

Lenses

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MIT EECS



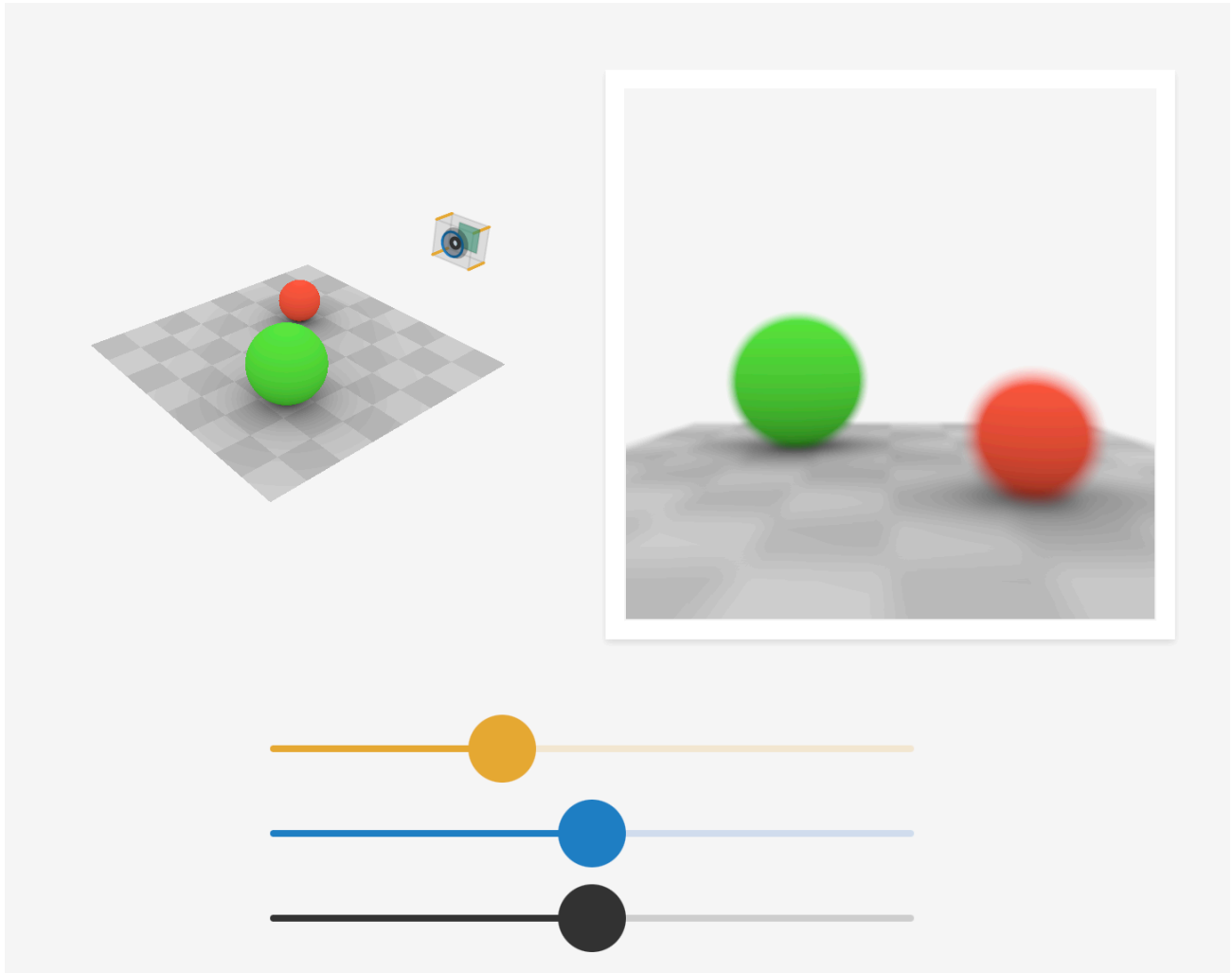
DO PINHOLES AGAIN?

Halide, impact, academia

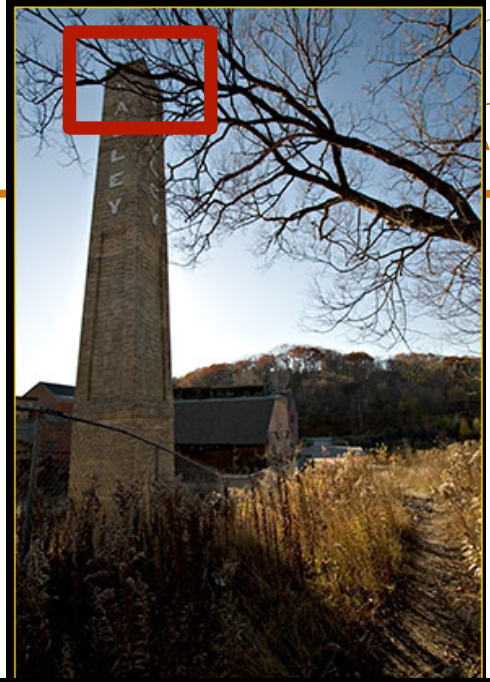
- **See also my slides**
- **https://docs.google.com/presentation/d/1lILcOIT0iS-UXfD9oiSZS_FUL0LktCvFczNN3YK8G4E/edit?slide=id.g15f11a8a27f_7_80#slide=id.g15f11a8a27f_7_80**

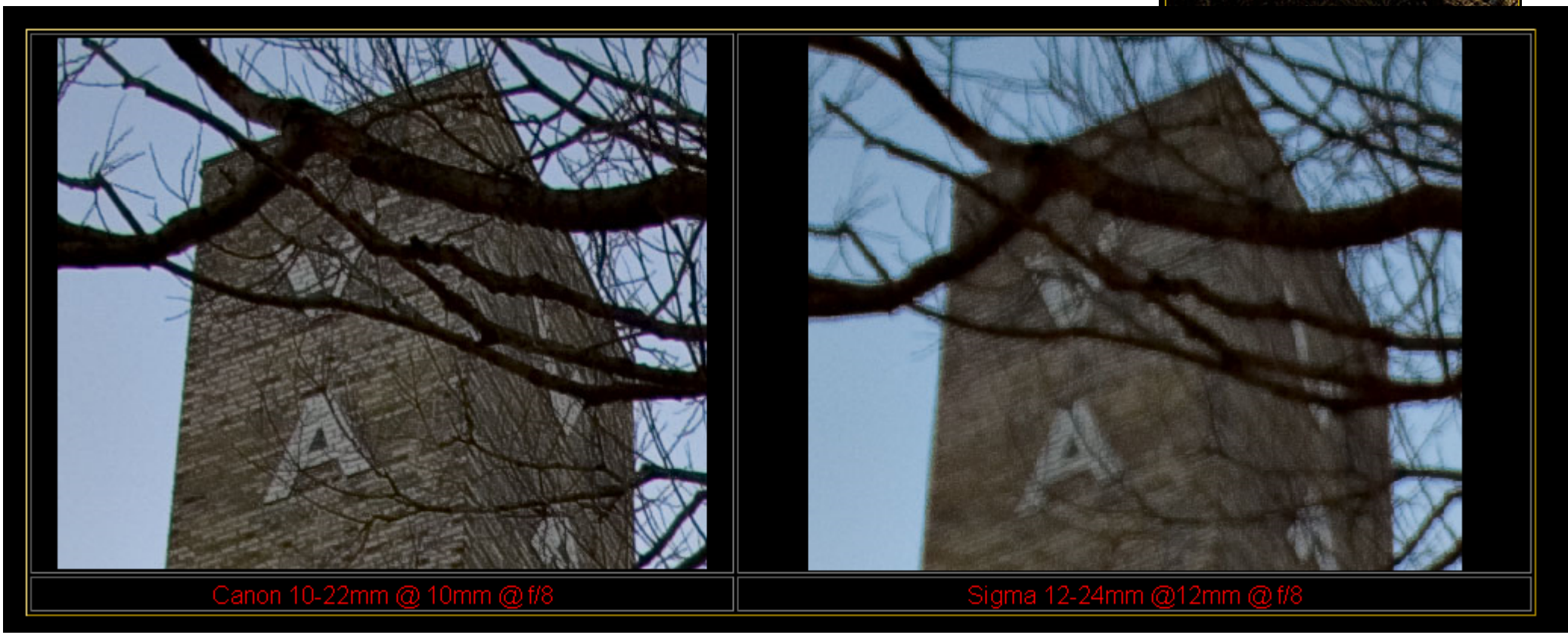
Cool ref on camera and lenses

- **https://ciechanow.ski/cameras-and-lenses/**



Lens quality varies!





source: the luminous landscape



source: the luminous landscape

Center is usually OK

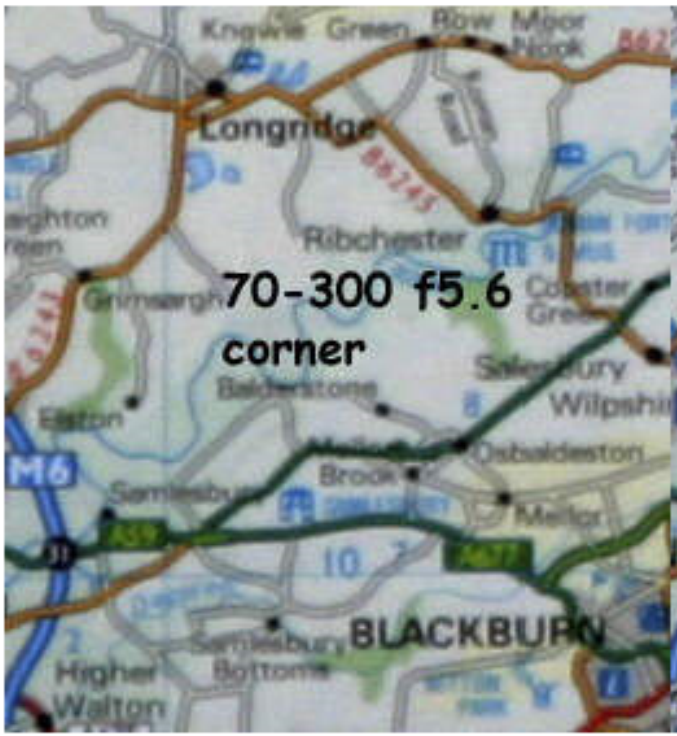
- **http://www.photo.net/equipment/canon/70-300do_2/**

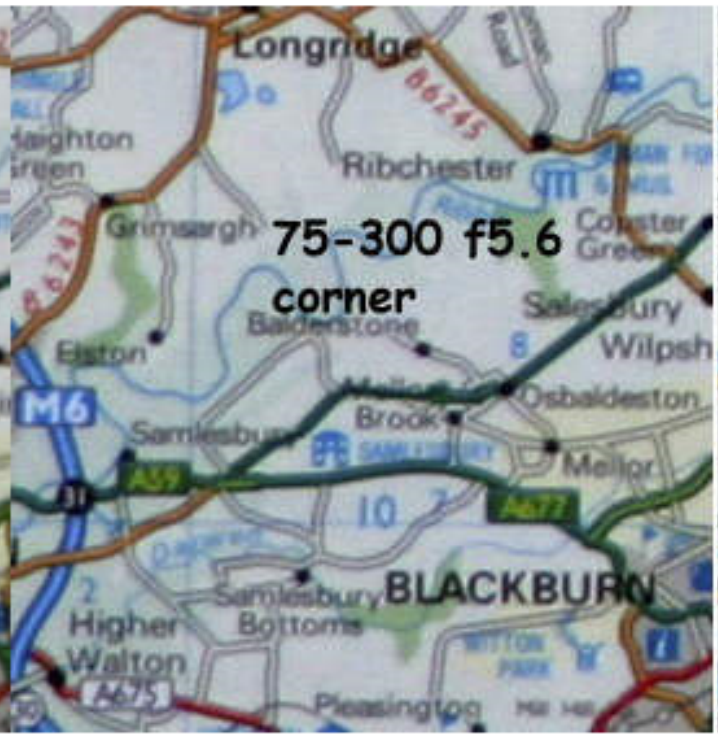


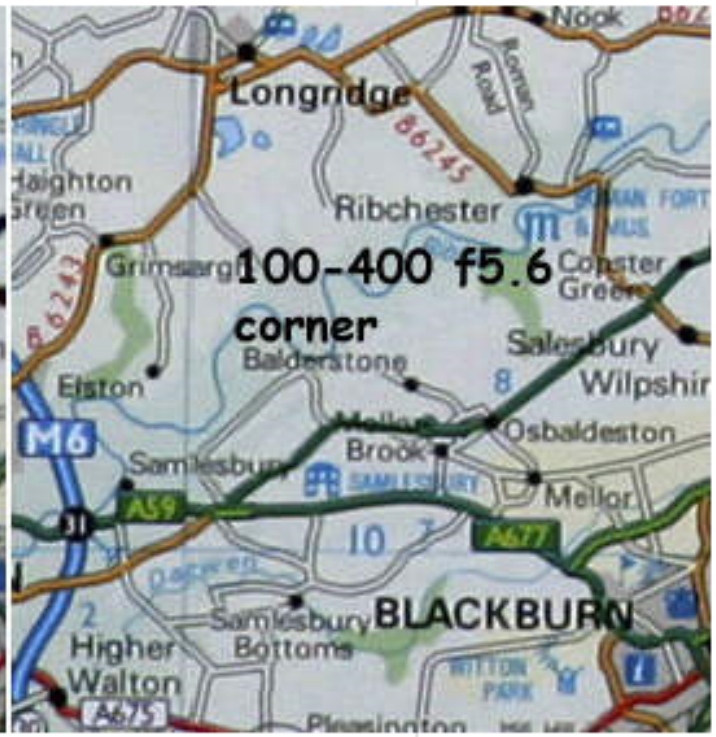
250x500 pixel crops, centre of frame f5.6

Image corners are often sacrificed

- **http://www.photo.net/equipment/canon/70-300do_2/**







250x500 pixel crops, corner of frame f5.6

Max aperture is tough

- **http://www.photo.net/equipment/canon/70-300do_2/**



250x500 pixel crops, centre of frame f5.6

Gets better when stopped down

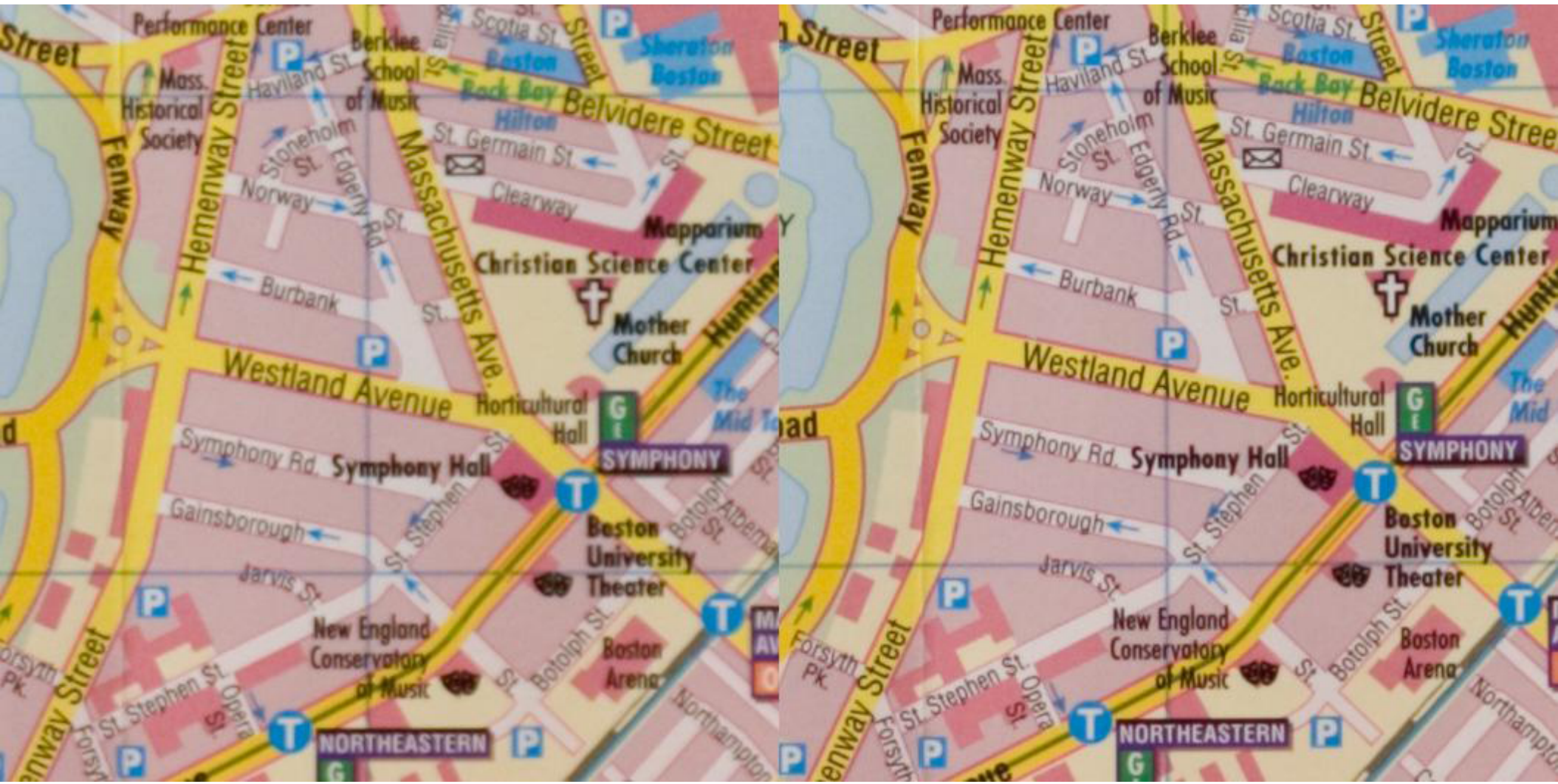
- **http://www.photo.net/equipment/canon/70-300do_2/**



250x500 pixel crops, centre of frame f11

Copy variation

- **Left: Addy's 100-400; Right: Frédo's**
- **(full aperture, 135mm)**



Why are lenses so complex?

- **It's not so easy to send light where it should go**

Figure-11
Cross-Section of the EF24-70mm f/2.8L USM

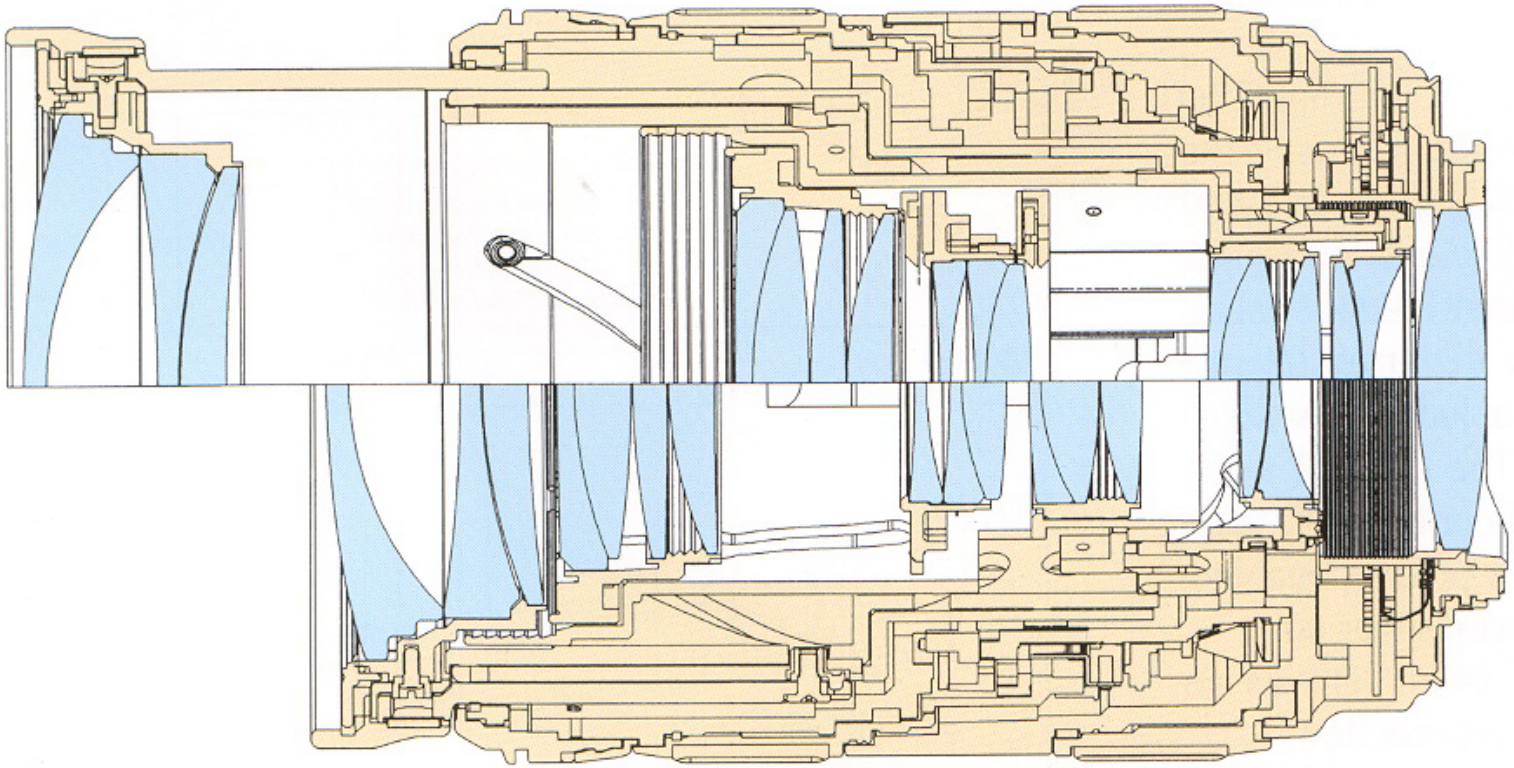


Photo-4 Precision Zoom Cam Lens Barrel



source: canon red book

Simple lenses are not so good

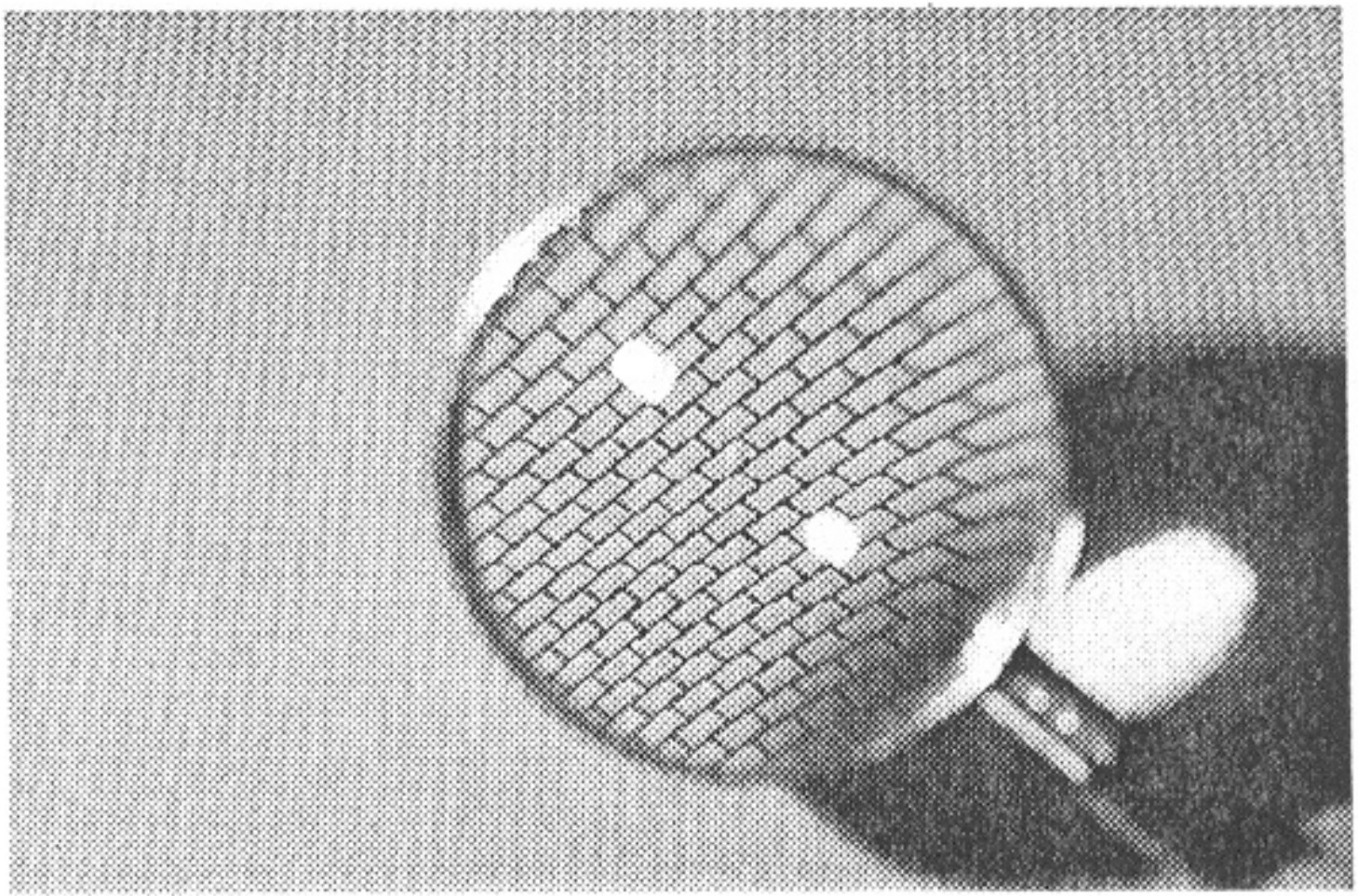


Plate 11.2 Aberrated imagery from a simple biconvex lens
The image of simple regular patterned subject shows increasingly poor quality off axis and the two uncoated surfaces of the lens both reflect the light source.

From Ray's Applied Photographic Optics

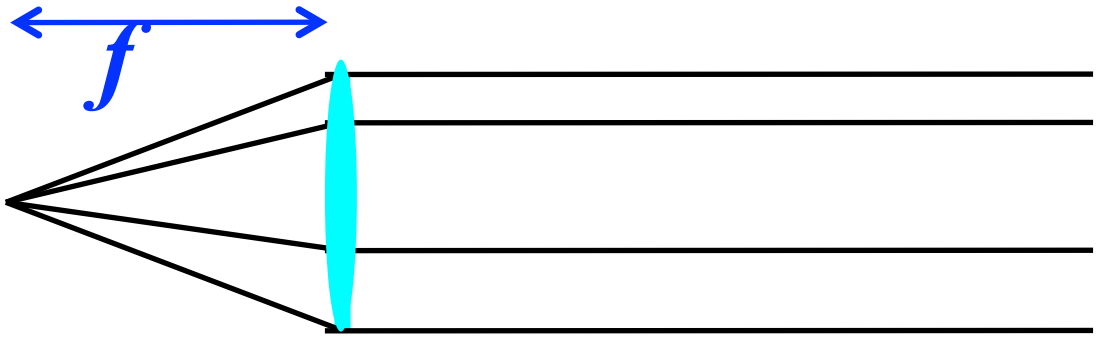
Question?

CSAIL

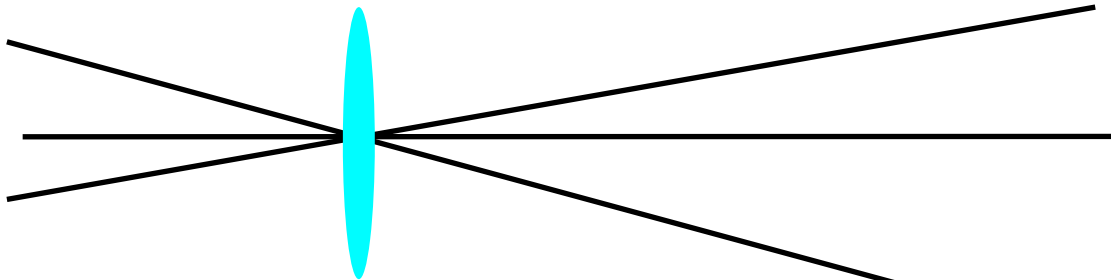
Lens 101 review

Thin lens optics

- **Simplification of geometrical optics All parallel rays converge to one point on a plane located at the focal length *f***



- **All rays going through the center are not deviated**
  - Hence same perspective as pinhole



TODAY WE GO BEYOND THESE SIMPLIFICATIONS

Image quality

- **Geometrical optics: hard to focus all rays**
- **Wave optics: diffraction problems**

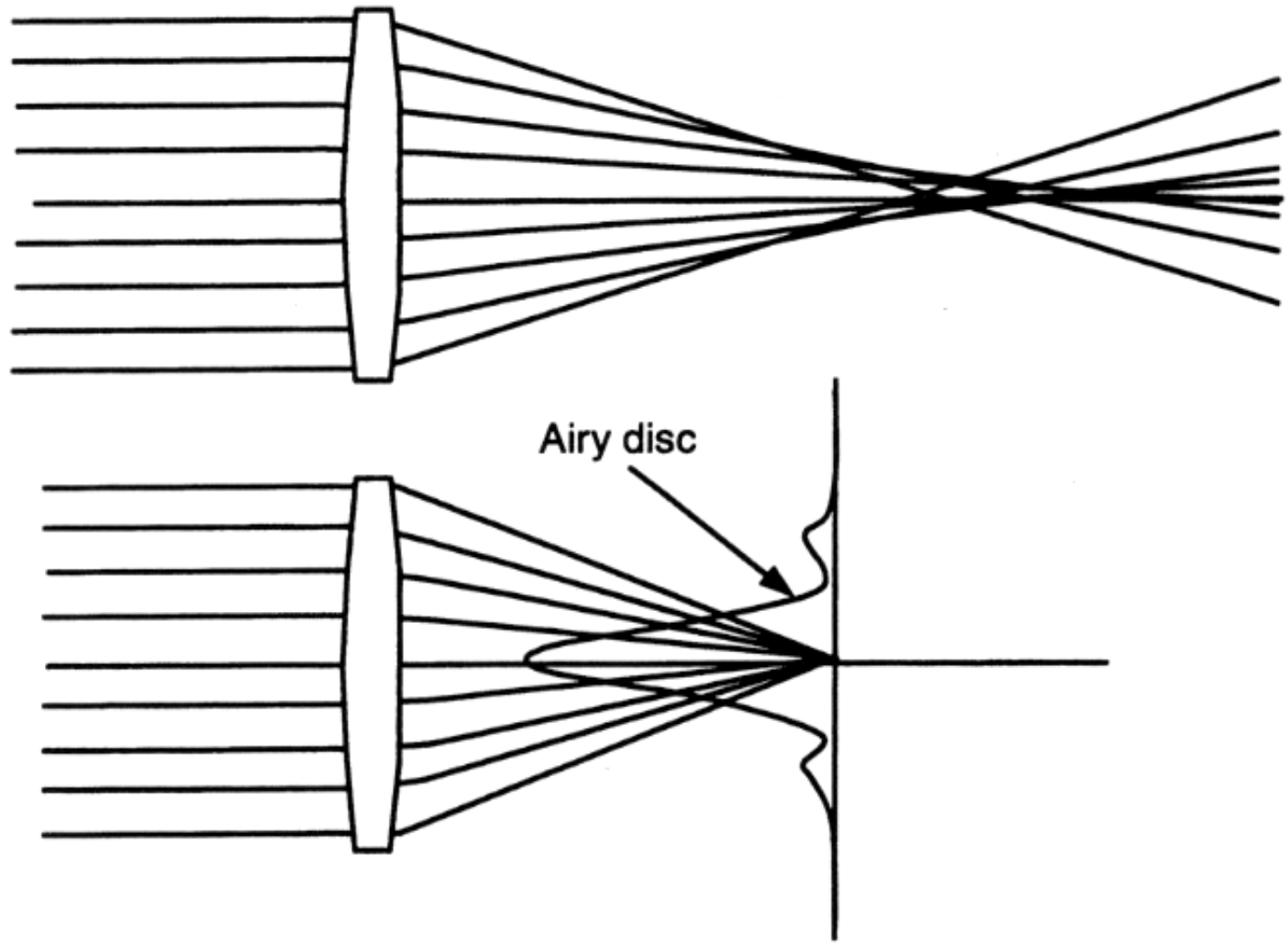


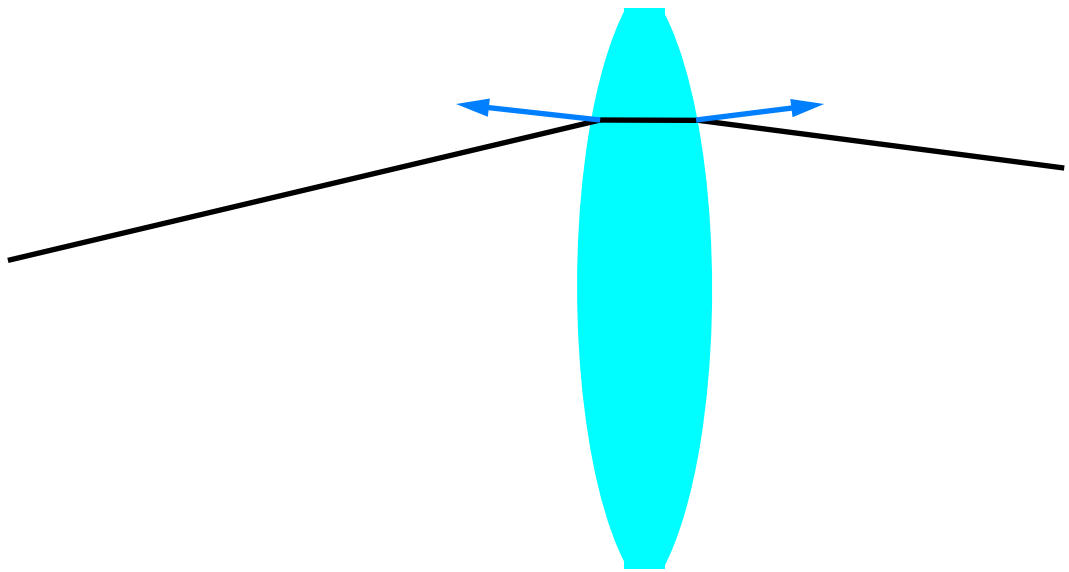
Figure 3.1
Image Quality, Geometrical Aberrations (Top) and Diffraction Limited (Bottom)

