EPFL

MICRO-517

Optical Design with ZEMAX OpticStudio

Lecture 1

26.09.2022

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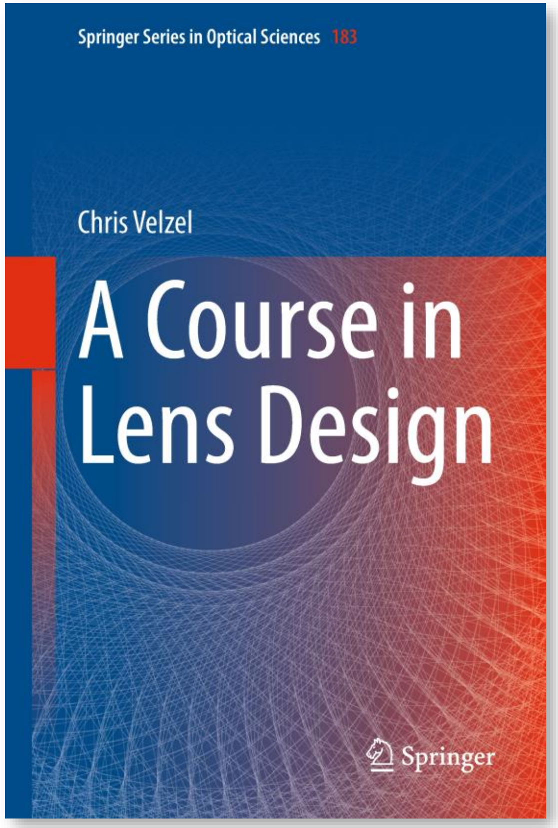
MICRO-517 Course Overview

- **Time:** Mondays 13h15 – 16h00
- **Location:** ME D2 2423
- Hybrid contents:
  - Theory of optical design
  - Design practice in ZEMAX OpticStudio
  - Understanding ZEMAX opportunity and pitfall
  - Final design project
- Contents may be adapted to the progress
- Laptop and software installation required
- New: Optional PCs available at DLL Photonics Lab
- Homework and reports submitted through One Drive
- Questions and suggestions welcome

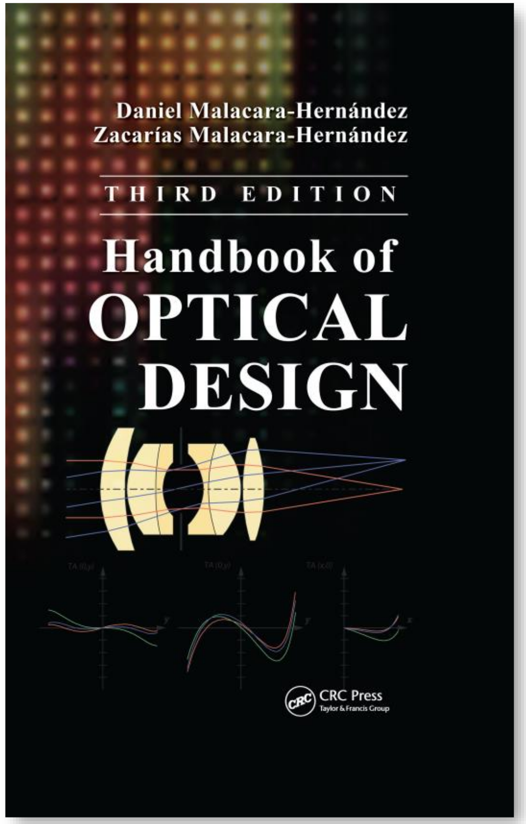
Preliminary Schedule

Lecture	Week	Content
1	37	Introduction to theory of optical design
2	38	Modeling of optical systems properties
3	39	Modeling of optical systems properties
4	40	Image formation and aberrations analysis
5	41	Image formation and aberrations analysis
6	42	Optimization of optical design
7	44	Imaging and transformation
8	45	Non-imaging design, illumination
9	46	Advanced topics
10	47	Design project
11	48	Design project
12	49	Design project
13	50	Design project

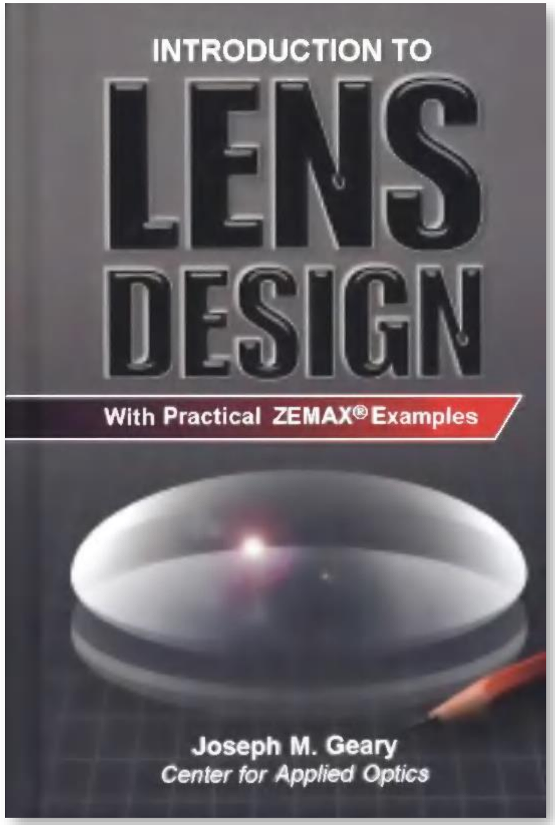
Reference Books on Optical Design



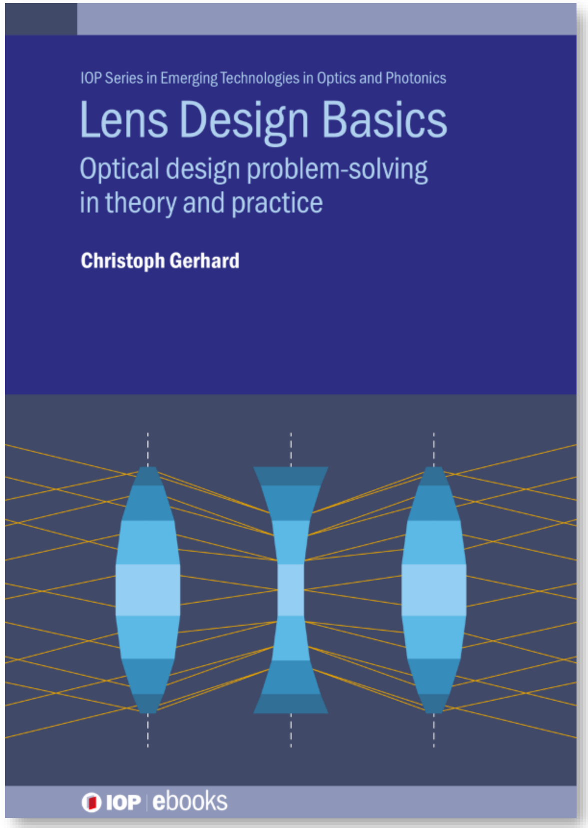
C Velzel, A Course in Lens Design (Springer, 2014)



D Malacara-Hernández and Z Malacara-Hernández, Handbook of Optical Design, 3rd Ed (CRC Press, 2013)



J M Geary, Introduction to Lens Design with Practical ZEMAX Examples (Willmann-Bell, 2002)



C Gerhard, Lens Design Basics: Optical Design Problem-Solving in Theory and Practice (IOP Publishing, 2021)

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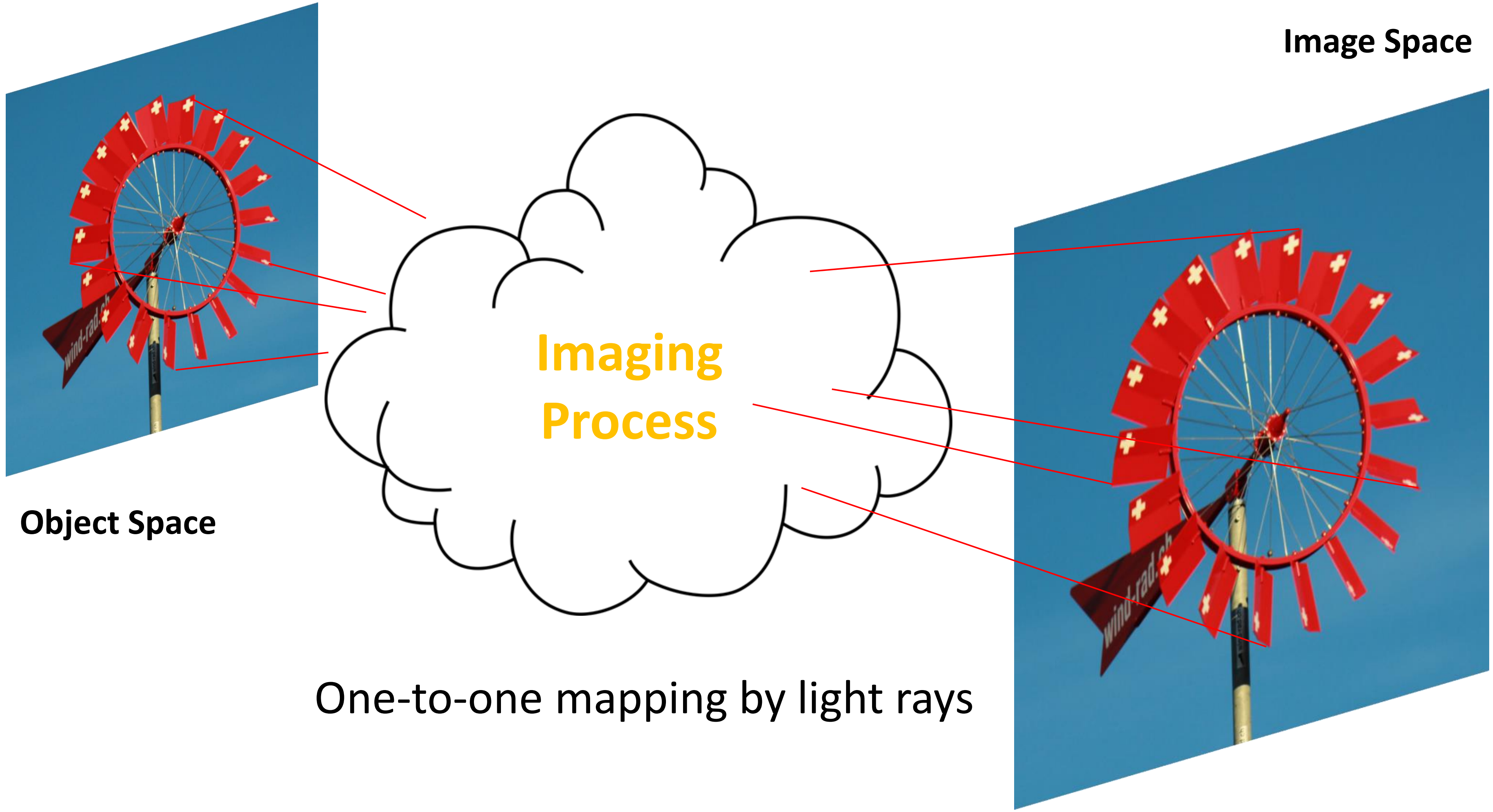
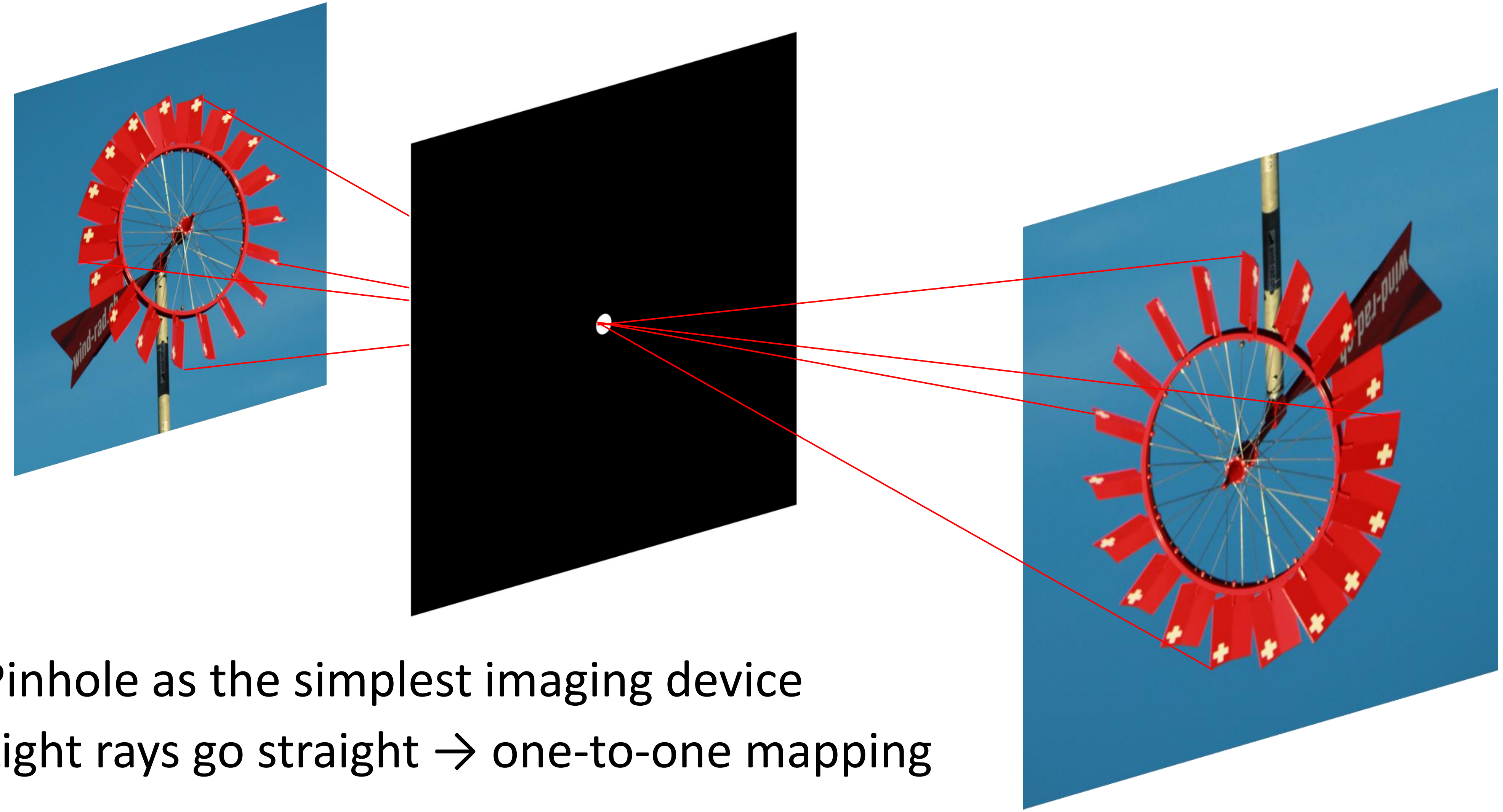
What is Imaging?



