Institute of Applied Physics
Friedrich-Schiller-Universität Jena

Lens Design I

Lecture 10: Optimization II

2024-06-20

Yueqian Zhang

Preliminary Schedule - Lens Design I 2024

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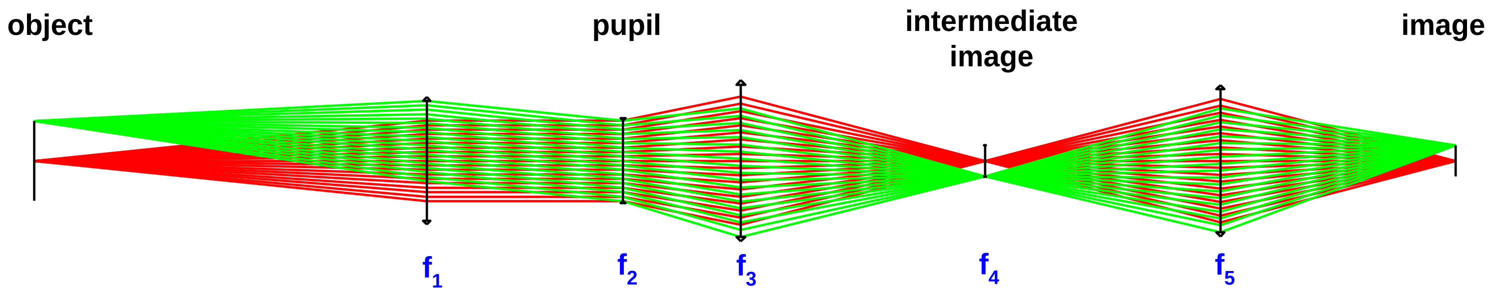
1	04.04.	Basics	Zhang	Introduction, Zemax interface, menues, file handling, preferences, Editors, updates, windows, coordinates, System description, 3D geometry, aperture, field, wavelength
2	18.04.	Properties of optical systems I	Tang	Diameters, stop and pupil, vignetting, layouts, materials, glass catalogs, raytrace, ray fans and sampling, footprints
3	25.04.	Properties of optical systems II	Tang	Types of surfaces, cardinal elements, lens properties, Imaging, magnification, paraxial approximation and modelling, telecentricity, infinity object distance and afocal image, local/global coordinates
4	02.05.	Properties of optical systems III	Tang	Component reversal, system insertion, scaling of systems, aspheres, gratings and diffractive surfaces, gradient media, solves
5	16.05.	Advanced handling I	Tang	Miscellaneous, fold mirror, universal plot, slider, multiconfiguration, lens catalogs
6	23.05.	Aberrations I	Zhang	Representation of geometrical aberrations, spot diagram, transverse aberration diagrams, aberration expansions, primary aberrations
7	30.05.	Aberrations II	Zhang	Wave aberrations, Zernike polynomials, measurement of quality
8	06.06.	Aberrations III	Tang	Point spread function, optical transfer function
9	13.06.	Optimization I	Tang	Principles of nonlinear optimization, optimization in optical design, general process, optimization in Zemax
10	20.06.	Optimization II	Zhang	Initial systems, special issues, sensitivity of variables in optical systems, global optimization methods
11	27.06.	Correction I	Zhang	Symmetry principle, lens bending, correcting spherical aberration, coma, astigmatism, field curvature, chromatical correction
12	04.07.	Correction II	Zhang	Field lenses, stop position influence, retrofocus and telephoto setup, aspheres and higher orders, freeform systems, miscellaneous

Contents

Optimization: Starting Point

- Existing solution modified
- Literature and patent collections
- Principal layout with ideal lenses

  successive insertion of thin lenses and equivalent thick lenses with correction control



- Approach of Shafer

  AC-surfaces, monochromatic, buried surfaces, aspherics
- Expert system
- Experience and genius

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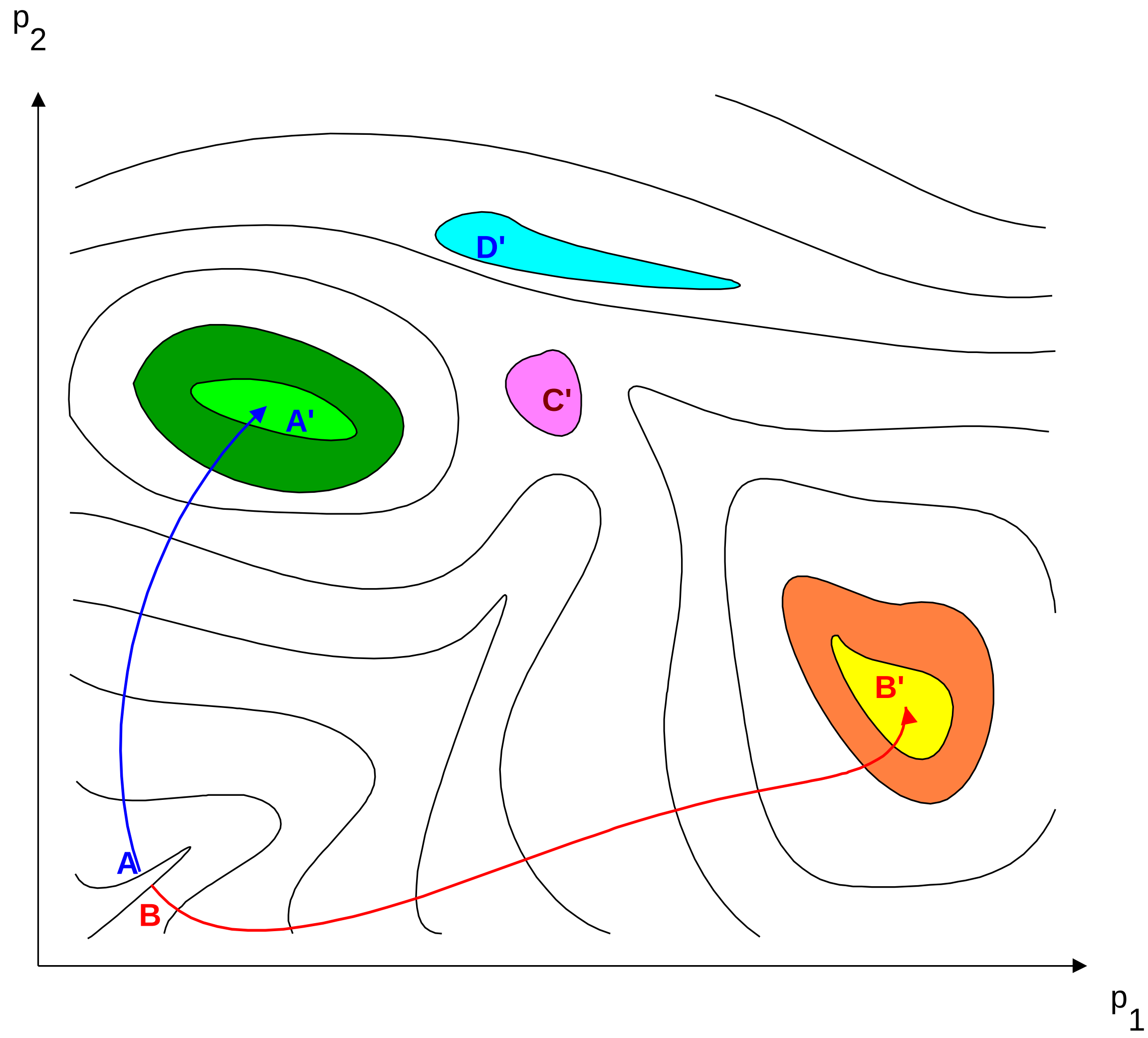
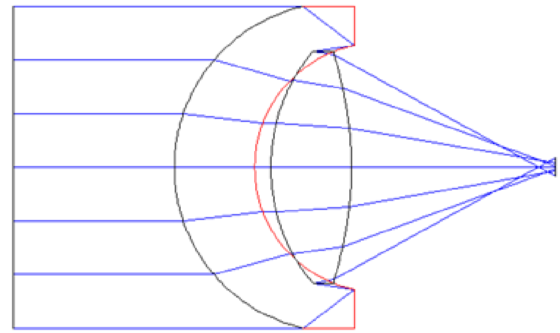
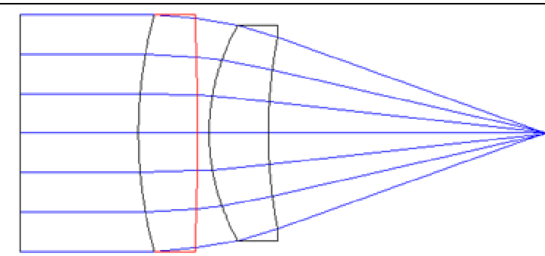
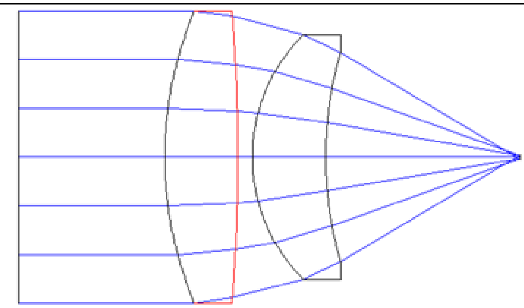
Optimization and Starting Point

