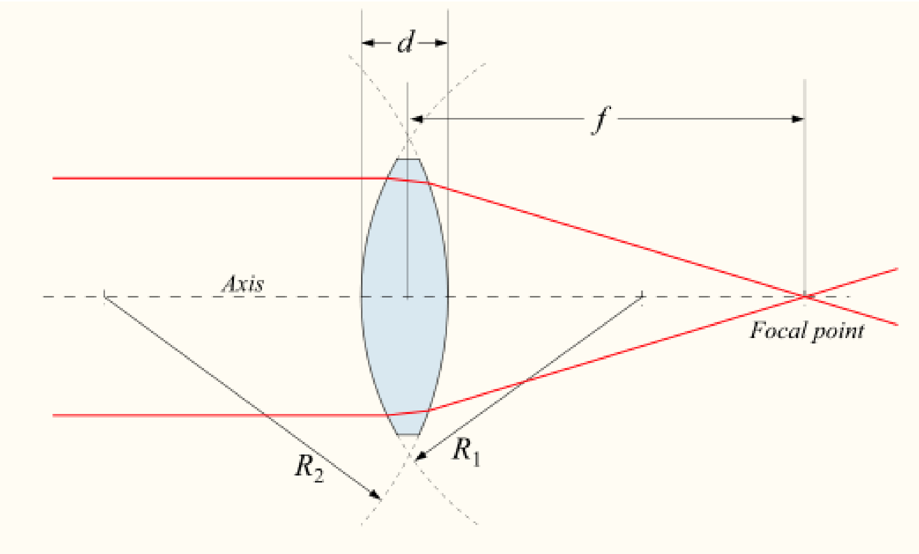
Thin Lens



Positive (converging) lens

Lens maker's formula

$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)d}{nR_1R_2}\right],$$

"Thin" lens➔ d is neglibile

$$\frac{1}{f} \approx (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right].$$

Paraxial approximation

$$\sin(\theta) \approx \tan(\theta) \approx \theta$$

$$\cos(\theta) \approx 1$$

See Hecht Ch. 5 and review the following Equations. Refer to lecture given on 10/01 for derivation of the following equations

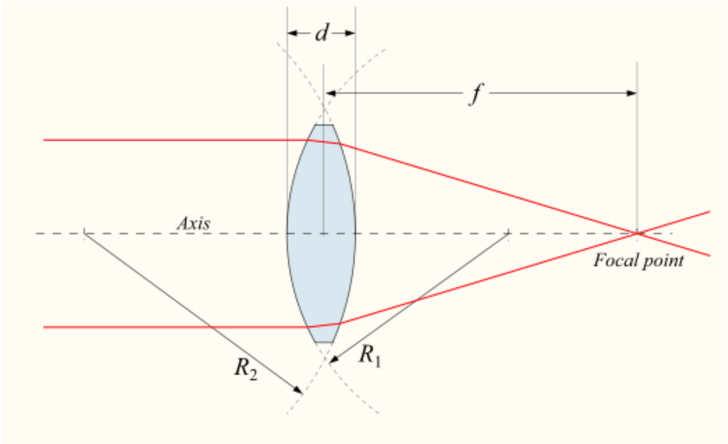
$$\frac{1}{f} = \frac{1}{s_0} + \frac{1}{s_i}$$

$$x_0 x_i = f^2$$

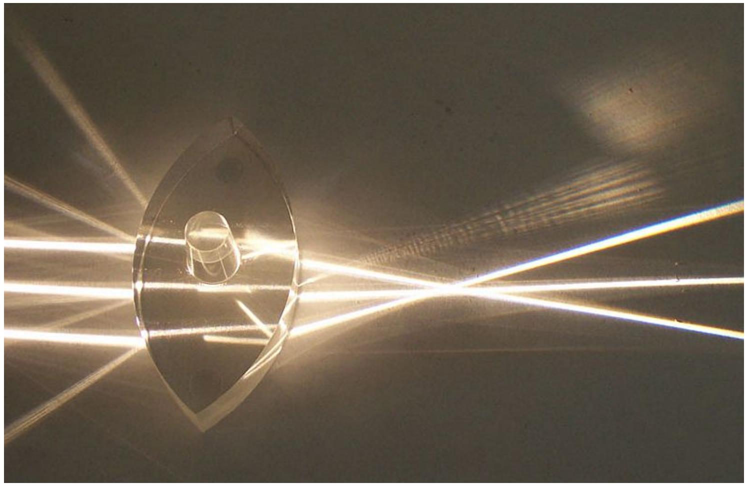
$$M_T \equiv \frac{y_i}{y_0} = -\frac{s_i}{s_o}$$

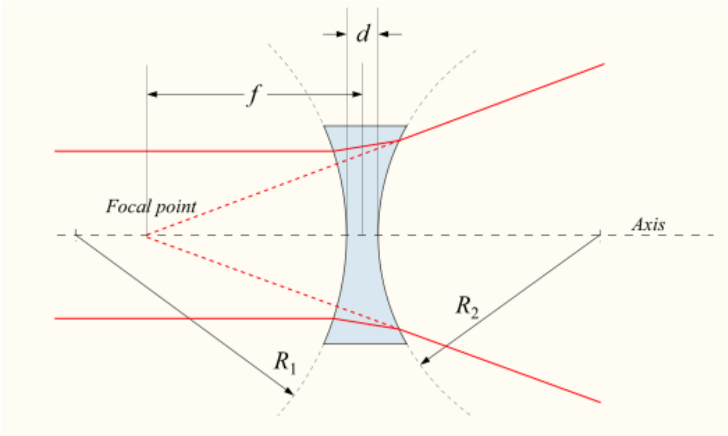
$$M_L \equiv \frac{dx_i}{dx_0} = -\frac{f^2}{x_0^2}$$

Converging and Diverging Lenses: Ray Diagrams

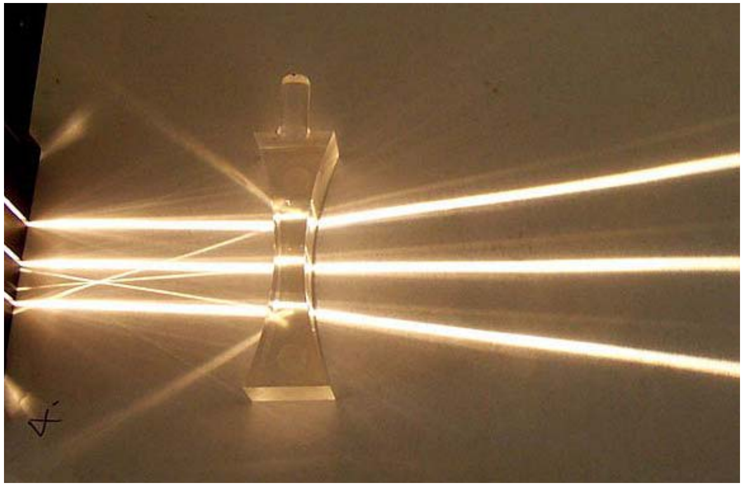


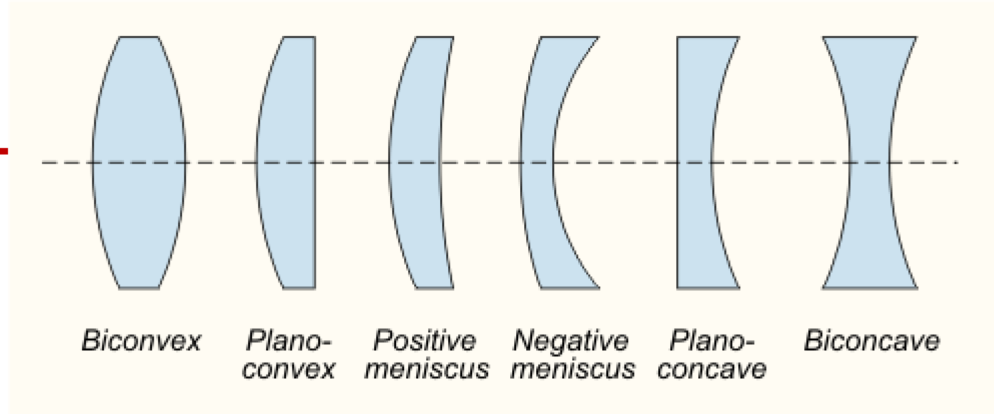
Positive (converging) lens





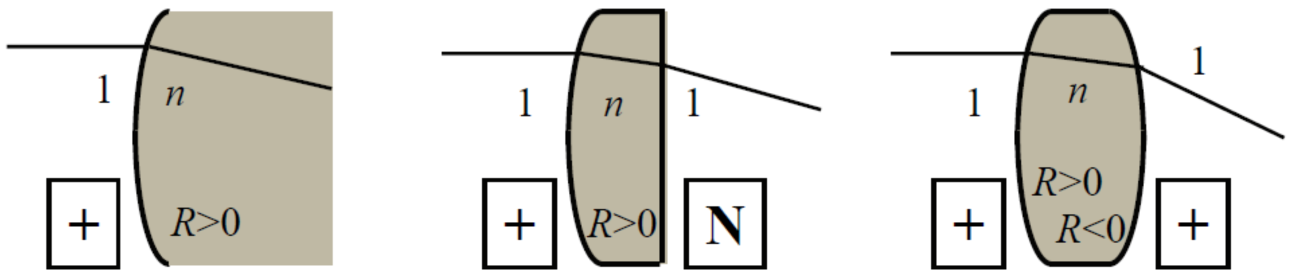
Negative (diverging) lens





$$\frac{1}{f} \approx (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right].$$

Positive power : exiting rays converge

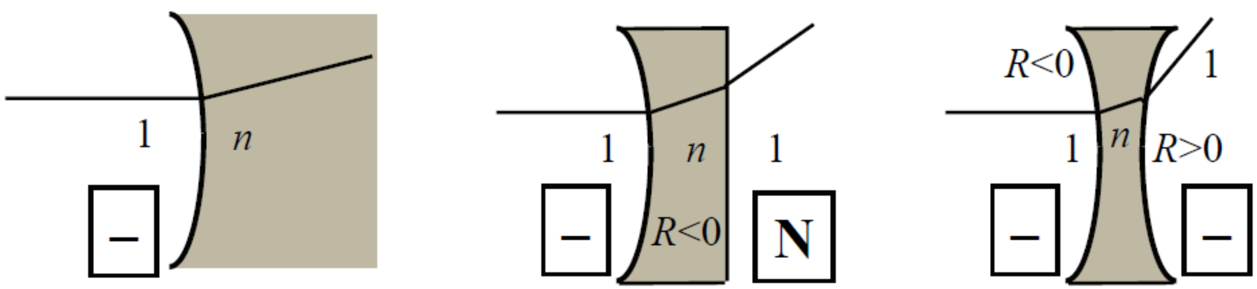


Simple spherical refractor (positive)

