Optics II: practical photographic lenses

CS 178, Spring 2011

Begun 4/7/11. Finished 4/12/11.

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Outline

- why study lenses?
- thin lenses
  - graphical constructions, algebraic formulae
- thick lenses
  - center of perspective, 3D perspective transformations
- depth of field
- aberrations & distortion
- vignetting, glare, and other lens artifacts
- diffraction and lens quality
- special lenses
  - telephoto, zoom

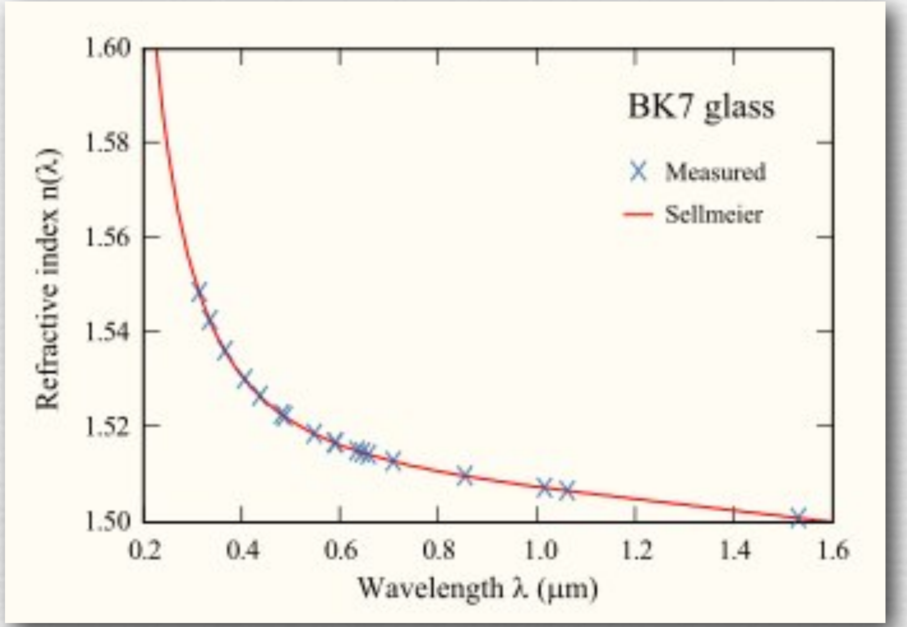
Lens aberrations

- 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

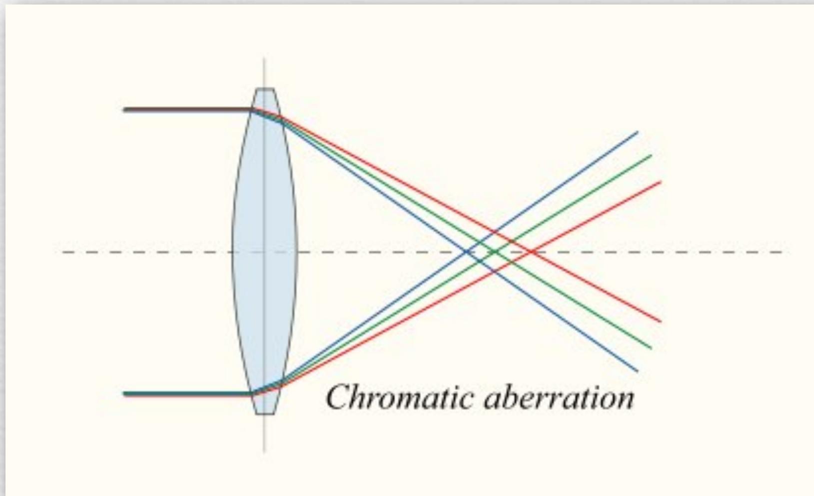


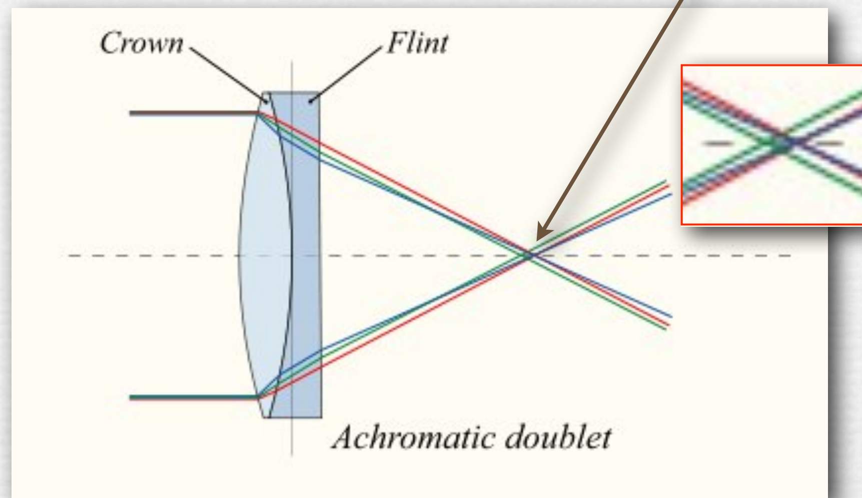
(wikipedia)

- 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

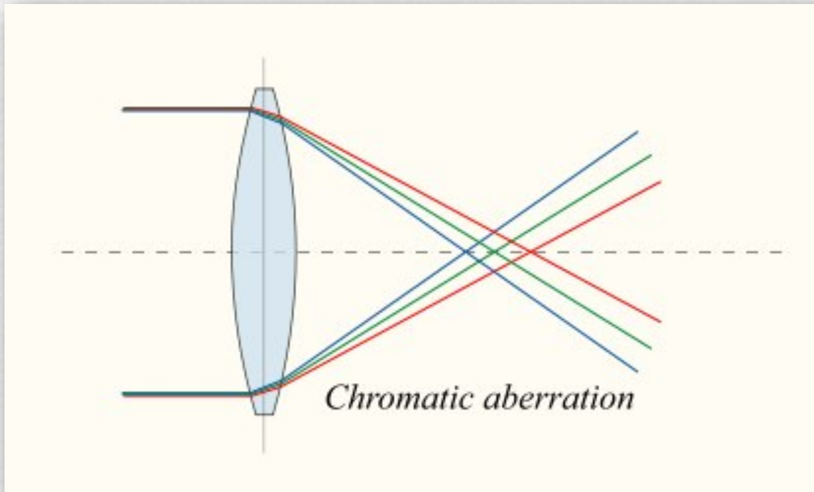


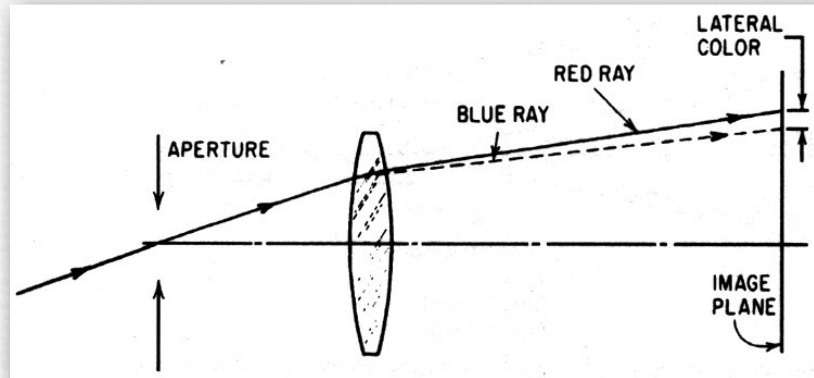


(wikipedia)

- 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

Examples

- correctable in software
- not

(wikipedia)

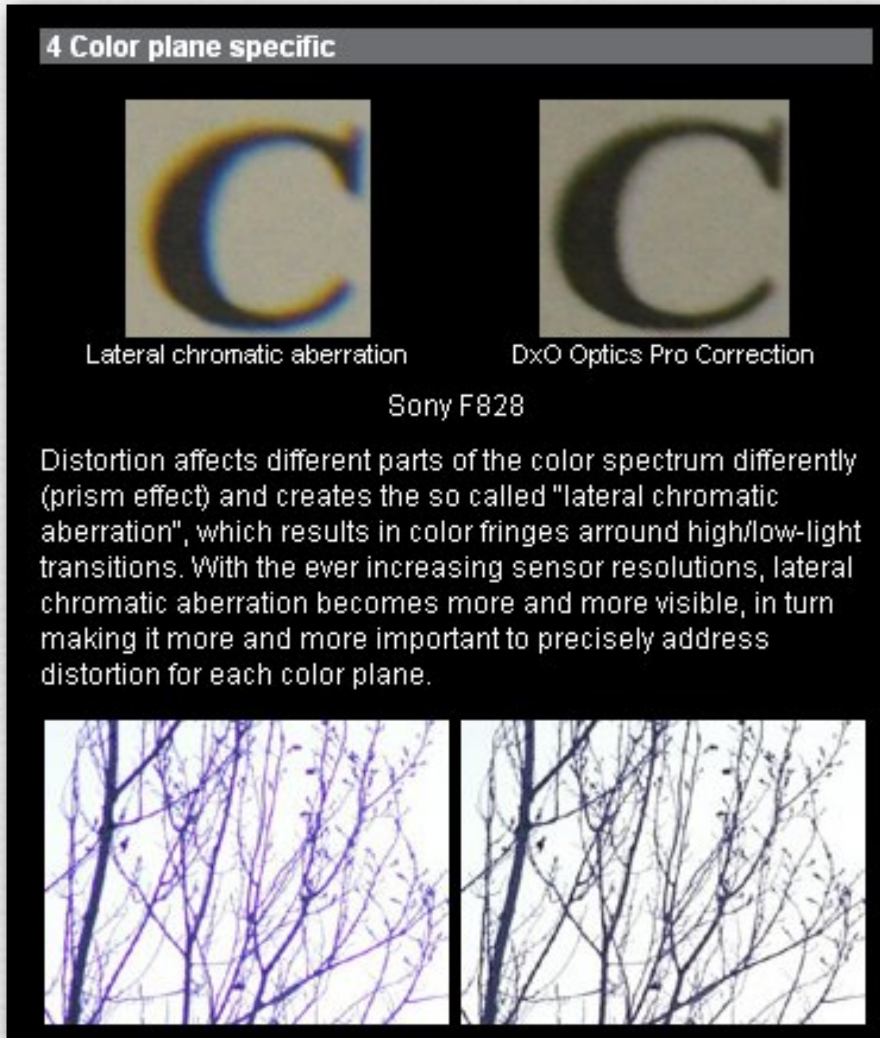
lateral

(toothwalker.org)

longitudinal

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

Software correction of lateral chromatic aberration

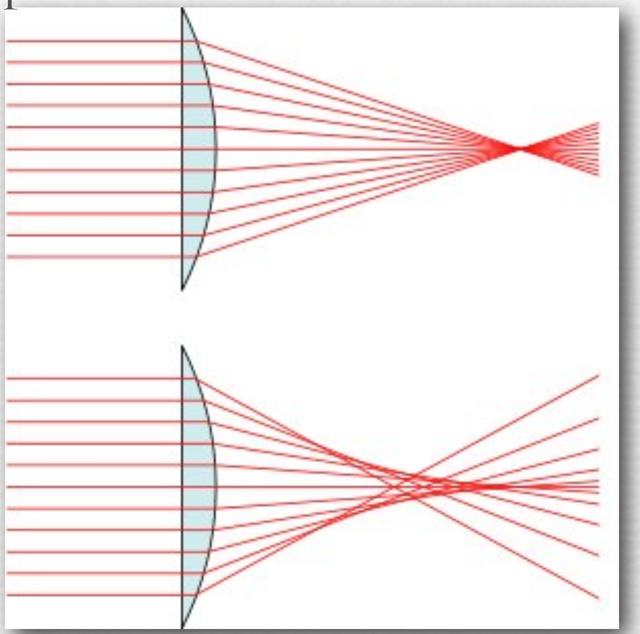


- Panasonic GF1 corrects for chromatic aberration in the camera (or in Adobe Camera Raw)
  - need focal length of lens, and focus setting