- The initial starting point determines the final result
- Only the next located solution without hill-climbing is found



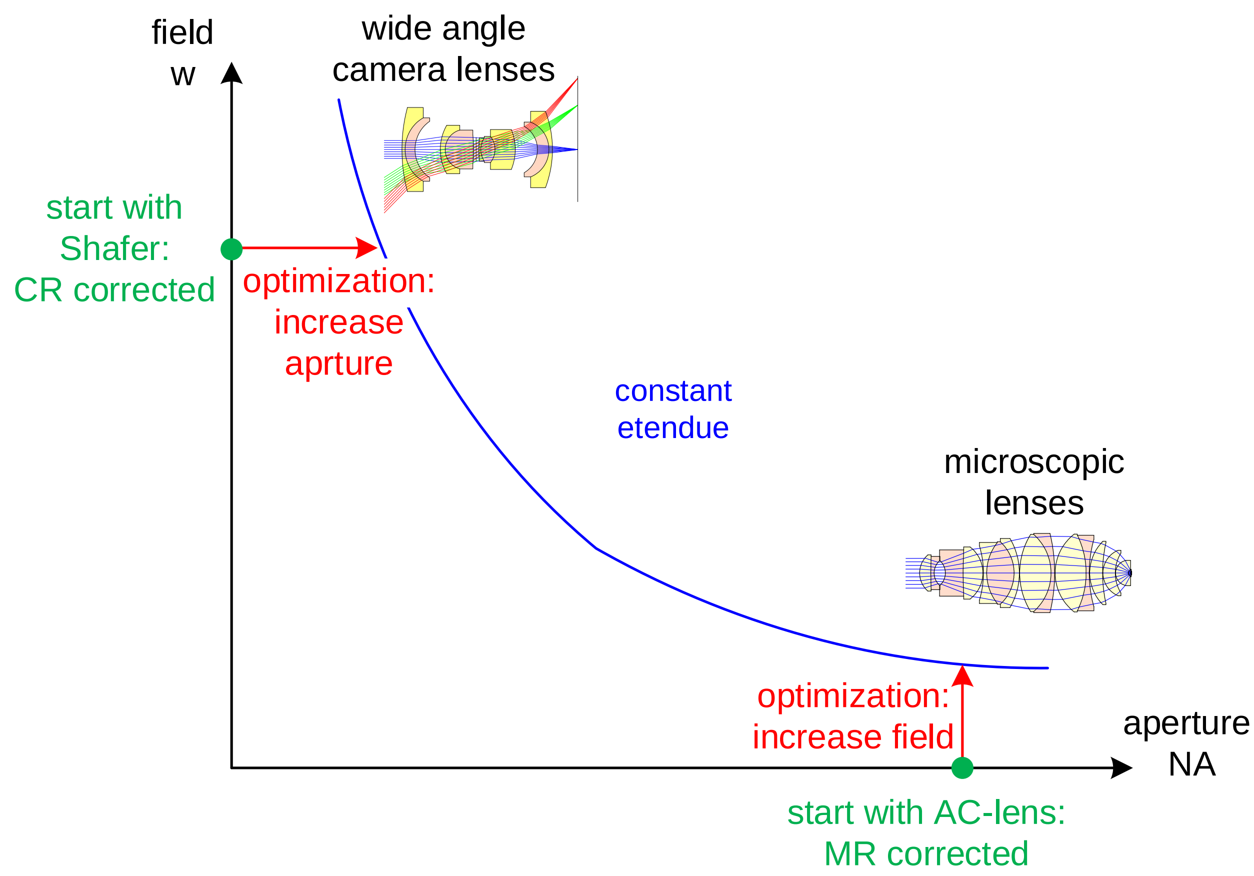
Initial System Influence

- Simple system of two lenses
- Criterion:
  spot on axis, one wavelength
- Starting with different radii of curvature:
  completly different solutions

No	Layout	Start radii	Rms spot size
a		0 - 0 - 0 - 0	184
b		0 - 0 - 0 - -20	39
c		+20 - 0 - 0 - 0	92

Initial Systems for Extreme Field / Aperture

- Large aperture: start with corrected marginal ray
- Large filed: start with corrected chief ray



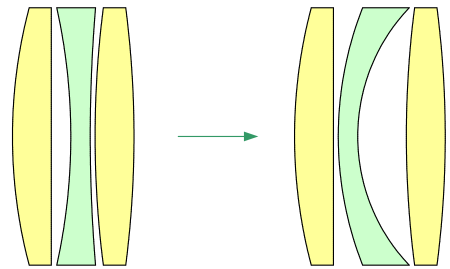
Zero-Operations

Operationen with zero changes in first approximation:

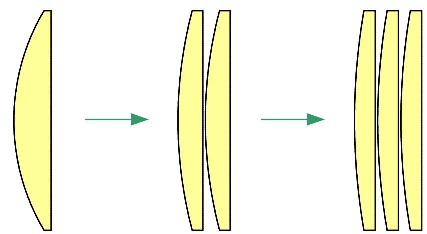
1. Bending a lens.
2. Flipping a lens into reverse orientation.
3. Flipping a lens group into reverse order.
4. Adding a field lens near the image plane.
5. Inserting a powerless thin or thick meniscus lens.
6. Introducing a thin aspheric plate.
7. Making a surface aspheric with negligible expansion constants.
8. Moving the stop position.
9. Inserting a buried surface for color correction, which does not affect the main wavelength.
10. Removing a lens without refractive power.
11. Splitting an element into two lenses which are very close together but with the same total refractive power.
12. Replacing a thick lens by two thin lenses, which have the same power as the two refracting surfaces.
13. Cementing two lenses a very small distance apart and with nearly equal radii.

