Optics II: practical photographic lenses

CS 178, Spring 2010

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Outline

- why study lenses?
- thin lenses
  - graphical constructions, algebraic formulae
- thick lenses
  - lenses and perspective transformations
- depth of field

- aberrations & distortion
- vignetting, glare, and other lens artifacts
- diffraction and lens quality
- special lenses
  - telephoto, zoom

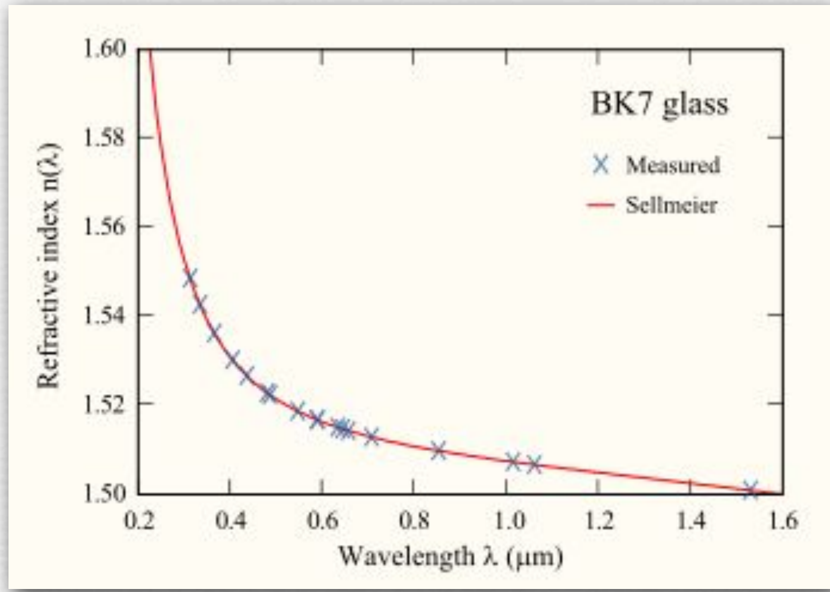
Lens aberrations

- chromatic aberrations
- Seidel aberrations, a.k.a. 3rd order aberrations
  - arise because of error in our 1st order approximation

$$\sin\phi \approx \phi \left(-\frac{\phi^3}{3!} + \frac{\phi^5}{5!} - \frac{\phi^7}{7!} + \ldots \right)$$

  - spherical aberration
  - oblique aberrations
  - field curvature
  - distortion

Dispersion

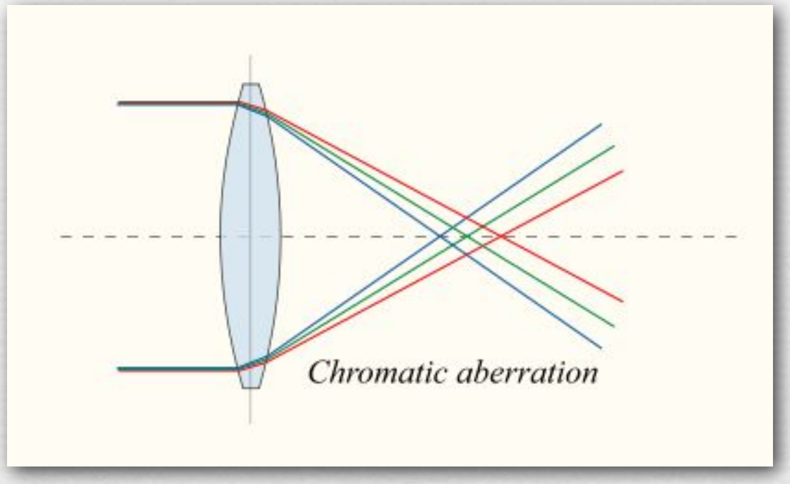


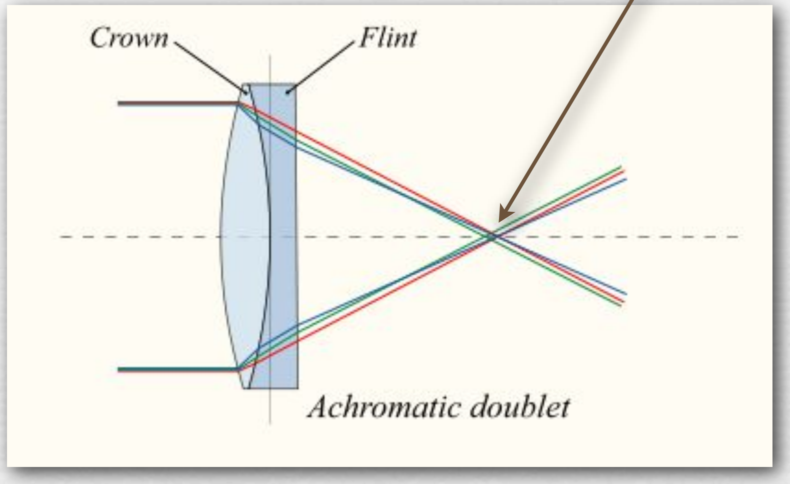
(wikipedia)

- index of refraction varies with wavelength
  - higher dispersion means more variation
  - amount of variation depends on material
  - index is typically higher for blue than red
  - so blue light bends more

Chromatic aberration

red and blue have the same focal length

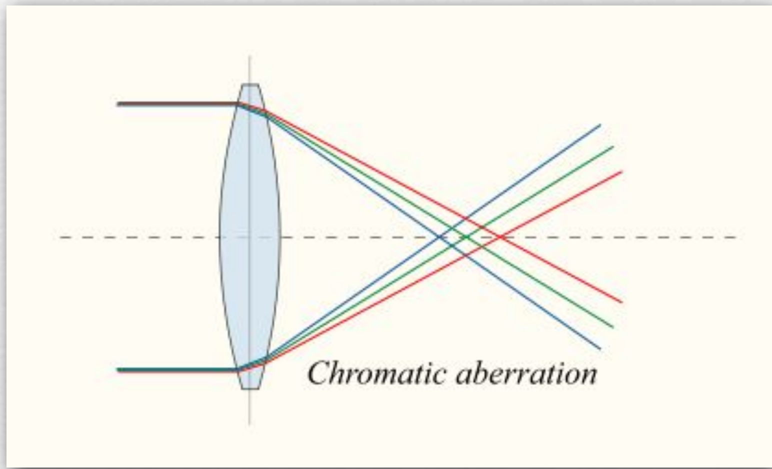


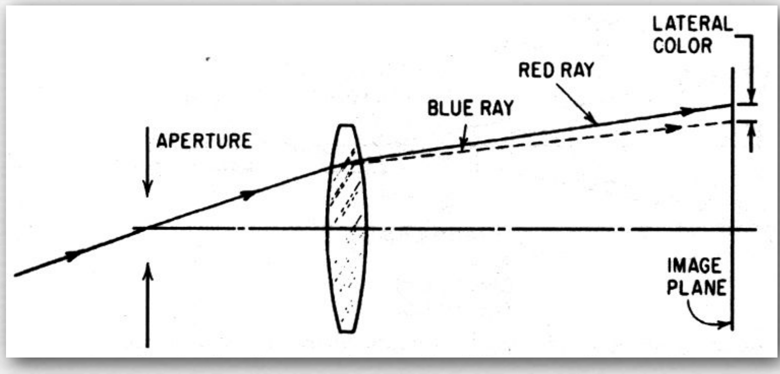


(wikipedia)

- dispersion causes focal length to vary with wavelength
  - for convex lens, blue focal length is shorter
- correct using *achromatic doublet*
  - strong positive lens + weak negative lens = weak positive compound lens
  - by adjusting dispersions, can correct at two wavelengths

The chromatic aberrations





(Smith)

- change in focus with wavelength
  - called *longitudinal (axial) chromatic aberration*
  - appears everywhere in the image
- if blue image is closer to lens, it will also be smaller
  - called *lateral (transverse) chromatic aberration*
  - only appears at edges of images, not in the center
- can reduce longitudinal by closing down the aperture

Comment on closing down the aperture fixed 5/1/10.

2nd comment on lateral aberration edited on 5/9/10.

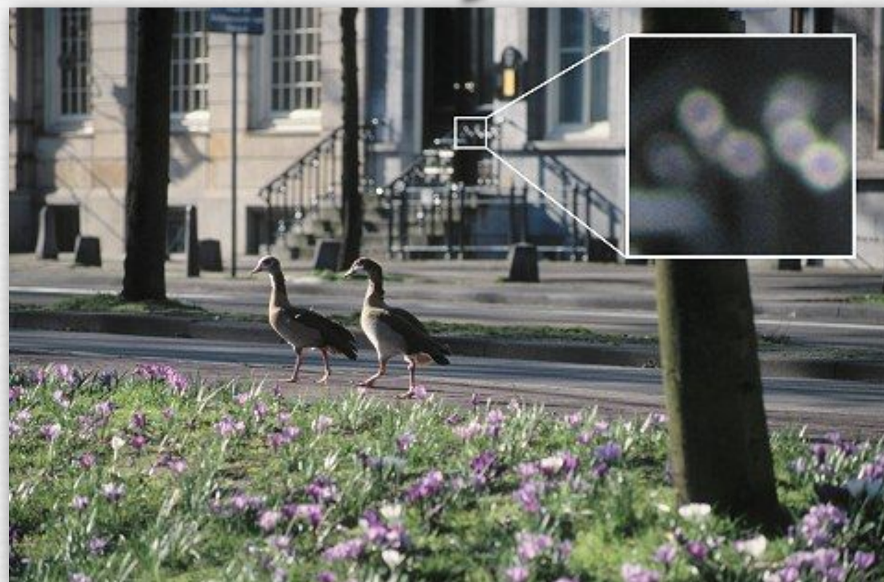
Examples

- correctable in software
- not

(wikipedia)

