MICRO-517

Optical Design with ZEMAX OpticStudio

Lecture 6

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Outline

Theory

- Principle of nonlinear optimization
- Merit function and constraints
- Local and global optimization
- ZEMAX specifics

ZEMAX Practice

- ZEMAX Optimization

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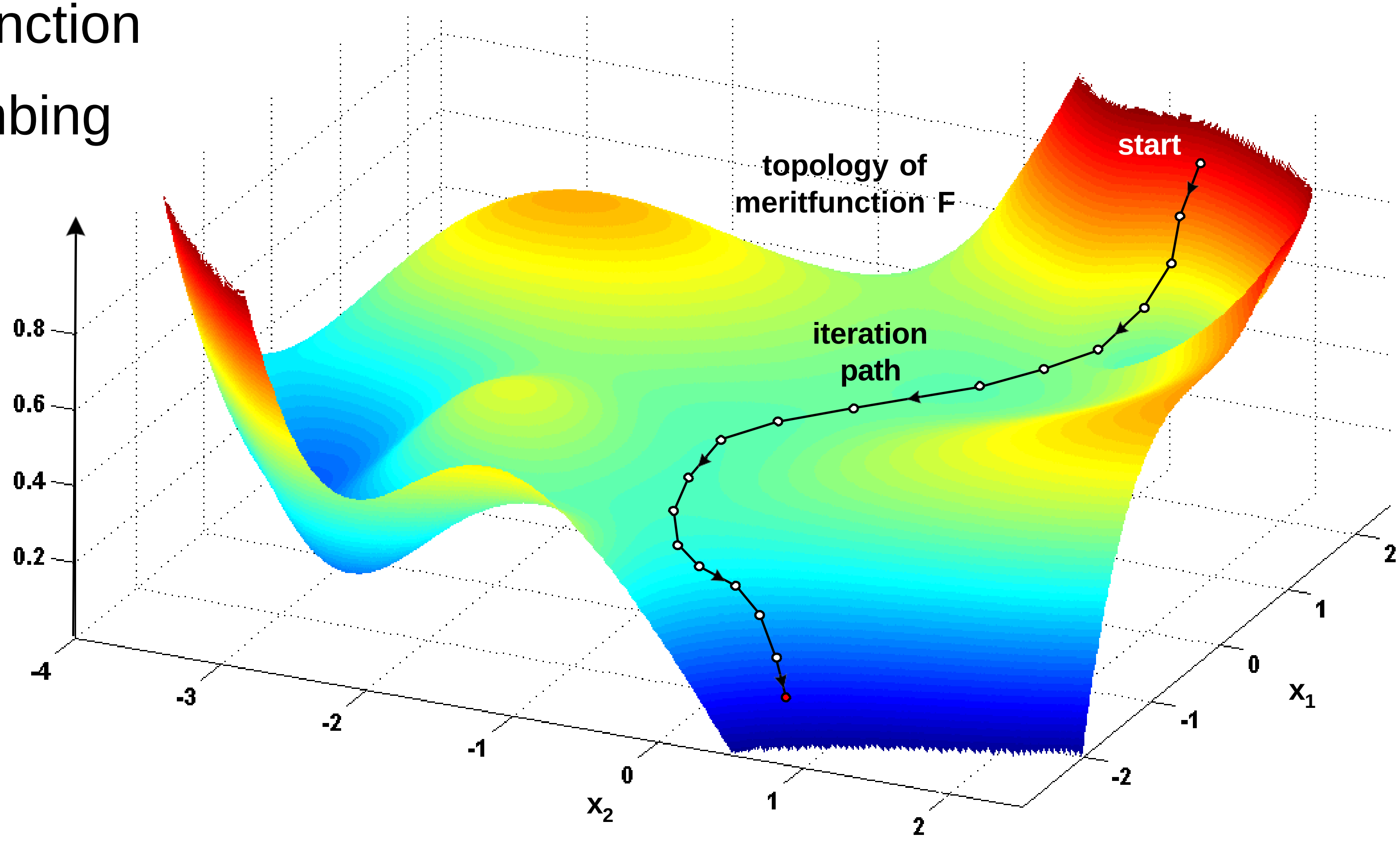
The Lens Design Process

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

Nonlinear Optimization Basics

- Defining a merit function
- Iterative down climbing in the topology



Nonlinear Optimization Basics

Mathematical description

n variable parameters $\mathbf{x} = x_j \quad j = 1, 2, \ldots, n$ $\qquad$ m target values $\mathbf{f}(\vec{x}) = f_i(x_j) \quad i = 1, 2, \ldots, m$

Jacobi system matrix of derivatives, Influence of a parameter change on the various target values, sensitivity function

$$\mathbf{J}_{ij} = \frac{\partial f_i}{\partial x_j}$$

Weight

Target value

Scalar merit function

$$F(\mathbf{x}) = \sum_{i=1}^{m} w_i \left[y_i - f_i(x_j) \right]^2$$

Gradient vector of topology

$$\mathbf{g}_j = \frac{\partial F}{\partial x_j}$$

Hesse matrix of 2nd derivatives

$$\mathbf{H}_{jk} = \frac{\partial^2 F}{\partial x_j \partial x_k}$$

Nonlinear Optimization Basics

- Linearize around working point with Taylor expansion of the target function
- Quadratic approximation of the merit function

$$\mathbf{f} = \mathbf{f}_0 + \mathbf{J} \cdot \Delta\mathbf{x}$$

$$F(\mathbf{x}) = F(\mathbf{x}_0) + \mathbf{J} \cdot \Delta\mathbf{x} + \frac{1}{2}\Delta\mathbf{x} \cdot \mathbf{H} \cdot \Delta\mathbf{x}$$

- Solution by linear Algebra system matrix **A**
- Cases depending on the numbers of *m* and *n*

$$\mathbf{A}^{\dagger} = \begin{cases} \mathbf{A}^{-1} & \text{if m = n} \\ \left(\mathbf{A}^T\mathbf{A}\right)^{-1} \cdot \mathbf{A}^T & \text{if m > n (under determined)} \\ \mathbf{A}^T \cdot \left(\mathbf{A}^T\mathbf{A}\right) & \text{if m < n (over determined)} \end{cases}$$

- Iterative numerical solution
  Strategy: optimization of direction and size of improvement step

Nonlinear Optimization Basics

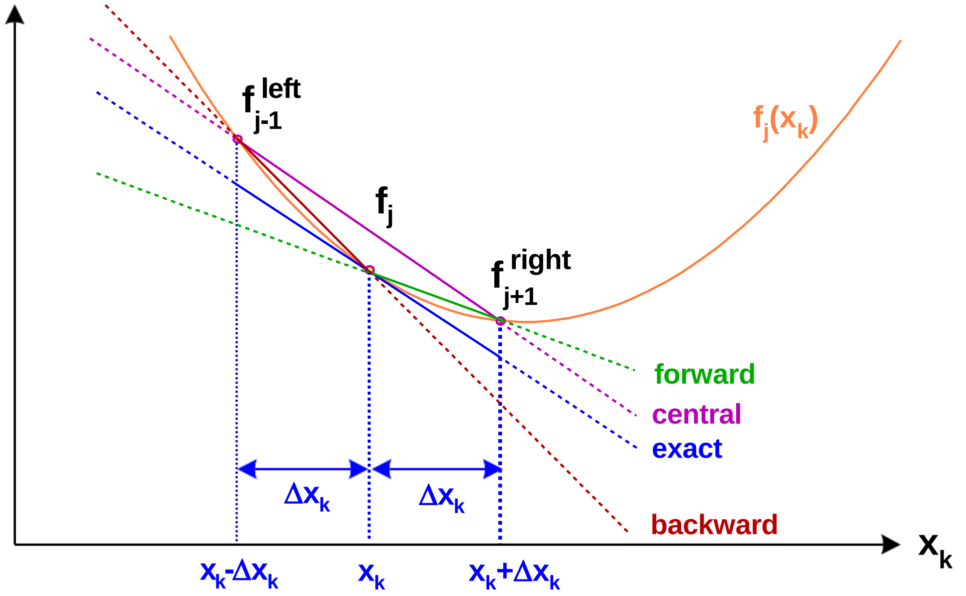
- Derivative vector in merit function topology: (Necessary for gradient-based methods)

$$\mathbf{g}_{jk} = \frac{\partial f_j(\mathbf{x})}{\partial x_k} = \nabla_{x_k} f_j(\mathbf{x})$$

