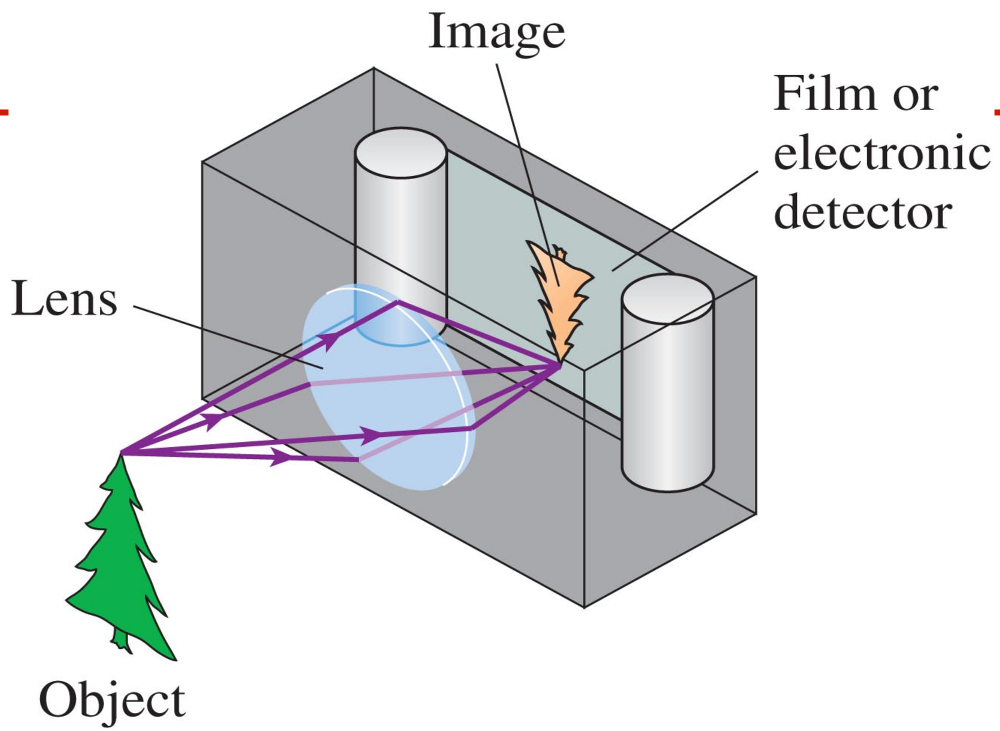
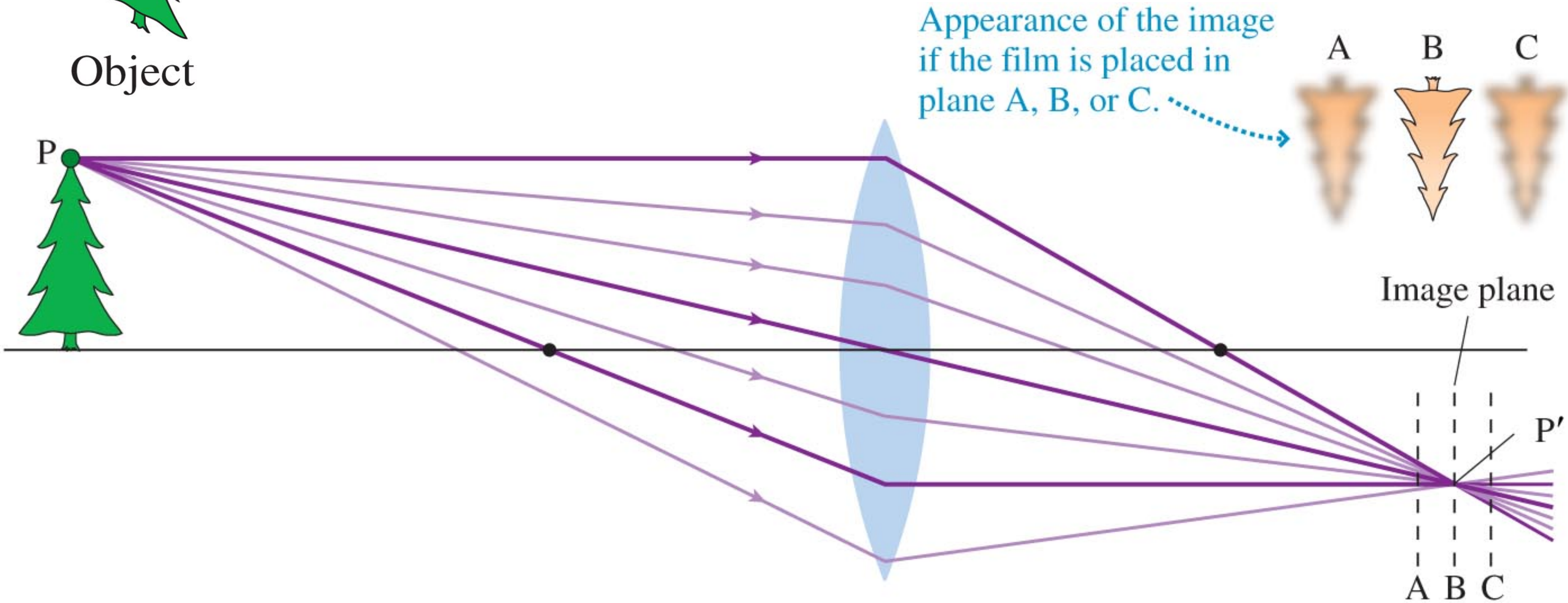
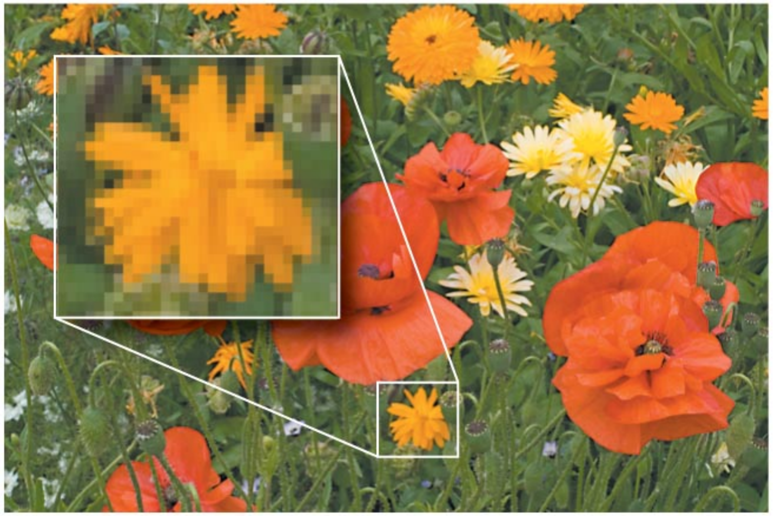
Focusing a Camera



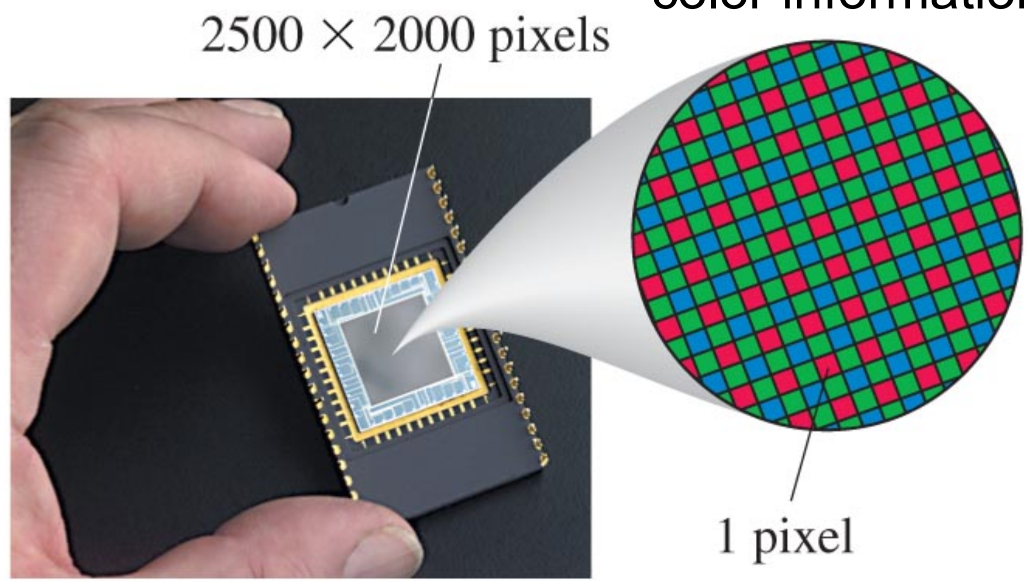


Digital Cameras



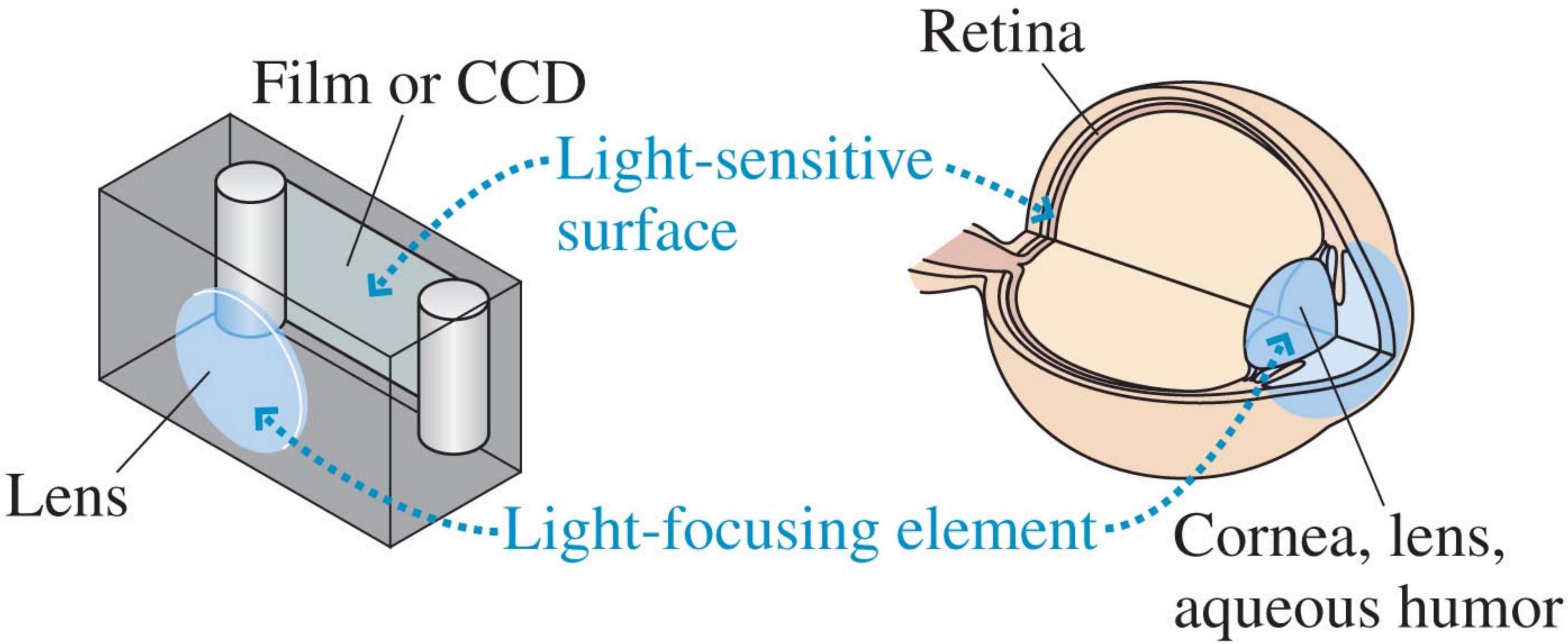
A digital image is made up of millions of *pixels*.

