Optics II:
practical photographic lenses

CS 178, Spring 2009

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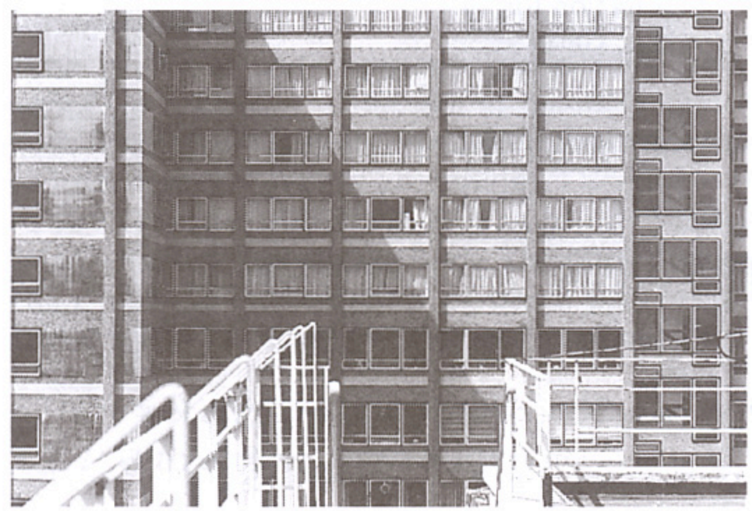
The advantage of compound lenses

(a)

(b)



(c)

Plate 11.1 Imaging by simple and compound lenses
(a) Simple biconvex one element lens of focal length 100 mm and diameter 50 mm giving *f*/2. Note poor edge detail and low overall contrast. (b) Same lens stopped down to *f*/11. Quality and contrast have improved. (c) A well-corrected five-element 105 mm lens used at *f*/11.

(Ray)

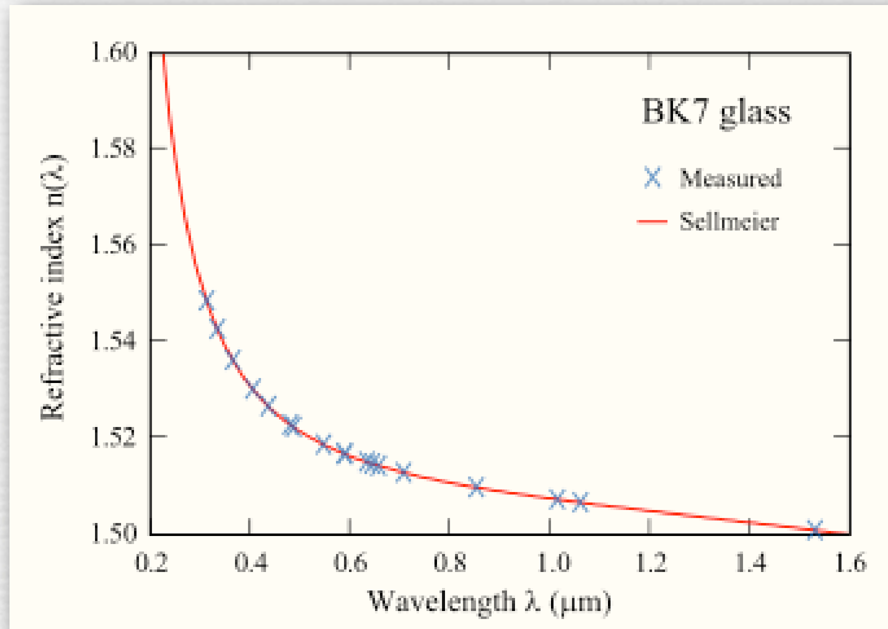
Lens aberrations

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

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

  - spherical aberration
  - oblique aberrations
  - field curvature
  - distortion

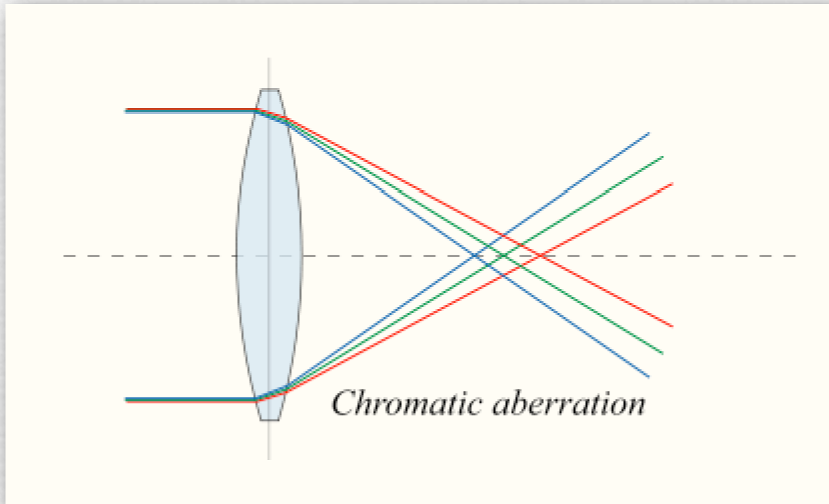
Dispersion

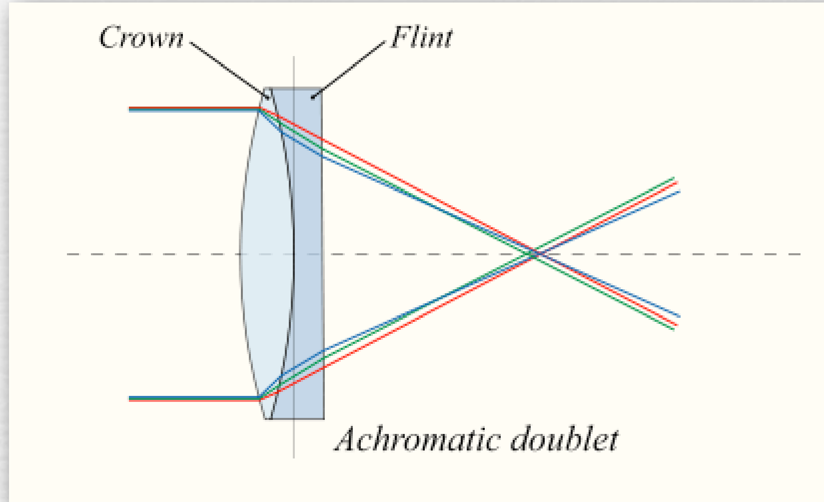


(wikipedia)

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

Chromatic aberration

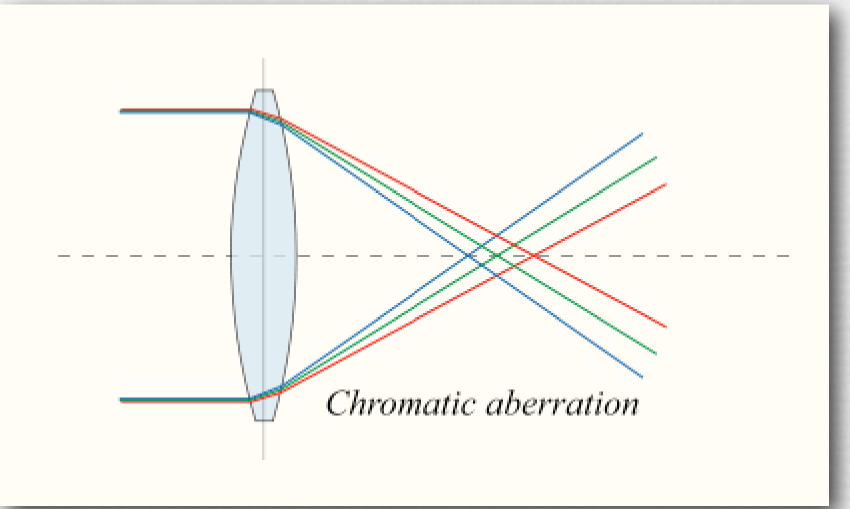


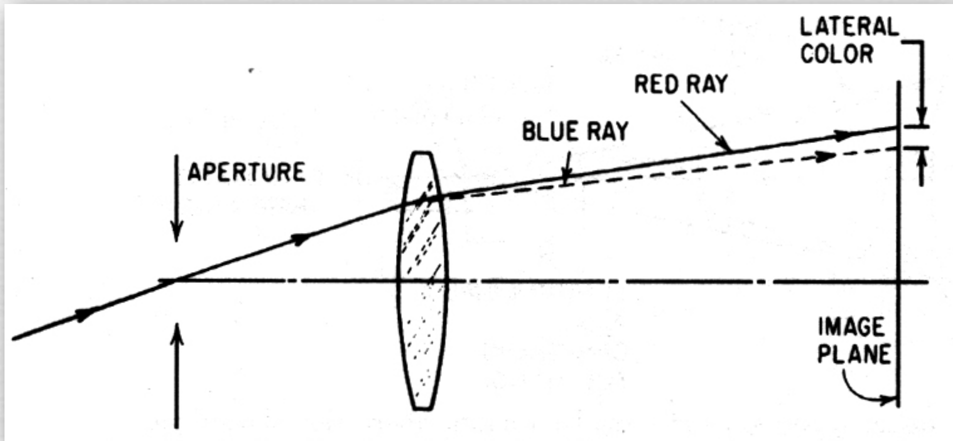


(wikipedia)

- dispersion causes focal length to vary with wavelength
  - for convex lens, blue focal length is shorter
- correct using *achromatic doublet*
  - low-dispersion positive lens + high-dispersion negative lens
  - can only correct at two wavelengths

The chromatic aberrations





(Smith)

- change in focus with wavelength
  - called *longitudinal chromatic aberration*
  - appears everywhere in the image
- if blue image is closer to lens, it will also be smaller
  - because $M_T = -\sqrt{M_L}$
  - called *lateral chromatic aberration*
  - worse at edges of images than in center

Photo-3 Axial chromatic aberration

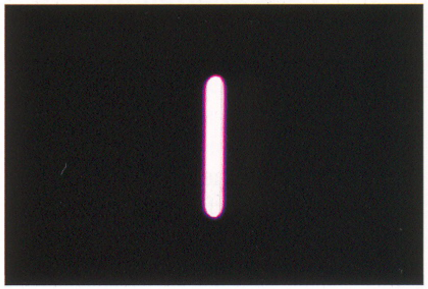
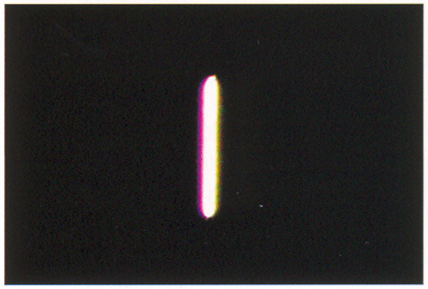


Photo-4 Transverse chromatic aberration



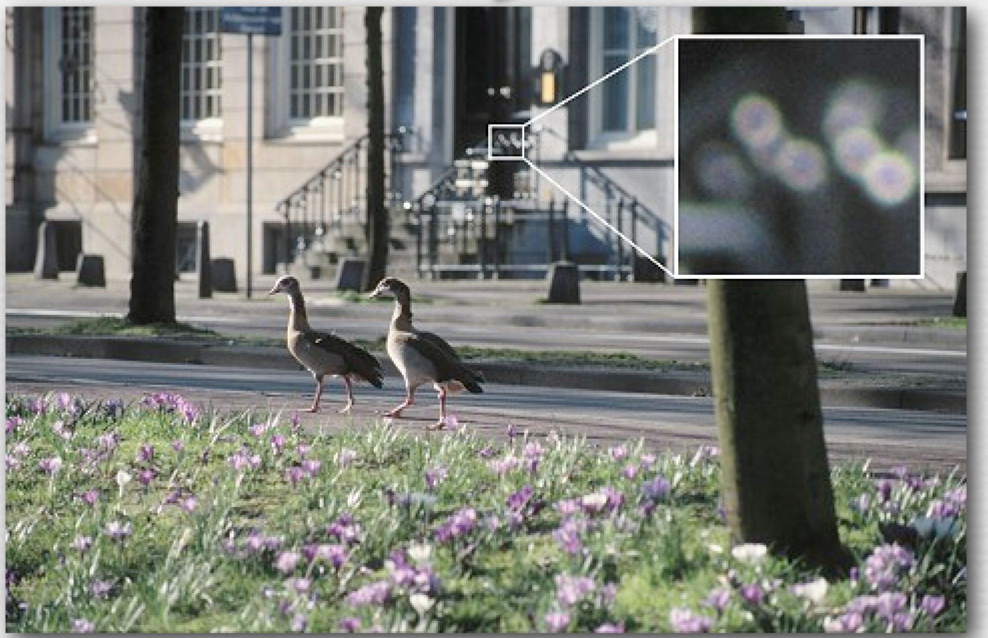
Examples

- correctable in software
- not

(wikipedia)

lateral

(toothwalker.org)



longitudinal

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

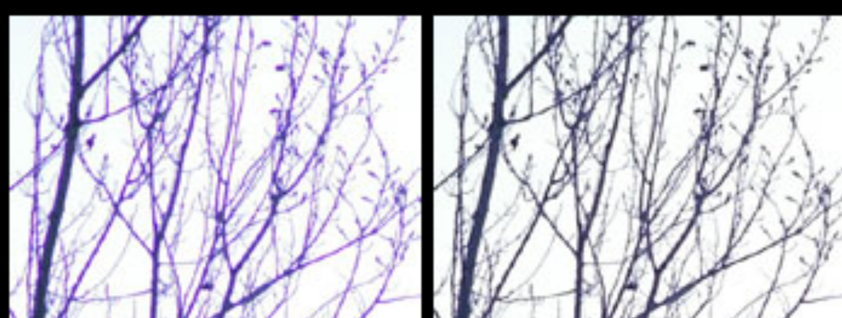
Software correction of lateral chromatic aberration

4 Color plane specific

Lateral chromatic aberration — DxO Optics Pro Correction

Sony F828

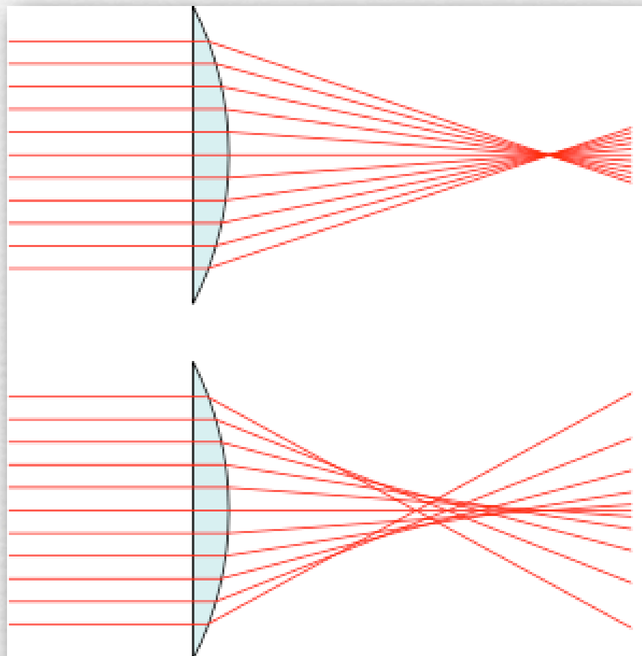
Distortion affects different parts of the color spectrum differently (prism effect) and creates the so called "lateral chromatic aberration", which results in color fringes arround high/low-light transitions. With the ever increasing sensor resolutions, lateral chromatic aberration becomes more and more visible, in turn making it more and more important to precisely address distortion for each color plane.



