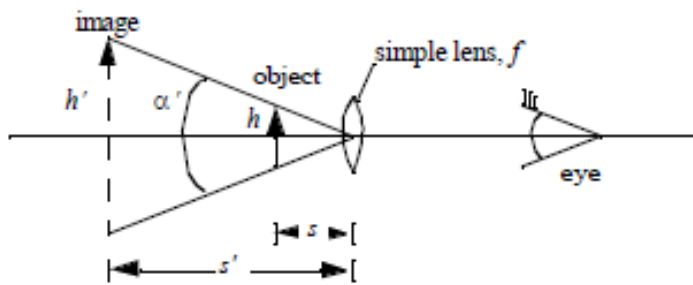# Microscope

Simple microscope (magnifier)

– object located inside lens focal length f

– virtual image is formed at s'

Simple application of the lens law gives:

$$h' = \frac{h(f-s')}{f}.$$

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

$$\alpha = \frac{-h[cm]}{25}.$$

The magnifier enlarges the object by the ratio

$$M = \frac{\alpha'}{\alpha} = \frac{h(f-s')}{fs'} \times \frac{-25}{h} = \frac{25}{f} - \frac{25}{s'} \quad (f, s' \text{ in cm}).$$
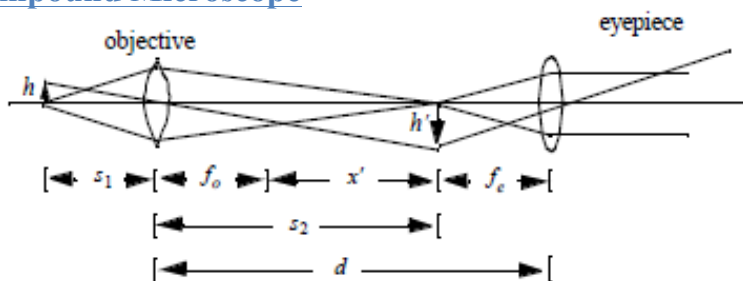
One may adjust the lens to put the image appearing at infinity, which means that it is viewed with a fully relaxed eye, then

$$M = \frac{25}{f}.$$

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

$$M = \frac{25}{f} + 1.$$

Compound Microscope

– 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.

1

$$M_0 = \frac{h'}{h} = -\frac{s_2}{s_1} = \frac{-x'}{f_0}$$

$$M_e = \frac{25}{f_e}$$

$$M_{total} = M_0 \times M_e = \frac{-x'}{f_0} \cdot \frac{25}{f_e}$$

In laboratory microscopes, x' is called the "tube length" and is ranging from 160 to 250 mm. So, the objective magnification is given by $M_0 = x' / f_0$. Thus, a 20x objective lens specified for a tube length of 160 mm has a focal length of 8 mm.

Older microscope objectives (before 1980) were designed to form an image at a given distance (the tube length) behind the objective flange. This distance varied between 160 mm and 210 mm depending on the manufacturer and the application. At the proper tube length, the objectives formed images at their nominal magnifications. Modern microscope objects are "infinity corrected." They are optimized to provide collimated light on their image side. A separate de-collimating or tube lens then forms the image. This design gives microscope manufactures flexibility to insert lighting and beam splitters in the collimated space behind the objective. The proper focal length tube lens is required to form an image at the objective nominal magnification.

Tube Lens

As the focal length of the tube lens is increased, the distance to the intermediate image plane also increases, which results in a longer overall tube length. Tube lengths between 200 and 250 millimeters are considered optimal, because longer focal lengths will produce a smaller off-axis angle for diagonal light rays, reducing system artifacts. Longer tube lengths also increase the flexibility of the system with regard to the design of accessory components.

(Check http://www.microscopyu.com/tutorials/java/infinityoptics/offaxisrays/ to see a java applet showing the results of varying tube lens focal length and pupil diameter).

Resolution

The aperture stop is usually set by the size of the objective (NA). The diffraction limited linear resolution based on Rayleigh criterion is

$$\Delta r = 0.61 \frac{\lambda}{\text{NA}}.$$

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

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

$$M = \frac{80[\mu m]}{0.61\lambda[\mu m]} \text{NA} = \frac{130}{\lambda[\mu m]} \text{NA}$$

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

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

Interested in learning more about microscopes?
Check Nikon Microscope U (http://www.microscopyu.com/) and
Olympus Microscopy Resource Center (http://www.olympusmicro.com/index.html).

