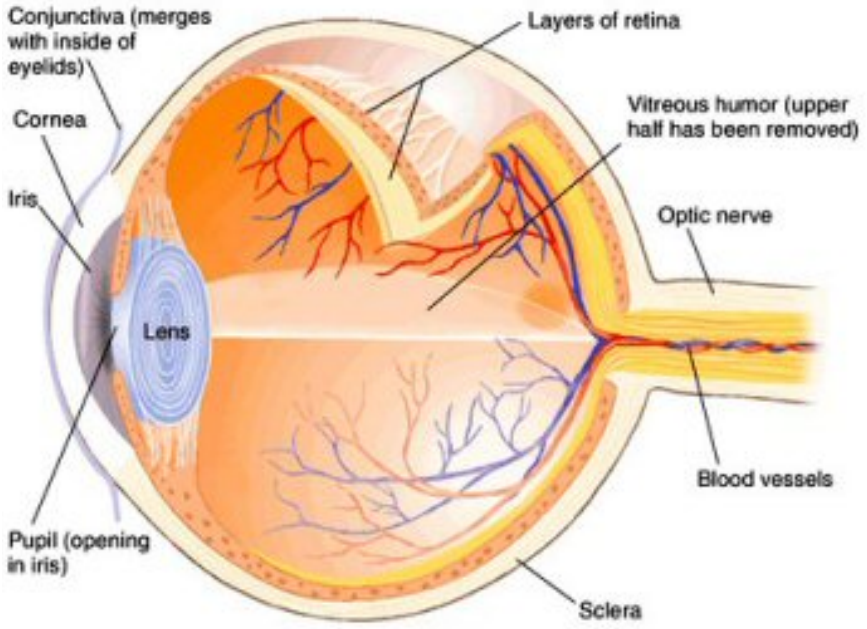


clicker question

Eye focusing

Q: You can't see the Flatirons and your thumb clearly *at the same time*

(a) because your pupil is too small
(b) because your iris can't change fast enough
(c) because your eye cannot accommodate
(d) because your eye does not have enough depth of field

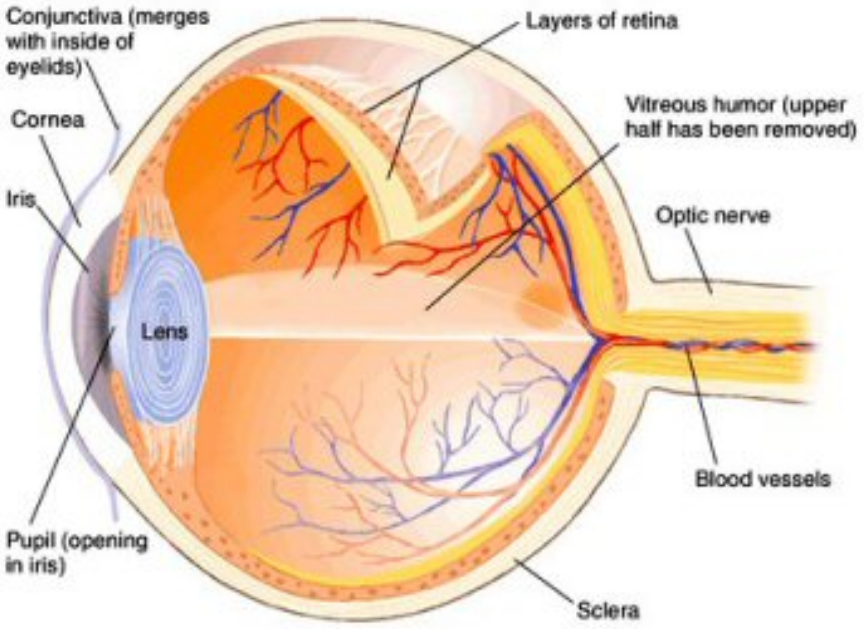


clicker question

Eye focusing

Q: When you see someone or something out-of-focus

(a) there is no image anywhere
(b) there is an in-focus image on your fovea
(c) there is an in-focus image on your retina
(d) there is an in-focus image either in *front* or in *back* of your retina

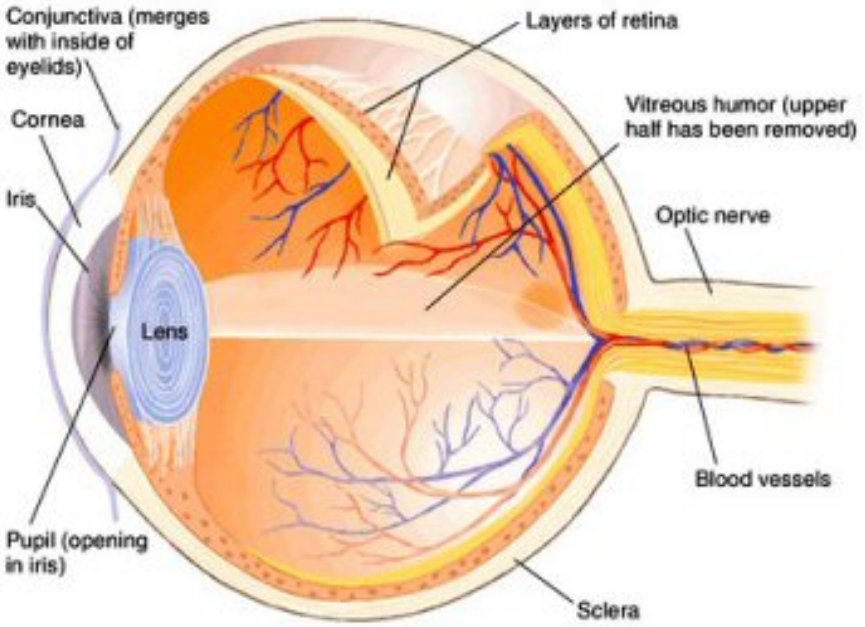


clicker question

Eye focusing

Q: In order to focus on a close object

(a) your eyelens bulges out
(b) your eyelens flatten
(c) your cornea bulge out
(d) your cornea flatten
(e) the distance, x_i between your eyelens and retina adjusts



clicker question

Eye light sensitivity

Q: The most important means by which you can see light intesity varying by over 13 orders of magnitude, i.e., by a factor of 10^{13} is:

(a) the variable opening of your iris, which acts like diaphram

(b) your retina's ability to change its sensitivity to light

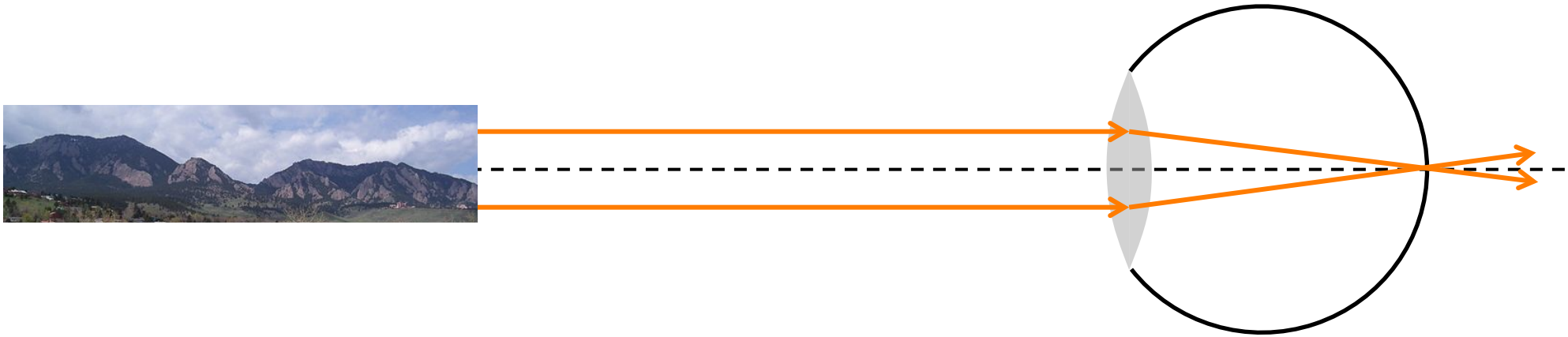
(c) your optic nerve

(d) your cornea letting in more light

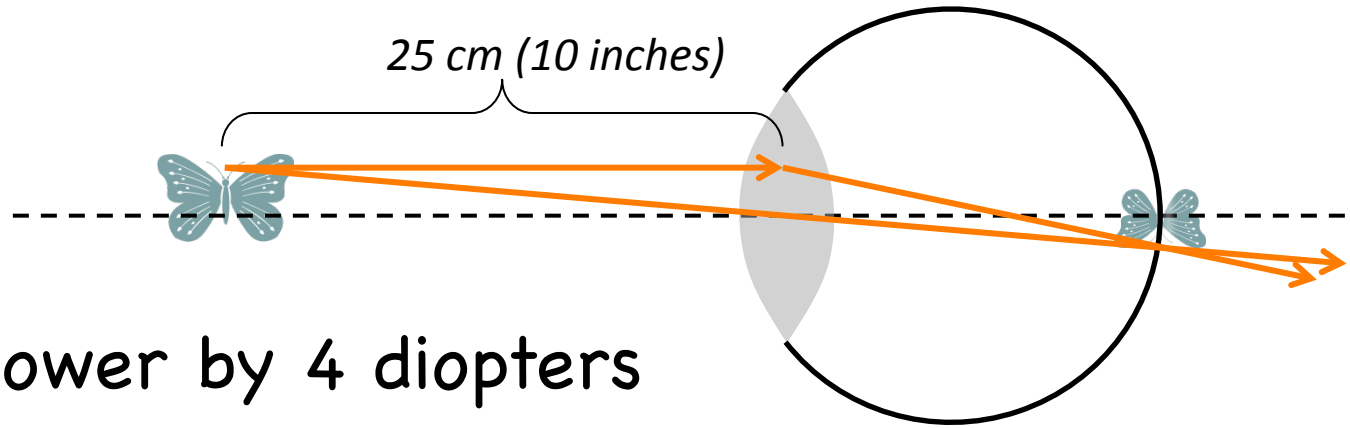
(e) your photoreceptors turning on and off faster and slower

