EPFL

MICRO-517

Optical Design with ZEMAX OpticStudio

Lecture 2

3.10.2022

Ye Pu
Sciences et techniques de l'ingénieur
École Polytechnique Fédérale de Lausanne
CH-1015 Lausanne

Outline

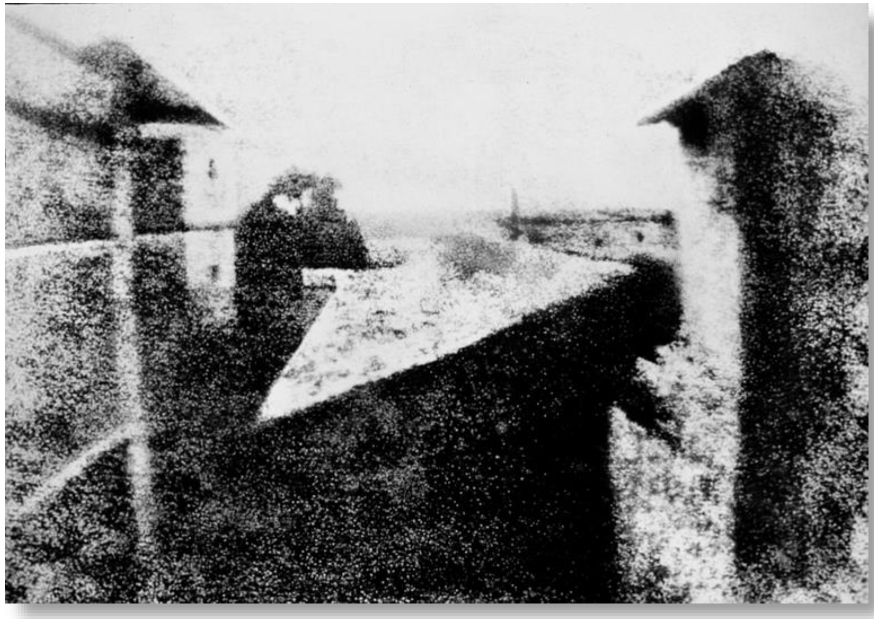
Theory

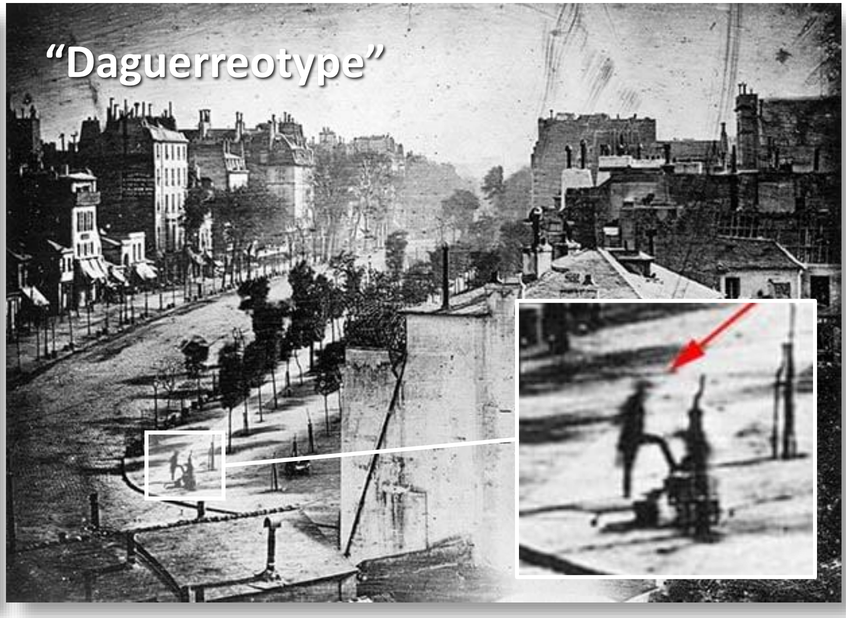
- Brief history of photographic lens design
- Paraxial theory of lenses

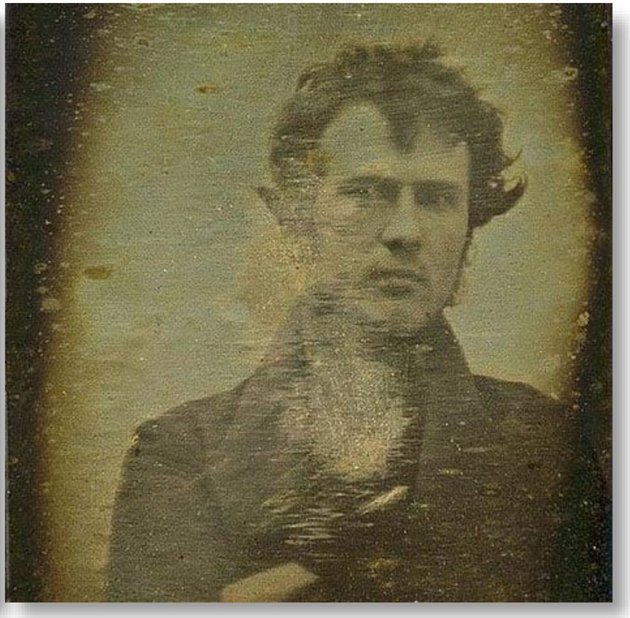
ZEMAX Practice

- First lens design

History of Photography







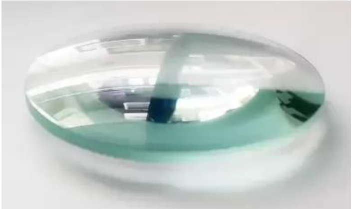
First known landscape photo (enhenced)
Joseph Nicéphore Niépce, c. 1826-1827
Material: asphalt film on pewter plate
Exposure: 8 hours (camera obscura)
Source: College of Liberal Arts, University of Minnesota

First known photo containing a human
Louis Daguerre, 1838
Material: polished silver surface
Exposure: 10 minutes
Source: Wikipedia.org

First successful portrait photo
Robert Cornelius, 1839
Material: silver and bromine
Exposure: 1 minutes
Source: PetaPixel.com

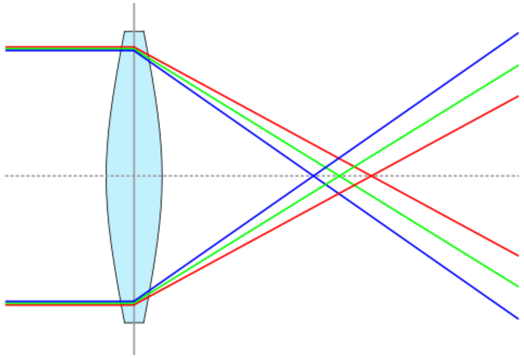
History and Evolution of Lens Forms

Lens: from Latin lēns ("lentil"), a curved transparent material that refracts light

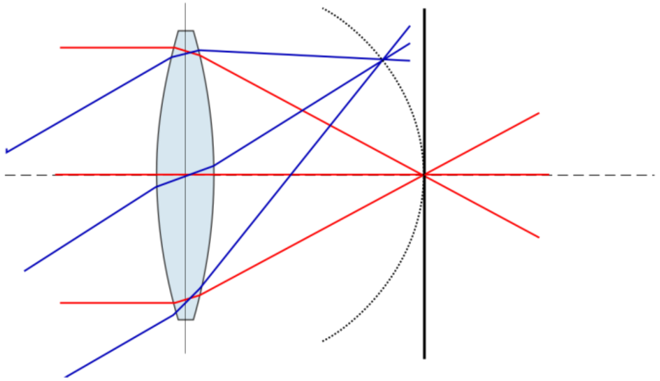


- First reference to a burning-glass: 424 BC
- First mentioning of magnifying effect: 1st century
- Spectacles: 13th century
- Microscopes and telescopes: 16th century

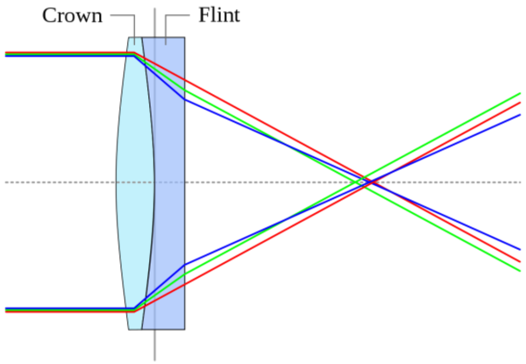
- Early photography: single convex lens
- Severe chromatic aberration and field curvature among other aberrations
- Achromatic doublet lens: Chester Moore Hall 1754 (for telescope)