Plano-convex lens

Bi-convex lens

Negative power : exiting rays diverge



Simple spherical refractor (negative)

Plano-concave lens

Bi-concave lens

Summary : Real and Virtual Images

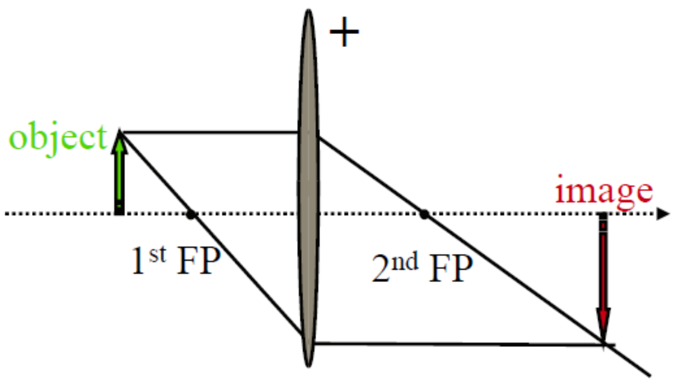


image: real & inverted; $M_T<0$

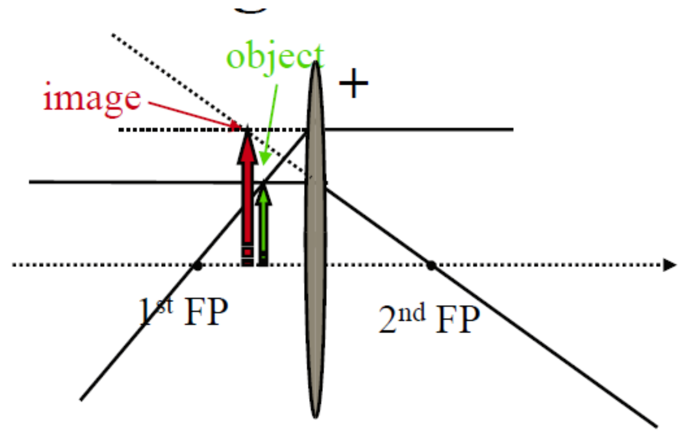


image: virtual & erect; $M_T>1$

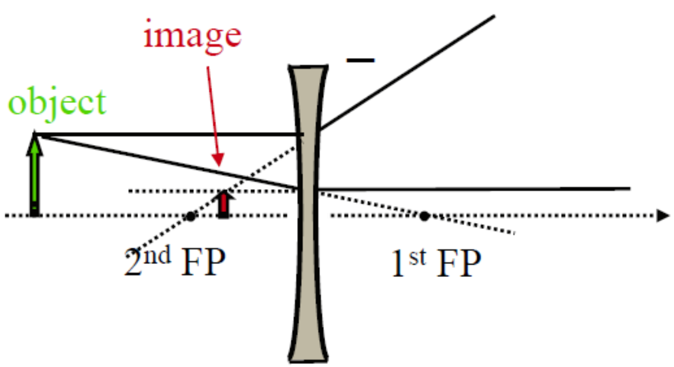


image: virtual & erect; $0<M_T<1$

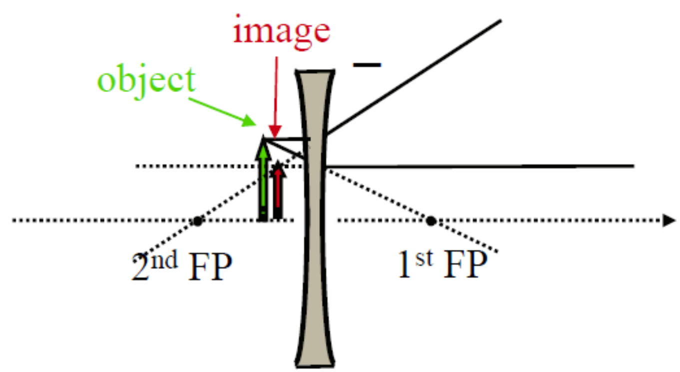
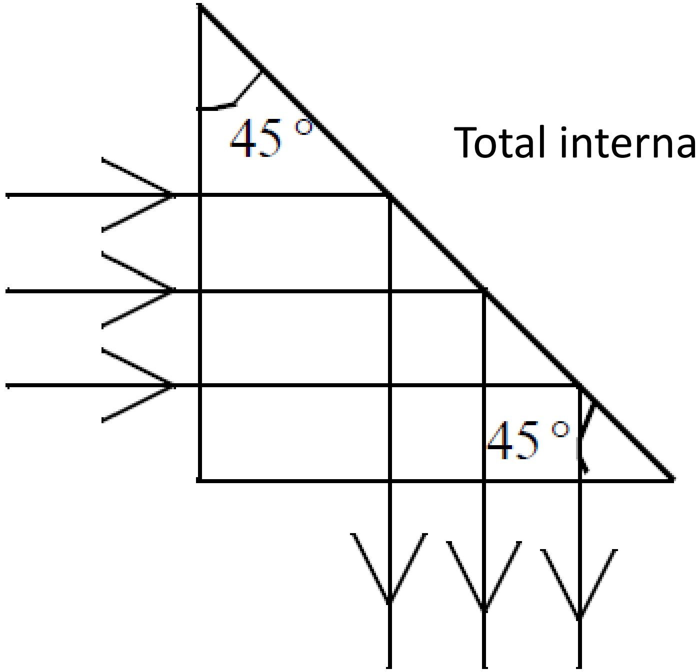


image: virtual & erect; $0<M_T<1$

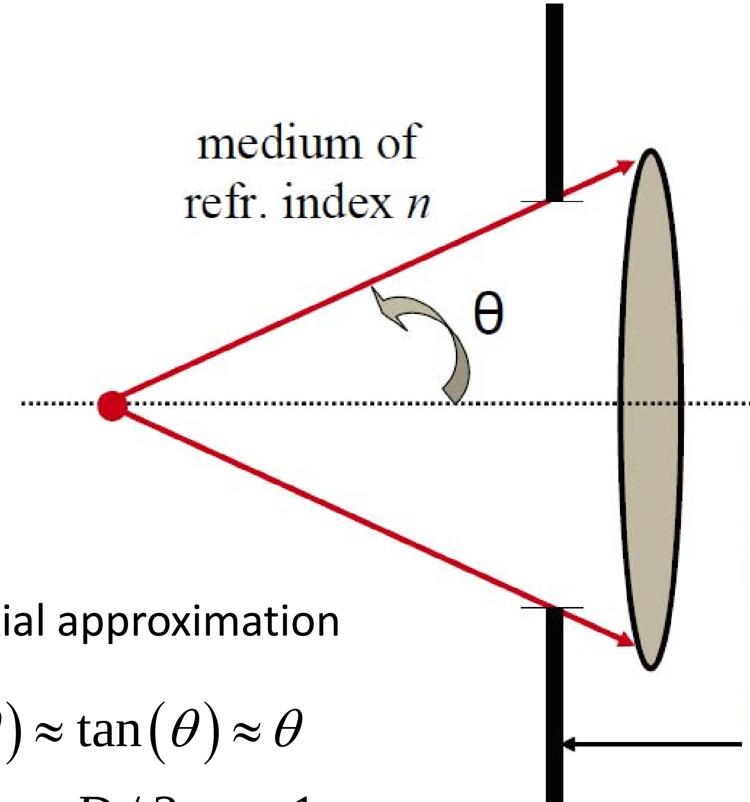
Prism as a mirror

Right Angle Prism



Total internal reflection

Numerical Aperture



θ: half-angle subtended by the imaging system from an *axial* object

Numerical Aperture
(NA) = $n \sin\theta$

Speed (f/#)=1/2(NA)
pronounced f-number, e.g. f/8 means (f/#)=8.

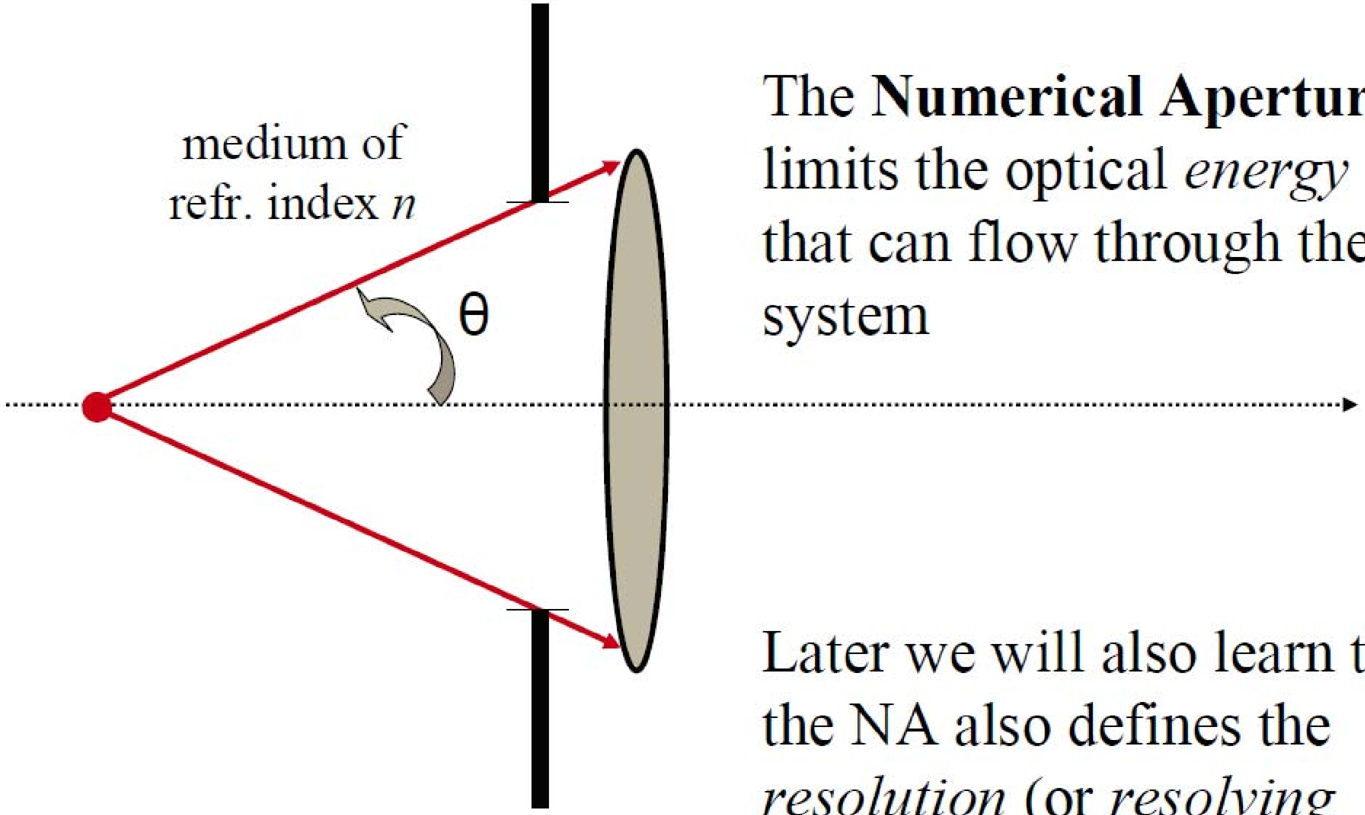
Aperture stop
the physical element which limits the angle of acceptance of the imaging system

