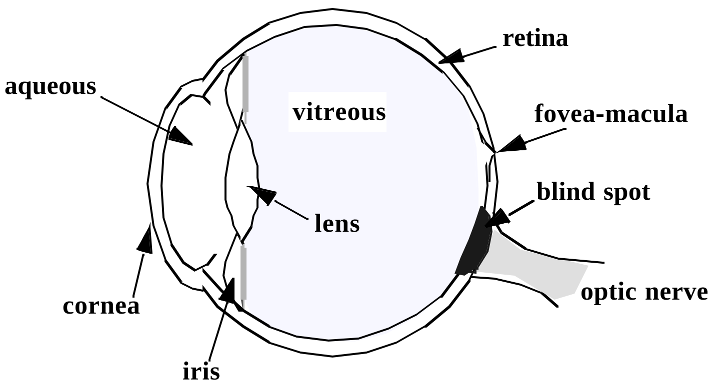
Chapter 3
Optical Systems

The Human Eye

[Reading Assignment, Hecht 5.7.1-5.7.3; see also Smith Chapter 5]



	t (mm)	n	R (mm)
cornea f			7.7
b			6.8
aqueous			
lens f			10.0 (relaxed), 5 (focused)
b			–6.0 (relaxed), –5 (focused)
vitreous			
retina			

The overall power of the eye is $\sim 58.6\ \mathrm{D}$. 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.

<u>Retina</u>

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.

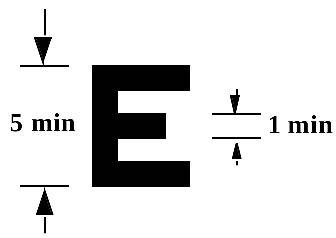
You can demonstrate to yourself that the fovea only consists of cones, and is less sensitive to light than the surrounding region of your visual field. To see this, look at a faint star in the center of your field of vision. Then look slightly to the side. You see the faint star better when it moves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

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.

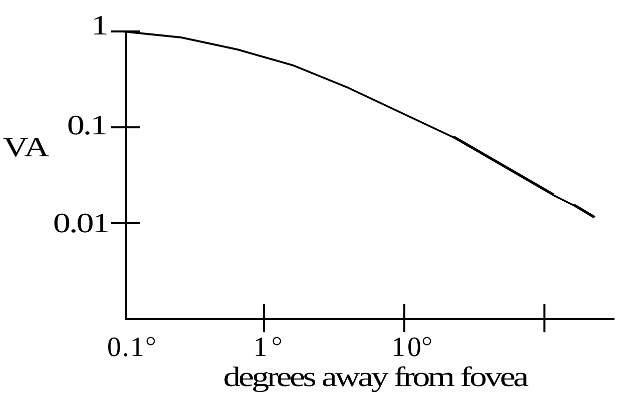
Visual acuity (VA) is defined relative to a standard of 1 minute of arc. VA = 1/(the angular size of smallest element of a letter that can be distinguished [in min])



VA is usually expressed as .

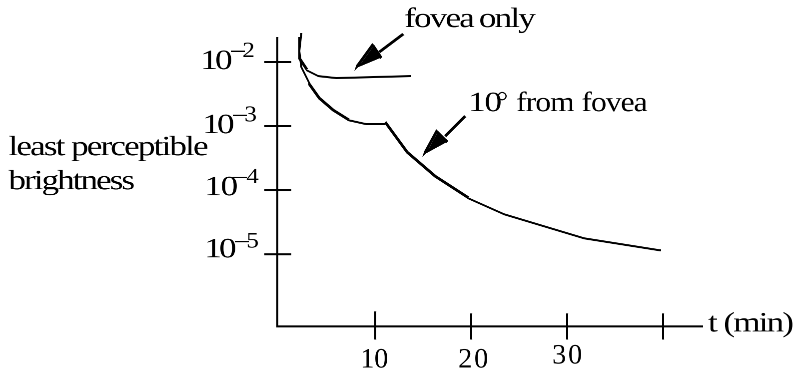
For 20/20 vision, the minimum element is 1 min at 20 ft.

