Optics for Engineers
Week 2

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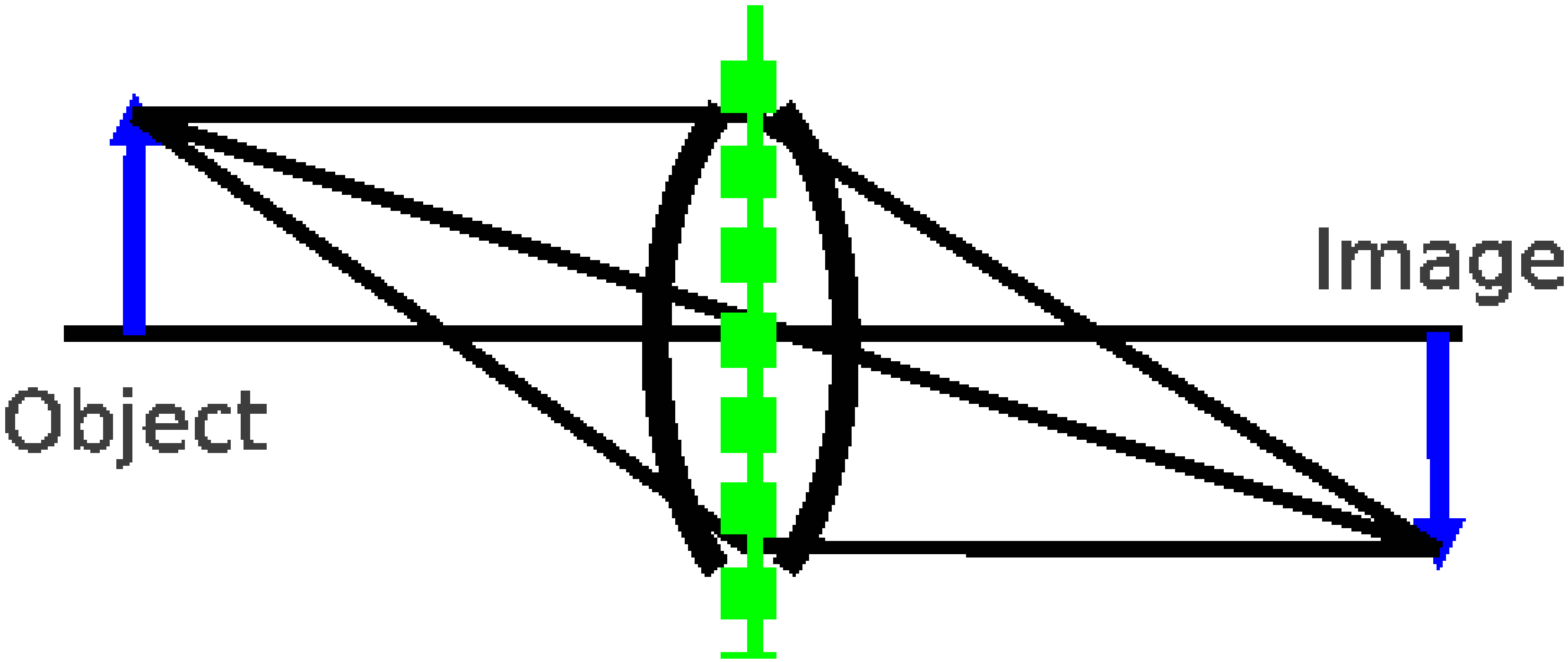
Week 2 Agenda

- One Lens (Simple Lens)
- Curved Mirrors Briefly
- Camera Lens, Magnifier, 1:1 Relay
- Two Lenses
- Microscope, Telescope

“High–School Optics”



“High–School Optics Rules”

- Find front and back focal points, F and F', located f in front of, and in back of, the lens.
- Trace the ray from the object arrow parallel to the axis, refracting out through the back focal point.
- Trace the ray from the object arrow through the front focal point, out parallel to the axis.
- They intersect at the image.
- Check by tracing the ray through the center of the lens which does not refract.

Thin Lens in Air

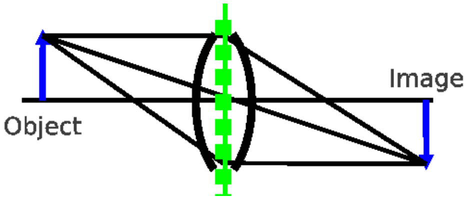
- Making The Lens (We Still Have Some Choices)

$$\boxed{\frac{1}{f} = \frac{1}{f'} = P_1 + P_2 = (n_\ell - 1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right)}$$

