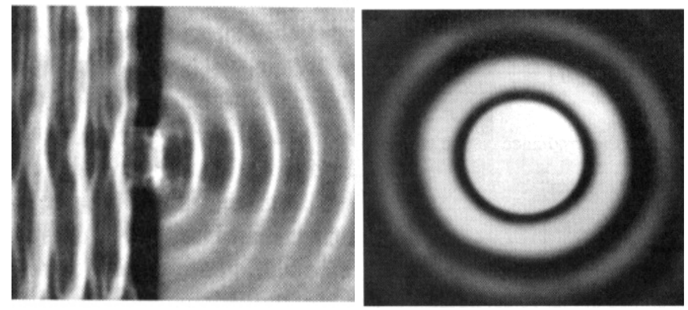
Lenses and Depth of Field

Prepared by Behzad Sajadi

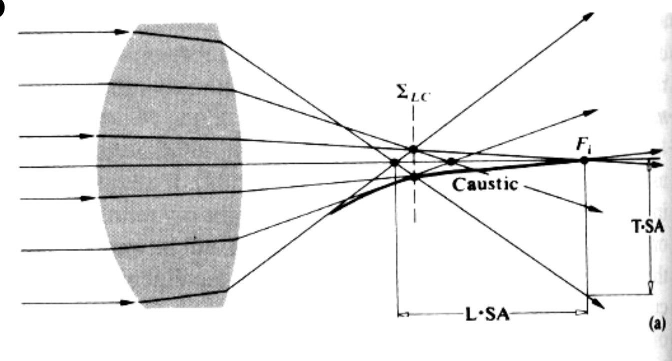
Borrowed from Frédo Durand's Lectures at MIT

3 major type of issues

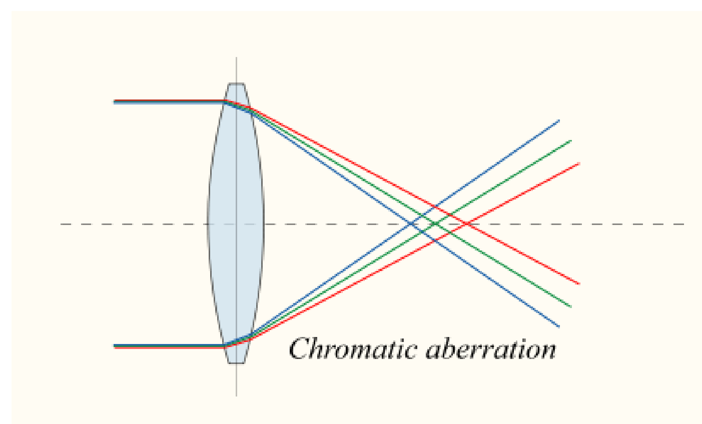
- **Diffraction**
  - ripples when aperture is small



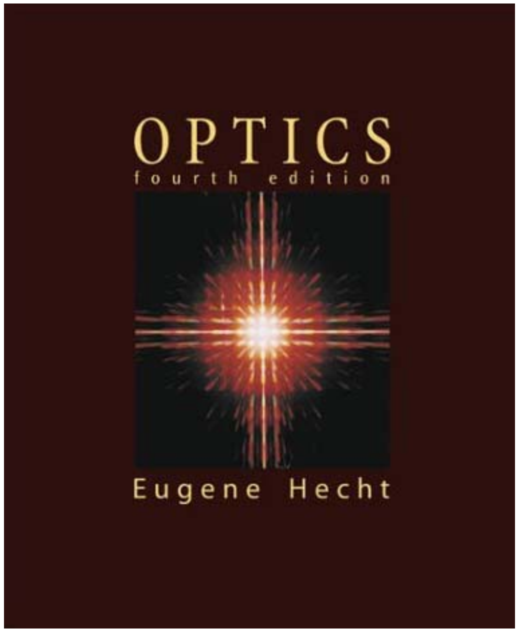
- **Third-order/spherical aberrations**
  - Rays don’t focus
  - Also coma, astigmatism, field curvature

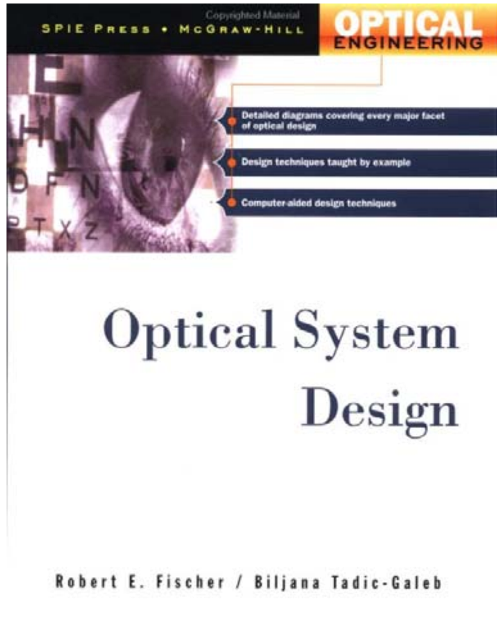


- **Chromatic aberration**
  - Focus depends on wavelength



References


OPTICS
fourth edition
Eugene Hecht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Detailed diagrams covering every major facet of optical design
Design techniques taught by example
Computer-aided design techniques
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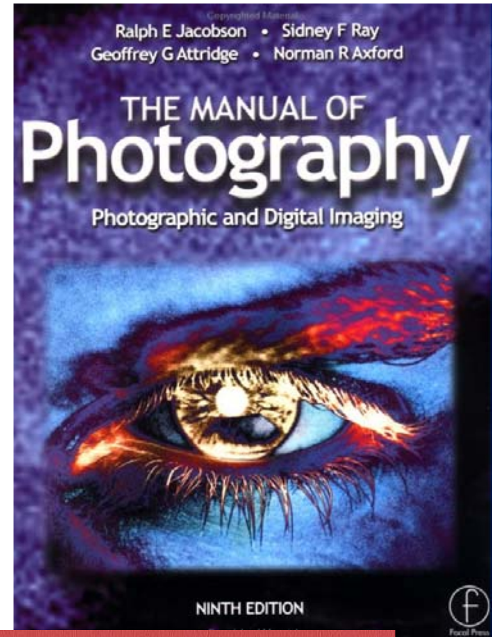
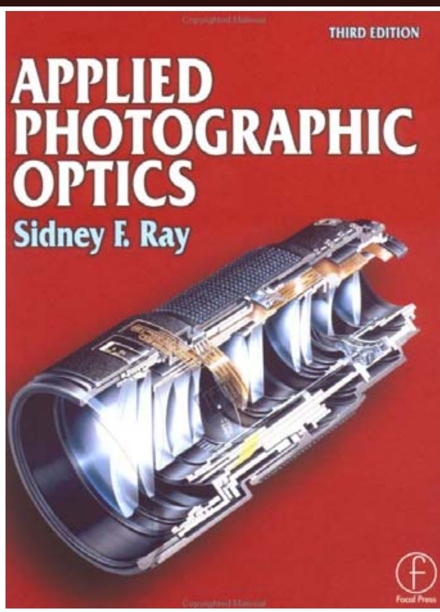

Ralph E Jacobson • Sidney F Ray
Geoffrey G Attridge • Norman R Axford
THE MANUAL OF
Photography
Photographic and Digital Imaging
NINTH EDITION


THIRD EDITION
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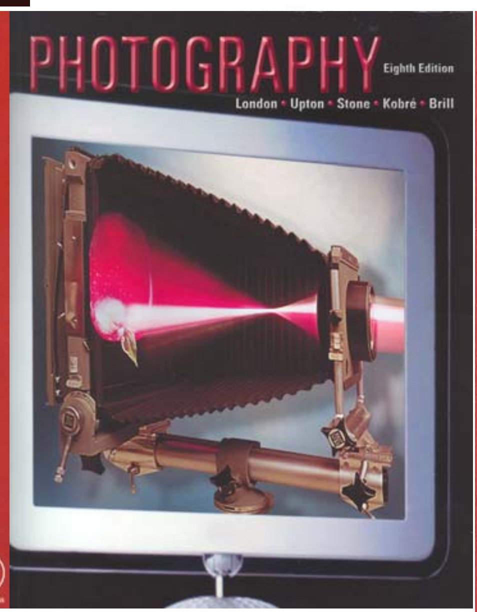
Sidney F. Ray


PHOTOGRAPHY
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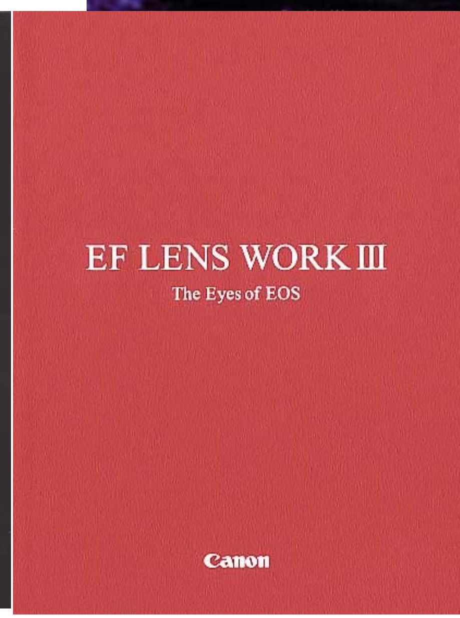

EF LENS WORK III
The Eyes of EOS
Canon

Links

- 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

Other quality issues

Flare

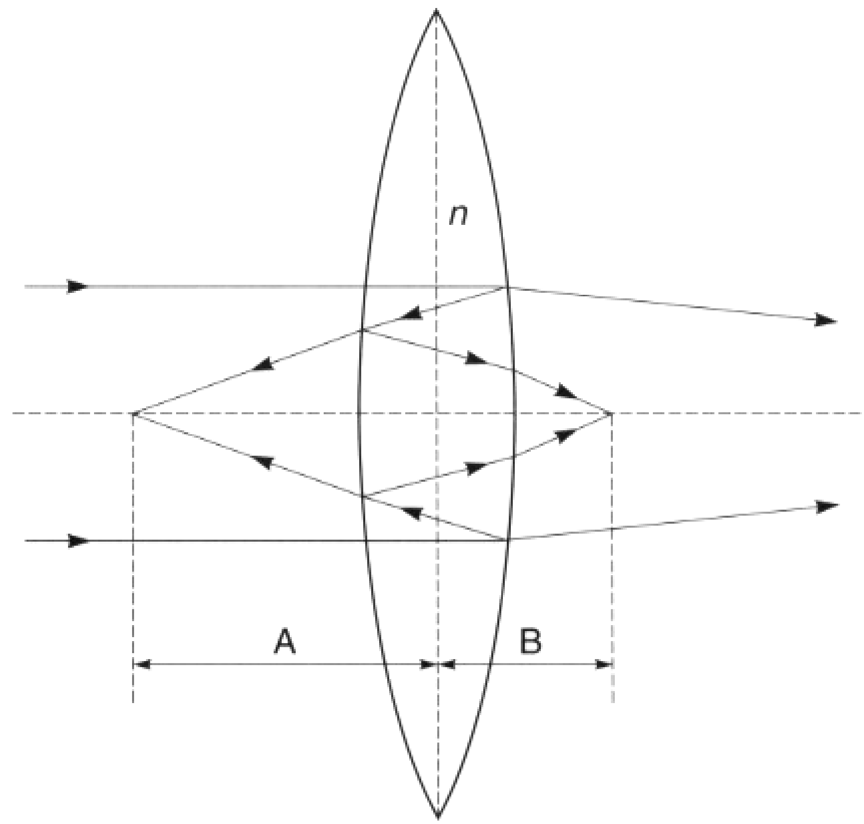


Figure 5.6 Formation of flare spots by a simple lens. Images of the source are formed at distances A and B, where:

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

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

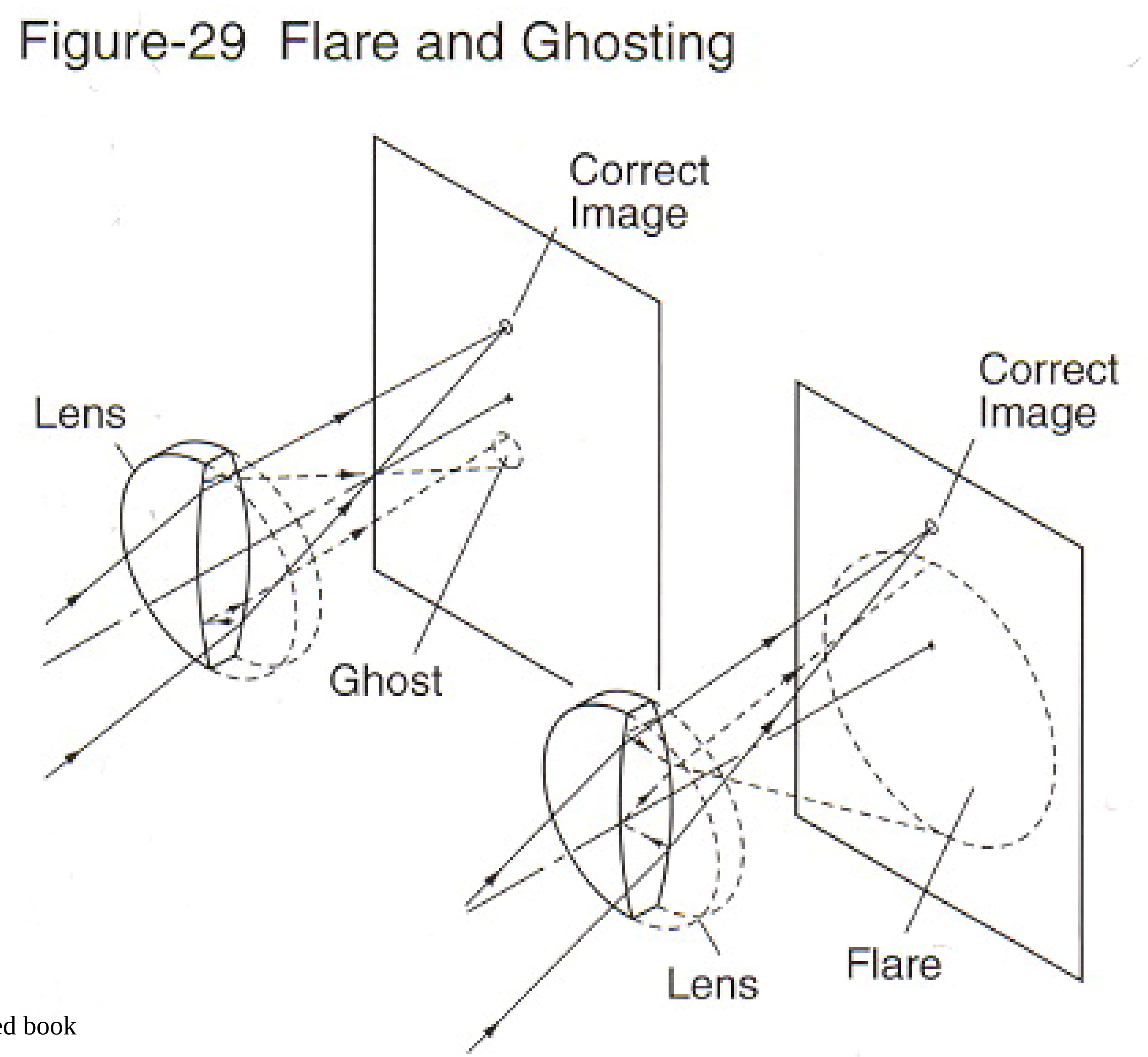
Example of flare "bug"

- **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

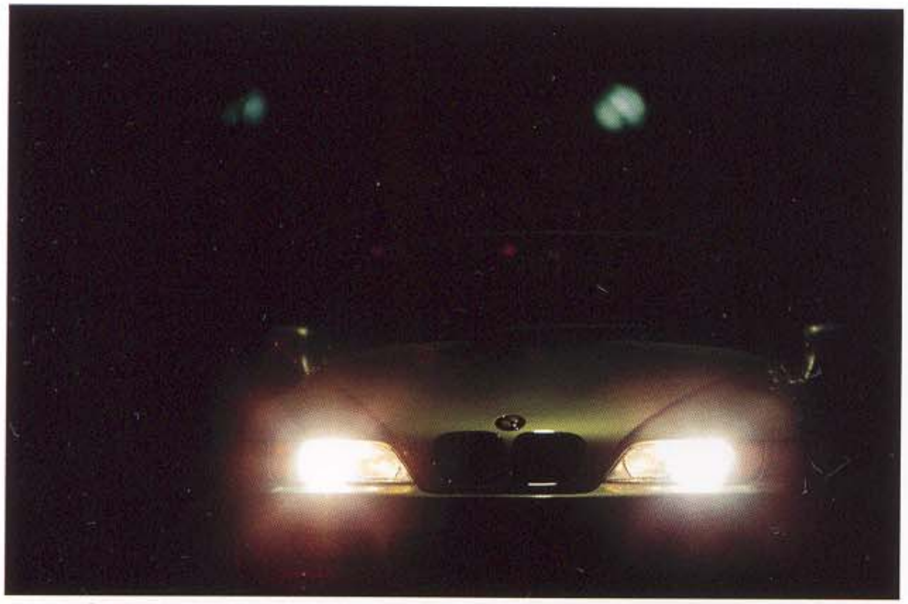
Flare and Ghosting



source: canon red book

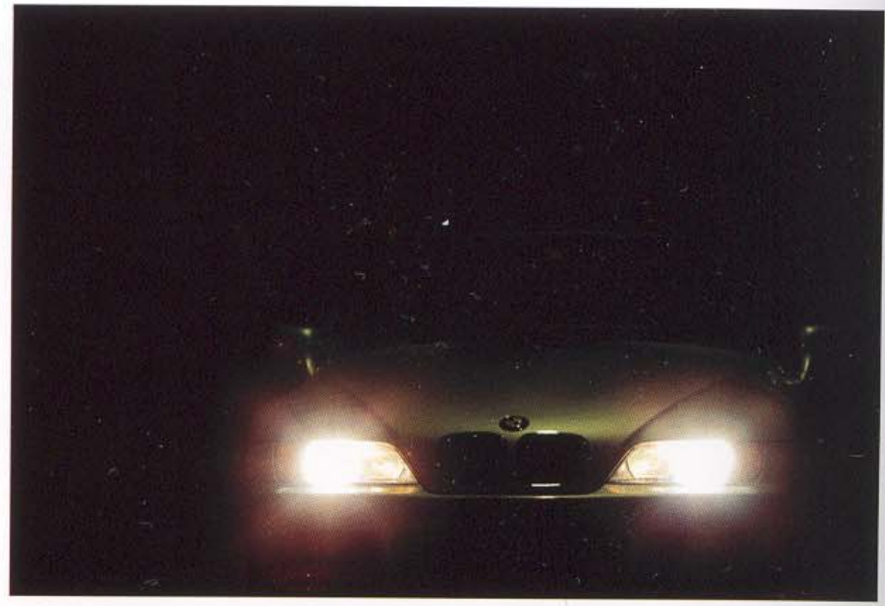
Flare/ghosting special to digital

For flat protective glass

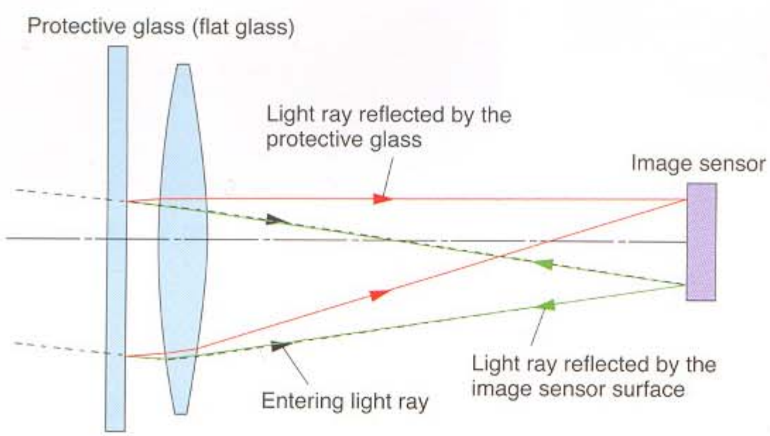


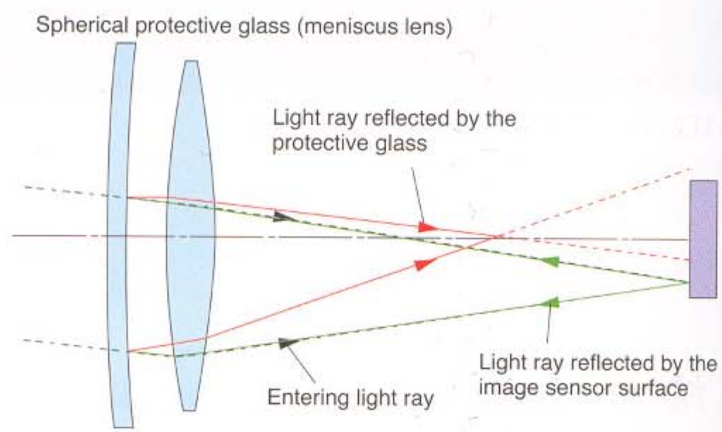
In lenses employing flat protective glass, a reflection occurs between the image sensor and the protective glass, which causes the subject to be photographed in a position different from the actual position.