Structural Changes for Correction

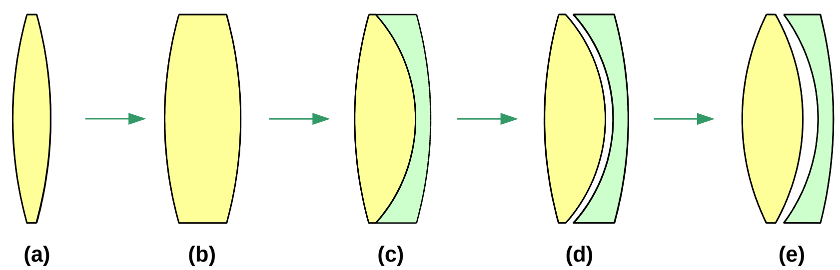
- Lens bending



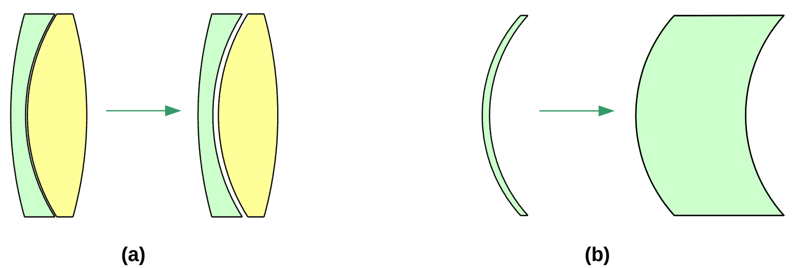
- Lens splitting



- Power combinations



- Distances



Ref : H. Zügge

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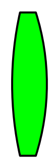
Principles of Glass Selection in Optimization

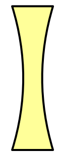
- Design Rules for glass selection

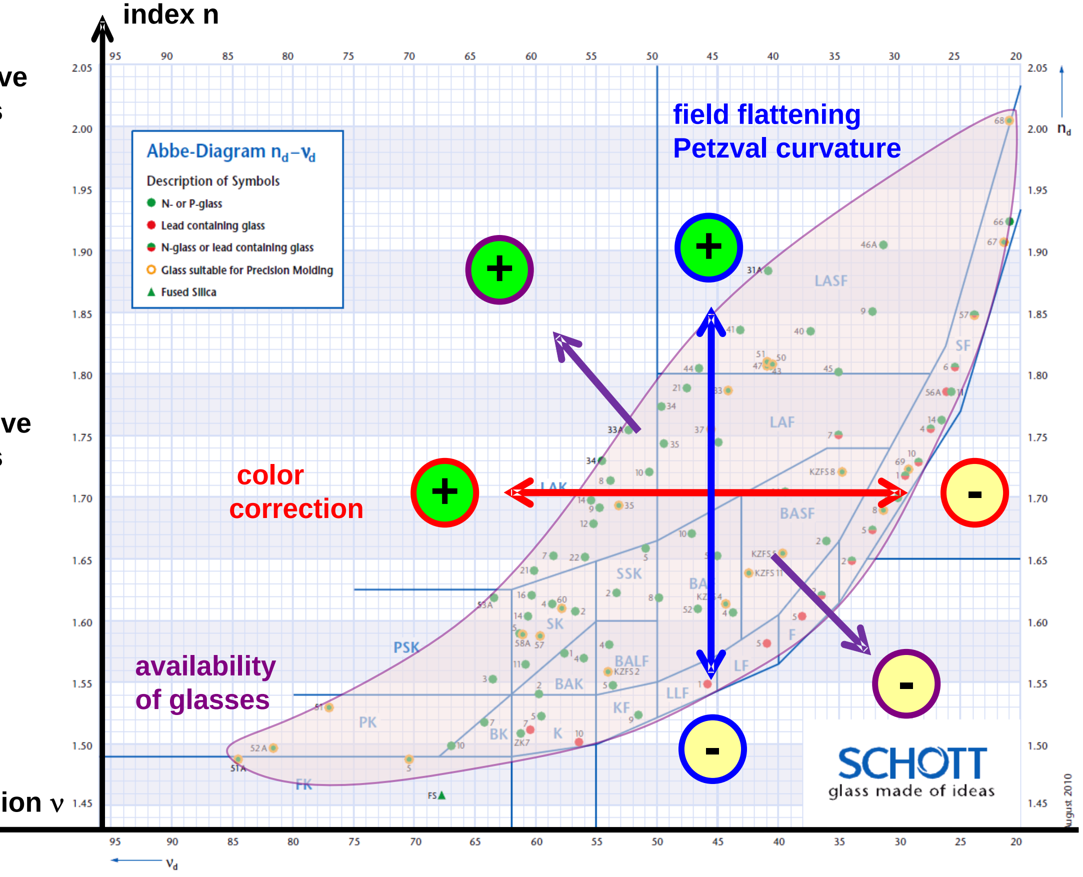
- Different design goals:
  1. Color correction:
     large dispersion
     difference desired
  2. Field flattening:
     large index difference
     desired

positive lens



negative lens





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Optimization: Discrete Materials