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



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



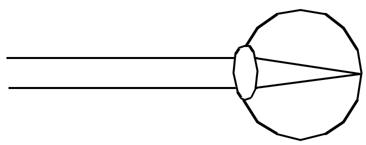
in the dark, the fovea becomes a blind spot

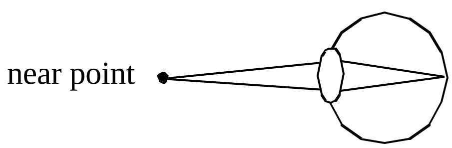
Min detectable flash: outside fovea 50-150 photons

inside fovea ~150,000 photons

<u>Accommodation</u> – Ability of eye to focus (automatically)

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



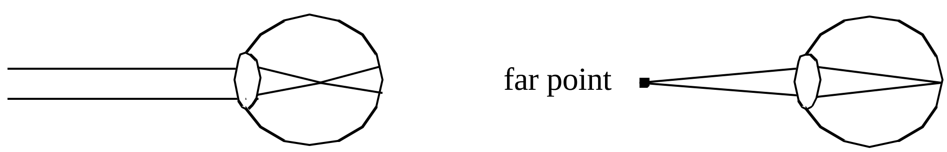


at maximum power of the eye, the closest image plane occurs at the “near point”

Amount of accommodation: 10 diopters at age 20

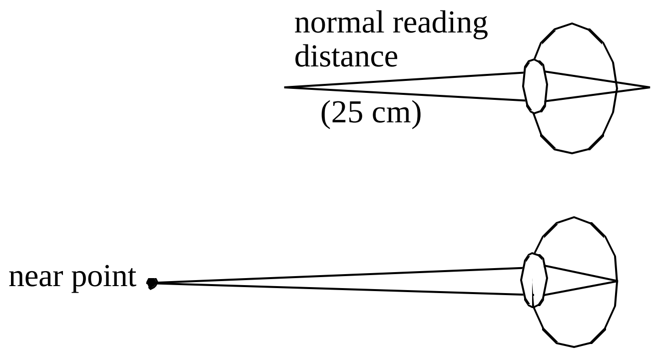
~2 diopters at age 60

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



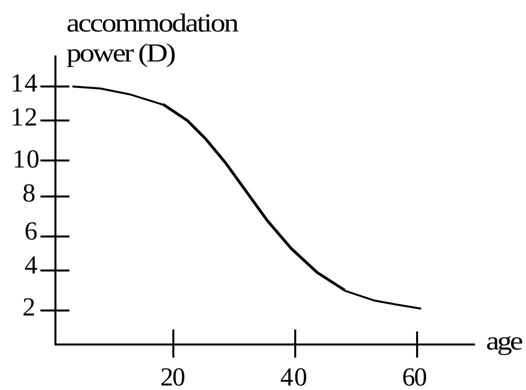
The myopic eye can only accommodate between a far point and the near point. This can be corrected by a negative lens, chosen so that an object at infinity has a virtual image at the far point.

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.

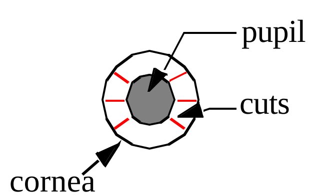
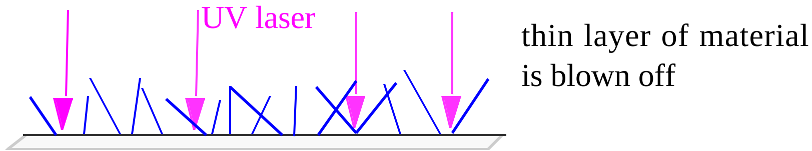


Photo-refractive keratotomy (PRK)

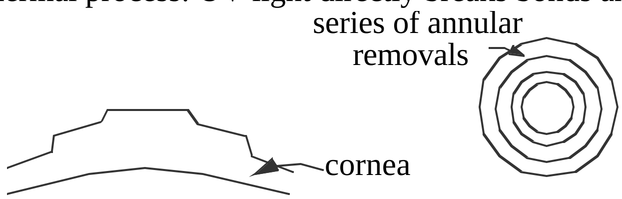
– In this case, we use laser ablation in the clear aperture of cornea.

– The idea is to reshape the cornea surface itself.