For a meniscus lens



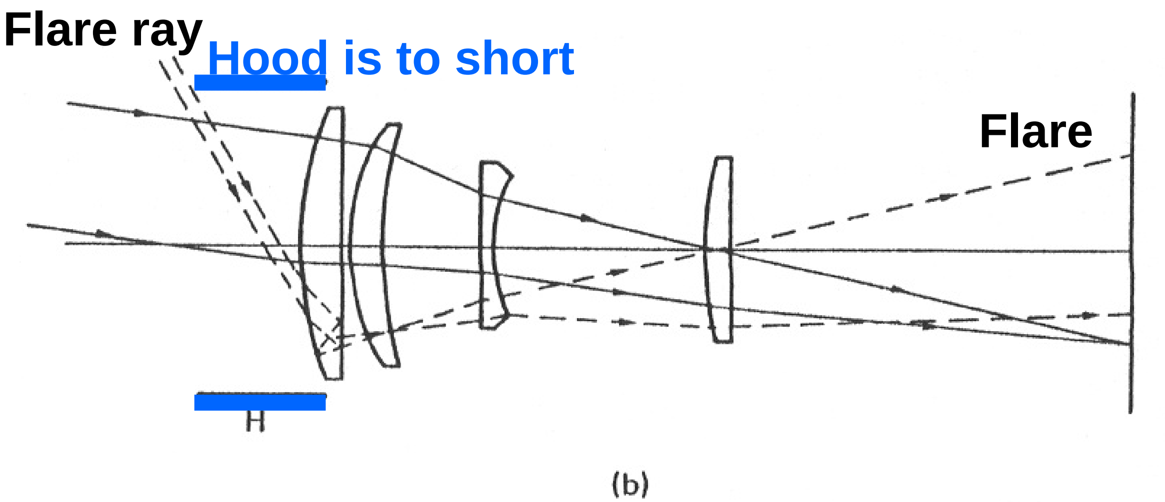
In lenses employing a meniscus lens, no reflection like that seen to the left occurs.

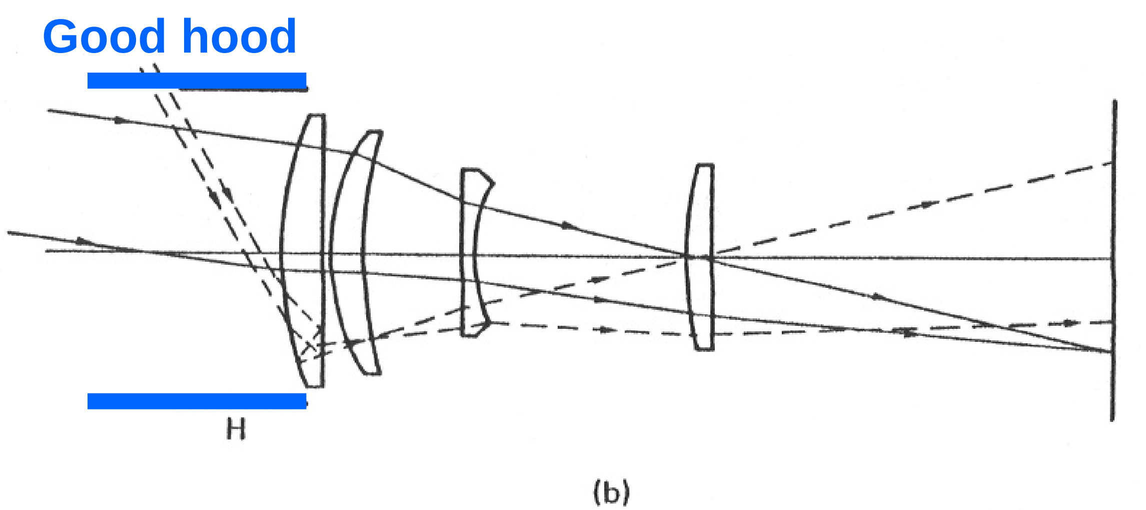




source: canon red book

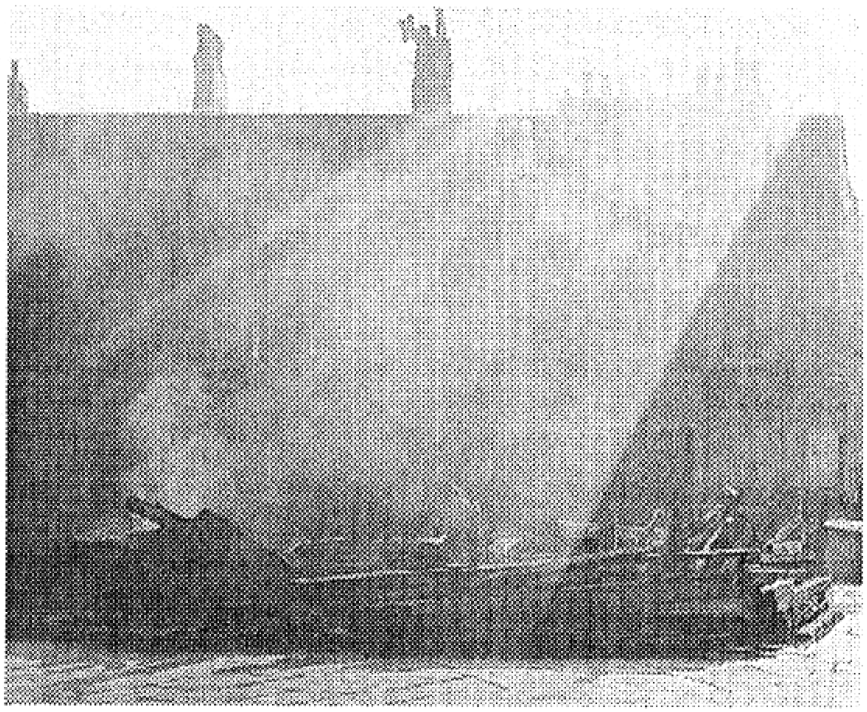
Use a hood! (and a good one)



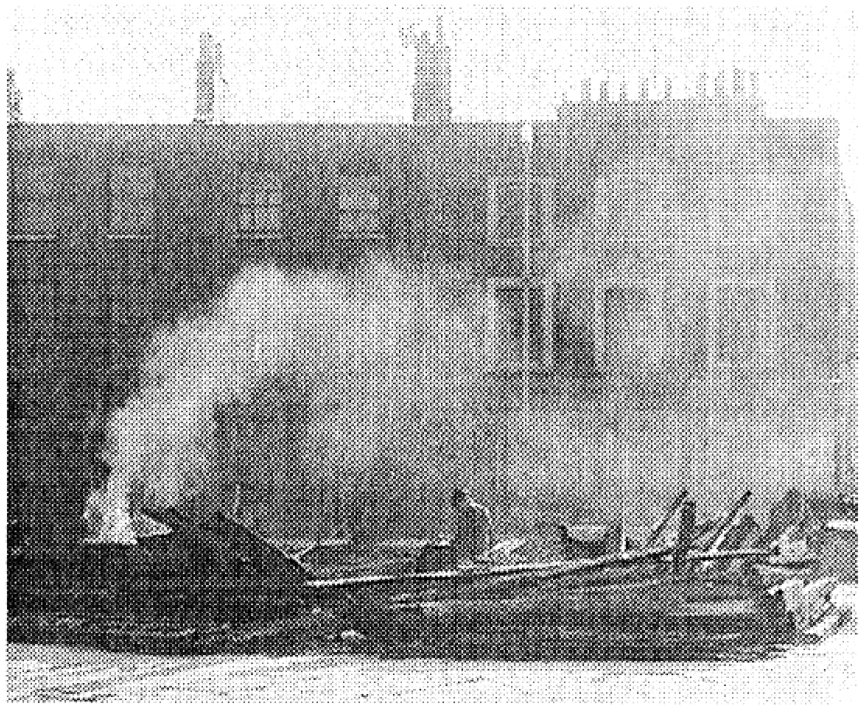


Adapted from Ray's Applied Photographic Optics

Lens hood



(a)



(b)

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

From Ray's Applied Photographic Optics

Coating

- **Use destructive interferences**
- **Optimized for one wavelength**

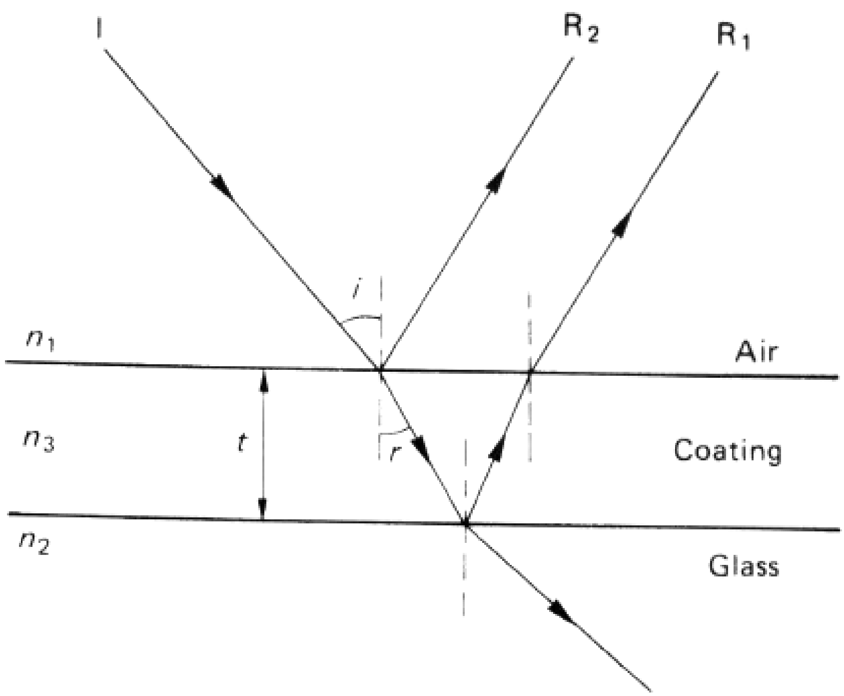


Figure 5.7 An anti-reflection coating on glass using the principle of destructive interference of light between reflections R_1 and R_2

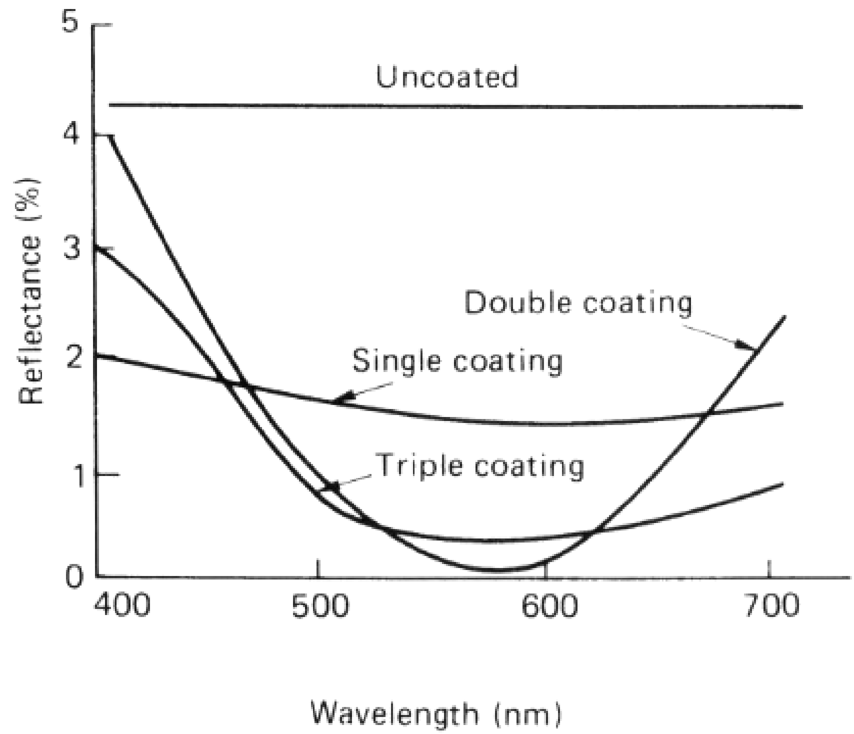
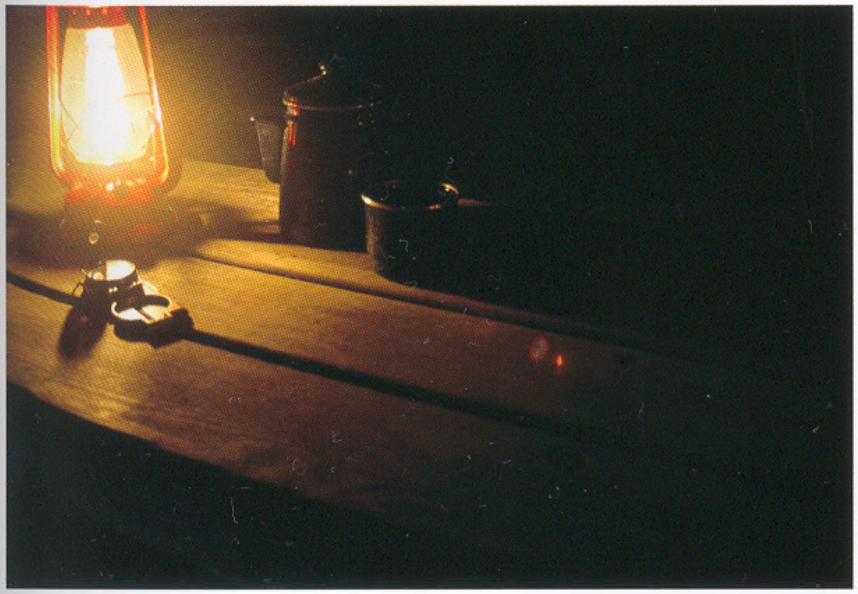


Figure 5.8 The effects on surface reflection of various types of anti-reflection coatings as compared with uncoated glass (for a single lens surface at normal incidence)

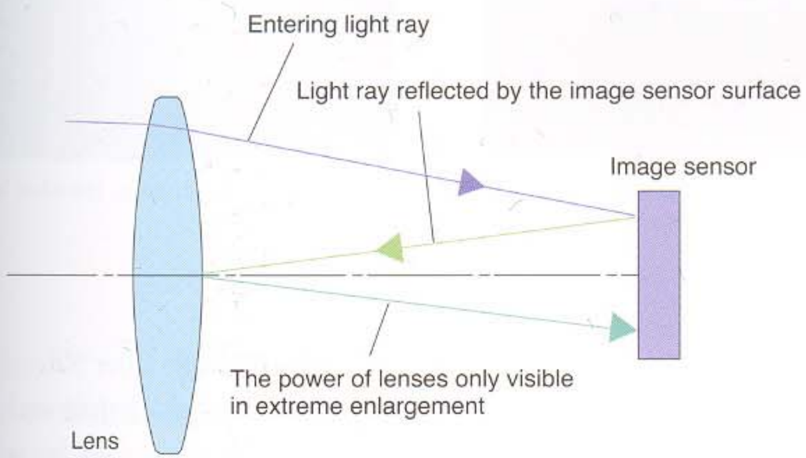
From "The Manual of Photography" Jacobson et al

Coating for digital

Lens for which the lens shape and coating have not been optimized

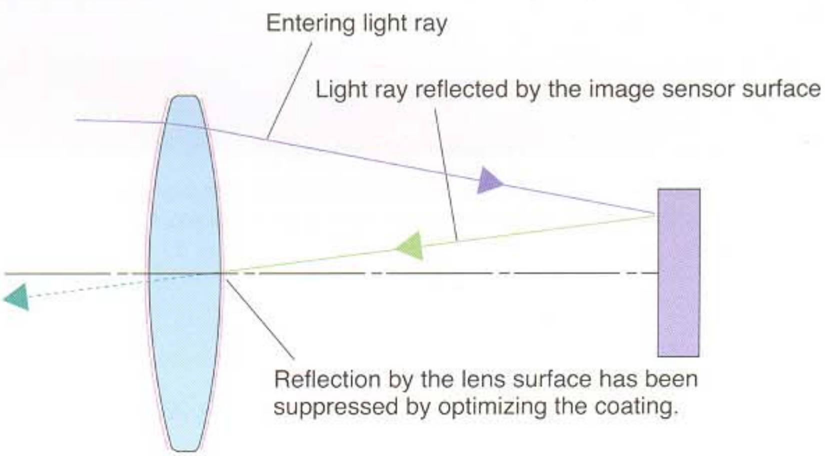


Flaring and ghosting occurs with lens for which the lens shape and coating have not been optimized.



Lens for which the lens shape and coating have been optimized

Flaring and ghosting are suppressed with lens for which the lens shape and coating have been optimized.