One-to-one mapping by light rays

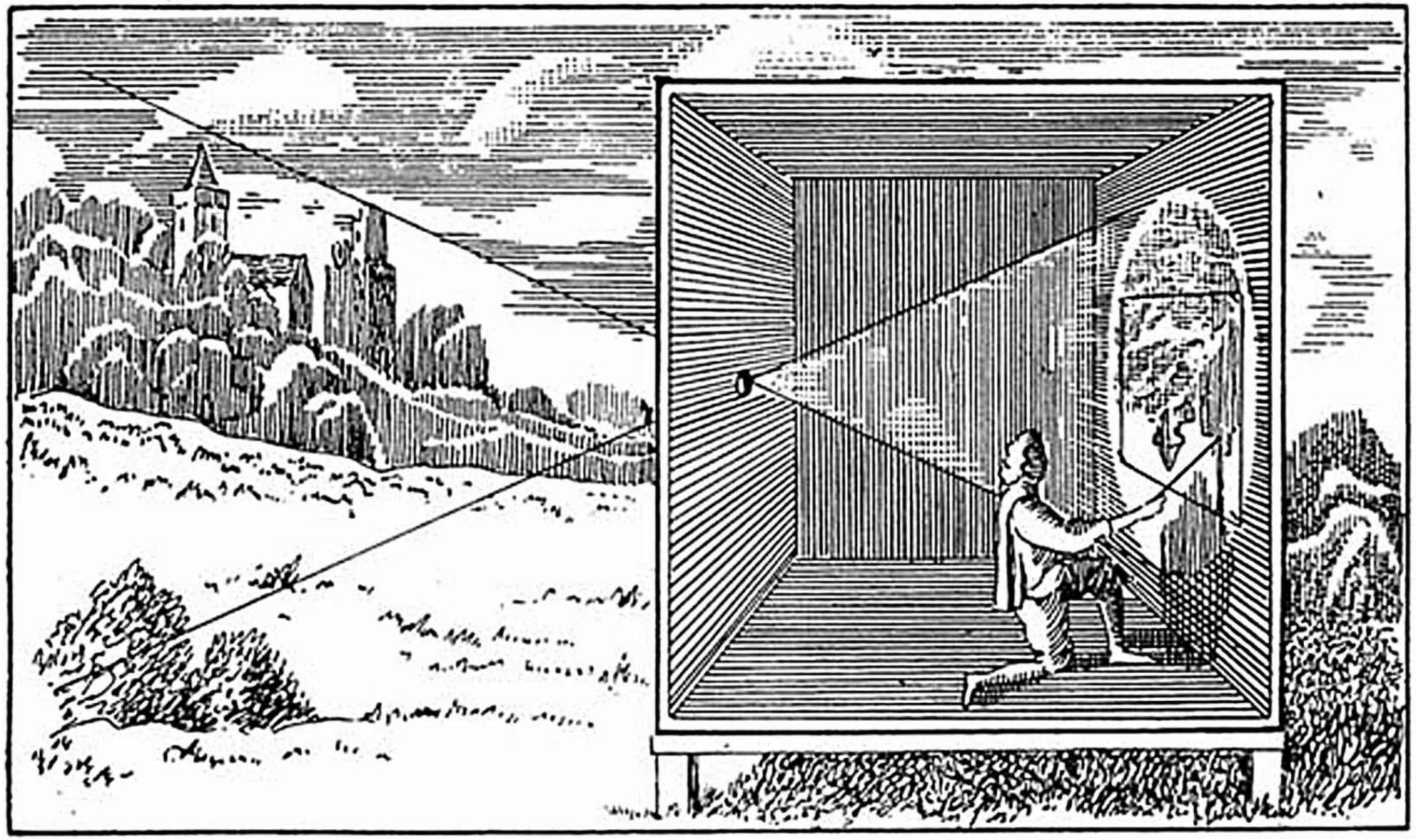
The "Camera Obscura"



Pinhole as the simplest imaging device

Light rays go straight → one-to-one mapping

The "Camera Obscura"



https://magazine.artland.com/agents-of-change-camera-obscura/

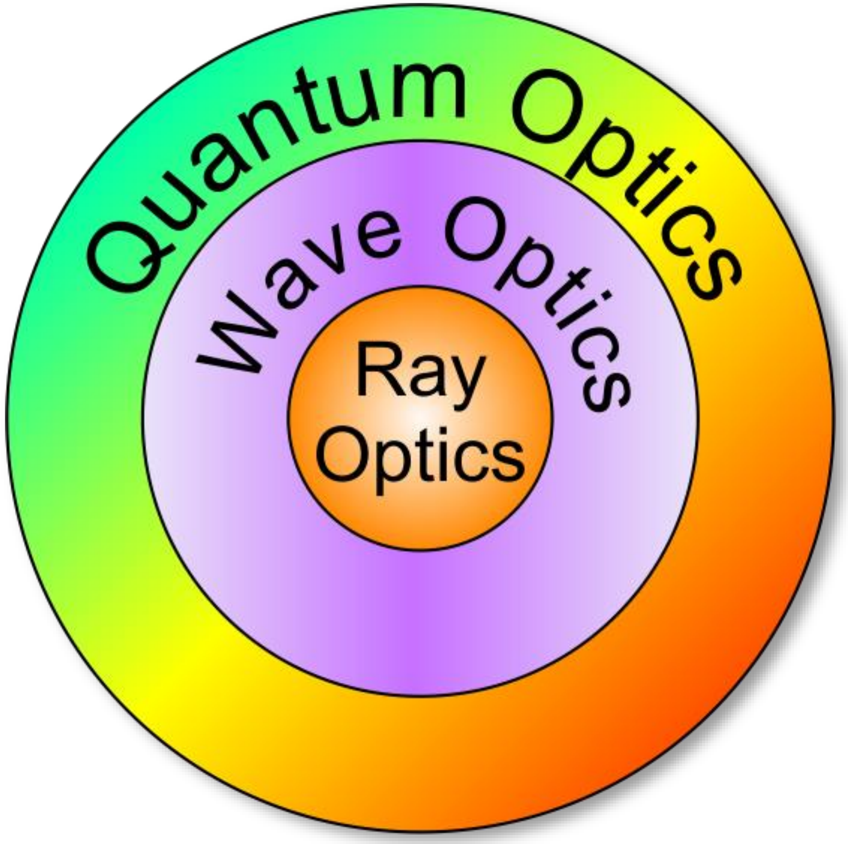
Earliest mention

- Ancient China:
  Mozi (c. 470 – c. 391 BC)
- Ancient Greece:
  Aristotle (384 – 322 BC)

Replacement of the pinhole with a converging lens

- First described by Daniel Barbaro in the 16th century

The Science of Light



GEOMETRICAL (RAY) OPTICS (macroscopic-scale phenomena)
- light travels in straight lines (rays)
- wavelength $\lambda \rightarrow 0$, frequency $\nu \rightarrow \infty$
- explains reflection and refraction
- useful for designing optical systems

WAVE OPTICS (microscopic-scale phenomena)
- light (electromagnetic radiation) is a wave
- action of light described by Maxwell's equations
- explains reflection, refraction, dispersion, interference, polarization, diffraction

QUANTUM OPTICS (atomic-scale phenomena)
- light is photon particles
- has both wave-like and particle-like characteristics
- used to analyze light-matter interactions
- explains photoelectric effect, lasers

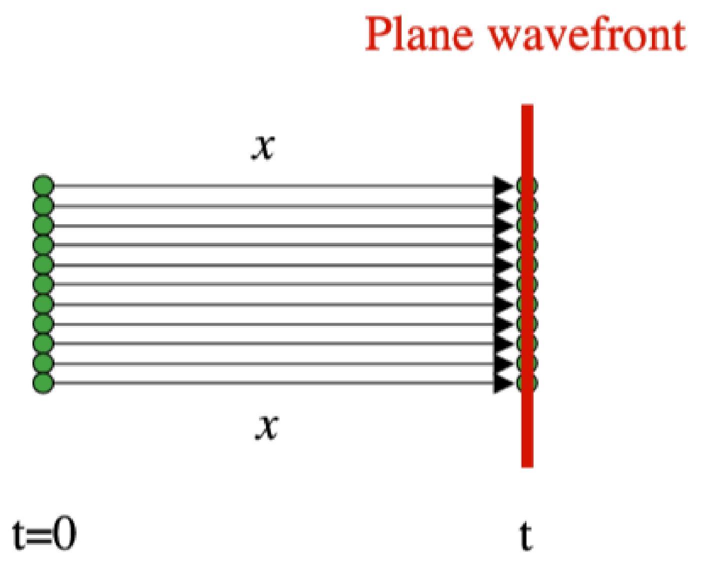
Light as Both Rays and a Wave

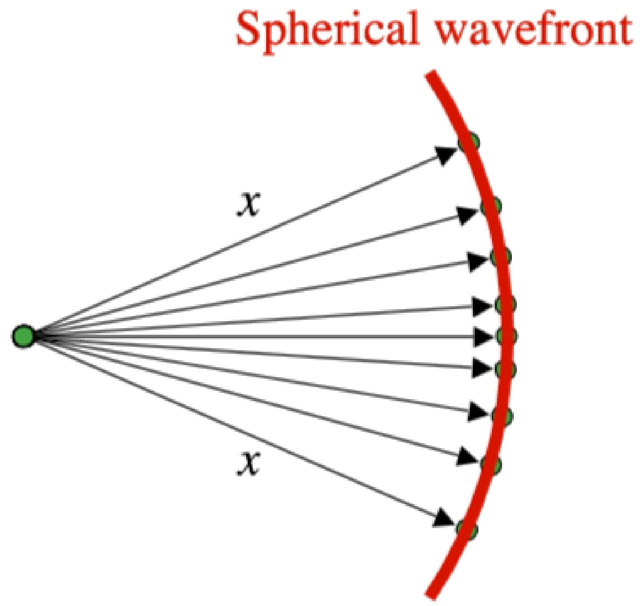
Wave front: a surface over which an optical disturbance has a constant phase