From Optical System Design by Fisher and Tadic

Geometrical perspective

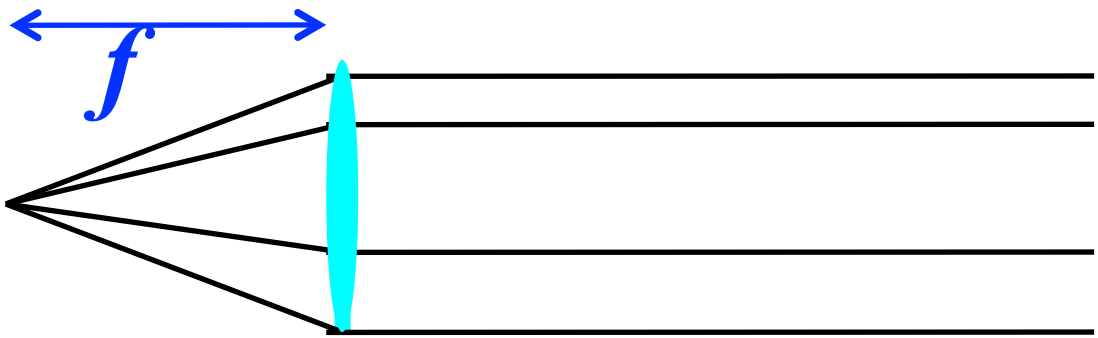
Back to thin lenses

- **Snell's law bends geometrical rays**

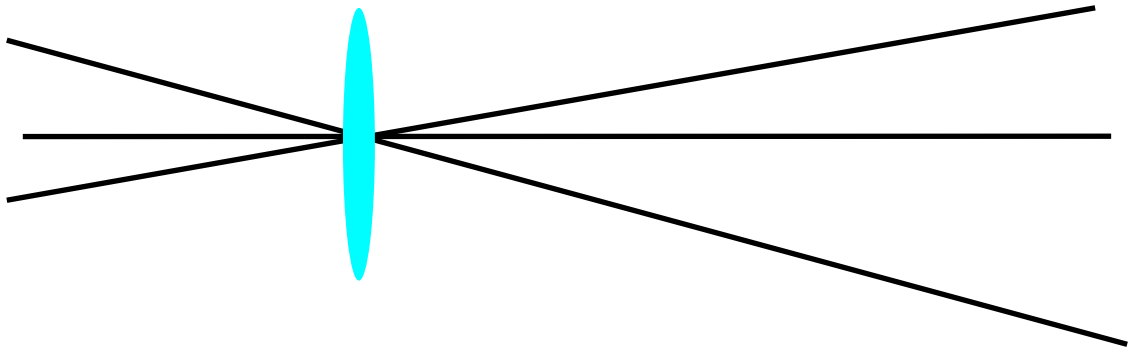


Thin lens optics

- **Simplification of geometrical optics for well-behaved lenses**
- **All parallel rays converge to one point on a plane located at the focal length *f***

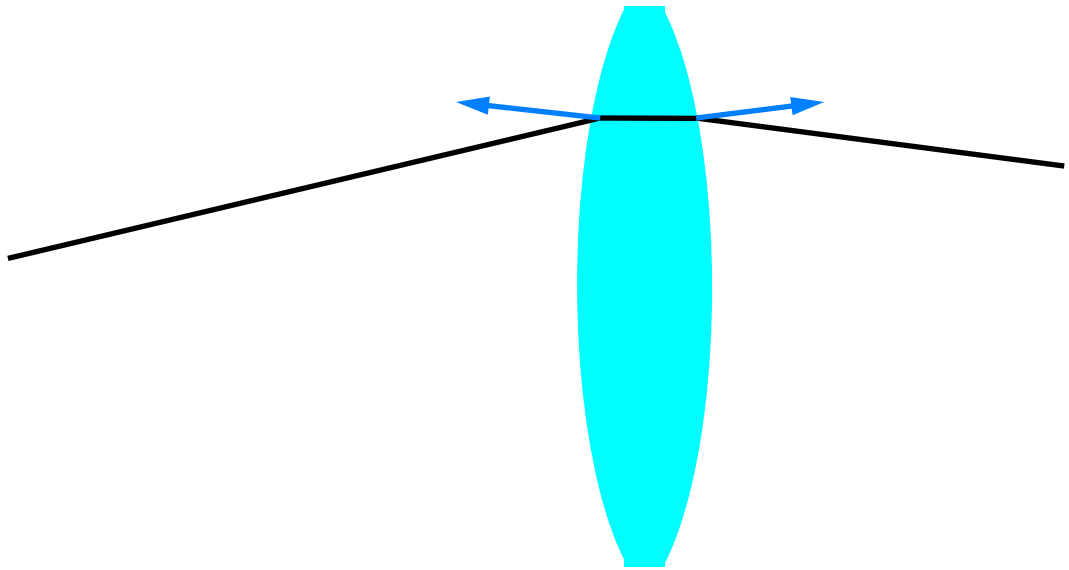


- **All rays going through the center are not deviated**
  - Hence same perspective as pinhole



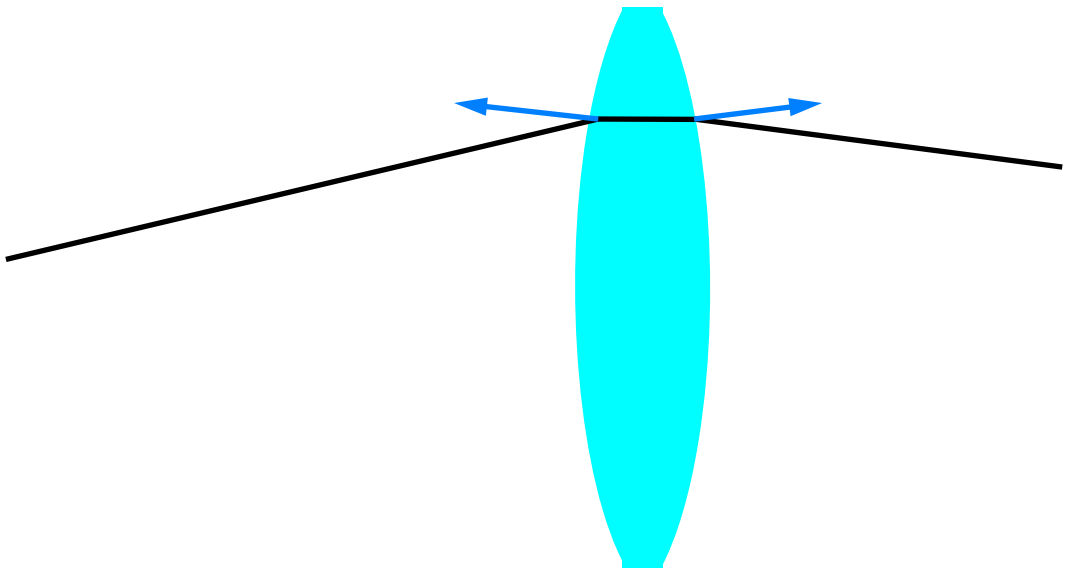
Simplification of first-order optics

- **Snell's law:** $\eta_1 \sin\theta_1 = \eta_2 \sin\theta_2$
- **First order/thin lens optics: use** $\sin\theta = \theta$



Third-order optics

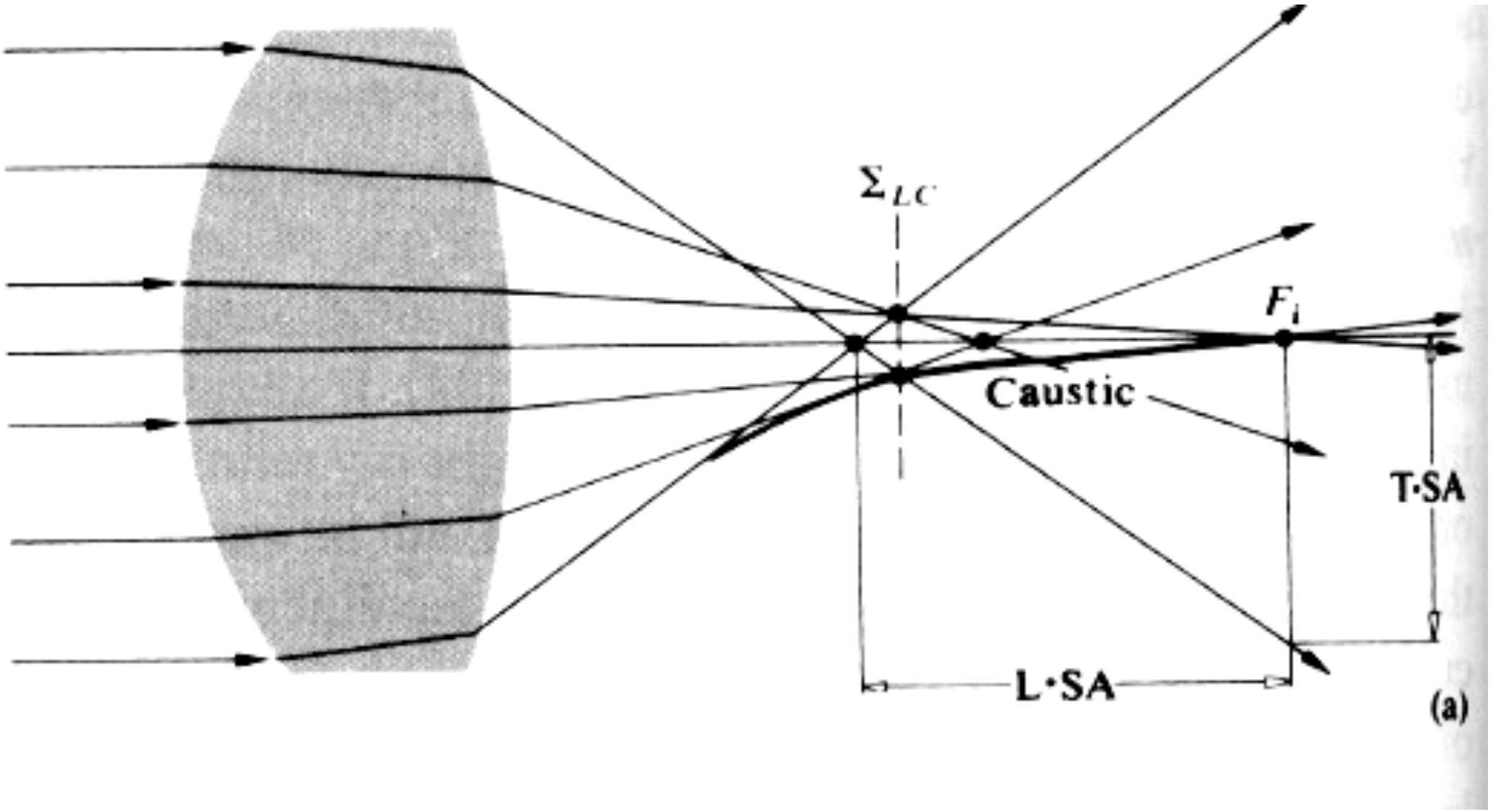
- **Sin $\theta = \theta - \theta^3/6$**
- **The extra term leads to third-order aberrations**



Third-order aberrations

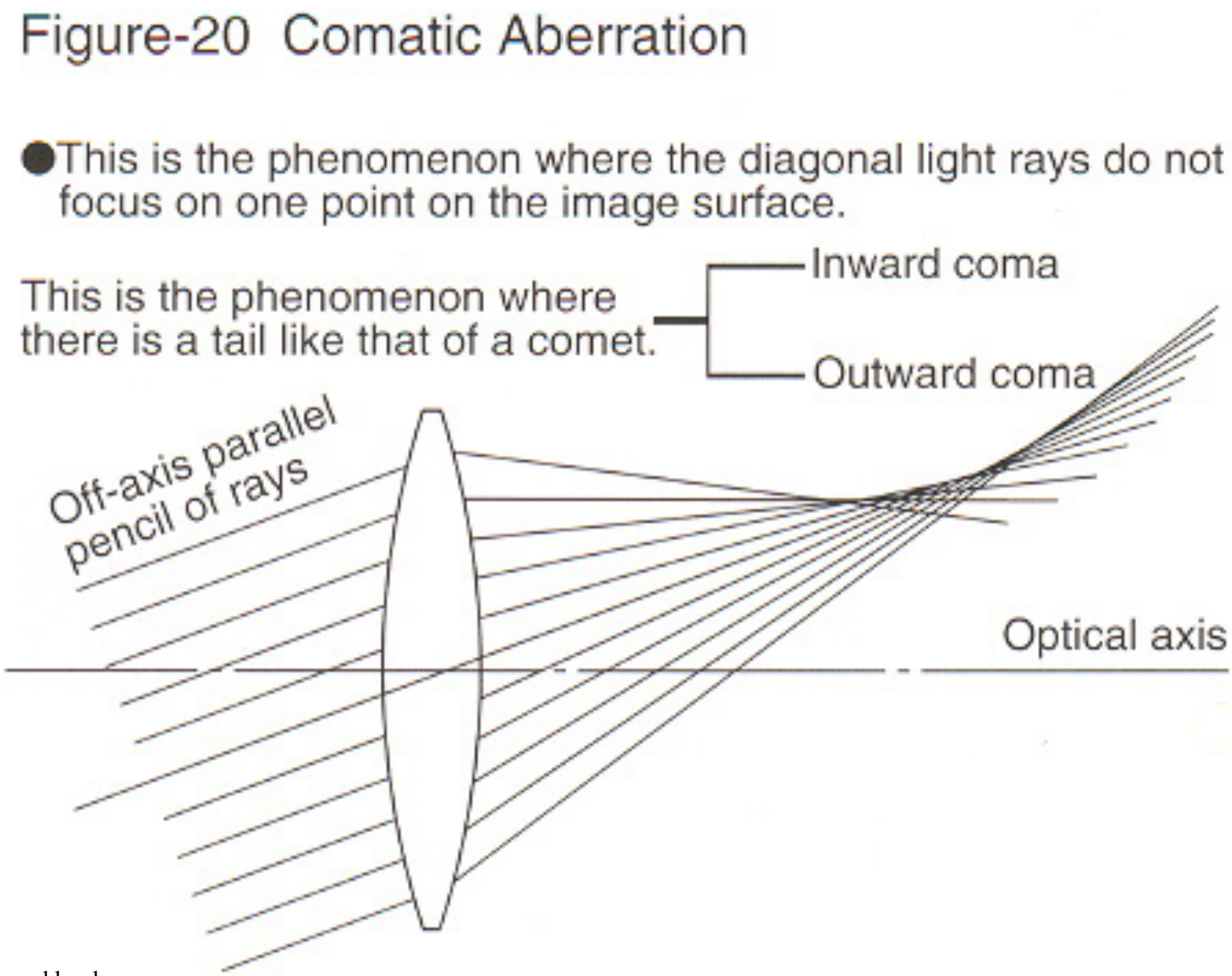
Spherical aberration

- **Rays don't focus at same position**



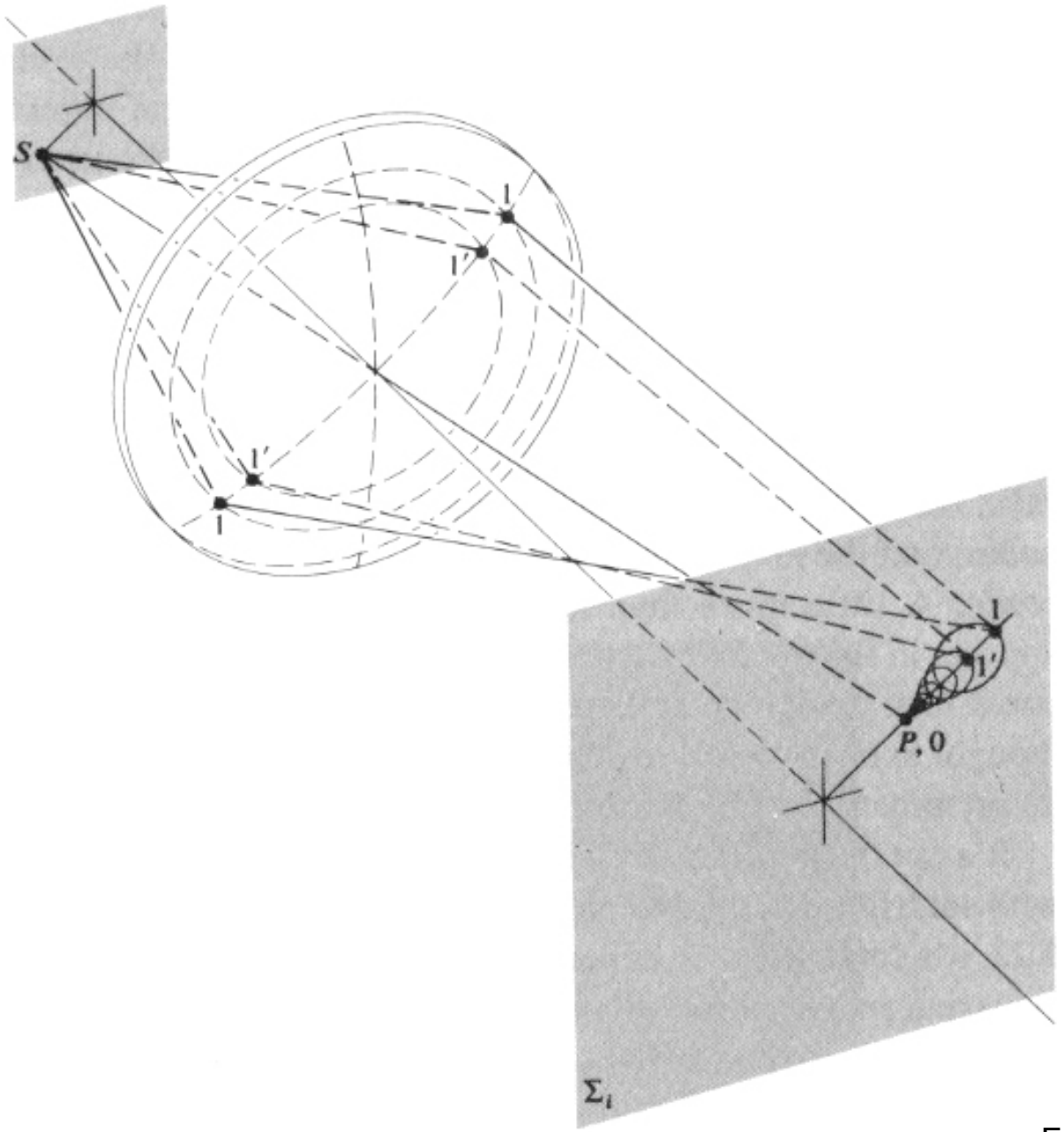
source: Hecht Optics

Comatic aberration



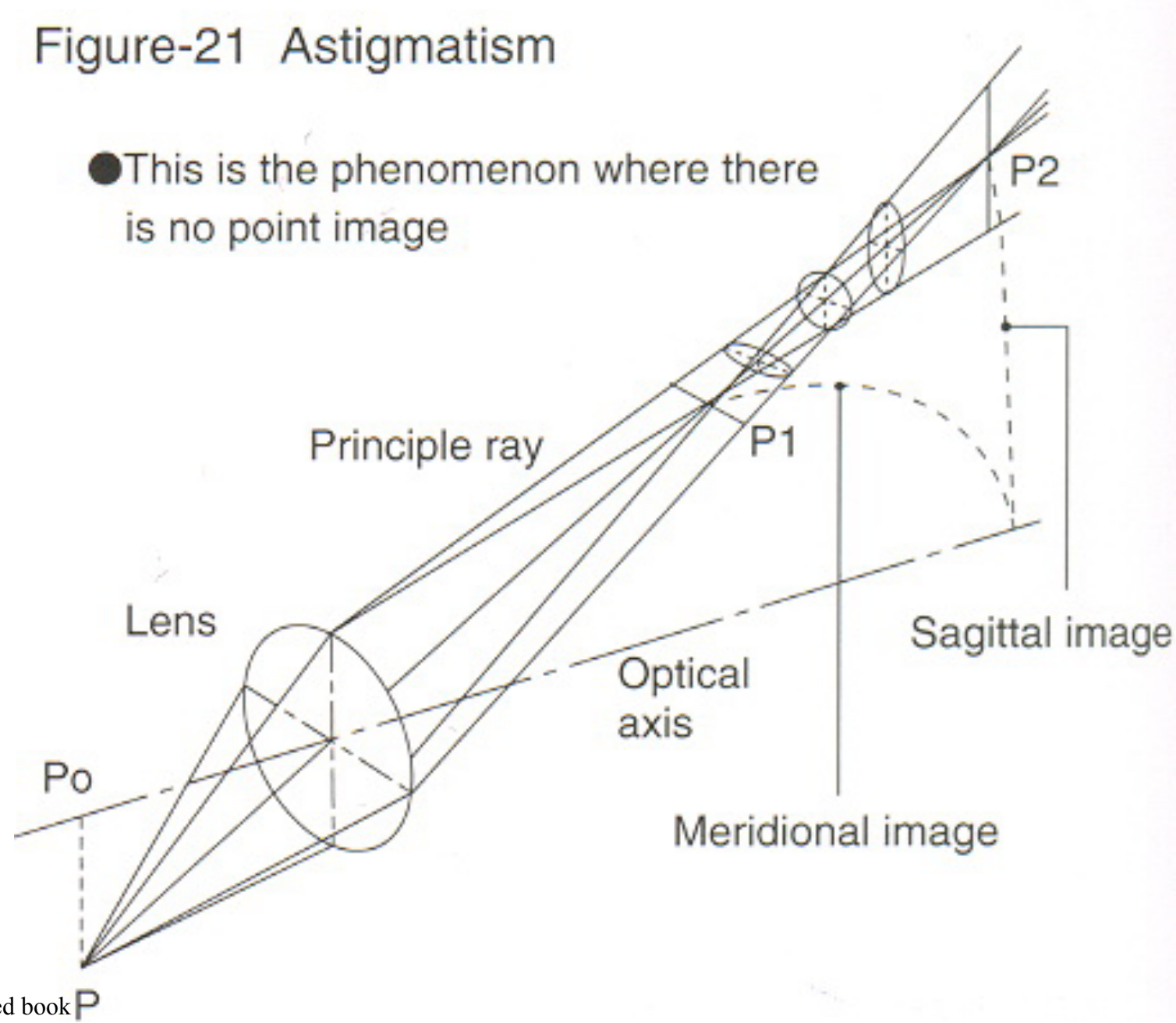
source: canon red book

Comatic aberration



From Hecht's Optics

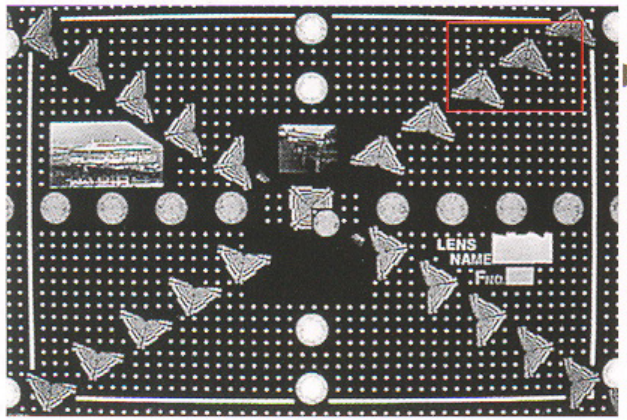
Astigmatism



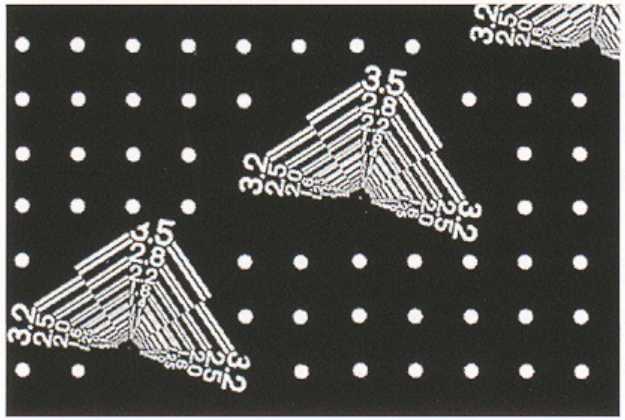
source: canon red book

Defects

Photo-2 The photographs are magnifications of the subject and surrounding area from part of a test chart photographed with a 24mm x 36mm film frame and printed on quarter size paper.

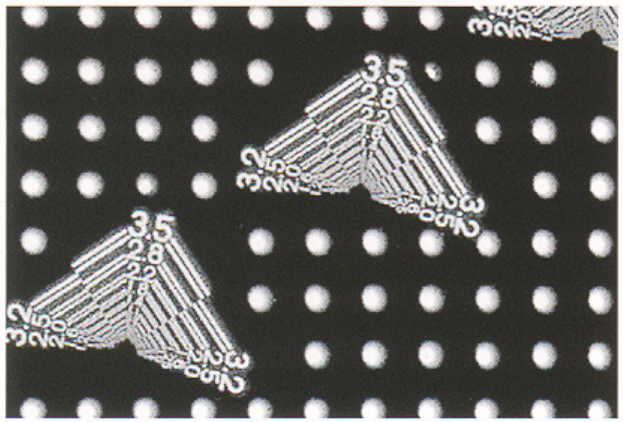


Almost ideal image formation

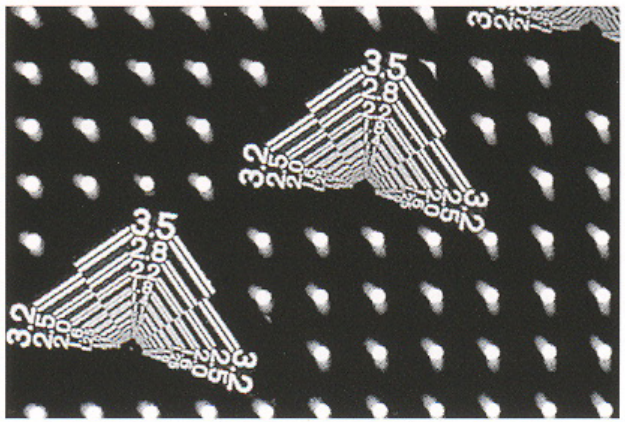


Paripheral ▭ part magnified

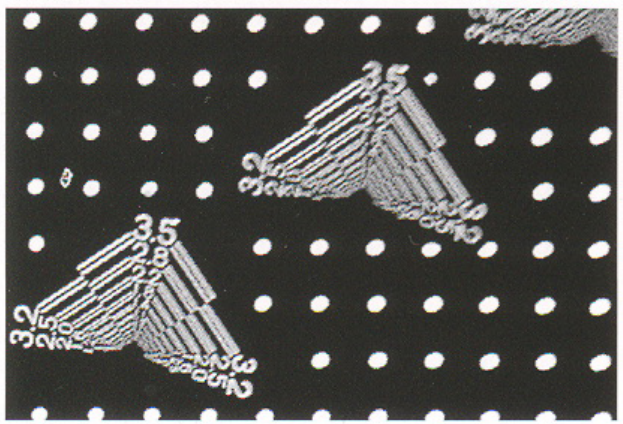
① Example of spherical aberration



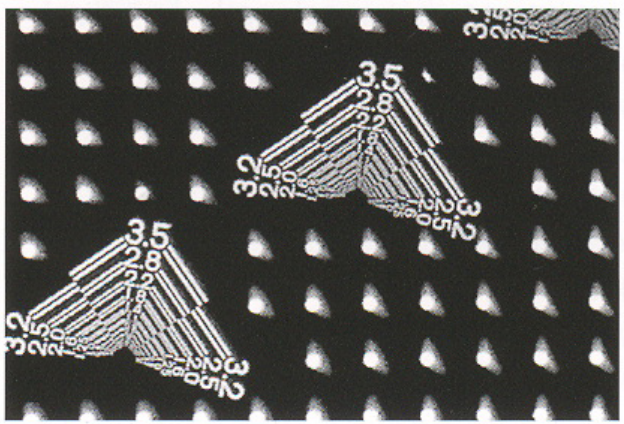
②-1 Example of inward coma



③ Example of astigmatism



②-2 Example of outward coma



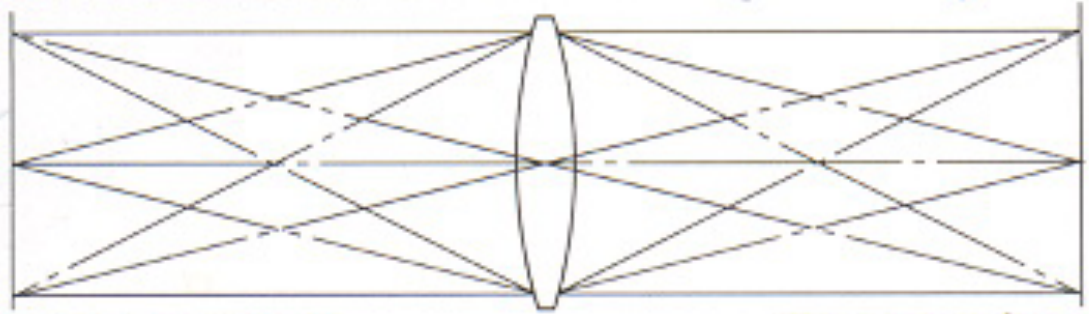
source: canon red book

Curvature of field

Figure-22 Curvature of field

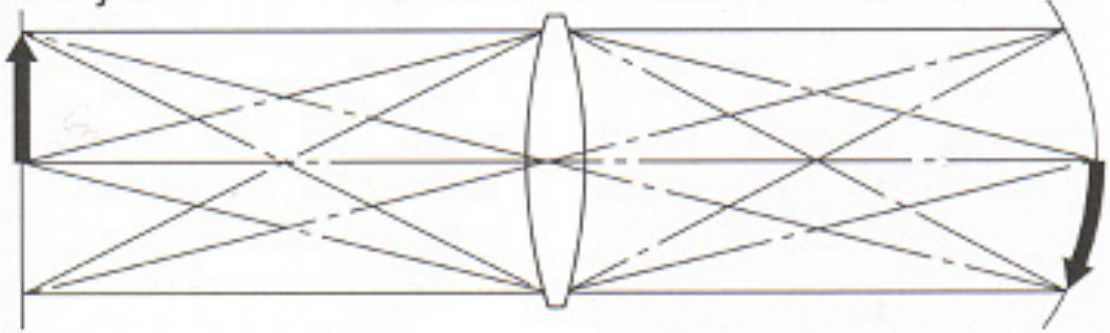
This is the phenomenon where a good image focus surface is bent.

●This is an ideal lens with no image bending.



