MICRO-517

Optical Design with ZEMAX OpticStudio

Lecture 5

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Outline

Theory

- Layout cont'd
  - Properties of optical glasses
  - Review of lens forms
- Thin-lens predesign
  - Shape and position factors
  - Correction of thin-lens system
- Surface model

ZEMAX Practice

- Seidel coefficients assessment of thin lens

The Lens Design Process

Role of Layout, Predesign, and Surface Model

- Optimization:
  - Computation-intensive
  - Time-consuming
  - Often fails to find global optimum
- ZEMAX OpticStudio cannot be treated as a video game
- Predesign helps you to land near the target so that the optimizer can find it
- In predesign, treat ZEMAX OpticStudio more like a specialized calculator

Layout cont'd

Layout cont’d

Component:

- A single lens
- A thin doublet or triplet
- More complicated group

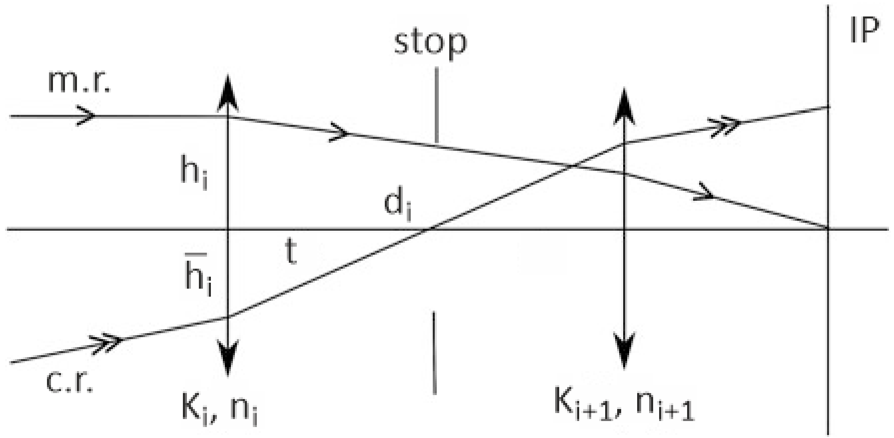
Steps of layout:

- Choice of the type of lens that looks promising to fulfil the specifications
- Choice of glasses for each lens component
- Paraxial model to decide component powers and verify lens behavior
- Initial assessments of aberrations with parameter adjustments

Four groups of lenses:

- **Camera lenses:** the largest number of different design forms due to the most diverse applications; projection lenses
- **Telescope objectives:** refractors (lenses) and reflectors (mirror systems)
- **Micro-objectives:** microscope objectives; objectives for optical recording; lens for laser focusing; projection lenses for opto-lithography (“stepper lenses”)
- **Oculars:** for visual observation in telescopes and microscopes

Total Degrees of Freedom



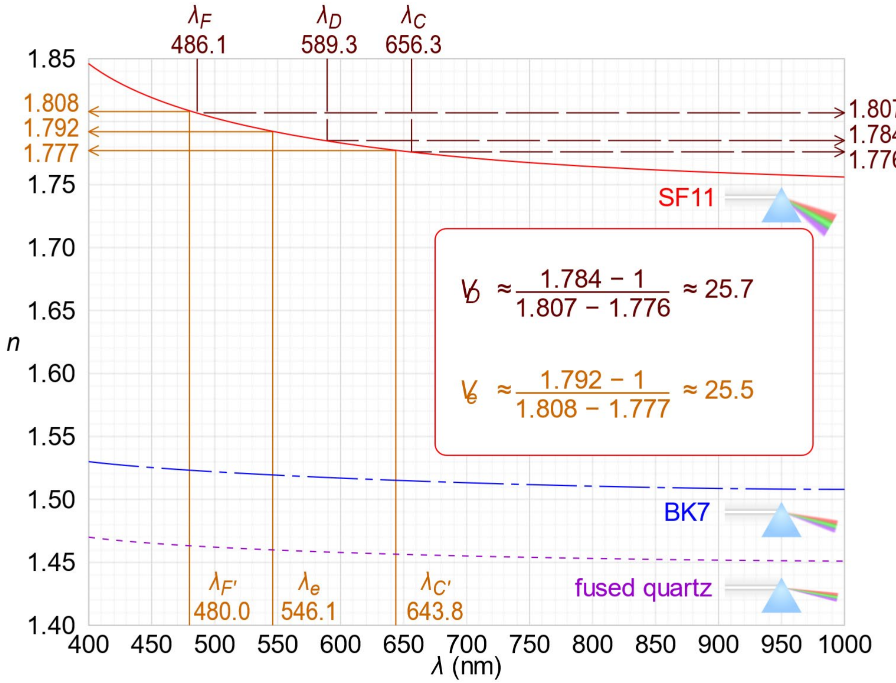
Optimization target:

- Seidel coefficients
  - Seven targets: $S_1, S_2, S_3, S_4, S_5, C_1, C_2$
  - Can be less in special cases

Degrees of freedom:

- System of k lenses
- DOM = 4k
  - Each lens: n_i, V_i, K_i, d_i (except last d)
  - Stop position

