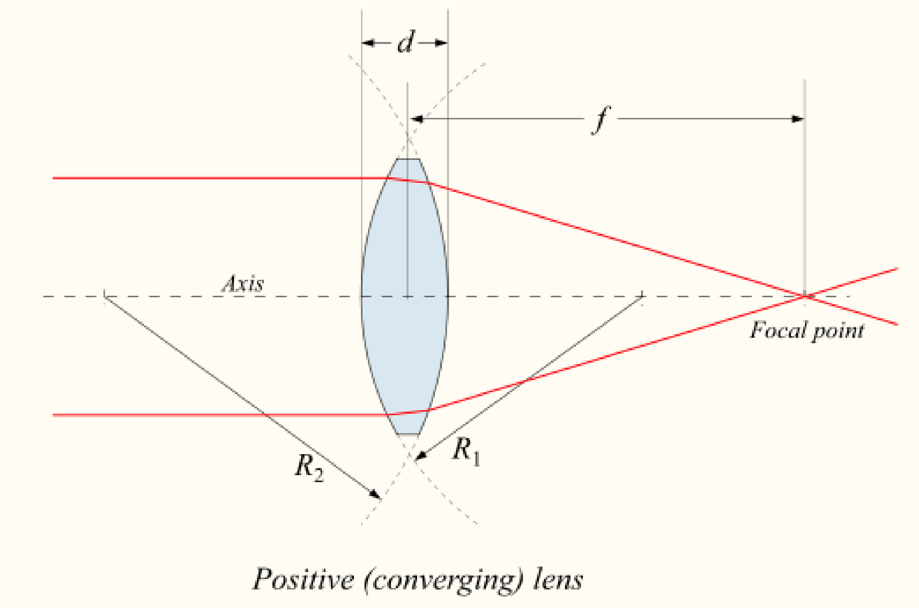
Summary: Thin Lens



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

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

$$x_0 x_i = f^2$$

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

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

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

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

"Sign" convention is of paramount importance!
(See Hecht Table 5.1, Fig. 5.12, Table 5.2)

Summary : Real and Virtual Images

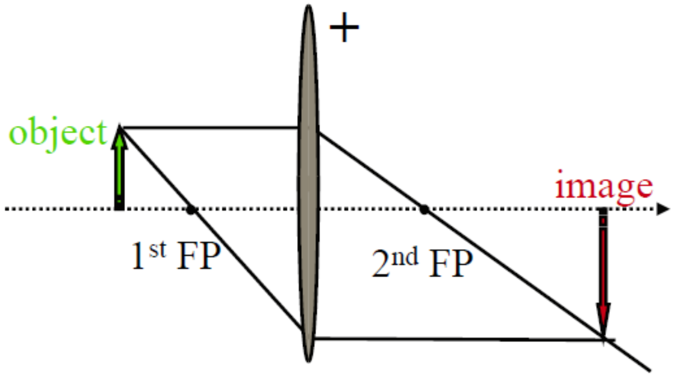


image: real & inverted; $M_T<0$

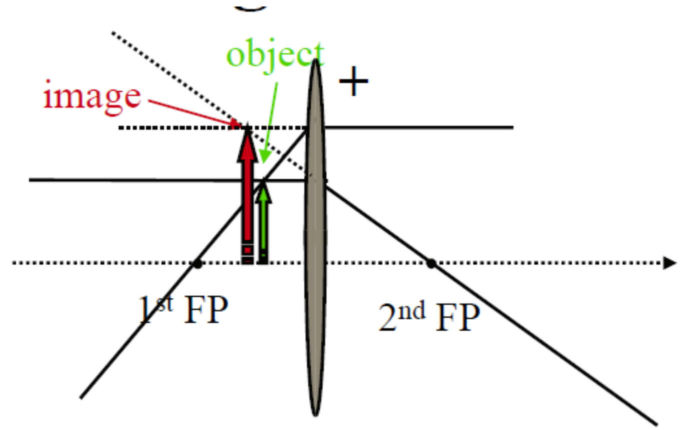


image: virtual & erect; $M_T>1$

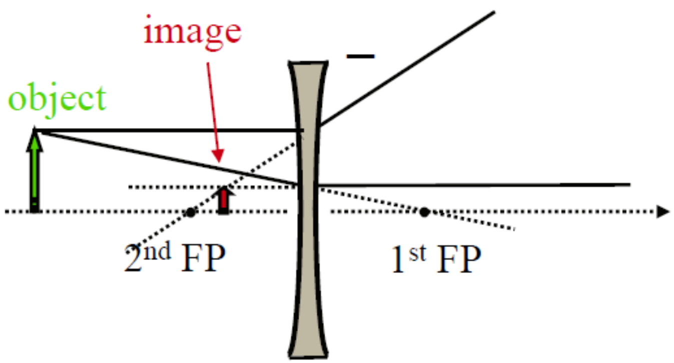


image: virtual & erect; $0<M_T<1$

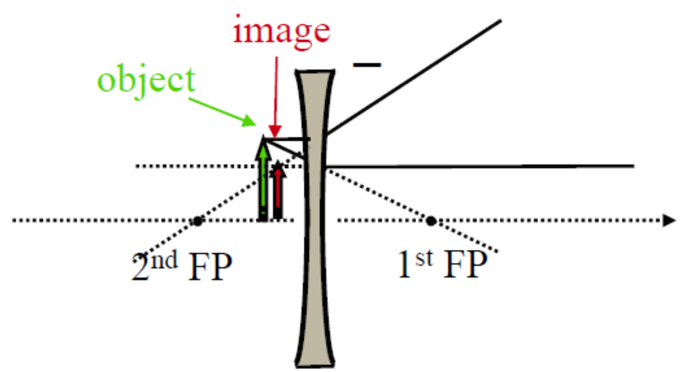
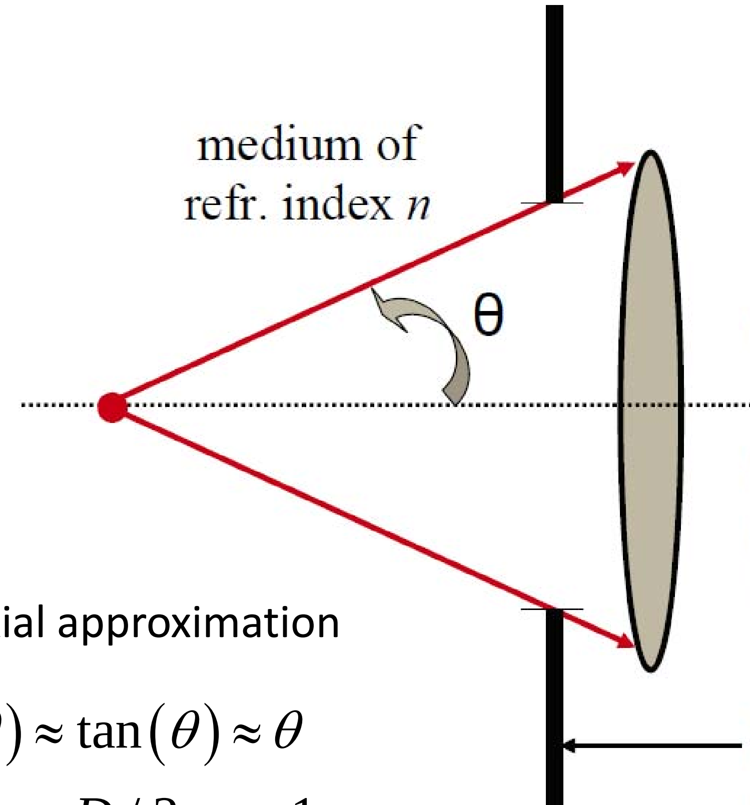