lateral

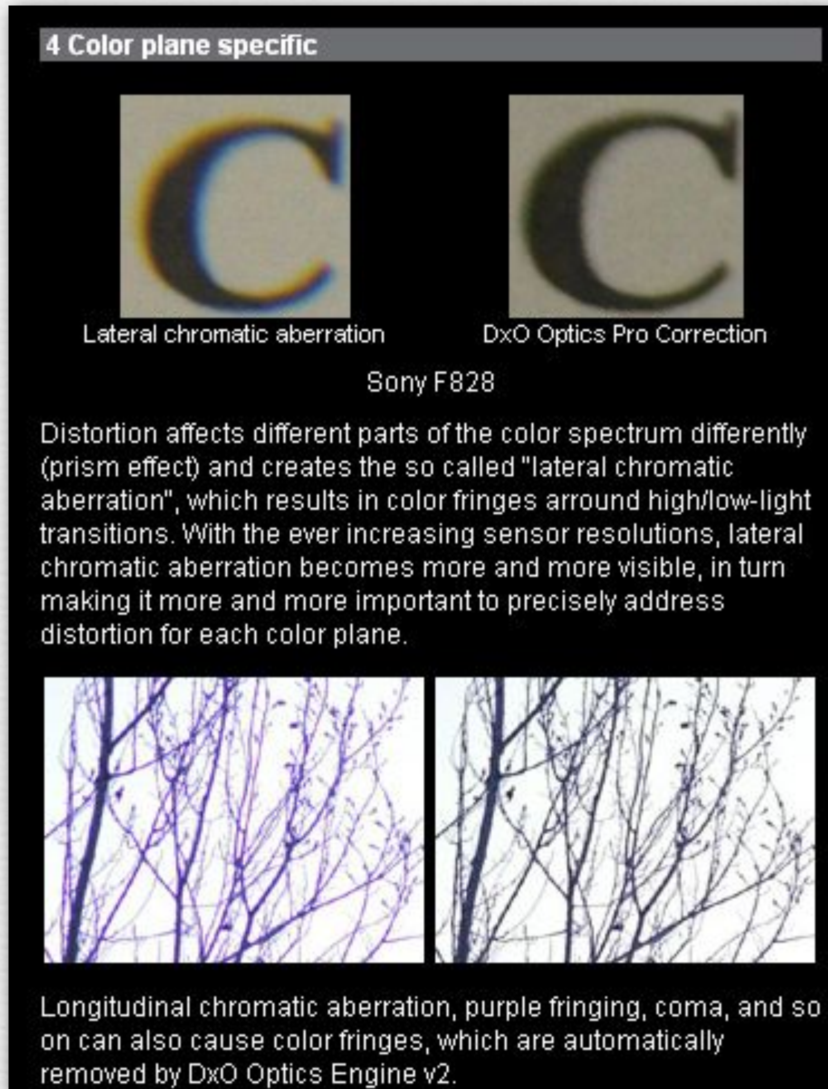
(toothwalker.org)



longitudinal

✦ other possible causes
  - demosiacing algorithm
  - per-pixel microlenses
  - lens flare

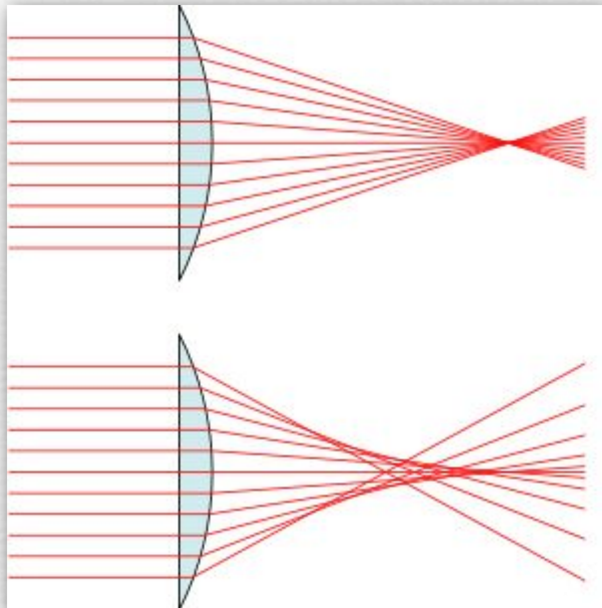
Software correction of lateral chromatic aberration



- Panasonic GF1 corrects for chromatic aberration in the camera (or in Adobe Camera Raw)
  - need focal length of lens, and focus setting

Q. Why don't humans see chromatic aberration?

Spherical aberration



(wikipedia)

- focus varies with ray height (distance from optical axis)
- can reduce by stopping down the aperture
- can correct using an aspherical lens
- can correct for this and chromatic aberration
  by combining with a concave lens of a different index

Examples

(Canon)

sharp

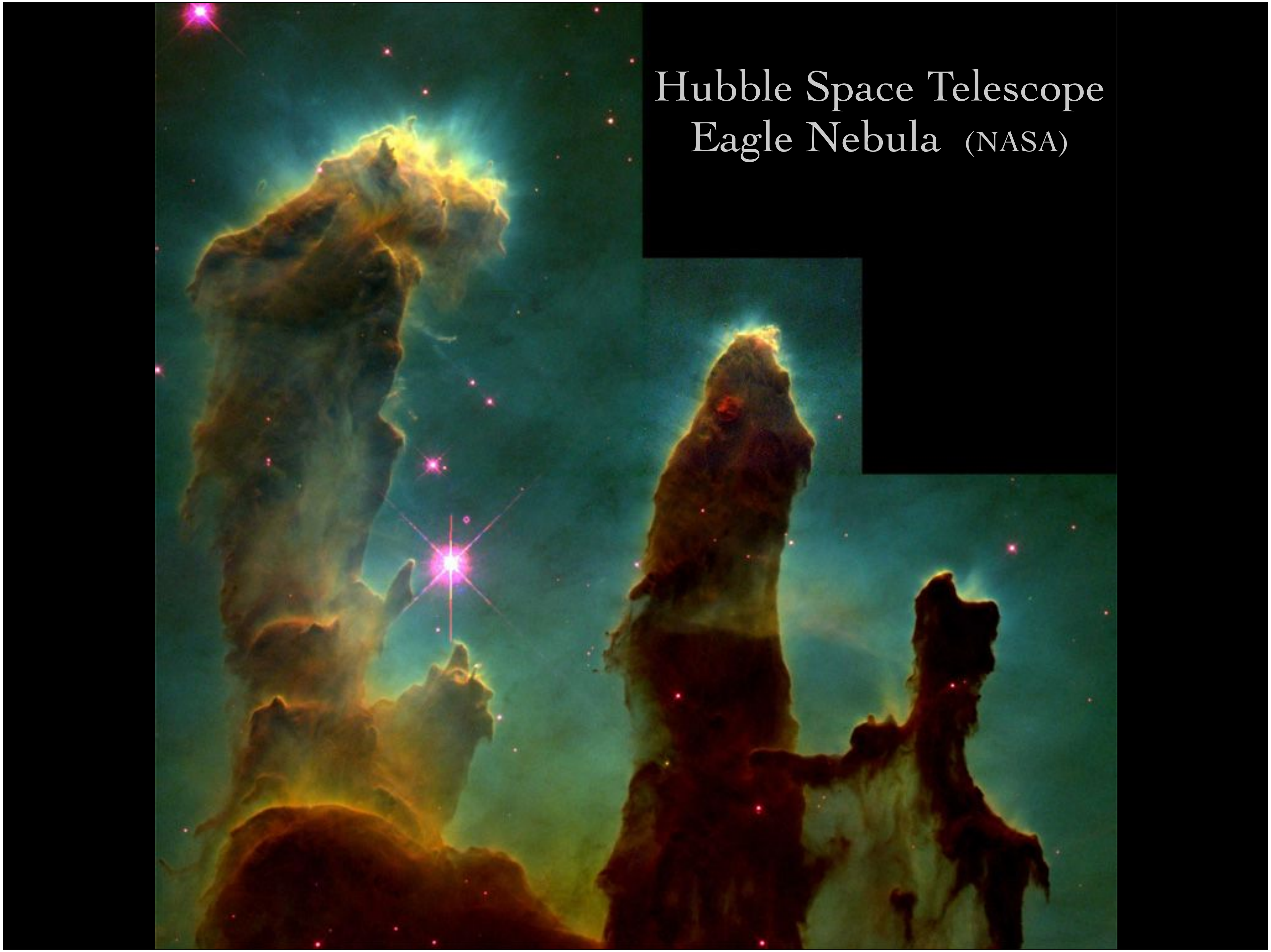
soft focus

Canon 135mm f/2.8 soft focus lens

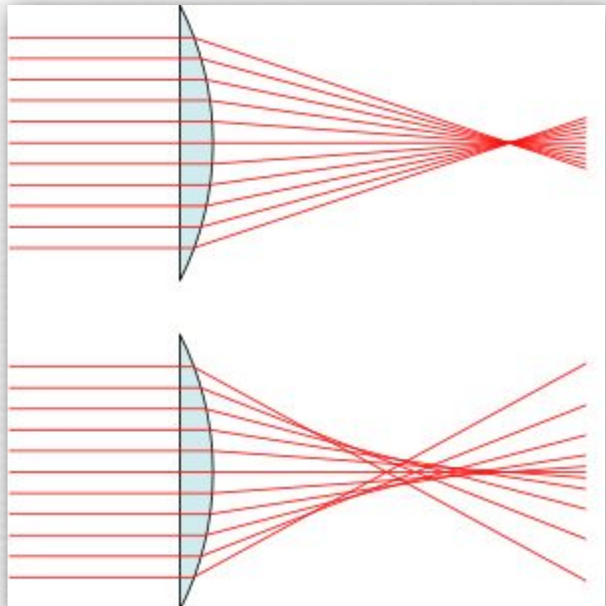
Hubble telescope

before correction

after correction


Hubble Space Telescope
Eagle Nebula (NASA)

Focus shift



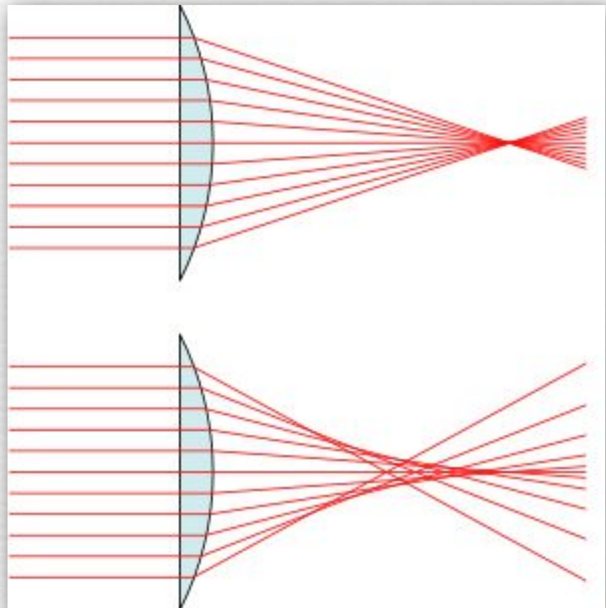
(wikipedia)

