Introduction to CODE V Training: Day 1

"Optics 101"
Digital Camera Design Study
User Interface and Customization

OPTICAL RESEARCH ASSOCIATES
3280 East Foothill Boulevard
Pasadena, California 91107 USA
(626) 795-9101 Fax (626) 795-0184
e-mail: service@opticalres.com
World Wide Web: http://www.opticalres.com

Section 1
Optics 101
(on a Budget)

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Goals and "Not Goals"

- Goals:
  - Brief overview of basic imaging concepts
  - Introduce some lingo of lens designers
  - Provide resources for quick reference or further study
- Not Goals:
  - Derivation of equations
  - Explain all there is to know about optical design
  - Explain how CODE V works

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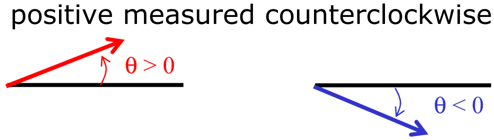
Sign Conventions

- Distances: positive to right

- Curvatures: positive if center of curvature lies to right of vertex

$c = 1/r > 0$ $c = 1/r < 0$

- Angles: positive measured counterclockwise



- Heights: positive above the axis

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Light from Physics 102

- Light travels in straight lines (homogeneous media)
- Snell's Law: $n \sin\theta = n' \sin\theta'$
- Paraxial approximation:
  - Small angles: $\sin\theta \sim \tan\theta \sim \theta$; and $\cos\theta \sim 1$
  - Optical surfaces represented by tangent plane at vertex
    - Ignore sag in computing ray height
    - Thickness is always center thickness
  - Power of a spherical refracting surface:
    $1/f = \phi = (n'-n)*c$
  - Useful for tracing rays quickly and developing aberration theory

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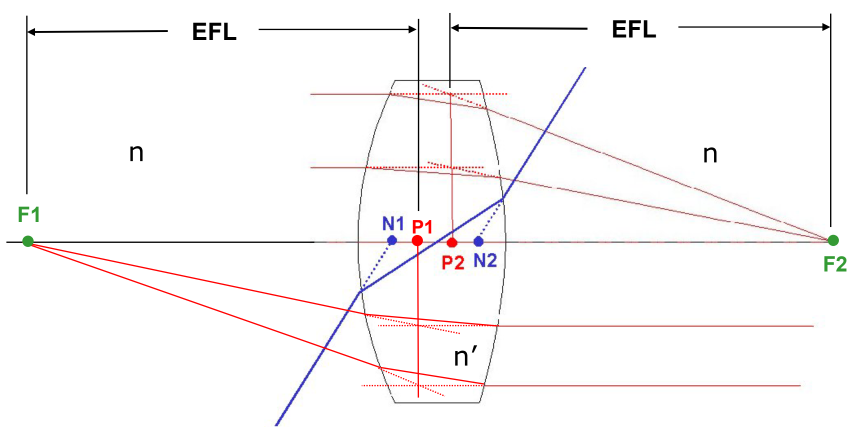
Cardinal Points Illustrated



- Effective Focal Length (EFL) = distance from principal point to focal point

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Cardinal Points

- 6 important points along the axis of an optical system
  - 2 focal points (front and back):
    Input light parallel to the axis crosses the axis at focal points F and F′
  - 2 principal points (primary and secondary):
    Extend lines along input ray and exiting focal ray; where they intersect defines principal "planes" which intersect the axis at the principal points
  - 2 nodal points (first and second):
    Rays aimed at the first appear to emerge from the second at the same angle
  - "First" points defined by parallel rays entering from the right; "second" points defined by parallel rays entering from the left

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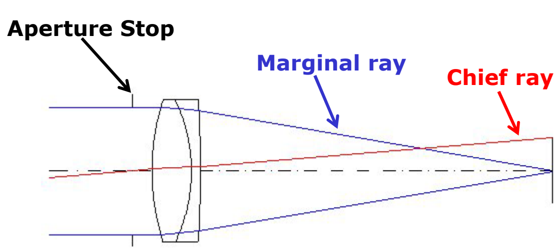
Aperture Stop

- Aperture stop: determines how much light enters the system
- 2 special rays
  - Marginal ray: from on-axis object point through the edge of the stop
  - Chief ray: from maximum extent of object through the center of the stop