Use red, green or blue filters to get color information



A CCD (charge-coupled device) chip records the digital image.

The Human Eye



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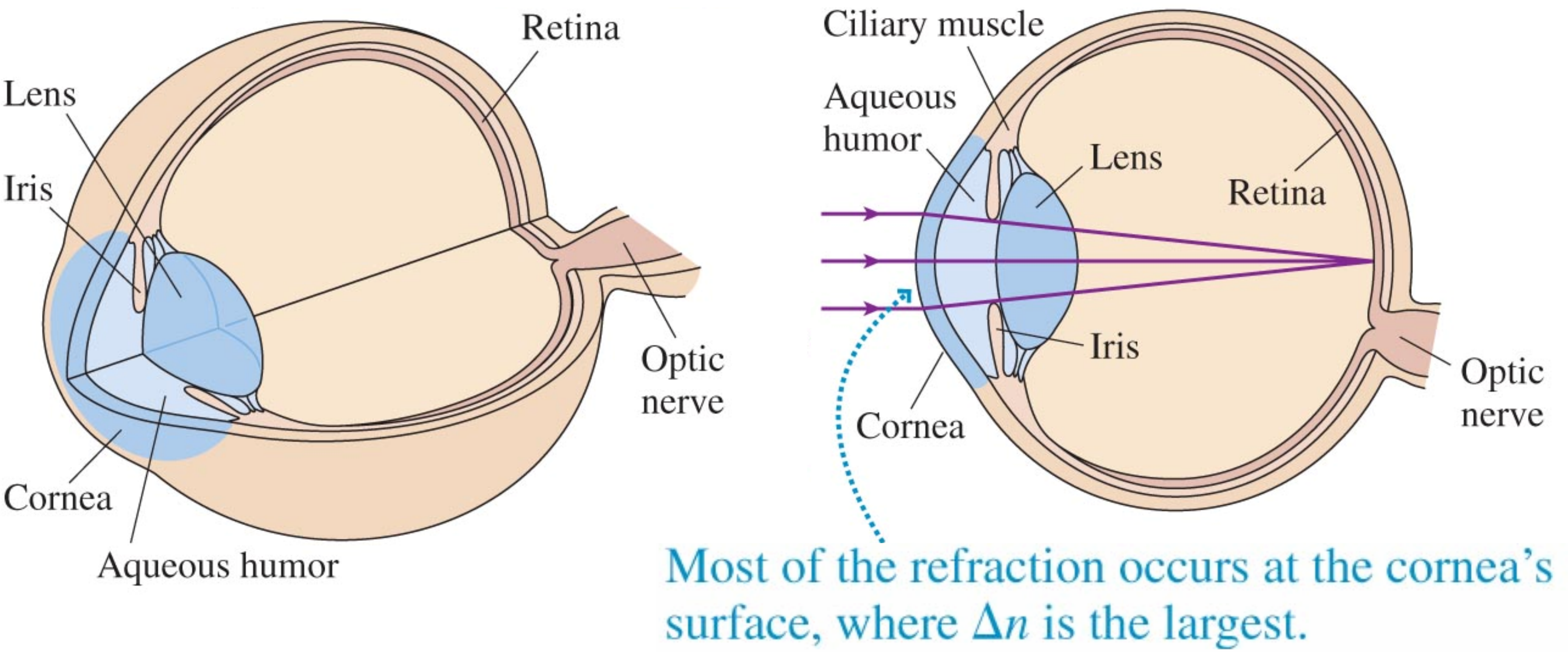
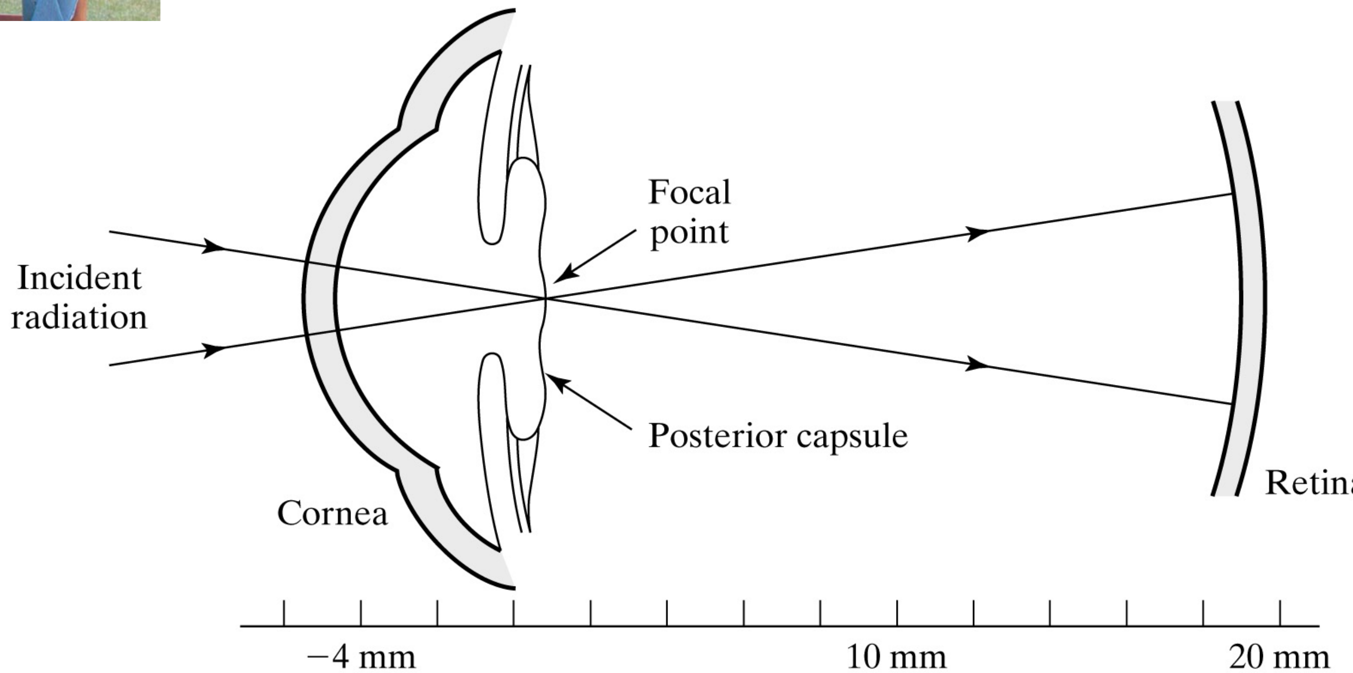
Your eye is like a camera with a **converging lens** but instead of changing the distance between the lens and the retina to get an image in focus the shape of the lens is changed by relaxing or contracting the ciliary muscles (called **accommodation**).

The Human Eye



Your eye is like a camera with a **converging lens** but instead of changing the distance between the lens and the retina to get an image in focus the shape of the lens is changed by relaxing or contracting the ciliary muscles (called **accommodation**).

Apparent Size



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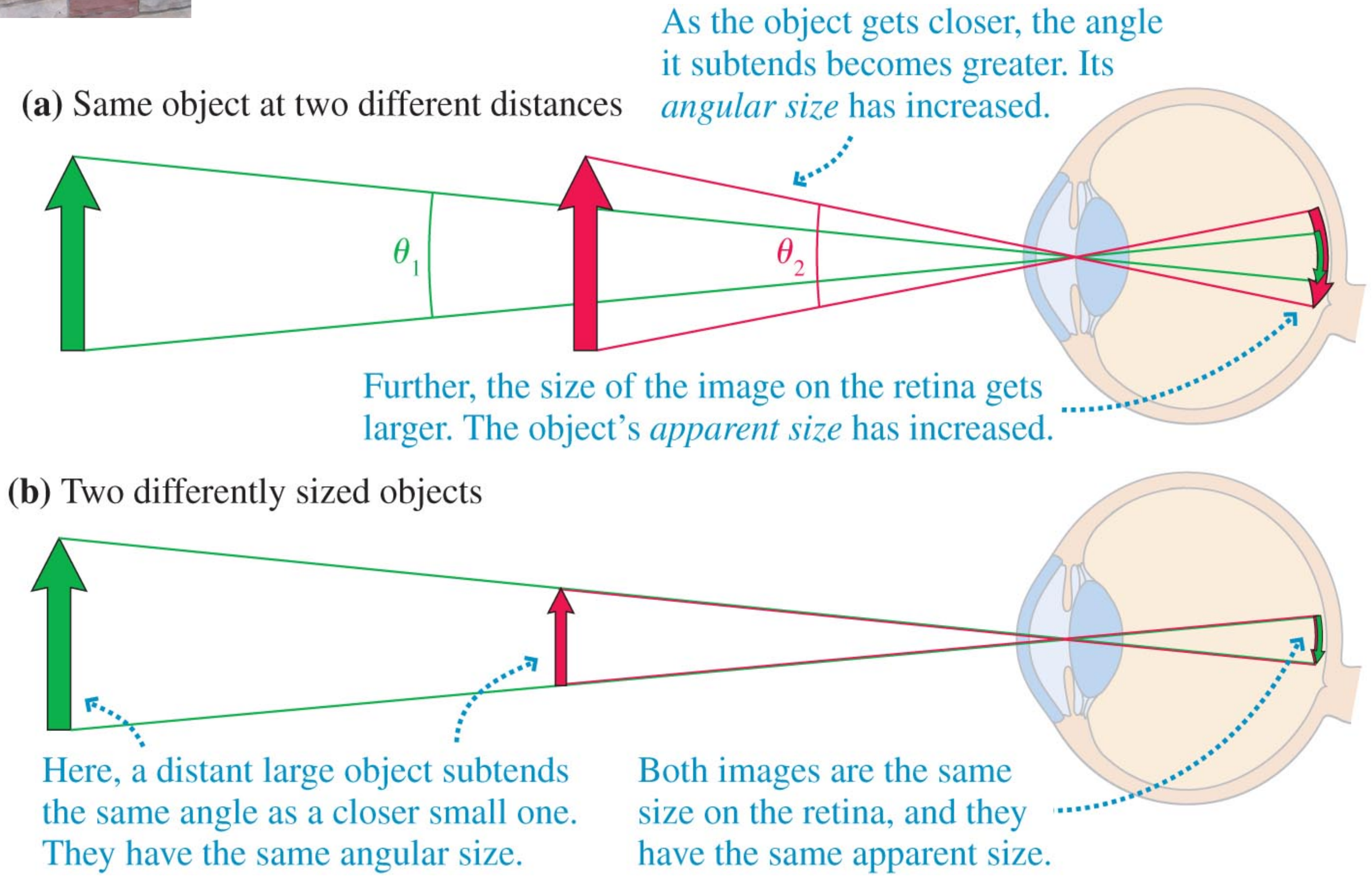
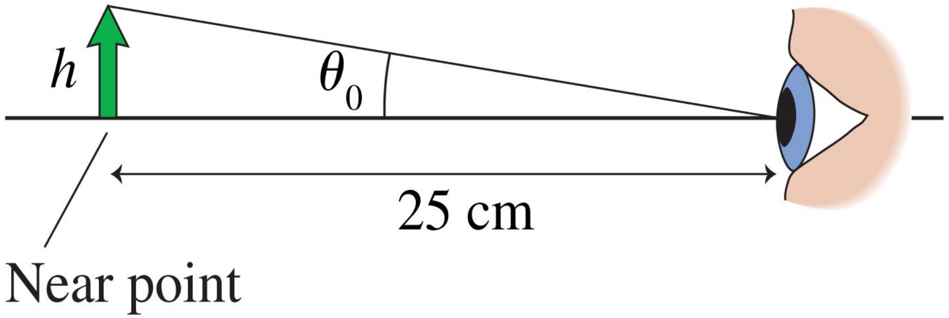
Apparent Size