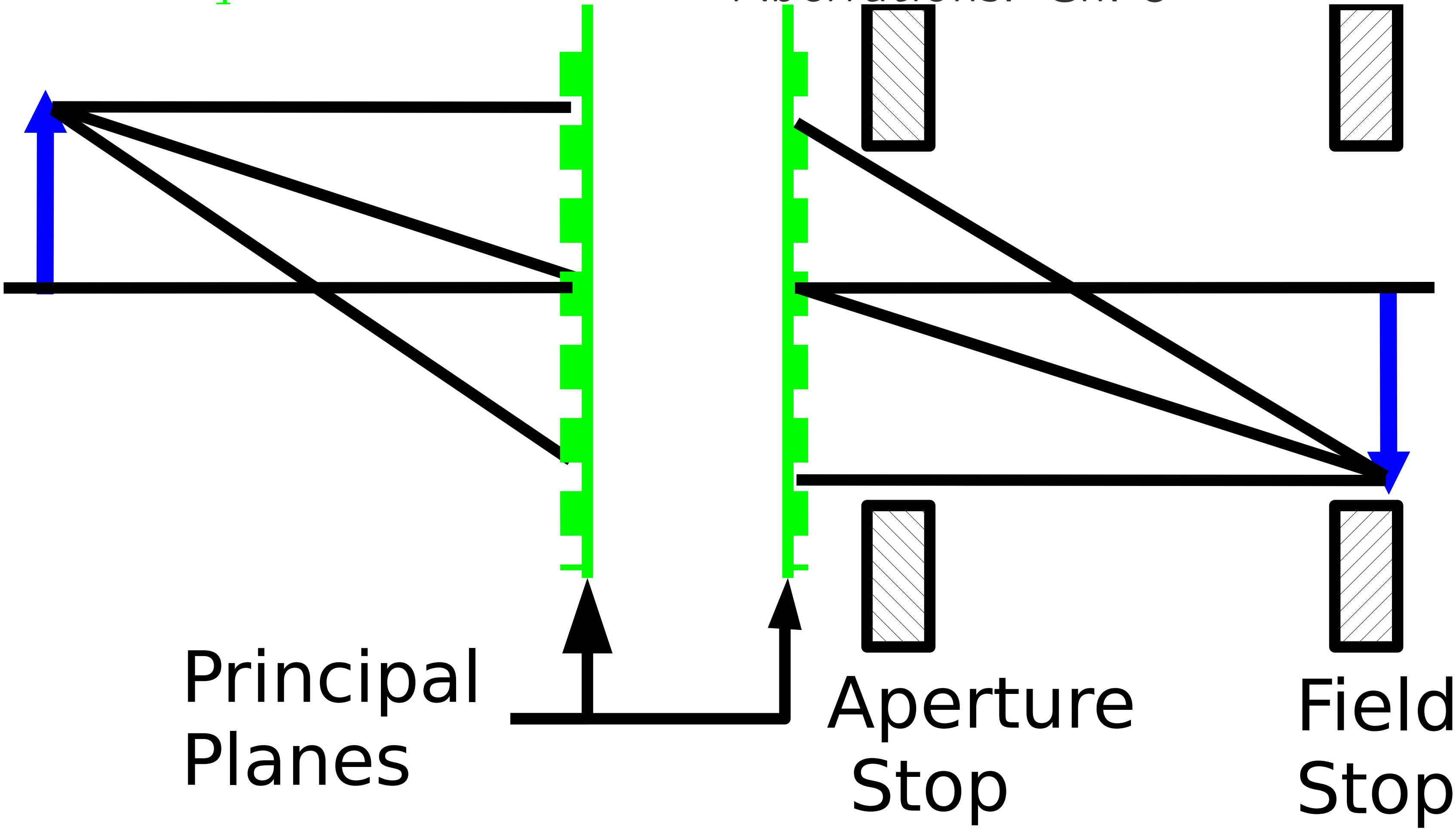
- Using the Lens

$$\boxed{\frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \qquad\qquad m = -\frac{s'}{s}}$$

“The AP Version”



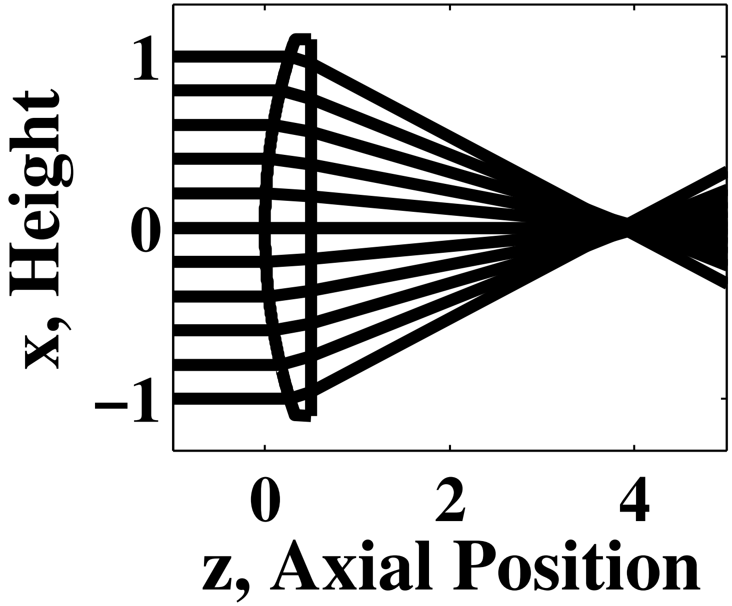
Principal Planes: Ch. 3
Stops: Ch. 4
Aberrations: Ch. 5



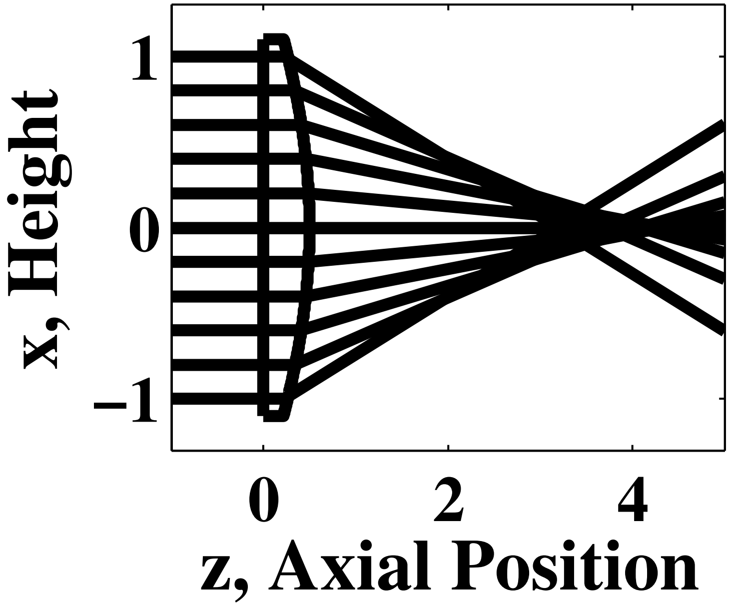
Share the Bending

Take–Away Message

- Share the Bending for Best Aberration
- Watch Principal Planes
  - IR Detector Lens Example