Q. Why don't humans see chromatic aberration?

Spherical aberration

hyperbolic lens



spherical lens (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

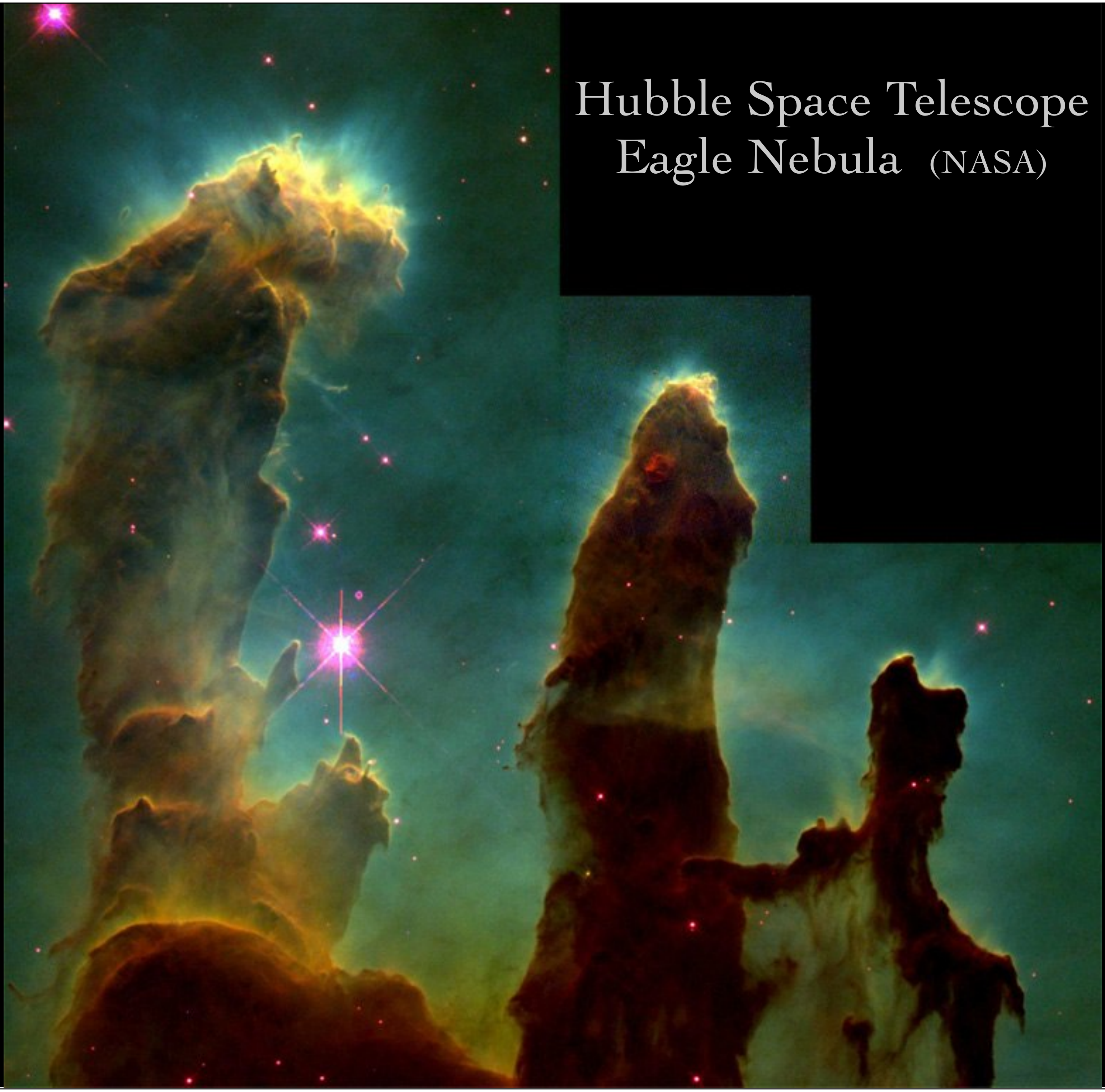
soft focus

Canon 135mm f/2.8 soft focus lens

Hubble telescope

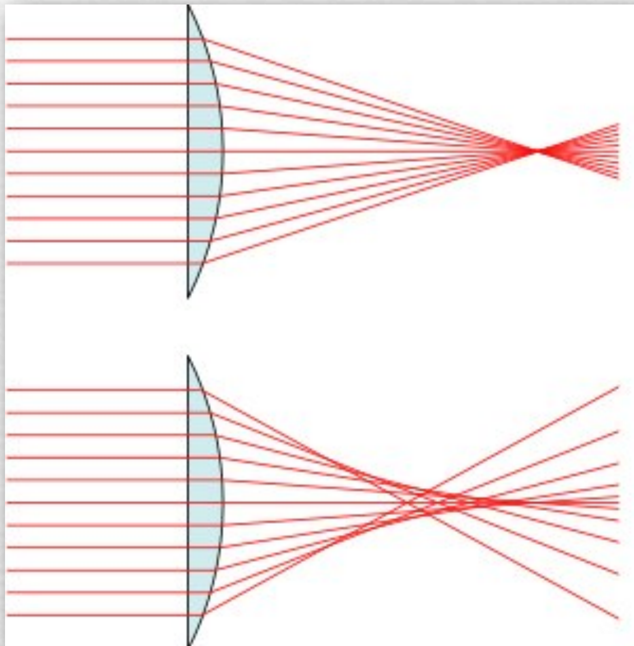
before correction

after correction



Hubble Space Telescope
Eagle Nebula (NASA)

Focus shift



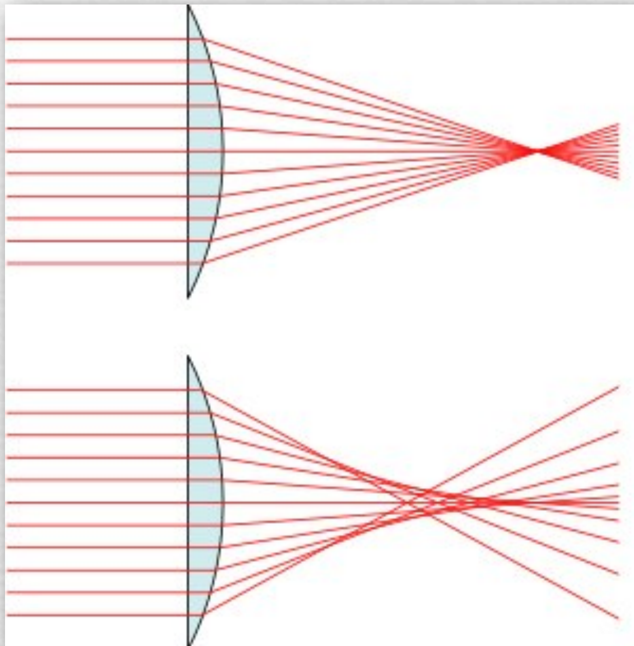
(wikipedia)

(diglloyd.com)

focused at f/1.2

- Canon 50mm f/1.2 L

Focus shift


(wikipedia)

(diglloyd.com)

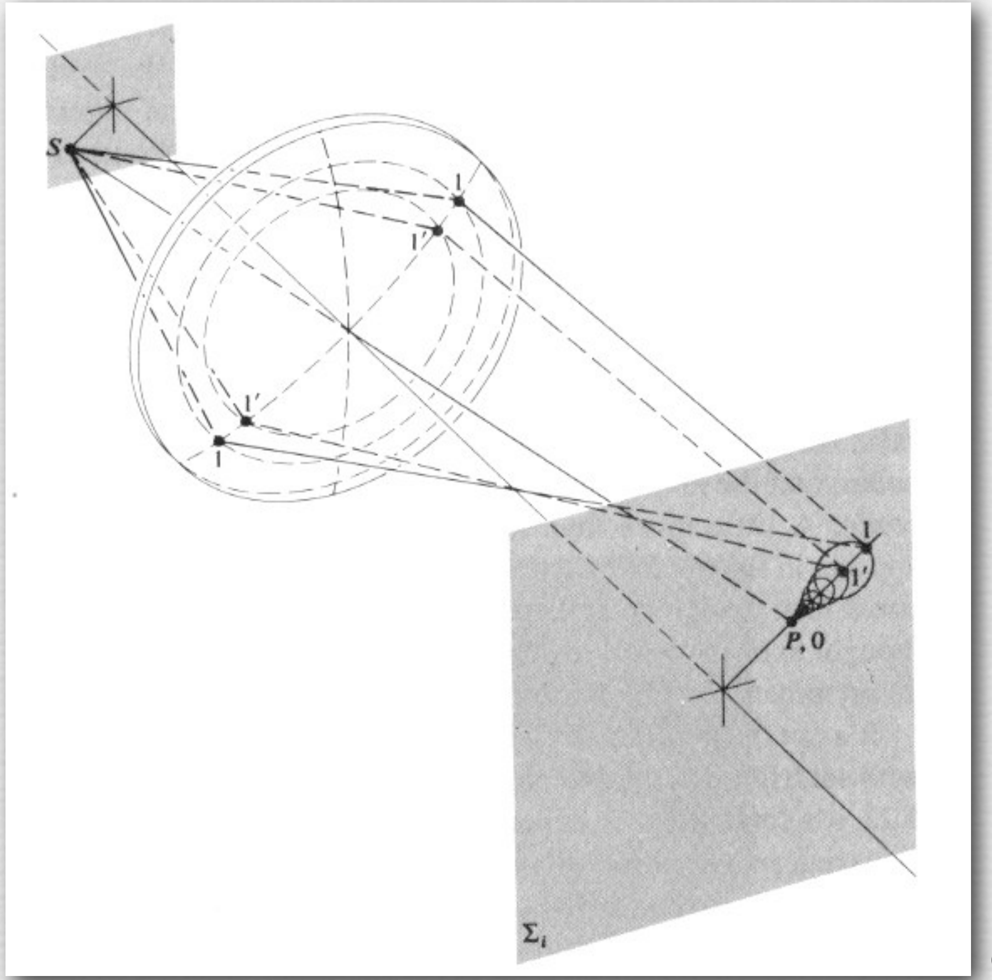

shot at f/1.8

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

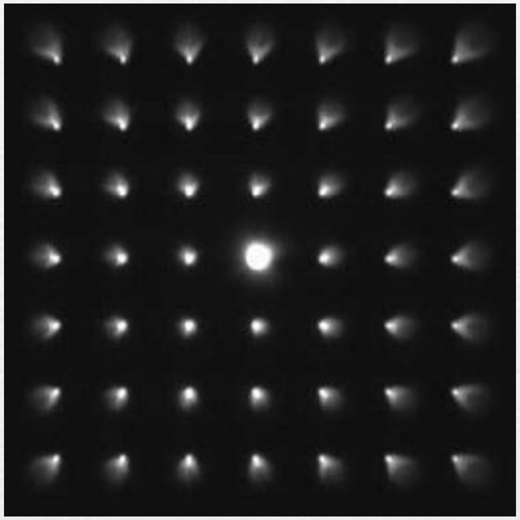
Oblique aberrations

- lateral chromatic aberrations do not appear in center of field
  - they get worse with increasing distance from the optical axis
  - cannot reduce by closing down the aperture
- longitudinal chromatic & spherical aberrations occur everywhere in the field of view
  - on and off the optical axis
  - can reduce by closing down the aperture
- oblique aberrations do not appear in center of field
  - they get worse with increasing distance from the optical axis
  - can reduce by closing down the aperture
  - coma and astigmatism