Rays: lines normal to the wave front at every point of intersection

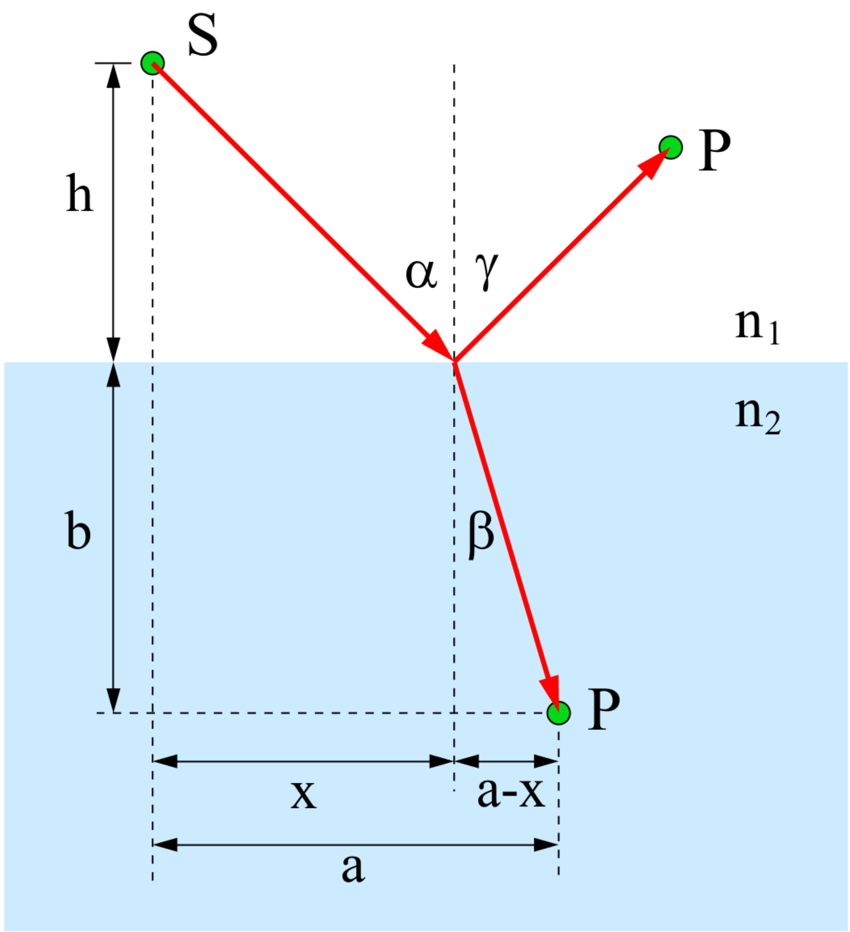
$$\psi(x,t) = A\sin(kx - \omega t) \qquad\qquad \psi(x,t) = \frac{A}{r}\sin(kr - \omega t)$$

Phase





Light at an Interface: Reflection and Refraction



The Fermat Principle

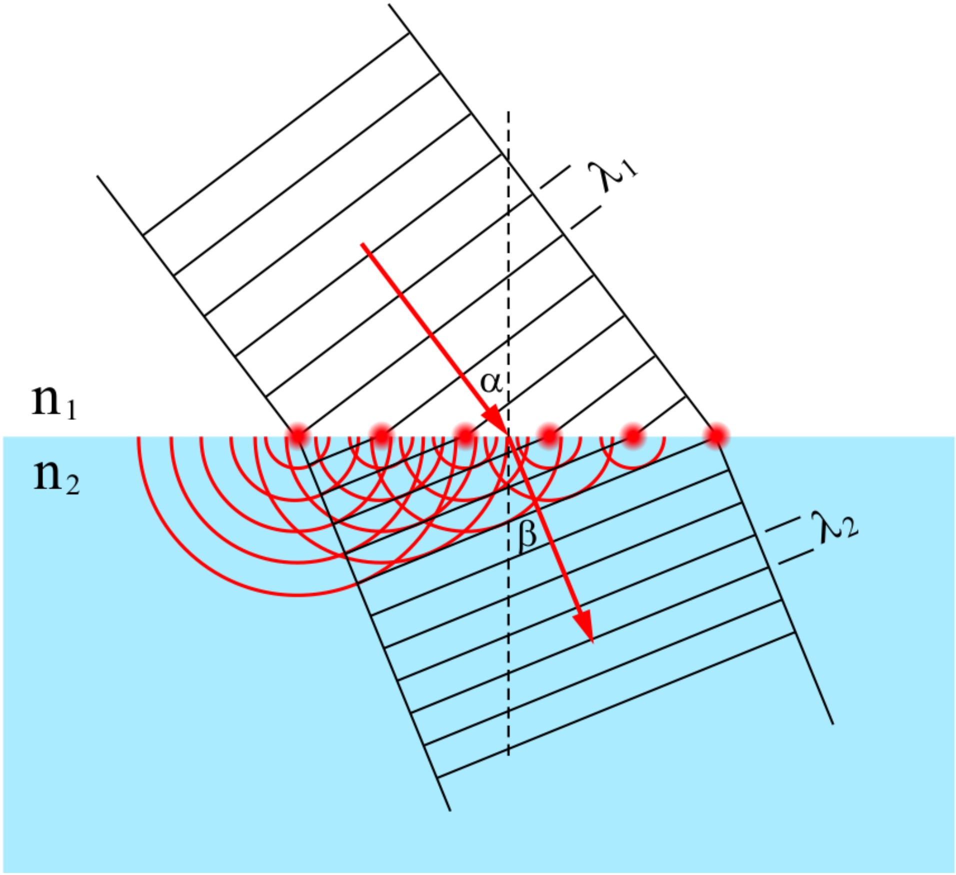
The path taken by a ray between two given points is the path that can be traversed in the shortest optical path (OPL).

$$OPL = n_1 |SO| + n_2 |OP|$$
$$= n_1 \sqrt{h^2 + x^2} + n_2 \sqrt{b^2 + (a-x)^2}$$

$$\frac{d}{dx} OPL = 0$$

$$n_1 \sin\alpha = n_2 \sin\beta$$ Snell's Law

Light at an Interface: Reflection and Refraction



Huygens Principle

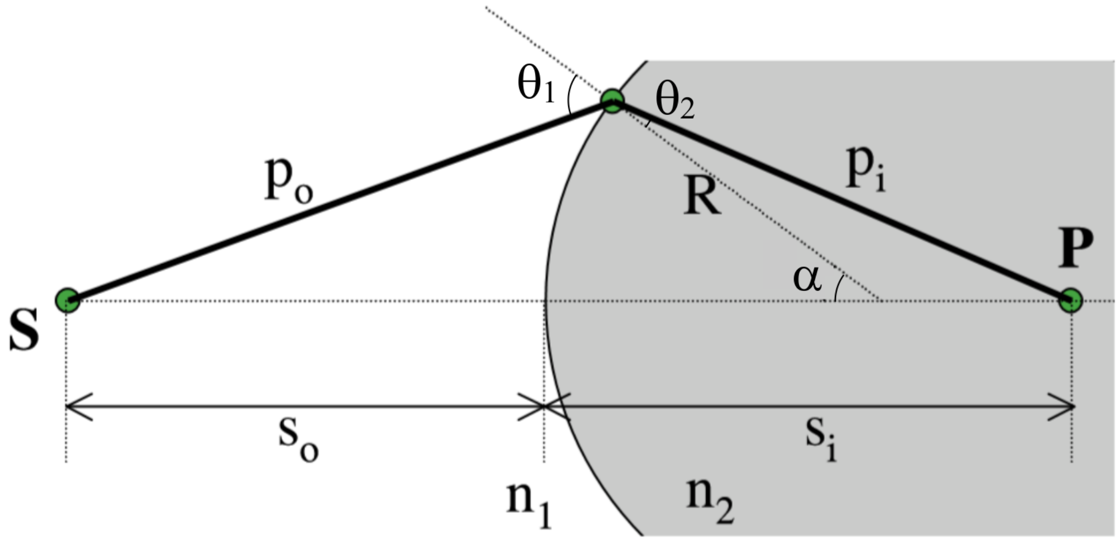
Every point on a wave front is a source of secondary spherical wavelets, and the secondary wavelets superimpose to form the next wave front.

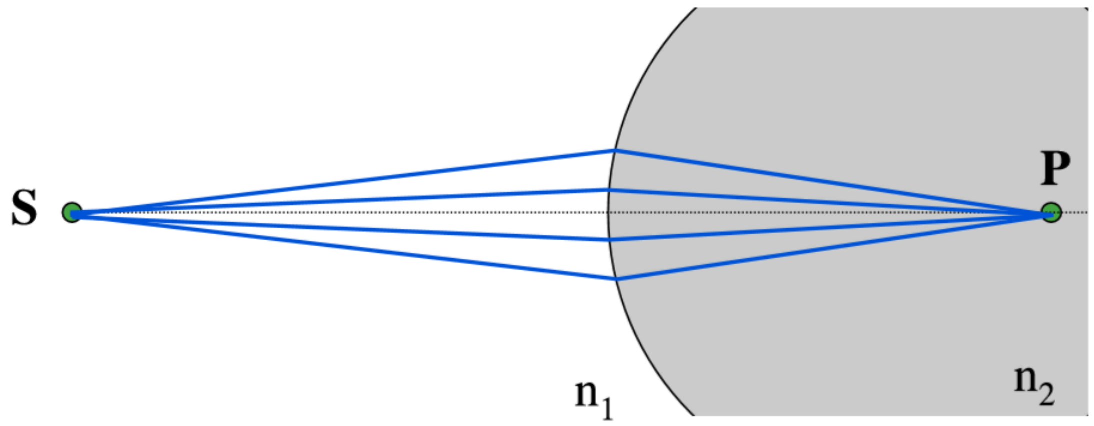
$$\lambda_1 = \frac{v_1}{f} = \frac{c}{n_1 f} \qquad \lambda_2 = \frac{v_2}{f} = \frac{c}{n_2 f}$$

$$\frac{\lambda_1}{\sin\alpha} = \frac{\lambda_2}{\sin\beta}$$

$$n_1 \sin\alpha = n_2 \sin\beta$$ Snell's Law

Light Passing a Spherical Surface: Paraxial





Snell's law $n_1 \sin\theta_1 = n_2 \sin\theta_2$

For small θ

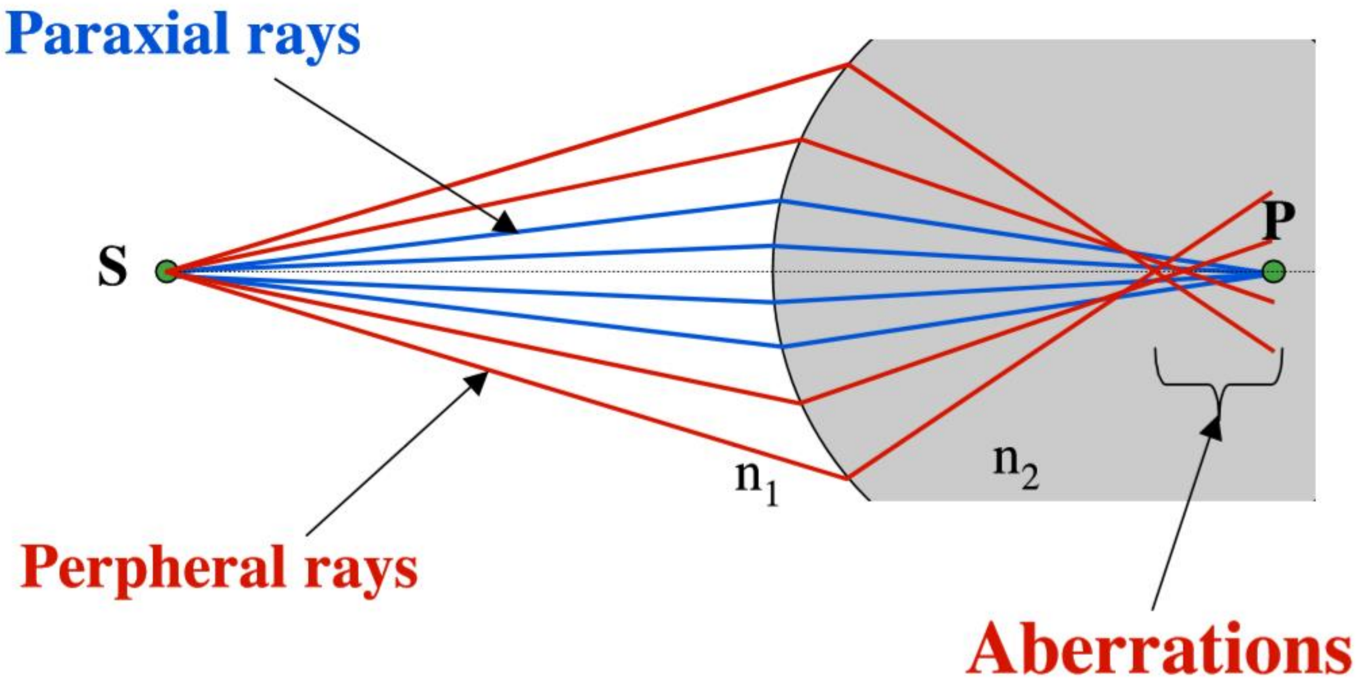
$\sin\theta \approx \theta$

$$\frac{n_1 (s_o + R)\sin\alpha}{p_o} = \frac{n_2 (s_i - R)\sin\alpha}{p_i}$$

$$\frac{n_1}{S_o} + \frac{n_2}{S_i} = \frac{n_2 - n_1}{R}$$

Under paraxial approximation, the emerging rays intersect at the same point P, forming a perfect image

