

# 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

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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

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# 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?

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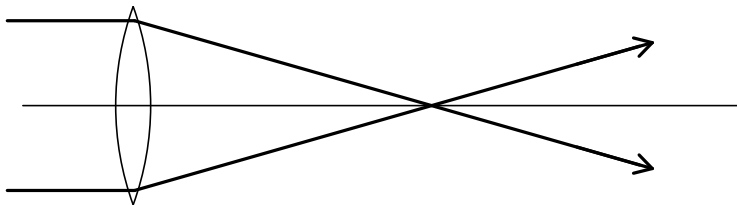
First, can we use ray optics?

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

$a$  = transverse size

$d$  = propagation distance

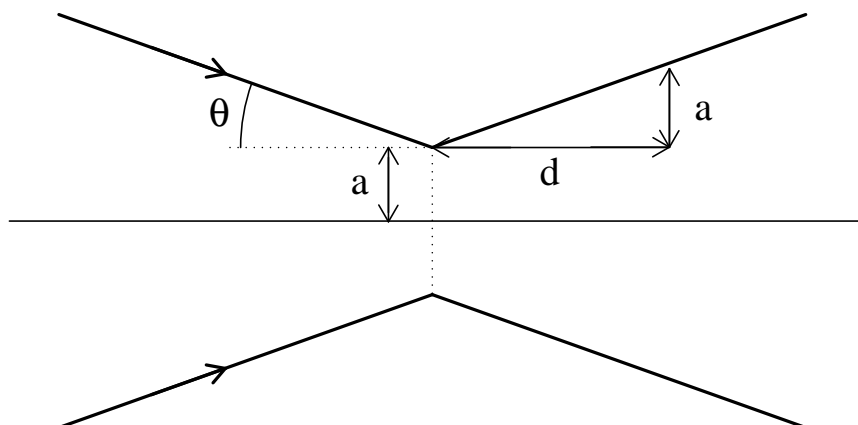
For focusing system,  $a$  is changing:



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

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Zoom in on focus point:



Focal spot radius  $a$

Incoming ray angle  $\theta$

Propagation distance  $d$

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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

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

$D$  = lens diameter

$f$  = lens focal length

(assuming distant object)

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

Actual result from wave optics:

$$a \geq 1.22 \frac{\lambda f}{D}$$

Write  $a_{\min} = a_{DL}$

= diffraction-limited spot size

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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  $a_R \approx a_{DL}$ , need surface accuracy  $\approx \lambda/4$

If  $a_R < a_{DL}$ , say system is

*diffraction limited*

= as good as possible

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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

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Numerical aperture (NA) (Hecht 5.7.5)

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

$\theta_{\max}$  = 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  
( $\theta_{\max}$  from exit pupil)

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Define  $f\text{-number} = f/D$  (Hecht 5.3.3)

$f$  = focal length

$D$  = lens diameter

Uses strange notation:

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

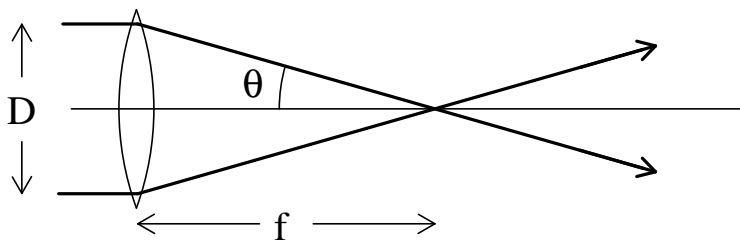
If  $f = 100$  mm and  $D = 10$  mm, lens is  $f/10$

Used for:

- simple lenses
- camera lenses
- telescopes

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



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

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Generally, fast lens is good

Large  $D$  = collect more light

Short  $f$  = use less space

But aberrations grow as  $\theta$  increases

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

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Trade off:

Note  $a_R$  decreases with  $f/\#$

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

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

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When can you ignore aberrations?