Coma



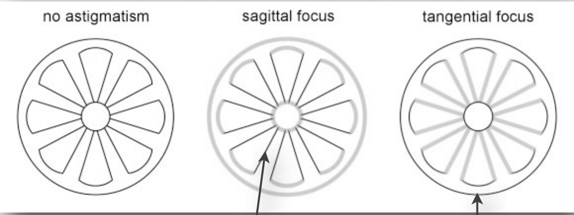
(Hecht)

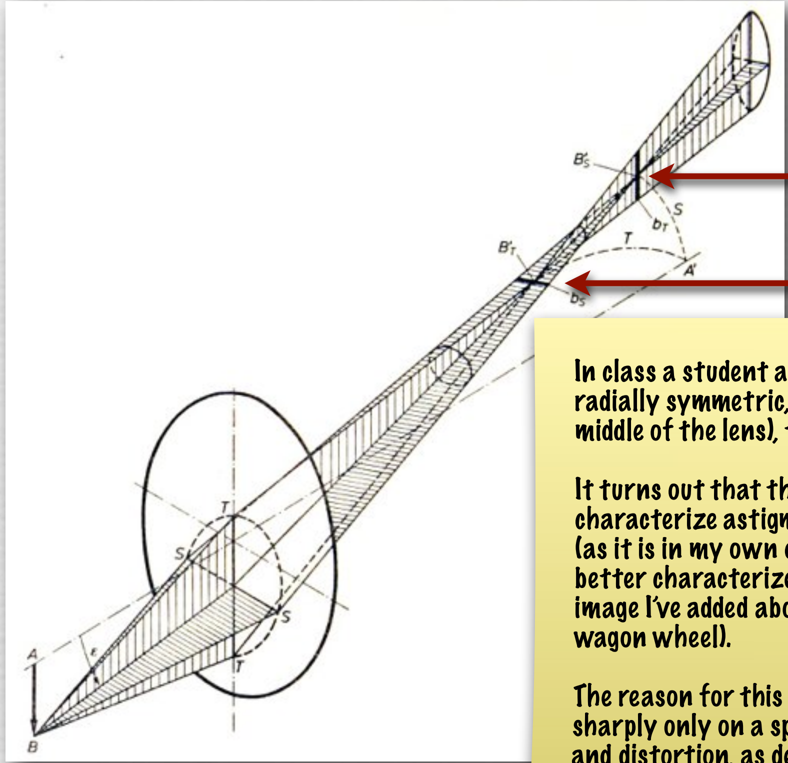


(ryokosha.com)

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

Astigmatism





focus of sagittal rays

focus of tangential rays

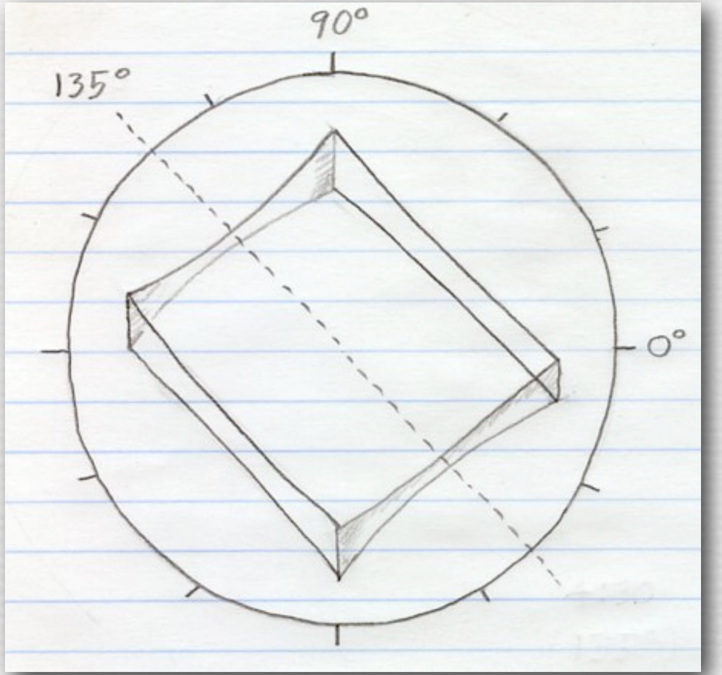
In class a student asked why spherical lenses should exhibit astigmatism. If they are indeed radially symmetric, i.e. the same cross-sectional shape when traveling in all directions from the middle of the lens), then horizontal and vertical lines in the scene should not focus differently.

It turns out that the diagram I used in this slide, taken from Hecht, is an appropriate way to characterize astigmatism in human eyes, where the eye or lens or cornea may actually be oblong (as it is in my own eyes). However, in photographic lenses, which are never oblong, astigmatism is better characterized by saying that radial features (like the spokes of the wagon wheels in the image I've added above) come to a focus at a different depth than circular features (the rim of the wagon wheel).

The reason for this astigmatism is not that the lens is oblong, but that spherical lenses can focus sharply only on a spherical surface, whereas a digital sensor is flat. This leads to field curvature and distortion, as described elsewhere in these slides. It also leads to astigmatism, as described in this sticky note. Thank you to this observant student; these questions help me improve my slides.

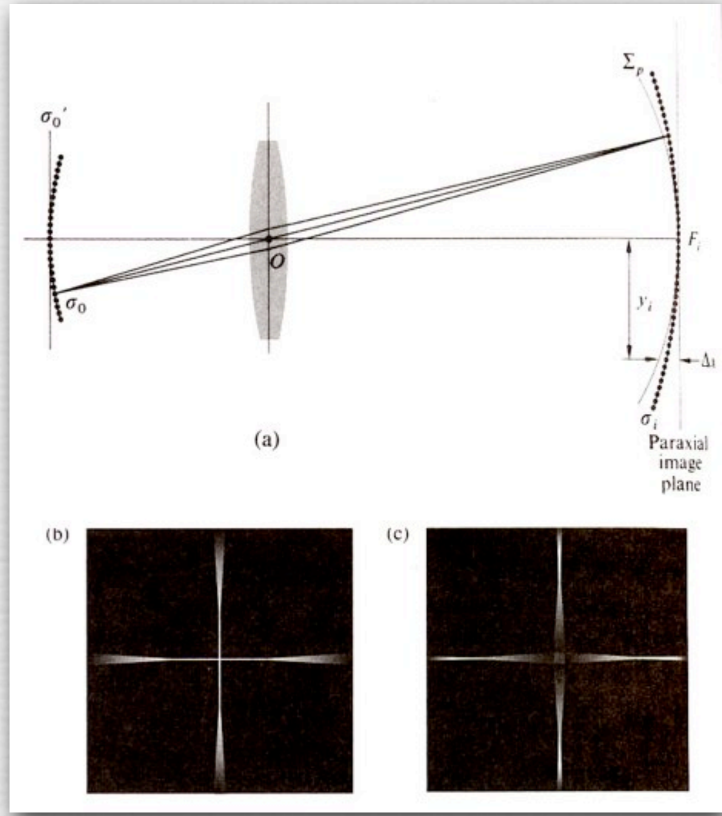
- tangential and sagittal rays focus at different depths
- my full eyeglass prescription
  - right: -0.75 -1.00 axis 135, left: -1.00 -0.75 axis 180

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 extrusion axis of second curvature is 135° (10:30 - 4:30 on the clock)

Field curvature



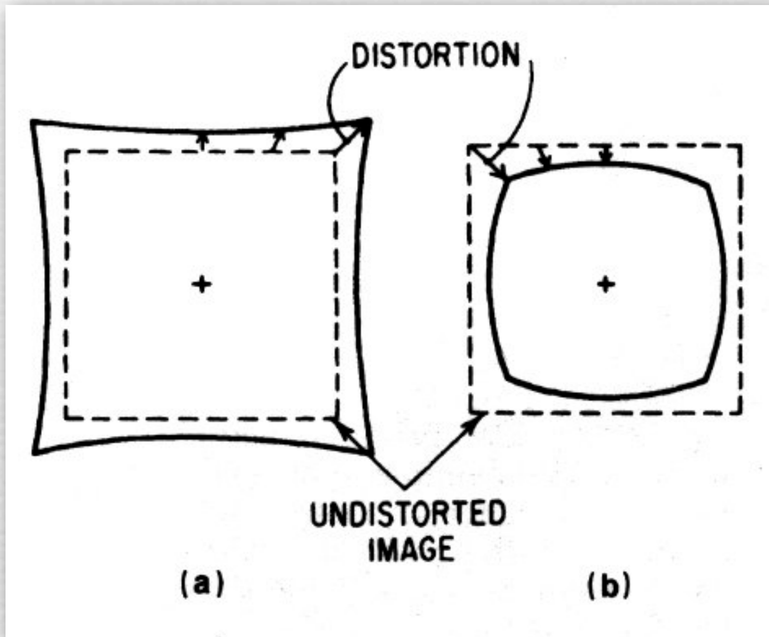
(Hecht)

- 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

- correctable in software

(Smith)

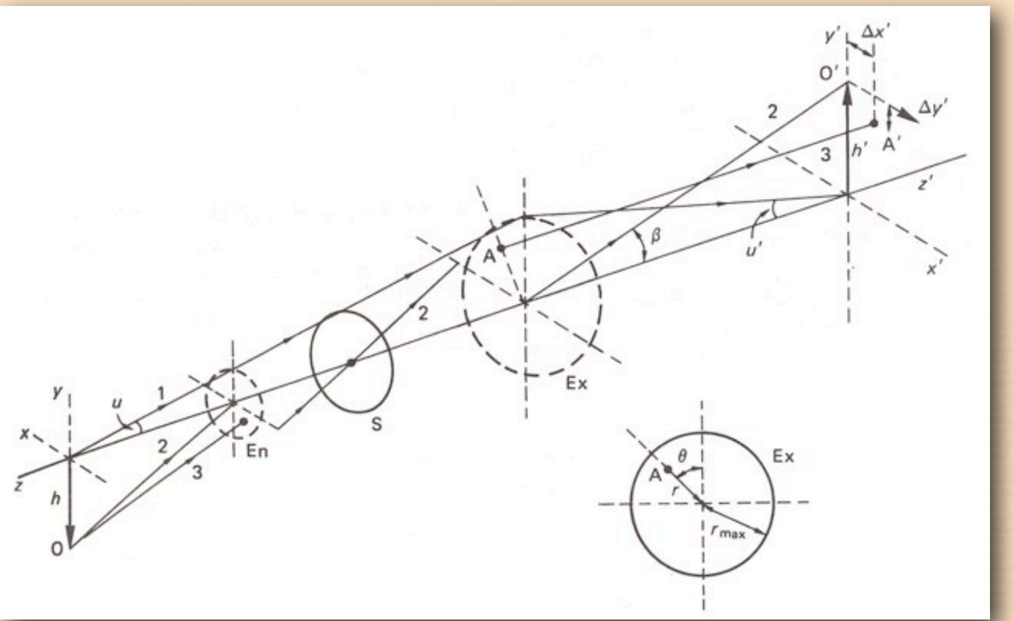


(Kingslake)

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

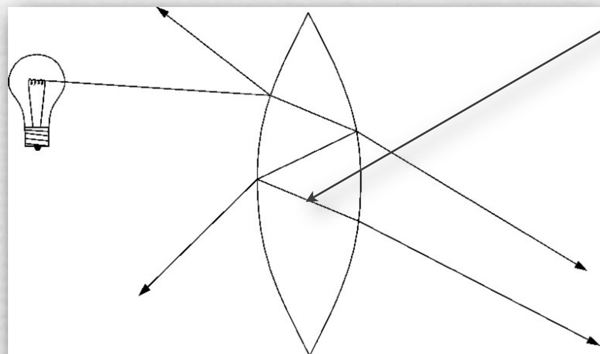
- all lenses are subject to chromatic aberration
  - longitudinal appears everywhere; lateral is worse at edges
  - only longitudinal can be reduced by closing down aperture
  - both can be partly corrected using more lenses, and lateral can be partly corrected using software