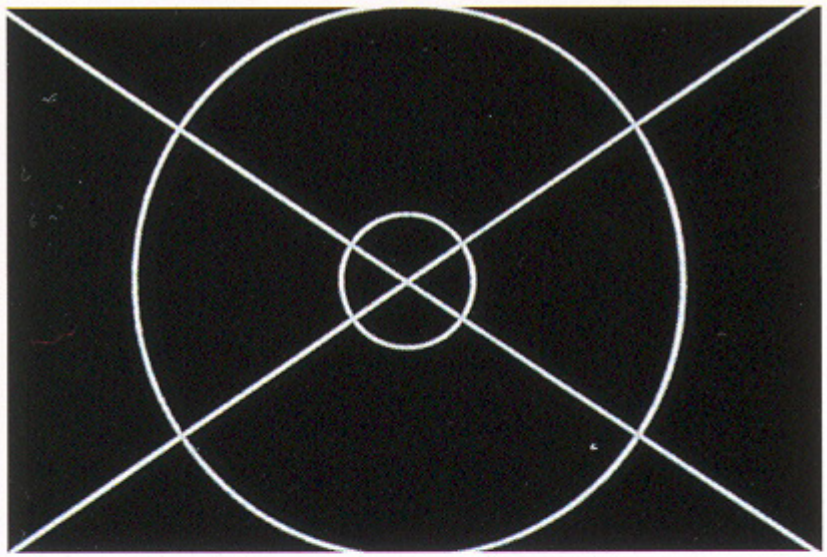
Subject surface Focus surface

Subject ●Occurrence of image bending



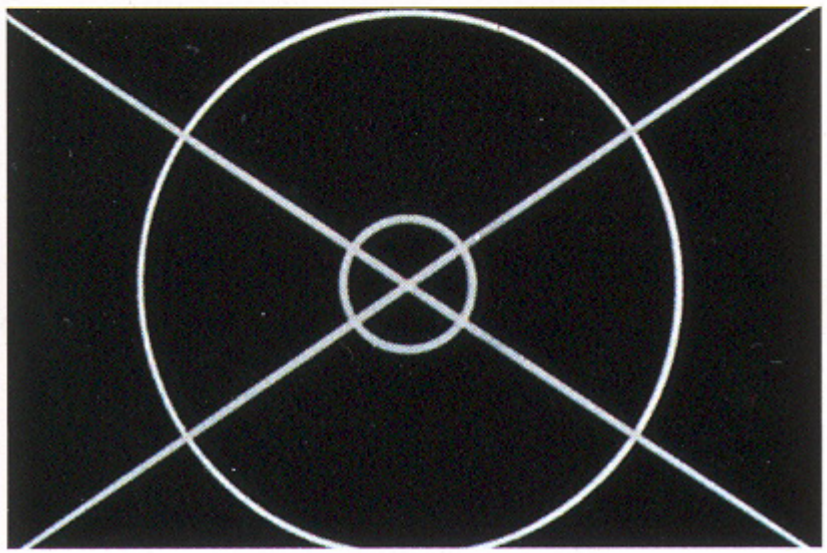
source: canon red book

Photo-5 Example of curvature of field



Focusing on center of screen causes corners to go out of focus.

Photo-6 Example of curvature of field

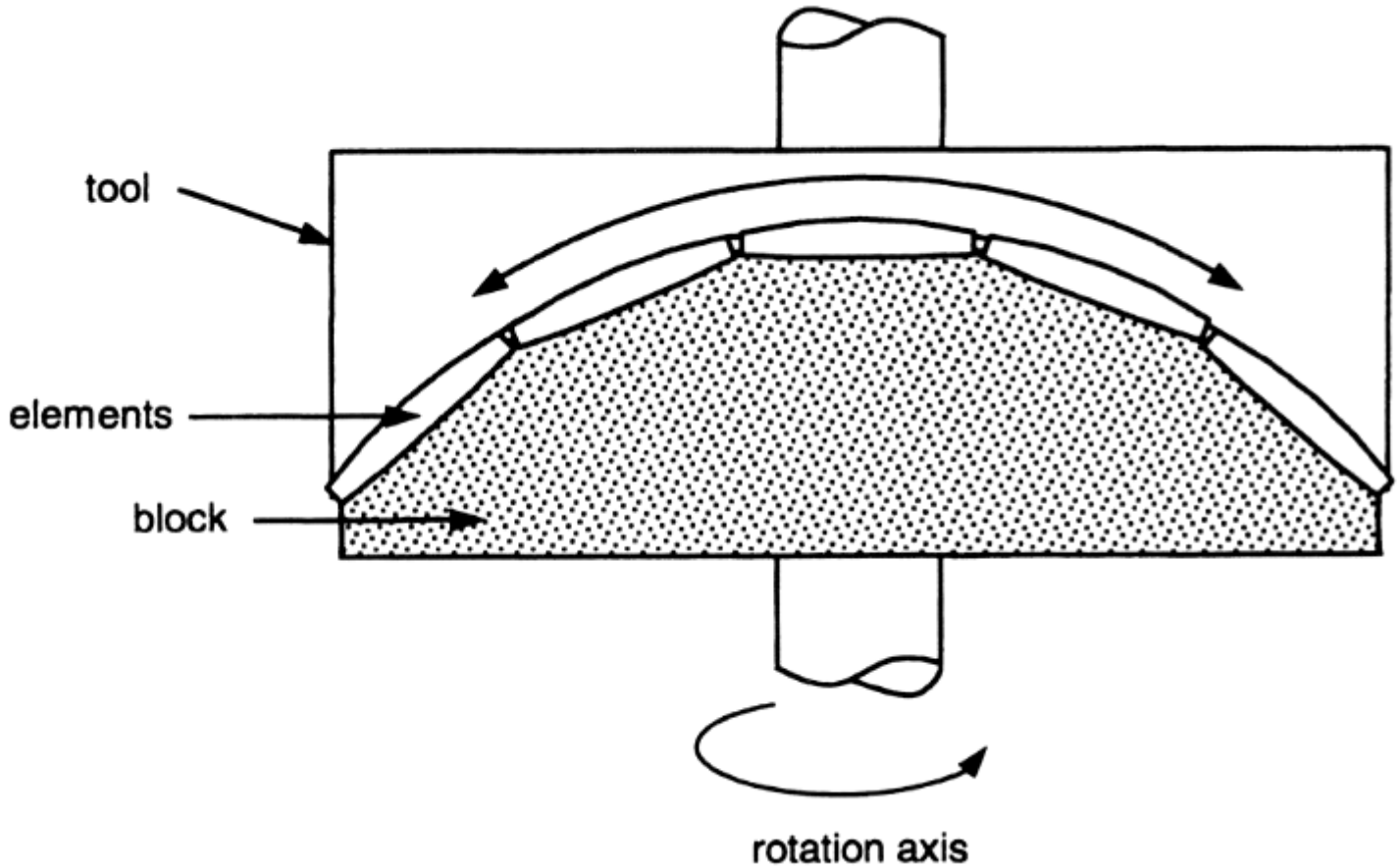


Focusing on corners of screen causes center to go out of focus.

Why spherical lenses?

- **Because they are easy to manufacture**
- **(Start from whatever shape, if you grind enough, it will become spherical)**

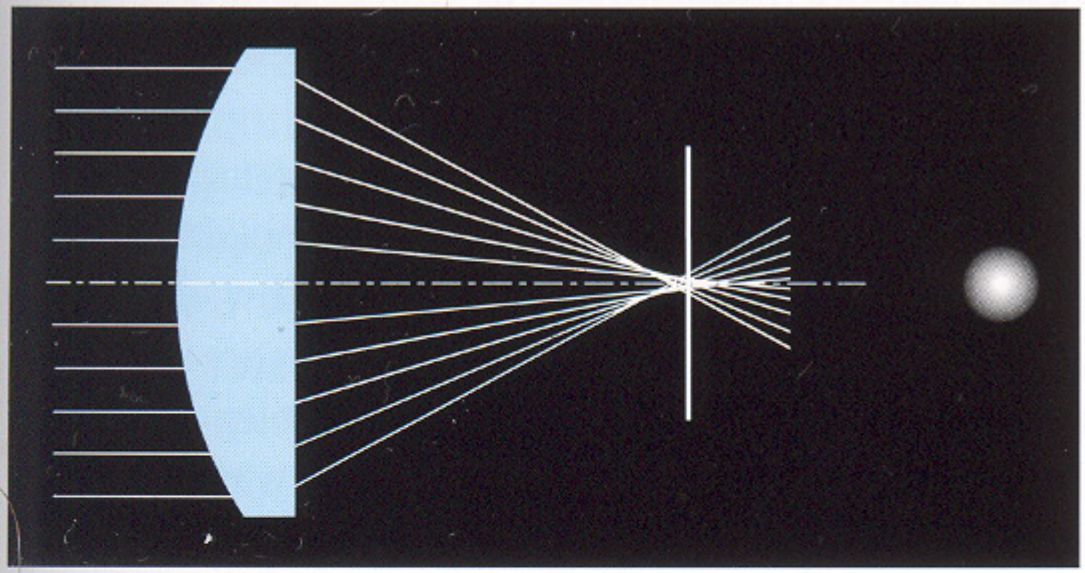
Figure 3.2
Manufacture of Spherical Lens Surfaces



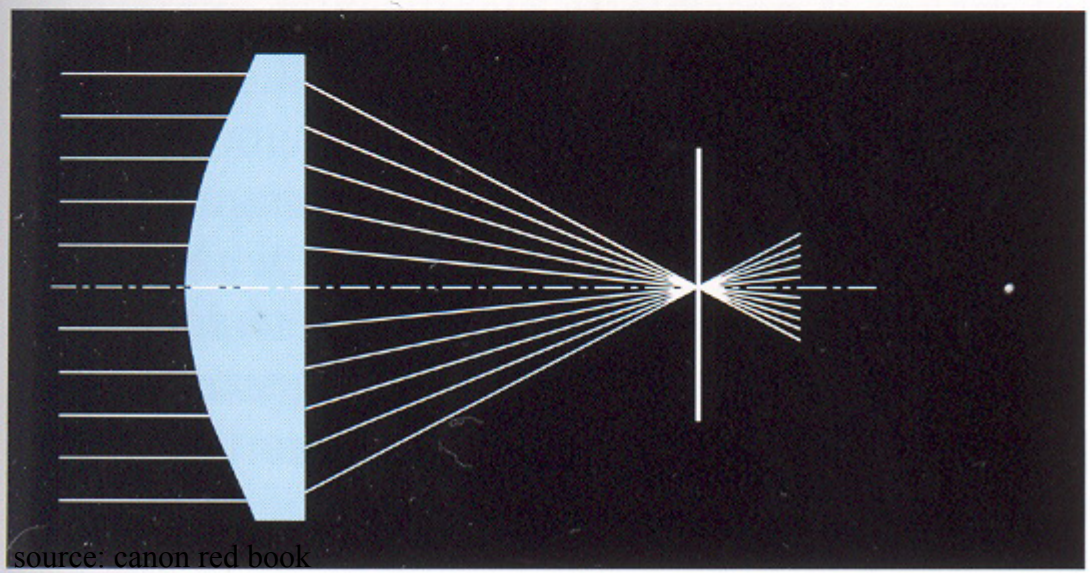
From Optical System Design by Fisher and Tadic

Aspherical lenses

Spherical aberration of spherical lens



Focal point alignment with aspherical lens



source: canon red book

Photo-9 Spherical Lens Example



Photo-10 Aspherical Lens Example



Aspherical lenses

- **Harder to manufacture → used with parsimony**

Figure -14 EF85mm f/1.2L USM Optical System - Ray Tracing Diagram

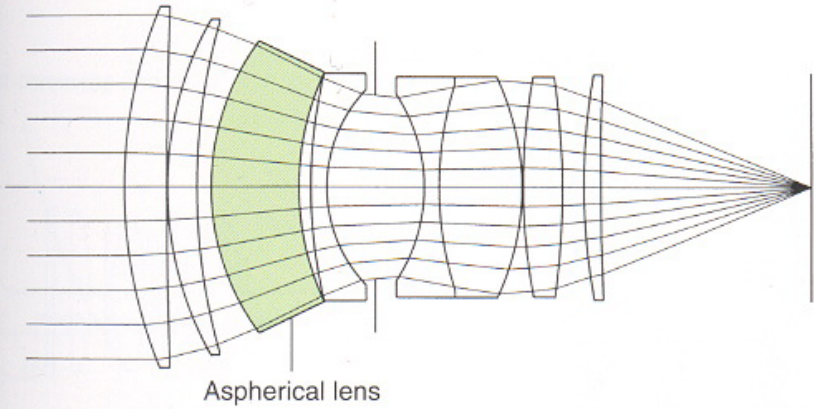
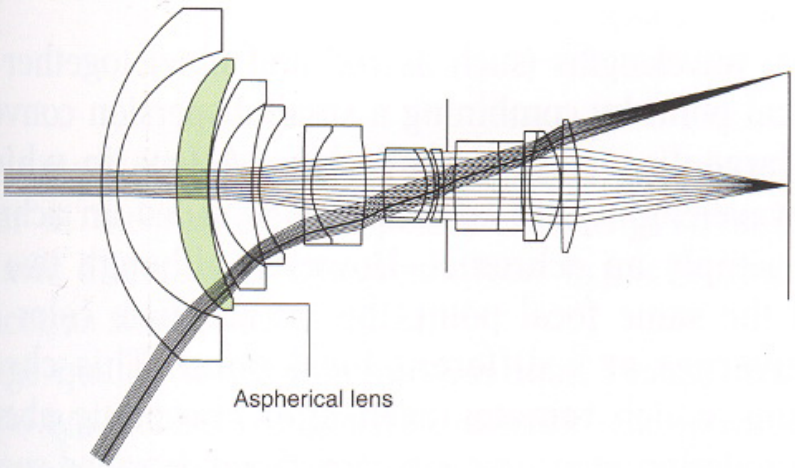


Figure-15 EF14mm f/2.8L USM Optical System - Ray Tracing Diagram



source: canon red book

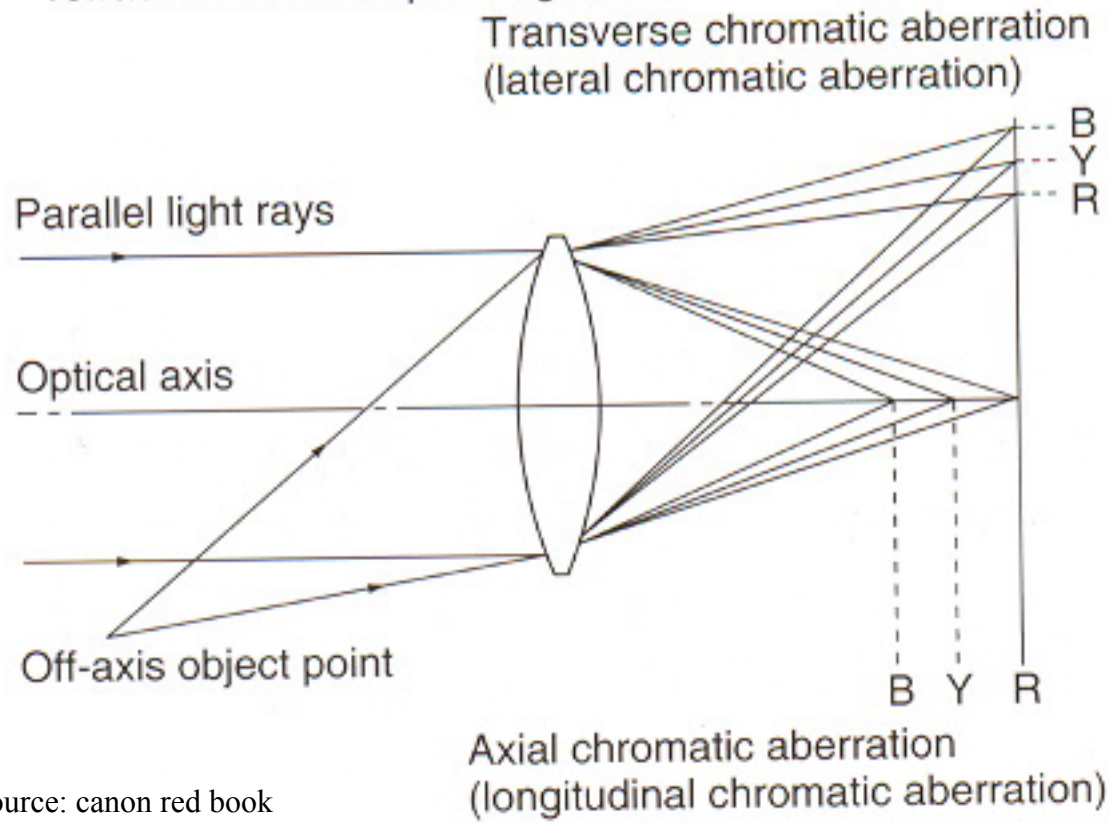
Chromatic aberrations

Chromatic aberration

- **The previous aberrations depend on wavelength (because of varying index of refraction)**

Figure-18 Chromatic Aberration

●This phenomenon occurs because the prism's index of refraction varies depending on the wavelength (color).



source: canon red book

Photo-3 Axial chromatic aberration

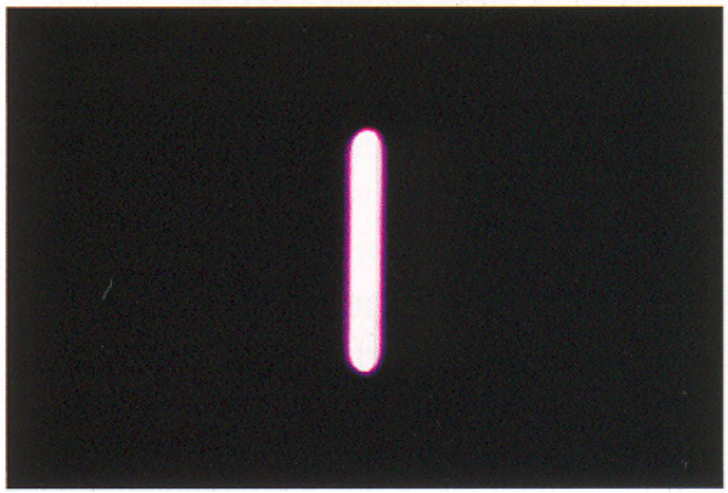
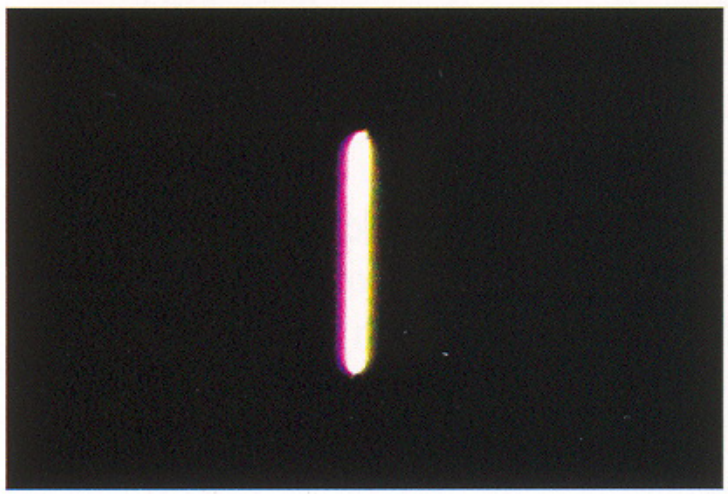


Photo-4 Transverse chromatic aberration

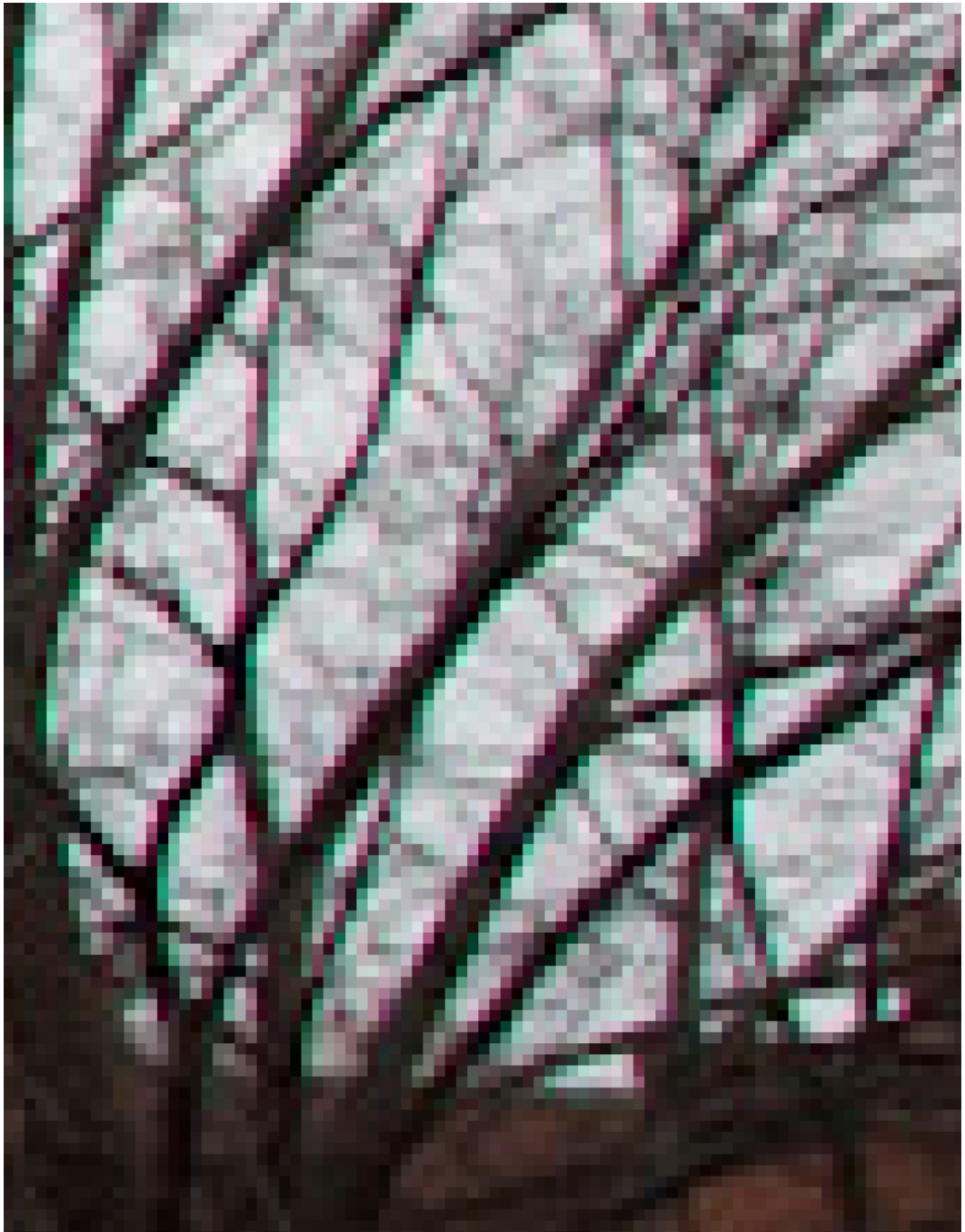


In images









Achromatic doublet

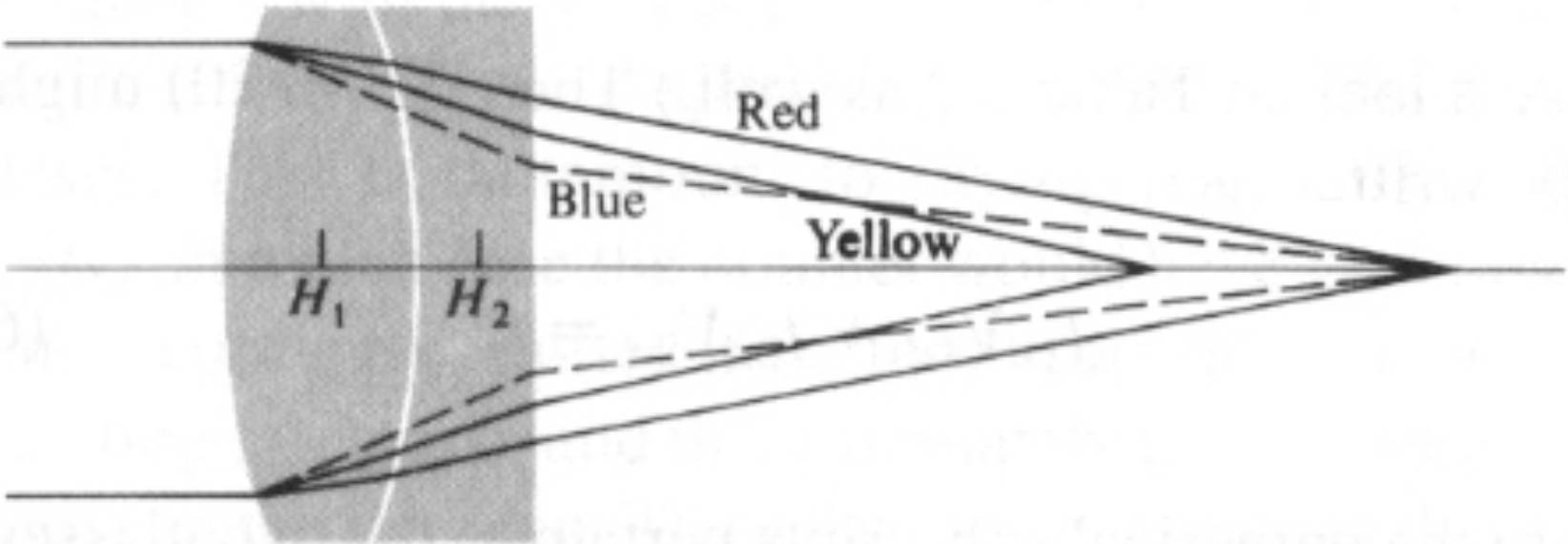


Figure 6.38 An achromatic doublet. The paths of the rays are much exaggerated.

From Hecht's Optics

Apochromatic & others

- **Optimize for multipel wavelengths**
- **http://www.vanwalree.com/optics/chromatic.html**

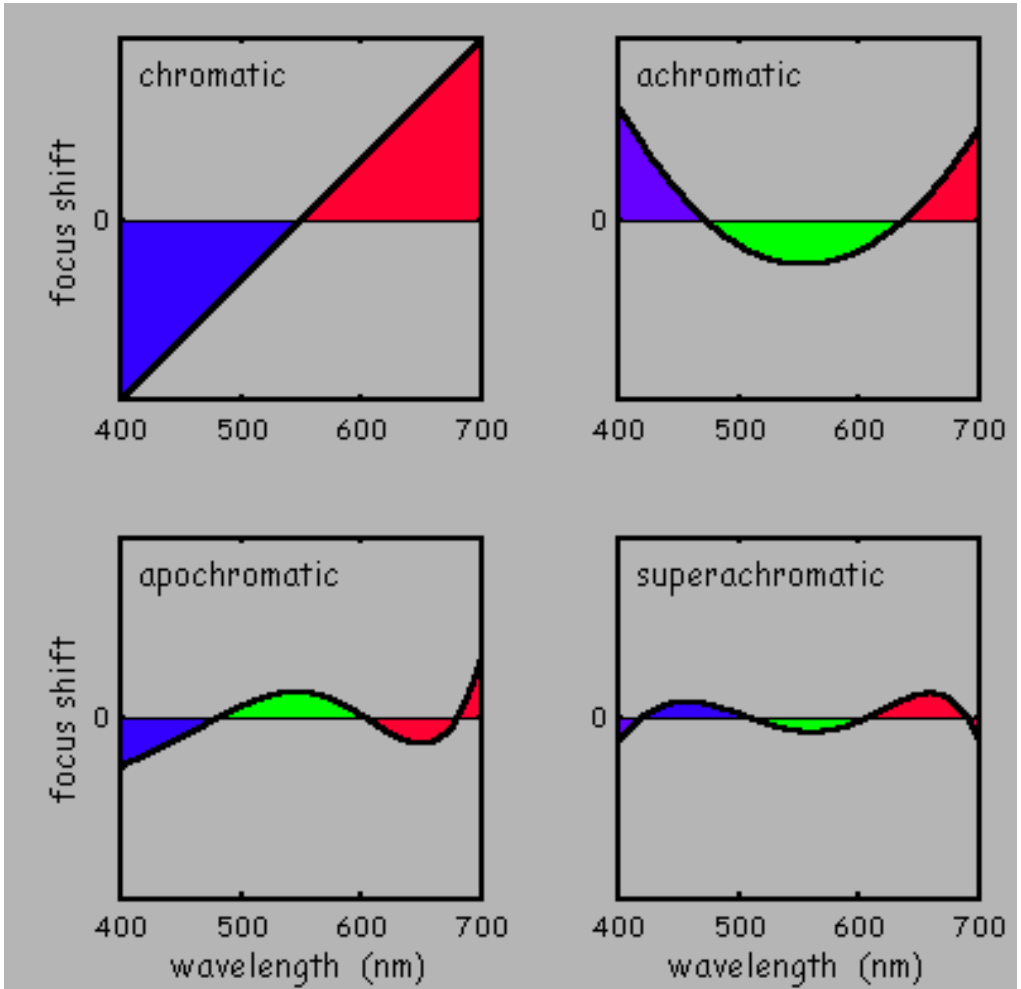


Figure 5. Principles of color correction. The colored faces are known as the secondary spectrum.

Fluorite

- **Low dispersion**

Figure-22 Comparison of Color Aberration Correction

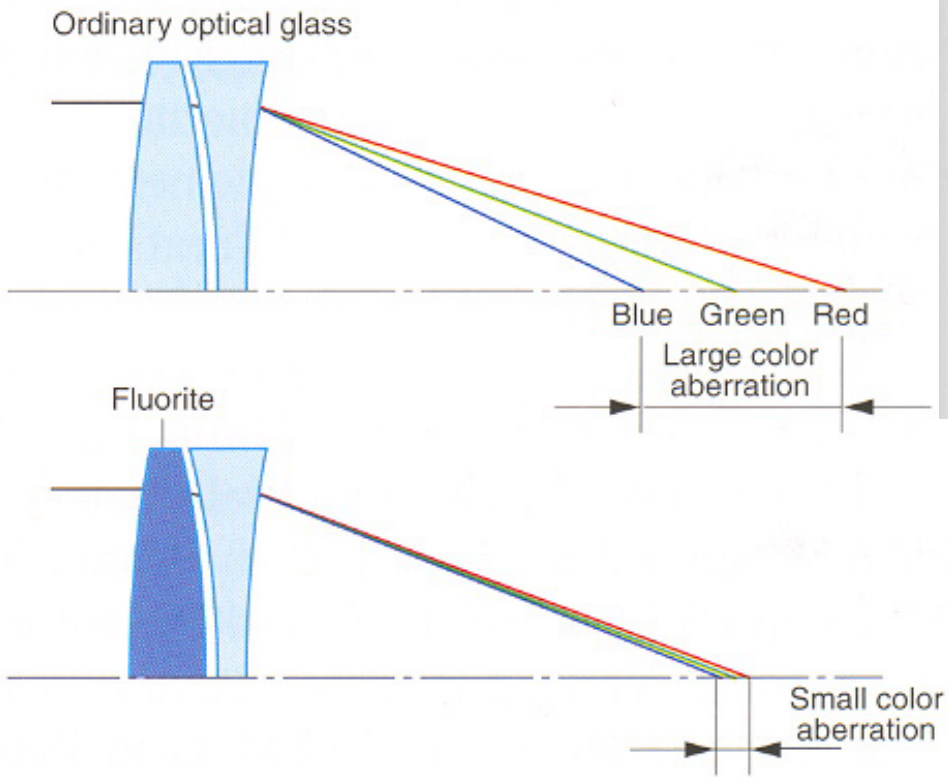


Figure-21 Secondary Spectrum

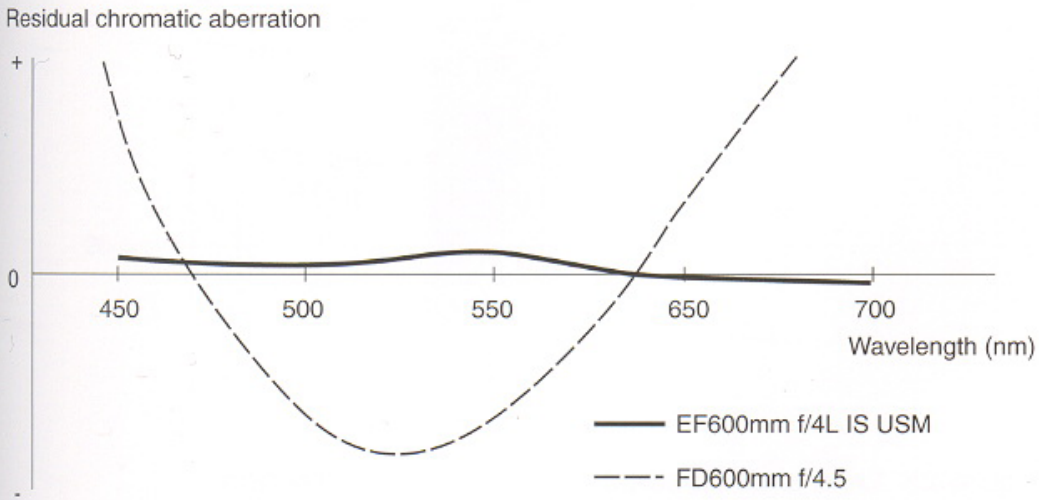


Photo-12 Artificial Fluorite Crystals and Fluorite Lenses



source: canon red book

Bottomline

- **Fighting chromatic aberrations is the main cause of lens complexity**

Chromatic aberration correction

Observation: radial structure

- **Here:**
  red towards center,
  blue towards periphery





Observation: radial structure

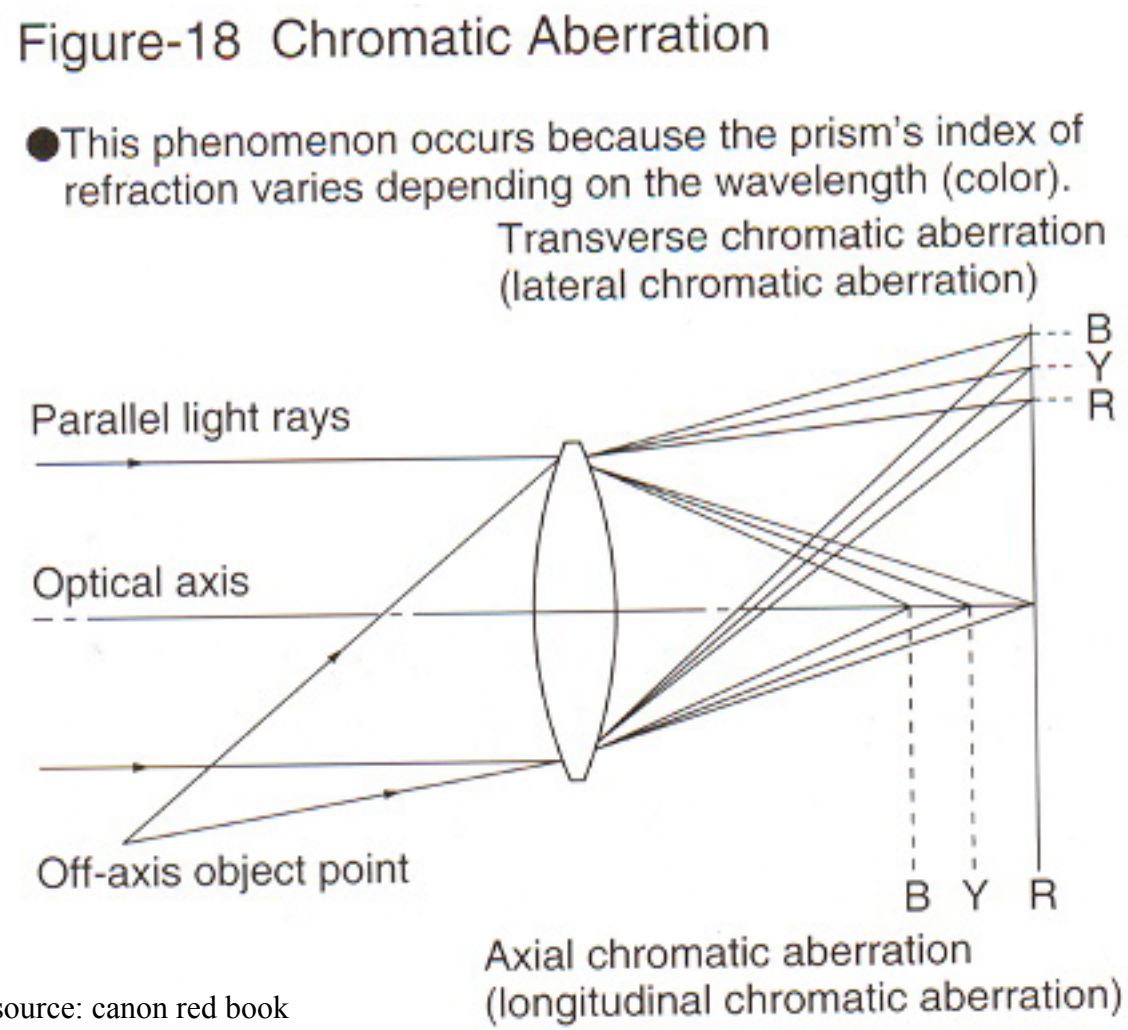
- **Here:**
  red towards center,
  blue towards periphery





