Institute of Applied Physics

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Lens Design I

Lecture 1: Basics

2024-04-04

Yueqian Zhang

Preliminary Schedule - Lens Design I 2024

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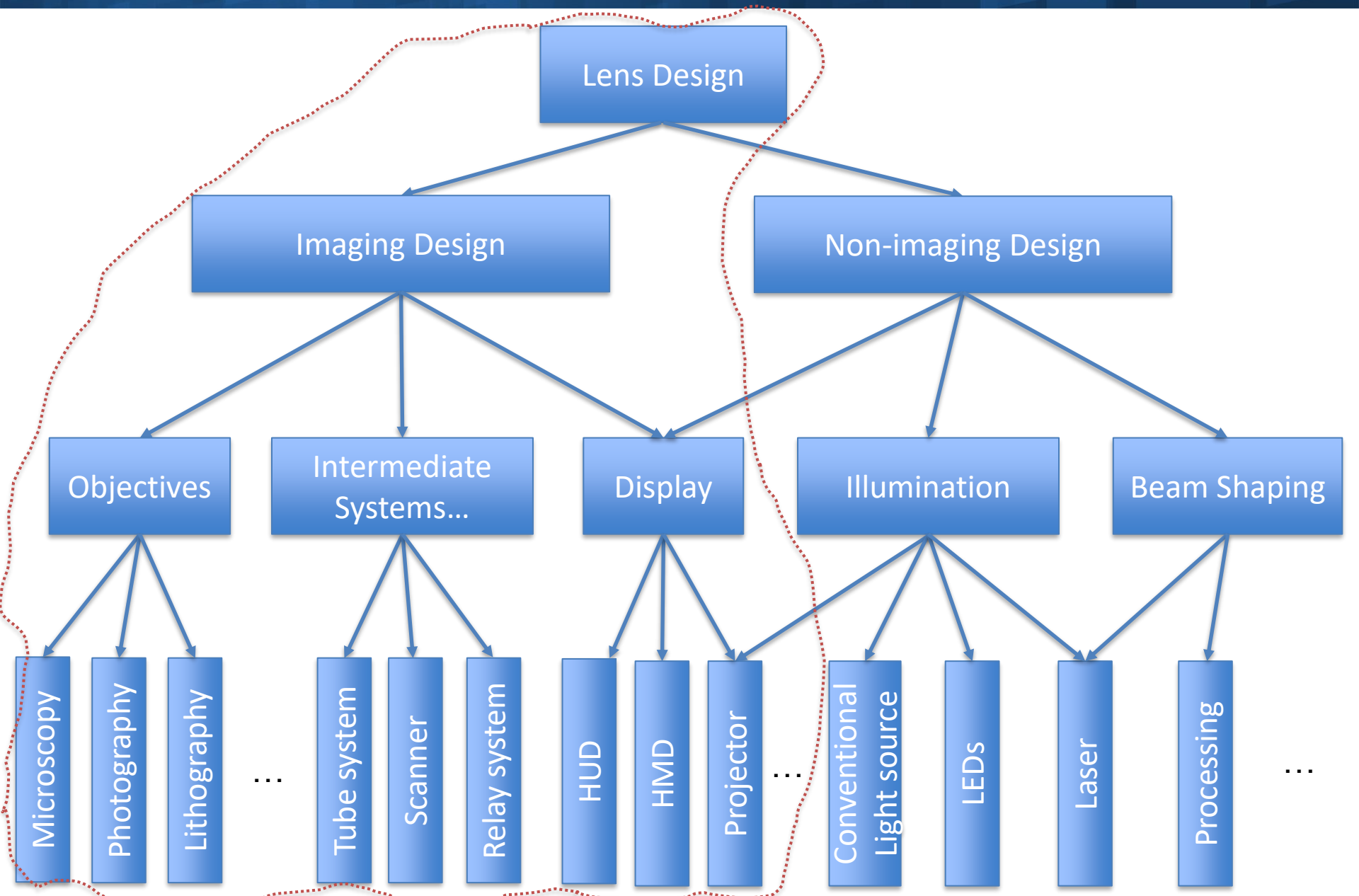
1	04.04.	Basics	Zhang	Introduction, Zemax interface, menues, file handling, preferences, Editors, updates, windows, coordinates, System description, 3D geometry, aperture, field, wavelength
2	18.04.	Properties of optical systems I	Tang	Diameters, stop and pupil, vignetting, layouts, materials, glass 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

Content 1st Lecture

1. Introduction
2. Zemax interface, menues, file handling, preferences
3. Editors, updates, windows
4. Coordinate systems and notations
5. Aperture, field, wavelength
6. System description
7. 3D geometry

What is Lens Design (Optical Design)

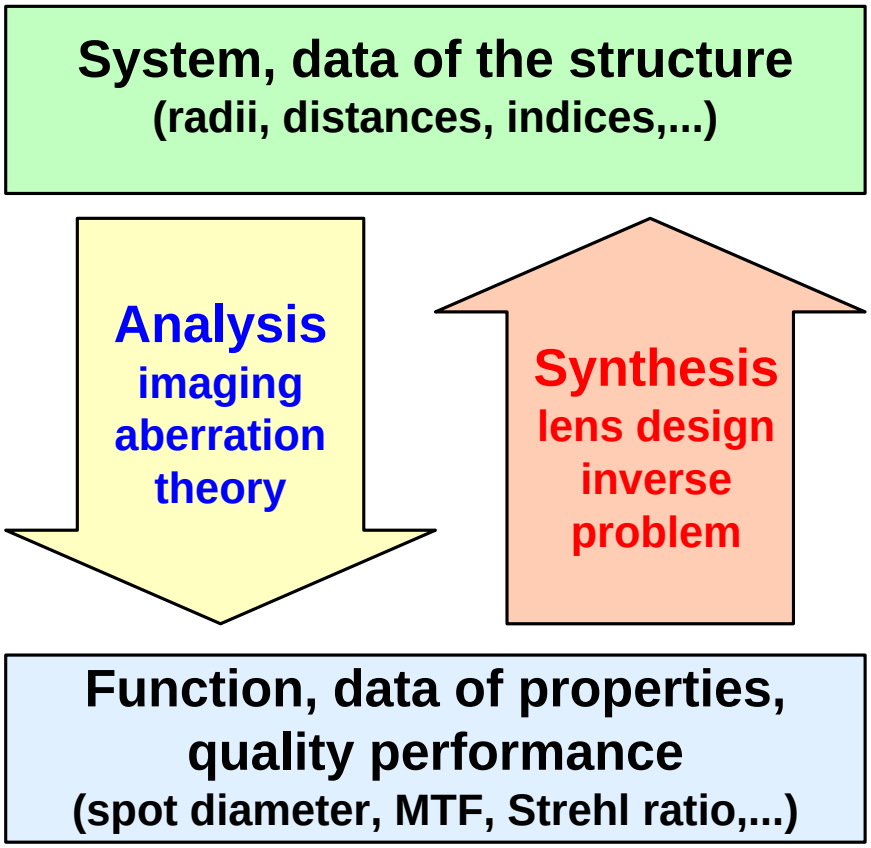


Modelling of Optical Systems

- Principal purpose of calculations:

1. Solving the direct problem of understanding the properties: analysis

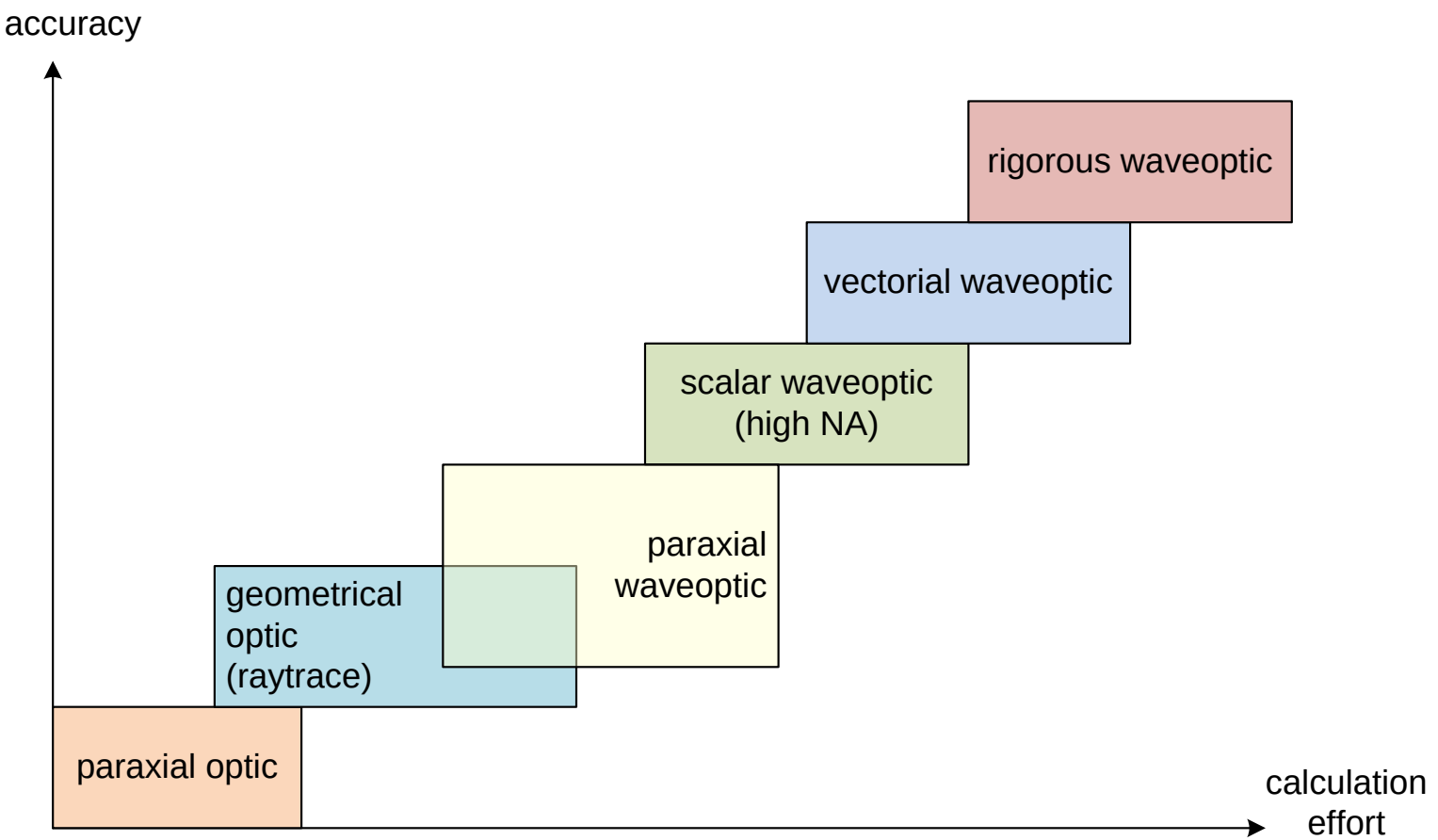
2. Solving the inverse problem: Finding the concret system data for a required functionality: synthesis



Ref: W. Richter

Model depth of Light Propagation

- Different levels of modelling in optical propagation
- Schematical illustration (not to scale)



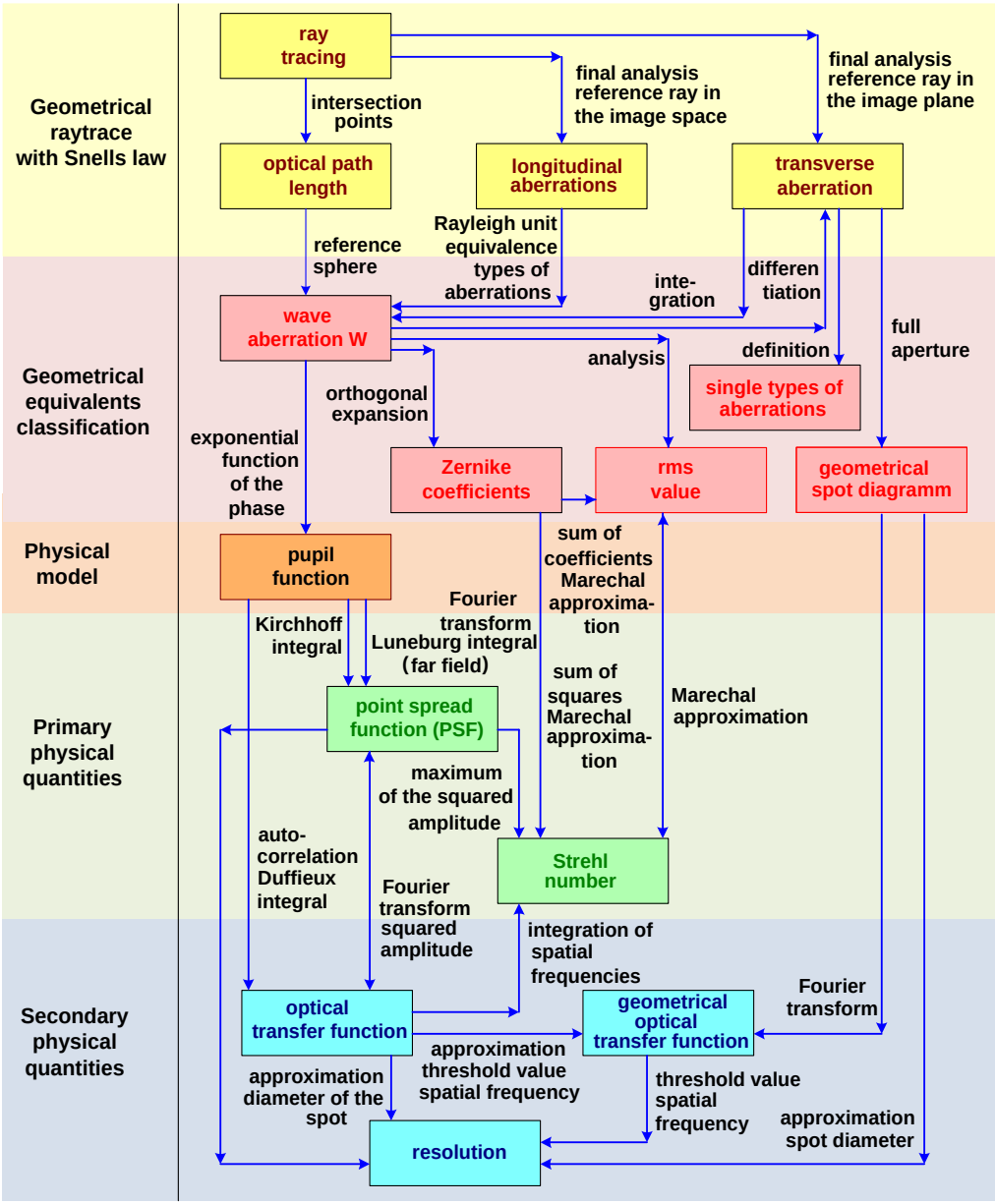
Ref: A. Herkommer

Modelling of Optical Systems

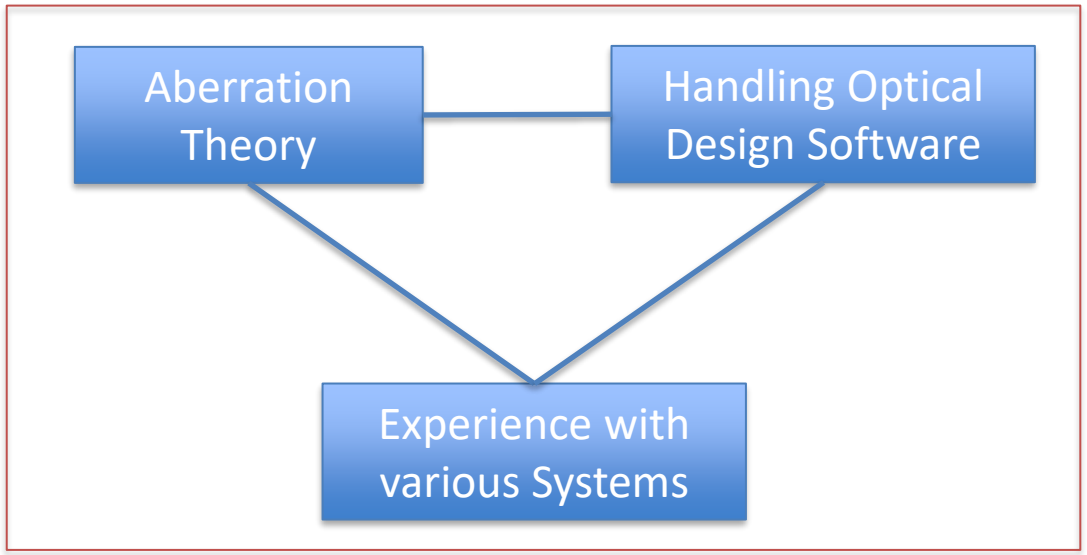
- Five levels of modelling:

1. Geometrical raytrace with analysis
2. Equivalent geometrical quantities, classification
3. Physical model: complex pupil function
4. Primary physical quantities
5. Secondary physical quantities

- Blue arrows: conversion of quantities



Key Skills of Optical Designers



Physical Simulation

- High NA
- High precision
- Near-field

Future: e.g. Metalens

Additional Programming Skill

- Advanced analysis
- Advanced optimization algorithm

Future: e.g. AI-aided

Construction and Manufacture

Zemax interface

- There are 4 types of windows in Zemax:

1. Editors for data input:
   lens data, extra data, multiconfiguration, tolerances
2. Output windows for graphical representation of results
   Here mostly setting-windowss are supported to optimize the layout
3. Text windows for output in ASCII numerical numbers (can be exported)
4. Dialog boxes for data input, error reports and more

- There are several files associates with Zemax

1. Data files (.ZMX)
2. Session files (.SES) for system settings (can be de-activated)
3. Glass catalogs, lens catalogs, coating catalogs, BRDF catalogs, macros, images, POP data, refractive index files,...

- There are in general two working modes of Zemax

1. Sequential raytrace (or partial non-sequencial)
2. Non-sequential

Literature on Lens Design

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1. Kingslake **Lens design fundamentals, SPIE Press, 2010**
2. Mouroulis / McDonald Geometrical Optics and Optical Design, Oxford, 1997
3. Fischer / Tadic-Galeb Optical System Design, McGraw Hill, 2000
4. Malacara / Malacara Handbook of Lens Design, Dekker, 2013
5. Laikin **Lens Design, Dekker, 2007**
6. W. Smith Modern Optical Engineering, Graw Hill, 2000
7. W. Smith Modern lens design, McGraw Hill, 2005
8. Geary Lens Design with practical Examples, Willmann-Bell, 2002
9. Gross (Ed.) **Handbook of optical systems, Vol 1-5, Wiley, 2005-2012**
10. Shannon The art and science of optical design, Cambridge Univ. Press, 1997
11. G. Smith Practical computer-aided lens design, Willman Bell, 1998
12. R. Kingslake/B. Johnson Lens Design Fundamentals, Academic Press, 2010
13. H. Sun Lens design a practical guide, CRC Press 2017
14. A. Yabe Optimization in Lens design, SPIE Press, 2018
15. Kidger **Fundamental Optical Design, SPIE Press, 2001**

System data

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- Necessary data for system calculation:

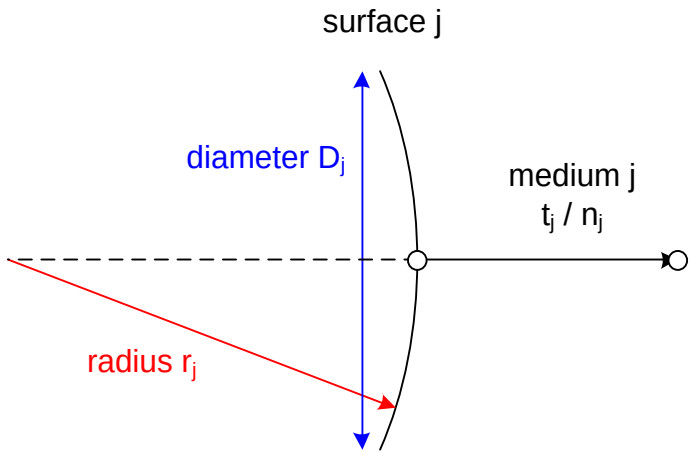
1. system surfaces with parameters (radius)
2. distances with parameters (length, material)
3. stop surface
4. wavelength(s)
5. aperture
6. field point(s)

- Optional inputs:

1. finite diameters
2. vignetting factors
3. decenter and tilt
4. coordinate reference
5. weighting factors
6. multi configurations
7. ...

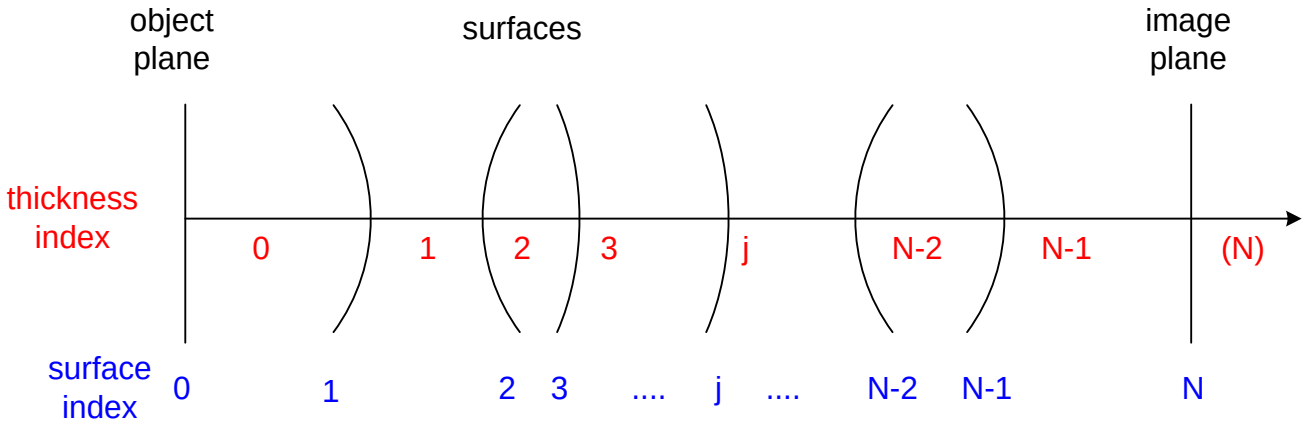
System model

- Single step:
  - surface and transition
  - parameters: radius, diameter, thickness,
    refractive index, aspherical constants,
    conic parameter, decenter, tilt,...



- Complete system:
  - sequence of surfaces
  - object has index 0
  - image has index N
  - tN does not exist