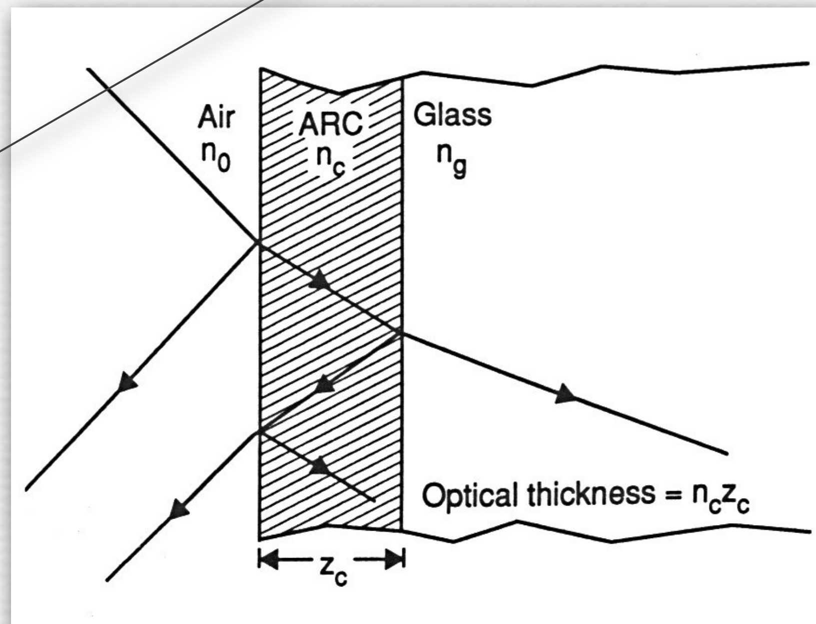
- all spherical lenses are subject to Seidel aberrations: spherical, coma, astigatism, field curvature, distortion
  - some appear everywhere; others only at edges
  - all but distortion can be reduced by closing down aperture
  - only distortion can be corrected completely in software

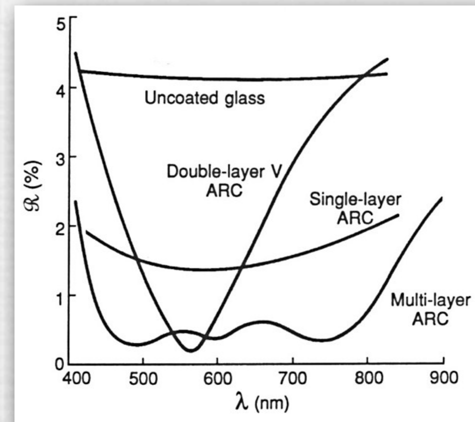
Questions?

Veiling glare

After class a student asked why we care about reducing reflections that are headed back into the scene, as the middle diagram below seems to be suggesting. We don't, but this same coating, placed on the outside of the outermost lens element, will also reduce reflections originating inside the camera, i.e. this unwanted reflection...



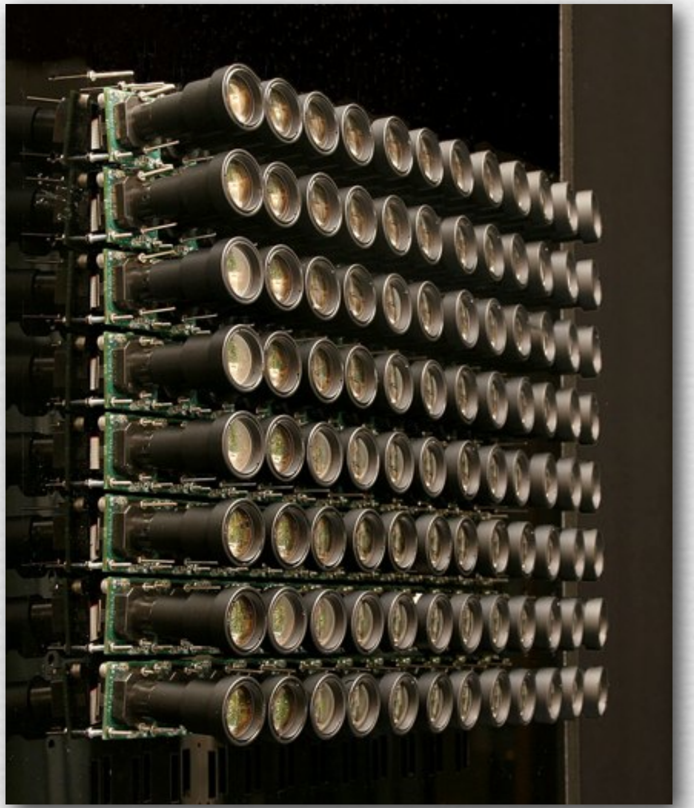




- contrast reduction caused by stray reflections
- can be reduced by anti-reflection coatings
  - based on interference, so optimized for one wavelength
  - to cover more wavelengths, use multiple coatings

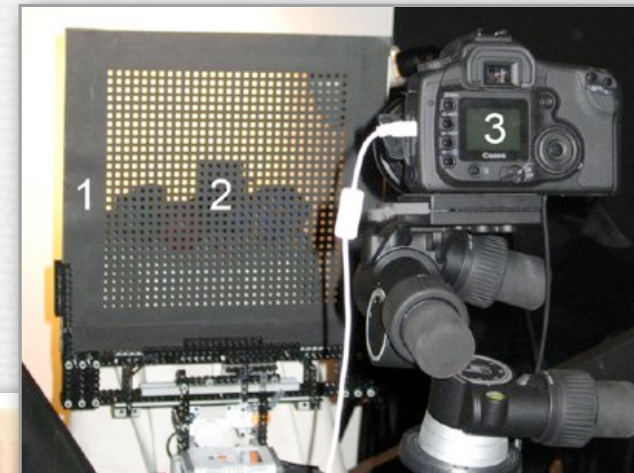
Camera array with too much glare

Stanford
Multi-Camera
Array

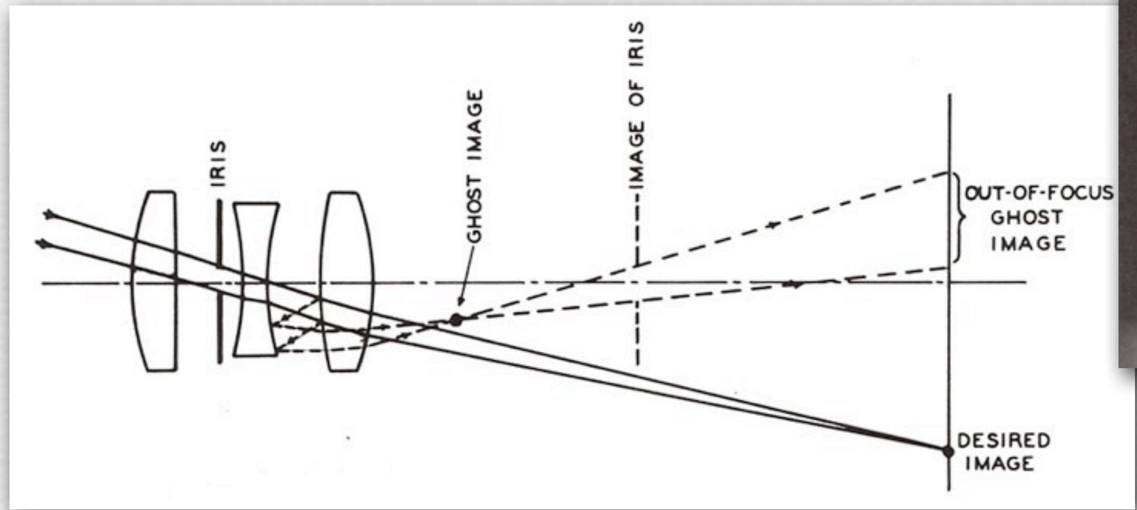


- 12 × 8 array of 600 × 800 pixel webcams = 7,200 × 6,400 pixels
- goal was highest-resolution movie camera in the world
- failed because glare in inexpensive lenses led to poor contrast

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



Flare and ghost images



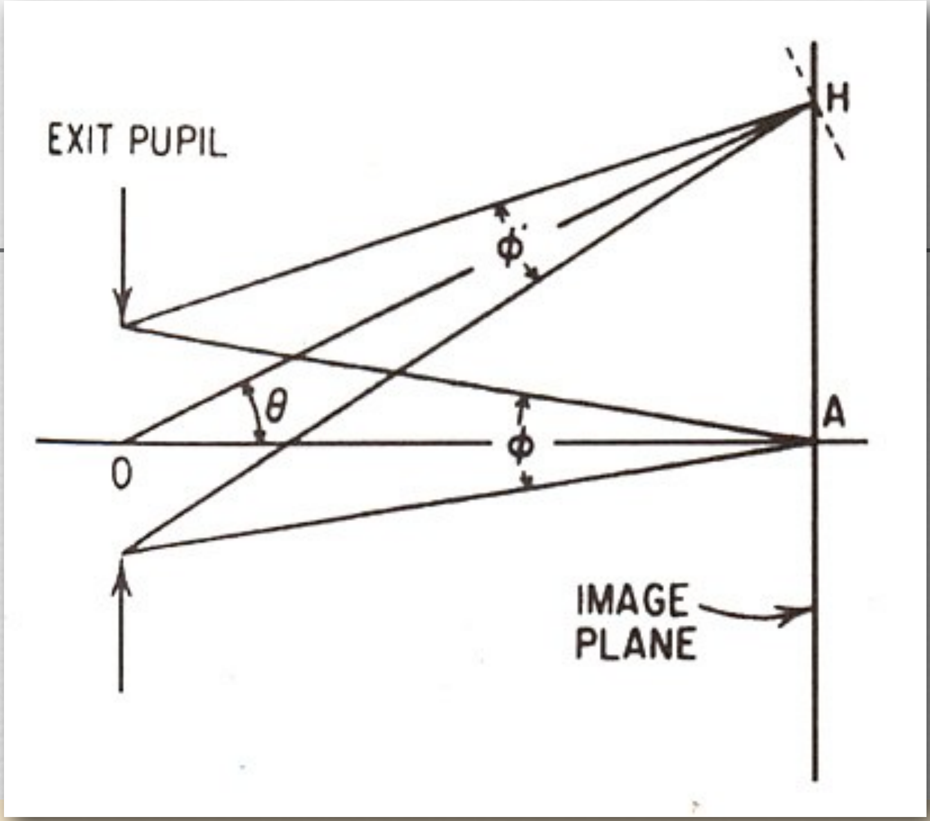
(Kingslake)

- 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)