image: virtual & erect; $0<M_T<1$

See also Hecht Table 5.3

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

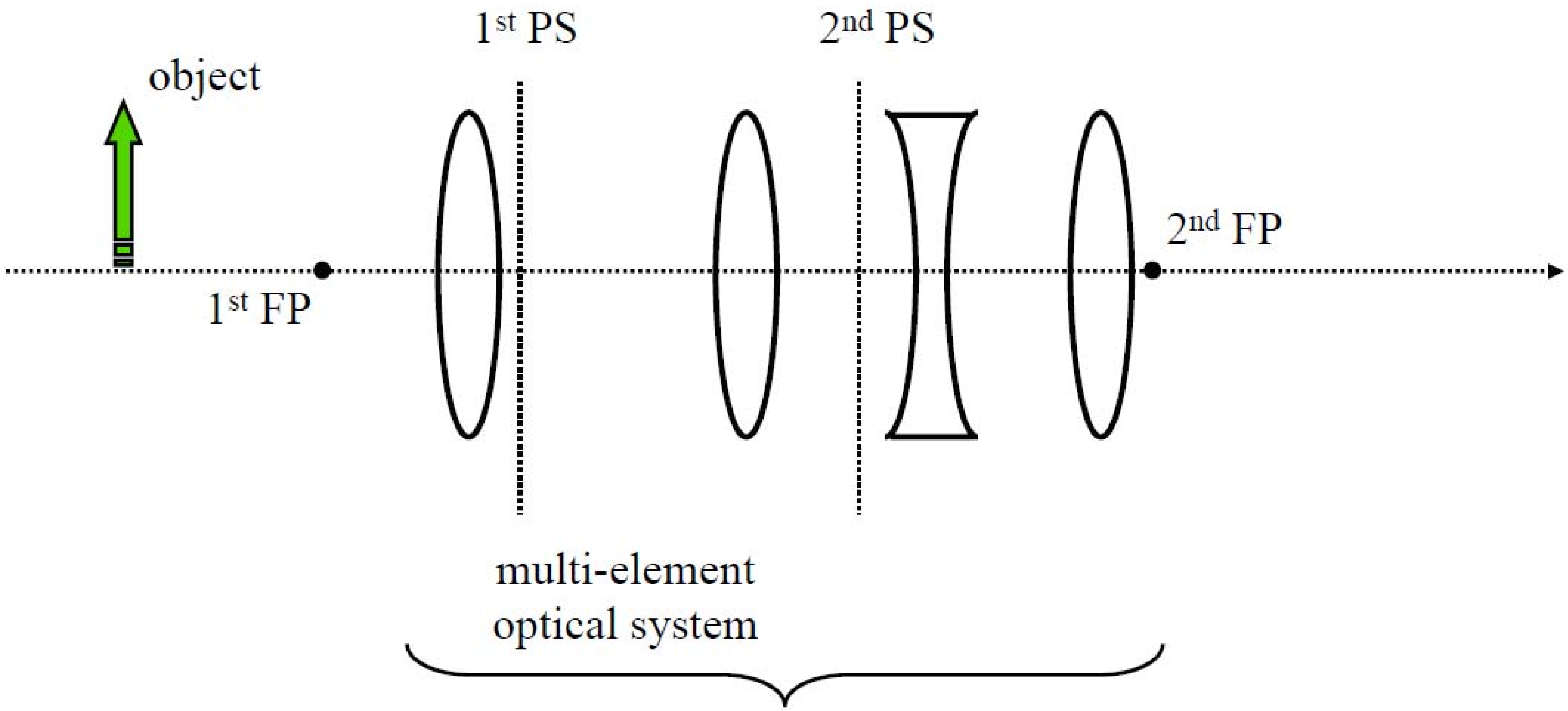
Paraxial approximation

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

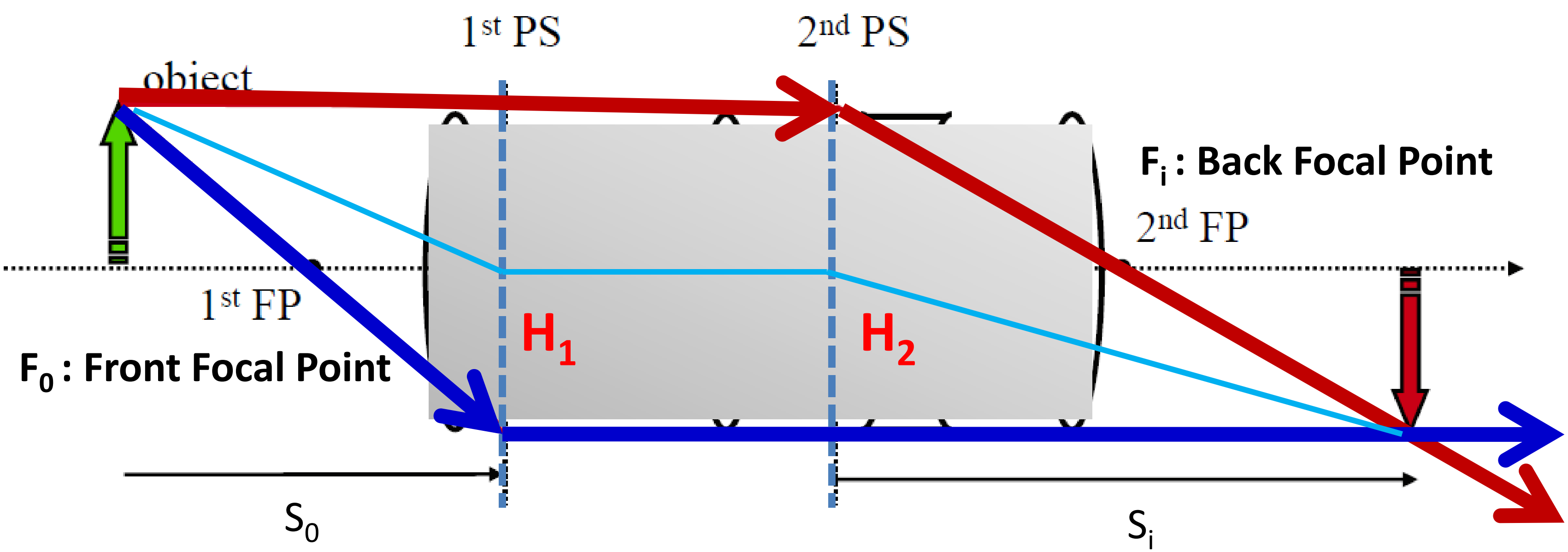
$$\rightarrow NA = \frac{D/2}{f} = \frac{1}{2f/\#}$$

We will learn that
the spatial resolution limit due to diffraction ≈ 1.22×f λ /D=0.61×λ/NA [Rayleigh Criterion].