Laser ablation

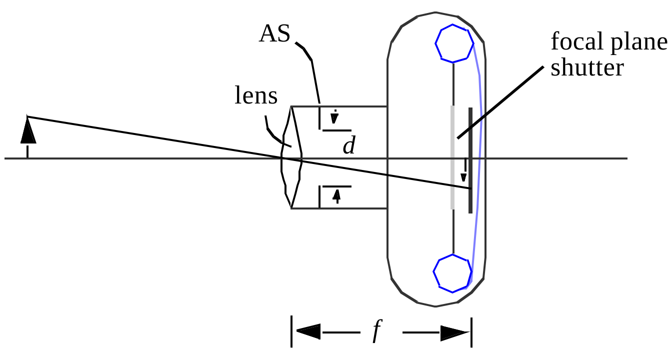


– Laser ablation is not a thermal process: UV light directly breaks bonds and decomposes the material.



Still Camera

[Reading assignment: Hecht 5.7.6]



The aperture stop (AS) is variable to control the amount of light reaching the film. By convention, the AS is normalized to the lens focal length to give a dimensionless parameter called *F number* or *F-stop*

usually written as $f/8$, which means F# = 8.

The amount of light reaching the film is also controlled by the shutter. Shutter speed is expressed as the inverse fraction of 1 sec.

$$s = 125 \quad \text{means} \quad 1/125 \text{ sec}$$

The energy density reaching the film (i.e., film exposure) is given by

where B is object brightness.

Film exposure variation by 2× is called 1-stop. Shutter speeds are usually varied by 1 stop, i.e., 1, 2, 4, 8, 16, 32, 64, 125, 250, 500, 1000.

Lens aperture also varies by stops. In F-number, one stop is a factor of $\sqrt{2}$. (Why?) Typical lens F# settings: 2, 2.8, 4, 5.6, 8, 11, 16. So an exposure setting with $S = 125, f/4$ is equivalent in terms of film exposure to $S = 64, f/5.6$.

How to choose? Trade-offs:

Shutter speed: Faster $\rightarrow$ less blur, slower $\rightarrow$ more light

F-stop: Wider (lower F#) $\rightarrow$ more light

Depth of focus (DOF): Range of object distances in ‘good’ focus

So lower F $\rightarrow$ less DOF.

In principle, lower F $\rightarrow$ higher resolution, but most consumer camera lenses are aberration limited, not diffraction limited. So, sharper pictures are usually obtained with larger F, since aberrations reduce at larger F.

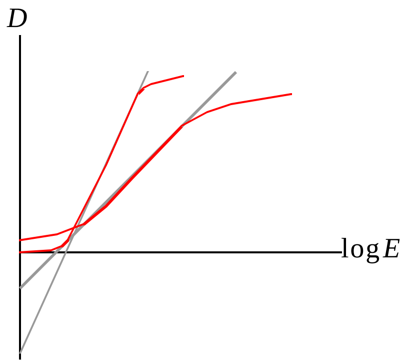
Modern cameras have auto-exposure. The exposure program steps S and F together in a compromise, middle range. Better cameras allow over-ride of one or the other. They also allow deliberate over- or under-exposure by ± 1 - ± 2 stops. A photodetector inside the camera is used to control the exposure.

<u>Film</u>

Photographic film is made by coating a special silver halide “emulsion” on an acetate film backing. The emulsion consists of silver halide particles suspended in some matrix. Light absorbed in a particle causes a photochemical change. Chemical *development* causes exposed grains to convert to silver. Unexposed grains are washed away. The result is a film density given by

where T_i is the intensity transmittance of film.

D relates to film exposure E as:



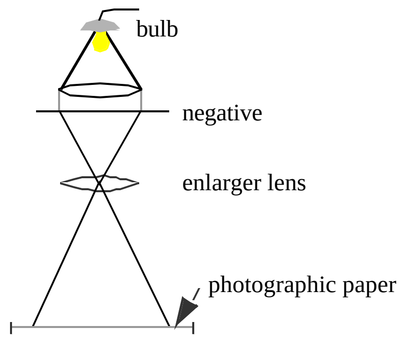
From the straight line part of the curve

Note the *negative* character: Film gets *darker* for more light *exposure*.

γ_n: contrast.

