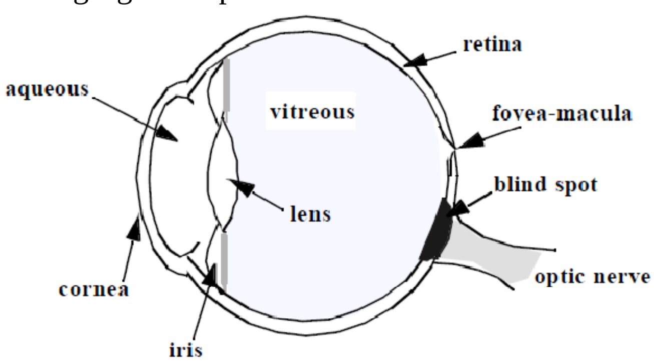
The Human Eyes [Hecht 5.7.1-5.7.3]

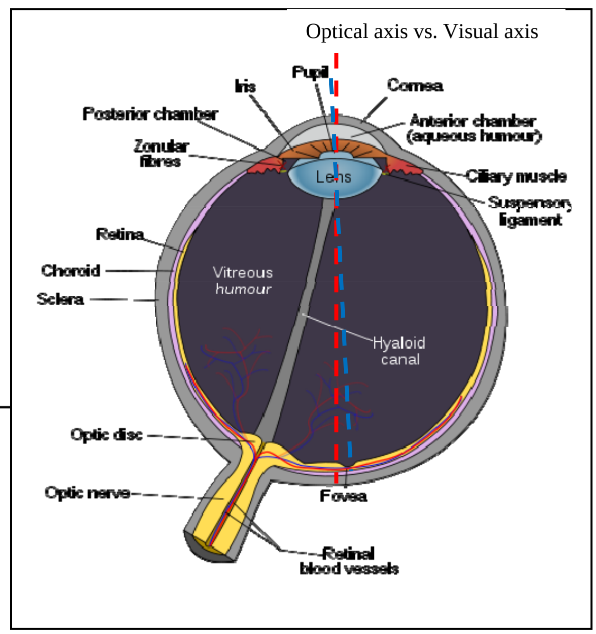
Eyes are organs that detect light, and send electrical impulses along the optic nerve to the visual and other areas of the brain. Complex optical systems with resolving power have come in ten fundamentally different forms, and 96% of animal species possess a complex optical system. The simplest "eyes", such as those in unicellular organisms, do nothing but detect whether the surroundings are light or dark, which is sufficient for the entrainment of circadian rhythms. From more complex eyes, retinal photosensitive ganglion cells send signals along the retinohypothalamic tract to the suprachiasmatic nuclei to effect circadian adjustment. (Wikipedia)
The **human eye** is an organ which reacts to light for several purposes. As a conscious sense organ, the eye allows vision. Rod and cone cells in the retina allow conscious light perception and vision including color differentiation and the perception of depth. The human eye can distinguish about 10 million colors. In common with the eyes of other mammals, the human eye's non-image-forming photosensitive ganglion cells in the retina receive the light signals which affect adjustment of the size of the pupil, regulation and suppression of the hormone melatonin and entrainment of the body clock…… (Wikipedia)

The human eye is the organ by means of which we obtain most of the knowledge we are concerned with in optical matters, and therefore a description of its construction is desirable. It will not be dealt with here from a physiological aspect, but more from the standpoint of an optical instrument. ("Optics and Optical Instruments", by B. K. Johnson)

The following figures represent a horizontal section of the human right eye (top view).



	t (mm)	n	R (mm)
cornea f	0	1.376	7.7
b	0.5		6.8
aqueous		1.336	
lens f	4.0	1.386-1.406	10.0 (relaxed), 5 (focused)
b	7.0		–6.0 (relaxed), –5 (focused)
vitreous		1.336	
retina	24.4		



The overall power of the eye is ~ 58.6 D. The lens surfaces are not spherical, and the lens index is higher at the center (on-axis). Both effects correct spherical aberration. The diameter of the iris ranges from 1.5 → 8 mm.
(What is the dioptric power, D? See Hecht p. 205)

Retina

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.