(diglloyd.com)

focused at f/1.2

- Canon 50mm f/1.2 L

Focus shift



(wikipedia)

(diglloyd.com)

shot at f/1.8

- Canon 50mm f/1.2 L
- narrowing the aperture pushed the focus deeper

Oblique aberrations

- lateral chromatic aberrations do not appear in center of field
  - they get worse with increasing distance from the axis
  - can reduce by closing down the aperture

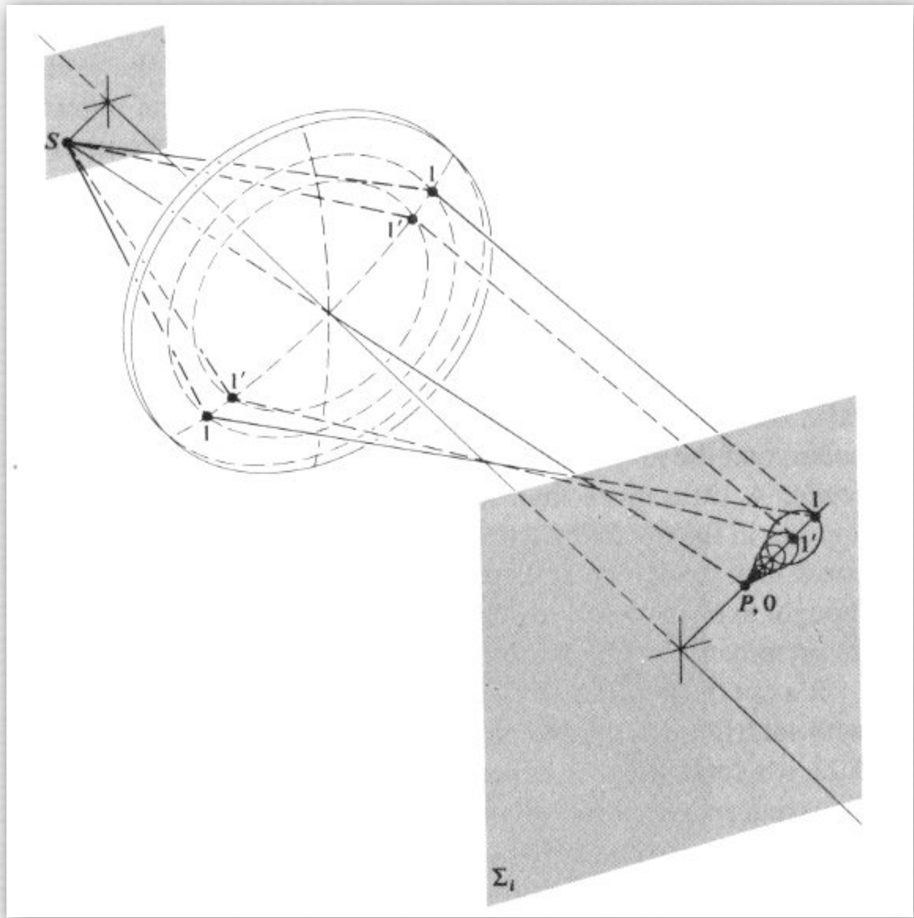
- spherical & longitudinal chromatic aberrations occur on the optical axis, as well as off the axis
  - they appear everywhere in the field of view
  - can reduce by closing down the aperture

Comment on closing down the aperture fixed on 5/1/10.

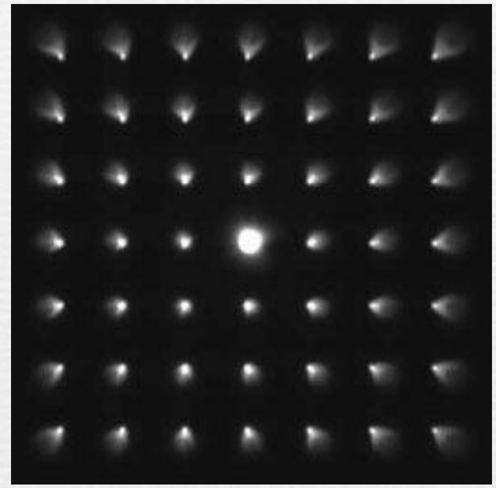
Lateral chromatic aberrations broken off into separate paragraph on 5/9/10.

- oblique aberrations do not appear in center of field
  - they get worse with increasing distance from the axis
  - can reduce by closing down the aperture
  - coma and astigmatism

Coma



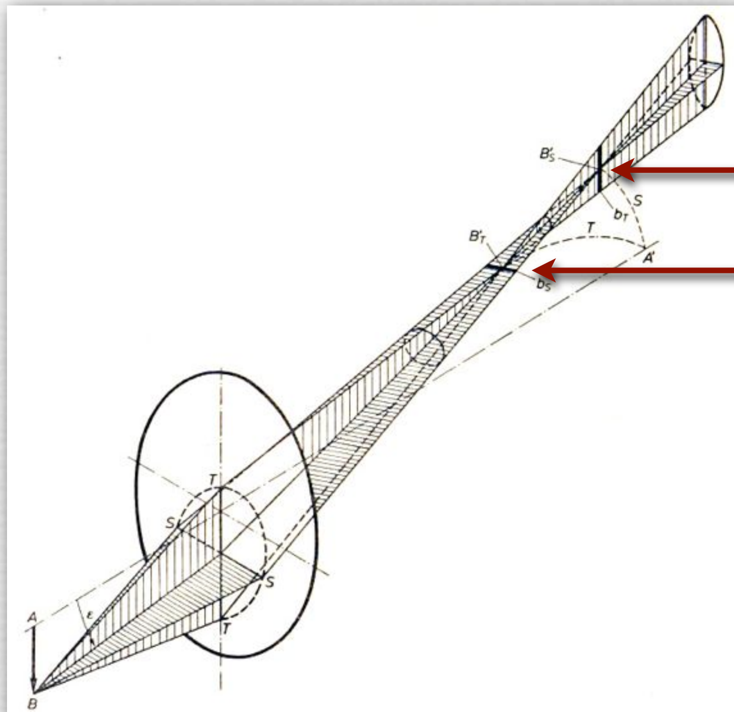
(Hecht)



(ryokosha.com)

- magnification varies with ray height (distance from optical axis)

Astigmatism



focus of sagittal rays

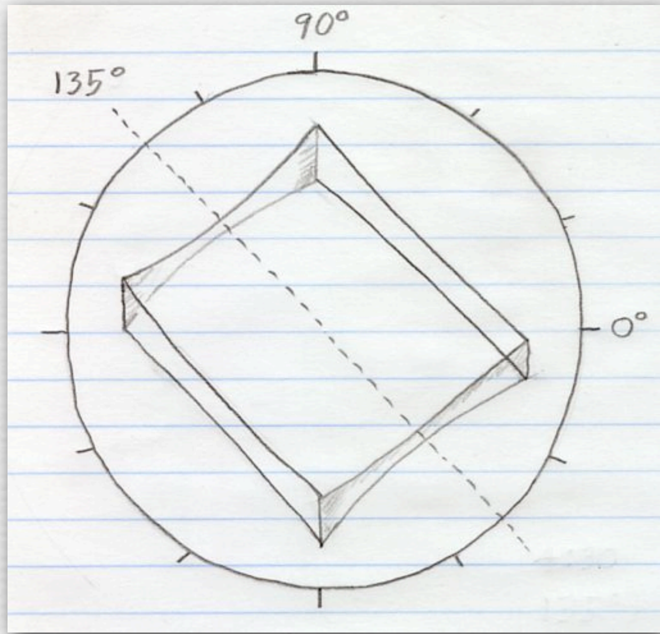
focus of tangential rays

(Pluta)

In class I declared my prescription incorrectly written on this slide. I was wrong; it is correctly written. The diagram I made on the whiteboard (see next slide) of a rotated bi-cylindrical lens (two perpendicular cylindrical lenses, of different curvatures, the whole affair made using a single piece of glass and rotated around the optical axis to a particular angle) was for my right eye, where the long axis of the second correction (-1.00 diopters) is at 135°. The correction for my left eye has different curvatures, and the long axis of the second correction (-0.75 diopters) is at 180°.

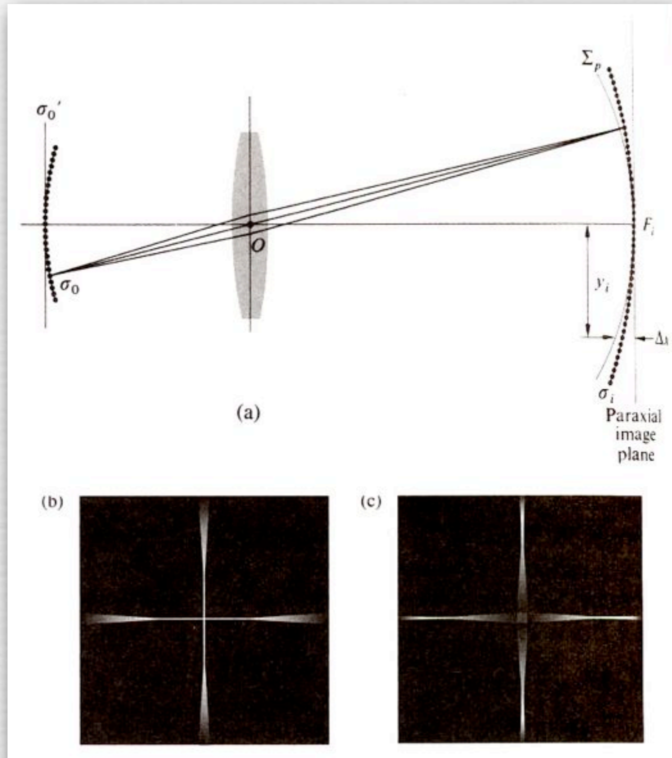
- tangential and sagittal rays focus at different depths
- my full eyeglass prescription
  - right: -0.75 -1.00 axis 135, left: -1.00 -0.75 axis 180

Correcting astigmatism using a cylindrical lens (contents of whiteboard)