Choice of Optical Glass



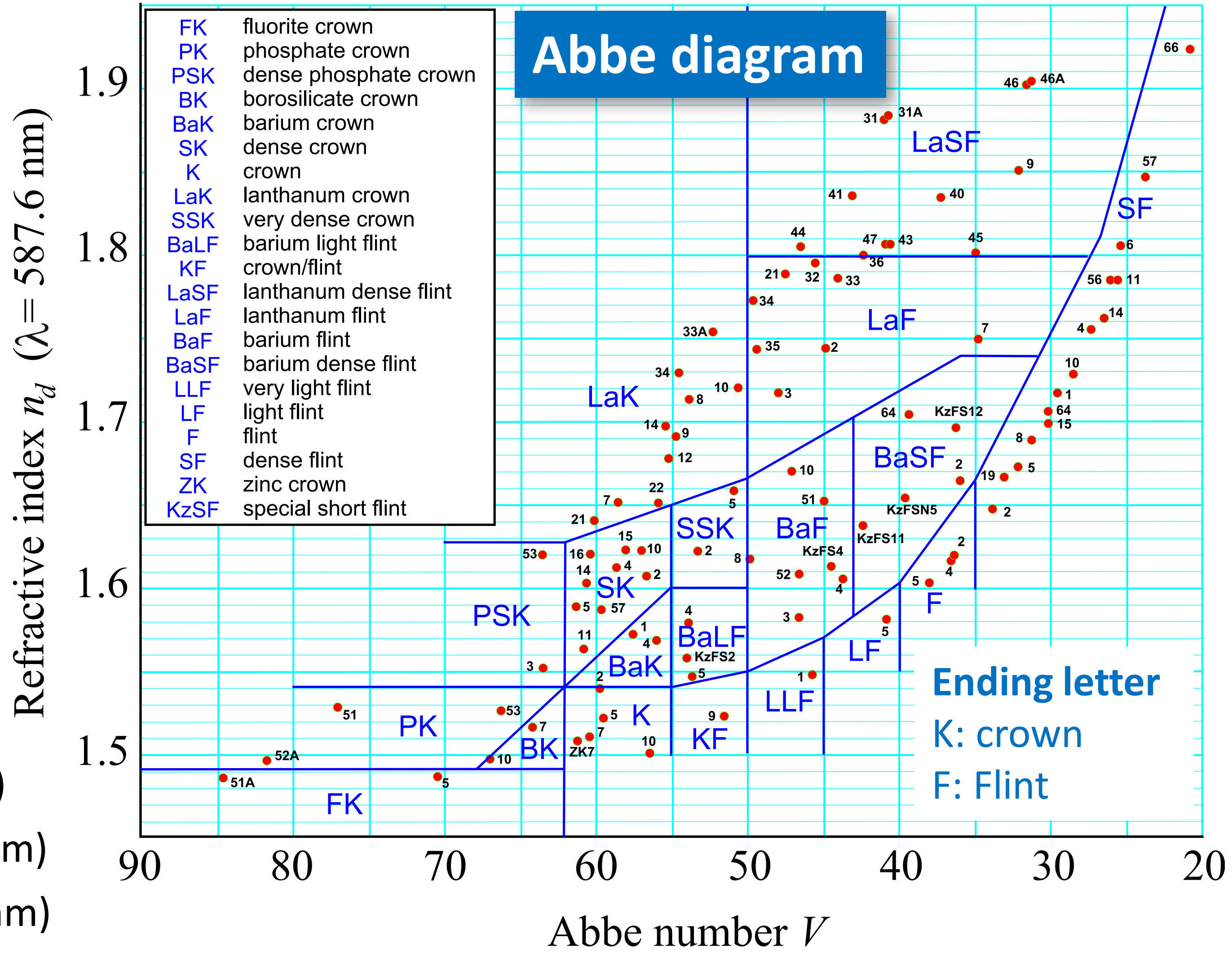
Abbe number (V number)

$$V = \frac{n_d - 1}{(n_F - n_C)}$$

n_d Helium d-line (588 nm)

n_F Hydrogen F-line (486 nm)

n_C Hydrogen C-line (656 nm)



About Glass Names

- Different glass company has different names for the similar types of glass
- ZEMAX OpticStudio provides a comprehensive library of glass

Names of BK7 according to the manufacturers[5]

Glass family	n_d	ν_d	International Coding MIL-G-174-B	Codifications of the main producers								
				Schott	Pilkington	Hoya	Ohara	Sumita	Corning	CDGM	Nikon-Hikari	Potapenko
Crown borosilicate	1.51680	64.17	517-642	N-BK7	BSC517642	BSC7[6]	S-BSL7[7]	K-BK7	B16-64[6]	D/H-K9L	J-BK7	K8[8]

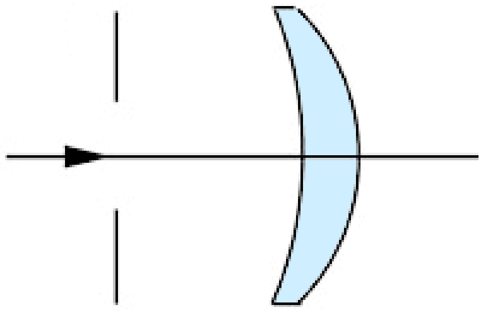
Source: Wikipedia.org

EPFL STI MICRO-517

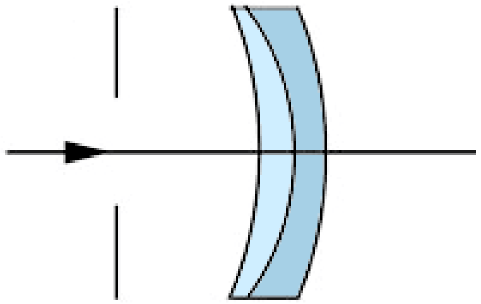
Camera Lens

- Historically (over 200 years) and still a rich mine
- Most important items in the specification:
  - F-number (the "speed" of the system)
  - Field angle (object field angle *w* or the full field angle 2*w*)
  - Image quality (resolution, modulation transfer function) on axis and its homogeneity in the field.
- Review of historically significant lens types and design strategy combating aberrations provides rich insights

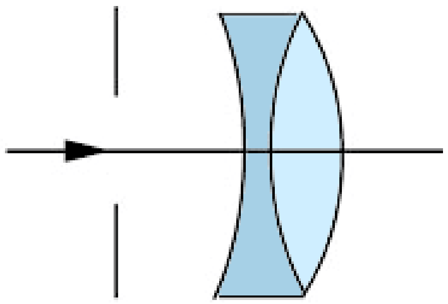
Camera Lens | Landscape Lens



Wollaston 1812



Chevalier 1840

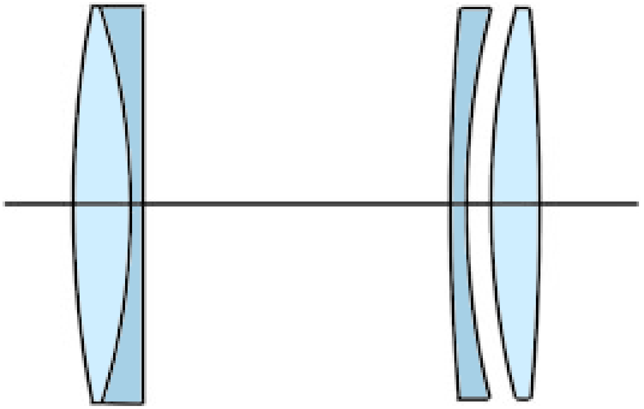


Grubb 1857

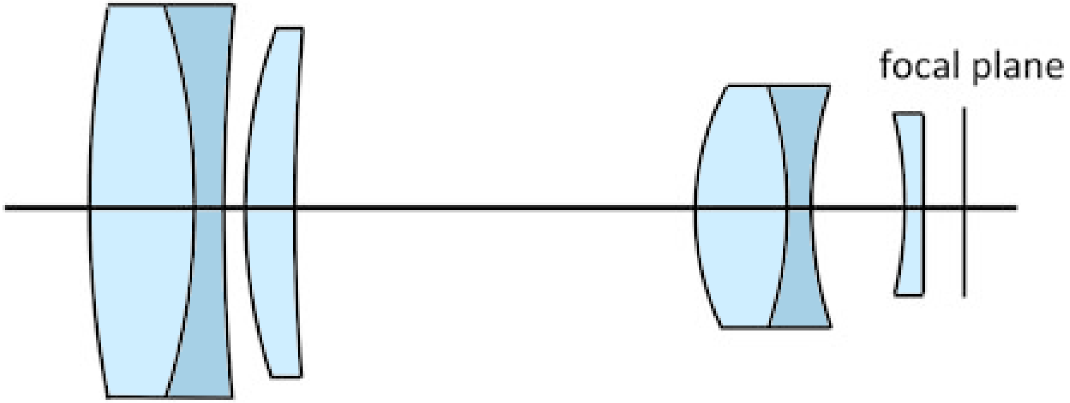
Landscape lens

- Single lens with a remote stop
- Two models: stop in front or behind the lens
- Uncorrected spherical and chromatic aberration
- Large F-number, typically F/15
- Moderate resolution: ~15 lp/mm on axis, ~10 lp/mm over a field of $2w$ = 30 – 40° with a focal length of f = 100 mm
- Color corrected model: Chevalier (1840) and Grubb (1857)

