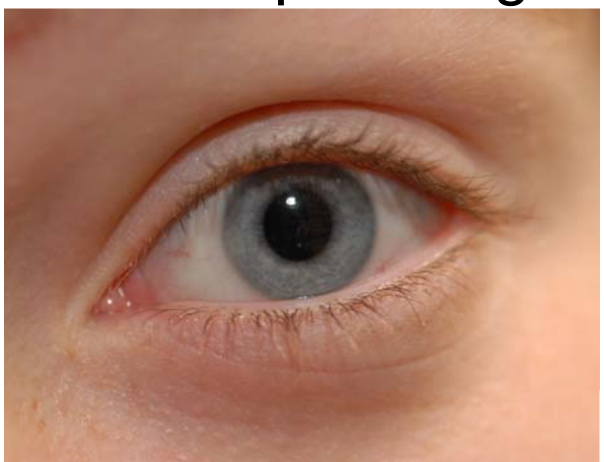
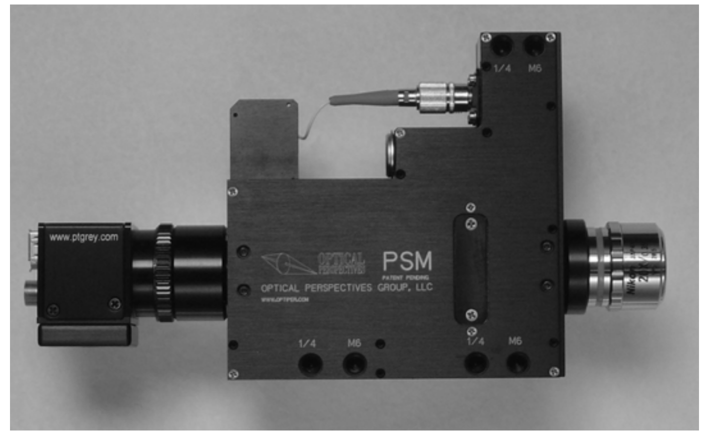
Opti 415/515

Introduction to Optical Systems

Optical Systems

Manipulate light to form an image on a detector.





Point source microscope

Hubble telescope (NASA)

Fundamental System Requirements

- Application / Performance
  - Field-of-view and resolution
  - Illumination: luminous, sunlit, …
  - Wavelength
  - Aperture size / transmittance
  - Polarization,
  - Coherence
  - …
- Producibility:
  - Size, weight, environment, …
  - Production volume
  - Cost
  - …
- Requirements are interdependent, and must be physically plausible:
  - May want more pixels at a faster frame rate than available detectors provide,
  - Specified detector and resolution requires a focal length and aperture larger than allowed package size.
  - Depth-focus may require F/# incompatible with resolution requirement.
- Once a plausible set of performance requirements is established, then a set optical system specifications can be created.

Optical System Specifications

First Order requirements

- Object distance ____________
- Image distance ____________
- F/number or NA ____________
- Full field-of-view ____________
- Focal length ____________
- Detector
  - Type
  - Dimensions ____________
  - Pixel size ____________
  - # of pixels ____________
  - Format ____________
- Wavelength
  - Central ____________
  - Range ____________
  - Weights (λ/wt) ____________
  - ____________
- Magnification ____________
- Transmittance ____________
- Vignetting ____________

Performance Requirements

- MTF vs. FOV ____________
- RMS wavefront ____________
- Encircled energy ____________
- Distortion % ____________

Mechanical Requirements

- Back focal dist. ____________
- Length & diameter ____________
- Total track ____________
- Weight ____________

Environmental

- Obj. space index ____________
- Img. space index ____________
- Shock ____________
- Vibration ____________
- Temperature ____________

“Orders” of optics

- First-order:
  - Defines the basic function of an optical system: object & image locations, magnification
  - “Perfect” optics
  - Small angle approximation: $\sin(\theta)=\tan(\theta)=\theta$
  - First term of a Taylor series expansion
- Third-order:
  - Imperfections of an optical system’s performance: Seidel aberrations
  - Small angle approximation is not valid
  - The second term in a Taylor series expansion
  - Perturbation theory used to design optical systems when ray tracing was hard
  - Important to understand behavior of an optical system due to misalignment or fabrication errors in optics and assemblies: tip/tilt, decenter, wedge, spacing errors
- Real rays
  - Ray tracing calculations with high precision
  - Computers are more than fast enough that real rays can be used instead of third order theory in design and analysis
  - Goal is to make a real system behave like the first-order idealization
- All three orders will be used during this course.

- We start with a review of the first-order properties of a system, which are critical to specification and to validation of the system performance.

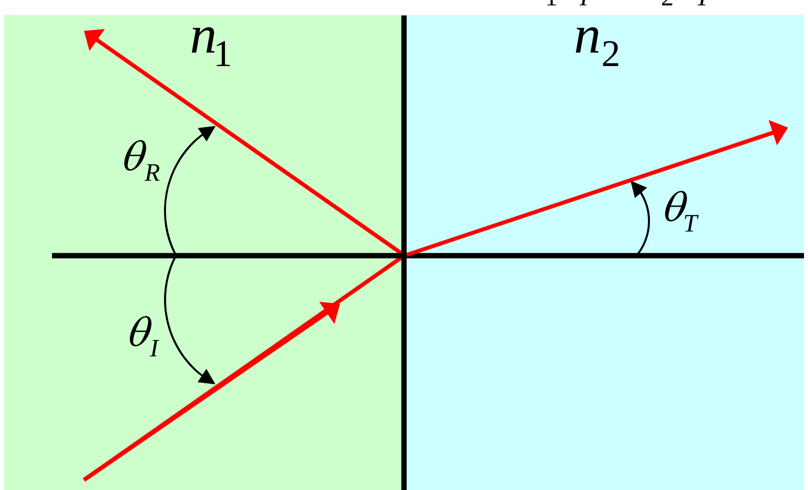
Refraction & Reflection

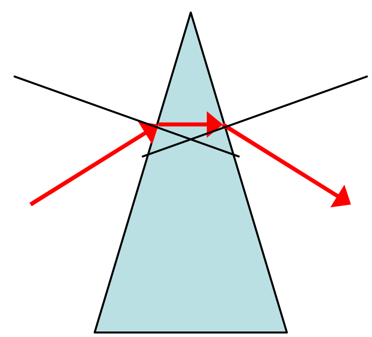
- Manipulation of light starts with Snell's law & Law of reflection.
- Incident ray, refracted ray, reflected ray and surface normal are coplanar.
- A ray bends towards the normal when going from low to high index of refraction material, and away from the normal when going from a high to low index of refraction material.
- What happens if $n_2 < n_1$ as the incident angle increases? When incident angle is greater than the critical angle all light is totally internally reflected.

$$\theta_I = -\theta_R$$

$$n_1 \sin(\theta_I) = n_2 \sin(\theta_T)$$

$$\Rightarrow n_1\theta_I = n_2\theta_T$$





Critical angle $\sin(\theta_C) = n_2 / n_1$

Refraction & Reflection

- Refraction → Snell's law
- Incident ray, refracted ray, reflected ray and surface normal are coplanar.
- Paraxial optics assumes all angles are small.
- Remember that the ray bends towards the normal when going from low to high index of refraction material, and away from the normal when going from a high to low index of refraction material.
- What happens if $n_2 < n_1$ as the incident angle increases? When incident angle is greater than the critical angle all light is totally internally reflected.