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

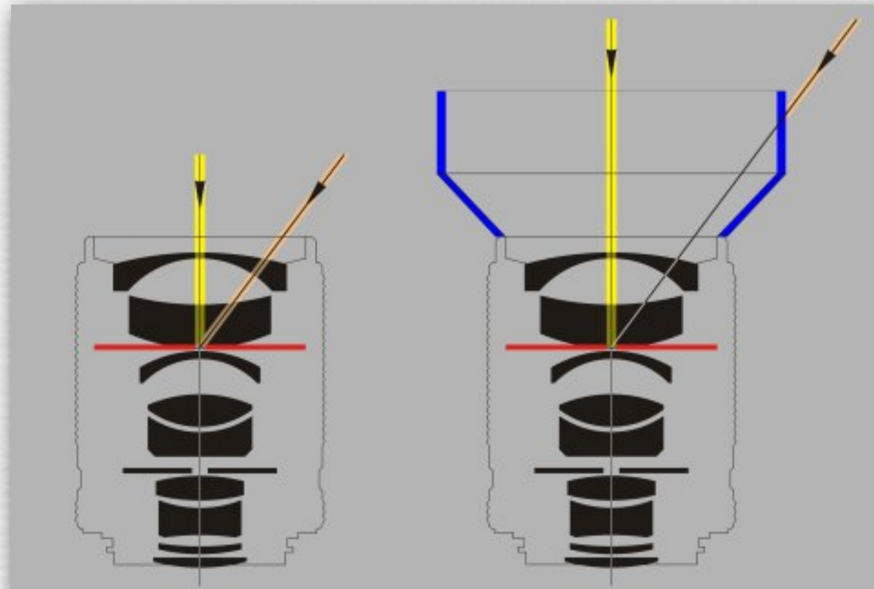
Other sources of vignetting

f/1.4 f/5.6

axial

semifield

(toothwalker.org)



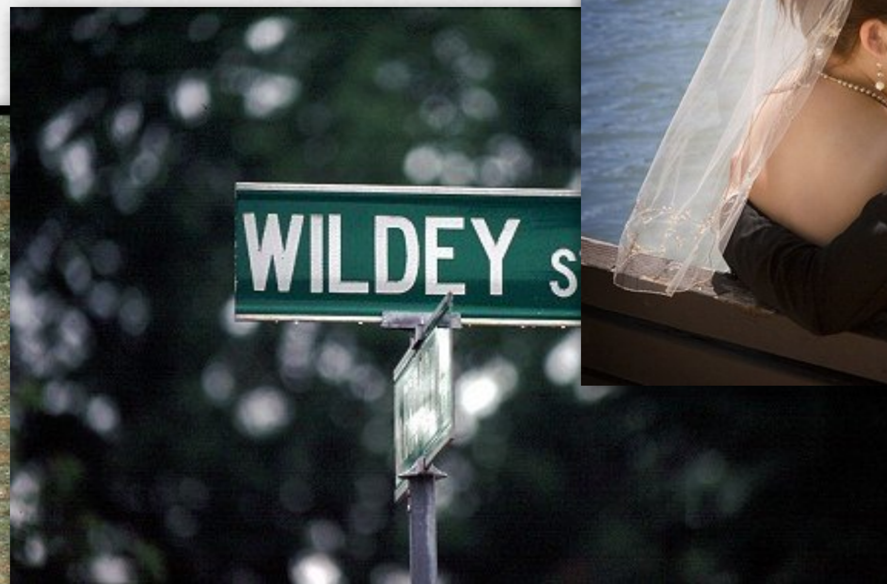
optical vignetting
from multiple lens elements,
especially at wide apertures

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)

Examples

(toothwalker.org)

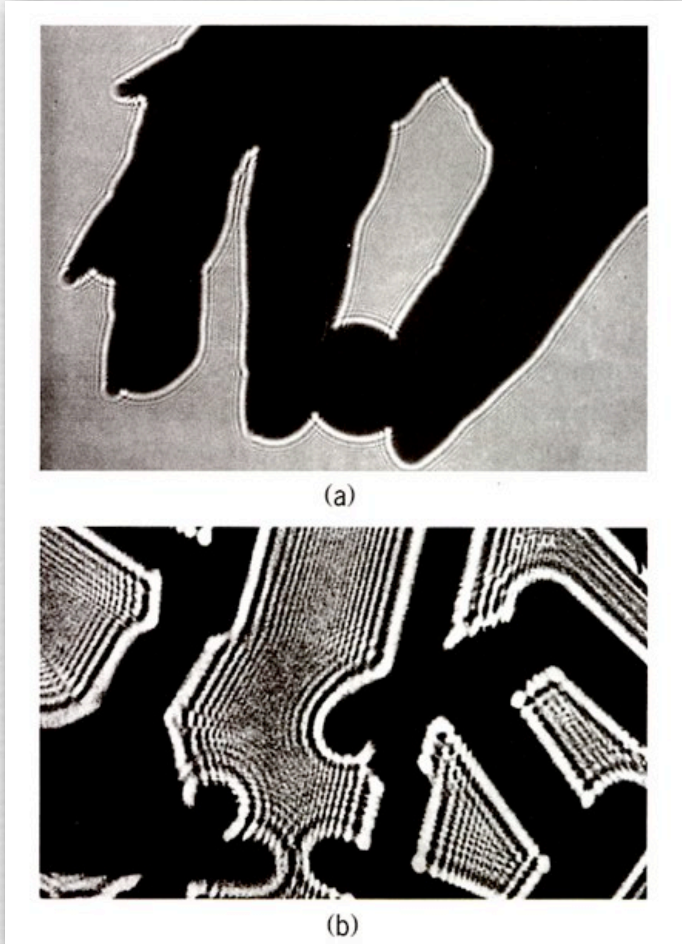


(toothwalker.org)

(wikipedia)

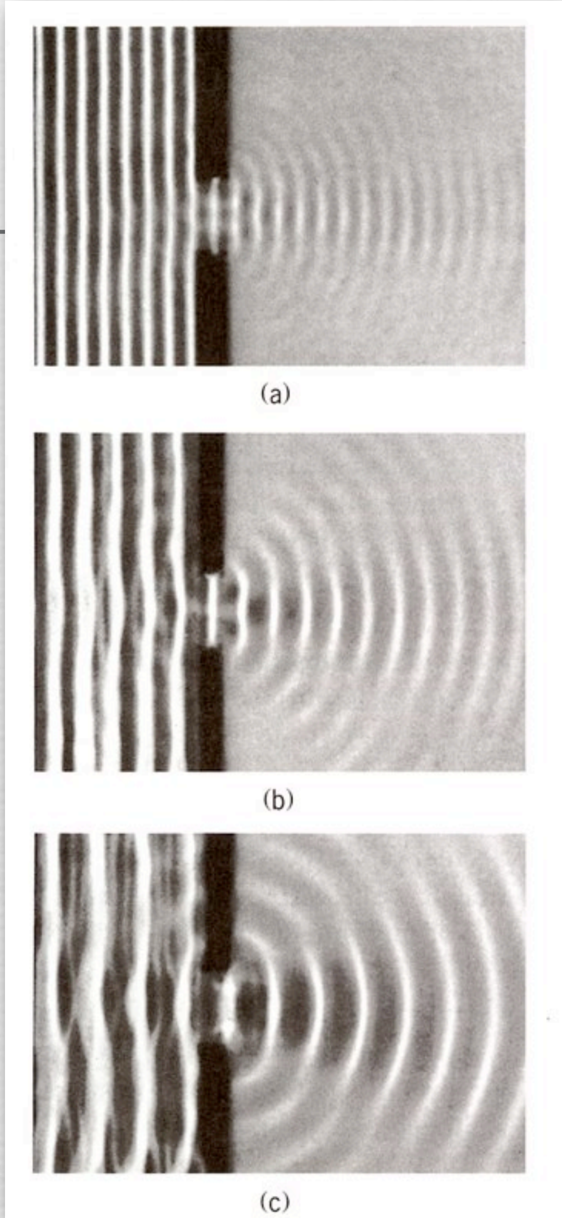
- vignetting affects the *bokeh* of out-of-focus features
- vignetting is correctable in software (except for bokeh effects), but boosting pixel values worsens noise
- vignetting can be appled afterwards, for artistic purposes

Diffraction



illuminated by a
(spread-out) laser beam
& recorded directly on film

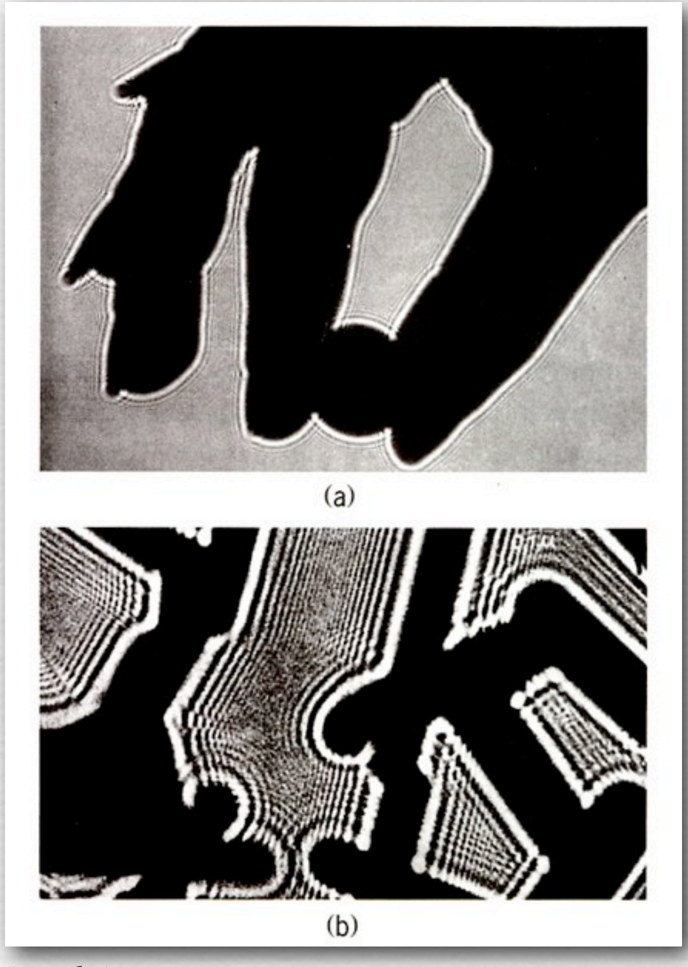
varying the wavelength
of waves passing through
a slit in a ripple tank



(Hecht)

- as wavelength decreases in the ripple tank, propagation becomes more ray-like

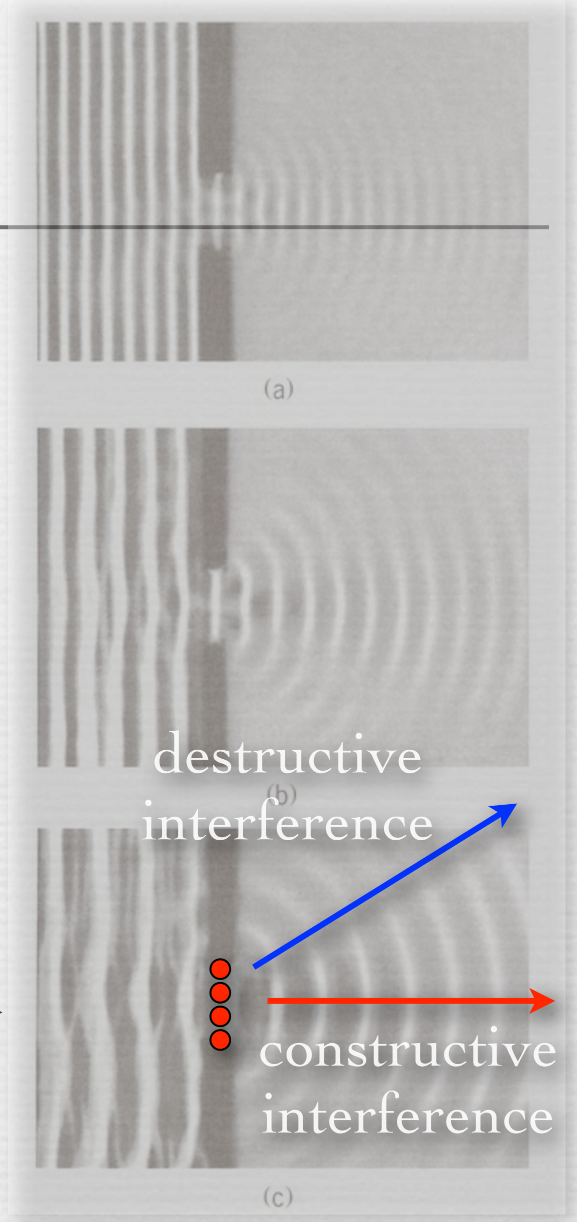
Diffraction



(Hecht)