- Ray path has fixed sequence
  0-1-2-...-(N-1)-N



Coordinate systems and sign of quantities

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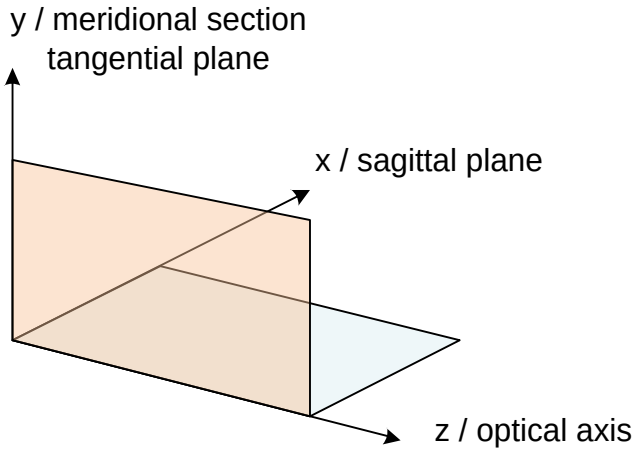
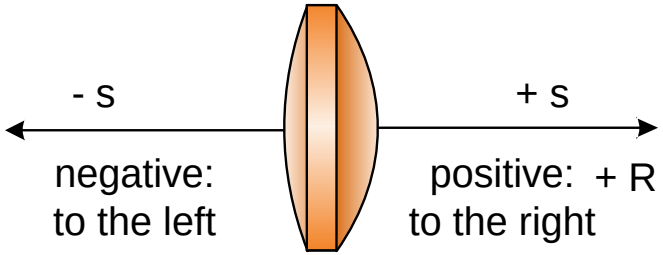
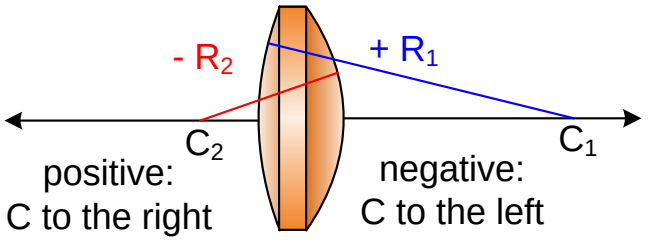
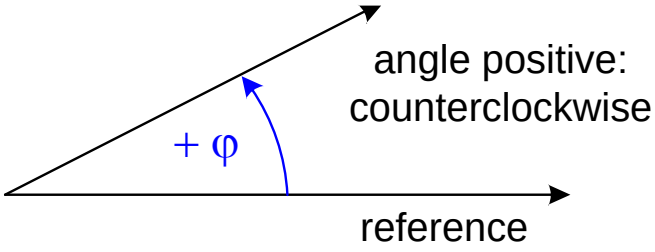
- Coordinate systems
  2D sections: y-z shown



- Sign of lengths, radii, angles:







Definition of Aperture and Field

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- Imaging on axis: circular / rotational symmetry
  Only spherical aberration and chromatical aberrations

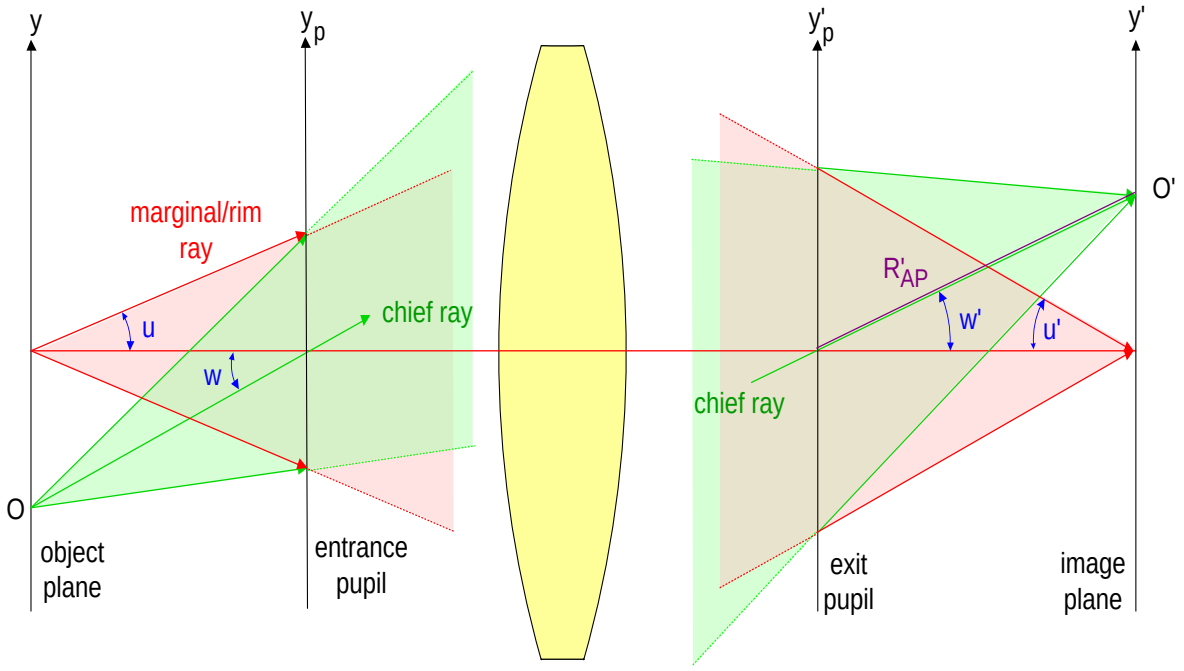
- Finite field size, object point off-axis:

  - chief ray as reference

  - skew ray bundels:
    coma and distortion

  - Vignetting, cone of ray bundle
    not circular symmetric

  - to distinguish:
    tangential and sagittal
    plane



Aperture Definition

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Quantitative measures of relative opening / size of accepted light cone

- Numerical aperture

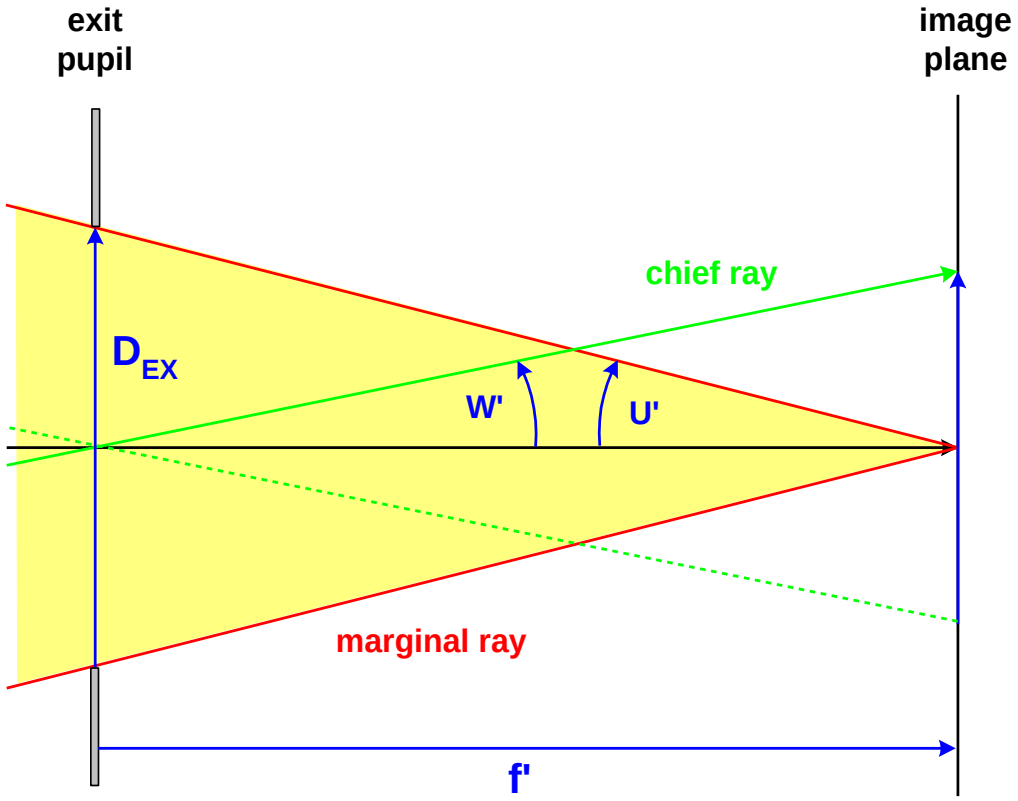
$$NA = n \cdot \sin u'$$

- F-number

$$F\# = \frac{f'}{D_{EX}}$$

- Approximation for small apertures:

$$F\# = \frac{1}{2 \cdot NA}$$



Important Test Wavelengths

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λ in [nm]	Name	Color	Element
248.3		UV	Hg
280.4		UV	Hg
296.7278		UV	Hg
312.5663		UV	Hg
334.1478		UV	Hg
365.0146	i	UV	Hg
404.6561	h	violett	Hg
435.8343	g	blau	Hg
479.9914	F'	blau	Cd
486.1327	F	blau	H
546.0740	e	grün	Hg
587.5618	d	gelb	He
589.2938	D	gelb	Na
632.8			HeNe-Laser
643.8469	C'	rot	Cd
656.2725	C	rot	H
706.5188	r	rot	He
852.11	s	IR	Cä
1013.98	t	IR	Hg
1060.0			Nd:YAG-Laser