Camera Lens | Petzval and Ektar Lens



Petzval 1840

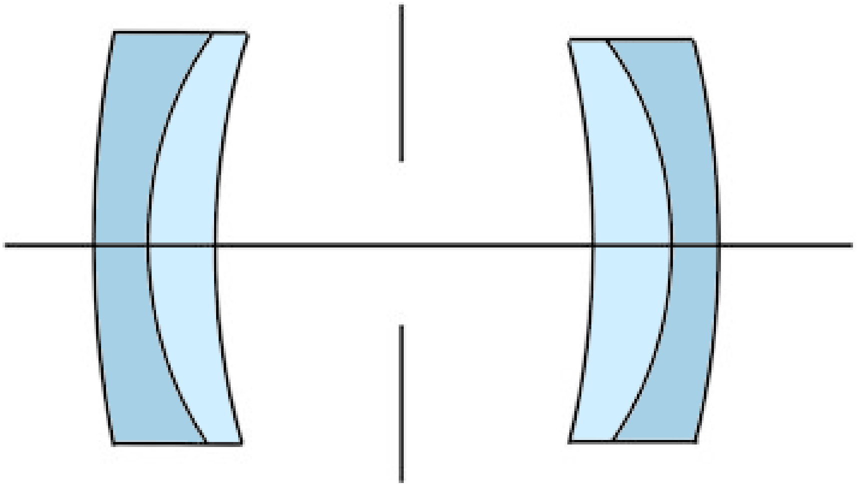


Kodak Projection Ektar, Schade 1948

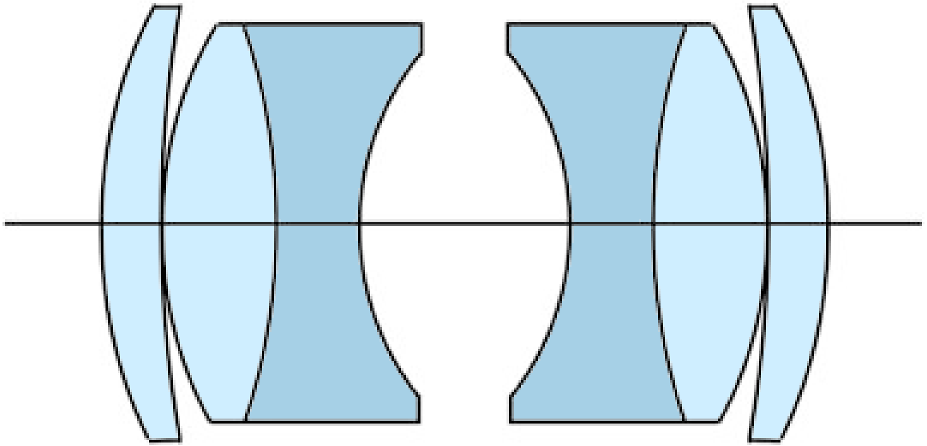
Petzval portrait lens

- Two doublets with an airspace in the second
- Much smaller F-number: F/3.4 over a field of 2*w* = 32°
- Excellent on-axis correction, resolution 25 lp/mm but much worse in the field
- Application: Kodak Projection Ektar, Schade (1948), f = 56 mm, F/1.5, field 16 mm
- Resolution 90 lp/mm over the entire field

Camera Lens | Rapid Rectilinear and Planar



Rapid Rectilinear Lens, Dallmeyer 1866



Zeiss Planar Lens, Rudolph 1896

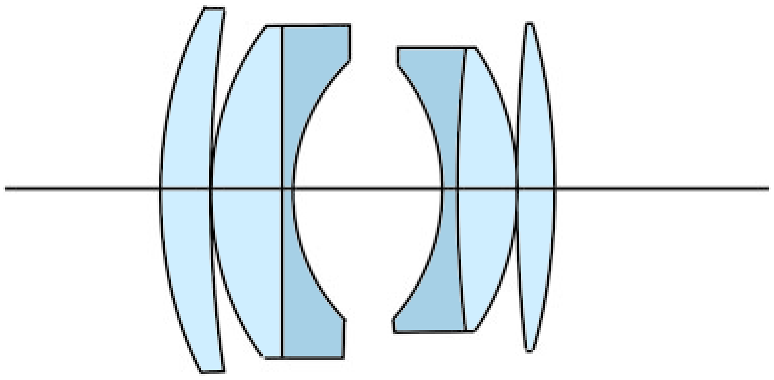
Rapid rectilinear lens

- Aberrations improved by larger distances between components and a symmetric structure
- F/8, 2*w* = 50°
- Excellent correction of coma, distortion and TCA
- Field curvature is well corrected
- Uniform resolution over the field ~20 lp/mm

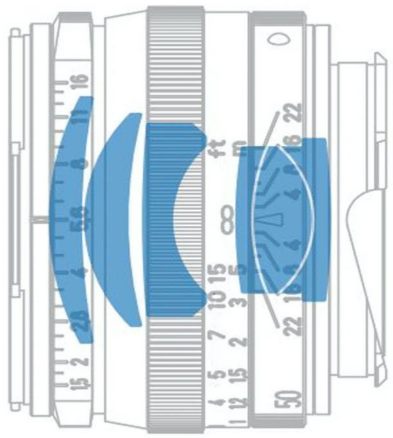
Zeiss Planar lens

- Further development of Rapid Rectilinear
- Two more components
- ''Buried surfaces'': small refractive index step, moderate V-number difference
- F/4.5, 2*w* = 40°, center resolution ~30 lp/mm
- Considered a prototype of double Gauss

Camera Lens | Double Gauss



Leica Leitz Summicron, Mandler 1976 (US4123144)