Paraxial approximation

$$\sin(\theta) \approx \tan(\theta) \approx \theta$$

$$\rightarrow NA = \frac{D/2}{f} = \frac{1}{2 f/\#}$$

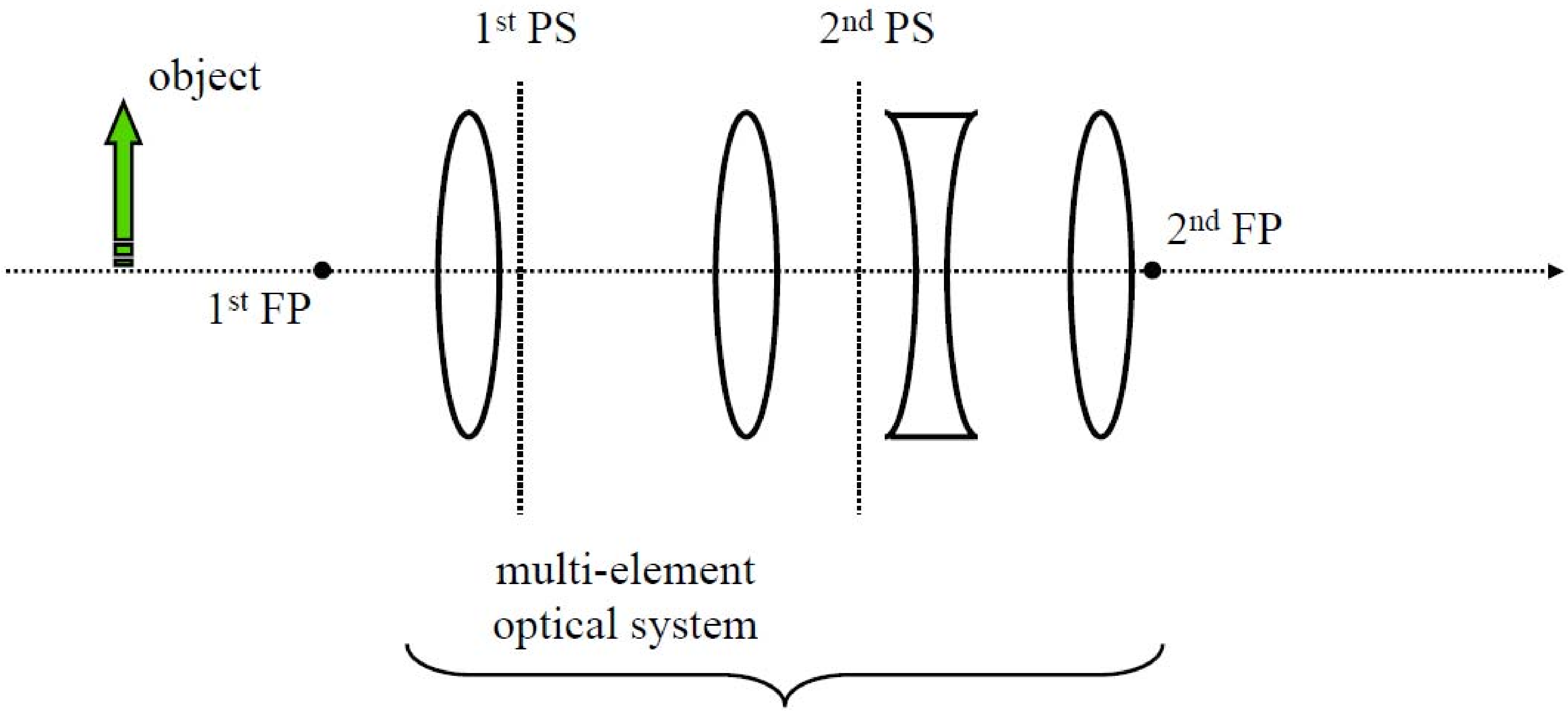
Physical Meaning of NA



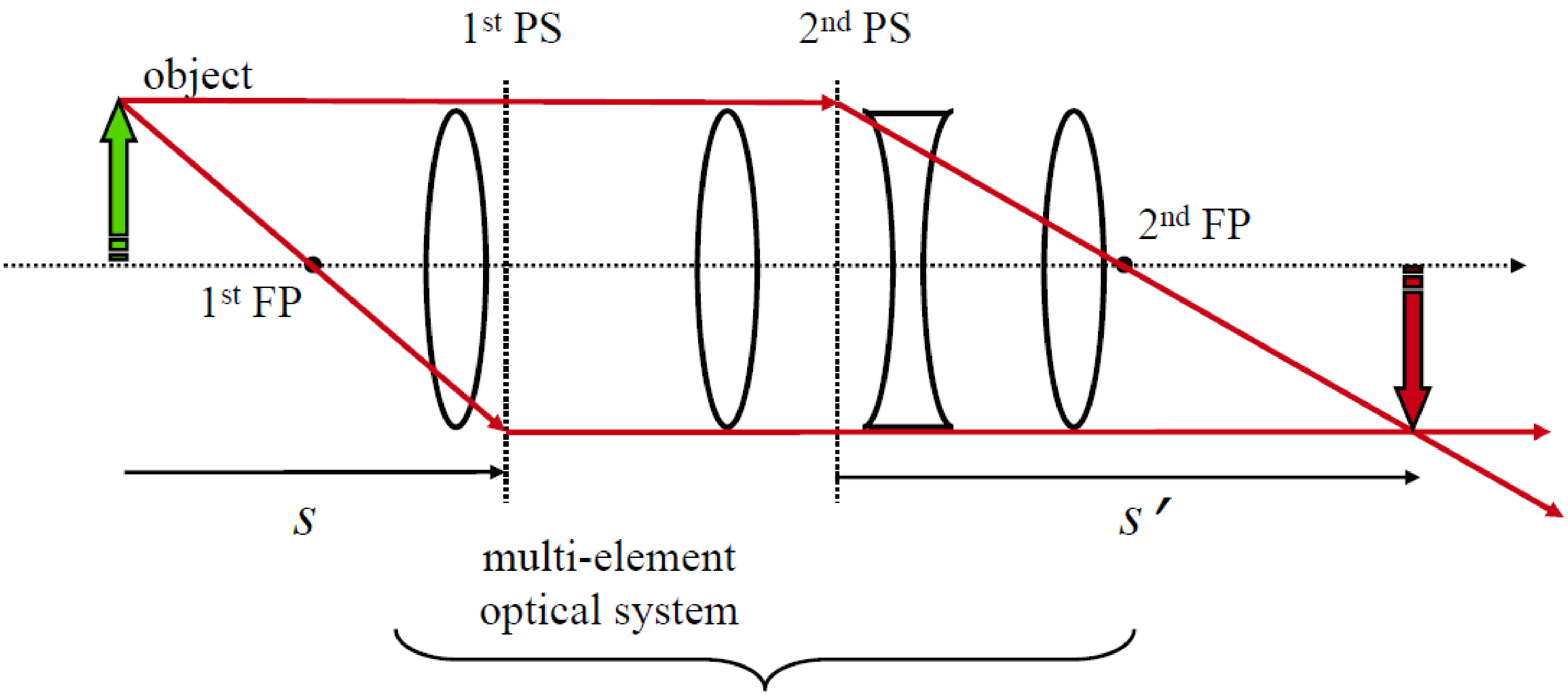
The **Numerical Aperture** limits the optical *energy* that can flow through the system

Later we will also learn that the NA also defines the *resolution* (or *resolving power*) of the optical system