A. Correct Orientation



B. Reversed

Reducing Aberrations

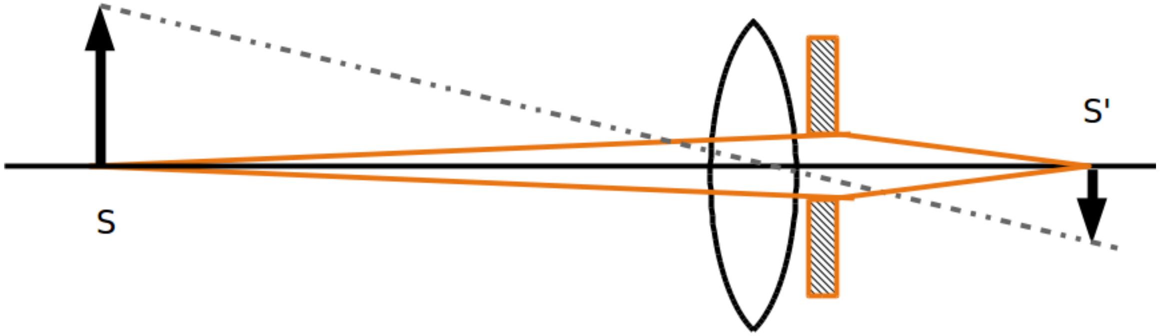
In Practice

- Close Object (Large Magnification): Plano–Convex with Plano Side toward Object
- Distant Object (Small Magnification): Plano–Convex with Convex Side toward Object
- Object and Image Distances Equal ($|m| \approx 1$): Biconvex

Some Lens Applications

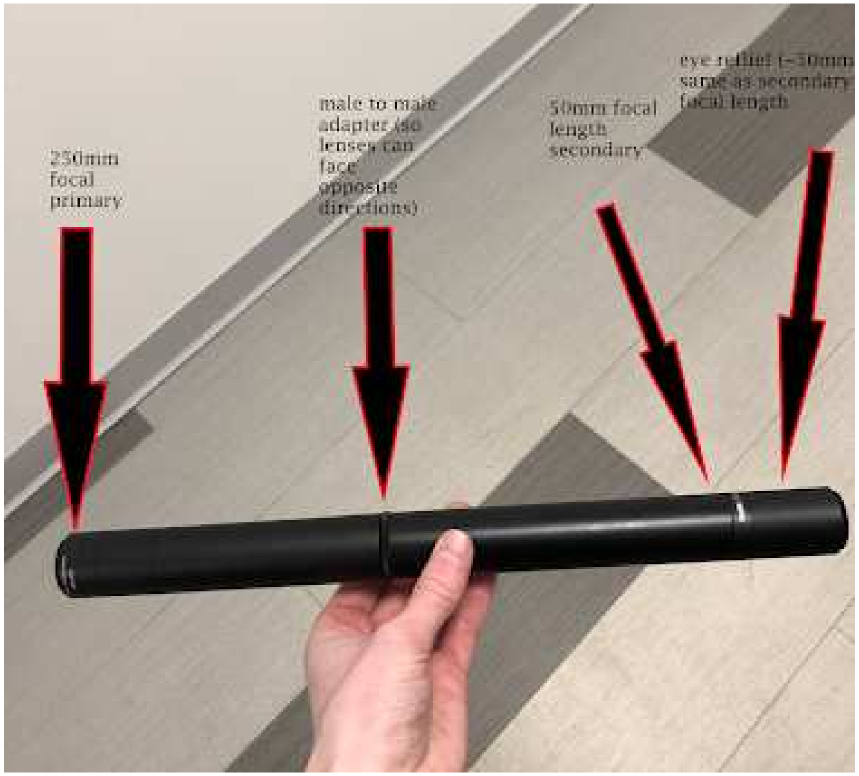
- Camera Lens
- Magnifier
- Simple Microscope
- 1:1 Relay