Eye focus: *near and far points*

- *eyelens* has two extreme conformation points:
  - *"far point"*: fully relaxed, focused at *distant* objects (infinity)



  - *"near point"*: fully bulged = fully accommodated, focused at *nearby* object at about 25cm (10in) away

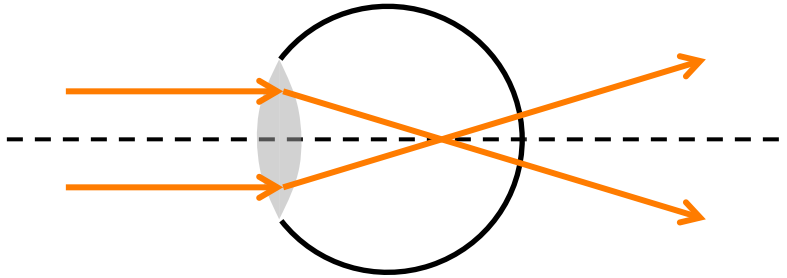


- *eyelens* changes power by 4 diopters

Imperfect vision

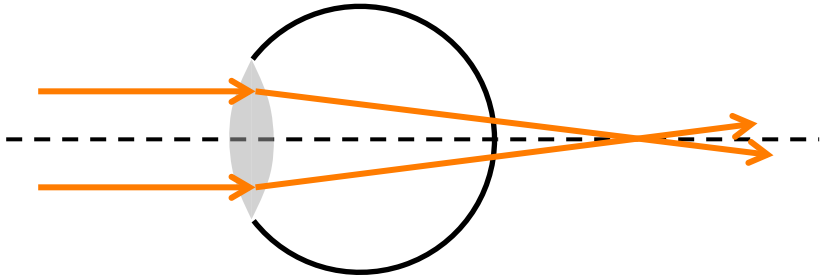
- Perfect vision: parallel rays of light coming from infinity, when eye is fully relaxed at a "far point", a distant object is *focused on the retina*

- Imperfect vision: for improperly-shaped cornea, these distant parallel rays are *not focused on the retina*



parallel rays focus in front of the retina

Myopia (near-sighted; young)

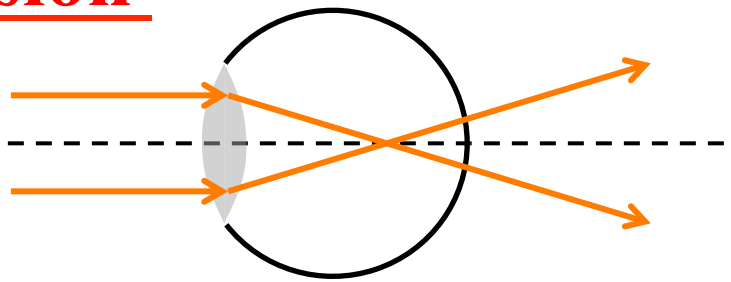


parallel rays focus past the retina

Hyperopia (far-sighted; old)

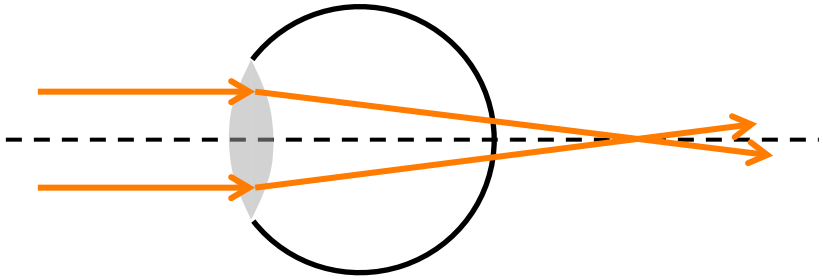
Imperfect vision

- Myopia *(near-sightedness; young)*:



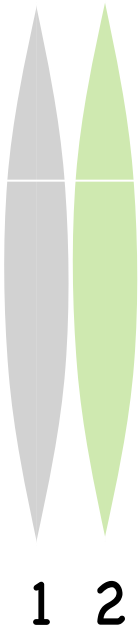
  - cornea is too powerful
  - fully relaxed eyelens -> far point not at infinity, closer
  - distant objects focus in front of retina, appear blurry
  - corrected with a divergent lens

- Hyperopia *(far-sightedness; old)*:



  - cornea is not powerful enough
  - distant objects focus in behind of retina, appear blurry
  - eyelens can partially accommodate to increase power of cornea-lens system and focus distant but not near objects on the retina
  - corrected with a convergent lens

Multiple lenses power



recall:

- The power of two lenses held together is equal to the sum of their individual powers:

$$P_{combined} = P_1 + P_2$$

- The focal length of the combined lenses is:

$$f_{combined} = 1/P_{combined}$$

- This can be used in the lens equation

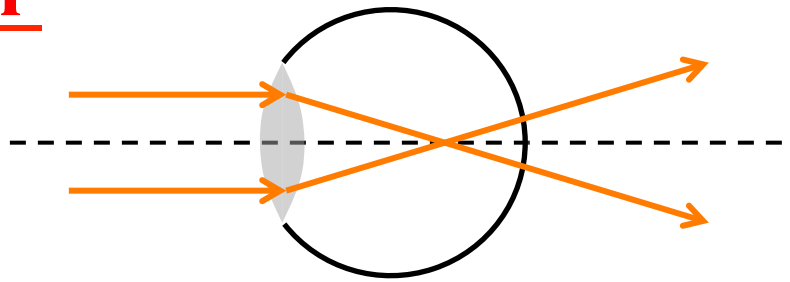
$$\frac{1}{x_o} + \frac{1}{x_i} = \frac{1}{f}$$

Combining lenses using diopters

recall: $P_{combined} = P_1 + P_2$

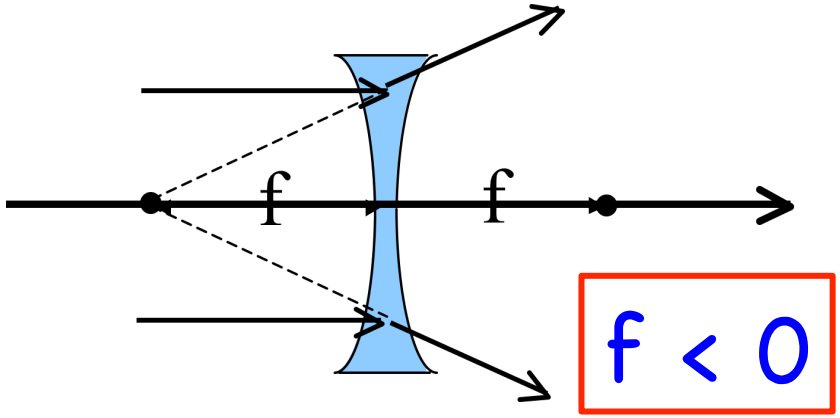
- Diopters power of a multi-lens combination?
- Example:
  - lens 1, $f_1 = 0.5$ m
  - lens 2, $f_2 = 2$ m
  - What is the power of combined lens?
  - What is the focal length $f_{combined}$ of combined lens?
- Solution:
  - power of lens 1 is 1/(0.5) = 2 diopters
  - power of lens 2 is 1/2 = 0.5 diopters
  - combined lens $P_{comb} = P_1 + P_2 = 2 + 0.5 = 2.5$ diopters
  - focal length of a combined lens, $f_{comb} = 1/P_{comb} = 0.4$m
  - only valid for *touching thin* lenses

Imperfect vision

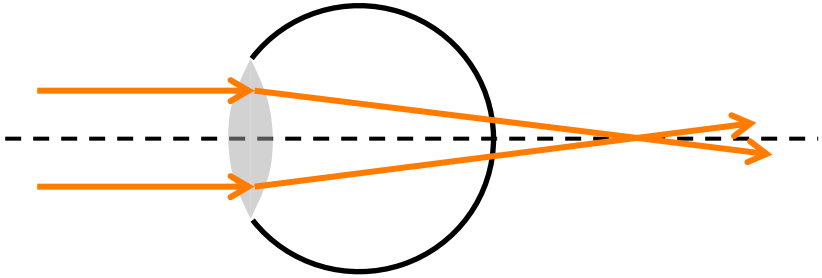


- Myopia *(near-sightedness)*:

  - corrected with a divergent lens

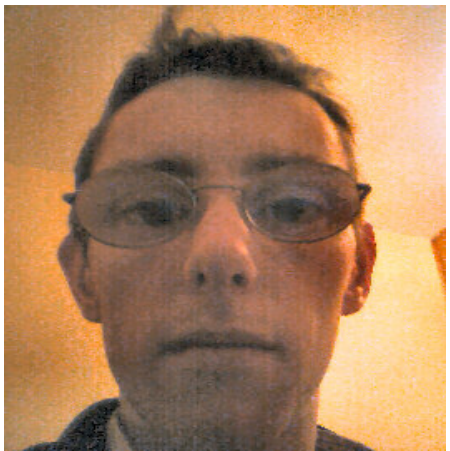


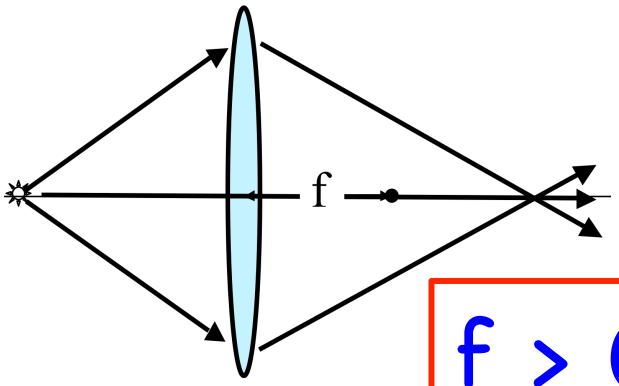
$f < 0$



- Hyperopia *(far-sightedness)*:

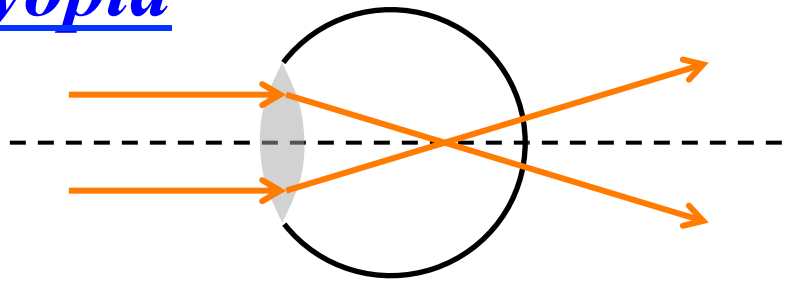
  - corrected with a convergent lens



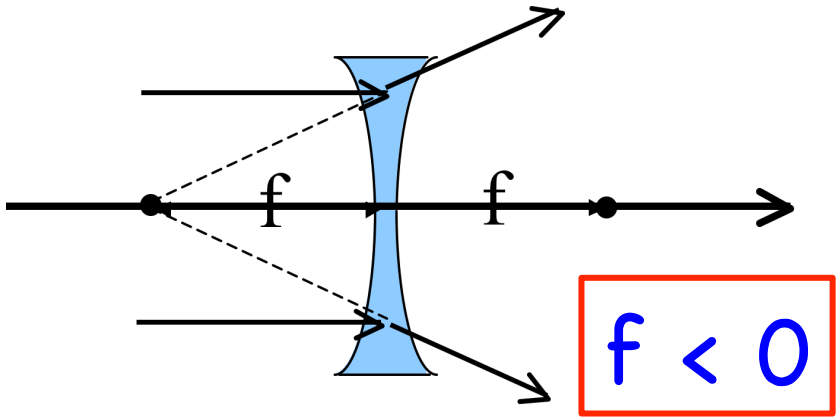


$f > 0$

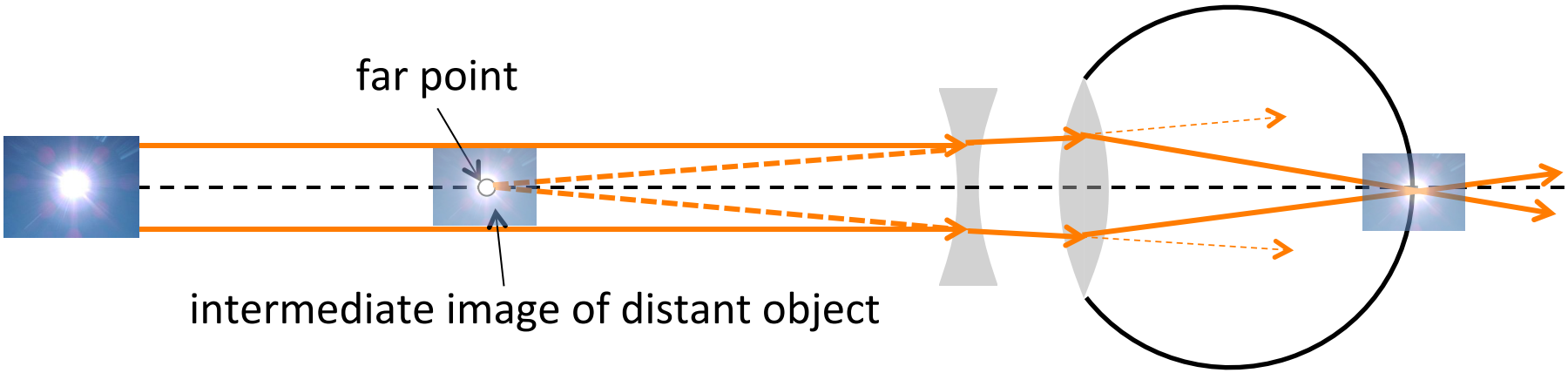
Imperfect vision: *myopia*



- Myopia *(near-sightedness)*:
  - corrected with a divergent lens

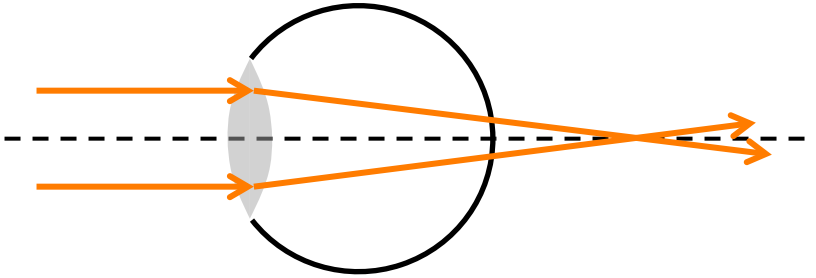


  - a divergent lens creates an *intermediate* image of a distant object at your "far point", so that your eye can see it even though the star is beyond your far point

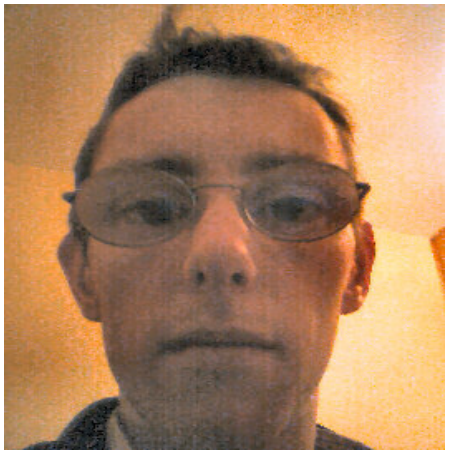


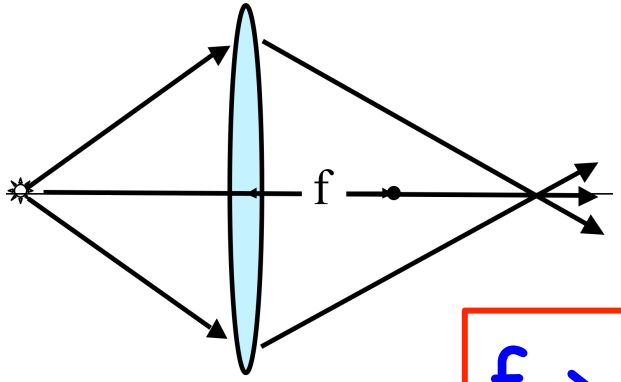
Imperfect vision: *hyperopia*

- Hyperopia *(far-sightedness)*:



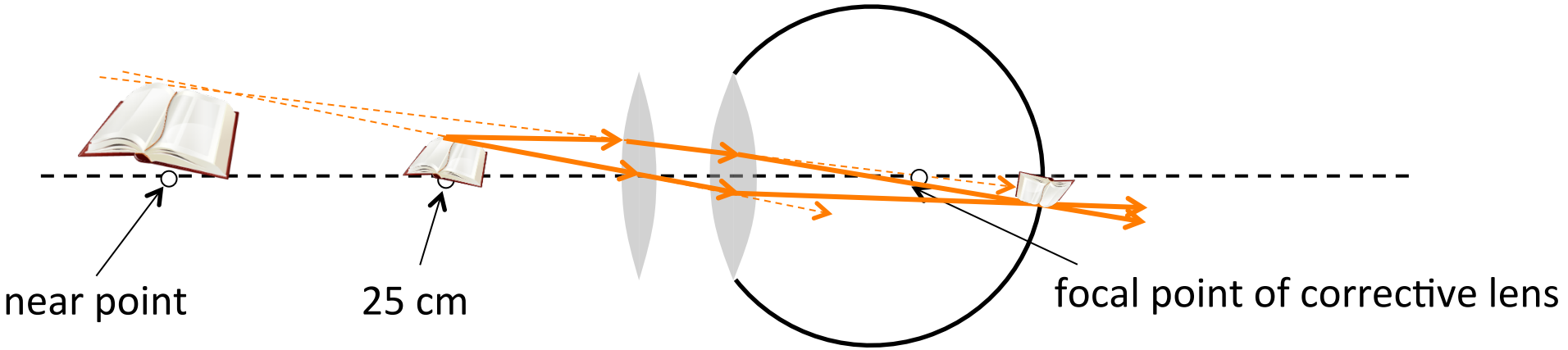
- corrected with a convergent lens





$f > 0$

- a convergent lens creates an *intermediate* image of a book 25 cm away at your "near point", so that your eye can see it even though it is closer than your near point



Determining prescription: *myopia*

- If you are near-sighted, you want the diverging corrective lens to create an intermediate image of a distant object at your far point:
  - -> the object distance $x_o = \infty$
  - -> the image distance is your near point, $x_i = - x_{farpoint}$
  - -> find the focal length and power from the lens equation

$$\frac{1}{x_o} + \frac{1}{x_i} = \frac{1}{f}$$

- The image distance x_i is *negative* (same side of the lens as the object)

Determining prescription: *hyperopia*

- If you are far-sighted, you want the converging corrective lens to create an intermediate image at your near point of an object at 25 cm:
  - -> the object distance x_o = 0.25m
  - -> the image distance is your near point, $x_i = -x_{nearpoint}$
  - -> find the focal length and power from the lens equation

$$\frac{1}{x_o} + \frac{1}{x_i} = \frac{1}{f}$$

- The image distance x_i is *negative* (same side of the lens as the object)

clicker question

Corrective lens power

Q: A myopic eye is too powerful, say it has power of 63 diopters. What power of lens should you put on it to get a combined power of 60 diopters (normal eye)?

(a) -2 diopters
(b) -3 diopters
(c) 2 diopters
(d) 3 diopters

A: $P_{combined} = P_1 + P_2 = 63 - 3 = 60$ diopters

clicker question

Corrective lens power

Q: If a person with hyperopic eyes of power 58 diopters, wears corrective lenses of power 2 diopters, what is the focal length of the combined set of lenses?