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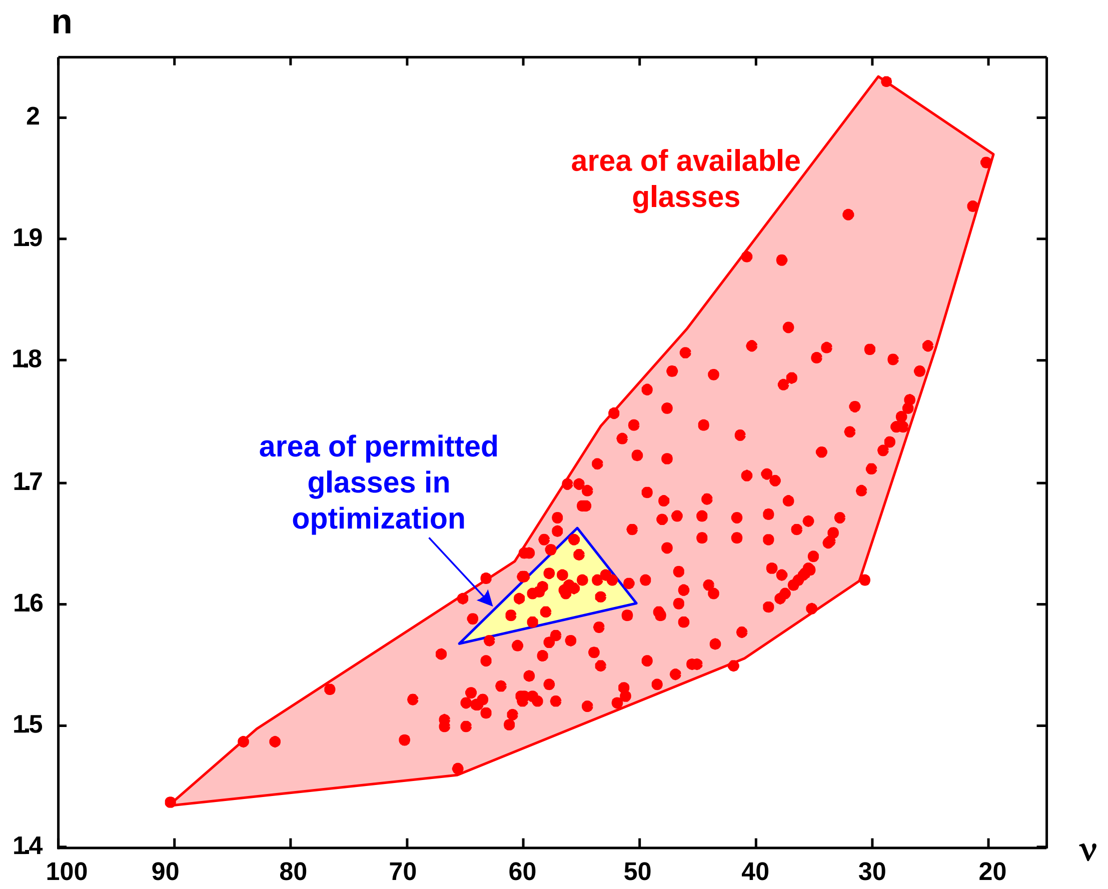
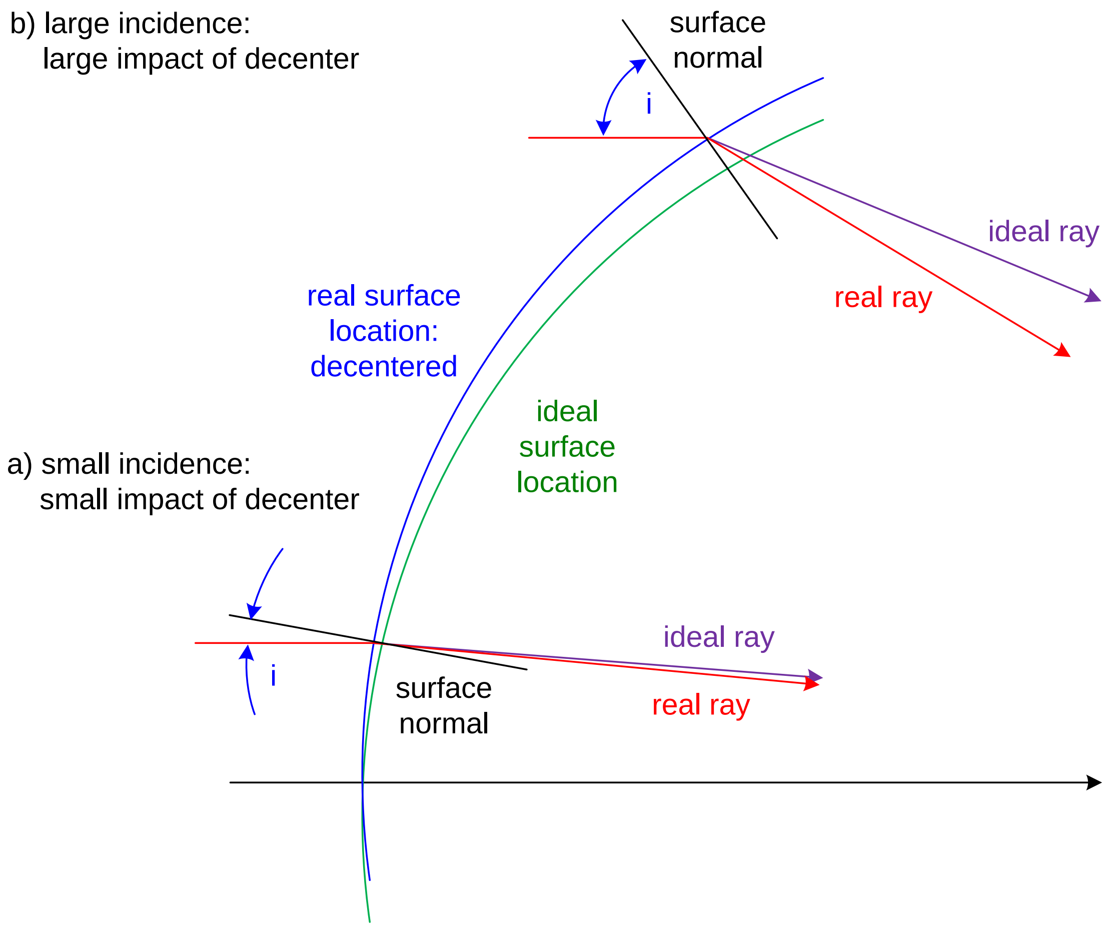
- Special problem in glass optimization: finite area of definition with discrete parameters n, ν
- Restricted permitted area as one possible contraint
- Model glass with continuous values of n, ν in a pre-phase of glass selection, freezing to the next adjacend glass



Sensitivity by large Incidence

- Small incidence angle of a ray:
  small impact of centering error
- Large incidence angle of a ray:
  - strong non-linearity range of sin(i)
  - large impact of decenter on
    ray angle



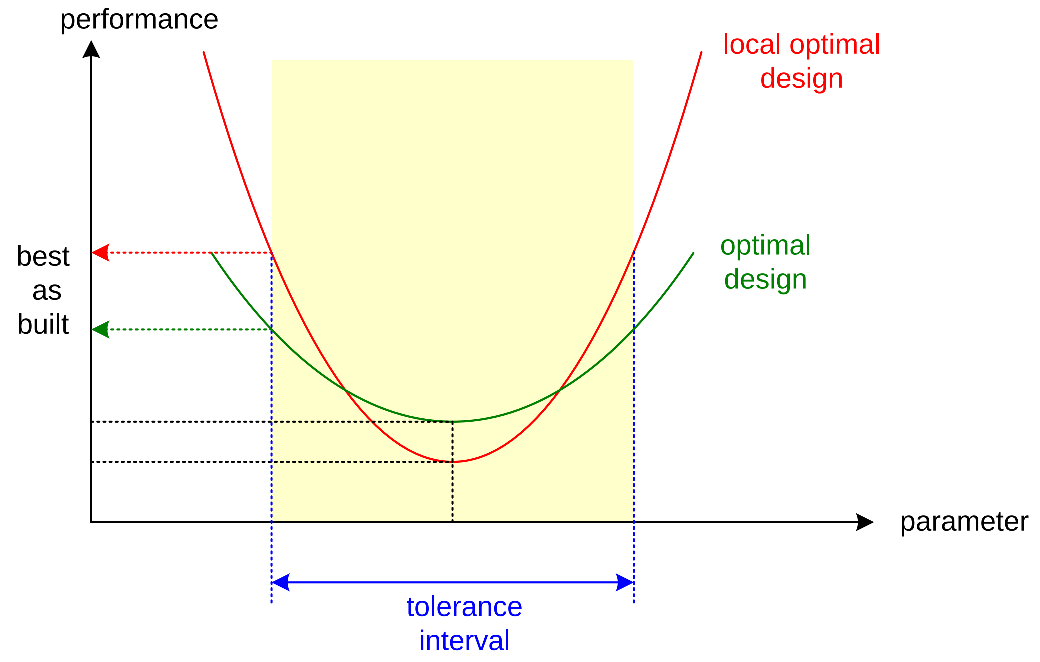
Ref: H. Sun

Sensitivity and Relaxation

- Reality:
  - as-designed performance: not reached in reality
  - as-built-performance: more relevant

- Possible criteria:
  1. Incidence angles of refraction
  2. Squared incidence angles
  3. Surface powers
  4. Seidel surface contributions
  5. Permissible tolerances

- Special aspects:
  - relaxed systems does not contain higher order aberrations
  - special issue: thick meniscus lenses