Telescope

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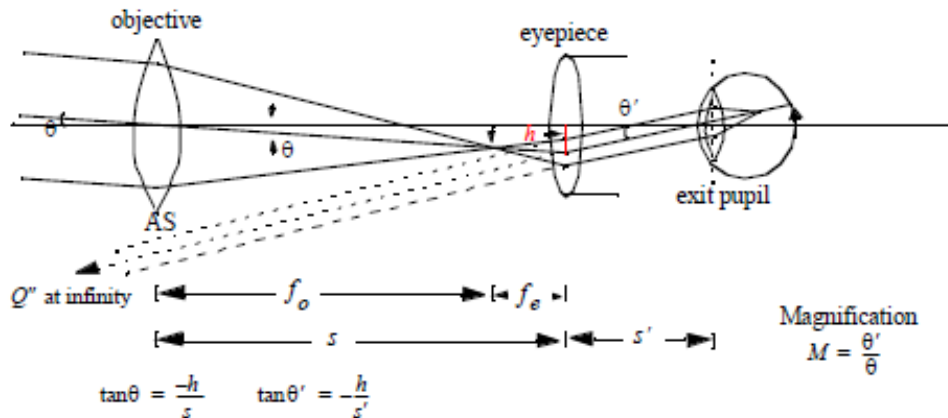The telescope is an *afocal system,* which means that both the object and image are at infinity.

Astronomical telescope
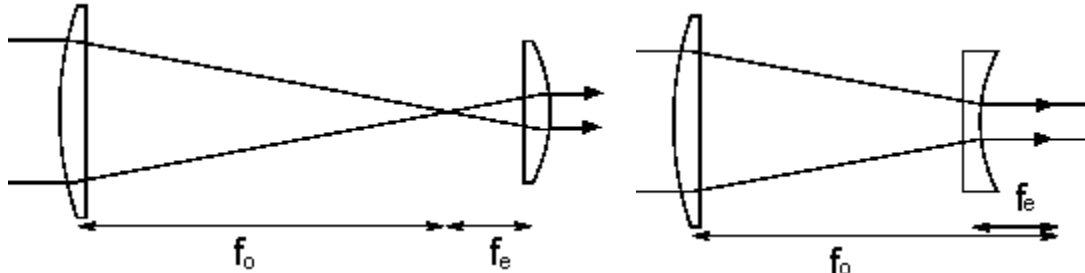
| Keplerian telescope | Galilean telescope |

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

Using the lens law for the eyepiece:

$$\frac{1}{s}+\frac{1}{s'}=\frac{1}{f_e} \quad (s=f_0+f_e)$$

$$\frac{1}{s'}+\frac{1}{f_0+f_e}=\frac{1}{f_e}$$

$$\frac{1}{s'}=\frac{1}{f_e}-\frac{1}{f_0+f_e}=\frac{f_0}{f_e(f_0+f_e)}$$

So $\tan\theta=\dfrac{h}{f_0+f_e}$, $\quad \tan\theta'=-\dfrac{h}{s'}=-\dfrac{hf_0}{f_e(f_0+f_e)}$.

For small angles, $\tan\theta\approx\theta \quad \tan\theta'\approx\theta'$, *then* $\quad M=\dfrac{\theta'}{\theta}=-\dfrac{f_0}{f_e}$. Note also that $\dfrac{s'}{s}=\dfrac{f_e}{f_0}$.

The **exit pupil** is the image of the aperture stop (AS).

Define CA_0 = entrance pupil clear aperture

CA_e = exit pupil clear aperture

From the diagram, it is clear that $\dfrac{CA_0}{CA_e} = \dfrac{s}{s'} = \dfrac{\theta'}{\theta} = M$.

The eye is placed at the exit pupil, so a CA_e much larger than 3 mm (~the diameter of the eye iris) is not very useful. However, making it somewhat larger makers it easier to align the eye to the eyepiece. Binoculars may have CA_e~5mm.

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 $M > 1/\alpha$ (α in min). However, the diffraction will limit M eventually. Example: 2.5" (=CA_0) refractor telescope, f_0=700 mm, f_e=25 mm (eyepiece) ➔ M = 28. This is approximately the maximal magnification (M_{max}~ 11 CA_0, the diffraction limit). Magnification much larger M_{max} means that the diffraction blur spot is larger than the smallest feature that they eye can resolve. The eye sees a rather blurry image.
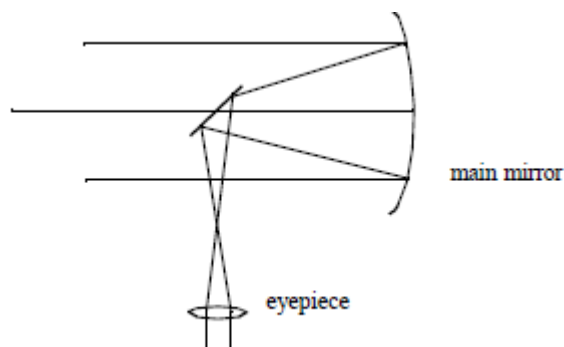
Galilean Telescope