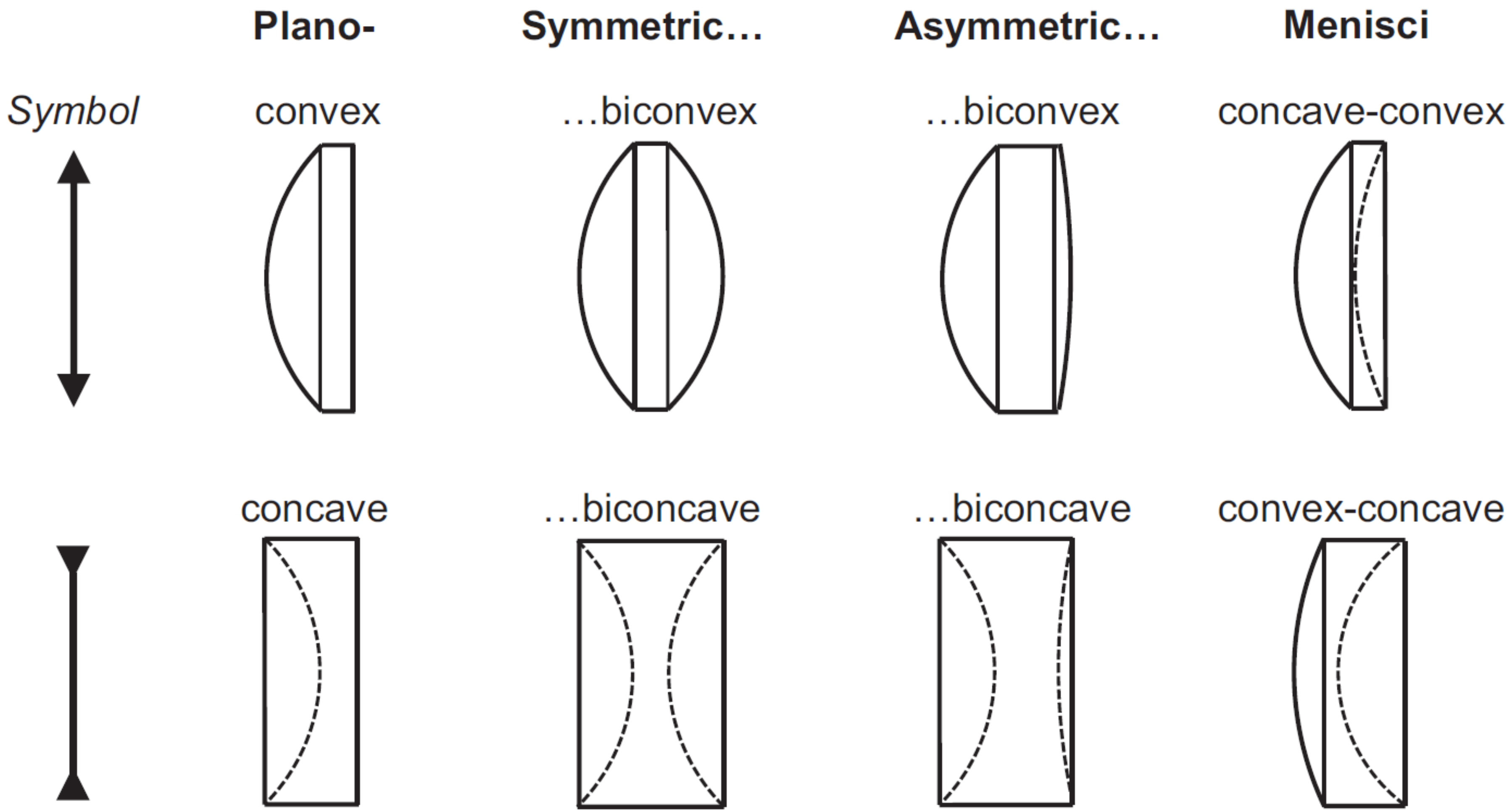
Light Passing a Spherical Surface: Actual



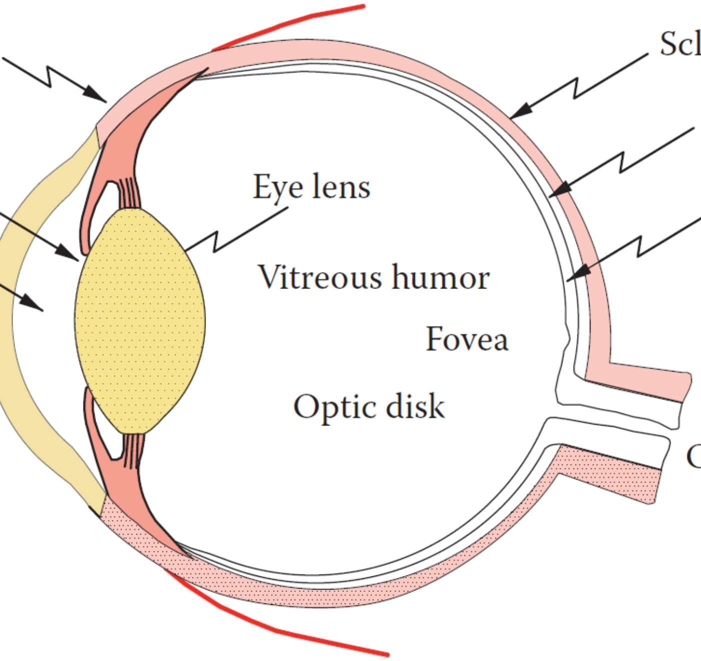
Paraxial approximation becomes increasingly unsatisfactory when larger angled peripheral rays are considered

$$\sin\theta = \theta - \frac{\theta^3}{3!} + \frac{\theta^5}{5!} - \frac{\theta^7}{7!}$$

Spherical Lenses



Typical Imaging System: the Human Eye



Decartes *Dioptrics*

- Plato: light emanated from the eye (4th century B. C.)
- Aristotle: the eye receives rays rather than directed them outward
- Galen: the crystalline lens is the principal organ of vision (2nd century A.D.)
- Kepler: first theory of the retinal image (1604)

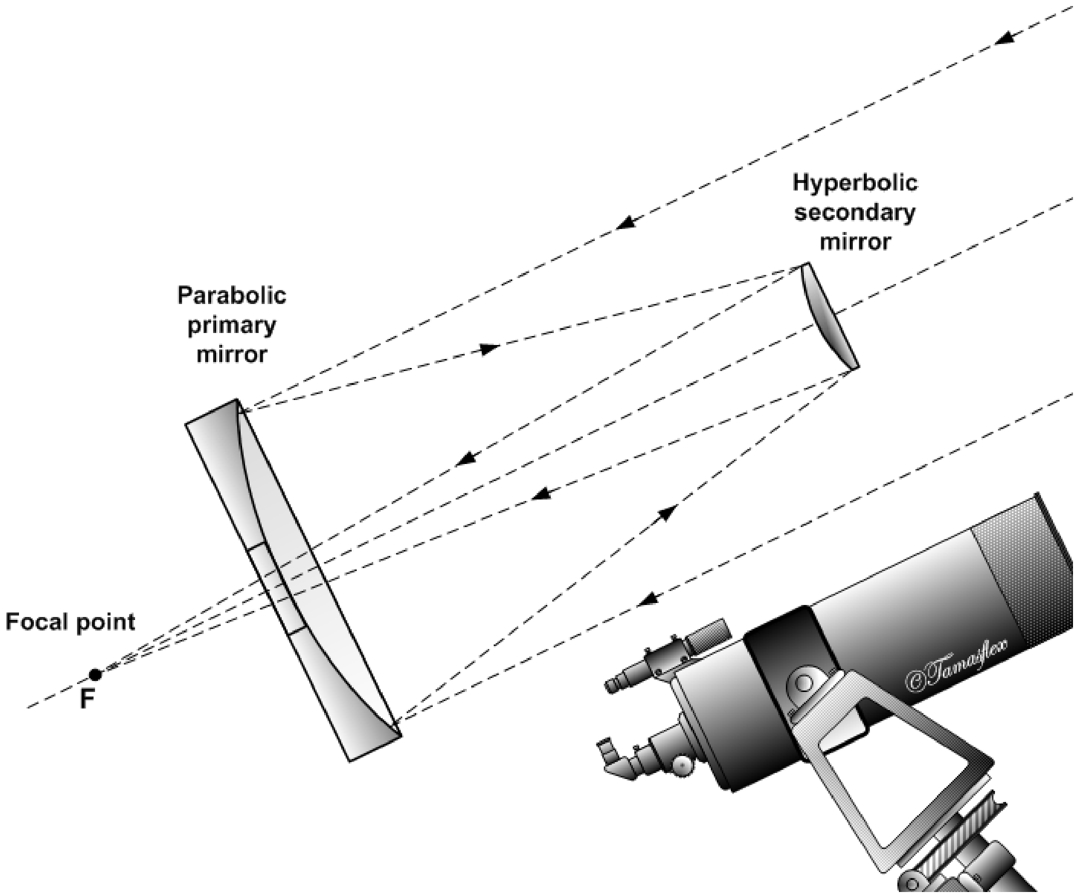
- High aberration system
- Structural basis for all imaging instruments

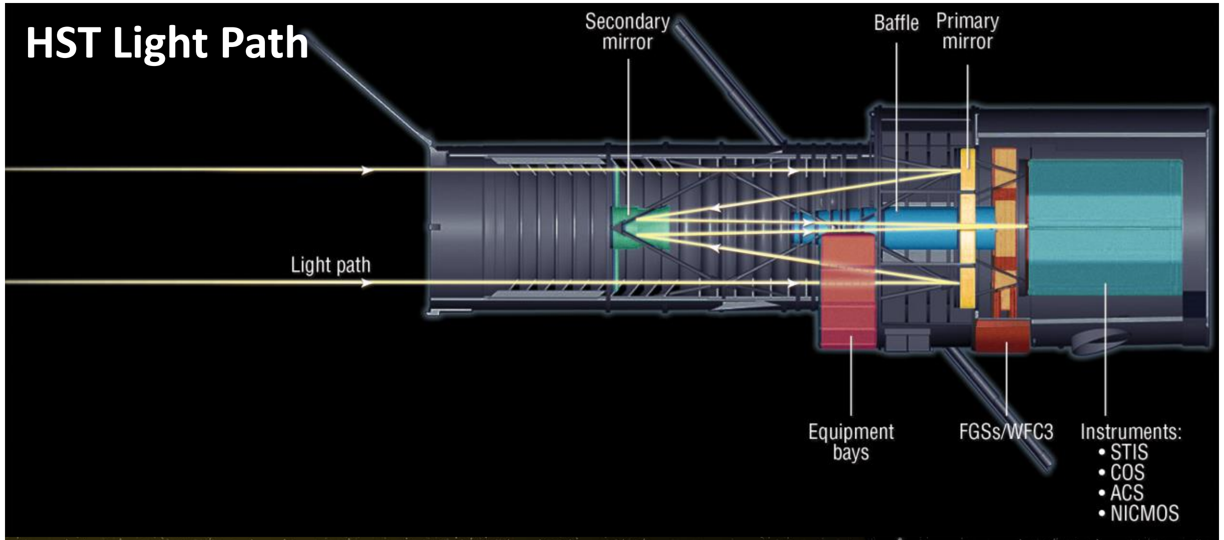
Typical Imaging System: Photographic Camera

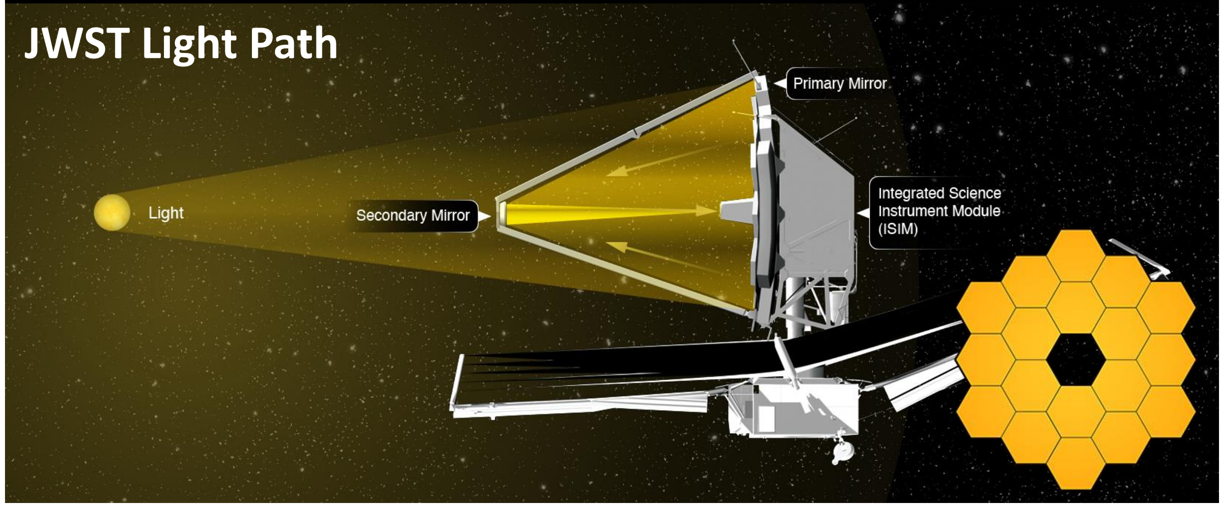
- Pinhole camera (camera obscura): 400 B.C.
- First photographic camera (hand flex reflex camera): 1816
- Daguerreotypes: 1829
- Instantaneous exposures: 1871
- Twin-lens reflex camera: 1885
- Single-lens reflex camera: 1936
- Digital SLR: 1999