$$\theta_I = -\theta_R$$

$$n_1 \sin(\theta_I) = n_2 \sin(\theta_T)$$

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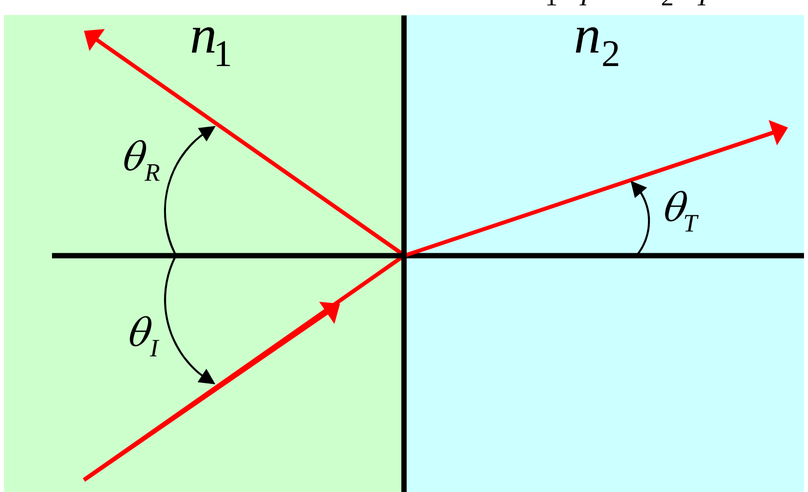
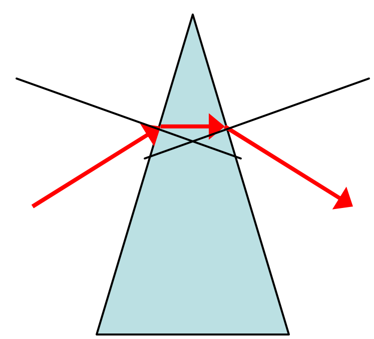
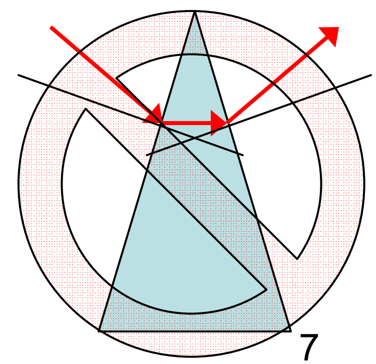


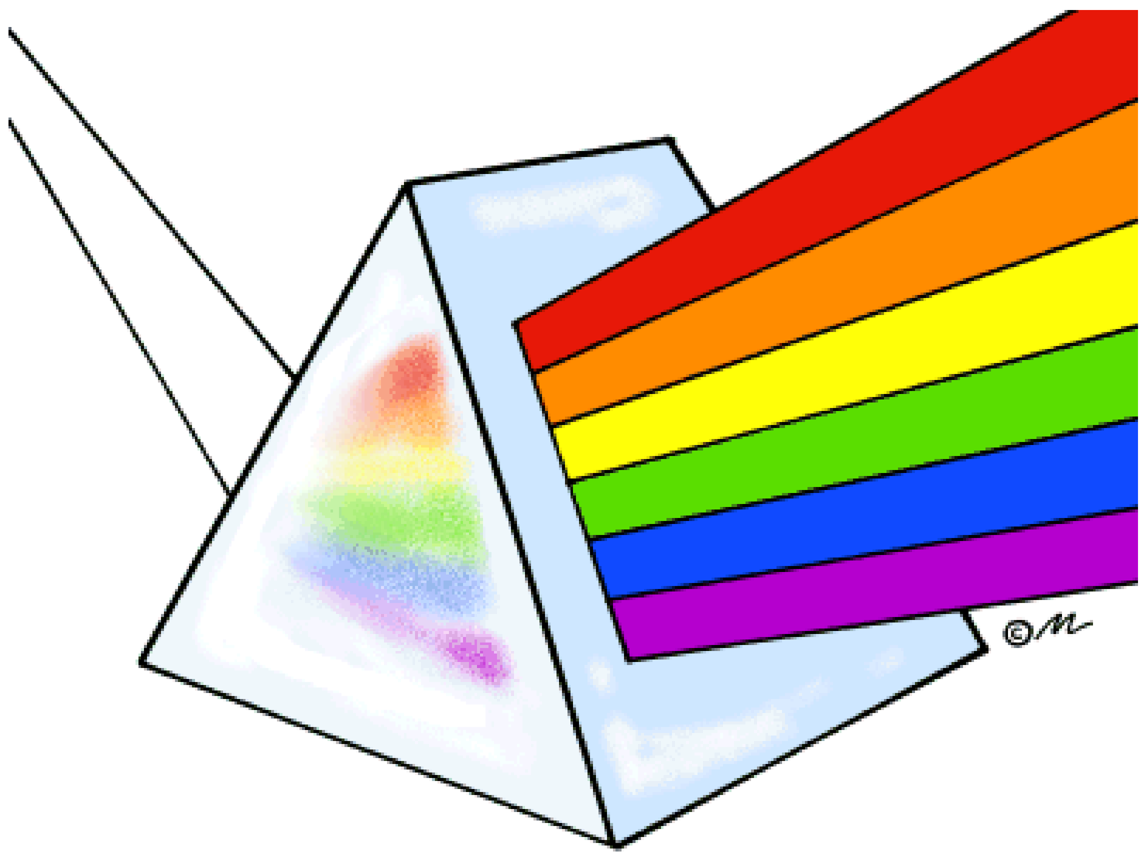
Critical angle $\sin(\theta_C) = n_2 / n_1$





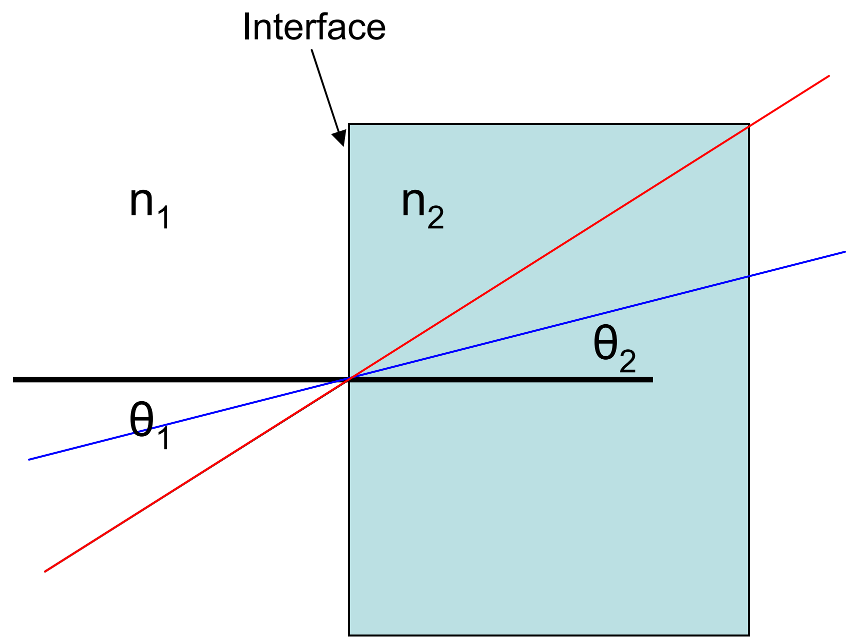
Discovery Education Website

- Hit number 7 on Google image search for “prism”



Optical Spaces

- An optical space – extends through all space and has an index of refraction
- A ray in an optical space is a straight line
- A real object is located before an optical surface, and a virtual object is located after an optical surface.
- A real image is located after an optical surface, and a virtual image is located before an optical surface
- A ray is in the object space of an optical surface until it interacts with the surface, and is image space after interacting with a surface.
- N surfaces → N+1 optical spaces
- Rays from adjacent optical spaces meet at an optical surface.