Observation: radial structure

- **Some wavelength are more deviated away from center**



source: canon red book

Photo-3 Axial chromatic aberration

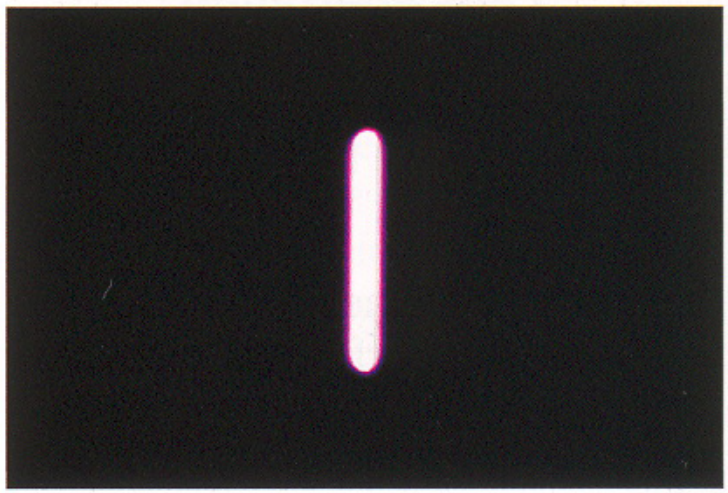
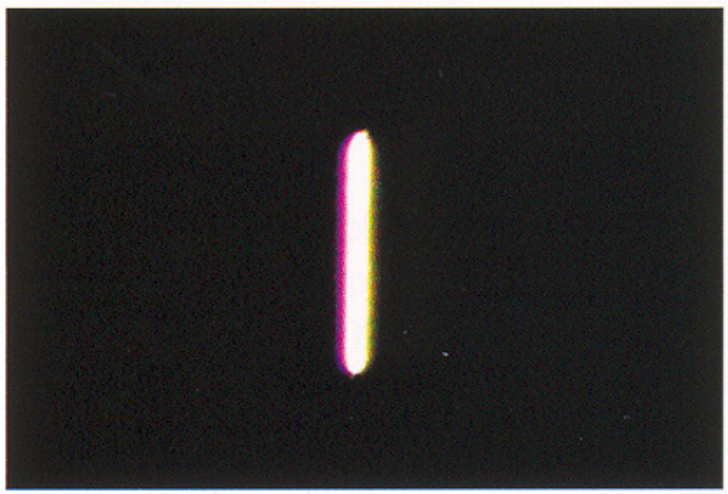
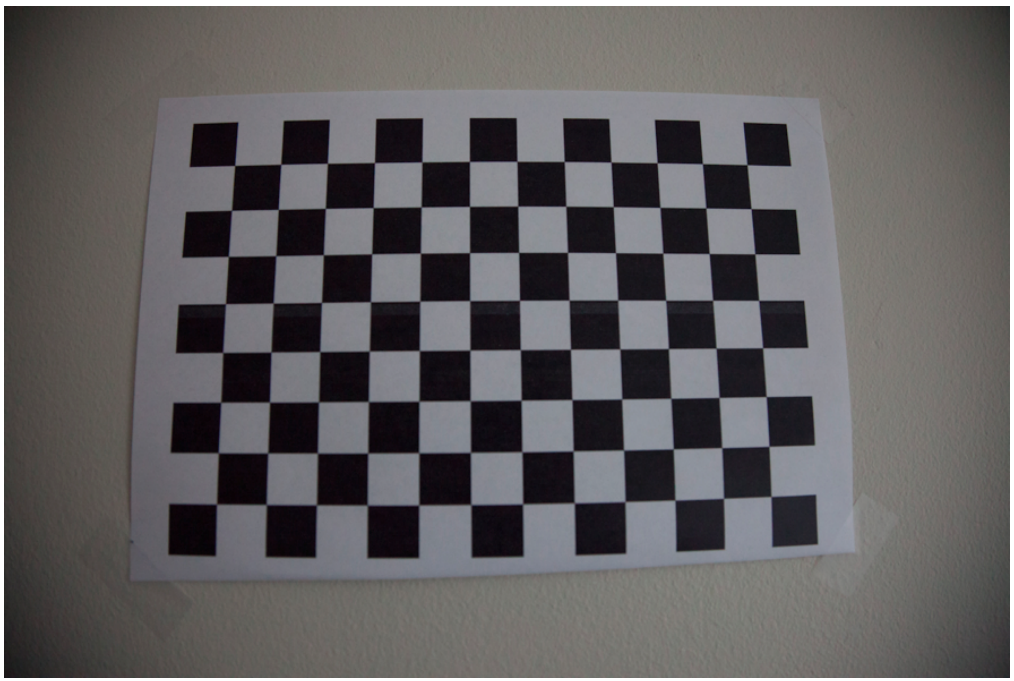


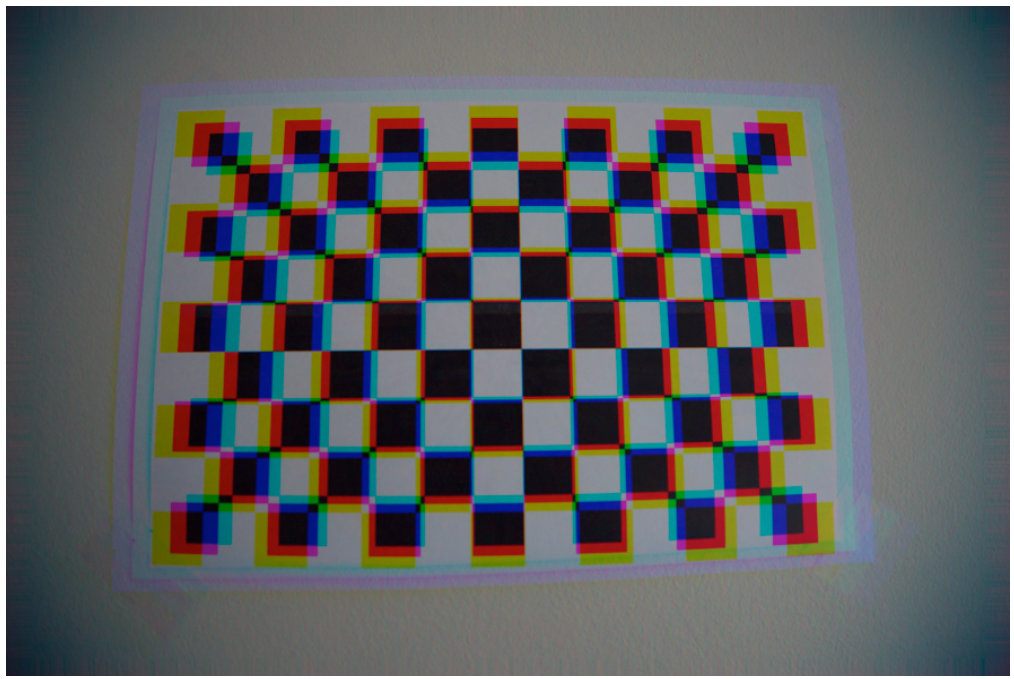
Photo-4 Transverse chromatic aberration



Idea

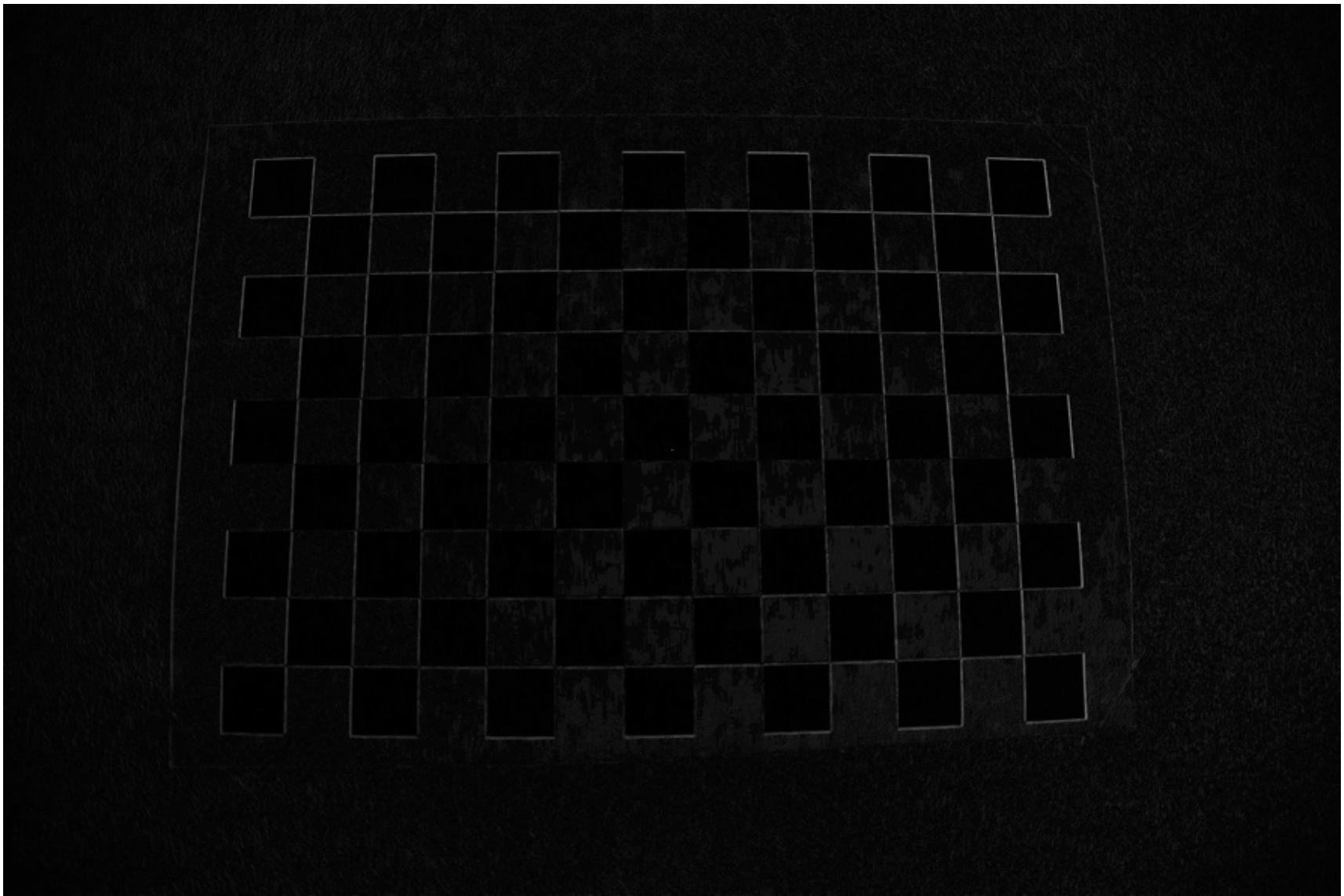
- **Calibrate using black-and-white target**
- **Scale the channels by a slightly different scale factor**
  - Try to align R, G & B





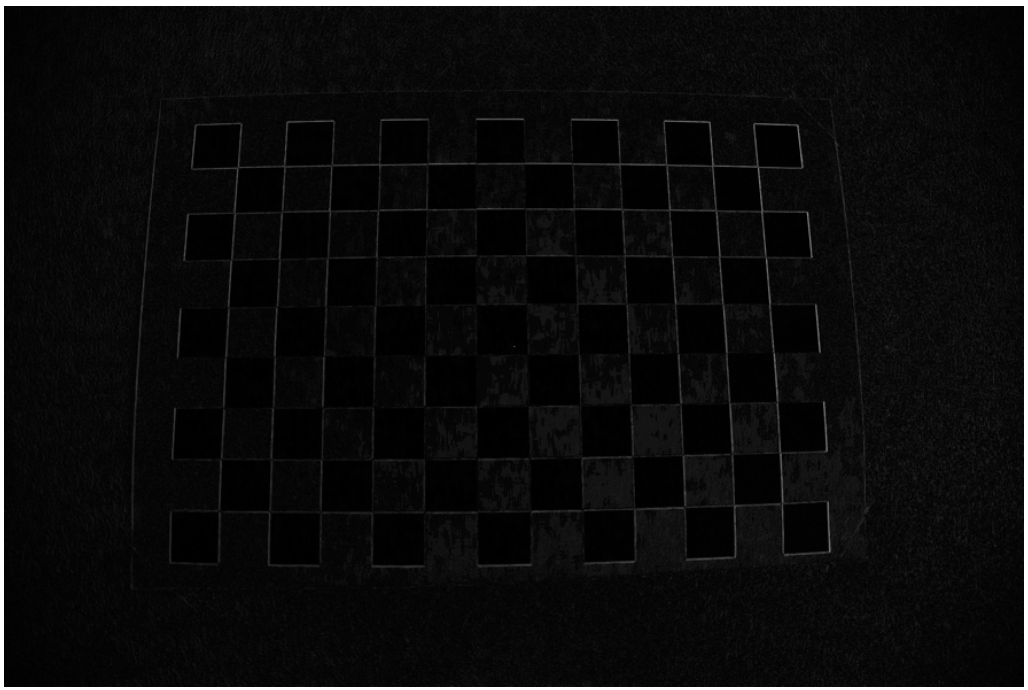
Procedure

- **Optimize error between Green channel and scaled other channel**



Procedure

- **Optimize error between Green channel and scaled other channel**



- **Make sure we normalize pixel values by a global factor average(G)/average(otherChannel)**
  - to avoid white balance issue

At the end of the day

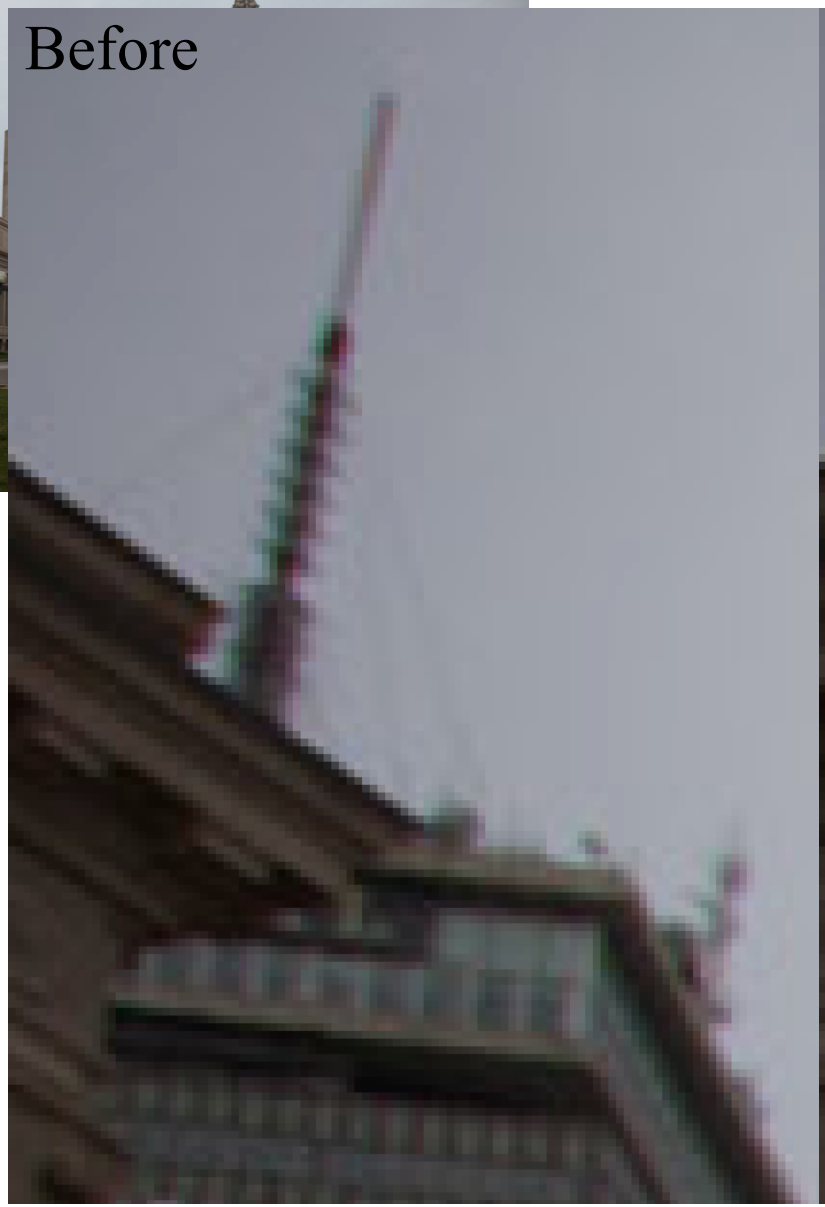
- **Red gets scaled by a factor kr**
- **Blue gets scaled by a factor kb**
  - Both factors are very close to 1
  - e.g. for my 24-105 at 24mm:
  - kr=1.0003125
  - kb=1.0006875
  - Not necessarily bigger than 1

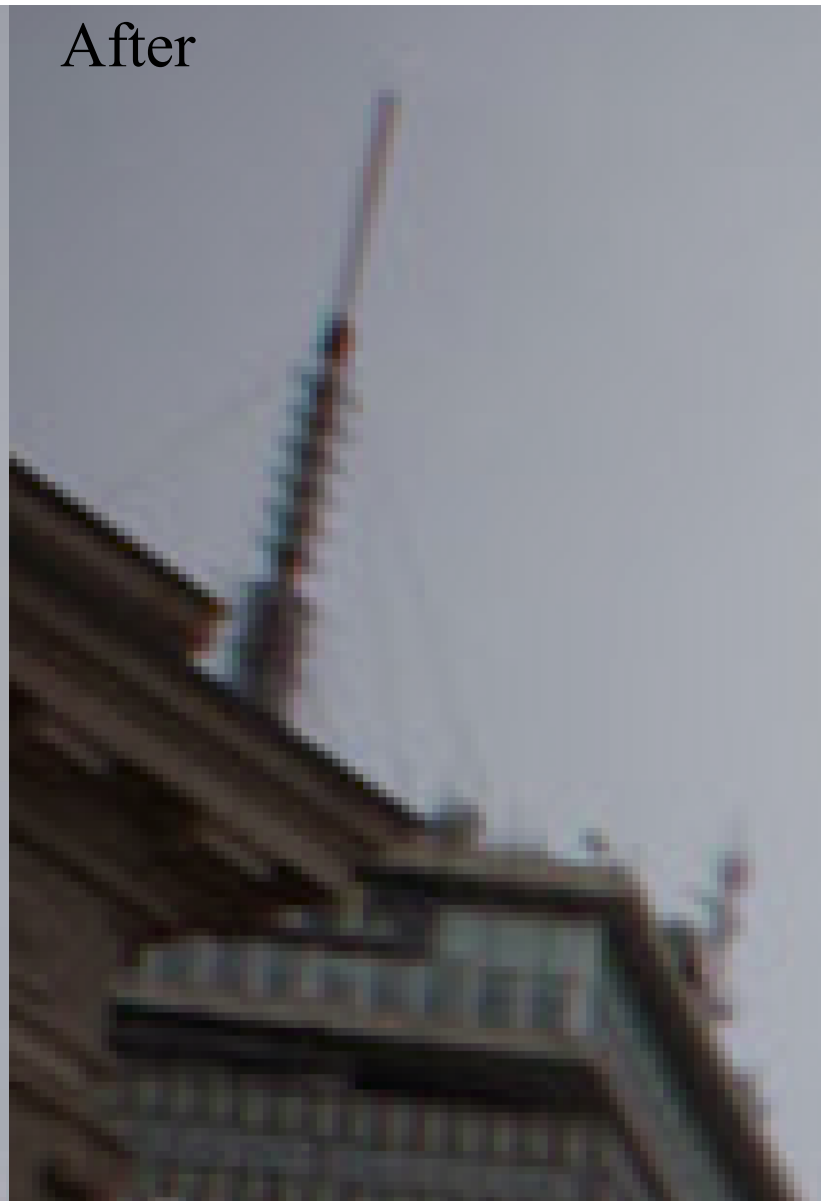
At the end of the day

- **Calibrate once, then**
  use for all images of that lens in that configuration
- **Ideally, calibrate for each**
  - focal length
  - focusing distance
- **e.g. on my 24-105**
  - At 24mm:
    - kr=1/1.0003125
    - kb=1/1.0006875
  - At 105mm
    - kr= 1/0.99953125
    - kb=1/1.0001875

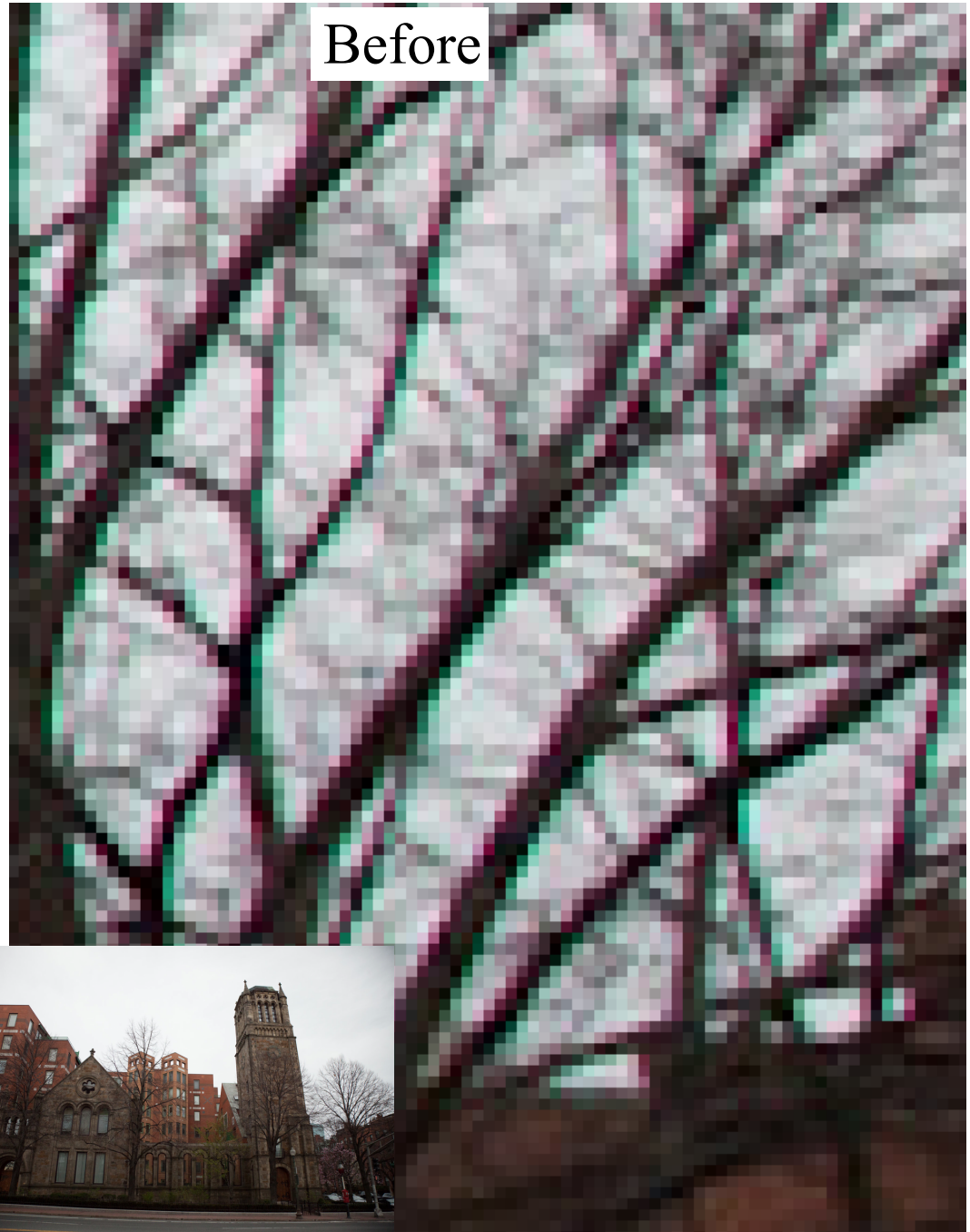
Results

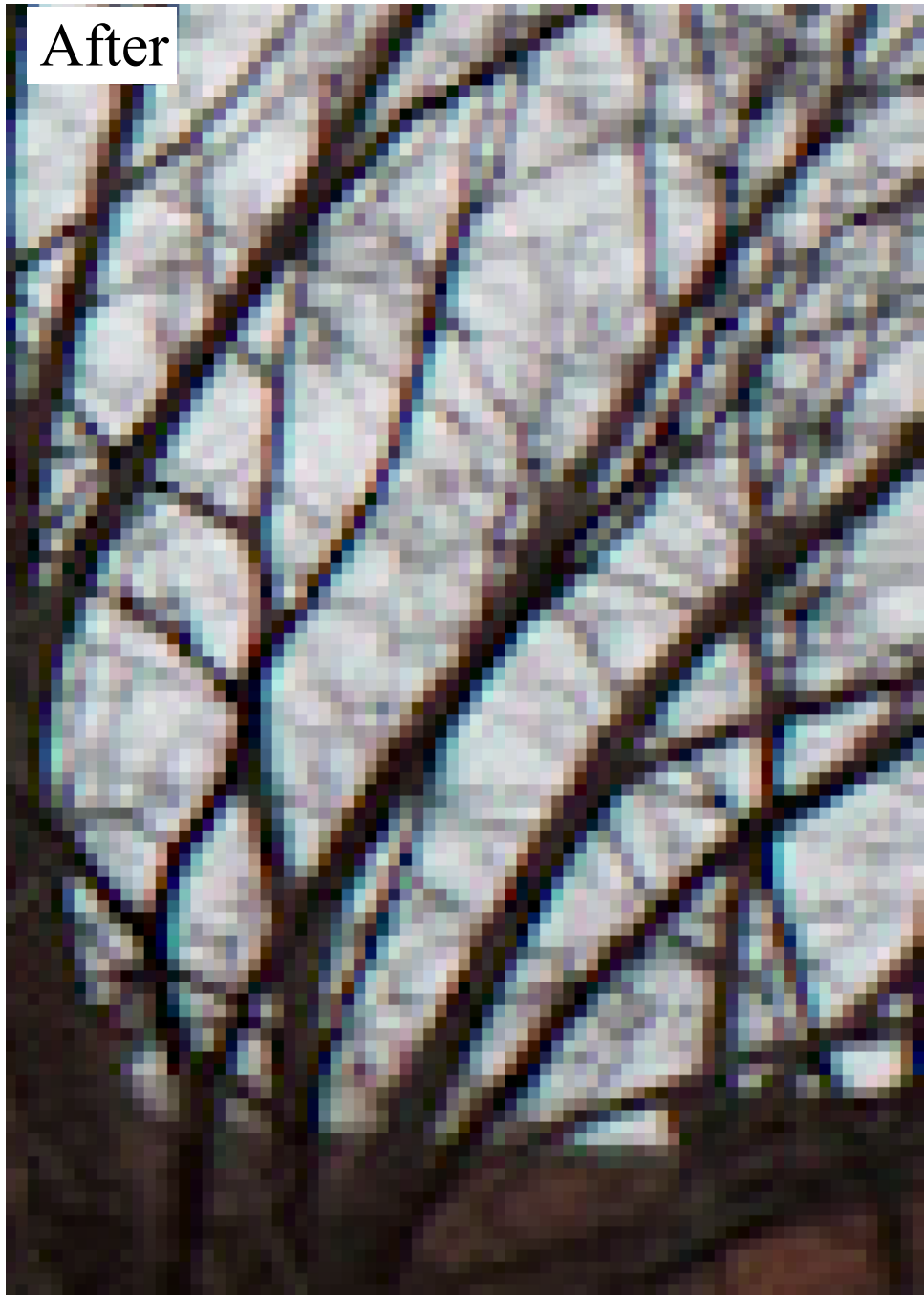






Results





Flare

Flare

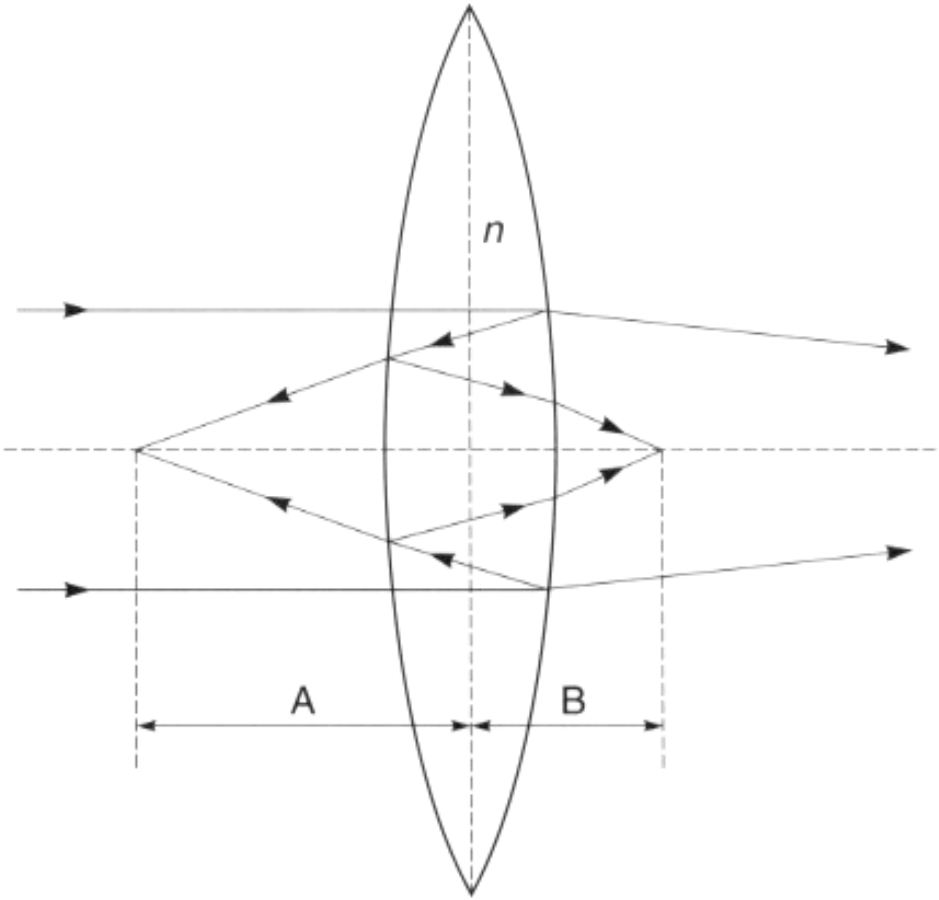


Figure 5.6 Formation of flare spots by a simple lens. Images of the source are formed at distances A and B, where:

$$A = \left(\frac{n-1}{an-1}\right) f \qquad B = \left(\frac{n-1}{bn-1}\right) f$$

and $a = 2, 4, 6 \ldots$, $b = 3, 5, 7, \ldots$ For $n = 1.5$, $A = f/4$, $f/10$, $f/16$ etc. and $B = f/7$, $f/13$, $f/19$ etc.