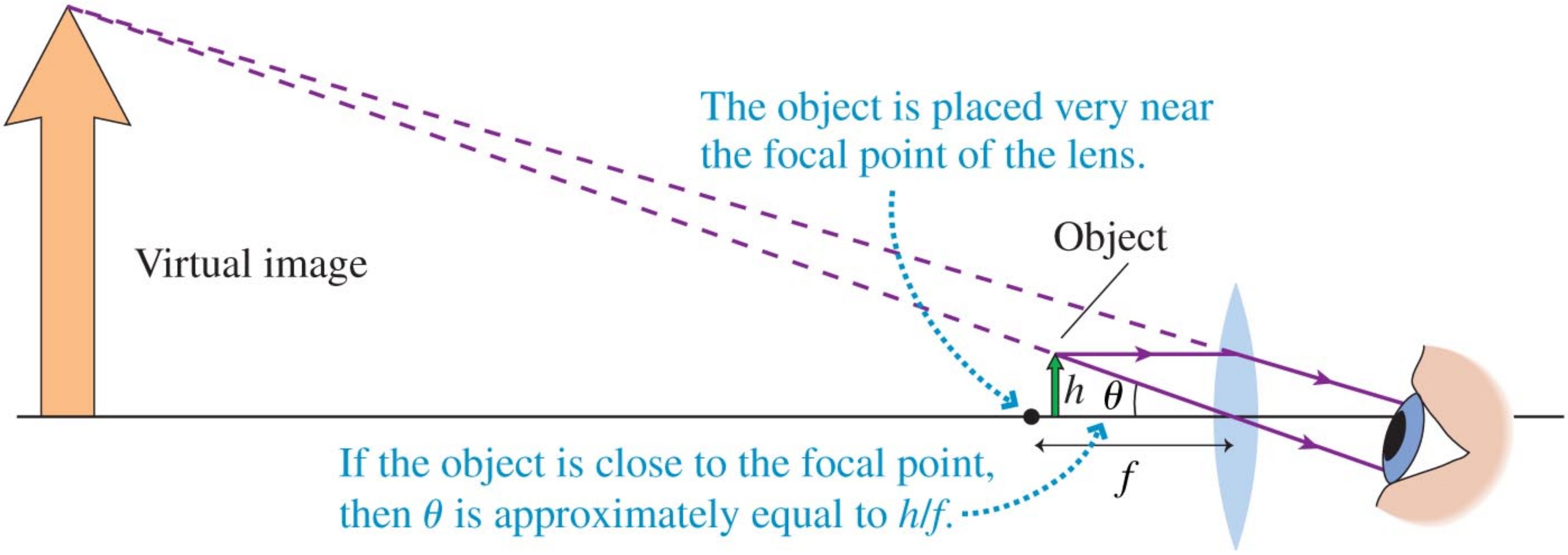


The Magnifying Lens

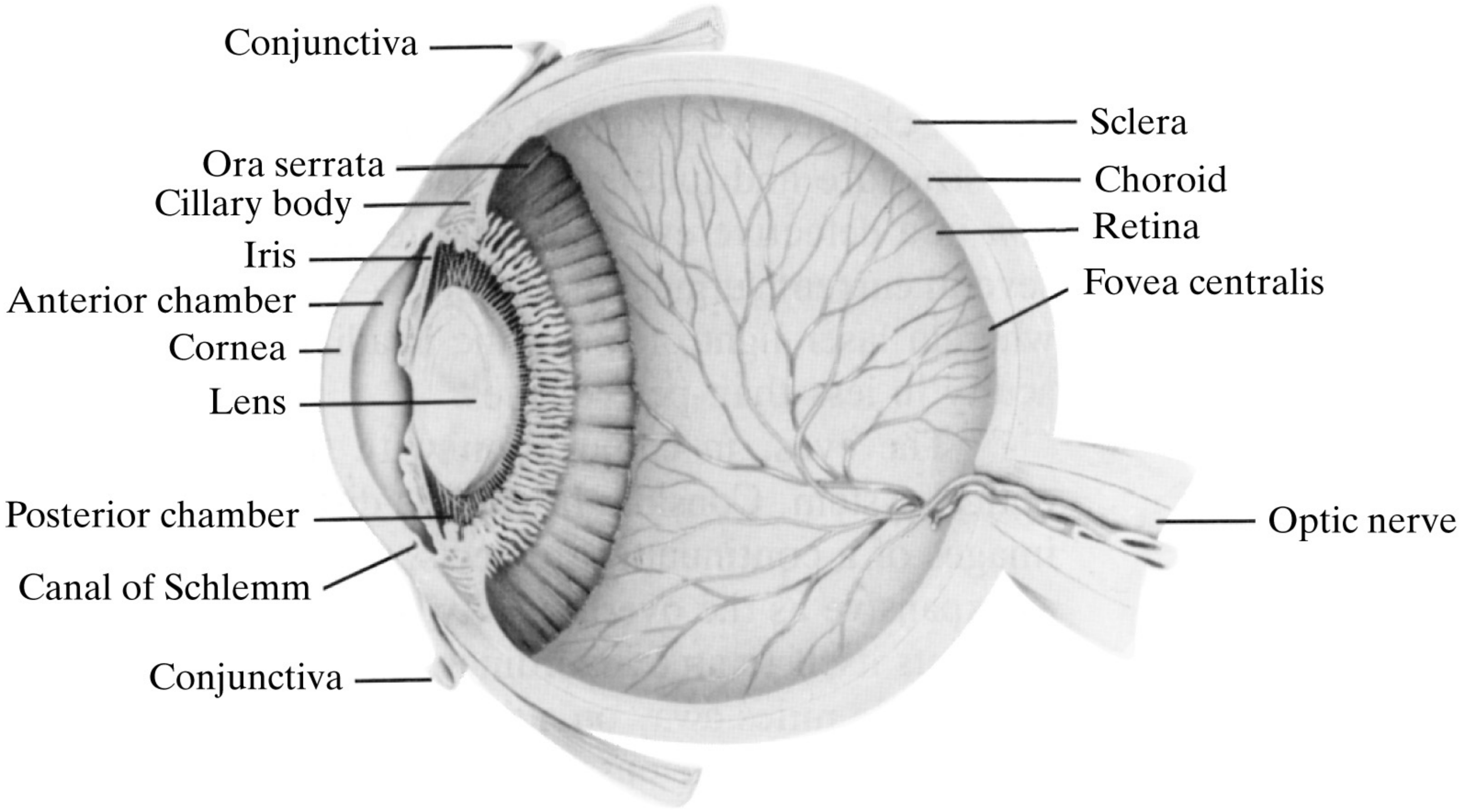
Largest angular size without a magnifier is

$$\theta_0 \approx \frac{h}{25\text{ cm}}$$





Parts of the Eye



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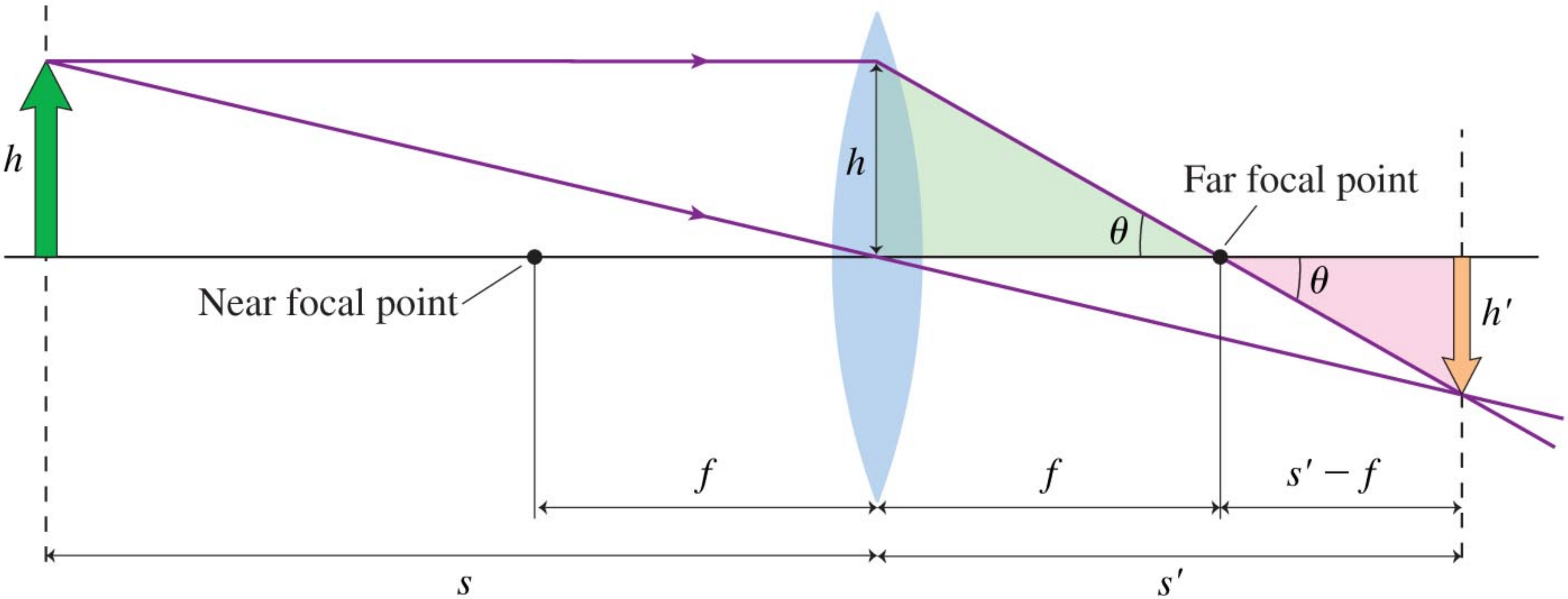
The Thin-Lens Equation