- for myopia + astigmatism, one needs a spherical lens + cylindrical lens, i.e. a lens with different radii of curvature in two perpendicular directions
  - in my right eye, first direction has focal length -1 /0.75 = -1.33 meters, and second direction has focal length -1 / 1.00 = -1.00 meters
- lens is then rotated around the optical axis before mounting in frame
  - in my case long axis of second curvature is 135° (10:30 - 4:30 on the clock)

Field curvature

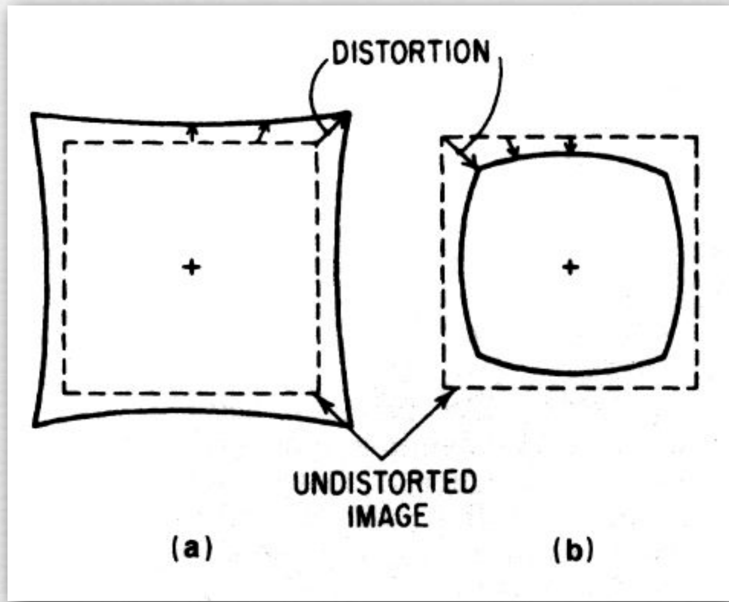


(Hecht)

- spherical lenses focus a curved surface in object space onto a curved surface in image space
- so a plane in object space cannot be everywhere in focus when imaged by a planar sensor

Distortion

(Smith)

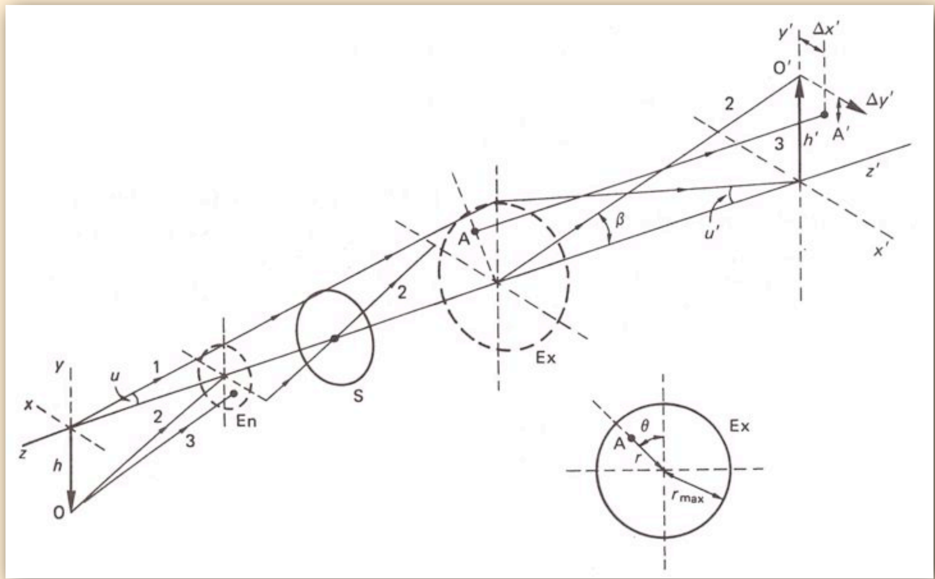


(Kingslake)

pincushion distortion

- change in magnification with image position
  - (a) pincushion
  - (b) barrel
- closing down the aperture does not improve this

Algebraic formulation of monochromatic lens aberrations



(Smith)

- spherical aberration $a_s r^4$
- coma $a_c h' r^3 \cos\theta$
- astigmatism $a_a h'^2 r^2 \cos^2\theta$
- field curvature $a_d h'^2 r^2$
- distortion $a_t h'^3 r \cos\theta$

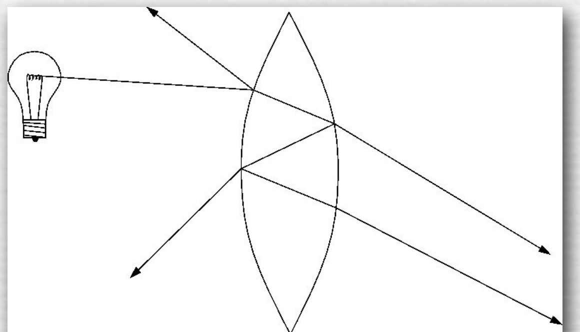
Recap

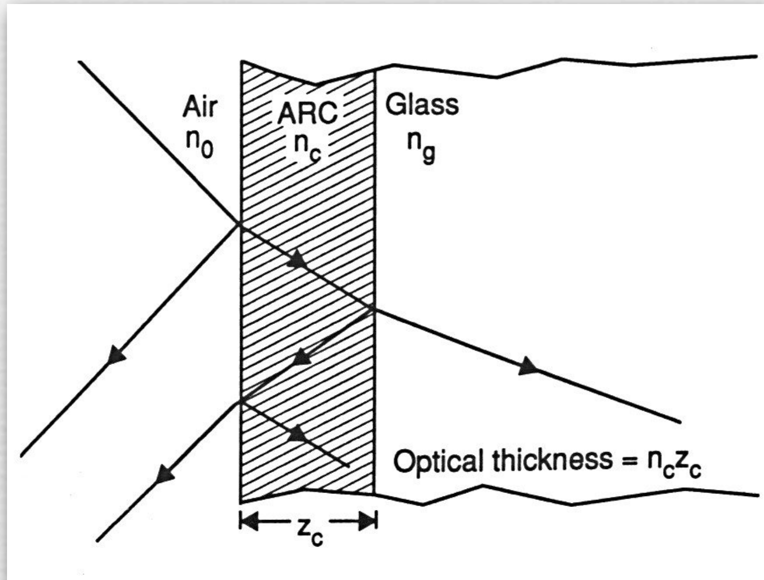
- all lenses are subject to chromatic aberration
  - longitudinal appears everywhere; lateral is worse at edges
  - cannot be reduced by closing down aperture
  - can be partly corrected using more lenses, and software

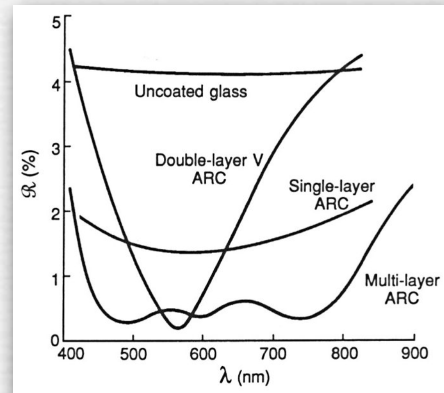
- all spherical lenses are subject to Seidel aberrations: spherical, coma, astigatism, field curvature, distortion
  - some appear everywhere; others only at edges
  - all but distortion can be reduced by closing down aperture
  - only distortion can be corrected completely in software

Questions?

Veiling glare



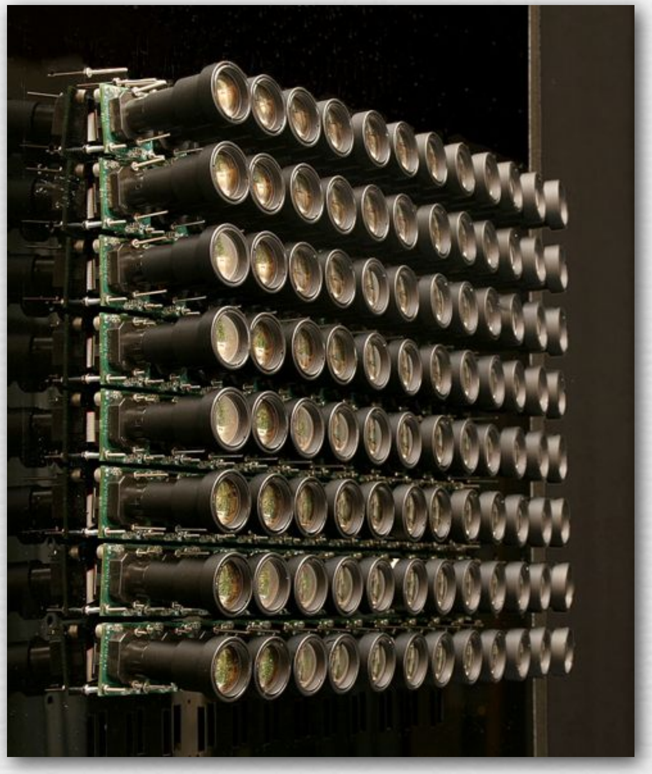




- contrast reduction caused by stray reflections
- can be reduced by anti-reflection coatings
  - based on interference, so optimized for one wavelength
  - to cover more wavelengths, use multiple coatings