From "The Manual of Photography" Jacobson et al

Example of flare "bug"

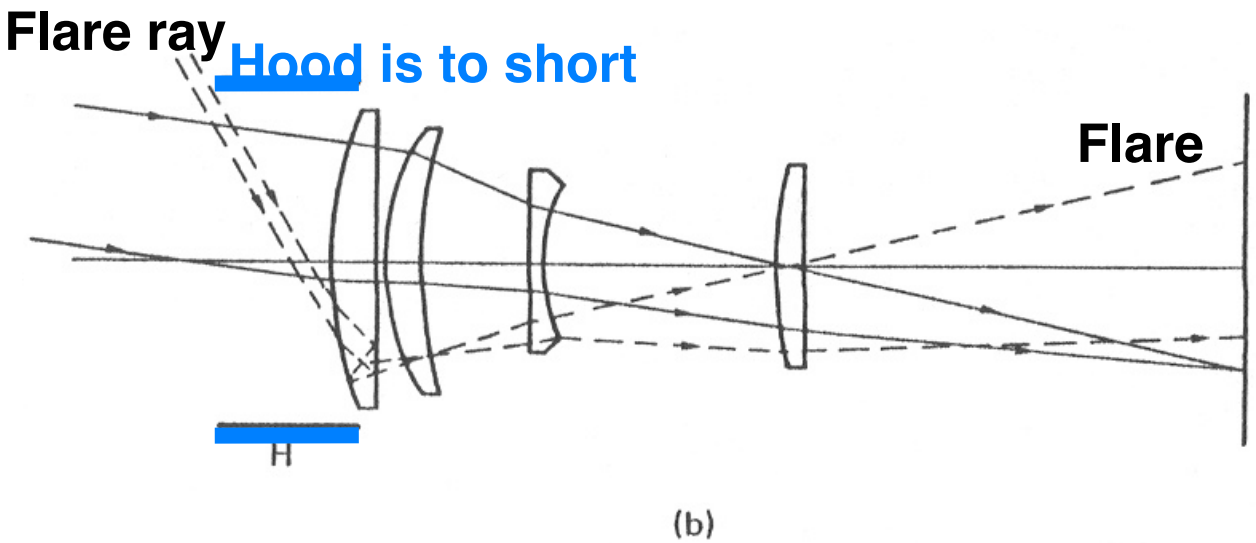
- **Some of the first copies of the Canon 24-105 L had big flare problems**
- **http://www.the-digital-picture.com/Reviews/Canon-EF-24-105mm-f-4-L-IS-USM-Lens-Review.aspx**
-

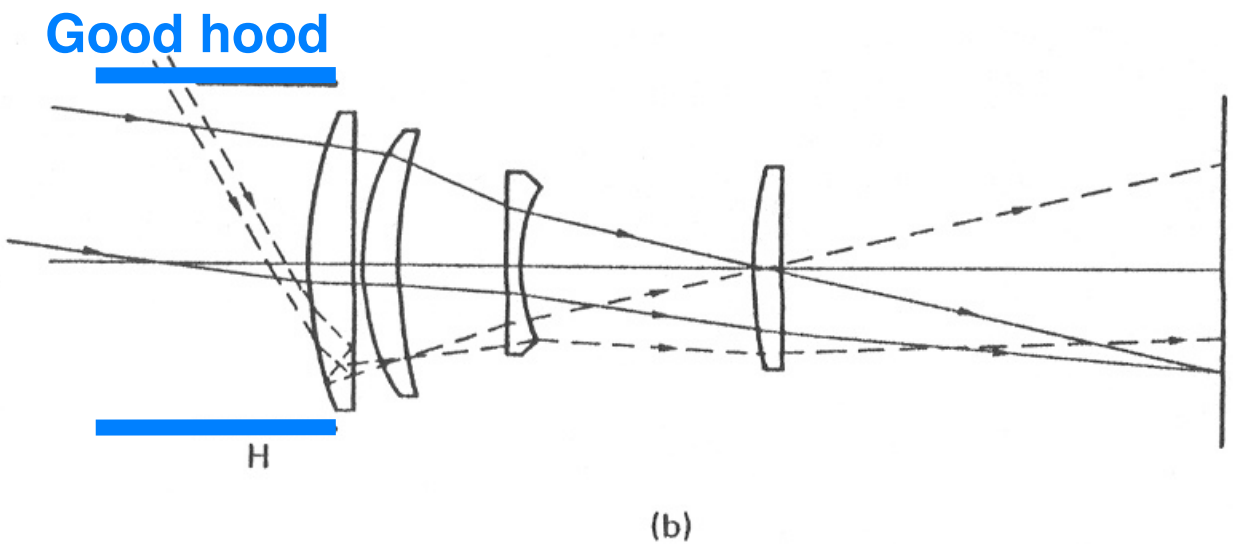
Canon 24-105mm f/4 L IS USM Lens Original Flare Problem



24mm f/4.0 24mm f/5.6 24mm f/8.0 35mm f/4.0

Use a hood! (and a good one)





Adapted from Ray's Applied Photographic Optics

Coating

- **Apply thin layer with different index of refraction**
- **Use destructive interferences**
- **One of the most important advances in optics**

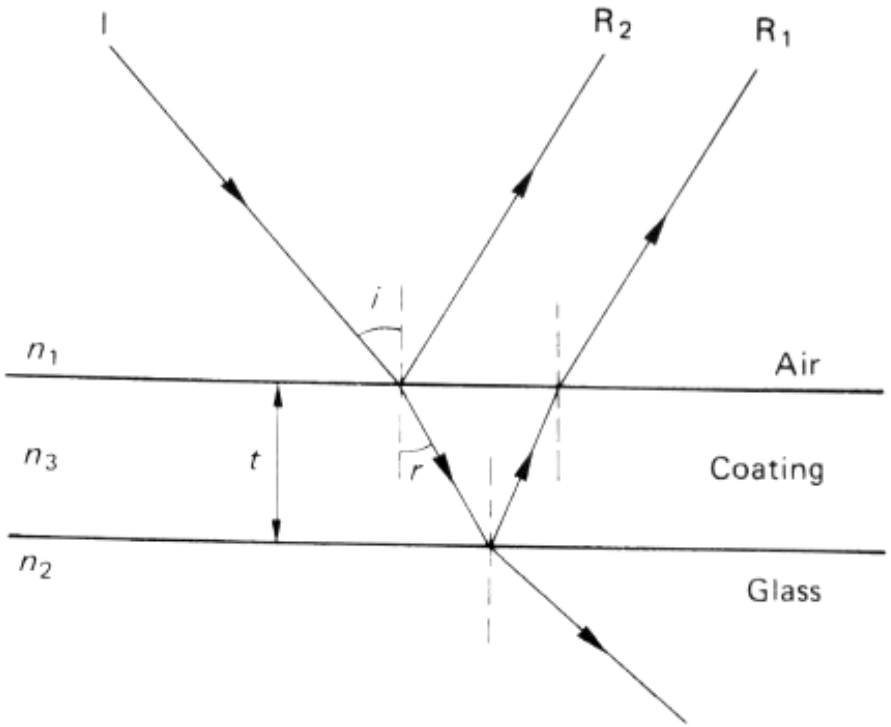
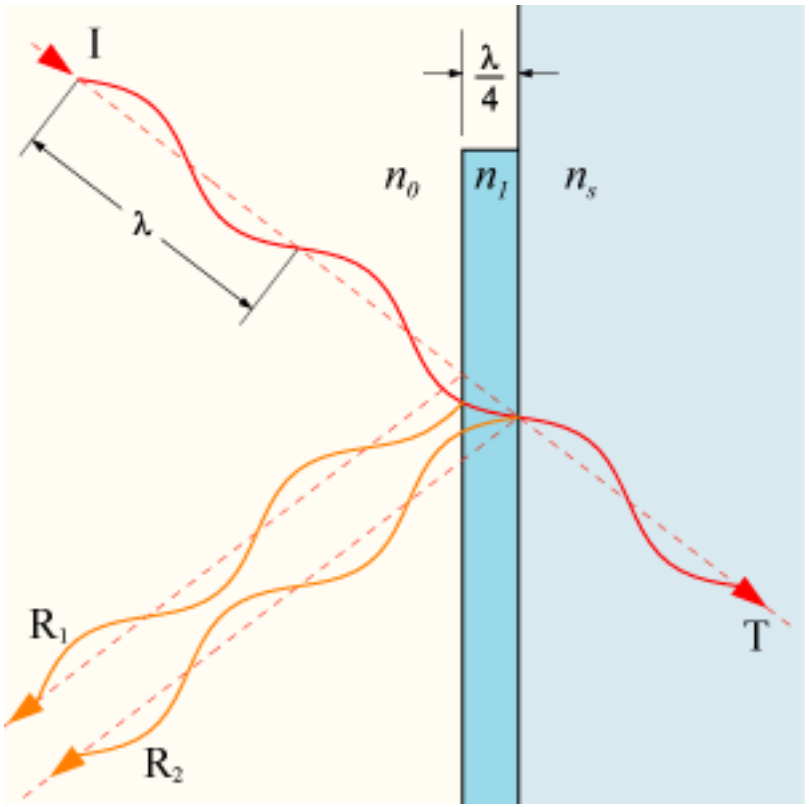


Figure 5.7 An anti-reflection coating on glass using the principle of destructive interference of light between reflections R_1 and R_2



From "The Manual of Photography" Jacobson et al

http://en.wikipedia.org/wiki/Optical_coating

Coating

- **Optimized for one wavelength**

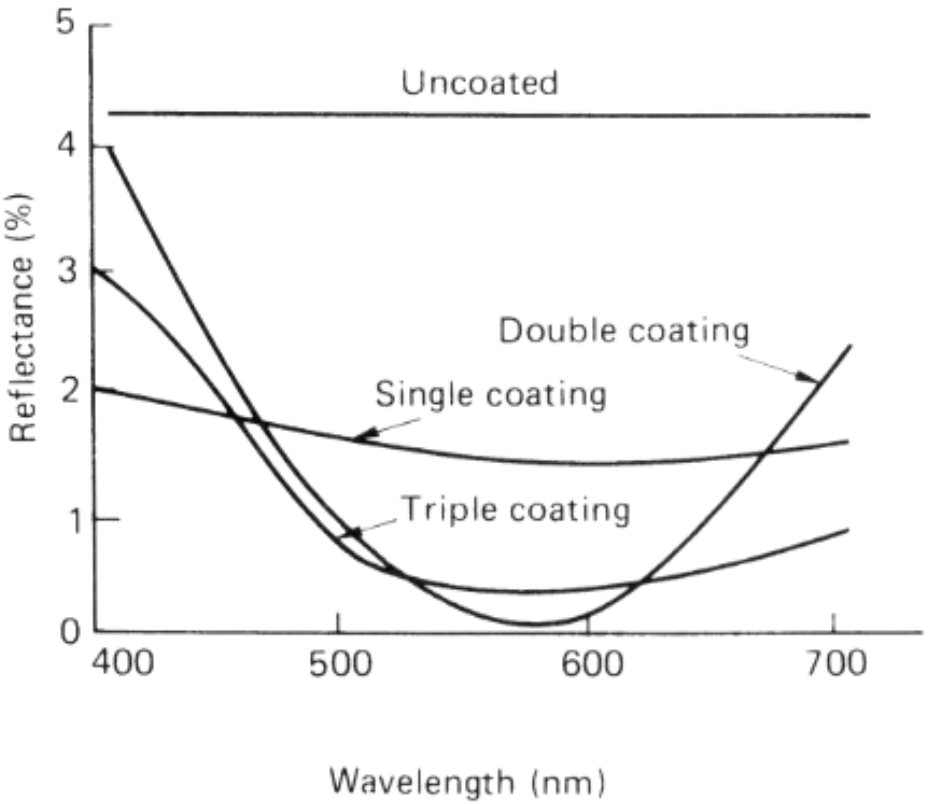
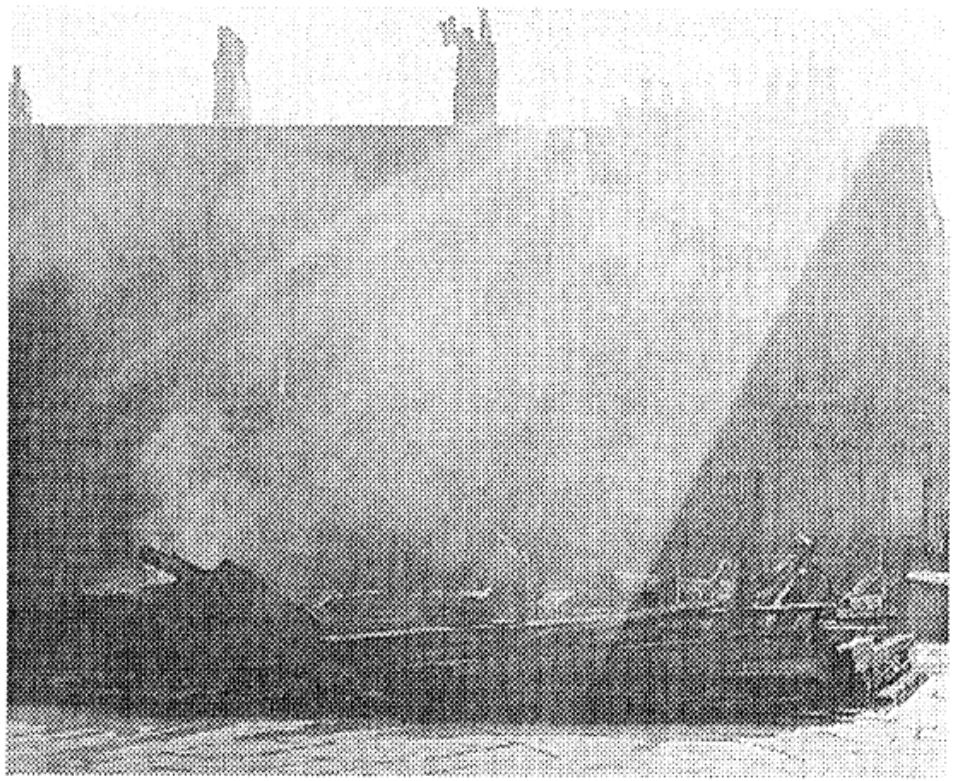


Figure 5.8 The effects on surface reflection of various types of anti-reflection coatings as compared with uncoated glass (for a single lens surface at normal incidence)

From "The Manual of Photography" Jacobson et al

Coating



(a)



(b)

Plate 15.1 Lens flare with an uncoated lens
(a) Flare effects. (b) Reduction of flare by use of a lens-hood.

From Ray's Applied Photographic Optics

Coating

- **Image taken with an uncoated lens**
- **Note the muted color**



http://www.alliedforum.net/viewtopic.php?f=106&t=2093

Radial distortion

Curvilinear/radial distortion

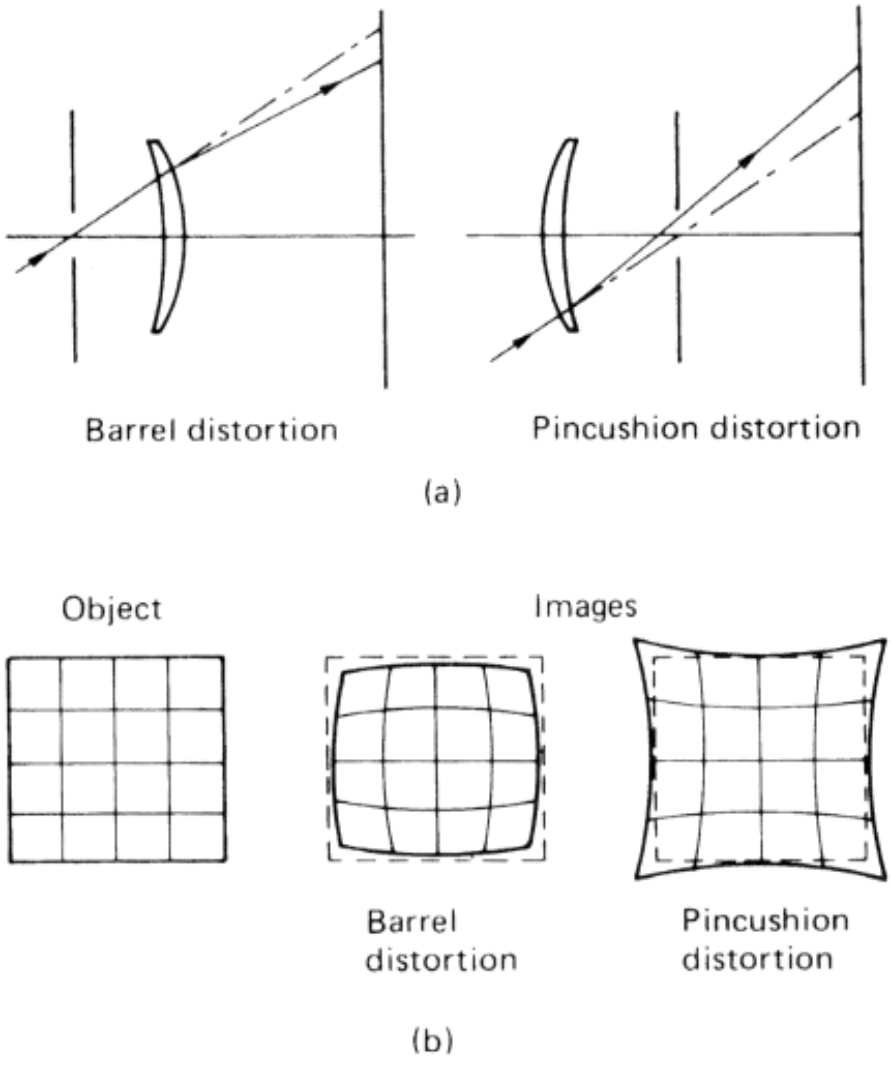
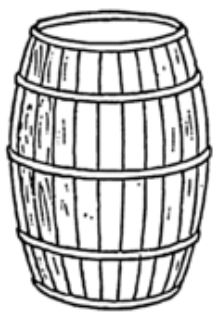


Figure 6.10 The effects of curvilinear distortion. (a) The selection of a geometrically incorrect ray bundle by asymmetric location of the aperture stop. (b) Image shape changes caused by barrel and pincushion distortion

From "The Manual of Photography" Jacobson et al



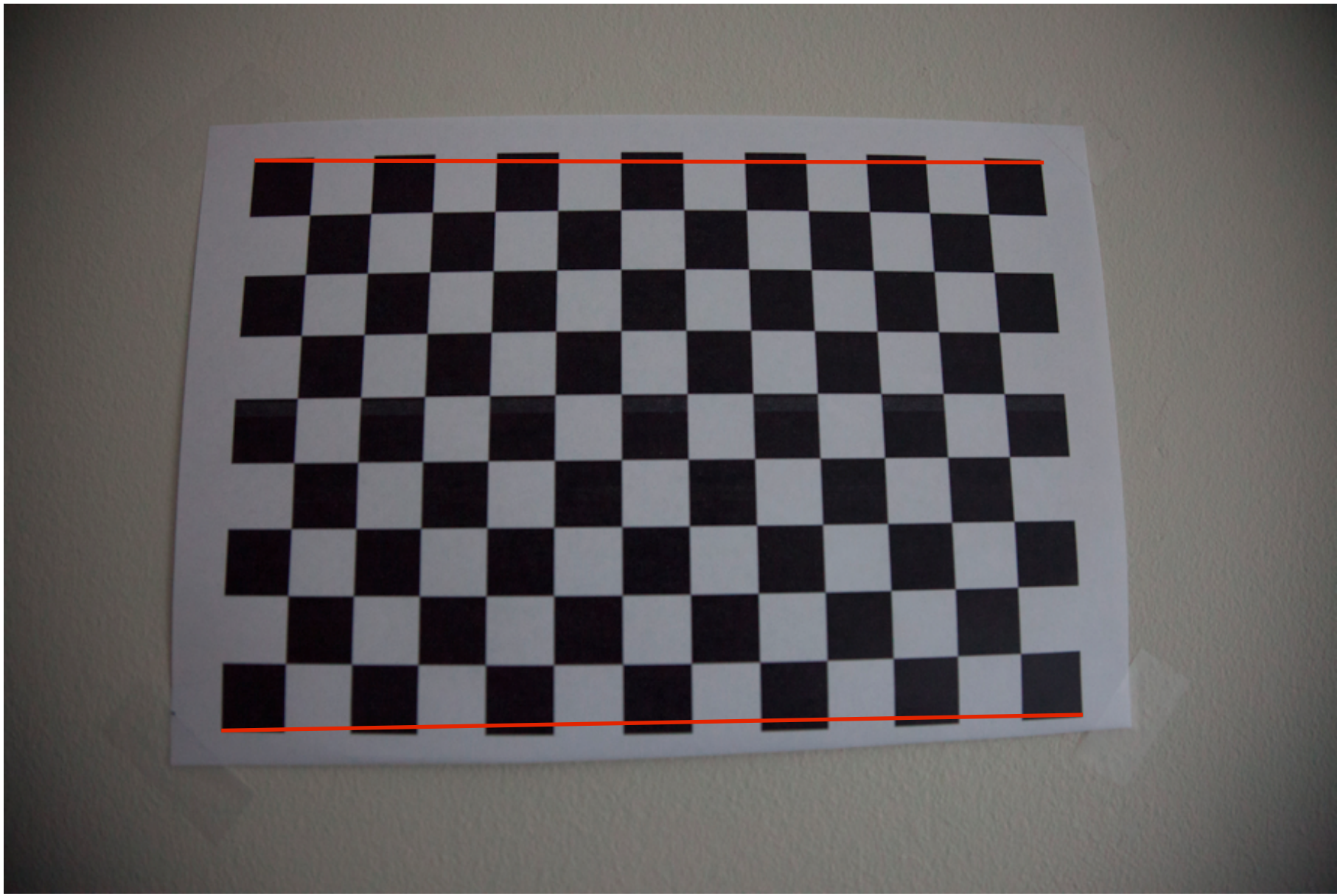
http://www.dxo.com/us/photo/dxo_optics_pro/optics_geometry_corrections/distortion





http://en.wikipedia.org/wiki/Distortion_(optics)

24-105

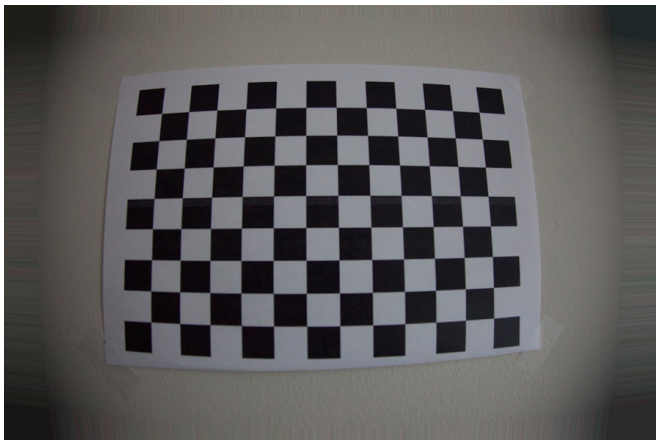


Correcting radial distortion

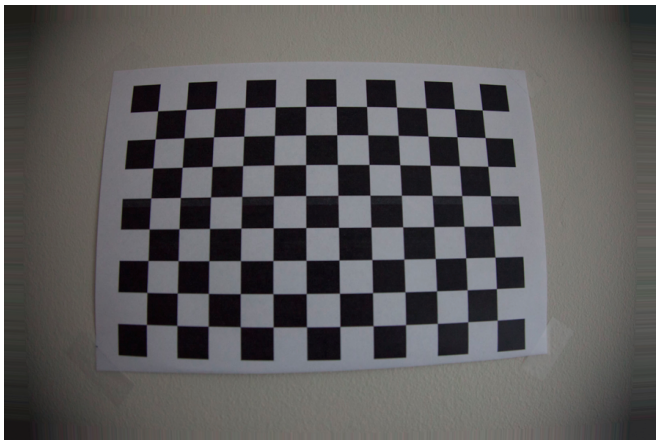
- **Warp!**
- **People have come up with parametric equations, e.g.**
  - e.g.

$$
\begin{aligned}
\hat{r}^2 &= \hat{x}^2 + \hat{y}^2 \\
\hat{x}' &= \hat{x}/(1 + \kappa_1 \hat{r}^2 + \kappa_2 \hat{r}^4) \\
\hat{y}' &= \hat{y}/(1 + \kappa_1 \hat{r}^2 + \kappa_2 \hat{r}^4) \\
x &= f\hat{x}'/\hat{z} + x_c \\
y &= f\hat{y}'/\hat{z} + y_c
\end{aligned}
$$

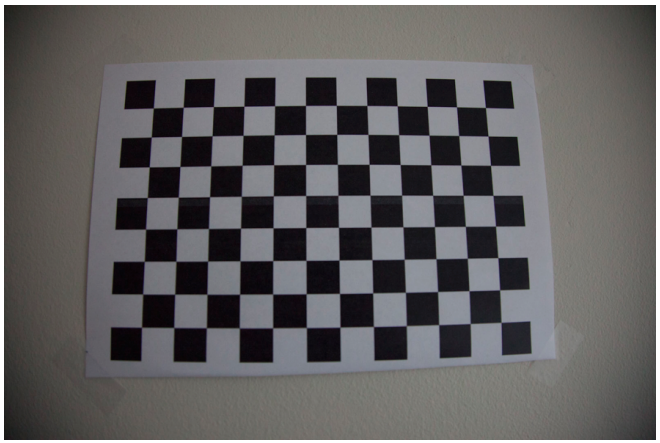
Warp



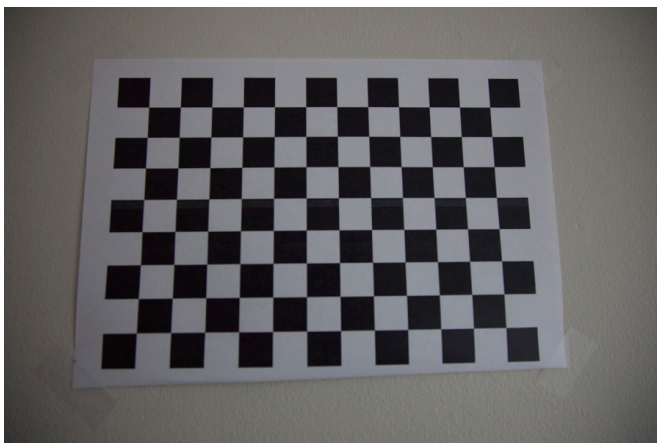
k1=-0.5



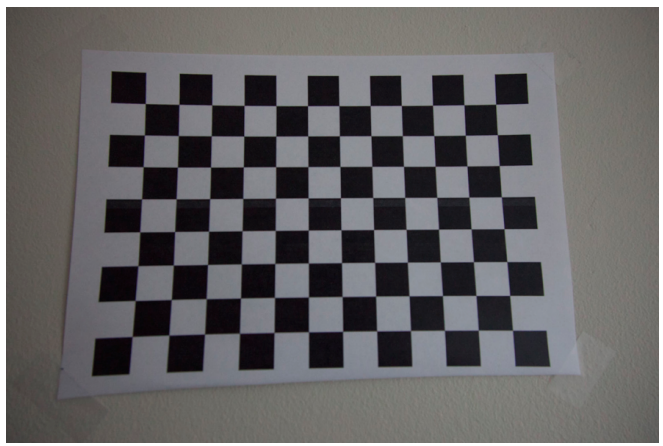
k1=-0.25



k1=0.0 (input)