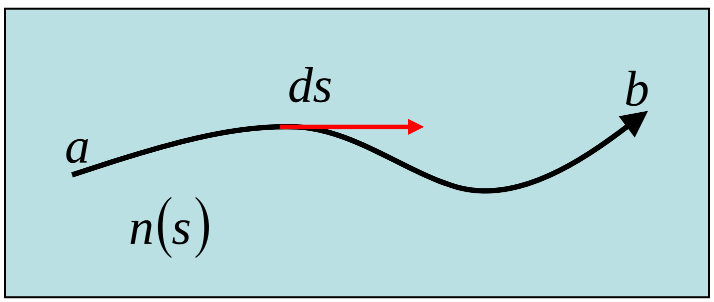
Red ray is in object space where index is n_1

Blue ray is in image space where index is n_2

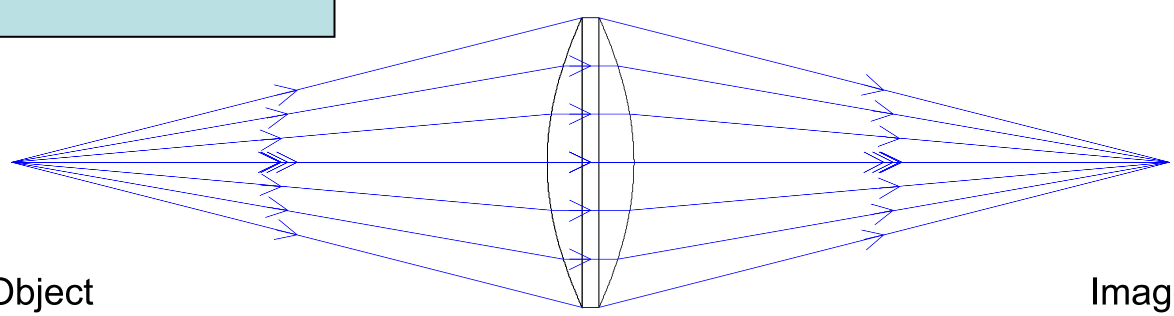
$n_1 < n_2$

Optical path length

- Proportional to the time it takes light to travel between two points.
- General form is an integral for materials with a variable index.
- Fermat's principle (original) – "The actual path between two points taken by a beam of light is the one which is traversed in the least time"
- Fermat's principle (modern) - "A light ray, in going between two points, must traverse an optical path length which is stationary with respect to variations of the path."
  - Stationary point → derivative is zero
- All ray paths from object point to corresponding image point have the same OPL

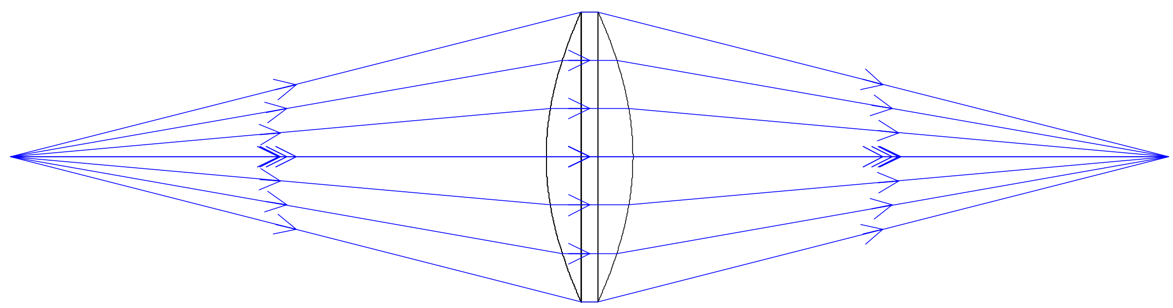


$$OPL = \int_a^b n(s)ds \Rightarrow \sum_{i=0}^{k} n_i d_i \Rightarrow nd$$



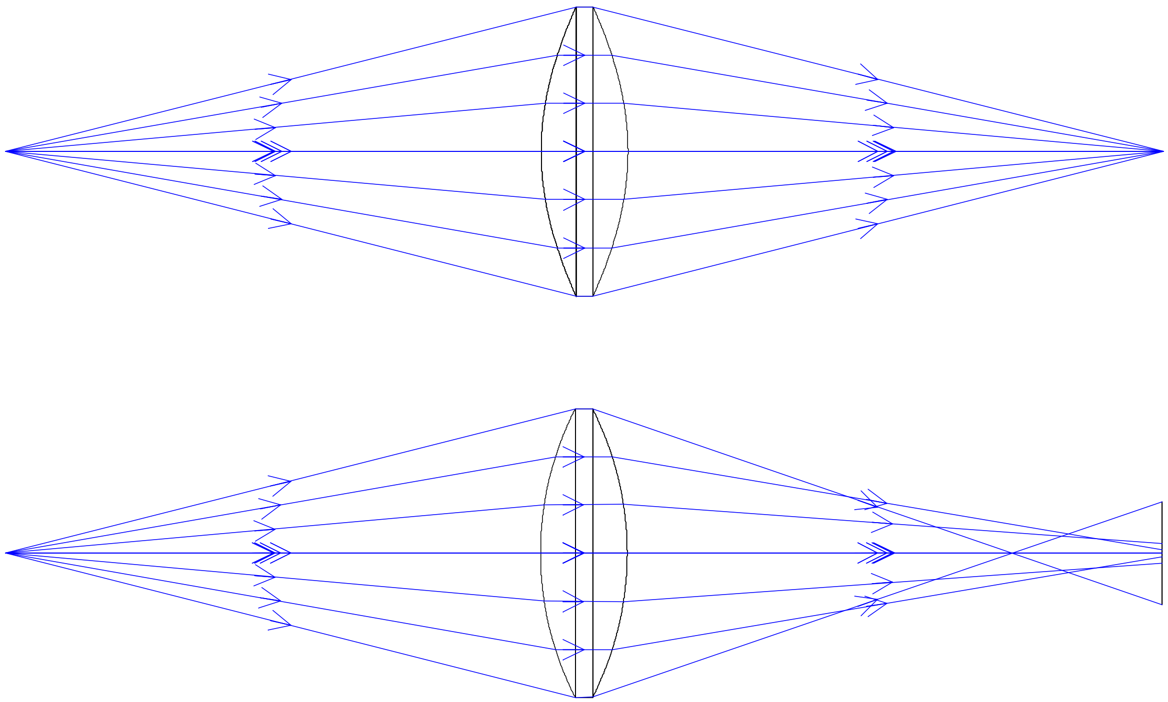
Singlet that good?

- Awfully tight focus for a fast, biconvex lens with spherical surfaces made of N-BK7.

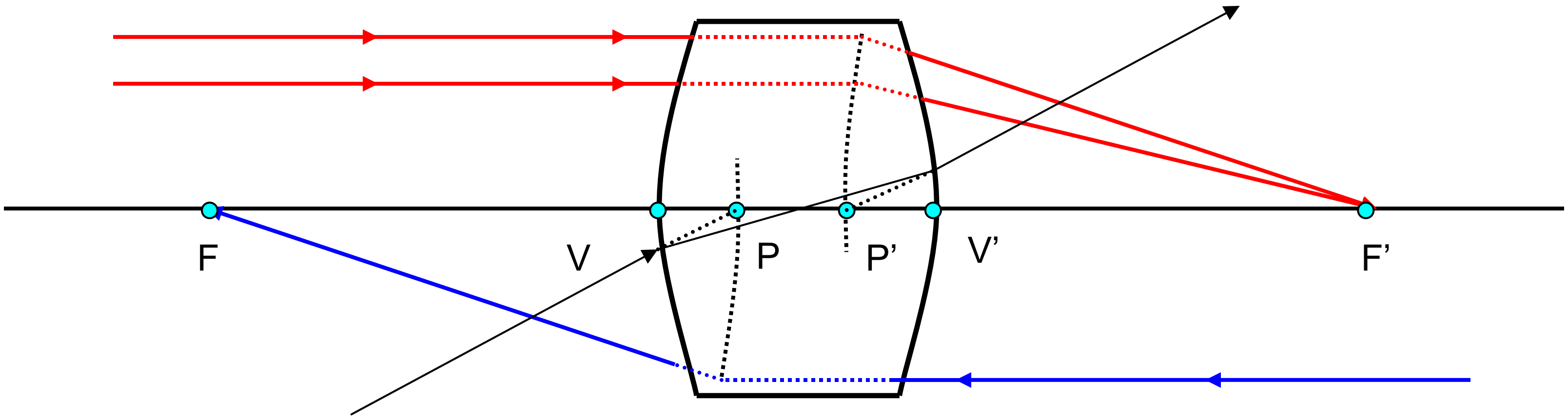


Singlet that good?

