Lens Design Lecture #1-3

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University of Arizona

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Tentative “syllabus”:

- Microscopes, mainly objectives, some eyepiece
  - ~3 weeks
- Telecentric systems
  - ~3 weeks
- Tolerancing
  - ~6 weeks
- Synopsis software
  - ~2 weeks

Microscope objectives

Magnification & designing backwards

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Characteristics of microscope objectives

- Historically, most microscope objectives were designed to operate at finite conjugates
  - "Infinity-corrected" becoming more prevalent
- Specified by NA in object space
  - object marginal angles tend to be large (fast)
- Must resolve fine detail or structure of SUT
- Design approach may require personalized optimization techniques
  - Modification of standard merit functions
- Important note: the object and image are reversed in design
  - Design from long conjugate to short
    - Helps the optimization process

Microscope objective

Some design techniques:

- Petzval lens
- Aplanatic surface
- Concentric surfaces
- Sort of new: object immersion (higher NA by higher n)

Optical systems for magnification

Why microscopes?

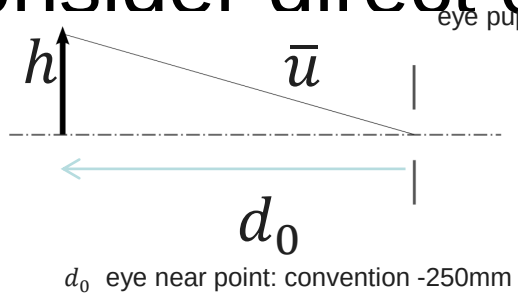
Possible methods for observing small objects:

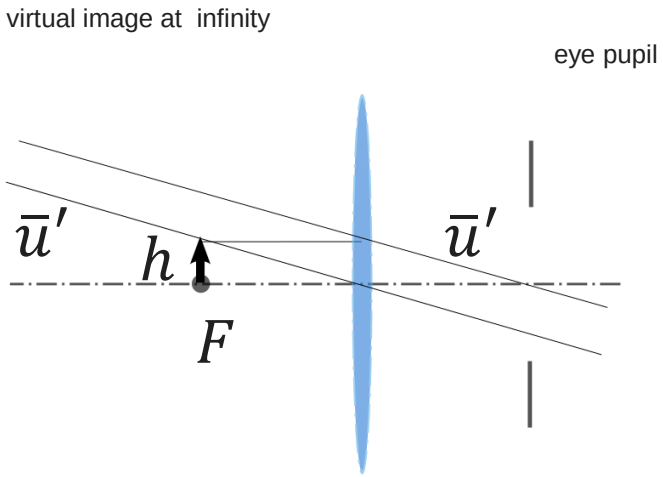
- The eye (observe directly)
- Simple magnifier AKA magnifying glass
  - Real image
  - Virtual image located at finite location
  - Virtual image at infinity
- Compound magnifier

Motivation

Why microscopes?:

- Consider direct observation and magnifier:





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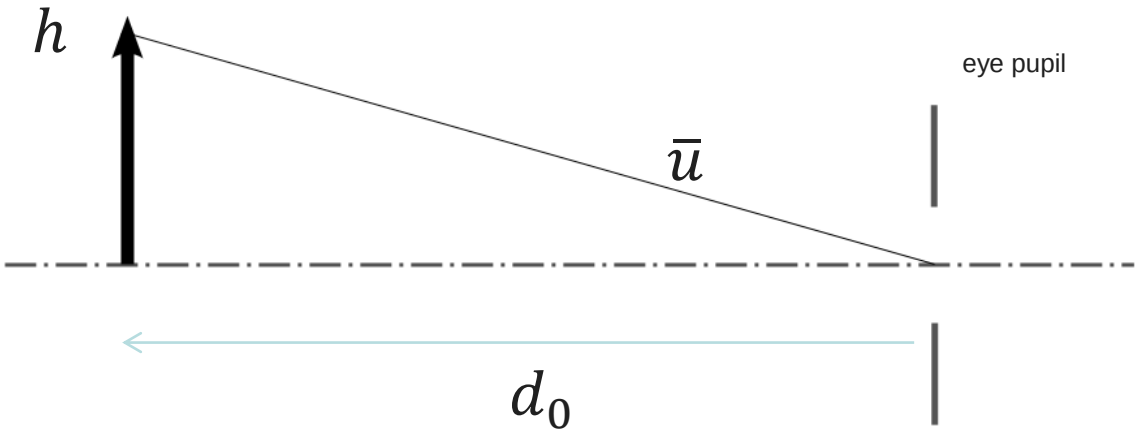
No microscope

Just look with your eye…



d_0 eye near point: convention -250mm

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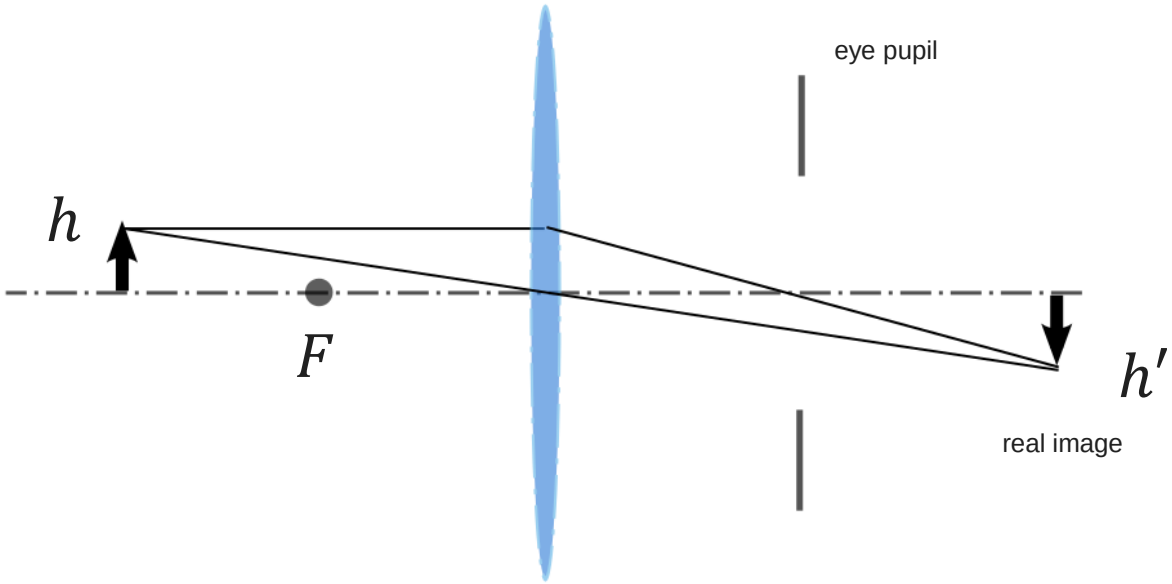
Simple magnifier 1

Forms a “real image” with the eye



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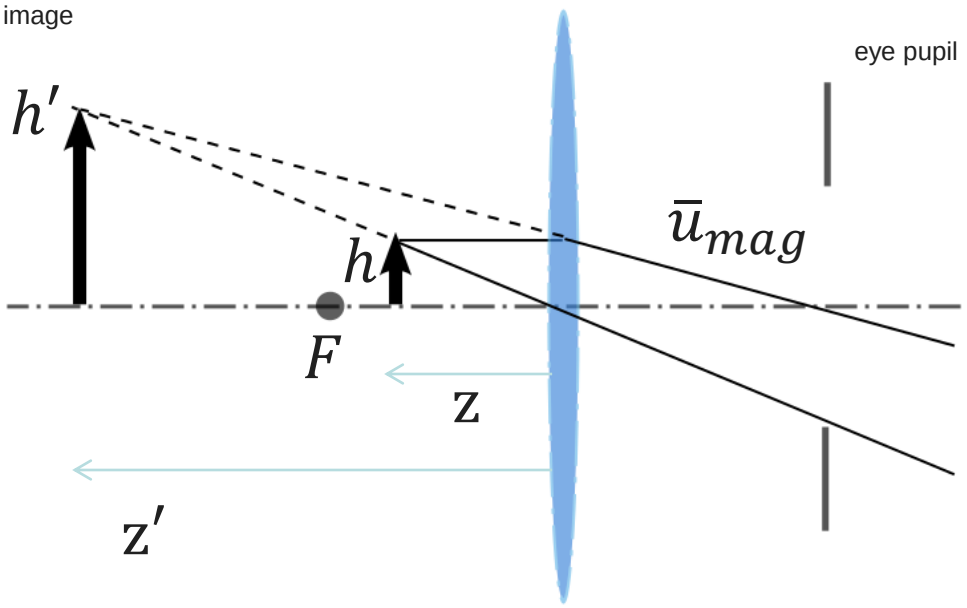
Simple magnifier 2

Simple magnifier: virtual image at finite distanc



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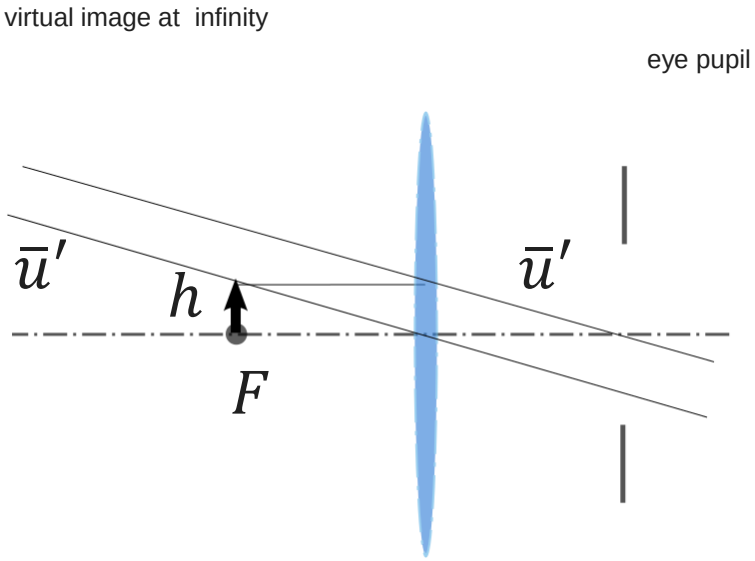
Simple magnifier 3

Forms a virtual image at infinity



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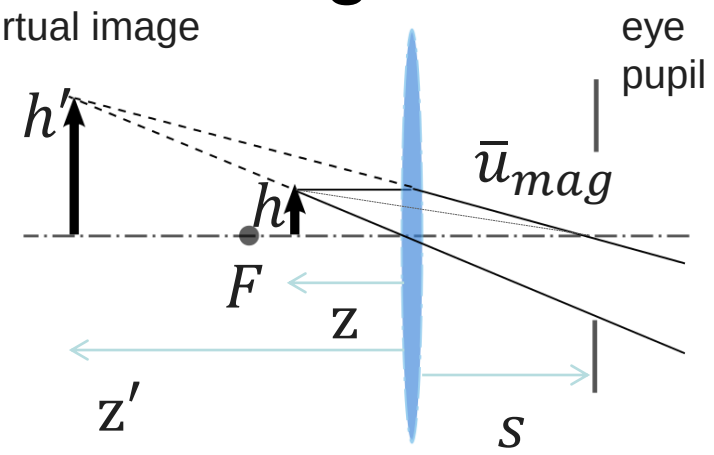
Magnification

Simple magnifier 2

Simple magnifier: virtual image at finite distance

Magnification $\bar{u}_{\substack{no \\ mag}} = \dfrac{h}{z - s}$

$$\bar{u}_{mag} = \frac{h'}{z' - s}$$



$$\bar{u}_{\substack{no \\ mag}} \cong \frac{h}{z} \qquad \bar{u}_{mag} \cong \frac{h'}{z'}$$

If magnifier is close to the eye, *s* may be negligible

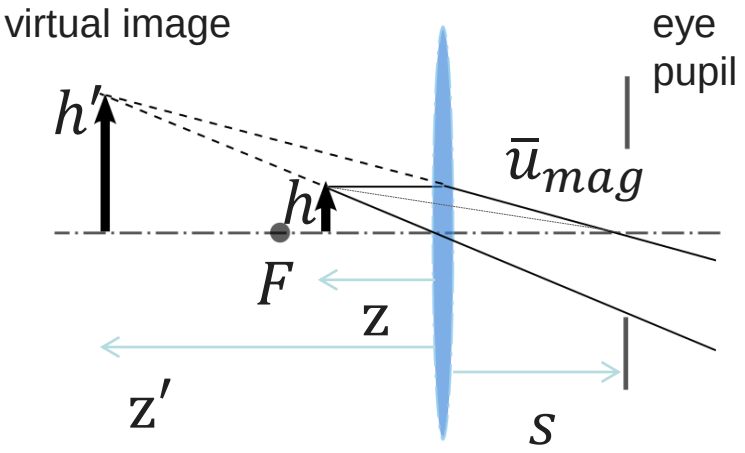
Magnifying power

Simple magnifier: virtual image at finite distance

Using the slopes

$$\bar{u}_{\substack{no\\mag}} = \frac{h}{z}$$

$$\bar{u}_{mag} = \frac{h'}{z'}$$



$$MP = \frac{\bar{u}_{mag}}{\bar{u}_{\substack{no\\mag}}} \cong \frac{h'/z'}{h/z}$$

Magnifying power (MP)

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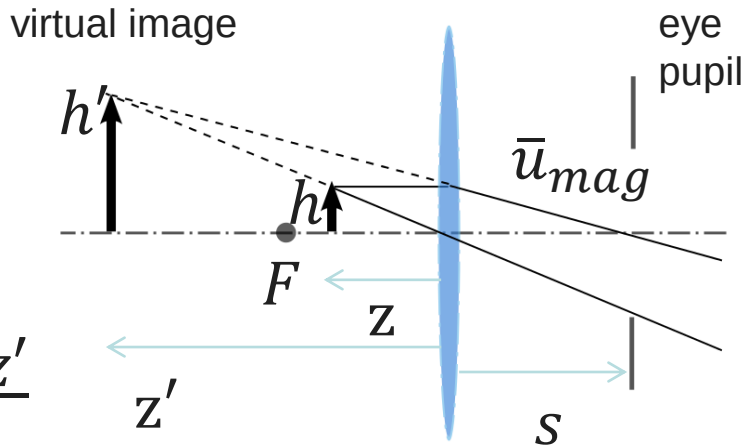
Simple magnifier