Sensitivity of a System

- Quantitative measure for relaxation

$$A_j = \omega_j \cdot \frac{F_j}{F} = \frac{h_j \cdot F_j}{h_1 \cdot F}$$

with normalization $\sum_{j=1}^{k} A_j = 1$

- Non-relaxed surfaces:
  1. Large incidence angles
  2. Large ray bending
  3. Large surface contributions of aberrations
  4. Significant occurence of higher aberration orders
  5. Large sensitivity for centering

- Internal relaxation can not be easily recognized in the total performance

- Large sensitivities can be avoided by incorporating surface contribution of aberrations into merit function during optimization

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Sensitivity of a System

- Sensitivity/relaxation:
  Average of weighted surface contributions of all aberrations

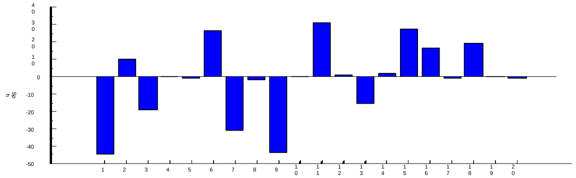
- Correctability:
  Average of all total aberration values

- Total refractive power

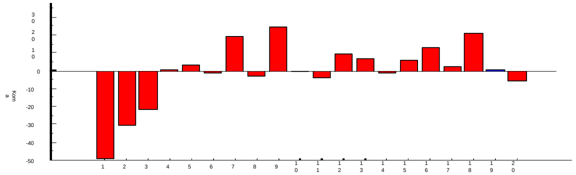
$$F = F_1 + \sum_{j=2}^{k} \omega_j F_j$$

- Important weighting factor:
  ratio of marginal ray heights

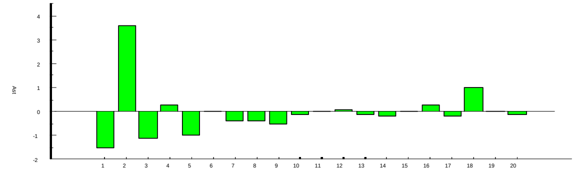
$$\omega_j = \frac{h_j}{h_1}$$



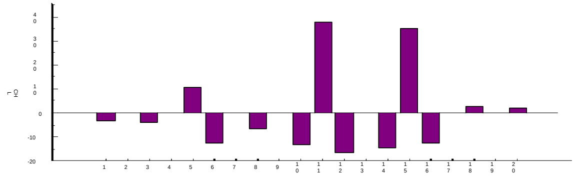
Sph



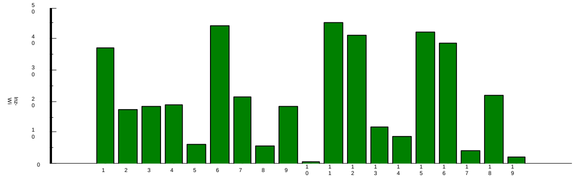
Coma



Ast



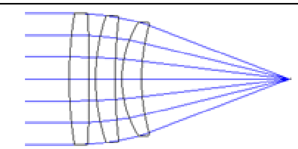
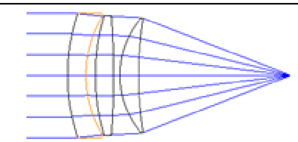
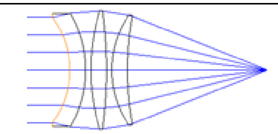
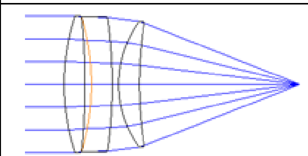
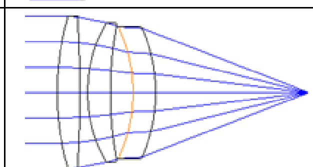
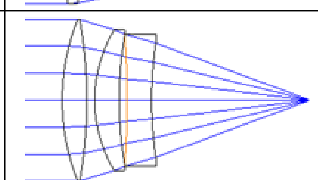
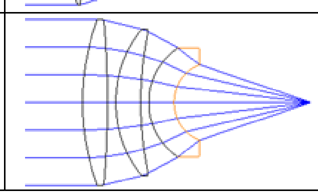
CHL



incidence angle

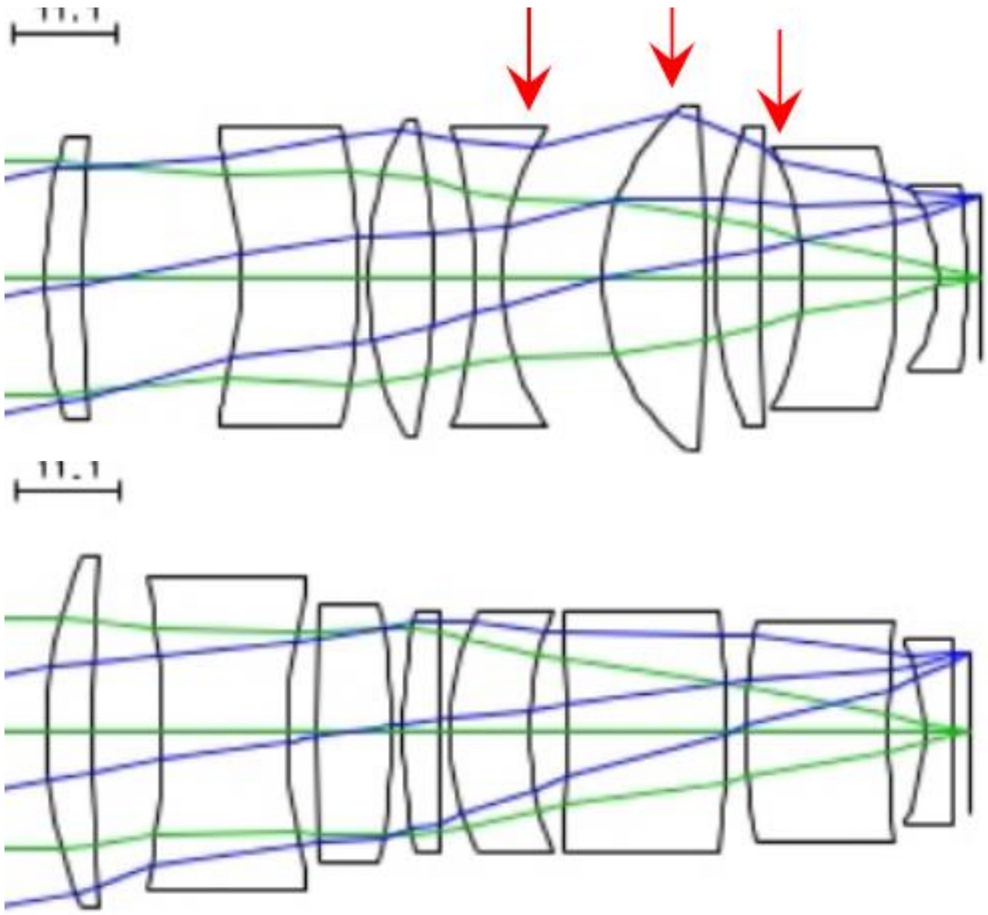
Design Solutions and Sensitivity

- Focussing
  3 lens with
  NA = 0.335
- Spherical correction with/without compensation
- Red surface: main correcting surface
- Counterbeding every lens in one direction

counterbending	Dspot	SPH-min	SPH-max	
no	10.9	0.63	3.7	
L1 +	0.38	4	151	
L1 -	0.28	12	105	
L2 -	0.19	14	95	
L2 +	0.65	4	292	
L3 -	0.18	5	151	
L3 +	0.50	5	151	