- Top lens surfaces are hyperbolas
- Bottom lens surfaces are spheres

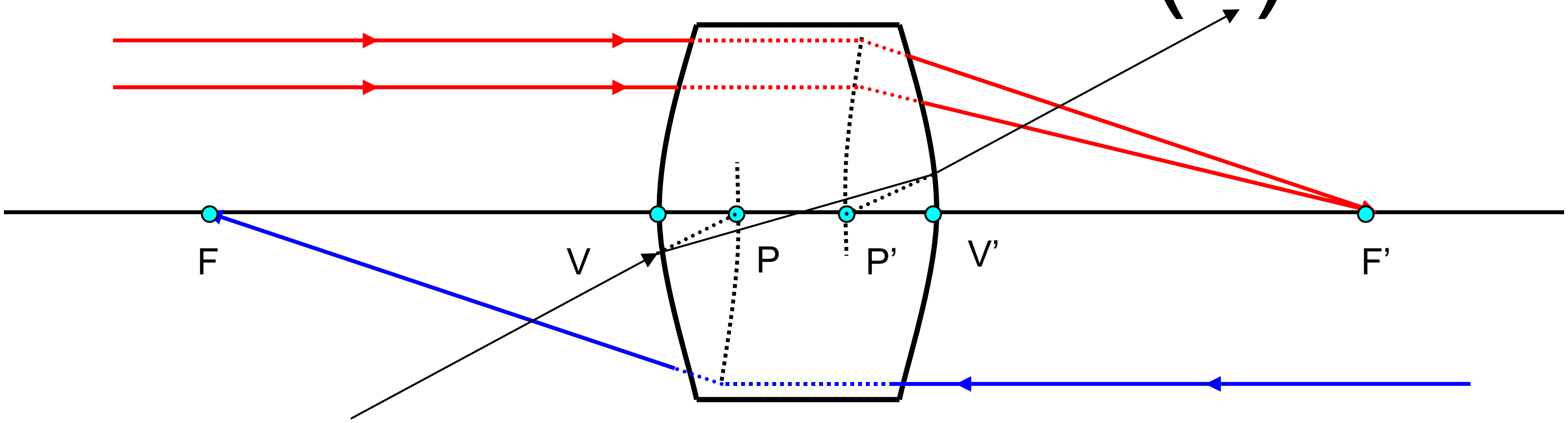


Cardinal Points



- A rotationally symmetric optical system can be represented by a single, thick lens
  - Optical axis is axis of rotational symmetry
  - Center-of curvature of every surface is on the optical axis
- Cardinal Points
  - Focal points – front F, rear F'
  - Principal points – front or first P, rear or second P'
  - Nodal points – N and N' (not shown) are the same as P and P' for optical system immersed in air
- Focal planes – not shown, normal to axis at focal points
- PF – front focal length and P'F' – rear focal length
- Principal surfaces - black dotted curves – planes near the axis, spheres in a corrected system
- Mechanical data, not a cardinal point
  - Vertex of lens – front – V and rear – V'
  - FV – front focal distance, V'F' – back focal distance

Cardinal Points (2)

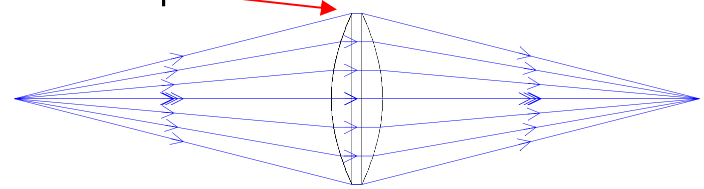


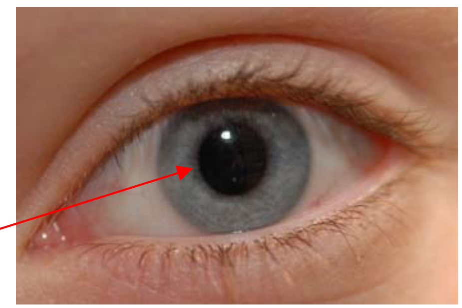
- Rays (red) parallel to axis in object space intersects optical axis in image space at F'
- Ray (blue) parallel to axis in image space intersects optical axis in object space at F
- Principal surfaces are the locus of points defined by the intersection of the projection of a ray parallel with the optical axis and the projection back of the corresponding output ray.
- Principal planes are the planes of unit lateral magnification
- Ray (black) directed at a nodal point emerges from lens at other nodal point, parallel to input ray
- Nodal points are the places of unit angular magnification
  - Angular subtense of object view from front nodal point equals the angular subtense of image viewed from rear nodal point.
- Thin lens → length of PP' is practically zero.

Stop and pupils

- Aperture stop is the physical opening that limits the bundle of light propagating through the system for an axial ray bundle.
- Entrance pupil – image of the aperture stop in object space
- Exit pupil – image of the aperture stop in image space
- Human eye – iris is the aperture stop, while the "pupil" you see when looking at someone is their entrance pupil.
- Vignetted rays are blocked by apertures other than the aperture stop for off-axis objects