> You can demonstrate to yourself that the fovea only consists of cones, and is less sensitive to light than the surrounding region of your visual field. To see this, look at a faint star in the center of your field of vision. Then look slightly to the side. You see the faint star better when it moves out of the fovea.

Rods and Cones (Wikipedia)

The retina contains two major types of light-sensitive photoreceptor cells used for vision: the rods and the cones.

Rods cannot distinguish colors, but are responsible for low-light (scotopic) monochrome (black-and-white) vision; they work well in dim light as they contain a pigment, rhodopsin (visual purple), which is sensitive at low light intensity, but saturates at higher (photopic) intensities. Rods are distributed throughout the retina but there are none at the fovea and none at the blind spot. Rod density is greater in the peripheral retina than in the central retina.

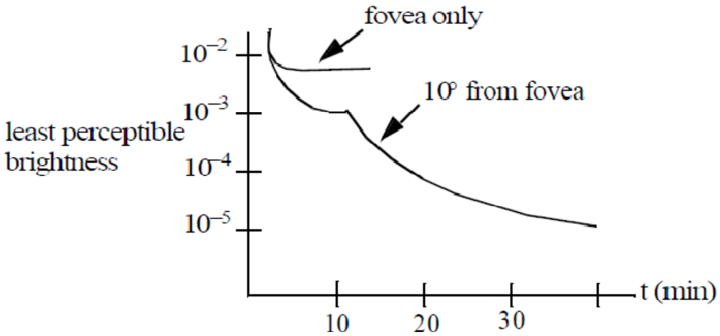
Cones are responsible for color vision. They require brighter light to function than rods require. There are three types of cones, maximally sensitive to long-wavelength, medium-wavelength, and short-wavelength light (often referred to as red, green, and blue, respectively, though the sensitivity peaks are not actually at these colors). The color seen is the combined effect of stimuli to, and responses from, these three types of cone cells. Cones are mostly concentrated in and near the fovea. Only a few are present at the sides of the retina. Objects are seen most sharply in focus when their images fall on this spot, as when one looks at an object directly. Cone cells and rods are connected through intermediate cells in the retina to nerve fibers of the optic nerve. When rods and cones are stimulated by light, the nerves send off impulses through these fibers to the brain.

Refractive index: cornea (n_C~1.376), aqueous humor (n_{ah} ~ 1.336) (Why can't you see very well under water? Recall water n_w~1.33)

Crystalline lens: The lens as a whole is quite pliable, albeit less so with age. Its index of refraction ranges from about 1.406 at the inner core to approximately 1.386 at the less dense cortex, and as such it represents a gradient-index or GRIN system (Hecht p. 273). It has alos a variable focal length.

Sensitivity of the eye

The eye is capable of "dark adaptation." This comes about by opening of the iris, as well as a change in rod cell photochemistry



in the dark, the fovea becomes a blind spot

Min detectable flash: outside fovea 50-150 photons

inside fovea ~150,000 photons

Dynamic Range

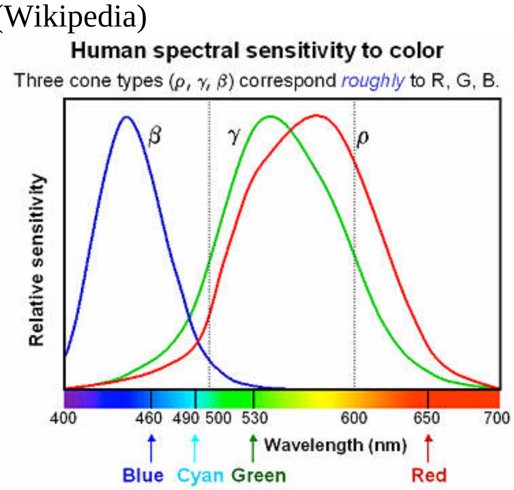
The retina has a static contrast ratio of around 100:1 (about 6 1/2 f-stops). As soon as the eye moves (saccades) it re-adjusts its exposure both chemically and by adjusting the iris. Initial dark adaptation takes place in approximately four seconds of profound, uninterrupted darkness; full adaptation through adjustments in retinal chemistry (the Purkinje effect) are mostly complete in thirty minutes. Hence, a dynamic contrast ratio of about 1,000,000:1 (about 20 f-stops) is possible. The process is nonlinear and multifaceted, so an interruption by light merely starts the adaptation process over again. (wikipedia)