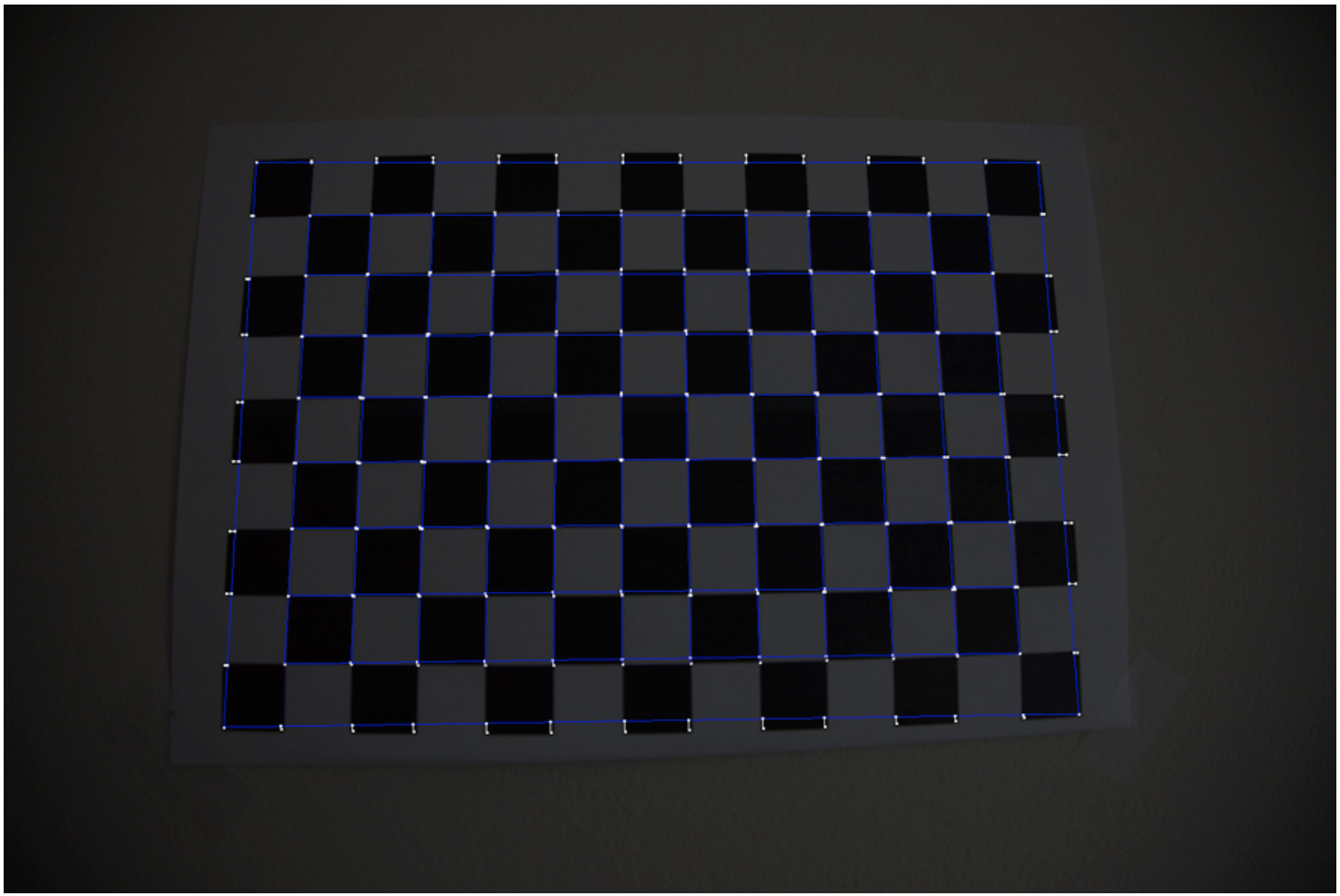
k1=0.25



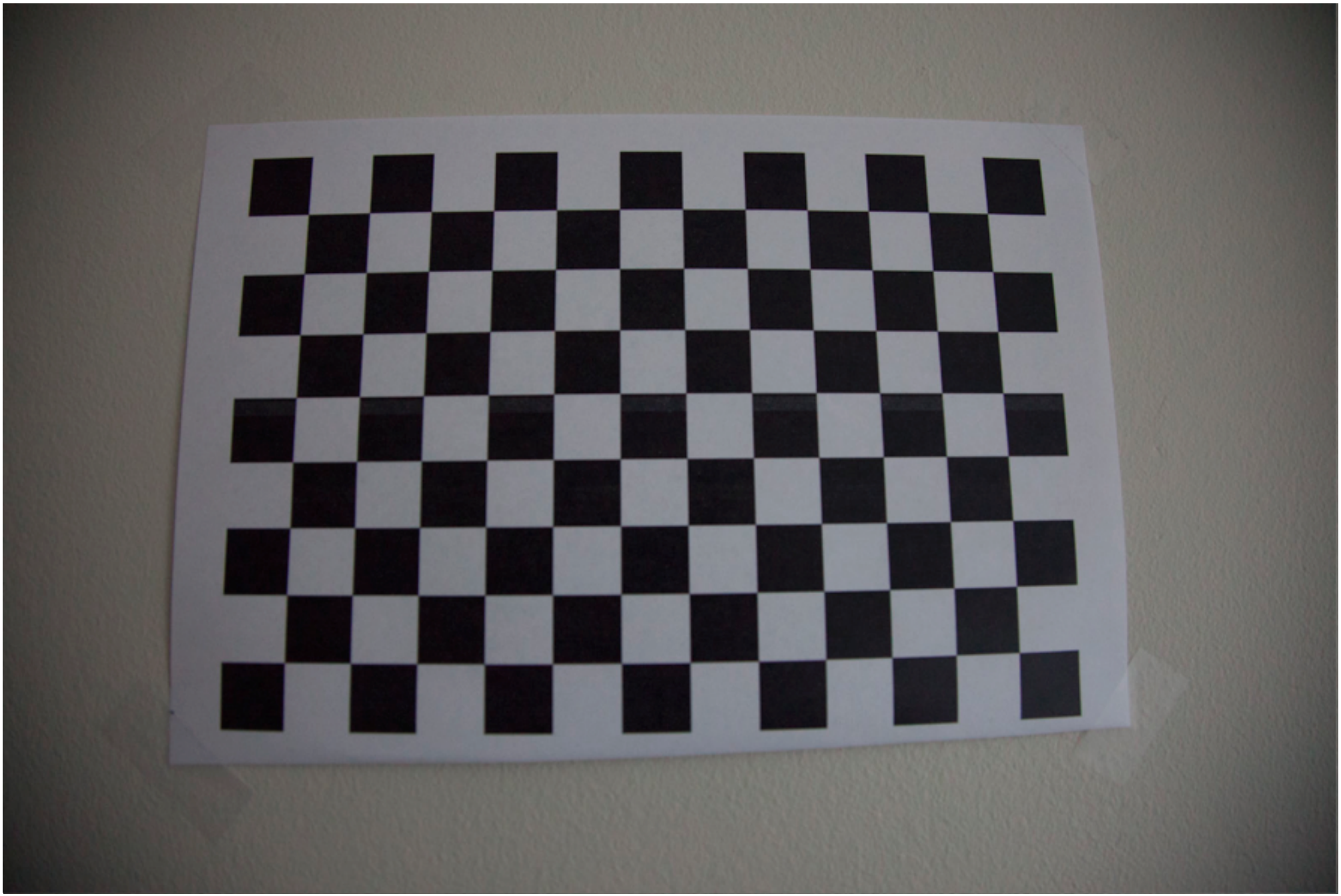
k1=0.5

Calibration

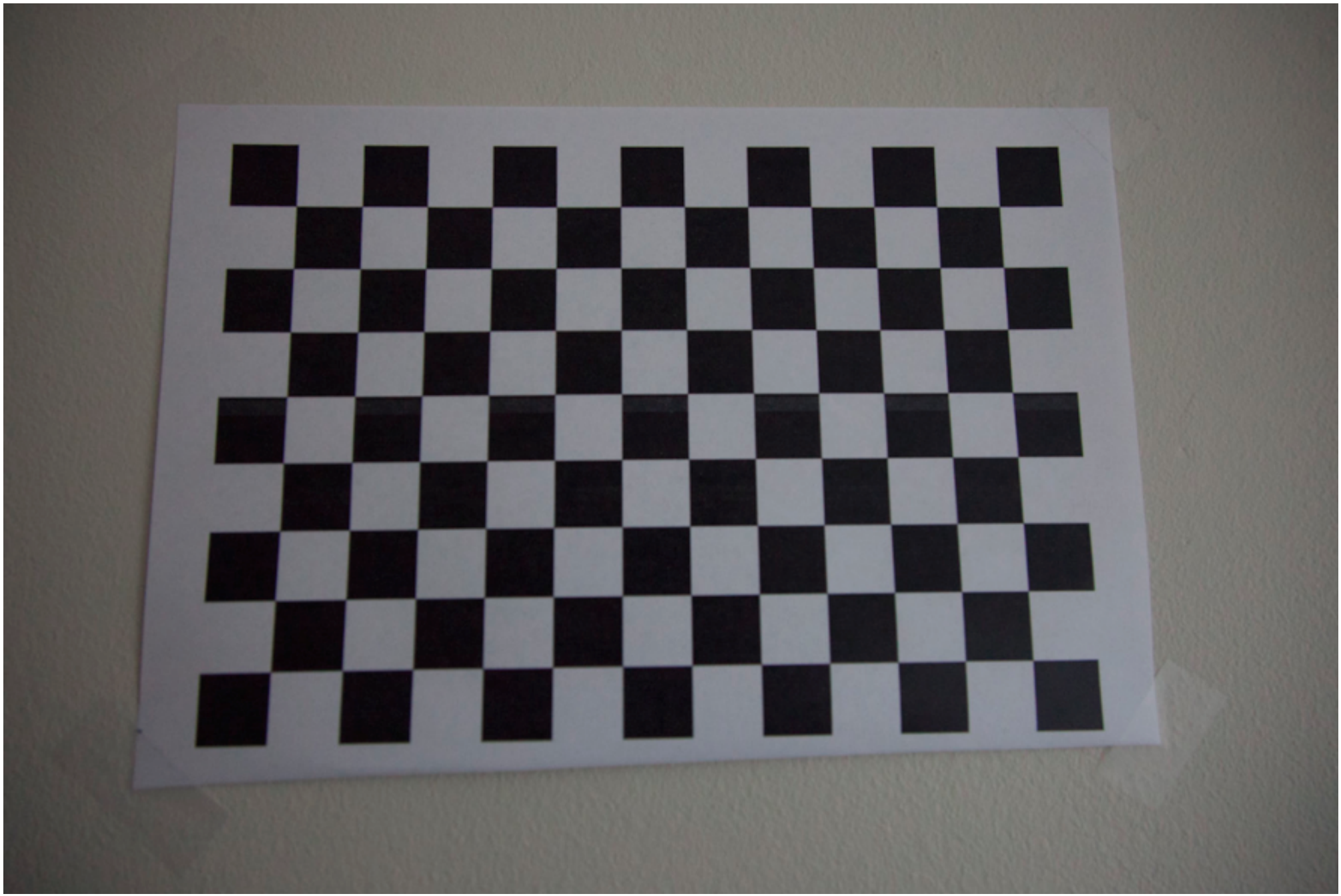
- **Harris, + measure of colinearity**
- **Only apply warp to corners**
- **Careful with forward/inverse warp**



Before



After (k1=0.33, k2=0)



Vignetting

Vignetting

- **Corners look darker**
- **http://www.photozone.de/3Technology/lenstec3.htm**

vignetting



no vignetting



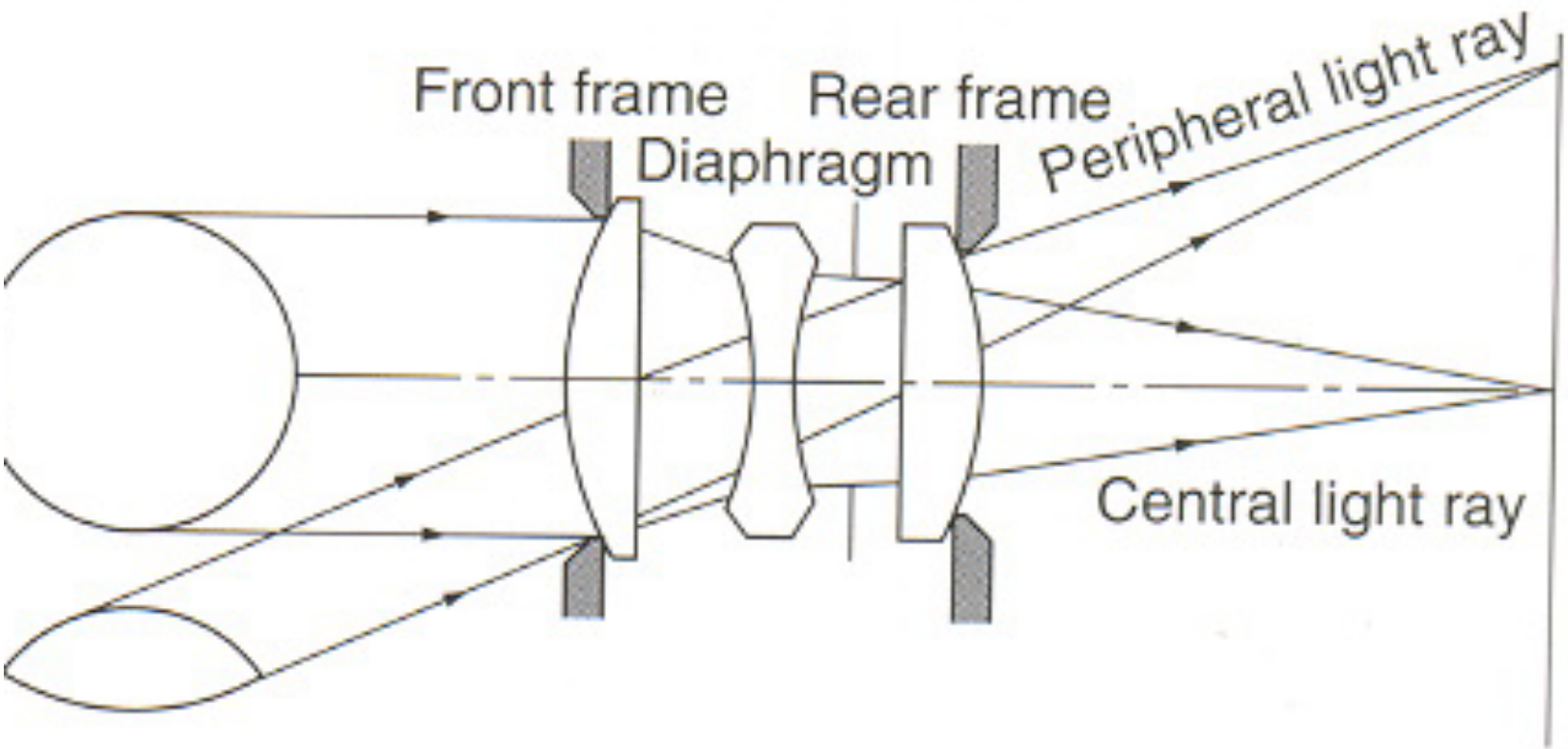
Why vignetting

- **Many factors!**
  - Angle of incidence
  - Occlusion by lens elements
  - Occlusion at the photosite

Vignetting

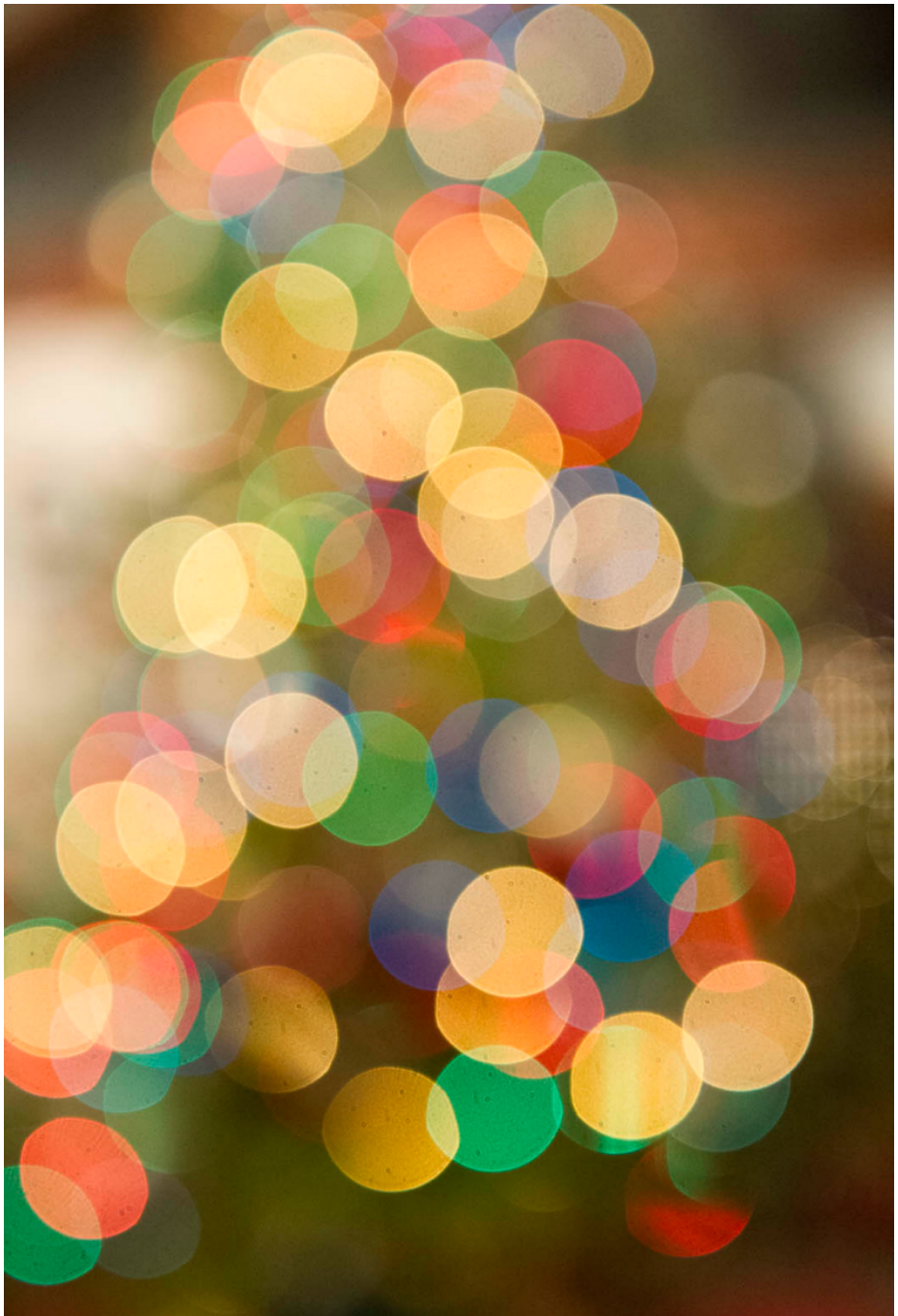
- **Occlusion by lens elements**
- **The periphery does not get as much light**

Figure-28 Vignetting



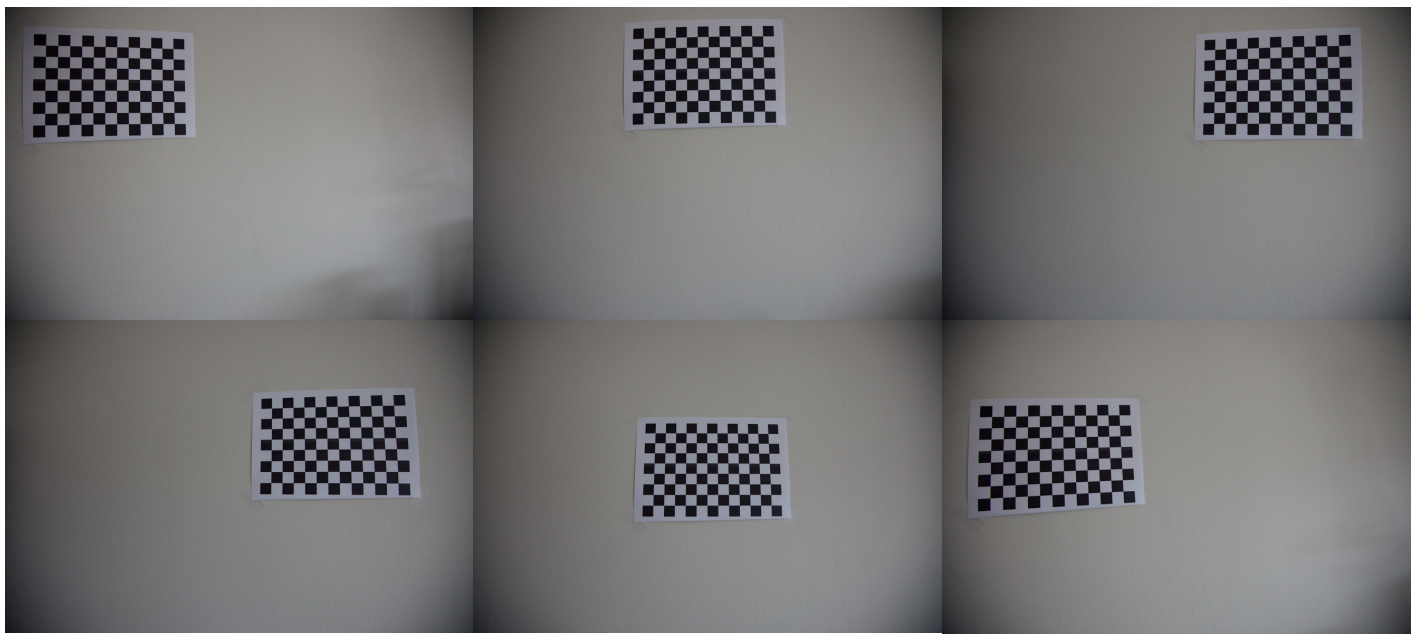
source: canon red book

Occlusion



Vignetting correction

- **Brighten periphery pixels**
  - Often using parametric curve f(r)
  - e.g. polynomial
  - Can be messy
- **Calibrate**
  - Multiple images of same subject at different locations



Vignetting correction (ACR)



Before



After

Special case: panorama

- **We have multiple observations of the same point in overlapping regions**
  - Can be used to calibrate vignetting
- **Discrepancy from homography reprojection can be used to correct for radial distortion**
- **e.g. http://www.cs.jhu.edu/~misha/ReadingSeminar/Papers/Triggs00.pdf**



Software

- **Panorama software**
- **DXO**
  - Also removes blur
  - http://www.dxo.com/us/photo
- **Adobe Camera Raw (Lightroom, Photoshop)**
  - http://labs.adobe.com/technologies/lensprofile_creator/

Lens design

Optimization software

- **Has revolutionized lens design**
- **E.g. zooms are good now**

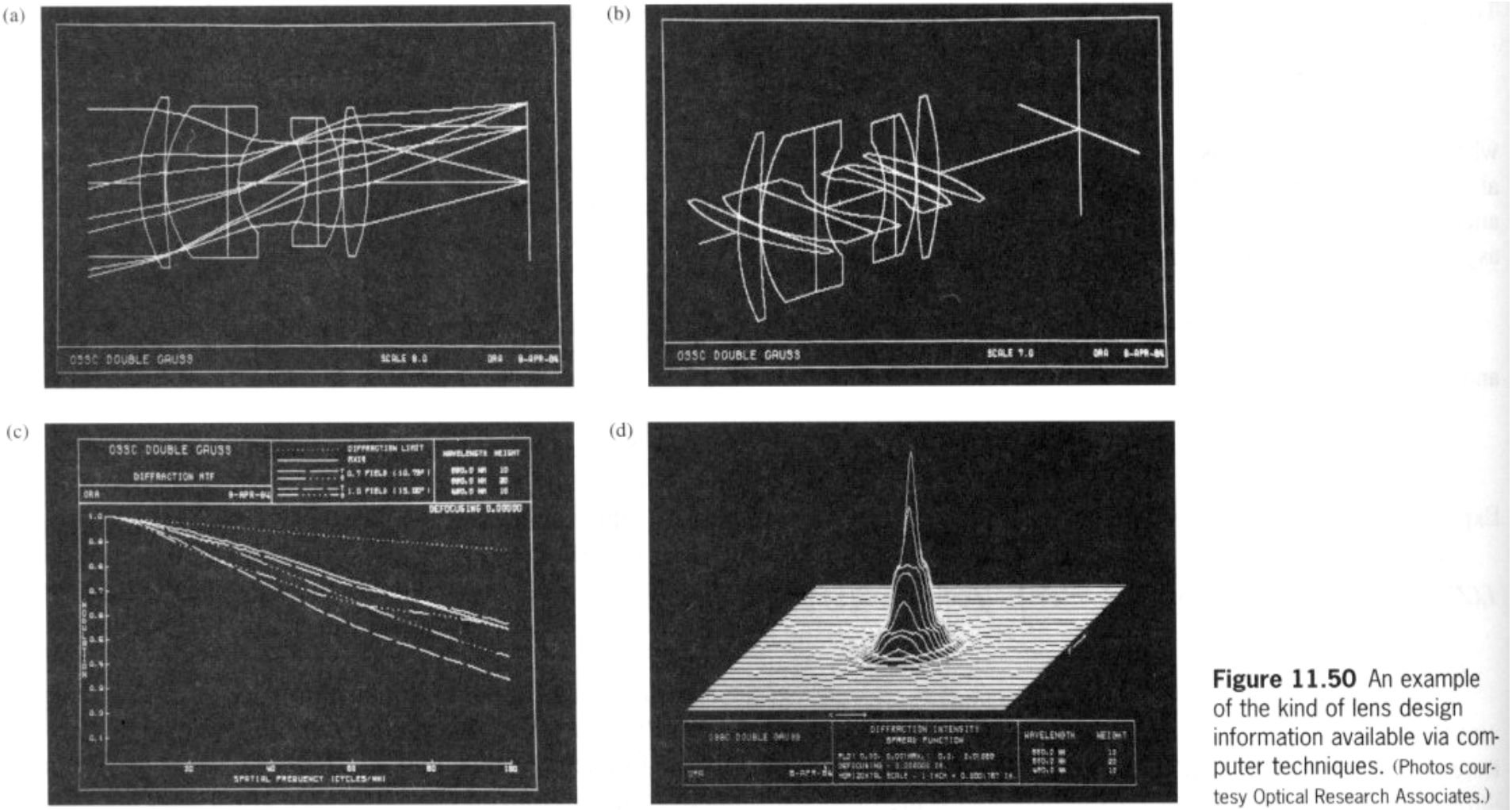


Figure 11.50 An example of the kind of lens design information available via computer techniques. (Photos courtesy Optical Research Associates.)

From Hecht's Optics

Lens design, ray tracing

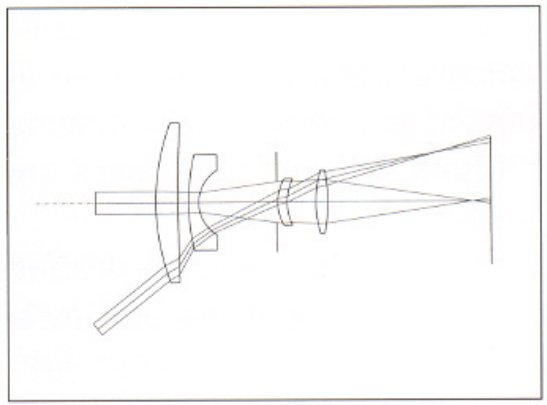


Figure-5

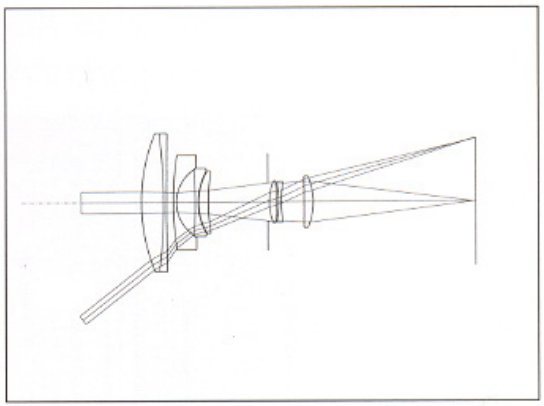


Figure-6

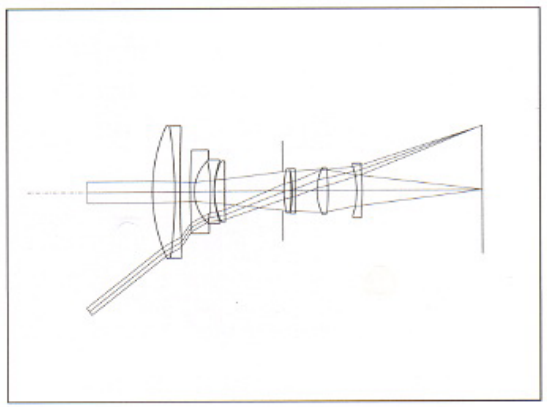


Figure-7

Spot diagram

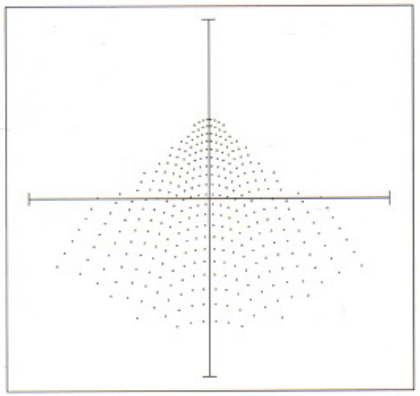


Figure-8

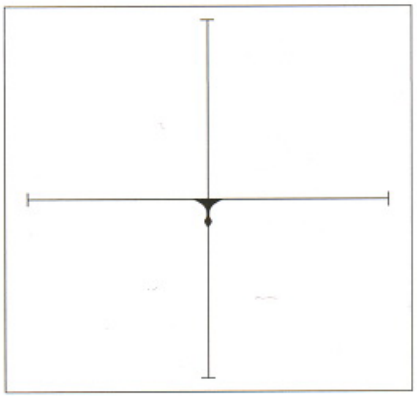


Figure-9

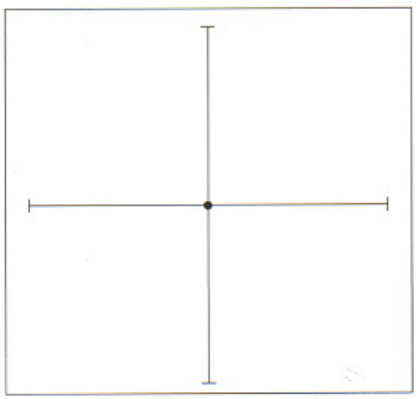


Figure-10

source: canon red book

Optimization

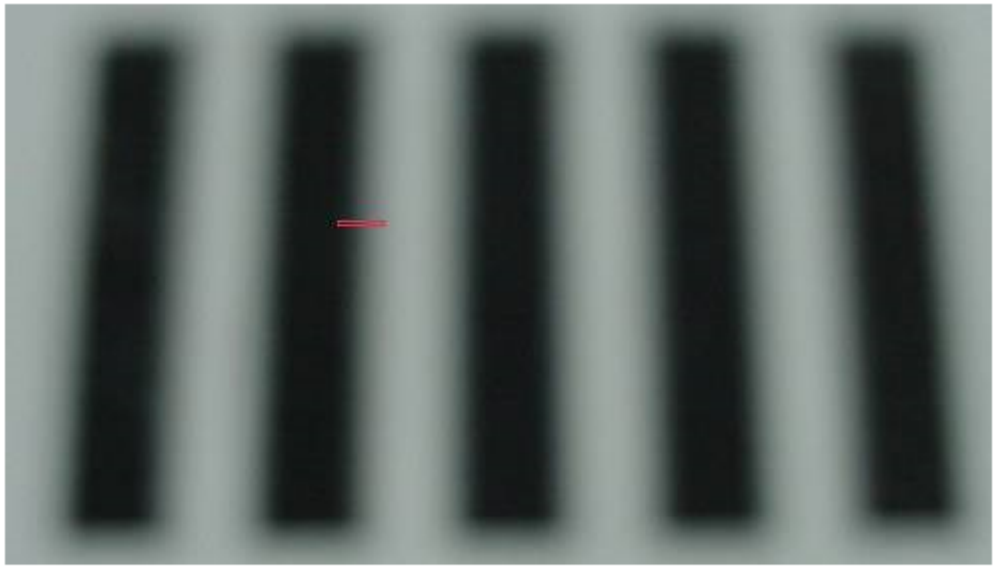
- **Free parameters**
  - Lens curvature, width, position, type of glass
  - Some can be fixed, other vary with focal length, focus (e.g. floating elements)
  - Multiplied by number of lens elements
- **Energy/merit function**
  - MTF, etc.
  - Black art of massaging the merit function
- **Optimize for**
  - All image locations
  - All wavelengths
  - All apertures
  - All focusing distances
  - All focal lengths (zoom only)
- **Usually uses simulated annealing**

Autofocus

How would you build an Auto Focus?

Contrast

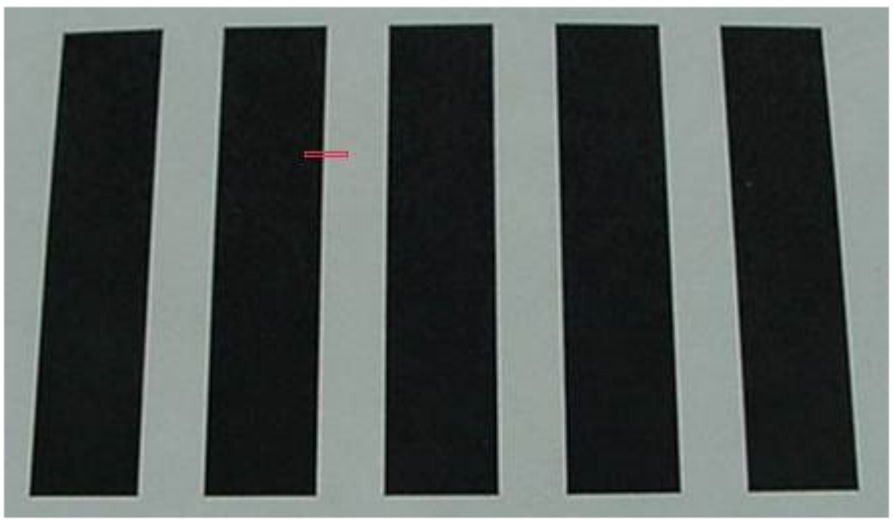
- **Focus = highest contrast**



Out-of-focus scene



Out-of-focus pixel strip

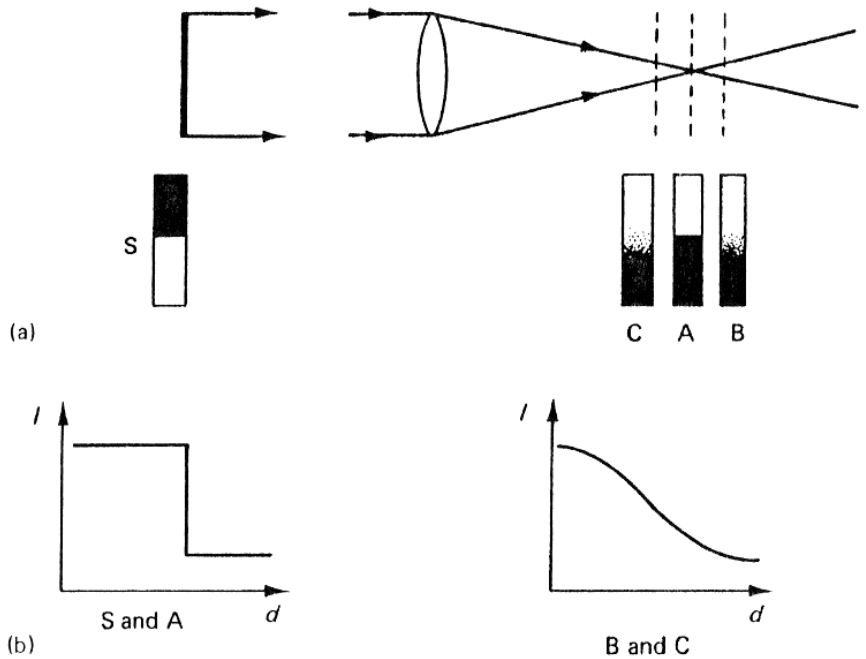


In-focus scene



In-focus pixel strip

http://electronics.howstuffworks.com/autofocus3.htm



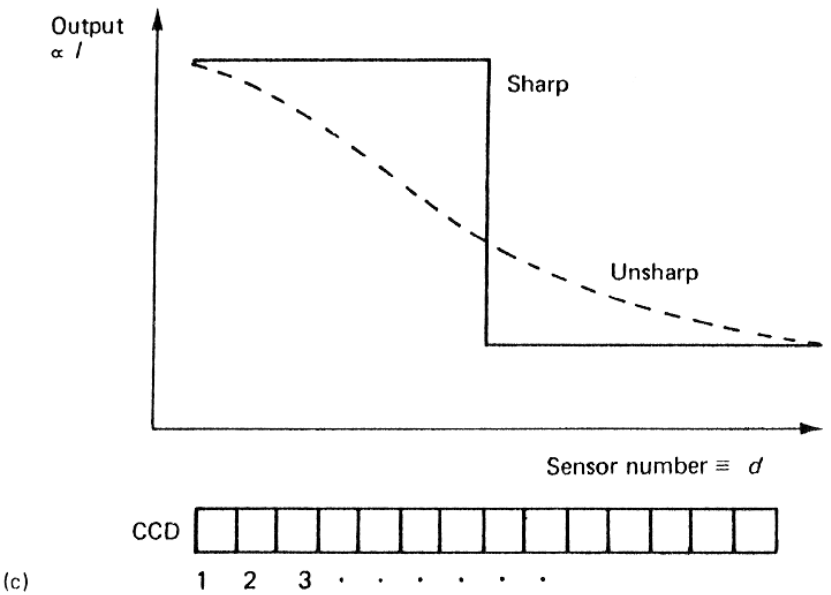


Figure 21.5 Focus detection by a linear CCD array
(a) Subject S imaged in sharp focus at A, but unsharp at C and B. (b) Intensity profiles of S and A and of B and C. (c) Intensity profile as measure of focus determined by linear array of charge coupled devices (CCD) whose output is proportional to intensity and where sensor number corresponds to distance. Signal-processing techniques detect the sharp or unsharp characteristic.

