Optical System Design

Last time:

Surveyed examples of optical systems

Today, discuss system design

Lens design = course of its own
(not taught by me!)

Try to give some general guidelines
Practical advice from my experience

Outline:

- Resolution limits
- Numerical aperture and f-number
- Aberrations
- Ray tracing software
- Lens design
- Laboratory systems

This will finish unit on ray optics

Next time:

Superposition and interference of waves

Resolution Limits

Basic question: given point-like object,
how sharp will image be?

Relevant to:

Imaging resolution -
Can two nearby stars be distinguished?

Focusing power -
How high an irradiance can be generated?

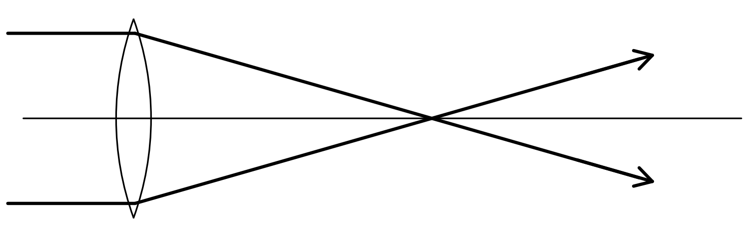
Question: Before talking about imaging, is it really possible to have a point object?

First, can we use ray optics?

Previous said ray optics valid for $d < \frac{a^2}{\lambda}$

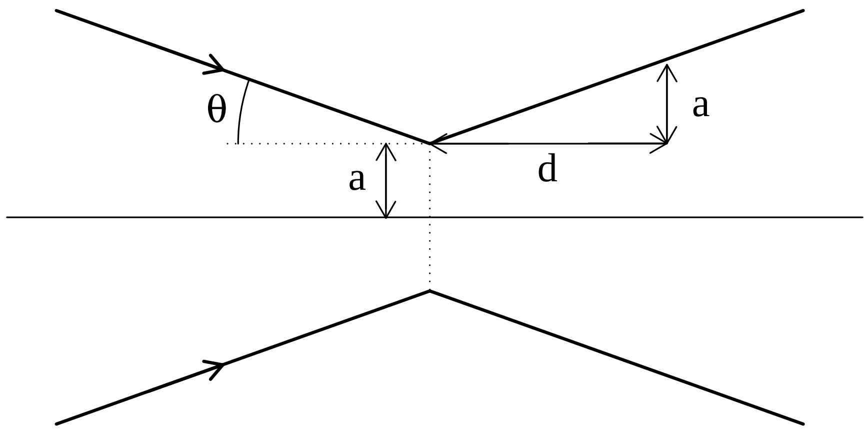
$a =$ transverse size
$d =$ propagation distance

For focusing system, a is changing:



Solve properly later. For now, use handwaving...

Zoom in on focus point:



Focal spot radius a
Incoming ray angle θ
Propagation distance d

Claim relevant propagation distance is

$$d = \frac{a}{\theta}$$

= enough distance for spot size to double

Want $d < \frac{a^2}{\lambda}$ so $a > \frac{\lambda}{\theta}$
For smaller a, ray optics not valid

In terms of lens, $\theta = \dfrac{D}{2f}$

D = lens diameter
f = lens focal length

Then need $a > 2\dfrac{\lambda f}{D}$

Actual result from wave optics:

$$\boxed{a >= 1.22\frac{\lambda f}{D}}$$

Write $a_{\text{min}} = a_{DL}$
= diffraction-limited spot size

So ray optics valid for image size $a > a_{DL}$

Within ray optics, get $a = a_R$
limited by lens imperfections = *aberrations*

Perfect lens makes $a_R = 0$: violates validity

No real lens is perfect
To get $a_R \approx a_{\text{DL}}$, need surface accuracy $\approx \lambda/4$

If $a_R < a_{\text{DL}}$, say system is
diffraction limited
= as good as possible

Spherical lenses:
aberrations increase with ray angle

Close to perfect for paraxial rays
(still limited by accuracy of sphere)

Characterize deviation from paraxial with:

- Numerical aperture
- f-number

Numerical aperture (NA) (Hecht 5.7.5)

Define NA = $\sin\theta_{max}$

θ_{max} = maximum acceptance angle
Set by entrance pupil

Low NA = more paraxial

NA used to describe:
- microscope objectives
- lamp condensers
  (collimates light from filament or arc)
- beam focusing optics
  (θ_{max} from exit pupil)