Simple magnifier: virtual image at finite distance

Back into imaging



Magnifying power (MP)

$$MP = \frac{\bar{u}_{mag}}{\bar{u}_{\substack{no \\ mag}}} \cong \frac{h'/z'}{h/z}$$

$$MP = \frac{(f - z')z}{f * z'} = \frac{z}{z'} - \frac{z}{f} = \frac{-250mm}{z'} + \frac{250mm}{f}$$

Magnifying power (MP) & focal length

Simple magnifier 2 -> 3

Important case:

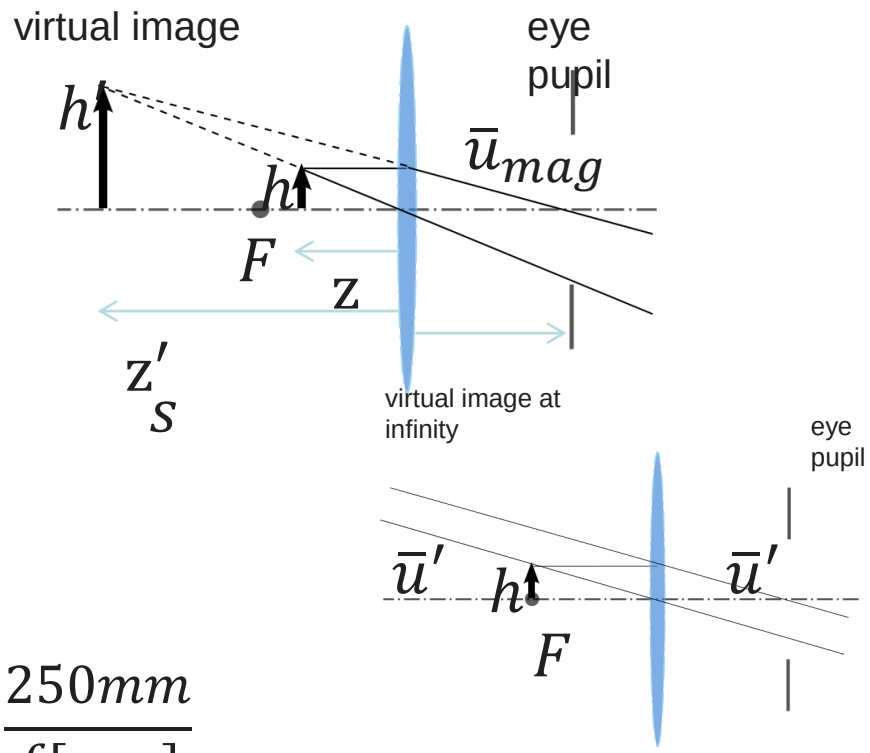
Let the image distance $z' \rightarrow \infty$

This is the “relaxed eye”

Magnifying power (MP)

when $z = -f, z' \rightarrow \infty$

So for an image at infinity



$$MP = \frac{-250mm}{z'} + \frac{250mm}{f} = \frac{250mm}{f[mm]}$$

0

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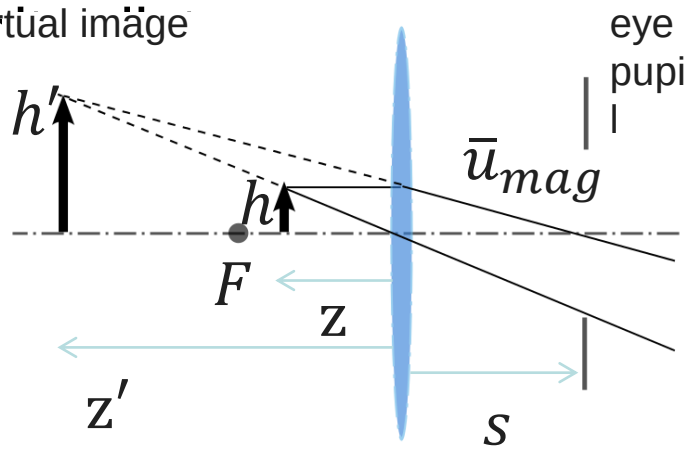
Magnifying power (MP) & focal length: example

Simple magnifier: virtual image at infi

Using the ***image at infinity*** case



Magnifying power (MP)when $z = -f, z' \to \infty$

So for an image at infinity, let's try a focal length of 25mm

$$MP = \frac{250mm}{f[mm]} = \frac{250mm}{25mm} = 10X$$

Magnifying power (MP) required to resolve by eye

Simple magnifier: virtual image versus direct view

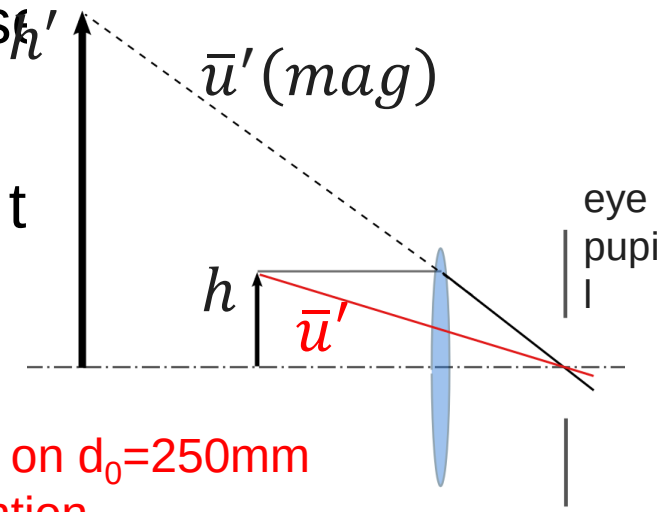
Using the ***image at infinity*** case

$(z = -f, z' \to \infty)$

Magnifying power (MP) for eye t

(1arc-min~0.3mrad)

an object of height ***h***



relying on d_0=250mm convention

$$MP = \frac{\bar{u}_{mag}}{\bar{u}_{\substack{no \\ mag}}} = \frac{0.3mrad}{h/d_0} = \frac{0.3mrad * 250mm}{h} = \frac{75um}{h[um]}$$

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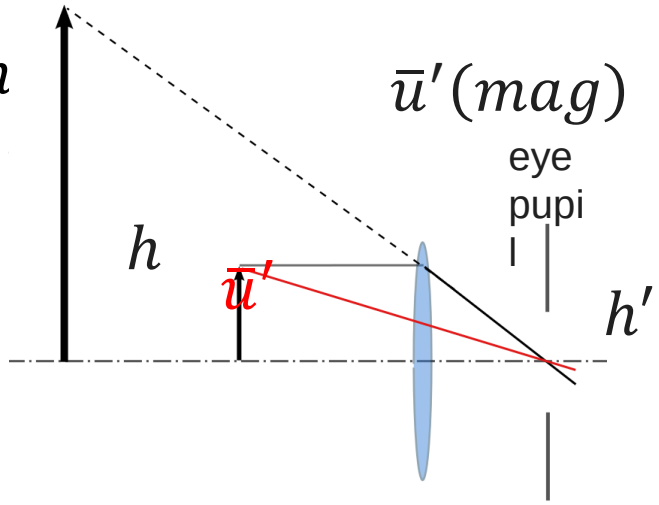
MP required to resolve by eye: example

Simple magnifier: virtual image versus direct view

Using the ***image at infinity*** case ($z = -f, z' \to \infty$), with $d_0 = 250m$

Magnifying power (MP) for eye to an object of 0.5um height



$$MP_{needed} = \frac{75um}{h[um]} = \frac{75um}{0.5um} = 150X \quad \text{needed to resolve}$$

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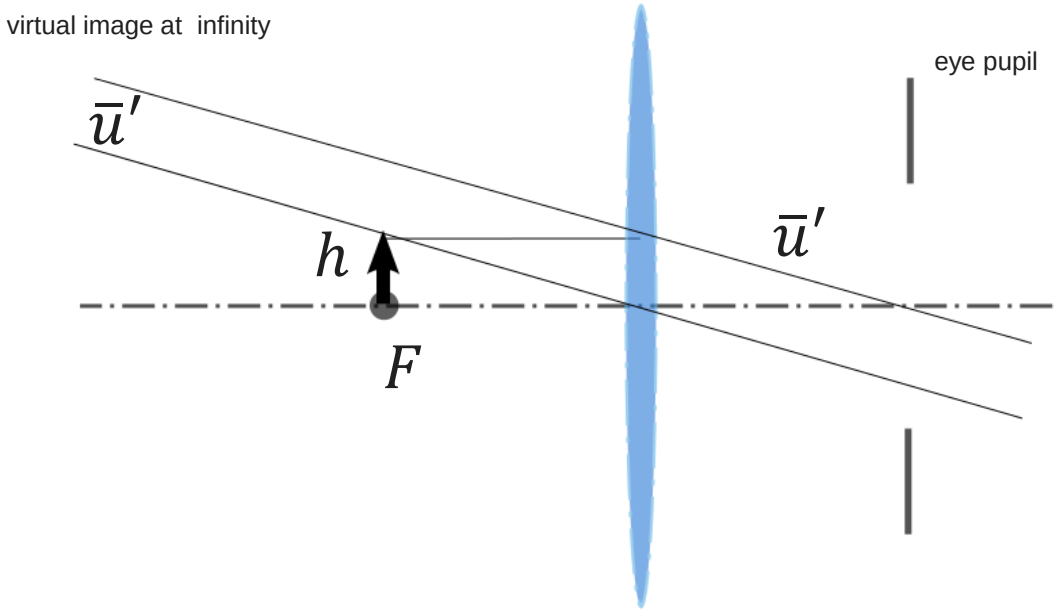
Simple magnifier, relaxed eye

Simple magnifier: virtual image at infinity (relaxed eye)



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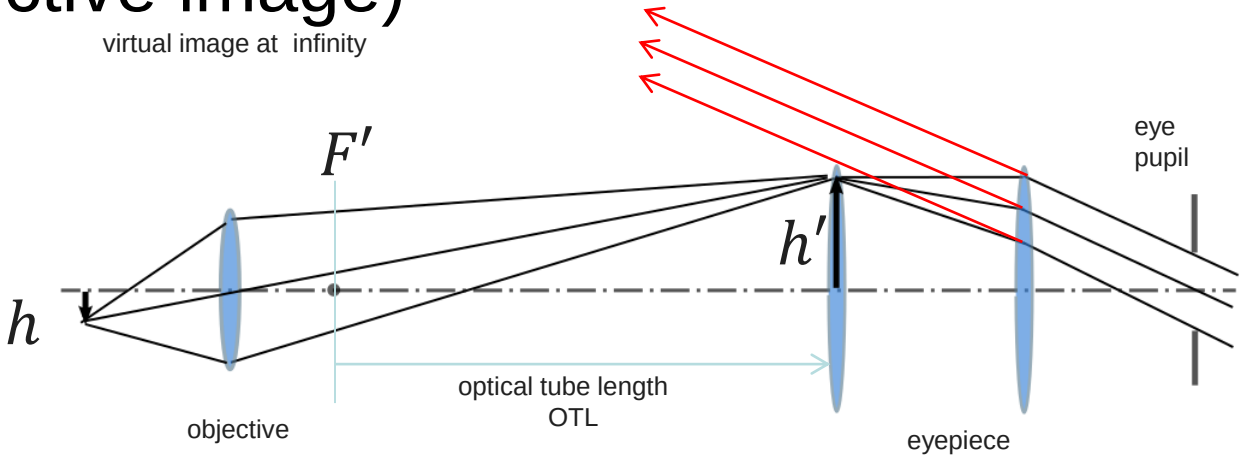
Compound magnifier (microscope

Compound magnifier:

- Virtual image at infinity (of an intermediate objective image)



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Microscope objectives

Magnifying Power and visual resolution

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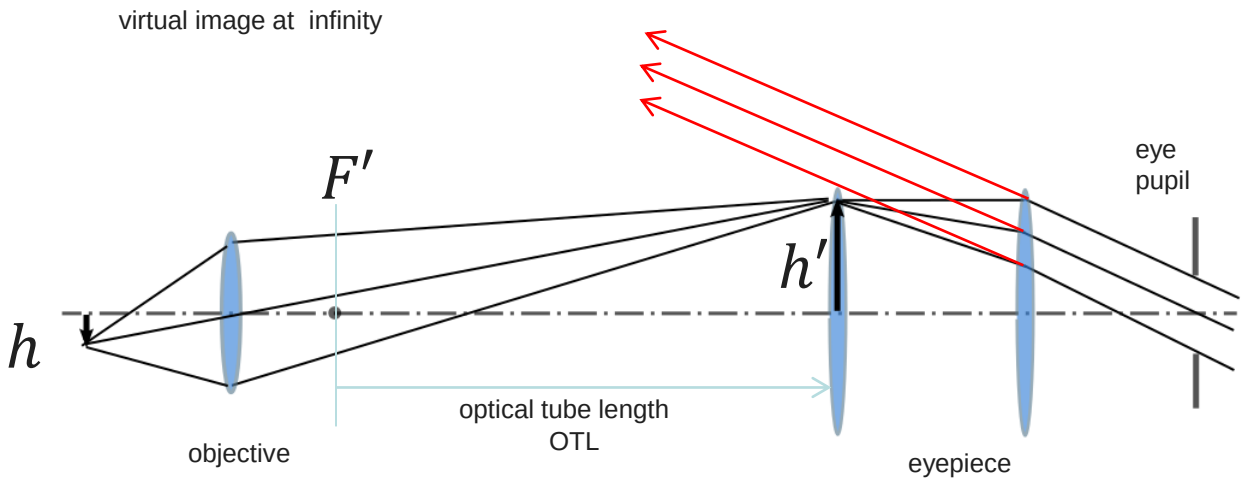
Microscopes

- A magnifier is the simplest microscope
  - Very limited in how much it can magnify
  - ~25X absolute limit
- Compound system has two sections
    - Objective
    - Eyepiece
  - Magnification product of both
    - $MP_{microscope} = M_{objective} * MP_{eyepiece}$
    - $MP_{microscope} = -\frac{OTL}{f_{objective}} * \frac{250}{f_{eyepiece}}$
- MP of microscope called visual resolution

Microscope

- A magnifier consists of an objective plus an eyepiece



- Assume 25X objective, 10X eyepiece
- MP=25*10=250

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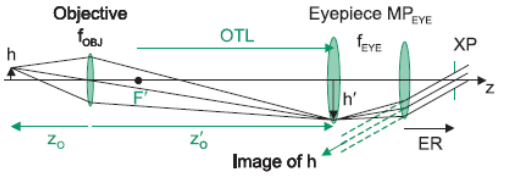
Microscopes

A **microscope** is a sophisticated magnifier consisting of an objective plus an eyepiece.