Relaxed Design

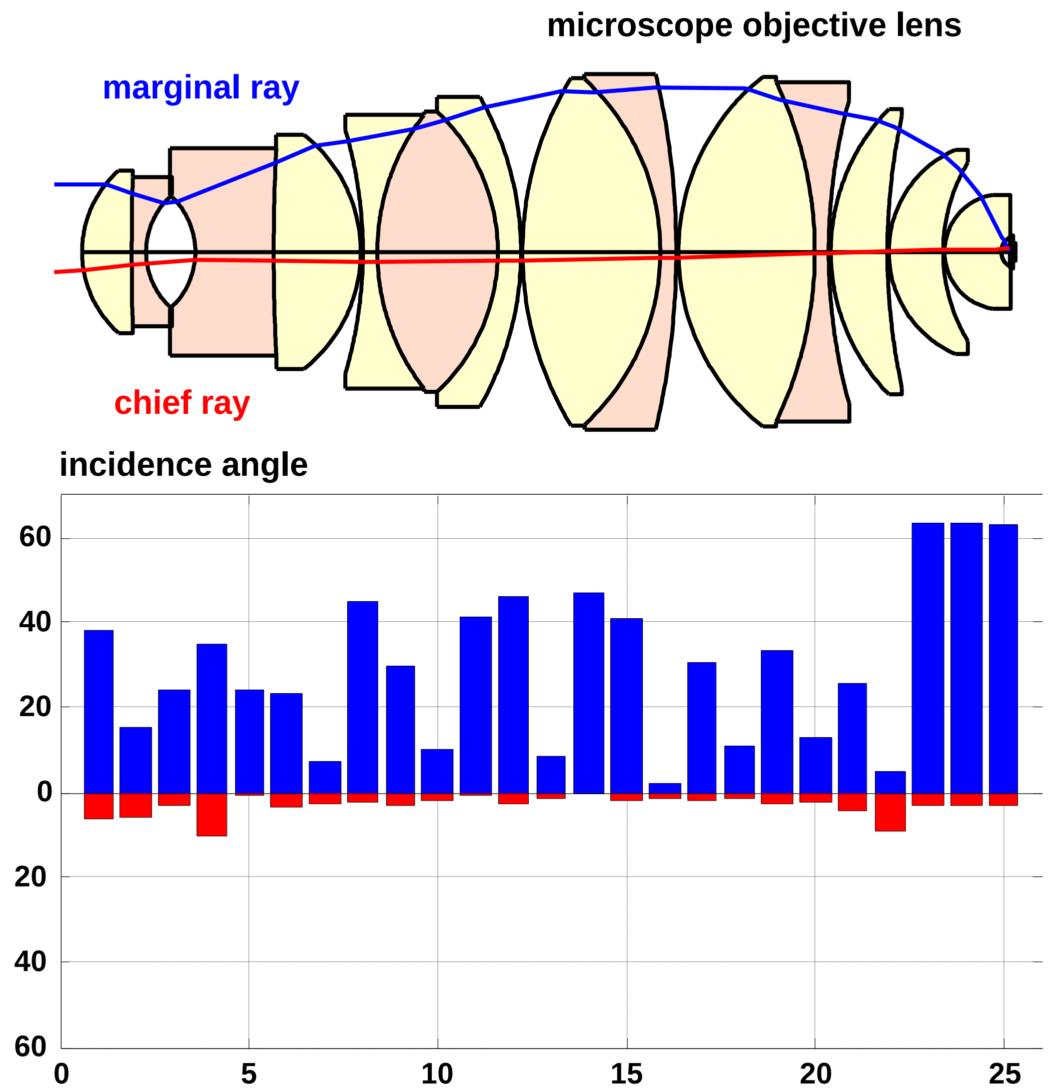
- Photographic lens comaprison
- Data:
  F# = 2.0
  f = 50 mm
  Field 20˚
- Same size and quality
- Considerably tigher tolerances in the first solution



Ref: D. Shafer

Microscopic Objective Lens

- Incidence angles for chief and marginal ray
- Aperture dominant system
- Primary problem is to correct spherical aberration

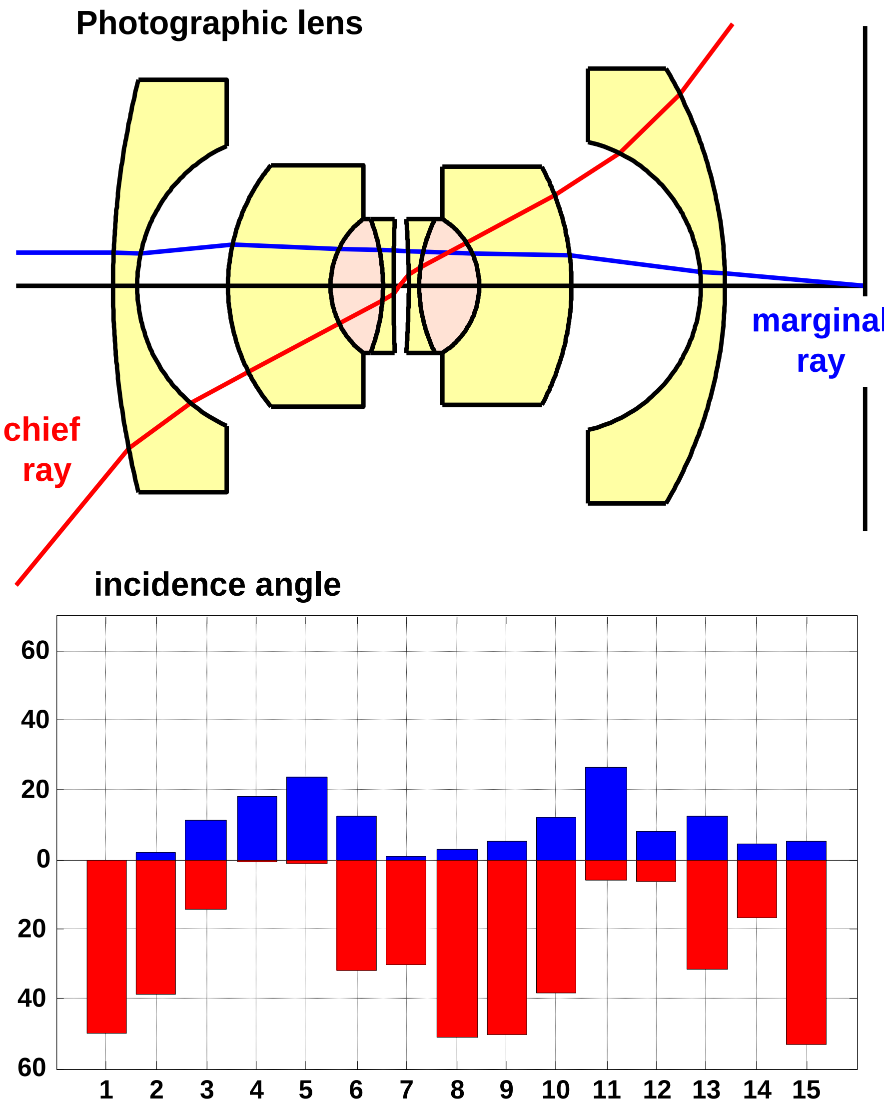


Photographic lens

- Incidence angles for chief and marginal ray

- Field dominant system

- Primary goal is to control and correct field related aberrations:
  coma, astigmatism, field curvature, lateral color