Longitudinal chromatic aberration, purple fringing, coma, and so on can also cause color fringes, which are automatically removed by DxO Optics Engine v2.

Q. Why don't humans see chromatic aberration?

Spherical aberration



(wikipedia)

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

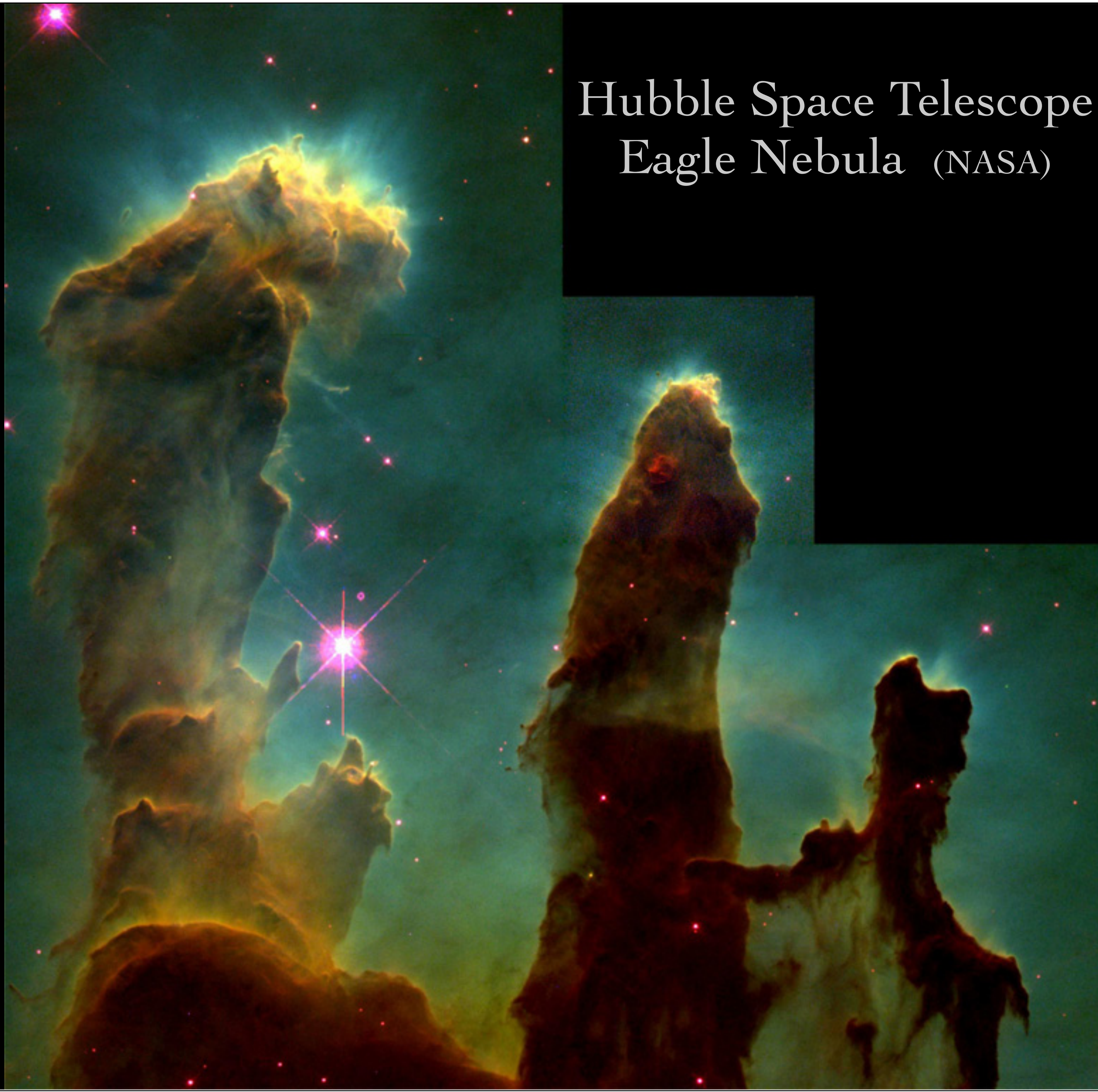
soft focus

Canon 135mm f/2.8 soft focus lens

Hubble telescope

before correction

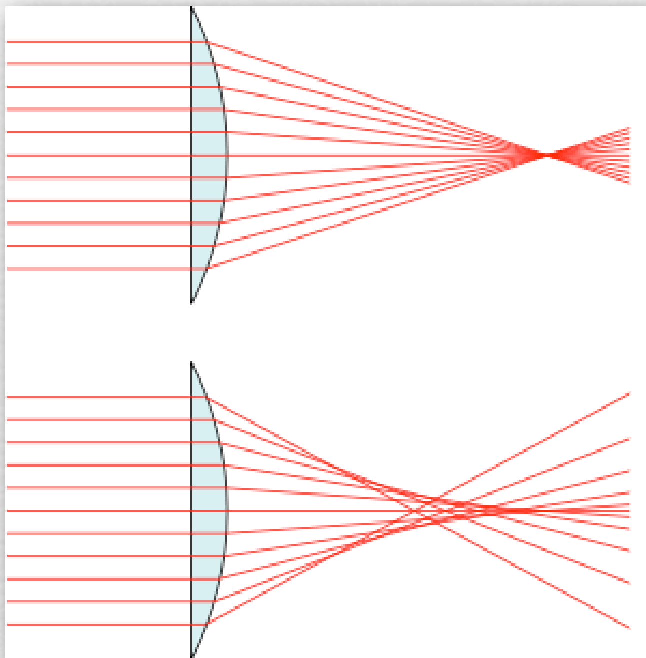
after correction



Hubble Space Telescope
Eagle Nebula (NASA)

Focus shift

(diglloyd.com)



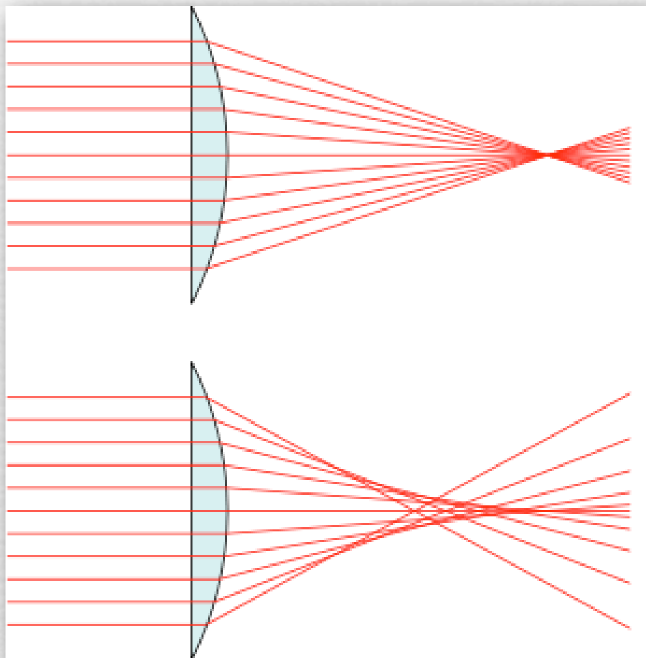
(wikipedia)

focused at f/1.2

- Canon 50mm f/1.2 L

Focus shift

(diglloyd.com)



(wikipedia)

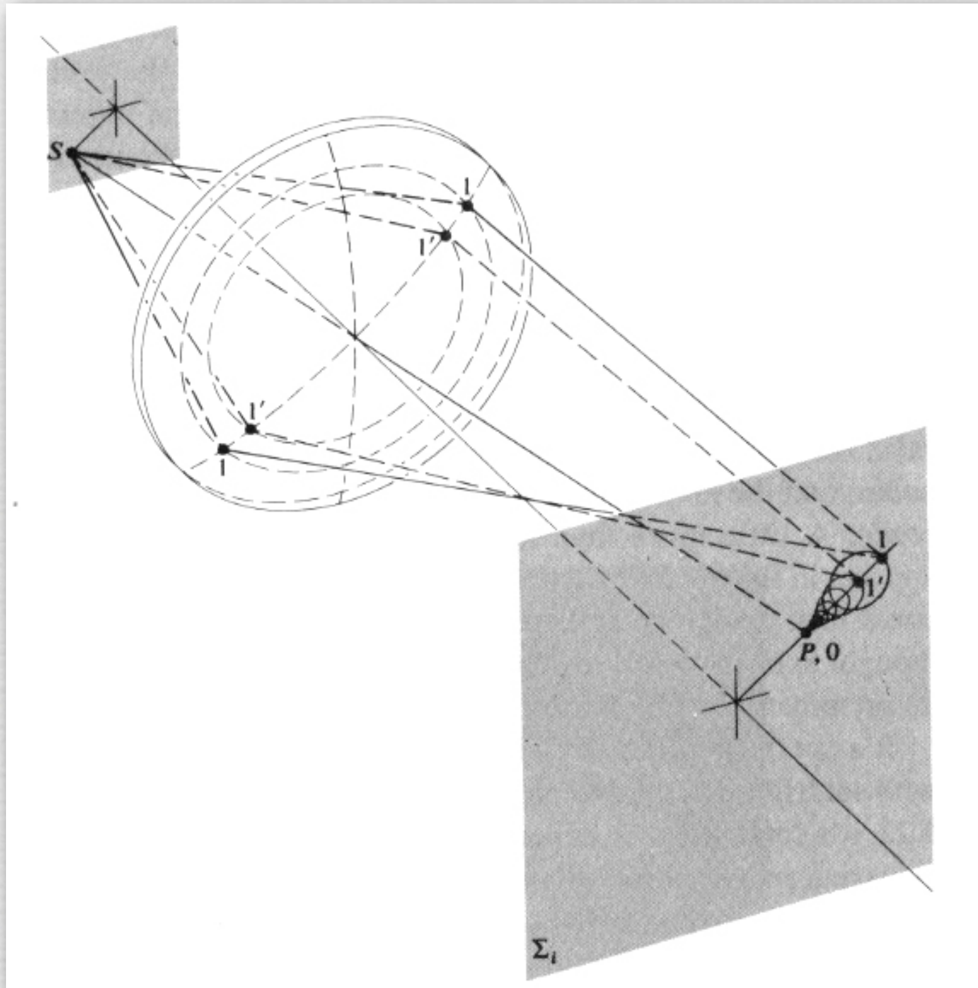
shot at f/1.8

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

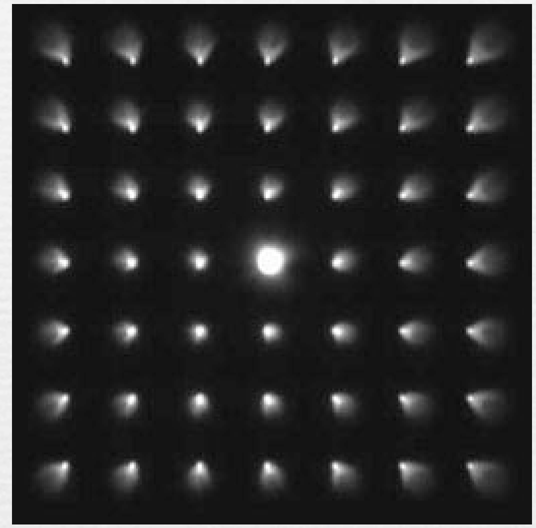
Oblique aberrations

- spherical & chromatic aberrations occur on the optical axis, as well as off the axis
  - they appear everywhere in the field of view
- oblique aberrations do not appear in center of field
  - they get worse with increasing distance from the axis
  - coma and astigmatism

Coma



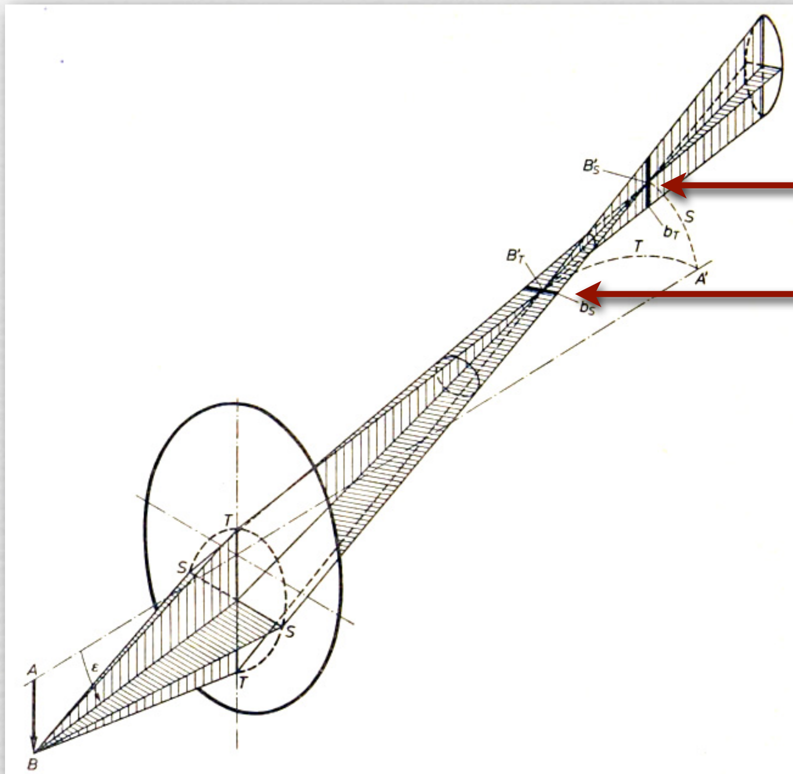
(Hecht)



(ryokosha.com)