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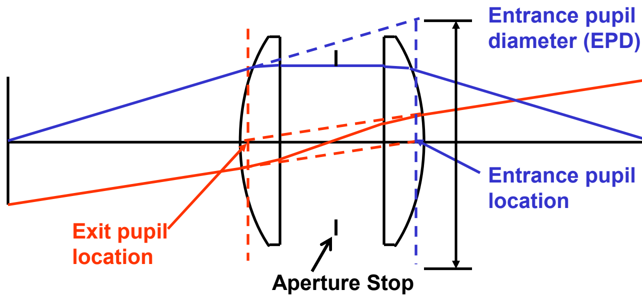
Pupils and the Aperture Stop

- Pupils
  - Entrance pupil: image of aperture stop viewed from object space
  - Exit pupil: image of aperture stop viewed from image space



Specifying the Aperture

- EPD = Entrance pupil diameter
- NAO = Numerical aperture in object space (finite object)
- NA = Numerical aperture in image space
- f/# = EFL/EPD
- **Note:** some NAO systems will not fill a physical aperture stop (common in photonics systems). You still must specify a stop surface.

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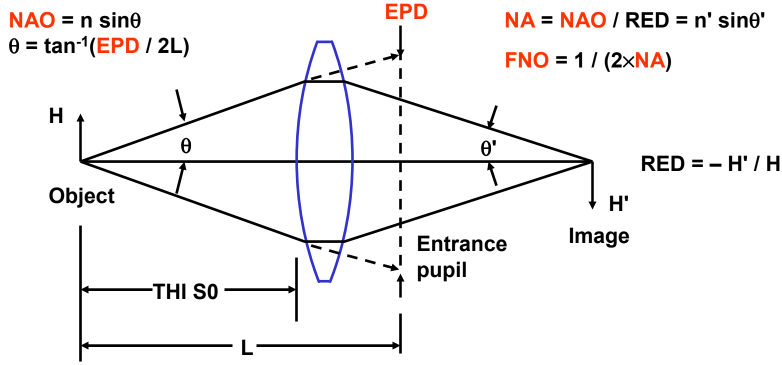
Specifying the Pupil



- Infinite object:
  - f/# = EFL/EPD
  - NAO not valid

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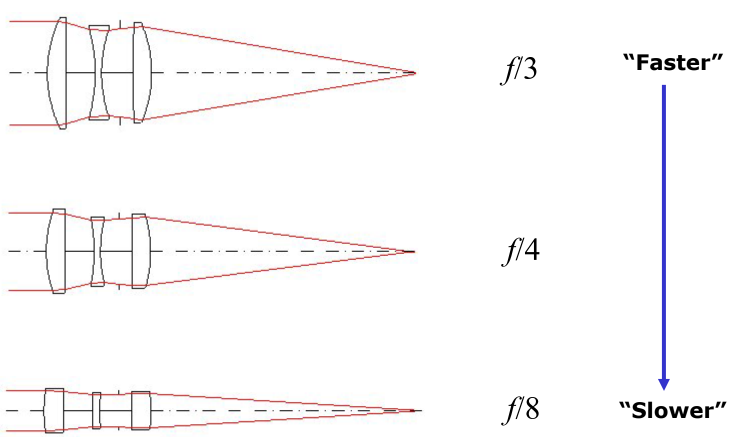
Same Triplet, Different *f*/#'s



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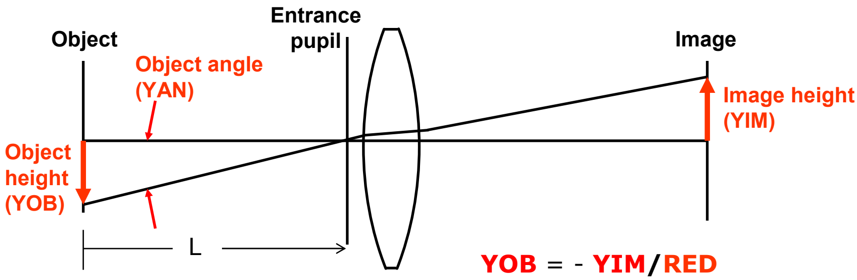
Field Definition

- Field definition describes how much of the object you image
- Specify object angle, object height (finite object), or image height



YOB = - **YIM**/**RED**
YOB = -L*tan(**YAN**)