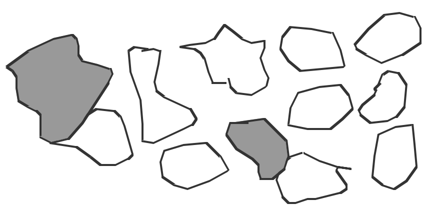
Prints or slides are made in a second step:

Paper also has a negative response, like the film. The combined response can be made linear.



Sensitivity $\rightarrow$ ***resolution*** trade-off

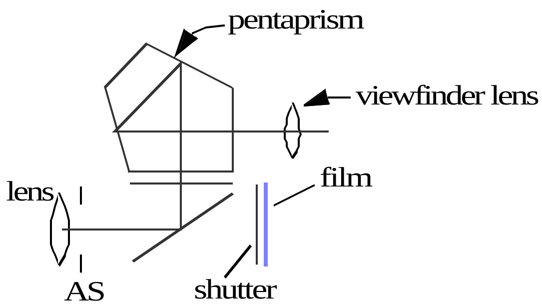
The photochemical reaction is catalytic,



that is, when part of a grain is exposed, the *whole grain* is converted in development. So, film with large grains is more sensitive.

But, the spatial resolution of the film is set by the grain size.

Single-lens Reflex Camera



- Facilitates interchangeable lenses. The finder shows exactly what goes on film.
- A focal plane shutter is required. To obtain high shutter speeds, the shutter is operated as a thin scanning slit.
- Automatic aperture: AS stays open until exposure, so the finder remains bright. During exposure, the AS automatically closes down to the appropriate F stop.

Electronic Camera

Film is replaced by an electronic detector. Most commonly, this is a CCD image array. The analog to grain size is the CCD resolution.

Consumer 35mm film is equivalent to 10-20 Mpixel. However, very acceptable pictures are obtained with 1-2 Mpixel, and consumer cameras today are available with up to 4 Mpixel CCDs.

Film format: Bigger negative → more resolution. Professionals use $2\frac{1}{4}'' \times 2\frac{1}{4}''$ or bigger film format.

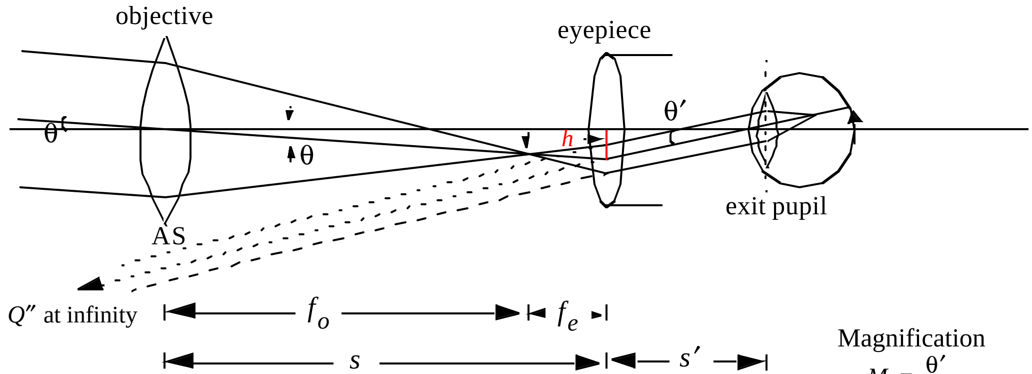
Telescope

[Reading assignment: Hecht 5.7.4, 5.7.7]

A telescope enlarges the apparent size of a distant object so that the image subtends a larger angle (from the eye) than does the object.

The telescope is an *afocal system*, which means that both the object and image are at infinity.

Astronomical telescope



Magnification $M = \frac{\theta'}{\theta}$

$\tan\theta = \frac{-h}{s}$ $\quad \tan\theta' = -\frac{h}{s'}$

Using the lens law for the eyepiece:

So $\tan\theta = \frac{+h}{+(f_o + f_e)}$ $\quad \tan\theta' = -\frac{hf_o}{f_e(f_o + f_e)}$.

For small angles, $\tan\theta \approx \theta$ $\quad \tan\theta' \approx \theta'$, then .

The *exit pupil* is the image of the AS.