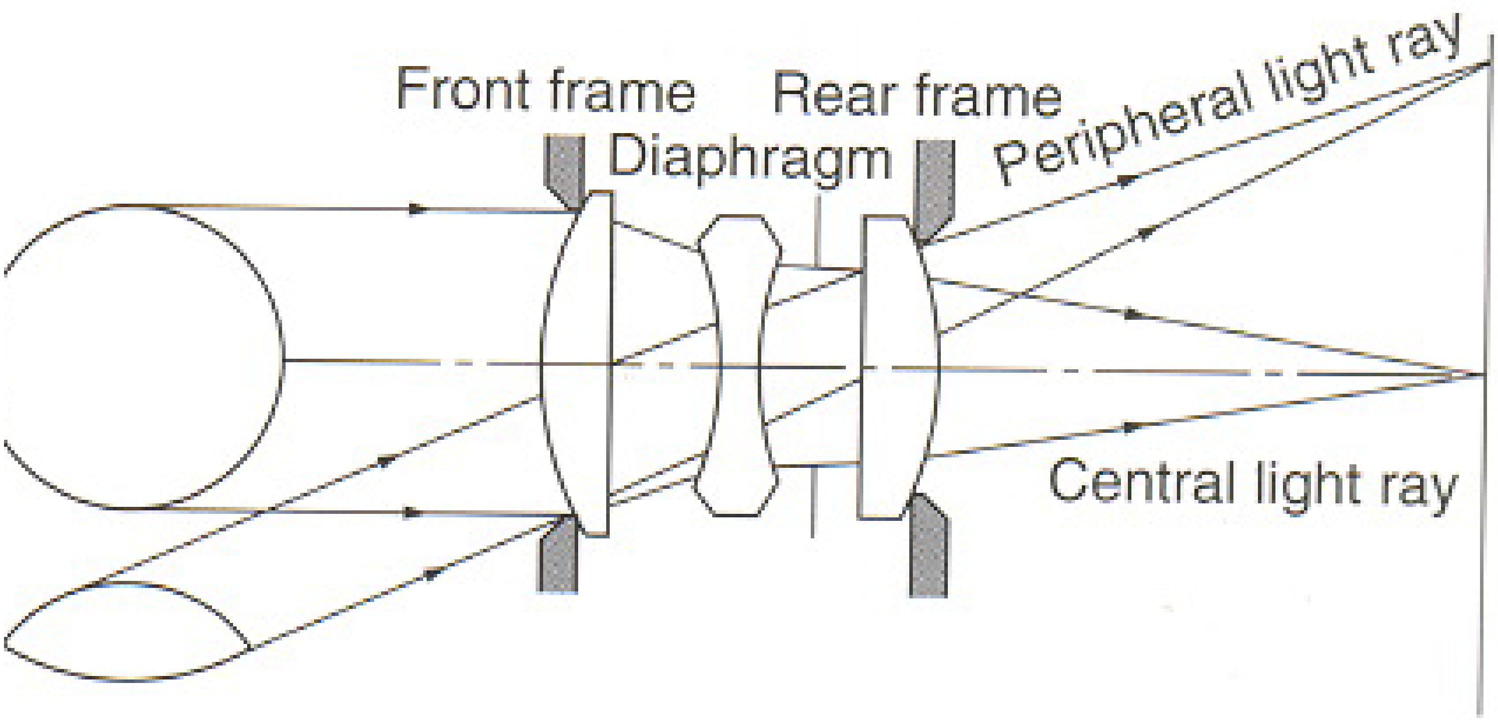


source: canon red book

Vignetting

- **The periphery does not get as much light**

Figure-28 Vignetting



source: canon red book

Vignetting

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

vignetting

no vignetting

Lens design

Optimization software

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

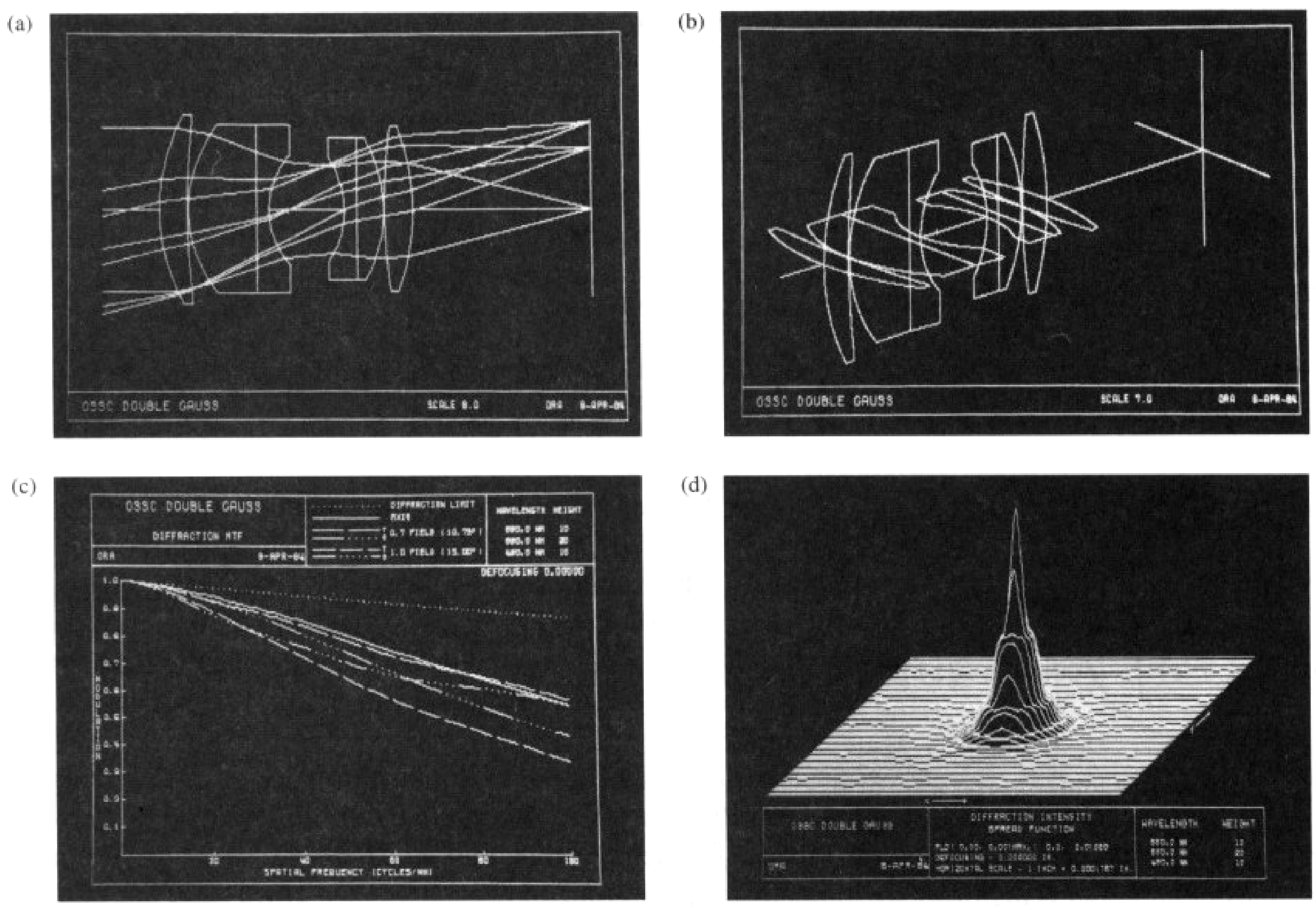


Figure 11.50 An example of the kind of lens design information available via computer techniques. (Photos courtesy Optical Research Associates.)

From Hecht's Optics

Lens design, ray tracing

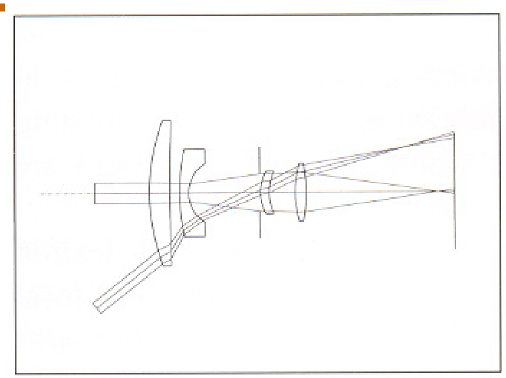


Figure-5

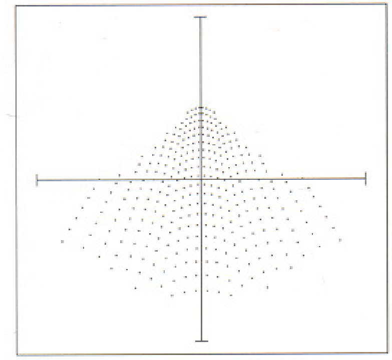


Figure-8

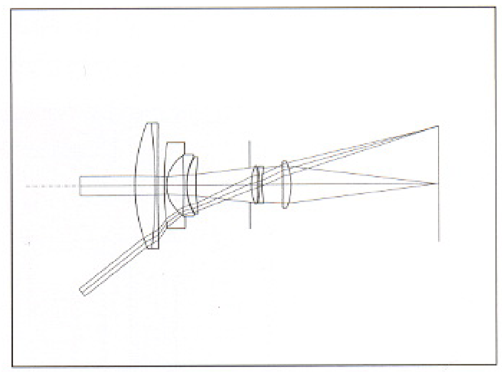


Figure-6

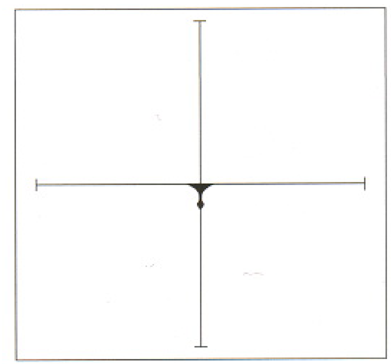


Figure-9

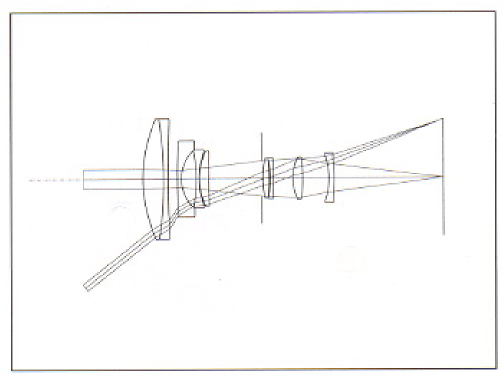


Figure-7

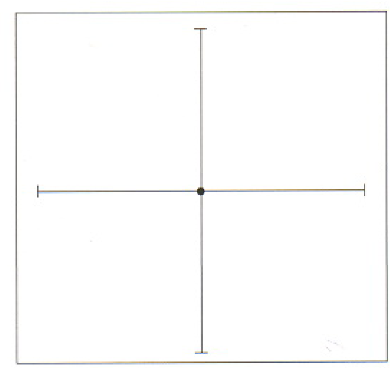


Figure-10

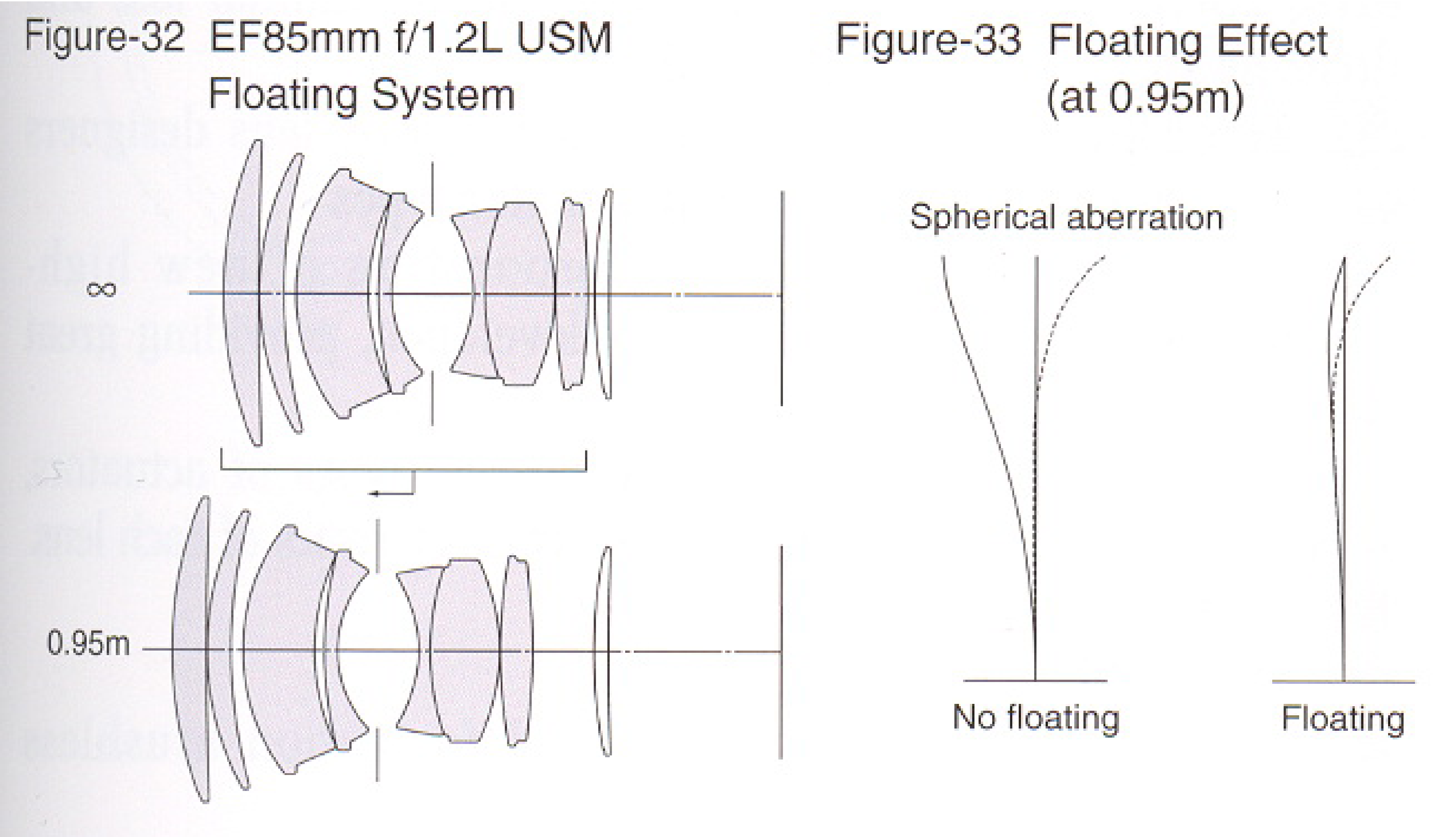
source: canon red book

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**

Floating elements

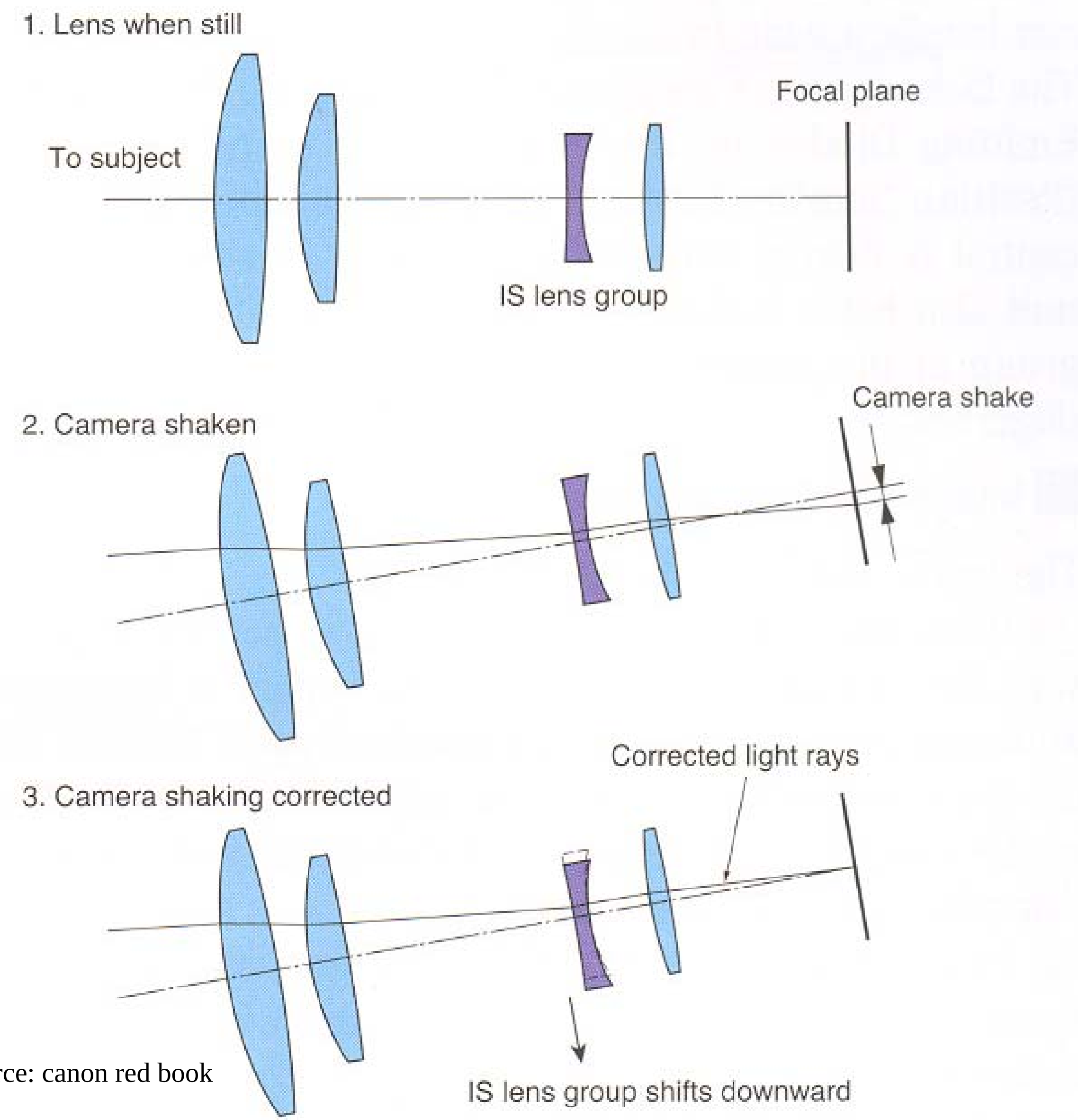
- **Move with focus to optimize response (but are not responsible for focusing)**