(a) 1.5 cm (0.015 m)

(b) 1.7 cm (0.017 m)

(c) 2.5 cm (0.025 m)

A: $P_{combined} = P_1 + P_2 = 58 + 2 = 60$ diopters

$f_{combined} = 1/P_{combined} = 1/60 = 0.017$m

clicker question

Determining prescription

Q: You are near-sighted and your *far point* is 1 meter away. What is your prescription?

(a) +1 diopter
(b) -1 diopter
(c) +2 diopter
(d) -2 diopter
(e) +3 diopter

$$\frac{1}{x_o} + \frac{1}{x_i} = \frac{1}{f}$$

A: $x_o = \infty$, x_i = -1 meter -> f = -1 meter -> P = -1 diopters

clicker question

Determining prescription

Q: You are far-sighted and your *near point* is 1 meter away instead of 25cm. What is your prescription?

(a) +1 diopter
(b) -1 diopter
(c) +2 diopter
(d) -2 diopter
(e) +3 diopter

$$\frac{1}{x_o} + \frac{1}{x_i} = \frac{1}{f}$$

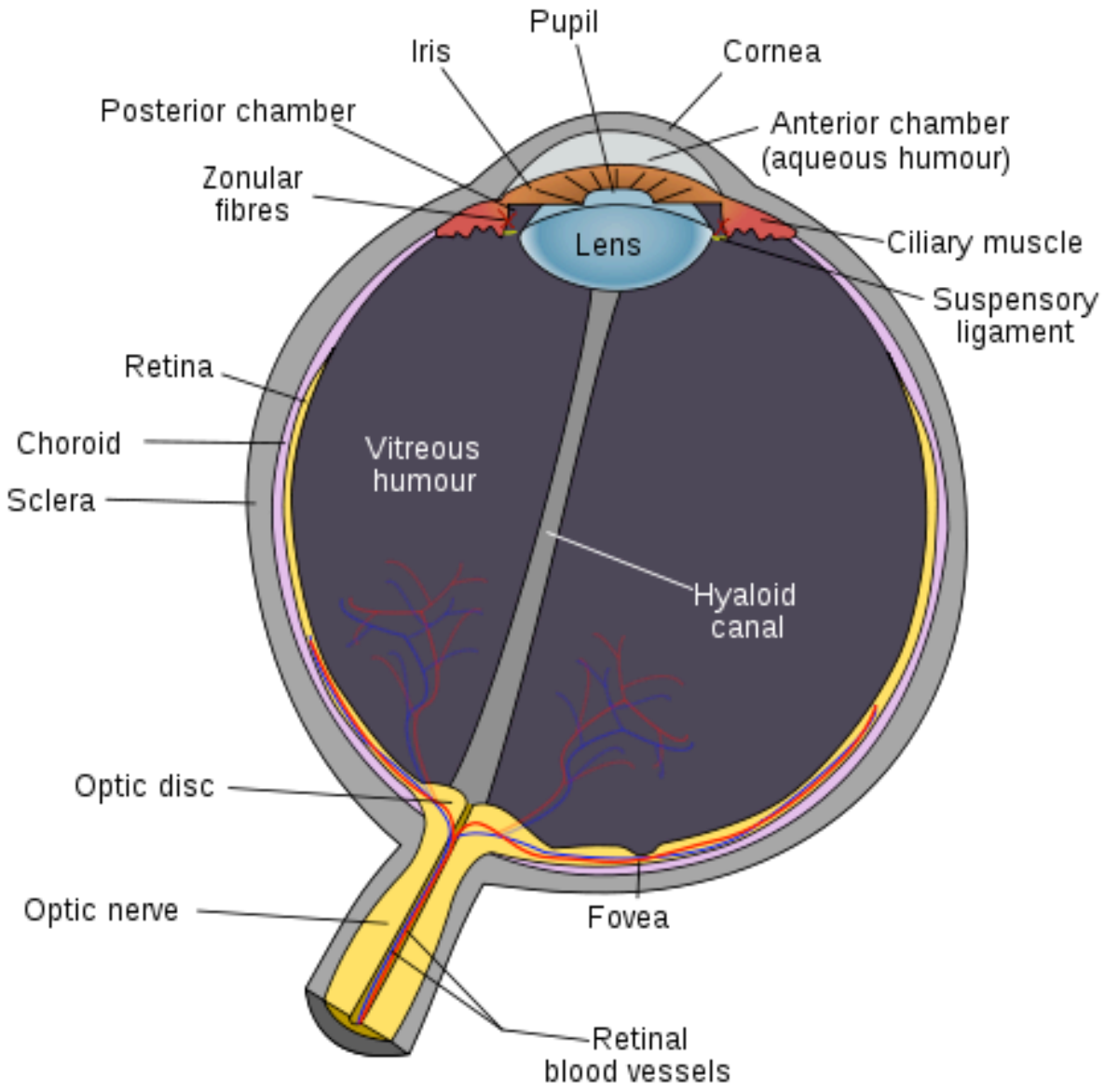
A: x_o = 0.25m, x_i = -1 meter

-> 1/f = 1/0.25 - 1/1 = 4 - 1 = 3 -> f = 1/3 meter

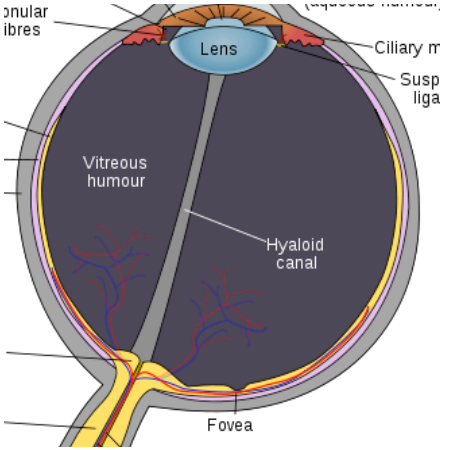
-> P = +3 diopters

Structure of the eye

- What is inside the eye?
  - vitreous humor
  - retina
  - optic nerve

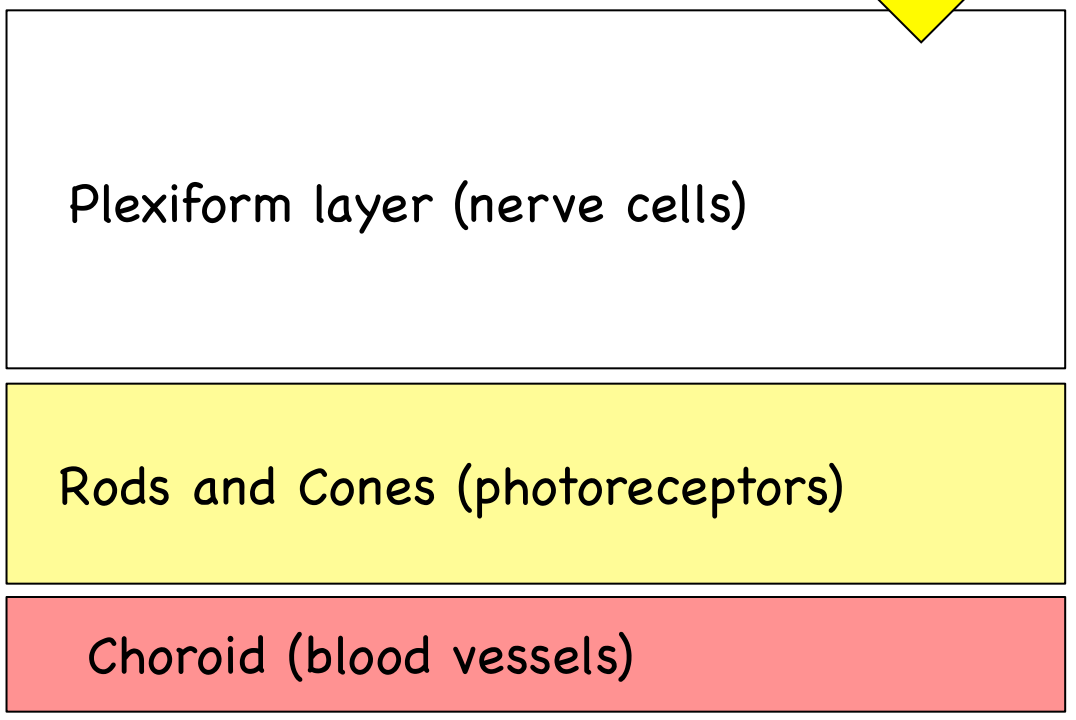


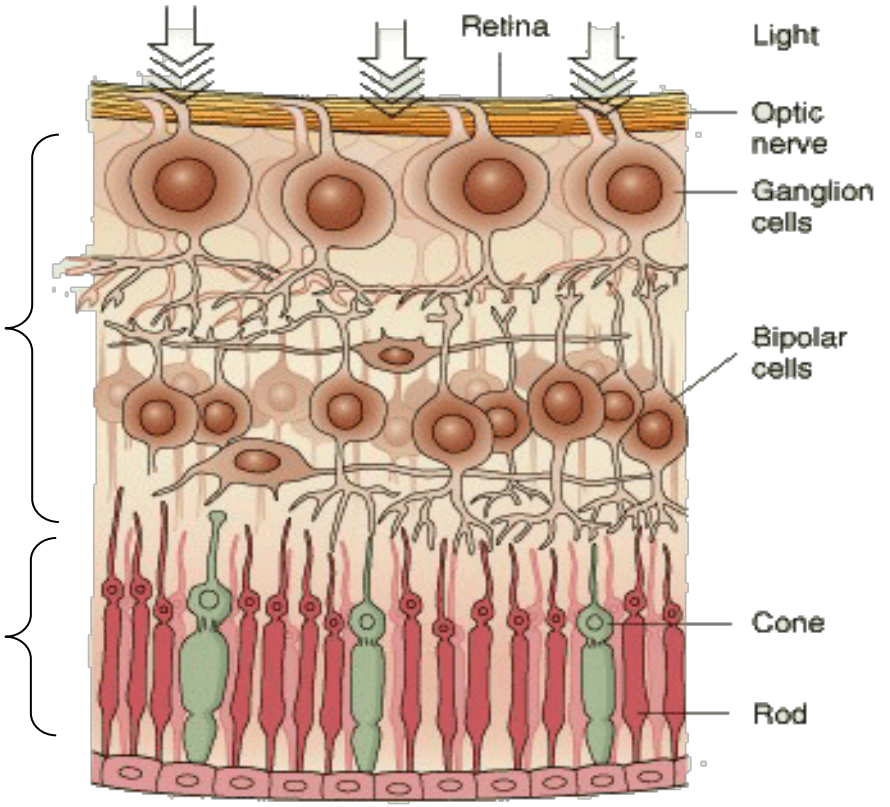
Structure of the eye: *retina*



- the retina is the sensor or "film" of the eye
- its layers serve three function:
  - *provides blood and nutrients (choroid)*
  - *absorb light and convert to an electrical signal (photoreceptors)*
  - *transfer the signal to the brain (nerve cells)*