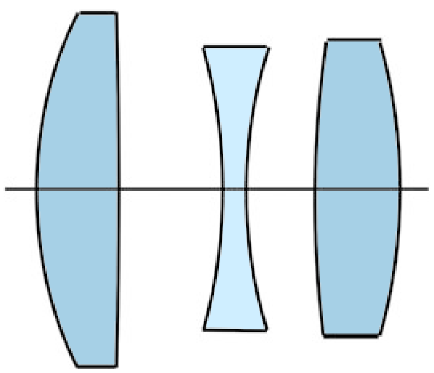


Carl Zeiss C Sonnar T* 50mm F/1.5 ZM, Today

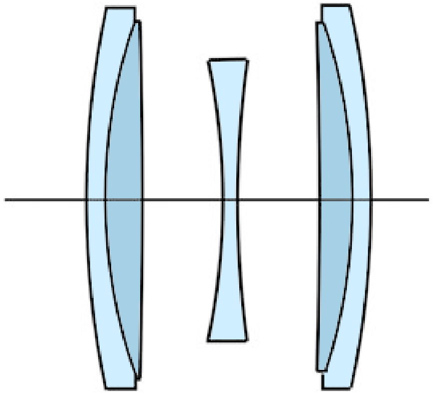
Double Gauss lens

- First made by H. W. Lee (Opic 1920): f = 50 mm, F/2, 2w = 44°, uniform resolution 30 lp/mm
- Further developed by von Hoegh (Celor 1897): f = 100 mm, F/5 (F/3.5 later), 2w = 60°
- Completely or nearly completely symmetric
- Large distances between elements: good correction for astigmatism
- Modest asymmetry: easy correction of asymmetric aberrations (coma, distortion, TCA)
- Most intensely studied lens structure in history

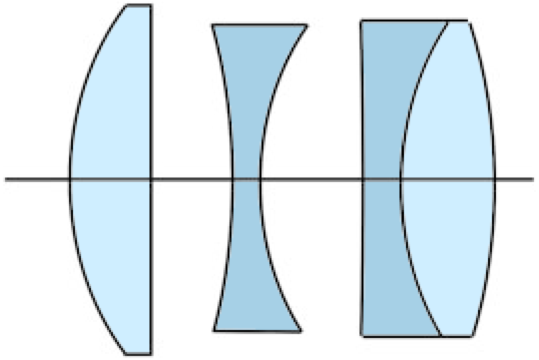
Camera Lens | Triplet



Cooke Triplet, Taylor (1895)



Heliar, Harting (1902)



Tessar, Rudolph 1901

Cooke triplet

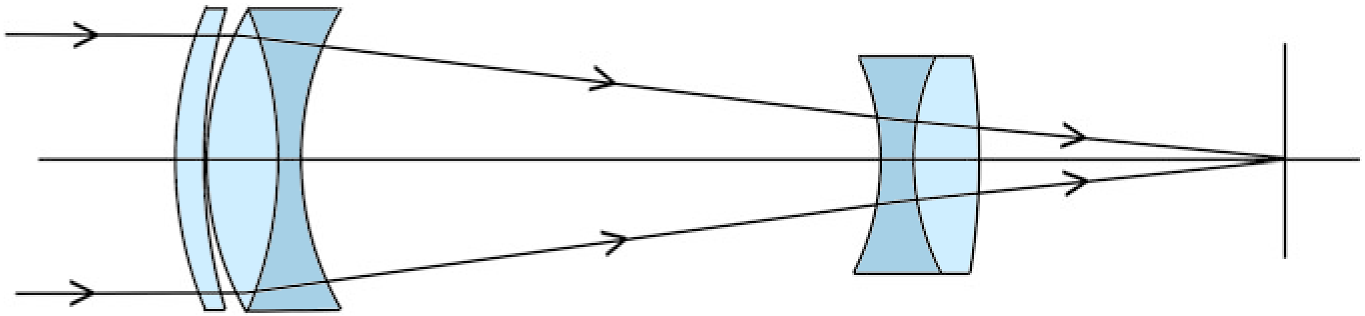
- Cooke Triplet: Designed using an analytical method
- Near-symmetric system, stop near the middle lens
- Field angles from 10° to 35°, F# 12 — 3
- 8 **degrees-of-freedom (DOM)** : 3 powers + 2 distances + 3 lens forms
    - Fix the system power and the Petzval sum (field curvature)
    - Correct LCA, TCA, and most of distortion
    - Lens forms: correction of spherical, coma and astigmatism
- Many different forms and variants (e.x. Heliar)

Zeiss Tessar

- Not developed as a triplet
- Usually assigned to triplet family

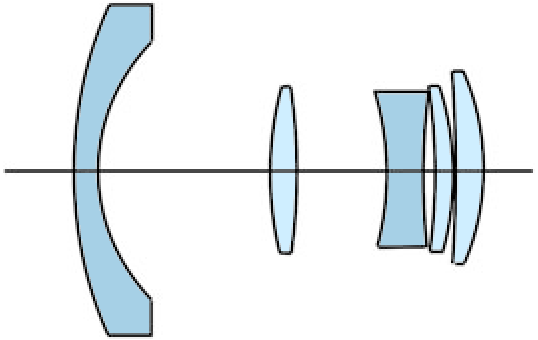
Camera Lens | Telephoto and Wide-angle Lens

Telephoto lens

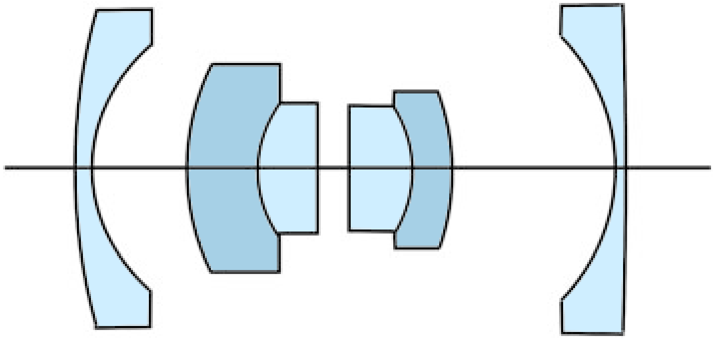


- Consists of a positive (first) and a negative (second) component
- Focal length much larger than the distance from its first surface to its focal plane
- Field curvature easy to correct
- Distortion more difficult to correct