Zemax Toolbars

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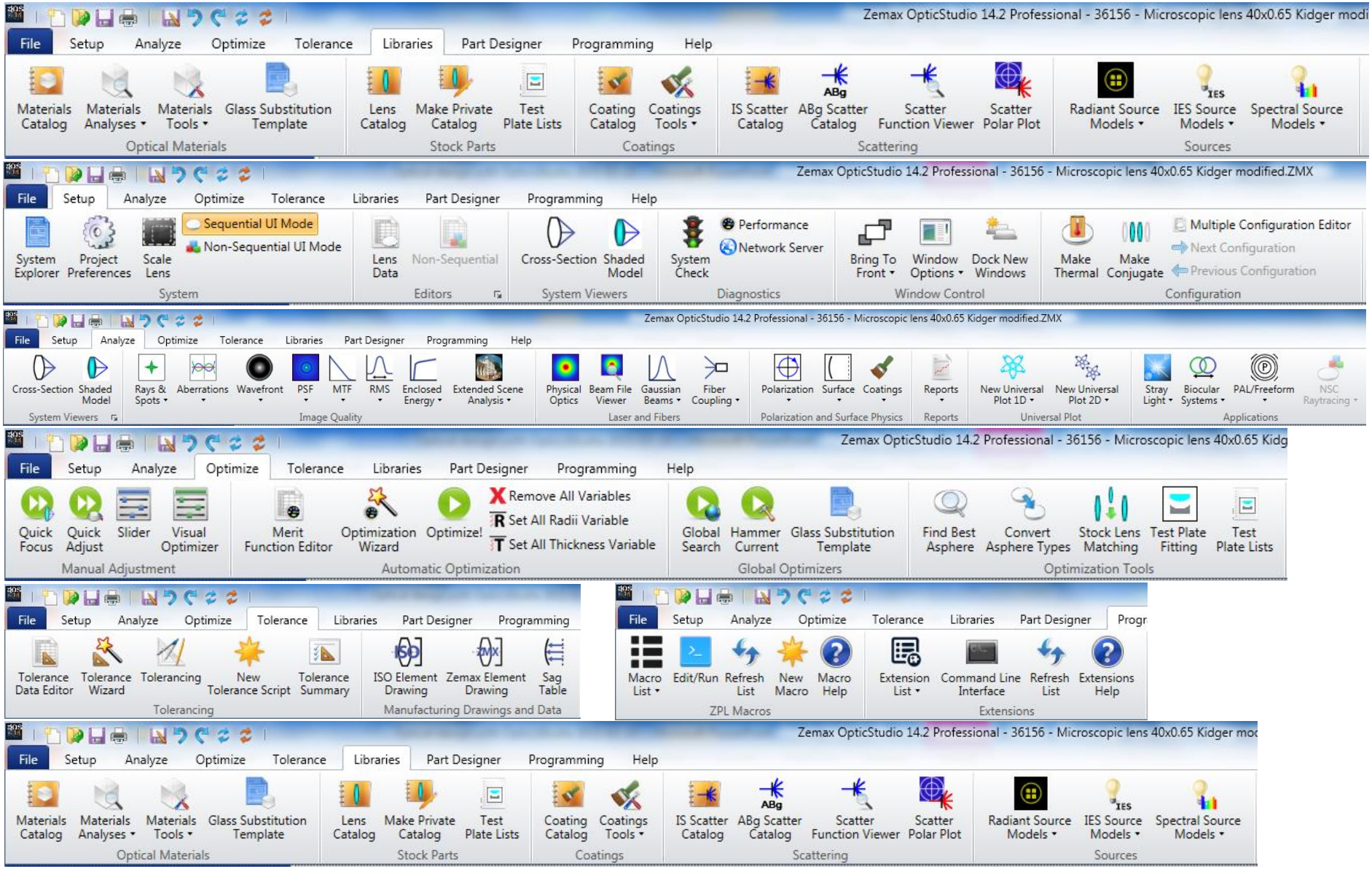

Settings and Environment

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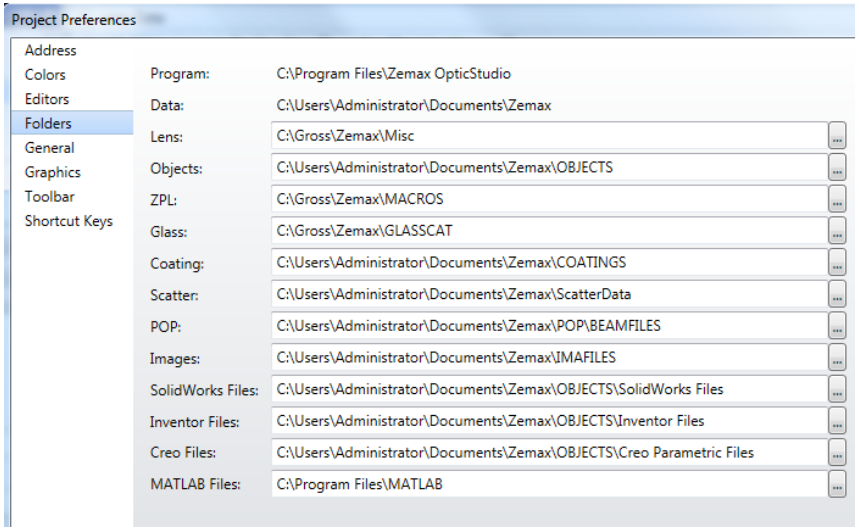
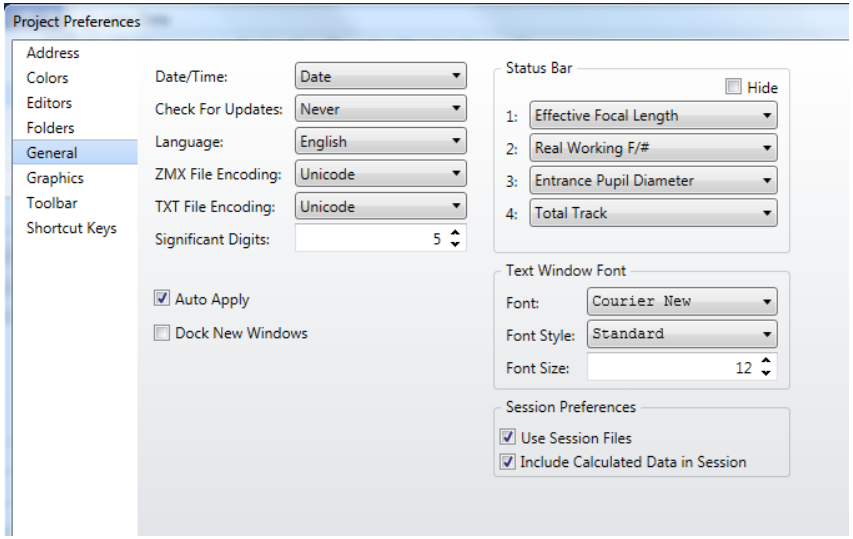
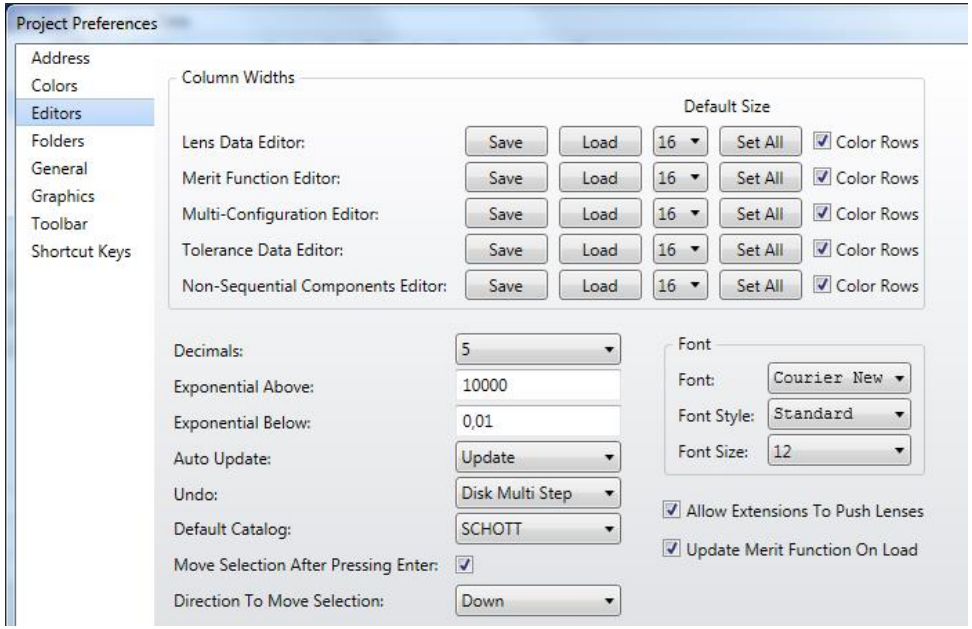
- The settings can be customized in the preferences
- All the settings can be saved
- Important:
  - data file folders
  - graphics parameters
  - editor cell size and Text font
  - preferred fast button functions
  - colors
  - language (don‘t use German !)