Eye vs. Camera

The eye includes a lens not dissimilar to lenses found in optical instruments such as cameras and the same principles can be applied. The pupil of the human eye is its aperture; the iris is the diaphragm that serves as the aperture stop. Refraction in the cornea causes the effective aperture (the entrance pupil) to differ slightly from the physical pupil diameter. The entrance pupil is typically about 4 mm in diameter, although it can range from 2 mm (f/8.3) in a brightly lit place to 8 mm (f/2.1) in the dark. (Wikipedia)

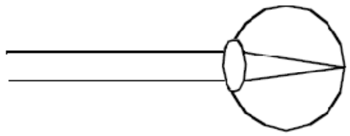
Field of view

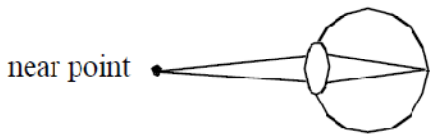
The approximate field of view of a human eye is 95° Out, 75° Down, 60° In, 60° Up. About 12-15° temporal and 1.5° below the horizontal is the optic nerve or blind spot which is roughly 7.5° in height and 5.5° in width. (Wikipedia)



Accommodation – Ability of eye to focus (automatically)

The relaxed lens focuses far (infinity). The lens "accommodates" to focus near.





at maximum power of the eye, the closest image plane occurs at the "near point"

Amount of accommodation: 10 diopters at age 20

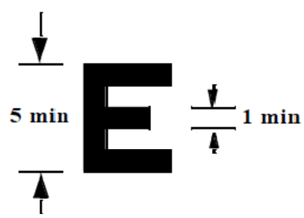
~2 diopters at age 60

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])

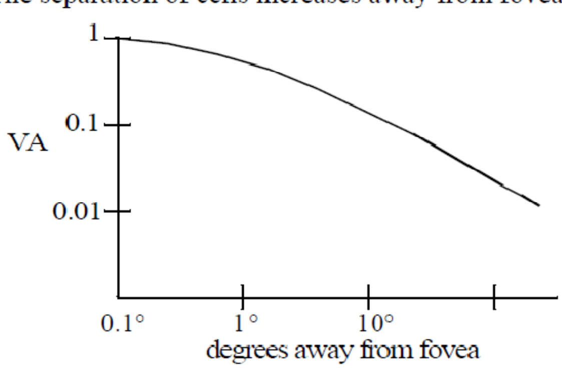


VA is usually expressed as

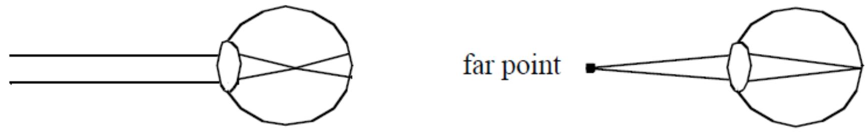
$$\frac{\text{dist to target (usually 20 ft)}}{\text{dist at which target element is 1 min}}$$

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:

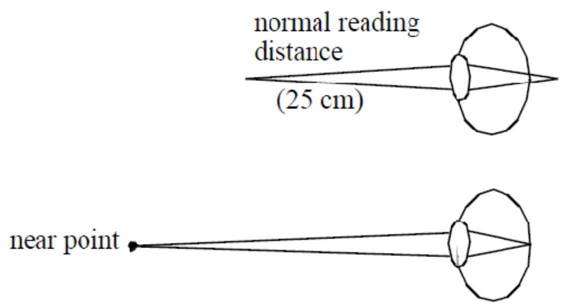


Myopia (nearsightedness) – lens power too large, or eyeball too long



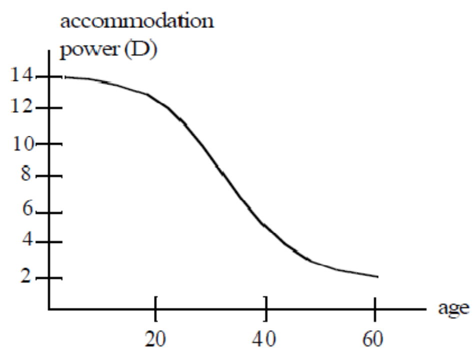
The myopic eye can only accommodate between a far point and the near point. This can be corrected by a negative lens, chosen so that an object at infinity has a virtual image at the far point.