Multiple Elements



Principle Planes for Thick Lenses and Lens Systems

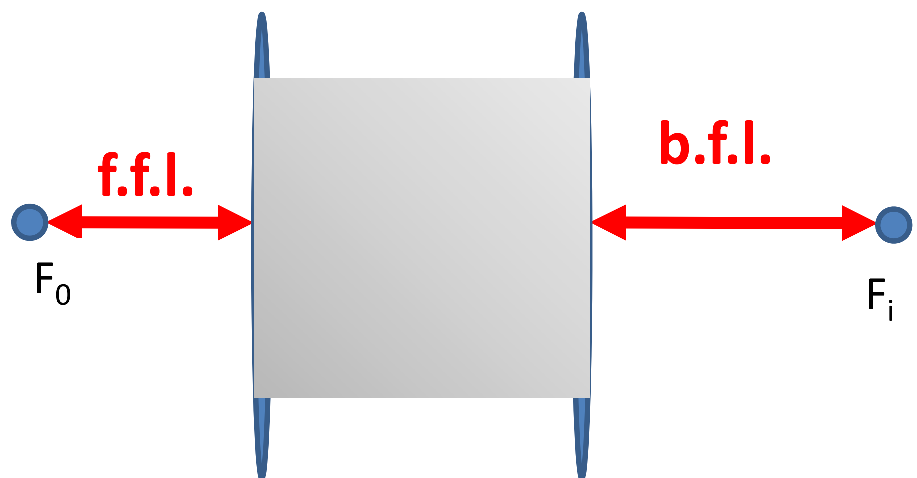


$$\frac{1}{f} = \frac{1}{s_0} + \frac{1}{s_i}$$

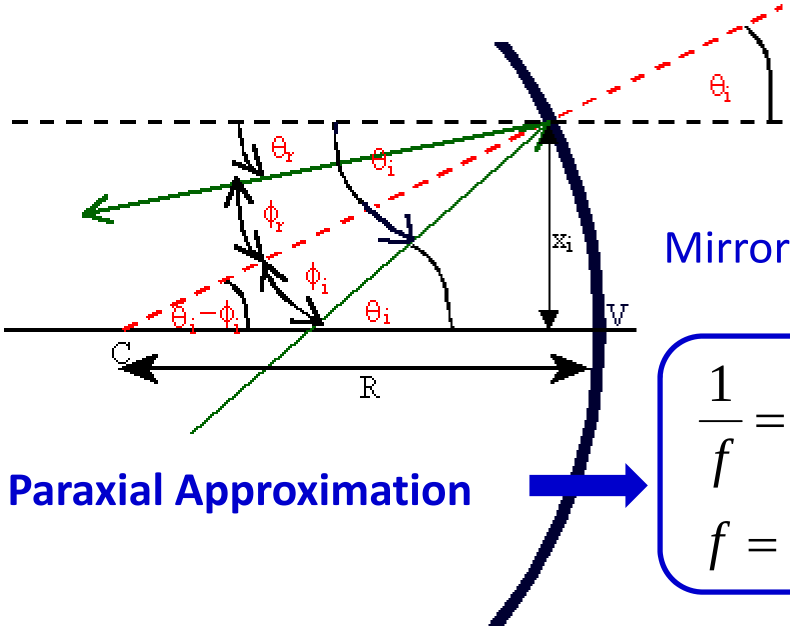
$$x_0 x_i = f^2$$

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

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



Spherical Mirror



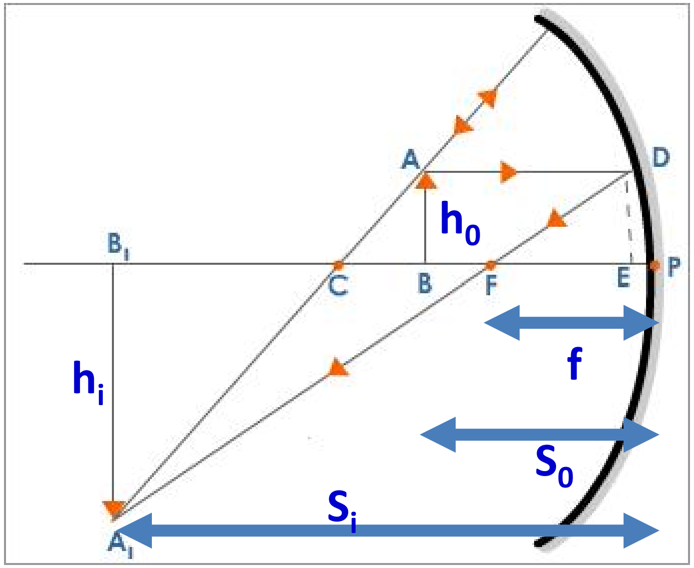
Mirror Formula

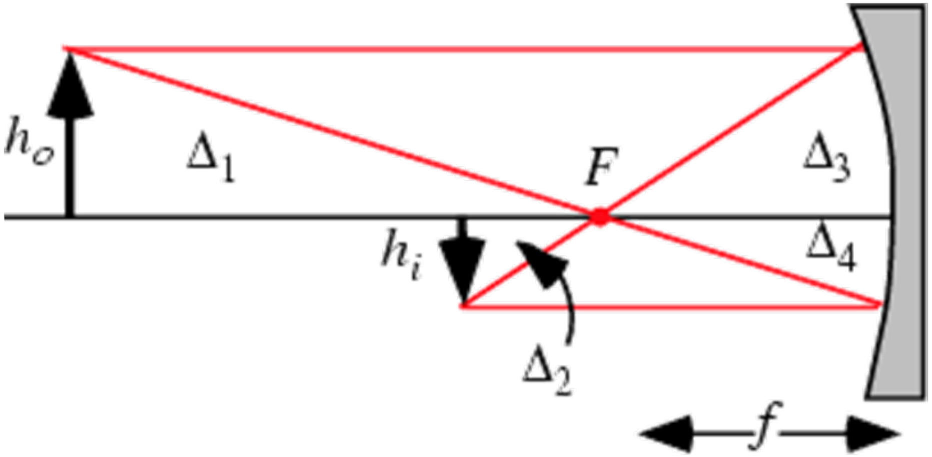
Paraxial Approximation

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

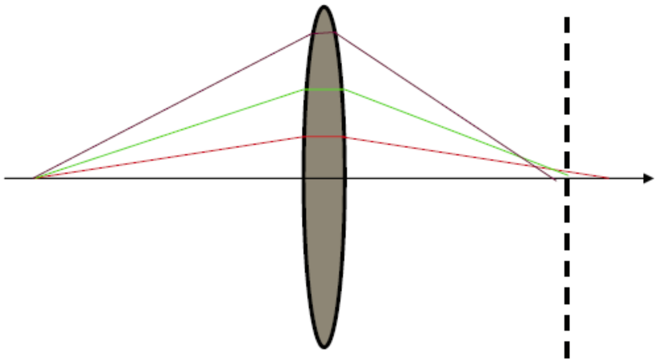
$$f = R/2$$

See Hecht Table 5.4 for sign convention

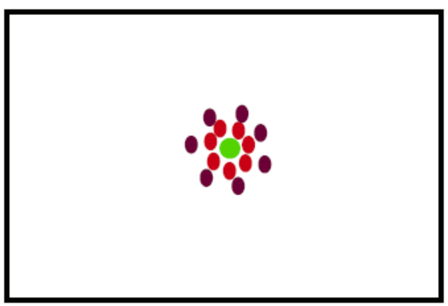




When Paraxial Approximation Fails: Ray Tracing + Diffraction



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)

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

Refractive index n is dispersive!

$$n(\omega)$$

- Geometrical (monochromatic)
  - 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

Deteriorate the image:
- Spherical aberration
- Coma
- Astigmatism

Deform the image:
- Field curvature
- Distortion

Departures from the idealized conditions of Gaussian Optics (e.g. paraxial regimes).

Spherical Aberration

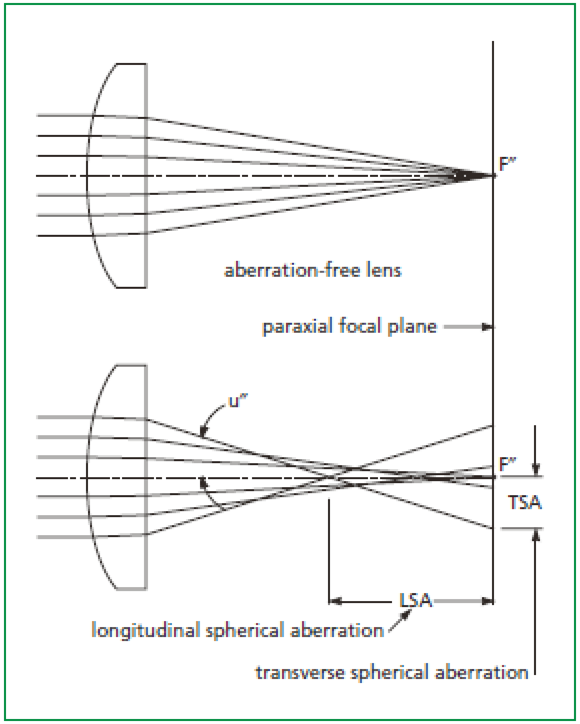
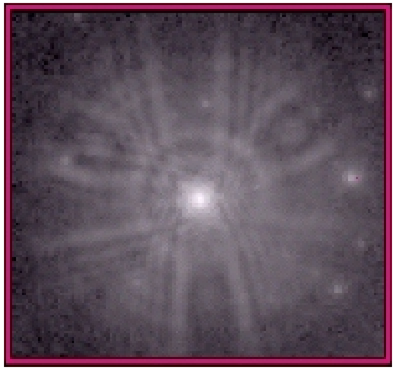
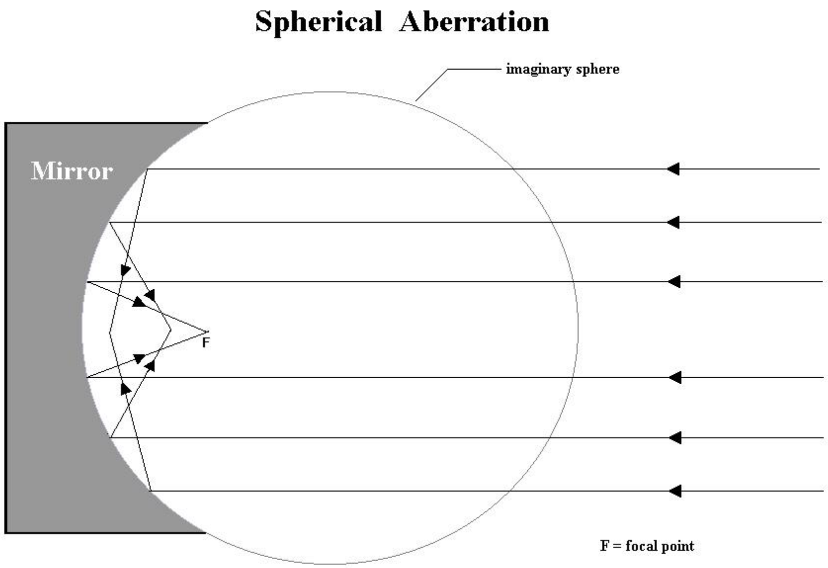
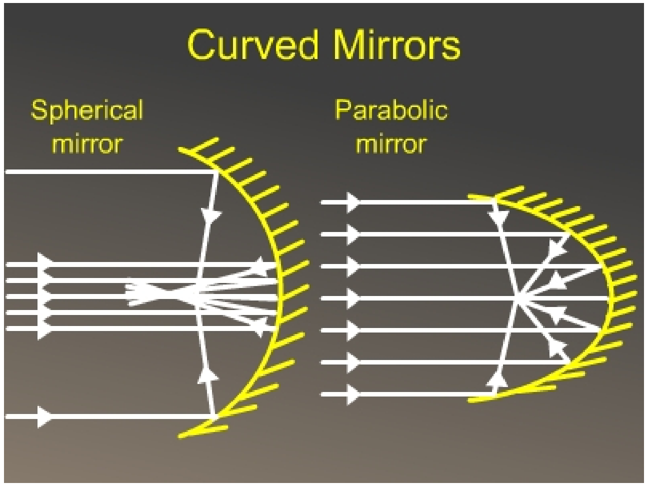