$$M = -\frac{f_o}{f_e}$$
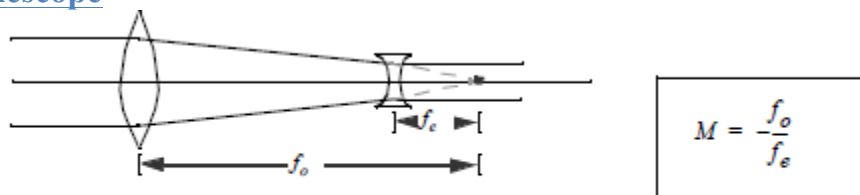
f_e is negative, so $M > 0$. **Non-inverting.**

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.
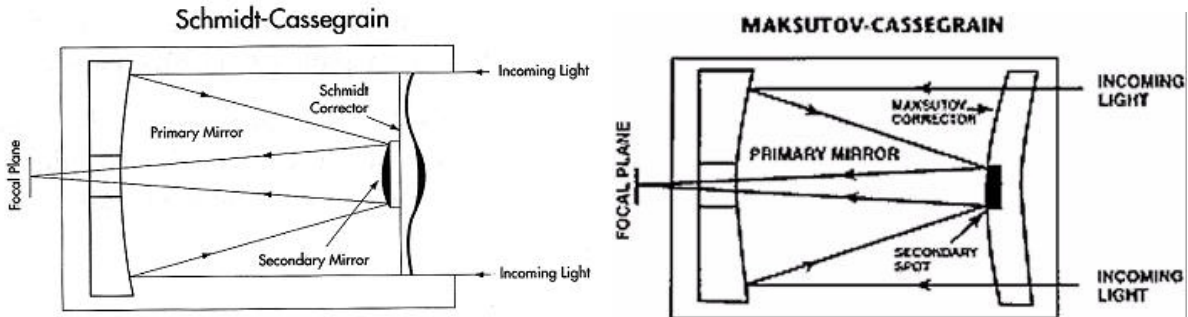

Check Wikipedia for more information about telescope (http://en.wikipedia.org/wiki/Telescope).

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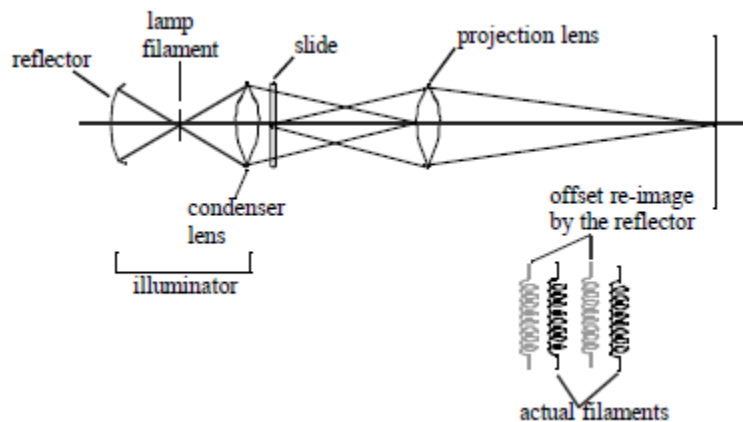
The illuminator has multiple jobs:
1.Efficiently collect light from the source (lamp filament)
2.Uniformly illuminate the object (slide)
3.Redirect light into the projection lens
• The condenser lens projects a magnified image of the source into the entrance pupil of the projection lens
• The reflector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

Still Camera [Reading Hecht 5.7.6]
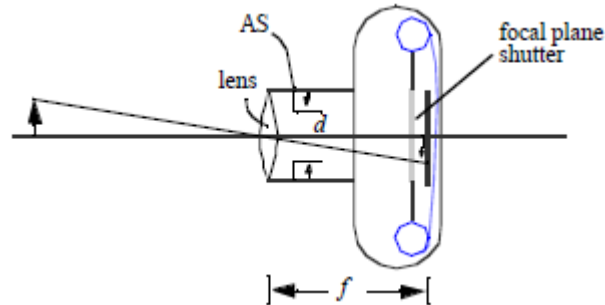
The aperture stop (AS) is variable to control the amount of light reaching the film. By convention, the AS is normalized to the lens focal length to give a dimensionless parameter called *F number* or *F-stop*

$$F = f/d \qquad \text{note: NA} \cong \frac{1}{2F}$$

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.