Define CA_o = entrance pupil clear aperture
CA_e = exit pupil clear aperture

From the diagram, it is clear that

The eye is placed at the exit pupil, so a CA_e much larger than 3 mm is not very useful. However, making it somewhat larger makes it easier to align the eye to the eyepiece. Binoculars may have $CA_e \sim 5$ mm.

Resolution

The resolution of the eye is 1 arc min = 60 arc sec. So in a telescope, the eye can resolve objects separated by an angle α if

$$M > \frac{1}{\alpha} \qquad (\alpha \text{ in min.})$$

Now, the diffraction limit of the telescope can be written as $\alpha_T = 5.5/CA_o$, with α_T in sec. and CA_o in inches (for 550nm wavelength).

At the diffraction limit, the finest detail in the image has an angular separation of $M\alpha_T$. If this angle is at least 60 sec, the eye can resolve the detail. So, with

At this magnification, the diffraction limit and the resolution of the eye are equal. Magnification much larger than this means that the diffraction blur spot is larger than the smallest feature that the eye can resolve. The eye sees a rather blurry image.

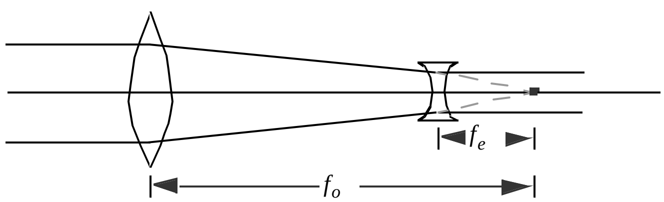
Example: $2\frac{1}{2}''$ refractor telescope $f_o = 700$ mm

$$M_{\max} \cong 28$$

$f_e = 25\text{mm objective} \rightarrow M = 28$

$f_e = 9\text{mm objective} \rightarrow M = 78$ – no increase in resolution
– hard to align the eye

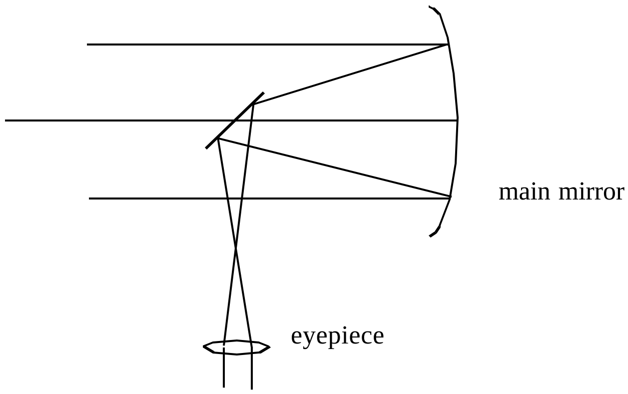
Galilean Telescope



f_e is negative, so $M > 0$. **Non-inverting**.

This telescope would seem to be a good candidate for binoculars. Inexpensive “field glasses” or “opera glasses” are indeed made according to this design, but it turns out to have a very limited field of view