Thin Lens Equation

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f}$$

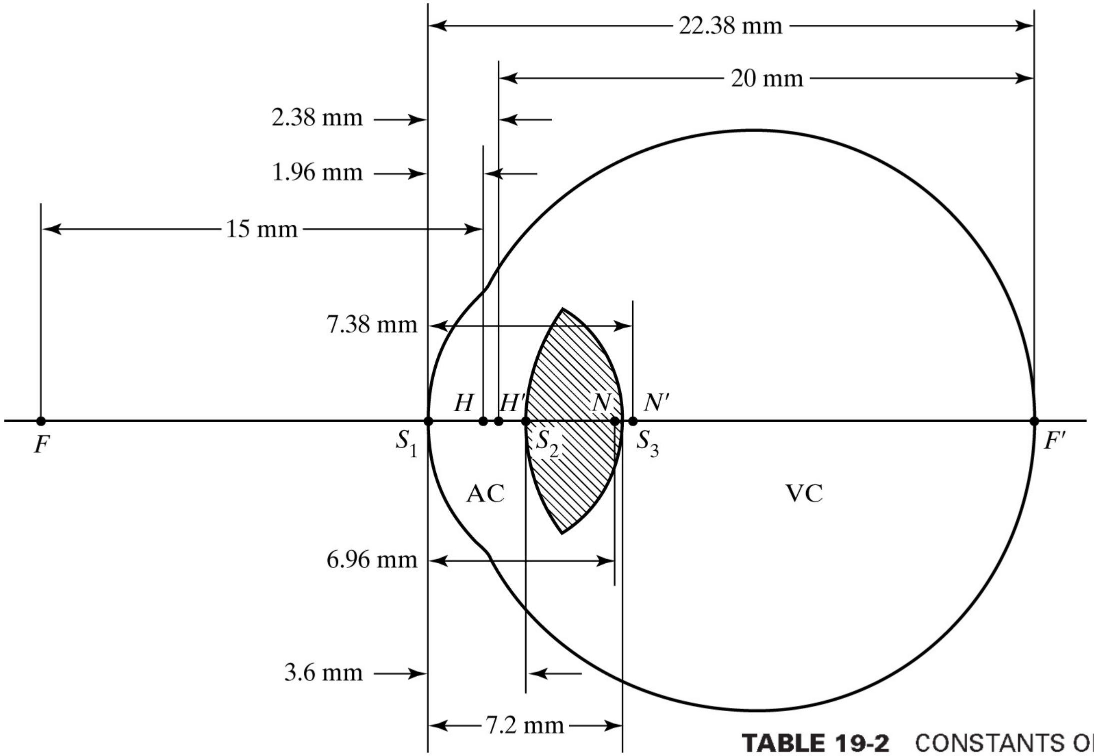
Thin-lens equation (also works for mirrors) relating object and image distance to focal length

$$D = \frac{1}{f}$$

Unit is **Diopter D**:
1 D = 1 m^{-1}

Refractive power P is the measure of the ability of a lens to bend rays.

Gullstrand Eye Model



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Diopters

$$D = \frac{1}{f}[m^{-1}]$$

TABLE 19-2 CONSTANTS OF A SCHEMATIC EYE

Optical surface or element	Defining symbol	Distance from corneal vertex (mm)	Radius of curvature of surface (mm)	Refractive index	Refractive power (diopters)
Cornea	S_1	—	+8[a]	—	+41.6
Lens (unit)	L	—	—	1.45	+30.5
Front surface	S_2	+3.6	+10[b]	—	+12.3
Back surface	S_3	+7.2	−6	—	+20.5
Eye (unit)	—	—	—	—	+66.6
Front focal plane	F	−13.04	—	—	—
Back focal plane	F'	+22.38	—	—	—
Front principal plane	H	+1.96	—	—	—
Back principal plane	H'	+2.38	—	—	—
Front nodal plane	N	+6.96	—	—	—
Back nodal plane	N'	+7.38	—	—	—
Anterior chamber	AC	—	—	1.333	—
Vitreous chamber	VC	—	—	1.333	—
Entrance pupil	E_nP	+3.04	—	—	—
Exit pupil	E_xP	+3.72	—	—	—

Retina – Cones and Rods

Rods are most sensitive to light, but do not sense color, motion

Cones are color sensitive in bright light.

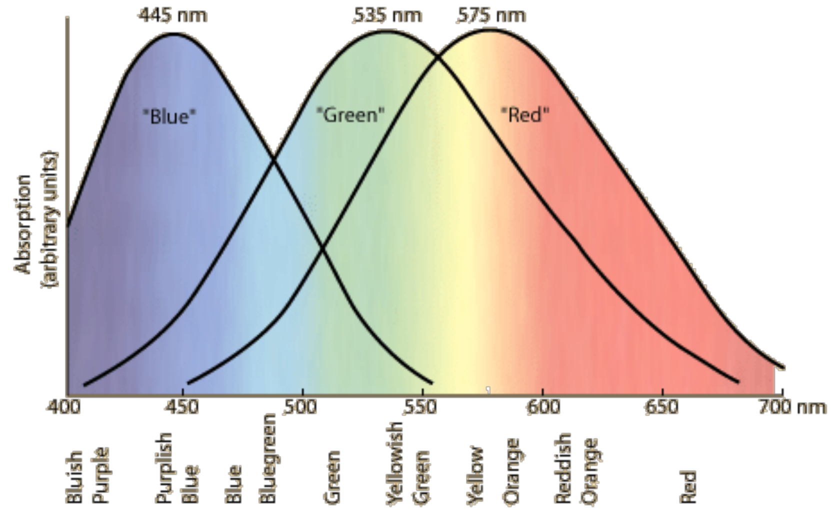
You have ~ 6 million cones, ~ 120 million rods, but only 1 million nerve fibers.

Cones are 1 -1.5 μm diameter, 2 –2.5 μm apart in the fovea.

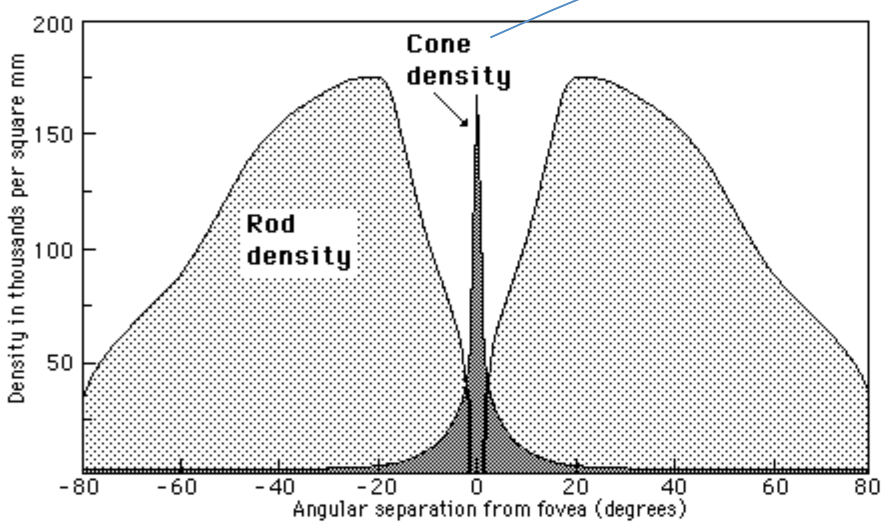
Rods are ~ 2 μm diameter

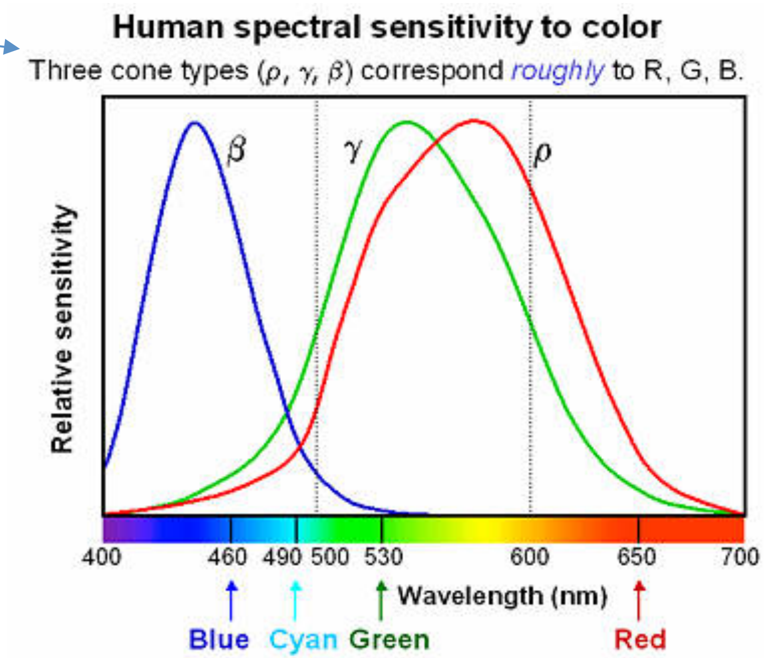
The macula is 5° to the outside of the axis.

The fovea is the central 0.3 mm of the macula. It has **only cones** and is the center of sharp vision.



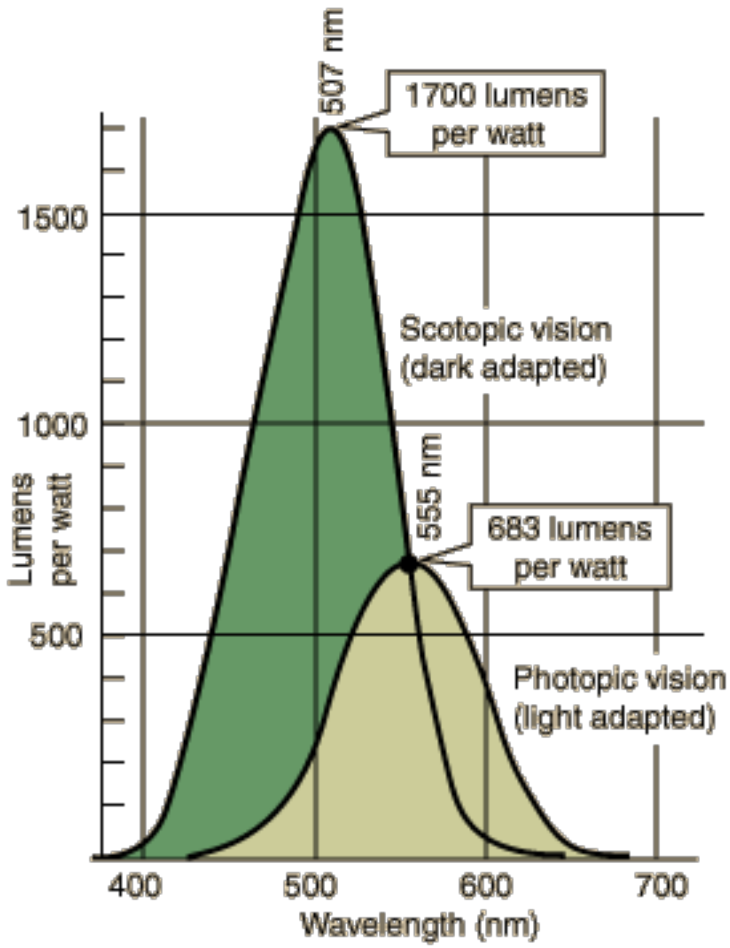
Current understanding is that the 6 to 7 million cones can be divided into "red" cones (64%), "green" cones (32%), and "blue" cones (2%) based on measured response curves.