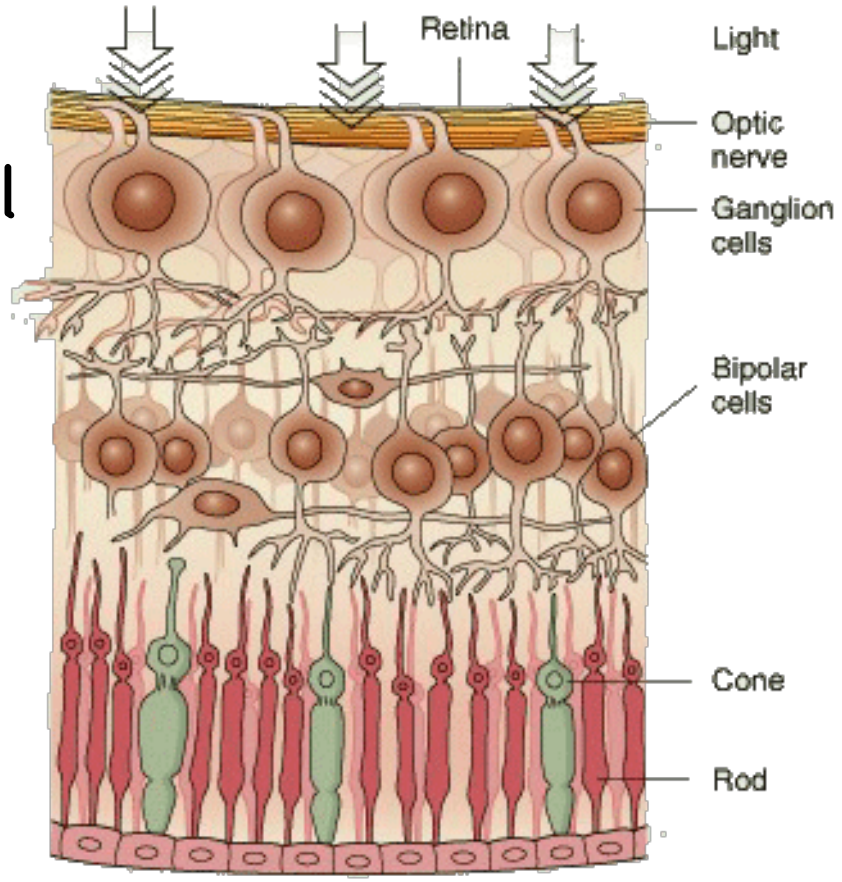
Light



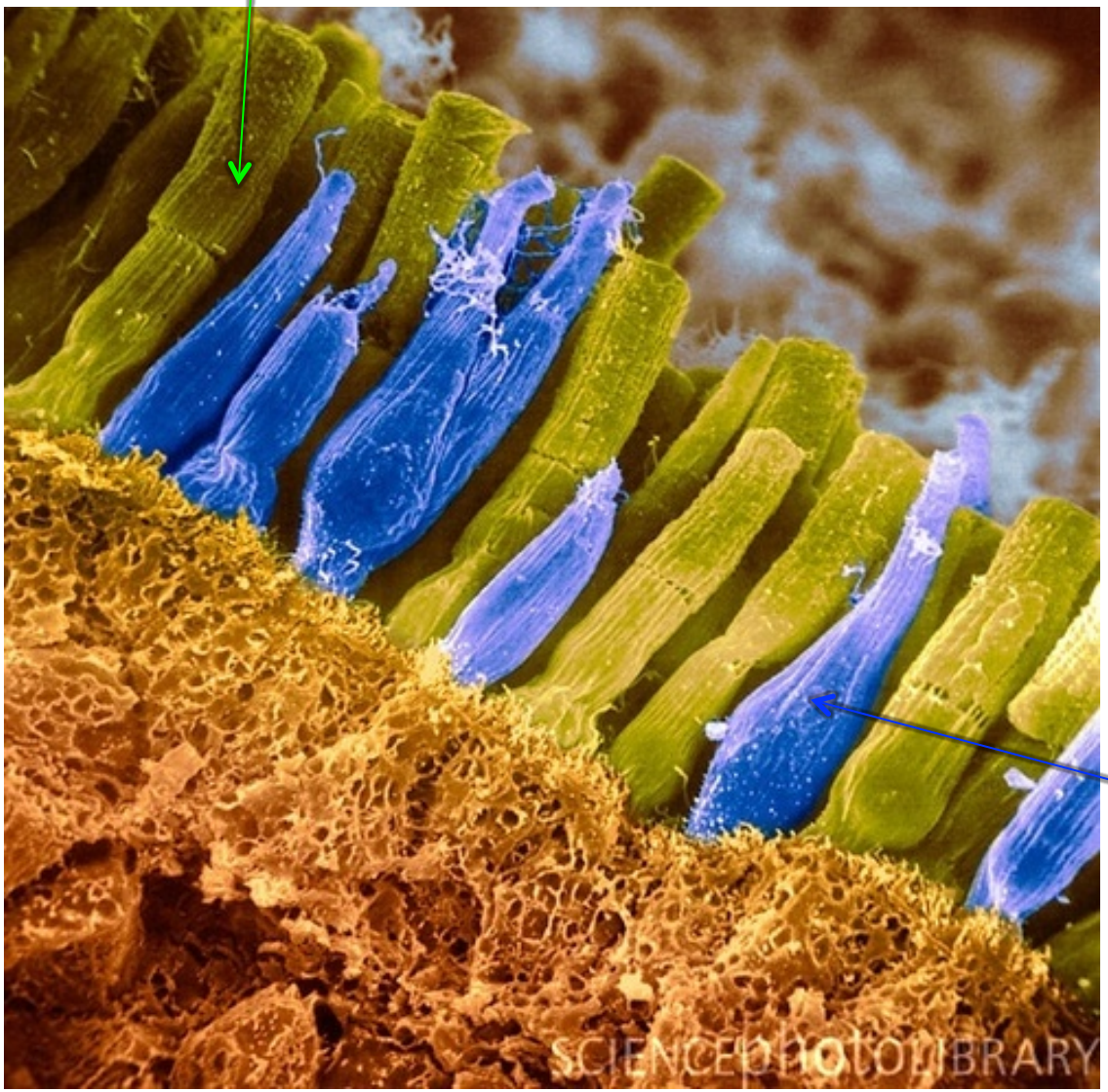


Photoreceptors: *rods and cones*

- Photoreceptors (rods and cones) convert light into electrical signal



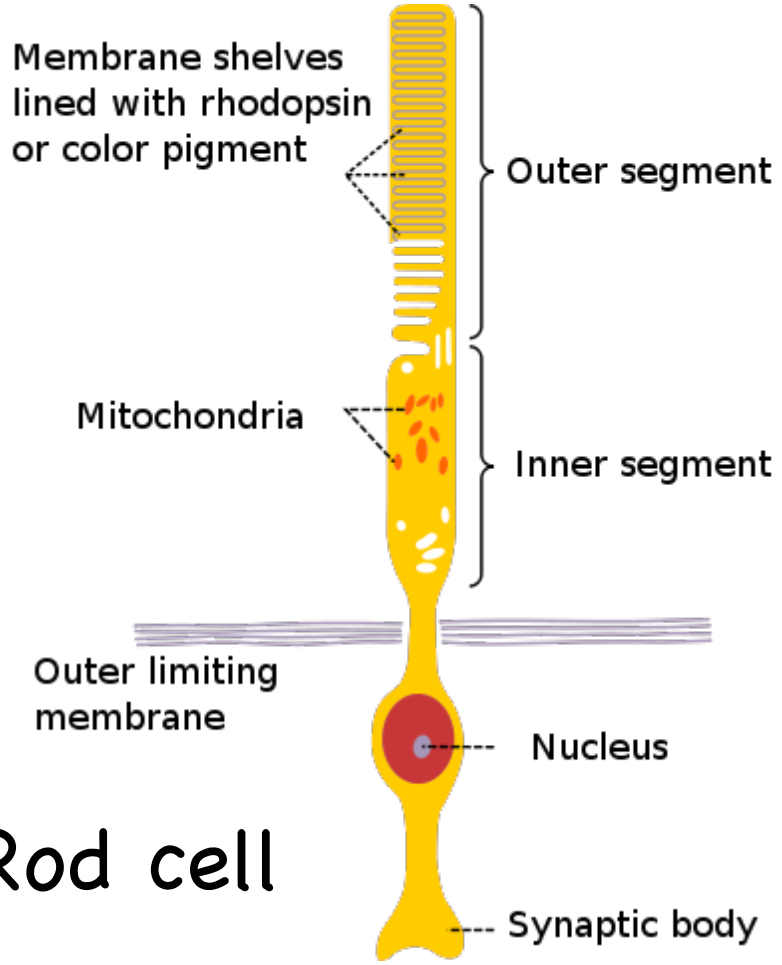
rod



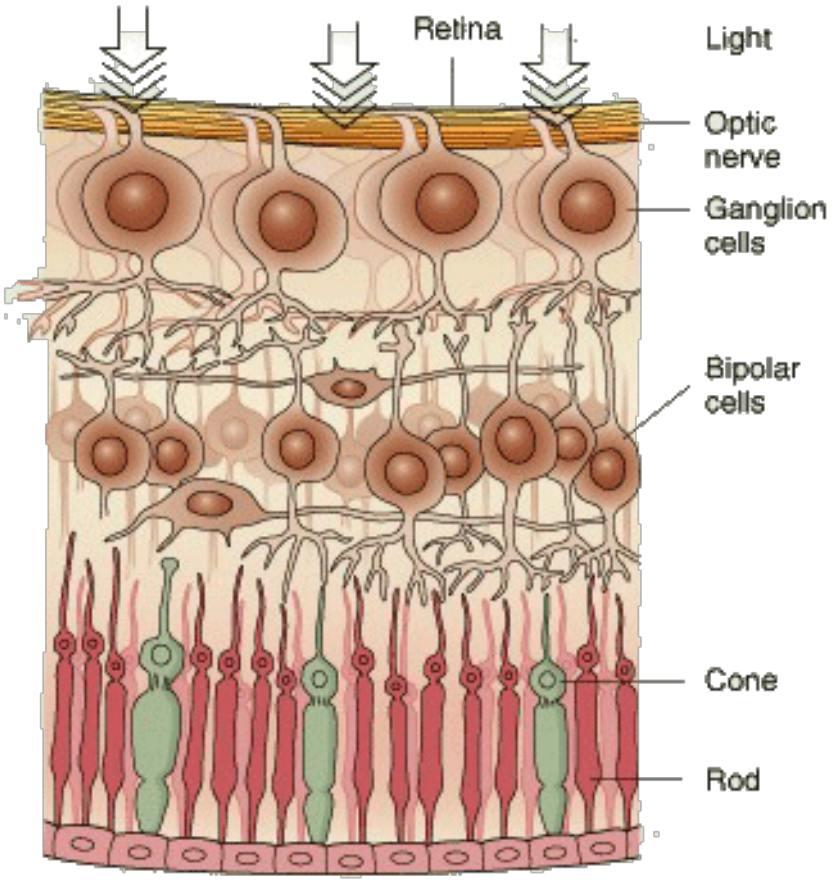
cone