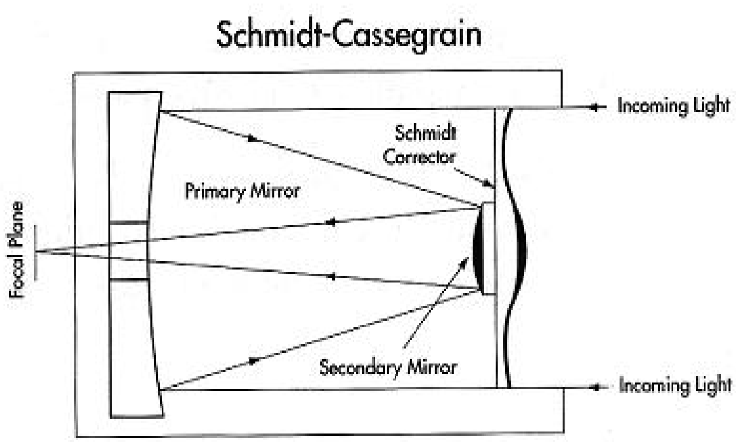
Reflecting Telescope



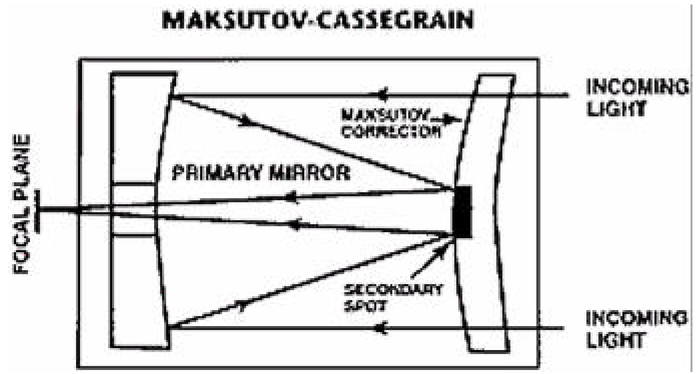
All modern astronomical telescopes have this basic configuration because it is much more practical to fabricate large mirrors than lenses. The size of the large main mirror (the entrance pupil) sets the diffraction limit. Also, a larger entrance pupil gathers more light, so that faint objects can be detected. Ground-based telescopes are limited by atmospheric turbulence, which introduces unavoidable aberrations. One solution is to go into space, above the atmosphere.

The configuration shown above, with a parabolic mirror is called a Newtonian reflector. It has fairly good performance and is inexpensive, but does suffer from coma aberration for off-axis objects.

“Catadioptric” designs use a combination of mirrors and lenses to fold the optics and form an image. There are two popular designs: the Schmidt-Cassegrain and the Maksutov-Cassegrain. In the Schmidt-Cassegrain the light enters through a thin aspheric “Schmidt” correcting lens, then strikes the spherical primary mirror and is reflected back up the tube and intercepted by a small secondary mirror which reflects the light out an opening in the rear of the instrument where the image is formed at the eyepiece. The corrector lens reduces the off-axis aberrations, giving good images over a wider field than the Newtonian. An additional advantage is that the lens seals the telescope tube, which protects the primary mirror from contamination, as well as stiffening the structure.



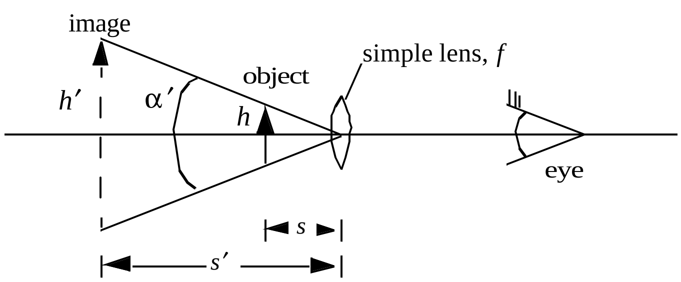
The Maksutov design uses a thick meniscus correcting lens with a strong curvature and a secondary mirror that is usually an aluminized spot on the corrector. The Maksutov secondary mirror is typically smaller than the Schmidt's giving it slightly better resolution, especially for observing extended objects, such as planets, galaxies, and nebulae.



Microscope

[Reading assignment: Hecht 5.7.3, 5.7.5]

Simple microscope (magnifier)



– object located inside lens focal length f

– virtual image is formed at s'

Simple application of the lens law gives:

If the eye is located at the lens, the angle subtended by the image is

$$\alpha' = h'/s' = \frac{h(f-s')}{fs'}$$

If the eye views the same object at standard viewing distance (25 cm), then the angle would be

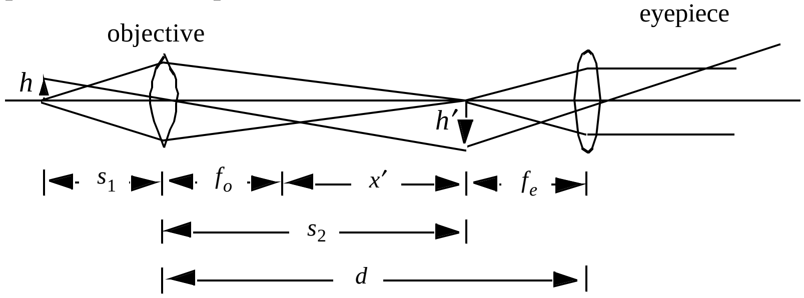
The magnifier enlarges the object by the ratio

$$M = \frac{\alpha'}{\alpha} = \frac{h(f-s')}{fs'} \cdot \frac{-25}{h} = \frac{25}{f} - \frac{25}{s'} \qquad (f,\ s' \text{ in cm})$$

One may adjust the lens to put the image appearing at ∞, which means that it is viewed with a fully relaxed eye, then

With the image appearing at 25 cm (standard viewing distance), then

<u>Compound Microscope</u>



– The objective lens produces a real (inverted), magnified image of the object.