source: canon red book

Image stabilization

Image stabilization



source: canon red book

Photo-21 Shake-detecting gyro sensor

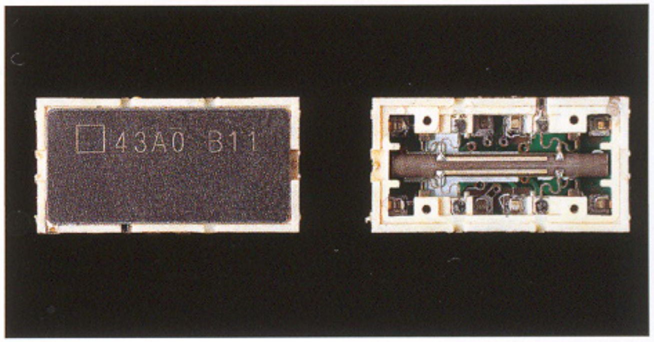
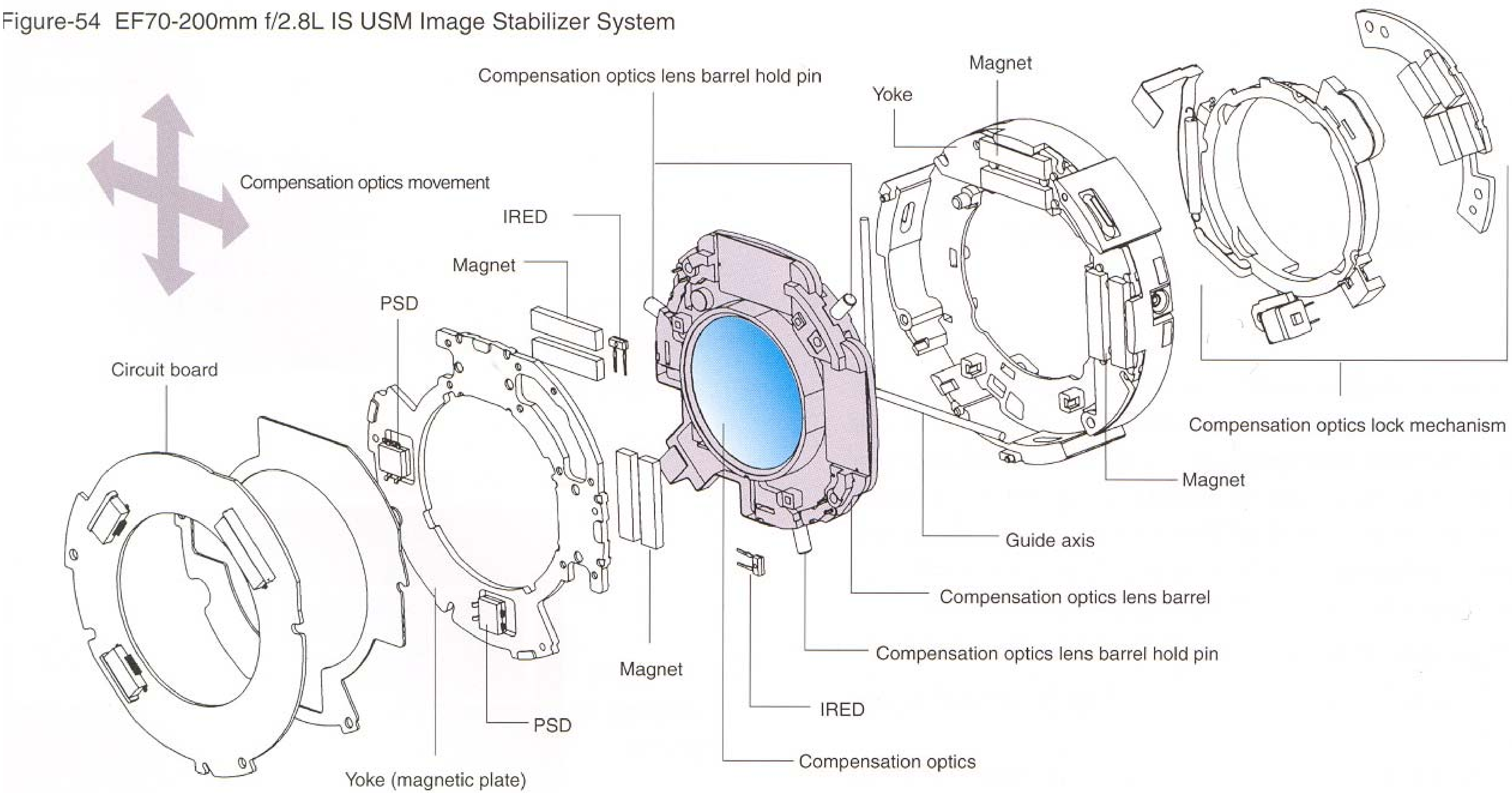
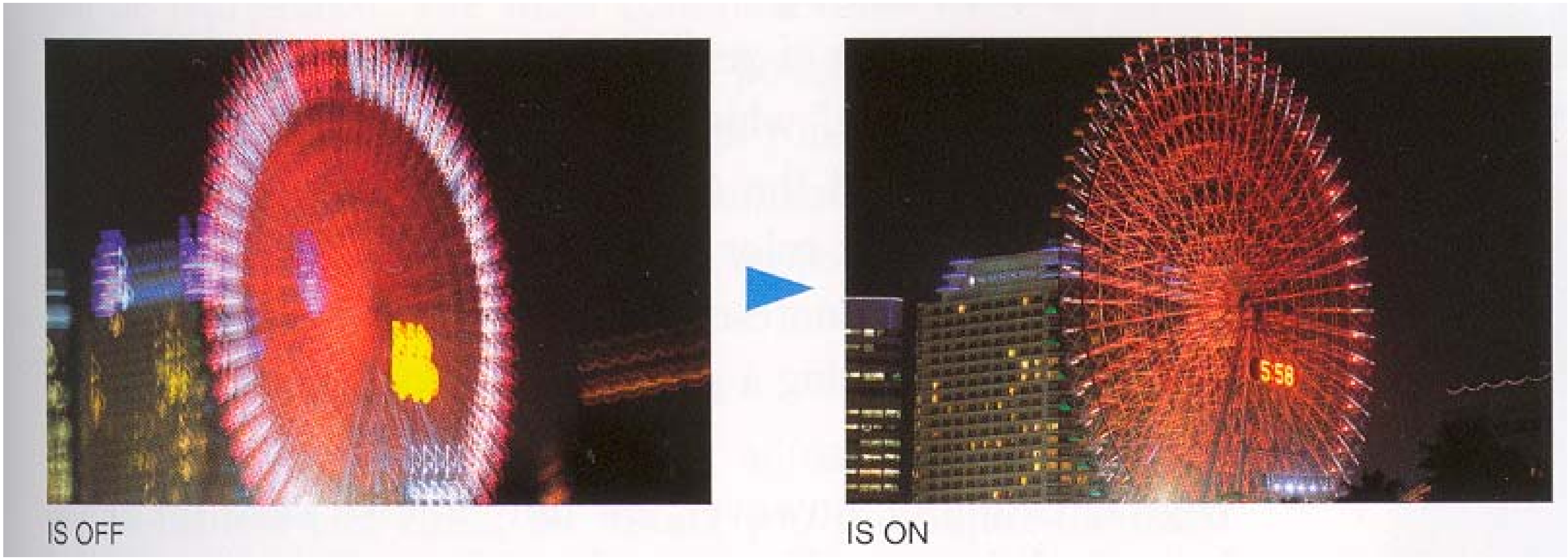


Image stabilization



source: canon red book

Image stabilization



source: canon red book

1000mm, 1/100s, monopod, IS

CSAIL

Different versions

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

6.088 Digital and Computational Photography
6.882 Advanced Computational Photography

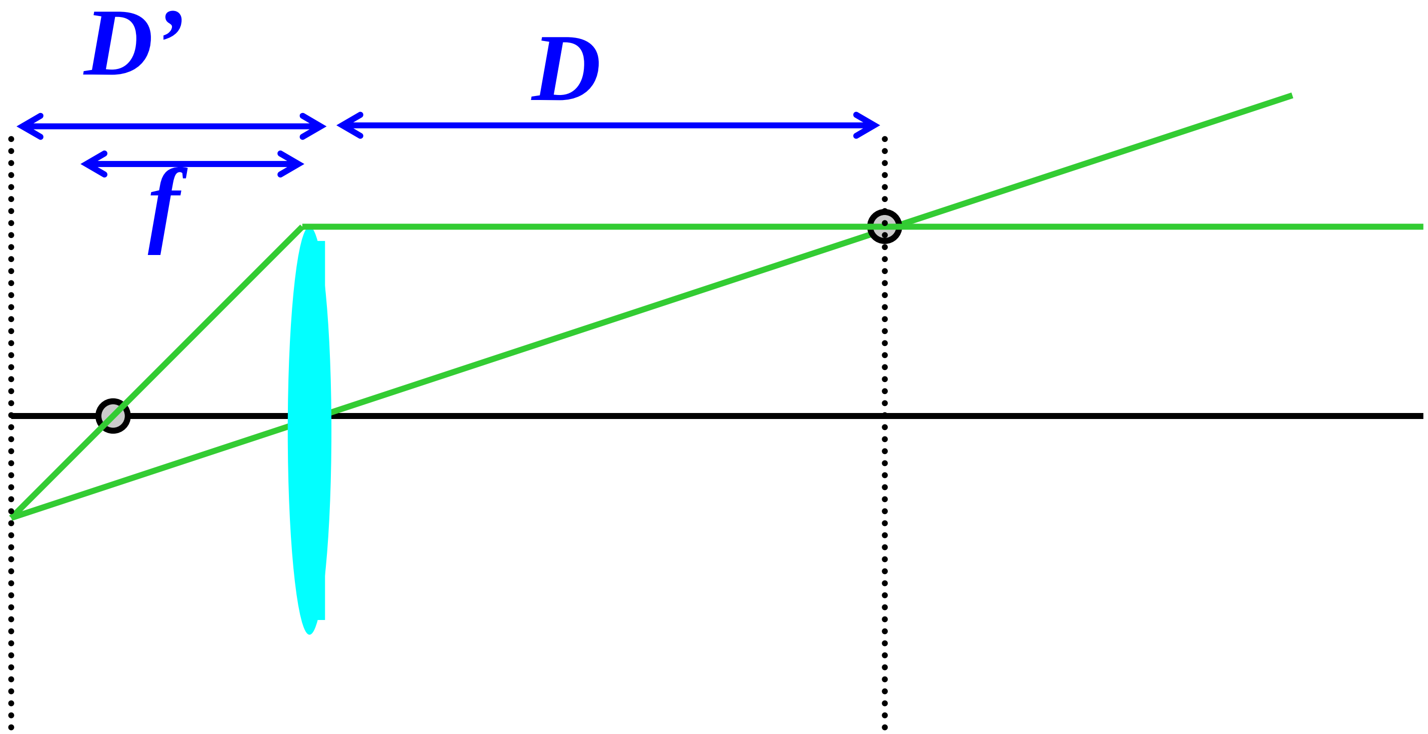
Focus and Depth of Field

Frédo Durand
MIT - EECS

Focusing

- **Move film/sensor**
- **Thin-lens formula**

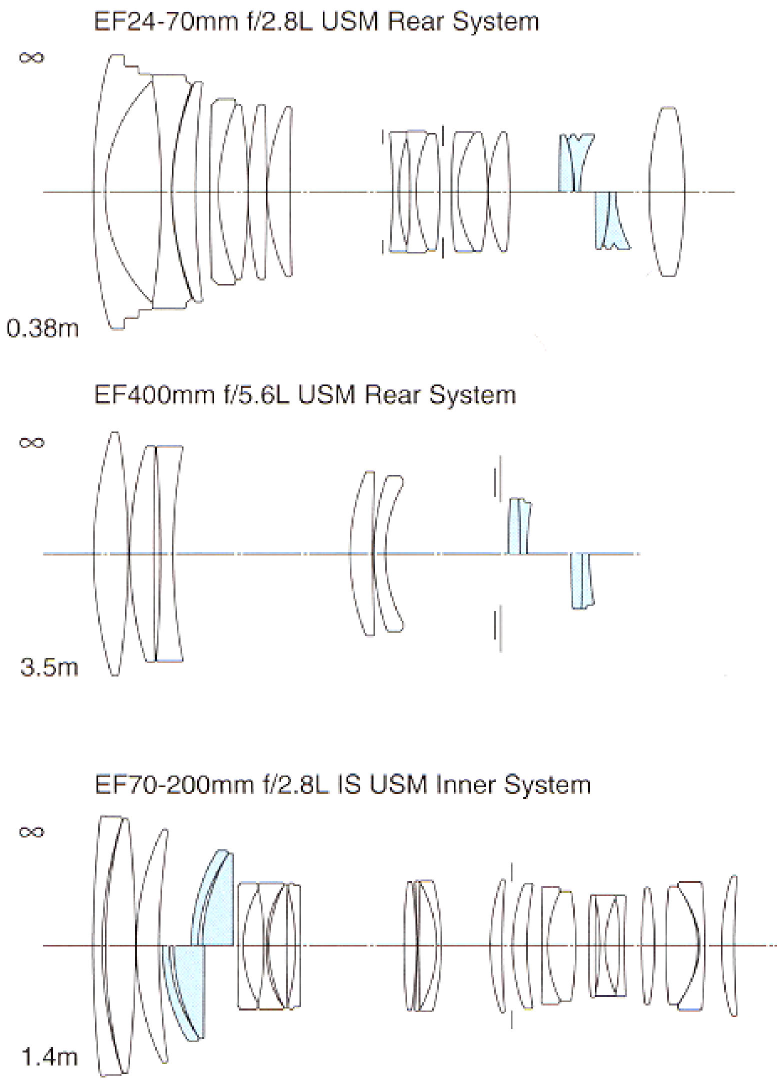
$$\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}$$



In practice, it's a little more complex

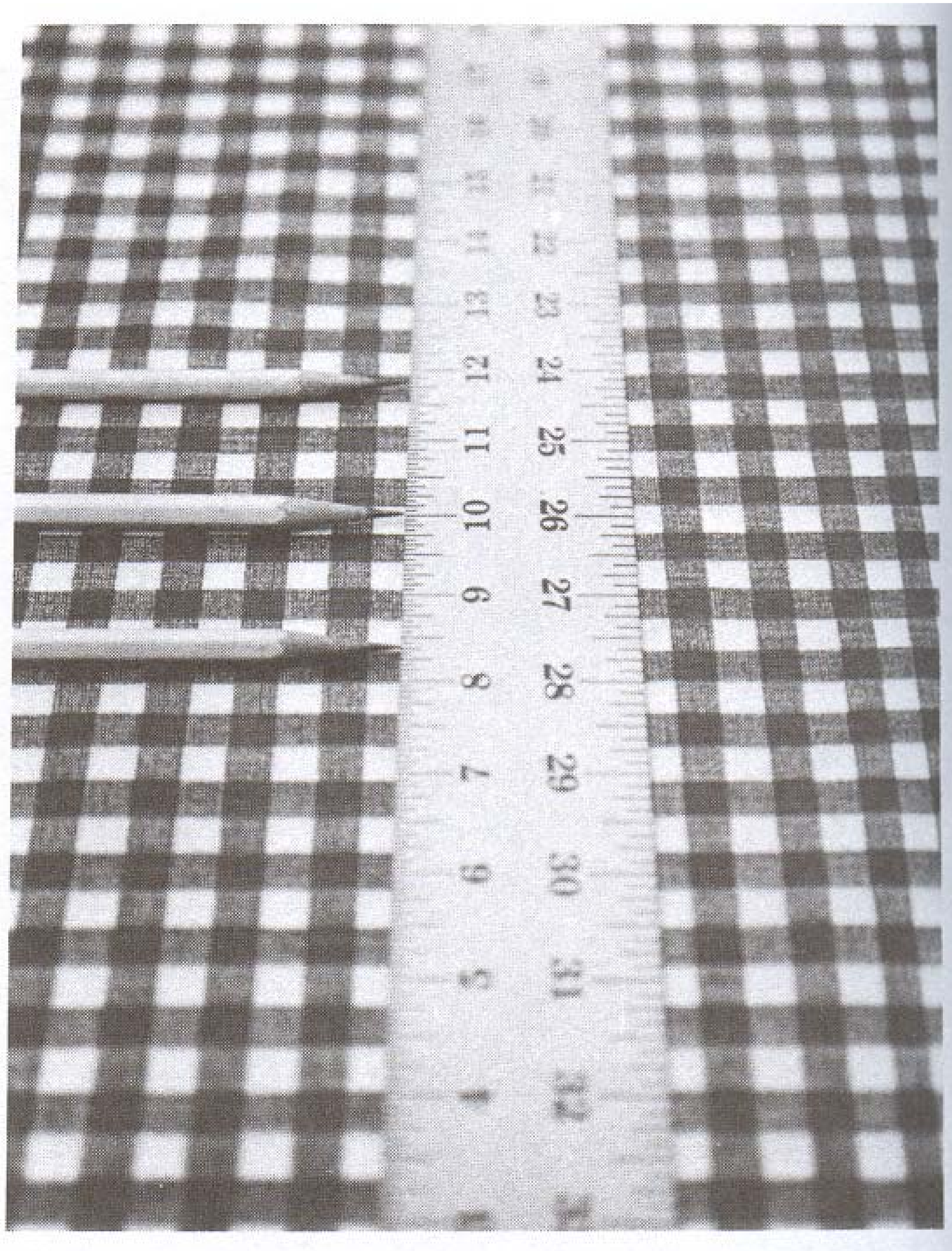
- **Various lens elements can move inside the lens**
  – Here in blue

Figure-29 Rear and Inner Focusing Systems



Source: Canon red book.

Defocus & Depth of field



23
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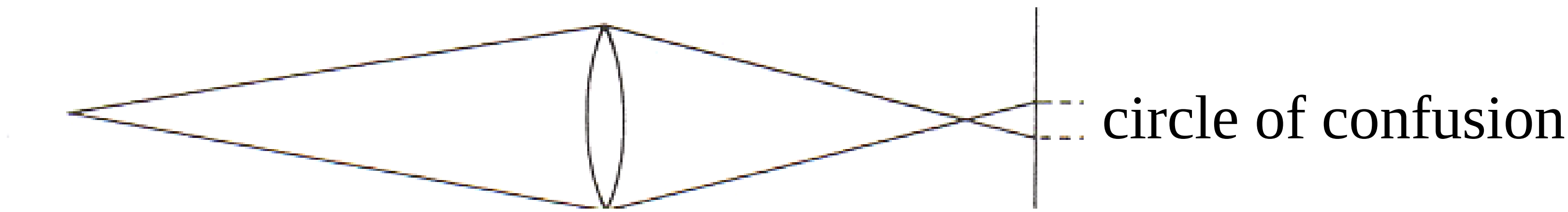
31

Circle of confusion



From Basic Photographic Materials and Processes, Stroebel et al.