Define *f-number* = f/D (Hecht 5.3.3)

f = focal length

D = lens diameter

Unusual notation:

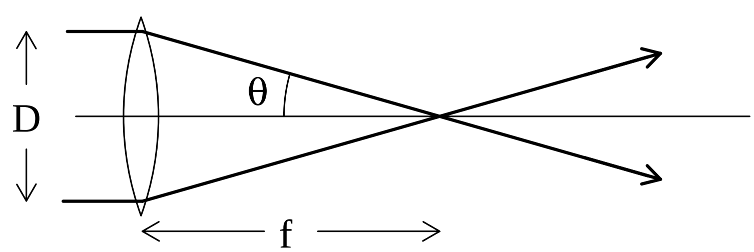
Write as: $f/\# = \dfrac{f}{D}$

If $f = 100$ mm and $D = 10$ mm, lens is $f/10$

Used for:

- simple lenses
- camera lenses
- telescopes

For paraxial rays, $f/\# = \dfrac{1}{2\theta} = \dfrac{1}{2\,\mathrm{NA}}$



So low NA = high f/# = paraxial system

Say lens is "slow"

High NA = low f/# = "fast" lens

Even slow lens nonparaxial for off-axis object

Usually limited by field stop

Generally, fast lens is good

Large D = collect more light

Short f = use less space

But aberrations grow as θ increases

Question: In bright light, your eye's pupil contracts. Do you think you have better visual resolution in sun light or moon light?

Trade off:

Note a_R decreases with $f/\#$

but $a_{DL} = 1.22\dfrac{\lambda f}{D} = 1.22\lambda \times (f/\#)$

increases with $f/\#$

Any lens system has optimum aperture stop

that gives best resolution

Larger AS still useful:

collect more light

sometimes resolution not important

When can you ignore aberrations?

- Working with narrow laser beams
  Typical beam diameter = few mm
  Typical f = 50 – 1000 mm
  Get large a_{DL} = 20 – 500 μm:
  aberrations not very important
- Non imaging detectors
  Just need image smaller than detector area
- Imaging smooth objects
  Resolution limits irrelevant if $a \ll$ feature size

Otherwise, aberrations important

Aberrations (Hecht 6.3)

Aberrations can be described analytically:
Third-order theory

Paraxial approximation: $\sin\theta \approx \theta$

Third-order theory: $\sin\theta \approx \theta - \dfrac{\theta^3}{6}$

Work out how additional terms affect a_R
Categorize effects

Third-order theory pretty messy

Also, still an approximation
  fails for high NA systems

Better to use computer to trace rays exactly
  Numerical ray tracing

But categorization still useful

Classification of aberrations:

- Spherical aberration
- Coma
- Astigmatism
- Field curvature
- Distortion

- Chromatic aberration

Hecht covers in some detail
More math: Klein and Furtak

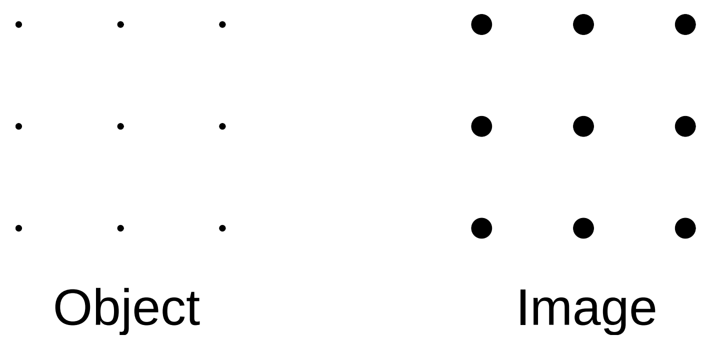
Spherical aberration

= basic error due to spherical surface

rays at edge of lens don't focus right

Blurs image uniformly

Also shifts image plane



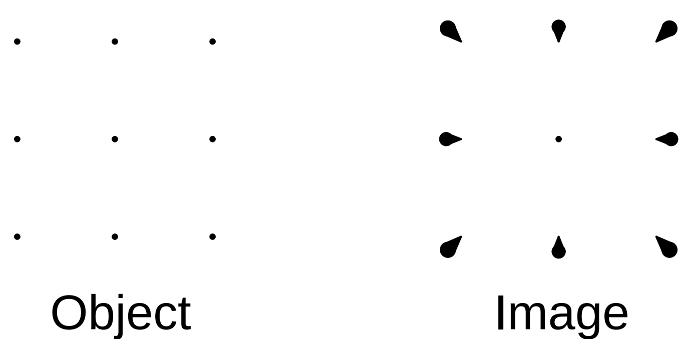
Often dominant error

19

Coma

= imaging error for off-axis points

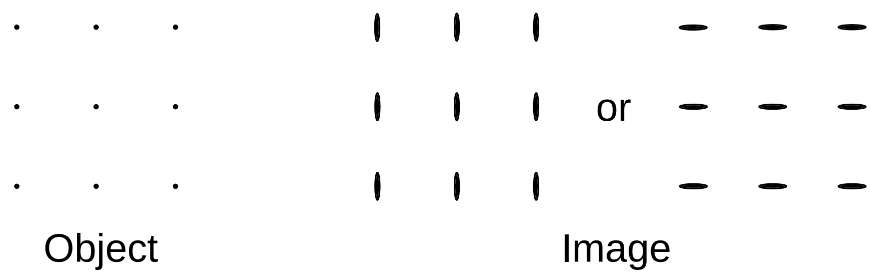
Limits useable field of view



Astigmatism
= asymmetry for horizontal and vertical rays

Rays focus in different planes

Caused by lens asymmetry or off-axis object



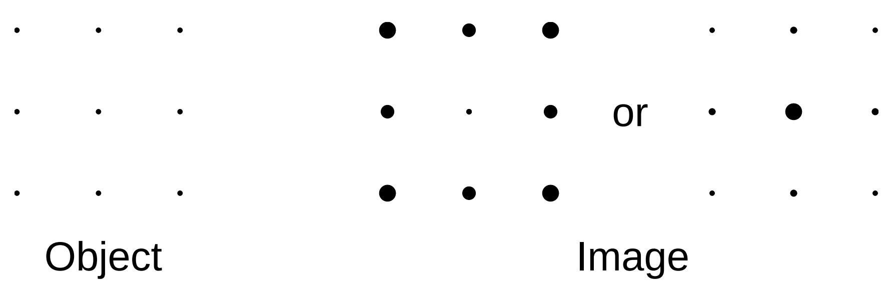
Best focus in between: get uniform blur

Laser beams often astigmatic

Field curvature:
= focal length different for off-axis points

Image "plane" is curved

With flat detector, can't focus all points at once

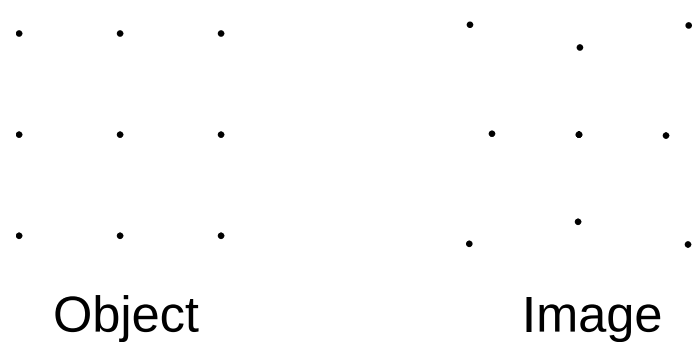


Again, best focus is compromise

Distortion:

= magnification depends on object location

Image in focus, but not accurate



Can correct with post-processing

Chromatic aberration

Different: not a surface error

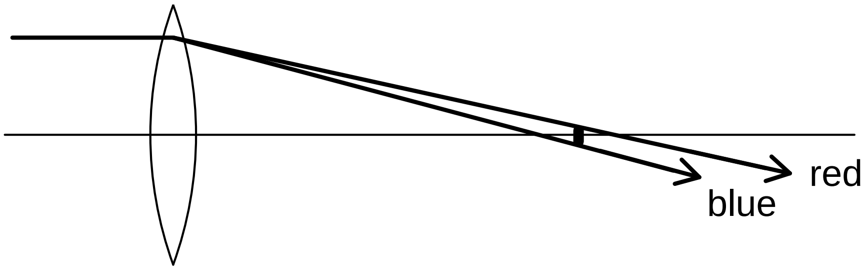
Due to $n = n(\omega)$

Focal length depends on n: depends on ω

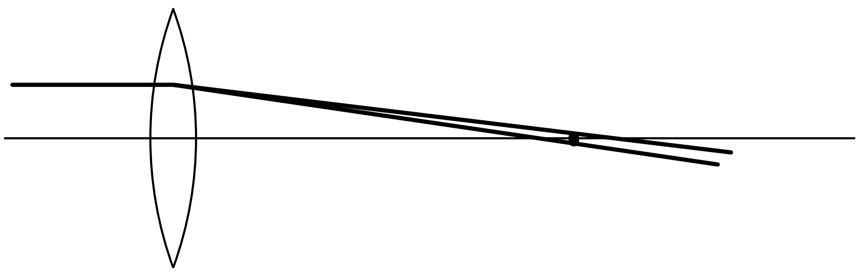
$\Rightarrow$ focal length different for different colors

Typically $\dfrac{\Delta f}{f} \approx$ few percent

Effect still worse for lower $f/\#$



vs:



Usually dominant for polychromatic imaging

Ray Tracing

Categories useful for talking about aberrations

What if you want to calculate them?
    Use ray tracing software

Many good programs

Industry standard: Zemax
    costs $2000

I've used OSLO: free student version

Many others. . . check the web

Basic job: trace rays through system exactly

Set up in many different ways
    gets pretty complicated
Generally hard to use

Most useful feature:
    Calculate point-spread function
    = (ray optics) image produced by point source
Pretty much all you need to know

Also nice:
Autofocus automatically finds best image plane

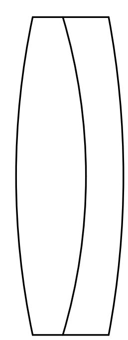
Lens Design

Use multiple surfaces, materials:
    more degrees of freedom

Allows you to cancel aberrations to some precision

Simplest example:
achromat doublet (Hecht 6.3.2)

Reduces chromatic aberration



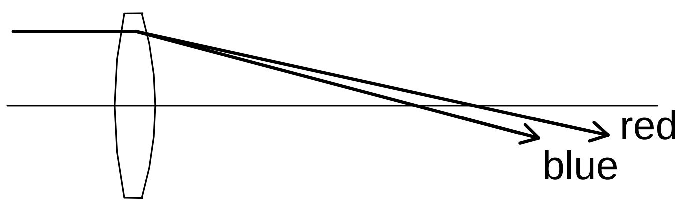
Idea: make positive f_{tot} lens using two pieces

1: strong positive lens $f < f_{\text{tot}}$
using glass with low $dn/d\omega$
Gives moderate positive aberration

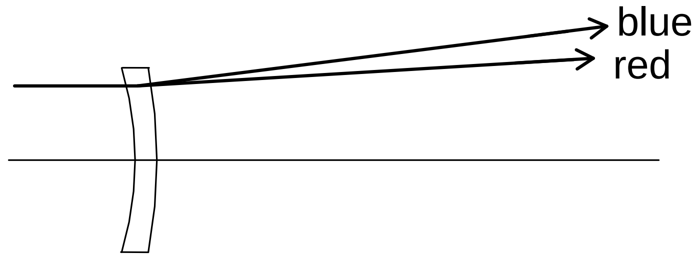
2: weak negative lens $|f| > f_{\text{tot}}$
using glass with high $dn/d\omega$
Gives moderate negative aberration

Put together, get desired f_{tot}
chromatic aberrations cancel

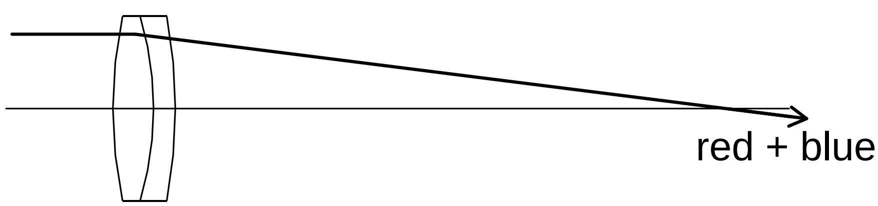
Positive:



Negative:



Total:



Do similar tricks with other aberrations

Use ray trace software to get right
(program has catalog of glasses already)

Good achromat design: other aberrations reduced
performance much better than singlet