– The eyepiece re-images to a comfortable viewing distance and provides additional magnification.

The total magnification is the product of the linear objective magnification times the eyepiece angular magnification.

In laboratory microscopes, x' is called the “tube length” and is standardized to 160 mm. So, the objective magnification is given by $M_o = \frac{16}{f_o}$. Thus, a 20× objective lens has a focal length of 0.8 cm.

Resolution. The aperture stop is usually set by the size of the objective (NA). Recall that the diffraction limited linear resolution is

. This is the smallest object that can be resolved.

The eye can resolve an object size of ~0.08 mm at the distance of 25 cm, so the equivalent object size in the microscope is

$$R = \frac{0.08\ \text{mm}}{M}$$

The magnification at which these two resolutions are equal is

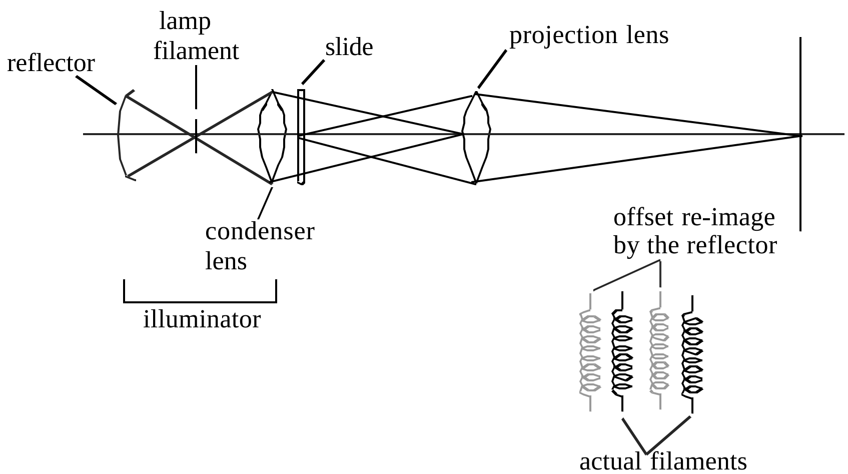
$$\frac{0.08\ \text{mm}}{M} = \frac{0.61\lambda}{\text{NA}}$$

$$M = \frac{0.08}{0.61\lambda}\text{NA} = \frac{0.13}{\lambda}\text{NA} \qquad \text{with } \lambda \text{ in mm}$$

Take $\lambda = 0.55\mu\text{m} \rightarrow M_{max} \cong 240\text{NA}$.

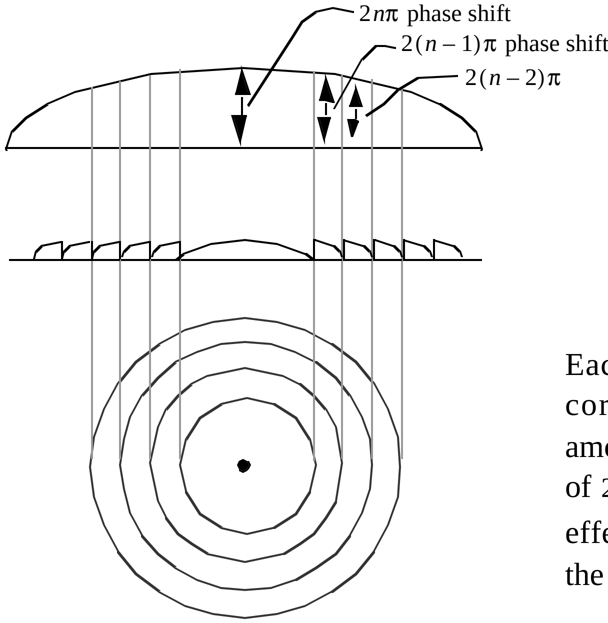
Increasing the magnification beyond this does not allow observation of smaller objects due to diffraction.