Depth of focus

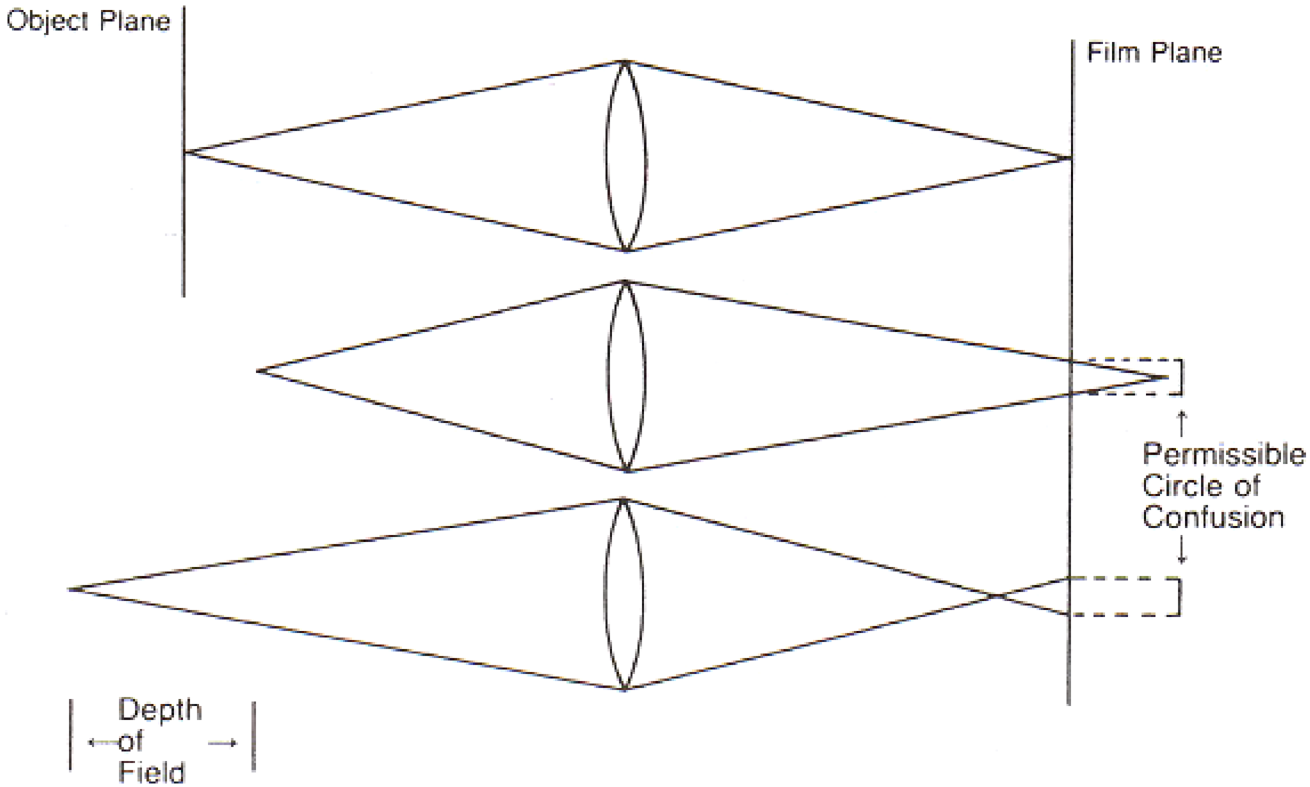


Figure 5–33A Depth of field is the range of distances within which objects are imaged with acceptable sharpness. At the limits, object points are imaged as permissible circles of confusion.

From Basic Photographic Materials and Processes, Stroebel et al.

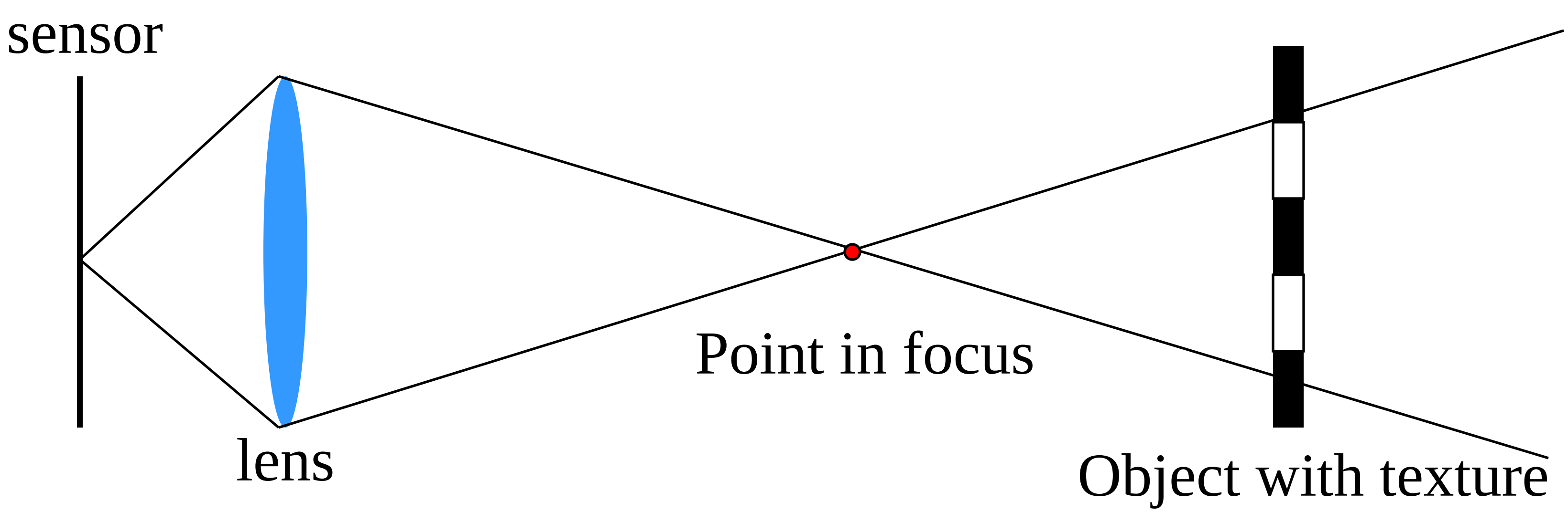
Size of permissible circle?

- **Assumption on print size, viewing distance, human vision**
  – Typically for 35mm film: diameter = 0.02mm

- **Film/sensor resolution (8μ photosites for high-end SLR)**
- **Best lenses are around 60 lp/mm**
- **Diffraction limit**

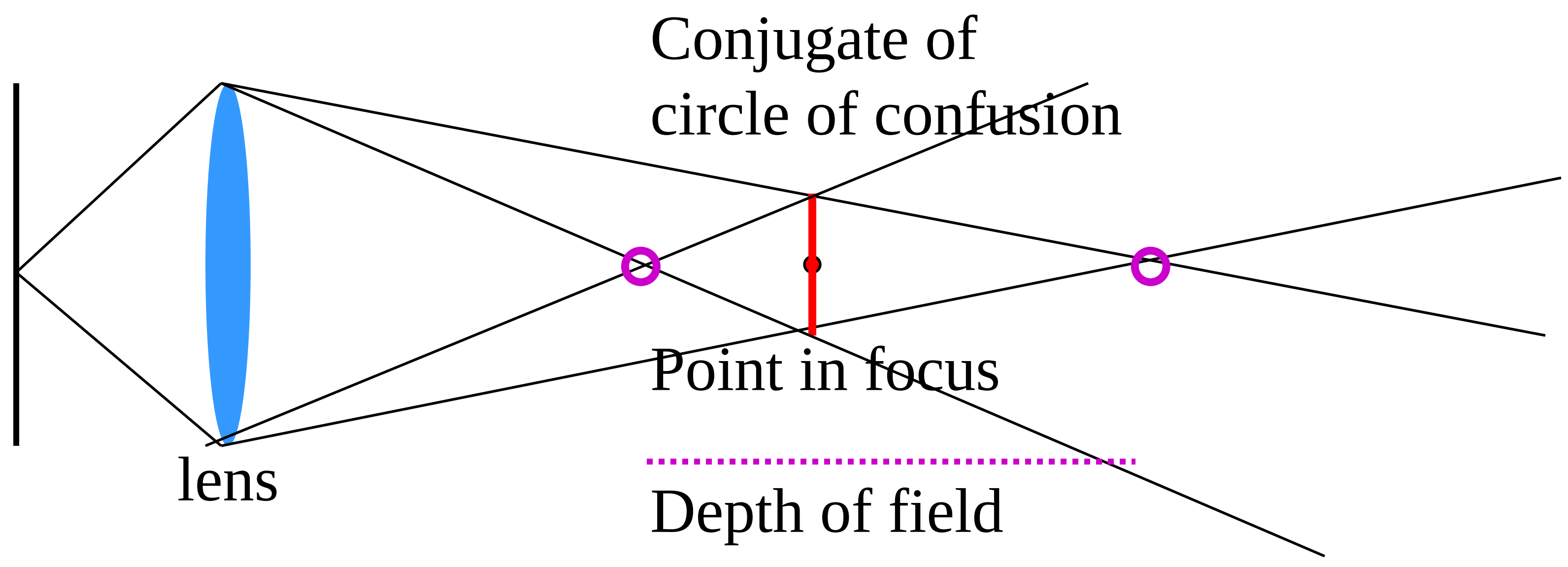
Depth of field: Object space

- **Simplistic view: double cone**
  - Only tells you about the value of one pixel
  - Things are in fact a little more complicated to asses circles of confusion across the image
  - We're missing the magnification factor (proportional to 1/distance and focal length)



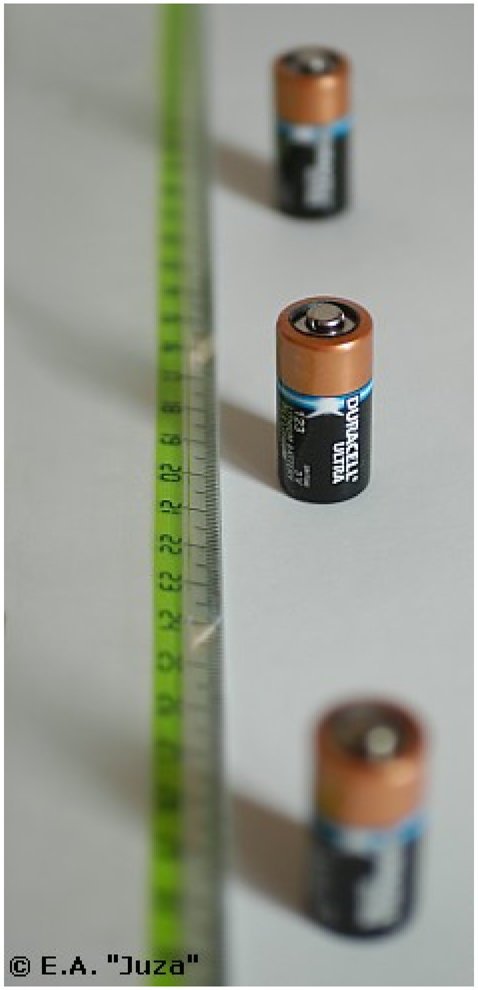
Depth of field: more accurate view

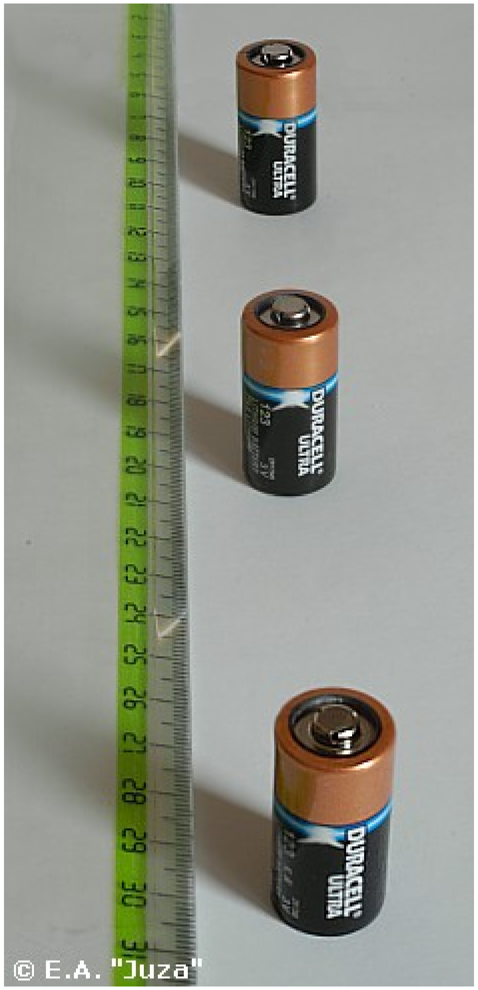
- **Backproject the image onto the plane in focus**
  - Backproject circle of confusion
  - Depends on *magnification factor*
- **Depth of field is slightly asymmetrical**



DoF & aperture

- **http://www.juzaphoto.com/eng/articles/depth_of_field.htm**



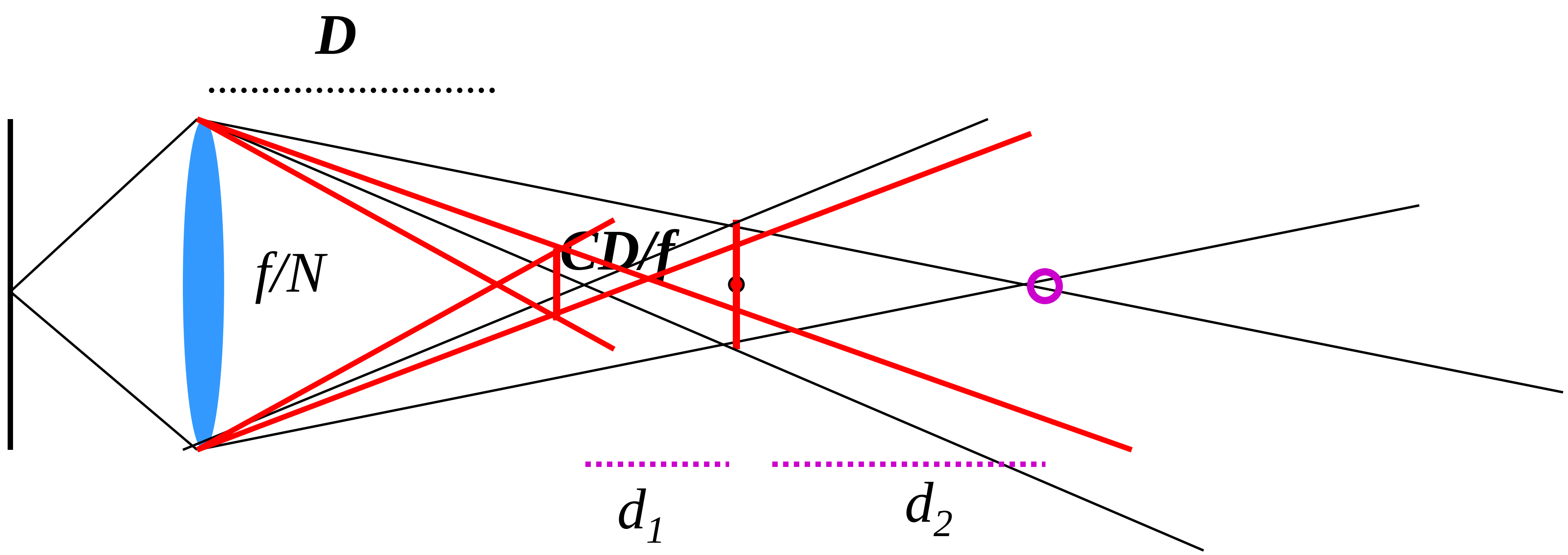


f/2.8 f/32

Depth of field and focusing distance

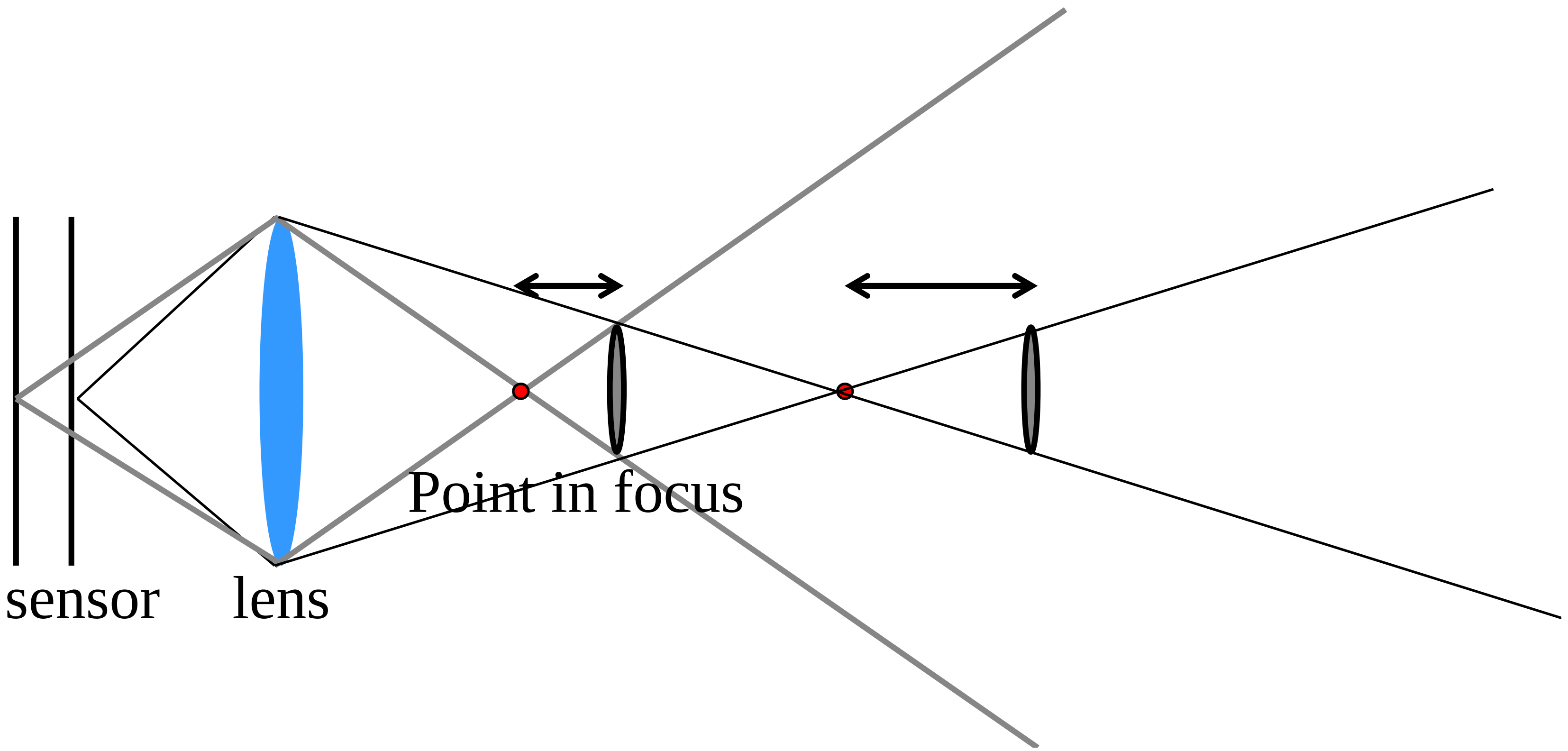
- **Quadratic (bad news for macro) (but careful, our simplifications are not accurate for macro)**

$$d = \frac{2NCD^2}{f^2}$$

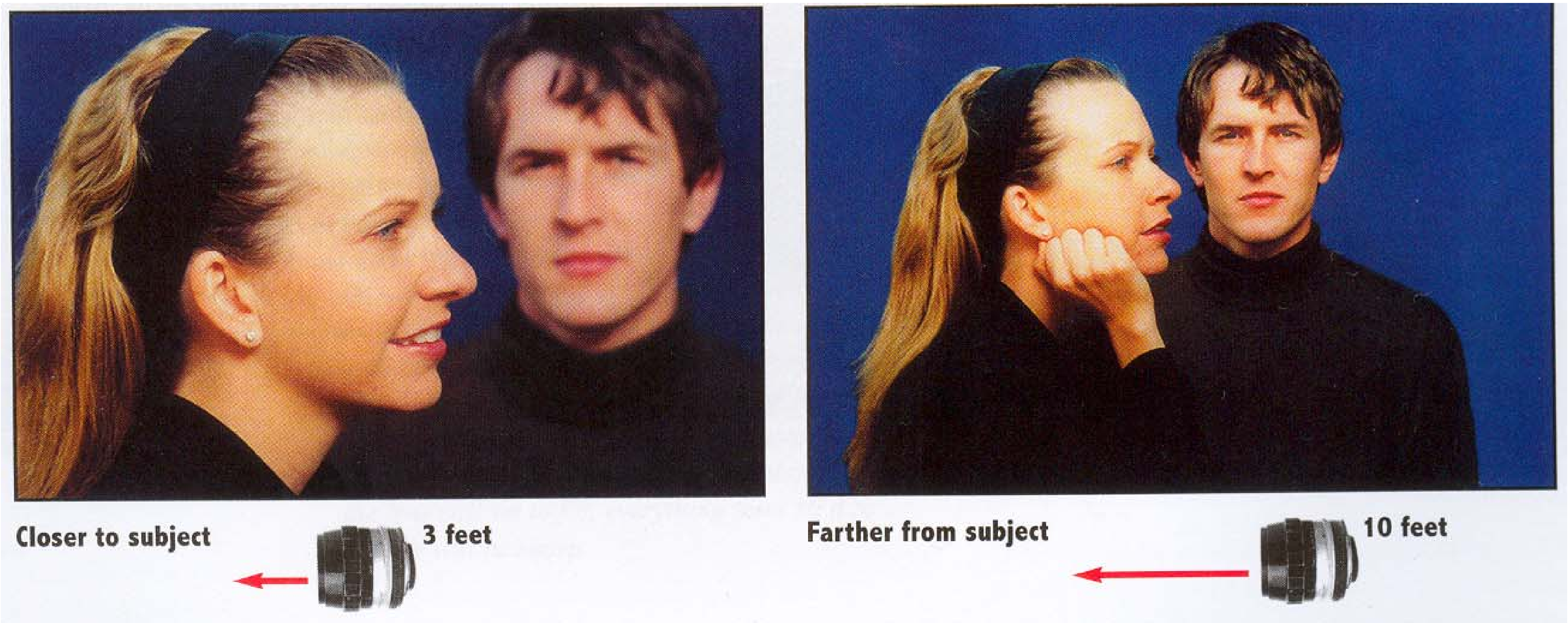


Double cone perspective

- **Seems to say that relationship is linear**
- **But if you add the magnification factor, it's actually quadratic**