Hyperopia (farsightedness) – too little power in lens, or the eyeball is too short



In this case the near point is too far for comfort. It is corrected with a positive lens.

Presbyopia



As we age, the eye loses the ability to accommodate. This is why "reading glasses" are used.

Astigmatism

– Shape of cornea is not radially symmetric.

– Focal power is different along 2 orthogonal axes.

– Must be corrected using a cylindrical lens, oriented along the proper axis.

Radial keratotomy (RK)

– Correction of shape of cornea by radial cuts (part way through cornea).

– This causes the cornea to bulge in the region of the cuts, changing the shape of the cornea.

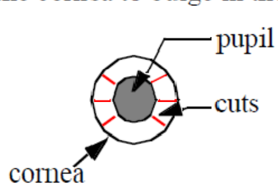
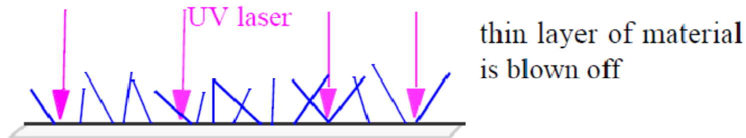


Photo-refractive keratotomy (PRK)

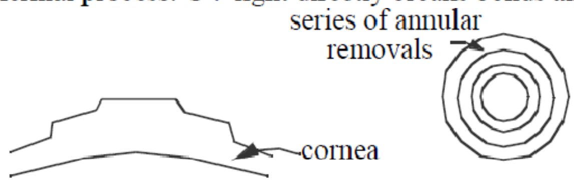
– In this case, we use laser ablation in the clear aperture of cornea.

– The idea is to reshape the cornea surface itself.