Correction Effectiveness

- Effectiveness of correction features on aberration types

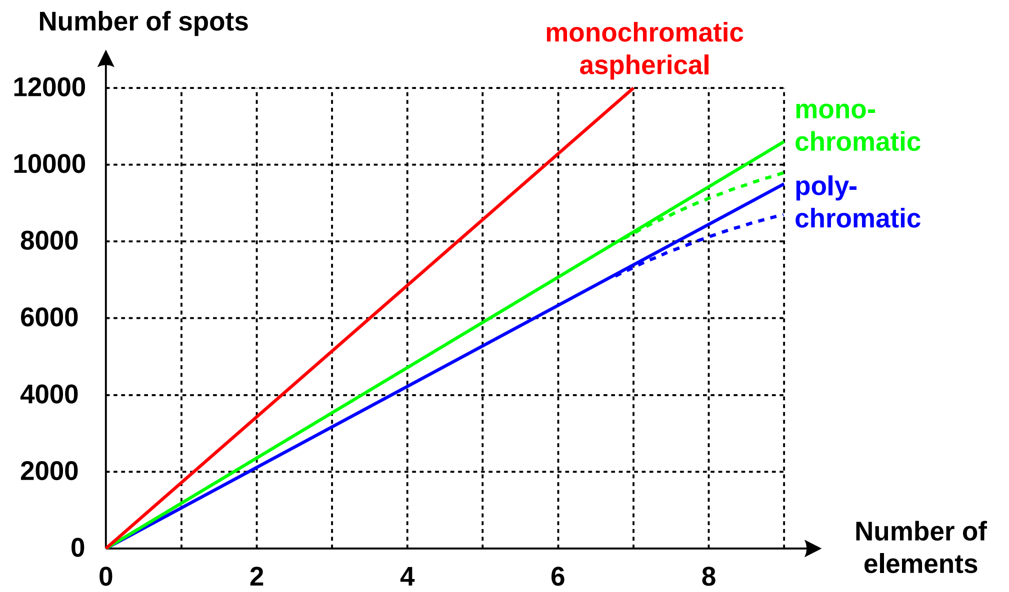
	Makes a good impact.
	Makes a smaller impact.
	Makes a negligible impact.
	Zero influence.

			Aberration									
			Primary Aberration					5th	Chromatic			
			Spherical Aberration	Coma	Astigmatism	Petzval Curvature	Distortion	5th Order Spherical	Axial Color	Lateral Color	Secondary Spectrum	Spherochromatism
Action	Lens Parameters	Lens Bending	(a)	(c)		e	(f)					
		Power Splitting										
		Power Combination	a	c			f		i	j		(k)
		Distances				(e)						k
		Stop Position										
	Material	Refractive Index	(b)	(d)			(g)	(h)				
		Dispersion							(i)	(j)		(l)
		Relative Partial Disp.										
		GRIN										
	Special Surfaces	Cemented Surface	b	d			g	h	i	j		l
		Aplanatic Surface										
		Aspherical Surface										
		Mirror										
		Diffractive Surface										
	Struc	Symmetry Principle										
		Field Lens										

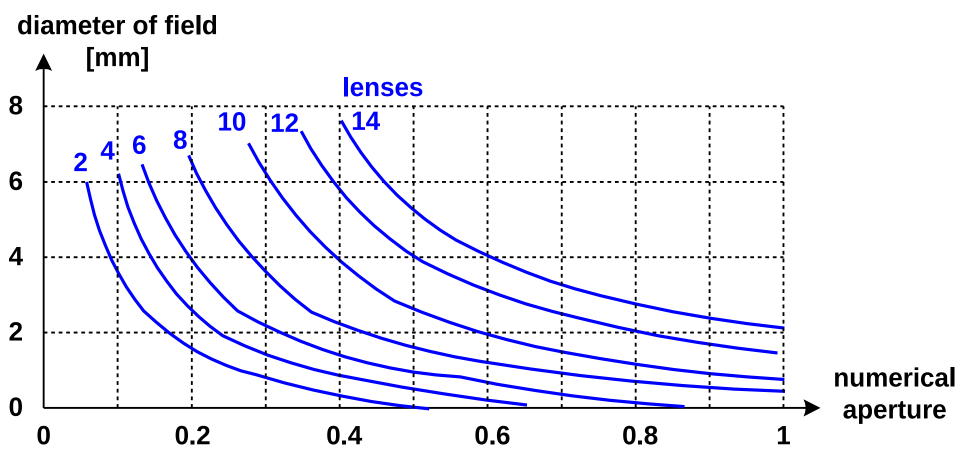
Ref : H. Zügge

Number of Lenses

- Approximate number of spots over the field as a function of the number of lenses
  Linear for small number of lenses.
  Depends on mono-/polychromatic design and aspherics.