- Numerical calculation by finite differences

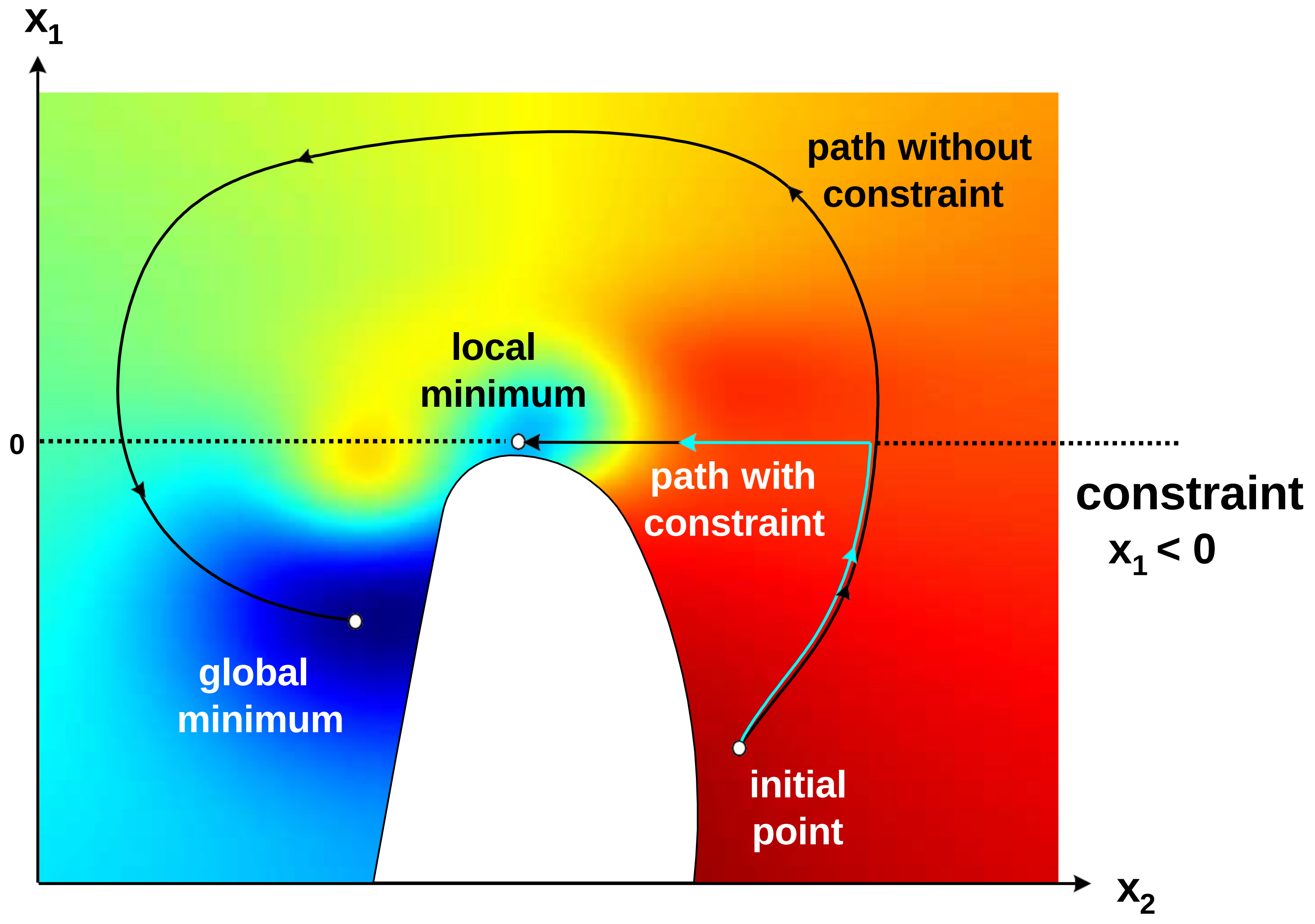
$$\mathbf{g}_{jk} = \frac{f_j^{right} - f_j}{\Delta x_k} \quad \Bigg| \quad \mathbf{g}_{jk} = \frac{f_j - f_j^{left}}{\Delta x_k} \quad \Bigg| \quad \mathbf{g}_{jk} = \frac{f_j^{right} - f_j^{left}}{2\Delta x_k}$$

- Possibilities and accuracy



Effects of Constraints

Effect of constraints



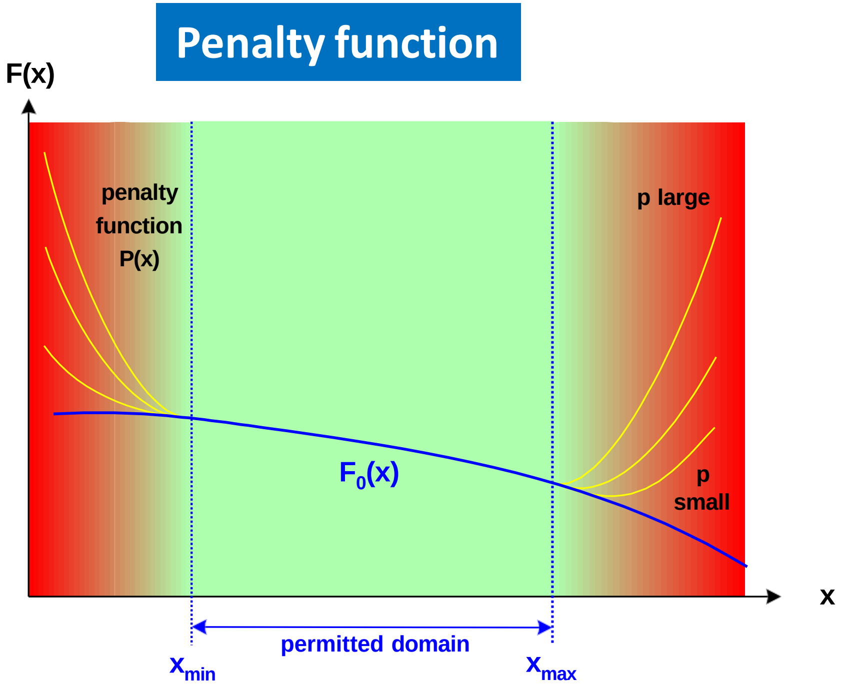
Boundary Conditions and Constraints

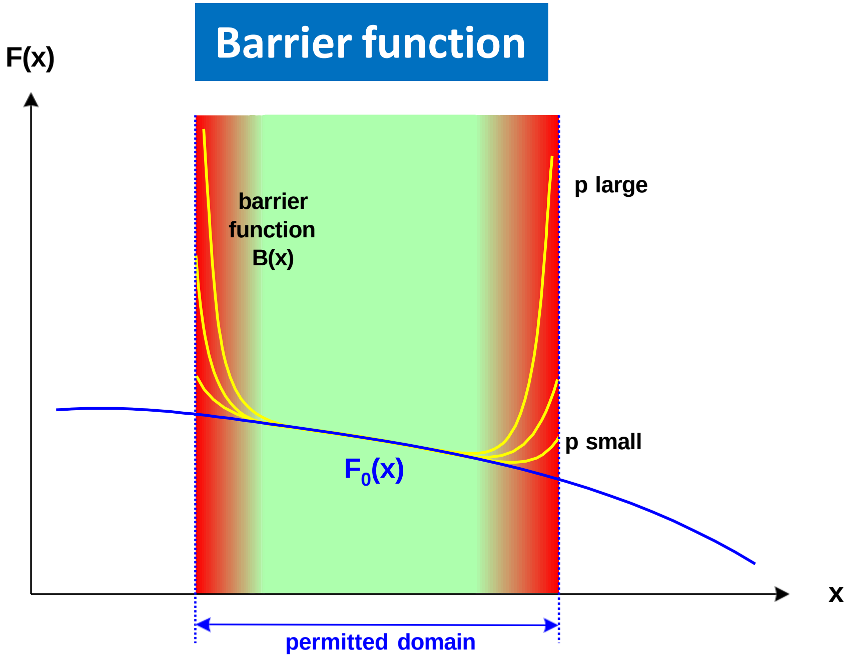
Types of constraints

- Equation, rigid coupling, pick up
- One-sided limitation, inequality
- Double-sided limitation, interval

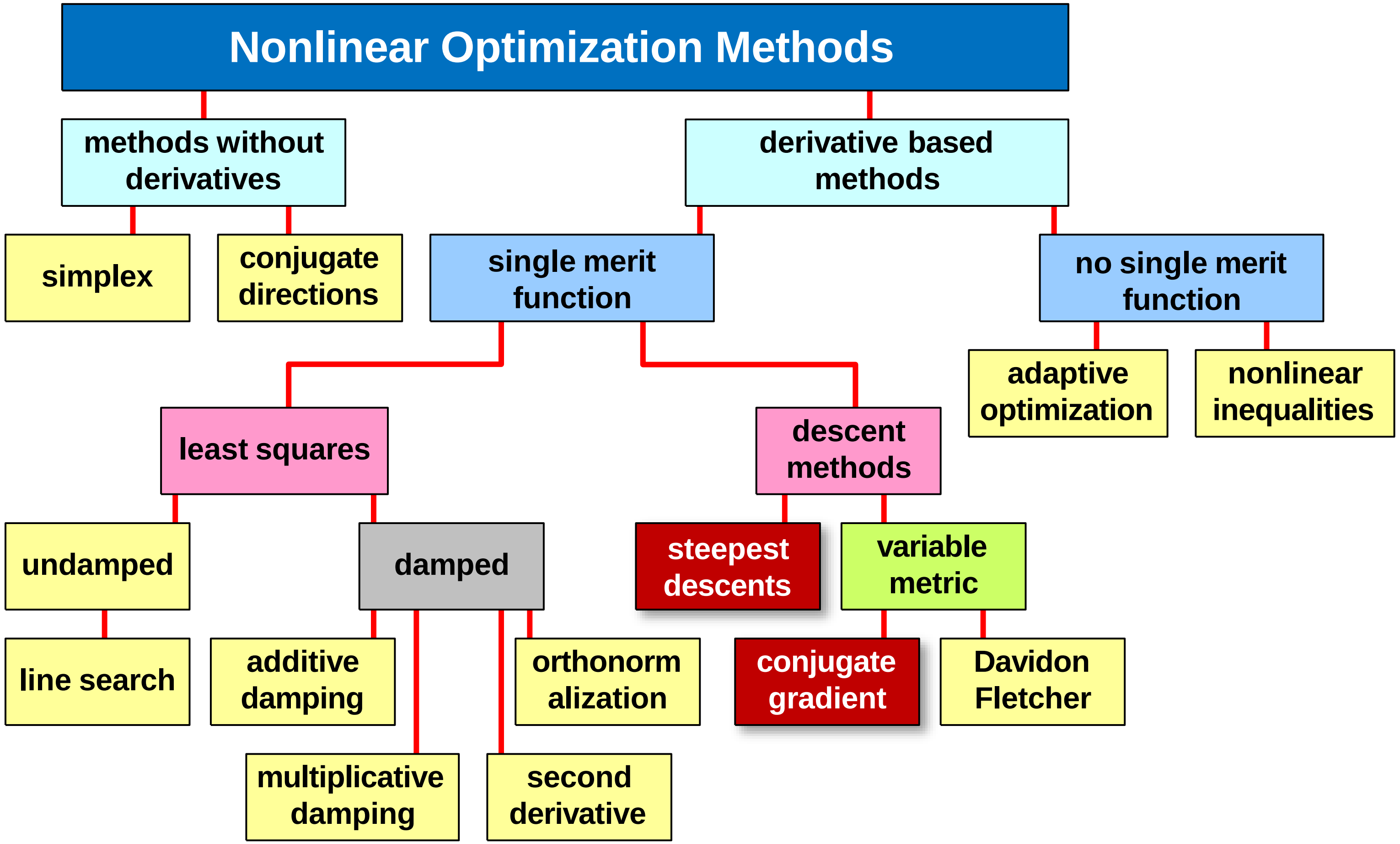
Numerical realizations

- Lagrange multiplier
- Penalty function
- Barrier function
- Regular variable, soft-constraint