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

Astigmatism



focus of sagittal rays

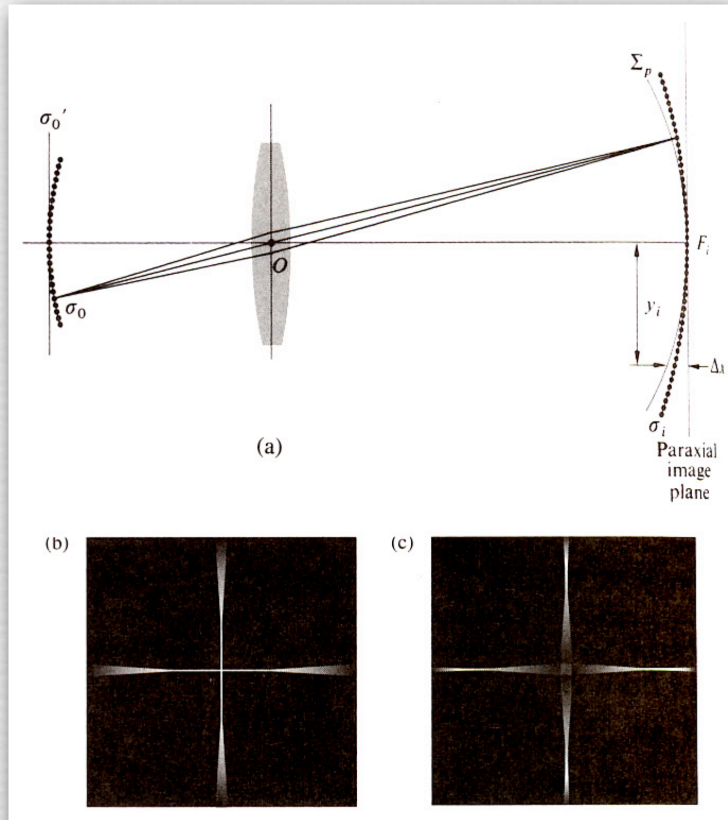
focus of tangential rays

(Pluta)

- 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 (included in an eyeglasses prescription)

Field curvature

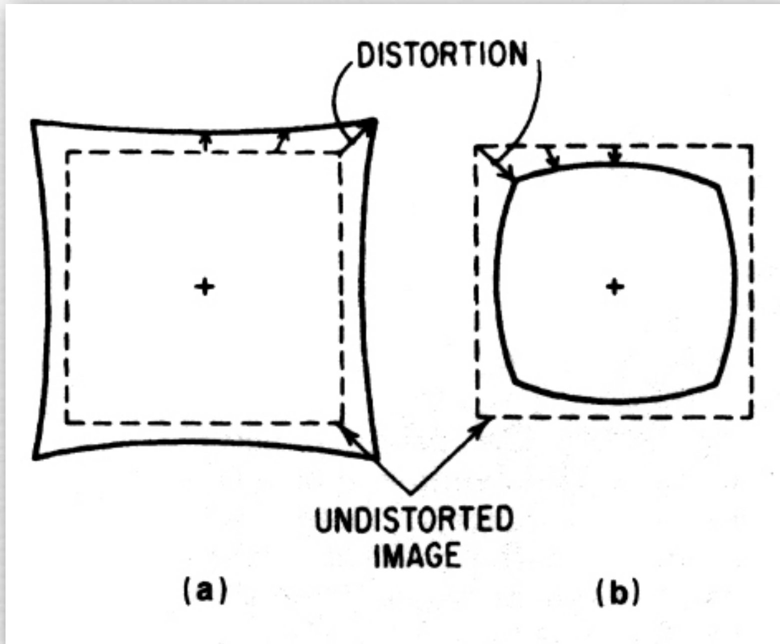


(Hecht)

- 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)

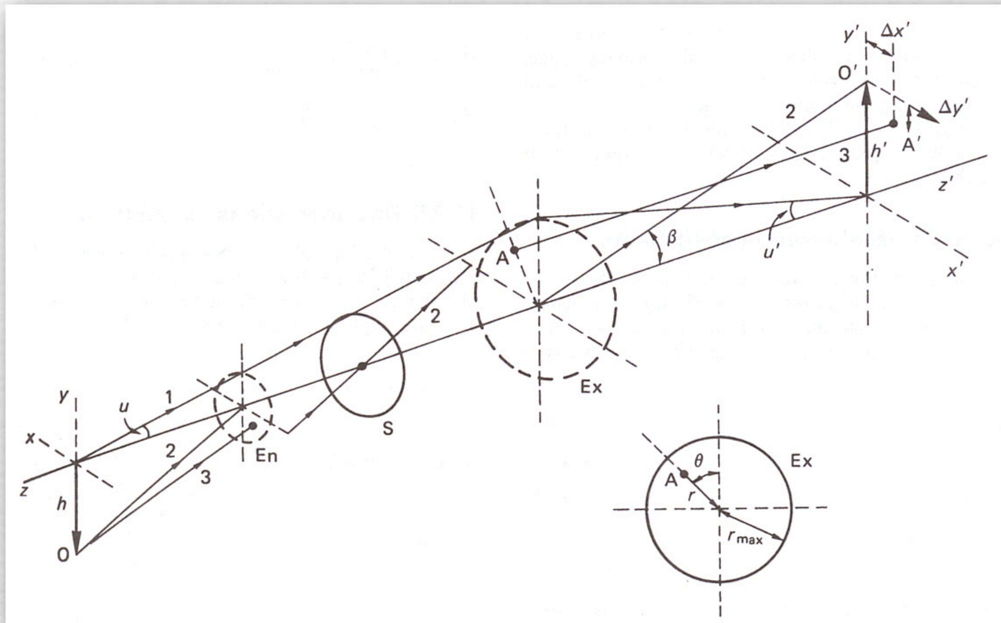


(Kingslake)

pincushion distortion

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

Algebraic formulation of monochromatic lens aberrations



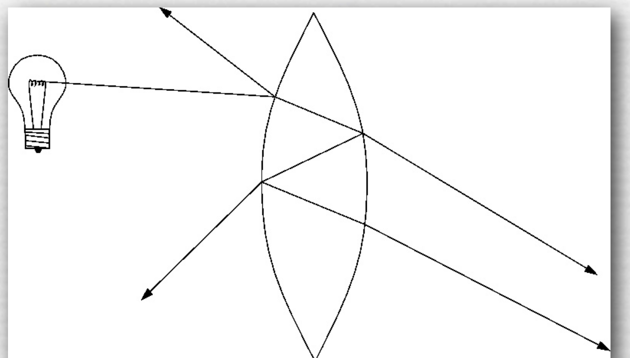
(Smith)

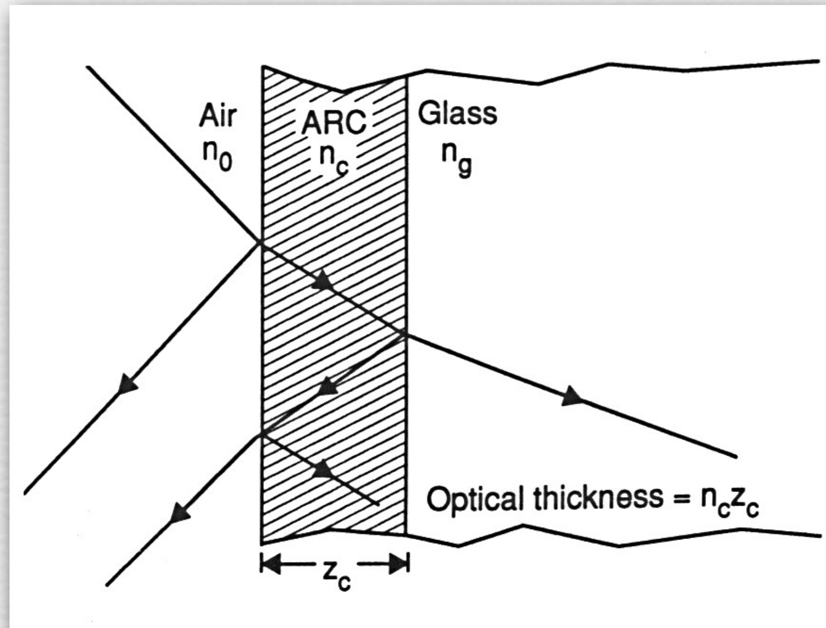
- spherical aberration $a_s r^4$
- coma $a_c h' r^3 \cos\theta$
- astigmatism $a_a h'^2 r^2 \cos^2\theta$
- field curvature $a_d h'^2 r^2$
- distortion $a_t h'^3 r \cos\theta$

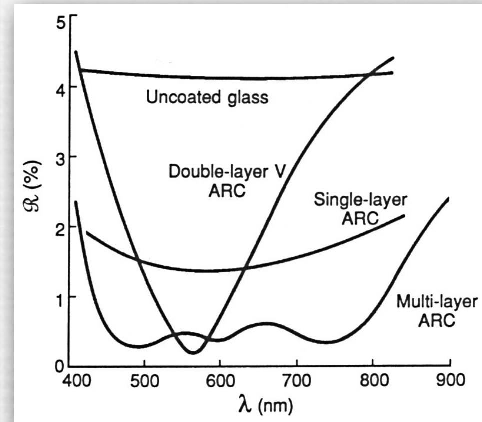
Other lens artifacts

- veiling glare
- flare and ghost images
- vignetting
- diffraction

Veiling glare



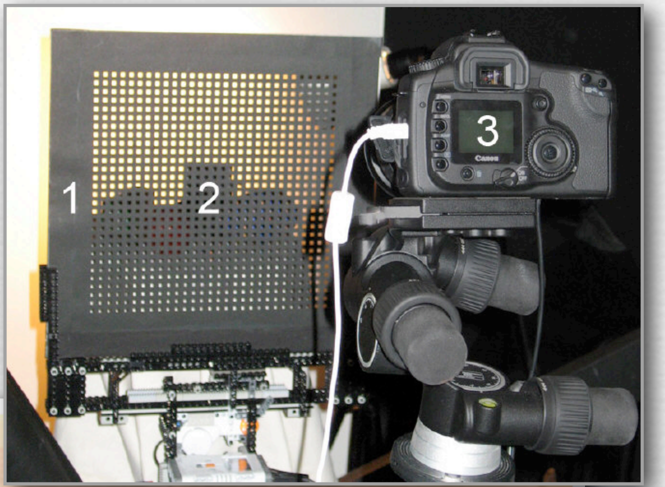




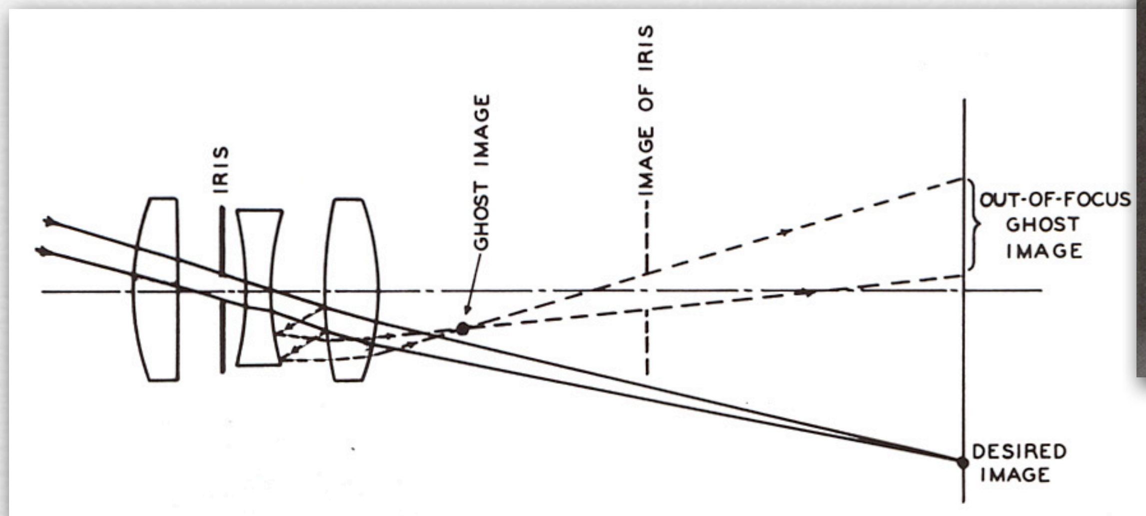
- contrast reduction caused by stray reflections
- can be reduced by anti-reflection coatings
  - based on interference, so optimized for one wavelength
  - to cover more wavelengths, use multiple coatings

Removing veiling glare computationally

[Talvala, Proc. SIGGRAPH 2007]



Flare and ghost images

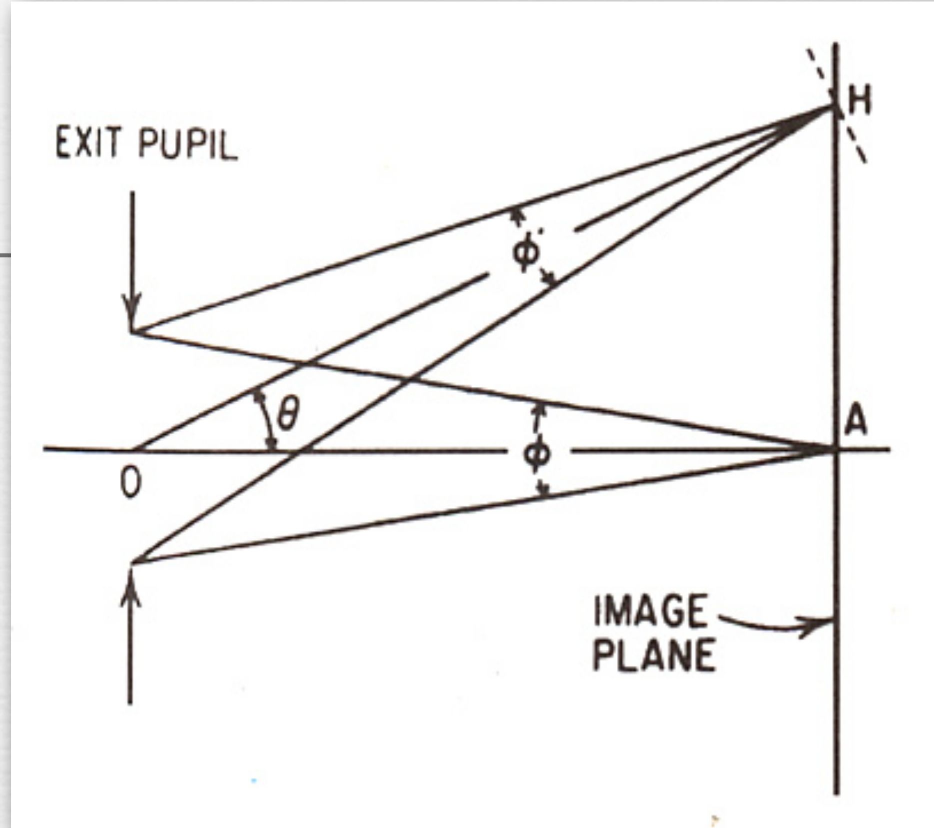


(Kingslake)