Chromatic Aberration



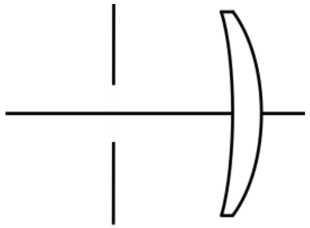
Field Curvature



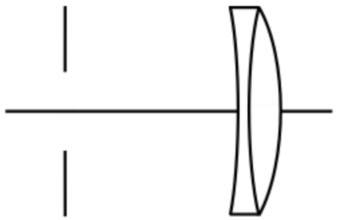
Achromatic Doublet Lens

History and Evolution of Lens Forms

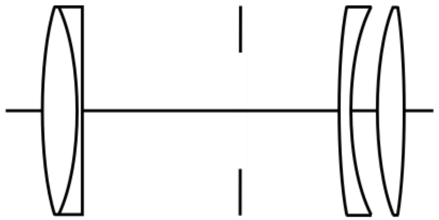
Early Work



Wollaston Meniscus, 1804



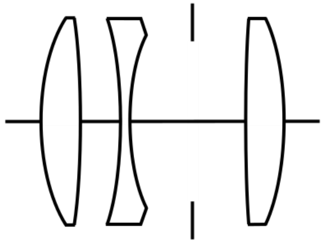
Chevalier Achromat Landscape, 1839



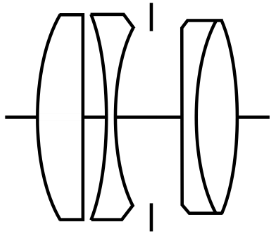
Petzval Portrait, 1840

First lens design by ray tracing F/3.6

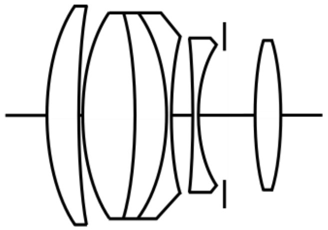
Cooke Triplet



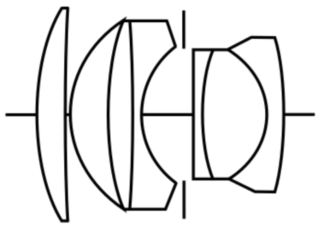
Taylor, Taylor & Hobson Cooke Triplet 1839



Zeiss Tessar 1902



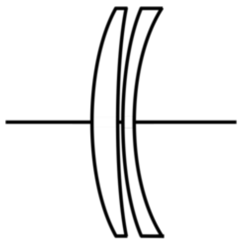
Ernemann Ernostar f/1.8 1924



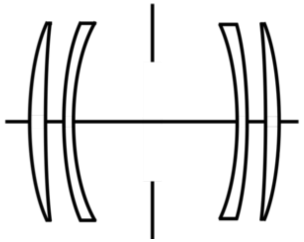
Zeiss Sonnar 50 mm f/1.5 1932

Corrects chromatic and spherical aberration, coma, and astigmatism. Standard in low-end cameras today

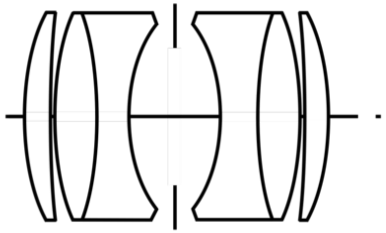
Double Gauss



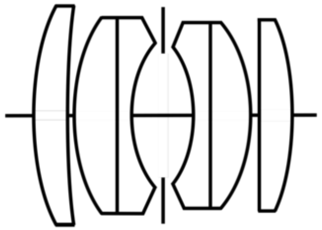
Gauss Objective 1817



Clark Double Gauss f/8 1817



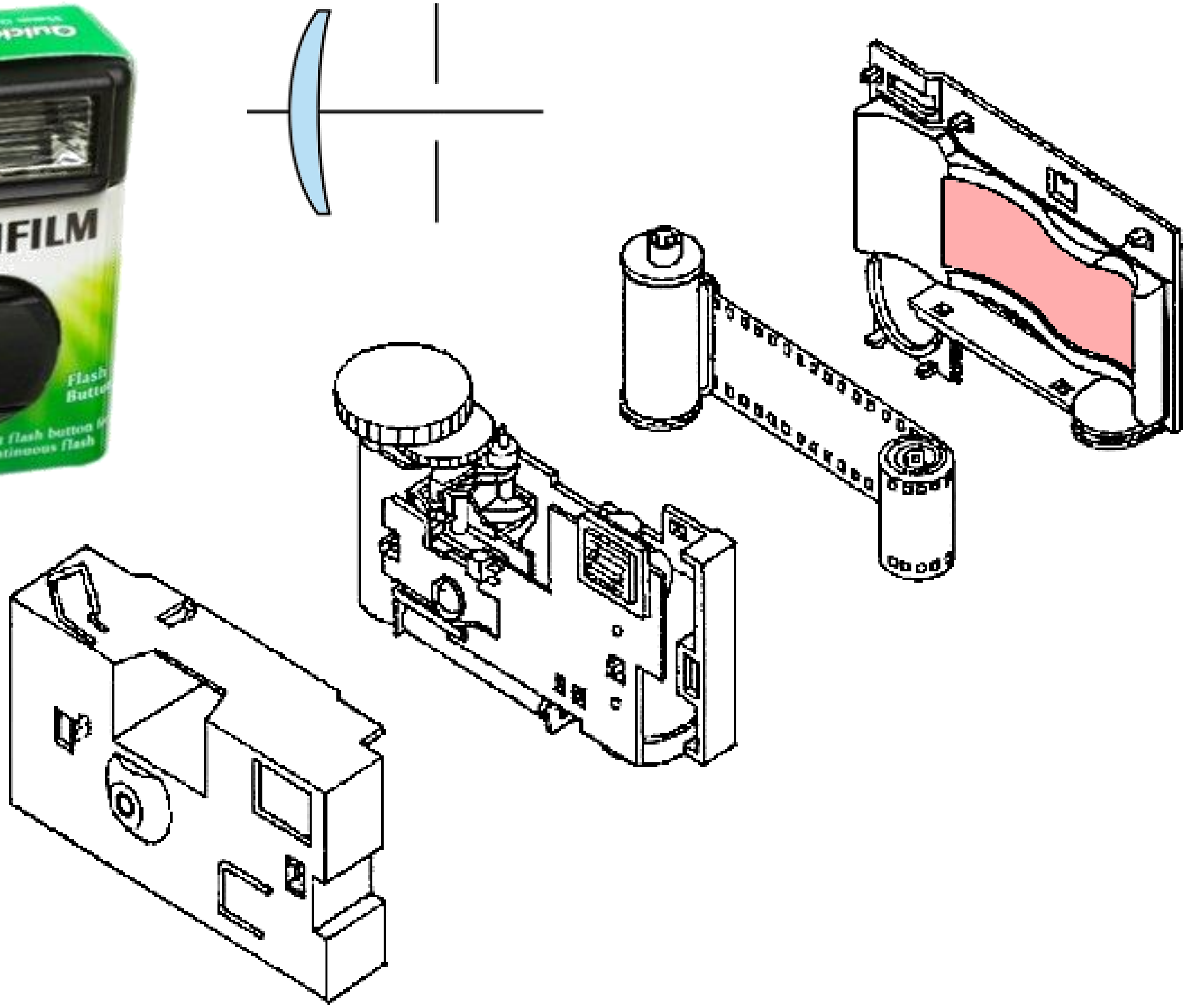
Taylor, Taylor & Hobson Series 0 (Opic) f/2 1920



Zeiss Plannar f/4.5 1896

Most intensively studied lens formula. Near perfect performance. Dominating lens design used today