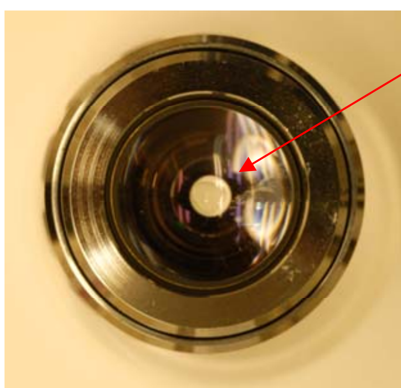
aperture stop

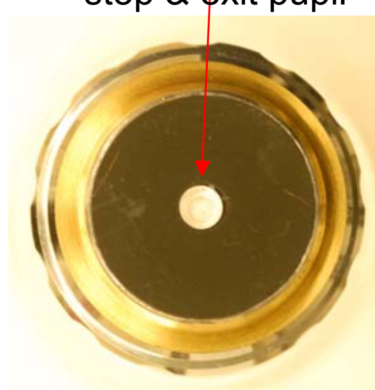


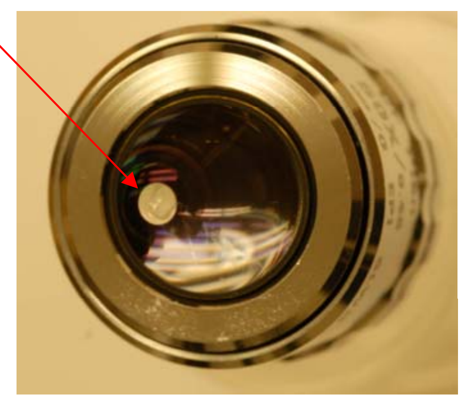


entrance pupil

stop & exit pupil

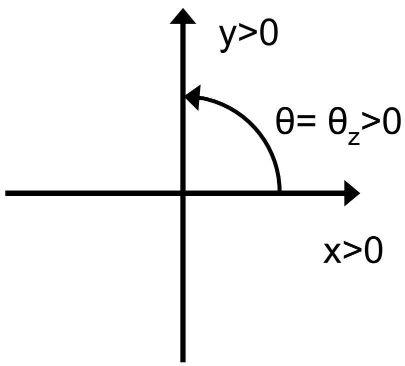




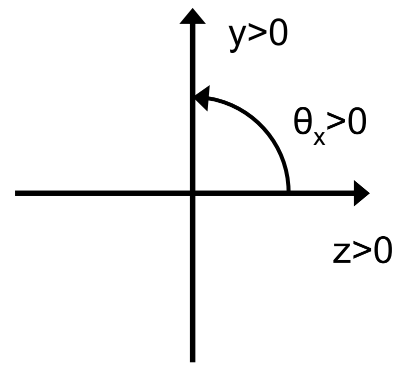


Coordinate systems

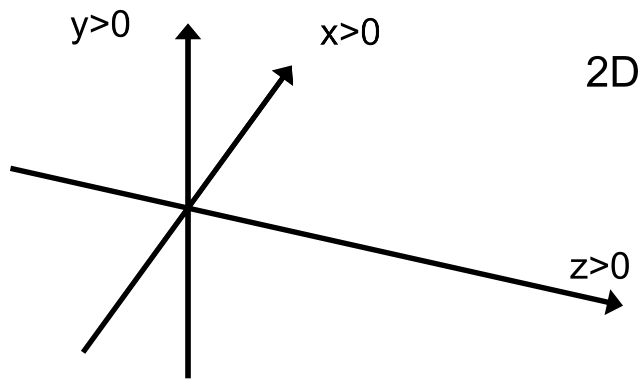
- Axis arrow indicates coordinate system > 0
- A directed distance is in a coordinate system.
- Positive rotation about an axis is counter-clockwise (CCW).



2D plot of transverse plane: object plane, image plane, etc.



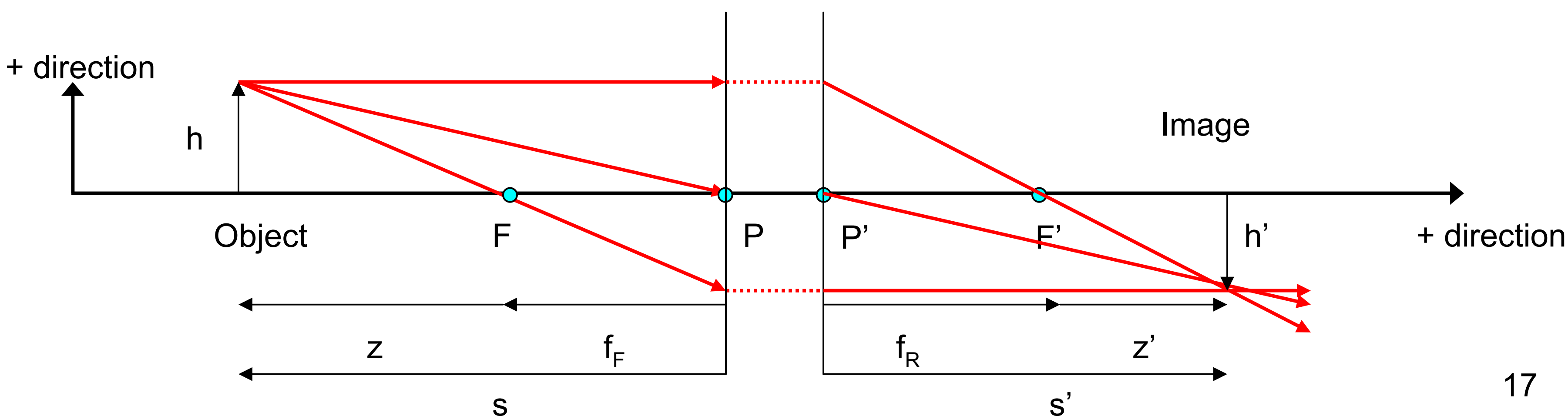
2D plot of cross-section: optical axis is z



3D sketch or plot – optical axis is z

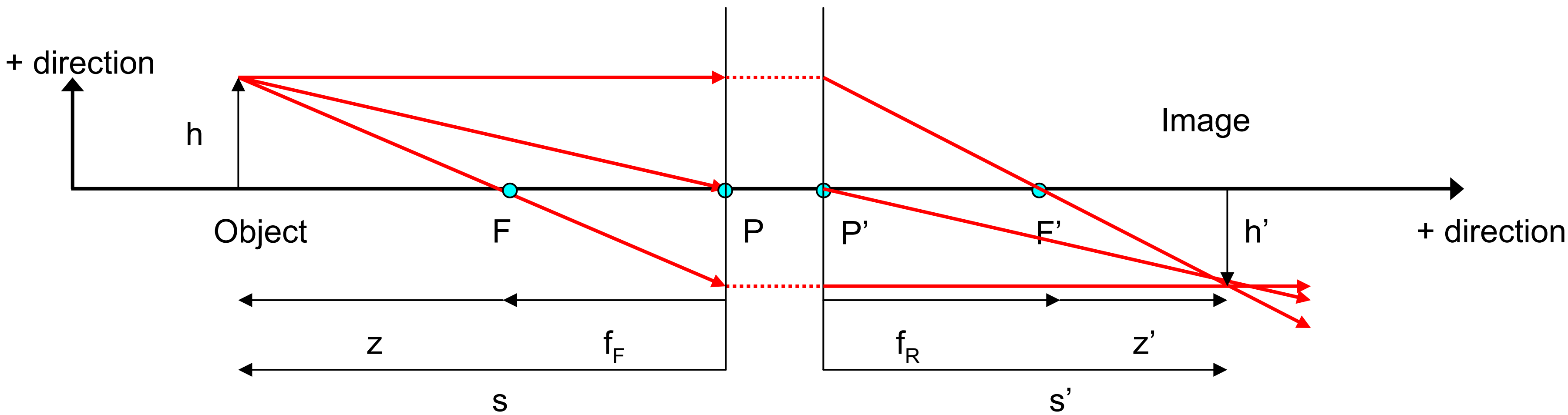
Coordinate systems in paraxial optics

- In stated coordinate system h, z', f_R, and s' are positive, and h', z, f_F, and s are negative
- Others might state that
  - object space distances are positive to the left, and
  - image space distances are positive to the right
- Paraxial equations depend upon the choice. Be consistent, state assumptions and know what to expect.
  - Conjugate planes to know: infinite and 1:1
  - Is magnification positive or negative?
  - Is image smaller or larger than object (magnitude of magnification >1 or <1)?
  - Real vs. virtual objects and images



Paraxial equations

- Focal length is directed distance from corresponding principal plane
- Object and image distance from corresponding principal plane for Gaussian form
- Object and image distance from corresponding focal plane for Newton form



Newtonian equations use distances measured from focal points.

$$zz' = f_F f_R = -f^2 \qquad f = f_R = -f_F$$

$$z = -f \Rightarrow z' = f \Rightarrow m = -1$$

$$z = -\infty \Rightarrow z' = 0 \qquad z = 0 \Rightarrow z' = \infty$$

Gaussian equations use distances measured from principal points.