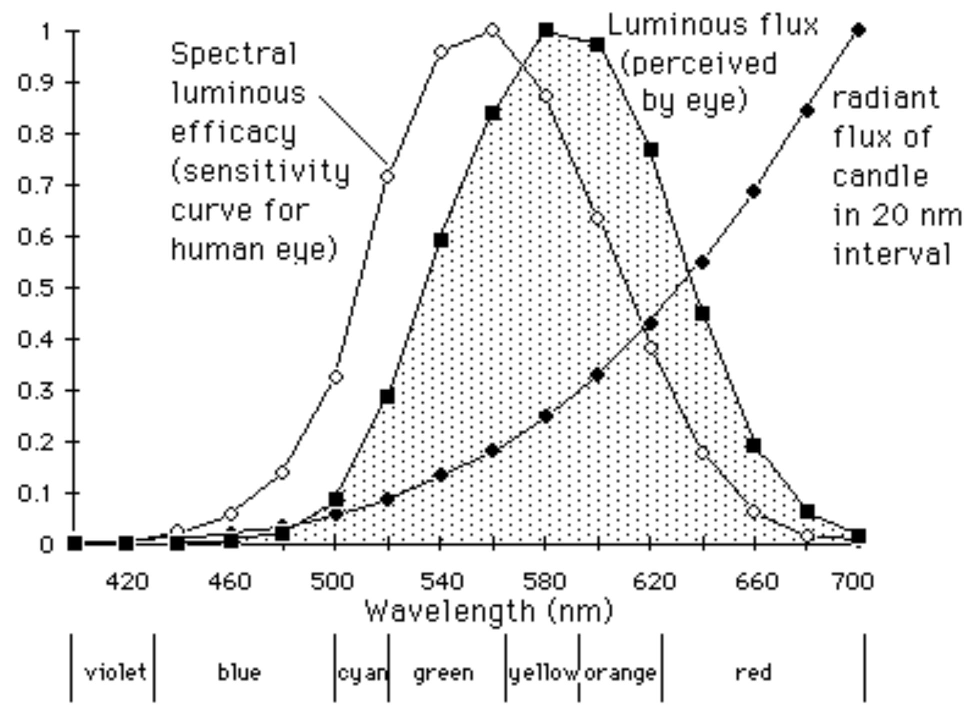




Scotopic Vision (vision in dim light)

Why is a candle flame yellow?

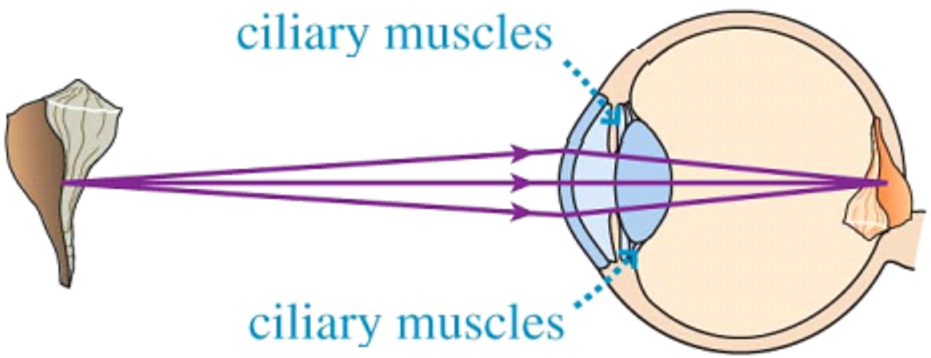




Red rose at twilight: In bright light, the color-sensitive cones are predominant and we see a brilliant red rose with somewhat more subdued green leaves. But at twilight, the less-sensitive cones begin to shut down for the night, and most of the vision comes from the rods. The rods pick up the green from the leaves much more strongly than the red from the petals, so the green leaves become brighter than the red petals!

Question

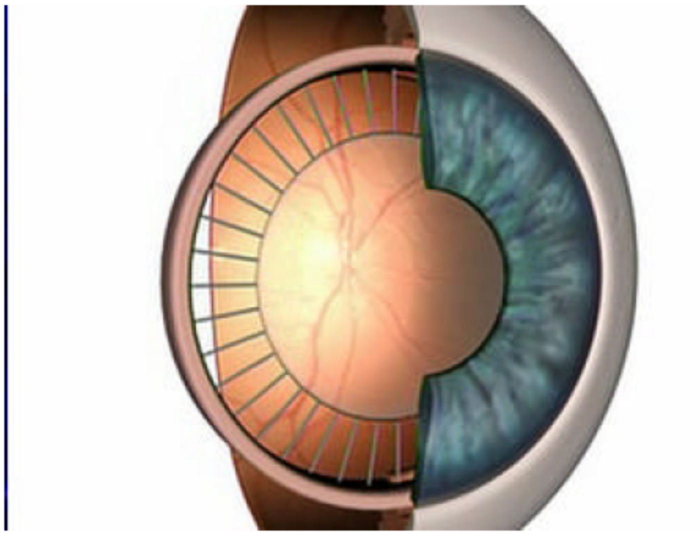
The picture shows a healthy eye focusing on a shell at a distance 30 cm. Suppose the shell is then moved to a distance of 3 m. Choose the scenario that will keep the object in focus:

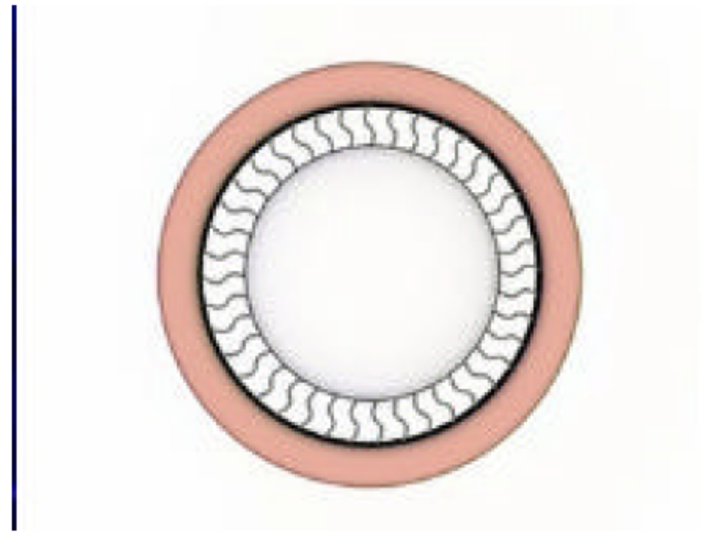


A. The ciliary muscles will relax, causing the lens to be less curved.
B. The ciliary muscles will contract, causing the lens to be more curved.
C. The eye cannot accommodate; the object will be blurry.

Answer: A, The reduced curvature increases the focal length of the lens, allowing the shell to stay in focus.

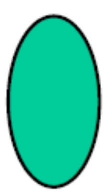
Accommodation



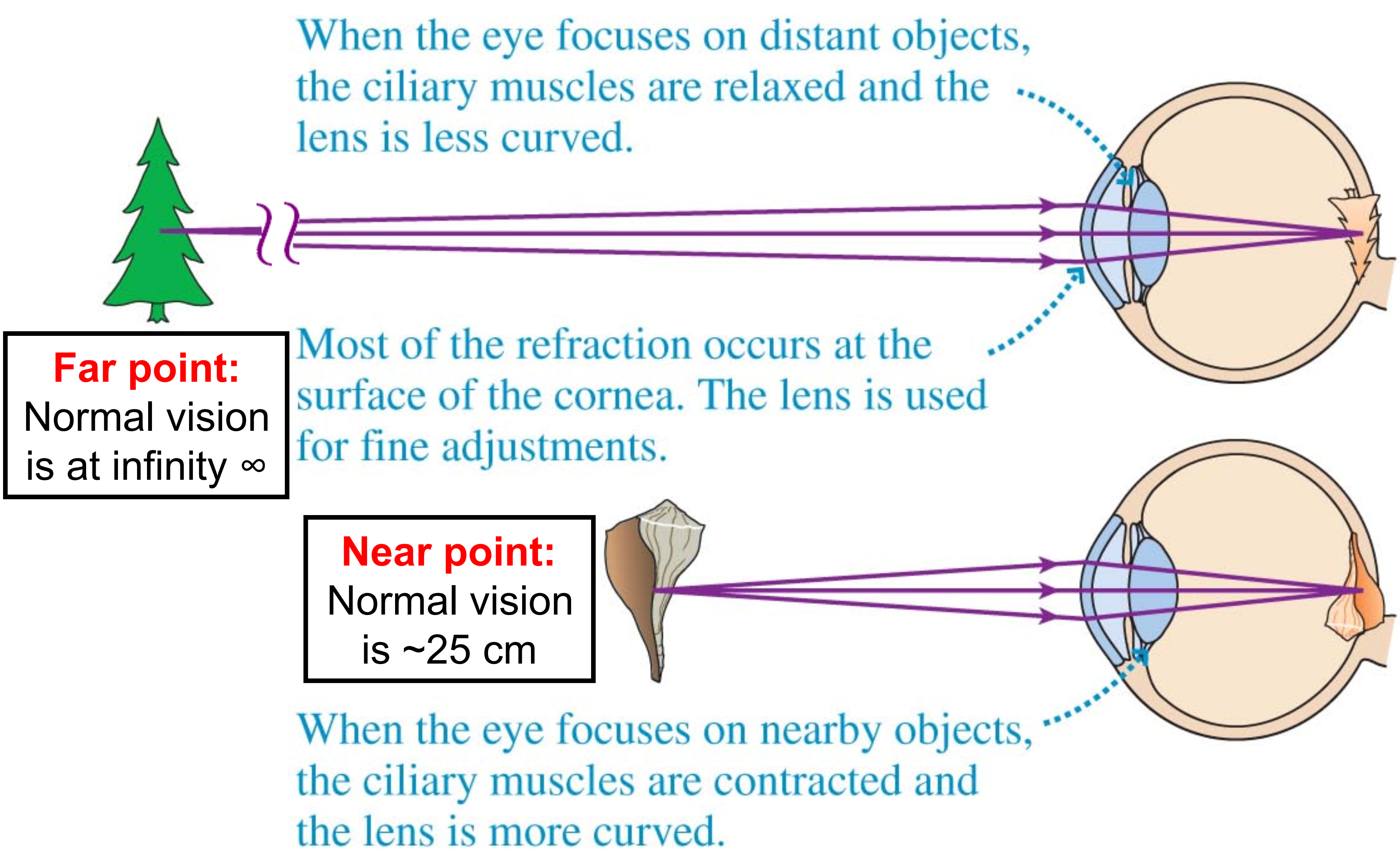


Relaxed ciliary muscle pulls zonules taut an flattens crystalline lens.