Design: Art of Balance and Compromise

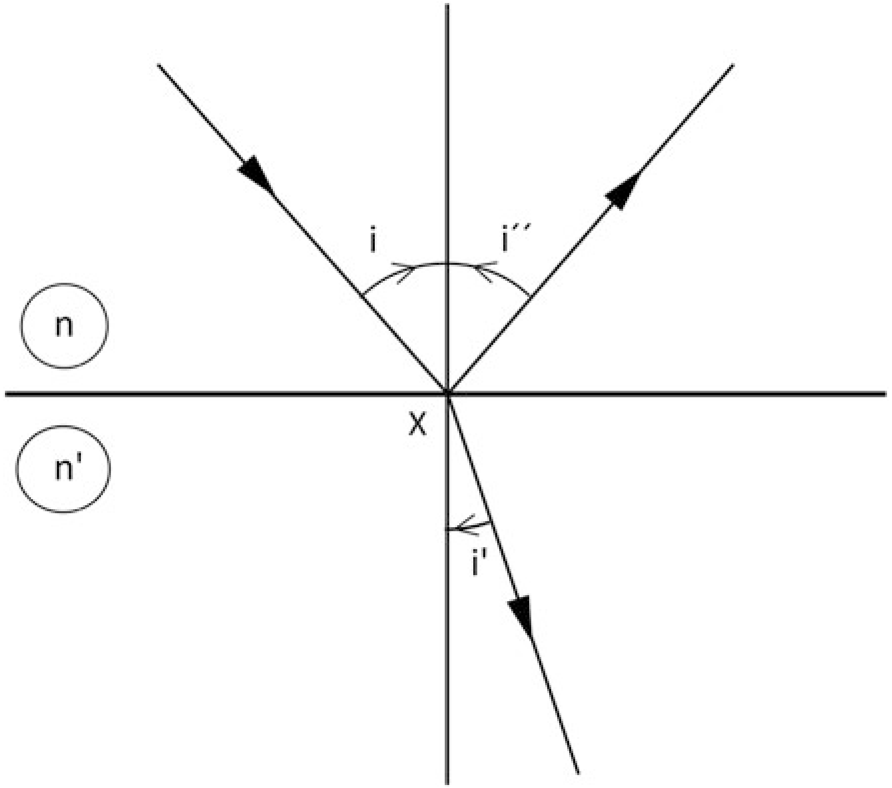


FUJIFILM QuickSnap Disposable Camera

- Single piece reversed landscape lens
- Curved image plane for field curvature

Paraxial Optics: Reflection

Reflection and Refraction at an Interface



Paraxial Approximation: $n'i' = ni$

Spherical Reflective Surface (Concave Mirror)

$VQ = s$ Object distance

$VQ' = s'$ Image distance

$VF = f$ Focal length

$VC = r$ Curvature radius

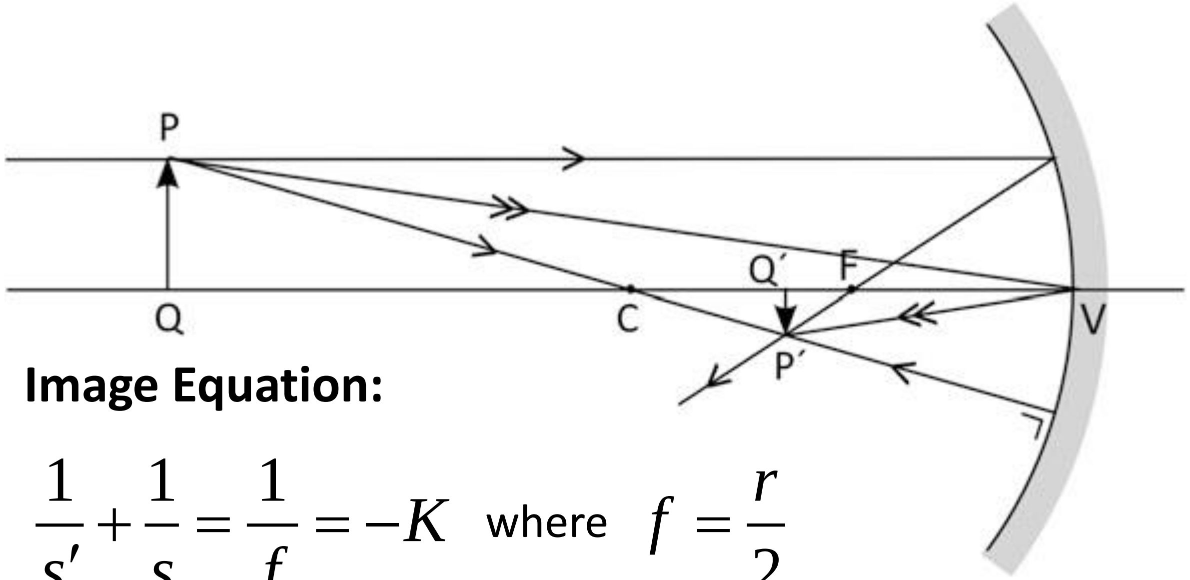


Image Equation:

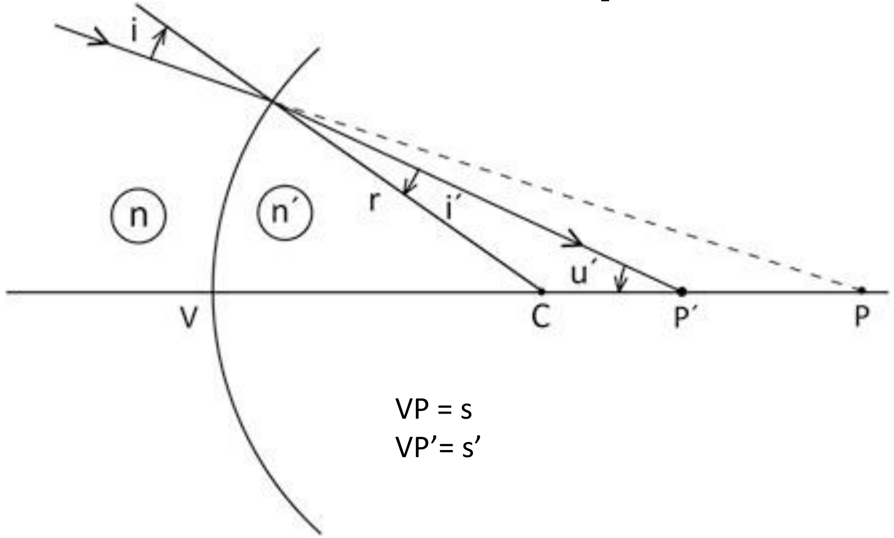
$$\frac{1}{s'} + \frac{1}{s} = \frac{1}{f} = -K \quad \text{where} \quad f = \frac{r}{2}$$

Magnification: $M \equiv \frac{P'Q'}{PQ} = -\frac{s'}{s}$

Power: $K \equiv -\frac{1}{f}$

Paraxial Optics: Refraction

Spherical Reflective Surface



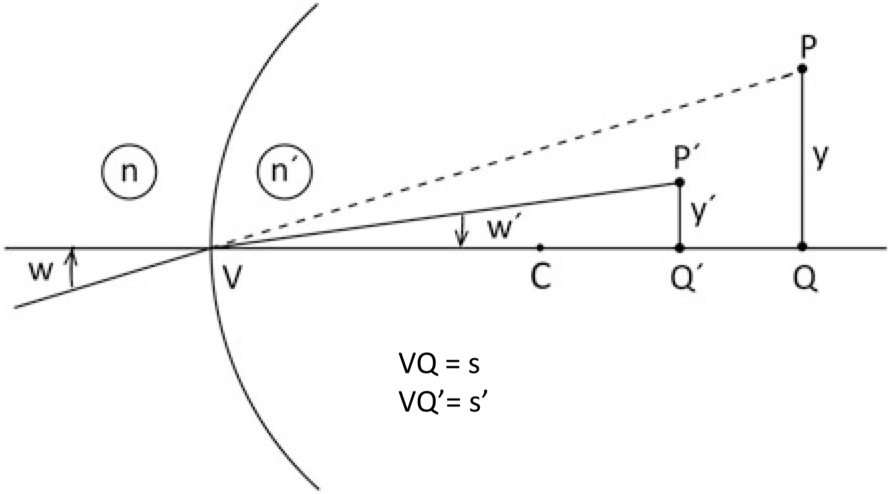


Image Equation:

$$\frac{n'}{s'} - \frac{n}{s} = \frac{1}{f} = K \quad \text{where} \quad f = \frac{r}{n'-n}$$