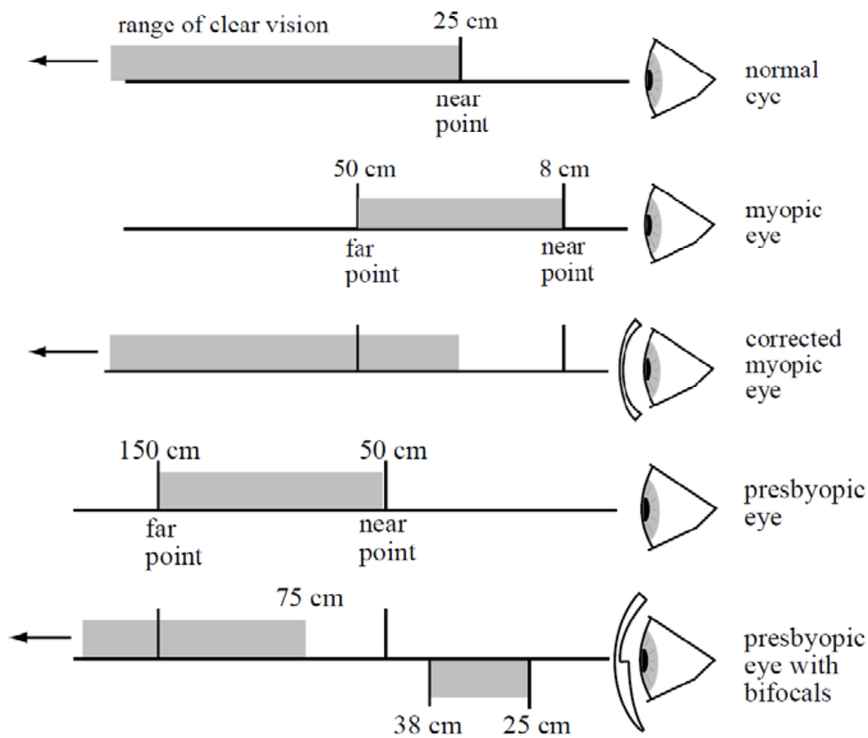
Laser ablation



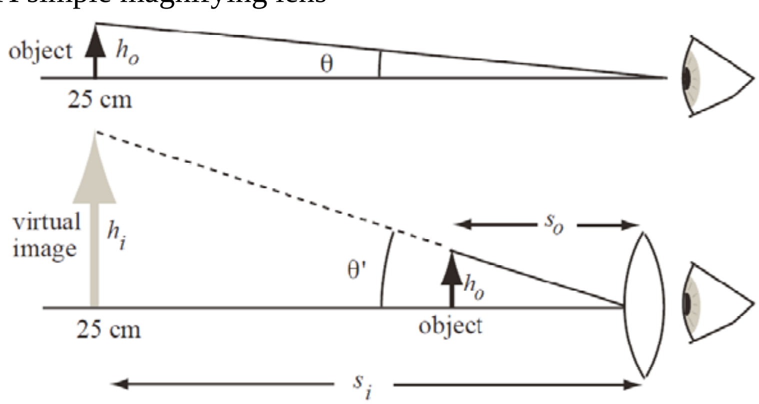
– Laser ablation is not a thermal process: UV light directly breaks bonds and decomposes the material.



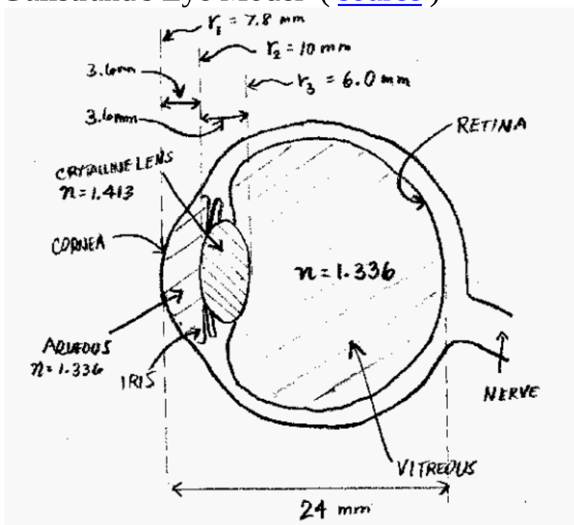
Eyeglasses (a few more examples)



A simple magnifying lens



Gullstrand's Eye Model (source)



In this model, the eye is roughly described as a ball with diameter 24 mm, divided into three regions. The front surface of the eye - the cornea - has radius of curvature of r_1=7.8 mm . The aqueous or anterior chamber - the region between the cornea and the crystalline lens - is treated as a uniform medium with index of n=1.336 . The crystalline lens itself is also treated as a uniform medium with index n =1.413. The front (anterior) surface of the lens has radius r_2=10mm and the rear (posterior) surface has radius r_3=6.0mm . The region to the right of the lens - the vitreous - has index n=1.336.

Most of the refraction of light occurs at the cornea. The total power of the optical system is 60 diopters (in Hecht it's said to be ~58.6D based on a slightly different model), with 43 diopters contributed by the cornea. The first figure for total power is verified by calculating, using paraxial matrix optics (also known as ABCD matrix, not covered in this class), a=-0.0596 mm^{-1}. This gives for the object space focal length f=1/a and the total power 1/f=-a=59.6 m^{-1}=60 D (diopters) . The figure of 43 diopters comes from
$n_1' - n_1 / r_1 = (1.336 - 1) / 7.8\,mm = 0.0431\,mm^{-1} = 43\,D$ (i.e. this is the value for n_1=1, **air**).
During accomodation or focusing on a nearby object, the lens of a real eye changes shape. This change may be modeled as a decrease in radius of curvature of the front surface of the lens from 10 mm to 5.3 mm.

Questions: Can you use the lens maker's formula to calculate the power of the crystalline lens in D (i.e. focal length in "air"? What is the actual focal length in the 'eye ball' (estimate it first)? How can we apply the lens maker's formula to calculate this?

Let's also think about "What are the factors that limiting the special resolution? Aberrations? Diffraction (i.e. use the fact that the diameter of the diffraction Airy pattern is about $1.22\lambda / N.A.$ *? Or sizes of the cones and rods or spacing between two adjacent rods/cones?*