false color image

Photoreceptors: *rods*

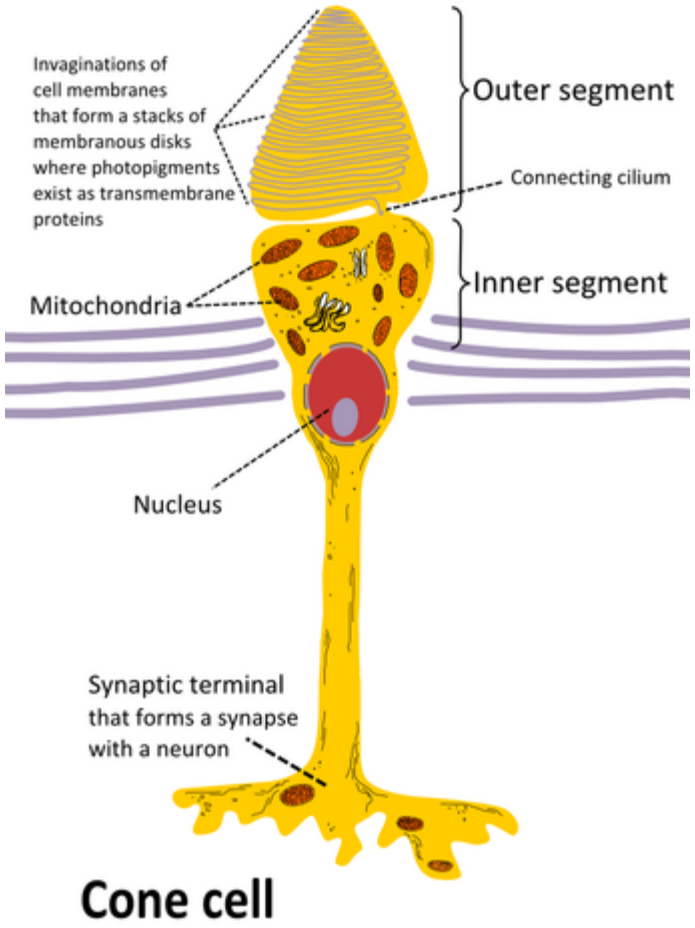


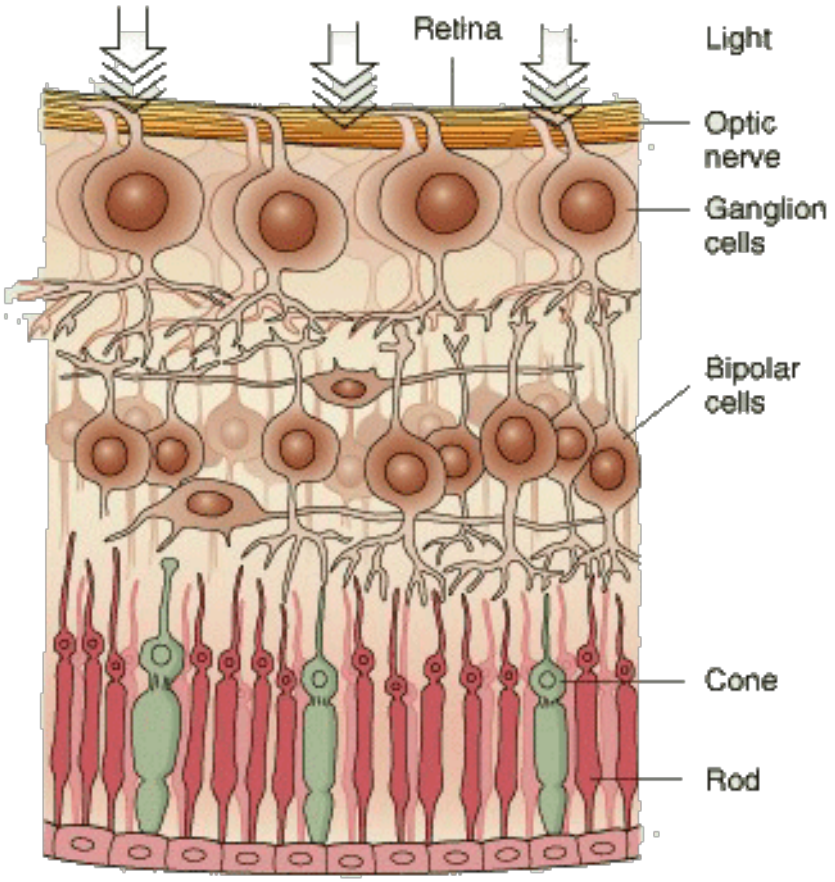
Rod cell



- responsible for low light, peripheral, black-white vision
- present everywhere in the retina, except *fovea*
- there are 125 million rods in the average retina