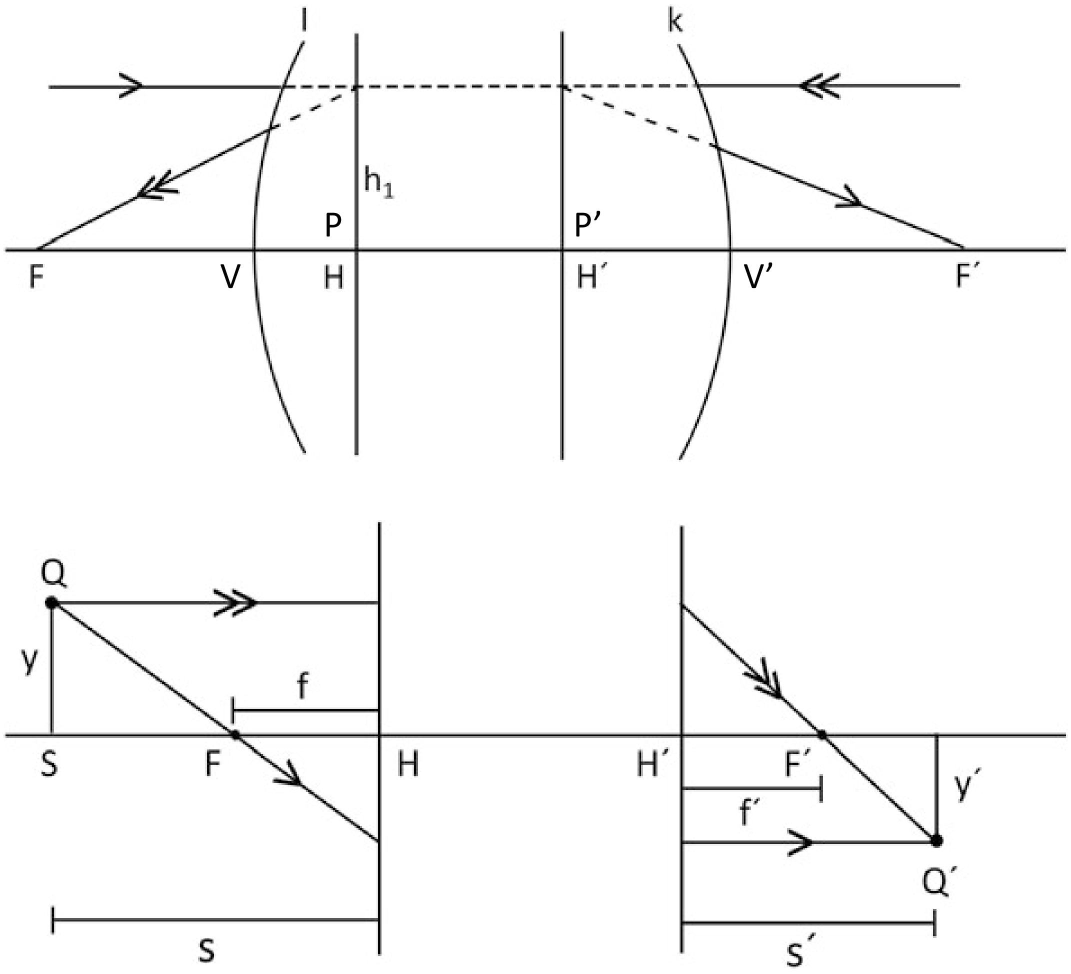
Power: $K \equiv \frac{1}{f} = \frac{n'-n}{r}$

Magnification:

$$M \equiv \frac{y'}{y} = \frac{ns'}{n's} \quad \text{since} \quad n'w' = nw$$

Abbe's Invariant: $n'\left(\frac{1}{s'} - \frac{1}{r}\right) = n\left(\frac{1}{s} - \frac{1}{r}\right)$

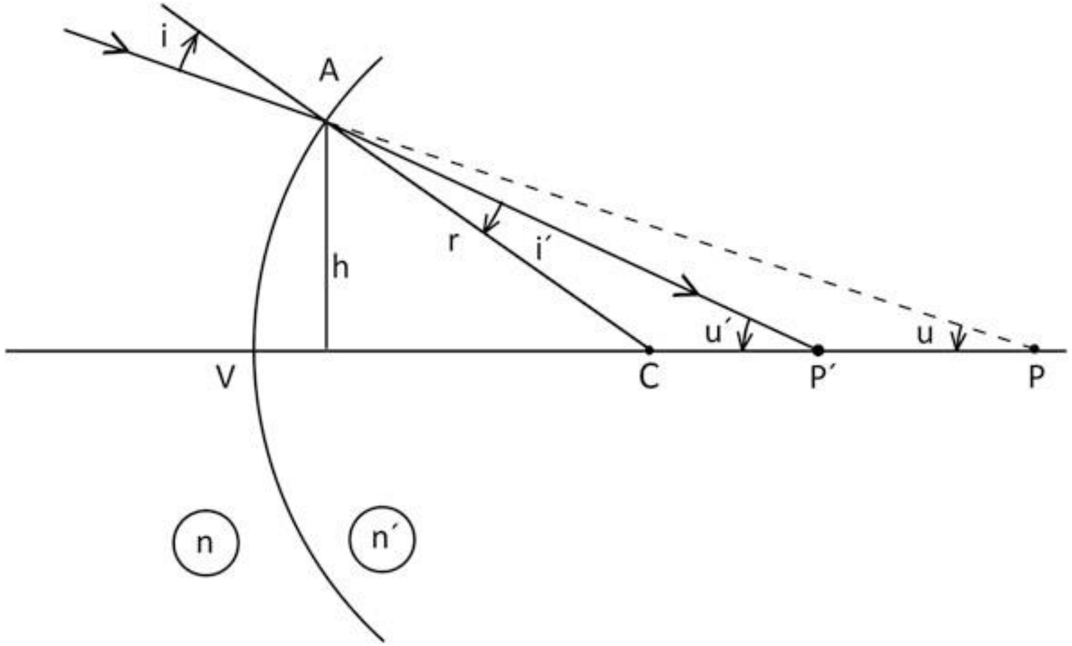
Paraxial Systems: Cardinal Points



Cardinal Points and Principal Planes

- Planes that have a magnification M = +1 are called the principal plane (H and H')
- Intersection points between the principal planes and the optical axis are principal points
- F, F', V, V', P, P' are called **cardinal points**
- Focal length is measured from the principal planes, i.e. HF = f, H'F' = f'
- Imaging process can be considered based on the principal planes and the cardinal points without surface detail

Paraxial Ray Tracing



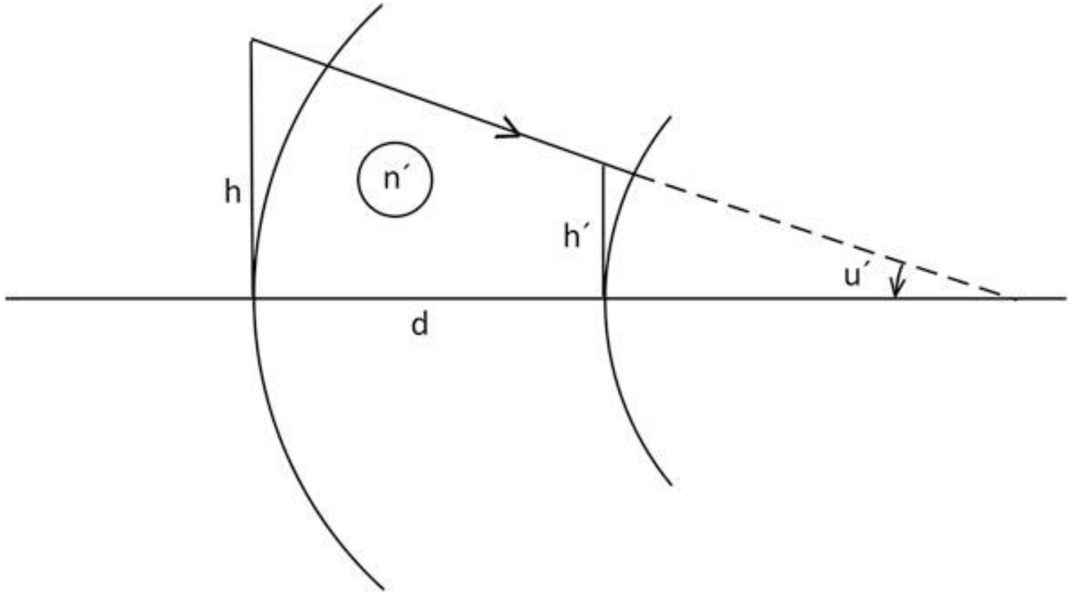


Image Equation:

$$i = u + h/r \qquad i' = u' + h/r \qquad n'i' = ni$$

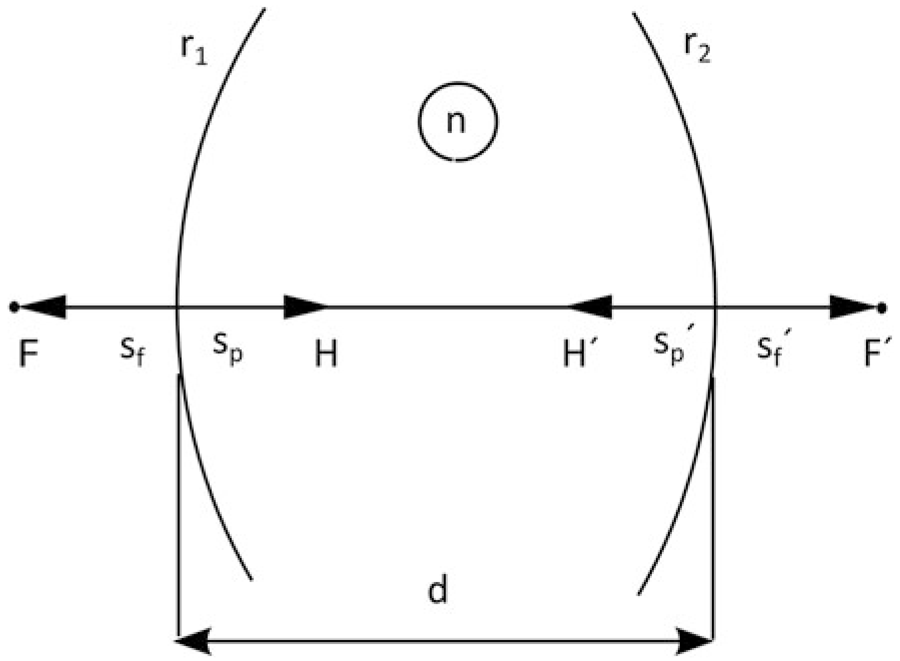
$$K = \frac{n' - n}{r}$$

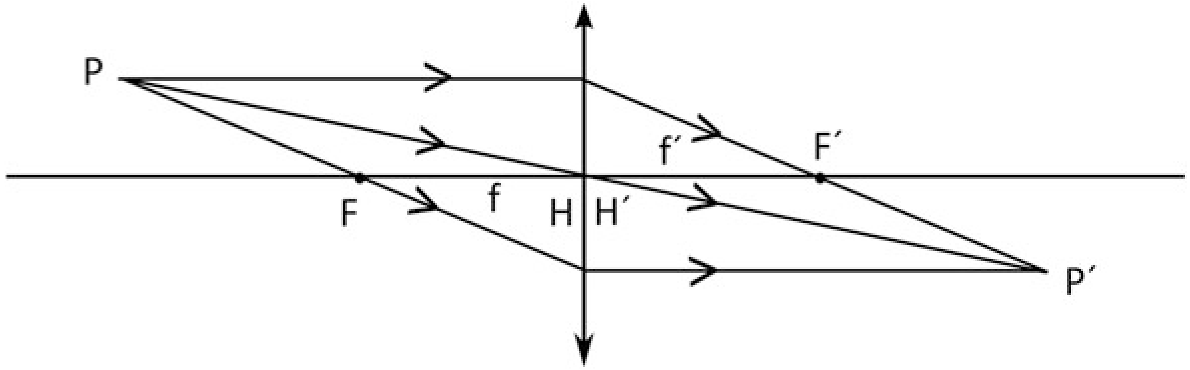
Transfer Equation:

$$h' = h - u'd$$

$$h_{i+1} = h_i - u_{i+1} d_i$$

Single Lens





$$K_1 = (n-1)/r_1 \qquad K_2 = (1-n)/r_2$$

$$K = K_1 + K_2 - dK_1K_2/n$$

$$S_p = -dK_2/nK \qquad S_p{}' = -dK_1/nK$$

Lens Maker's Formula:

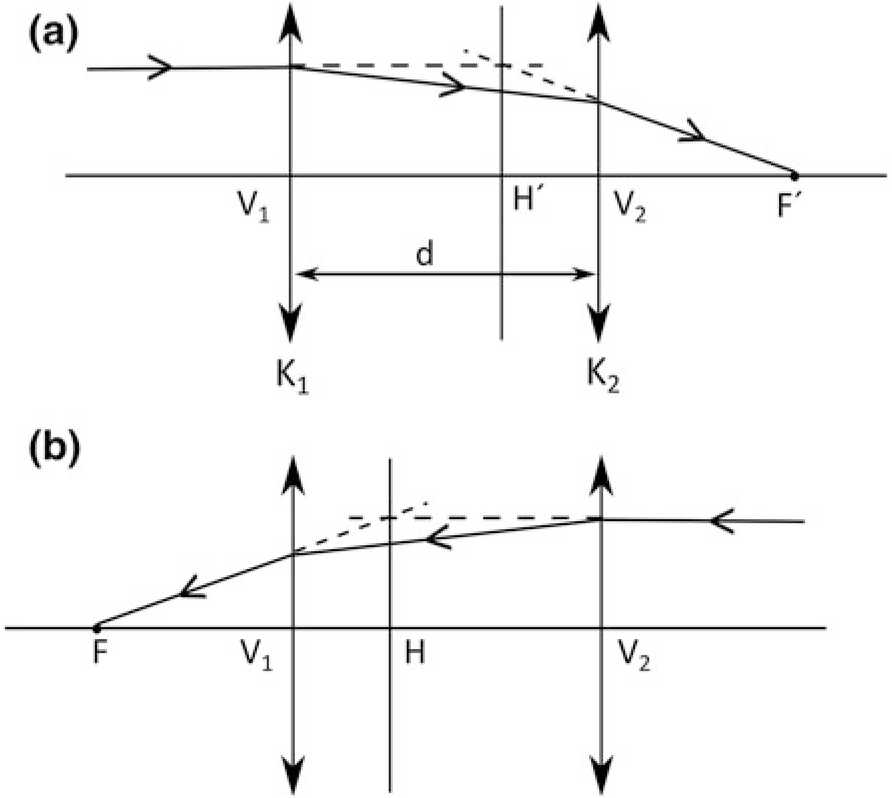
$$K = \frac{1}{f} = (n-1)\left[\frac{1}{r_1} - \frac{1}{r_2} + \frac{(n-1)d}{nr_1r_2}\right]$$

Thin Lens:

$$d \rightarrow 0$$

$$K = \frac{1}{f} = (n-1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

Paraxial Ray Tracing in Thin Lenses



Location of Principal Plane:

$$K = K_1 + K_2 - dK_1K_2/n$$

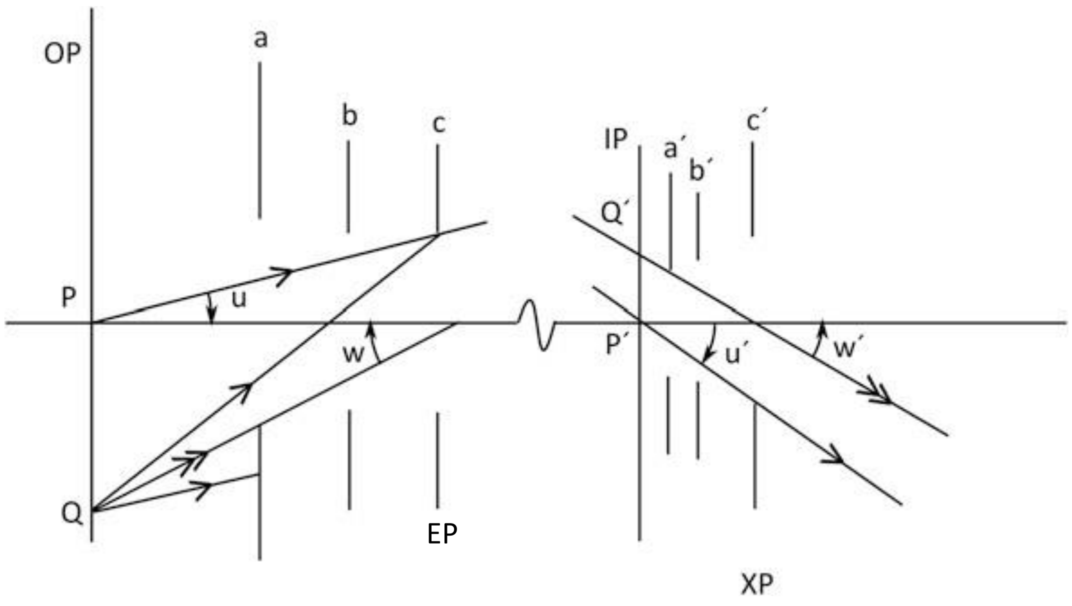
$$V_1H = K_2d/K$$

$$V_2H' = -K_1d/K$$

Power of a System of Thin Lenses:

$$h_1K = \sum_{i=1}^{k} h_iK_i$$

Apertures, Stops, and Pupils



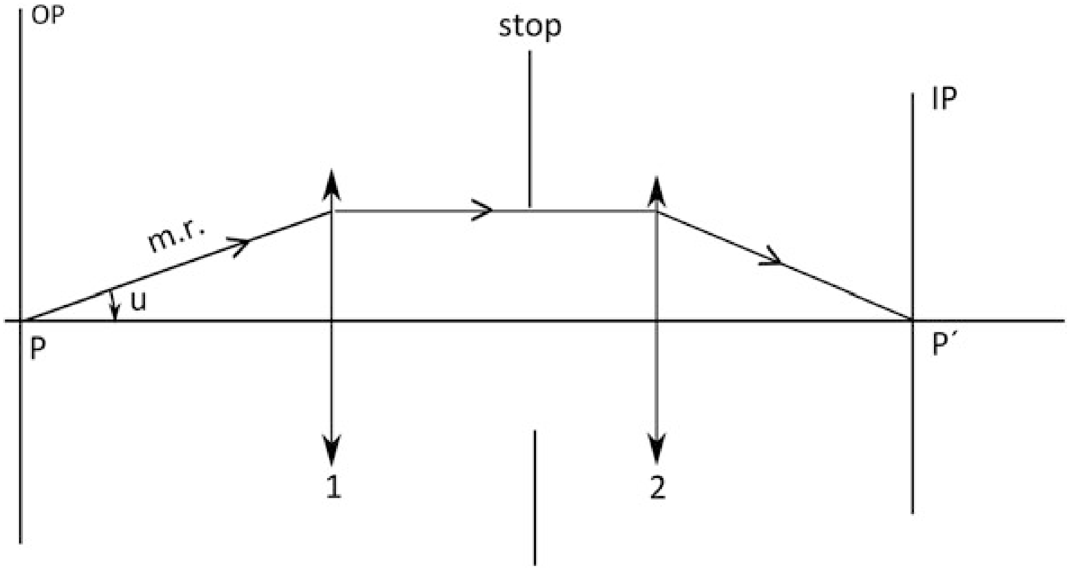
EP: Entrance pupil
XP: Exit pupil
Image a: field stop