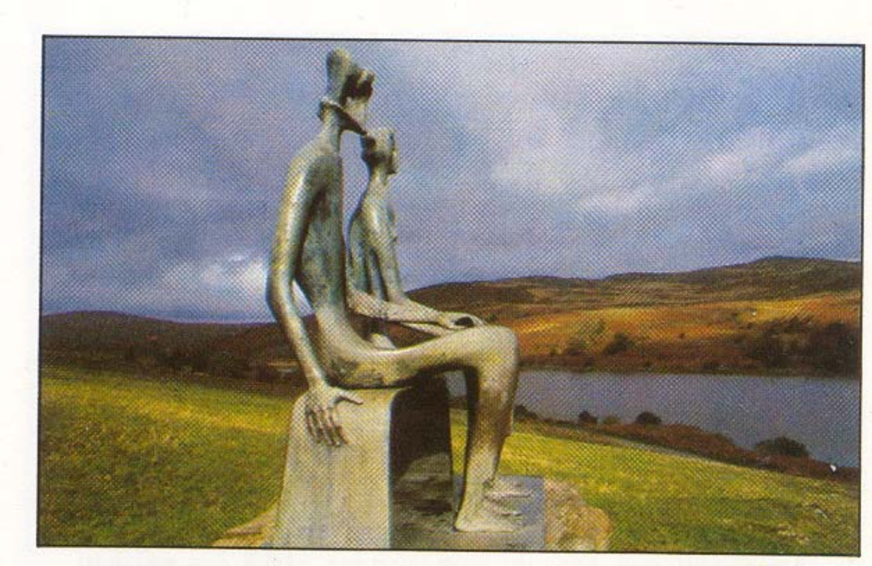
Depth of field & focusing distance



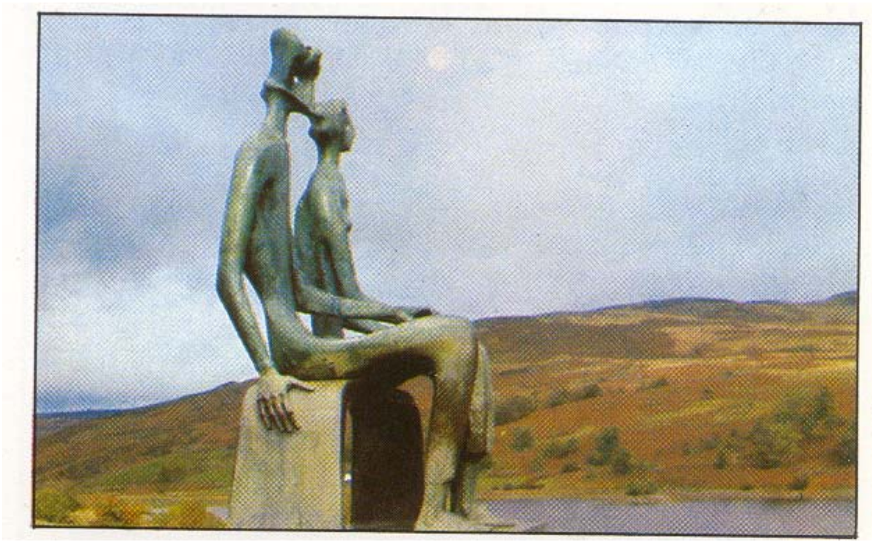
From Photography, London et al.

Depth of field & focal length

- **Recall that to get the same image size, we can double the focal length and the distance**
- **Recall what happens to physical aperture size when we double the focal length for the same f number?**
  - It is doubled



24mm

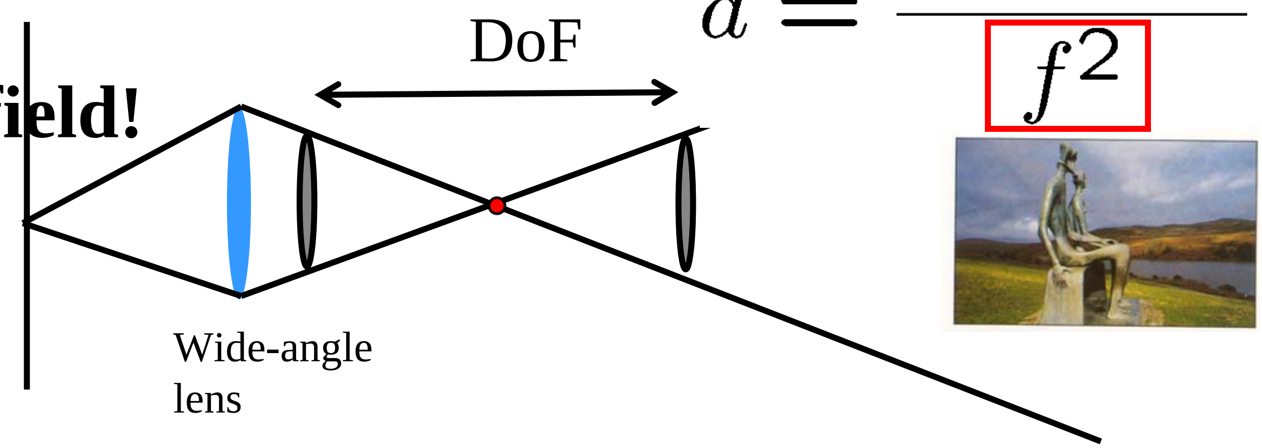


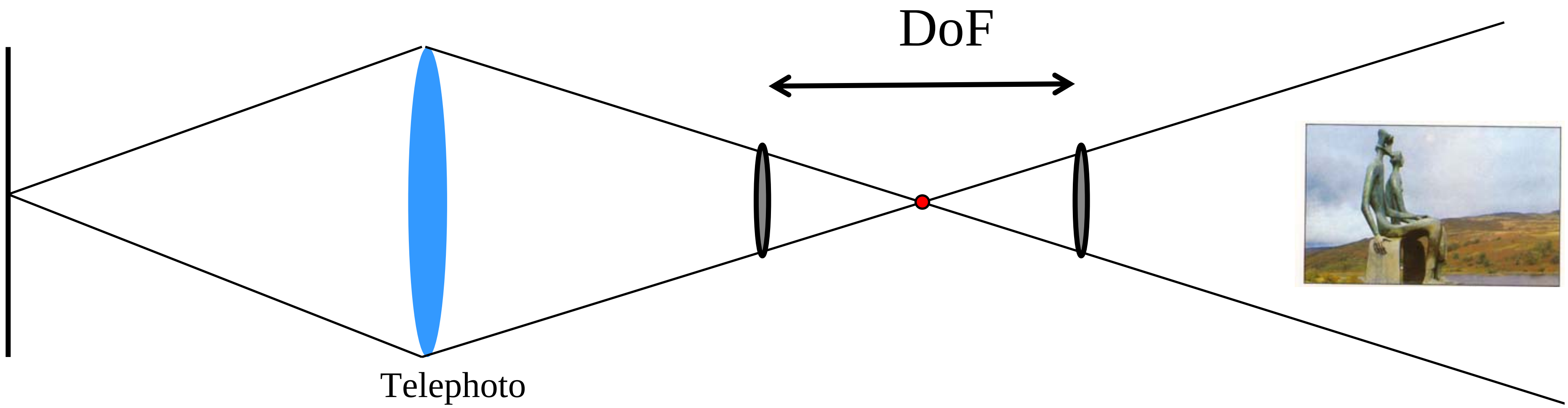
50mm

Depth of field & focal length

- **Same image size (same magnification) same f number**
- **Same depth of field!**

$$d = \frac{2NCD^2}{f^2}$$





DoF & Focal length

- **http://www.juzaphoto.com/eng/articles/depth_of_field.htm**

50mm f/4.8

200mm f/4.8
(from 4 times farther)

See also http://luminous-landscape.com/tutorials/dof2.shtml

Important conclusion

- For a given image size and a given f number, the depth of field (in object space) is the same.
- Might be counter intuitive.

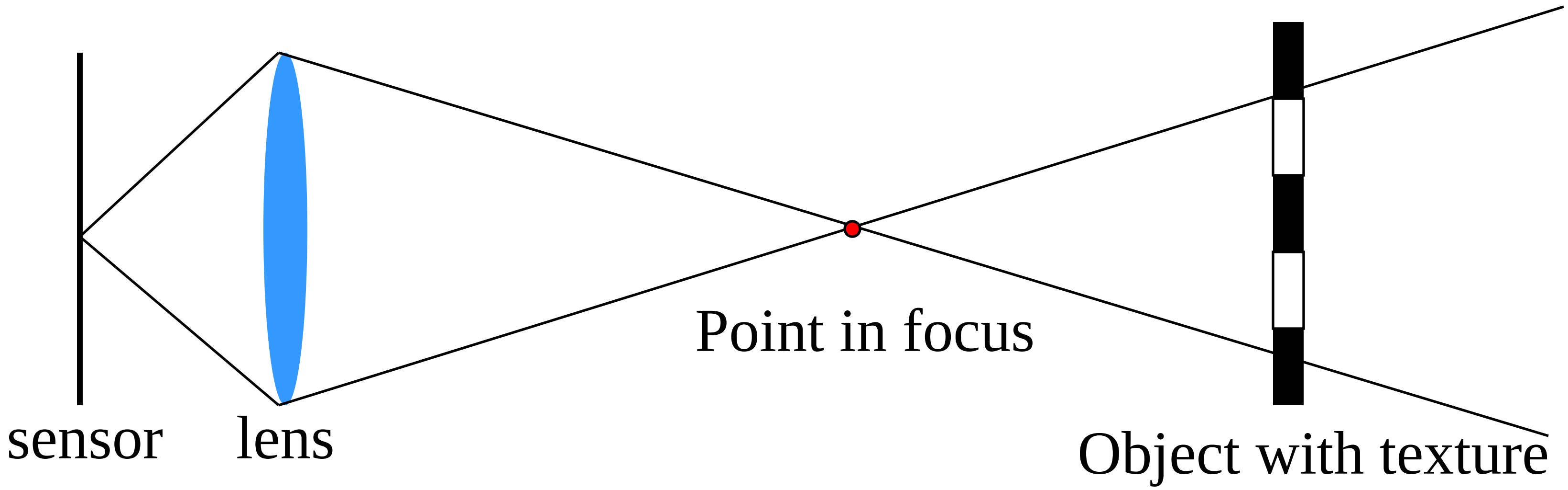
- Very useful for macro where DoF is critical. You can change your working distance without affecting depth of field

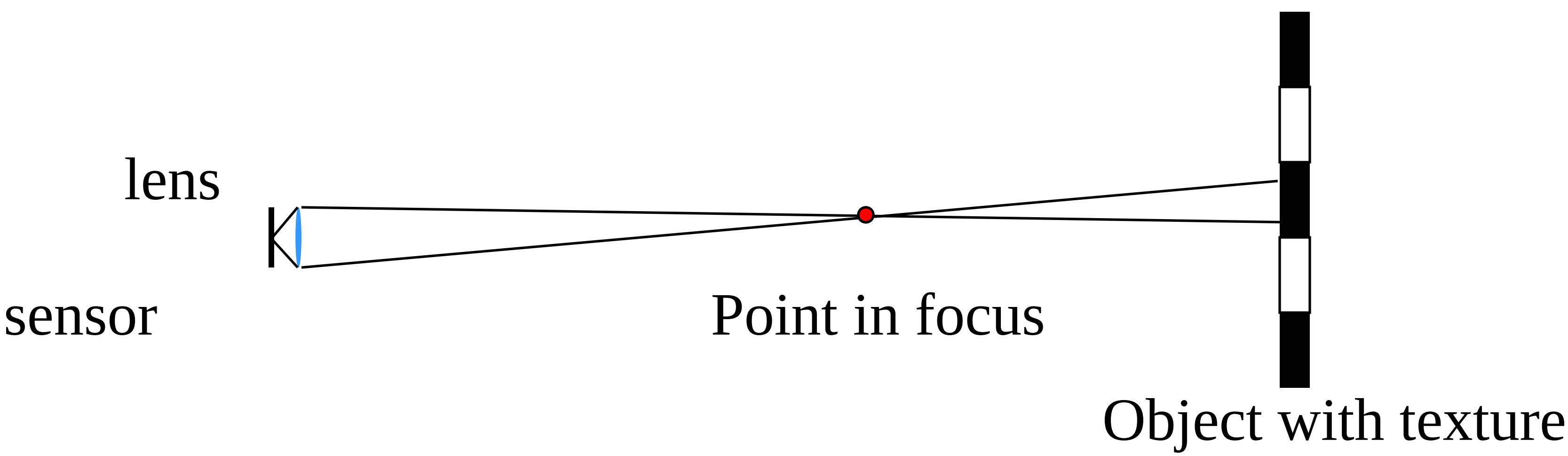
- Now what happens to the background blur far far away?

Sensor size

Depth of field

- **It's all about the size of the lens aperture**





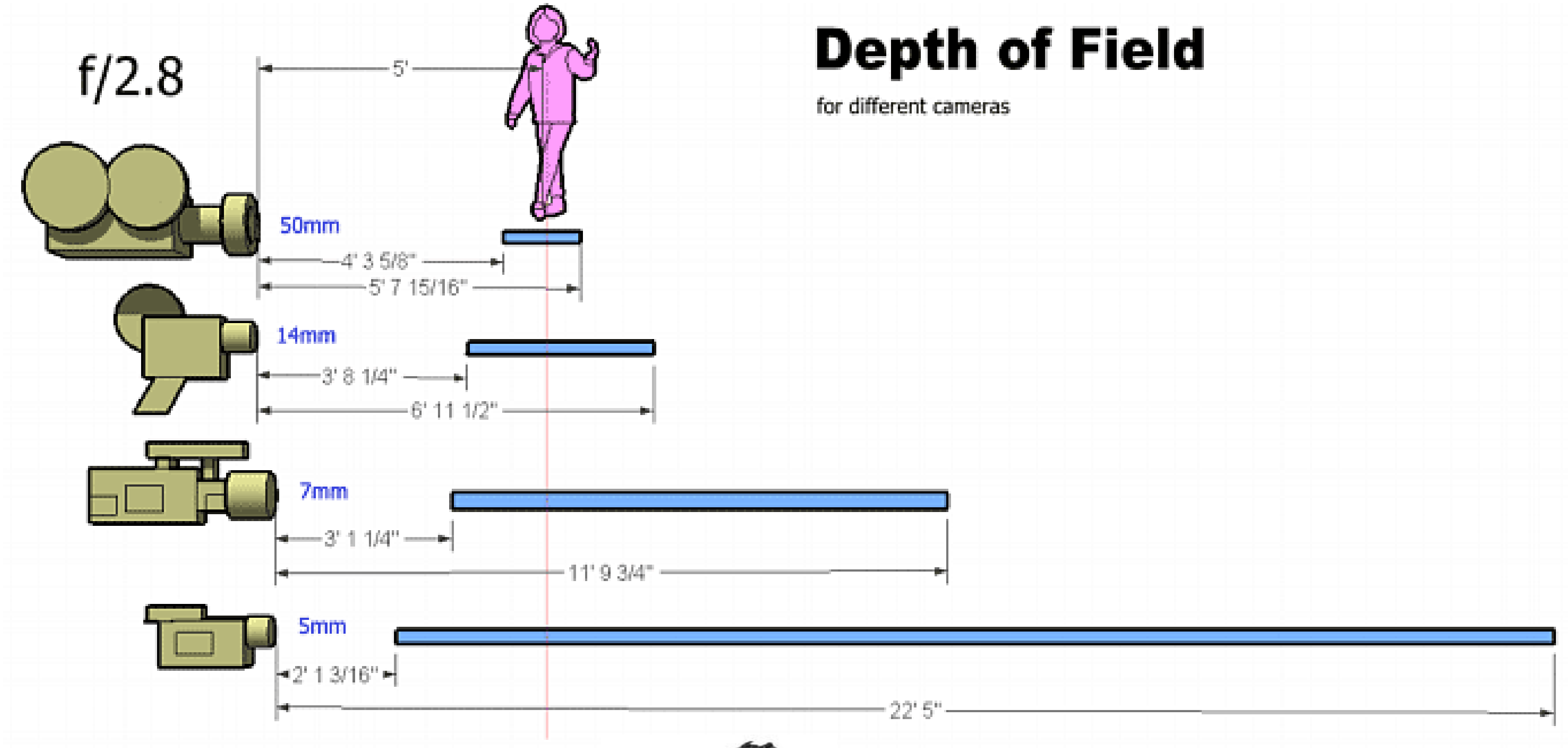
Equation

- **Smaller sensor**
  - smaller C
  - smaller f
- **But the effect of f is quadratic**