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Aberrations

- Perfect imaging: point on object maps to point on the image, for all points on object and all rays through the aperture stop.
- Aberrations: deviations from perfect imaging
- "1st order" aberrations:
  - Defocus: wrong image location
  - Tilt: wrong image orientation
- "3rd order" aberrations:
  - Used in classical aberration theory
    - Spherical aberration
    - Coma
    - Astigmatism
    - Field Curvature
    - Distortion

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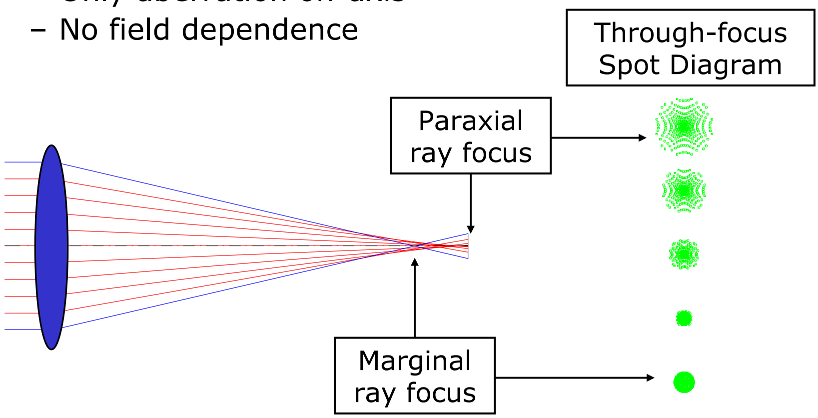
Spherical Aberration

- Focal length (EFL) varies with aperture height
  - Only aberration on-axis
  - No field dependence



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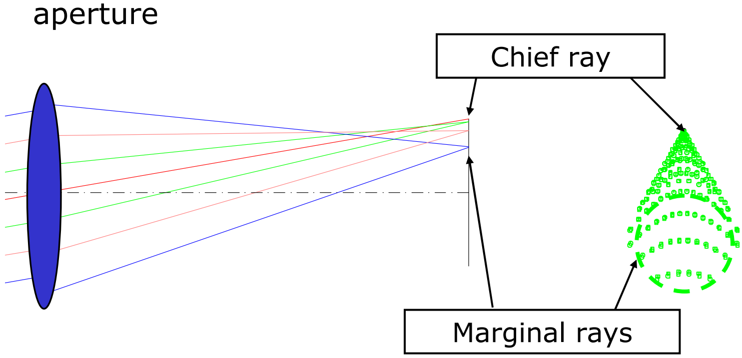
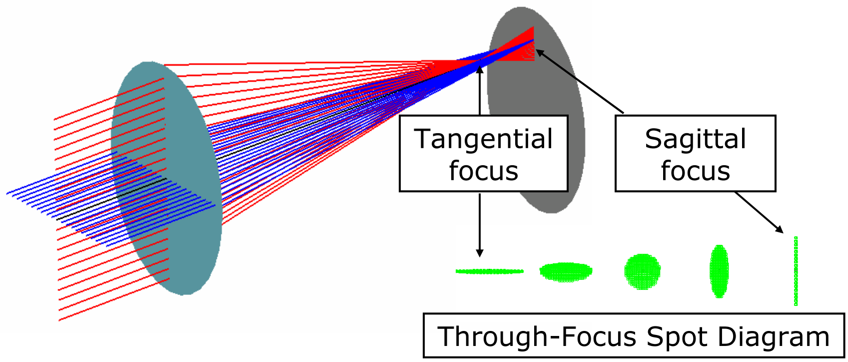
Coma

- Magnification varies with aperture
  - Rays through edge of aperture hit image at different height than rays through center of aperture



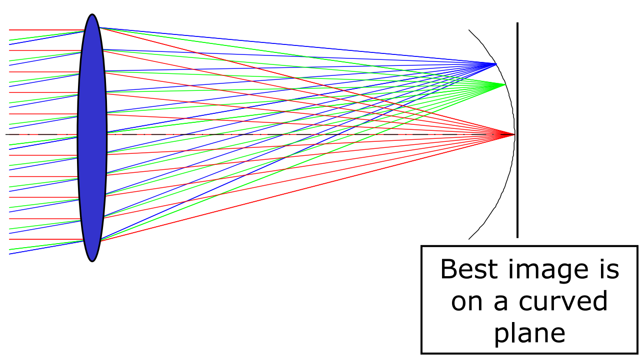
Astigmatism

- Sagittal (x-axis) and tangential (y-axis) ray fans have different foci



Field Curvature

- Planar object forms curved image
  - Depends on index of refraction of lens material and lens power