- All cameras are structurally and conceptually very closely mimics of the eye

Typical Imaging System: Astronomical Telescope

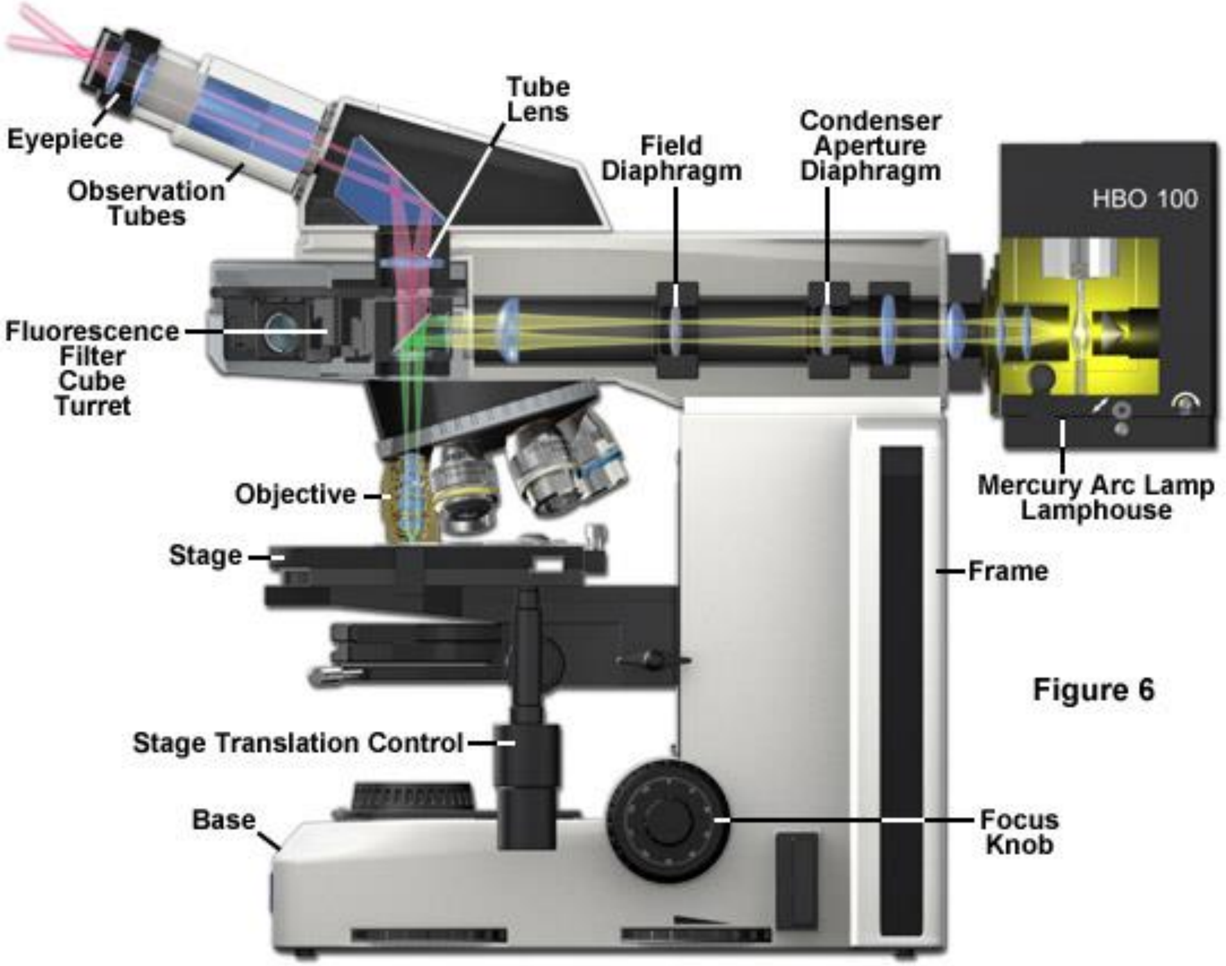




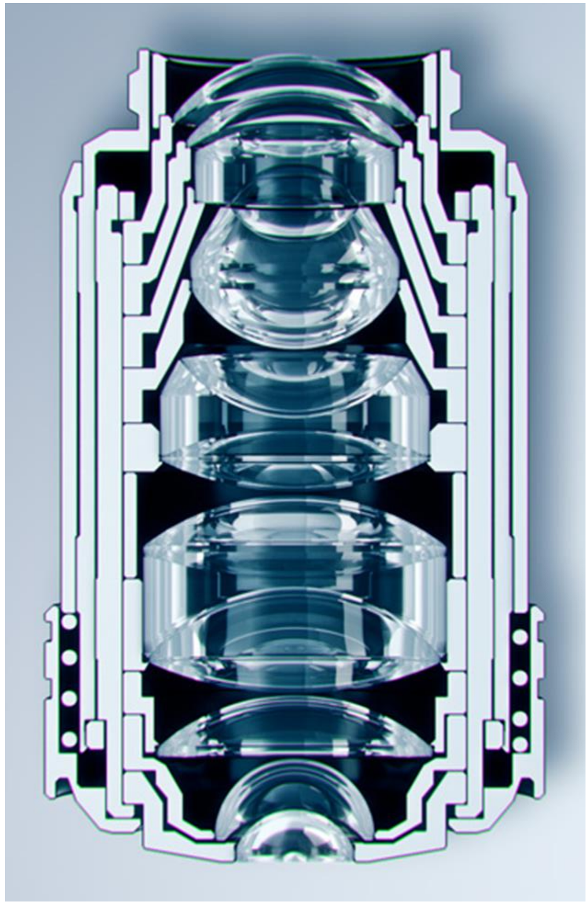


Typical Imaging System: Microscope

ZEISS Epi-Fluorescence Microscope



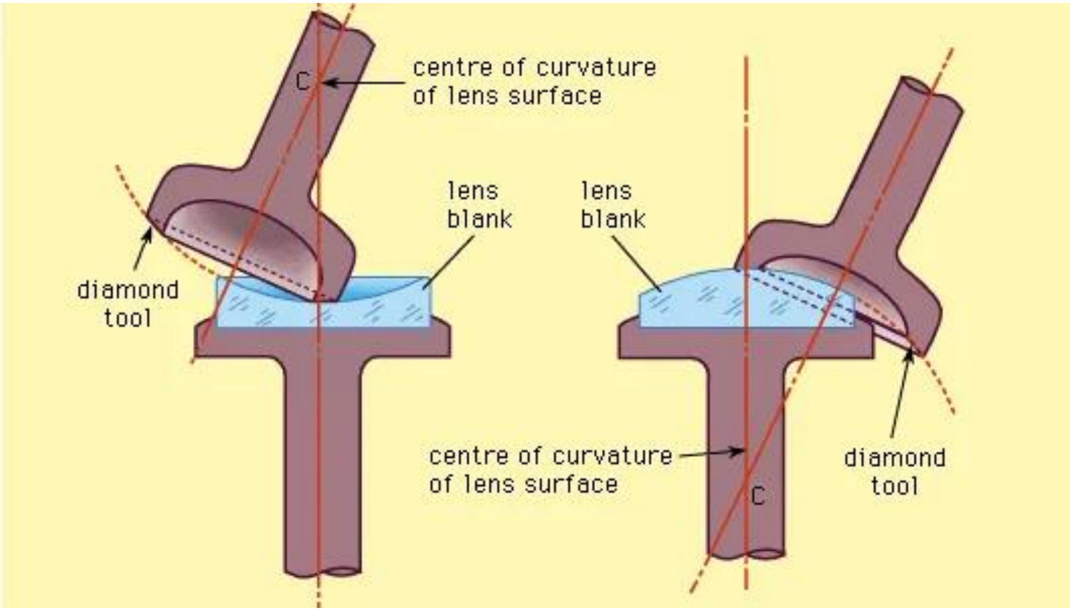
Olympus Oil-immersion Microscope Objective



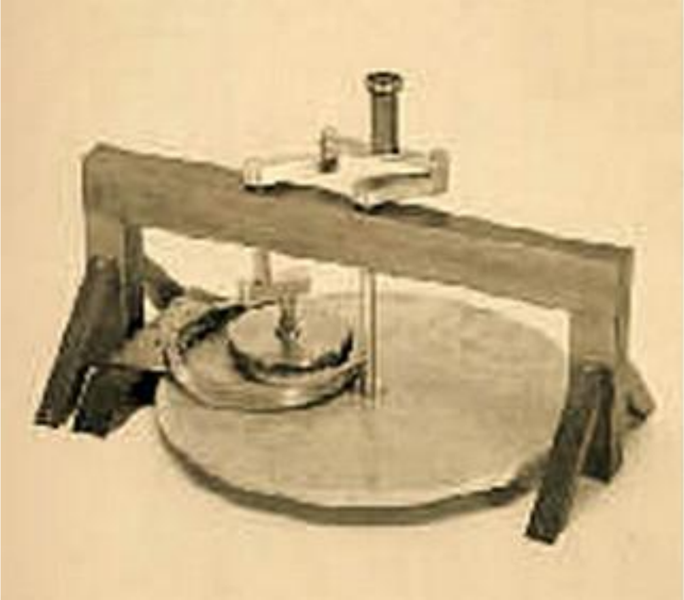
Manufacturing of Lenses

Blank → Grinding → Polishing → Testing → Coating → Mounting → Product

How grinding/polishing works



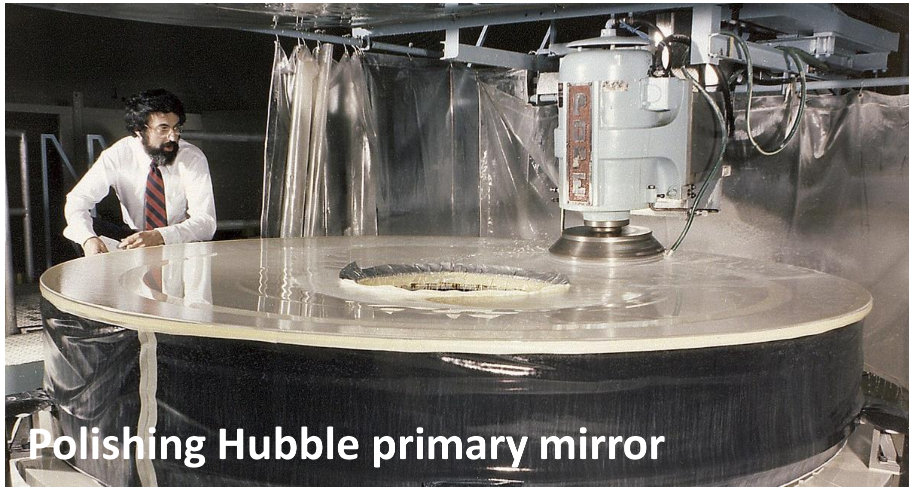
Models of Da Vinci's design of mirror grinder and polisher