The **visual magnification** is the product of the objective magnification and the eyepiece MP.

$$m_{OBJ} = \frac{z'_O}{z_O} \qquad MP_{EYE} = \frac{250\text{ mm}}{f_{EYE}}$$

$$m_V = m_{OBJ} MP_{EYE} = \frac{z'_O}{z_O}\frac{250\text{ mm}}{f_{EYE}}$$

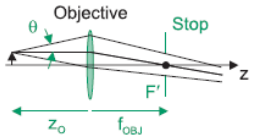
The **optical tube length** OTL of a microscope is defined as the distance from the rear focal point of the objective to the front focal point of the eyepiece (intermediate image). Standard values for the OTL are 160 mm and 215 mm. The OTL is a Newtonian image distance:

$$m_{OBJ} = -\frac{OTL}{f_{OBJ}} \qquad m_V = -\frac{OTL}{f_{OBJ}}\frac{250\text{ mm}}{f_{EYE}}$$

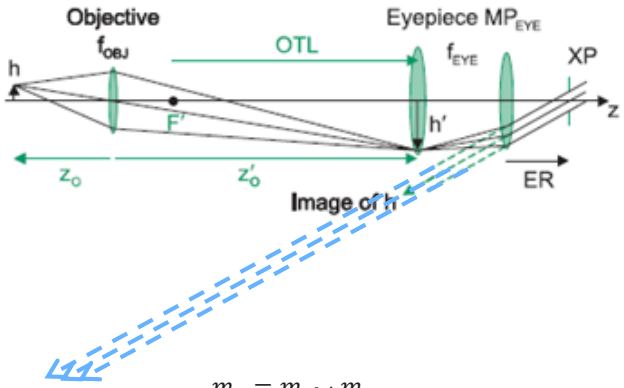
The NA of a microscope objective is defined in object space by the half-angle of the accepted input ray bundle. Along with the objective magnification, the NA is inscribed on the objective barrel.

$$NA = n\sin\theta$$

Microscope objectives are often telecentric in object space. The stop is placed at the rear focal point of the objective so that the magnification does not change with object defocus.



Visual magnification m_V



$$m_v = m_{obj}\, m_{eyep}$$

Example: 25 X objective with 10X eyepiece

$$m_v = 25 \times 10 = 250$$

Much greater than a simple magnifier

Greivenkamp, Field Guide to Geometrical Optics

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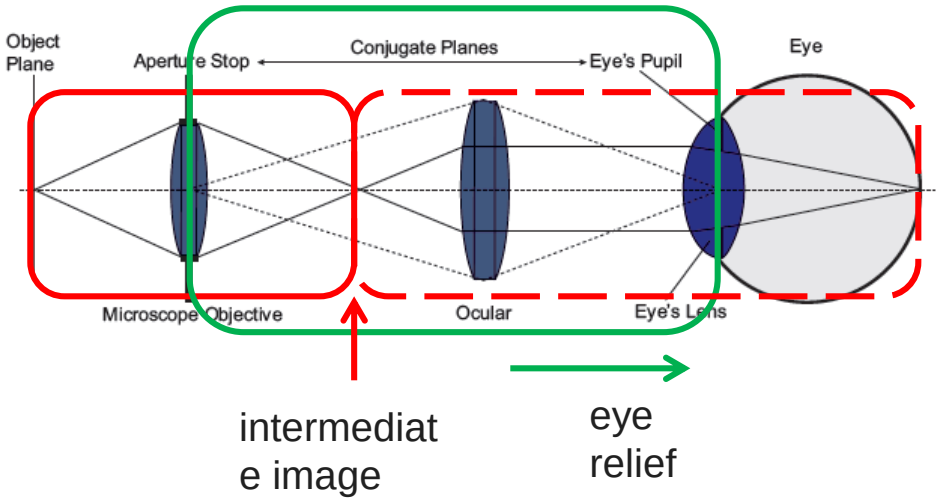
Two sets of conjugate planes

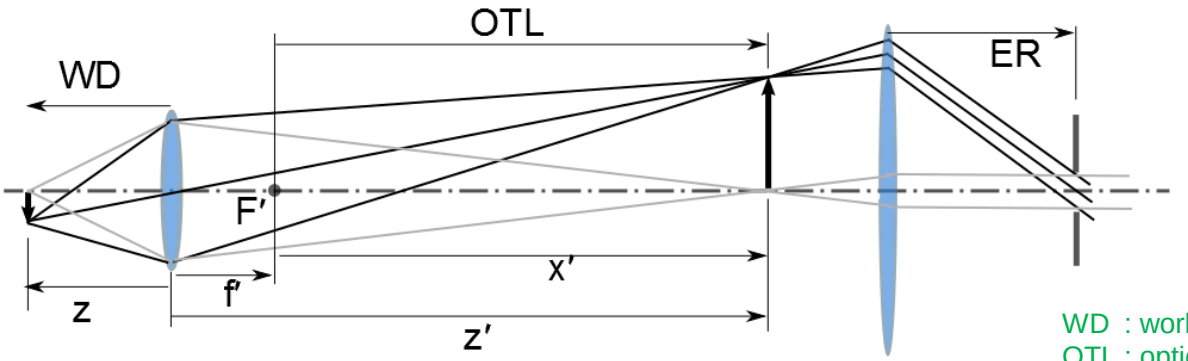
- image conjugates
  - object
  - intermediate image
  - eye image
- pupil conjugates
  - objective internal stop
  - eye pupil



Tkaczyk , Field Guide to Microscopy

Visual magnification m_v

Optical tube length is Newtonian image distance.



WD : working distance (objective)
OTL : optical tube length
ER : eye relief (eyepiece)

$$m_{obj} = -\frac{OTL}{f_{obj}}$$

$$m_{eyepiece} = \frac{250mm}{f_{eyepiece}}$$

by Newtonian relation

$$m_v = m_{obj} \cdot m_{eyepiece}$$

$$m_{obj} = \frac{h'}{h} = \frac{-f}{z} = \frac{-x'}{f_{obj}}$$

$$m_{obj} = \frac{h'}{h} = \frac{z'}{z}$$ by Gaussian relation

Microscope resolution

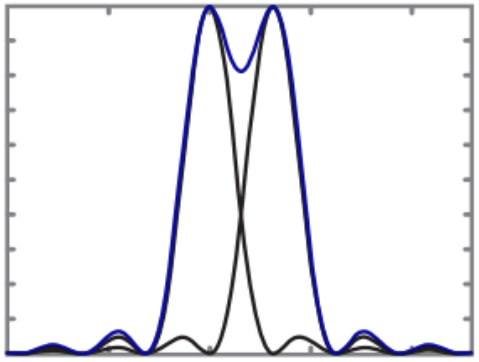
Resolution limit 1

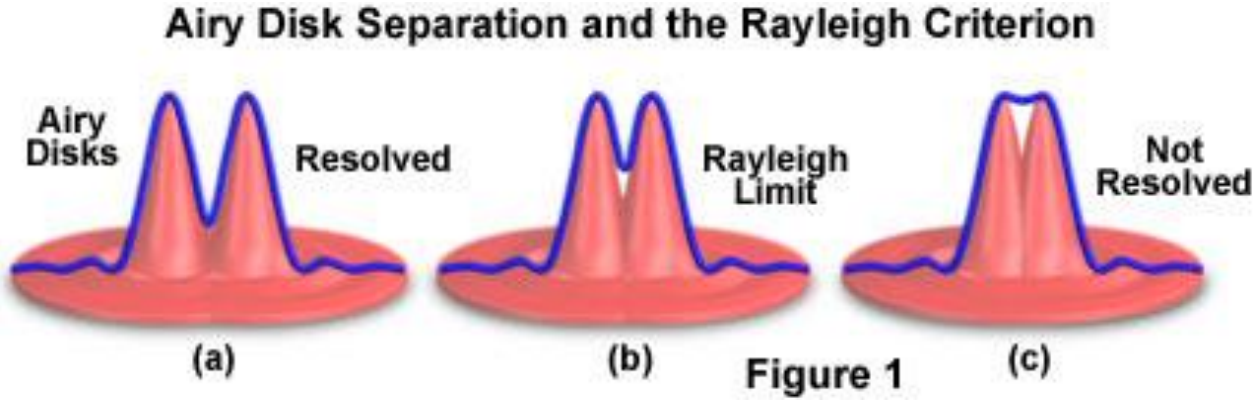
- Rayleigh criterion

  overlapping Airy disks

  – First minimum of one at the maximum of the ot

  – In





http://www.olympusmicro.com/primer/digitalimaging/deconvolution/deconresolution.html

Resolution limit 2

Rayleigh & Sparrow criteria

Overlap of Airy disks to differ

Rayleigh is most commonly

Sparrow has no dip

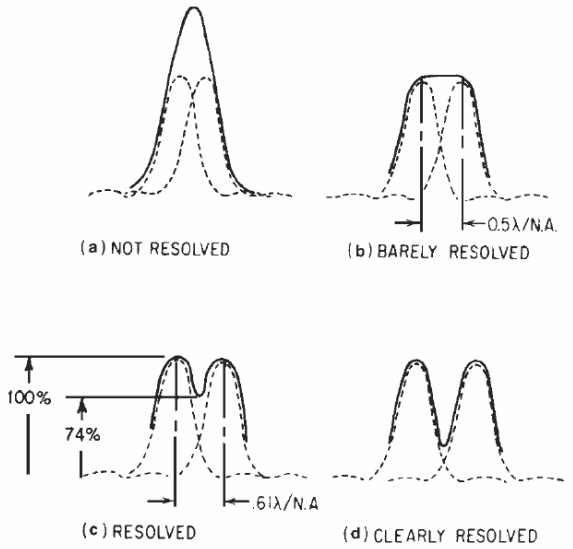


Figure 6.17 The dashed lines represent the diffraction patterns of two point images at various separations. The solid line indicates the combined diffraction pattern. Case (b) is the Sparrow criterion for resolution. Case (c) is the Rayleigh criterion.

Smith, Modern Optical Engineering

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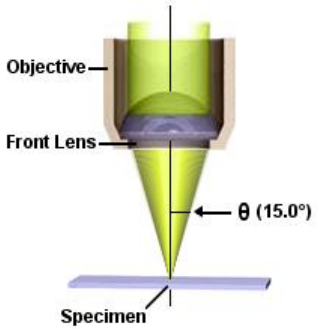
Resolution limit

- overlapping Airy disks
  - Rayleigh criterion

$$0.61\frac{\lambda}{NA}$$

where $NA = n\ \sin\theta$



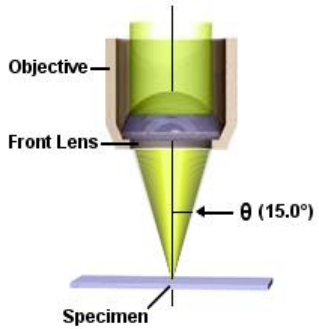
Kidger, Intermediate Lens Design p. 133

http://www.microscopyu.com/tutorials/java/objectives/nuaperture/index.html

- Higher resolution requires working at higher NA or ~~lower wavelength~~
  - angle θ is limited
- Raise index in object space
  - liquid immersion: oil (cedar* ; n ~ 1.515, V ~41.5), water (n ~ 1.333)
  - solid immersion (Solid Immersion Lens, SIL, GaP n ~3)

*Smith, Modern Optical Engineering

Resolution limit 3



http://www.microscopyu.com/tutorials/java/objectives/nuaperture/index.html

Overlapping Airy disks

- Rayleigh criterion
  - $0.61\,\frac{\lambda}{NA}$
  - where $NA = n\ \sin\theta$

Higher resolution requires working at higher NA or ~~lower wavelength~~

- angle θ is limited

Raise index in object space

- liquid immersion: oil (cedar* ; n ~ 1.515, V ~41.5), water (n ~ 1.333)
- solid immersion (Solid Immersion Lens, SIL, GaP n >3)