- 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

(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

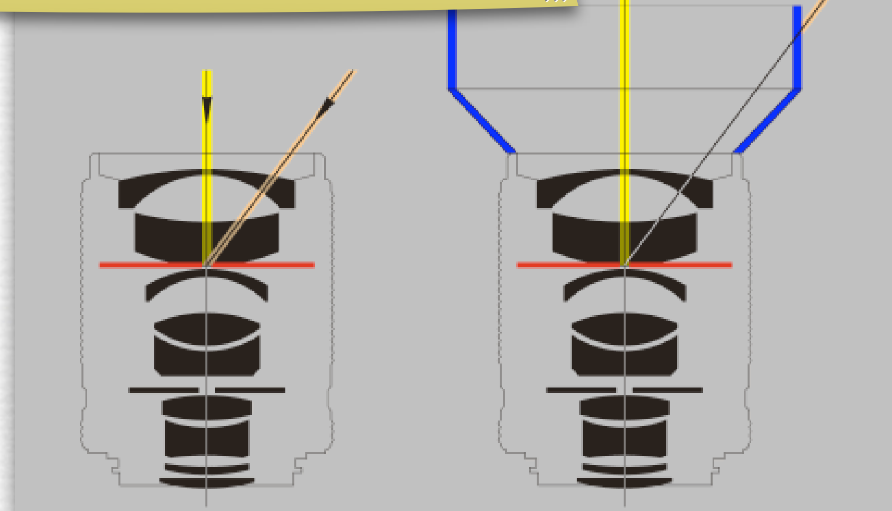
In textbook treatments of vignetting (and wikipedia), cos^4 falloff is called "natural vignetting". The additional vignetting in lenses, illustrated by the picture at left below, is called "optical vignetting", problems caused by lens hoods and fingers are called "mechanical vignetting", and internal shadowing in pixels is called "pixel vignetting".

f/1.4 f/5.6

axial

semifield

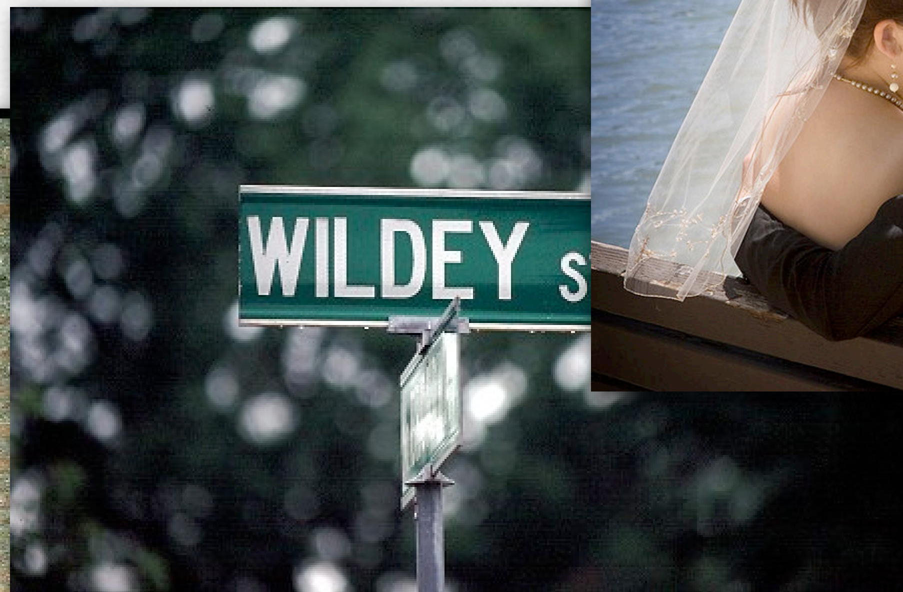
(toothwalker.org)



- some lenses exhibit vignetting when wide open (lowest F-number)
- filters and lens hoods (and fingers) can produce vignetting
- pixels have internal vignetting (we'll come back to this)

Examples

(toothwalker.org)

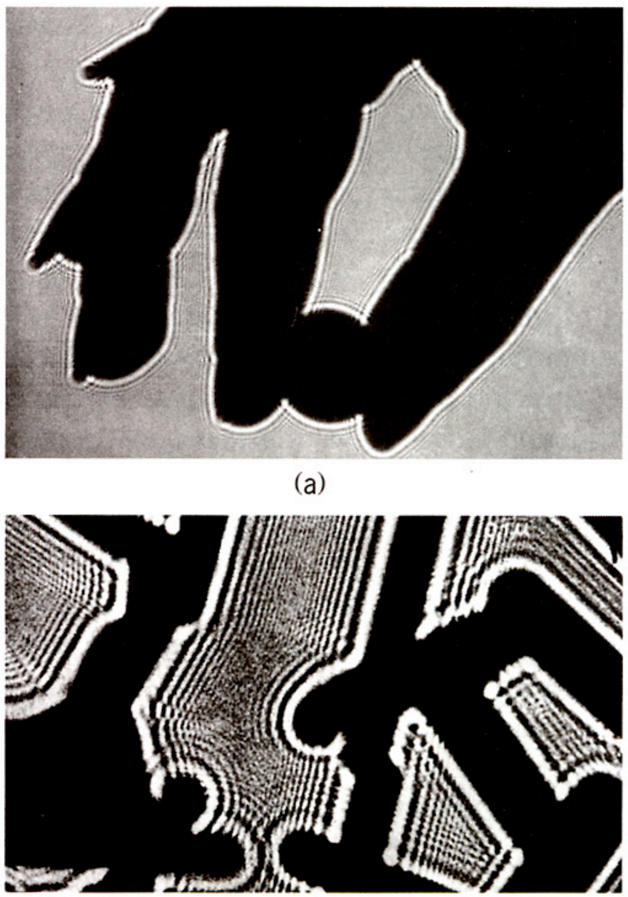


(toothwalker.org)

(wikipedia)

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

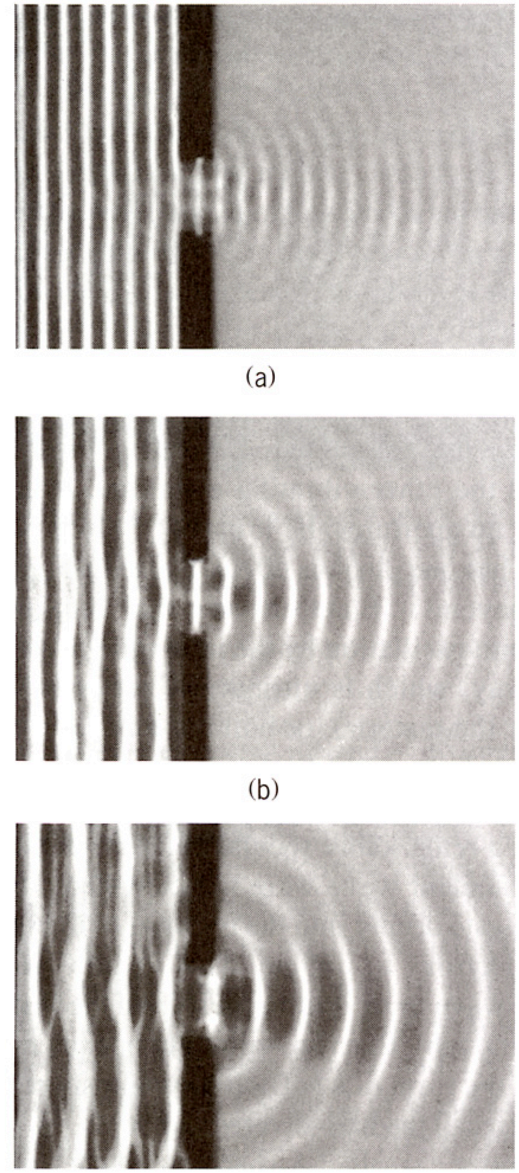
Diffraction



(a)

(b)

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



(a)

(b)

(c)

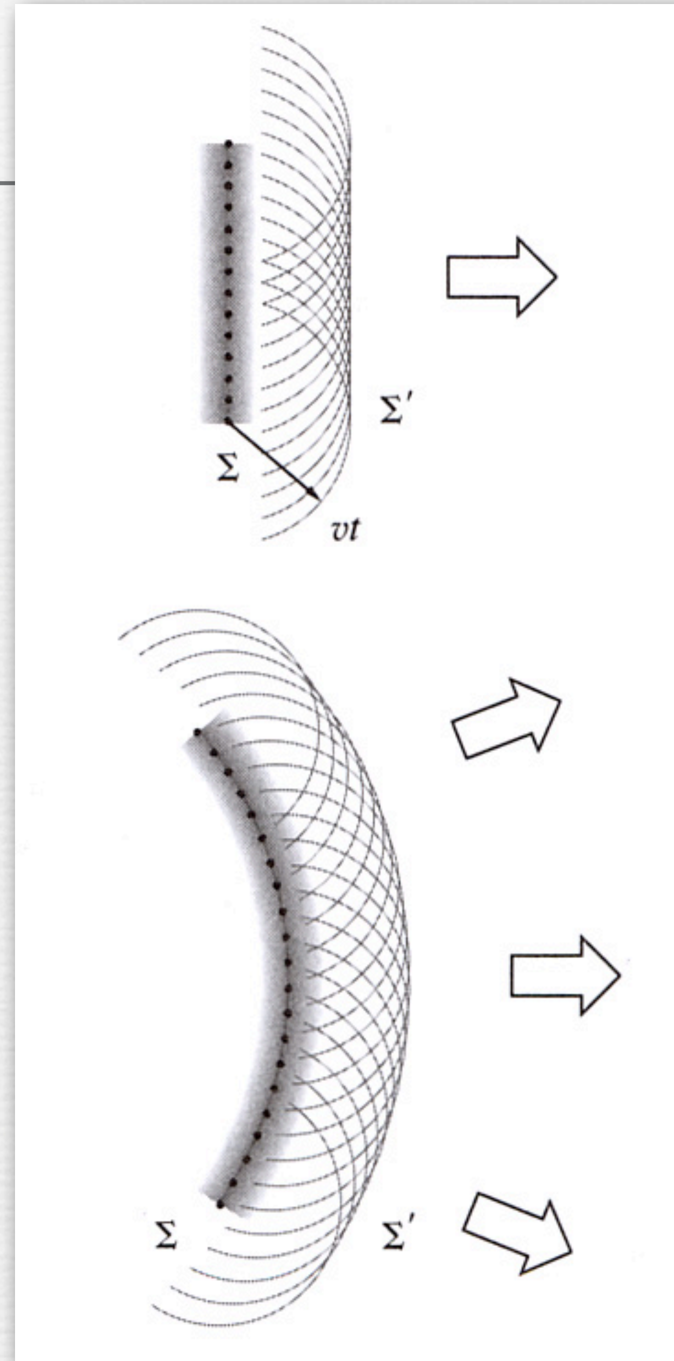
varying the wavelength of waves passing through a slit in a ripple tank

(Hecht)

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

Huygens wavelets

(Hecht)

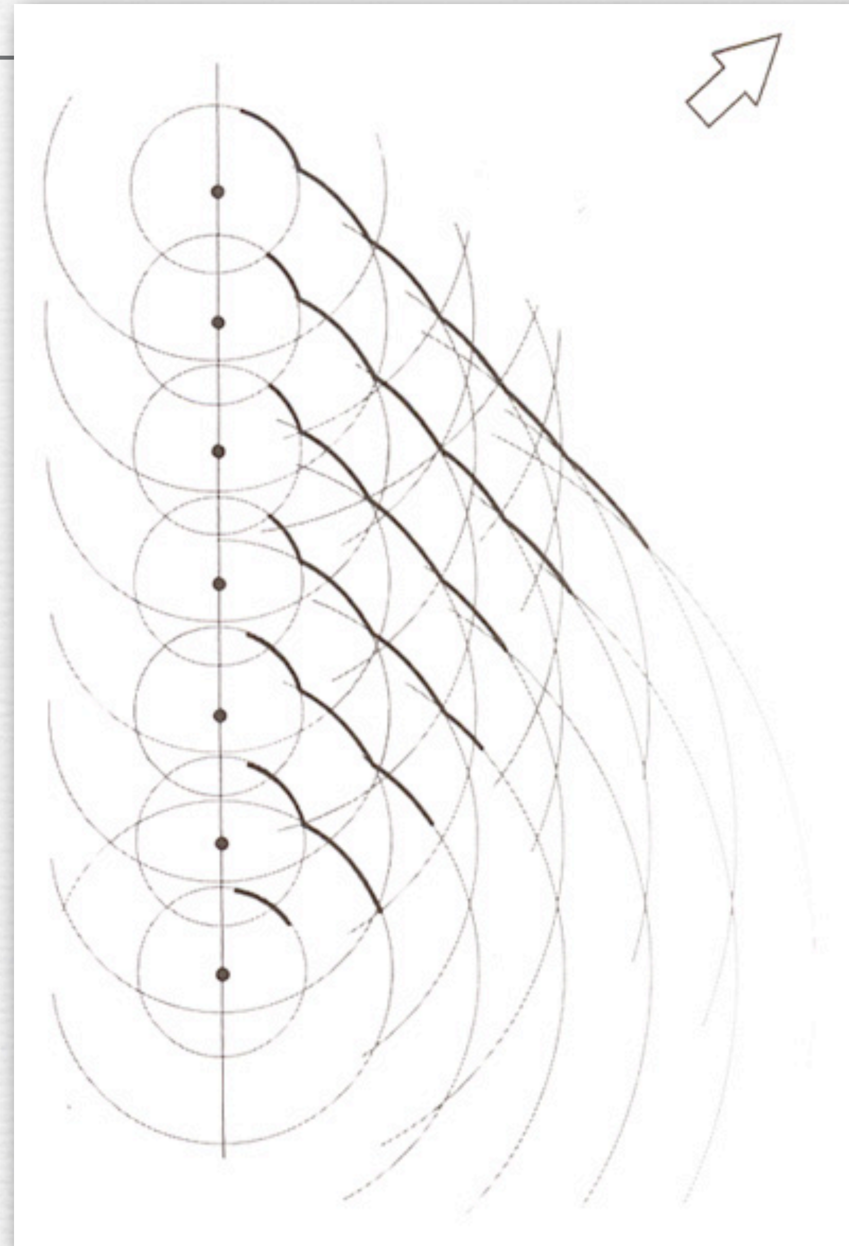


- every point on a wavefront can be considered as a source of spherical wavelets
- the optical field is the superimposition of these waves, after allowing for constructive or destructive interference