From Ray's Applied Photographic Optics

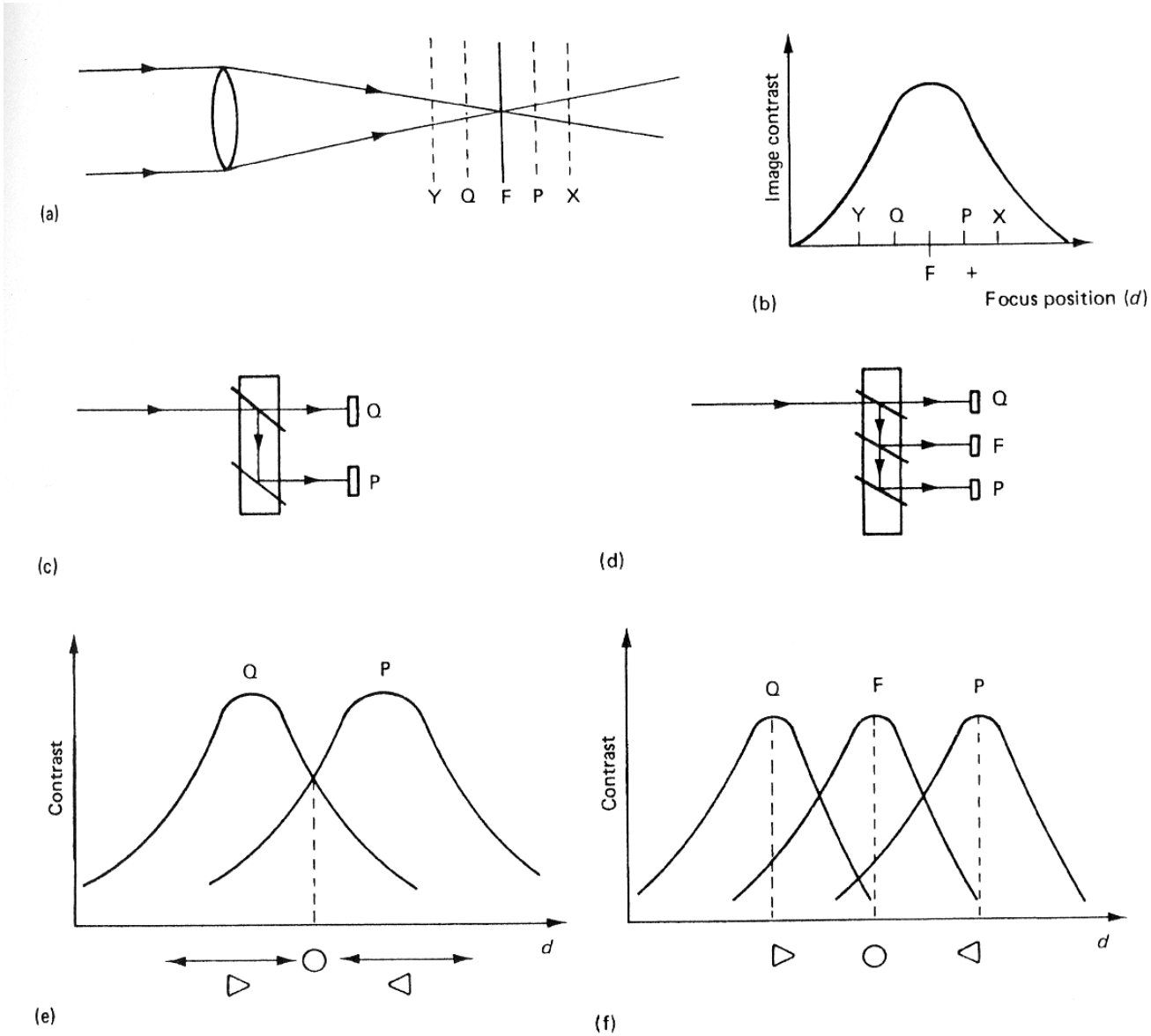
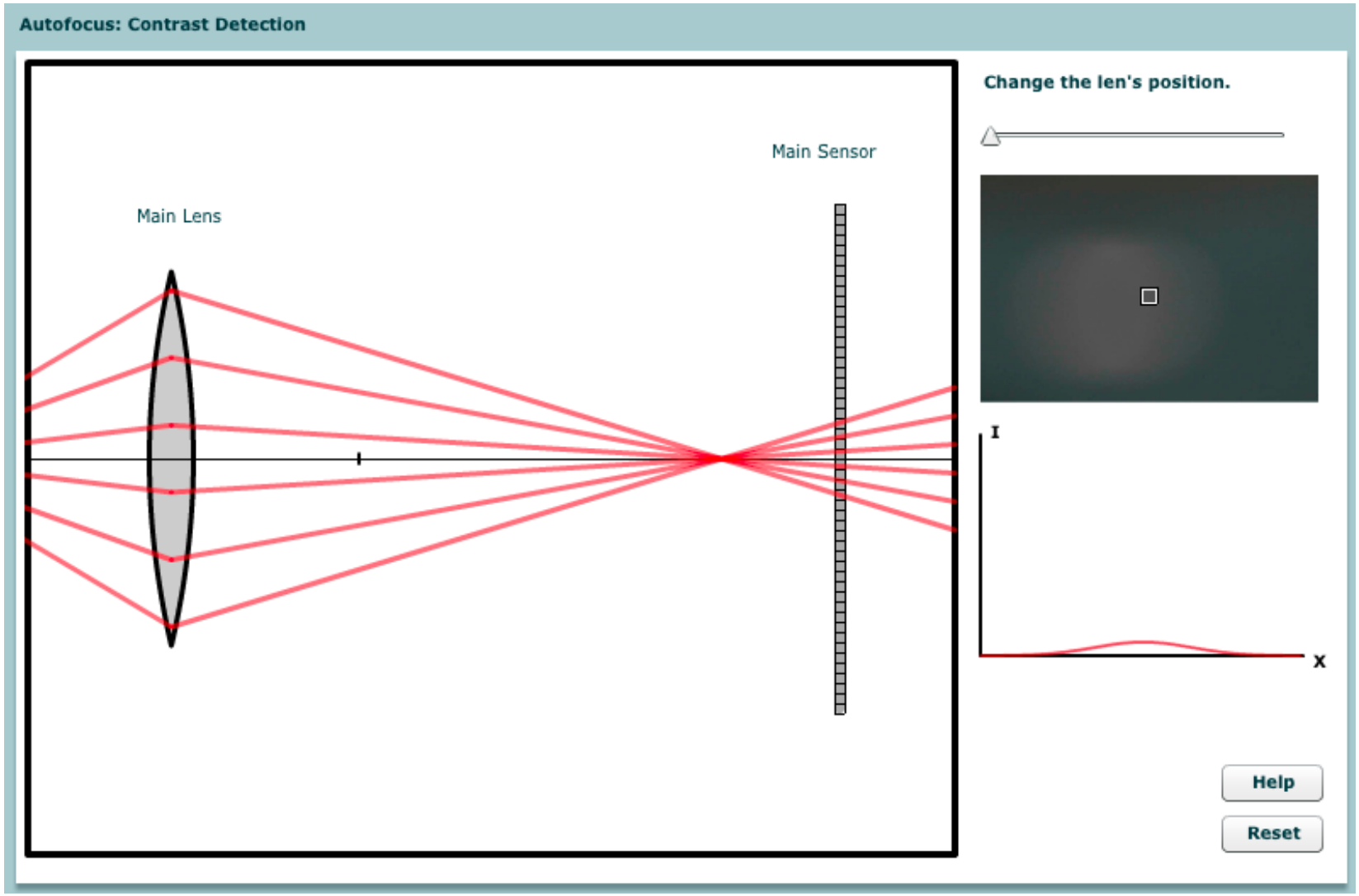


Figure 21.6 Autofocus using image contrast measurements
(a) Sharp image at F with maximum contrast. (b) Variation of contrast with focus position. (c) and (d) Beamsplitters in equivalent focal planes to compare contrast at Q and P or at Q, F and P using linear CCD arrays. (e) and (f) Double or triple outputs of CCD arrays compared by signal-processing techniques to indicate best focus at O or generate signals in viewfinder or operate a servomotor.

From Ray's Applied Photographic Optics

- **http://graphics.stanford.edu/courses/cs178/applets/autofocusCD.html**



Phase detection focusing

- **Used e.g. in SLRs**

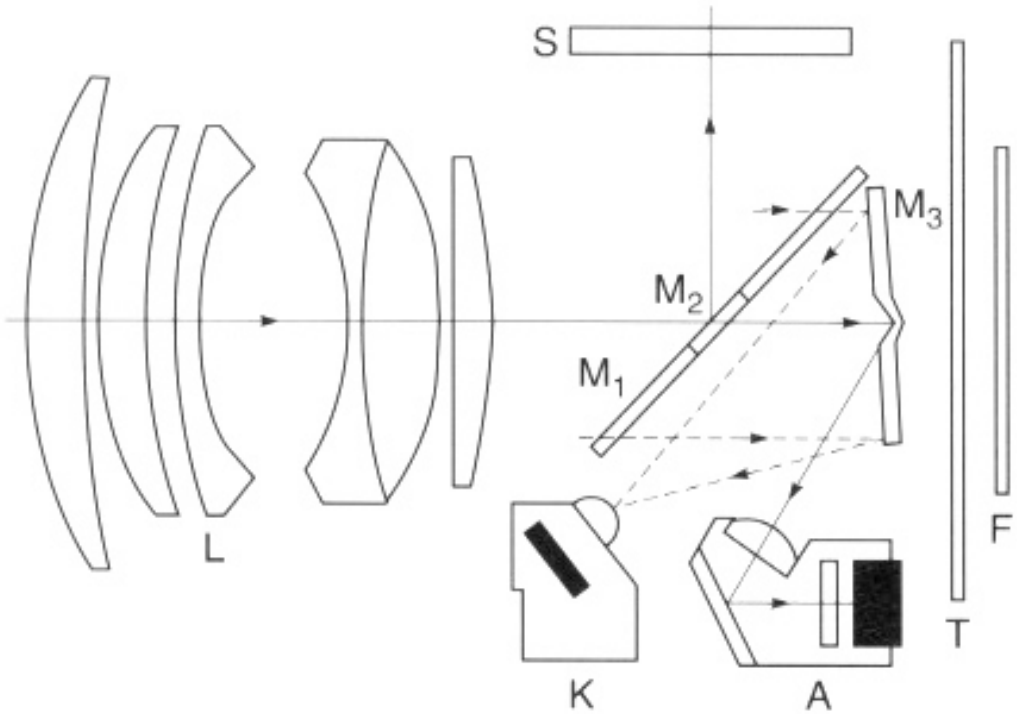
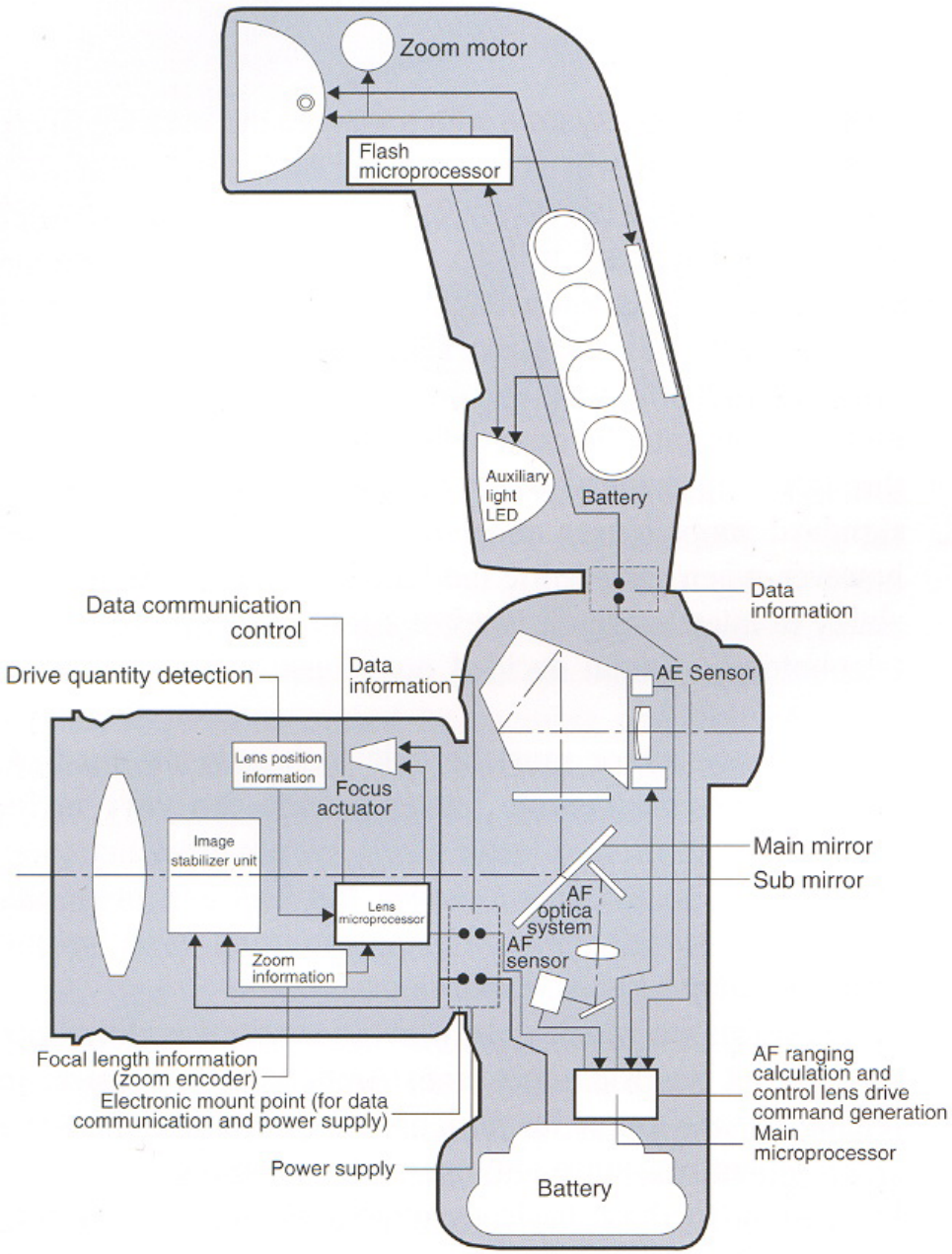


Figure 9.24 Location of autofocus and metering modules. L, camera lens; S, focusing screen; F, film in gate; M_1, reflex mirror with 30 per cent transmission; M_2, central region with 50 per cent transmission; M_3, secondary mirror with two focusing regions; A, autofocus module; K, metering module; spot or centre-weighted

From The Manual of Photography



From the Canon red book

Phase detection focusing

- **Stereo vision from two portions of the lens on the periphery**
- **Not at the equivalent film plane but farther ➔ can distinguish too far and too close**
- **Look at the phase difference between the two images**

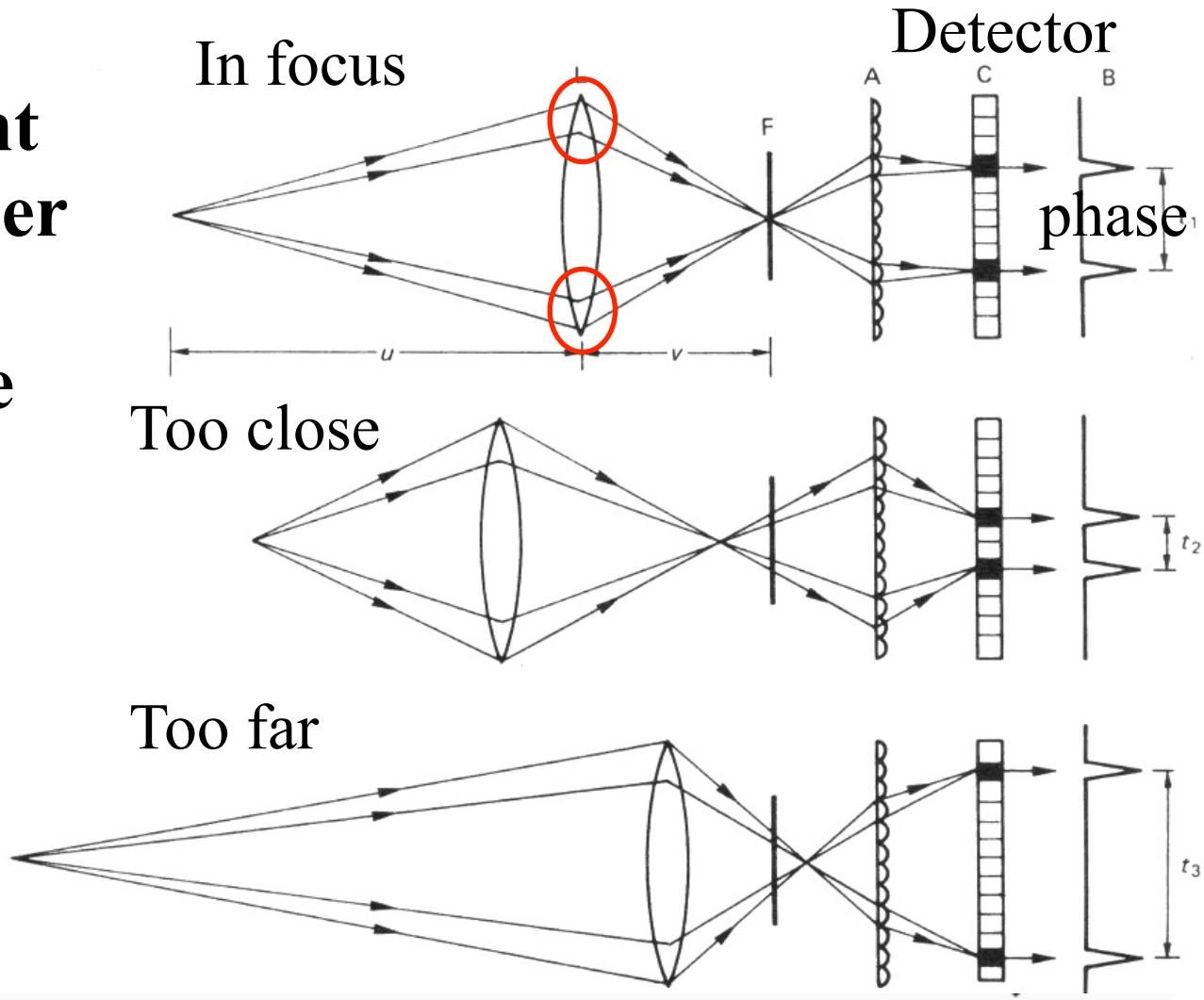
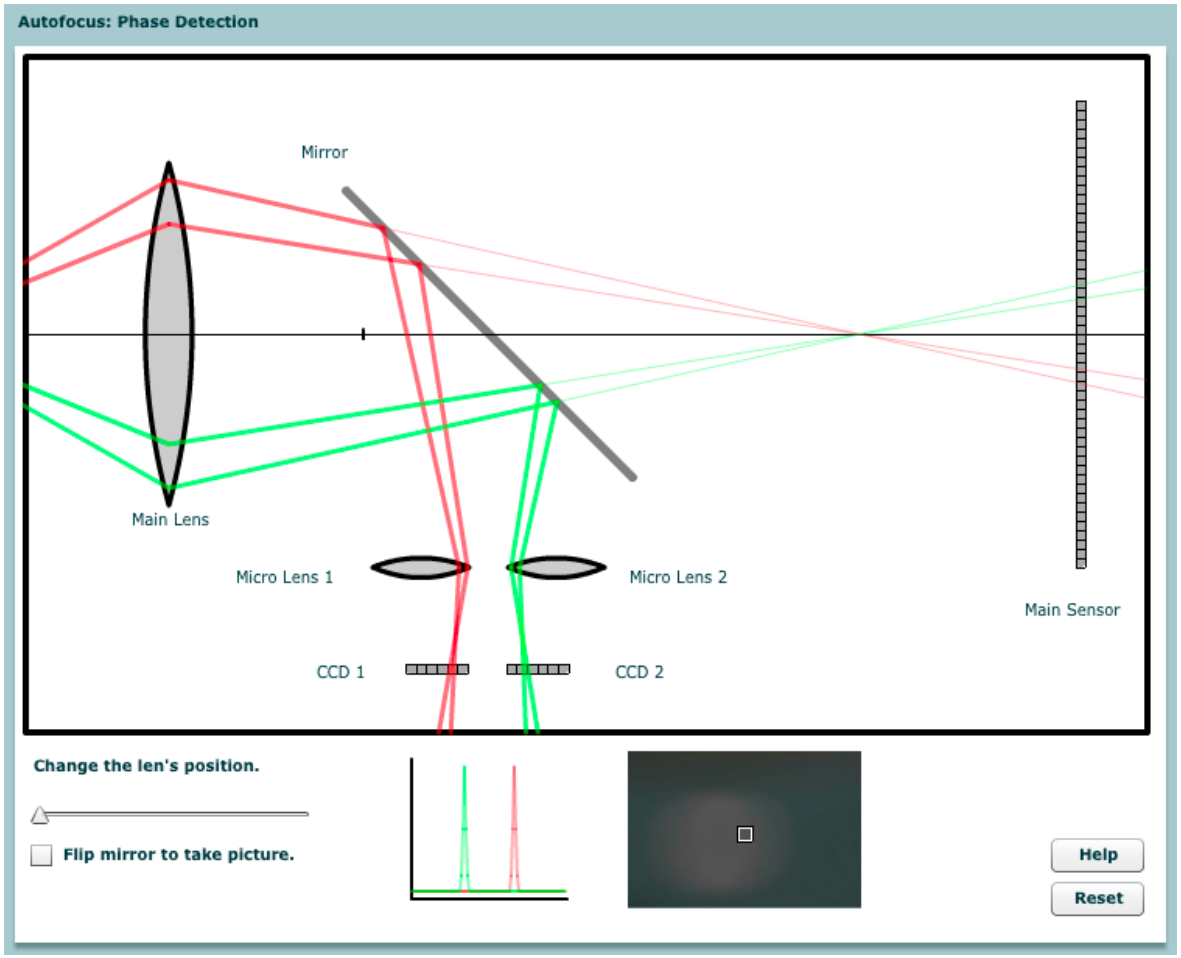


Figure 9.25 Principles of autofocus by phase detection. (a) Subject in focus. (b) Focus in front of subject. (c) Focus beyond subject. Key: L camera lens; F equivalent focal plane; A lenslet array; C CCD linear array; B output signals with time delay t_1 etc.

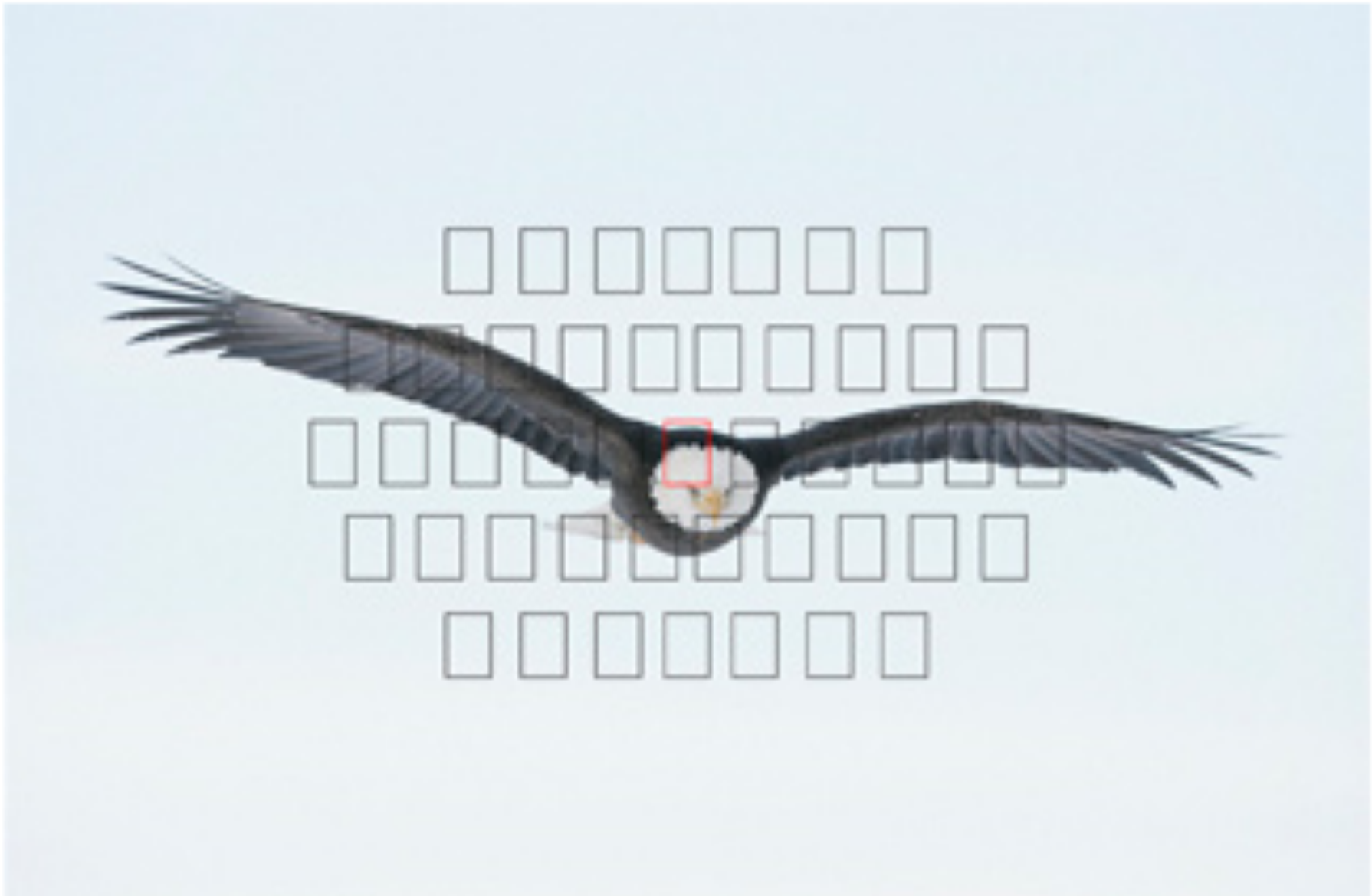
From The Manual of Photography

Applet

- **http://graphics.stanford.edu/courses/cs178/applets/autofocusPD.html**



Multiple focus sensors



source arthur morris

Polaroid Ultrasound (Active AF)

- **Time of flight (sonar principle)**
- **Limited range, stopped by glass**
- **Paved the way for use in robotics**

- http://www.acroname.com/robotics/info/articles/sonar/sonar.html
- http://www.uoxray.uoregon.edu/polamod/
- http://electronics.howstuffworks.com/autofocus2.htm



http://www.uoxray.uoregon.edu/polamod/

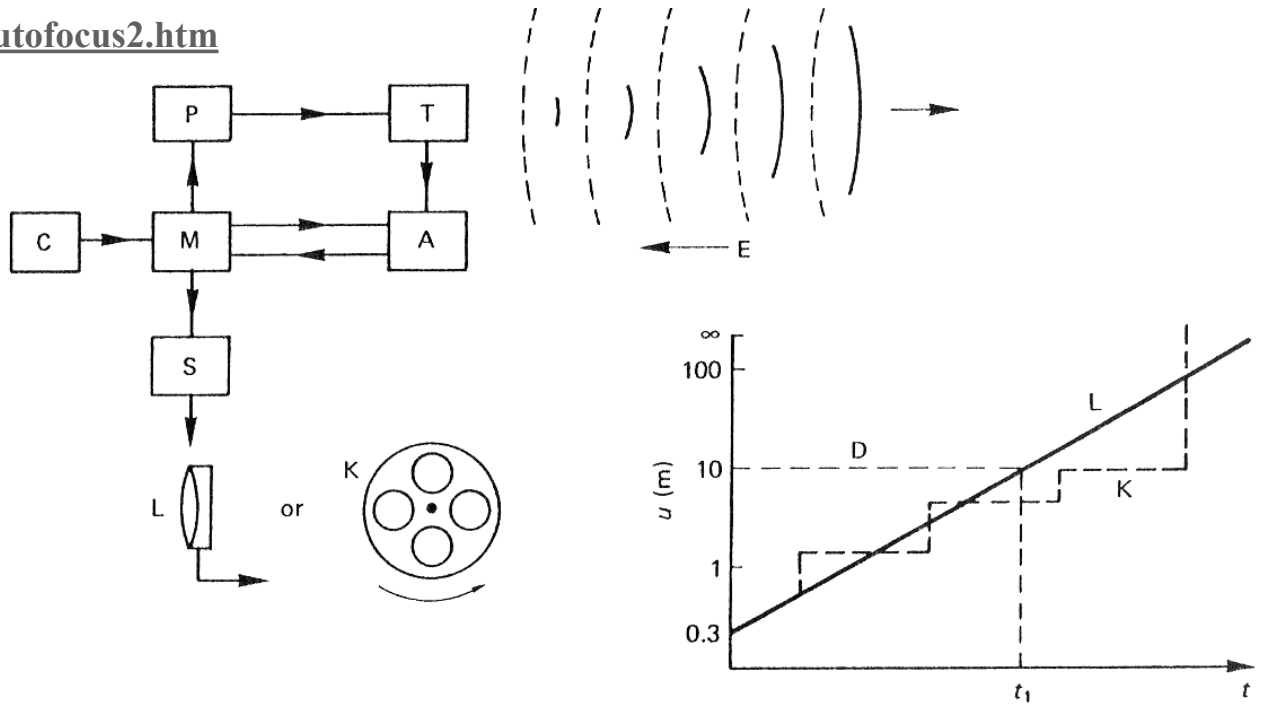


Figure 21.3 Polaroid sonar autofocusing
Ultrasonic pulse emitted by transducer T from power unit P under control of microprocessor M and clock C. Echo E also received by T, digitized by analogue–digital circuitry A, returns to M to control focusing motor S. This halts axial movement of lens L or a rotation of disc K of supplementary lenses behind L. Graph of elapsed time t against u shows focusing behaviour.