Factors in resolution

Animations from web sites

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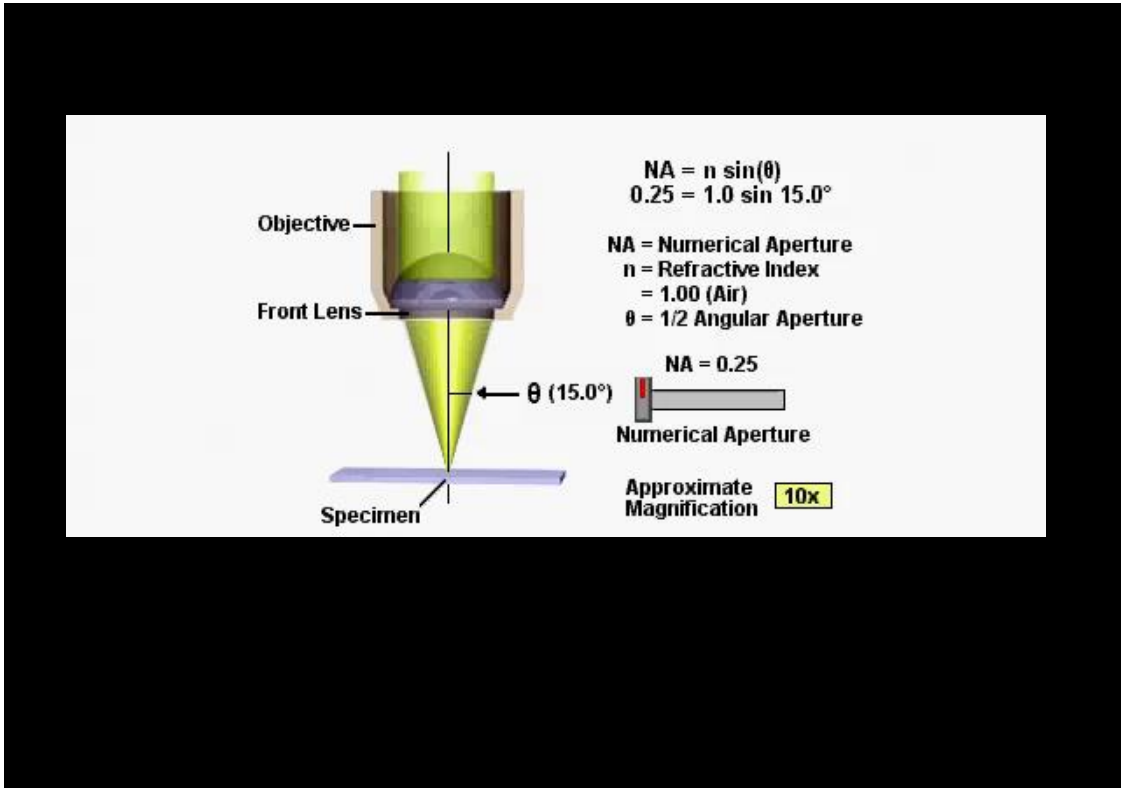
Animation of microscope objective numerical aperture (Nikon)



http://www.microscopyu.com/tutorials/java/objectives/nuaperture/index.html

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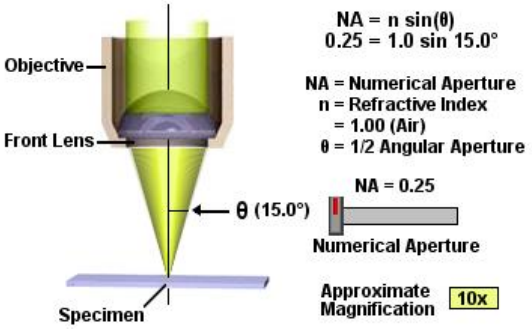
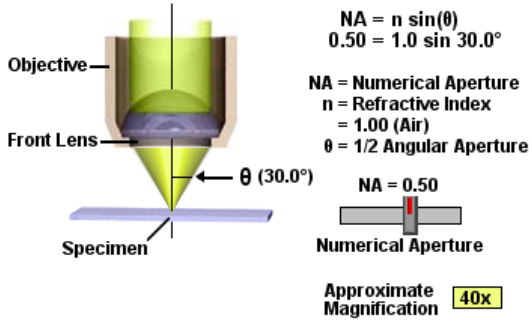
Animation of microscope objective numerical aperture (Nikon)

- a few captures at various NA for non-video use

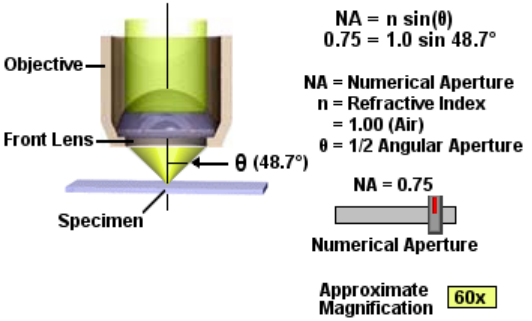
NA 0.25

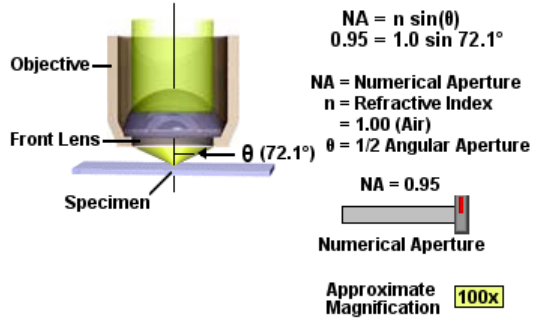




NA 0.50

NA 0.75





NA 0.95

http://www.microscopyu.com/tutorials/java/objectives/nuaperture/index.html

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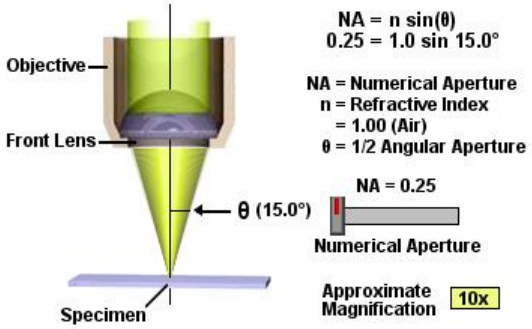
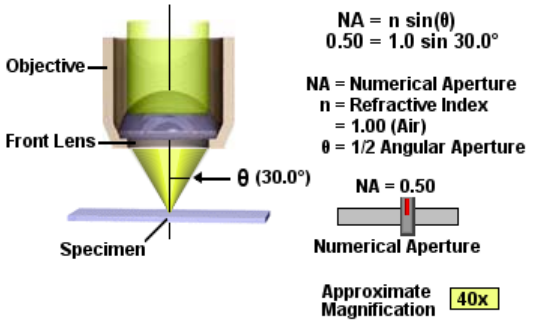
Microscope objective numerical aperture (Nikon)

Comparing several NA values if video not availab

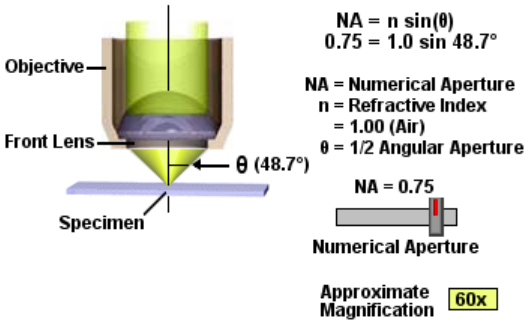
NA 0.25

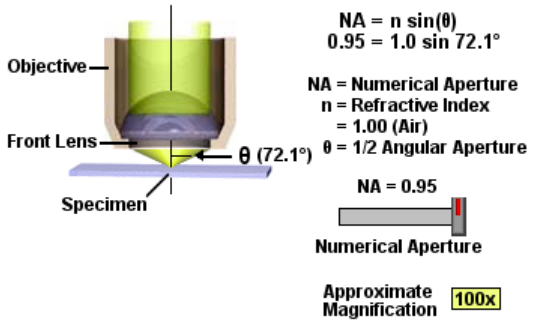




NA 0.50

NA 0.75





NA 0.95

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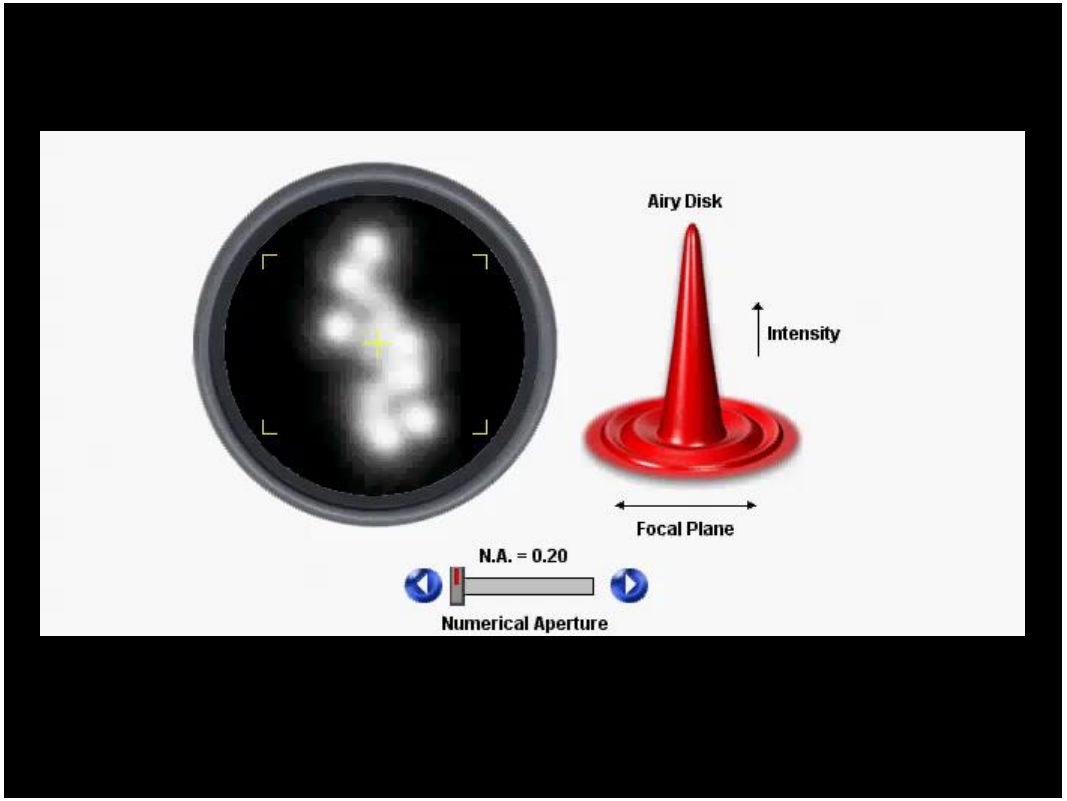
Resolution of a cluster of points (Olympus)



http://www.olympusmicro.com/primer/java/imageformation/airyna/index.html

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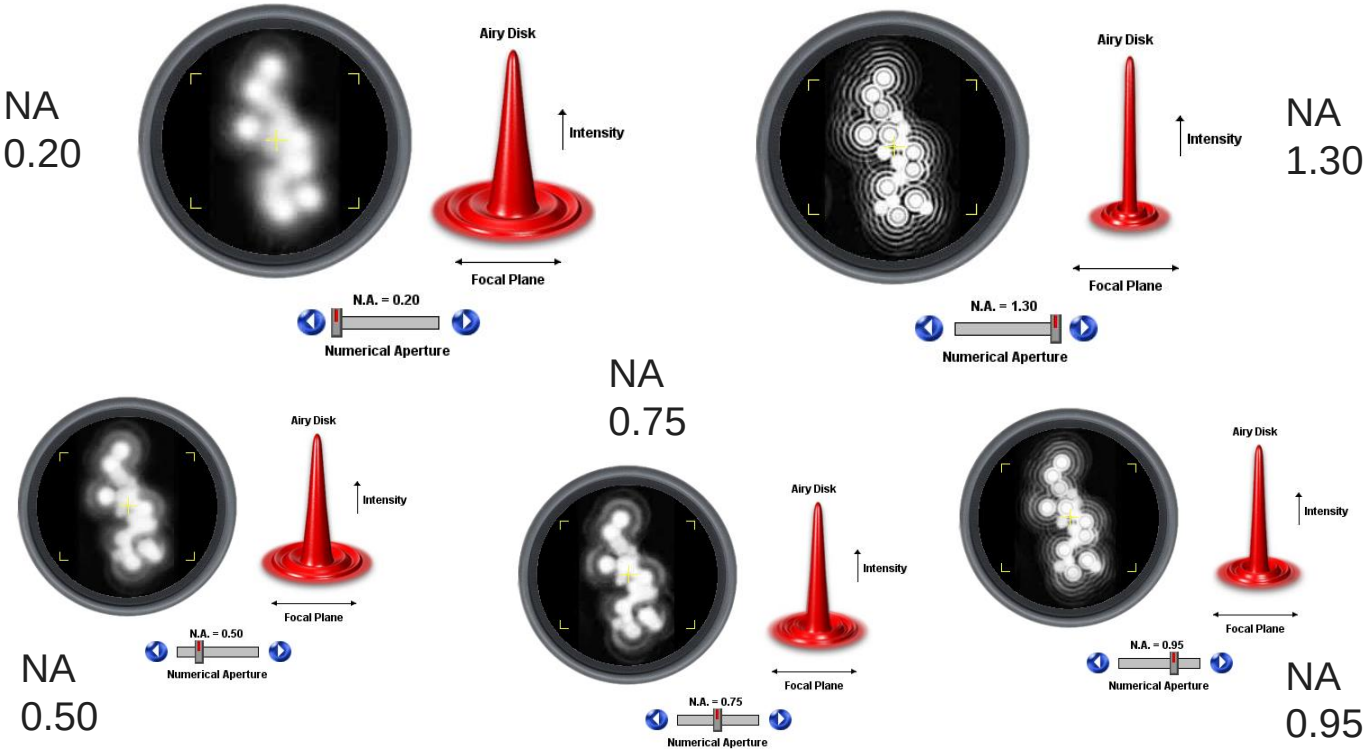
Resolution of a cluster of points (Olympus)

- A few samples:



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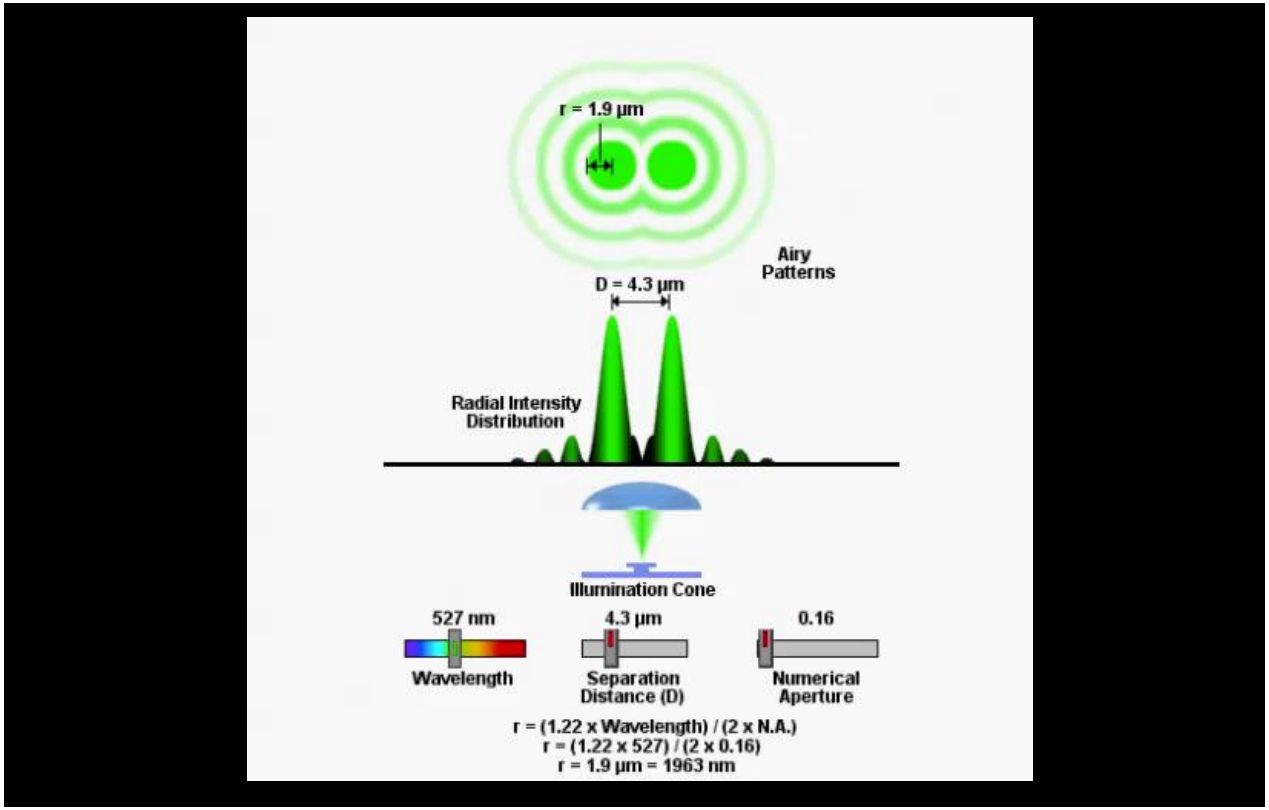
Animation of microscope objective resolution (Olympus)



http://www.olympusmicro.com/primer/java/imageformation/rayleighdisks/index.html

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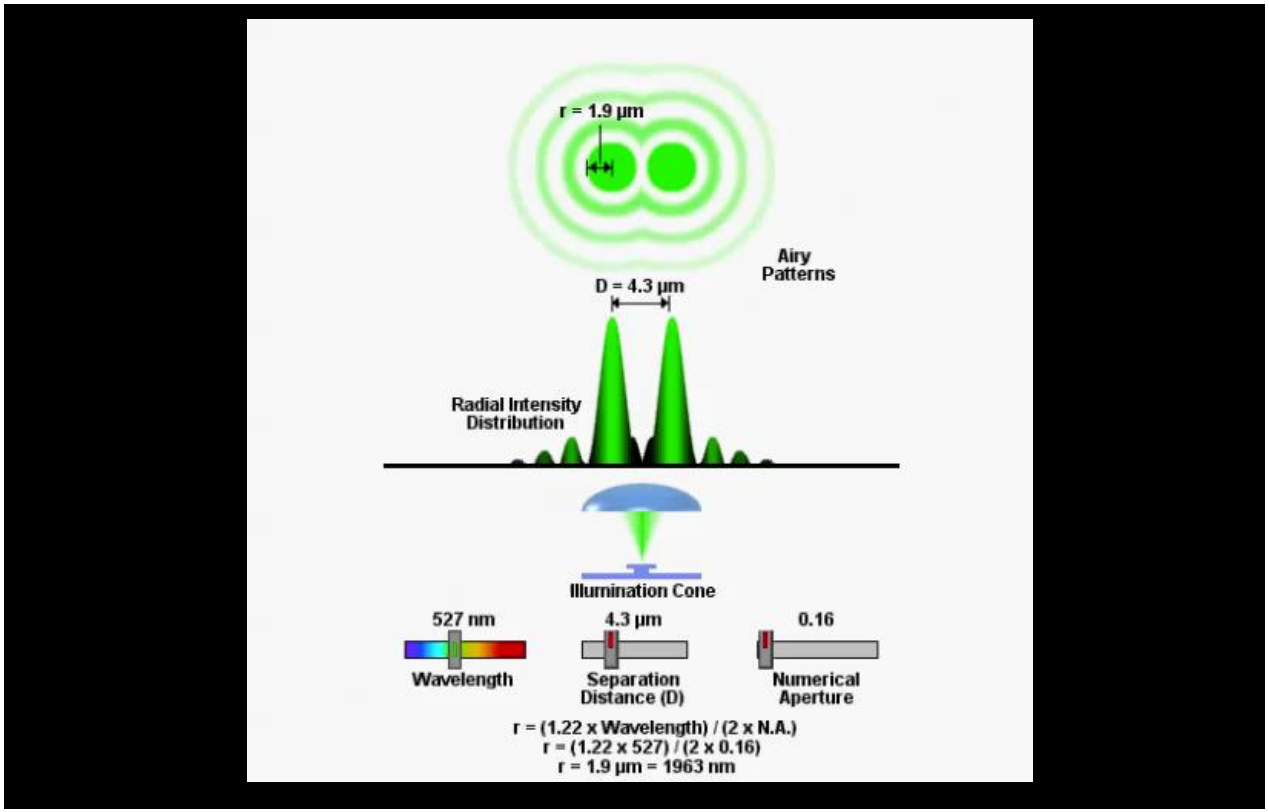
Microscope objective resolution (Olympus)



http://www.olympusmicro.com/primer/java/imageformation/rayleighdisks/index.html

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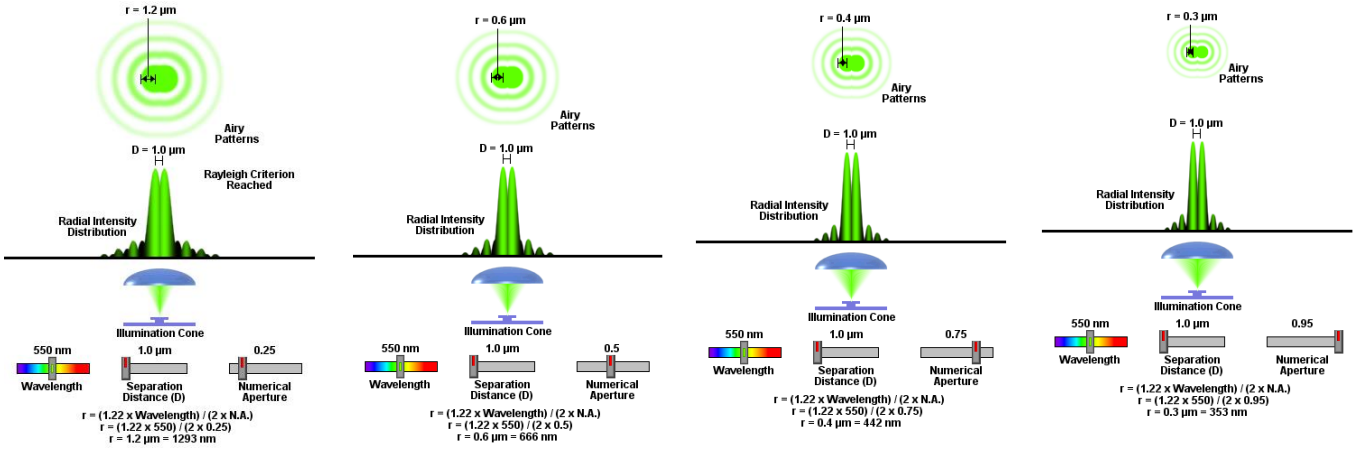
Microscope objective resolution (Olympus)

- Varying only NA



NA 0.25 NA 0.50 NA 0.75 NA 0.95

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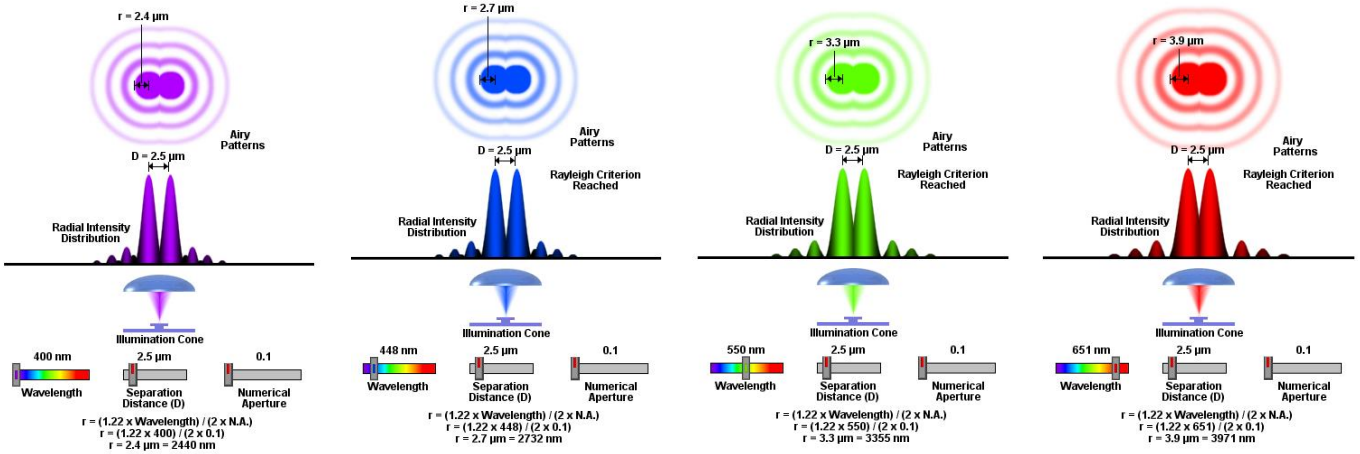
Microscope objective resolution (Olympus)

- Varying only wavelength



400 nm 448 nm 550 nm 651 nm

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Microscope objectives

Design forms

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In order of increasing NA

Aplanatic, concentric surfaces

- Amici-type

Immersion type

- Oil
- Water
- Solid

- CaF_2
  - Control secondary color
- Fluorite elements (shaded)
  - Reduce dispersion

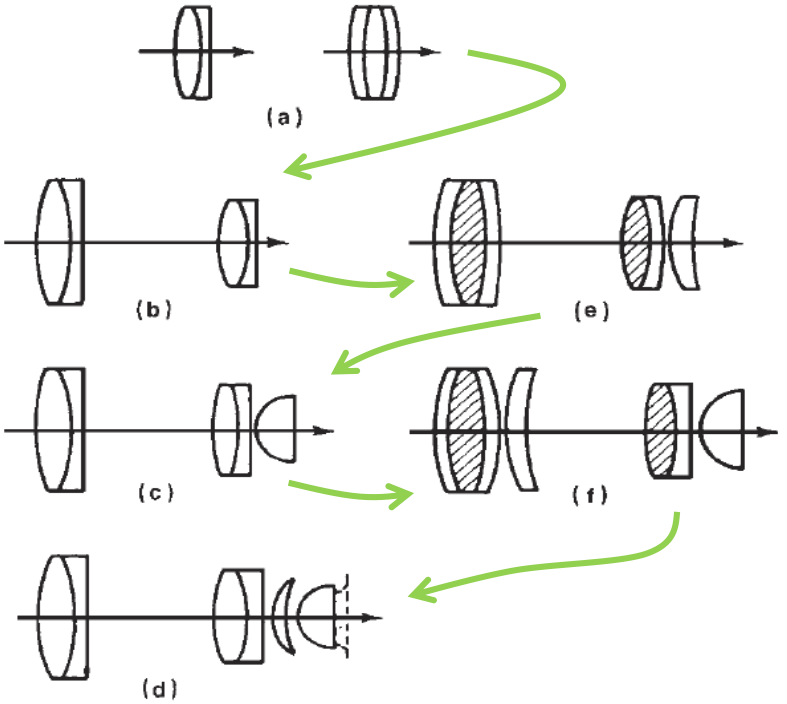
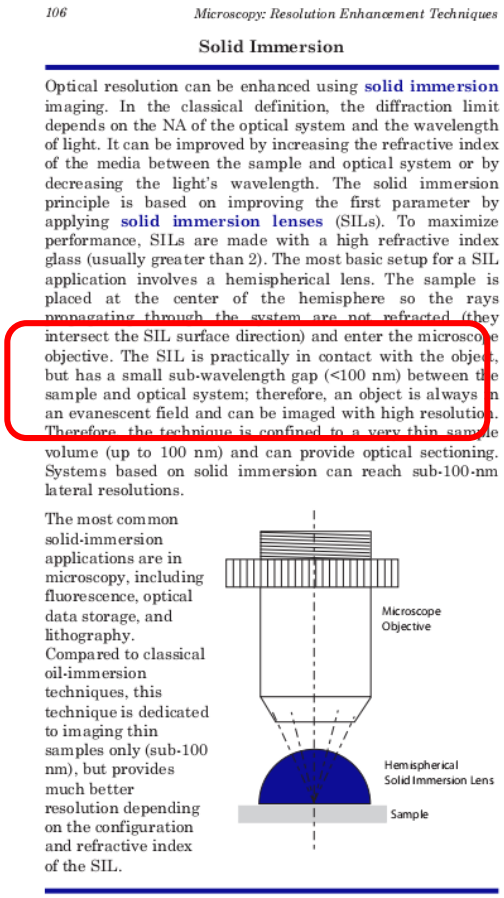


Figure 13.6 Microscope objectives. (a) Low-power achromatic doublet or triplet. (b) 10 × NA 0.25. (c) Amici objective 20 × NA 0.5 to 40 × NA 0.8. (d) Immersion objective. (e) Apochromatic 10 × NA 0.3. Shading indicates fluorite (CaF_2). (f) Apochromatic 50 × NA 0.95.