System design guidelines

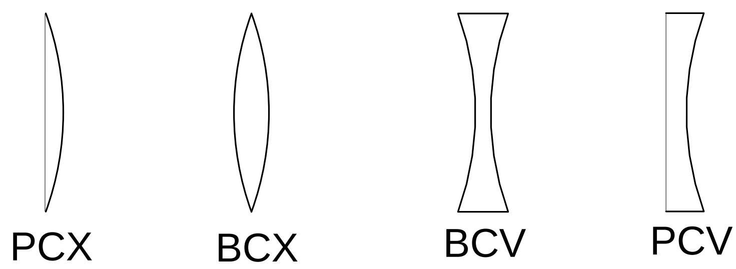
In laboratory research, don't want to design lenses

Use off-the-shelf components

Some recommended companies:
ThorLabs - best price
CVI Laser - good quality
Melles Griot - wide selection
Newport - wide selection + good quality
Oriel - specialized components

What can you buy?

Singlet lenses:



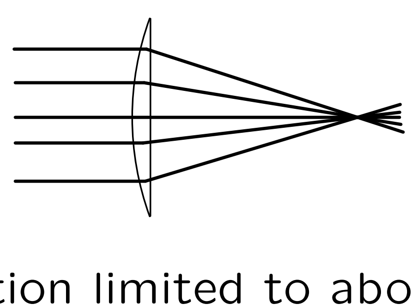
(PCX = plano-convex; BCV = biconcave; etc)

Cost about $25 for 25 mm diameter lens
$10 more for anti-reflection coating

Singlet Performance

Proper use:
PCX and PCV lenses best at *infinite conjugate*
= image or object at ∞

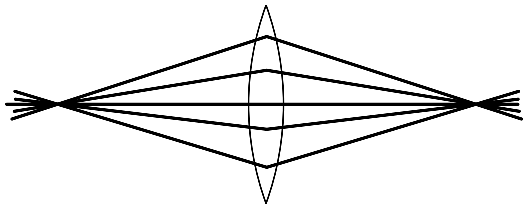
Want collimated rays on curved side:
"flat to focus"



Diffraction limited to about $f/15$
(for on-axis, monochromatic aberrations)

BCX and BCV lenses best at unity conjugate

$s_i = s_o$



Again, diffraction limited to $f/15$

Question: What angle θ does $f/15$ correspond to?

Generally, conjugate ratio = $s_{\text{max}}/s_{\text{min}}$

for conjugate ratio > 5, use plano lens

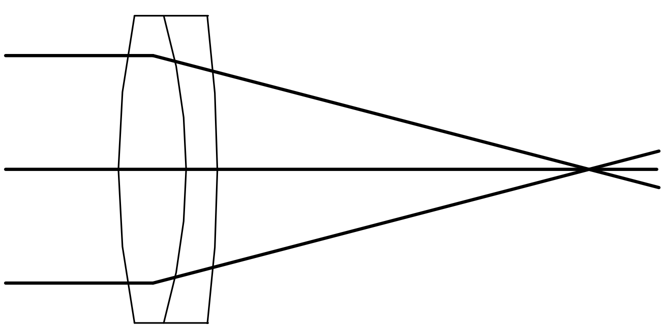
for conjugate ratio < 5, use symmetric lens

Can also buy achromat doublets

Cost \$100 (with coating)

Optimized for infinite conjugate

- flatter side still faces focus



Diffraction limited to about $f/5$

For lower $f/\#$, use microscope objective
$\rightarrow$ higher NA

Wide variety: cost \$100 to \$5000

Typically up to NA = 0.9
even better with tricks

Limited to small aperture, short focal length
problem if you can't get close to object
or if you have a big beam

Can get apertures up to about 1 cm

Can also get custom optical systems
optical engineer will design and build to spec

Typically costs \$10k or more

When should you consider this?
- Custom materials for IR or UV applications
- Require high NA with large aperture

For ordinary imaging, camera lenses good

Wide range of choices (too wide!)
cost $100 and up

Features:
- Low off-axis aberrations
- Excellent chromatic correction
- Variable aperture, magnification

Disadvantages:
- Usually not diffraction limited
- Rarely work well with laser beams

Summary

- Non-paraxial rays often important in practice
- Classify imaging errors with aberration theory
- Calculate errors with ray tracing software
- Lab design: use singlets and doublets
  Need to know performance limitations