$$d = \frac{2NCD^2}{f^2}$$

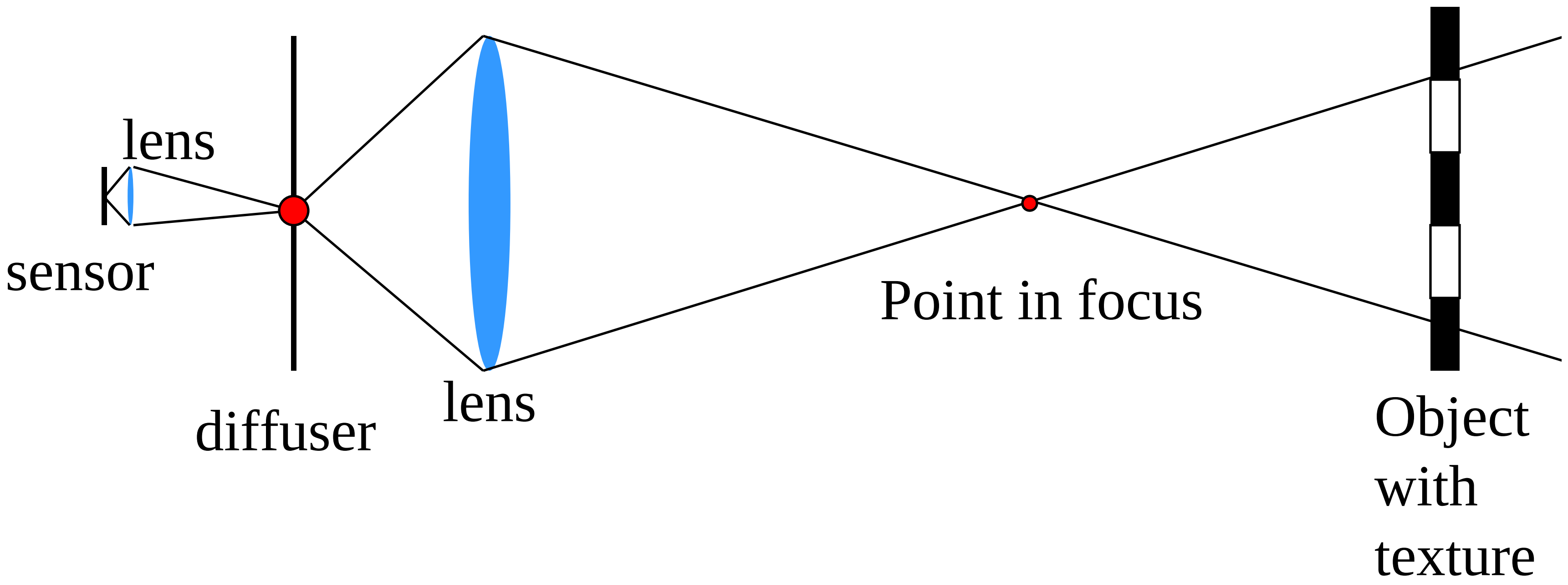
Sensor size

- http://www.mediachance.com/dvdlab/dof/index.htm



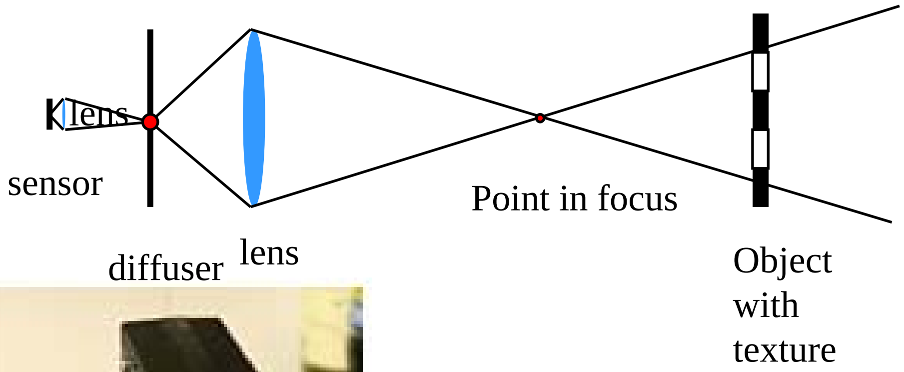
The coolest depth of field solution

- http://www.mediachance.com/dvdlab/dof/index.htm
- **Use two optical systems**



The coolest depth of field solution

- http://www.mediachance.com/dvdlab/dof/index.htm



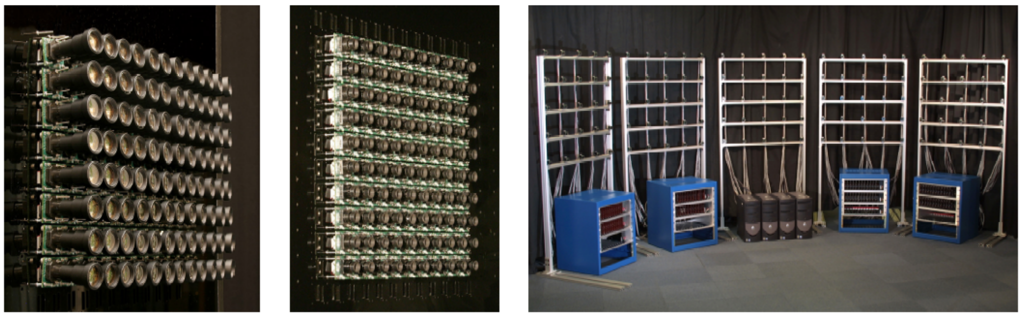
Seeing through occlusion

Seeing beyond occlusion

- Photo taken through zoo bars
- Telephoto at full aperture
- The bars are so blurry that they are invisible

Synthetic aperture

- **Stanford Camera array (Willburn et al. http://graphics.stanford.edu/papers/CameraArray/)**



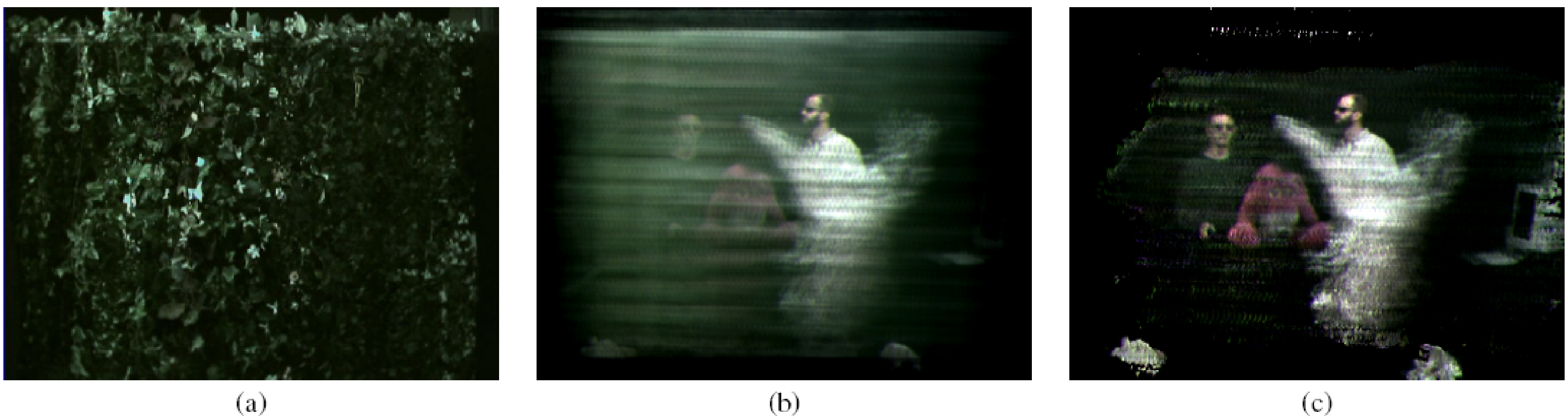


Figure 11: Matted synthetic aperture photography. (a) A sample image from one of 90 cameras used for this experiment. (b) The synthetic aperture image focused on the plane of the people, computed by aligning and averaging images from all 90 cameras as described in the text. (c) Suppressing contributions from static pixels in each camera yields a more vivid view of the scene behind the occluder. The person and stuffed toy are more clearly visible.

Autofocus

How would you build an Auto Focus?

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/

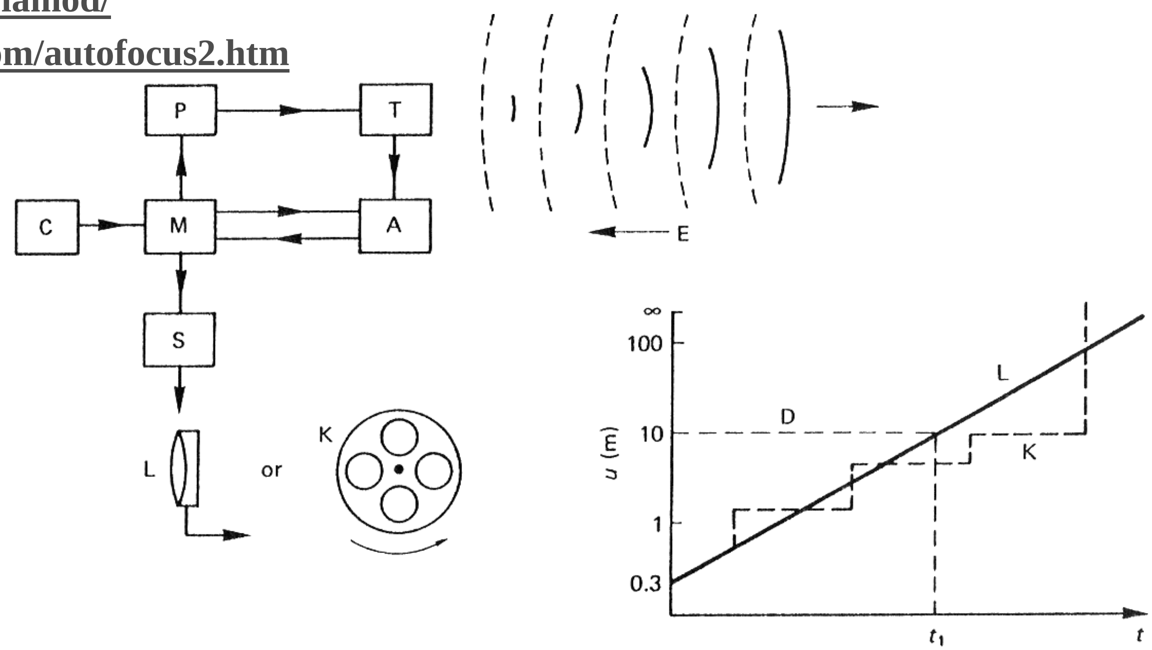


Figure 21.3 Polaroid sonar autofocusing
Ultrasonic pulse emitted by transducer T from power unit P under control of microprocessor M and clock C. Echo E also received by T, digitized by analogue-digital circuitry A, returns to M to control focusing motor S. This halts axial movement of lens L or a rotation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

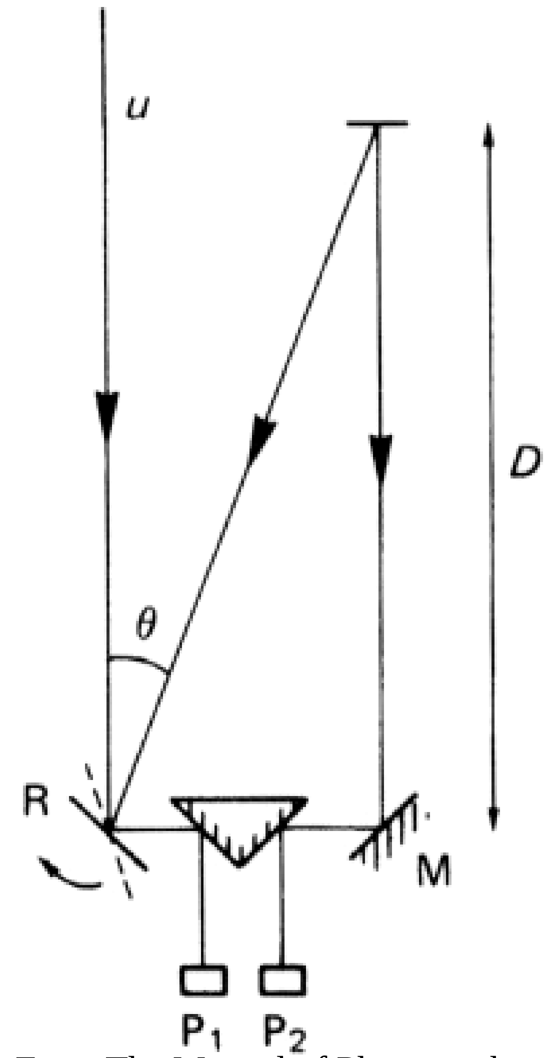
From Ray's Applied Photographic Optics

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

Triangulation

- **Rotating mirror sweeps the scene until the image is aligned with fixed image from mirror M**
  - pretty much stereovision and window correlation)



From The Manual of Photography

Different types of autofocus

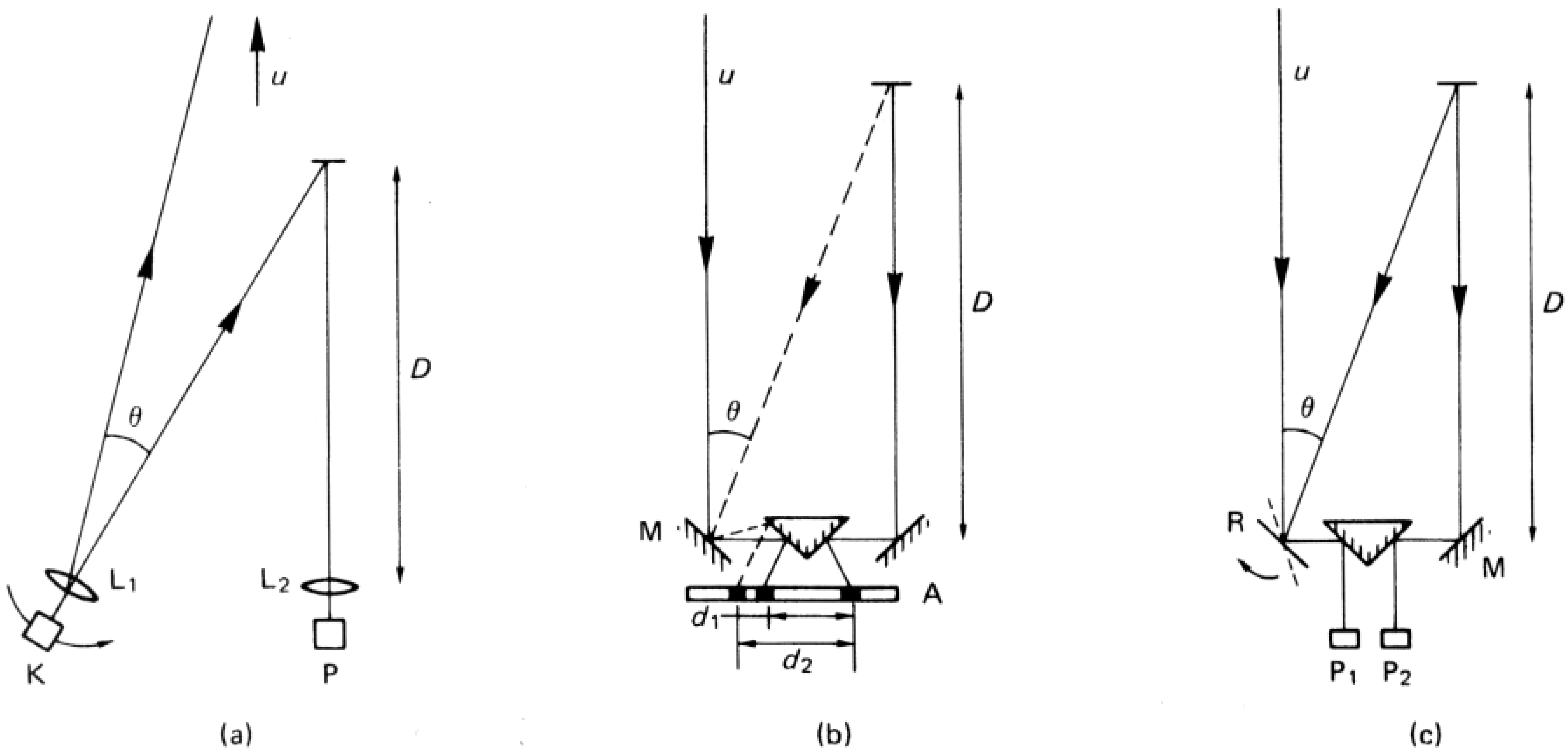
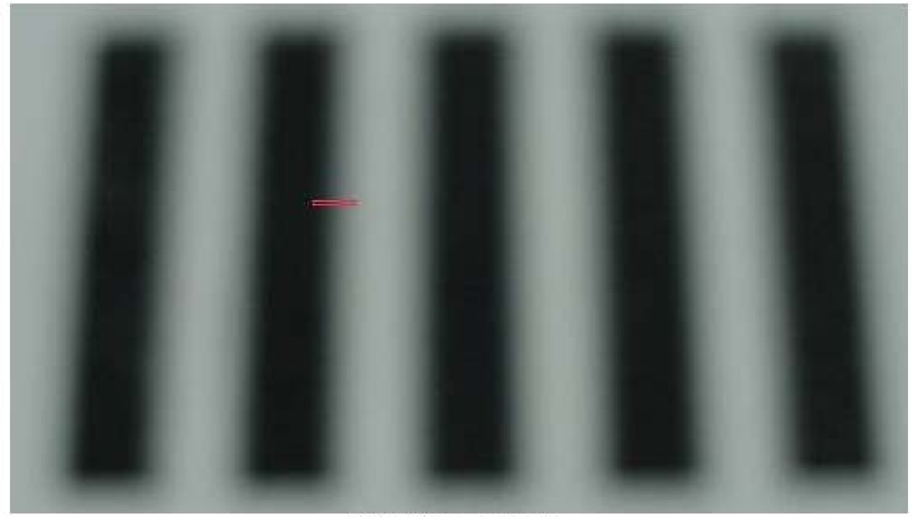


Figure 9.23 Ranging systems for autofocus cameras. (a) Scanning IR-emitting diode K with aspheric lenses L_1 and L_2 and photocell P. (b) Static system with linear CCD array A. The correlated images at separations d_1 and d_2 correspond to distances u and D respectively. (c) Scanning mirror R to correlate images on twin photocells P_1 and P_2