illuminated by a (spread-out) laser beam & recorded directly on film

varying the wavelength of waves passing through a slit in a ripple tank



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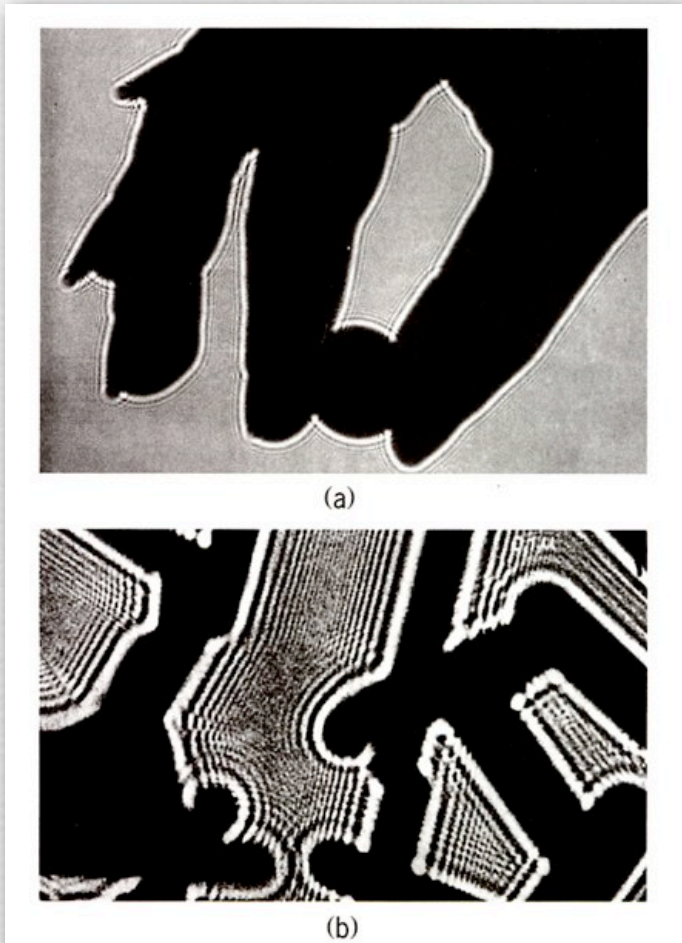
Diffraction



(Hecht)

illuminated by a (spread-out) laser beam & recorded directly on film

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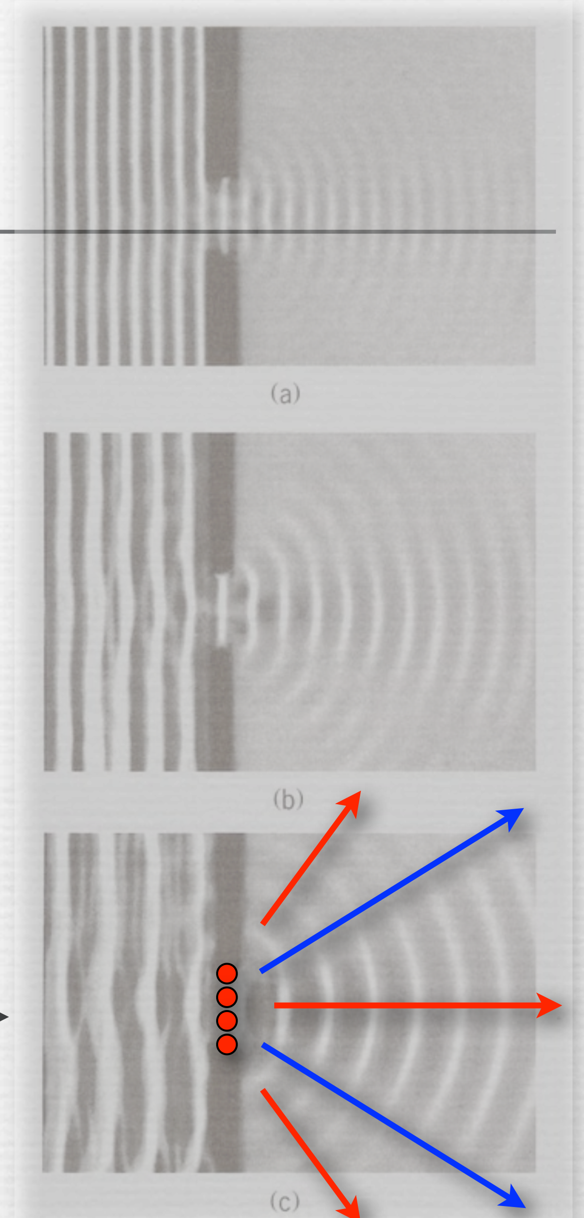
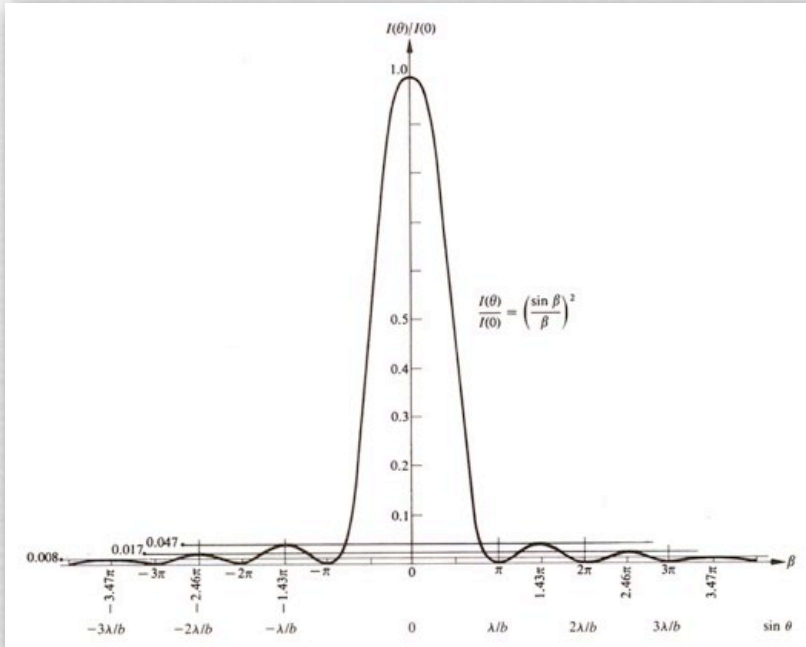
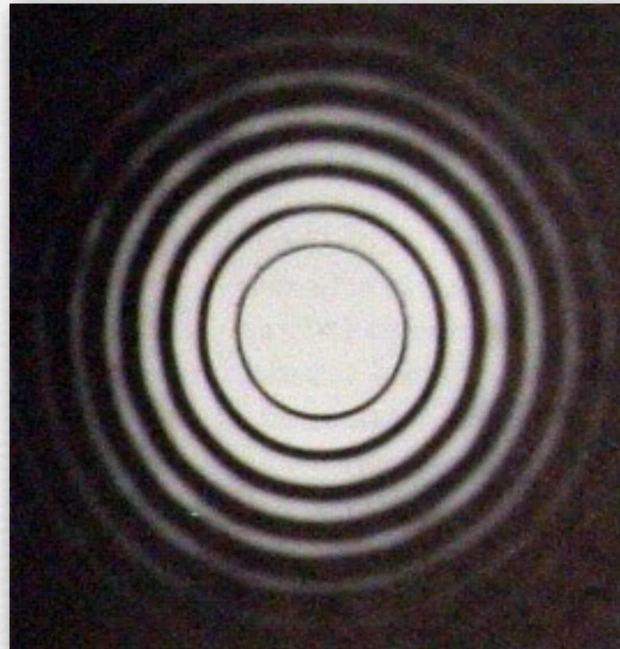


- as wavelength decreases in the ripple tank, propagation becomes more ray-like

Airy rings



diffraction from a slit



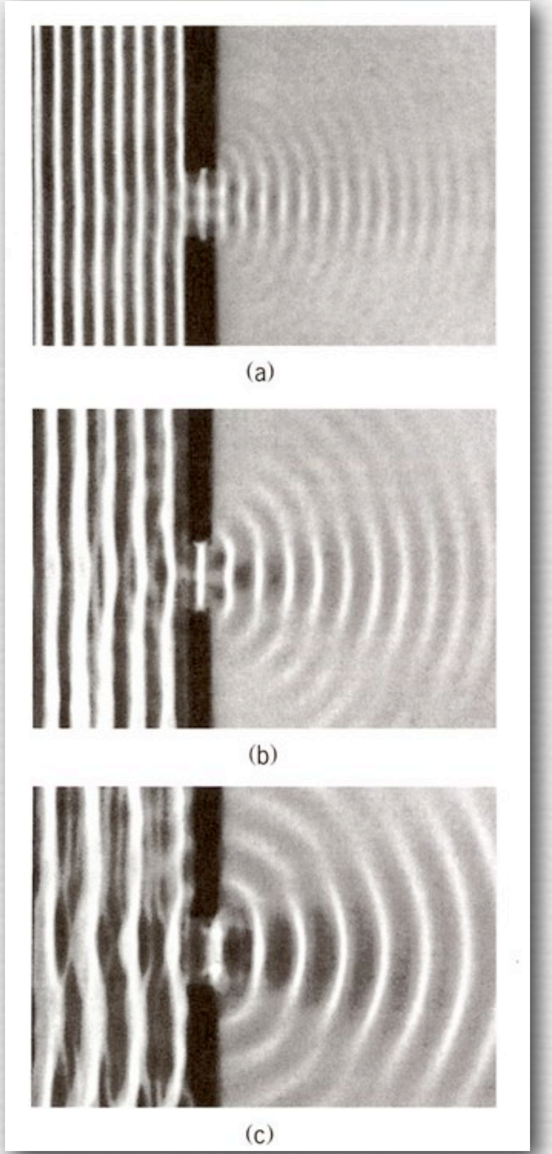
(Hecht)

