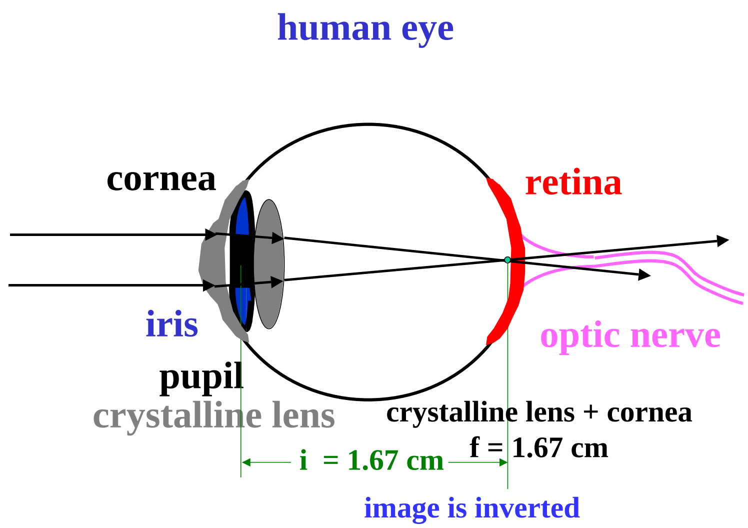
You need to learn the concepts and formulae highlighted in red. The rest of the text is for your intellectual enjoyment, but is not a requirement for homework or exams.

Chapter 3
THE EYE

The lenses discussed in the previous chapter are useful to understand how the eye works. The description of the eye, as well as the eye defects and corrections with lenses have been adapted from Eugene Hecht, *Optics*, Addison-Wesley Publishing Company, Reading MA.

The human eye is a complex organ composed of several parts, arranged as drawn in the diagram below.

Rays of light traverse a system of two lenses and converge in focus on the retina to form ***a real inverted image***. The image has to be real, that is, actual rays must converge on the retina, so that the cone and rod cells in the retina can detect the image, convert it into a train of pulses, and transmit it to the brain via the optic nerve. Two eyes produce two different upside down images, which are then blended together and inverted again by the brain. The two images seen by two eyes are identical to each other when the objects are very far away, while their difference increases as object distance decreases. We do not realize that our two eyes see two different images until we close them alternately, and observe the right and the left image separately. This difference makes it possible for our brain to observe the three-dimensionality of nearby objects, as well as their distance.



The eye is an almost spherical jellylike mass contained within a tough flexible shell, ***the sclera***. Except for the front portion, ***the cornea***, the sclera is white and opaque. Bulging out from the sphere is the curved surface of the cornea, which is slightly flattened at the center to reduce spherical aberration. The cornea is a hard, transparent, convex layer of cells, and it is a converging lens, the strongest of the two lenses in the eye, that is, it has the lowest focal length and the highest curvature. In addition, most of the deflection imparted to light rays takes place at the air-cornea interface, because the refraction index of the cornea (n_{cornea} = 1.376) is much greater than the one for air (1). It is similar to that of water (1.33), which is why we can't see well underwater: rays are not deflected much at the water-cornea interface, and reach the retina out of focus. After the cornea, and immersed in watery fluid, is ***the iris***, which serves as a lens iris aperture (or the aperture stop in a camera) controlling the amount of light entering the hole, or ***the pupil***. Made of circular and radial muscles, the iris can expand or contract, so that its diameter varies between 2 mm in bright light and 8 mm in darkness.

Immediately behind the pupil is ***the crystalline lens***. This lens has the shape of a small lentil bean (or an M&M), with a diameter of 9 mm and a thickness at the center of ~4 mm. The crystalline has a very complex structure, with 22,000 concentric layers (as an onion), with indices of refraction that vary slightly from one layer to the next. At the denser inner core n = 1.406, while at the surface n = 1.386. A man-made lens with these characteristic is called a GRIN lens, from GRadient INdex.

The crystalline lens provides fine-focusing through changes in its shape. Behind the crystalline lens is another gelatinous fluid called ***vitreous humor***. This contains microscopic particles, which are dead cell debris, floating around. You can see these floaters looking at the sky on a bright day: they appear as transparent amoeba-like objects floating across the field of view.

At the back inner surface of the eye-ball is ***the retina***. This is a thin semitransparent layer of light receptor cells. The human eye has two kinds of light sensitive cells: the ***rod cells*** and the ***cone cells***. The rods provide low-resolution vision and function well in dim light, while the cones provide color vision, with high-resolution, but only function in bright light. At the center of the retina there is a small depression, 2.5-3 mm in diameter known as the yellow spot, or ***macula*** which only contains cones, and no rod cells. At the center of the macula is ***the fovea***, with a diameter of 0.3 mm. By comparison the image of the full Moon on the retina is 0.2 mm. In the fovea the cones are thinner (diameter 1.5-3 µm) and more densely packed than anywhere else in the retina. Since the fovea provides the sharpest and most detailed information, the eyeball is continuously moving so that light coming from the object of primary interest always falls on the fovea.