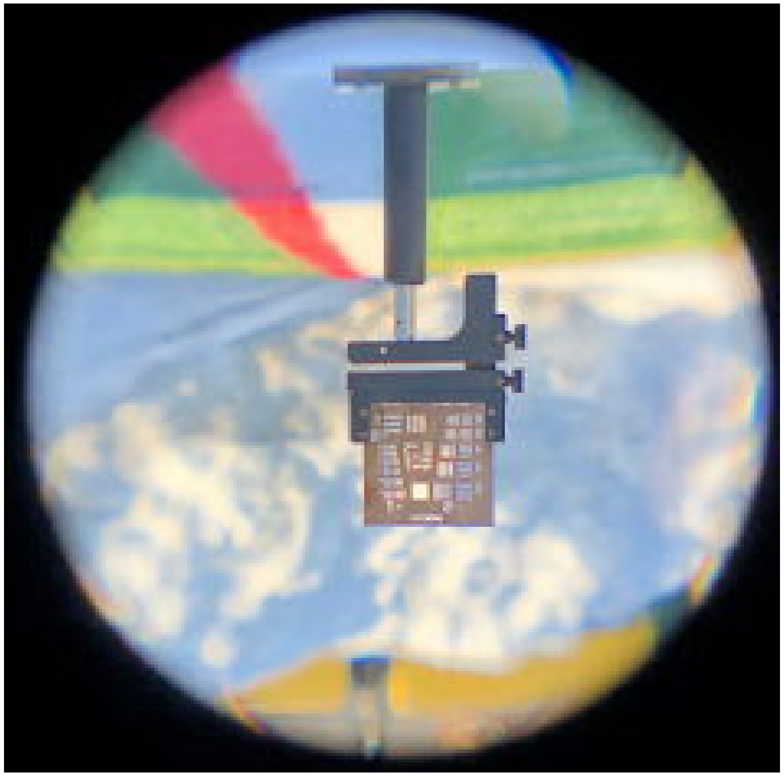
Camera Lens



In Class: $x' = 35$mm, $x = 500$m, $s = 1$km, $f = ?$

Telescope



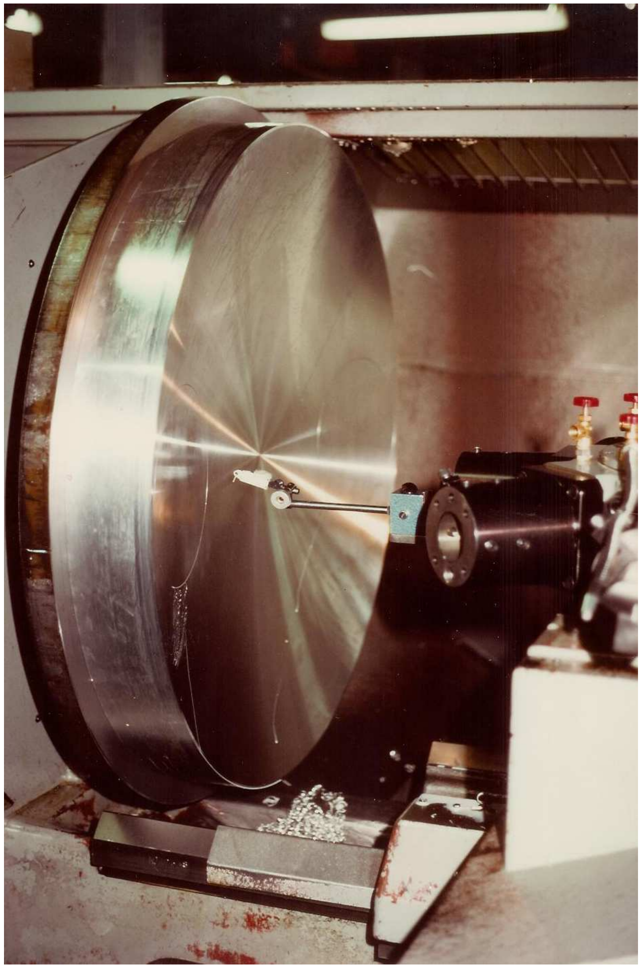


5x (angular) 1inch optics. $f_1 =$, $f_2 =$, image of lens 1?

Magnifier

- Goal is upright image, magnified.
- Where is object? Image?
- Write the equation for s, s', f

Large Reflective Optics

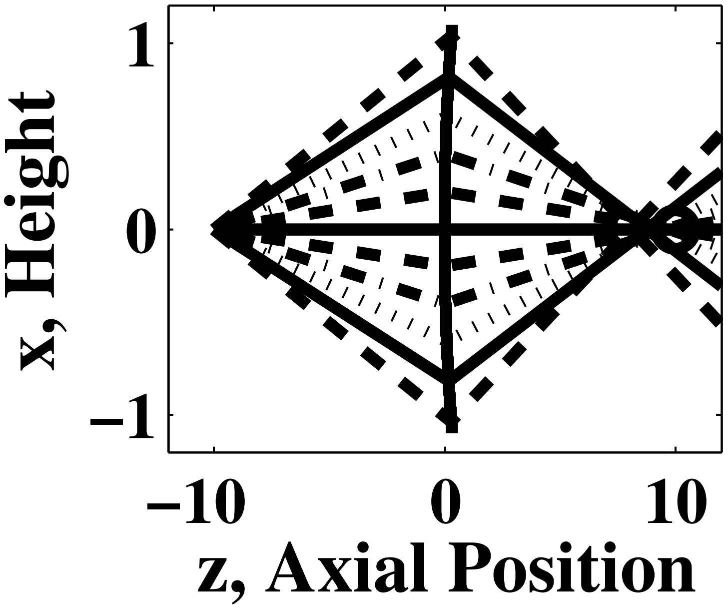


"Every Material that Transmits 10μm Light is Expensive."

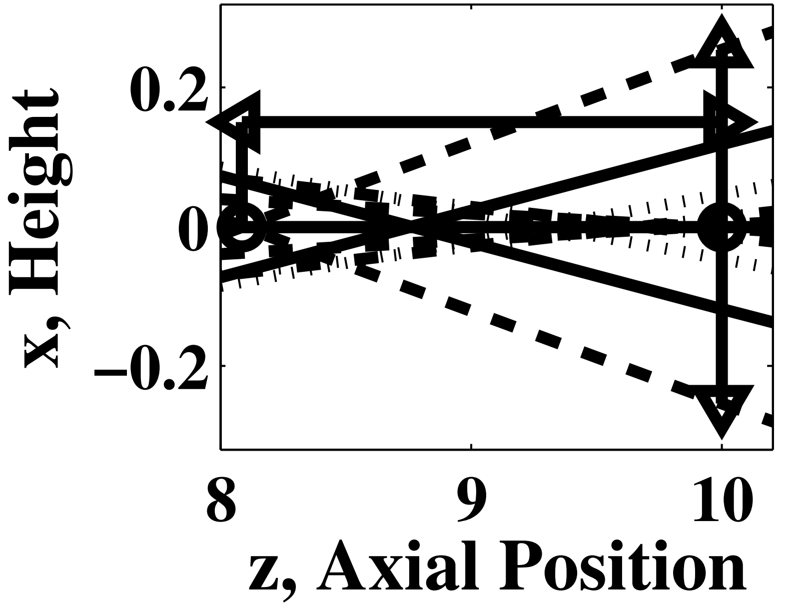
Not Completely True, but Close.