Smith, Modern Optical Engineering

Solid immersion

- High NA Amici-like
- Immersion without the liquid
- Evanescent coupling between a hemispherical immersion optic and the object
- For thin, flat object



106 *Microscopy: Resolution Enhancement Techniques*

Solid Immersion

Optical resolution can be enhanced using **solid immersion** imaging. In the classical definition, the diffraction limit depends on the NA of the optical system and the wavelength of light. It can be improved by increasing the refractive index of the media between the sample and optical system or by decreasing the light's wavelength. The solid immersion principle is based on improving the first parameter by applying **solid immersion lenses** (SILs). To maximize performance, SILs are made with a high refractive index glass (usually greater than 2). The most basic setup for a SIL application involves a hemispherical lens. The sample is placed at the center of the hemisphere so the rays propagating through the system are not refracted (they intersect the SIL surface direction) and enter the microscope objective. The SIL is practically in contact with the object, but has a small sub-wavelength gap (<100 nm) between the sample and optical system; therefore, an object is always in an evanescent field and can be imaged with high resolution. Therefore, the technique is confined to a very thin sample volume (up to 100 nm) and can provide optical sectioning. Systems based on solid immersion can reach sub-100-nm lateral resolutions.

The most common solid-immersion applications are in microscopy, including fluorescence, optical data storage, and lithography. Compared to classical oil-immersion techniques, this technique is dedicated to imaging thin samples only (sub-100 nm), but provides much better resolution depending on the configuration and refractive index of the SIL.

Tkaczyk , Field Guide to Microscopy

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Solid immersion

- High NA Amici-like
  - Aplanatic & concentric
- Central homogeneous cone is concentric on bottom planar surface, resulting in plane-wave propagation
- Ring (cored cone) couples evanescently

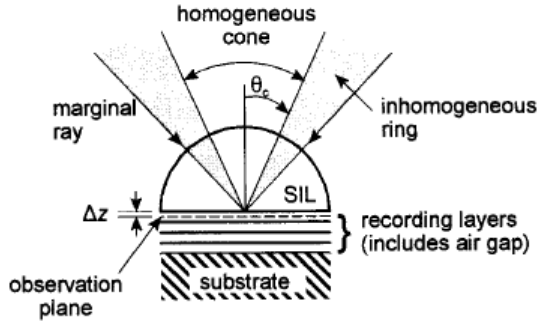

Fig. 4. Light incident on the recording layers can be divided into two parts: the homogeneous cone and the inhomogeneous ring. In the ring, light couples evanescently into the recording layers through the gap. In the cone, light propagates directly across the gap as a homogeneous plane wave.

Roles of propagating and evanescent waves in solid immersion lens systems
By Tom D. Milster, Joshua S. Jo, and Kusato Hirota
APPLIED OPTICS y Vol. 38, No. 23 y 10 August 1999

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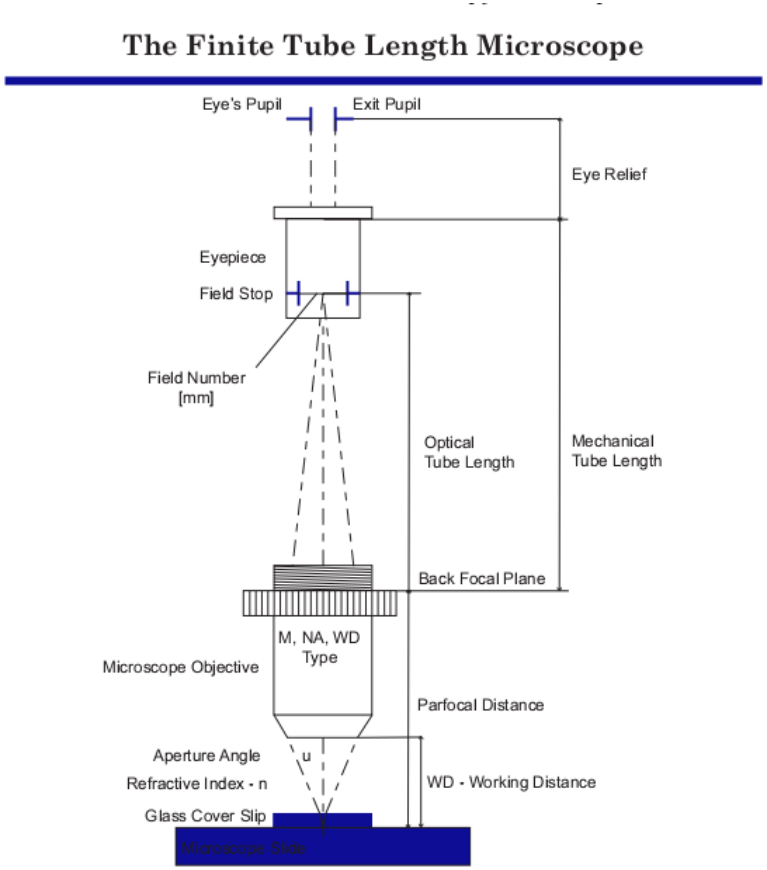
Basic microscope layout

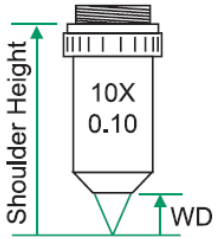
- Important issues
  - cover slip
  - working distance
  - optical tube length
  - mechanical tube length
  - pupil matching: microscope exit pupil to eye pupil



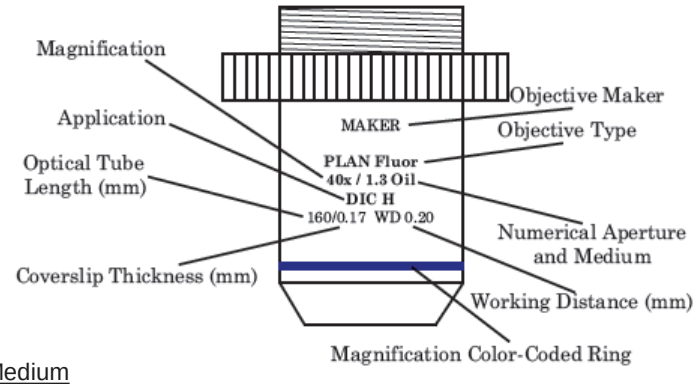
Tkaczyk , Field Guide to Microscopy

- In design, we will mostly talk about optical tube length
- Do not confuse mechanical tube length with optical tube length
- Objectives are marked for identification of key specifications

- The **working distance** WD is the distance from the object to the first element of the objective; can be less than 1 mm for high-power objectives.
- The **mechanical tube length** is separation between the shoulder of the threaded mount of the objective and the end of the tube into which the eyepiece is inserted. Objectives and eyepieces must be used at their design conjugates and are not necessarily interchangeable between manufacturers.



Greivenkamp, Field Guide to Geometrical Optics



Medium
Oil
W: water
Gly: glycerin

Tkaczyk , Field Guide to Microscopy

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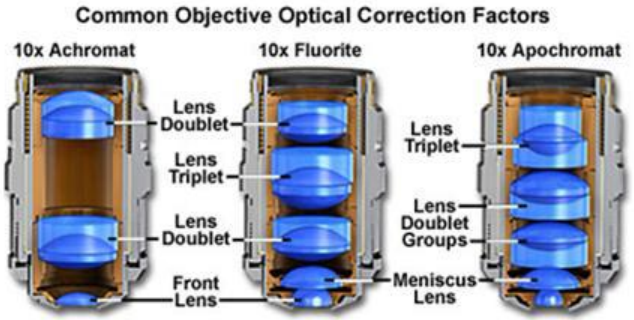
Correction types

Plan: field corrected

Apo: color corrected

Plan Apo: both



http://micro.magnet.fsu.edu/primer/anatomy/objectives.html

http://www.microscopyu.com/articles/optics/objectivespecs.html/

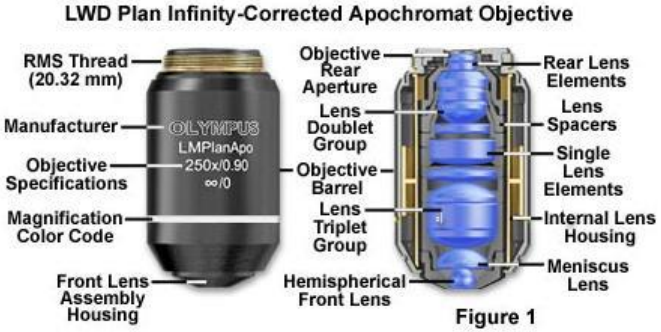


Figure 1

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Continuing the tour of objectives

The hierarchy of commercial objectives begins with simple **achromats.** Next, **Fluorites** or **semi-apochromats** have similar color correction to achromats, but they correct for spherical aberration for two or three colors. The name "fluorites" was assigned to this type of objective due to the natural mineral originally used to build this type of objective. 'Fluor' (CaF2, n =1.43, V = 95!! very low dispersion). There are also **plan-achromats**, achromats with field correction. The most advanced microscope objectives are **apochromats**, which are usually chromatically corrected for three colors, with spherical aberration correction for at least two colors. They are similar in construction to fluorites but with different thicknesses and surface figures. With the correction of field curvature, they are called **plan-apochromats.**

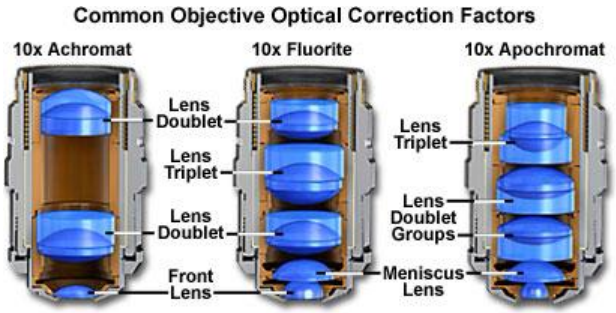

Figure 2

Objective Correction for Optical Aberration

Objective Type	Spherical Aberration	Chromatic Aberration	Field Curvature
Achromat	1 Color	2 Colors	No
Plan Achromat	1 Color	2 Colors	Yes
Fluorite	2-3 Colors	2-3 Colors	No
Plan Fluorite	3-4 Colors	2-4 Colors	Yes
Plan Apochromat	3-4 Colors	4-5 Colors	Yes

Table 1

http://micro.magnet.fsu.edu/primer/anatomy/objectives.html

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Microscope objectives

The Petzval lens & classic design

Designing microscope objectives

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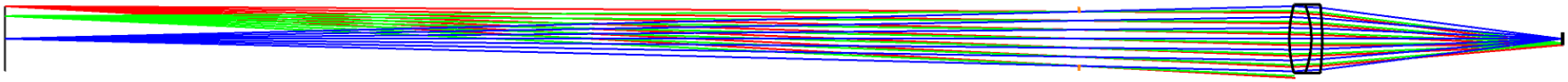
About designing microscopes

- Disclaimer:
  - This is not legal advise
- A vast array of design examples are available in the literature and from patents
- It is highly recommended that some of these be examined before starting on more complex designs
- We will start from the simplest

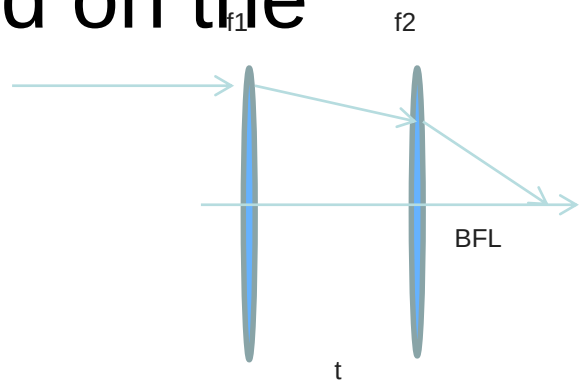
An achromat

- An “Off-the-shelf” achromat can serve as a simple microscope:
  - Use at finite conjugates



The Petzval objective

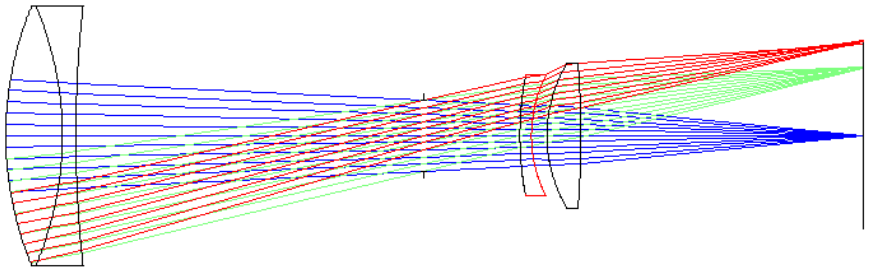
A more useful design is based on the Petzval objective