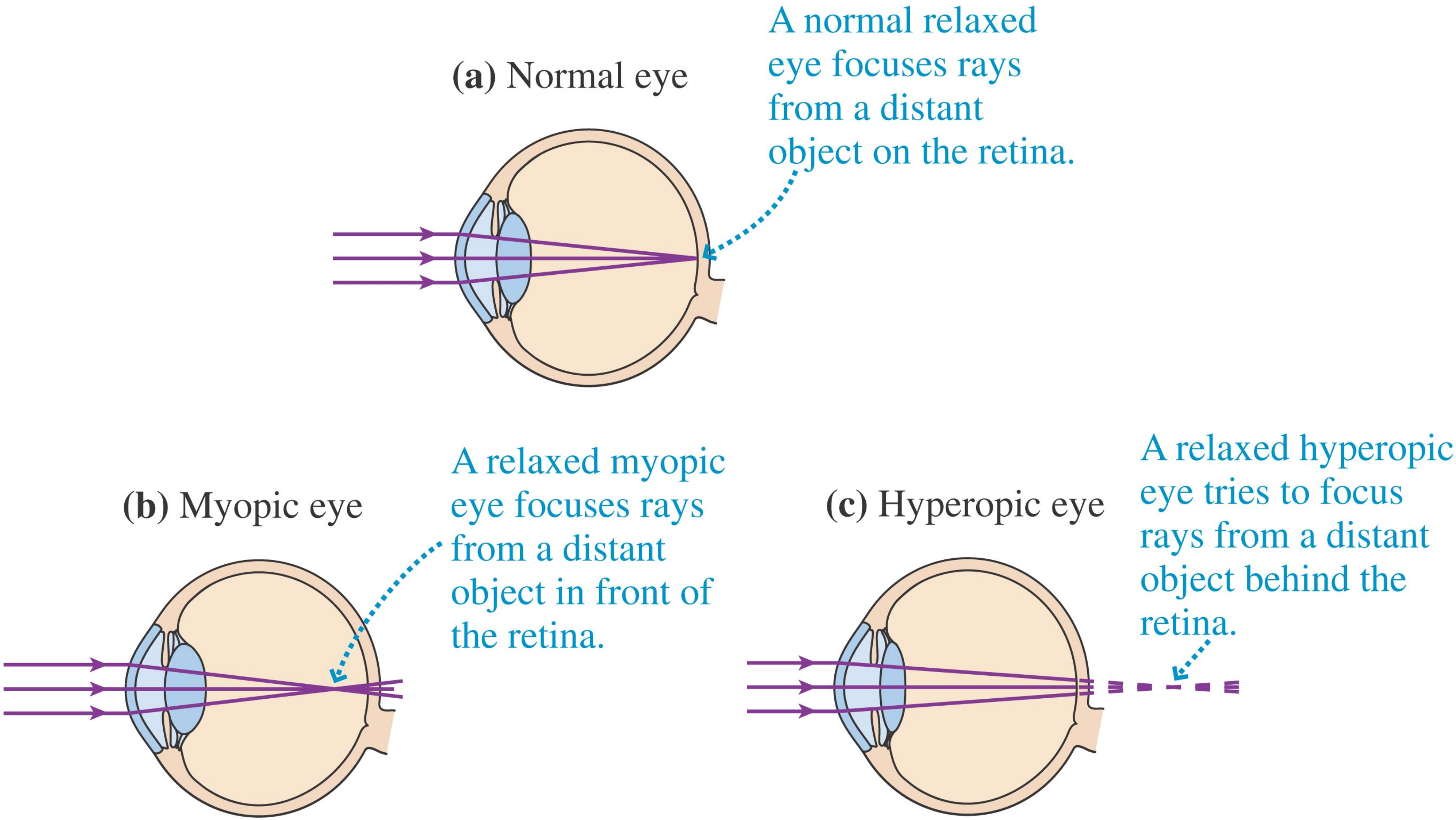
Constrict ciliary muscle releases tension on zonules and crystalline lens bulges.



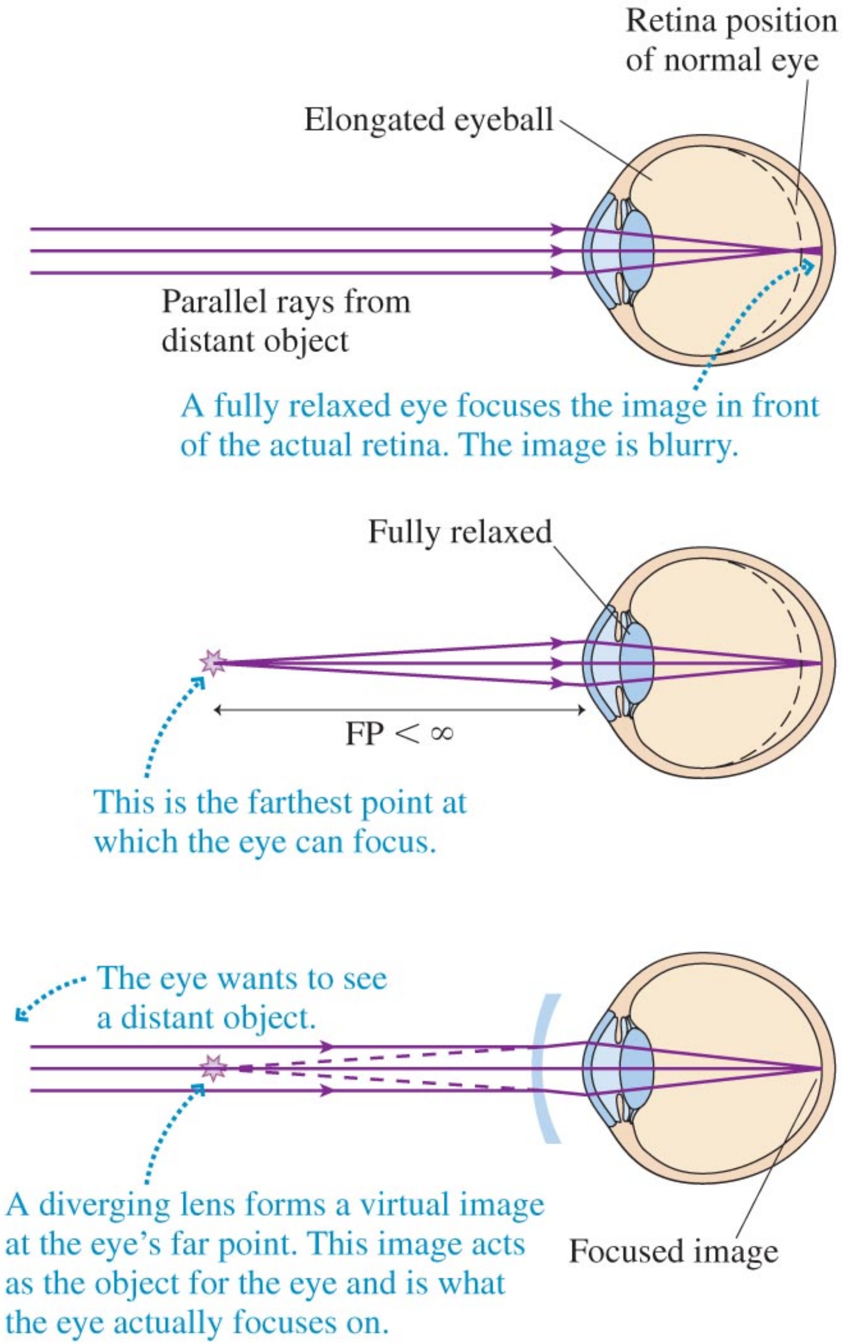
Focusing and Accommodation



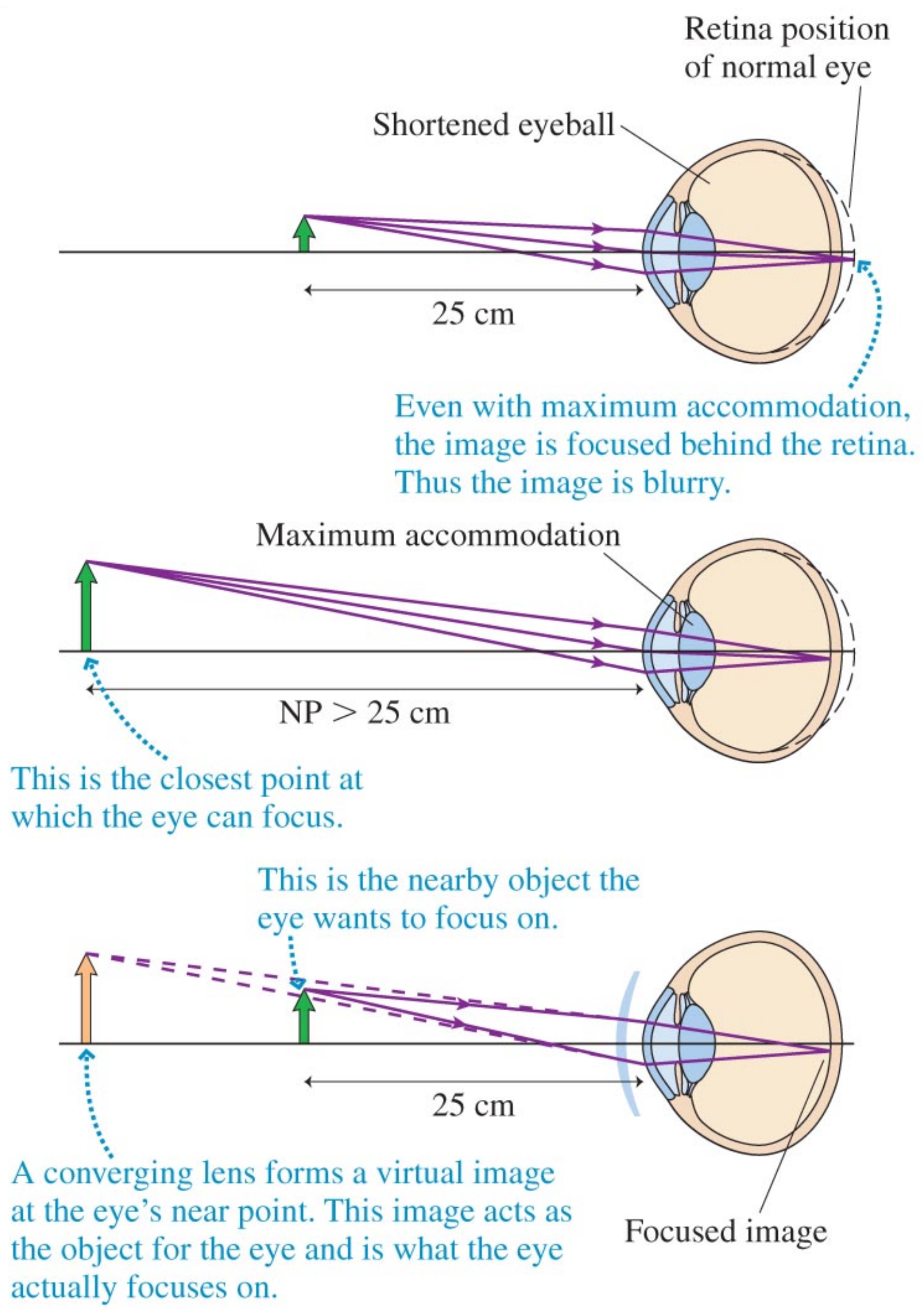
Myopia and Hyperopia (Nearsightedness and Farsightedness)



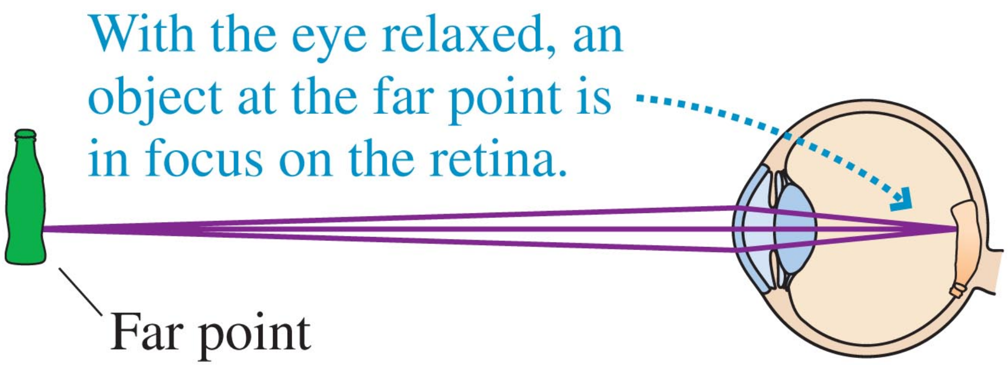
Myopia (Nearsightedness)