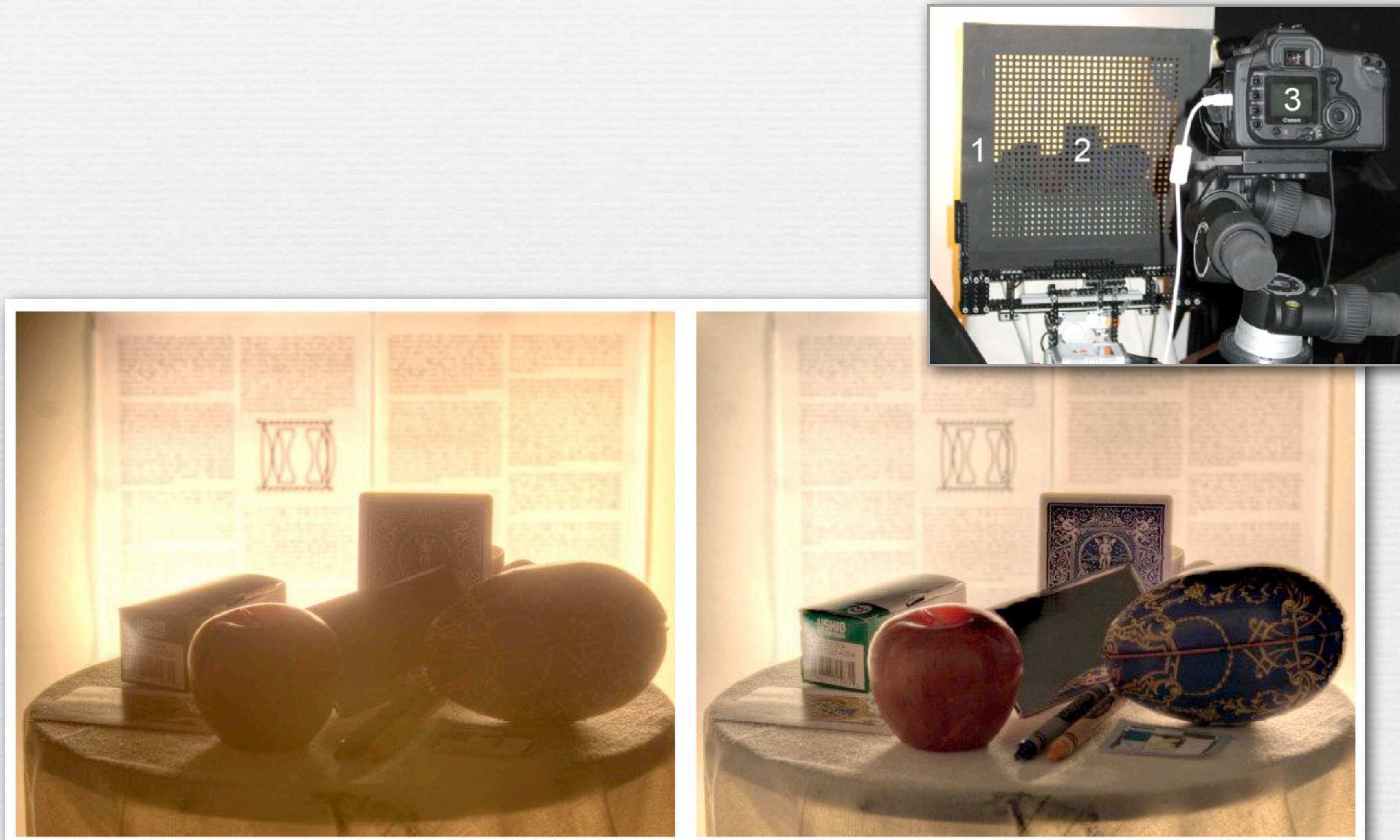
Camera array with too much glare

Stanford
Multi-Camera
Array



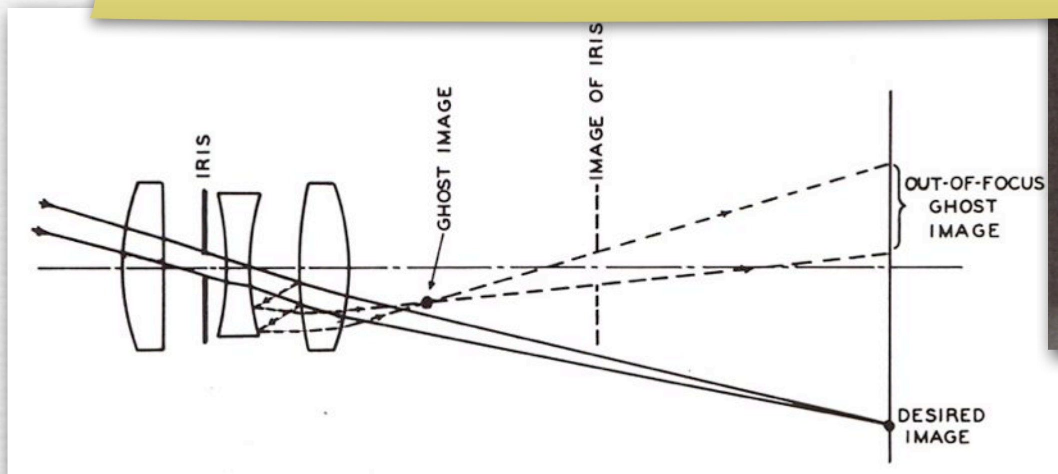
- 12 × 8 array of 600 × 800 pixel webcams = 7,200 × 6,400 pixels
- goal was highest-resolution movie camera in the world
- failed because glare in inexpensive lenses led to poor contrast

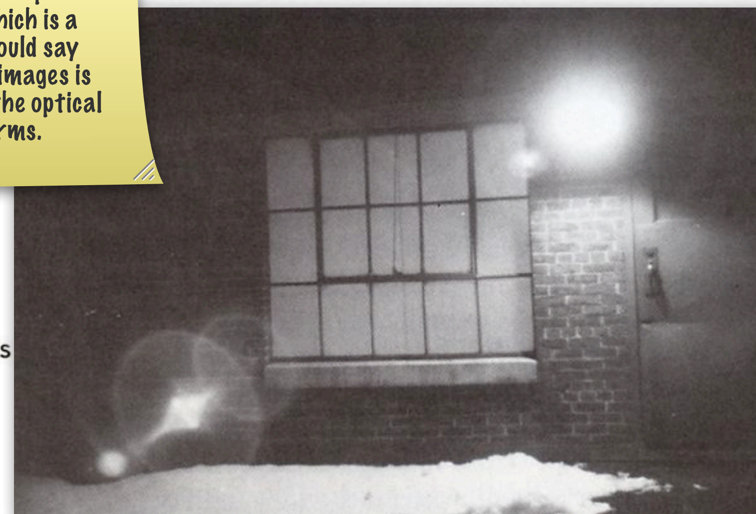
Removing veiling glare computationally
[Talvala, Proc. SIGGRAPH 2007]



Flare and ghost images

After the discussion in class I looked at a few sources. Most seem to agree (including wikipedia) that lens **flare** is structured in some way. This differentiates it from **veiling glare**, which is a relatively unstructured loss of contrast. From a signal processing point of view, we would say that flare is a high-frequency artifact, while glare is a low-frequency artifact. Ghost images is a special case of flare, where the structure looks like the aperture or another part of the optical system. Don't worry too much about these definitions; they're not precise technical terms.





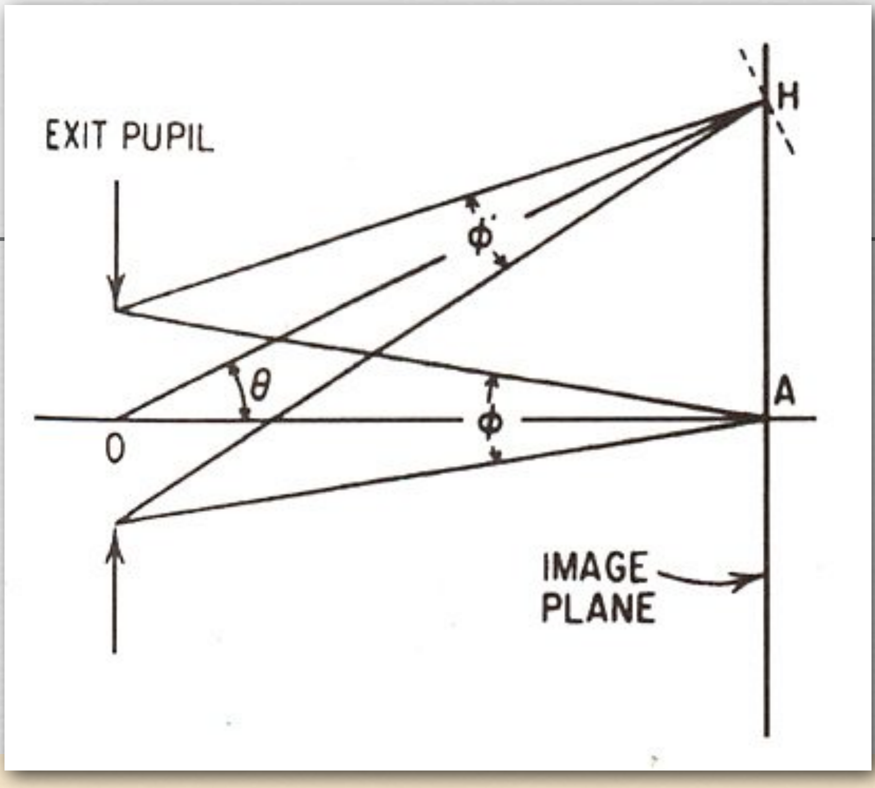
(Kingslake)

- reflections of the aperture, lens boundaries, etc., i.e. things inside the camera body
- removing these artifacts is an active area of research in computational photography
- but it's a hard problem

Vignetting

(a.k.a. **natural** vignetting)

(Smith)



You should know that natural vignetting is $\cos^4\theta$, but I won't hold you responsible for its derivation.