Multiple Elements



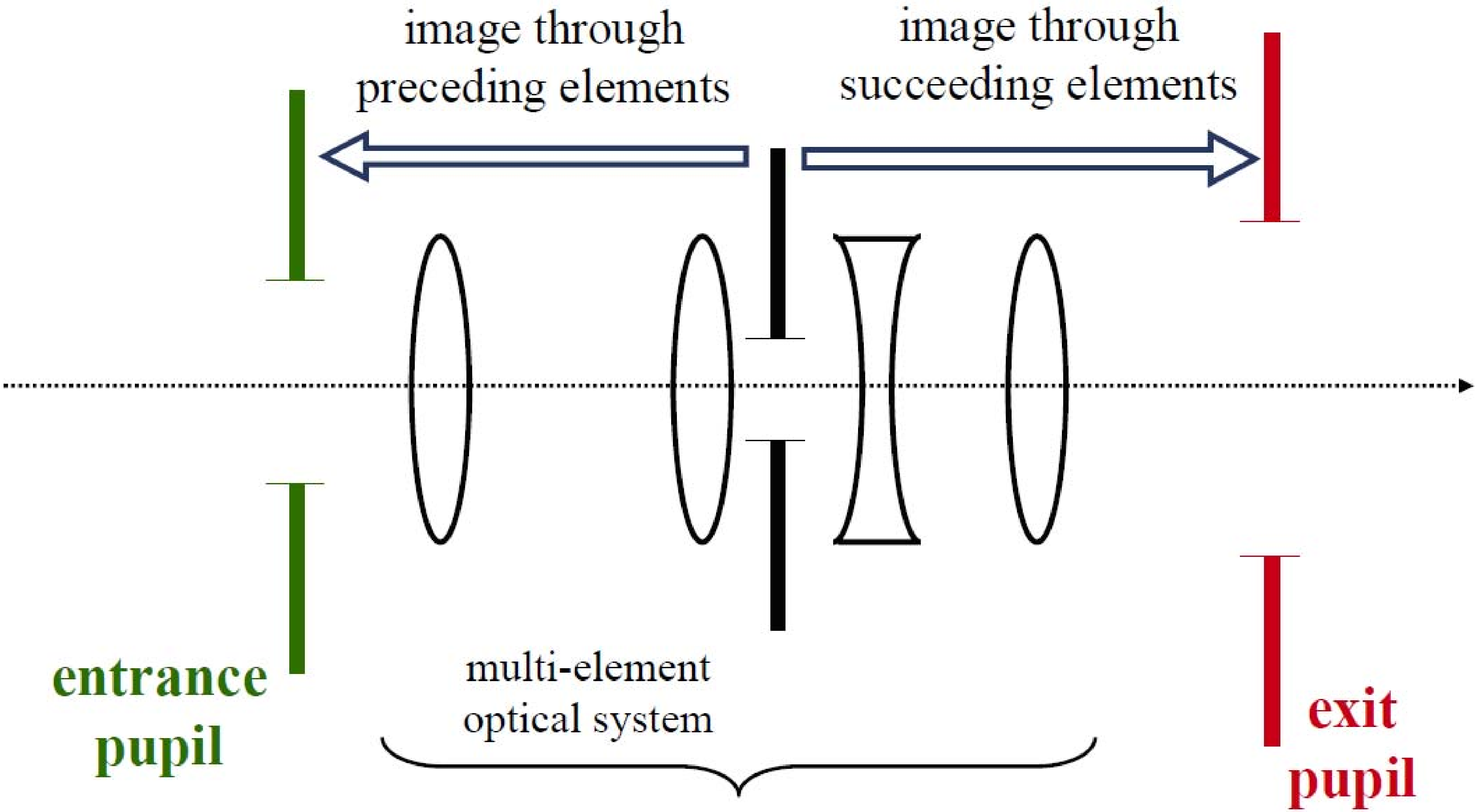
Principle Planes



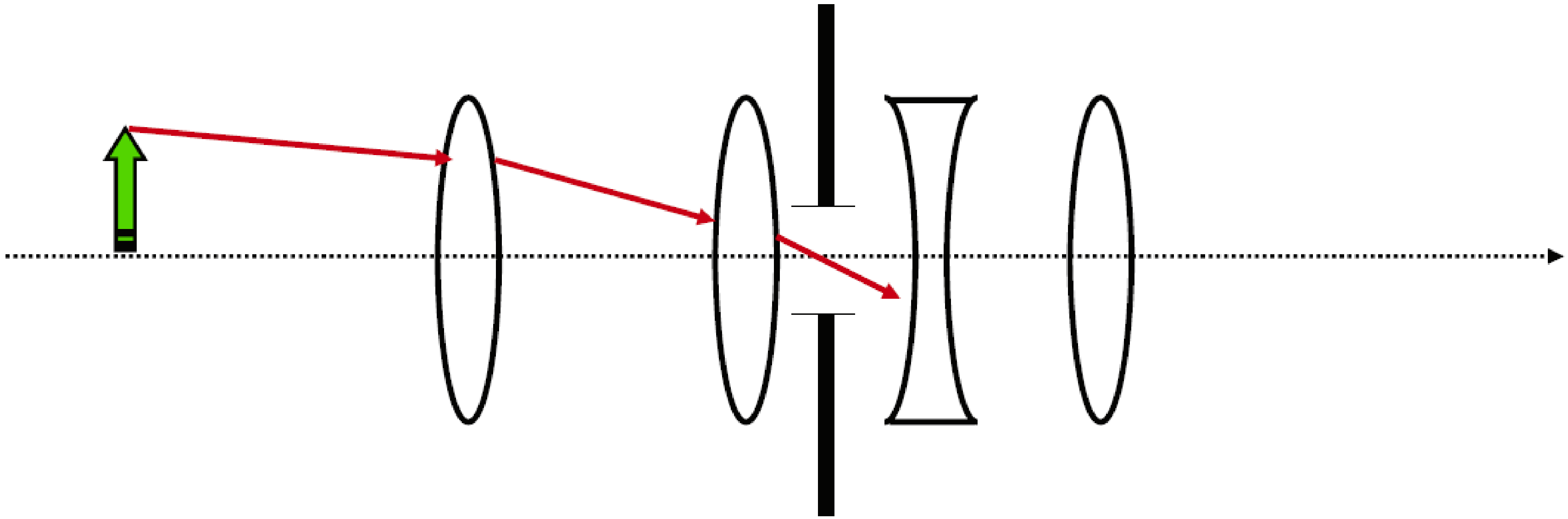
$$\frac{1}{s}+\frac{1}{s'}=\frac{1}{f}, \qquad m_{\text{lateral}}=-\frac{s'}{s} \qquad \text{hold, where } f = (\text{EFL})$$