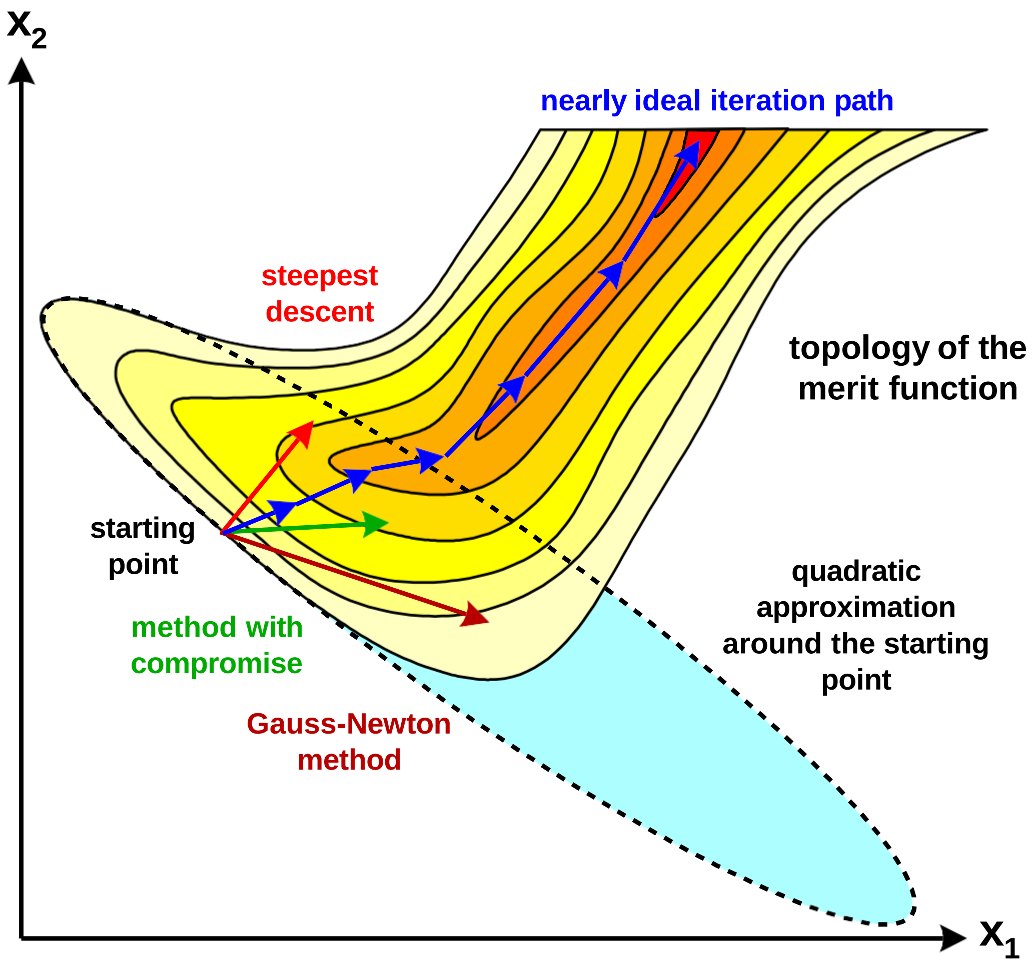




Local Optimization Algorithms in Optics

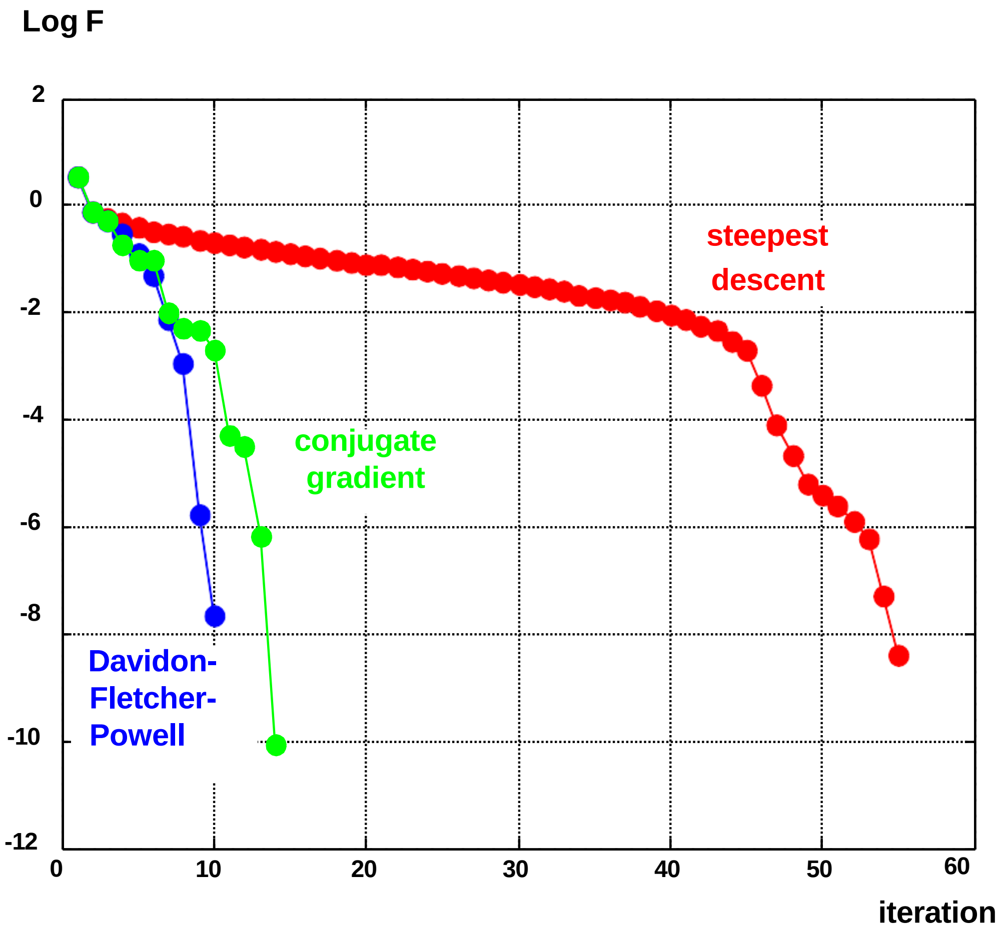


Searching the Local Minimum



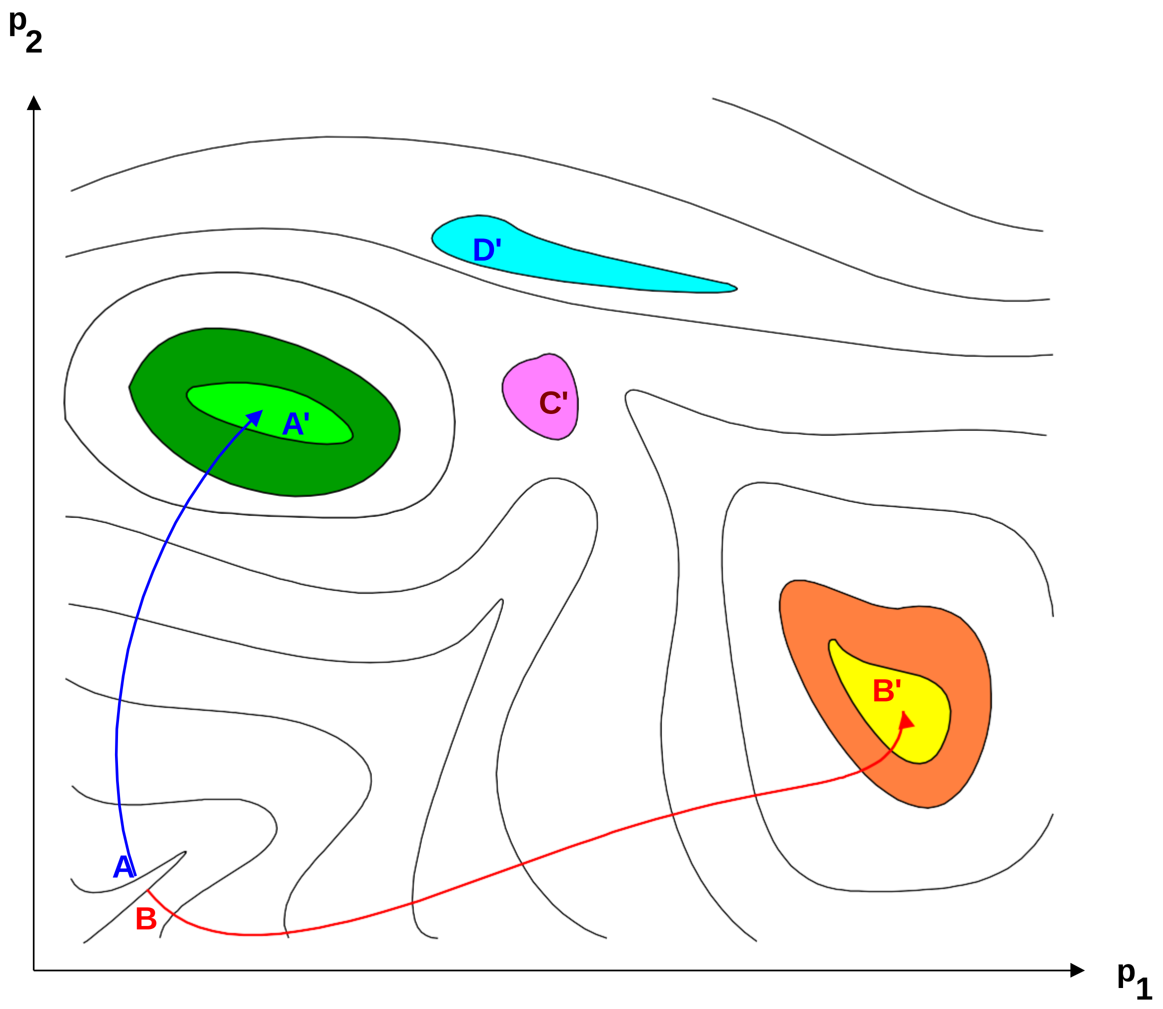
Convergence of Optimization

- Adaptation of direction and length of steps: rate of convergence
- Gradient method: slow due to zig-zag



Effects of Starting Point

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



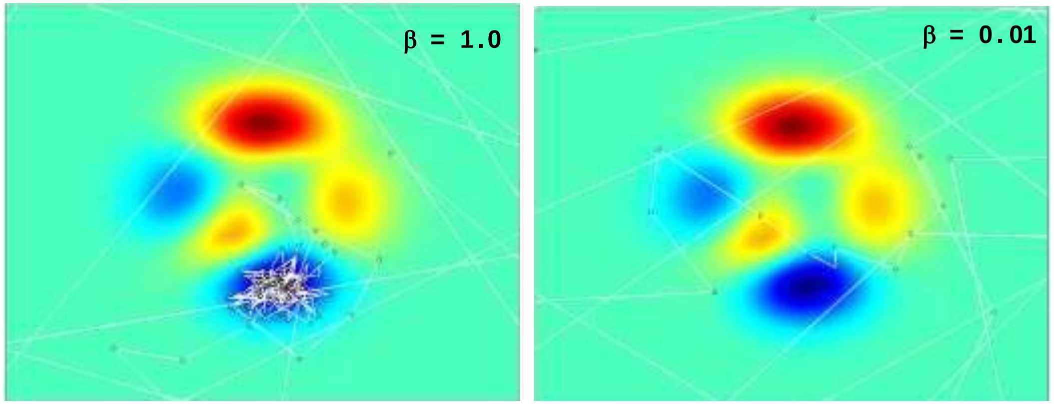
Global Optimization: Simulated Annealing

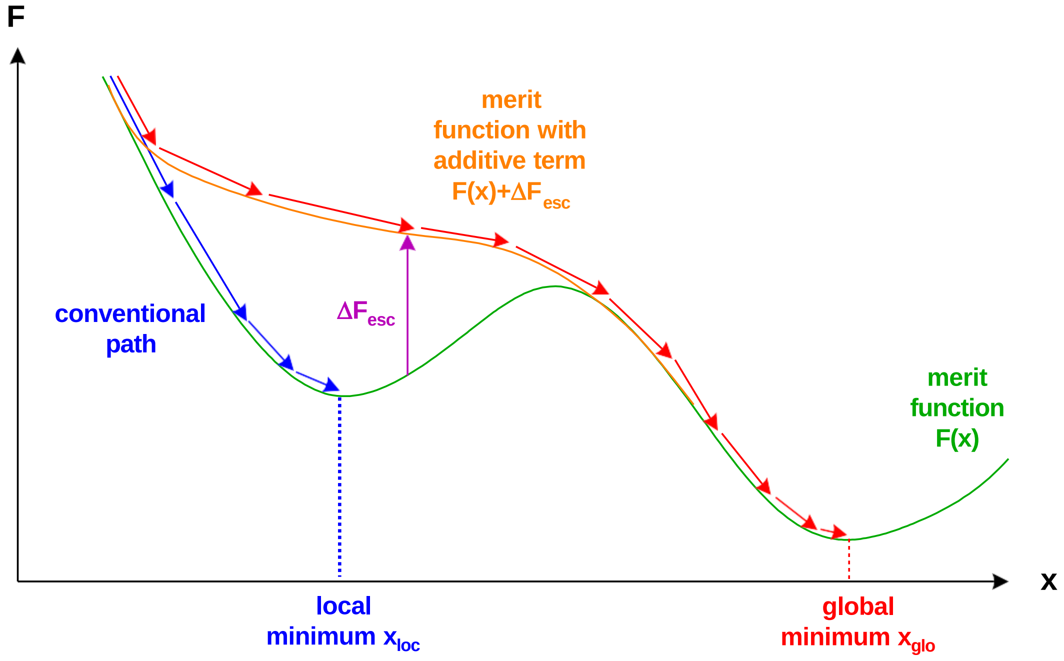
Simulated Annealing: temporarily added term to overcome local minimum

Slow Cooling Temperature

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

Optimization and adaptation of annealing parameters





Merit Function in Optical Design

- **Goal of optimization:** Find a system layout that meets the performance targets according of the specification
- Formulation of performance criteria must be created for:
  - Aperture rays
  - Field points
  - Wavelengths
  - Optional several zoom or scan positions
- Selection of performance criteria depends on application:
  - Ray aberrations
  - Spot diameter
  - Wave front error
  - Strehl ratio
  - Point spread function
  - Modulational transfer function
  - Uniformity of illumination