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

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

$$E \propto \frac{BA}{sf^2} = \frac{B\pi d^2}{4sf^2} = \frac{B\pi}{4sF^2}$$

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 → less blur, slower → more light

F-stop: Wider (lower F#) → more light

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

$$\text{DOF} \propto F^2$$

So lower F → less DOF.

In principle, lower F → 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.
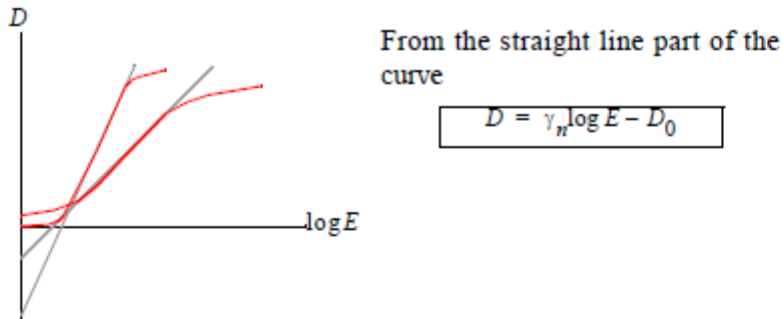
Film

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

$$D \equiv -\log T_i$$

where T_i is the intensity transmittance of film.
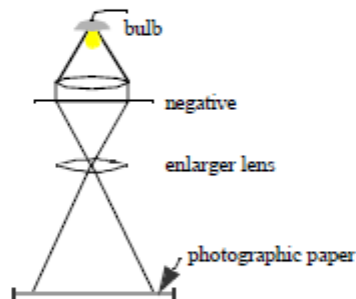
D relates to film exposure E as:

From the straight line part of the curve

$$D = \gamma_n \log E - D_0$$

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.
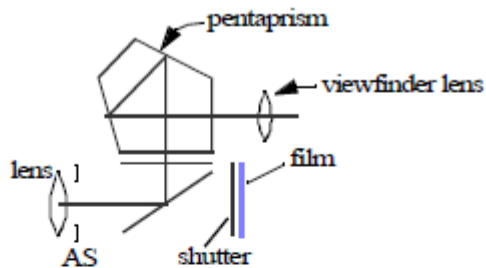

Sensitivity → resolution trade-off

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 charge-coupled device (CCD). The analog to grain size is the CCD pixel size. Consumer 35 mm film is equivalent to 10-20 Mpixel. However, very acceptable picture are obtained with 1-2 Mpixel, and consumer camera are available with up to 24 Mpixel CCDs (24 M ones cost ~$2000, 12 M ones cost ~$500 as in 2009).

*The 2009 Nobel Prize for Physics went, in part, to the inventors of the charge-coupled device George Smith and Willard Boyle. Their innovation, sketched out in 1969, is now the imager in millions of digital cameras and telescopes.

(http://nobelprize.org/nobel_prizes/physics/laureates/2009/index.html)

**The other ½ of the 2009 Nobel Prize for Physics went to Charles Kao, who conceived the original idea to use fibers for optical communication.
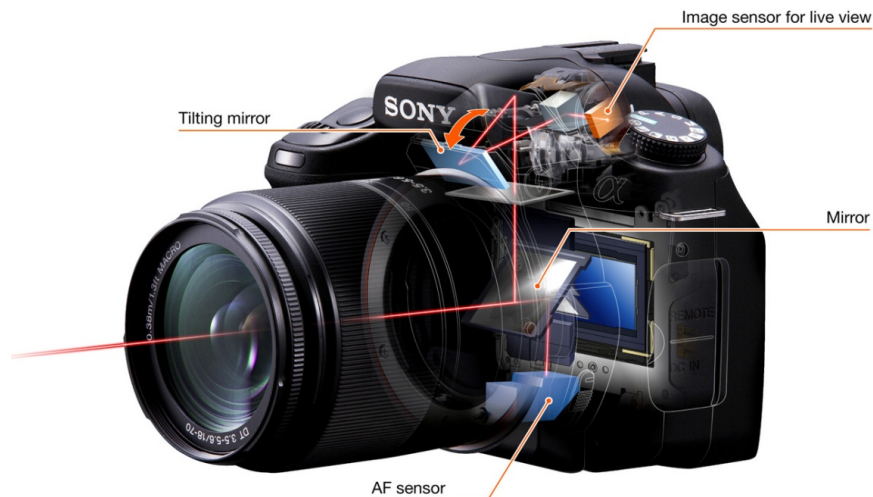
Interested in learning more about digital cameras and camera lenses?
Check, for example, http://www.dpreview.com/ .