Using Snell's Law Exactly

- Example: Single Convex Air–to–Glass Interface
- Paraxial Rays Follow Small–Angle Approximation
- Edge Rays May Focus Quite Differently
- Rays Do Not Intersect at a Single Point (or at all in 3D)
- Large "Shot Pattern" at "Paraxial" Focus
- "Best" Focus Translated and Depth of Focus Increased



Complete Ray Trace



Expanded View Near Image

Looking Ahead: Diffraction

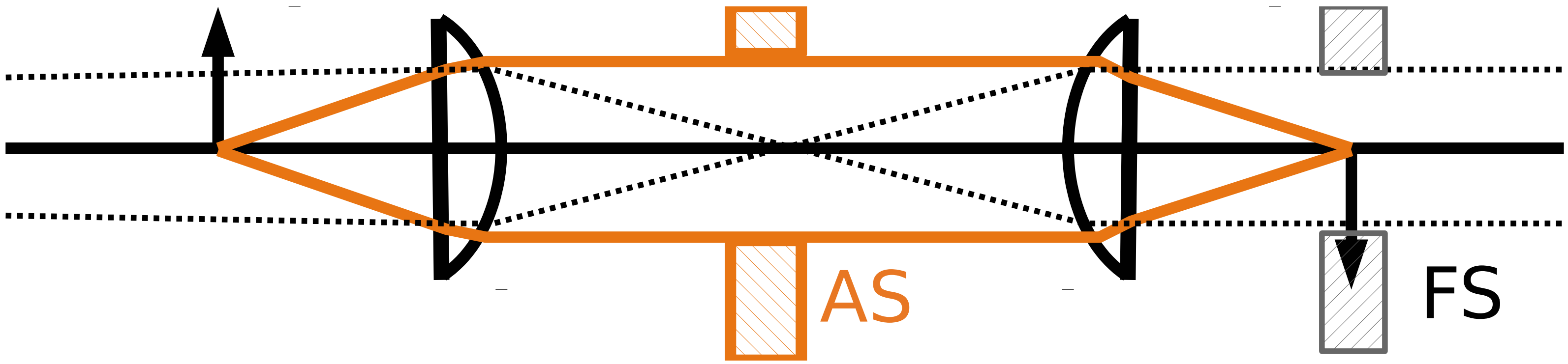
- Diffraction Theory (Ch. 8) Predicts a Minimum Spot Size
  - Rooted in Fundamental Physics
  - $\approx \frac{\lambda}{D_{pupil}} z$
- Ray Tracing Result Below this Limit is "Good Enough"
  - Characterized as "Diffraction–Limited"
- Larger Ray–Tracing Result Indicates Degraded Imaging
  - Can Characterize Roughly by "XDL"

Diffraction Limit of 1inch lens with $f = 20$cm?

Ray Tracing: Overview

- Setup: Launch a Fan of Rays (*eg.* Fill FOV and Pupil)
- Loop On Rays
  - Loop On Elements (Like Matrix But No Approximations)
    - Translation (Straight–Line Propagation)
    - Refraction or Reflection (Interfaces)
  - Close (End the Ray Calculation)
- Report (*eg.* Spot Size *vs.* Field Position)
- Homework: Try it (OSLO.edu).

Two Simple Lenses

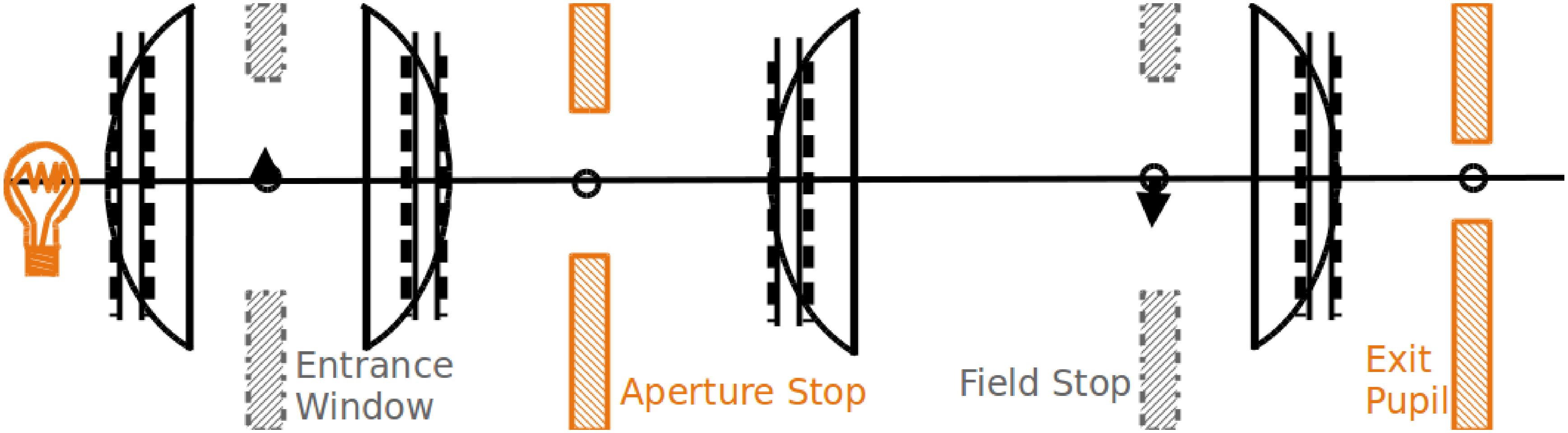


- Separation: $f_1 + f_2$

- Microscope: $s = f_1$, $s' = f_2$ as shown
  Magnification $m = -\frac{f_2}{f_1}$