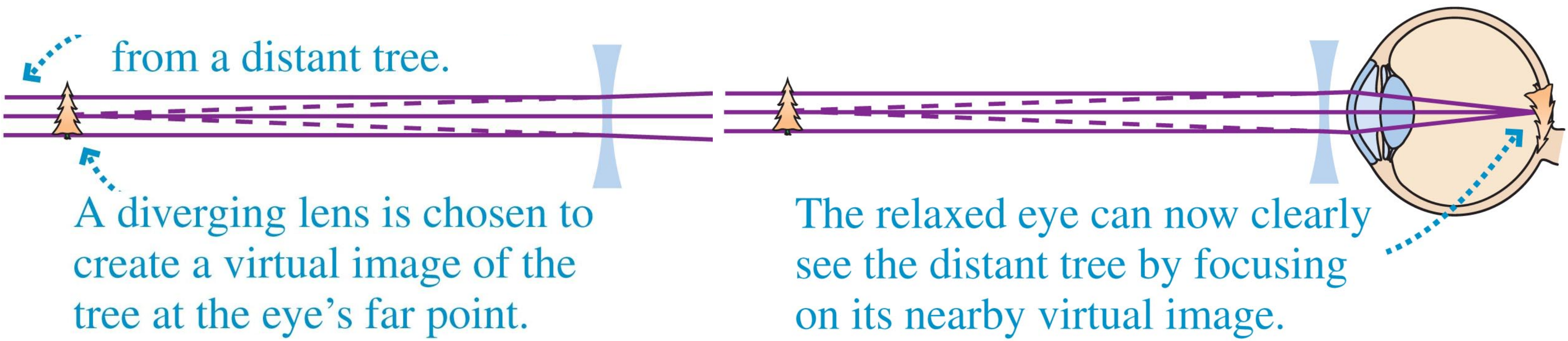
Hyperopia (Farsightedness)



Myopia = Nearsightedness



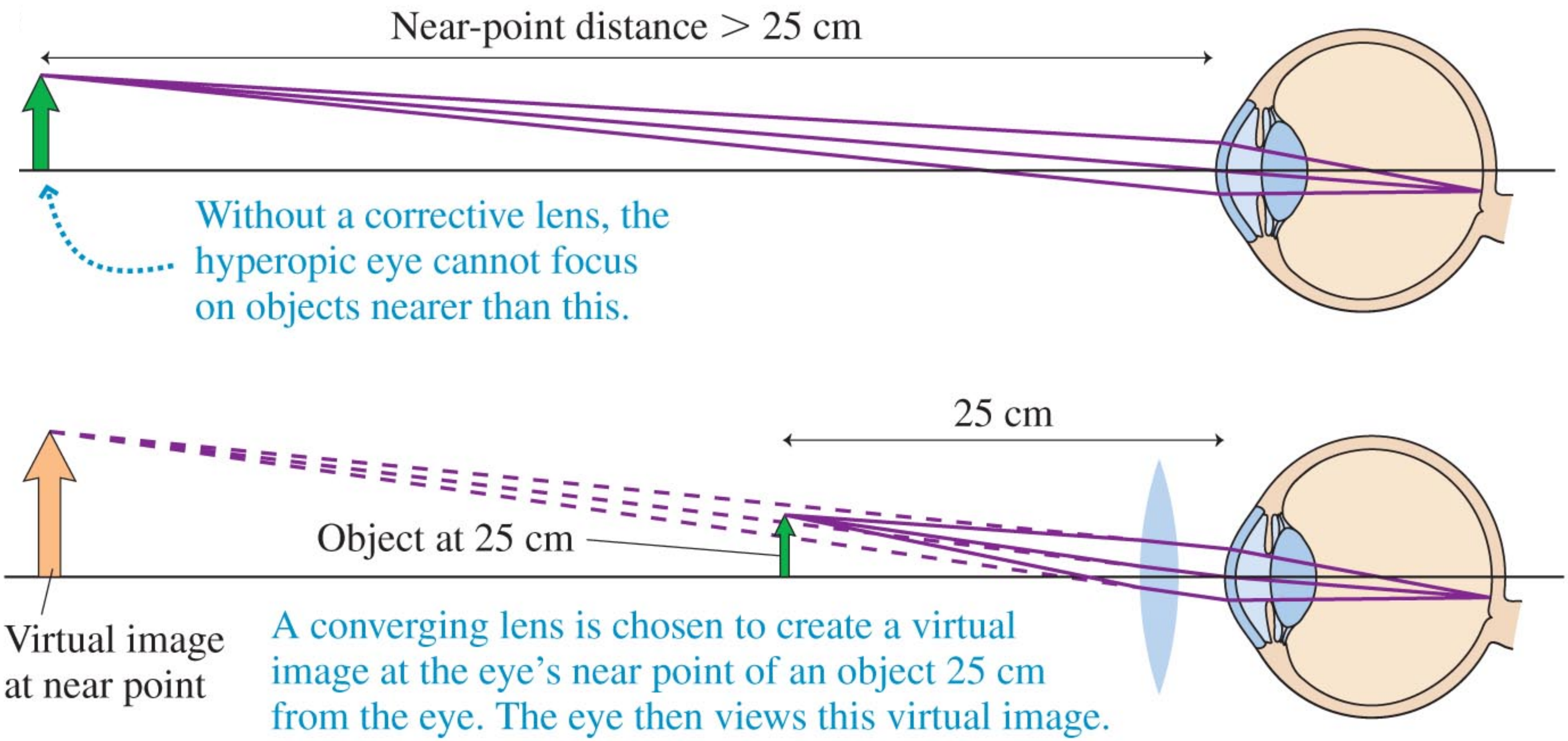
The nearsighted eye cannot focus on objects beyond their “Far point”. Far point is < infinity.



$$D = \frac{1}{f} = \frac{1}{s} + \frac{1}{s'}$$

s = ∞ so 1/s = 0
s’ = eye’s far point (**negative value** because it’s a virtual image)
f and D are **negative** for a diverging lens

Hyperopia = Farsightedness



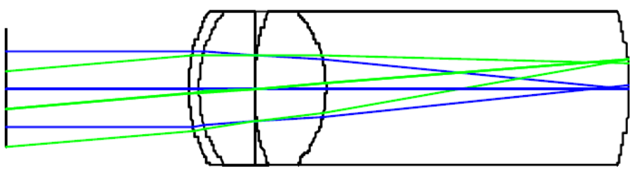
$$D = \frac{1}{f} = \frac{1}{s} + \frac{1}{s'}$$

s = 25 cm
s' = eye's near point (**negative value** because it's a virtual image)
f and P are **positive** for converging lens

Modern Eye Models

Gullstrand-LeGrand Eye Model

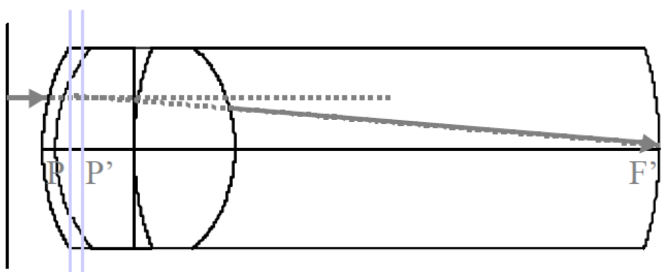
		Anterior Cornea		Posterior Cornea		Anterior Lens		Posterior Lens		Retina
R (mm)		7.8		6.5		10.2		-6		-13.4
ϕ (mm^{-1})		-0.04835		0.006108		-0.0081		-0.014		
t (mm)	Infinity		0.55		3.05		4		16.59655	
n	1		1.3771		1.3374		1.42		1.336	
t/n (mm)			0.39939		2.280544		2.816901		12.42257	
y (mm)		1		0.980691		0.884095		0.744614		0
nu (rad)	0		-0.04835		-0.04236		-0.04952		-0.05994	
yc (mm)		-0.30376		-0.25796		0		0.31862		1.668325
nuc (rad)	0.1		0.114686		0.11311		0.11311		0.108649	

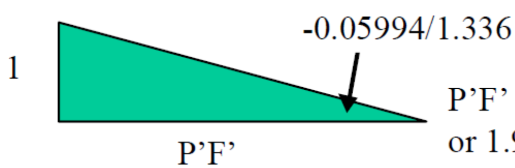


Accommodated Gullstrand Model

	R (mm)	n	t' (mm)
Anterior Cornea	7.8	1.3771	.55
Posterior Cornea	6.5	1.3374	2.65
Anterior Lens	6.0	1.4270	4.50
Posterior Lens	-5.5	1.3360	16.497

Principal Planes





P'F' = -22.28896
or 1.908 mm from corneal vertex

Total Power

Total Power $\Phi = n' / P'F'$

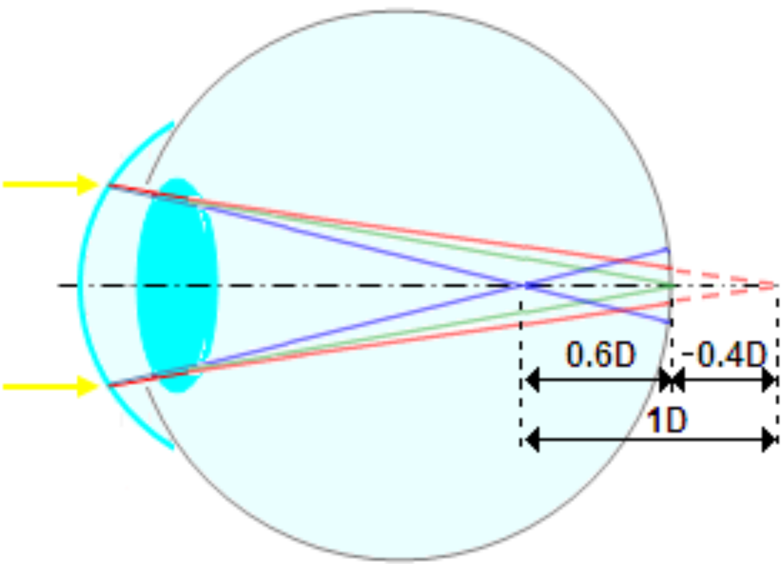
$$\Phi = 1.336 / 22.28896 \text{ mm} = 0.05994 \text{ mm}^{-1} = 59.94 \text{ D}$$

Total Power $\Phi = 1 / PF$

$$PF = -16.683 \text{ mm}$$

or the front focal point is –15.089 mm from corneal vertex (about where your spectacles sit).