Wide-angle lens

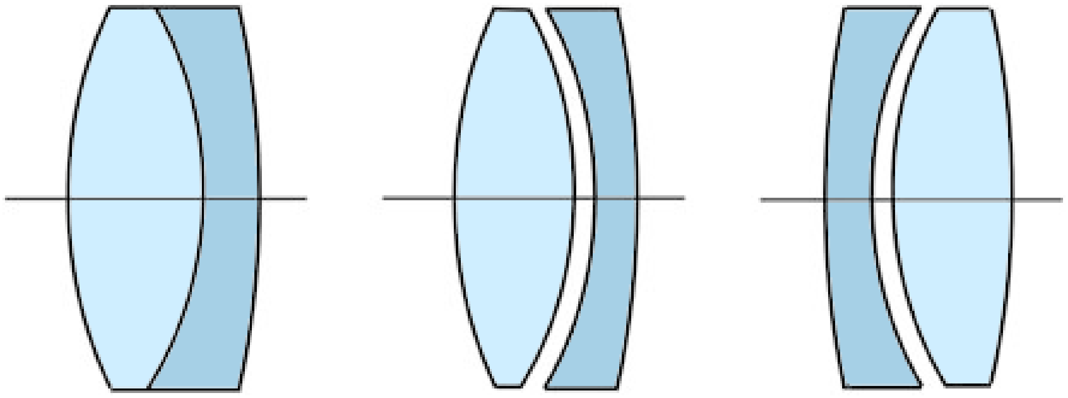


Retrofocus Lens

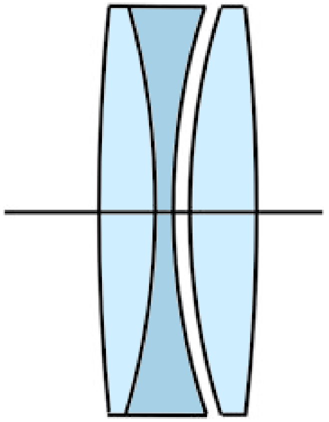


Angulon, Bertele 1951

Refracting Telescope Objective



Cemented Fraunhofer Steinheil



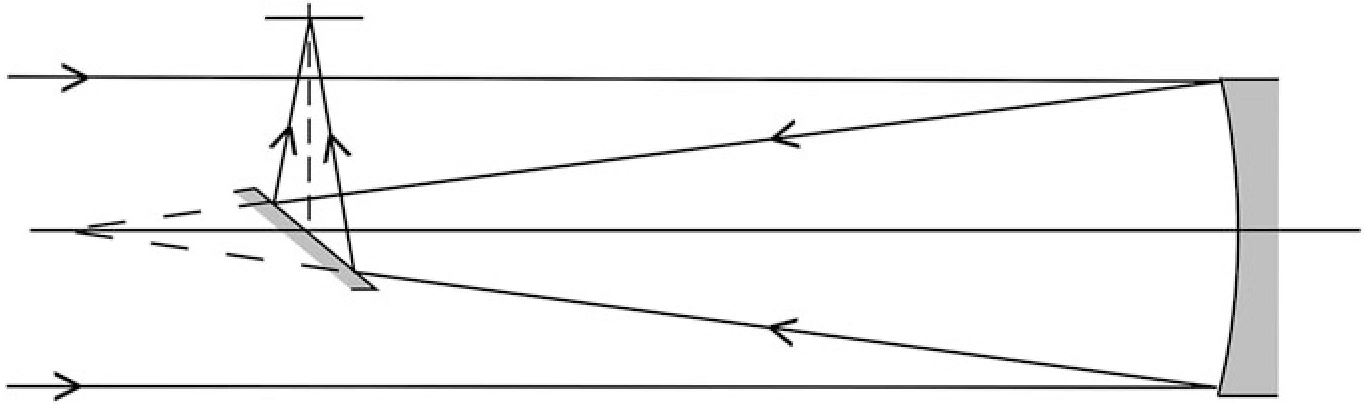
Doublets

- Telescopes:
  - Small field angle (w ~ 3°)
  - Modest aperture (~ F/5)
- Correction for spherical aberration
- Correction for two colors (**achromatic**)
- Secondary color
- Terrestrial use

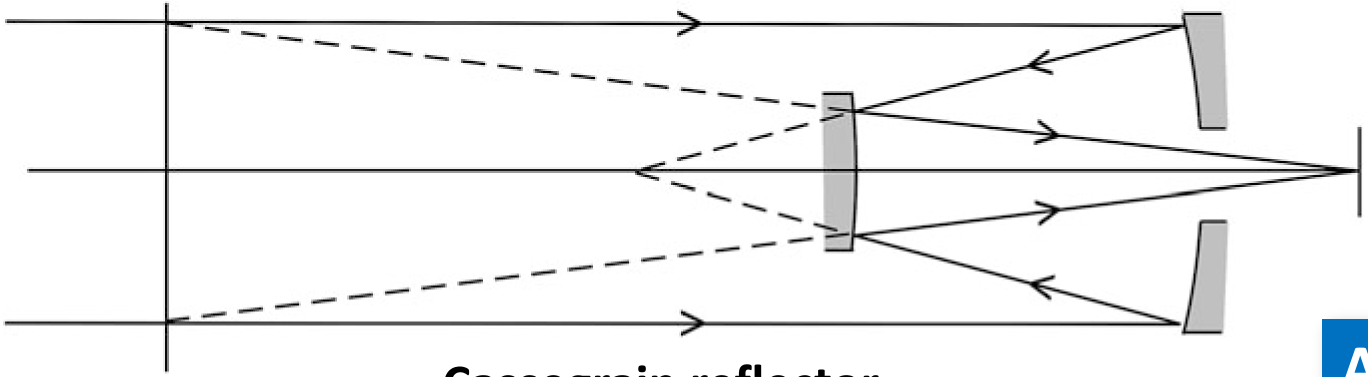
Triplets

- Correction for three colors (**Apochromatic**)
- For astronomical use

Astronomical Telescope



Newton's telescope



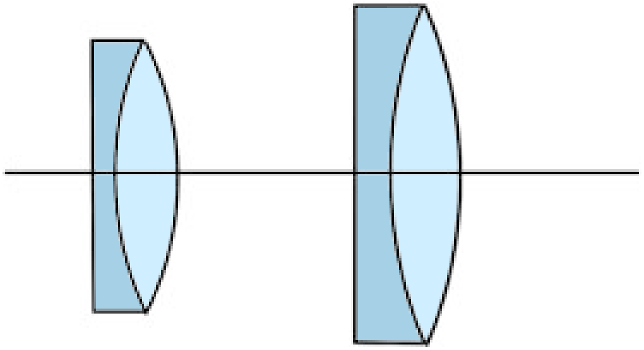
Cassegrain reflector

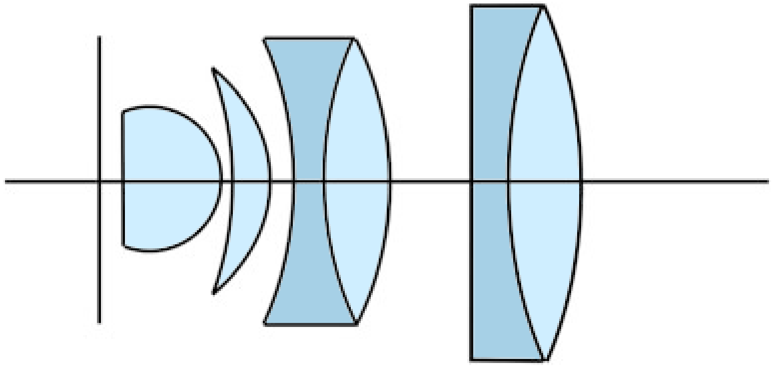
- Used in all modern large astronomical telescopes
- Aspheric (paraboloid) primary mirror
  - Perfect on-axis
  - Coma in the field
  - Field limited to 10 min of arc at aperture angle *u'* = 5° (~ F/5)
- Aspheric (hyperboloid) secondary mirror improves correction
  - Field of 1° at ~ F/5
- With concentric surfaces and an aspheric corrector plate
  - Field of 6° at ~ F/3