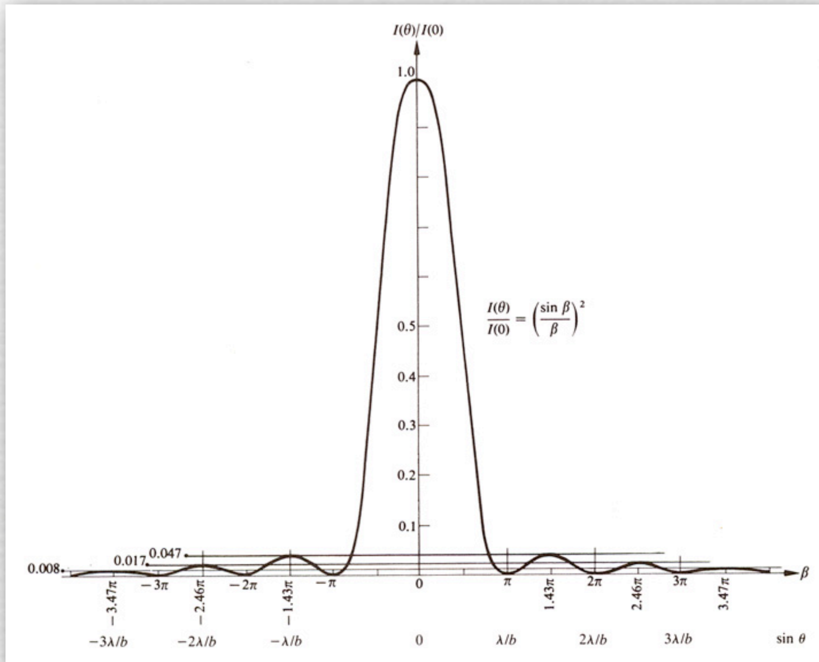
Huygens wavelets

- every point on a wavefront can be considered as a source of spherical wavelets
- the optical field is the superimposition of these waves, with interference
- at some angles there is constructive interference; at other angles there is destructive interference

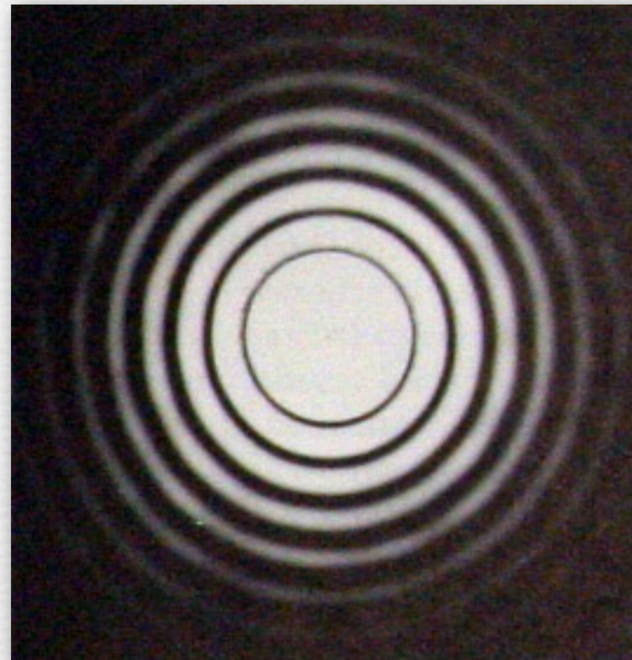
(Hecht)



Frauenhofer diffraction



diffraction from a slit



(Hecht)

diffraction from a circular aperture: Airy rings

- diffraction viewed from a long distance ("far field")

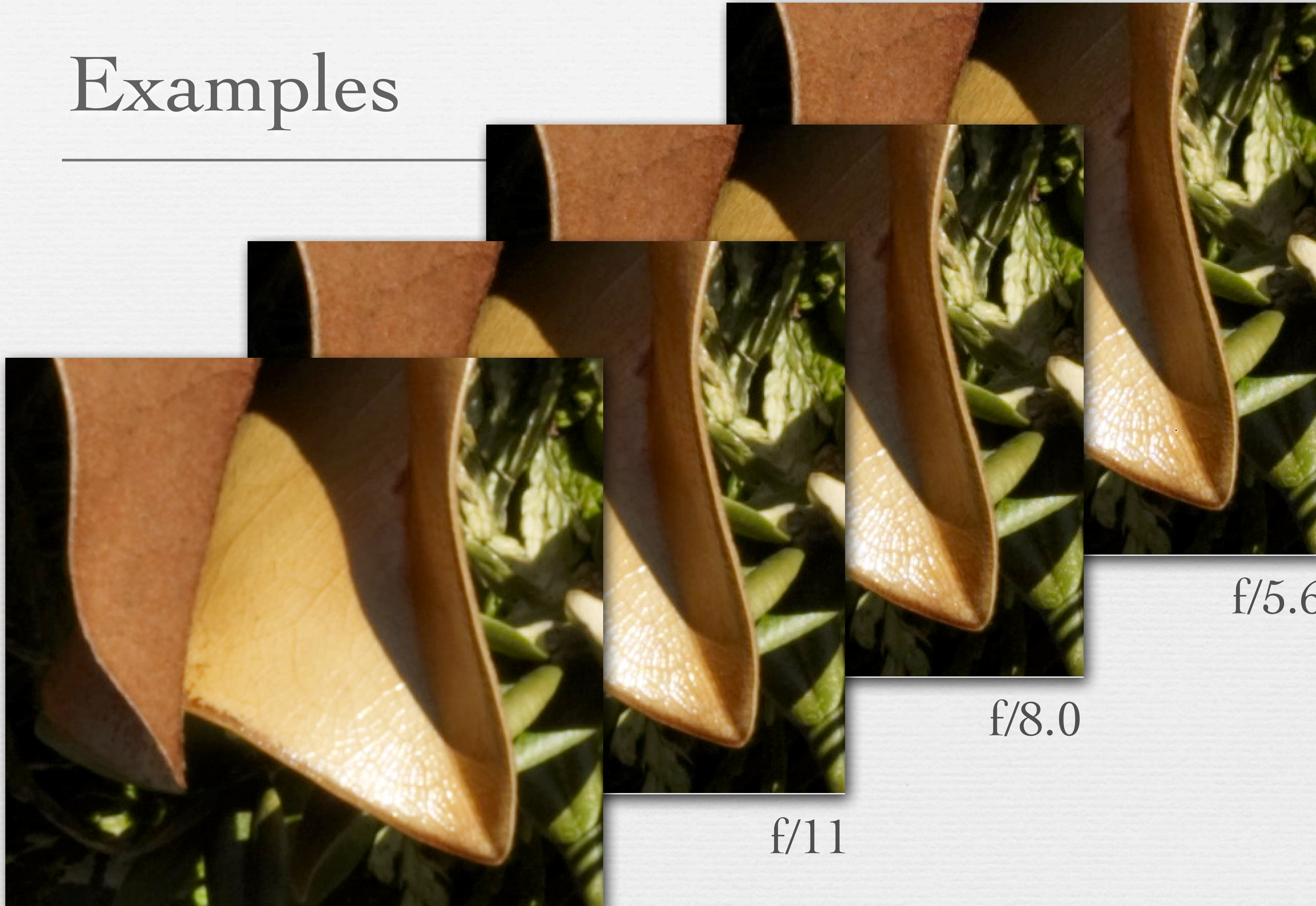
Diffraction in photographic cameras

- well-corrected lenses are called *diffraction-limited*

- the smaller the aperture (A), 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 F-number $N = f\,/\,A$

Examples



f/5.6

f/8.0

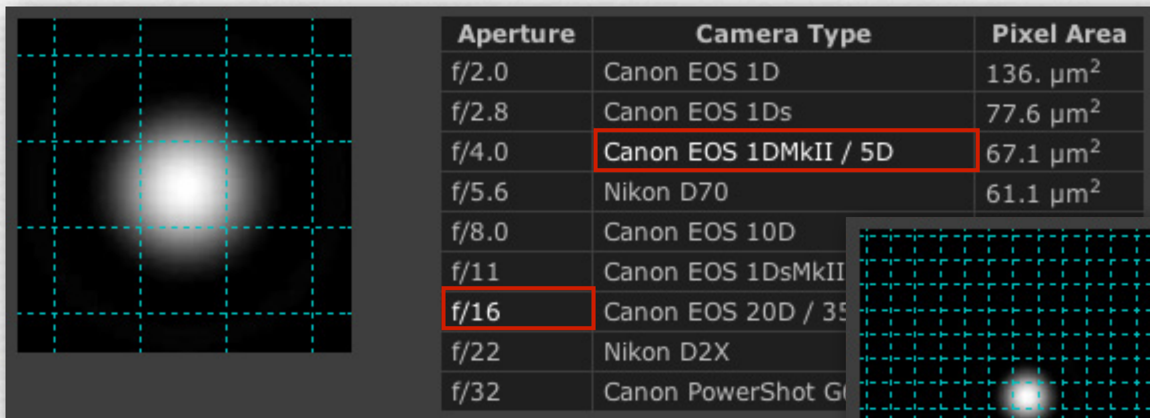
f/11

f/22

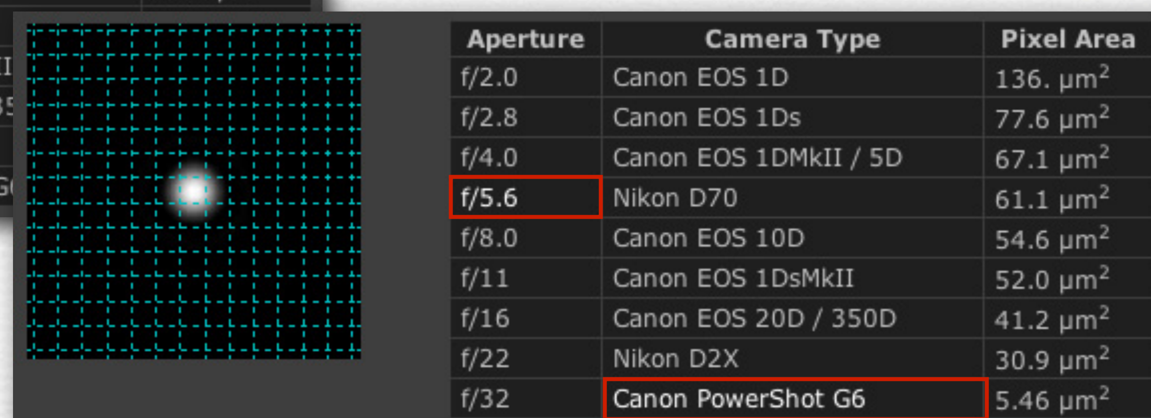
(luminous-landscape.com)

Diffraction in photographic cameras

- the smaller the pixels, the more of them the pattern covers
  - if the pattern spans >> 1 pixel, the image becomes blurry



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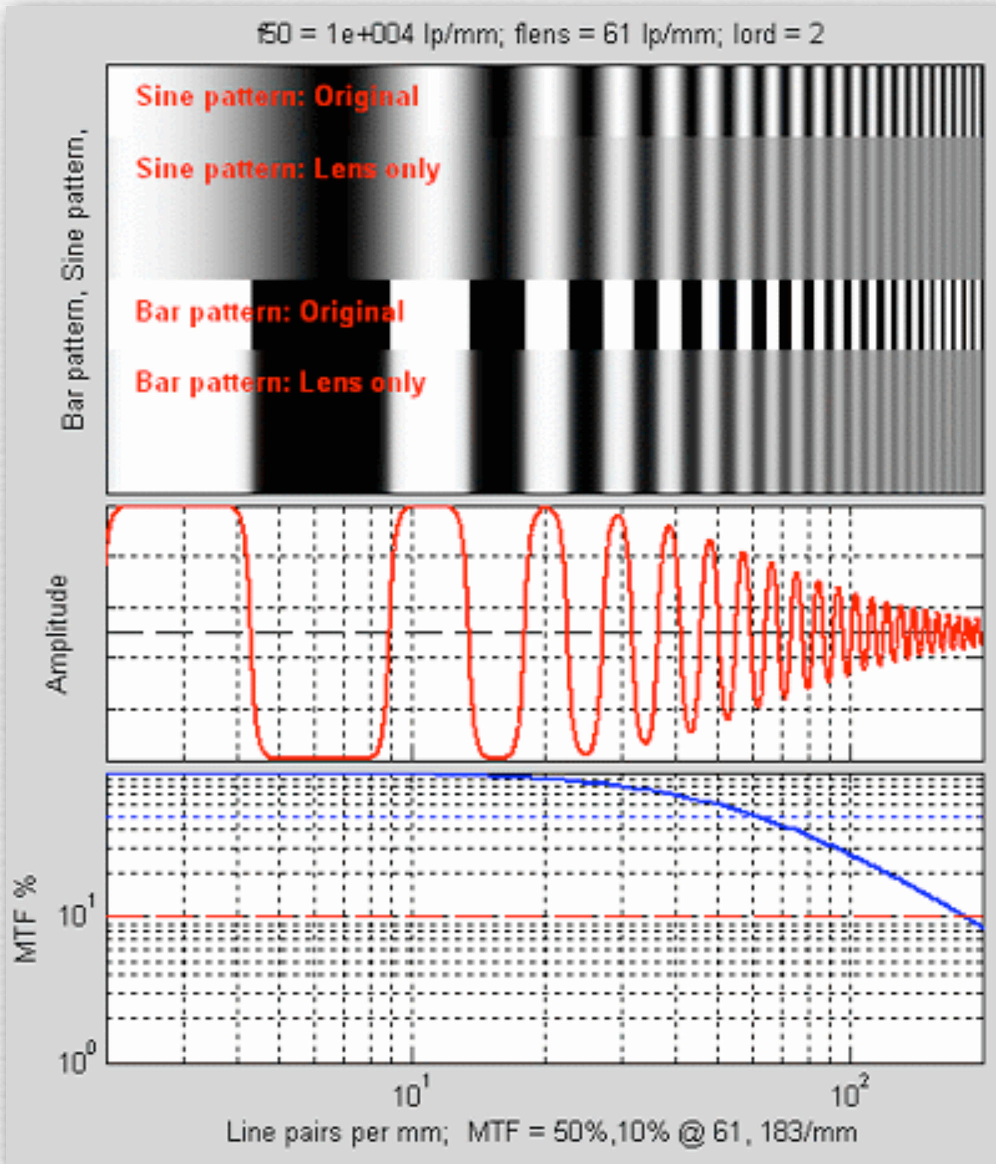
f/5.6	Nikon D70	61.1 μm²
f/8.0	Canon EOS 10D	54.6 μm²
f/11	Canon EOS 1DsMkII	52.0 μm²
f/16	Canon EOS 20D / 350D	41.2 μm²
f/22	Nikon D2X	30.9 μm²
f/32	Canon PowerShot G6	5.46 μm²