Aperture Stop of a Lens System

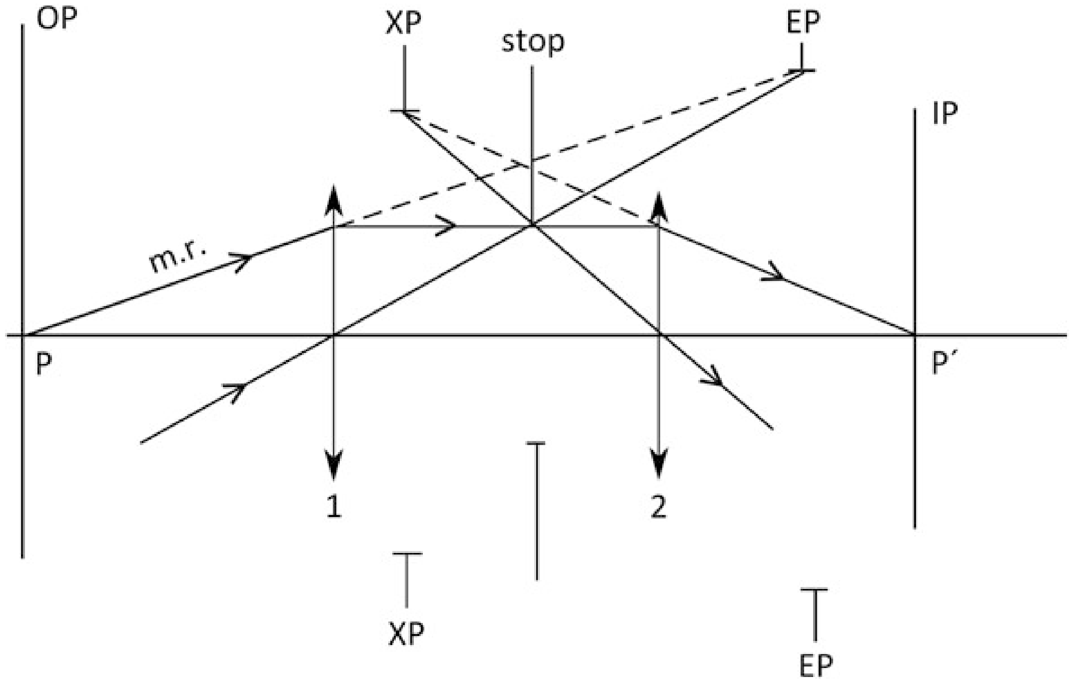
- A lens system may consist of many lenses
- Each lens may have different diameter
- May also possess an iris inside the system
- The component that limit the light rays is an **aperture stop**
- A ray from an on-axis point passing the edge of the aperture stop is the **marginal ray**
- Can be located anywhere in the system
- Determining aperture stop
  - Find images of all lens edges and diaphragms in the object space
  - The ray-limiting one is called the **entrance pupil** (object-side image of the aperture stop)
  - The image-side image of the aperture stop is the **exit pupil**

Apertures, Stops, and Pupils

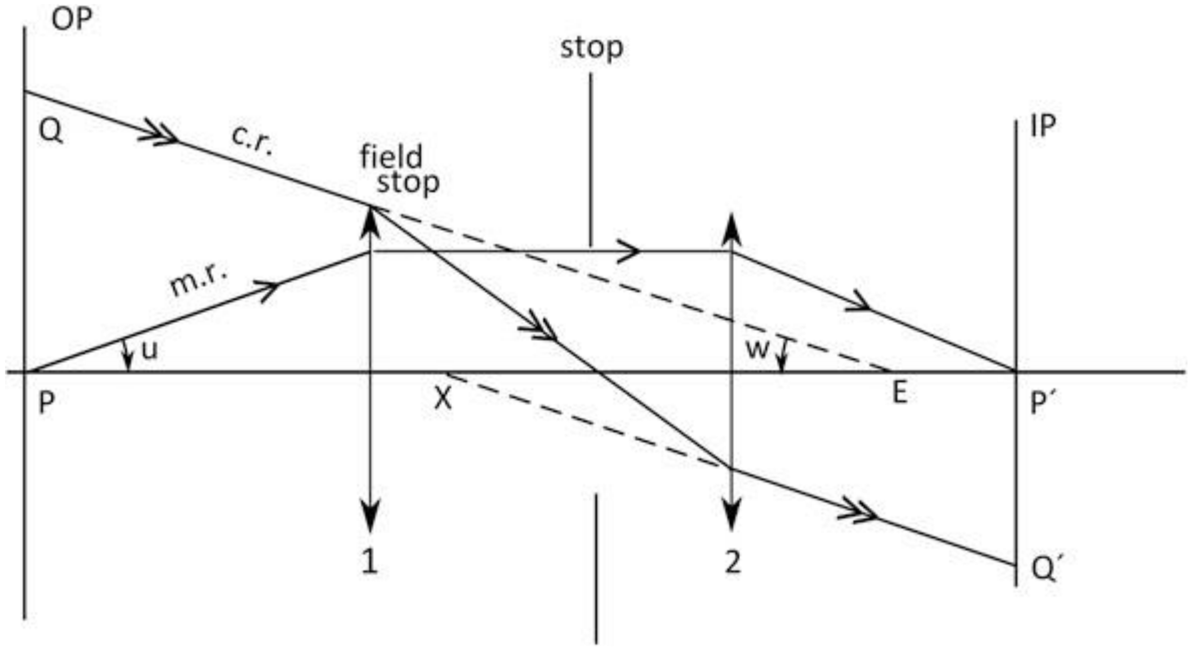
Aperture Stop



Entrance and Exit Pupil



Apertures, Stops, and Pupils



Field Stop

- The edge that limits the angle of the **chief ray** passing the center of the aperture stop is the **field stop**
- More light energy is blocked by field stop as the angle of the chief ray increases, causing **vignetting**
- The angle of the chief ray with the axis is called the **field angle**
- Placing entrance pupil on the object plane removes vignetting (as in a telescope or a microscope)