- Working with narrow laser beams  
Typical beam diameter = few mm  
Typical  $f = 50 - 1000$  mm  
So have  $f/15$  or greater  
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

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## Aberrations (Hecht 6.3)

Aberrations can be described analytically:

Third-order theory

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

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

Work out how additional terms affect  $a_R$

Categorize effects

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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

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Classification of aberrations:

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

Hecht covers in some detail

More math: Klein and Furtak

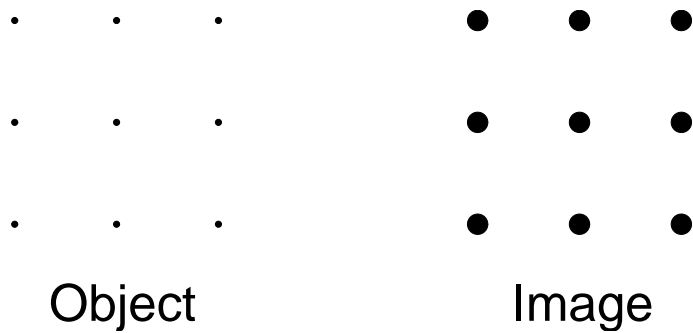
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## Spherical aberration

= basic error due to spherical surface  
rays at edge of lens don't focus right

Blurs image uniformly

Also shifts image plane



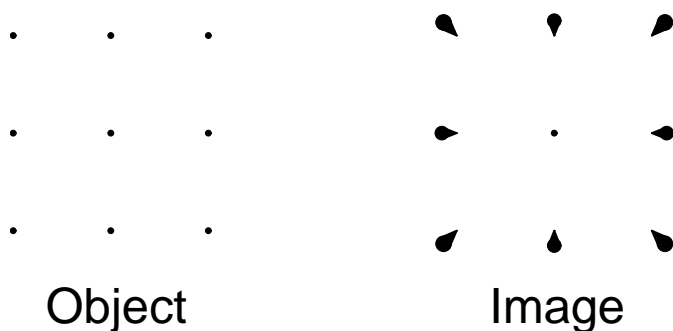
Often dominant error

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## Coma

= imaging error for off-axis points

Limits useable field of view



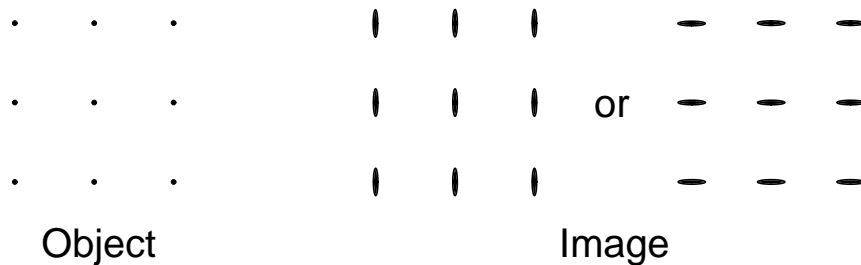
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## Astigmatism

= 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

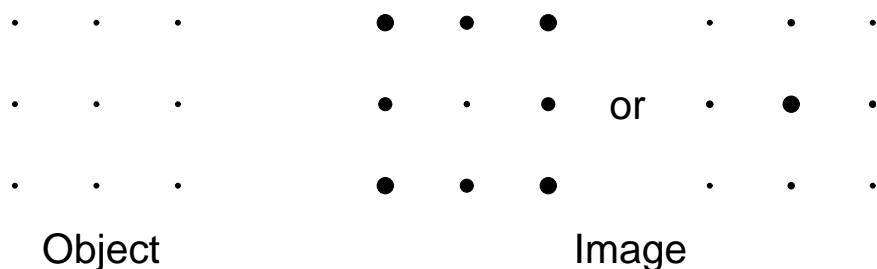
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## Field curvature:

= focal length different for off-axis points

Image “plane” is curved

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



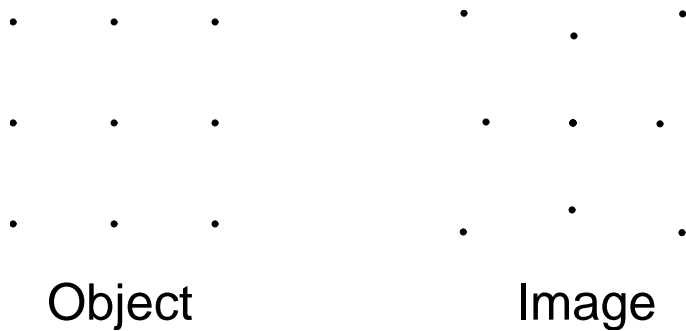
Again, best focus is compromise

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Distortion:

= magnification depends on object location

Image in focus, but not accurate



Can correct with post-processing

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Chromatic aberration

Different: not a surface error

Due to  $n = n(\omega)$

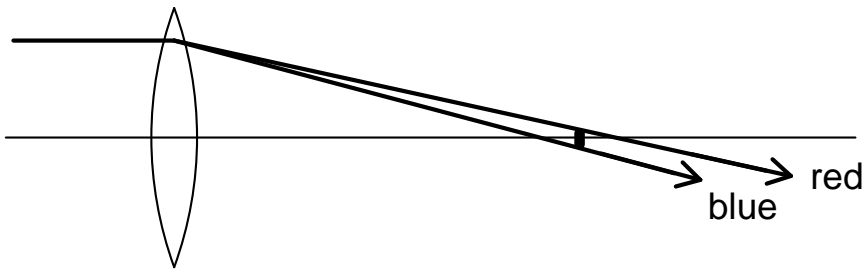
Focal length depends on  $n$ : depends on  $\omega$

$\Rightarrow$  focal length different for different colors

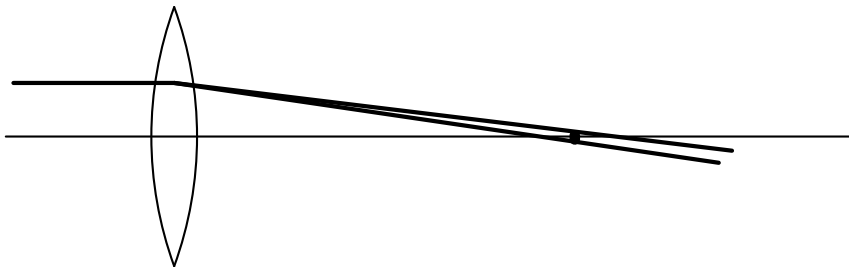
Typically  $\frac{\Delta f}{f} \approx$  few percent

Effect still worse for lower  $f/\#$

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vs:



Chromatic aberration usually very important

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## 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

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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

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## Lens Design

Use multiple surfaces, materials:

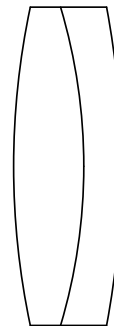
more degrees of freedom

Allows you to cancel aberrations to some precision

Simplest example:

achromat doublet (Hecht 6.3.2)

Reduces chromatic aberration



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Idea: make positive  $f_{\text{tot}}$  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  $|f| > f_{\text{tot}}$

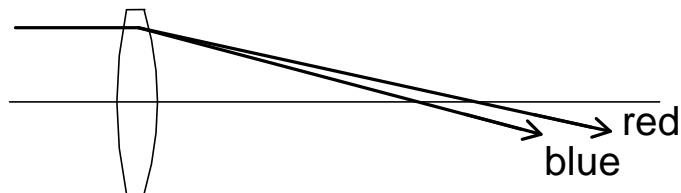
using glass with high  $dn/d\omega$

Gives moderate negative aberration

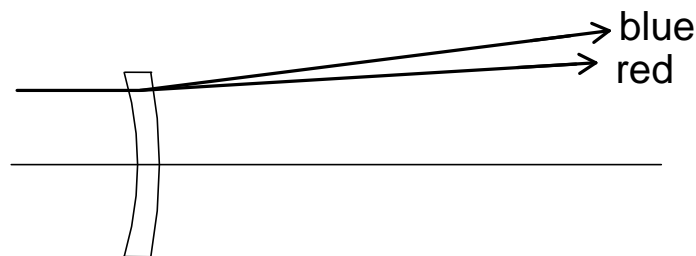
Put together, get desired  $f_{\text{tot}}$   
chromatic aberrations cancel