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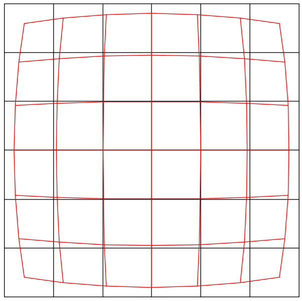
Distortion

- Image magnification depends on image height
  - Image is misshapen, but focus isn't changed

Vertical FOV



Horizontal FOV

Paraxial chief ray location
Real chief ray location

Barrel Distortion

Pincushion Distortion

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Qualitative Effects of Aberrations on Image Quality

- Aberrations may cause uniform blur over the field:
  - Defocus
  - Spherical aberration

- Aberrations may cause field-dependent blur:
  - Tilt
  - Coma
  - Astigmatism
  - Field curvature
  - Distortion

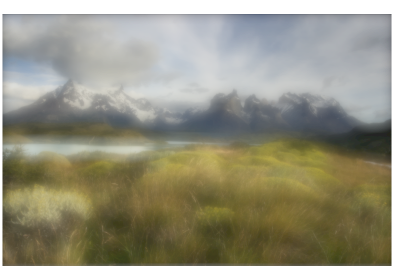

Image with Spherical Aberration

Image with Field Curvature

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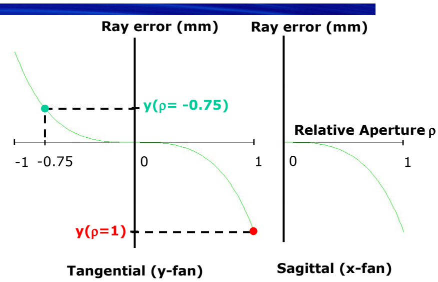
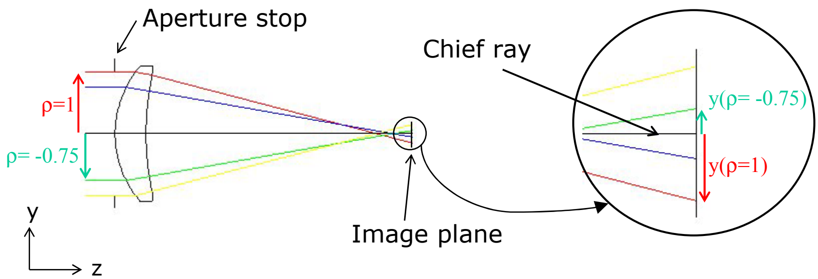
Ray Aberration Curves

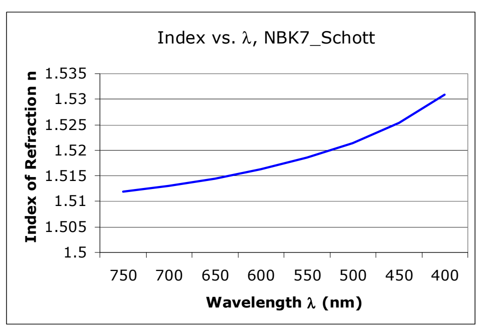
- Vertical axis: distance on image plane between chief ray and current ray
- Horizontal axis: relative height of ray in aperture stop (or entrance/exit pupil)





Chromatic Aberration

- Index is function of wavelength: $n = n(\lambda)$
- Abbe number describes the dispersion: $V_d = (n_d - 1)/(n_F - n_c)$
  - λ_d = 587.6 nm (yellow)
  - λ_F = 486.1 nm (blue)
  - λ_c = 656.3 nm (red)
- Small V_d (V_d ~ 20 - 50): very dispersive, colors spread a lot
- Large V_d (V_d ~ 55 - 90): less dispersion