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

Let's not even talk about diffraction in cell phone cameras

Describing sharpness: the modulation transfer function (MTF)

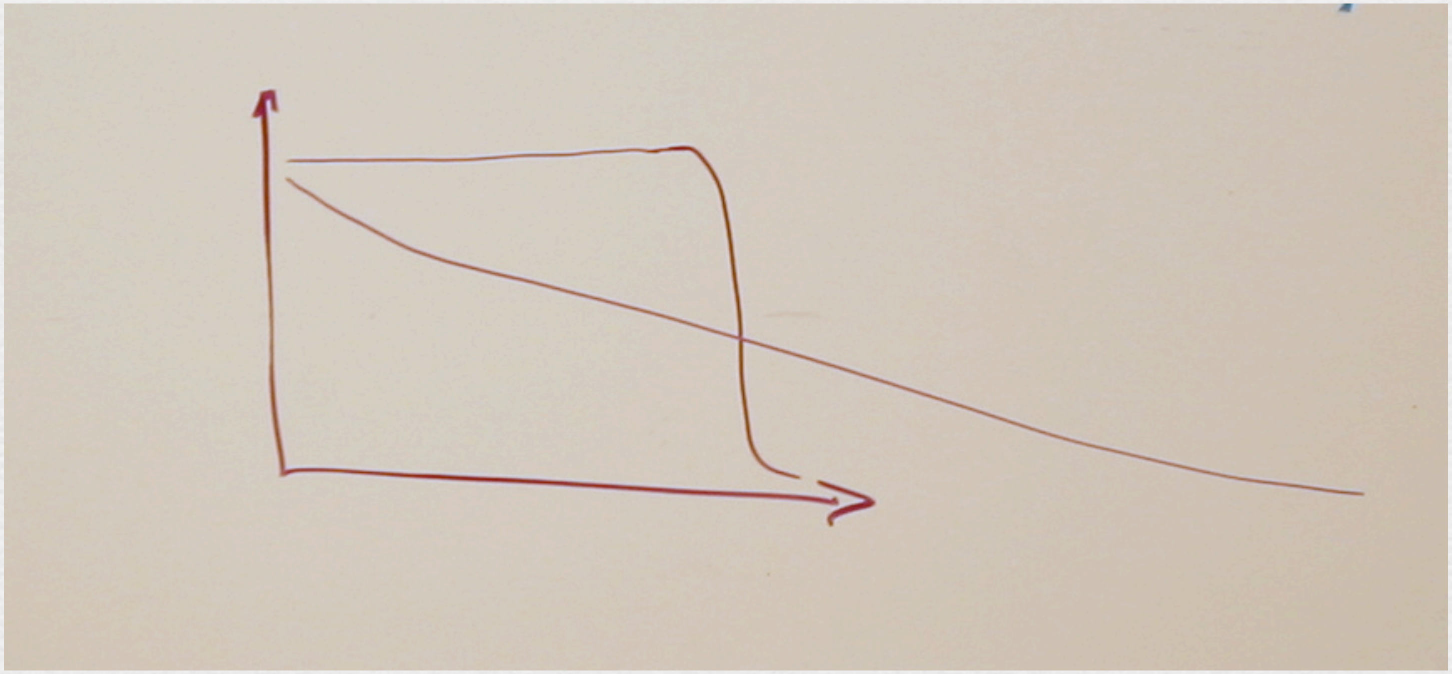


(imatest.com)

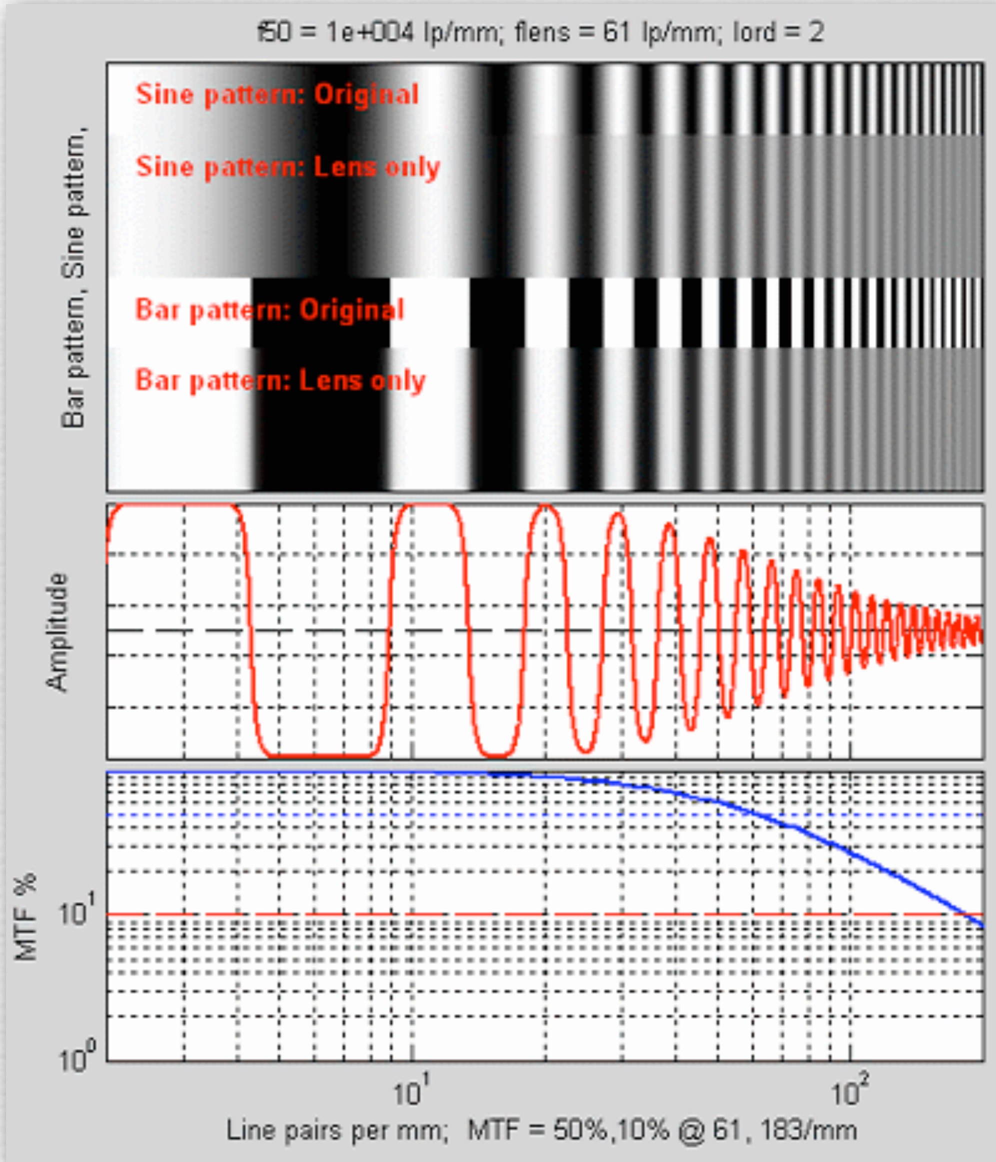
- the amount of each spatial frequency that can be reproduced by an optical system

Two different MTF curves

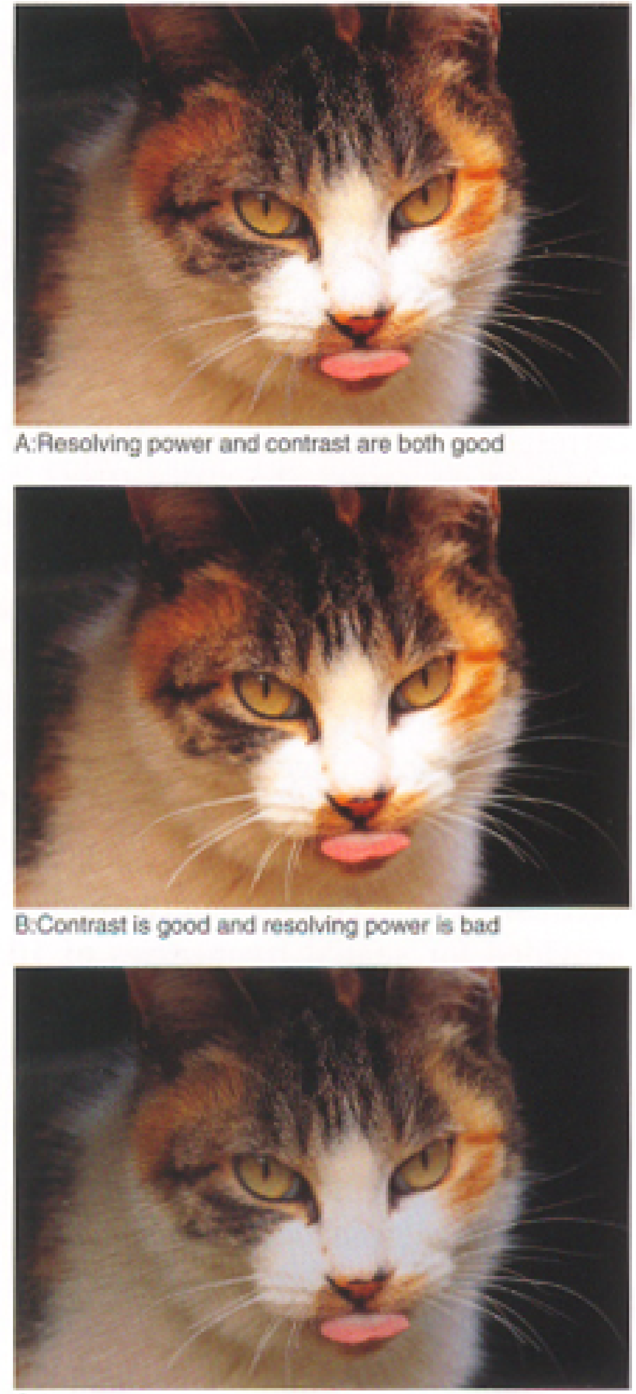
- in one curve, contrast stays high, but drops off at a relatively low resolution
- in the other curve, higher-resolution features are preserved, but contrast is low throughout



Sharpness versus contrast



(imatest.com)



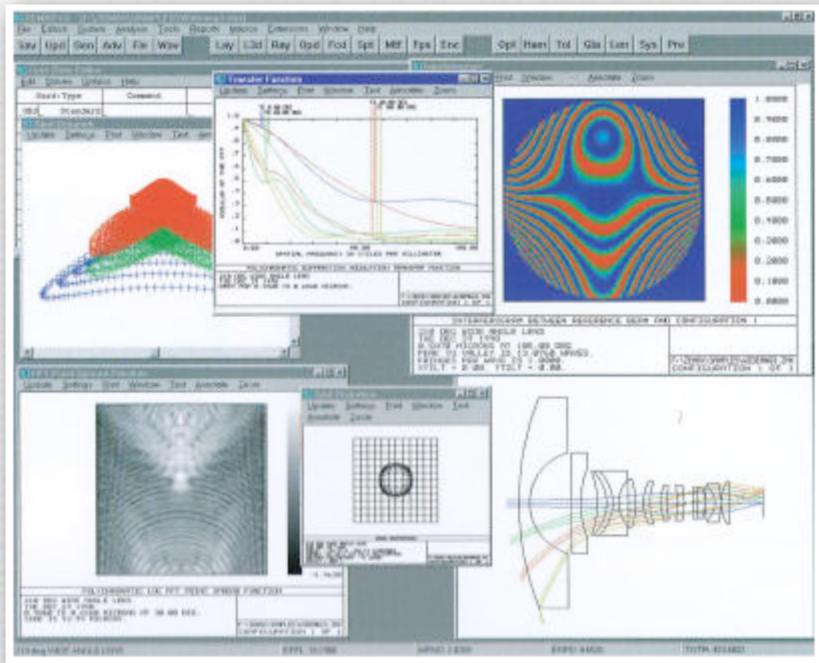
A:Resolving power and contrast are both good

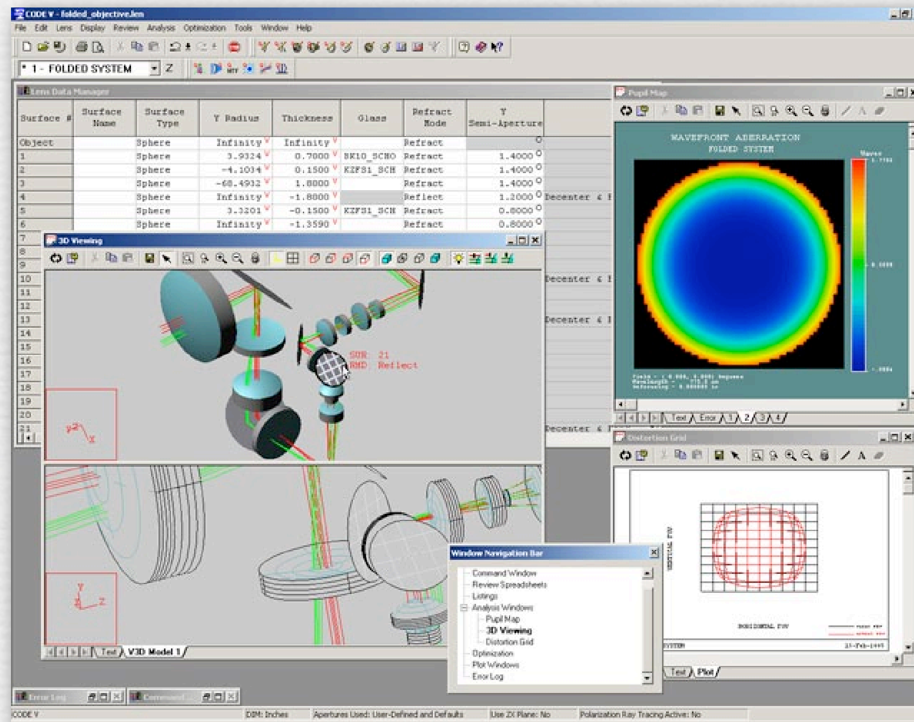
B:Contrast is good and resolving power is bad

C:Resolving power is good and contrast is bad

(Canon)