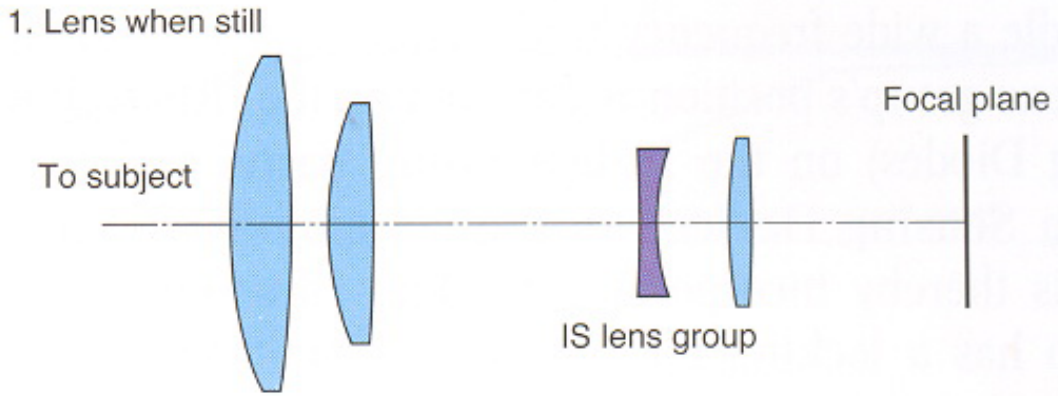
From Ray's Applied Photographic Optics

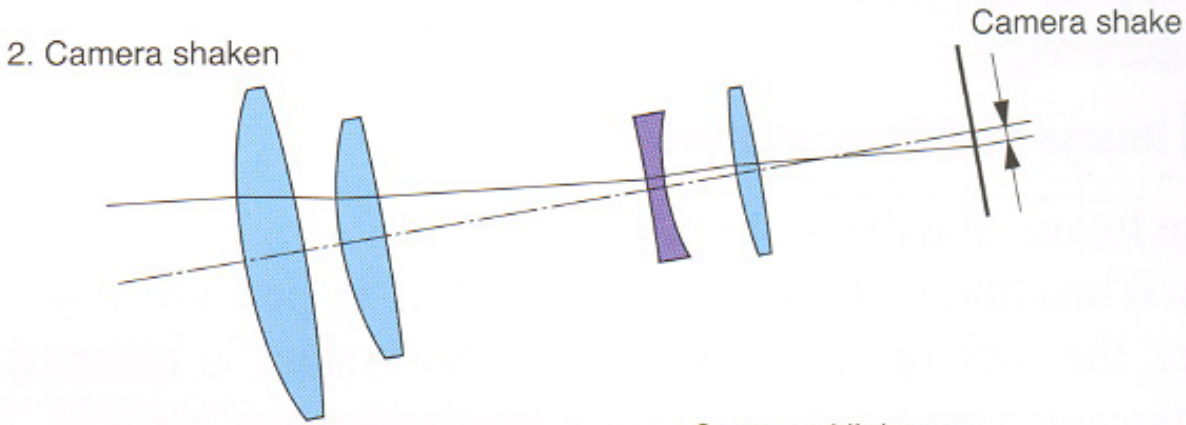
Infrared (Active AF)

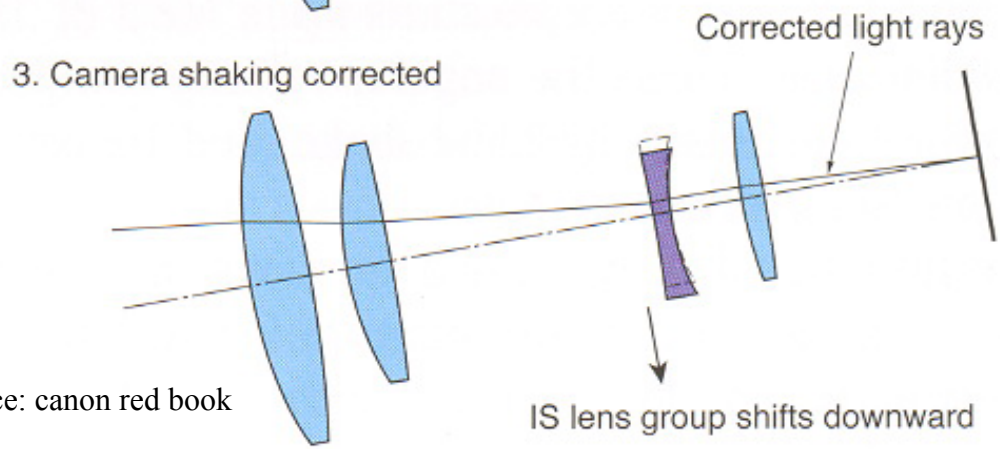
- **Intensity of reflected IR is assumed to be proportional to distance**
- **There are a number of obvious limitations**
- **Advantage: works in the dark**
- **This is different from Flash assistant for AF where the IR only provides enough contrast so that standard passive AF can operate**

Image stabilization

Image stabilization







source: canon red book

Photo-21 Shake-detecting gyro sensor

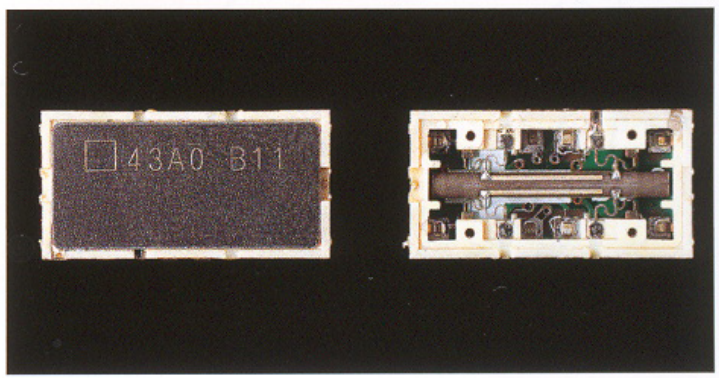
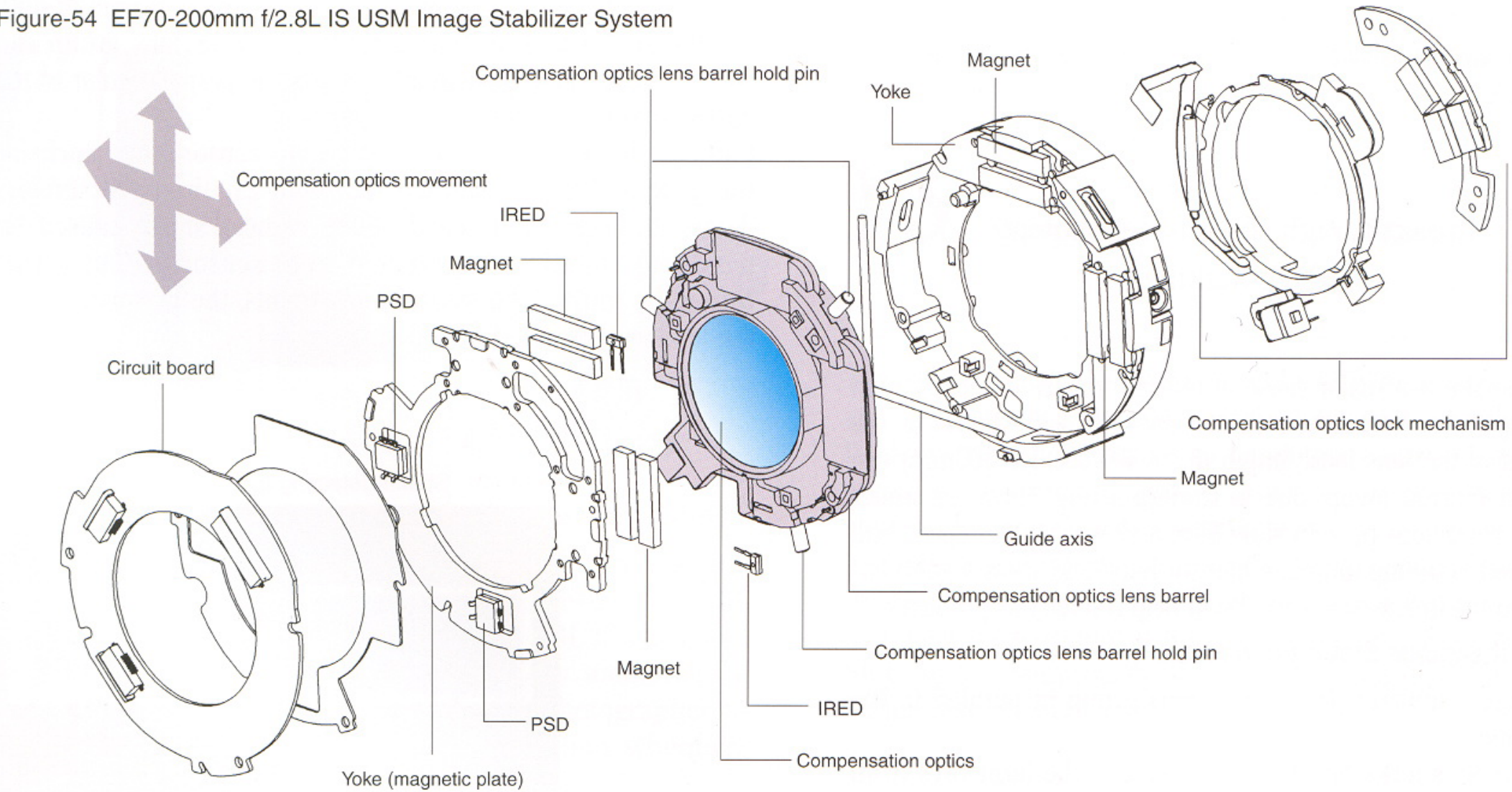
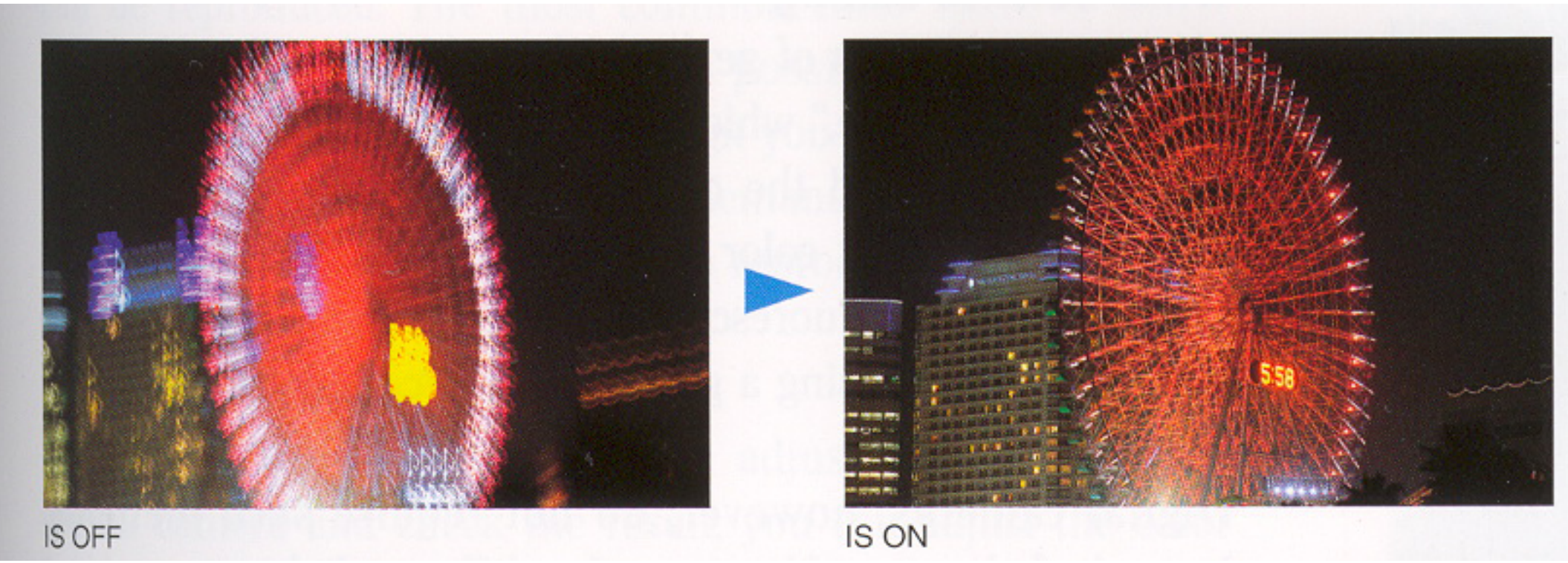


Image stabilization



source: canon red book

Image stabilization



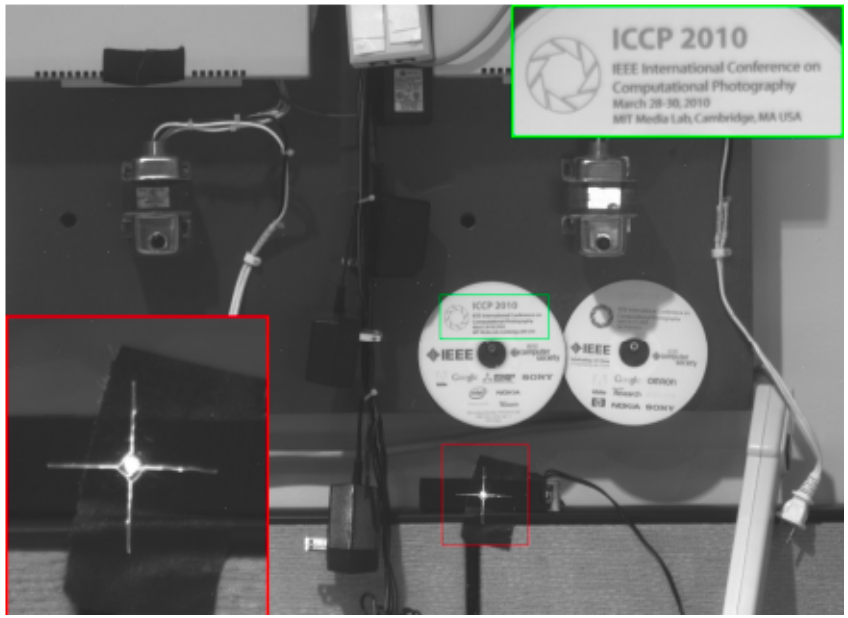
source: canon red book

1000mm, 1/100s, monopod, IS



Image stabilization hacking

- **http://www.cim.mcgill.ca/~scott/papers/ICCP_2011.pdf**
- **Enables custom blur**



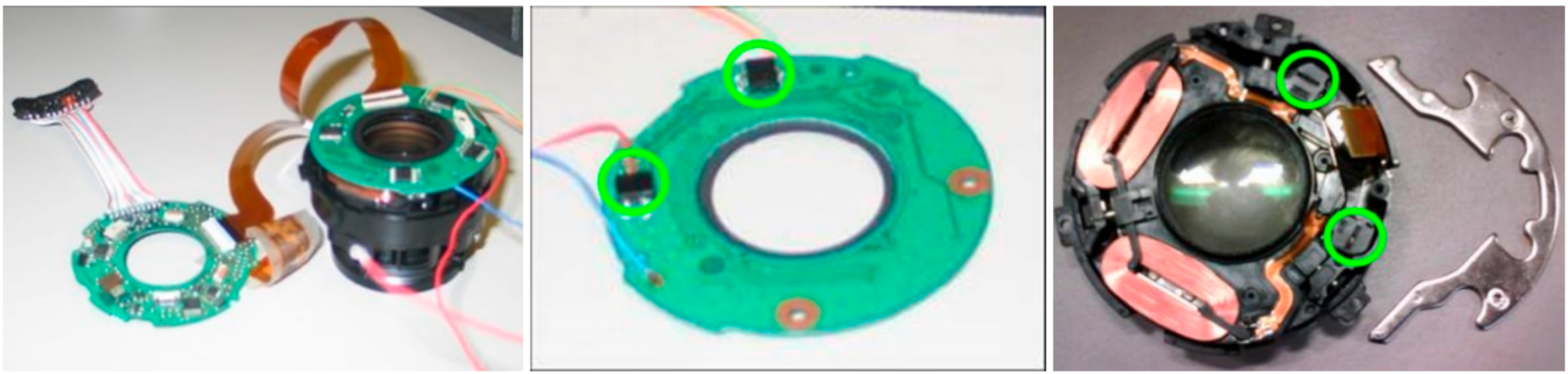
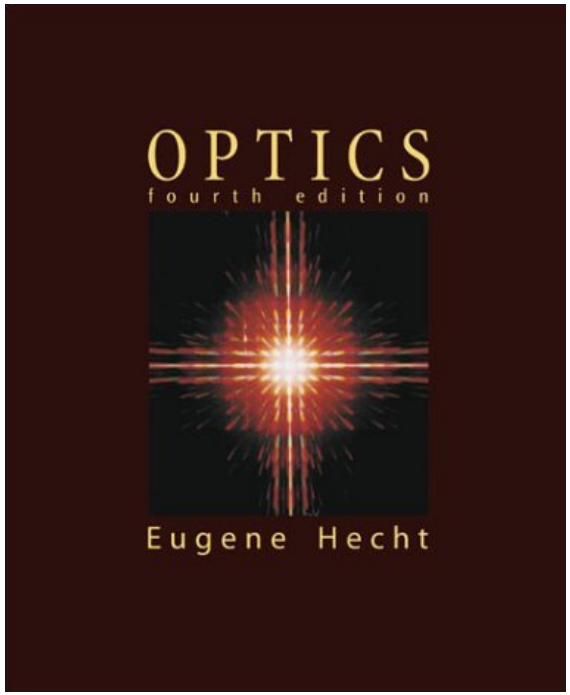


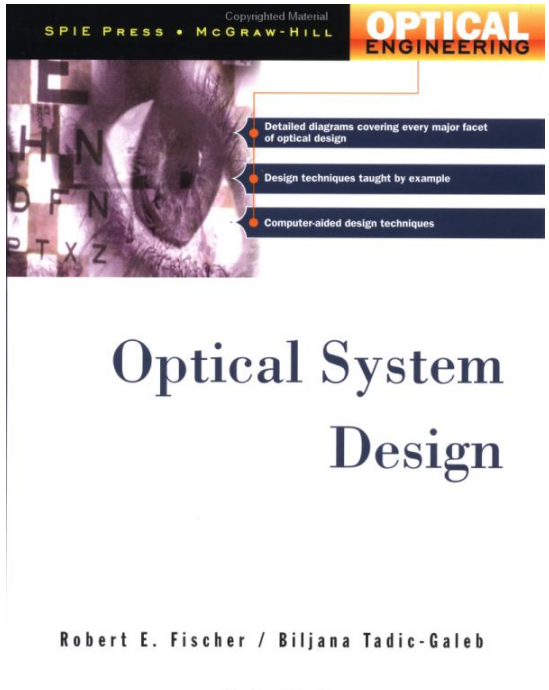
Figure 1. Stabilizing elements of the Canon EF70-200mm F/4L IS USM lens. (Left) We sever the flex cable connection between the position-sensing and motion compensating lens sub-systems. (Center) Lens motion is measured in the circled chips by the position of a laser spots relative to two orthogonal axes of motion. (Right) The floating element projects laser points (from circled slots at 1 and 4 o'clock), and moves the encased lens element using magnets (under red coils) and a yoke.

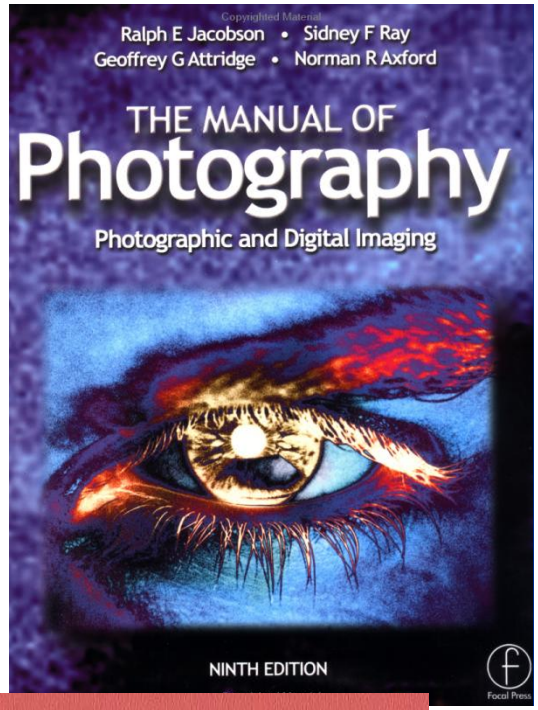
Different versions

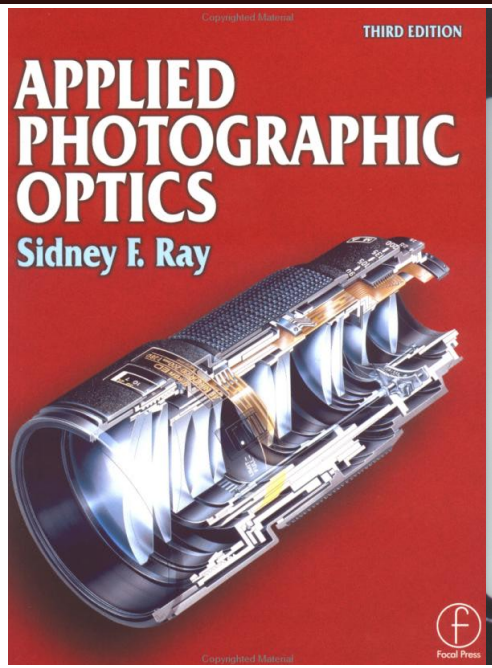
- **Canon, Nikon: in the lens**
- **Panasonic, Konica/Minolta: move sensor**

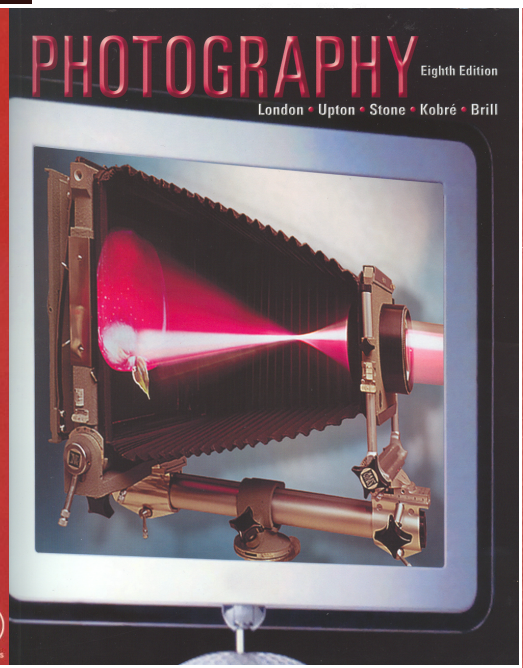
References

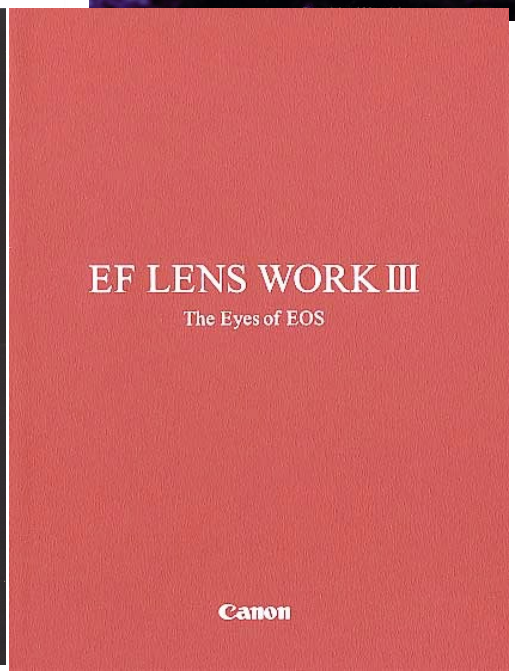

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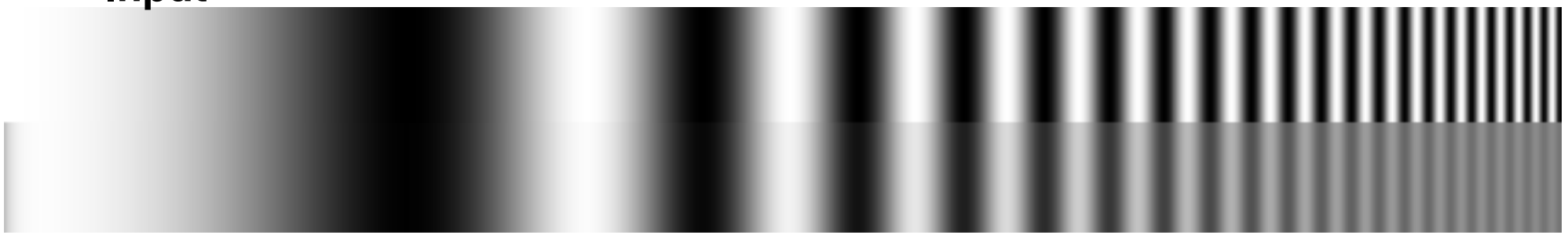
- http://en.wikipedia.org/wiki/Chromatic_aberration
- http://www.dpreview.com/learn/?/key=chromatic+aberration
- http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/aberrcon.html#c1
- http://en.wikipedia.org/wiki/Spherical_aberration
- http://en.wikipedia.org/wiki/Lens_(optics)
- http://en.wikipedia.org/wiki/Optical_coating
- http://www.vanwalree.com/optics.html
- http://en.wikipedia.org/wiki/Aberration_in_optical_systems
- http://www.imatest.com/docs/iqf.html
- http://www.luminous-landscape.com/tutorials/understanding-series/understanding-mtf.shtml
- http://mansurovs.com/what-is-chromatic-aberration
- **http://www.dvinfo.net/articles/optics/lensdefects.php**
-

Quality evaluation

LPIs

- **Line pair per inch**

Input

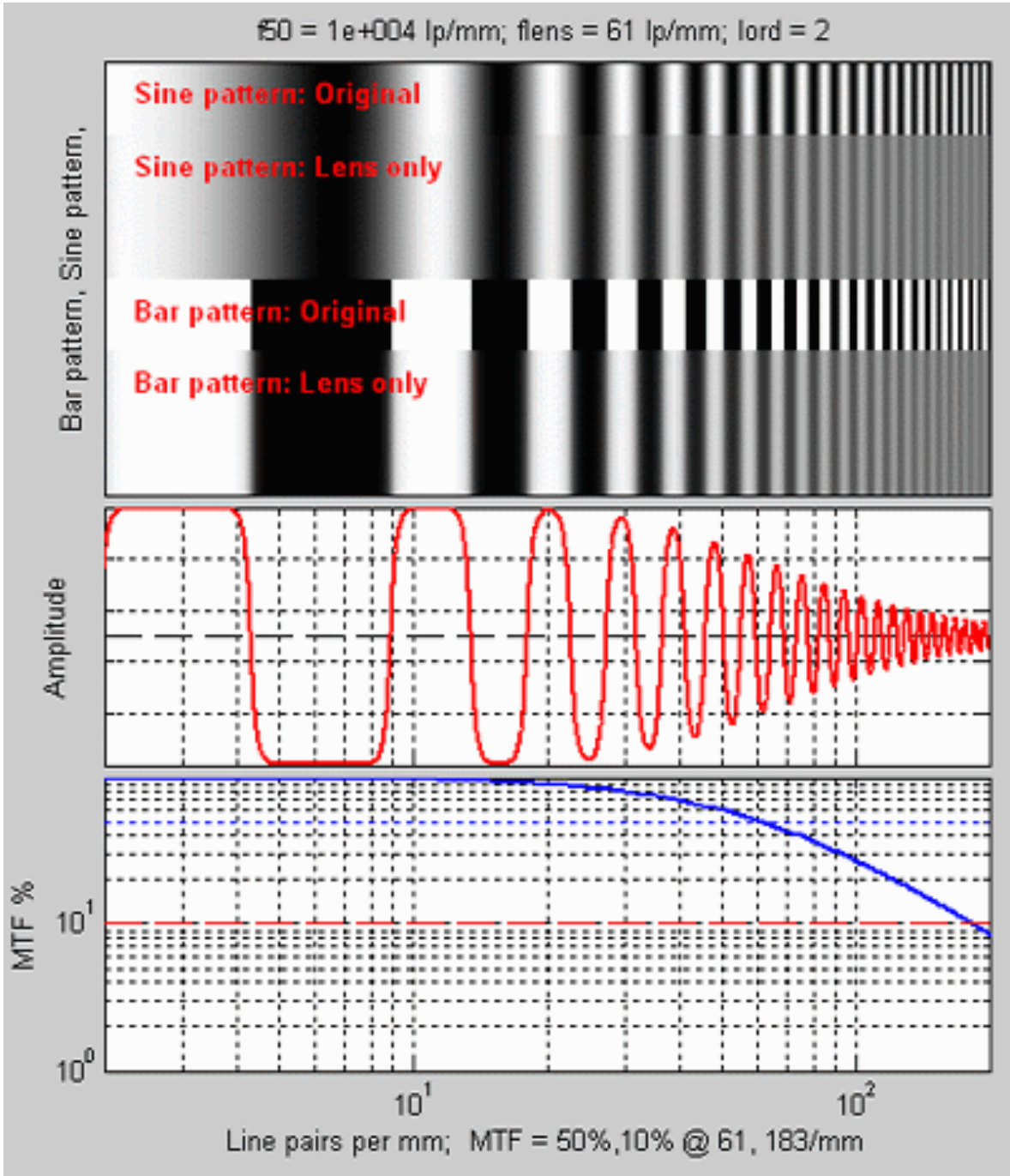


After lens

http://www.imatest.com/docs/sharpness.html

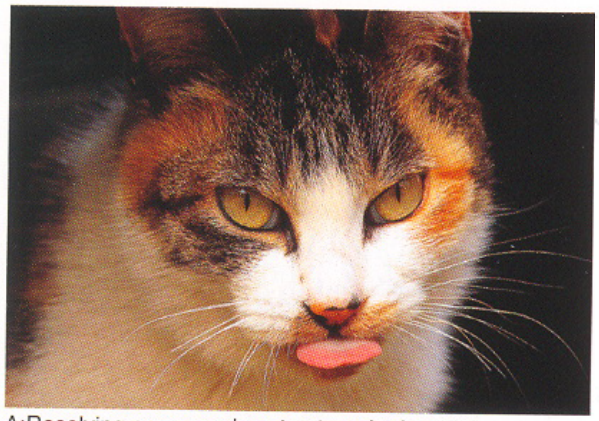
- http://www.optikos.com/Pdf_files/how_to_measure_mtf.pdf
- http://www.imatest.com/docs/tour.html

Sharpness

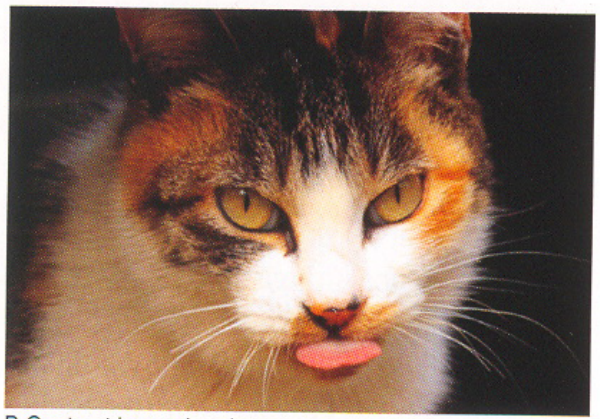

f50 = 1e+004 lp/mm; flens = 61 lp/mm; lord = 2
Sine pattern: Original
Sine pattern: Lens only
Bar pattern: Original
Bar pattern: Lens only
Bar pattern, Sine pattern,
Amplitude
MTF %
10^1
10^0
10^1
10^2
Line pairs per mm; MTF = 50%,10% @ 61, 183/mm

MTF

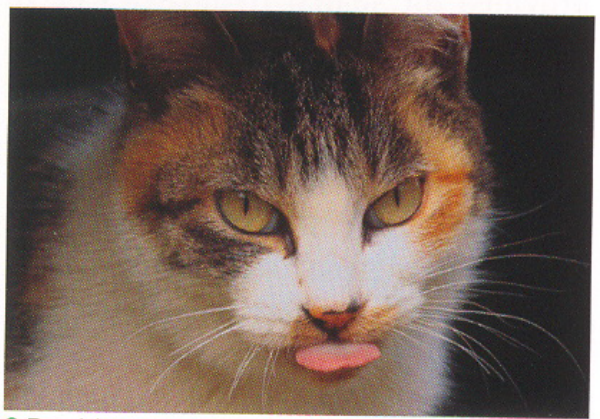
- **Modulation Transfer Function**
- **Preety much Fourier transform of lens response**
- **Complex because needs to be measured at multiple location**



A:Resolving power and contrast are both good



B:Contrast is good and resolving power is bad

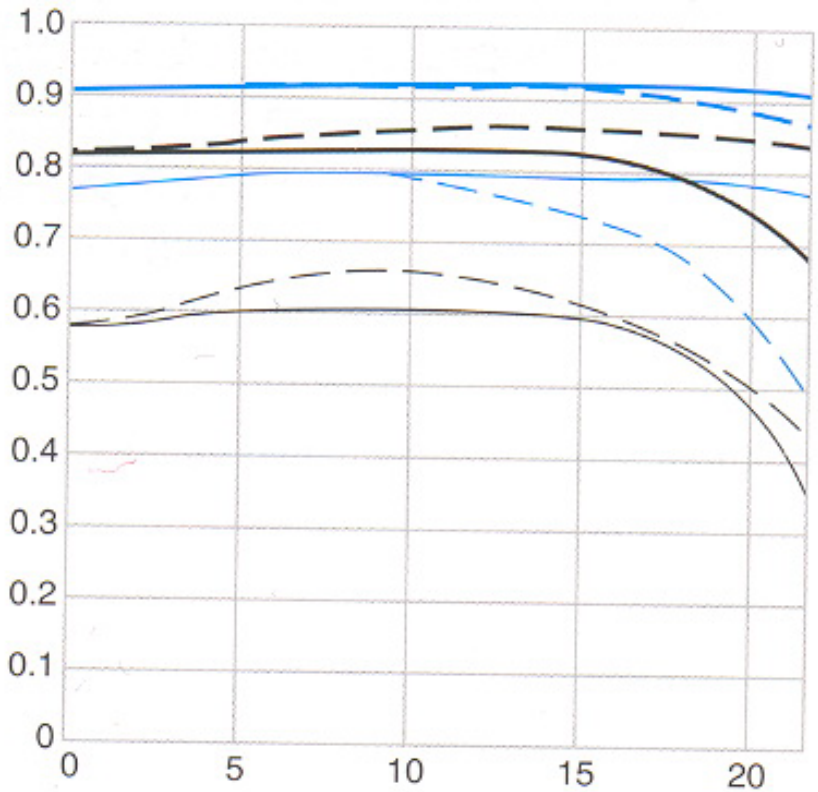


C:Resolving power is good and contrast is bad

Table-3

Spatial frequency	Maximum aperture		F 8	
	S	M	S	M
10 lines/mm	———	- - -	———	- - -
30 lines/mm	———	- - -	———	- - -

Graph-5 MTF Characteristics



Here the x axis is image location

source: canon red book

Blur index based on Photoshop!

- **Lens sharpness (or lack thereof) expressed as the amount of Photoshop blur that would blur the image similarly**
- **http://www.imatest.com/**
- **http://www.dxo.com/en/measure/dxo_analyser/default.php**
- **Cool vis at http://www.slrgear.com/reviews/index.php**

- **100 macro: http://www.slrgear.com/reviews/showproduct.php/product/157/sort/2/cat/10/page/1**
- **50mm f/1.4 http://www.slrgear.com/reviews/showproduct.php/product/140/sort/2/cat/10/page/2**
- **16-35mm http://www.slrgear.com/reviews/showproduct.php/product/142/sort/2/cat/11/page/1**
- **55-200 http://www.slrgear.com/reviews/showproduct.php/product/141/sort/2/cat/11/page/1**
- **28-135 http://www.slrgear.com/reviews/showproduct.php/product/139/sort/2/cat/11/page/1**
- **18-55 http://www.slrgear.com/reviews/showproduct.php/product/137/sort/2/cat/11/page/1**
- **17-85 http://www.slrgear.com/reviews/showproduct.php/product/136/sort/2/cat/11/page/1**
- **10-22 http://www.slrgear.com/reviews/showproduct.php/product/135/sort/2/cat/11/page/1**