Usual scenario

- Number of requirements and targets quite larger than available DOM
- Only compromised solutions possible

Parameters of Optical Systems

- Free variable parameters of the system:
  - Surface curvature radii
  - Thickness of lenses, air distances
  - Tilt and decenter
  - Free diameter of components
  - Material parameter, refractive indices and dispersion
  - Aspherical coefficients
  - Parameter of diffractive components
  - Coefficients of gradient media
- General experience:
  - Surface curvature radii very effective
  - Benefit of thickness and distances only weak
  - Material parameter can only be changes discretely

Constraints in Optical Systems

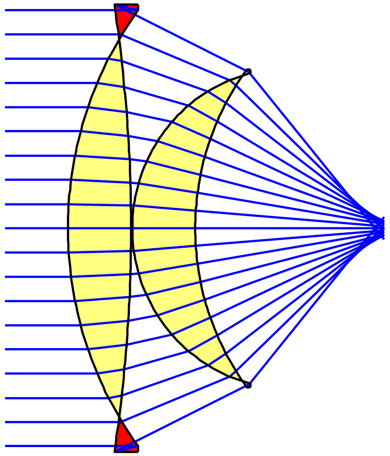
Constraints in the optimization of optical systems:

- Discrete standardized radii (tools, metrology)
- Discrete choice of glasses
- Edge thickness of lenses (handling)
- Center thickness of lenses(stability)
- Coupling of distances (zoom systems, forced symmetry, ...)
- Focal length, magnification, working distance
- Image location, pupil location
- Avoiding ghost images (no concentric surfaces)
- Use of given components (vendor catalog, availability, costs)

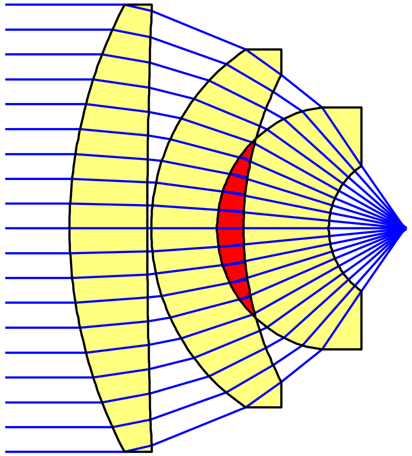
Insufficient Constraints in Optimization