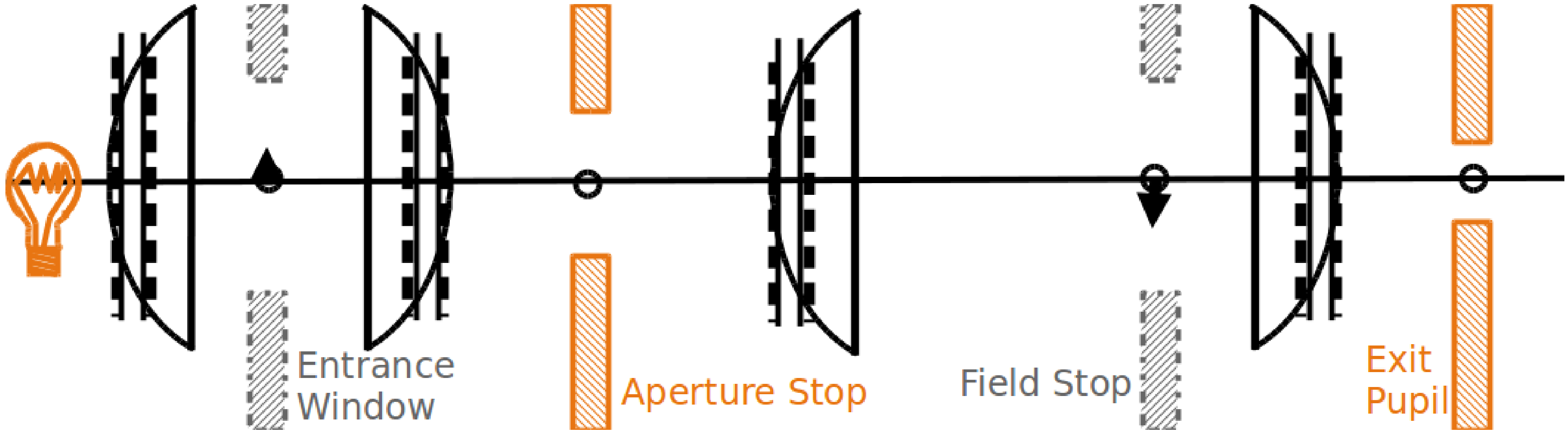
- Telescope: $s \rightarrow \infty$, $s' \rightarrow -\infty$
  Angular Magnification: $m_\alpha = 1/m$
  Which way do the plano–convex lenses go?

Infinity–Corrected Microscope



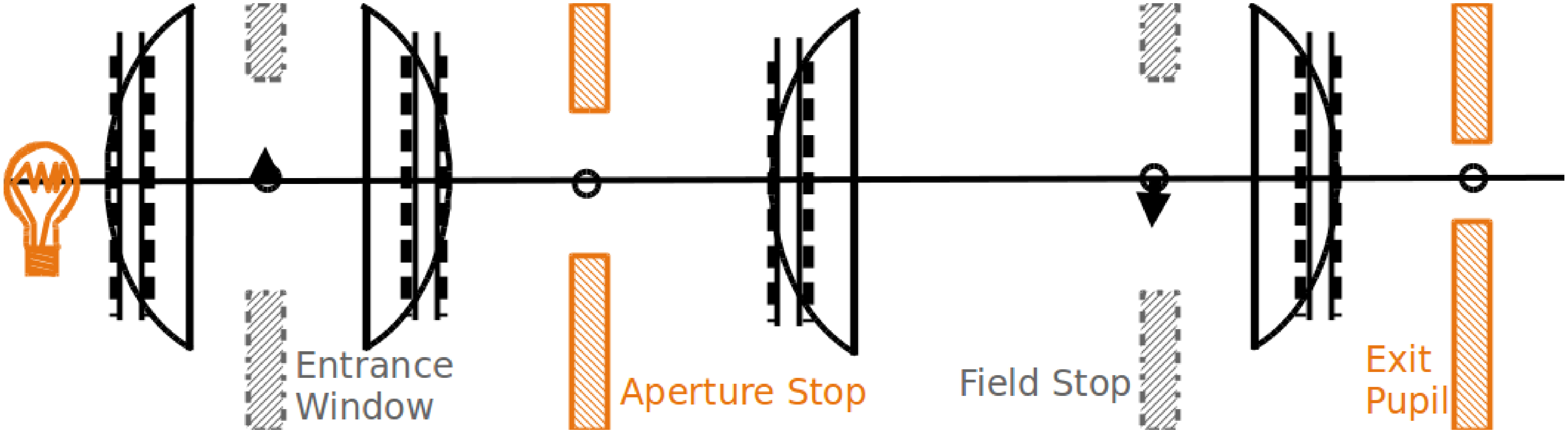
Camera at field stop: Chip = 1 cm, Tube lens $f_{tube} = 200$mm, $m = 10$. $f_1 =$?, $FOV =$?. Pixel on object?

Infinity–Corrected Microscope



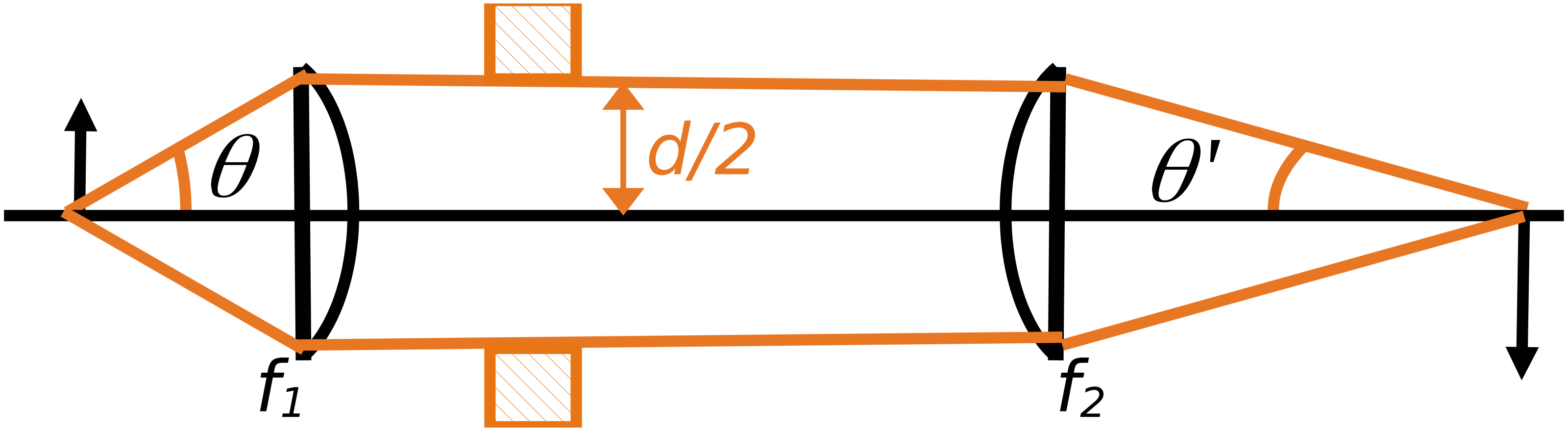
Camera at field stop: Chip $= 1$ cm, Tube lens $f_{tube} = 200$mm, $m = 10$. $f_1 = 20$, $FOV = 1$cm$/10$. Pixel on object. $FOV/1000 = 1\mu$m