Angular Resolution

$$\delta\overline{u} = \frac{0.6\lambda}{f \sin u'}$$

Microscope Objective





Lister objective

- Microscope objective:
  - Small field angle ($w \sim 2$–$3°$)
  - Large aperture ($n \sin u \sim 0.25$–1.4)
- Lister objective: simplest objective
- f = 9.5 mm 10× 0.2 NA

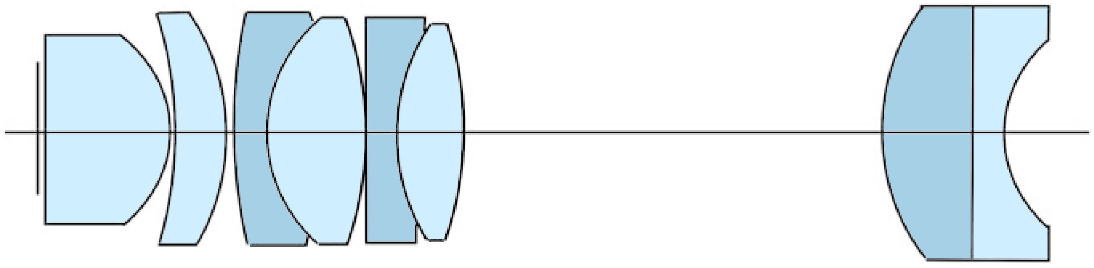
Amici objective

- Amici objective: Lister objective + aplanatic front lenses
- f = 4.4 mm 40 × 0.6–0.7 NA
- Achromatic (secondary color)
- Large field curvature

Magnification $M = -\left(1 + \frac{t}{f'}\right)$

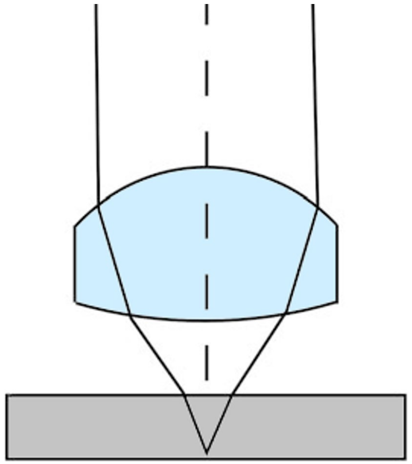
Spatial resolution $\delta\eta = \frac{0.6\lambda}{n \sin u} = \frac{0.6\lambda}{NA}$

Microscope Objective



Plan-apochromatic objective

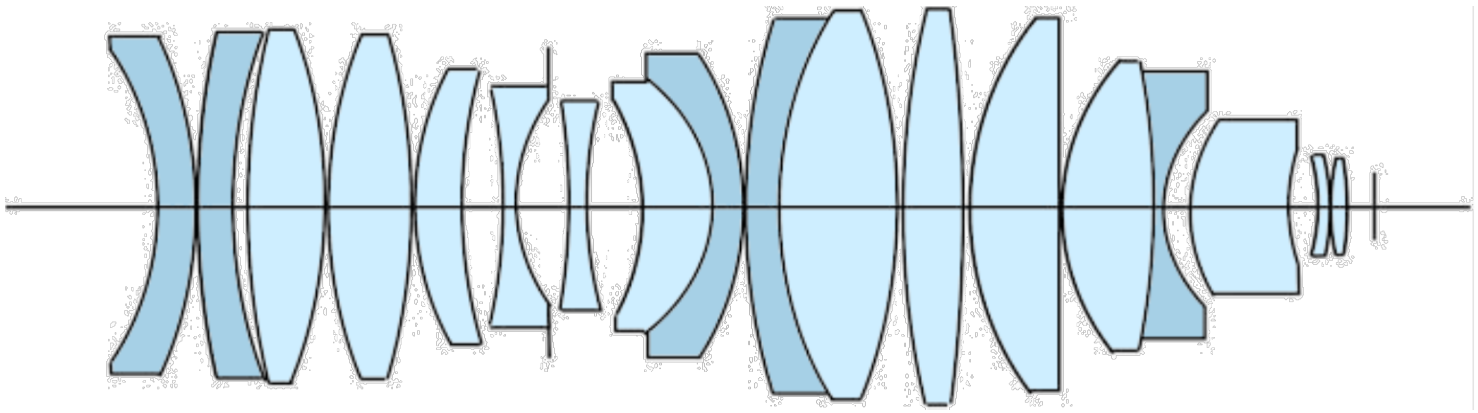
- Correction for
- Secondary color
- Field curvature
- f = 3 mm 0.7 NA



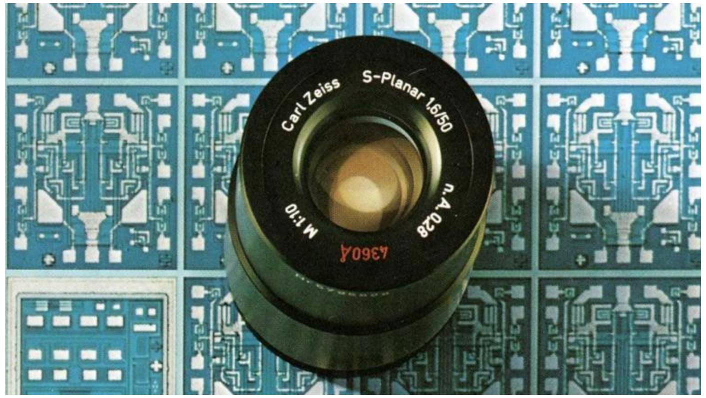
Optical disc player objective

- Related to microscope objectives
- A single lens with aspheric surfaces
- Aplanatic system
- 0.45–0.55 NA
- Field <0.2 mm
- Diameter of focus spot ~ 1 µm