- irradiance is proportional to projected area of aperture as seen from pixel on sensor, which drops as $\cos\theta$
- irradiance is proportional to projected area of pixel as seen from aperture, which also drops as $\cos\theta$
- irradiance is proportional to distance^2 from aperture to pixel, which rises as $1/\cos\theta$
- combining all these effects, light drops as $\cos^4\theta$

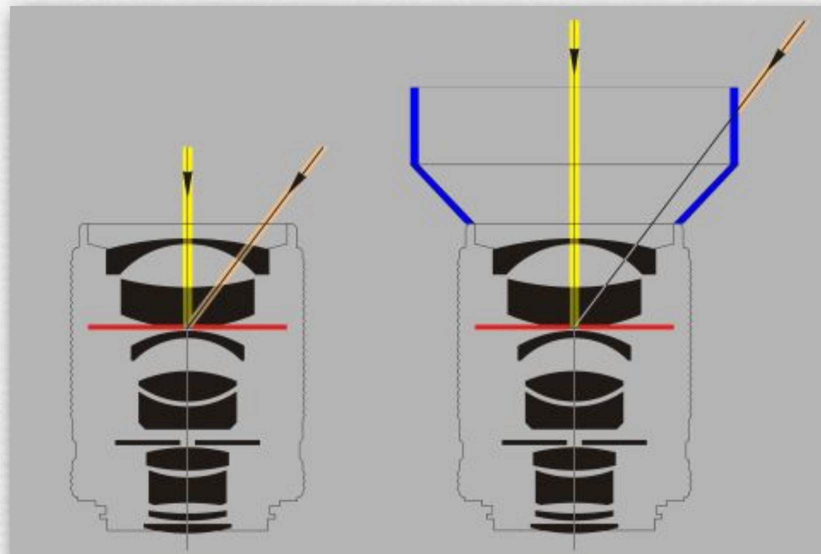
Other sources of vignetting

f/1.4 f/5.6

axial

semifield

(toothwalker.org)



optical vignetting
from multiple lens elements,
especially at wide apertures

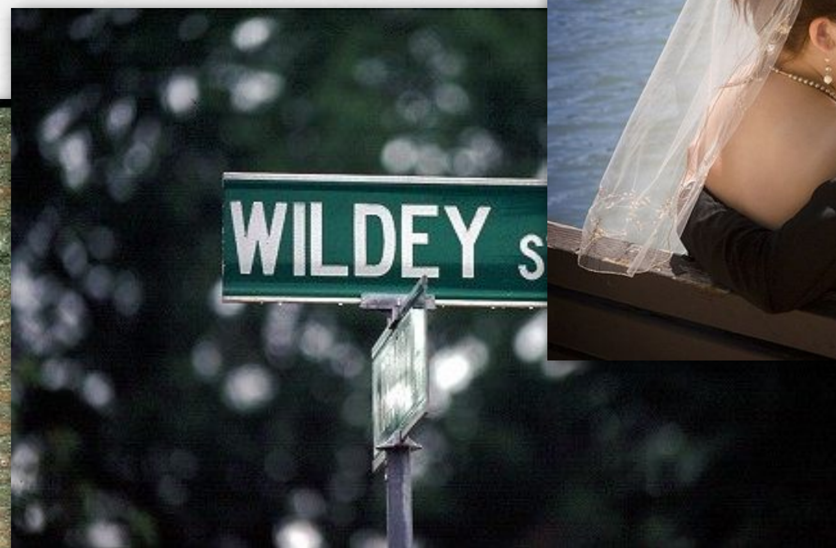
mechanical vignetting
from add-on lens hoods
(or filters or fingers)

- **pixel** vignetting due to shadowing inside each pixel (we'll come back to this)

Oops, I forgot to mention pixel vignetting in class. We'll talk about when we cover sensors and pixels.

Examples

(toothwalker.org)



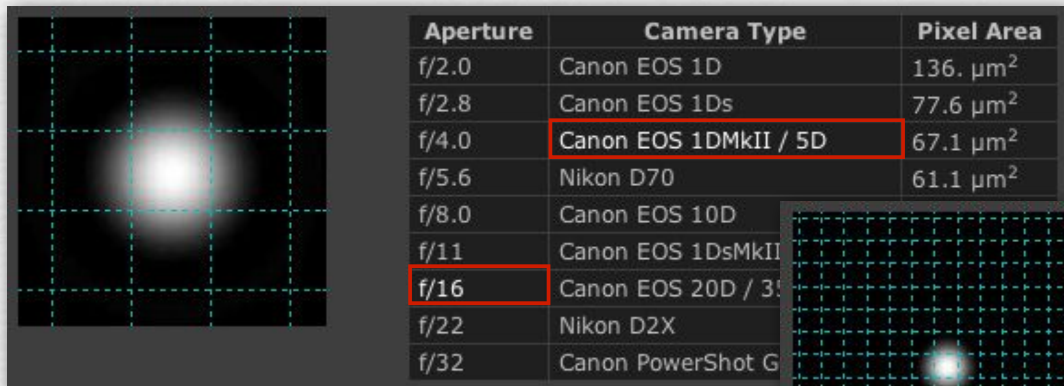
(toothwalker.org)

(wikipedia)

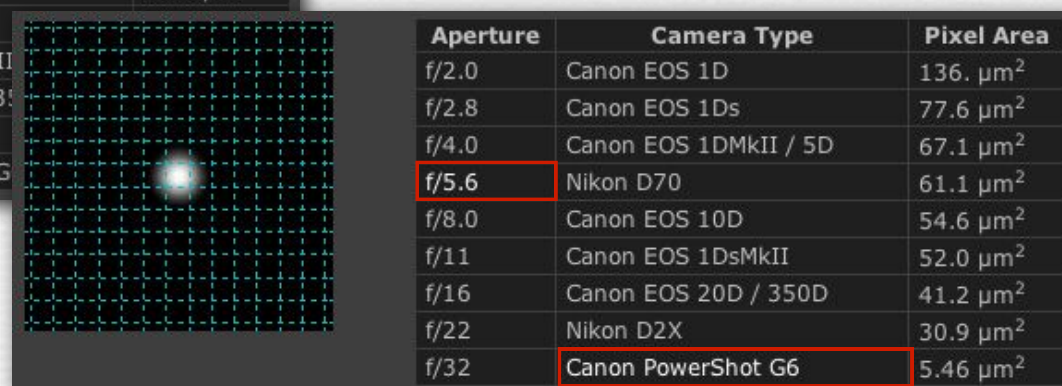
- vignetting affects the *bokeh* of out-of-focus features
- vignetting is correctable in software,
  but boosting pixel values worsens noise
- vignetting can be appled afterwards, for artistic purposes

Diffraction in photographic cameras

- the smaller the pixels, the more of them the pattern covers
  - if the pattern spans >> 1 pixel, we begin to complain



Aperture	Camera Type	Pixel Area
f/2.0	Canon EOS 1D	136. μm^2
f/2.8	Canon EOS 1Ds	77.6 μm^2
f/4.0	Canon EOS 1DMkII / 5D	67.1 μm^2
f/5.6	Nikon D70	61.1 μm^2
f/8.0	Canon EOS 10D	
f/11	Canon EOS 1DsMkII	
f/16	Canon EOS 20D / 3	
f/22	Nikon D2X	
f/32	Canon PowerShot G	



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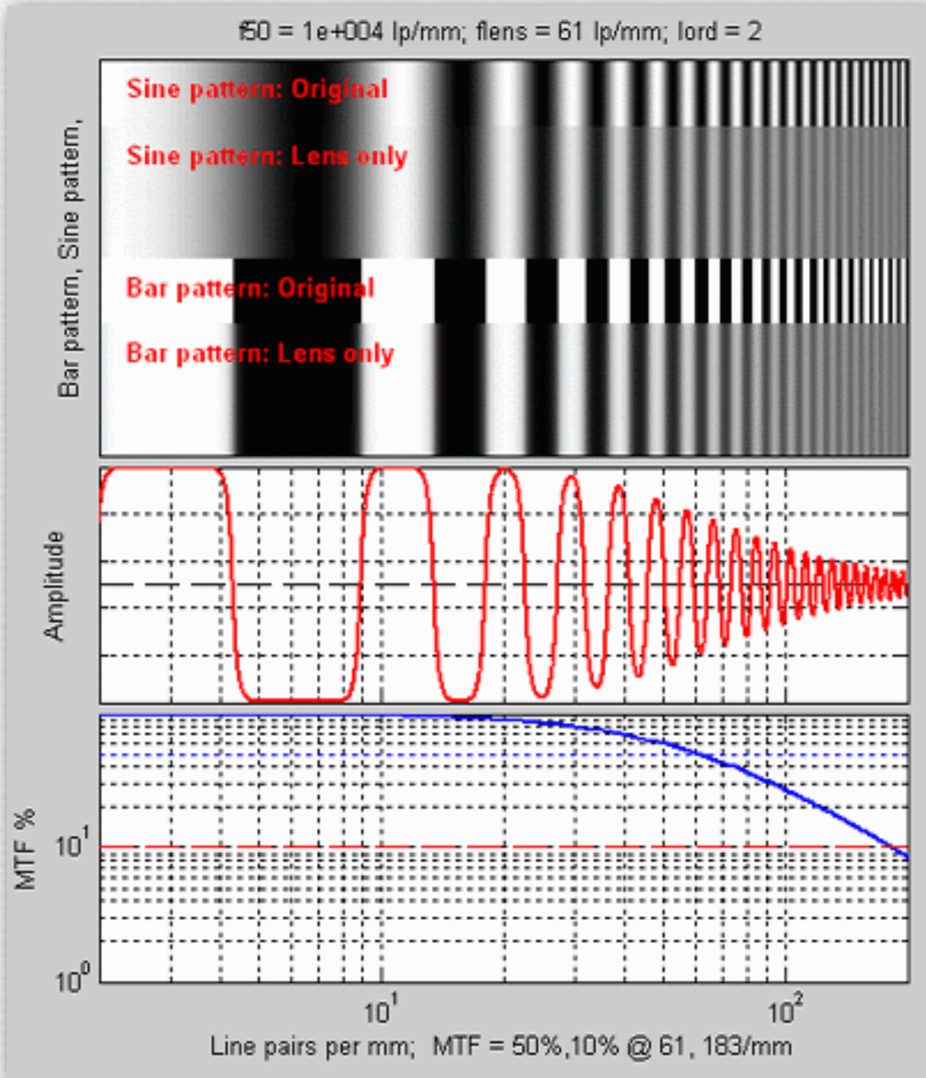
f/5.6	Nikon D70	61.1 μm^2
f/8.0	Canon EOS 10D	54.6 μm^2
f/11	Canon EOS 1DsMkII	52.0 μm^2
f/16	Canon EOS 20D / 350D	41.2 μm^2
f/22	Nikon D2X	30.9 μm^2
f/32	Canon PowerShot G6	5.46 μm^2

(http://www.cambridgeincolour.com/tutorials/diffraction-photography.htm)