Stops, Pupils and Windows



- Aperture Stop Limits Light Collection
- Aperture Stop Determines Diffraction Limit
- Field Stop Limits Field of View

Numerical Aperture (NA)



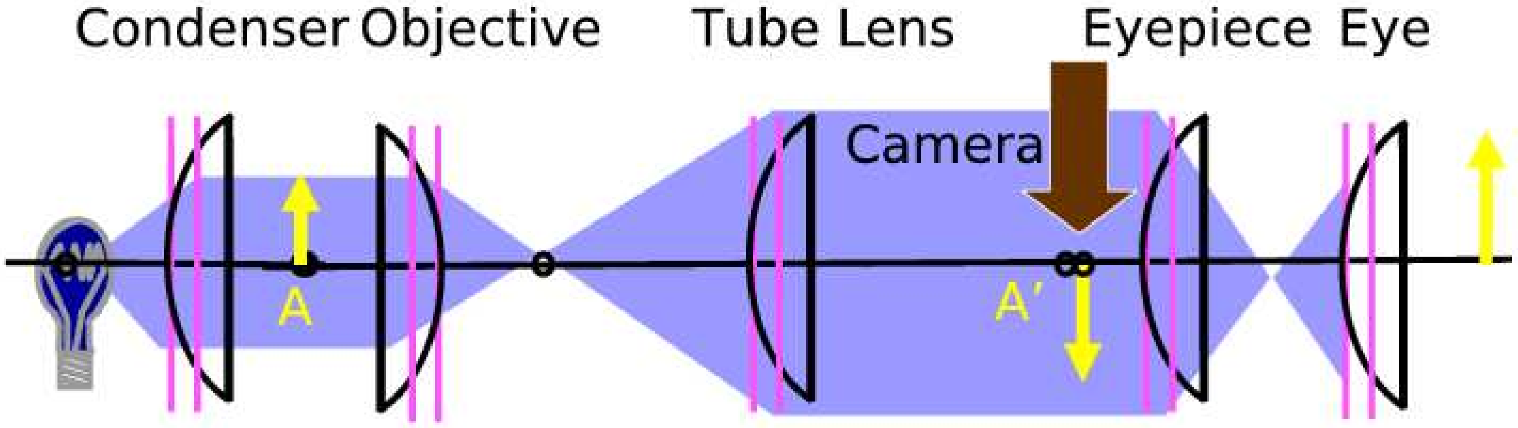
$$NA = n \sin\theta \qquad NA' = n' \sin\theta'$$

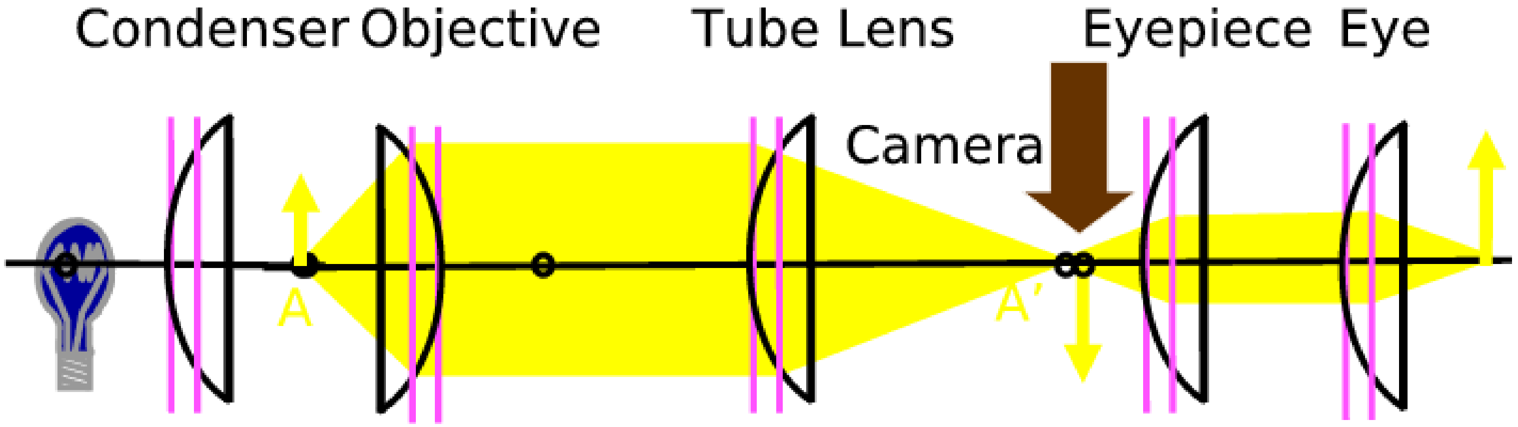
Specifically, In Air. . .