Some useless results due to insufficient constraints

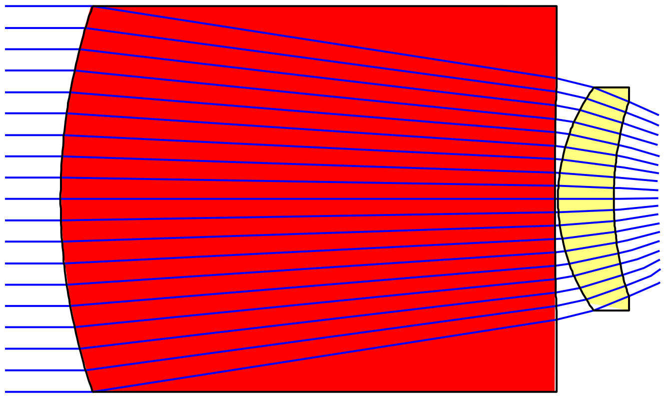
negative edge thickness



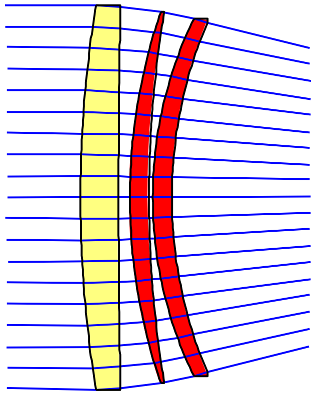
negative air distance



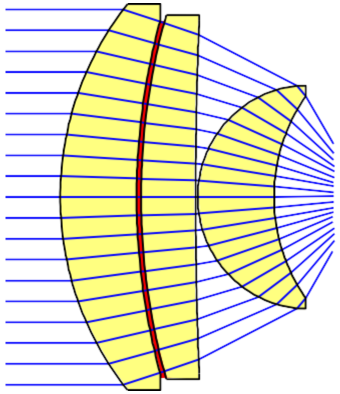
lens thickness too large



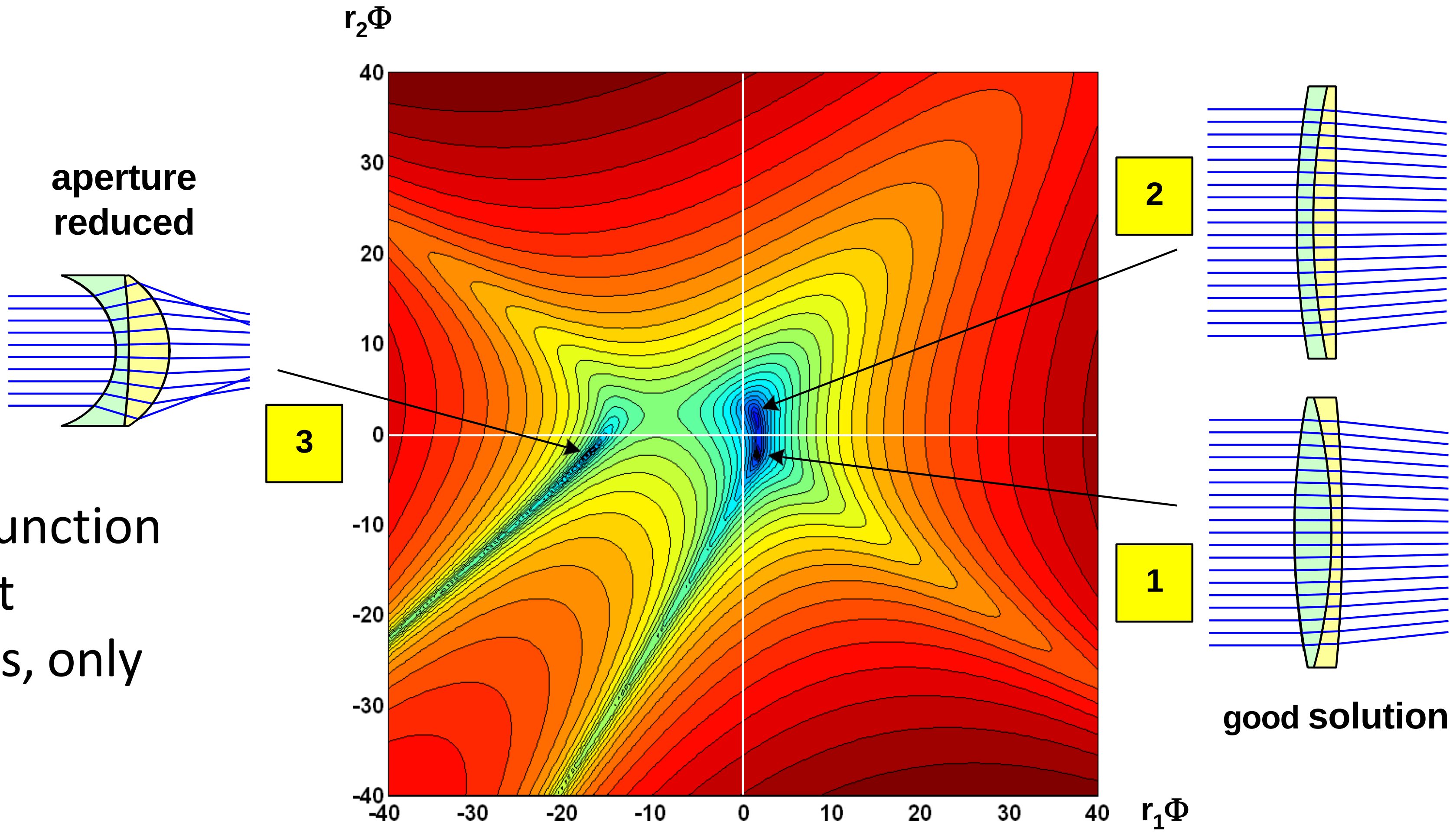
lens stability too small



air space too small



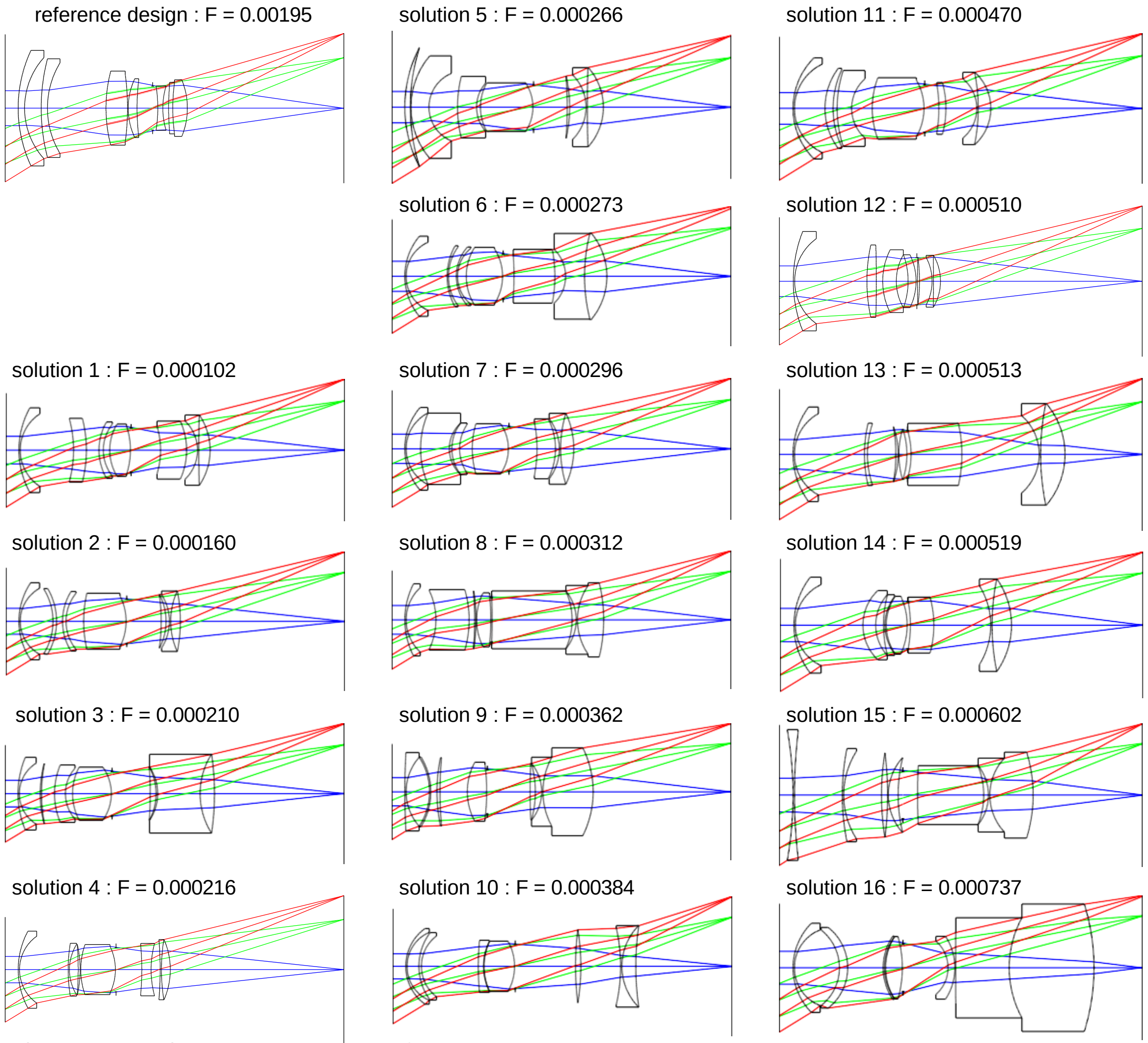
Optimization Landscape of an Achromat



- Typical merit function of an achromat
- Three solutions, only two are useful

Global Optimization

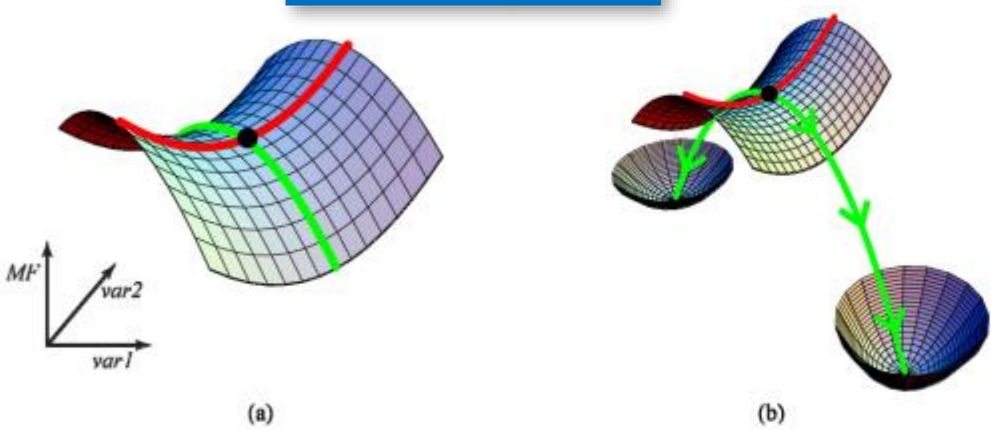
- No unique solution
- Insufficient constraints: unwanted lens shapes
- Many local minima with nearly the same performance