Lithographic (Stepper) Lens



Stepper Lens, Williamson 1992

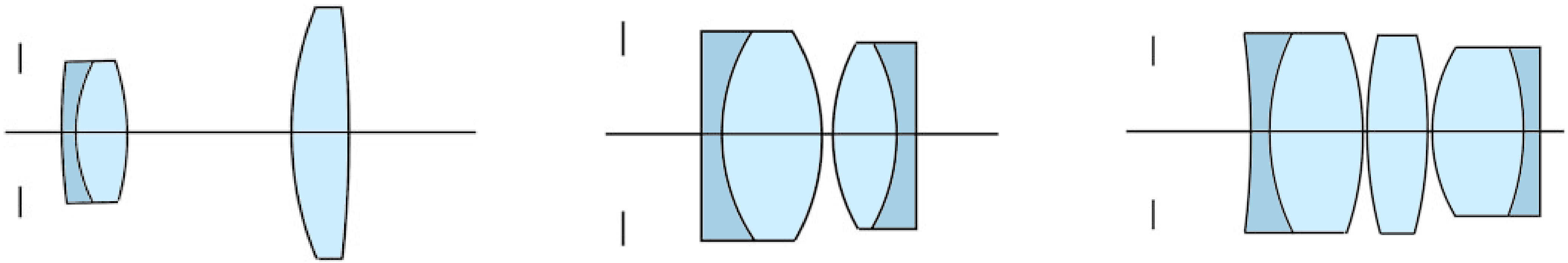


Zeiss S-Planar 10/0.28, 1977

Zeiss DUV Stepper Lens

- Projection systems for photolithography
- Considered stemming from flat-field microscope objectives
- Zeiss S-Planar objective: crucial for the development
- Williamson 1992 stepper lens:
  - Field diameter 24 mm 5× reduction 0.42 NA
  - Working with mercury I-line (366.5 nm). Resolution 0.5 µm
  - Wavefront errors < λ/4 over whole field, Distortion < 50 nm

Ocular (Eyepiece)



Kellner, 1849   Plössl, 1860   Erfle, 1917

Kellner ocular

- First modern eyepiece
- Resembles Ramsden with better color and coma correction
- Eye relief ~ 0.5 *f*
- *w* ~ 25°

Plössl ocular

- a.k.a. symmetrical ocular
- Two cemented doublets
- Eye relief up to 0.8 *f*
- *w* ~ 30°

Erfle ocular

- Further development of Plössl
- One additional lens
- Wide field ocular
- *w* > 40°

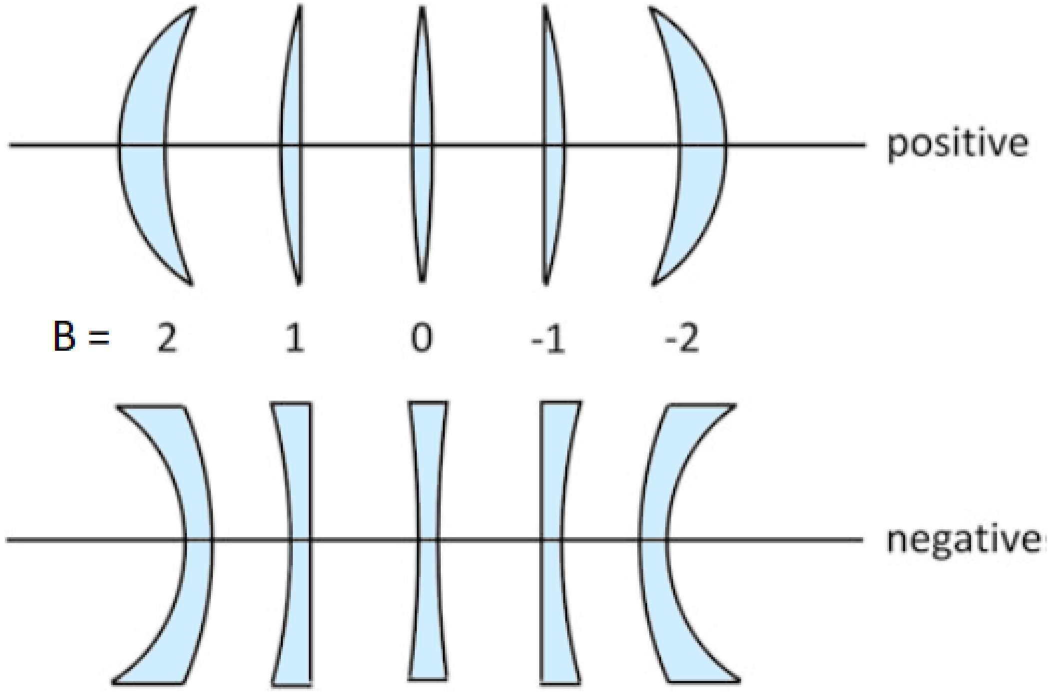
From Layout to Surface Model

Specification → Layout → Thin-lens Predesign → Surface Model → Optimization → Tolerancing

- Transition steps between the lay-out and optimization
- Insight in the overall the aberrations of the system
- After lay-out completed:
  - Component powers of the lens is known
  - Distances between the components (and to object and image) is known
  - Optical glasses have been chosen
  - Longitudinal and transverse chromatic aberrations have been corrected
  - Petzval sum is given (to a first approximation)
  - Distortion has been corrected (to a first approximation)
- Remaining degrees of freedom (bending of lenses, stop position):
  - Other aberrations can be corrected
  - Distortion can be fine-tuned
- After transition to real lenses (surface model), the system is ready for optimization

Thin-lens Predesign

- Important feature: Analytical Seidel coefficients



Shape factor: $$B = \frac{c_1 + c_2}{c_1 - c_2}$$

Position factor: $$G = \frac{s' + s}{s' - s} = \frac{M + 1}{M - 1}$$

Given K and B:

$$c_1 = \frac{1}{2}(B+1)\frac{K}{n-1}$$

$$c_2 = \frac{1}{2}(B-1)\frac{K}{n-1}$$

Thin-lens Predesign

Seidel coefficients (lens at the stop):

$$S_1 = \frac{h^4 K^3}{4}\left\{\frac{n+2}{n(n-1)^2}B^2 + \frac{4(n+1)}{n(n-1)}BG + \frac{3n+2}{n}G^2 + \frac{n^2}{(n-1)^2}\right\}$$ **Spherical**

$$S_2 = -\frac{h^2 K^2 H}{2}\left(\frac{n+1}{n(n-1)}B + \frac{2n+1}{n}G\right)$$ **Coma**

$$S_3 = H^2 K$$ **Astigmatism**

$$S_4 = \frac{H^2 K}{n}$$ **Field curvature**

$$S_5 = 0$$ **Distortion**

$$C_1 = \frac{h^2 K}{V}$$ **LCA**

$$C_2 = 0$$ **TCA**

K, H, n, G, and V are known from layout

Thin-lens Predesign

Seidel coefficients (remote stop):

$$S_1^* = S_1$$ **Spherical**

$$S_2^* = S_2 + \frac{\bar{h}}{h} S_1$$ **Coma**

$$S_3^* = S_3 + 2\frac{\bar{h}}{h} S_2 + \left(\frac{\bar{h}}{h}\right)^2 S_1$$ **Astigmatism**