diffraction from a circular aperture: Airy rings

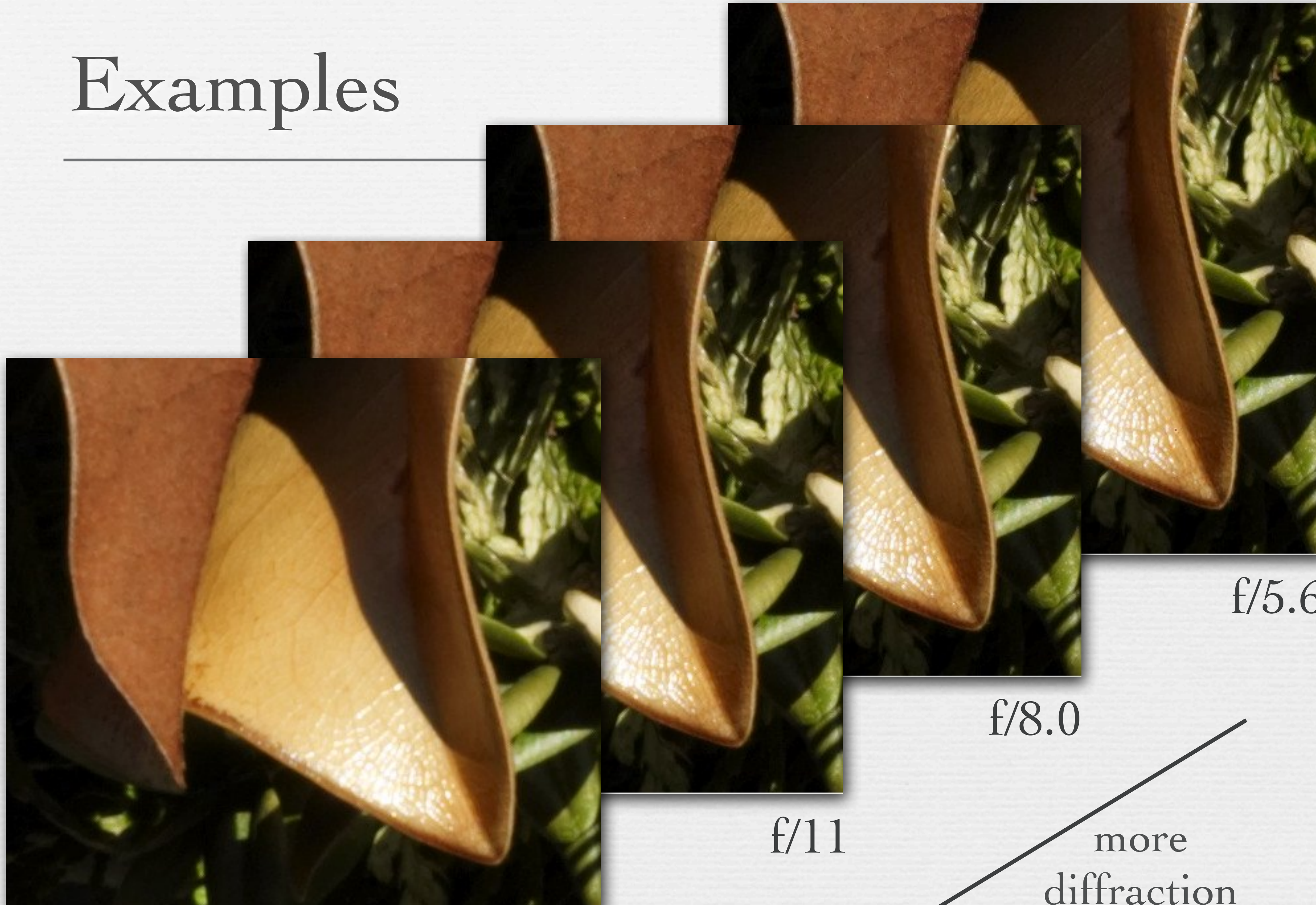
- if the illumination were a laser, a lens would produce this pattern
- but considering all wavelengths, the dark rings vanish, leaving a blur

Diffraction in photographic cameras

- well-corrected lenses are called *diffraction-limited*
- the smaller the aperture (A) (or the longer the wavelength), the larger the diffraction blur
- the longer the distance to the sensor (f), the larger the blur
- thus, the size of the blur varies with $N = f / A$



Examples



f/5.6

f/8.0

f/11

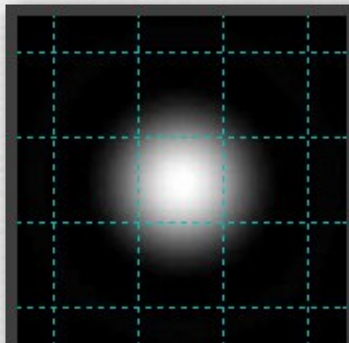
f/22

more diffraction

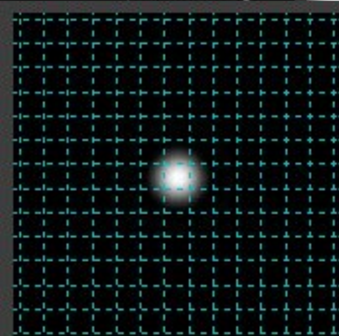
(luminous-landscape.com)

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. μm²
f/2.8	Canon EOS 1Ds	77.6 μm²
f/4.0	Canon EOS 1DMkII / 5D	67.1 μm²
f/5.6	Nikon D70	61.1 μm²
f/8.0	Canon EOS 10D	
f/11	Canon EOS 1DsMkII	
f/16	Canon EOS 20D / 35	
f/22	Nikon D2X	
f/32	Canon PowerShot G	



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f/5.6	Nikon D70	61.1 μm²
f/8.0	Canon EOS 10D	54.6 μm²
f/11	Canon EOS 1DsMkII	52.0 μm²
f/16	Canon EOS 20D / 350D	41.2 μm²
f/22	Nikon D2X	30.9 μm²
f/32	Canon PowerShot G6	5.46 μm²

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

The Abbe diffraction limit

$$d = \frac{.61\,\lambda}{NA} \approx 1.2\,N\,\lambda$$

- where
  - λ = wavelength
  - *NA* = numerical aperture ≈ 1 / 2*N*

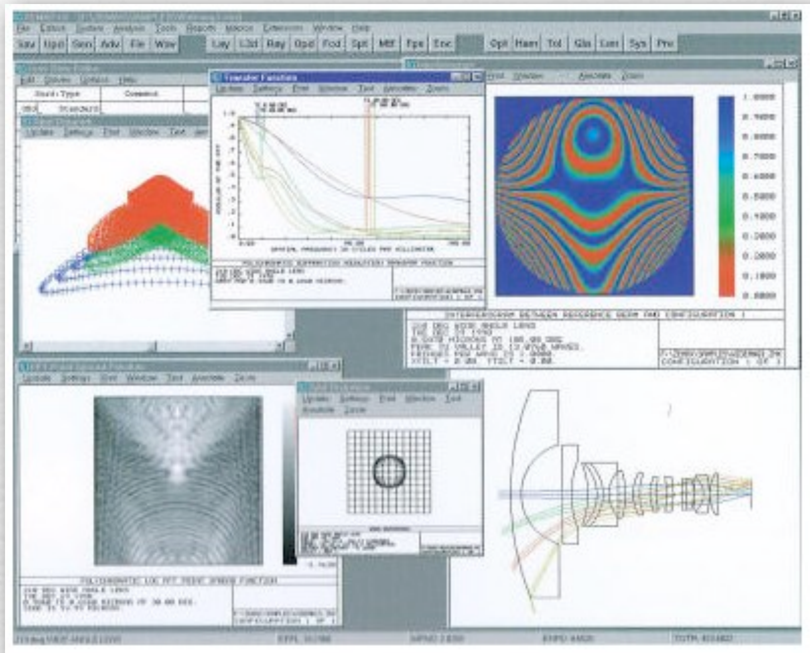
- <u>Example</u>: iPhone 4 when looking at green
  - λ = 550nm
  - *N* = f/3
  - *d* = 2μ
  - pixels are 1.75μ wide, so the iPhone 4 would be roughly diffraction-limited if its lenses were free of aberrations

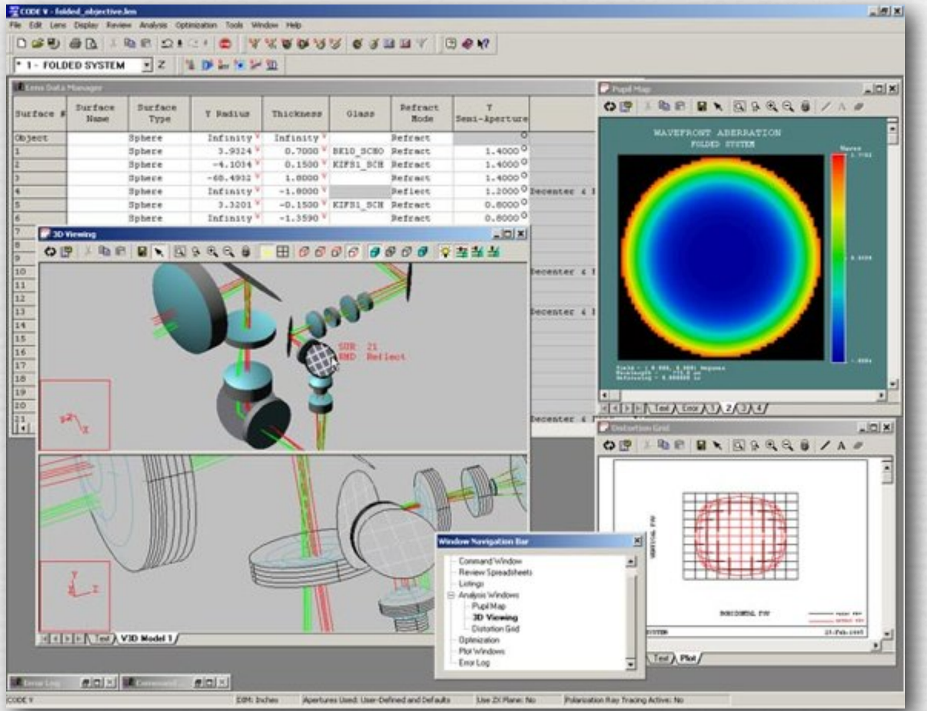
Recap

- 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?