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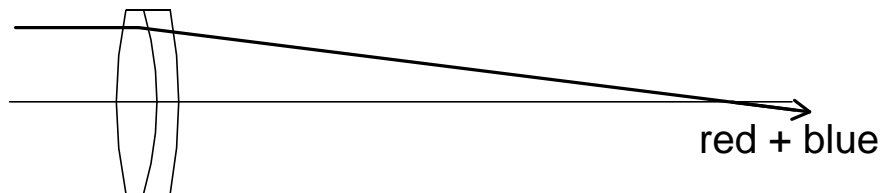
Positive:



Negative:



Total:



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Do similar tricks with other aberrations

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

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

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## System design guidelines

In laboratory research, don't want to design lenses

Use off-the-shelf components

Some recommended companies:

- ThorLabs - good price

- CVI Laser - good quality

- Melles Griot - wide selection

- Newport - wide selection + good quality

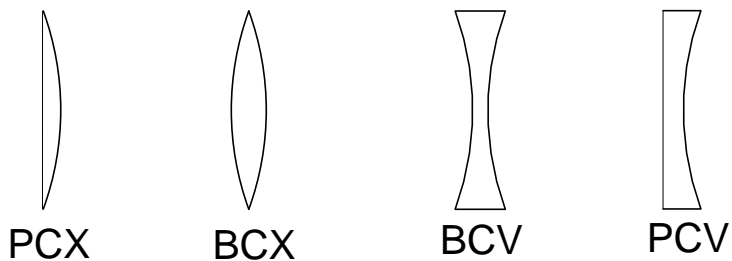
- Oriel - specialized components

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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

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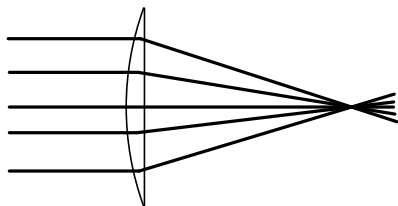
## Singlet Performance

Proper use:

PCX and PCV lenses best at *infinite conjugate*  
= image or object at  $\infty$

Want collimated rays on curved side:

“flat to focus”



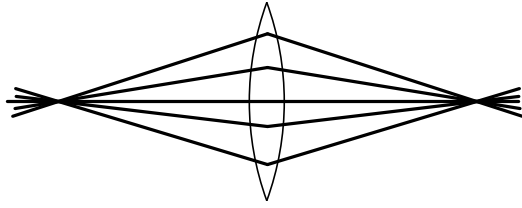
Diffraction limited to about  $f/15$

(for on-axis, monochromatic aberrations)

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BCX and BCV lenses best at unity conjugate

$$s_i = s_o$$



Again, diffraction limited to  $f/15$

**Question:** What angle  $\theta$  does  $f/15$  correspond to?

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

for conjugate ratio  $> 5$ , use plano lens

for conjugate ratio  $< 5$ , use symmetric lens

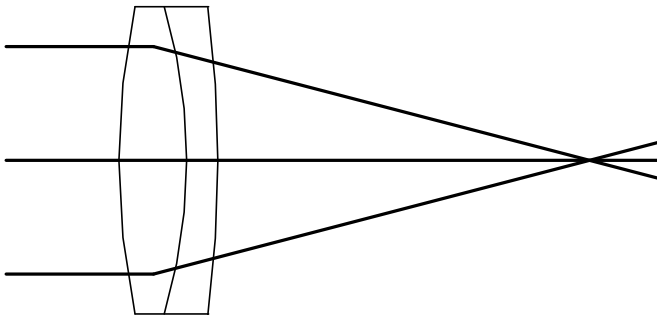
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Can also buy achromat doublets

Cost \$100 (with coating)

Optimized for infinite conjugate

- flatter side still faces focus



Diffraction limited to about  $f/5$

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For lower  $f/\#$ , use microscope objective  
→ 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

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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

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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

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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

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