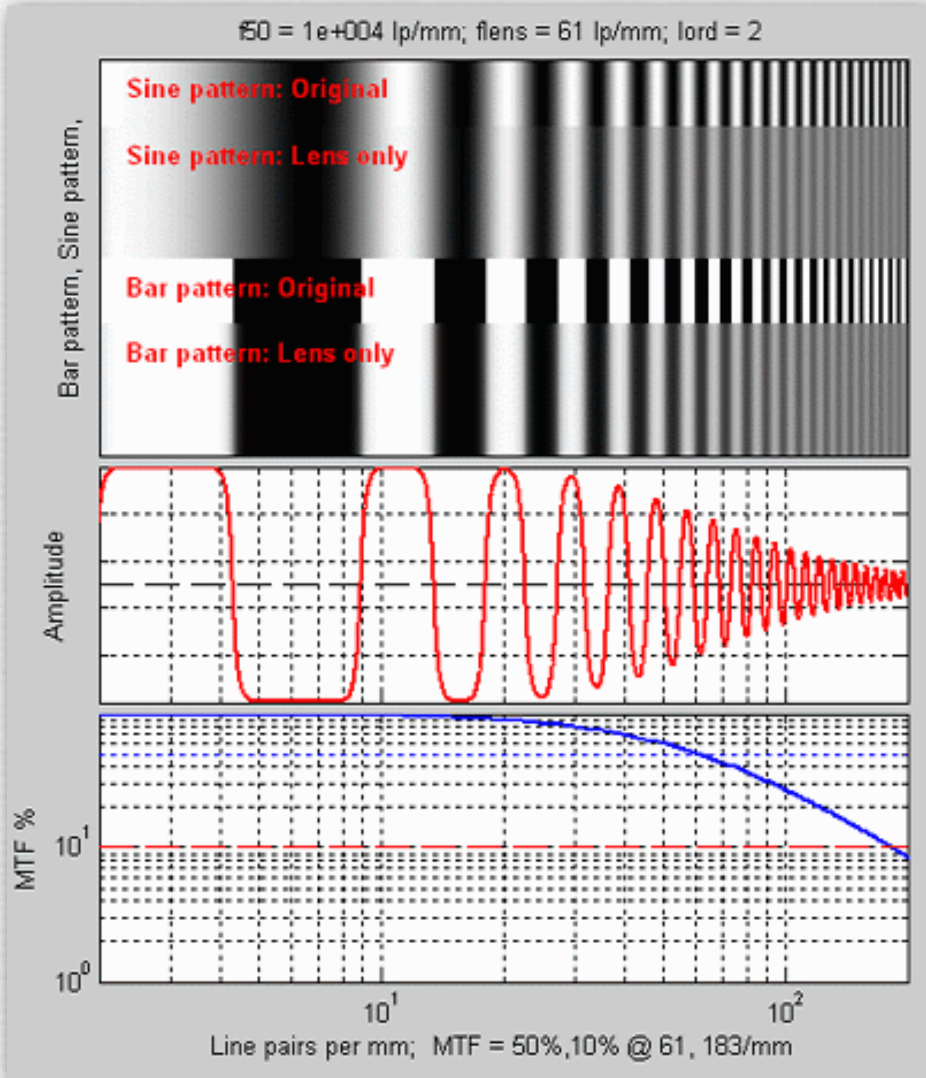
Describing sharpness: the modulation transfer function (MTF)



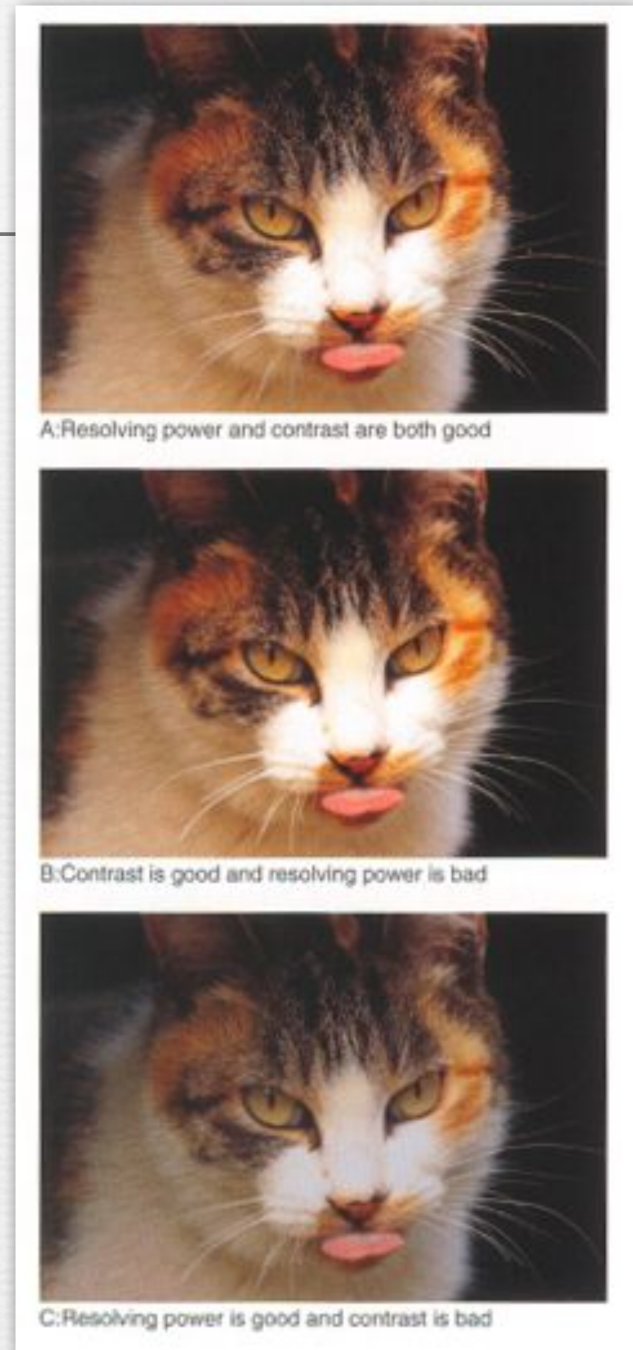
- the amount of each spatial frequency that can be reproduced by an optical system

(imatest.com)

Sharpness versus contrast



(imatest.com)



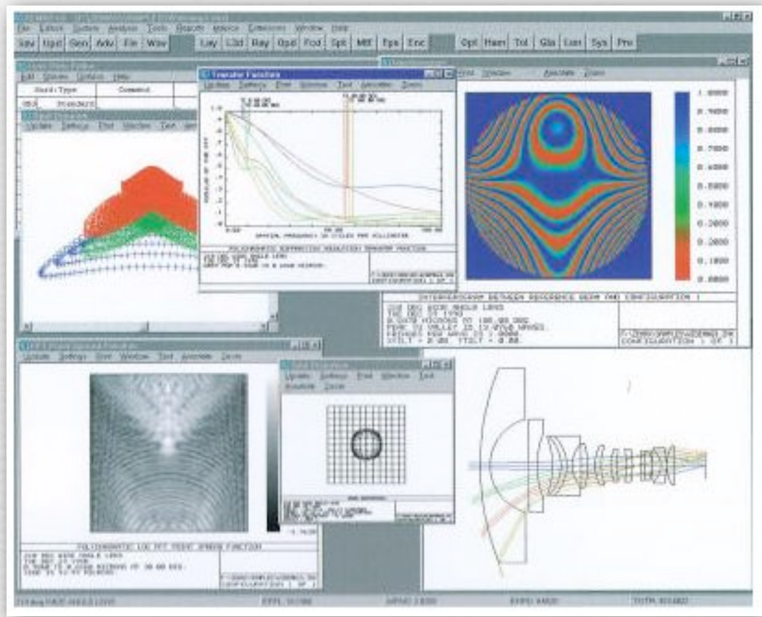
(Canon)

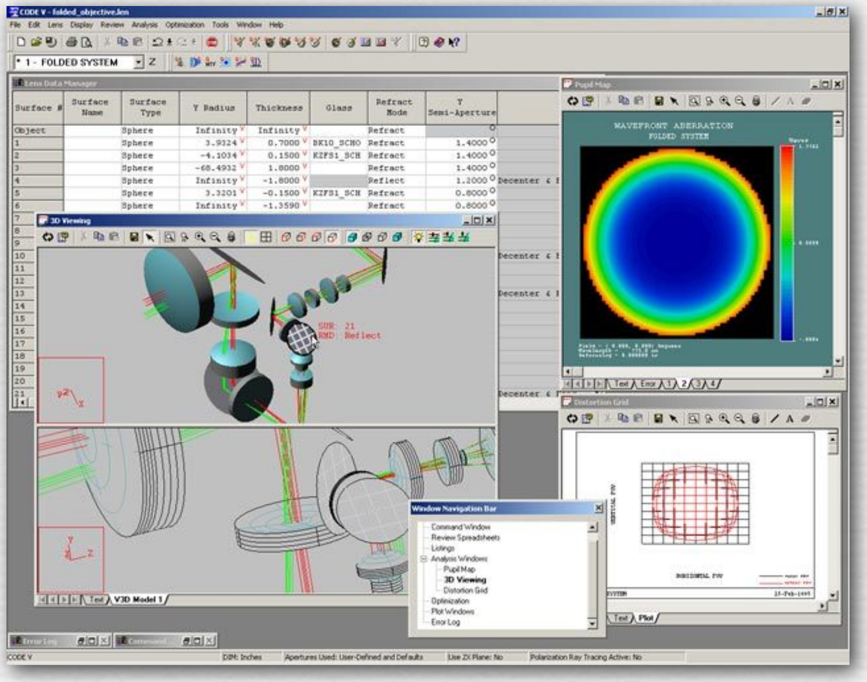
Recap

- all optical systems suffer from veiling glare
  - anti-reflection coatings help
- all optical systems suffer from flare and ghosts
  - don't point your camera at bright lights; use lens hoods
- vignetting arises from many sources
  - natural - falloff at the edges of wide sensors
  - optical - caused by apertures, lens barrels
  - mechanical - caused by wrong lens hoods, hands, straps
  - pixel - caused by shadowing inside pixel structures
- diffraction - blur that varies with $N = f / A$
  - avoid F-numbers above f/16 (for full-frame camera)
  - subjective image quality depends on both sharpness and contrast

Questions?