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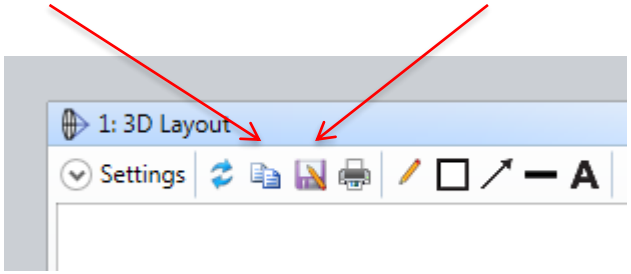
Zemax interface

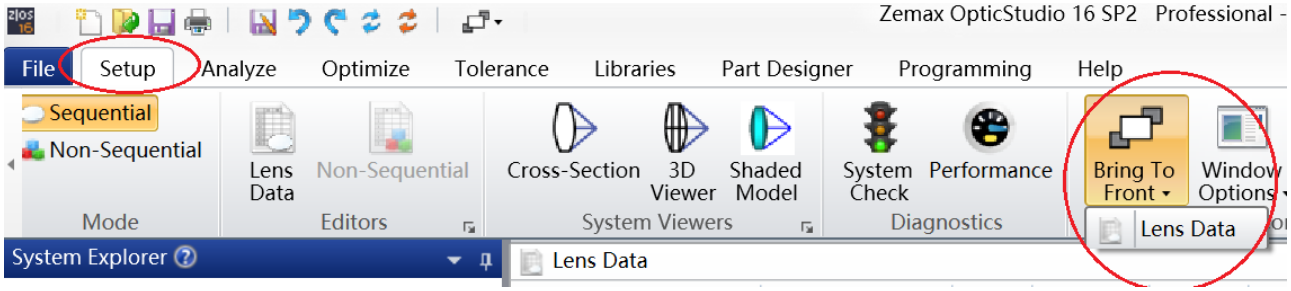
- Helpful shortcuts:

1. F3 undo
2. F2 edit a cell in the editor
3. cntr A multiconfiguration toggle
4. cntr Z variable toggle
5. F6 merit function editor
6. cntr U update
7. shift cntr Q quick focus

- Window options:
  1. several export options:
  2. fixed aspect ratios
  3. clone
  4. adding comments or graphics

save clipboard - save as BMP/JPEG/PNG





Description of optical systems

- Interface surfaces
  - mathematical modelled surfaces
  - planes, spheres, aspheres, conics, free shaped surfaces,…
- Size of components
  - thickness and distances along the axis
  - transversal size,circular diameter, complicated contours
- Geometry of the setup
  - special case: rotational symmetry
  - general case: 3D, tilt angles, offsets and decentrations, needs vectorial approach
- Materials
  - refractive indices for all used wavelengths
  - other properties: absorption, birefringence, nonlinear coefficients, index gradients,…
- Special surfaces
  - gratings, diffractive elements
  - arrays, scattering surfaces

3D Geometry

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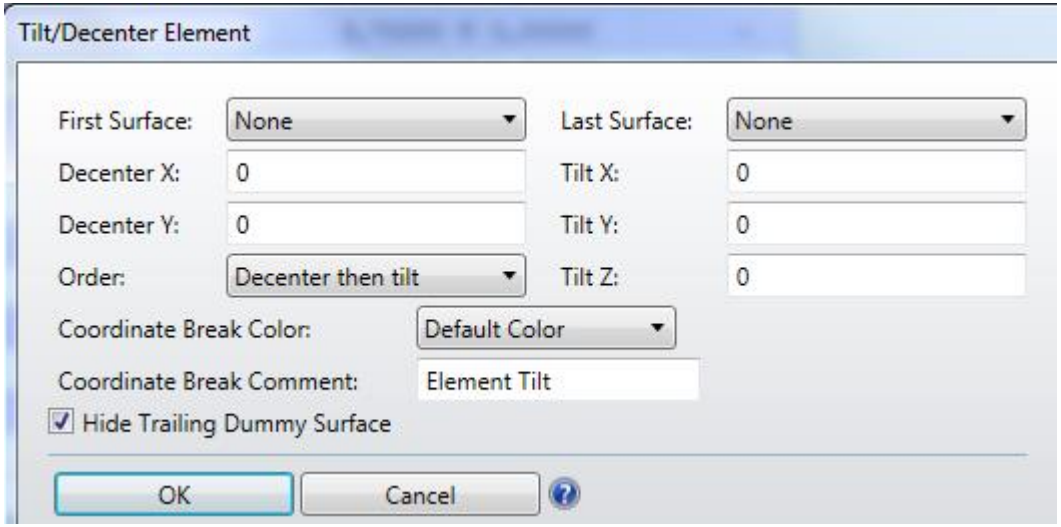
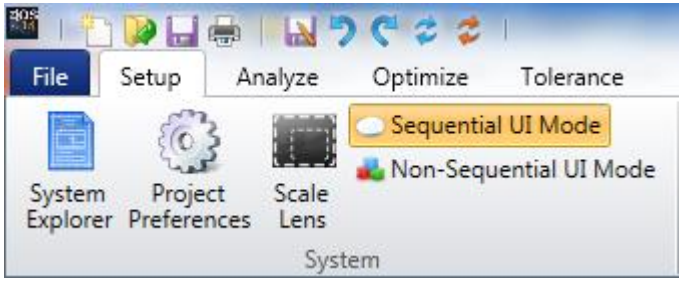
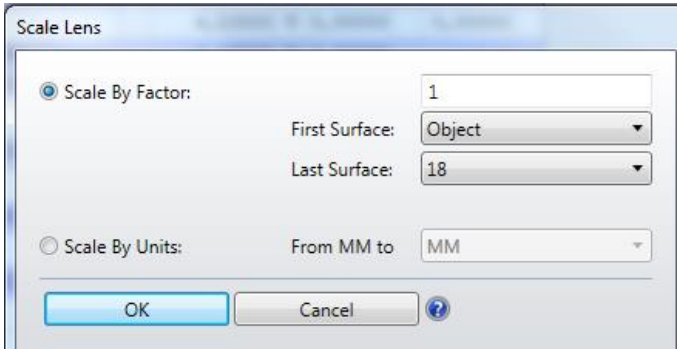
- Auxiliary menus:

1. Tilt/Decenter element



2. Scale lens





3D Geometry

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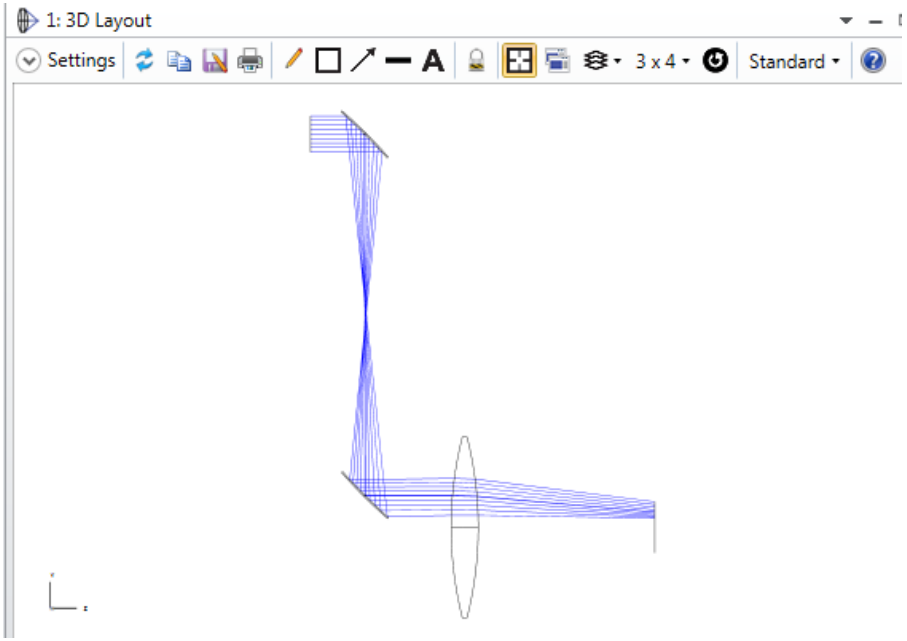
- General input of tilt and decenter: Coordinate break surface
- Change of coordinate system with lateral translation and 3 rotations angles
- Direct listing in lens editor
- Not shown in layout drawing



Lens Data

Surface 0 Properties — Configuration 1/1

	Surf:Type	Comment	Radius		Thickness	Material	Coating	Semi-Diameter		Conic	TCE x 1E-6	Par 1 (unused)	Par 2 (unused)	Par 3 (unused)		Par 4 (unused)	Par 5 (unused)
0	OBJECT Standard		Infinity		Infinity			0,00000		0,00000	0,00000						
1	Standard		Infinity		30,00000			10,00000		0,00000	0,00000						
2	Coordinate Break				0,00000	-		0,00000			-	0,00000	0,00000	-45,00000		0,00000	0,00000
3	(aper) Standard		-282,00000		0,00000	MIRROR		18,00000	U	0,00000	0,00000						
4	Coordinate Break				-200,00000	-		0,00000			-	0,00000	0,00000	-45,00000	P	0,00000	0,00000
5	Coordinate Break				0,00000	-		0,00000			-	0,00000	0,00000	45,00000		0,00000	0,00000
6	(aper) Standard		282,00000		0,00000	MIRROR		18,00000	U	0,00000	0,00000						
7	Coordinate Break				30,00000	-		0,00000			-	0,00000	-25,00000	45,00000	P	0,00000	0,00000
8	(aper) Standard		205,00000		15,00000	BK7		50,00000	U	0,00000	-						
9	STOP (aper) Standard		-205,00000	P	97,56052			50,00000	U	0,00000	0,00000						
10	IMAGE Standard		Infinity		-			14,14302		0,00000	0,00000						

3D Geometry

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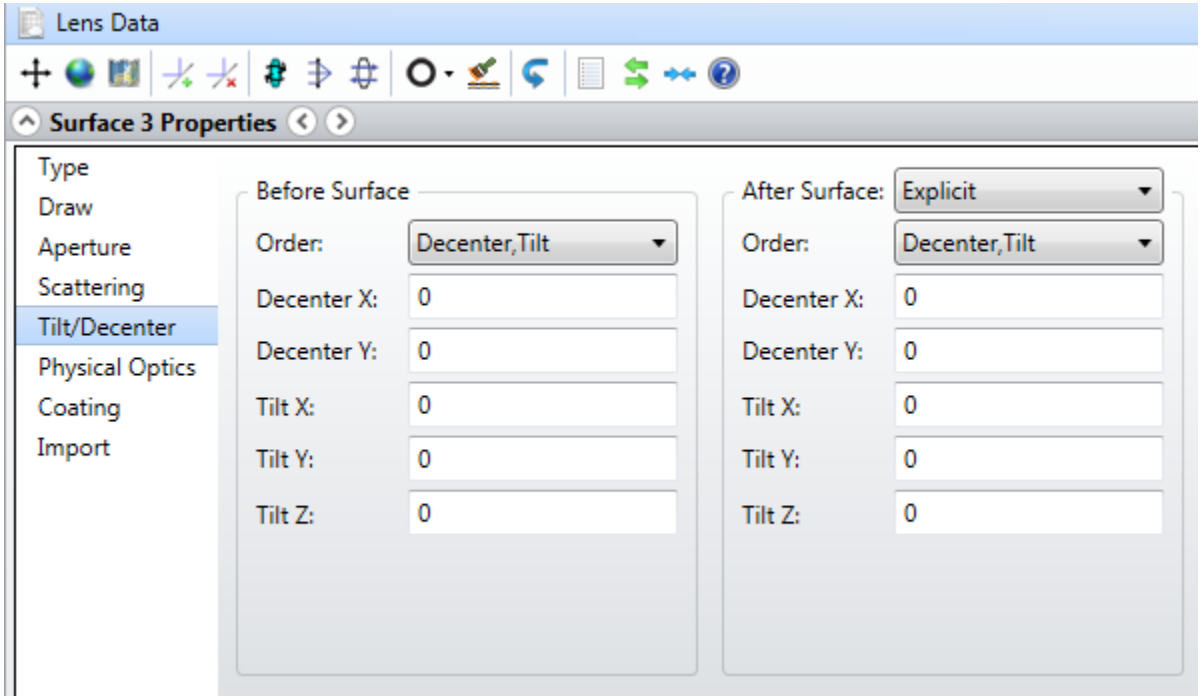
- Local tilt and decenter of a surface
  1. no direct visibility in lens editor
     only + near surface index
  2. input in surface properties
  3. with effect on following system surfaces



System data tables

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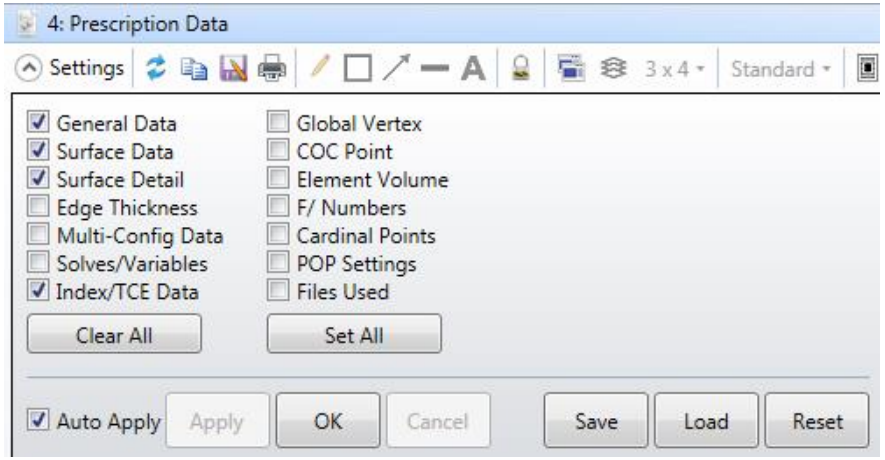
4: Prescription Data

Settings | 3 x 4 | Standard

```
System/Prescription Data

File : C:\Gross\Zemax\Misc\Microscopic lens 40x0.65 Kidger modified.ZMX
Title: Lens has no title.
Date : 20.03.2015


LENS NOTES:

Notes...



GENERAL LENS DATA:

Surfaces                 :                18
Stop                     :                11
System Aperture          :   Entrance Pupil Diameter =   5,85
Fast Semi-Diameters      :   On
Field Unpolarized        :   On
Convert thin film phase to ray equivalent : On
J/E Conversion Method    :   X Axis Reference
Glass Catalogs           :   SCHOTT
Ray Aiming               :   Off
Apodization              :   Uniform, factor =     0,00000E+000
Reference OPD            :   Exit Pupil
Paraxial Rays Setting    :   Ignore Coordinate Breaks
Method to Compute F/#    :   Tracing Rays
Print Coordinate Breaks  :   On
Multi-Threading          :   On
OPD Modulo 2 Pi          :   Off
Temperature (C)          :      2,00000E+001
Pressure (ATM)           :      1,00000E+000
Adjust Index Data To Environment  : Off
Effective Focal Length   :          4,499996    (in air at system temperature and pressure)
Effective Focal Length   :          4,499996    (in image space)
Back Focal Length        :          3,804983
Total Track              :          33,00199
Image Space F/#          :         0,7692301
Paraxial Working F/#     :         0,7692301
Working F/#              :         0,7695343
Image Space NA           :         0,5449887
Object Space NA          :        2,925e-010
Stop Radius              :          4,320451
Paraxial Image Height    :         0,2358348
Paraxial Magnification   :                 0
Entrance Pupil Diameter  :              5,85
Entrance Pupil Position  :          19,19687
Exit Pupil Diameter      :          11,07531
Exit Pupil Position      :         -8,520728
Field Type               :   Angle in degrees
Maximum Radial Field     :                 3
Primary Wavelength [µm]  :         0,546074
Angular Magnification    :         0,5282022
Lens Units               :      Millimeters
Source Units             :      Watts
Analysis Units           :      Watts/cm^2
Afocal Mode Units        :      milliradians
MTF Units                :      cycles/millimeter
Include Calculated Data in Session File  :  On
```