EFL: Effective focal length

Entrance and Exit Pupil

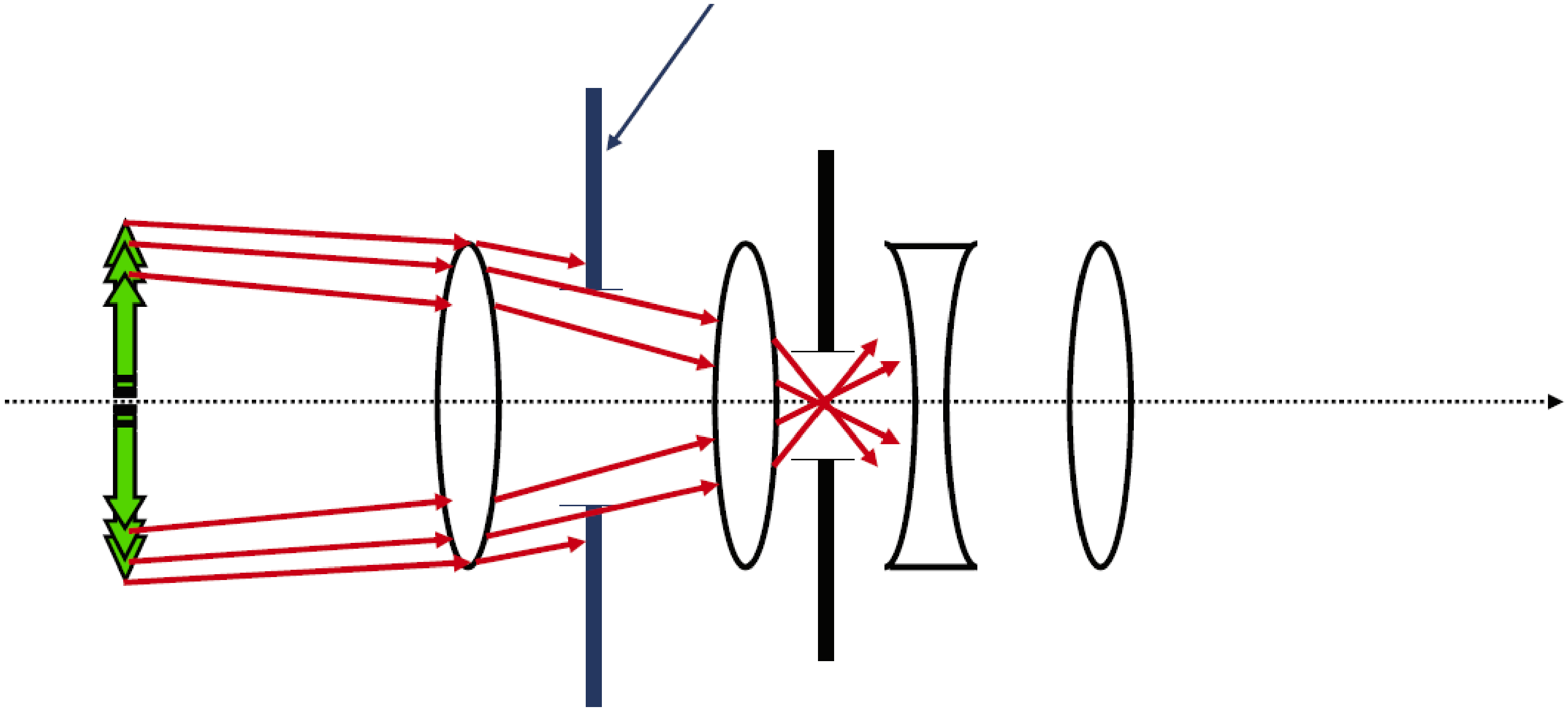


The Chief Ray



Starts from off-axis object,
Goes through the center of the Aperture

The Field Stop



Limits the angular acceptance
of Chief Rays

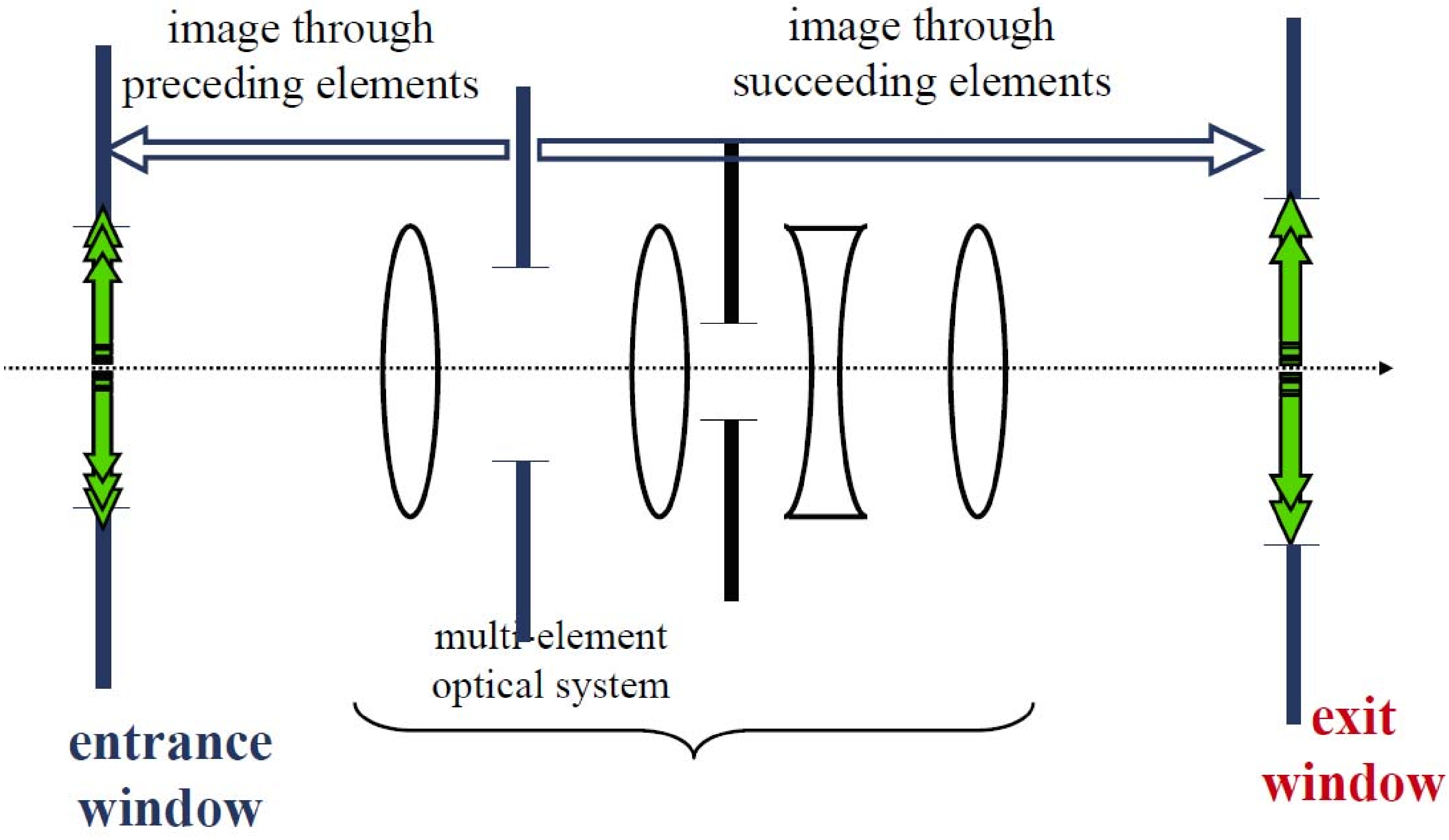
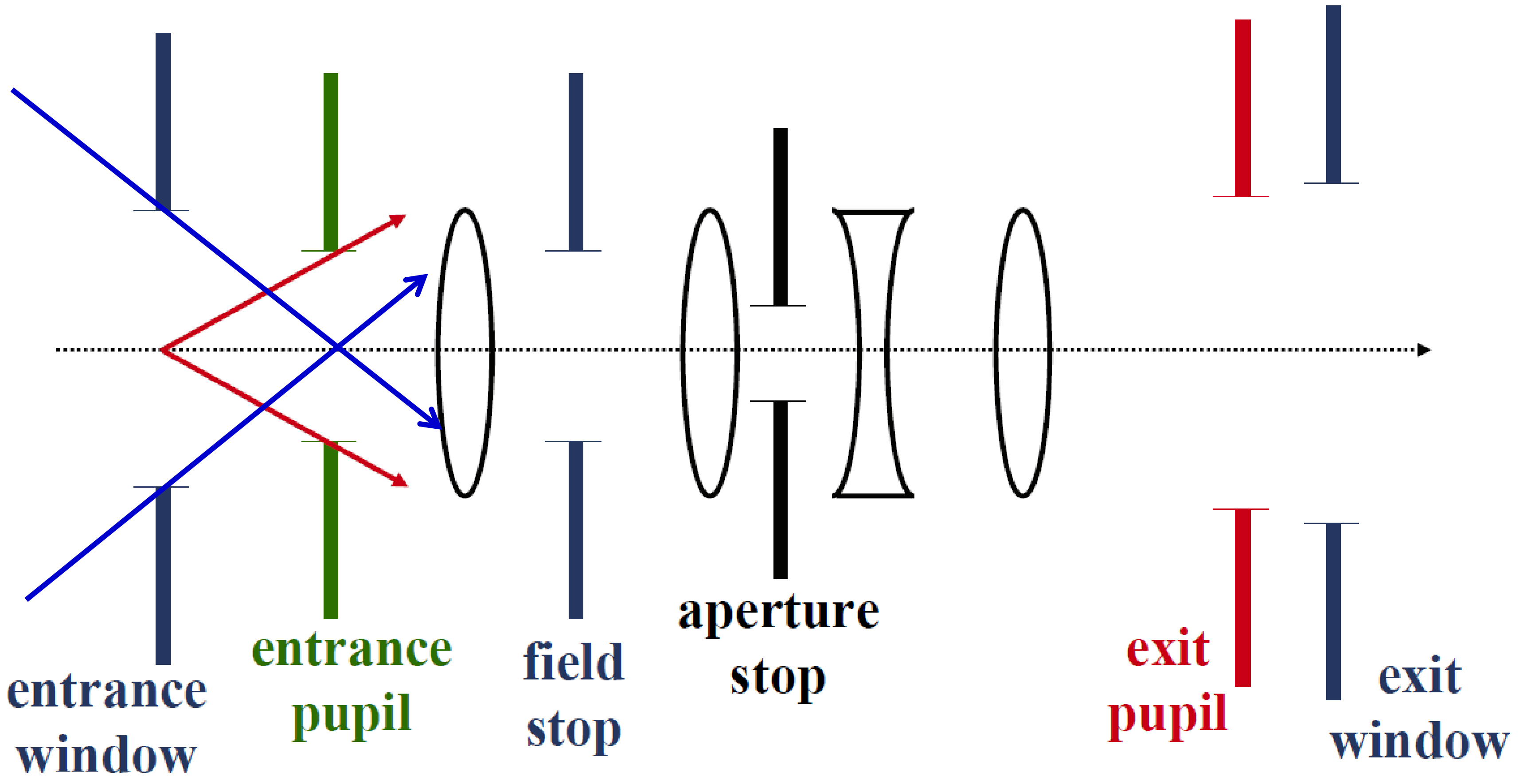
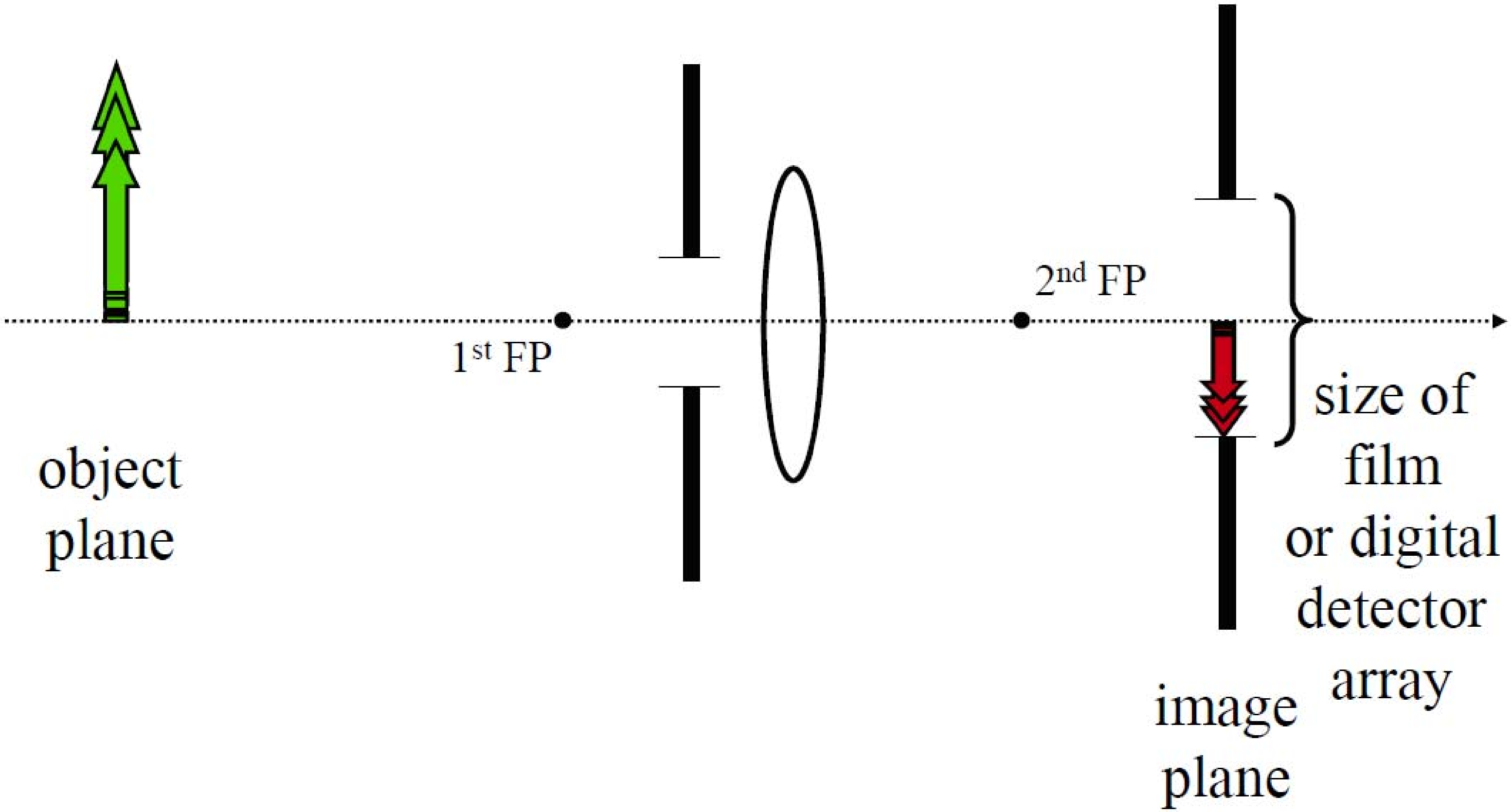