For system focal length f_P

- Front group has focal length $f_1 = f_P * 2$
- Rear group has focal length $f_2 = f_P * 1$
- spacing between groups $t = f_P * 1$
- Back focal length $BFL = f_P / 2$

front group: achromat



rear group: achromatized pair using Celor equations

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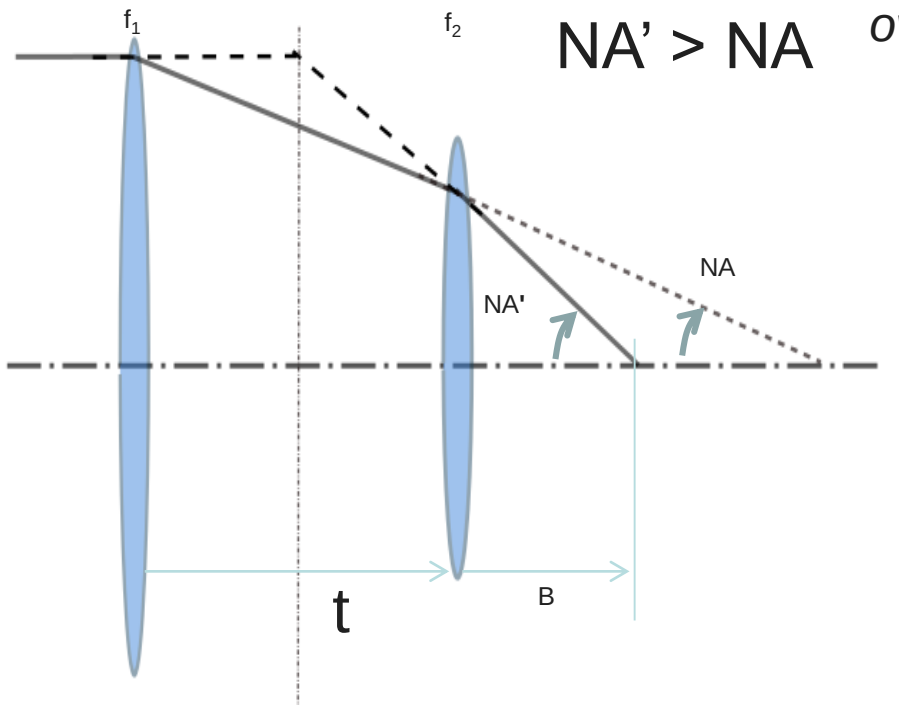
The Petzval objective

- Start with a f_2 Petzval lens of focal length f_P



NA' > NA

overall focal length f_P

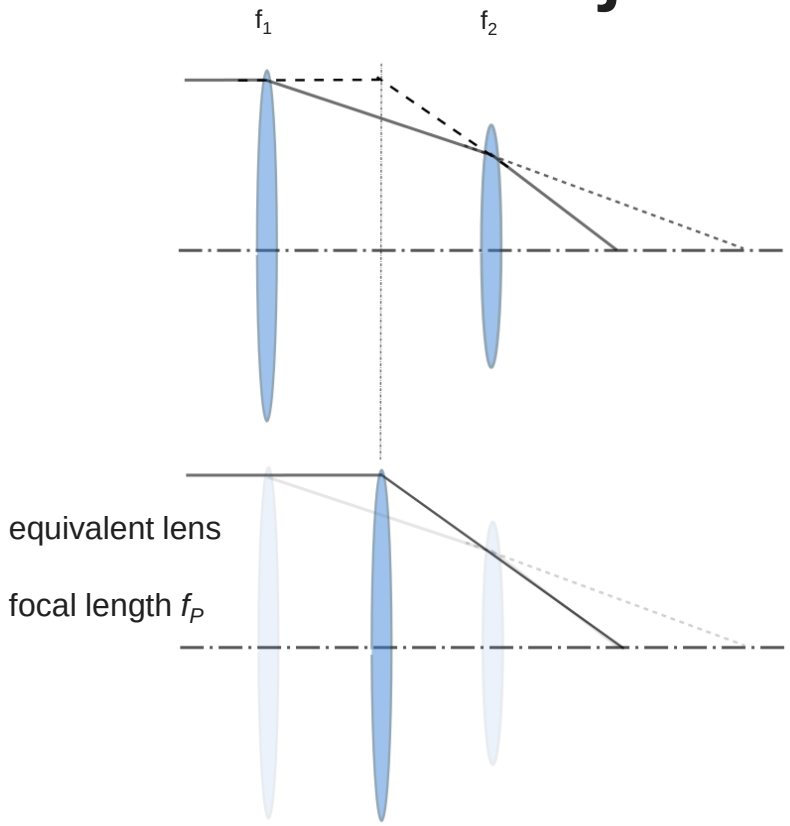
$$f_1 = 2 \cdot f_P$$

$$f_2 = f_P$$

$$t = f_P$$

$$B = f_P / 2$$

Starting point for designing objective



overall focal length f_P

- Two positive lenses
- increased NA
- weaker surfaces share ray bending

$$f_1 = 2 \cdot f_P$$

$$f_2 = f_P$$

$$t = f_P$$

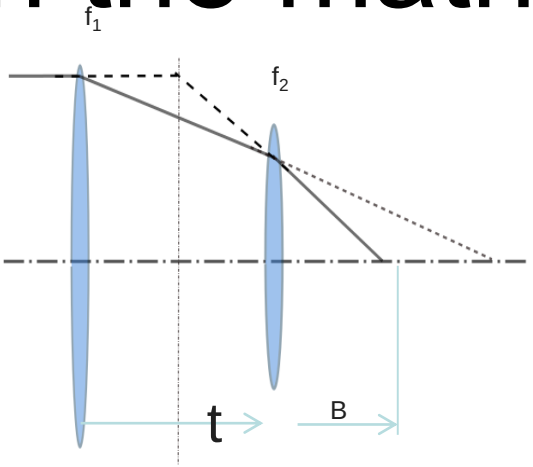
$$B = f_P / 2$$

The Lister objective

Again with the math….

$$\phi_1 = 1/f_1 = 1/2f_P = \tfrac{1}{2}\phi$$

$$\phi_2 = 1/f_2 = 1/f_P = \phi$$



$$\phi = \phi_1 + \phi_2 - \phi_1\phi_2\tau$$
$$= \phi_1 + \phi_2 - \phi_1\phi_2 t$$
$$= \tfrac{1}{2}\phi + \phi - \tfrac{1}{2}\phi^2 t$$
$$= \tfrac{3}{2}\phi - \tfrac{1}{2}\phi^2 t$$
$$2\phi = 3\phi - \phi^2 t$$
$$\phi = \phi^2 t$$

$$\Rightarrow \quad t = 1/\phi = f_P$$

$$f_1 = 2 \cdot f_P$$

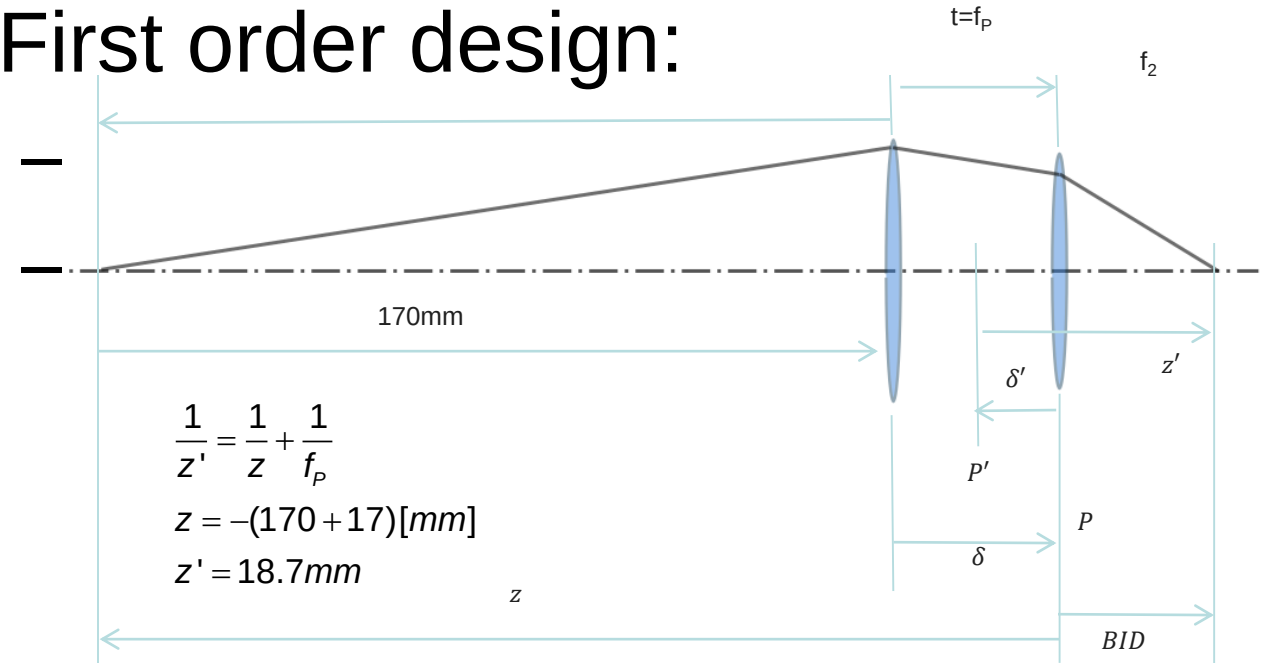
$$f_2 = f_P$$

$$t = f_P$$

$$B = f_P/2$$

Petzval into Lister

- First order design:



$$\frac{1}{z'} = \frac{1}{z} + \frac{1}{f_P}$$

$$z = -(170 + 17)[mm]$$

$$z' = 18.7mm$$

$$\delta = \frac{\phi_2}{\phi} t = \frac{f_P}{f_2} f_P = \frac{f_P}{f_P} f_P = f_P$$

$$\delta' = -\frac{\phi_1}{\phi} t = -\frac{f_P}{f_1} f_P = -\frac{f_P}{2f_P} f_P = -\frac{f_P}{2}$$

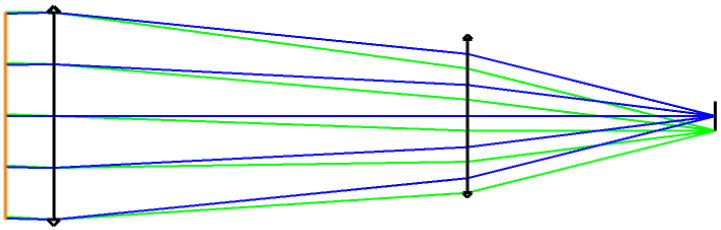
$$z' = 18.7mm\ ,\quad \delta' = -17/2 = -8.5mm$$

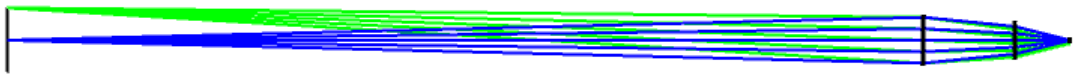
$$BID = z' + \delta' = 10.2mm$$

Lister 10X microscope objective

- Start with perfect optics

$$FL(objective) = 17mm$$
$$FL_1 = 2 * FL = 34mm$$
$$FL_2 = FL \quad = 17mm$$
$$t = FL \quad = 17mm$$





10X, 0.25NA

Now add real optics

- Achromatic doublet for front lens:
  - 34mm FL
    - Use N-BK7 and N-SF6.
    - N-BK7: n = 1.51680, V = 64.17
    - N-SF6: n = 1.80518, V = 25.36

$$\varphi_1 = \frac{64.17}{64.17 - 25.36} \cdot \left[\frac{1}{34}\right] = 0.04863 = 2(n-1)/R1$$

$$\varphi_2 = \frac{25.36}{25.36 - 64.17} \cdot [1/34] = -0.01922$$

Let R1=-R2=-R3= 21.25mm (1st element symmetric)

R4 = -43.14mm

Finish adding lenses

- Achromatic doublet for the back:
  - 17mm FL
    - Use N-BK7 and N-SF6.
    - N-BK7: n = 1.51680, V = 64.17
    - N-SF6: n = 1.80518, V = 25.36

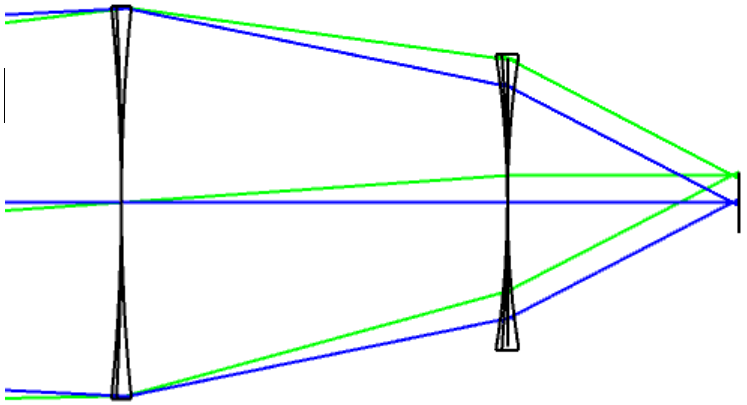
$$\varphi_1 = \frac{64.17}{64.17 - 25.36} \cdot [1/17] = 0.09726$$

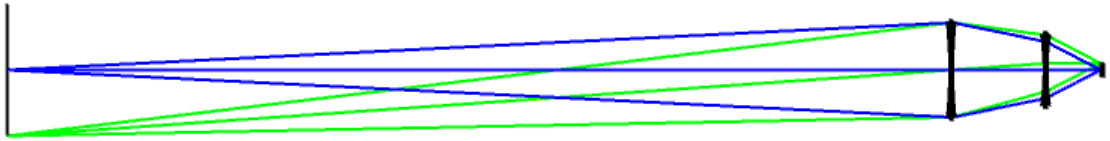
$$\varphi_2 = \frac{25.36}{25.36 - 64.17} \cdot [1/17] = -0.03844$$

  - Let R1=-R2=-R3= 10.63mm (1st element symmetric)
    - R4 = -21.57mm

Now put it into the design program

- Start with “thin” lenses
  - Lens thickness not useful
  - PMAG: -0.10 (10X)
  - u’: 0.25