- Diffraction limited systems with different field size and aperture

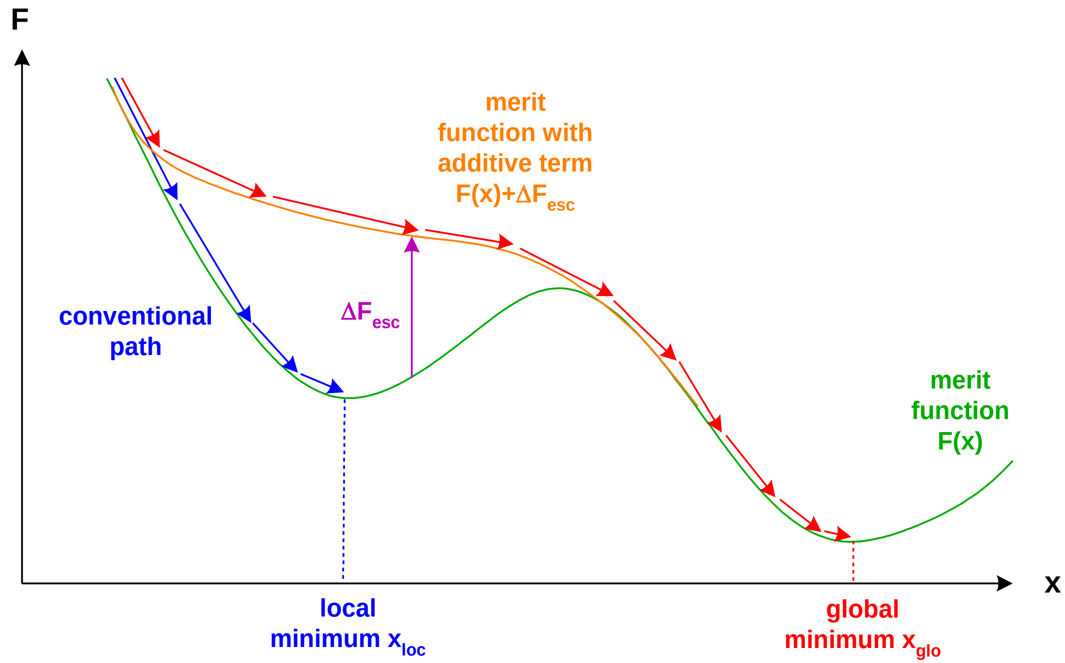


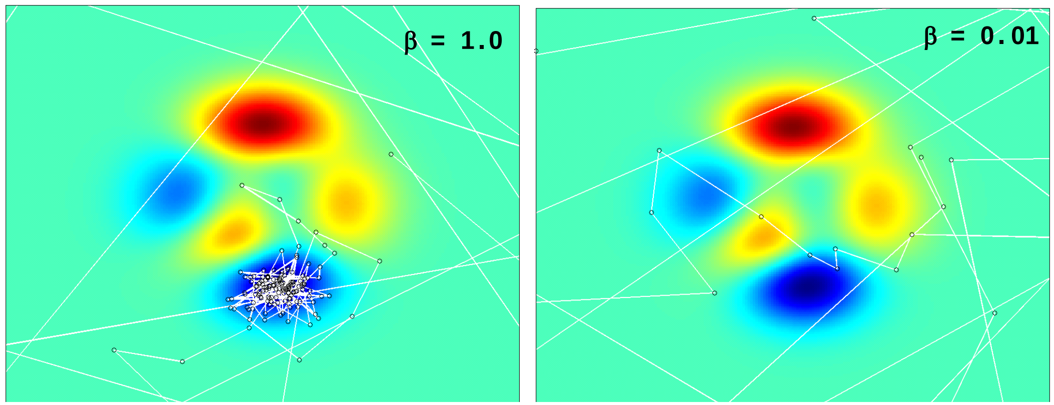
Global Optimization: Escape method of Isshiki

- Simulated Annealing: temporarily added term to overcome local minimum

$$\Delta F_{esc}(\vec{x}) = \Delta F_0 \cdot e^{-\beta \cdot \left(F(\vec{x}) - F_0\right)^2}$$

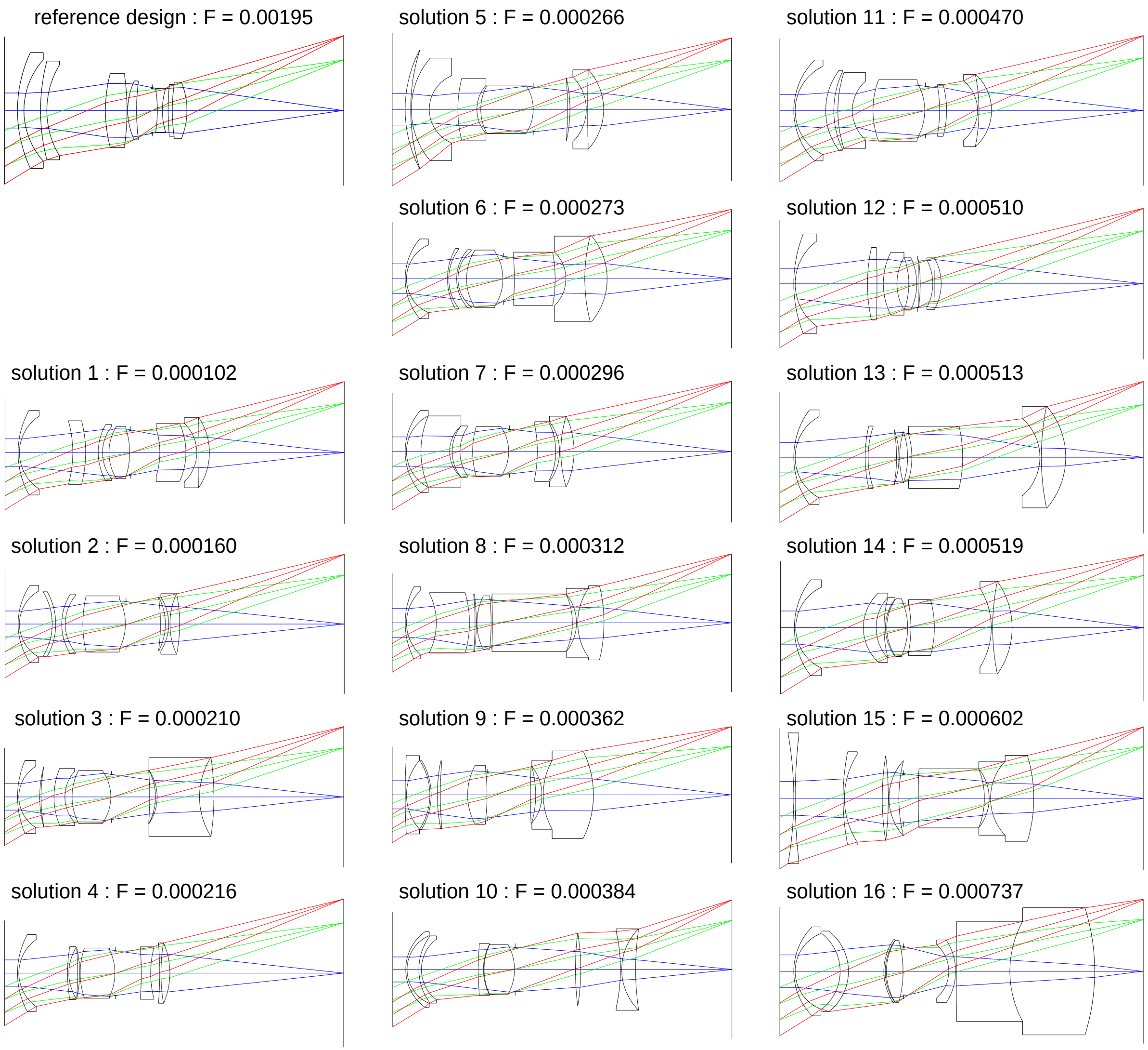
- Optimization and adaptation of annealing parameters





Global Optimization

- No unique solution
- Contraints not sufficient
  fixed:
  unwanted lens shapes
- Many local minima with nearly the same performance



Exercise I: Influence of initial system

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Consider a system with two lenses, made of BK7 and K5 at 587.56 nm. Both lenses have the thickness 5 mm, between both lenses the air distance is 1 mm. The incoming light bundle is collimated with diameter D = 20 mm, the focal length should be f = 30 mm. The system should be optimized by bending of the lenses only with a simple spot criterion on axis. The optimization result now depends strongly on the initial values of the radii. Try and compare the following possibilities:

a) start with plane surfaces only
b) start with a final radius of R4 = -20 mm
c) start with a first radius R1 = +20 mm

and compare the different results.

Exercise II: Optimization of Insensitivity

In the usual optimization, only the overall result of the system is minimized with the merit function. Due to the compensation effects, this can cause by quite different orders of magnitude in the size of the various surface contributions. By fixing the surface contributions, this effect of unequal weighting can be reduced and we get a rather uniform aberration loading and as a benefit a tolerance insensitive design, which can be easier to manufacture. To get this result, a poorer performance should be accepted.

a) We are looking for a system with an collimated input ray bundle of diameter D = 10 mm, a wavelength of 546.07 nm and a focal length of 5 mm to obtain a high numerical aperture in the image. This task should be performed by 3 spherical lenses made of BK7 with thicknesses of 2 mm and distances of 1 mm respectively. For the initial setup, we introduce a radius of -10 mm on the last surface. Optimize the system by changing all the radii and the final image distance. Show the result for the spot diameter and the Seidel surface contributions.

b) Now we add the SPHA operator for the individual spherical aberration contributions for every surface. In addition, the sum of squares is formulated by the operand QSUM. Now re-optimize the system by looking for the minimum value of this sum of squares, which then guarantees nearly equal values for the spherical surface contributions. What at the end is the performance in comparison to the previous solution ? What is the spreading of the spherical surface contributions ?

c) Finally as more automatic solution, use the operand EQUA to force the spherical Seidel contributions to have the same values. Start with the result of b). Is the performance now better than in b) ?