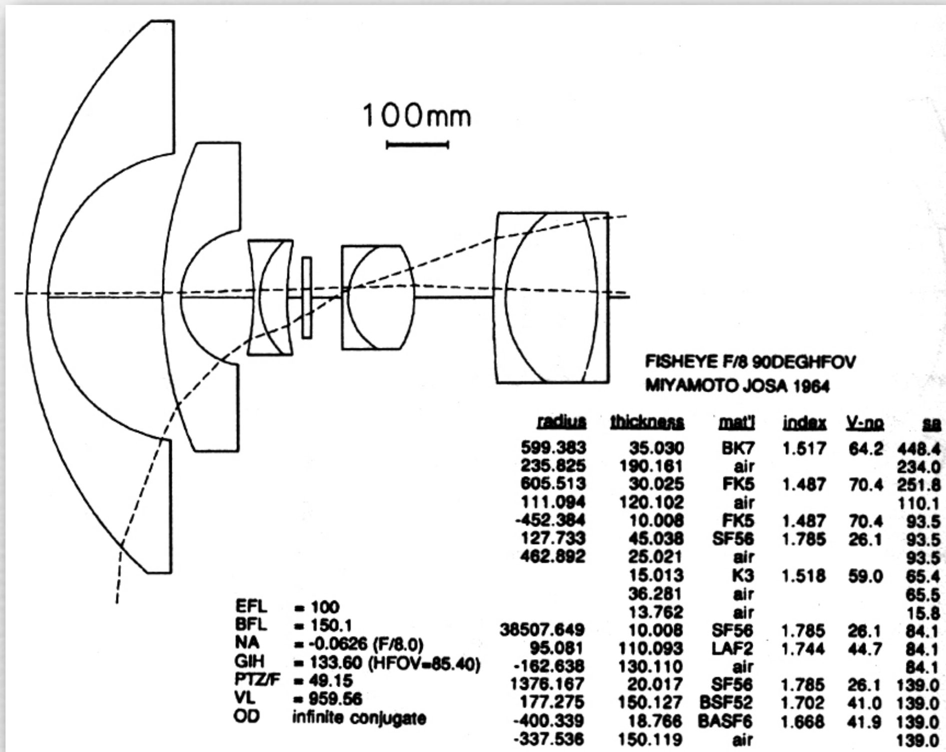
Lens design software





- ✦ uses optimization to make good recipes better

Lens catalogs and patents

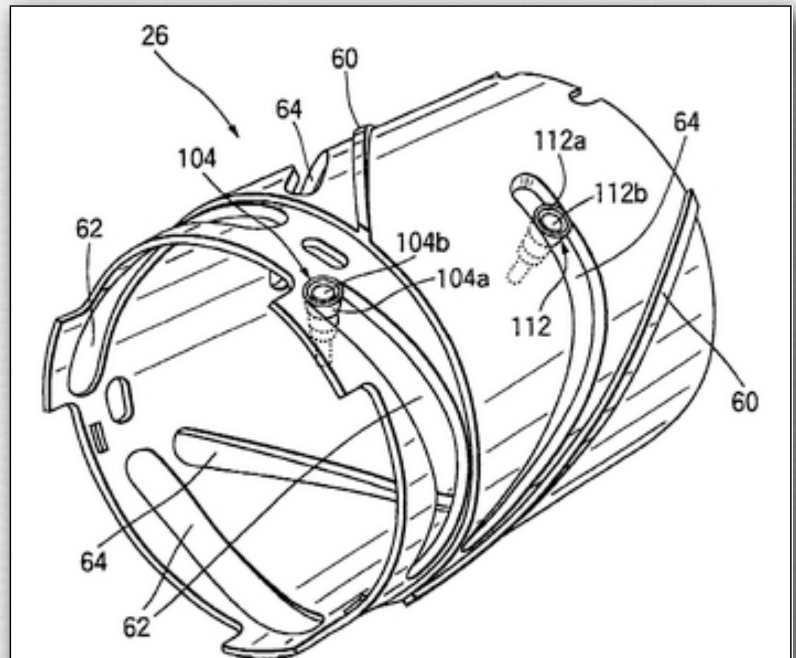


100mm

FISHEYE F/8 90DEGHFOV
MIYAMOTO JOSA 1964

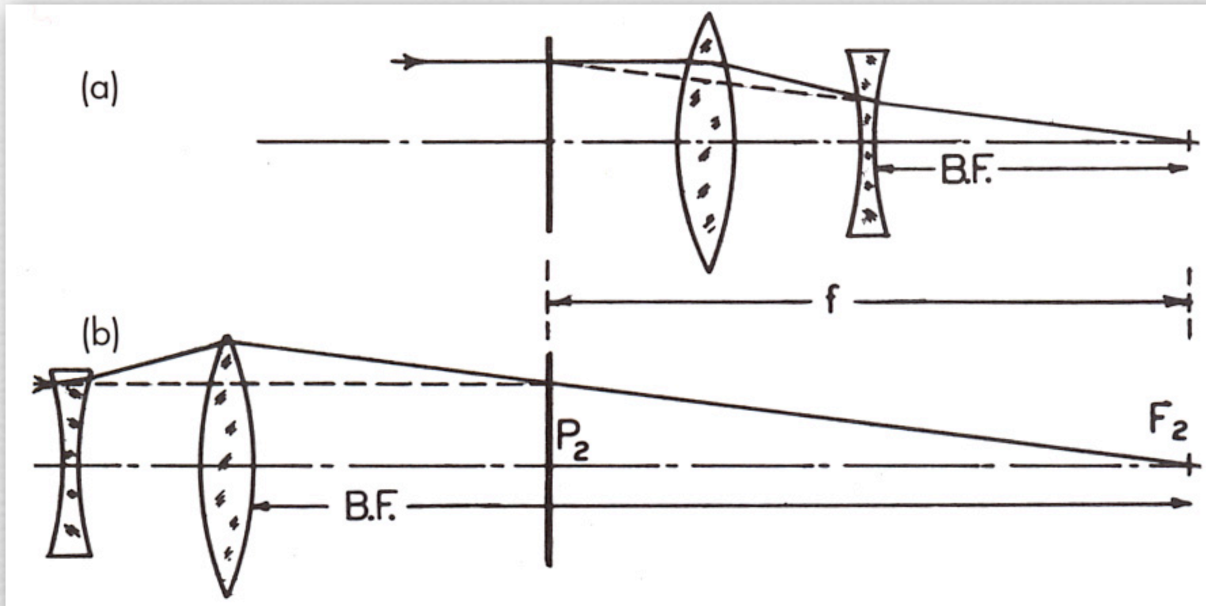
radius	thickness	mat'l	index	V-no	sa
599.383	35.030	BK7	1.517	64.2	448.4
235.825	190.161	air			234.0
605.513	30.025	FK5	1.487	70.4	251.8
111.094	120.102	air			110.1
-452.384	10.008	FK5	1.487	70.4	93.5
127.733	45.038	SF56	1.785	26.1	93.5
462.892	25.021	air			93.5
	15.013	K3	1.518	59.0	65.4
	36.281	air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

Special-purpose lenses: telephoto

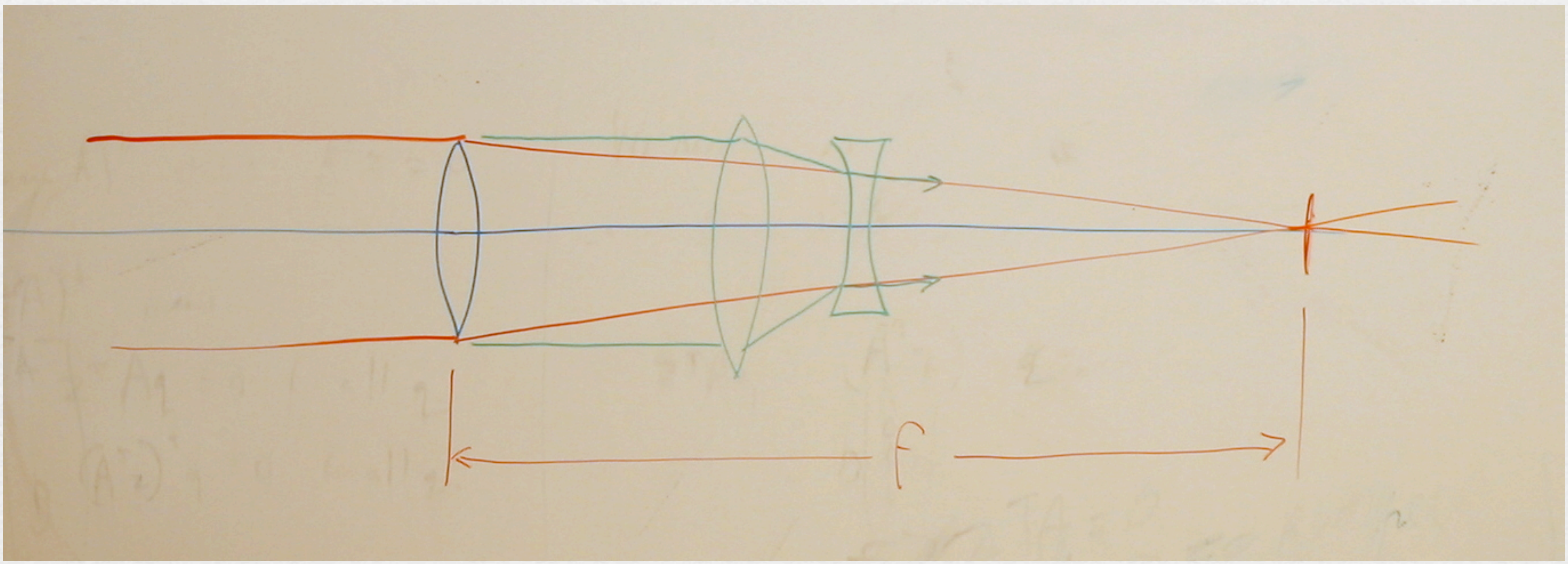


(Kingslake)

- 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)



Special-purpose lenses: telephoto

(wikipedia)

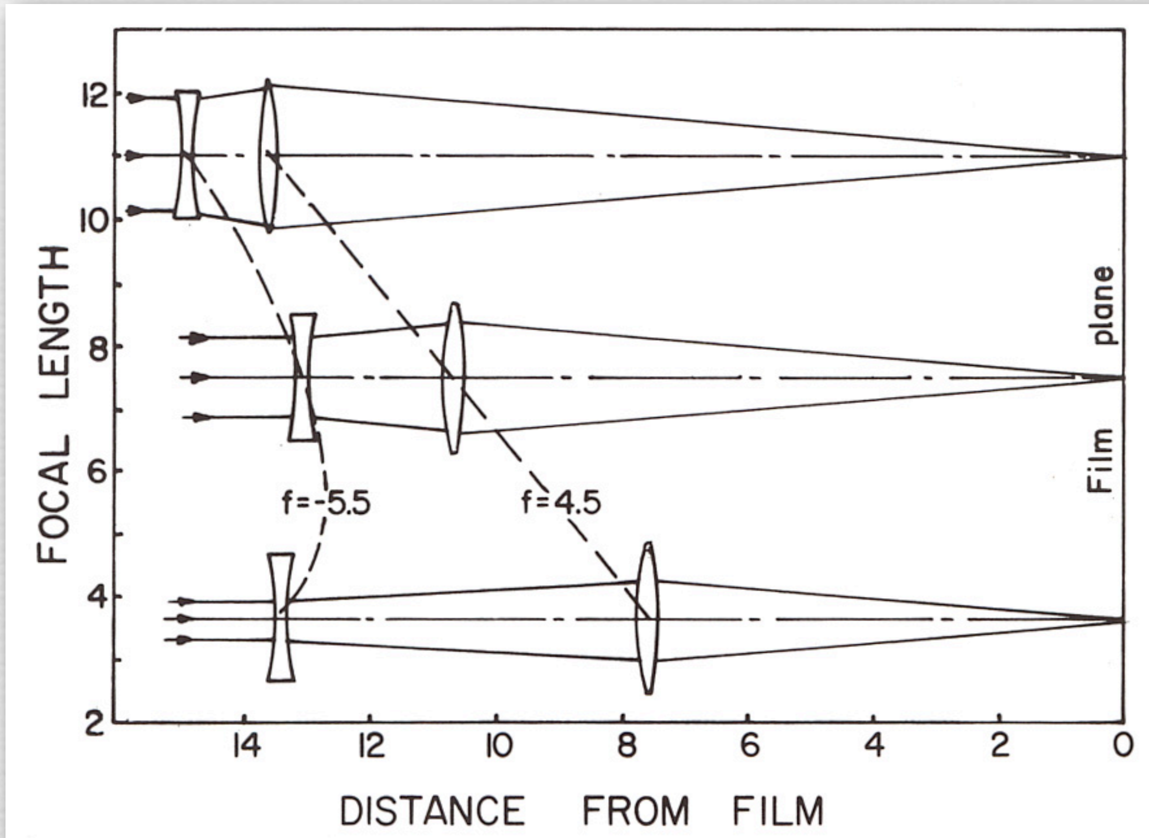
500mm non-telephoto

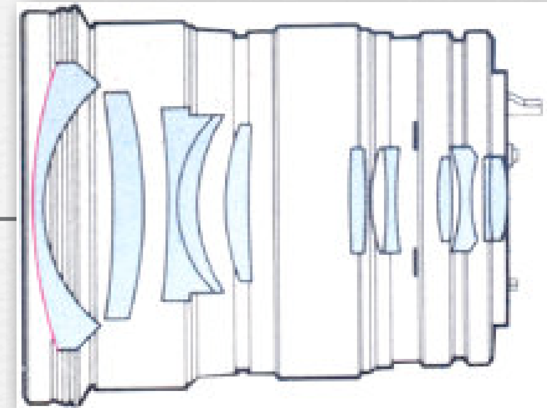
Canon 500mm telephoto

Canon 1200mm telephoto

Lens combinations: zoom

This slide added 4/14/09.