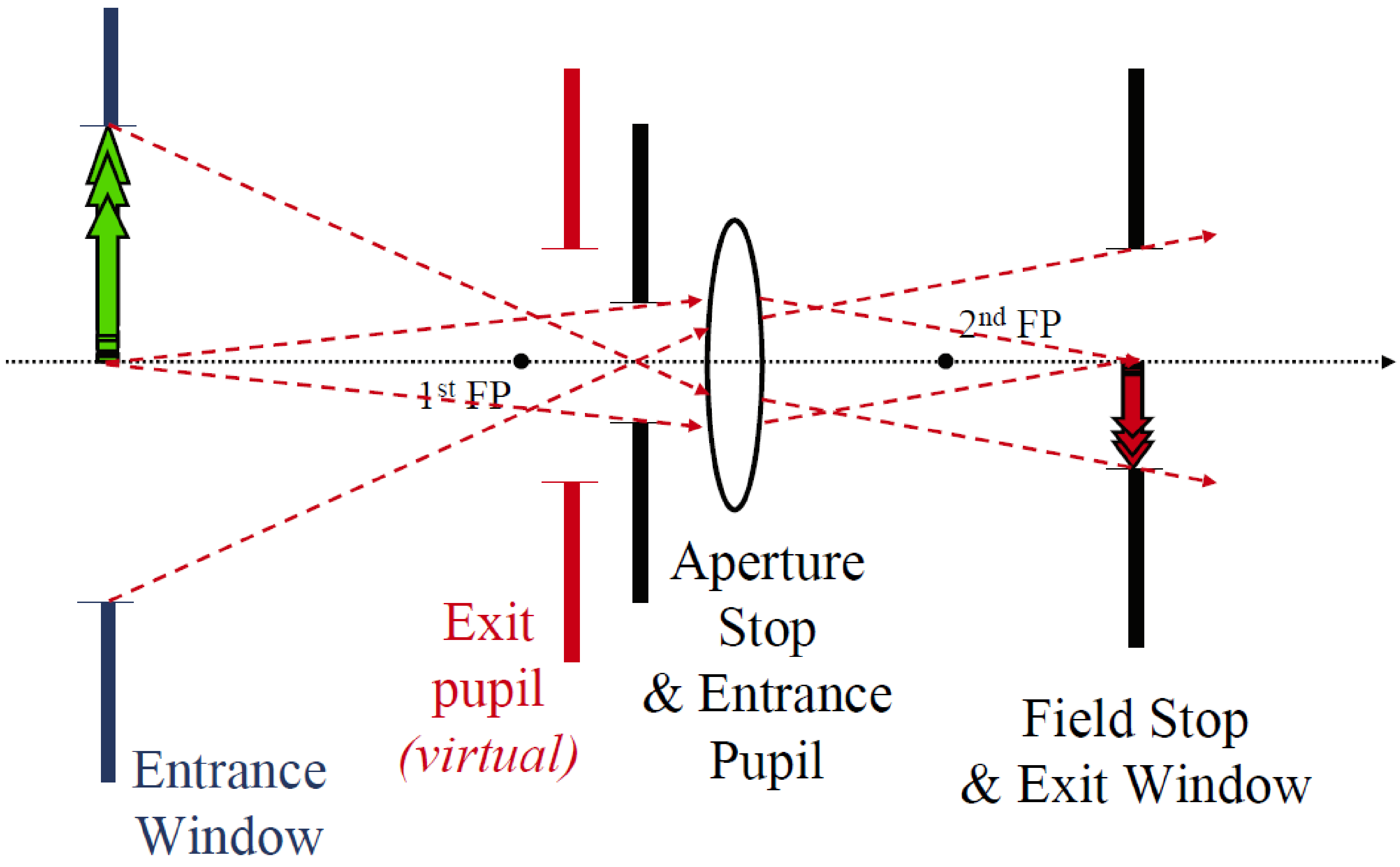
image through
preceding elements
image through
succeeding elements
multi-element
optical system
entrance
window
exit
window

All together



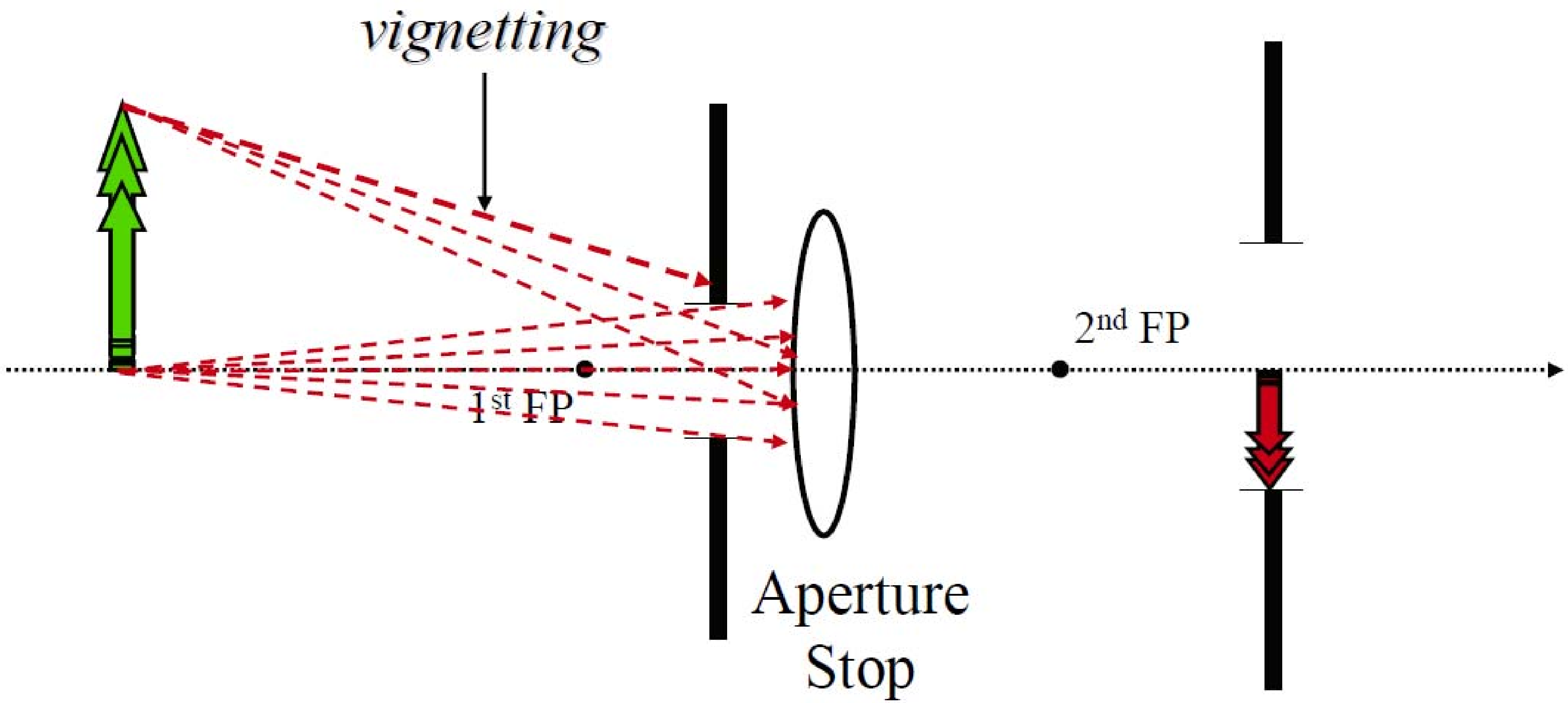
Example: Single Lens Camera



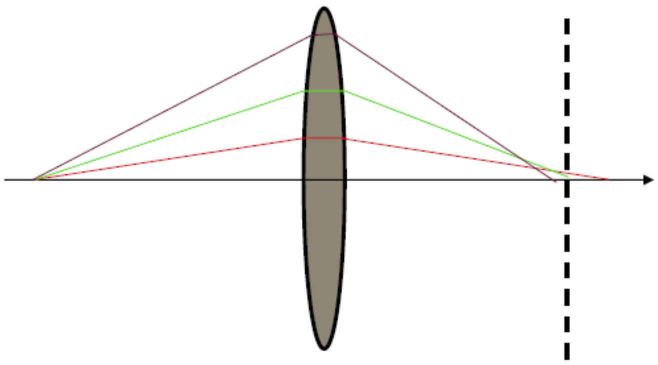


1st FP
2nd FP
Entrance Window
Exit pupil (virtual)
Aperture Stop & Entrance Pupil
Field Stop & Exit Window

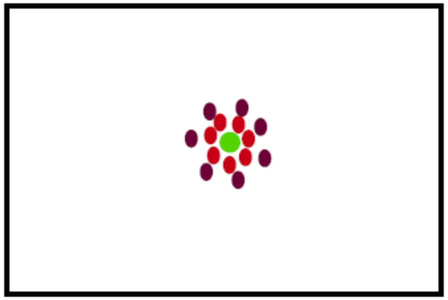
Vignetting



Ray Tracing



Exact ray-tracing



ray scatter diagram (⇔ defocus)

•Databases of common lenses and elements
•Simulate aberrations and ray scatter diagrams for various points along the field of the system (PSF, point spread function)
•Standard optical designs (e.g. achromatic doublet)

•Permit optimization of design parameters (e.g. curvature of a particular surface or distance between two surfaces) *vs designated functional requirements (e.g. field curvature and astigmatism coefficients)*

•Also account for diffraction by calculating the at different points along the field modulation transfer function (MTF)

Vendors for Optics, Optical Design Software

Optical design

–Code V

–**Oslo → OSLO EDU**
http://www.lambdares.com/education/oslo_edu/

–Zemax

Optics & opto-mechanics

–Newport / New Focus

–Opto-Sigma

–Thorlabs

–Edmund Optics

Transfer Matrix Method (not covered yet)

The ray transfer matrix method (ABCD matrix) is a commonly used method to deal with complicate multiple optical elements , see, for example:

http://en.wikipedia.org/wiki/Ray_transfer_matrix_analysis

We may cover this method if time permitted.

Aberrations

- Chromatic
  - is due to the fact that the refractive index of lenses, etc. varies with wavelength; therefore, focal lengths, imaging conditions, etc. are wavelength-dependent
- Geometrical
  - are due to the deviation of non-paraxial rays from the approximations we have used so far to derive focal lengths, imaging conditions, etc.; therefore, rays going through imaging systems typically do not focus perfectly but instead scatter around the "paraxial" (or "Gaussian") focus

Spherical Aberration

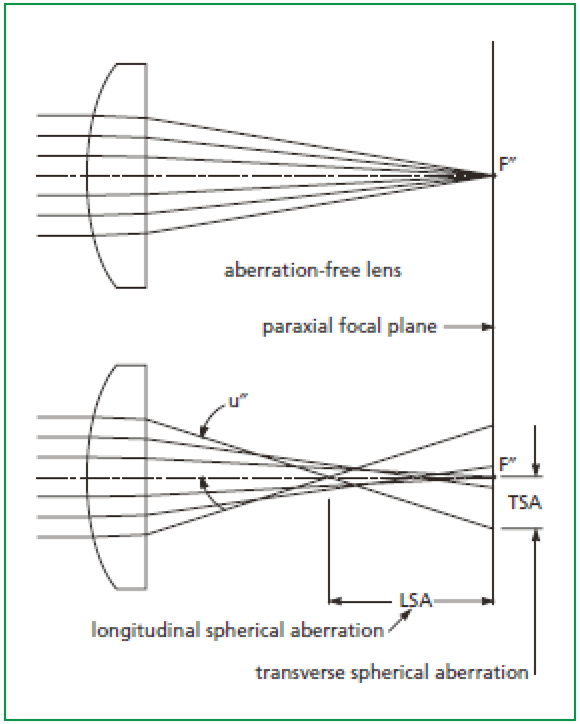
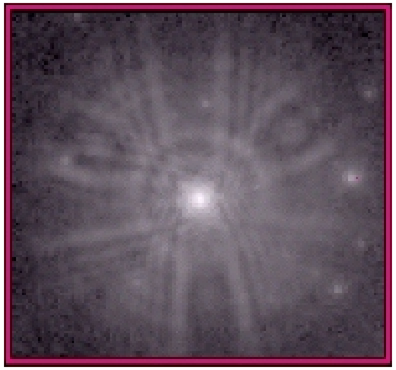
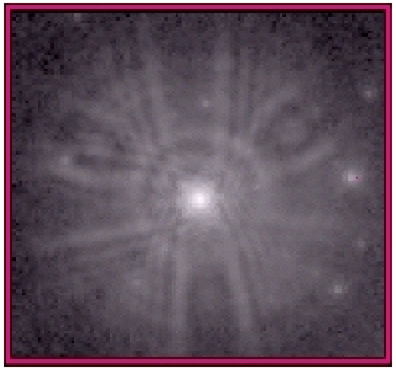
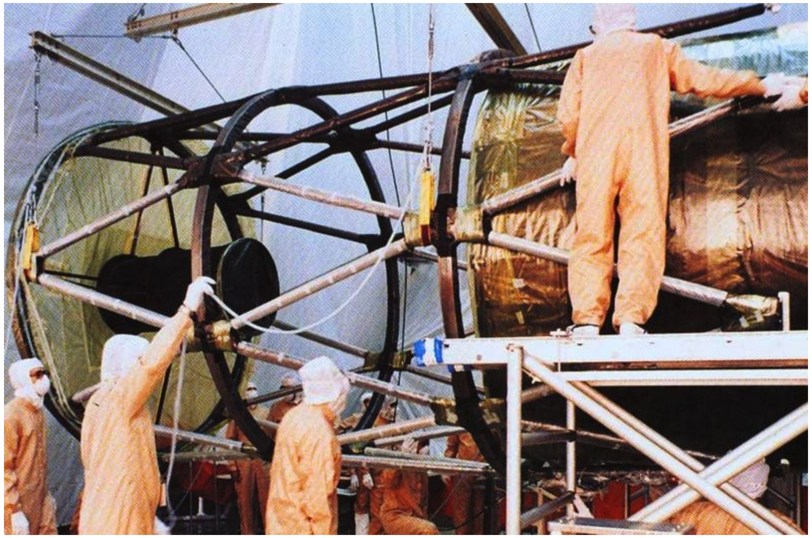