Photoreceptors: *cones*

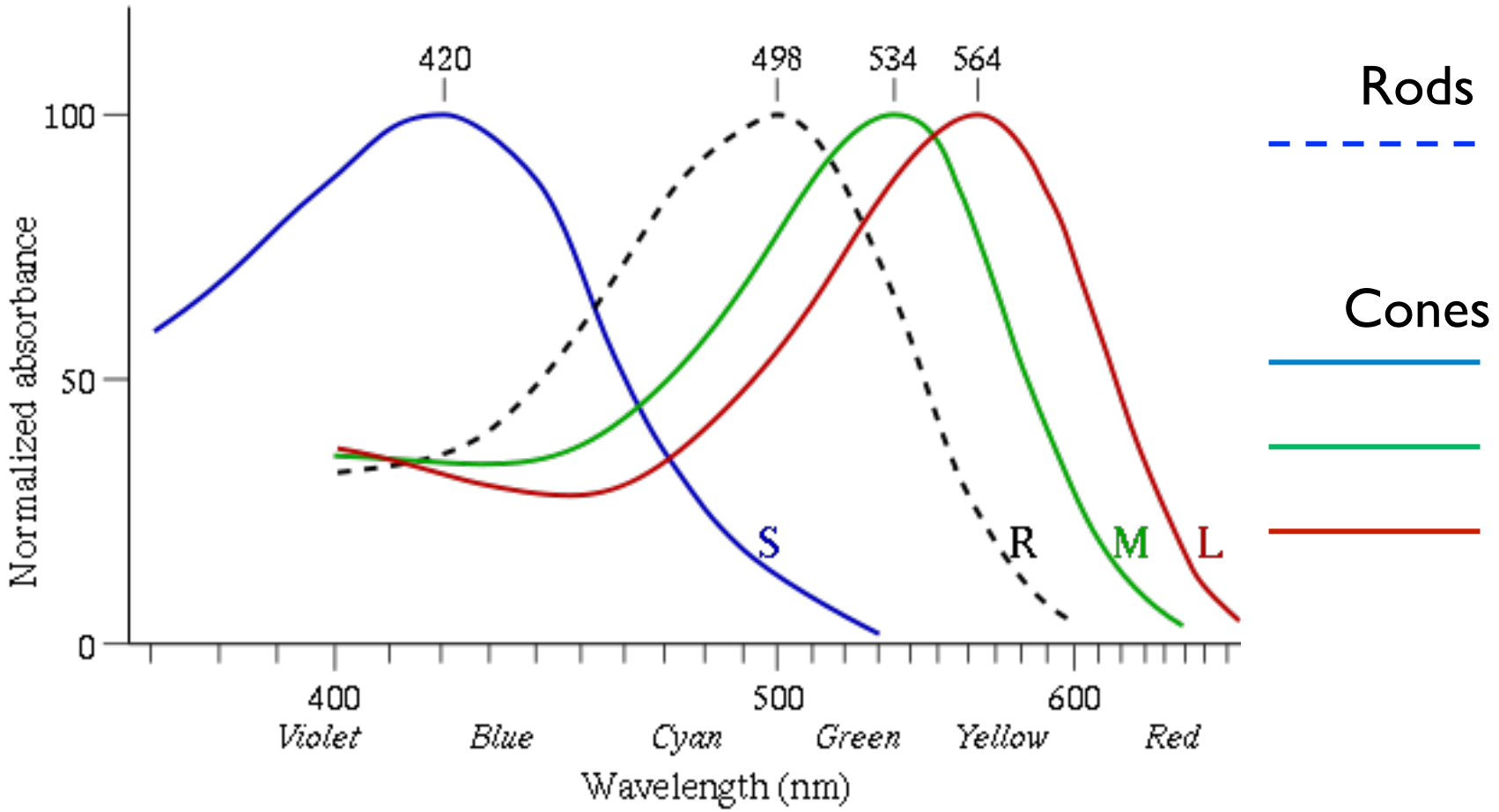




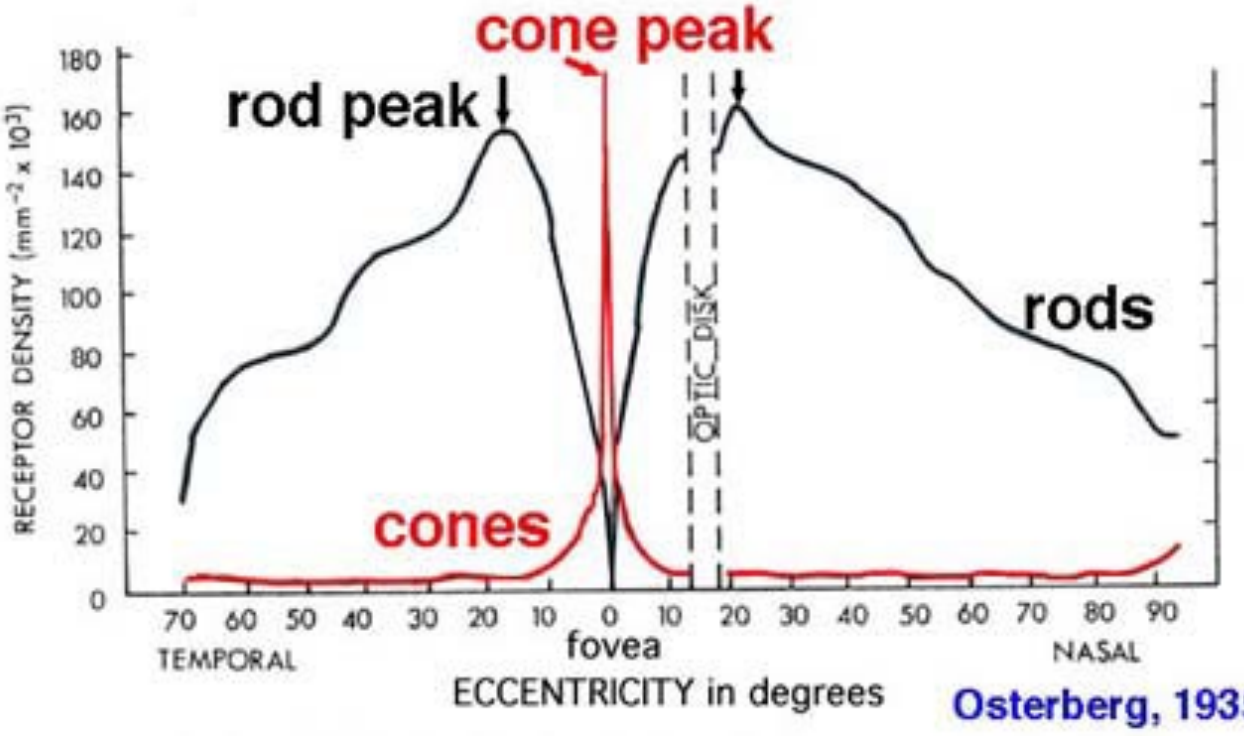
- responsible for fine detailed and color vision
- clustered near the center of the retina, called *fovea*
- there are 5 million cones in the average retina

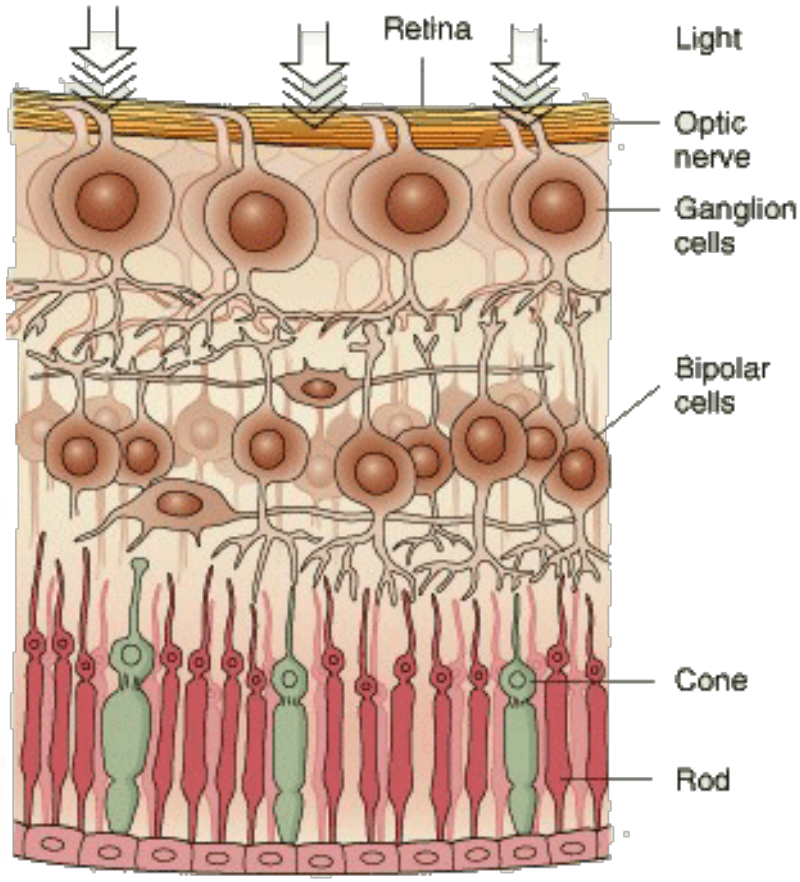
Color effects: *rods and cones*

- *rods* are only sensitive to green, blue; *not* sensitive to red, yellow
  -> in low light, red objects appear very dim
  -> relative brightness of different colors changes when viewed under different lighting conditions