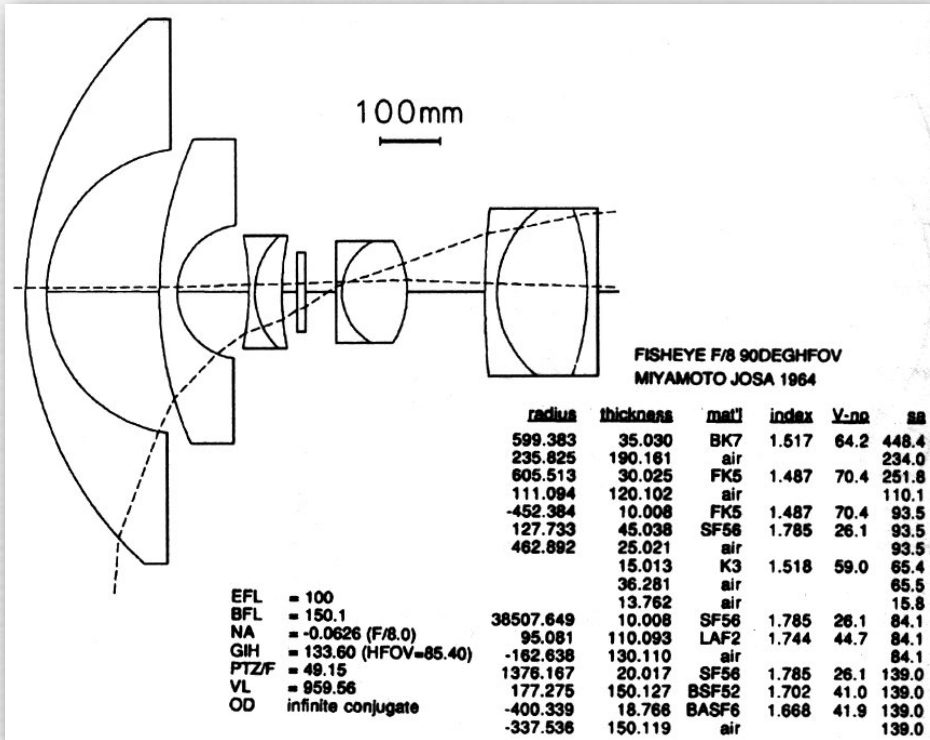
Lens design software





- ✦ uses optimization to make good recipes better

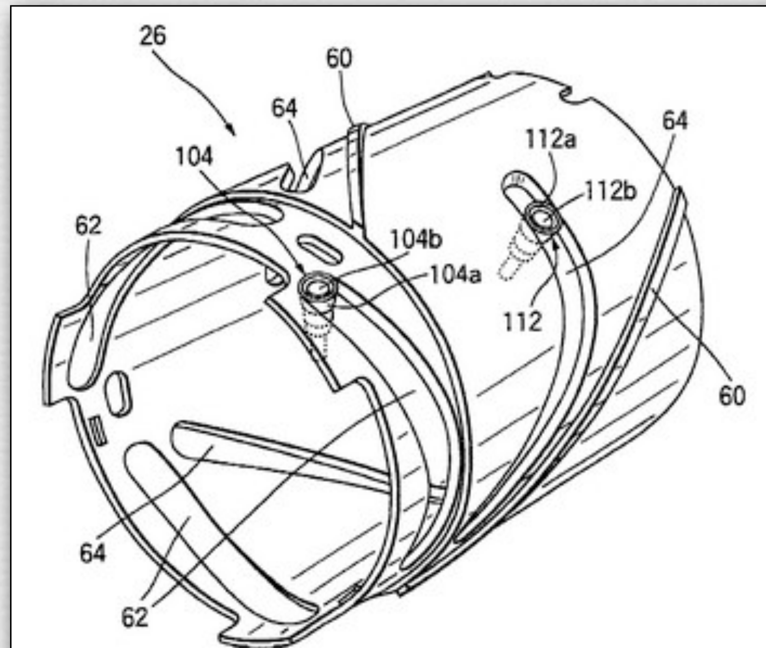
Lens catalogs and patents



FISHEYE F/8 90DEGHFOV
MIYAMOTO JOSA 1964

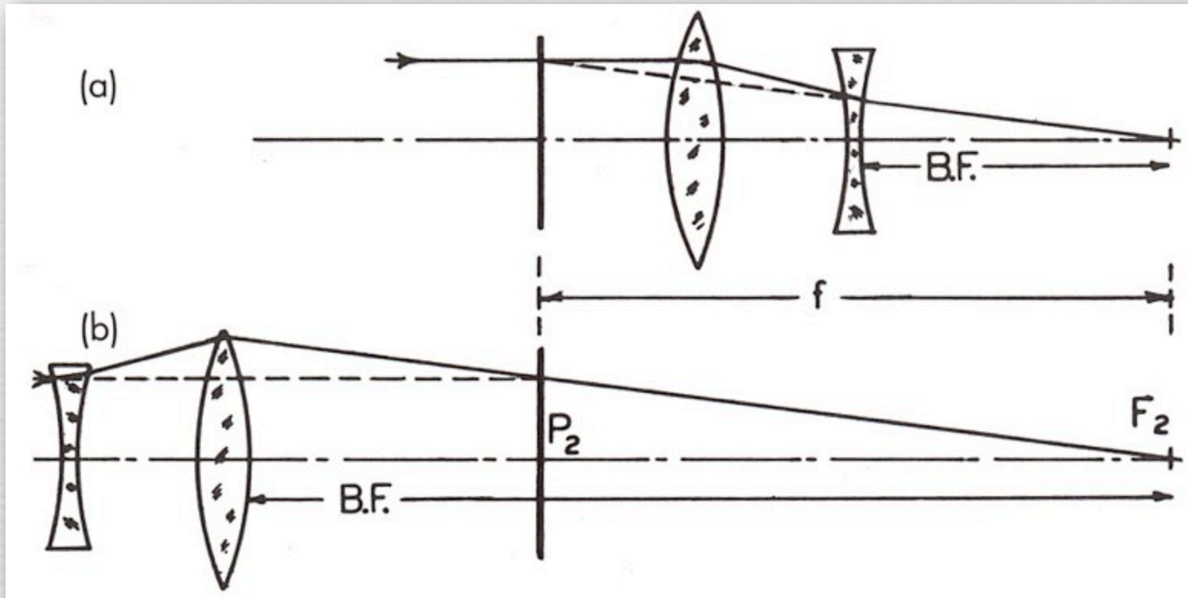
radius	thickness	mat'l	index	V-no	sa
599.383	35.030	BK7	1.517	64.2	448.4
235.825	190.161	air			234.0
605.513	30.025	FK5	1.487	70.4	251.8
111.094	120.102	air			110.1
-452.384	10.008	FK5	1.487	70.4	93.5
127.733	45.038	SF56	1.785	26.1	93.5
462.892	25.021	air			93.5
	15.013	K3	1.518	59.0	65.4
	36.281	air			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

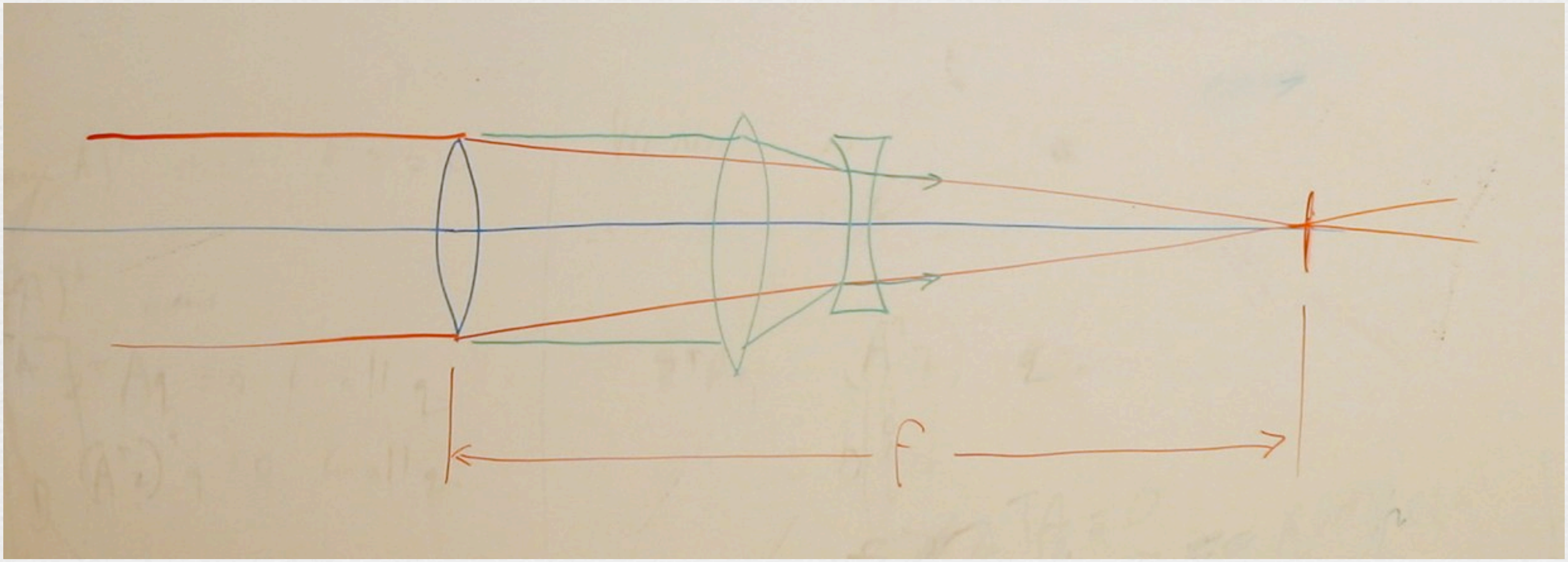


(Kingslake)

- 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

Telephoto lens

- the blue lens is replaced with the two green ones, thereby reducing the physical size of the lens assembly, while preserving its focal length (hence magnification)

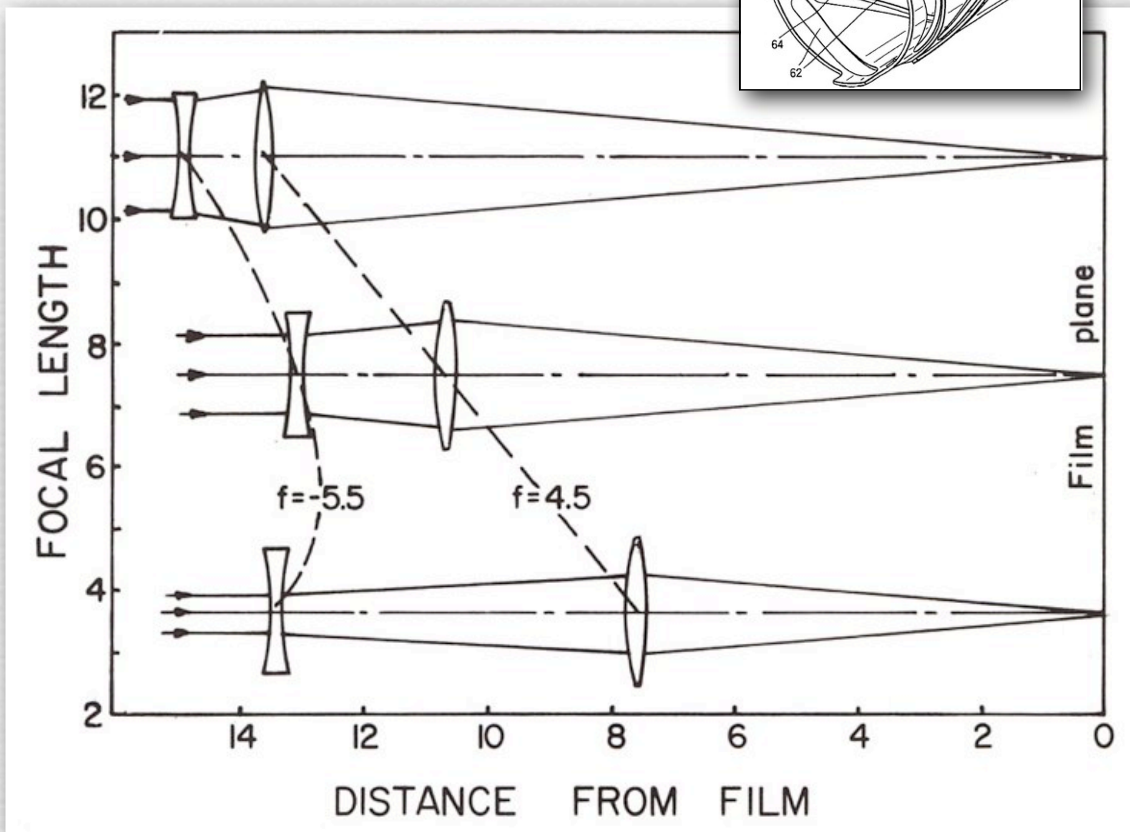


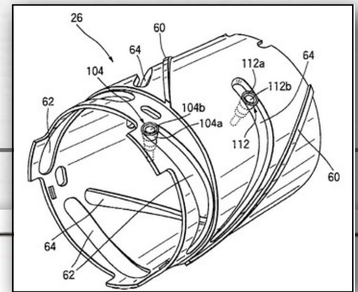
Lens combinations: telephoto

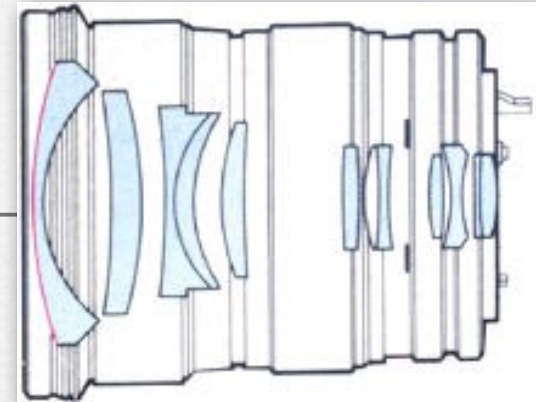
Nikon 500mm telephoto

Opteka 500mm <u>non</u>-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

Recap

- telephoto lenses separate focal length & back focal distance
  - for long focal length lenses, to reduce their physical size
  - for wide-angle lenses, to ensure room for the reflex mirror

Questions?

Slide credits

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- Fredo Durand

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