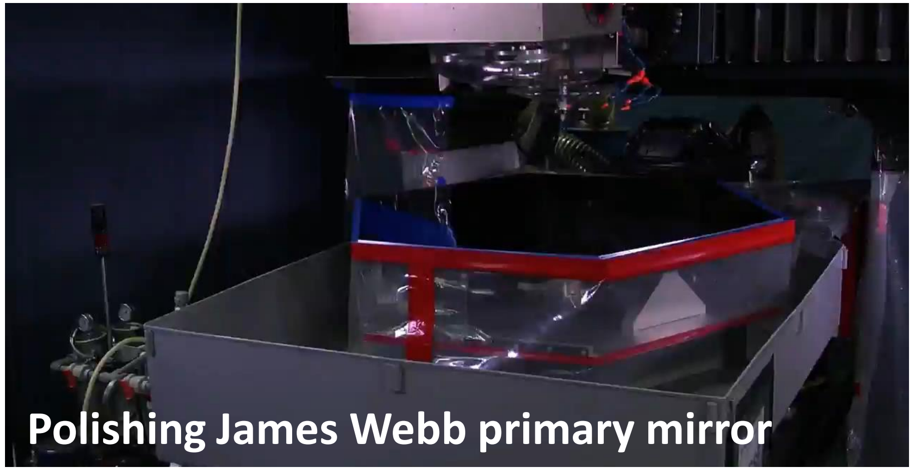
Manufacturing of Lenses

Grinding/polishing

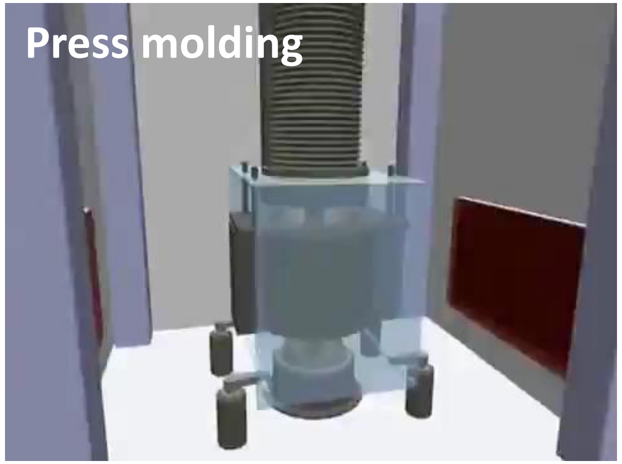

Computer-controlled polisher

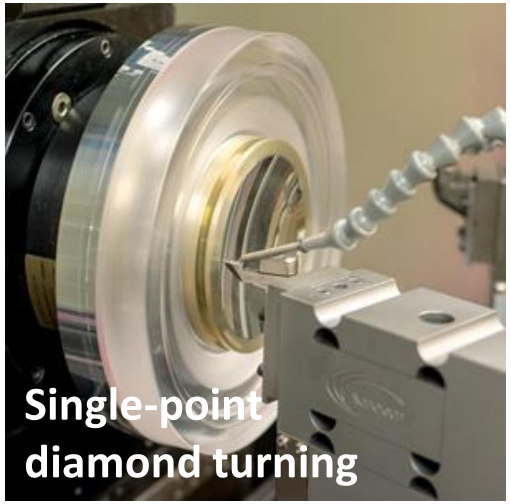

Polishing Hubble primary mirror


Polishing machine in action

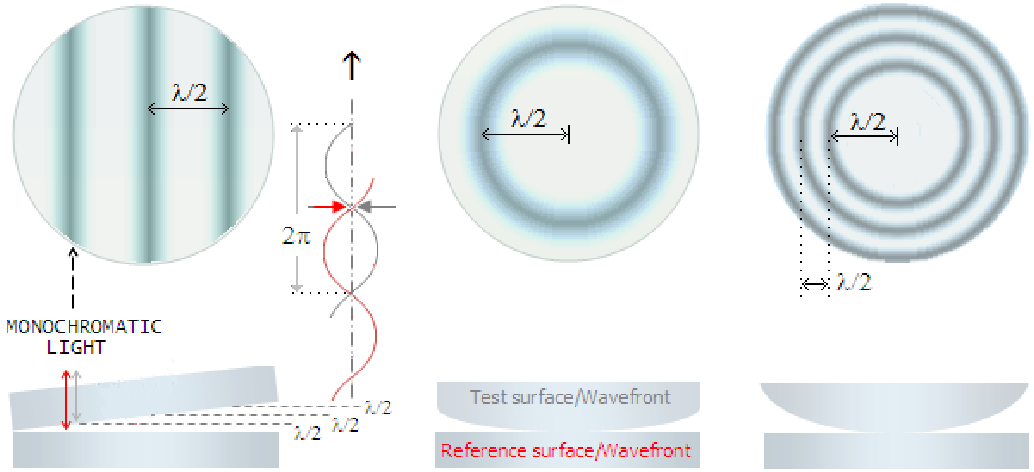

Polishing James Webb primary mirror

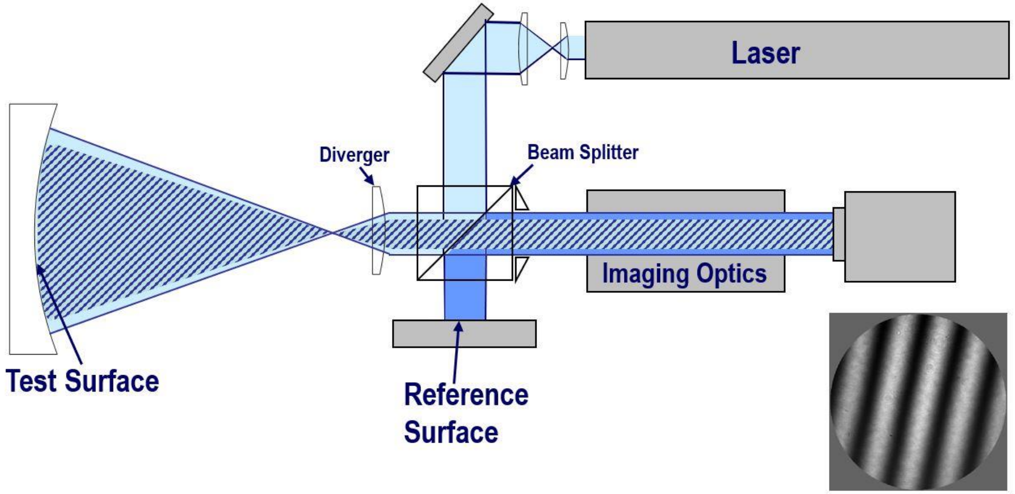
New techniques

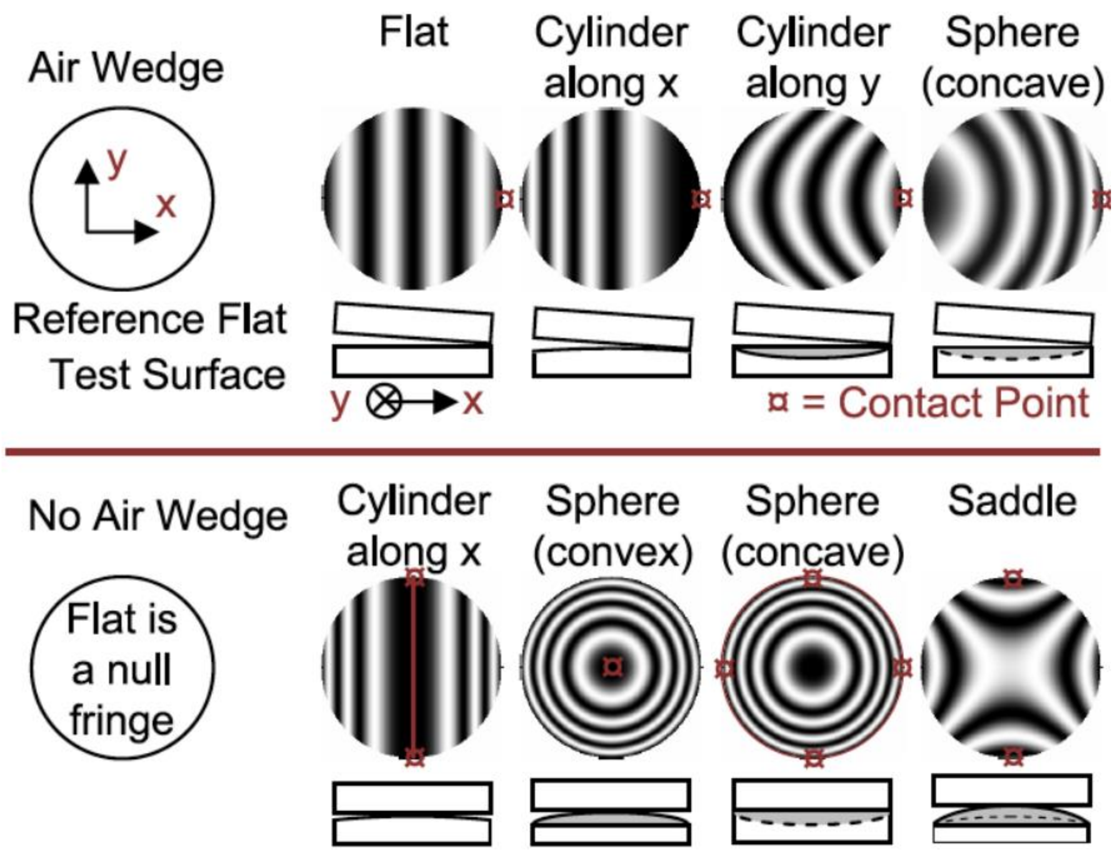
Press molding



Single-point diamond turning

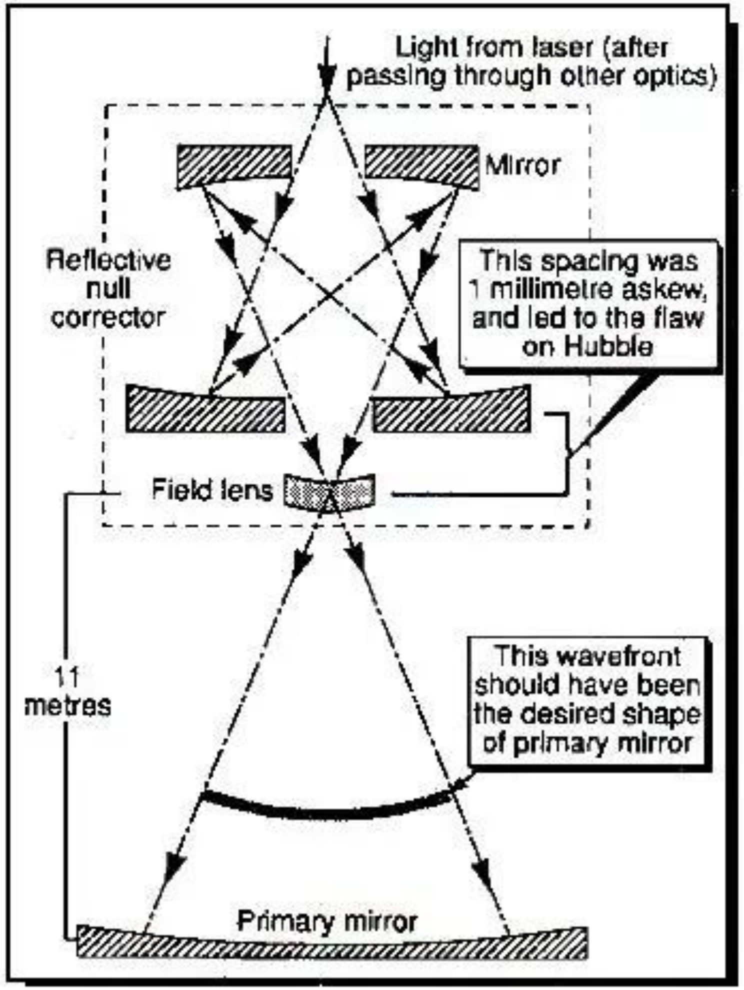
Testing of Optical Surfaces

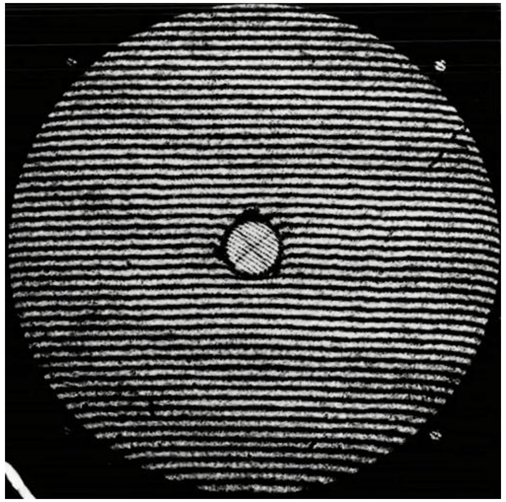


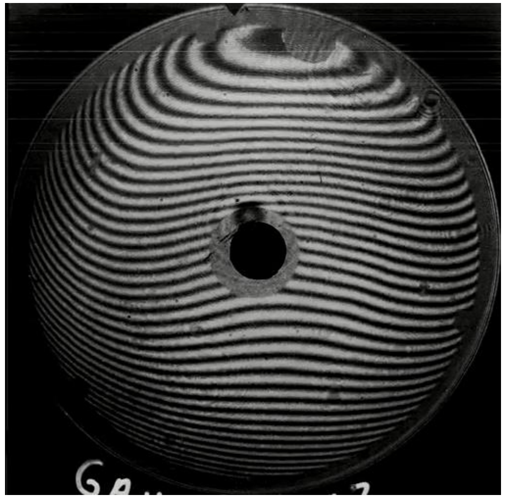


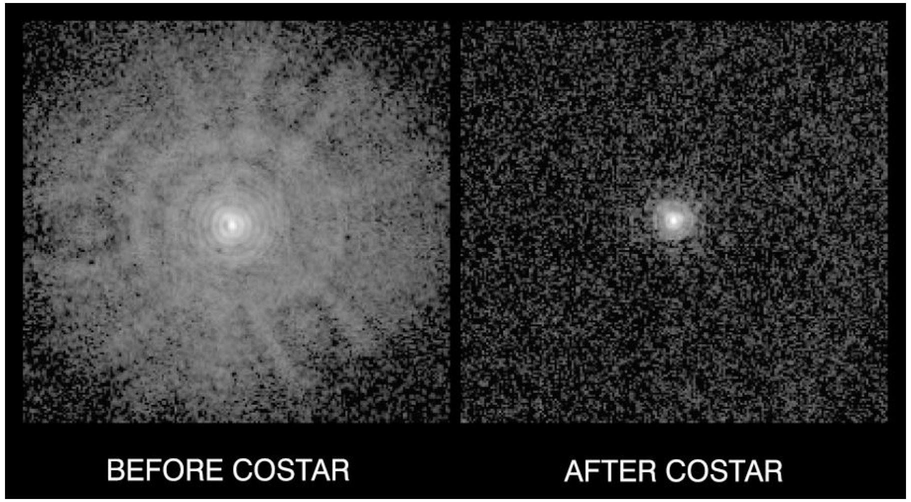


Manufacturing Flaw in Hubble Primary Mirror









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Why Computer-aided Optical Design

"Time is money!"