Rays and Waves

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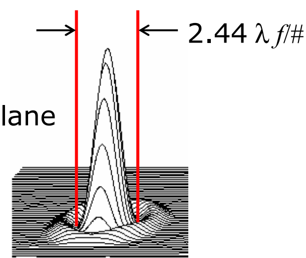
- Rays are normal to wavefront
- Waves diffract at apertures and can interfere
- Rays can image perfectly; waves can't due to diffraction at apertures
  - A point images to Airy disk
  - Diffraction-limited spot size (diameter) = 2.44 λ *f/#* (microns)

Intensity at image plane



Modulation Transfer Function (MTF)

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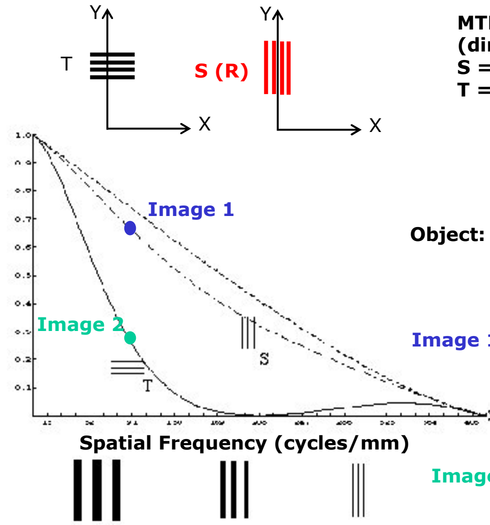
- Start with black and white bars (or sinusoid) with specified frequency.
- Frequency in "lines/mm," where "lines" = "line pairs" (1 black line + 1 white line)= cycle
- Modulation = contrast

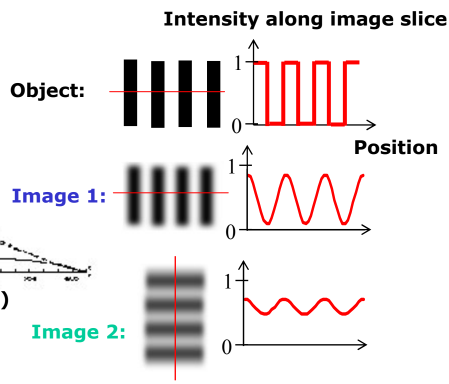
$$MTF = Contrast = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

  - I_{max} = maximum intensity
  - I_{min} = minimum intensity
  - for object, contrast = 1 (pure black and white)

MTF

MTF depends on target orientation:
(direction of variation of intensity)
S = Sagittal (a.k.a. R = Radial) or
T = Tangential





MTF (cont.)

- Image is not perfect; contrast drops due to:
  - Aberration
  - Diffraction
  - Vignetting
- Varies with:
  - Field point considered
  - Orientation of target (radial or tangential)

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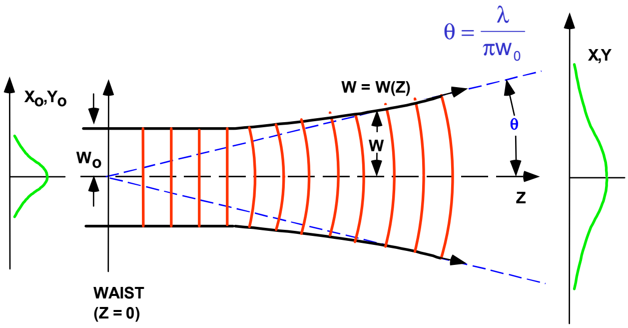
Gaussian Beams



w_0 is $1/e^2$ spot radius at waist

$w(z)$ is $1/e^2$ spot radius at distance z from the waist

Beam wavefront is planar at waist

θ is laser divergence angle = $\lambda/\pi w_0$

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References for Optics Library

- General references
  - R. Fischer, *Optical System Design*
  - J. Greivenkamp, *Field Guide to Geometrical Optics*
  - D. Malacara, *Optical Shop Testing*
  - R. Shannon and B. Tadic, *The Art and Science of Optical Design*
  - W. Smith, *Modern Optical Engineering*
  - W. Smith, *Modern Lens Design*
- Classics (may be difficult to locate)
  - R. Kingslake, *Lens Design Fundamentals*
  - Rudolf Kingslake, *Applied Optics and Optical Engineering*, Vol. 1-5
  - R. Shannon and J. Wyant, *Applied Optics and Optical Engineering*, Vol. 6-10
  - W. Welford, *Symmetrical Optical Systems*
  - U.S. Government, *Mil. Handbook 141*