10X, 0.25NA

$$FL(objective) = 17mm$$

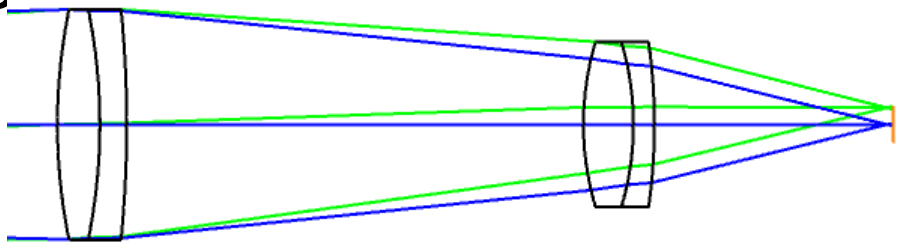
$$FL_1 = 2 * FL = 34mm$$

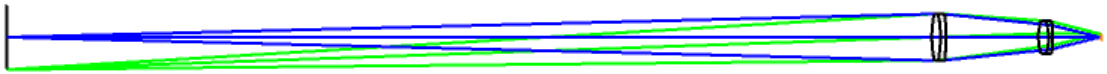
$$FL_2 = FL \quad = 17mm$$

$$t = FL \quad = 17mm$$

Optimize

- Add lens thickness
  - EFFL: 17
  - EFLY 1 3: 34
  - EFLY 4 6: 17





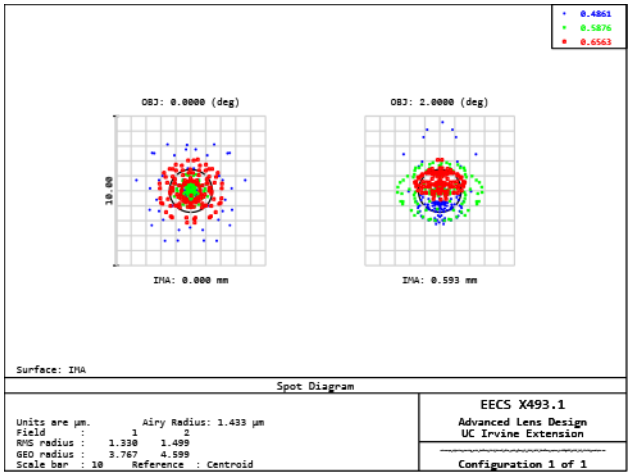
10X, 0.25NA

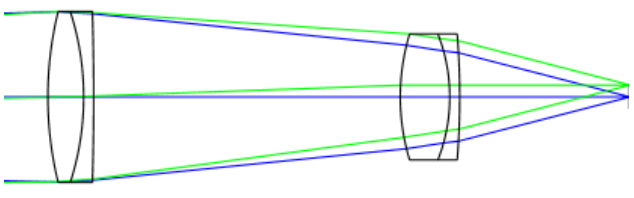
Lister 10X microscope objective

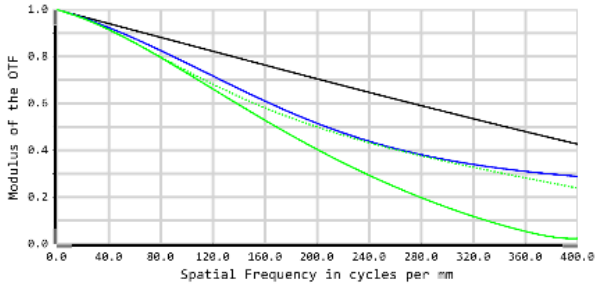
(Petzval objective) typical optimized results

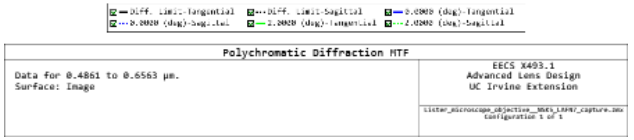
10X, 0.25NA

10X (PMAG= -10, u' = 0.25)









$$FL(objective) = 17mm$$

$$FL_1 = 2 * FL = 34mm$$

$$FL_2 = FL \quad = 17mm$$

$$t = FL \quad = 17mm$$

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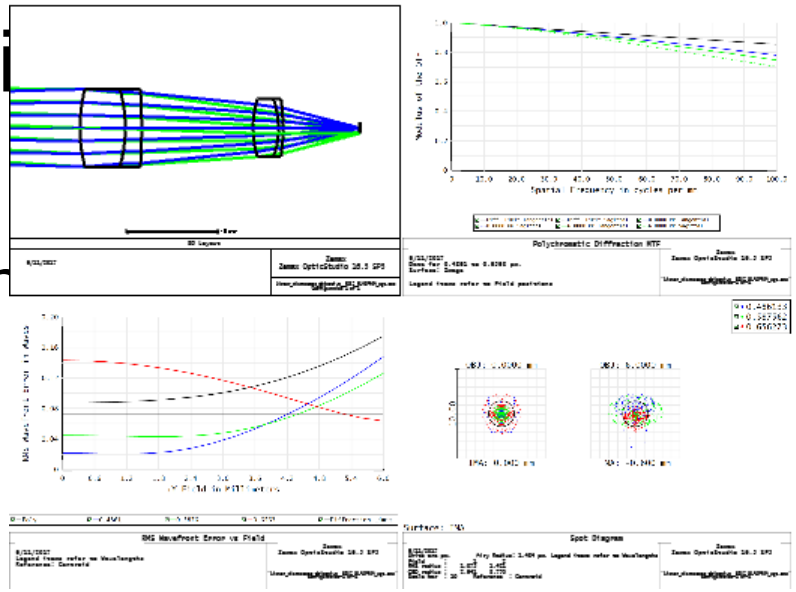
Final design

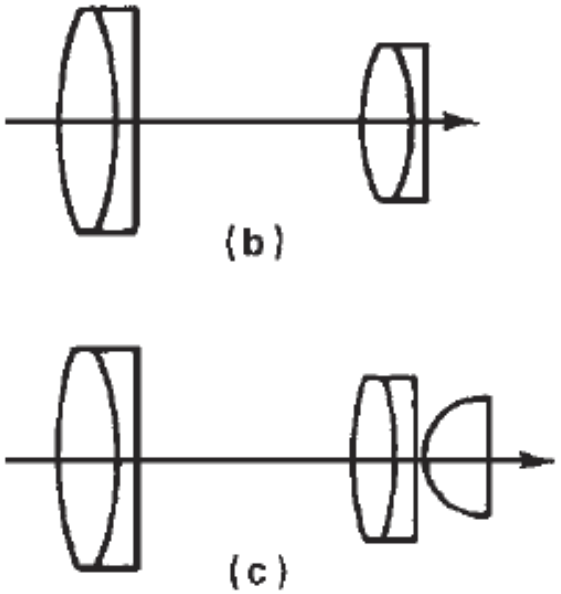
- Constrain glass thickness
- Allow glass selecti
  - Restrict choices:
  - Preferred, inexper



Amici modification

Comparing “conventional” objective to Amici

- Comparable form, ignoring the Amici hemisphere
  - 10X, 0.25 NA conventional
  - 20X NA 0.5 - 40X NA 0.8 Am
- Amici
  - Aplanatic surface
  - Greater NA, MP
  - Small working distance



Smith, Modern Optical Engineering

Modified Lister objective

- Element added:
  - increase NA (40X , NA 0.65)

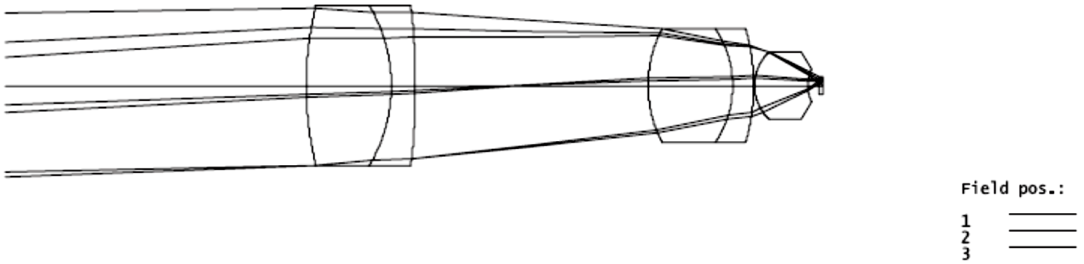
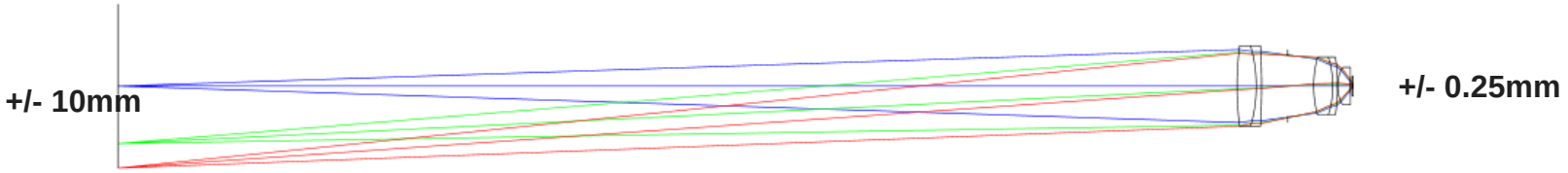


Figure 7.1 Classical Lister objective with aplanatic element.

Kidger, Intermediate Lens Design

Modified Lister: Zemax

- Zemax layout
  - Stretched in Y to show some detail
  - Some/ slight vignetting seen

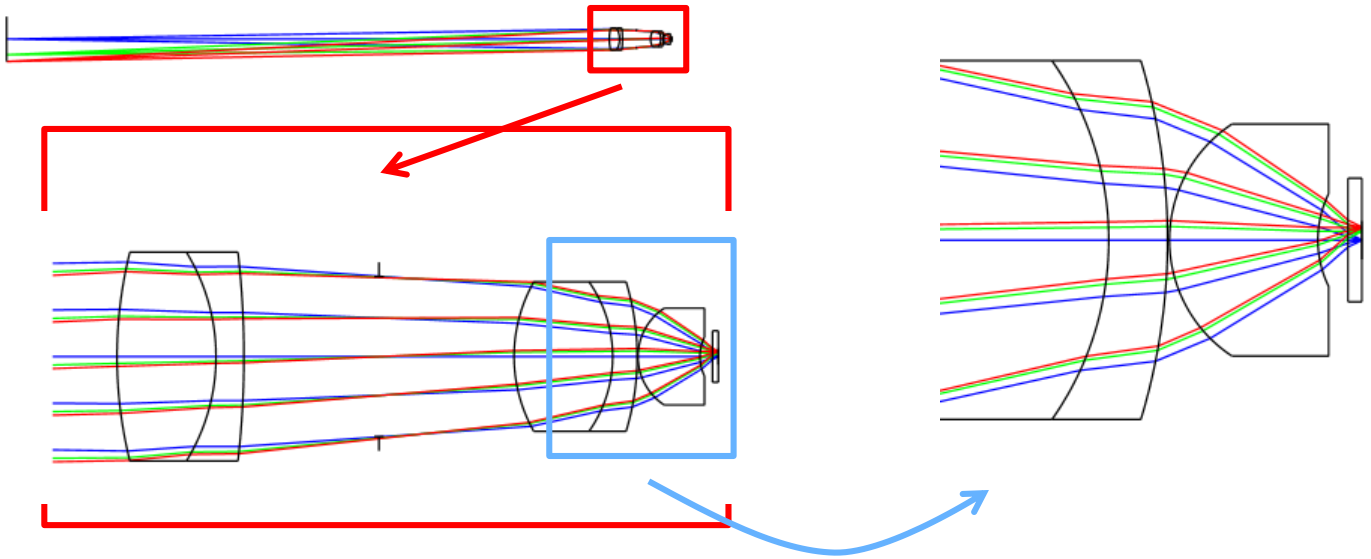


Object in Zemax (Intermediate image plane)

Image in Zemax (Actually the Object)

Lister with Amici modification

- Isolate the Amici optic:
  - First surface: “Almost” aplanatic
  - Second surface: Concave Petzval corrector



Complex objective designs

- Examples of correction by section

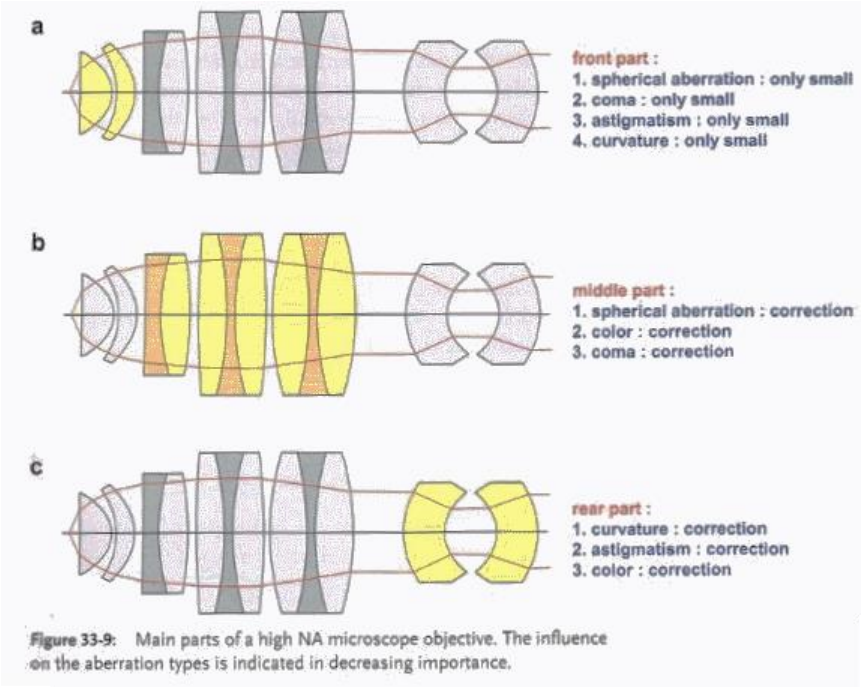


Figure 33-9: Main parts of a high NA microscope objective. The influence on the aberration types is indicated in decreasing importance.

Gross, Handbook of Optical System, V.3