Projection Systems



- The illuminator has multiple jobs:
  1.Efficiently collect light from the source (lamp filament)
  2.Uniformly illuminate the object (slide)
  3.Redirect light into the projection lens
- The condenser lens projects a magnified image of the source into the entrance pupil of the projection lens
- The reflector collects more light from the source, and also creates a more uniform effective source.

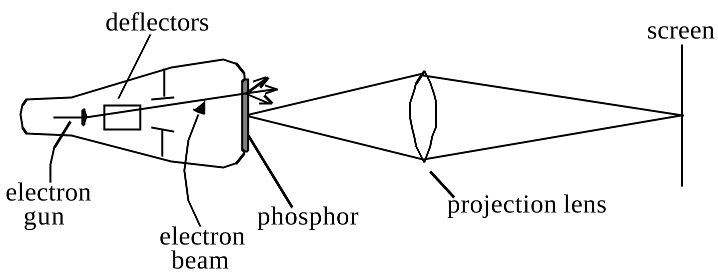
A Vugraph projector uses a *Fresnel lens* for the condenser



Each annular zone has the same slope as the corresponding surface of the full lens. An amount of glass corresponding to a phase shift of $2n\pi$ is "removed" from each zone so that the effect on the light phase is the same as that of the full lens.

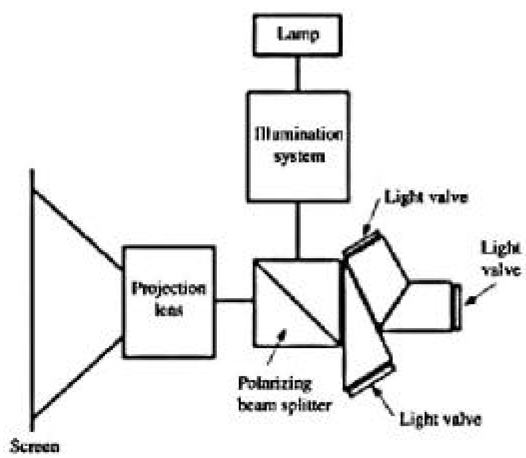
<u>CRT based Projection TV</u>

- High output phosphor

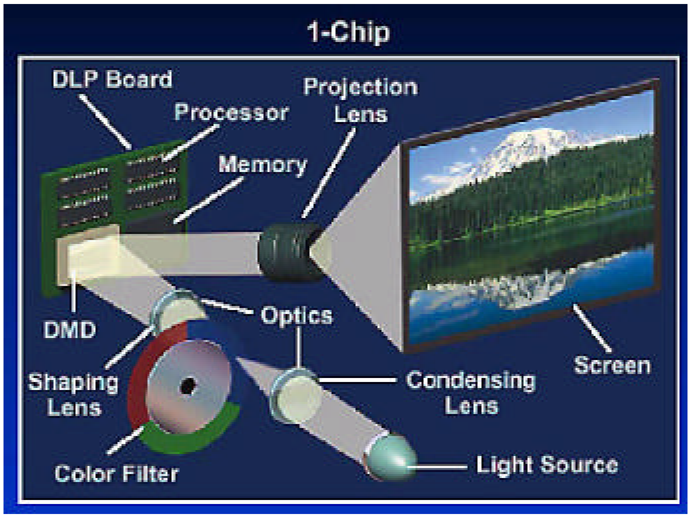


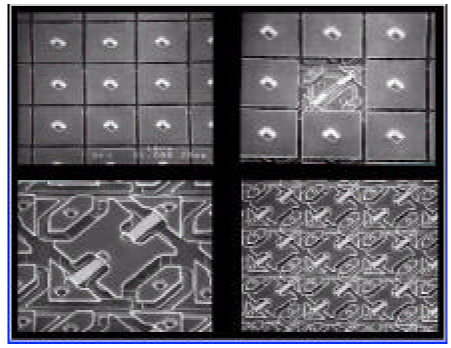
For color, 3 separate systems, merged images on the screen.

- LCD Projector



- Digital Mirror Device (DMD) based display





Micrograph of DMD chip