Figure 1.15 **Spherical aberration of a plano-convex lens**



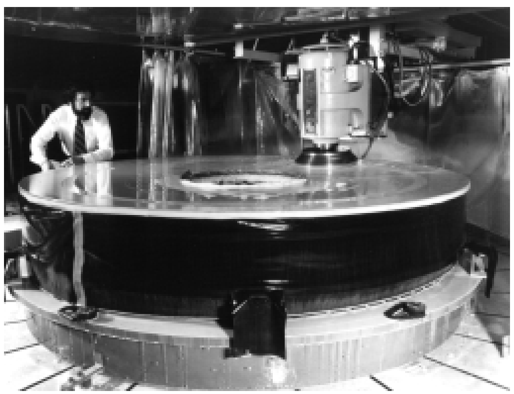


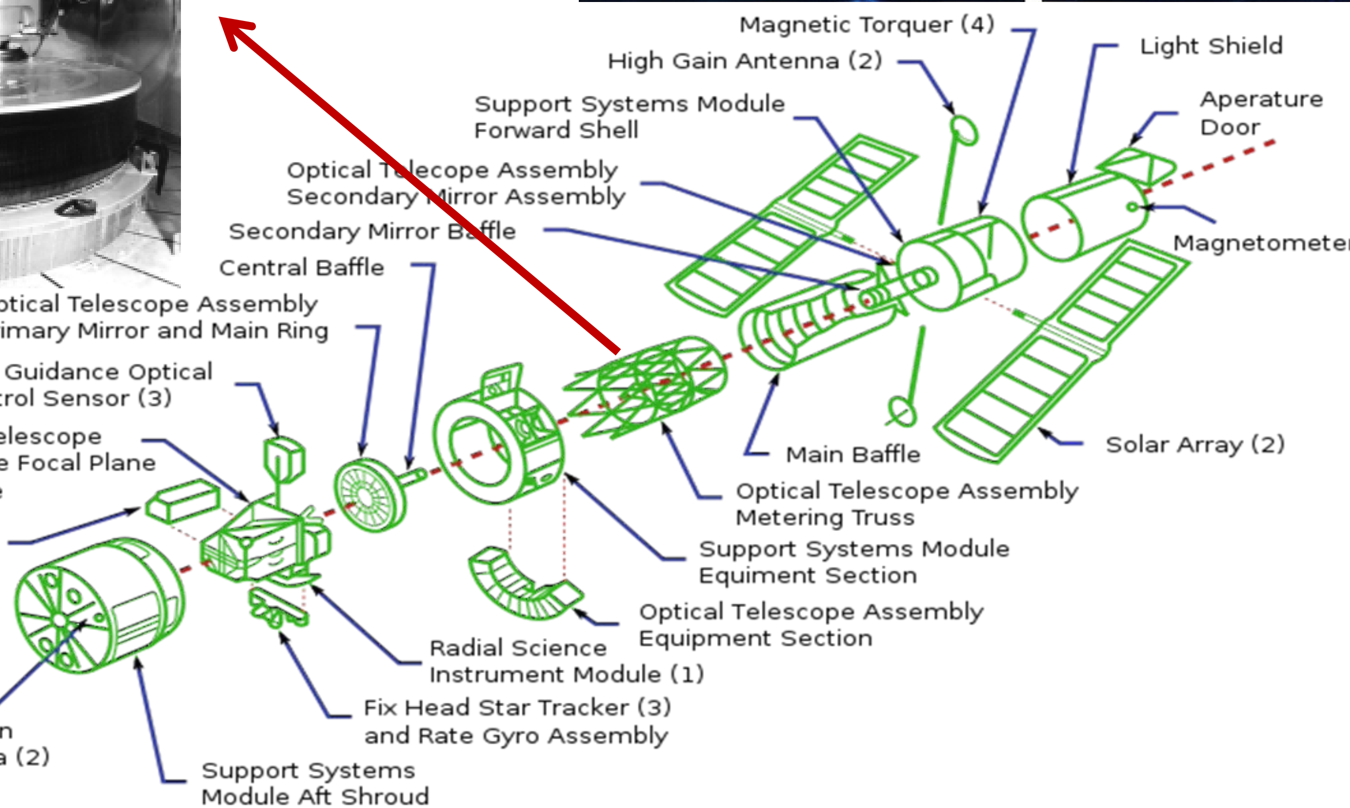


Solution I: Aspheric Mirrors or Lenses

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





Lens Shape

Solution II: Chose a proper shape of a singlet lens for a given image-object distance.

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

For a given desired focal length, there is freedom to choose one of the radii for a singlet. The spherical aberration and coma depend on the particular choice, so these aberrations can be minimized by the designed form.

$$q = \frac{(R_1 + R_2)}{(R_2 - R_1)}$$

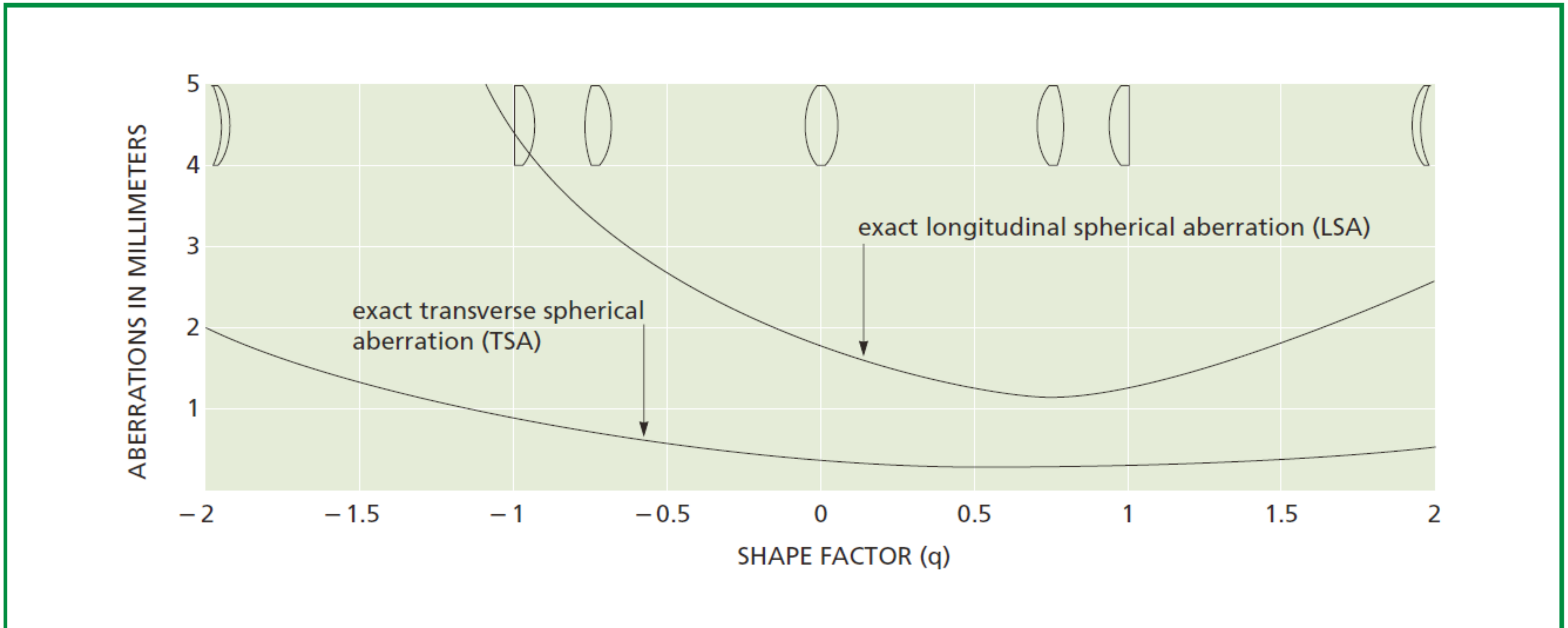
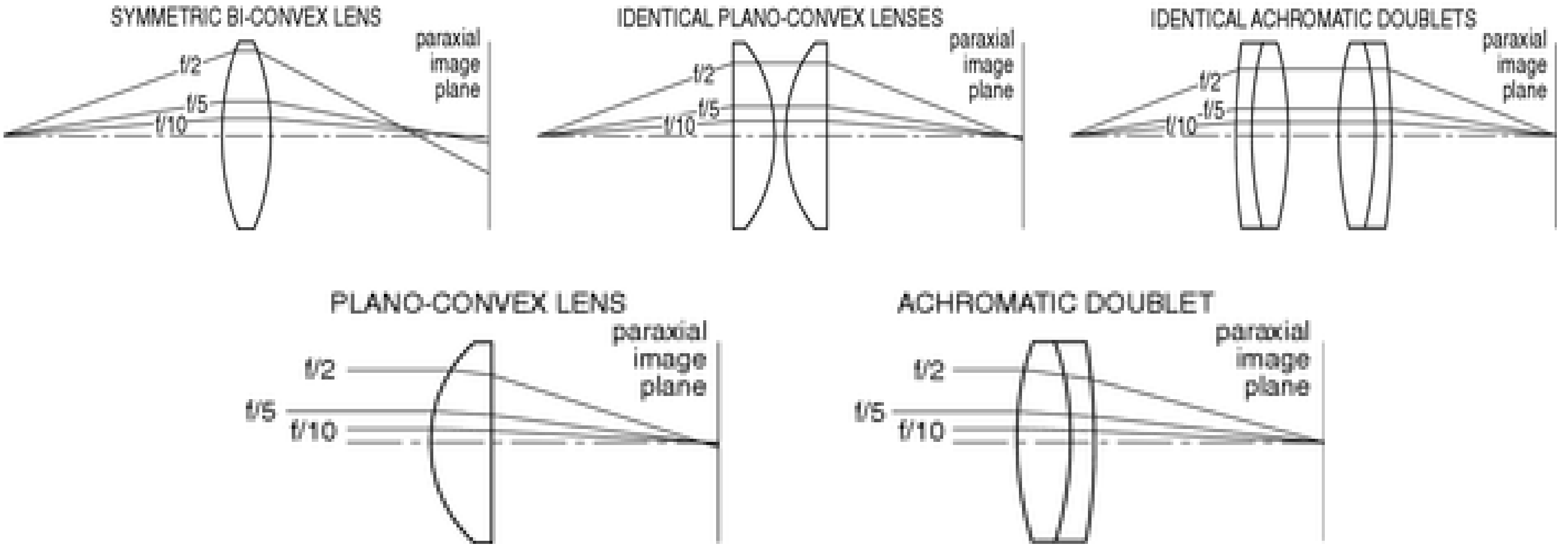


Figure 1.23 **Aberrations of positive singlets at infinite conjugate ratio as a function of shape**