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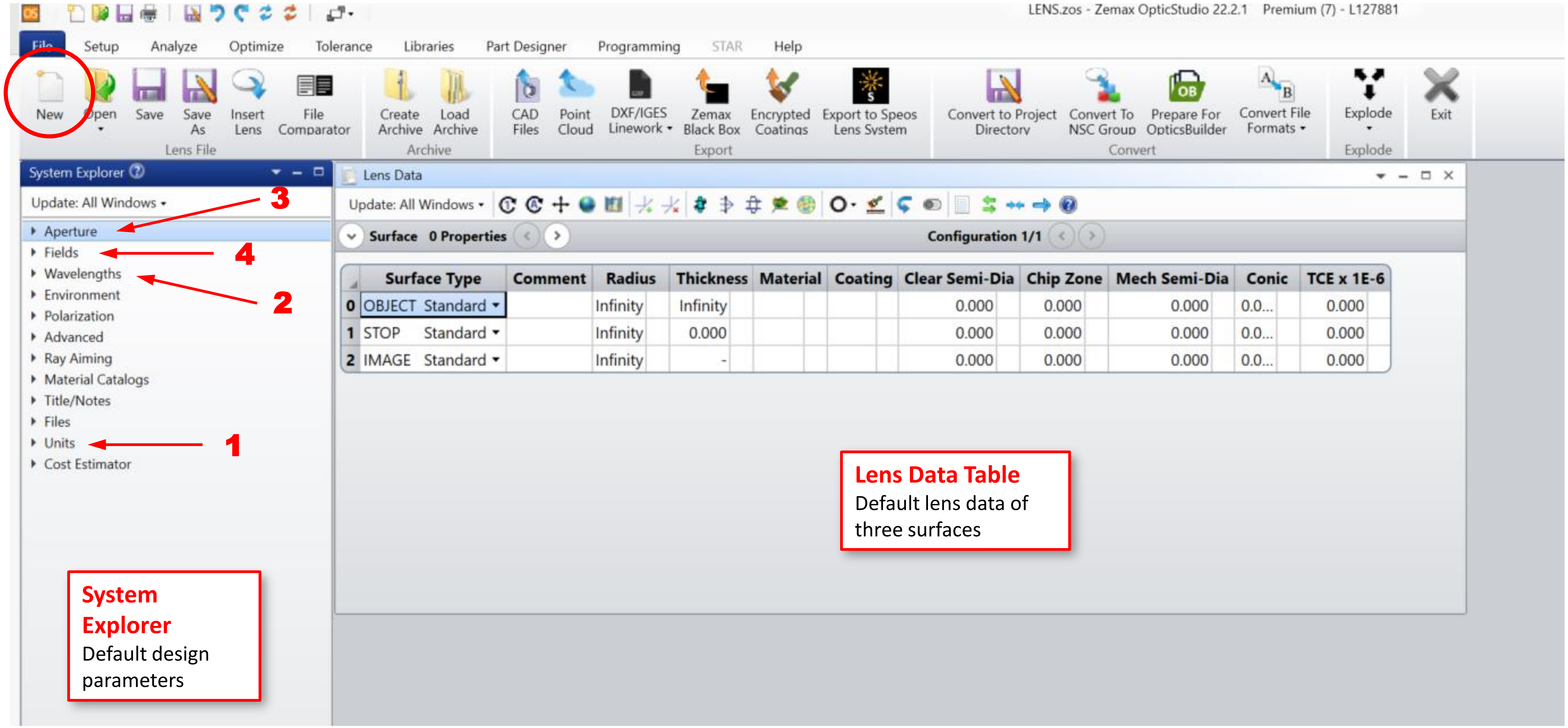
The First Lens Design Project

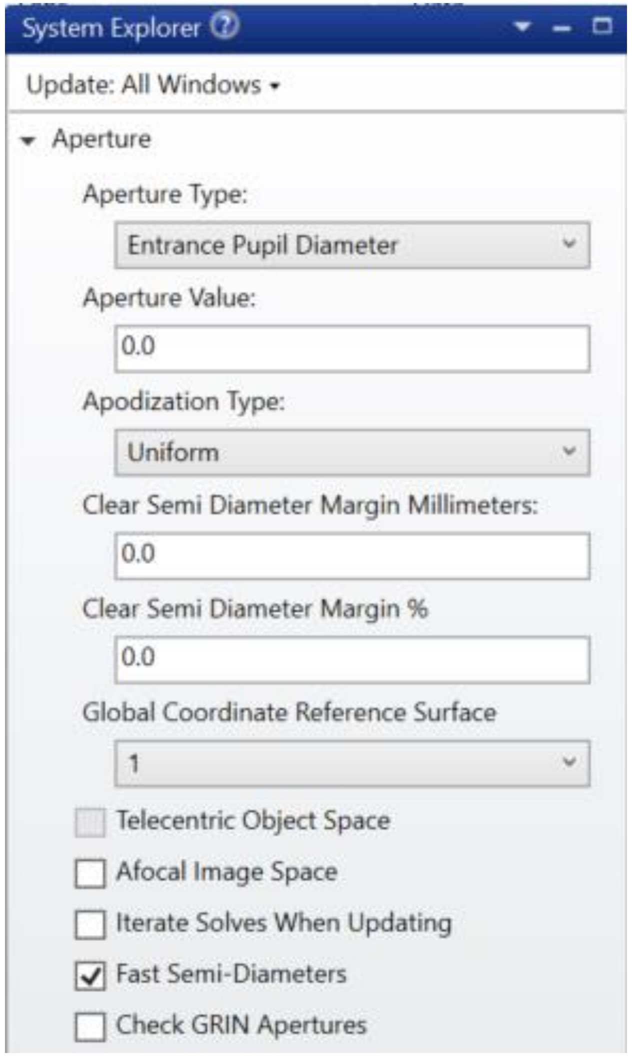
Lens Design Specifications

Specification	Constraint
Focal Length	100 mm
Semi-Field of View (SFOV)	5 degrees
Wavelength	632.8 nm (HeNe)
Center Thickness of singlet	Between 2 mm and 12 mm
Edge Thickness of singlet	Larger than 2 mm
Optimization criteria	RMS Spot Size averaged over FOV
Object location	At infinity

Initiating a Design

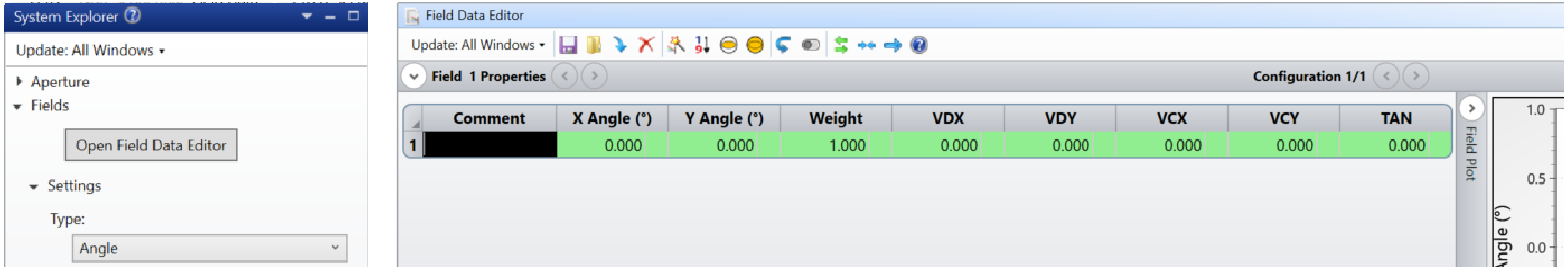


Defining the Aperture



Aperture type	Description
Entrance Pupil Diameter	Diameter of the pupil as seen from object space
Image Space F/#	Infinite conjugate paraxial F/# in image space
Object Space Numerical Aperture	Numerical aperture (NA = n sin θm) of the marginal ray in object space.
Float By Stop Size	Defined by the clear semi-diameter or semi-diameter of the stop surface.
Paraxial Working F/#	Paraxial F/# in image space for the defined conjugates.
Object Cone Angle	Half angle in degrees of the marginal ray in object space, which may exceed 90 degrees. May not be used if the entrance pupil is virtual and the distance from the object to the entrance pupil is negative. The default “Uniform” apodization of rays in the pupil is uniform in angle space, while “Cosine Cubed” apodization of rays is uniform in solid angle.

Defining the Field



Field Type	Description
Angle	Angle that the chief ray (the ray passing the center of the entrance pupil) makes with respect to the object space Z axis. Positive field angles → positive ray slope → negative object coordinates. Most useful when at an infinite conjugates.
Object Height	The X and Y heights on the object (OBJ) surface. Cannot be used when at infinite conjugates.
Paraxial Image Height	Paraxial height on the image (IMA) surface. Useful for fixed frame-size designs (e.g., a camera system). Only works well with systems that are well described by paraxial optics.
Real Image Height	Real image height on the image surface. Also useful for fixed-frame designs but use actual ray tracing rather than paraxial calculation. Slightly slower due to an iterative approach used to determine the coordinates of the chief ray on the IMA plane.
Theodolite Angle	Azimuth θ and elevation ϕ polar angles in degrees. These angles are commonly used in surveying and astronomy.