Plan → Design → Build → Test → Produce

Sample manual ray tracing calculation sheet

Surface	0	1	2	3	4	5	6
C		-0.0100	0.0100	0.0000	0.0250	-0.0250	
t	5	5.00	25.00	25.00	8.00	115.4897	
n	1.000	1.517	1.000	1.000	1.517	1.000	
- Φ		0.0052	0.0052	0.0000	-0.0129	-0.0129	
t/n	5.0000	3.2960	25.0000	25.0000	5.2736	115.4897	
MARGINAL RAY							
y	0.00000	0.71203	1.19354	5.00000	8.80646	9.00915	0.00000
nu	0.14241	0.14609	0.15226	0.15226	0.03843	-0.07801	
CHIEF RAY							
$\bar{y}$	5.0000	4.0902	3.5602	0.0000	-3.5602	-4.0685	-9.1277
$n\bar{u}$	-0.1820	-0.1608	-0.1424	-0.1424	-0.0964	-0.0438	
CA		12.5	12.5	10.0	30.0	30.0	
CA/(y + $\bar{y}$)		2.603	2.630	2.000	2.426	2.294	

- Design by simulation
- Fast calculations over a large number of rays and surfaces
- Opportunity of efficient design optimization
- Removal of human mistakes and errors

What ZEMAX OpticStudio Can Do?

- Design by simulation
- Imaging and afocal design
- Lighting and illumination design
- Lasers and fibers
- Analysis in ray and wave optics
- Stray light analysis
- Programming interface
- Design optimization
- CAD integrations
- Tolerancing and manufacturing tools
- Phosphor & fluorescence modeling

Alternatives to ZEMAX

- Professional software:
  Code V, OSLO, COMSOL, Win Lens
- Academia:
  MATLAB, PYTHON, C/C++

What ZEMAX OpticStudio Cannot Do?

WARNING: Running ZEMAX does not make You an Optics Expert

- Optical design is not just about knowing how to run ZEMAX
- It is a tool used in designing and analyzing optical systems
- You must know optics before you can effectively use ZEMAX
- There are many pitfalls with optical design programs
- You don't know what to watch for
- "One should take the classes, learn form the experts while slowly coming up to speed." –– Paul Manhart, NASA Langley

Practical Information

- An "up to date" laptop with Intel CPU and Windows 10/11 is recommended
- Apple Macbooks with Intel CPU can run ZEMAX OpticStudio in Windows OS or in a virtual environment
- Apple Macbooks with M1/M2 CPU are not compatible with ZEMAX OpticStudio
- Individual installation of ZEMAX OpticStudio with proper license

Accessing ZEMAX

Link to ZEMAX EPFL Central Distribution

https://distrilog-etudiants.epfl.ch/

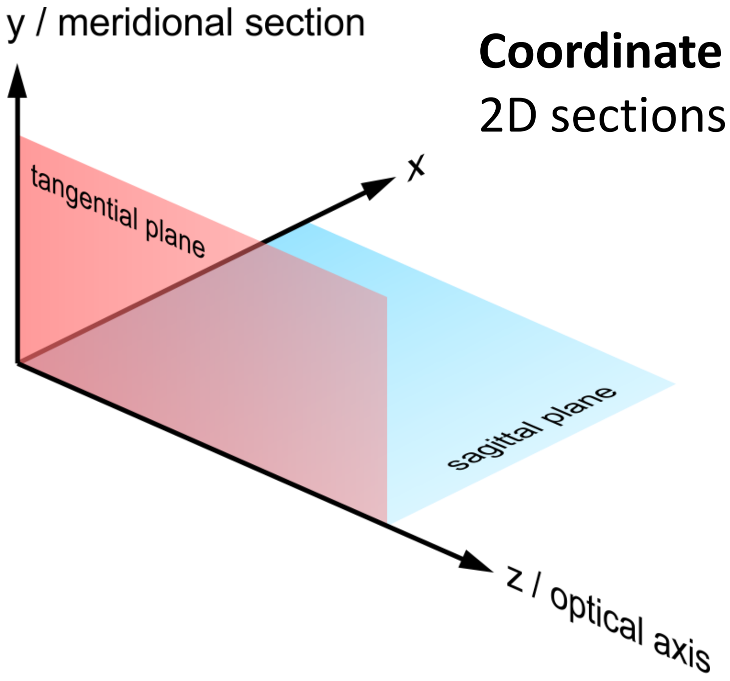
Also available through Virtual Desktop

https://vdi.epfl.ch

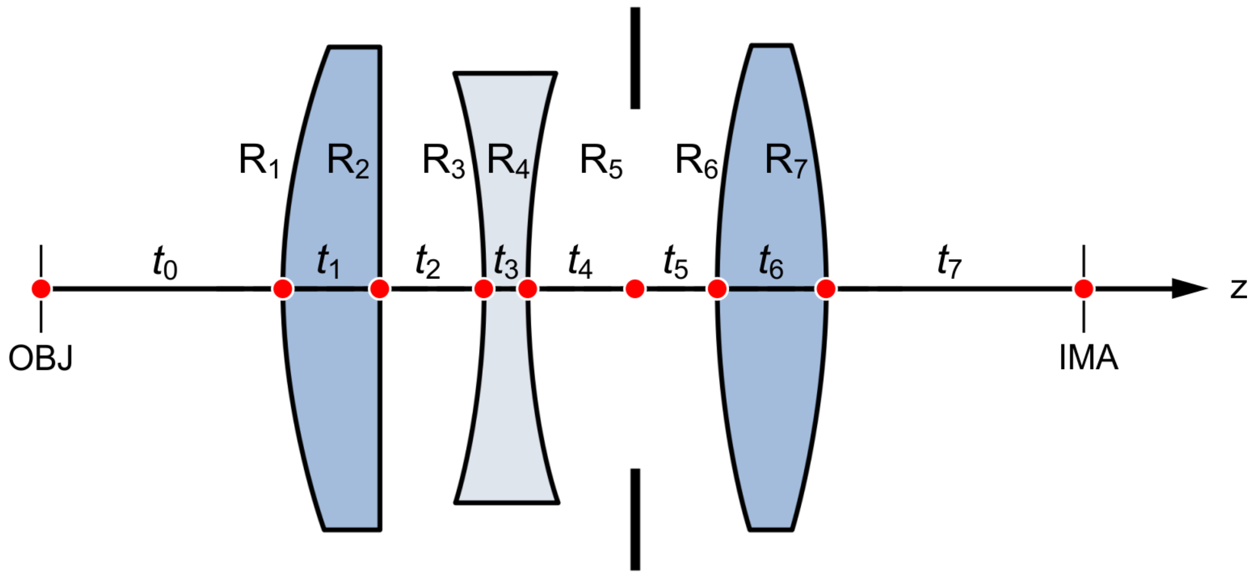
Some Basics of ZEMAX OpticStudio

Coordinate system

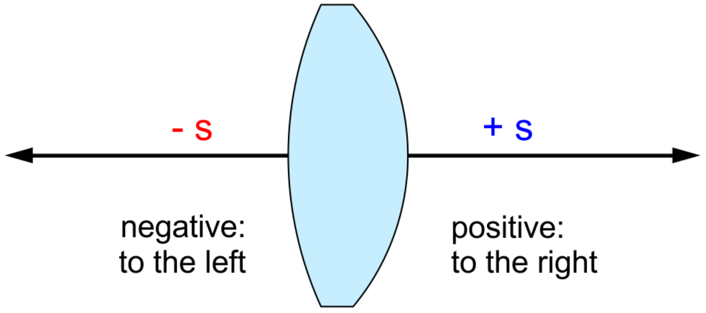
2D sections: y-z

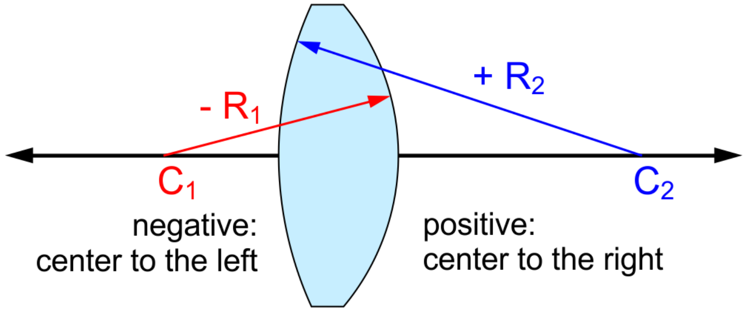


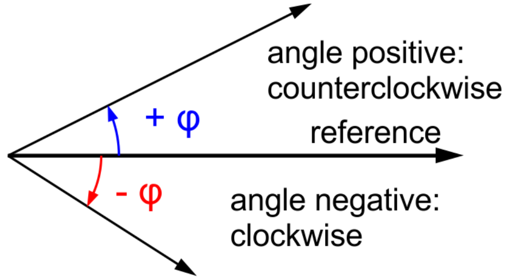
Representation of optical surfaces



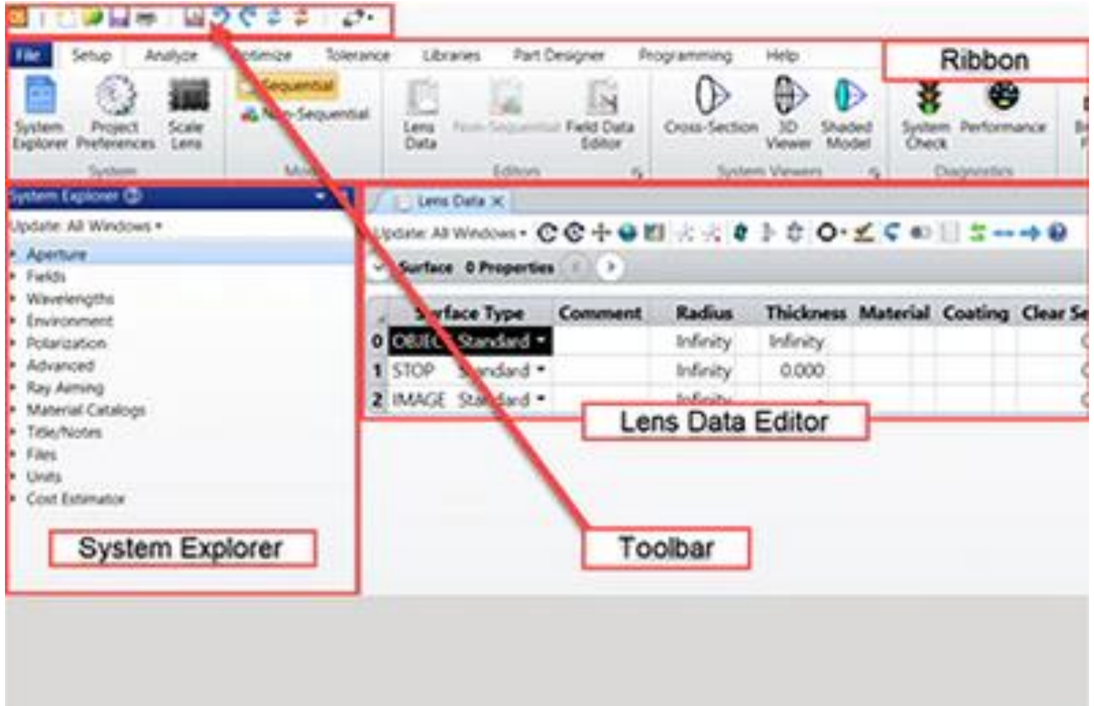
Sign of lengths, radii, angles







ZEMAX OpticStudio User Interface



Window types:

- Lens Data Editors for data input (lens data, extra data, multiconfiguration, tolerances)
- Output windows for graphical representation of results
- Text windows for output in ASCII numerical numbers (can be exported)
- Dialog boxes for data input, error reports

File formats:

- Data files: .zmx (depricated), .zno
- Configuration files: .cfg, e.g. zemax.cfg, ray.cfg, pop.cfg
- Session files: .zda or .ses for session settings (deprecated)
- Archive files: .zar, all lens design files in a single file
- Catalog files: .agf, .bgf (glasses catalog), .zmf (lens catalog)
- Macros, images, POP data, refractive index files, ...