Lens Selection Guide

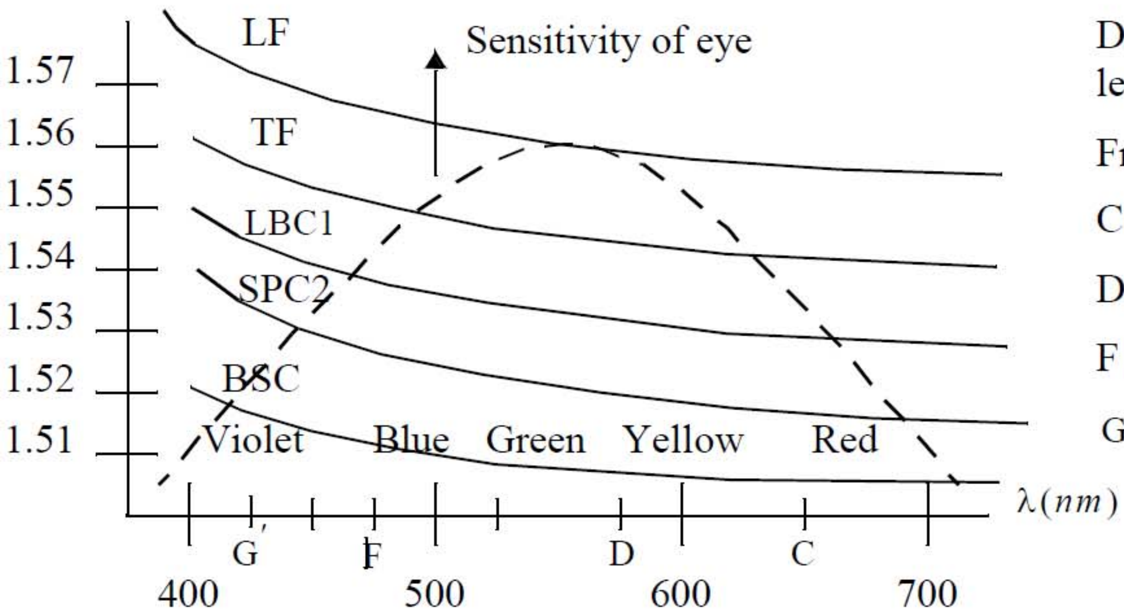


http://www.newport.com/Lens-Selection-Guide/140908/1033/catalog.aspx#

Chromatic Aberration

Hecht 6.3.2

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

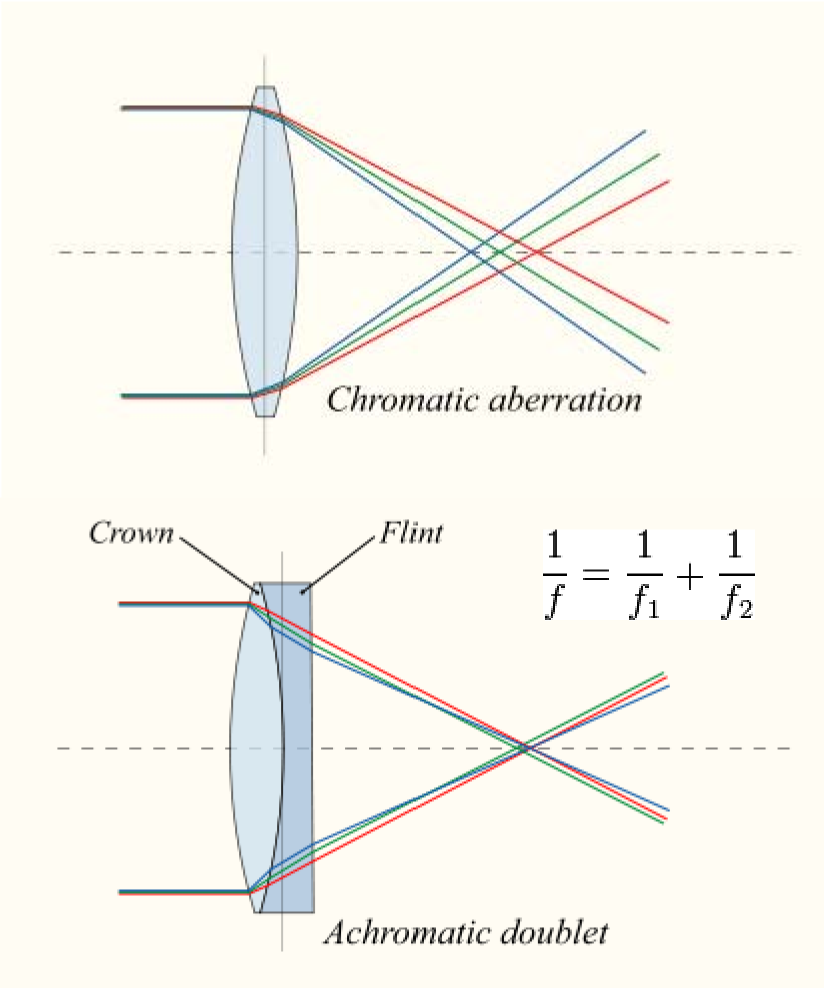


Different glasses for use in lenses.

Fraunhofer designations.

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

Chromatic Aberration



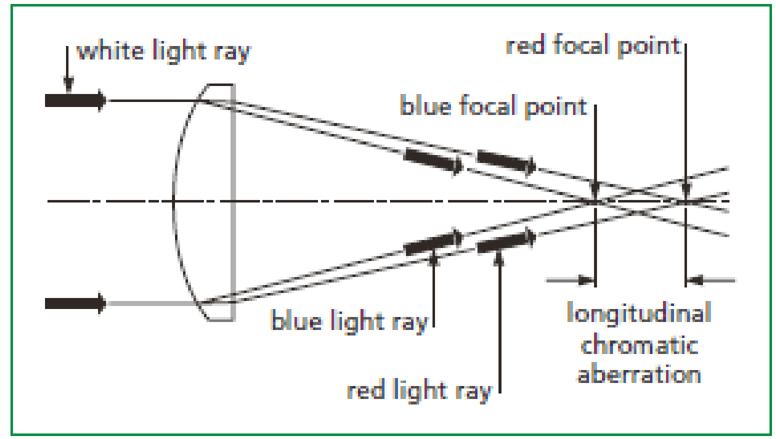


Figure 1.21 **Longitudinal chromatic aberration**

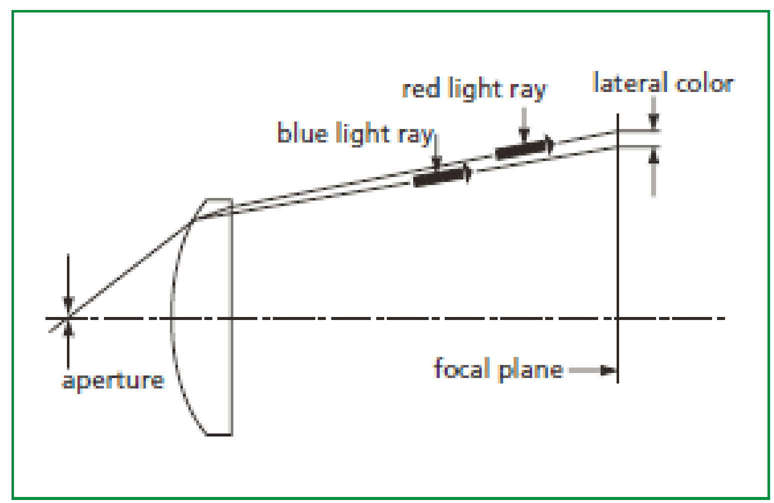


Figure 1.22 **Lateral color**

Solutions:

1. Combine lenses (achromatic doublets)
2. Use mirrors

Melles Griot “Fundamental Optics”