$$S_4^* = S_4$$ **Field curvature**

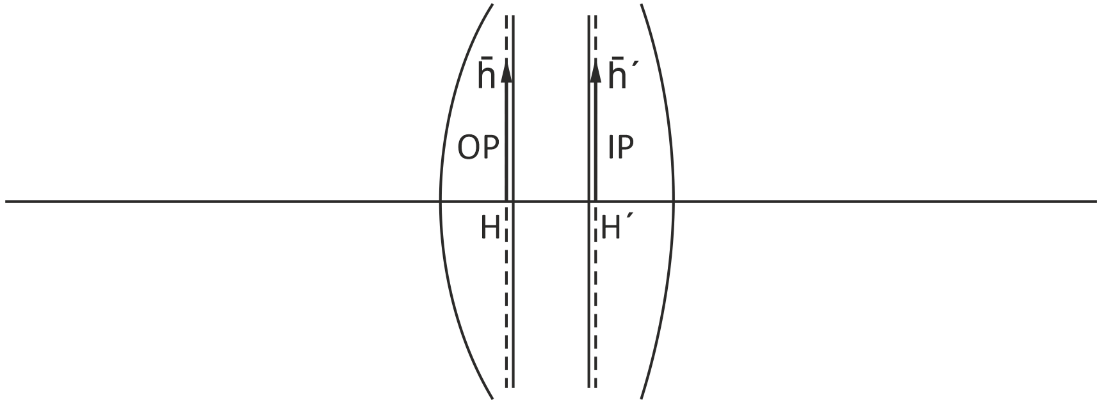
$$S_5^* = S_5 + \frac{\bar{h}}{h}\left(3S_3 + S_4\right) + 3\left(\frac{\bar{h}}{h}\right)^2 S_2 + \left(\frac{\bar{h}}{h}\right)^3 S_1$$ **Distortion**

$$C_1^* = C_1$$ **LCA**

$$C_2 = C_2 + \frac{\bar{h}}{h} C_1$$ **TCA**

Thin-lens Predesign

Seidel coefficients (thin lens on plane conjugated to object, field lens):



$$S_1 = S_2 = S_3 = S_5 = 0$$

~~Spherical~~ **~~Coma~~** **~~Astigmatism~~** **~~Distortion~~**

$$S_4 = \frac{H^2 K}{n}$$ **Field curvature**

$$C_1 = \frac{h^2 K}{V}$$ **LCA**

$$C_2 = \frac{h\bar{h}K}{V}$$ **TCA**

Thin-lens Predesign

Zero spherical aberration condition:

From definition $$B = \frac{2\left(1-n^2\right)}{n+2}G \qquad n = 1.5 \;\Rightarrow\; B \approx -0.7G$$

Minimum value $$S_{1,\min} = \frac{h^4K^3}{4}\left(\frac{n^2}{\left(n-1\right)^2} - \frac{n}{n+2}G^2\right)$$

$S_{1,\min} = 0$ for $n = 1.5$ when $G^2 = 21$

Zero Coma condition: $$B = \frac{\left(n-1\right)\left(2n+1\right)}{n+1}G$$ for $n = 1.5$ $\quad B = -0.8G$

Correction of Thin-lens Systems

Knowing h, H, K, n, and G from layout:

When lens is at the stop

S1 is quadratic of B

S2 is linear of B

S3 and S4 are constants

S5 is zero

When lens has a remote stop

Paraxial ray trace for $\bar{h}$

S1* is quadratic of B

S2* is linear of B

S3* is quadratic of B

S4* does not depend on B

S5* is quadratic of B

Seidel sum $S_j = \sum_{i=1}^{k} S_{j,i}, j = 1,2,3,5$ is a quadratic function of Bi

Setting target aberration coefficients, solve the equations (*k* lenses, *m* aberrations) for Bi

Degree of freedom: *k* + 1 ➡

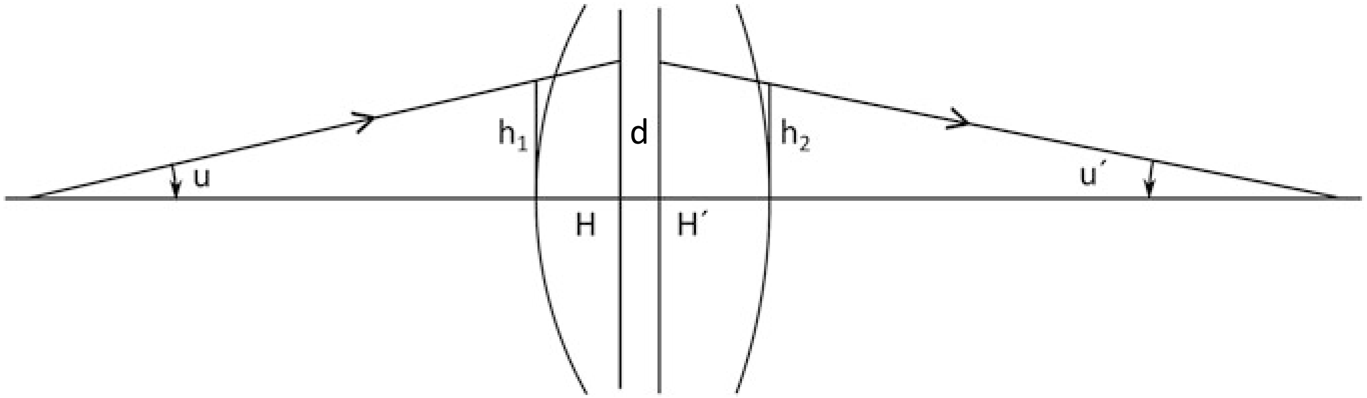
k + 1 > m: possible to correct all aberrations

k + 1 = m: hopeful to correct all aberrations

k + 1 < m: not possible to correct all aberrations

Surface Model

- **Purpose:** to give the thin lens a thickness to build a real lens
- **Problem:** optical power changes with thickness!
- **Solution:** Adjustments in the surface curvature



In a thin lens (d = 0) $K^{(thin)} = K_1^{(thin)} + K_2^{(thin)}$

When d is nonzero $K^{(new)} = K_1^{(thin)} + K_2^{(thin)} - \dfrac{dK_1^{(thin)} K_2^{(thin)}}{n}$

Procedure

- Insert a thickness between surfaces 1 and 2 of each lens
  - 10–15% of its diameter for a positive lens
  - Minimum 1.5 mm at the edge
  - Thickness > 6% of lens diameter for a negative lens
- Calculate the new power $K^{(new)}$
- Scale r_1, r_2, and d by

$$\frac{K^{(new)}}{K_1^{(thin)} + K_2^{(thin)}}$$

- After adjustment, K is restored to its original value:

$$K^{(thick)} = K^{(thin)} = K_1^{(thin)} + K_2^{(thin)}$$

Homework

To be announced