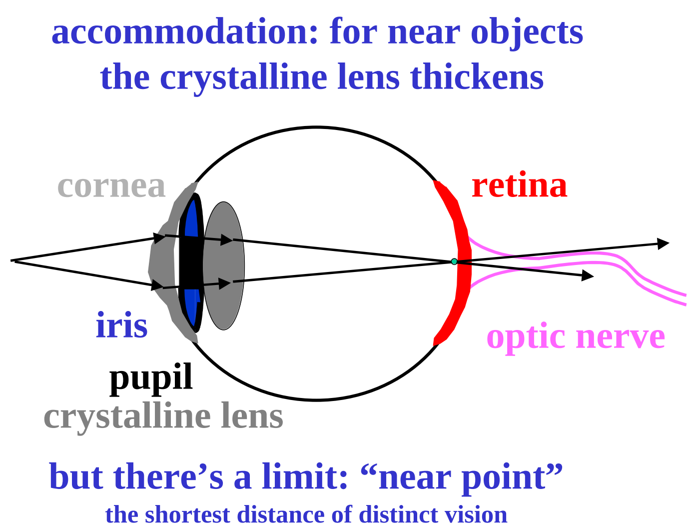
Each cone cell has a connection with an individual nerve fiber, while approximately 100 rod cells are connected to a single nerve fiber. All nerve fibers coalesc in the ***optic nerve***, which from the back of the retina brings the signal to the brain. The optic nerve connects with all the nerve fibers converging from all over the retina. In the point in which the optic nerve is attached to the retina, however, there's a region in which we do not see. This is called ***the blind spot***.

X **1** **2**

If you look at the figure at the bottom of the previous page, stand at a distance of about 10 inches, close your left eye, and focus your right eye on the X, you can only see the number 1, and not the number 2, because the 2 falls on the blind spot. If you now move closer the 2 reappears and 1 vanishes. You can test this on your left eye as well, but you have to rotate the printout or the computer screen upside down.

ACCOMMODATION

As mentioned, the crystalline lens provides fine-focusing of the image from the cornea and the pupil. The focal distance of the system of two lenses, the cornea and the crystalline, is 1.67 cm. If an object is at infinity, the image is exactly in the focal point, on the retina. If the object comes closer, the image will be formed after the retina, and the image on the retina will appear fuzzy. The crystalline lens, which is flexible, can compensate for this effect, become thicker in the middle, and provide a stronger lens, with smaller radius of curvature and shorter focal distance. The image, after crystalline lens thickening, will therefore be perfectly in focus on the retina. This is called ***accommodation***.



As the object comes closer to the eye, the crystalline lens accommodates more and more, until it reaches a point, beyond which it cannot thicken more. That maximum crystalline thickness defines ***the near point***, which is the shortest distance of distinct vision. You can easily find your own near point. With one hand cover one eye, extend your other arm and look at your finger. Now, bend your arm and slowly bring that finger closer to the eye, while keeping it in focus: as you do so, your crystalline lens is thickening. When the finger approaches the eye and passes the near point, you can't focus on the finger anymore.

The shortest distance at which you can focus varies from person to person, and also for the same person, with ageing. As the person ages, the crystalline lens loses elasticity, and the near point lies at greater distance. For a normal eye, the near point is 7 cm for a teenager, 12 cm for a young adult, 28-40 cm in the middle-aged, and about 100 cm for the 60 year-old. That is why everybody after a certain age needs reading glass. These make the near point come closer. As you may have imagined already, this correction is done with converging lenses as glasses.

All mammals accommodate as described, while fish move the lens only, away or towards the retina to adjust the focus, just as we do in a camera. Some mollusks elongate or contract the eyeball depth, birds of prey accommodate by changing the curvature of the cornea.

EYEGALSSES

Macfarlane and Martin, an anthropologist and a historian of glass instruments from Cambridge, United Kingdom, speculate that the development of glass was fundamental for science itself: lenses are the major components of telescopes to look at the stars, and microscopes to look at cells. Imagine life without glass, before the first synthesis of transparent acrylics and plexiglass. There would have been no windows to keep the warm air inside, and the reading and studying time would have been far less, slowing down progress considerably. There would have been no airplanes, no bottles to develop alchemy and chemistry. Cultures that drank tea instead of wine, such as the Chinese and the Japanese, never had a good reason to develop glass blowing skills, because ceramic pottery had far superior characteristics to hold high temperature liquids without cracking. They attribute the stagnation of those cultures in and after the Middle Ages to the absence of glass. Furthermore, ink drawings and paintings from the Far East always had a well defined central figure in the foreground and blurry, poorly described figures all around it, presumably intended to be in the background, but out of focus because of the myopic vision of most artists. Perspective is completely absent from Eastern art, possibly for the same reason. These are only speculations, and there is of course no proof of would have happened if those cultures had developed glass instead of pottery.

Eyeglasses were first invented in Florence, Italy, in 1299. These were convex, converging lenses only, while glasses using diverging lenses trailed by about 150 years. Negative, diverging lenses where actually first produced in 1267, but not used for glasses for about 200 years. Interestingly, it was considered improper in Europe, until the 1800s, to use eyeglasses in public, and we have very few paintings showing glass users.