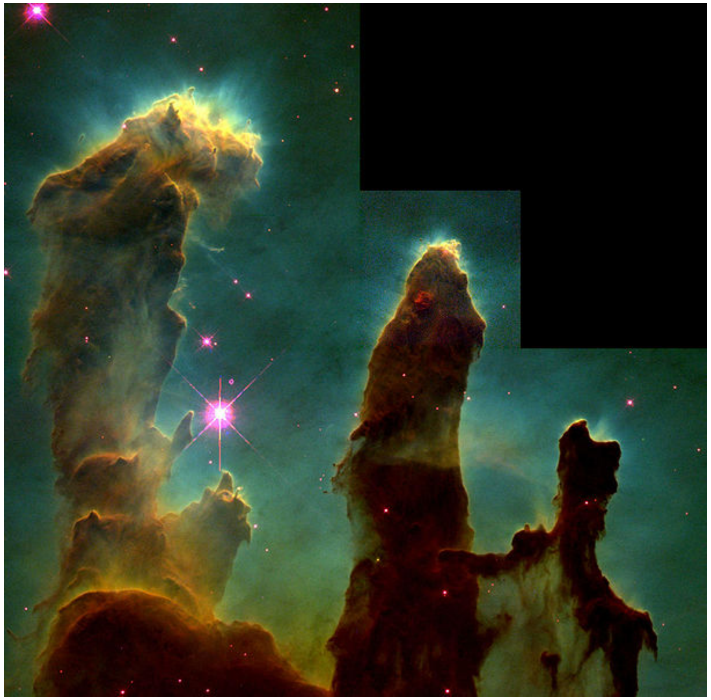
Figure 1.15 **Spherical aberration of a plano-convex lens**



Spherical Aberration - example

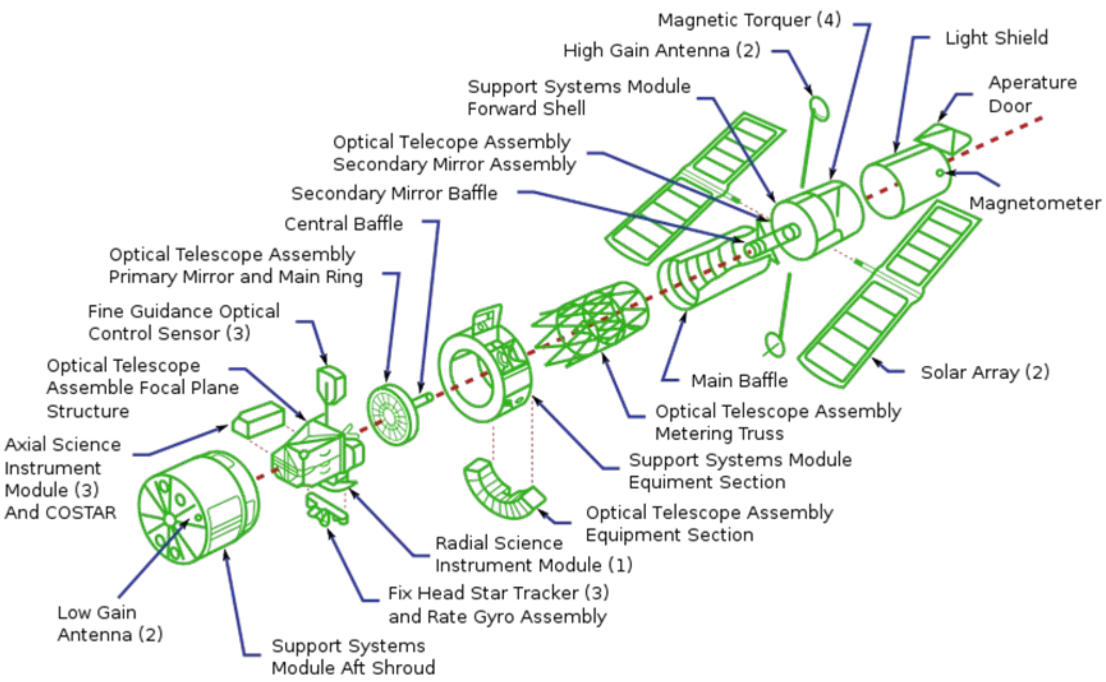






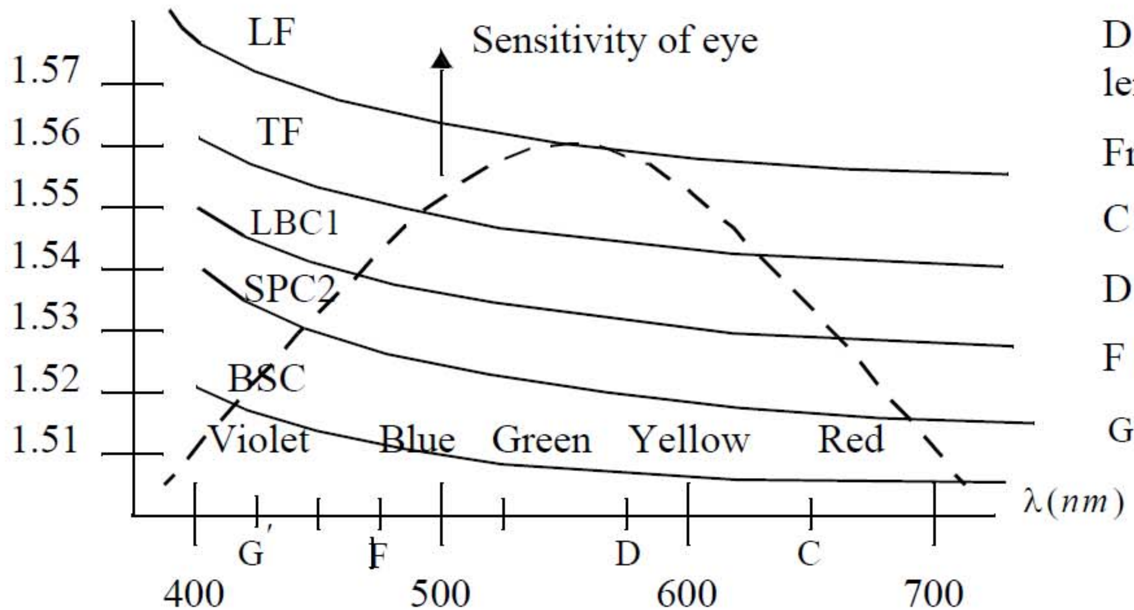
Stars forming in the Eagle Nebula
(the most famous image form …)

Hubble Telescope



it was probably the most precisely figured mirror ever made, with variations from the prescribed curve of only 10 nanometers, it was too flat at the edges by about 2.2 microns.
Source: wikipedia

Chromatic Aberration

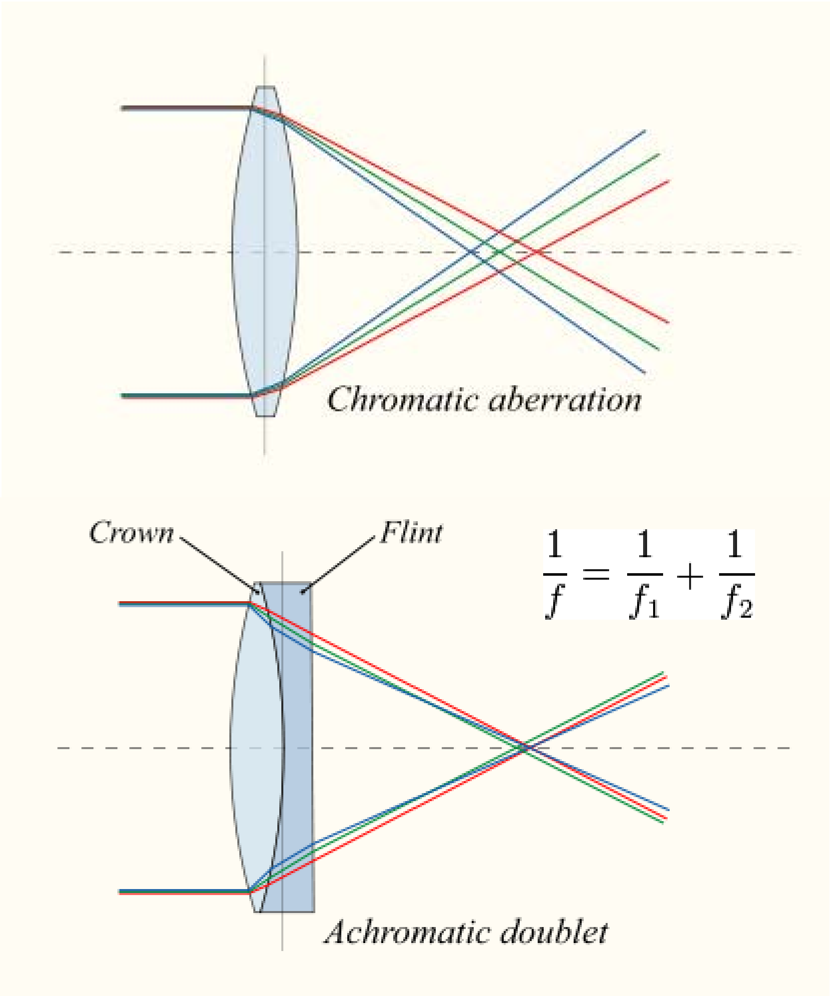


Different glasses for use in lenses.