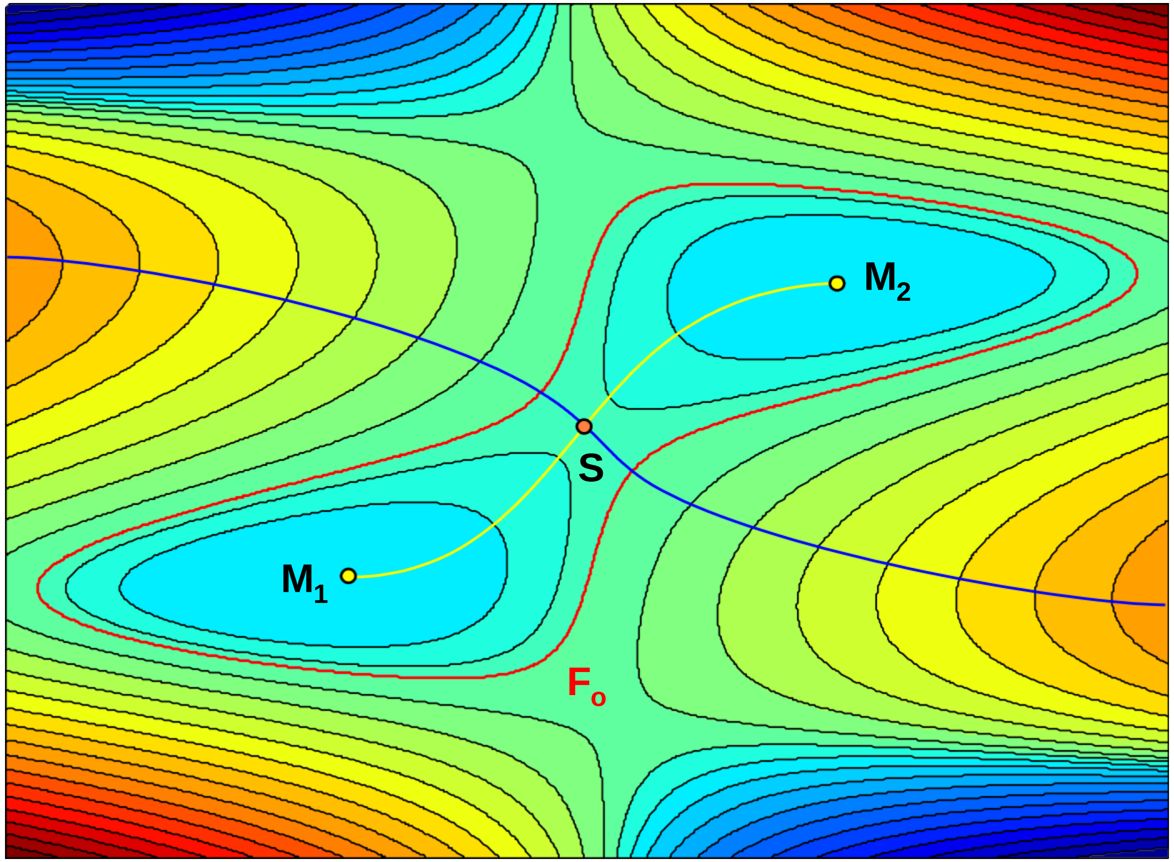
Saddle Point Method

- Systematic search of adjacend local minima is possible
- Exploration of the complete network of local minima via saddle points