$$1/f = 1/s' - 1/s$$

$$s = -f \Rightarrow s' = \infty$$

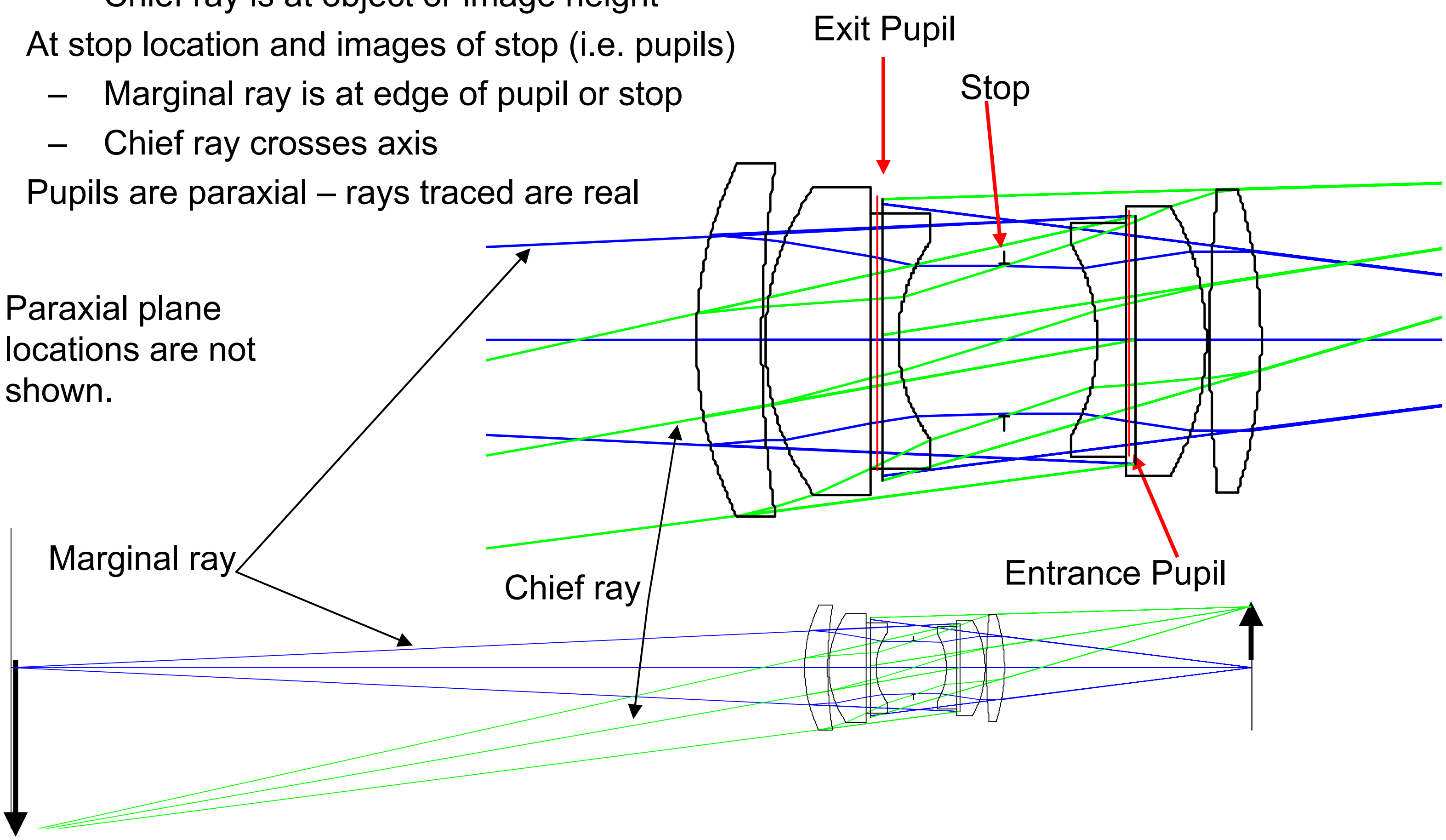
Transverse or lateral magnification

$$m = h'/h = s'/s = -f/z = -z'/f$$

Marginal and chief rays

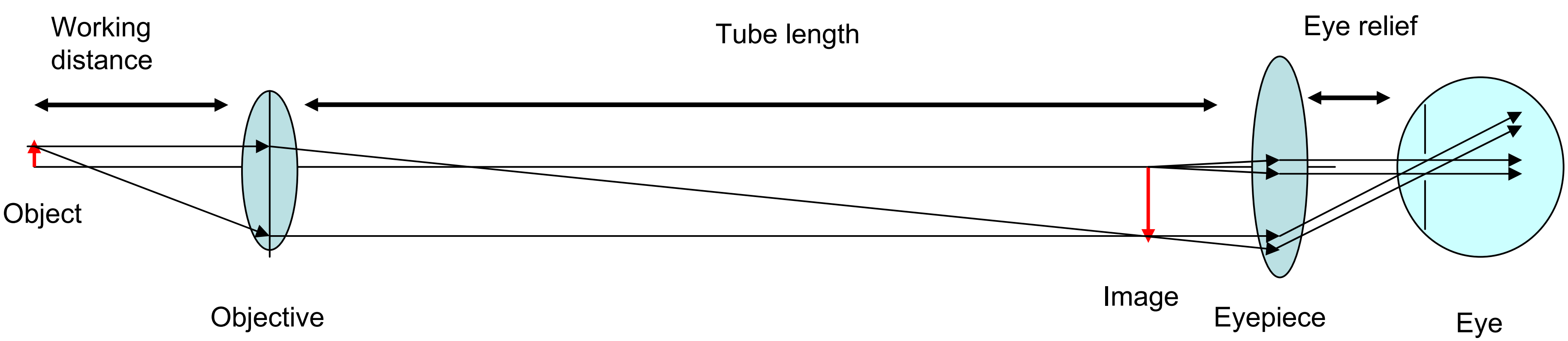
- At location of object and its images :
  - Marginal ray crosses the axis
  - Chief ray is at object or image height
- At stop location and images of stop (i.e. pupils)
  - Marginal ray is at edge of pupil or stop
  - Chief ray crosses axis
- Pupils are paraxial – rays traced are real

- Paraxial plane locations are not shown.