Menu:

reports / prescription data



System data tables

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SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Diameter	Conic
OBJ	STANDARD	Infinity	Infinity		0	0
1	STANDARD	Infinity	5		7,86213	0
2	STANDARD	17,35664	2,60396	FK51	6,8	0
3	STANDARD	-21,74533	0,2		6,44	0
4	STANDARD	5,97609	2,63782	LLF1	6	0
5	STANDARD	3,06343	1,83096		4,2	0
6	STANDARD	-3,01507	3,90374	SF5	4,2	0
7	STANDARD	18,74531	2,93552	FK51	7,4	0
8	STANDARD	-5,87789	0,2		8,2	0
9	STANDARD	59,18729	0,7	KZFSN4	8,86	0
10	STANDARD	8,38842	2,52456	FK54	9,2	0
STO	STANDARD	-17,32874	0,2		9,4	0
12	STANDARD	12,83435	1,95758	FK54	9,86	0
13	STANDARD	-30,45877	0,2		9,82	0
14	STANDARD	10,76567	1,95157	FK51	9,42	0
15	STANDARD	-26,59881	0,2		9,2	0
16	STANDARD	4,31068	2,15003	SK11	6,94	0
17	STANDARD	6,00286	3,806254		5,46	0
IMA	STANDARD	Infinity			0,4751514	0

INDEX OF REFRACTION DATA:

System Temperature: 20,0000 Celsius
System Pressure : 1,0000 Atmospheres
Absolute air index: 1,000273 at wavelength 0,546074 µm
Index data is relative to air at the system temperature and pressure.
Wavelengths are measured in air at the system temperature and pressure.

Surf	Glass	Temp	Pres	0,479991	0,546074	0,643847	
0		20,00	1,00	1,00000000	1,00000000	1,00000000	
1		20,00	1,00	1,00000000	1,00000000	1,00000000	
2	FK51	20,00	1,00	1,49088232	1,48793656	1,48507869	
3		20,00	1,00	1,00000000	1,00000000	1,00000000	
4	LLF1	20,00	1,00	1,55724847	1,55098671	1,54513009	lead containing glass type
5		20,00	1,00	1,00000000	1,00000000	1,00000000	
6	SF5	20,00	1,00	1,68875714	1,67763914	1,66756173	lead containing glass type
7	FK51	20,00	1,00	1,49088232	1,48793656	1,48507869	
8		20,00	1,00	1,00000000	1,00000000	1,00000000	
9	KZFSN4	20,00	1,00	1,62389433	1,61669235	1,60990058	was replaced by N-KZFS4
10	FK54	20,00	1,00	1,44060795	1,43815076	1,43575617	
11		20,00	1,00	1,00000000	1,00000000	1,00000000	
12	FK54	20,00	1,00	1,44060795	1,43815076	1,43575617	
13		20,00	1,00	1,00000000	1,00000000	1,00000000	
14	FK51	20,00	1,00	1,49088232	1,48793656	1,48507869	
15		20,00	1,00	1,00000000	1,00000000	1,00000000	
16	SK11	20,00	1,00	1,57081059	1,56605180	1,56146150	
17		20,00	1,00	1,00000000	1,00000000	1,00000000	
18		20,00	1,00	1,00000000	1,00000000	1,00000000	

Important Surface Types

Standard	spherical and conic sections
Even asphere	classical asphere
Paraxial	ideal lens
Paraxial XY	ideal toric lens
Coordinate break	change of coordinate system
Diffraction grating	line grating
Gradient 1	gradient medium
Toroidal	cylindrical lens
Zernike Fringe sag	surface as superposition of Zernike functions
Extended polynomial	generalized asphere
Black Box Lens	hidden system, from vendors
ABCD	paraxial segment

Selection of Wavelengths

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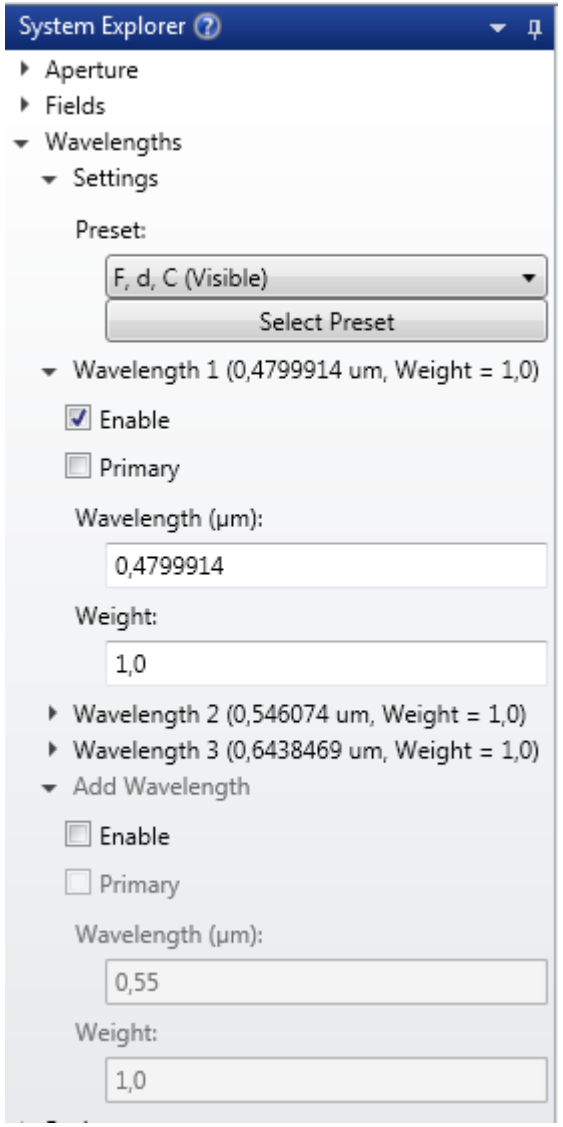
- Setting of wavelengths:
  - maximum of 24 values
  - weighting factors allow for spectral modelling
  - unit is always µm
  - selection of primary wave-length: paraxial data are based on it



System changes

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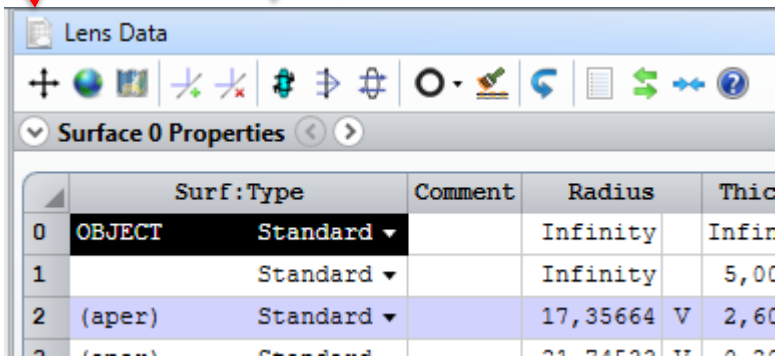
- Useful commands for system changes:
  1. Make double pass
  2. Scale to focal length
  3. Reverse element
  4. Add / delete folding mirror
  5. Tilt/decenter elements
     (see next page)



2. Insert system
   with other system file