Astigmatism

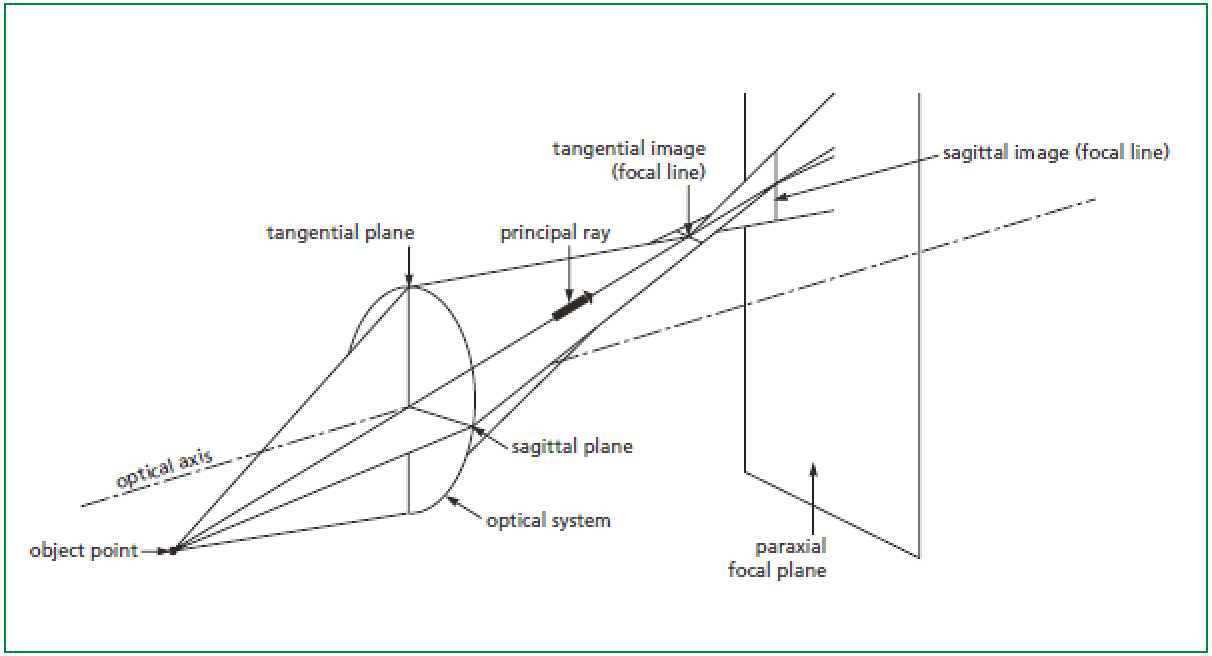


Figure 1.16 **Astigmatism represented by sectional views**

Coma and Deformation

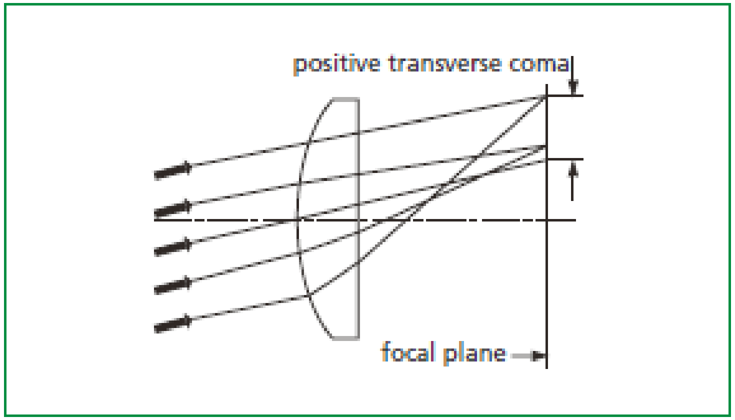
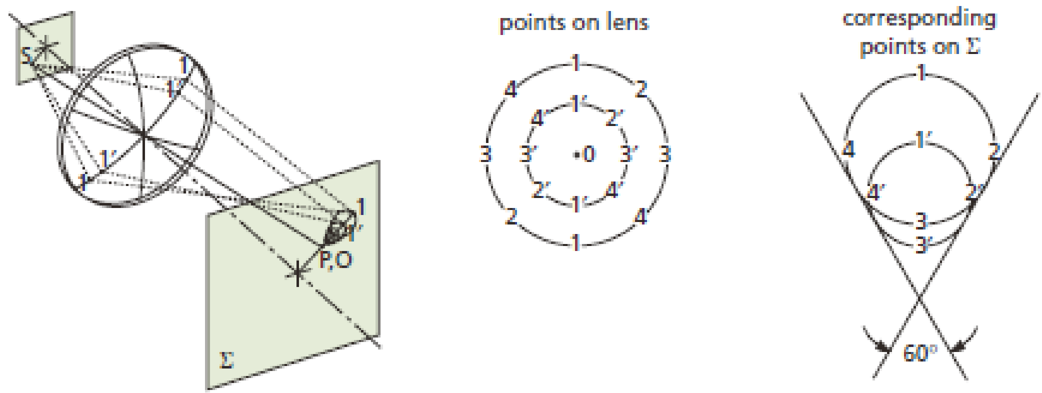


Figure 1.18 **Positive transverse coma**



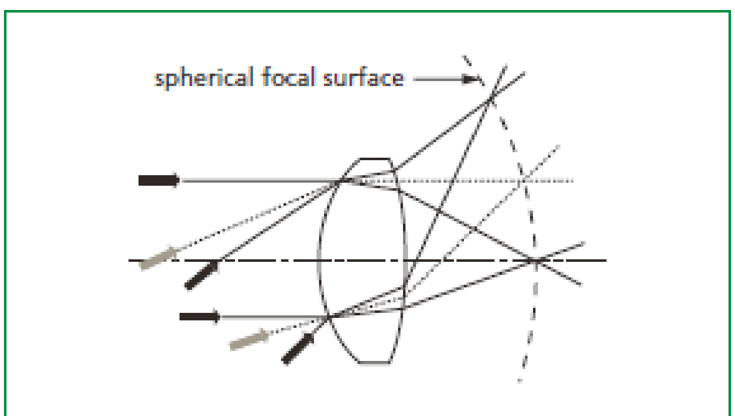


Figure 1.19 **Field curvature**

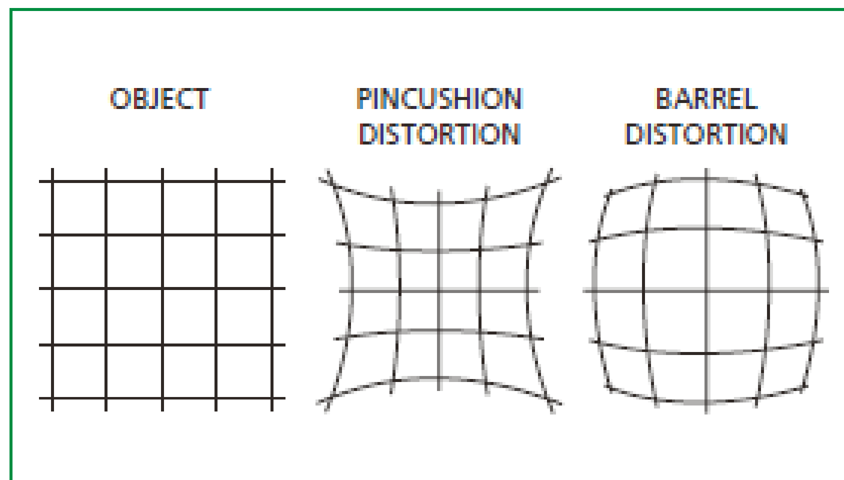
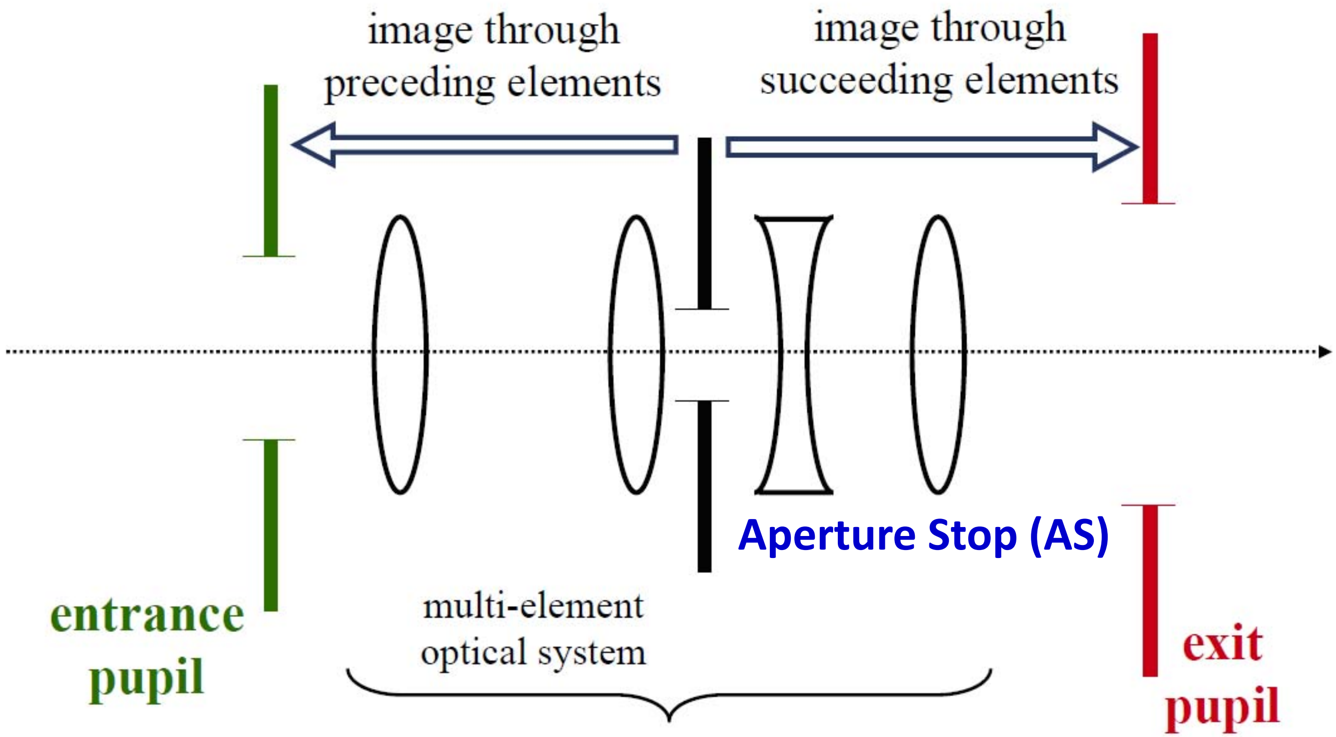


Figure 1.20 **Pincushion and barrel distortion**

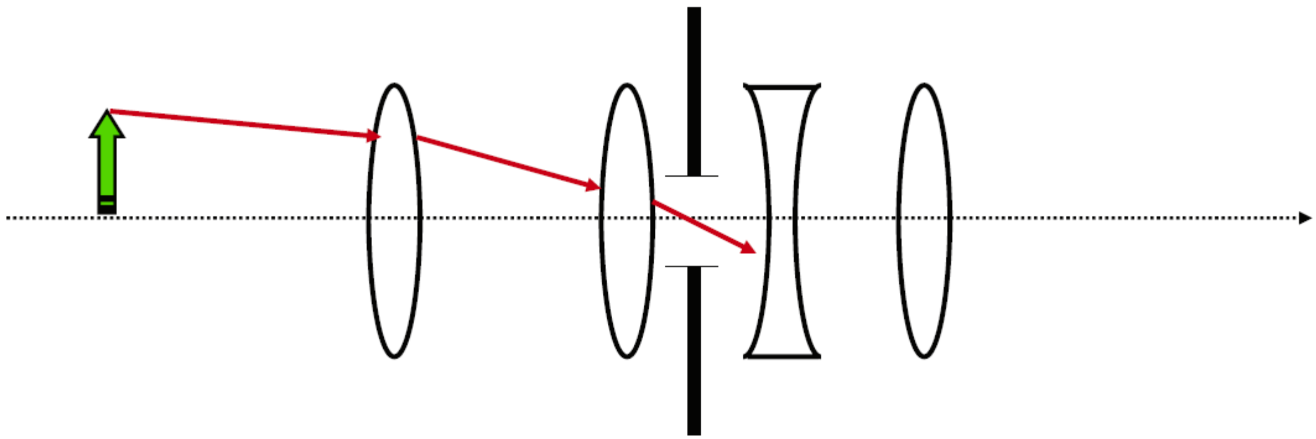
Aperture Stop and Entrance & Exit Pupil



The **aperture stop** (AS) is defined to be the stop or lens ring, which physically limits the solid angle of rays passing through the system from an **on-axis** object point. The aperture stop limits the brightness of an image.