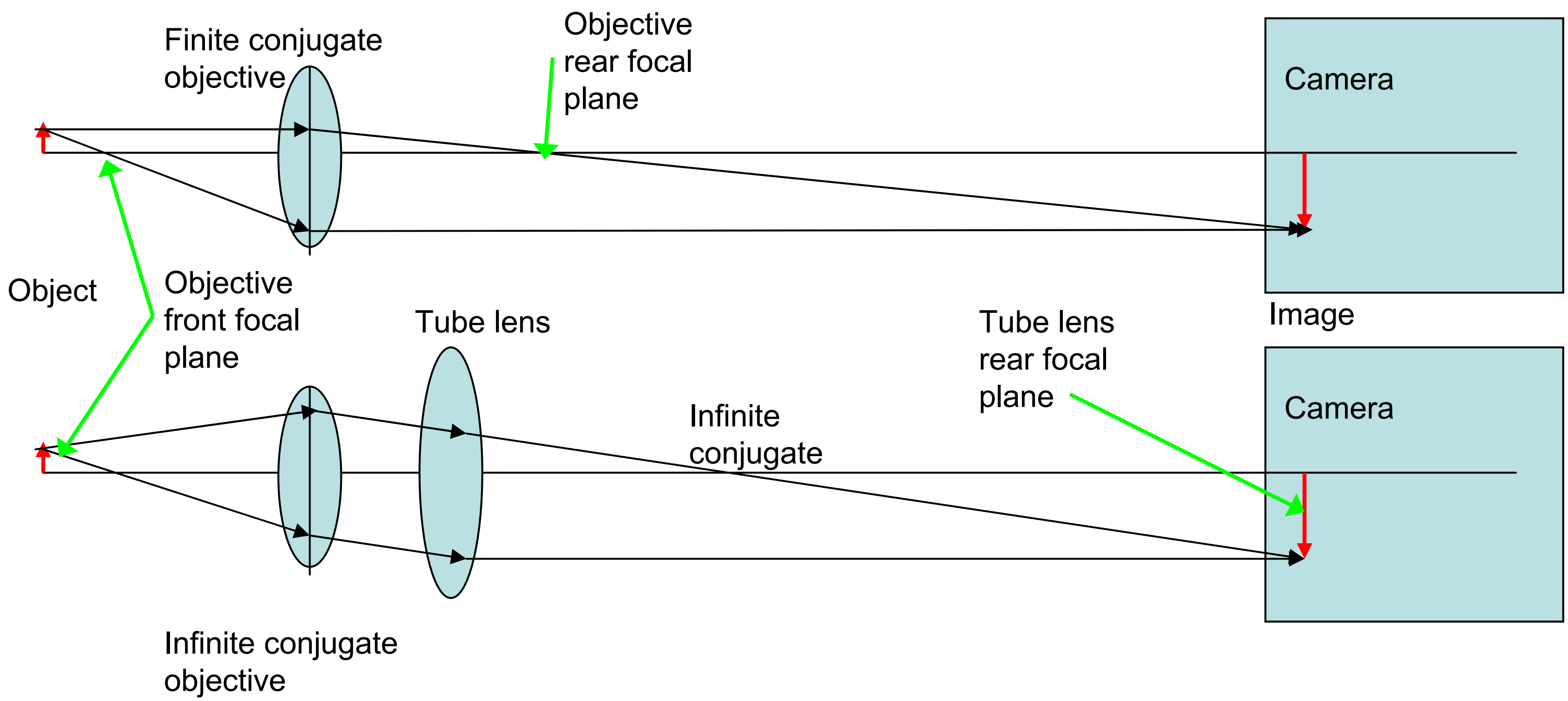
Microscopes

- Microscopes produce an enlarged image of a nearby object either on a detector or for viewing by eye, usually with an eyepiece. May be used to:
  - examine the quality of a point image produced by an optical system,
  - measure the size of surface defects,
  - measure surface roughness interferometrically,
- Many types of microscopes exist: reflection / transmission, bright-field, dark-field, Nomarski, phase contrast, Mirau, etc.
- First look is at microscopes suitable for examination of a point image.
  - DIN type microscope: 195 mm object to image plane, 160 mm tube length, 150 mm image distance (objective mounting flange to image), 45 mm parfocal distance (flange to object)
- To use with a camera remove the eyepiece and place the detector at the image plane.
- Parts for microscopes like this are available from Rolyn Optics, Edmund Optics, Thorlabs, CVI Laser, Newport, etc.
- Magnification = objective magnification * eyepiece magnification.
- Focal length is not defined exactly by magnification.



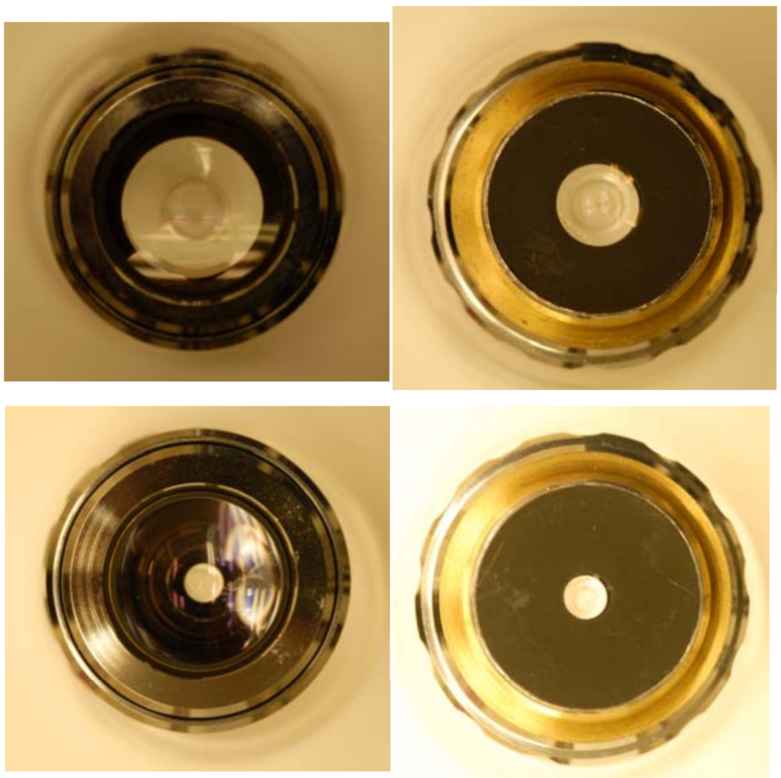
Infinite conjugate objectives

- Most new microscopes use infinite conjugate objectives:
  - Object is in front focal plane
  - A tube lens is required to focus the light from the objective onto a detector
  - Distance between objective and tube lens can vary significantly allowing for insertion of optional optics
- Objective magnification is the ratio between design tube lens focal length and objective focal length.
  - Manufacturers use different tube lens focal lengths: Nikon, Leica & Mitutoyo 200 mm, Zeiss 164.5 mm, Olympus 180 mm



Microscope objectives

- Left – object side, Right – image side



$\infty/0$ means the image is at infinity, and no cover glass.

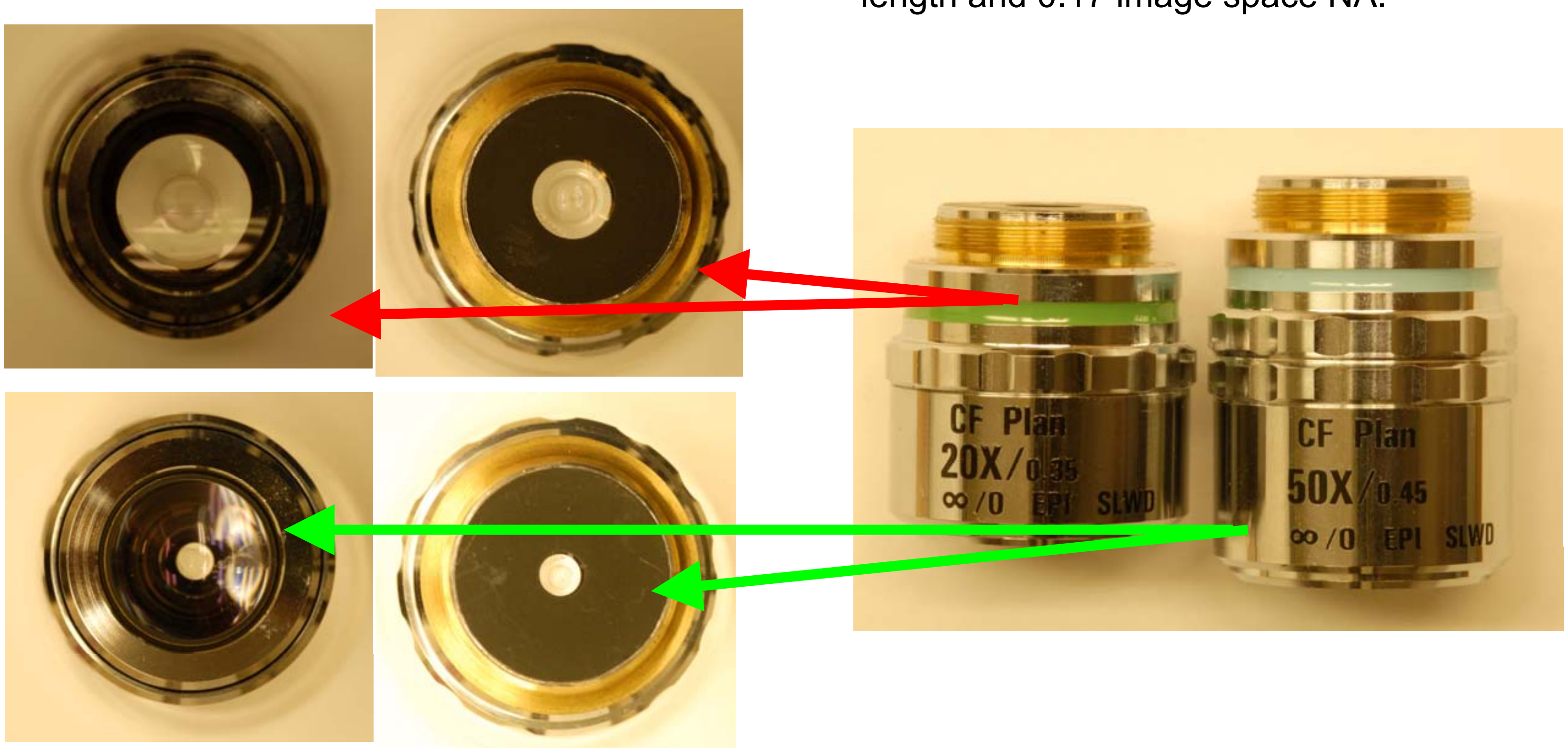
Finite conjugate objectives might be marked 160/0.17 for a 160 mm tube length and 0.17 cover glass thickness.