Saddle point

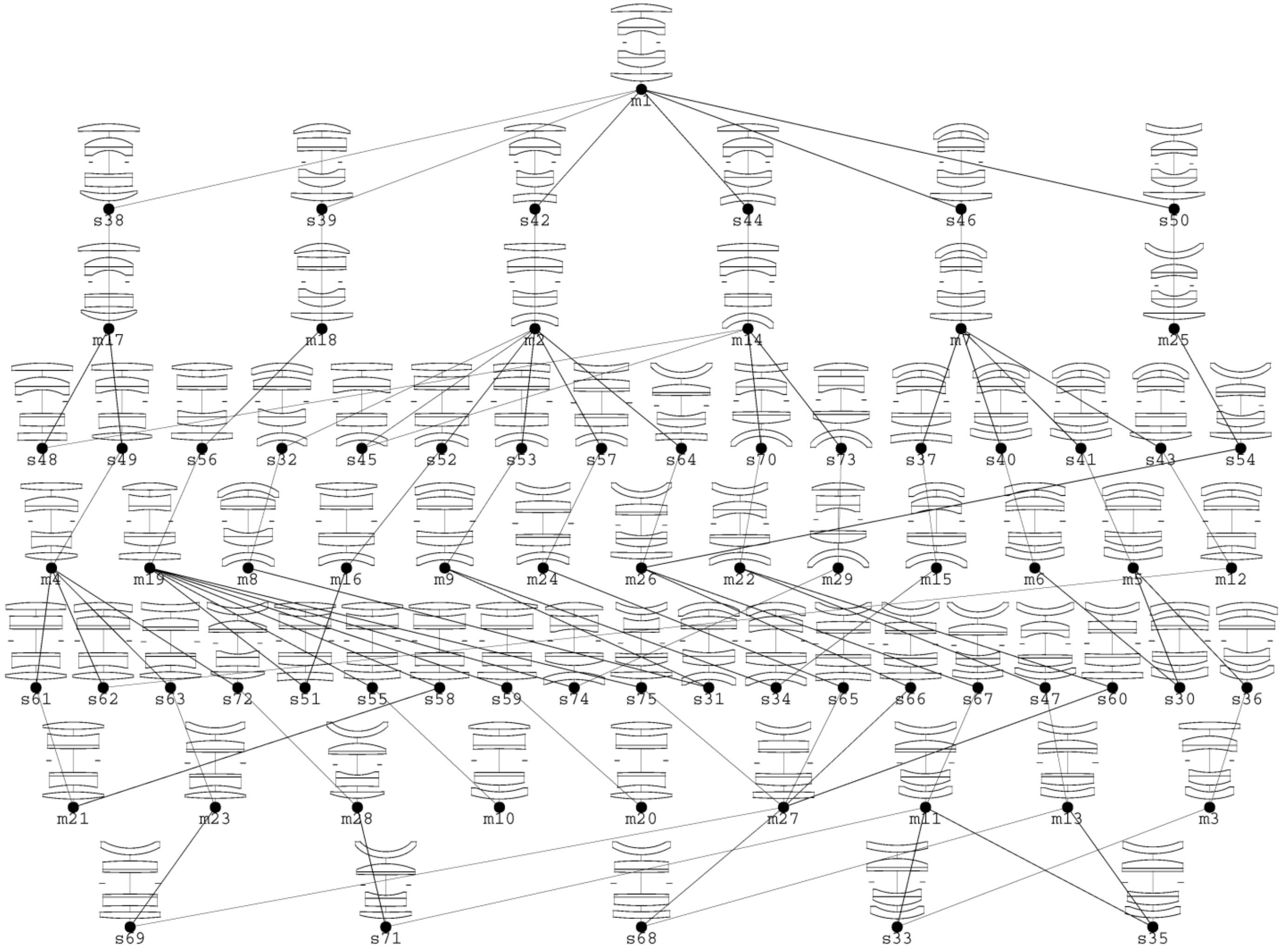


Saddle points in the merit function topology



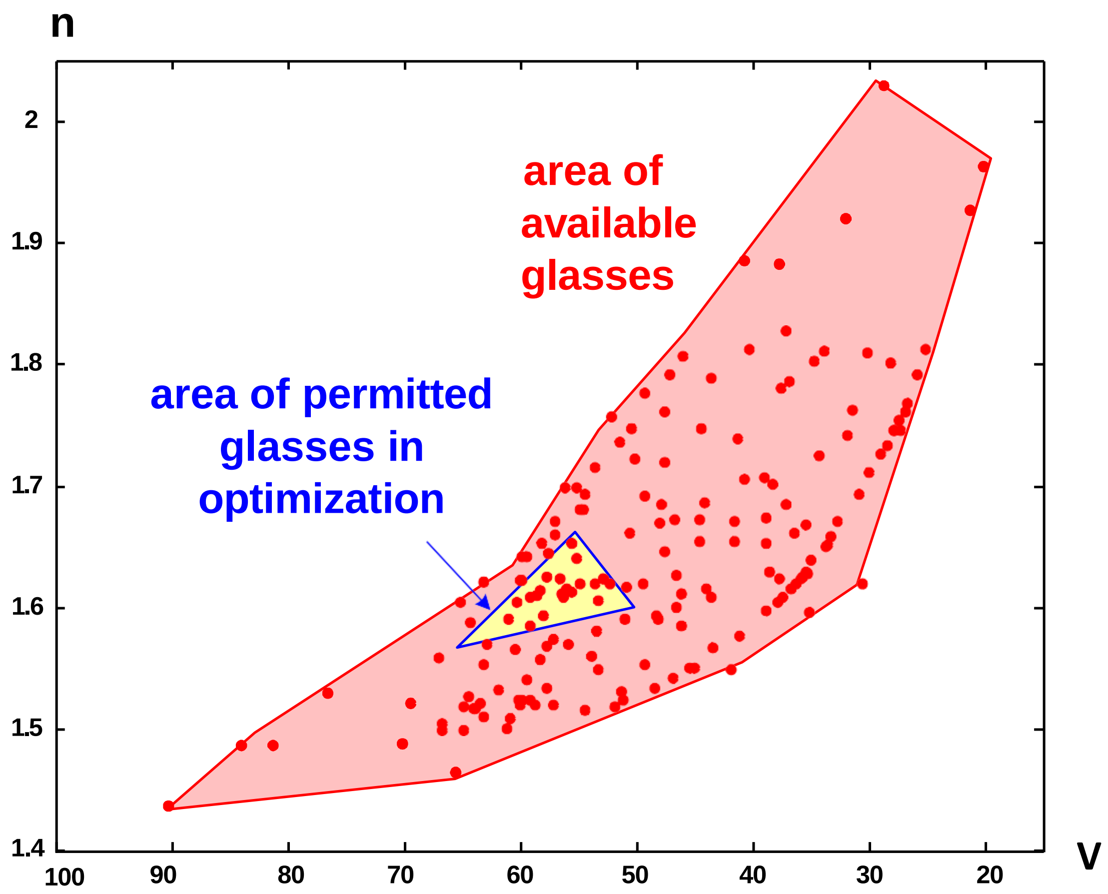
Saddle Point Method

Network of local minima corresponding to a double Gauss global search



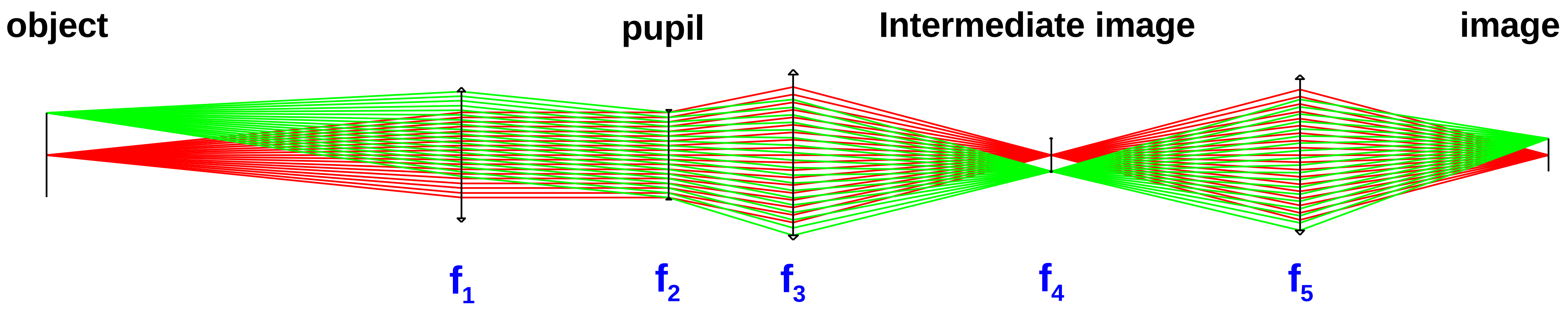
Material Optimization

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



Optimization: Where to Start

- Existing solution modified
- Literature and patent collections
- Paraxial layout + thin-lens predesign + surface model with correction



- Approach of Shafer: AC-surfaces, monochromatic, buried surfaces, aspherics
- Expert system / artificial intelligence
- Experience and genius

Correction Effectiveness

Effectiveness of correction features on aberration types

Action			Aberration: Primary: Spherical	Coma	Astigmatism	Field Curvature	Distortion	5th: 5th Order Spherical	Chromatic: LCA	TCA	Secondary Spectrum	Tertiary Spectrum
Action	Lens Parameters	Lens Bending	Good	Good	Good	Good	Good	Negligible	Negligible	Negligible	Negligible	Smaller
		Power Splitting	Good	Smaller	Negligible	Negligible	Good	Good	Negligible	Negligible	Negligible	Smaller
		Power Combination	Good	Smaller	Negligible	Negligible	Good	Negligible	Good	Good	Negligible	Good
		Distances	Negligible	Negligible	Negligible	Good	Negligible	Good	Negligible	Negligible	Negligible	Good
		Stop Position	Zero	Smaller	Smaller	Zero	Smaller	Zero	Zero	Smaller	Zero	Zero
	Material	Refractive Index	Smaller	Negligible	Negligible	Smaller	Smaller	Negligible	Negligible	Negligible	Negligible	Negligible
		Dispersion	Zero	Zero	Zero	Zero	Zero	Zero	Good	Good	Smaller	Smaller
		Relative Partial Dispersion	Zero	Zero	Zero	Zero	Zero	Zero	Zero	Zero	Good	Zero
		Gradient-Index	Good	Smaller	Negligible	Zero	Smaller	Good	Negligible	Negligible	Negligible	Negligible
	Special Surfaces	Cemented Surface	Good	Smaller	Negligible	Negligible	Smaller	Good	Good	Good	Smaller	Smaller
		Aplanatic Surface	Good	Good	Negligible	Zero	Zero	Good	Zero	Zero	Zero	Zero
		Aspherical Surface	Good	Smaller	Smaller	Zero	Good	Good	Zero	Negligible	Zero	Zero
		Mirror	Negligible	Negligible	Negligible	Smaller	Negligible	Negligible	Smaller	Negligible	Smaller	Negligible
		Diffractive Surface	Good	Smaller	Negligible	Smaller	Good	Good	Good	Smaller	Good	Smaller
	Struc	Symmetry	Zero	Good	Zero	Zero	Good	Zero	Zero	Good	Zero	Zero
		Field Lens	Negligible	Negligible	Smaller	Good	Smaller	Negligible	Negligible	Negligible	Negligible	Negligible

(dark blue)	Makes a good impact
(medium blue)	Makes a smaller impact
(light blue)	Makes a negligible impact
(white)	Zero influence

Different System, Different Concerns

- Telescope objective: longitudinal chromatic aberration, transverse chromatic aberration, spherical aberration, coma
- Collimator lens: longitudinal chromatic aberration, spherical aberration, coma
- Eyepieces: longitudinal chromatic aberration, transverse chromatic aberration, astigmatism, field curvature, maybe distortion (depending on the field of view)
- Camera lenses: all seven (and most certainly more for modern lenses)
- Microscope objective: both chromatic aberrations, spherical aberration, coma

Merit Function in ZEMAX OpticStudio

- **Special merit function options can be composed:**
  - sum, diff, prod, division,... of lines, which have a zero weight itself
  - mathematical functions sin, sqrt, max ....
  - less than, larger than (one-sided intervals as targets)
- **Negative weights:**
  - Requirement is considered as a Lagrange multiplier and is fulfilled exactly
  - Similar to a weight of infinity but numerically more stable
  - Useful to meet exact target like focal length or magnification
- **Optimization operands with derivatives:**
  - Building a system insensitive for small changes (wide tolerances)
- **Further possibilities for user-defined operands:**
  - Construction with macro language (ZPLM)
- **General outline:**
  - Use simple operands in a rough optimization phase
  - Use more complex, application-related operands in the final fine-tuning phase

Classical definition of the merit function in ZEMAX

$$F^2 = \frac{\sum W_i \left(V_i - T_i\right)^2}{\sum W_i}$$

Final optimization:
- Do not optimize individual aberration coefficients
- Always optimize measurable quantities

Optimization Operands in ZEMAX OpticStudio

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Important

If the number of field points, wavelengths, or configurations is changed, the merit function must be updated explicitly

Optimization Operand Definitions

ZEMAX supports optimization operands which are used to define the merit function. Each operand may be assigned a weight which indicates the relative importance of that operand, as well as a target, which is the desired value for that operand.

First-order optical properties:
AMAG, ENPP, EFFL, EFLX, EFLY, EPDI, EXPD, EXPP, ISFN, LINV, OBSN, PIMH, PMAG, POWF, POWP, POWR, SFNO, TFNO, WFNO

Aberrations:
ABCD, ANAC, ANAR, ANAX, ANAY, ANCX, ANCY, ASTI, AXCL, BIOC, BIOD, BSER, COMA, DIMX, DISA, DISC, DISG, DIST, FCGS, FCGT, FCUR, LACL, LONA, OPDC, OPDM, OPDX, OSCD, PETC, PETZ, RSCE, RSCH, RSRE, RSRH, RWCE, RWCH, RWRE, RWRH, SPCH, SPHA, TRAC, TRAD, TRAE, TRAI, TRAR, TRAX, TRAY, TRCX, TRCY, ZERN

MTF data:
GMTA, GMTS, GMTT, MSWA, MSWS, MSWT, MTFA, MTFS, MTFT, MTHA, MTHS, MTHT

PSF/Strehl Ratio Data:
STRH

Encircled energy:
DENC, DENF, ERFP, GENC, GENF, XENC, XENF

Constraints on lens data:
COGT, COLT, COVA, CTGT, CTLT, CTVA, CVGT, CVLT, CVVA, DMGT, DMLT, DMVA, ETGT, ETLT, ETVA, FTGT, FTLT, MNCA, MNCG, MNCT, MNCV, MNEA, MNEG, MNET, MNPD, MXCA, MXCG, MXCT, MXCV, MXEA, MXEG, MXET, MXPD, MNSD, MXSD, TTGT, TTHI, TTLT, TTVA, XNEA, XNET, XNEG, XXEA, XXEG, ZTHI