ZEMAX OpticStudio User Interface

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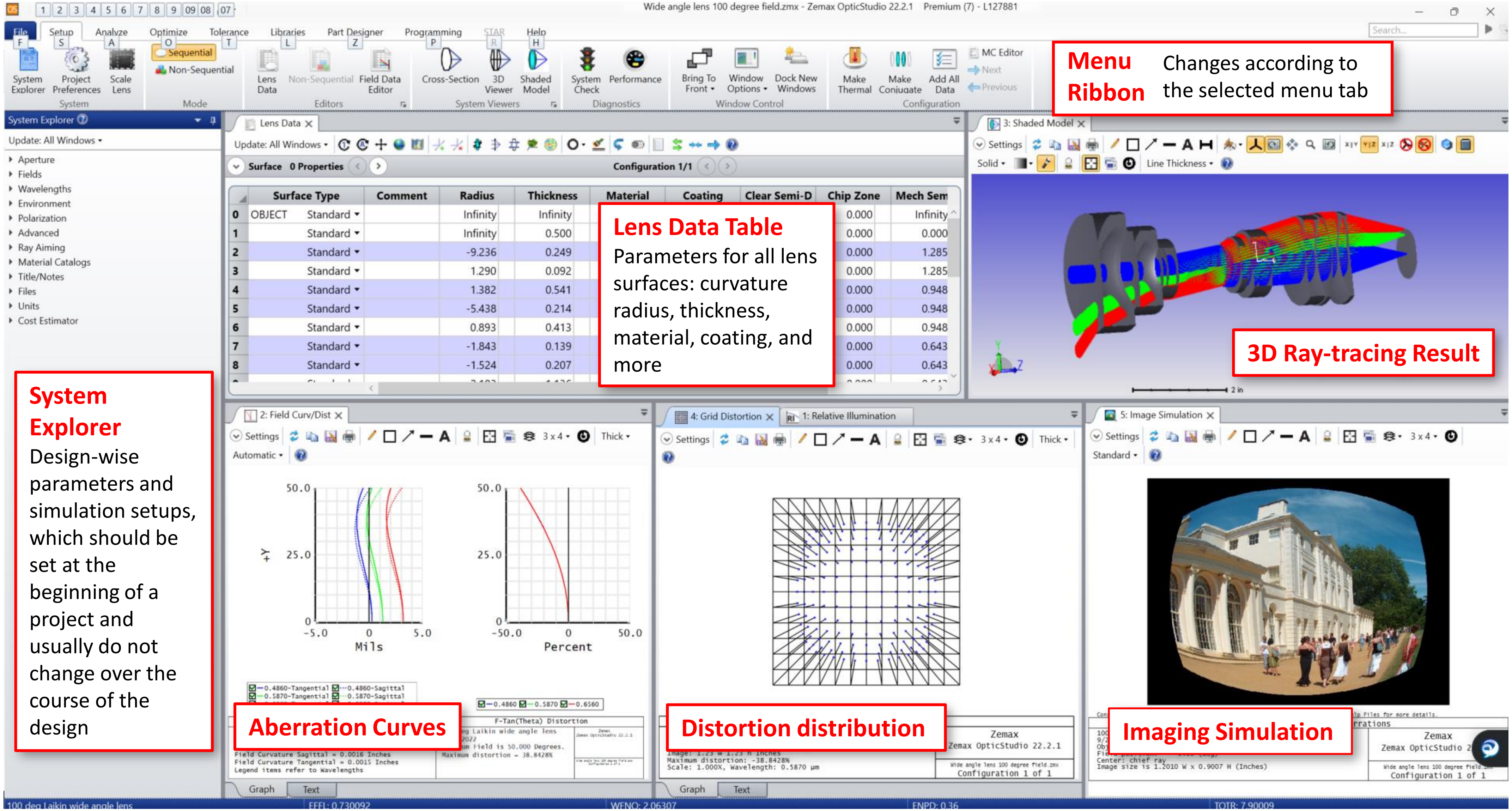
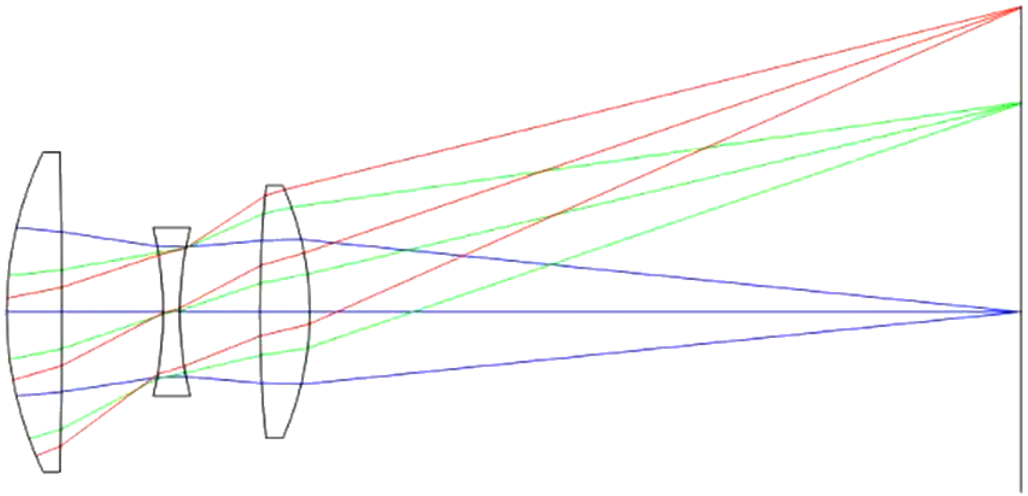


Basic Modes: Sequential vs Nonsequential

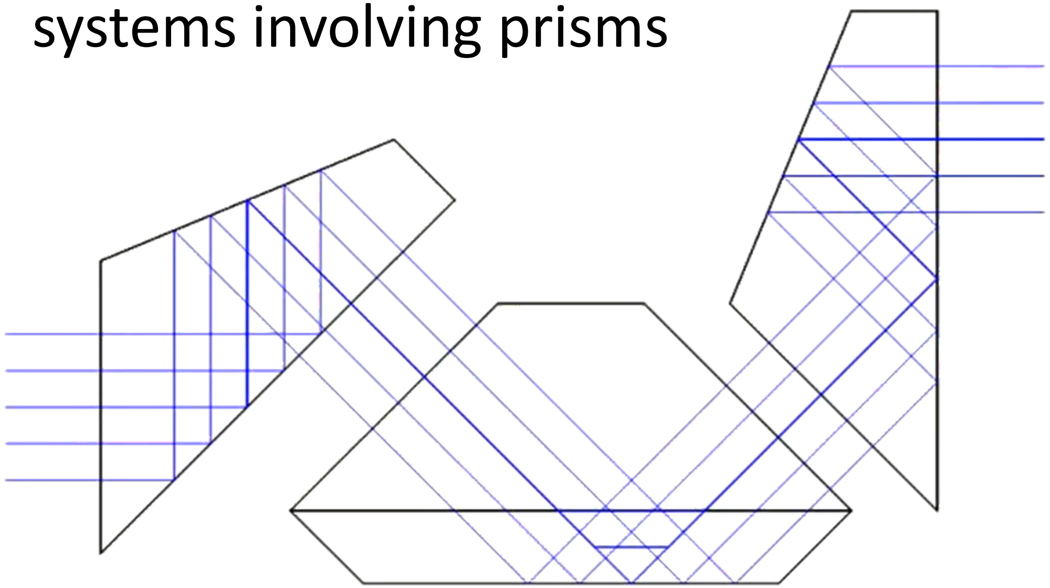
Sequential Mode:

- Rays pass each surface only once
- Computation proceeds in the order of surfaces
- Most useful for imaging systems



Nonsequential Mode:

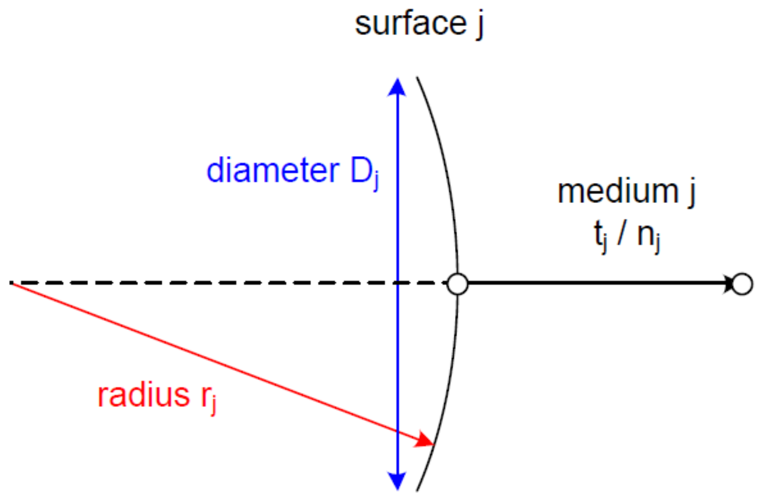
- Rays pass some surfaces multiple times
- Computation does not proceed in the order of surfaces
- Most useful for illumination systems or systems involving prisms



System Model

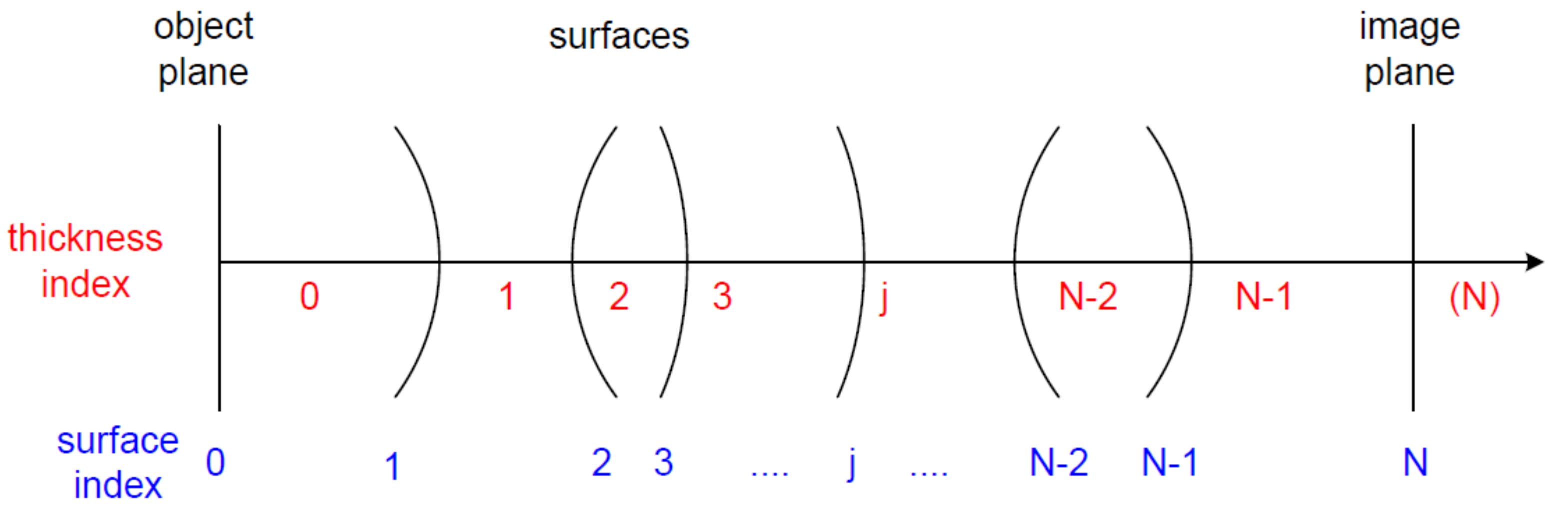
Single step:

- 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
- t_N does not exist
- Ray paths follow 0-1-2-...-(N-1)-N



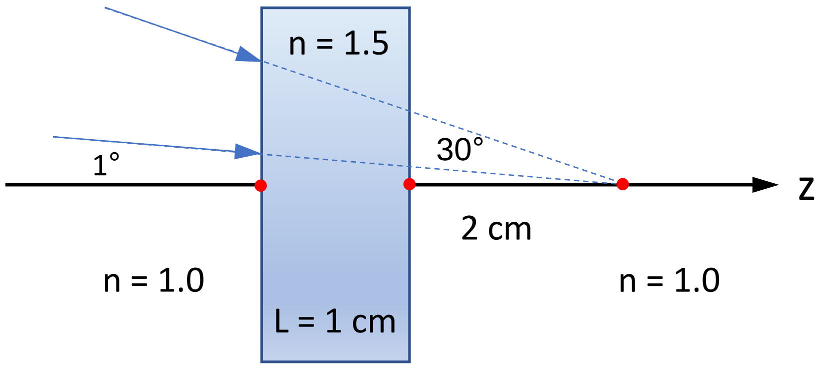
Homework

Objective

- Verification of your access to ZEMAX
- Review of Snell's law
- Familiarize yourself with ray tracing calculations

1. Verify your virtual VMWare VDI access and ZEMAX

2. Aberration in a flat plate:
   manually calculate two rays as below and compare their intersection on z-axis



3. Aberration in a sphere:
   manually calculate two rays as below and compare their intersection on z-axis