Microscope objectives

- Left – object side, Right – image side
- Top – 20x, NA 0.35, WD 20.5 mm
- Bottom – 50x, NA 0.45, WD 13.5 mm

$\infty/0$ means the image is at infinity, and the image space NA is 0.

Finite conjugate objectives might be marked 160/0.17 for a 160 mm tube length and 0.17 image space NA.



Lagrange invariant

- Paraxial optics is linear → any ray can be formed as combination of two rays.
- Marginal ray starts at axial location of object and goes to edge of entrance pupil. Marginal ray:
  - height is zero at object and all image locations,
  - angle defines numerical aperture or F/# of space, and
  - defines image location and pupil (aperture) sizes.
- Chief ray starts at object point in field to center of entrance pupil. Chief ray:
  - height is zero at aperture stop and all pupils (images of aperture stop),
  - angle defines the field angle, and
  - defines object and image heights and pupil locations.
- Lagrange invariant is constant through a system
- What happens if microscope tube lens focal length is reduced to 100 mm from 200 mm?
  - Lagrange invariant in object space is unchanged, so it is unchanged throughout system:
  - Magnification is ½ original value
  - Image space numerical aperture is 2x original value

Chief ray $\bar{u}, \bar{y}$

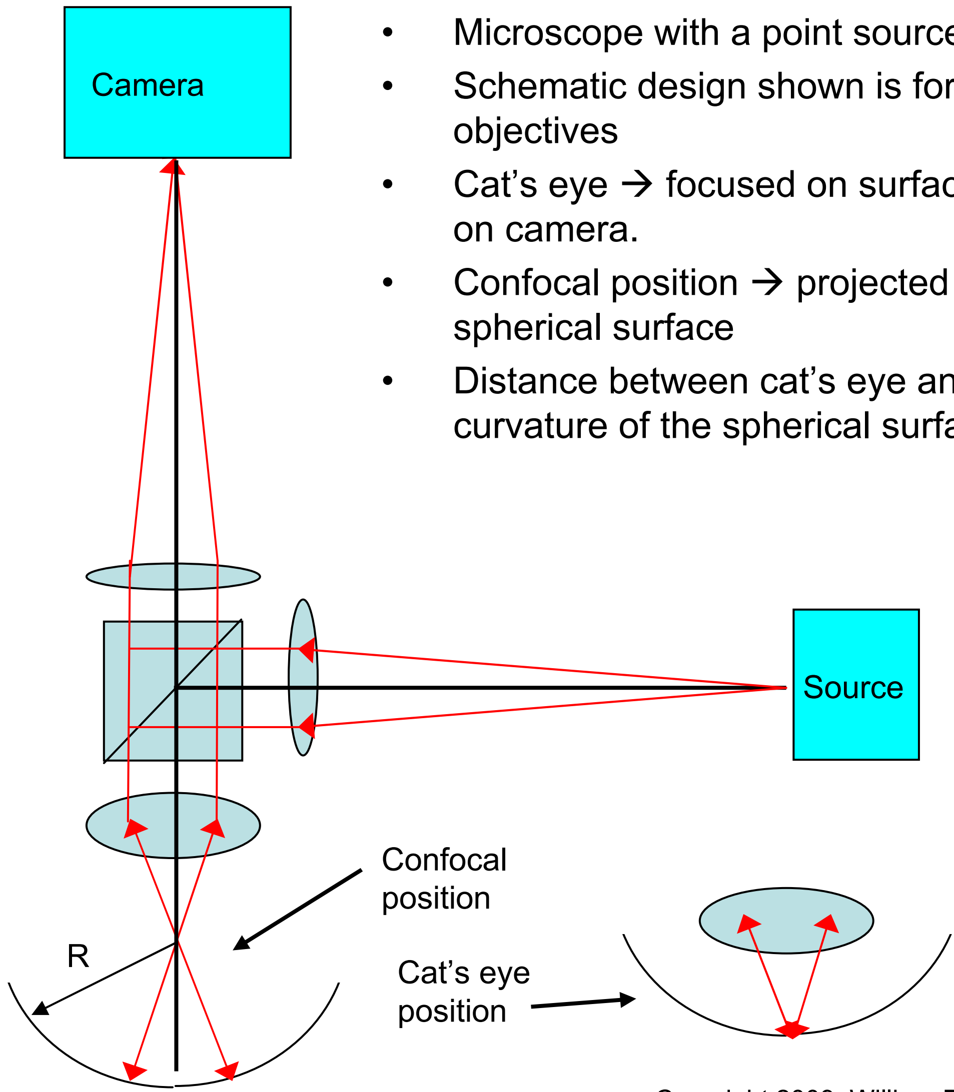
Marginal ray u, y

Lagrange Invariant $\mathrm{H} = n\bar{u}y - nu\bar{y}$

At object or image $y = 0 \Rightarrow \mathrm{H} = -nu\bar{y}$

At a pupil $\bar{y} = 0 \Rightarrow \mathrm{H} = n\bar{u}y$

Autostigmatic microscope



- Microscope with a point source conjugate to detector
- Schematic design shown is for a system using infinite conjugate objectives
- Cat’s eye → focused on surface, can establish a reference coordinate on camera.
- Confocal position → projected spot is at center-of-curvature of a spherical surface
- Distance between cat’s eye and confocal position is the radius of curvature of the spherical surface in air.

- Two points are stigmatic if for a cone of rays originating from one point there is a cone passing through the other. A pair of stigmatic points are also referred to as conjugate points.
- Autostigmatic – self imaging – instrument projects and images a point
- Autocollimator – projects and images a point at infinity

Websites

- Links are to fantastic sites for understanding microscopes.
- Olympus Microscopy Resource Center
- Nikon MicroscopyU – Nikon microscopy home page with JAVA tutorials and more.
  - Nikon CFI60 optics – explanation of their infinite conjugate microscope design with 60 mm parfocal distance.
- Edmund Optics - Understanding Microscopes – a good description of microscopes based on a 160 mm tube length (no tube lens).