The **entrance pupil** of a system is **the image of the aperture stop as seen from an axial point on the object through those elements preceding the stop**. (Hecht p. 171)
The **exit pupil** of a system is **the image of the aperture stop as seen from an axial point on the image plane through the interposed lenses, if there is any**. (Hecht p. 172)

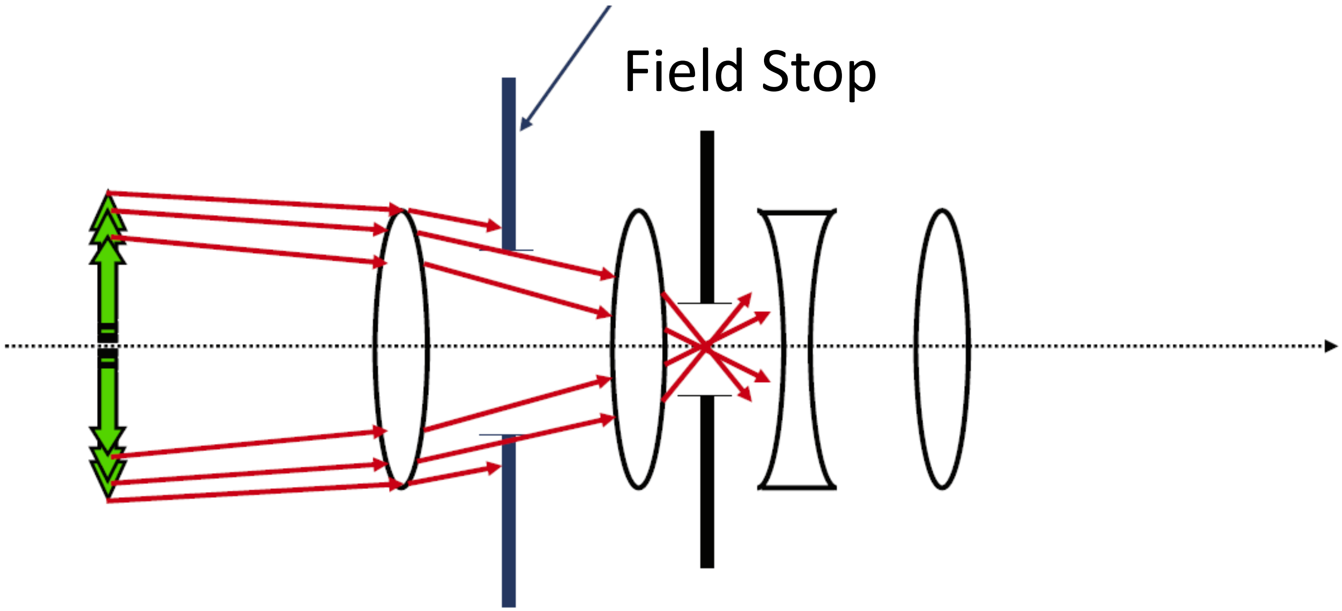
The Chief Ray



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

For an off-axis object, the chief ray (CR) is the ray that passes through the center of the aperture stop. Rays that pass through the edge of the aperture stop are marginal rays (MR).

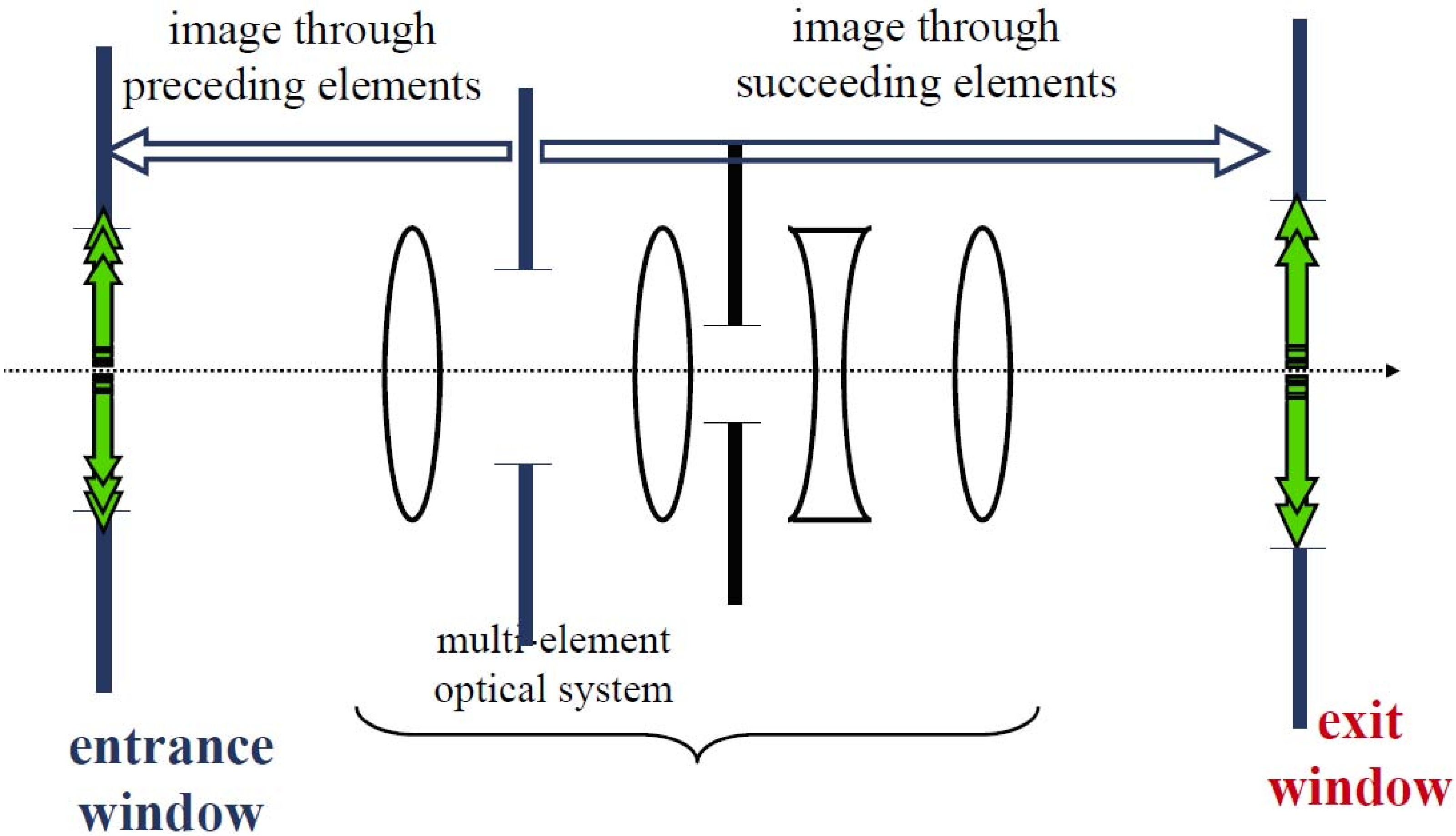
The Field Stop and Aperture Stop



Limits the angular acceptance
of Chief Rays

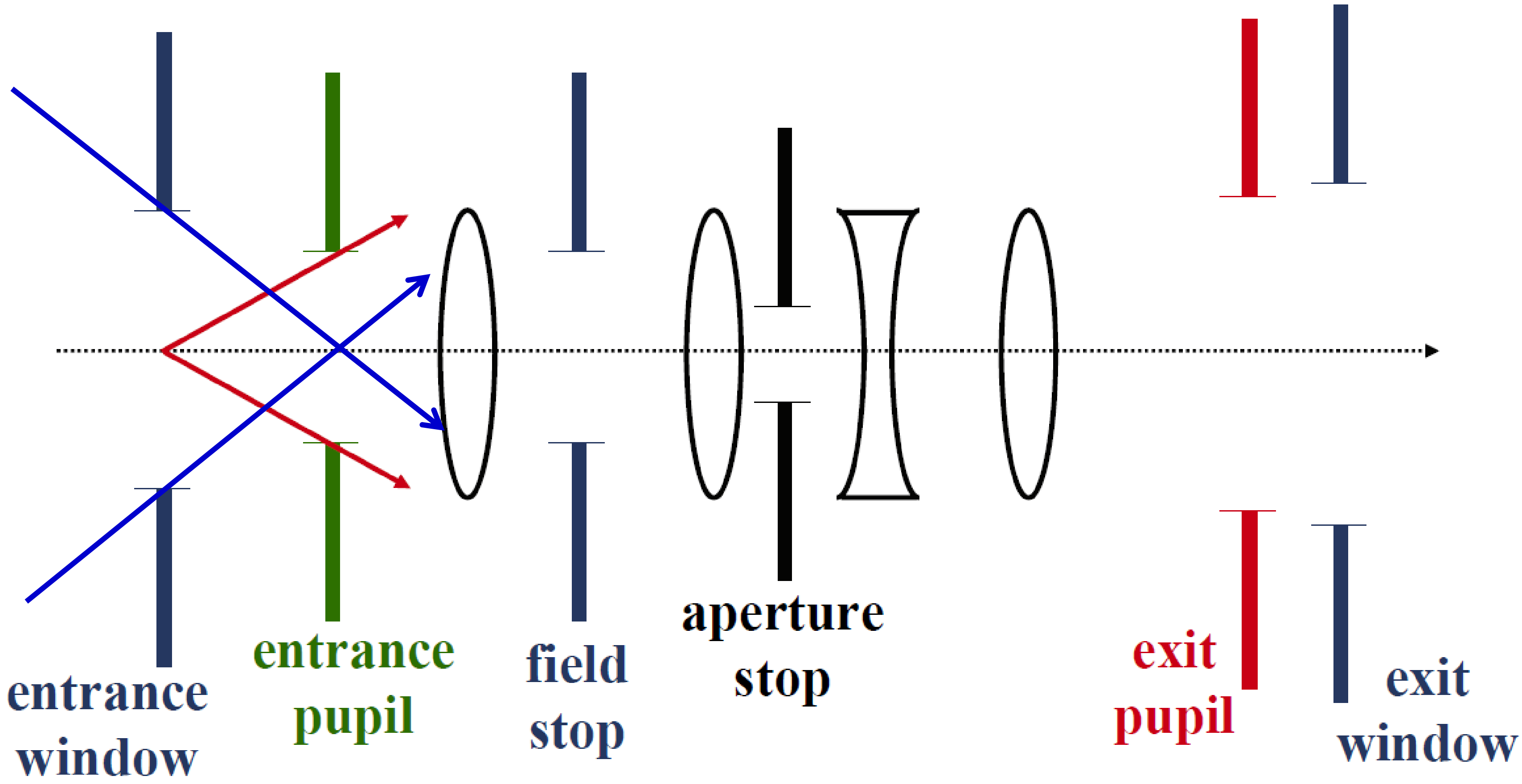
The aperture stop determines the solid angle of the transmitted light cone for an on-axis object. It limits the brightness of an image. The **field stop** determines the solid angle formed by chief rays from **off-axis** objects. It limits the field of view of an optical instrument.
(source: http://electron9.phys.utk.edu/optics421/modules/m3/Stops.htm)