From The Manual of Photography

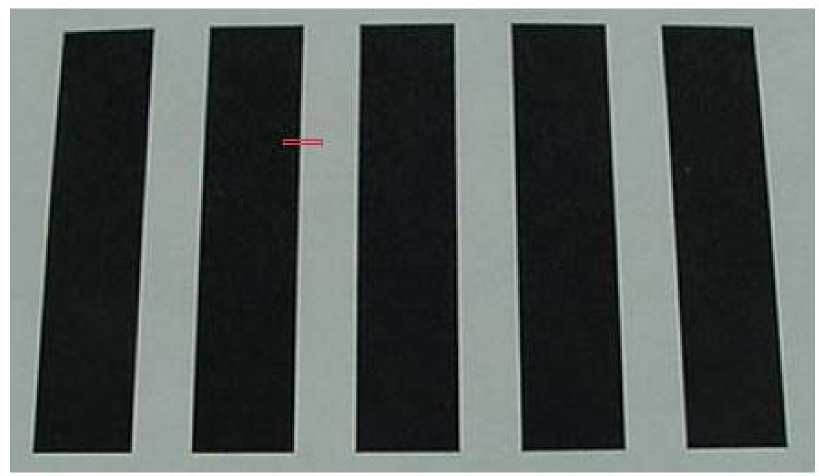
Contrast

- **Focus = highest contrast**

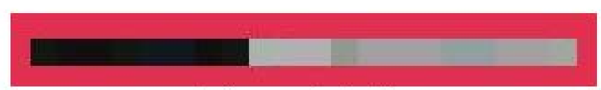


Out-of-focus scene

Out-of-focus pixel strip



In-focus scene



In-focus pixel strip

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

Phase detection focusing

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

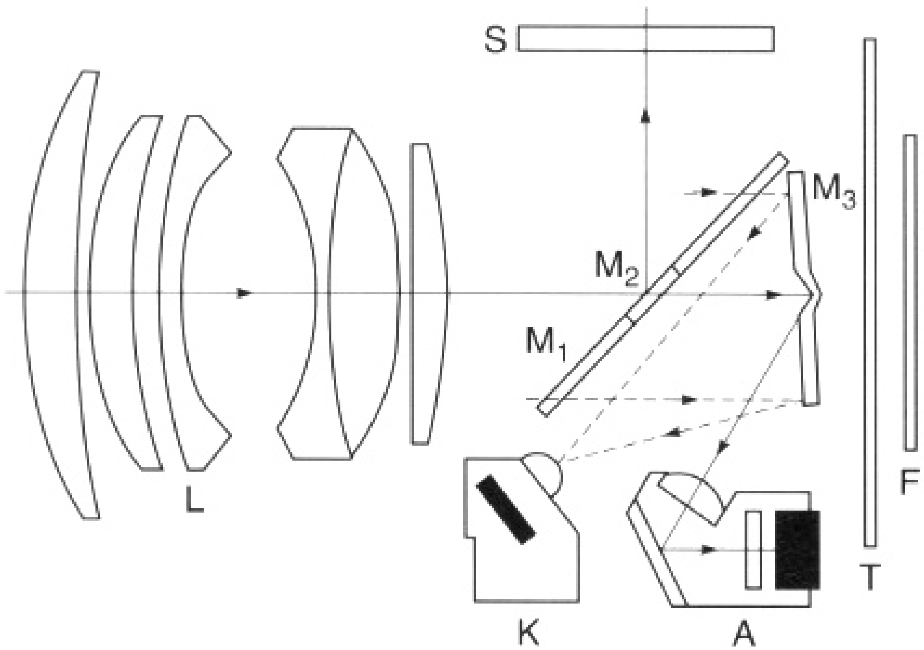
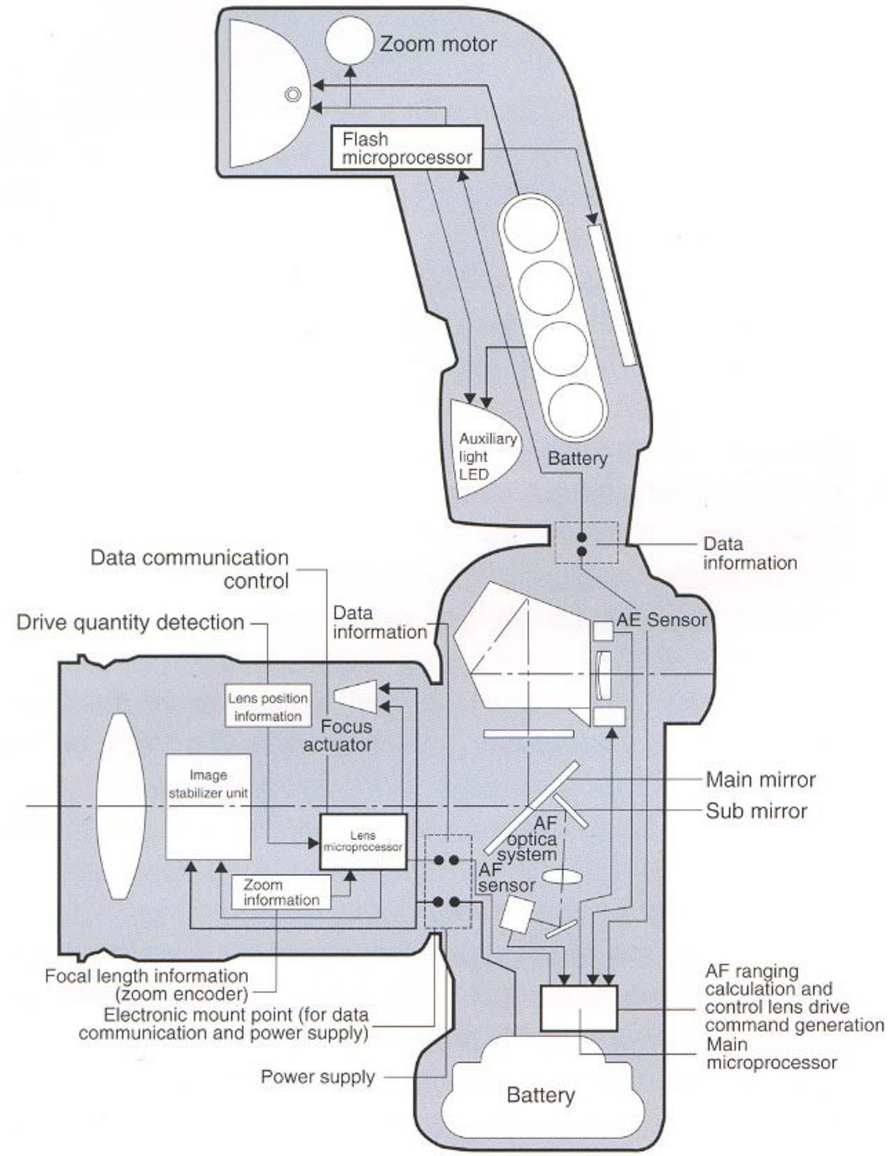


Figure 9.24 Location of autofocus and metering modules. L, camera lens; S, focusing screen; F, film in gate; M_1, reflex mirror with 30 per cent transmission; M_2, central region with 50 per cent transmission; M_3, secondary mirror with two focusing regions; A, autofocus module; K, metering module; spot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

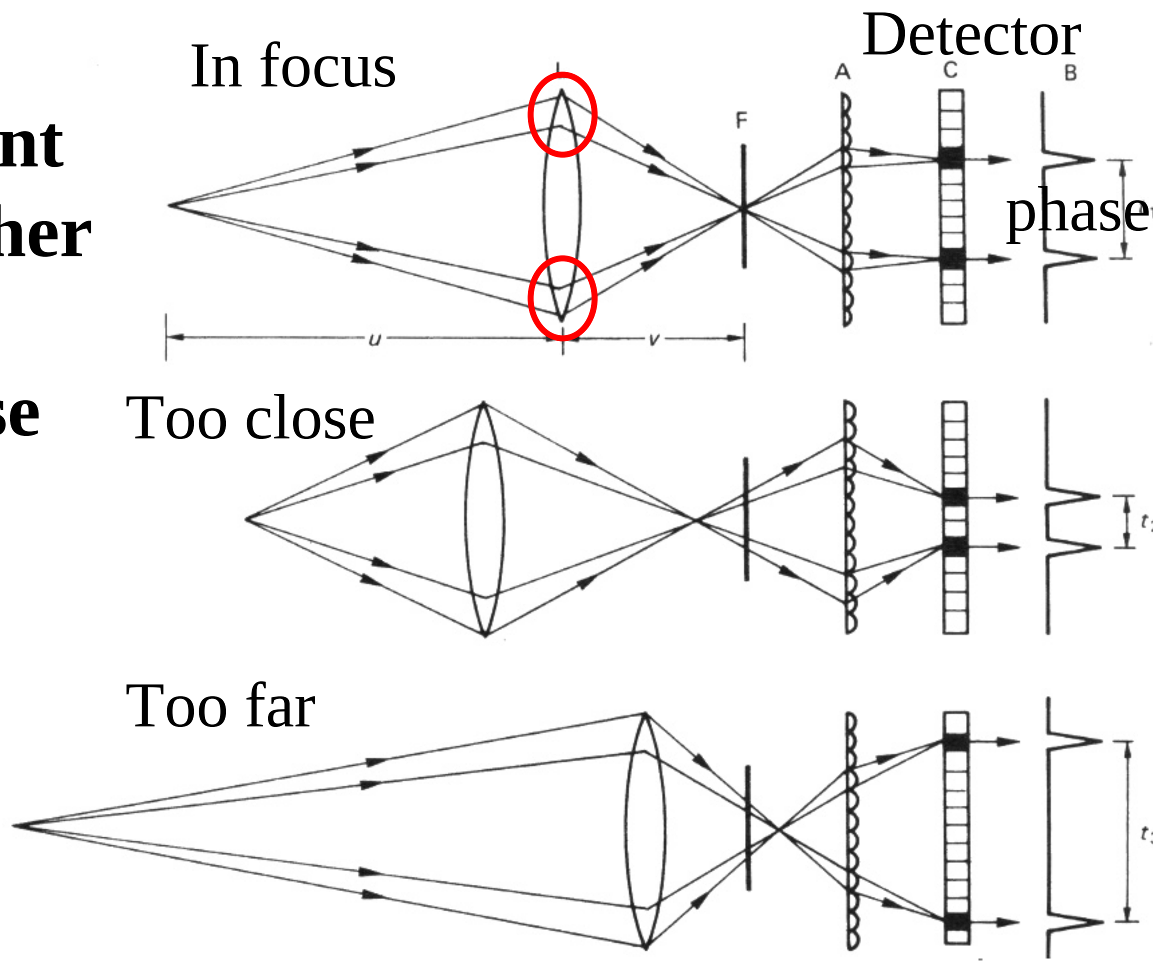
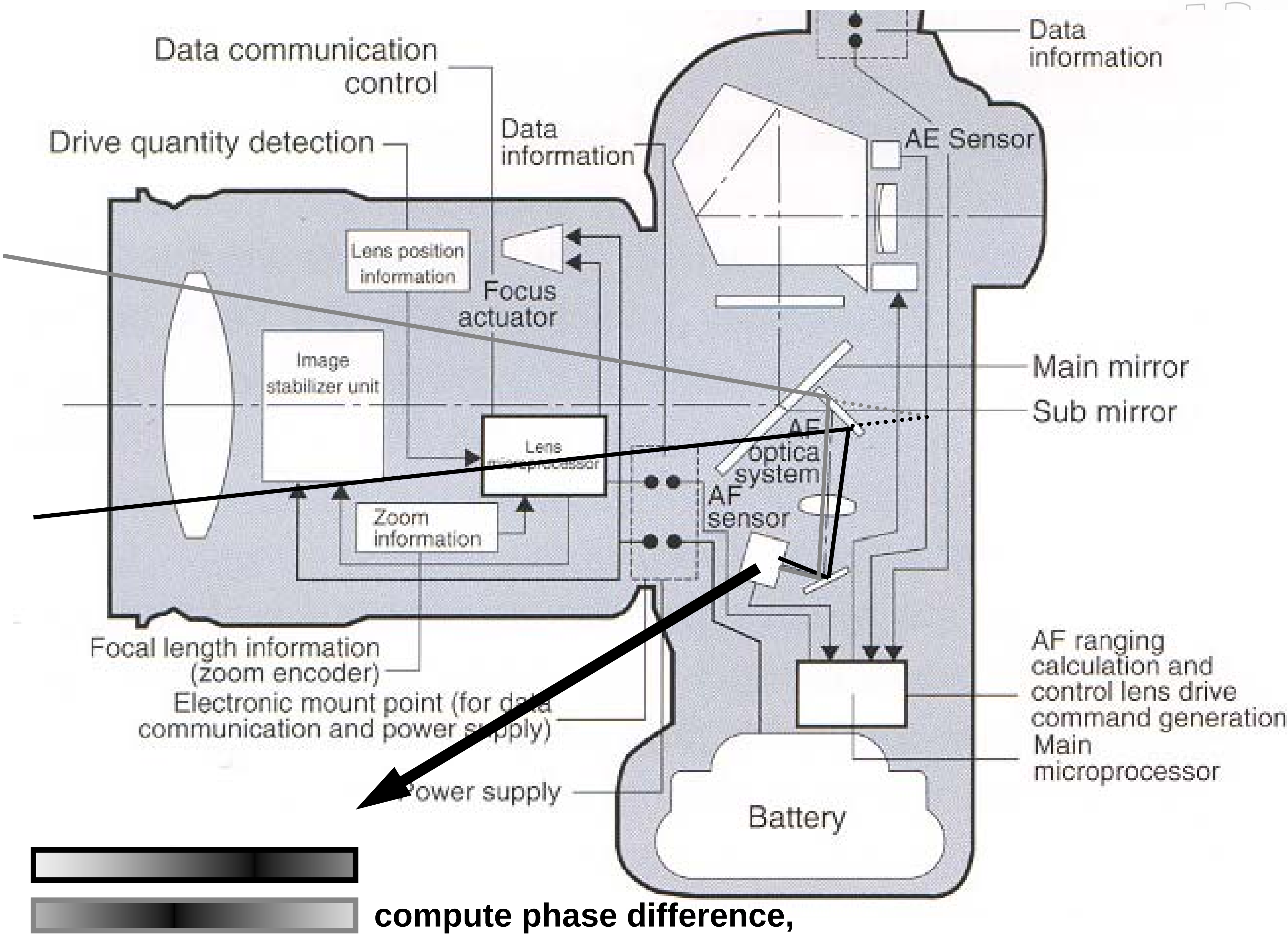


Figure 9.25 Principles of autofocus by phase detection. (a) Subject in focus. (b) Focus in front of subject. (c) Focus beyond subject. Key: L camera lens; F equivalent focal plane; A lenslet array; C CCD linear array; B output signals with time delay t_1 etc.

From The Manual of Photography

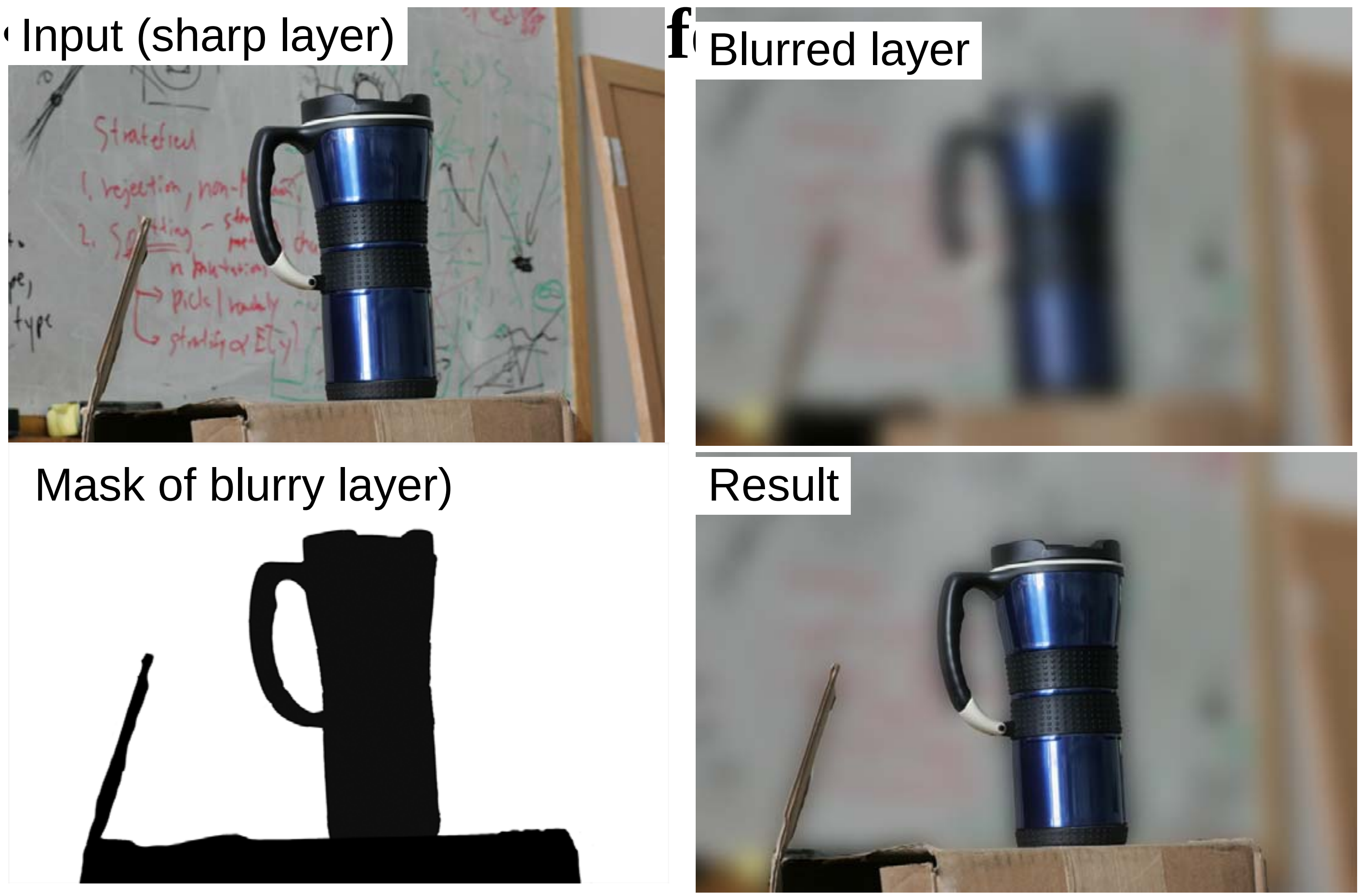


compute phase difference, deduce distance

Fake Depth of Field

Photoshop

- **Using layers:**
- **One sharp layer, one blurry layer (using Gaussian blur)**



Photoshop

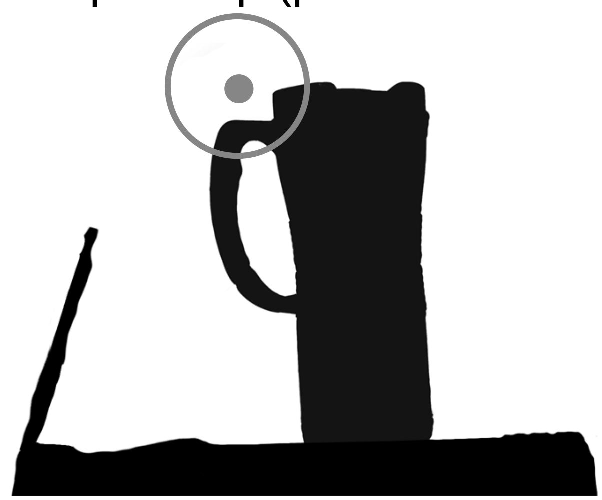
- **Problem: halo around edges**

Photoshop lens blur

- **Reverse-engineered algorithm: average over circle**
- **Size of circle depends on pseudo depth**
- **Discard pixels that are too much closer**

Input

Depth map (painted manually)



Photoshop lens blur

- **Filter>Blur>Lens blur**

Depth map (painted manually)