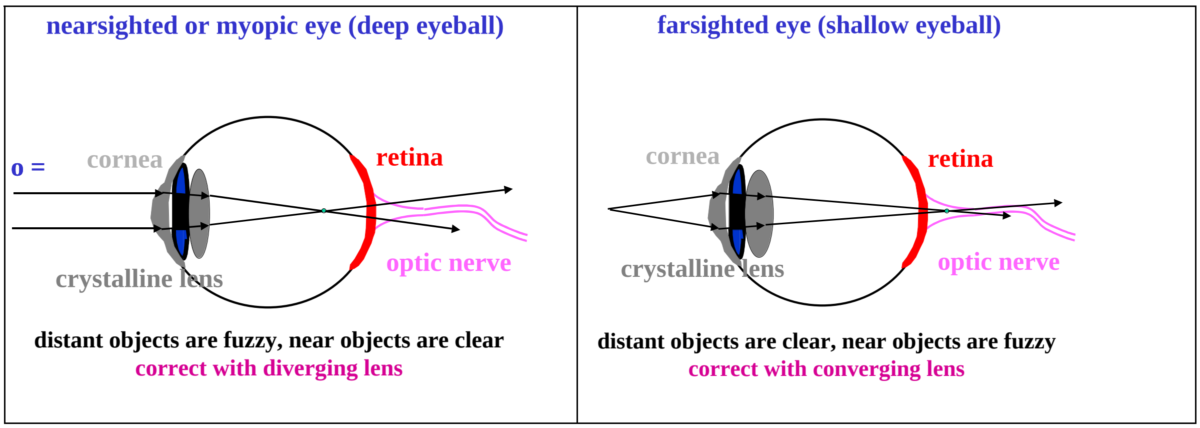
The ***normal eye*** is an eye capable of focusing parallel rays on the retina while in relaxed condition.

The ***dioptric power*** [DP = 1/f (m)] of the unaccommodated normal eye is 60 D (1 diopter = 1 D = 1 m^{-1}), of which 43 D from the cornea and 17 from the crystalline lens. 60 D corresponds to a combined focal length of the two lenses of 1.67 cm (1/60 x 100).

We define the ***far point*** as the maximum distance of a point whose image lies on the retina, or the maximum distance of distinct vision. Thus, for the normal eye, the farthest point focused on the retina, the far point, is located at infinity. Infinity, for all practical purposes, is anywhere beyond about 5 m. When the focal point of the system of two lenses does not lie on the retina, the eye is nearsighted, farsighted or astigmatic. This may depend on abnormal changes in the lenses (refractive index, or curvature) or on the dimensions of the eyeball, which alter the distance between the lens system and the retina. The latter is the most common cause of imperfect vision.

NEARSIGHTED EYE

A deep eyeball causes the eye to be ***nearsighted or myopic***, and can be corrected using a negative lens. Parallel rays converge before the retina, and diverge again by the time they reach the retina. Far away objects appear blurred and larger. The near point is closer than 5 m, e.g. 2 m. To correct for this problem, we add a lens to the optical system, so that the three lenses combined (the eyeglass lens, the cornea and the crystalline lens) produce an image of parallel rays in focus on the retina. Since the nearsighted eye can clearly see objects nearer than the far point, we add a ***diverging lens*** which casts relatively nearby images of distant objects. For objects at infinity, the lens creates a virtual image located at the far point (2 m). No accommodation of the crystalline is required. If the object is closer than infinity, the virtual image is closer than the far point, say 1 m away in the above example. This image is then viewed by the cornea and crystalline lenses, which cast a real image on the retina, but only after accommodation. The use of these diverging lenses also moves the near point a little further, which is why nearsighted people prefer to take their spectacles off when performing precision tasks, such as threading needles or reading small print. They can then bring the object closer to the eye, and increase the magnification.



Note that the distance between the eye and the eyeglasses lens is optimized, so that the image position may change but the magnification never changes. Since many people have unequal eyes, a change in magnification would be a disaster!

FARSIGHTED EYE

A shallow eyeball causes the eye to be ***farsighted*** or ***hypermetropic***. Objects at infinity are seen clearly, but nearby objects are blurred, because the rays converge after the retina. The crystalline lens accommodates up to a point, but reaches its limit, the near point, which is further than norm for this eye. This defect can be corrected with a ***converging lens***, which makes the rays converge faster on the retina. Such lens effectively moves a close object further away, beyond the near point where the eye can see clearly. The lens will form a distant virtual image, then seen by the cornea-crystalline lens clearly.

ASTIGMATIC EYE

Astigmatism is the most common eye defect. It arises from an uneven curvature of the cornea. This eye cannot focus vertical and horizontal lines at the same time. Imagine two planes, both containing the optical axis. On one of the planes the curvature of the cornea is maximal, on the other is minimal. If these two planes are perpendicular to each other the astigmatism is ***regular***, and can easily be corrected. Otherwise the astigmatism is ***irregular***, and can't be corrected with commercial lenses. Regular astigmatism is corrected with ***cylindrical lenses***, first introduced in 1825 but only widely spread after 1862.