Entrance and Exit Window



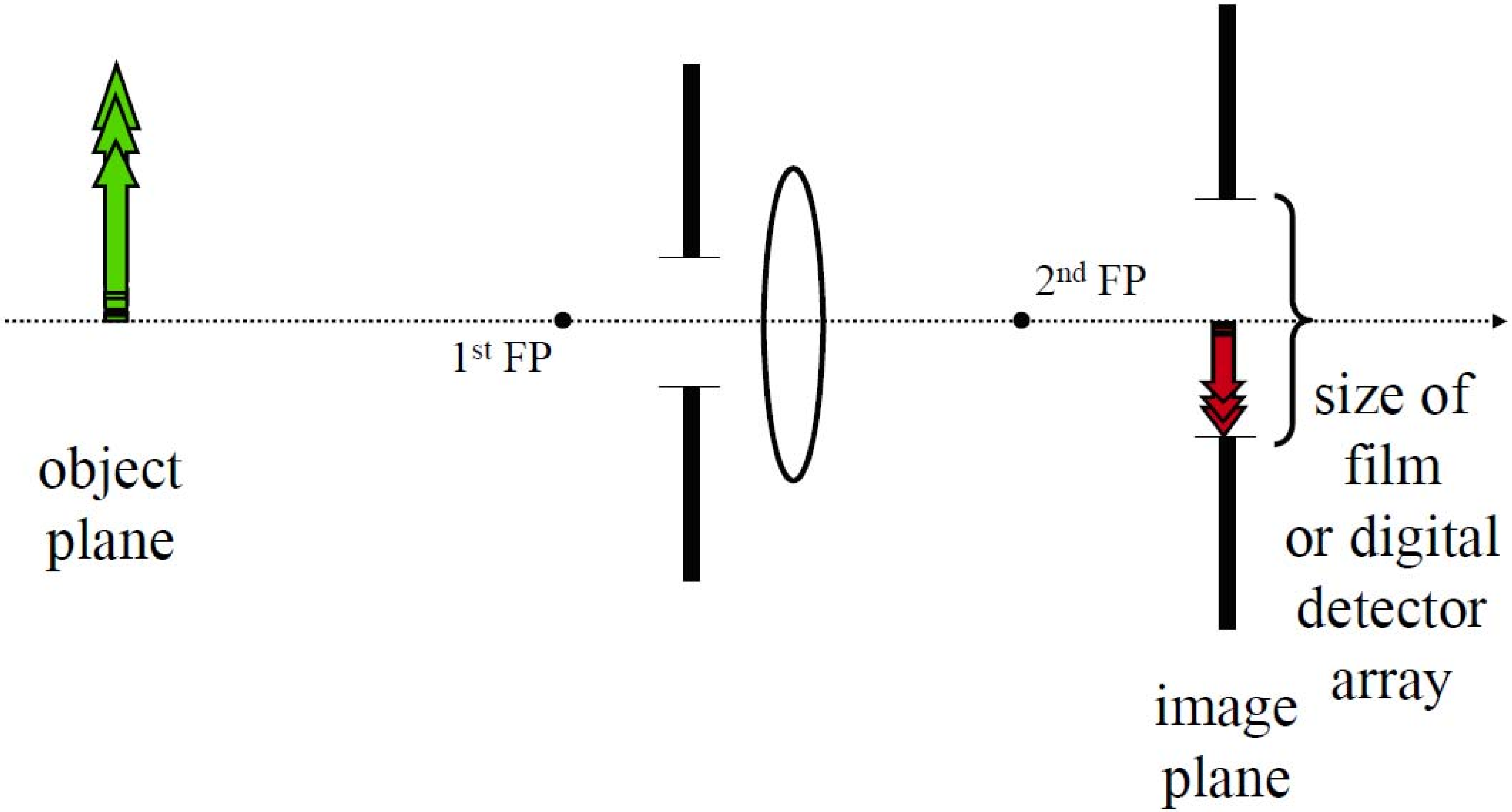
The image of the field stop as seen through all the optics before the field stop is called the **entrance window**. The image as seen through all the optics after the field stop is called the **exit window.**

All together

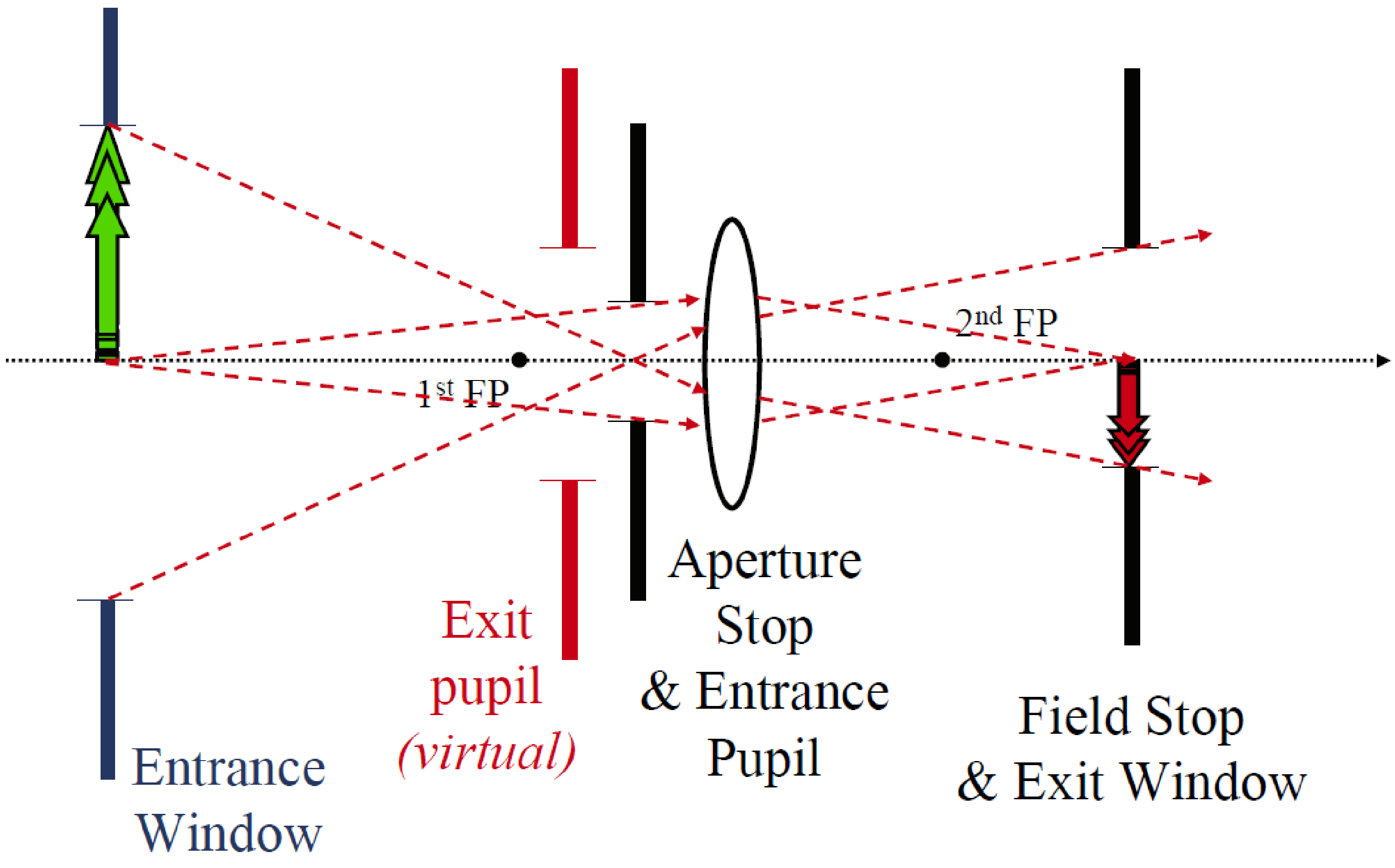


Two important aspects of any imaging system are the amount of radiation passed by the system and the extent of an object that is seen by the system. Stops and apertures limit the brightness of an image and the field of view of an optical system.

Example: Single Lens Camera



Example II: Aperture Stop + Field Stop



Vignetting