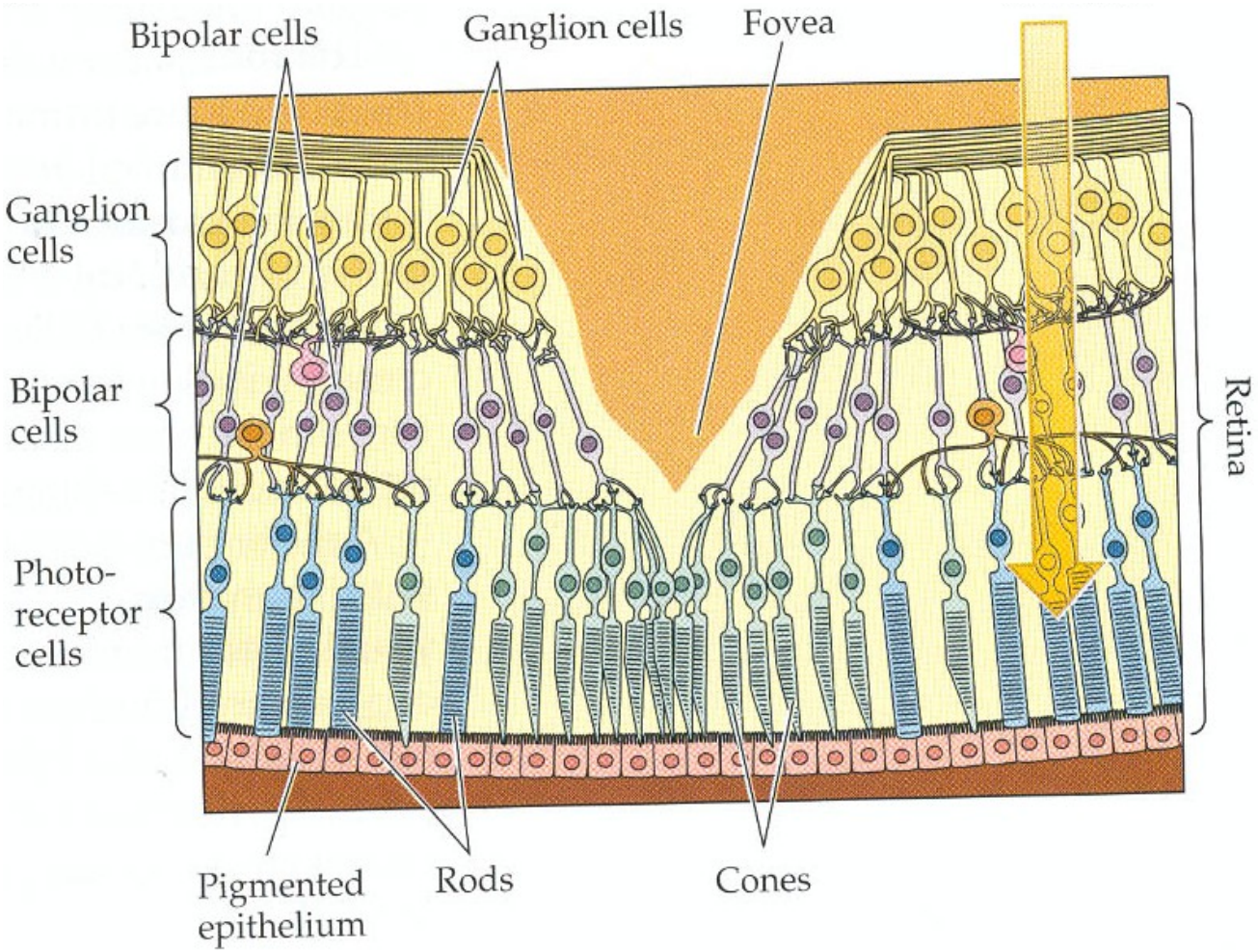
Photoreceptors: *rods and cones*

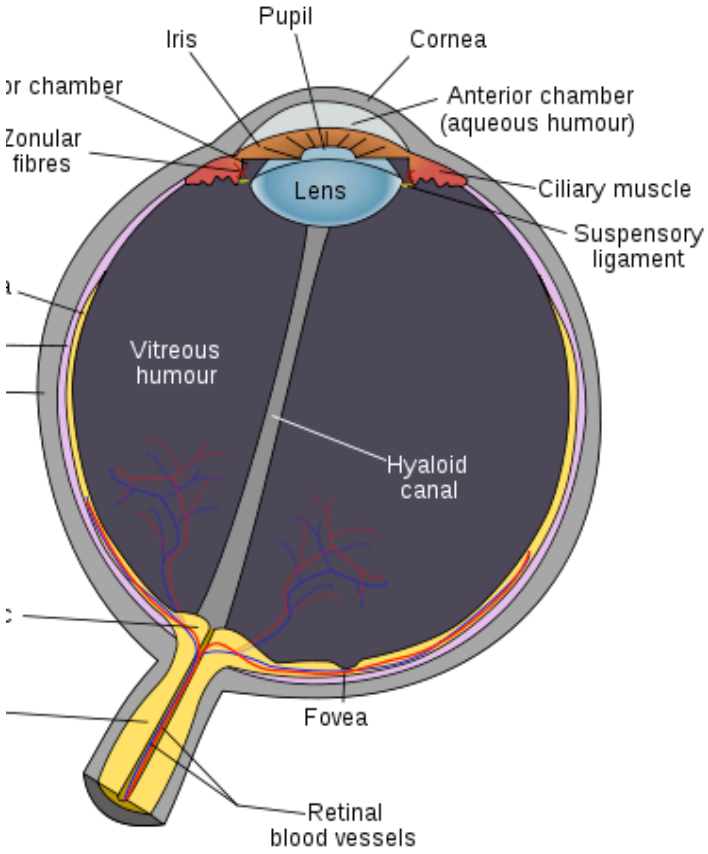




- Because of their different functions, rods and cones are present in varying densities in the retina. The blind spot is due to the connection of the optic nerve
- Signal goes to the brain through optic nerve, no rods and cones there -> blind spot

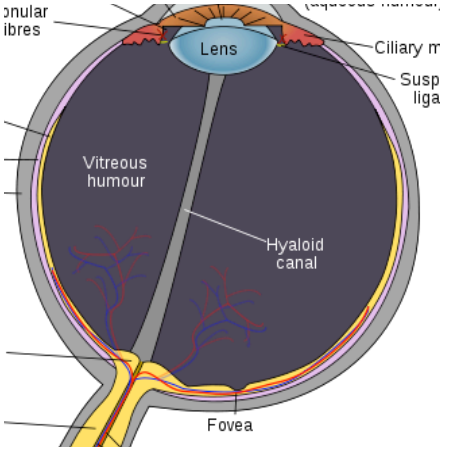
Photoreceptors: *rods and cones*





- Because of their different functions, rods and cones are present in varying densities in the retina. The blind spot is due to the connection of the optic nerve
- Signal goes to the brain through optic nerve, no rods and cones there -> blind spot

Structure of the eye: *retina*



- retina blood supply
- red eye
  - light bounces off blood vessels see red
  - red eye reduction via pre-flash to close pupil

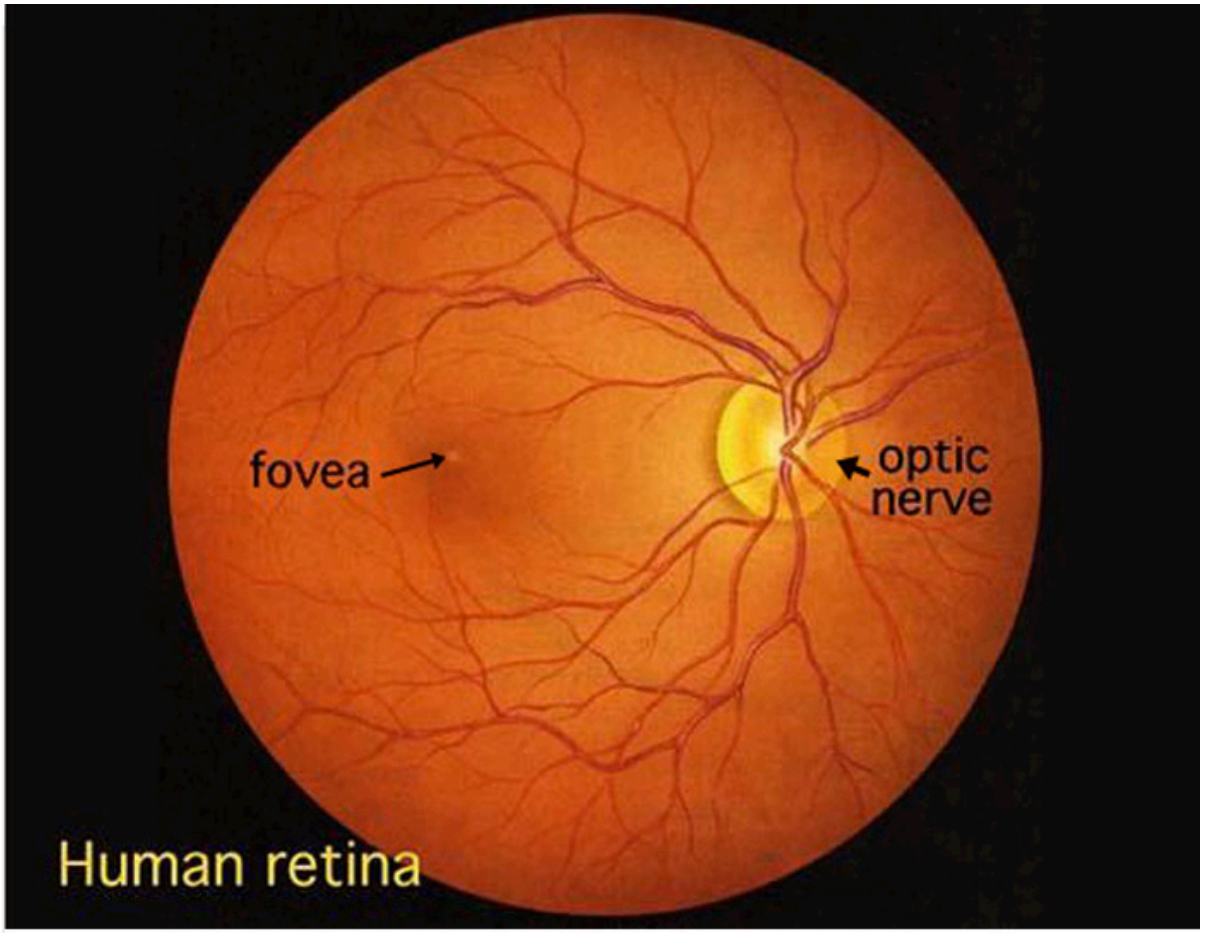
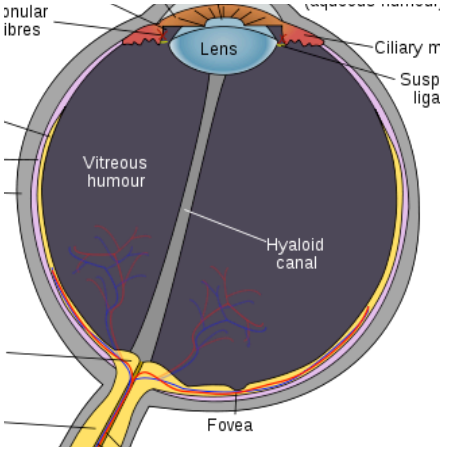


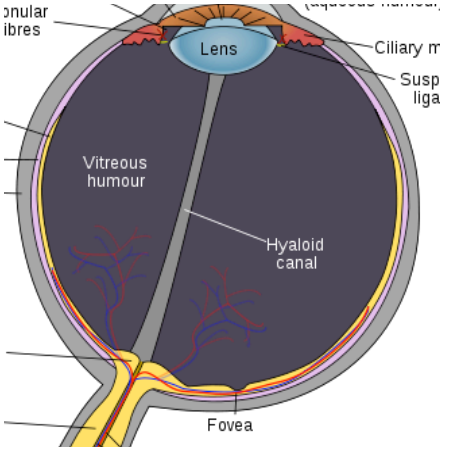
Fig. 1. Human retina as seen through an opthalmoscope.

Persistence of vision



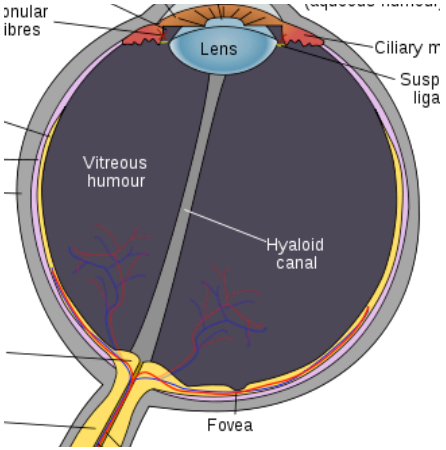
- "persistence of response" (shutter speed)
  - time during which photoreceptor is active and is responding to light
- images remain on receptors
  - for 1/25 second in low light
    -> movies 24 frames/sec in dark room
  - for 1/50 second in bright light
    -> TV 60 frames/sec, OK in lighted room
  - compare to a camera, which has shutter speed from more than 1 second to 1/1000 second

Light sensitivity & dark adaptation



- Even within the cone and rod system, your retina adjusts its sensitivity over a huge range (10^{13}) in response to the overall light levels
- When you walk into a dark/bright room, you cannot see anything, but after a few minutes, you adapt and can start to see things
- After about 30 minutes of adaptation can see an equivalent to a candle 10 miles away

Dark adaptation



- rods in dark, cones in light
- takes about 7 minutes to switch to using all rods, 25 minutes for full adaptation