$$NA = \sin\theta \qquad NA' = \sin\theta'$$

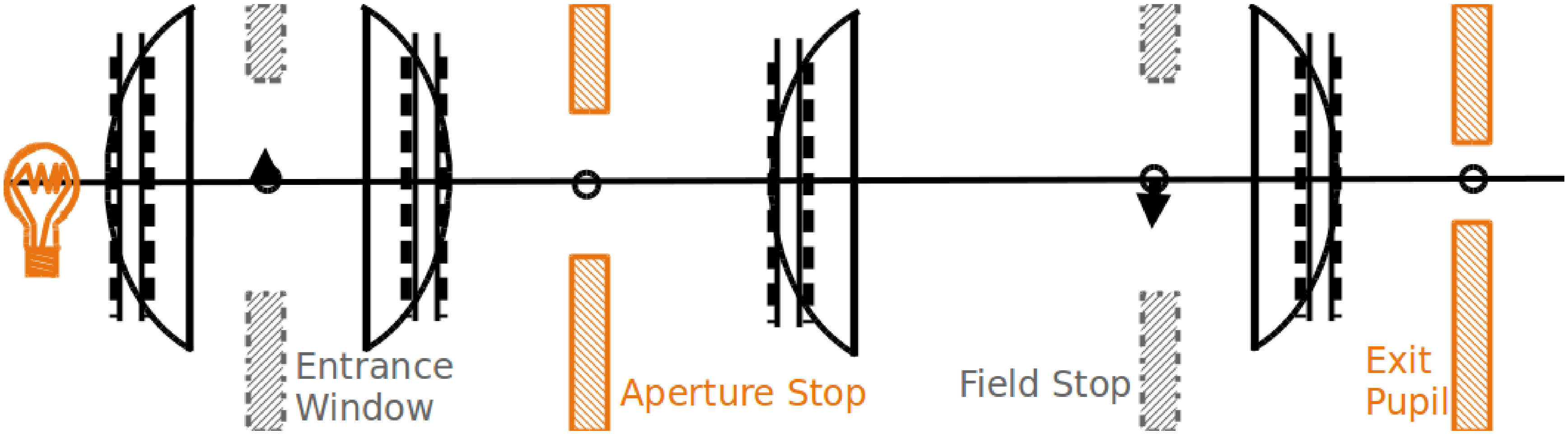
n is the index of refraction of the medium, not the lens.

Brightfield Microscopy





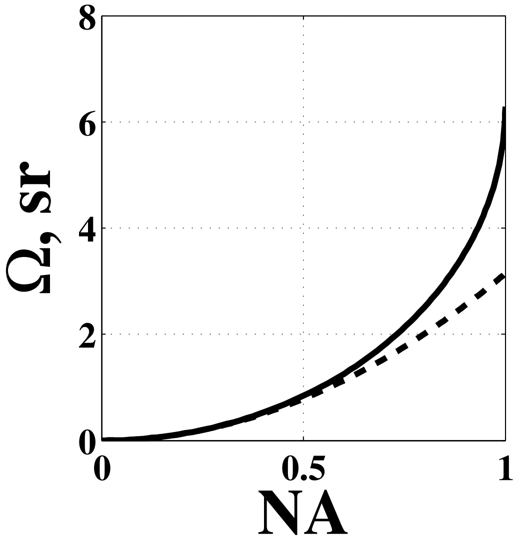
Infinity–Corrected Microscope



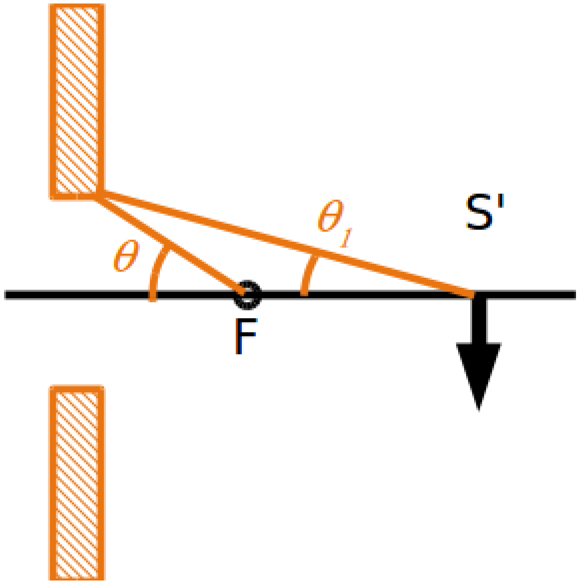
Camera at field stop: Chip = 1 cm, Tube lens $f_{tube} = 200$mm, $m = 10$. $f_1 = 20$, $FOV = 1\text{cm}/10$. Pixel on object. $FOV/1000 = 1\mu m$

$NA = 0.75$. Aperture Stop? Exit Pupil?

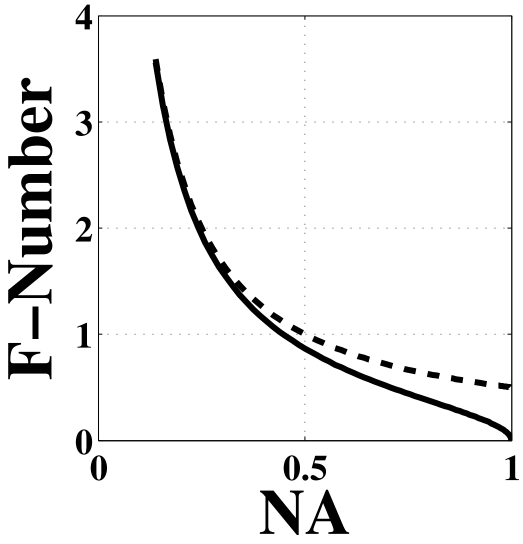
f/# and NA



A



B



C

$$NA_{image} = n' \frac{1}{\sqrt{\left[|m-1| \times 2(f/\#)\right]^2 + 1}}$$

$$NA_{image} = n' \frac{1}{|m-1| \times 2(f/\#)}$$ Small NA, large $(f/\#)$