Fraunhofer designations.

C H	656.3 nm
D Na	589.2
F H	486.1
G' H	434.0

Chromatic Aberration



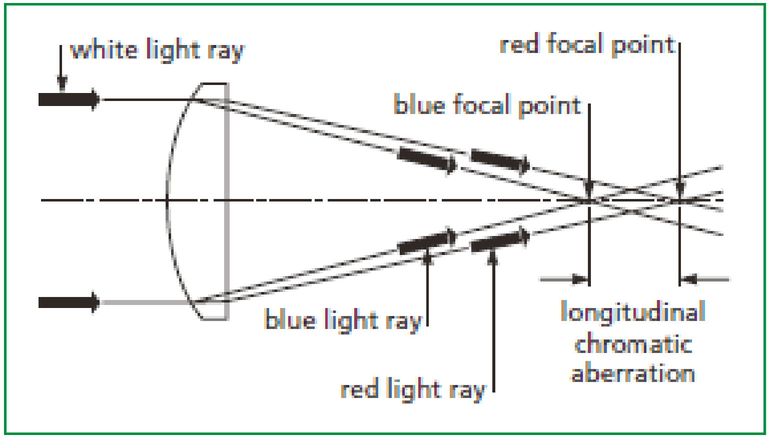


Figure 1.21 **Longitudinal chromatic aberration**

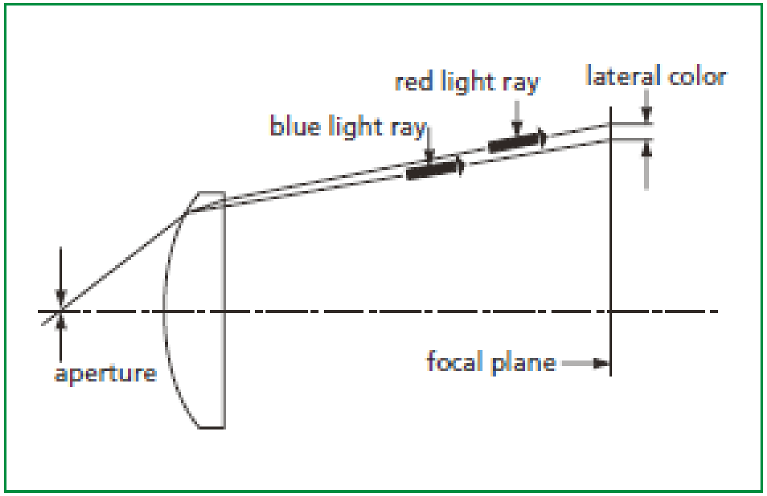


Figure 1.22 **Lateral color**

Melles Griot "Fundamental Optics"

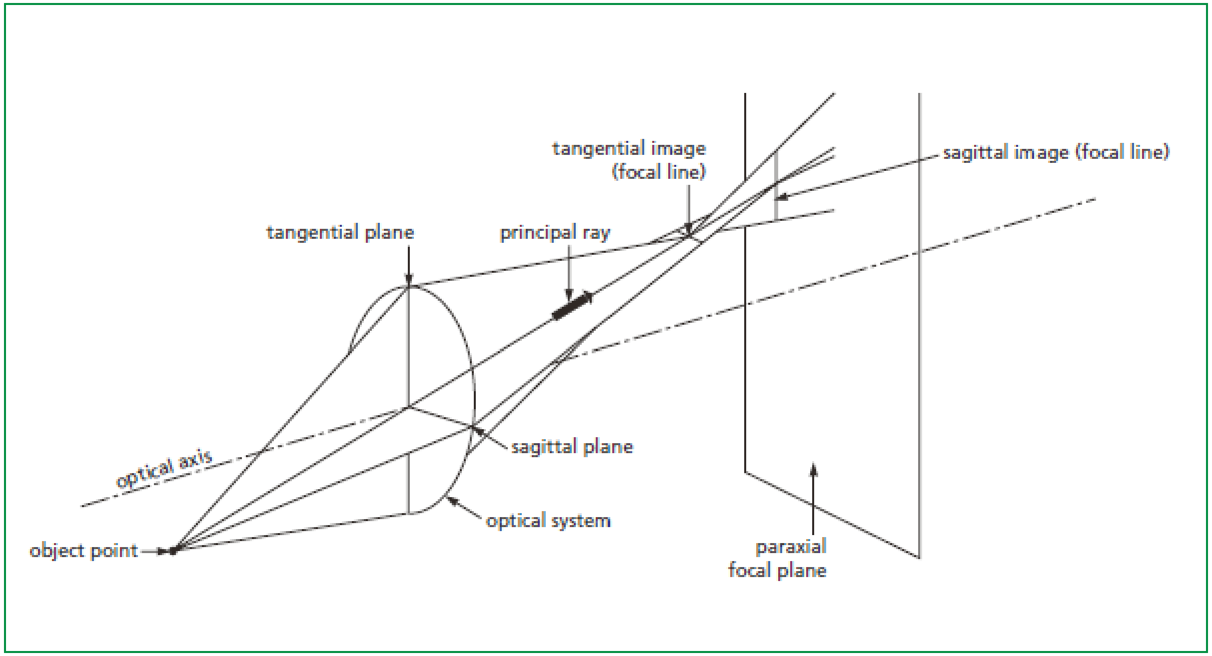


Figure 1.16 **Astigmatism represented by sectional views**

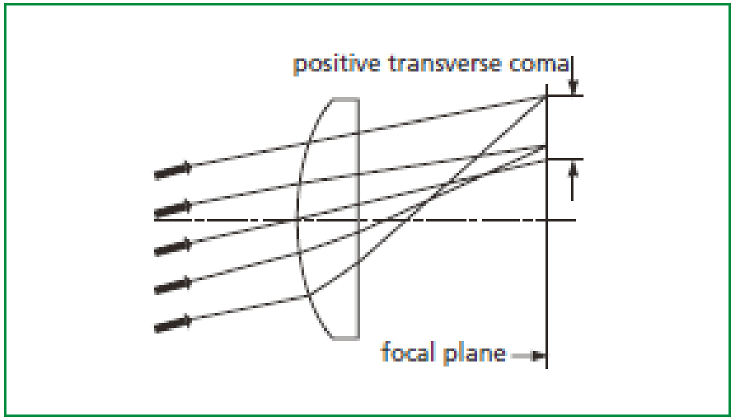
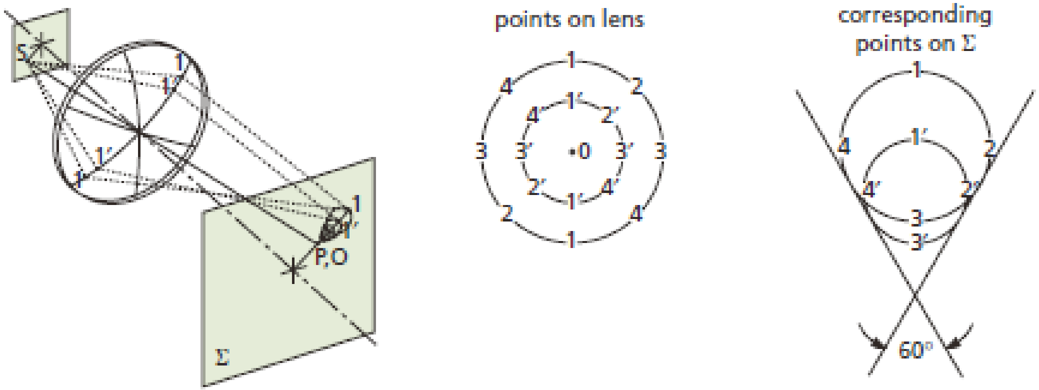


Figure 1.18 **Positive transverse coma**



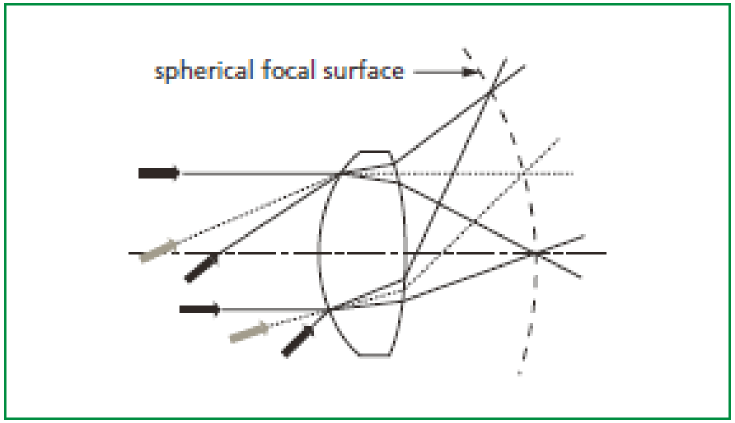


Figure 1.19 **Field curvature**

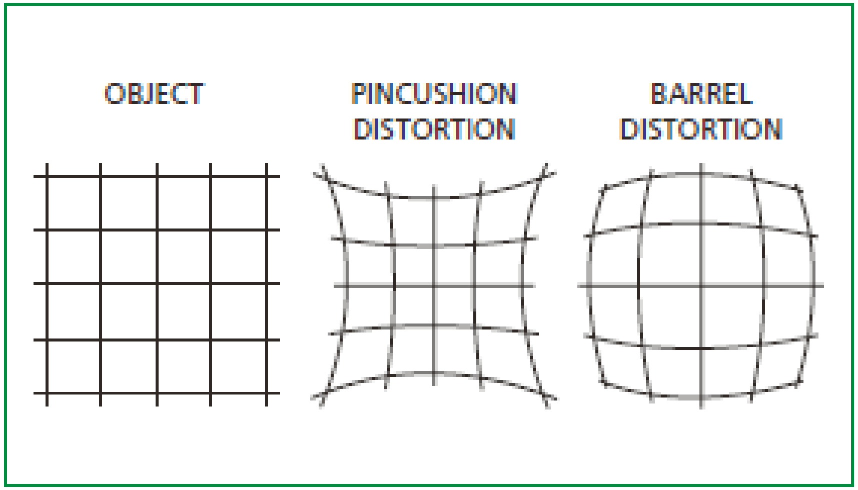


Figure 1.20 **Pincushion and barrel distortion**