Constraints on lens properties:
CVOL, MNDT, MXDT, SAGX, SAGY, SSAG, STHI, TMAS, TOTR, VOLU, NORX, NORY, NORZ, NORD

Constraints on parameter data:
PMGT, PMLT, PMVA

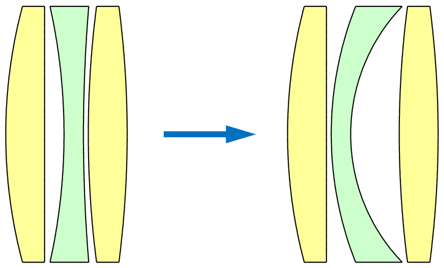
Optimization Strategy

Options for accelerating a stagnated optimization:

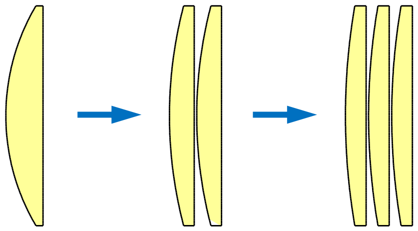
- Split a lens
- Insert a lens
- Increase refractive index of positive lenses
- Lower refractive index of negative lenses
- Make surface with large spherical surface contribution aspherical
- Break cemented components
- Use glasses with anomalous partial dispersion

Optimization Strategy

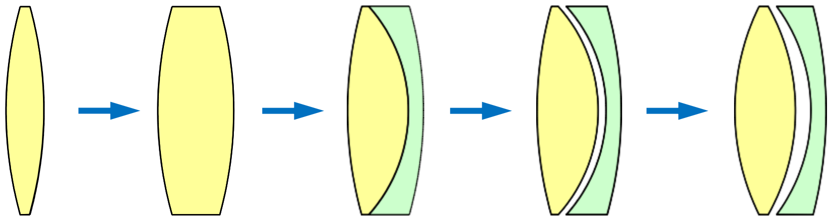
- Lens bending



- Lens splitting

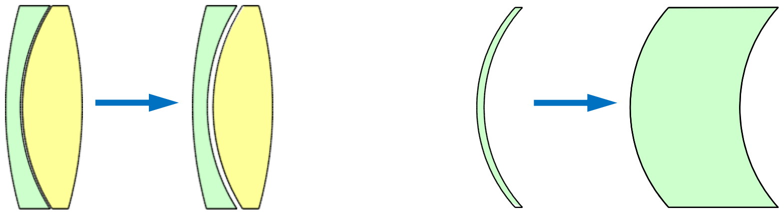


- Power combinations



(a) (b) (c) (d) (e)

- Distances



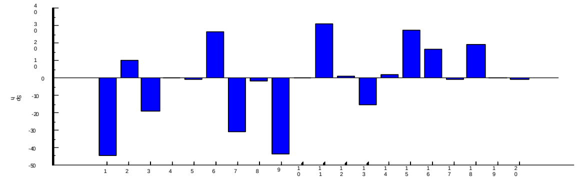
(a) (b)

Sensitivity of a System

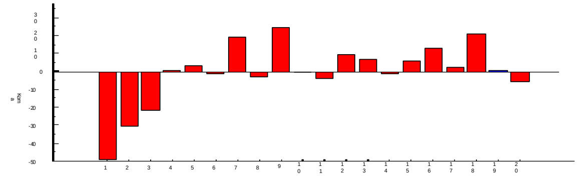
Quantitative measure for relaxation $$A_i = \frac{h_i}{h_1}\frac{K_i}{K}$$

with normalization $$\sum_{i=1}^{k} A_i = 1$$

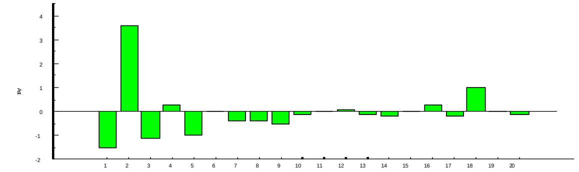
- Non-relaxed surfaces:
  - Large incidence angles
  - Large ray bending
  - Large surface contributions of aberrations
  - Significant occurence of higher aberration orders
  - Large sensitivity for centering
- Internal relaxation can not be easily recognized in the total performance
- Large sensitivities can be avoided by incorporating surface contribution of aberrations into merit function during optimization



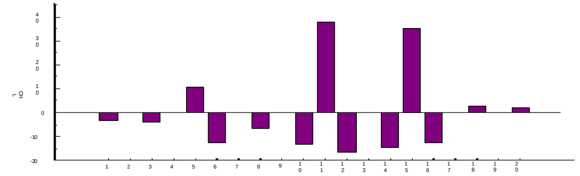
Spherical



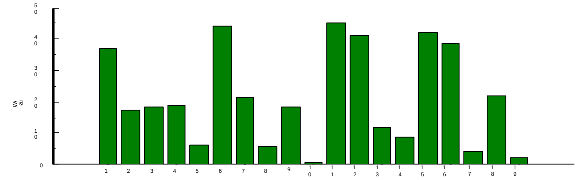
Coma



Astigmatism



LCA



incidence angle

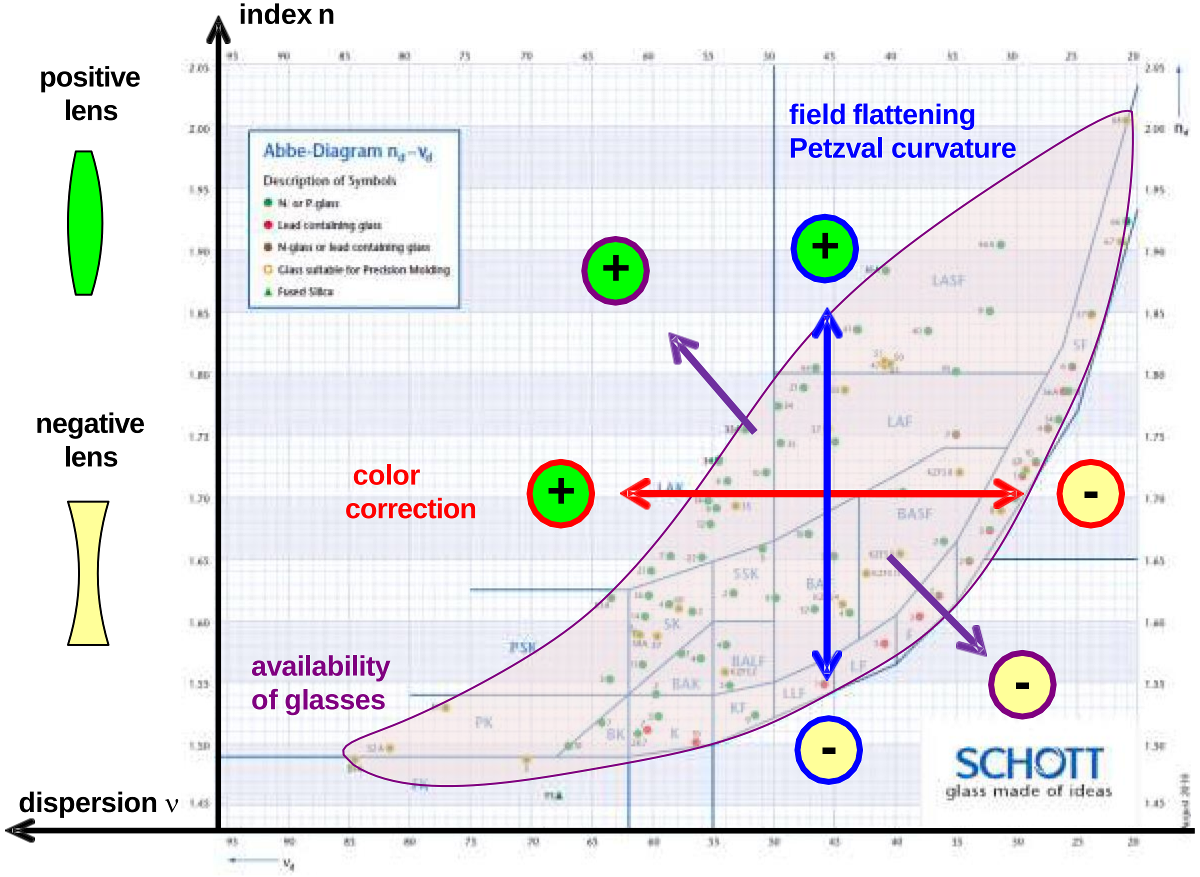
Glass Selection in Optical Optimization

Design Rules for glass selection

Different design goals:

- Color correction:
  Large dispersion difference
- Field flattening:
  Large index difference

ZEMAX can optimize Choices of Glasses too



Methods Available in ZEMAX OpticStudio

- General optimization methods
  - Local optimization
  - Global optimization
- Easy-one-dimensional optimizations
  - Quick focus
  - Adjustment
  - Slider, for visual control
- Special aspects:
  - Solves
  - Aspheres
  - Glass substitutes

Global optimization methods

- Global search:
  - Search the full parameter space subject to constraints
  - Good at finding promising design forms
  - Run indefinitely while saving the 10 best systems found
- Hammer optimization:
  - Exhaustively search for optimum solution near a given starting point
  - May take a long time
  - Run indefinitely, must be stopped explicitly

Dogma in System Structure

- Even distribution of refractive power among component lenses
- High symmetry
- Cost:
  - long systems
  - many lenses

Homework

To be announced