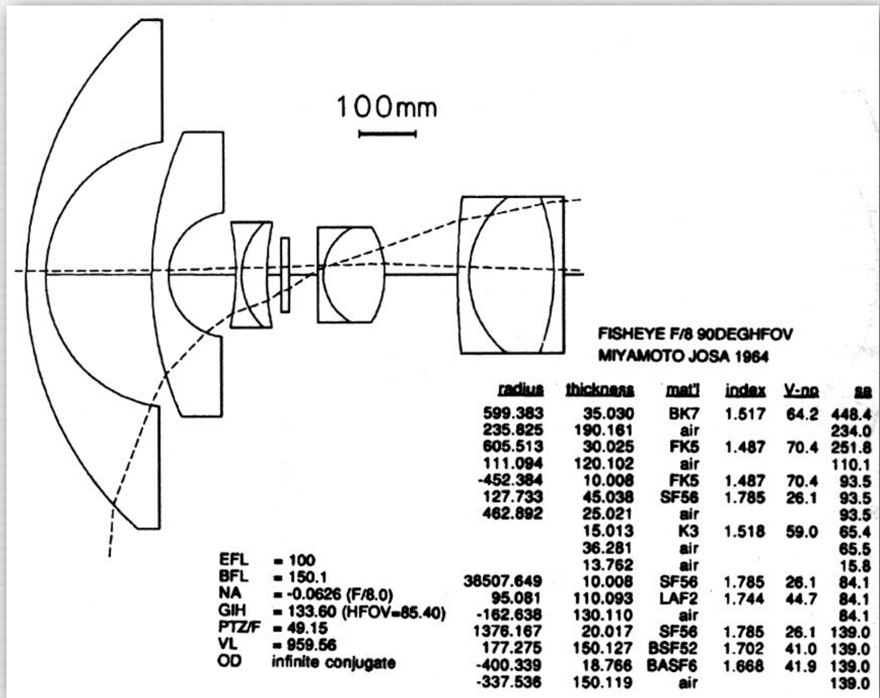
Lens design software





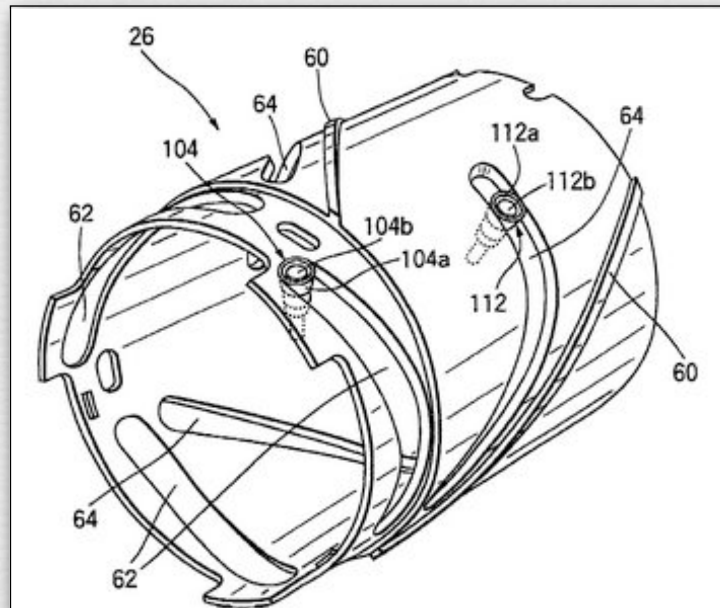
- ✦ uses optimization to make good recipes better

Lens catalogs and patents



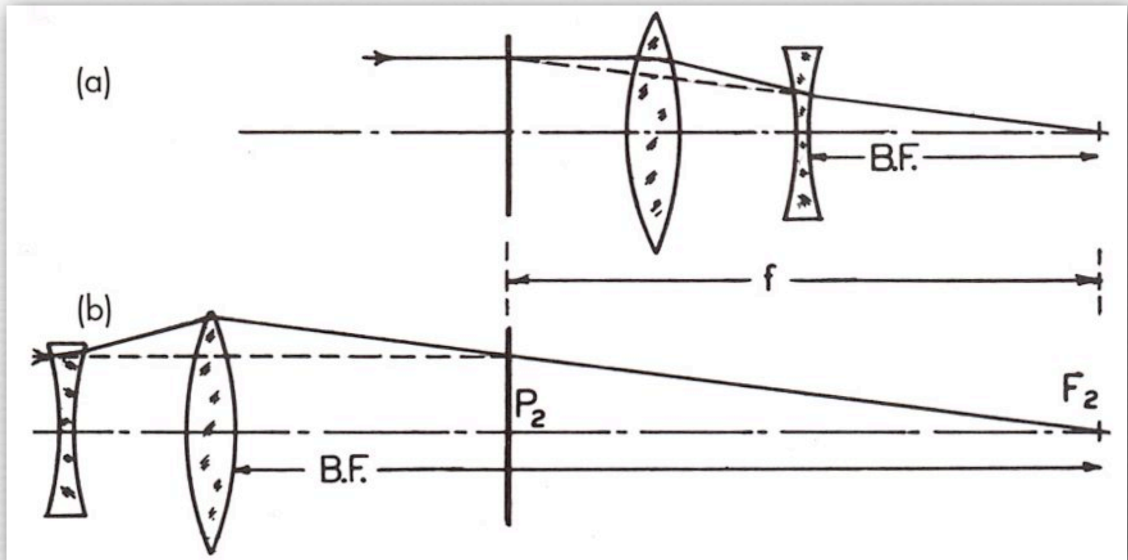
radius	thickness	mat'l	index	V-no	sa
599.383	35.030	BK7	1.517	64.2	448.4
235.825	190.161	air			234.0
605.513	30.025	FK5	1.487	70.4	251.8
111.094	120.102	air			110.1
-452.384	10.008	FK5	1.487	70.4	93.5
127.733	45.038	SF56	1.785	26.1	93.5
462.892	25.021	air			93.5
	15.013	K3	1.518	59.0	65.4
	36.281	air			65.5
	13.762	air			15.8
38507.649	10.008	SF56	1.785	26.1	84.1
95.081	110.093	LAF2	1.744	44.7	84.1
-162.638	130.110	air			84.1
1376.167	20.017	SF56	1.785	26.1	139.0
177.275	150.127	BSF52	1.702	41.0	139.0
-400.339	18.766	BASF6	1.668	41.9	139.0
-337.536	150.119	air			139.0

EFL = 100
BFL = 150.1
NA = -0.0626 (F/8.0)
GIH = 133.60 (HFOV=85.40)
PTZ/F = 49.15
VL = 959.56
OD infinite conjugate



- hard to find optical recipe for commercial camera lenses

Lens combinations: telephoto



(Kingslake)

- telephoto (a) reduces the back focal distance B.F. relative to *f*
  - for long focal length lenses, to reduce their physical size
- reversed telephoto (b) increases B.F. relative to *f*
  - for wide-angle lenses, to ensure room for the reflex mirror

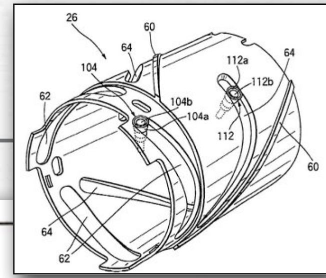
Lens combinations: telephoto

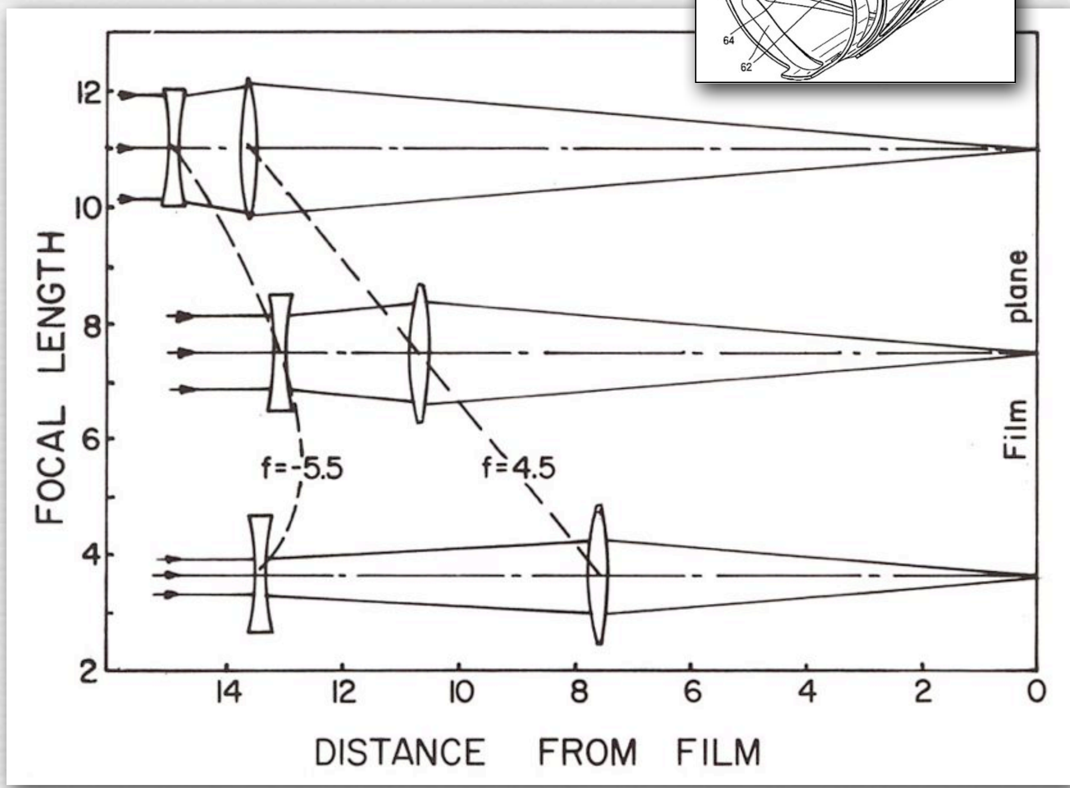
(wikipedia)

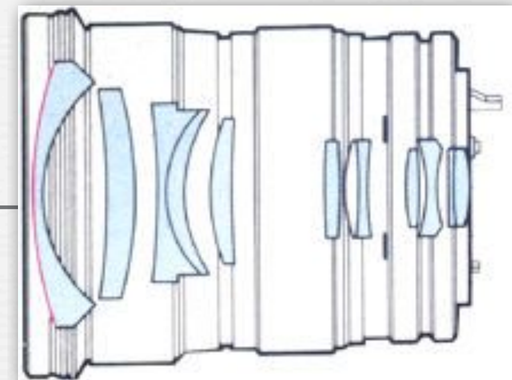
500mm non-telephoto

Canon 500mm telephoto

Lens combinations: zoom







Canon FD 24-35mm
f/3.5 L manual focus lens

(FLASH DEMO)

http://graphics.stanford.edu/courses/cs178/applets/zoom.html

- called *optically compensated zoom*, because the in-focus plane stays (more or less) stationary as you zoom
- to change focus, you move both lenses together

Slide credits

- Steve Marschner
- Fredo Durand

- Cole, A., *Perspective*, Dorling Kindersley, 1992.
- Kemp, M.,*The Science of Art*,Yale University Press, 1990.
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