Inserting Surfaces with Lens Parameters

Lens Data

Update: All Windows

Surface 2 Properties

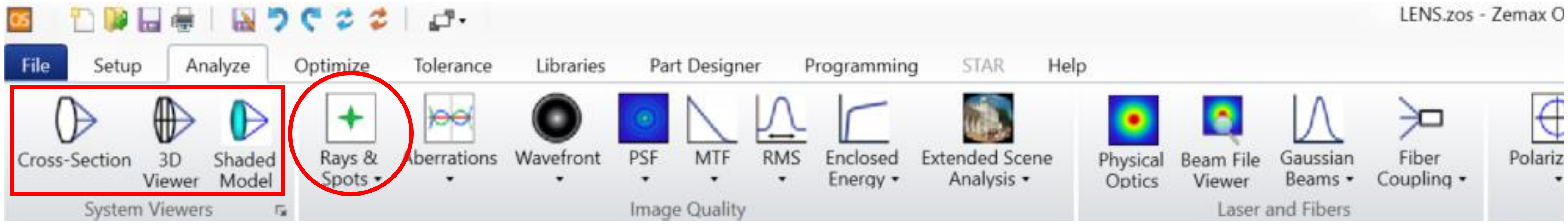
Configuration 1/1

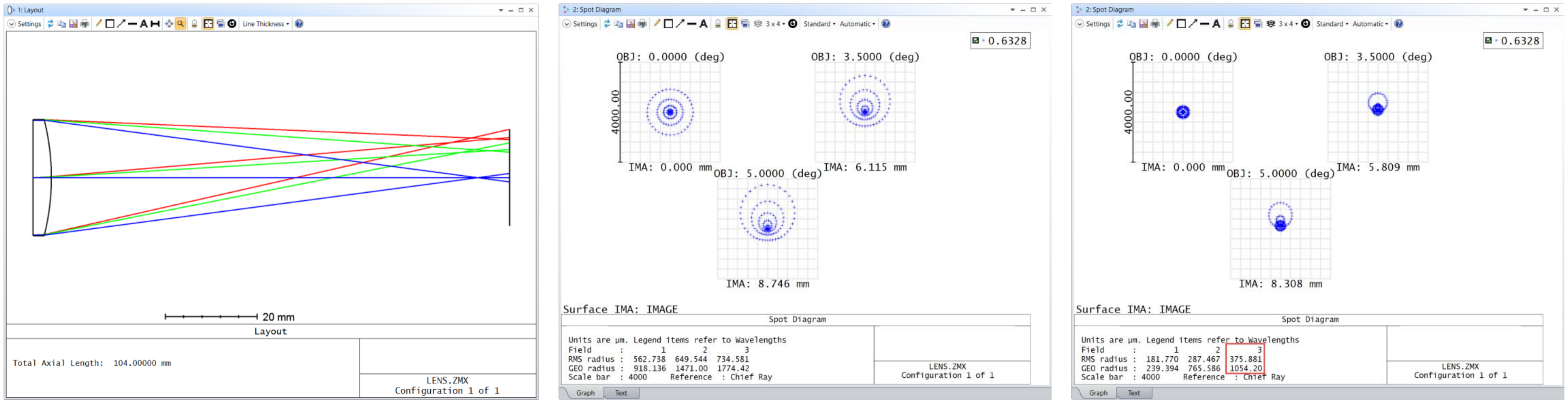
	Surface Type		Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6
0	OBJECT	Standard		Infinity	Infinity			Infinity	0.000	Infinity	0.000	0.000
1	STOP	Standard		Infinity	0.000			12.500	0.000	12.500	0.000	0.000
2		Standard		Infinity	0.000			12.500	0.000	12.500	0.000	0.000
3	IMAGE	Standard		Infinity	-			12.500	0.000	12.500	0.000	0.000

Column	Description
Surface Type	Type of surface (Standard, Even Asphere, Diffraction Grating, ...)
Comment	Optional field for surface-specific comments
Radius	Surface radius of curvature in lens units
Thickness	Distance separating the current surface and the next
Material	Type of material (glass, air, ...) separating the current surface and the next
Semi-Diameter	Half-size of the surface

Analyzing

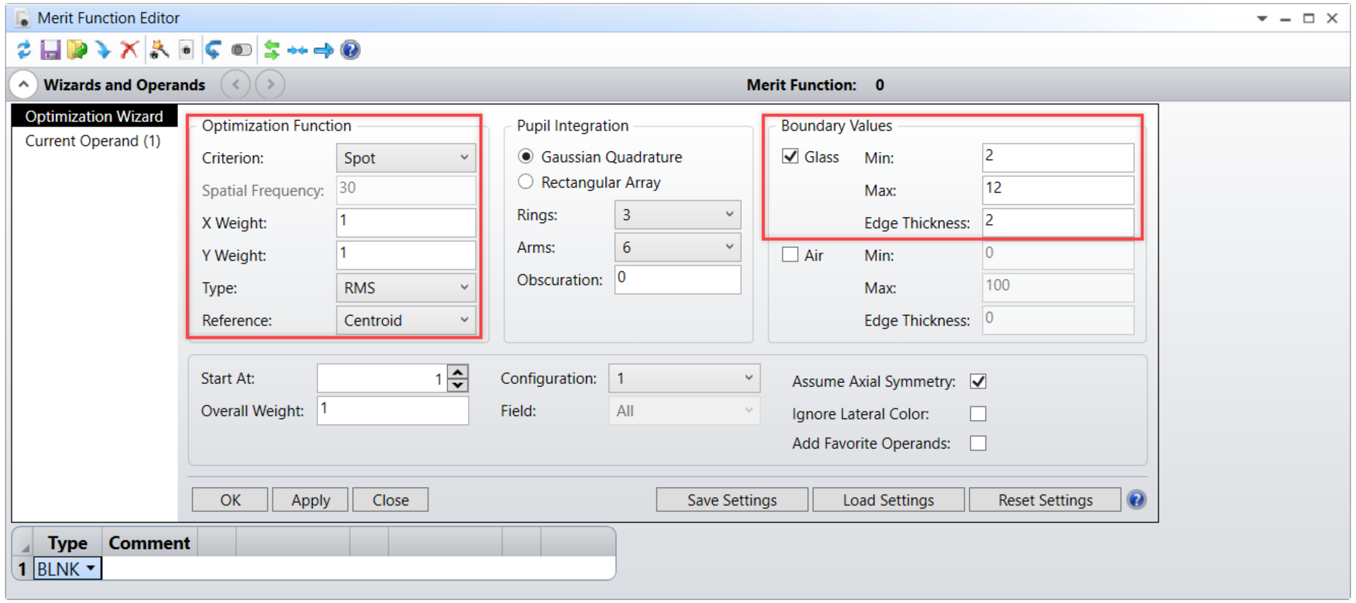
Analyze Menu

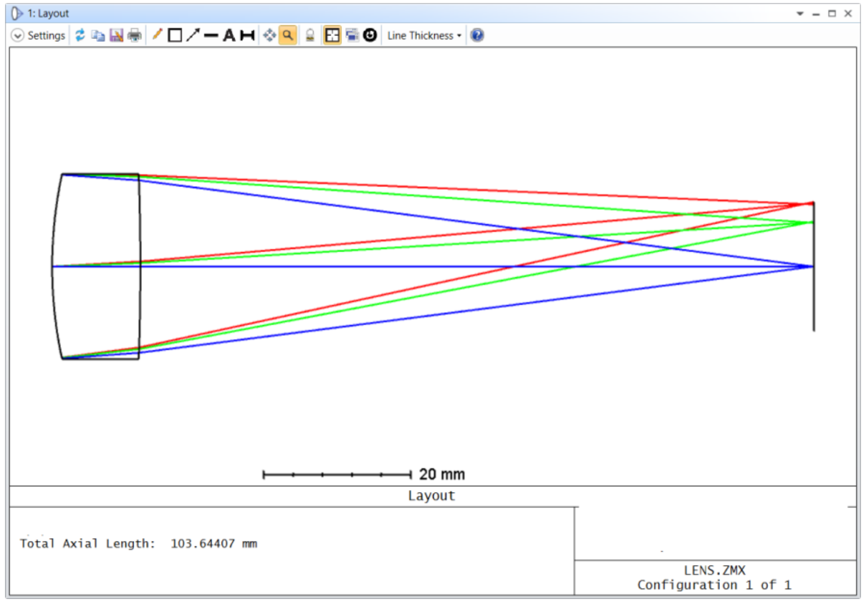




Optimizing

Optimize Menu





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Hands-on Time

Homework

Objective

- Familiarize yourself with basic ZEMAX ray tracing
- Understand basic relationship between lens shapes and aberrations

1. Analyze the compound lens consisting a pair of identical planoconvex lenses of material N-BK7, a surface curvature radius of 55 mm and a center thickness 3 mm, with their spherical side facing each other and 1 mm between the two surfaces. The object is located 100 mm in front of the first surface of the compound lens with heights 0, 5, 7 mm. You can use Quick Focus tool to locate the image plane. Report the 2D cross-section of the ray tracing result, the spot diagram, and the cardinal points of the compound lens.
2. Flip the two lenses (now with the flat surface facing each other with 1 mm distance in between) and perform the above analysis. Compare the results in terms of the spot diagram.
3. Analyze a single biconvex lens with identical 55 mm curvature radii of the two spherical surfaces, a center thickness of 6 mm, and the same field settings. Compare the results in terms of the spot diagram.

You should submit the ZEMAX design files (.zos) and a PDF (preferred) or Word report containing the requested figures and cardinal point data.