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

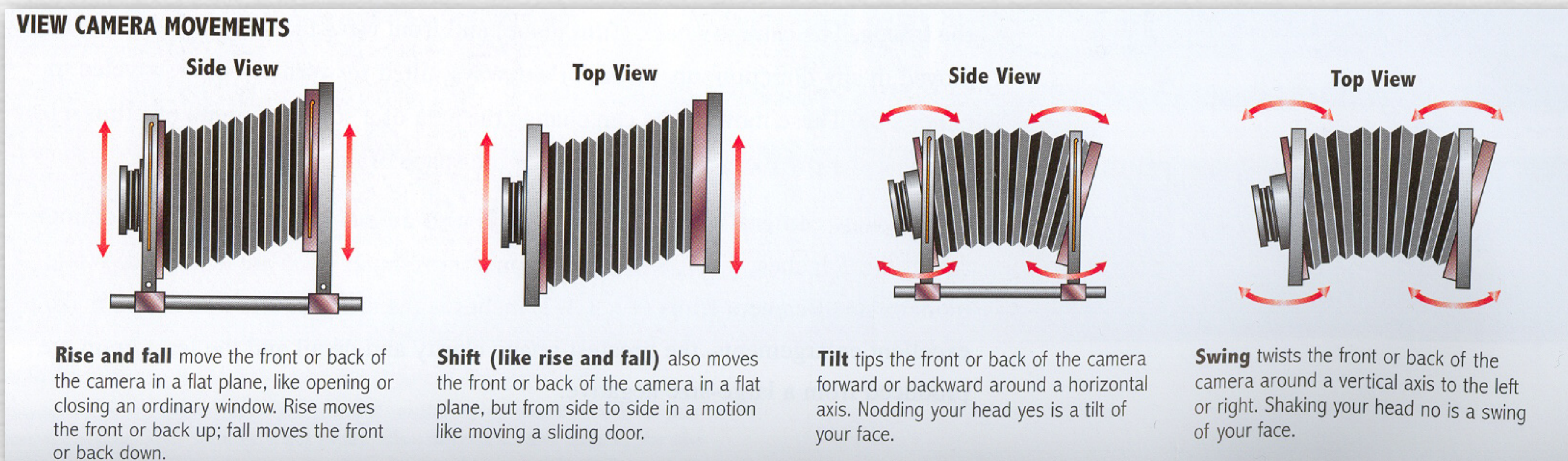
(FLASH DEMO)

http://graphics.stanford.edu/courses/cs178-09/applets/zoom.swf

- 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

Special-purpose lenses: view camera

Sinar view camera with digital back

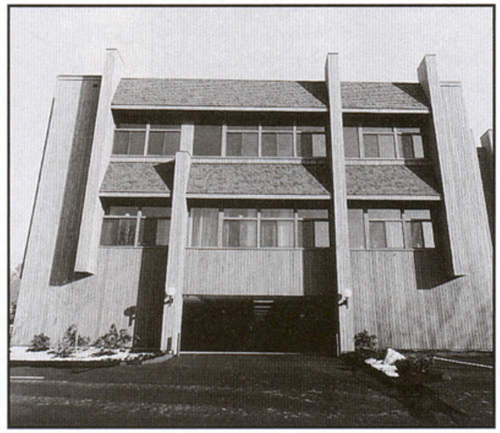


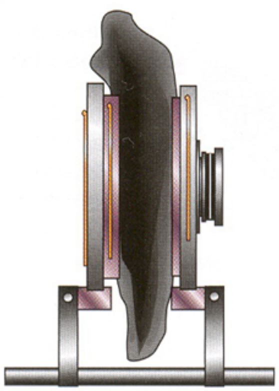
(London)

Off-axis perspective

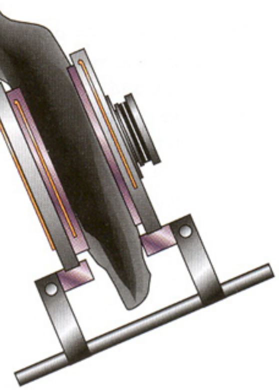
NOW AVAILABLE IN PHOTOSHOP !!

CONTROLLING CONVERGING LINES: THE KEYSTONE EFFECT

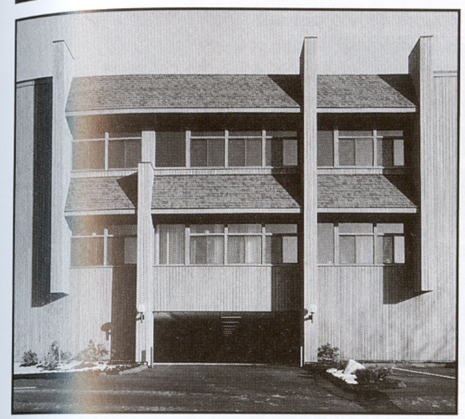


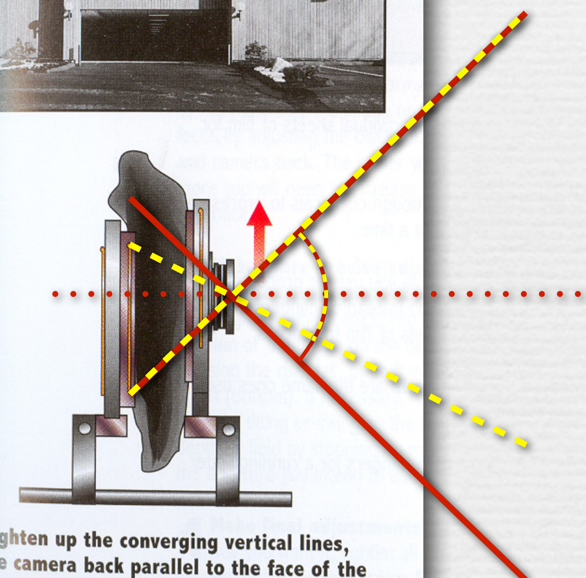


Standing at street level and shooting straight at a building produces too much street and too little building. Sometimes it is possible to move back far enough to show the entire building while keeping the camera level, but this adds even more foreground and usually something gets in the way.



Tilting the whole camera up shows the entire building but distorts its shape. Since the top is farther from the camera than the bottom, it appears smaller; the vertical lines of the building seem to be coming closer together, or converging, near the top. This is named the keystone effect, after the wedge-shaped stone at the top of an arch. This convergence gives the illusion that the building is falling backward—an effect particularly noticeable when only one side of the building is visible.

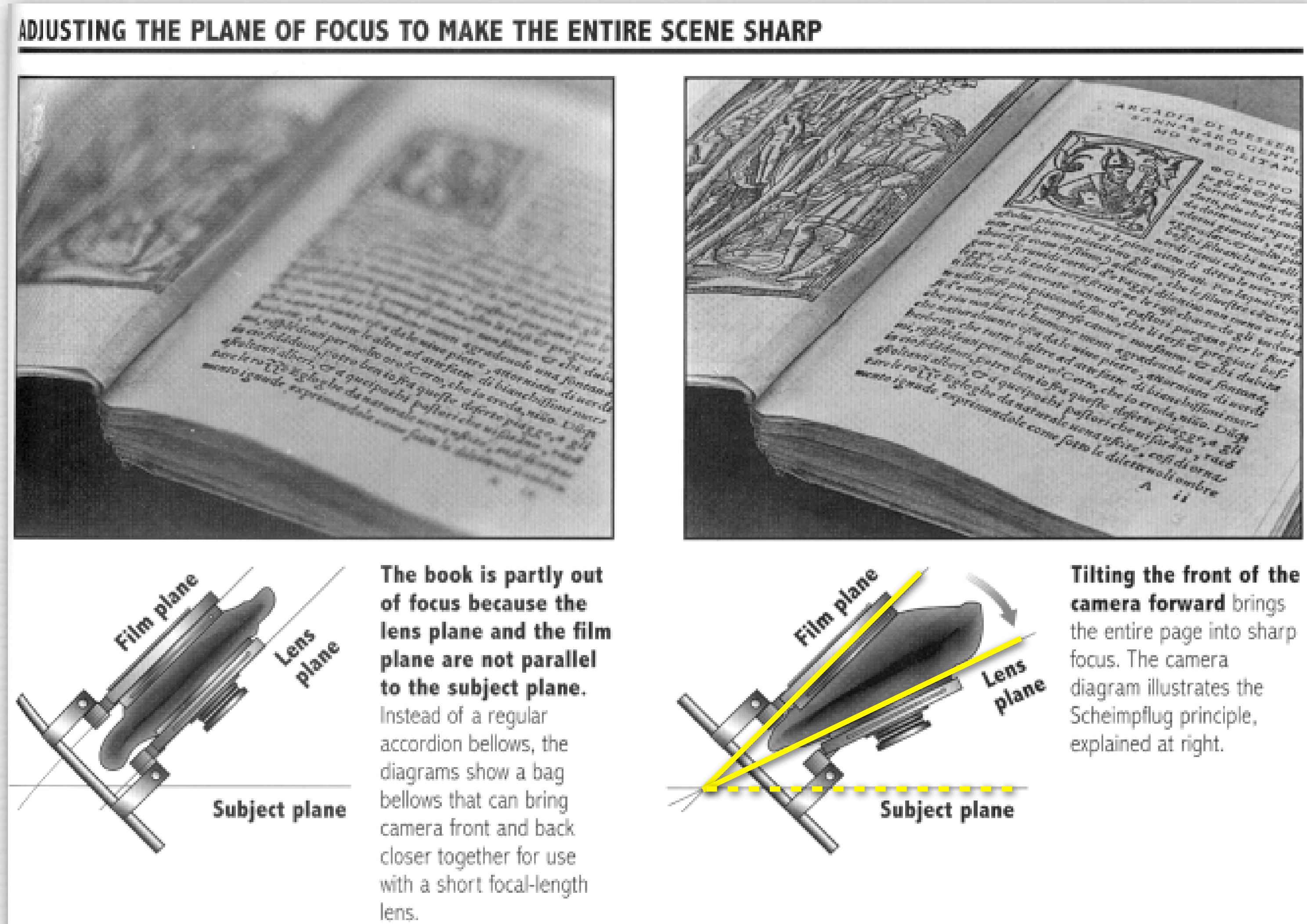




To straighten up the converging vertical lines, keep the camera back parallel to the face of the building. To keep the face of the building in focus, make sure the lens is parallel to the camera back. One way to do this is to level the camera and then use the rising front or falling back movements or both.

Another solution is to point the camera upward toward the top of the building, then use the tilting movements—first to tilt the back to a vertical position (which squares the shape of the building), then to tilt the lens so it is parallel to the camera back (which brings the face of the building into focus). The lens and film will end up in the same positions with both methods.

Tilted focal plane



ADJUSTING THE PLANE OF FOCUS TO MAKE THE ENTIRE SCENE SHARP

The book is partly out of focus because the lens plane and the film plane are not parallel to the subject plane. Instead of a regular accordion bellows, the diagrams show a bag bellows that can bring camera front and back closer together for use with a short focal-length lens.

Tilting the front of the camera forward brings the entire page into sharp focus. The camera diagram illustrates the Scheimpflug principle, explained at right.

(London)

- Scheimpflug condition

✦ cannot be done after the photograph is taken

Ansel Adams, Railroad Tracks

Ansel Adams, Monument Valley

Tilt-shift lenses

Canon TS-E
90mm lens

Tilt-shift lenses

Canon TS-E
90mm lens

Not a tilt-shift lens

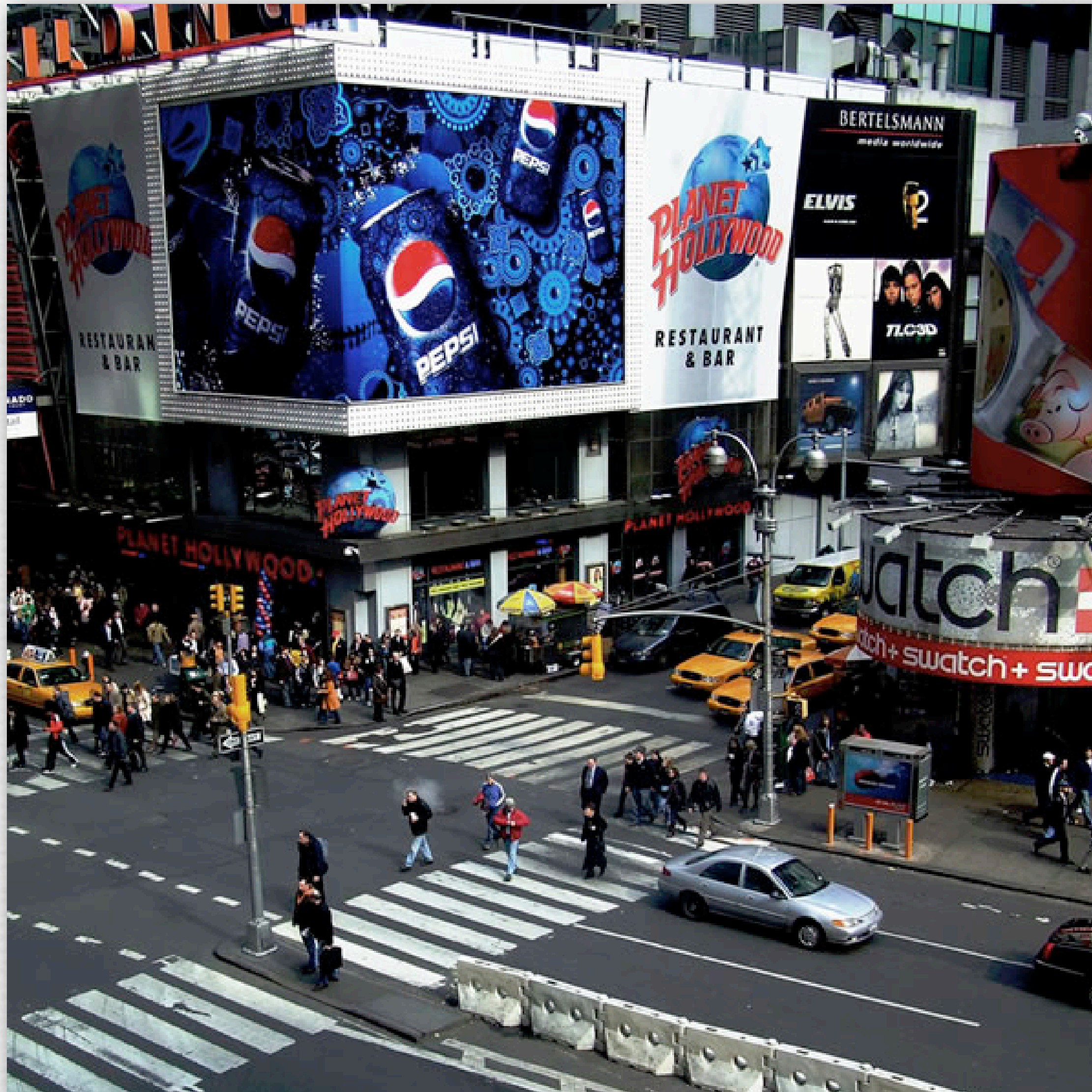
(http://www.tiltshiftphotography.net/)

- selective blurring in Photoshop
- simulates a macro lens, hence looks like a miniature, but not like a tilt-shift lens

Not a tilt-shift lens

- selective blurring in Photoshop
- simulates a macro lens, hence looks like a miniature, but not like a tilt-shift lens

(http://www.tiltshiftphotography.net/)



original

Slide credits (for optics I and II lectures)

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- Fredo Durand

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