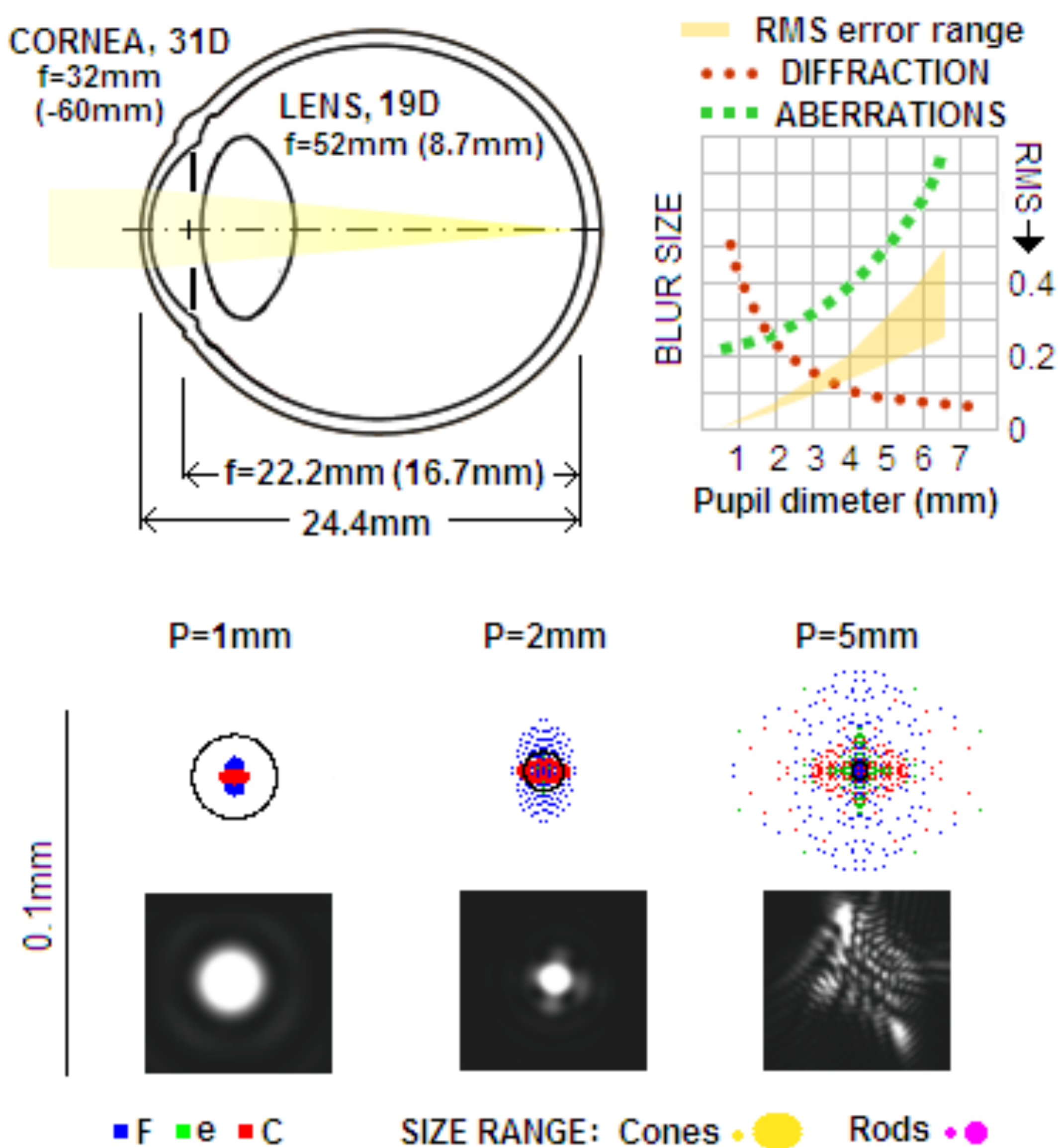
Similarly, the front principal plane P is located 1.595 mm from corneal vertex.



Average chromatism:
0.5D or
1/120 of the eye’s focal length

~16-20 times more than in a doublet achromat

Diffraction Limited?



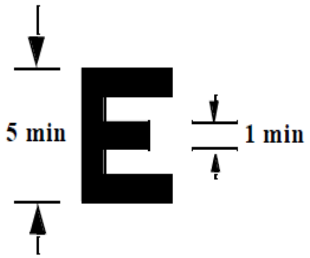
http://www.telescope-optics.net/eye_aberrations.htm

Visual Acuity (VA)

The separation between cone cells in the fovea corresponds to about $1'$ (0.3 mrad). At close viewing distance of 25 cm, this gives a resolution of $75\ \mu m$.

This is close to the diffraction limit imposed by NA of the eye.

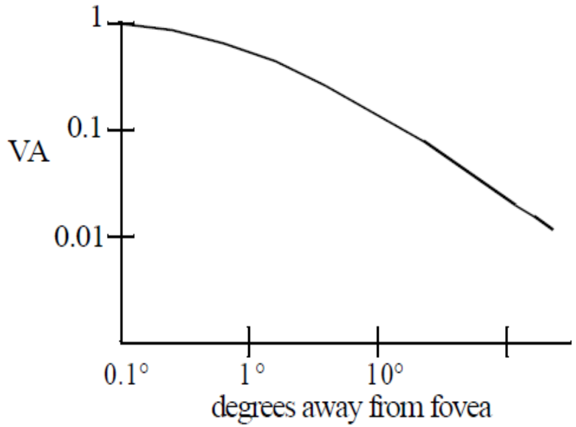
Visual acuity (VA) is defined relative to a standard of 1 minute of arc. VA = 1/(the angular size of smallest element of a letter that can be distinguished [in min])



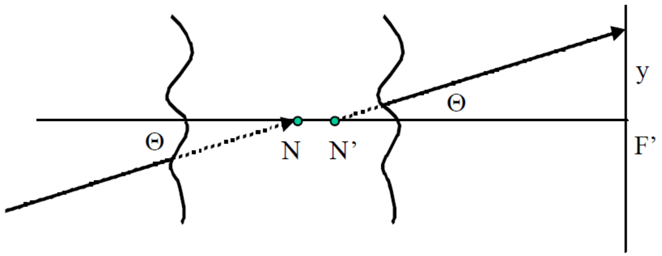
VA is usually expressed as $\dfrac{\text{dist to target (usually 20 ft)}}{\text{dist at which target element is 1 min}}$.

For 20/20 vision, the minimum element is 1 min at 20 ft.

The separation of cells increases away from fovea. This gives a variation of VA with retinal position:



Angular Subtense



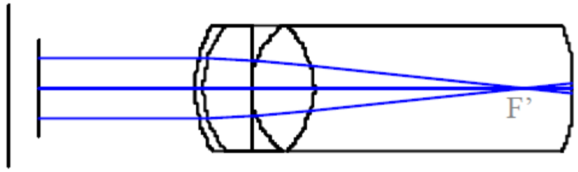
Typically, 1 minute of arc is stated as the eye's limit of resolution. This leads to y ~ 5 microns (two points separated by 5 microns on the retina can just be resolved.

1 minute of arc ~ 0.3 mrad

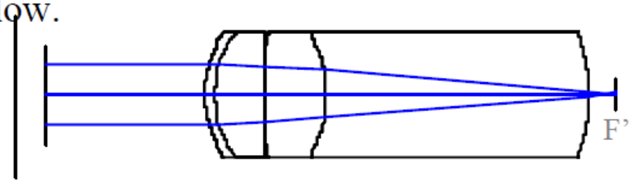
$$20\,mm \times 3 \times 10^{-4} \approx 6\mu m$$

Definitions – Refractive Error

- Myopia – near-sightedness. F' is in front of retina because eye is too long or power is too high

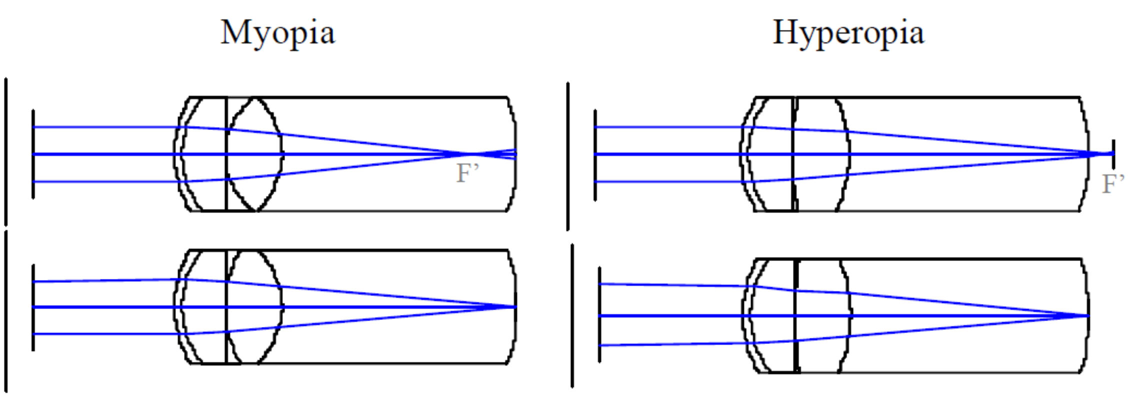


- Hyperopia – far-sightedness. F' is behind retina because eye is too short or power is too low.



- Emmetropia – perfect vision. F' at retina.

- Far Point – point conjugate to the retina when eye is unaccommodated.

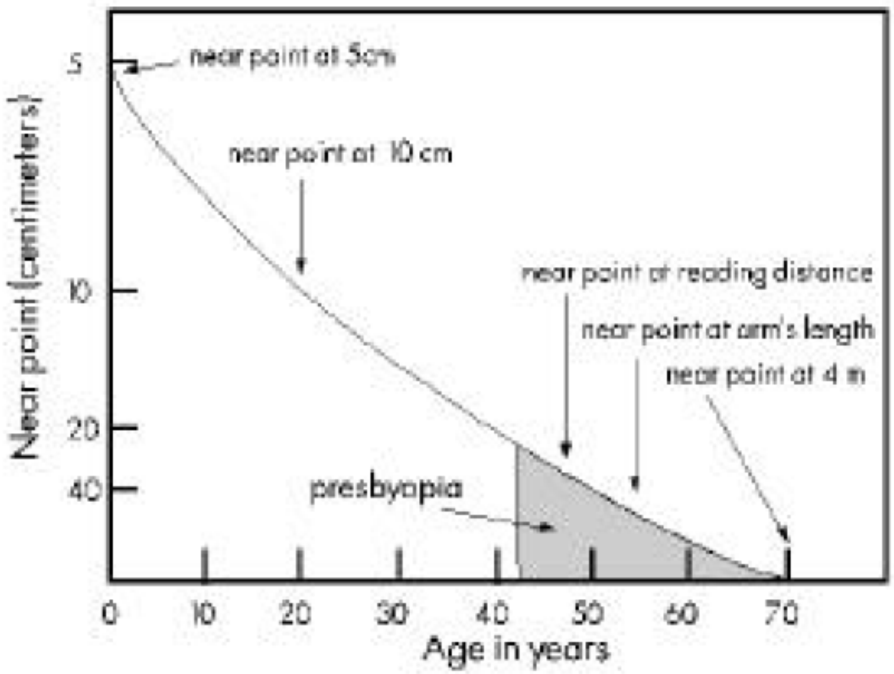


- Near point – point conjugate to the retina when the eye is fully accommodated.

Presbyopia

Eye as an optical device: http://extraphysics.com/java/models/eye.html

Presbyopia



Your ability to accommodate reduces steadily with age. Typically, you don't notice the effects until it affects your ability to read comfortably. This is presbyopia.