6.098 Digital and Computational Photography
6.882 Advanced Computational Photography

Focus and Depth of Field

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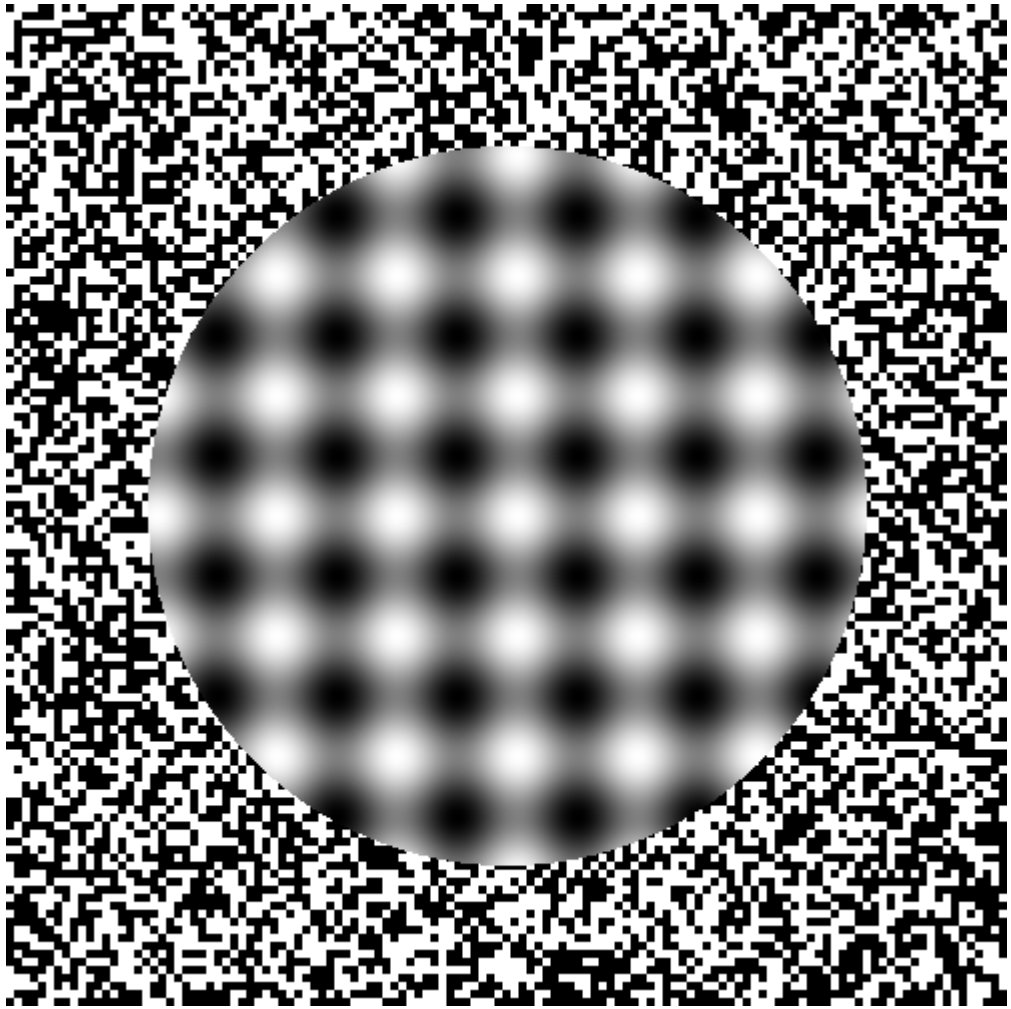
Fun

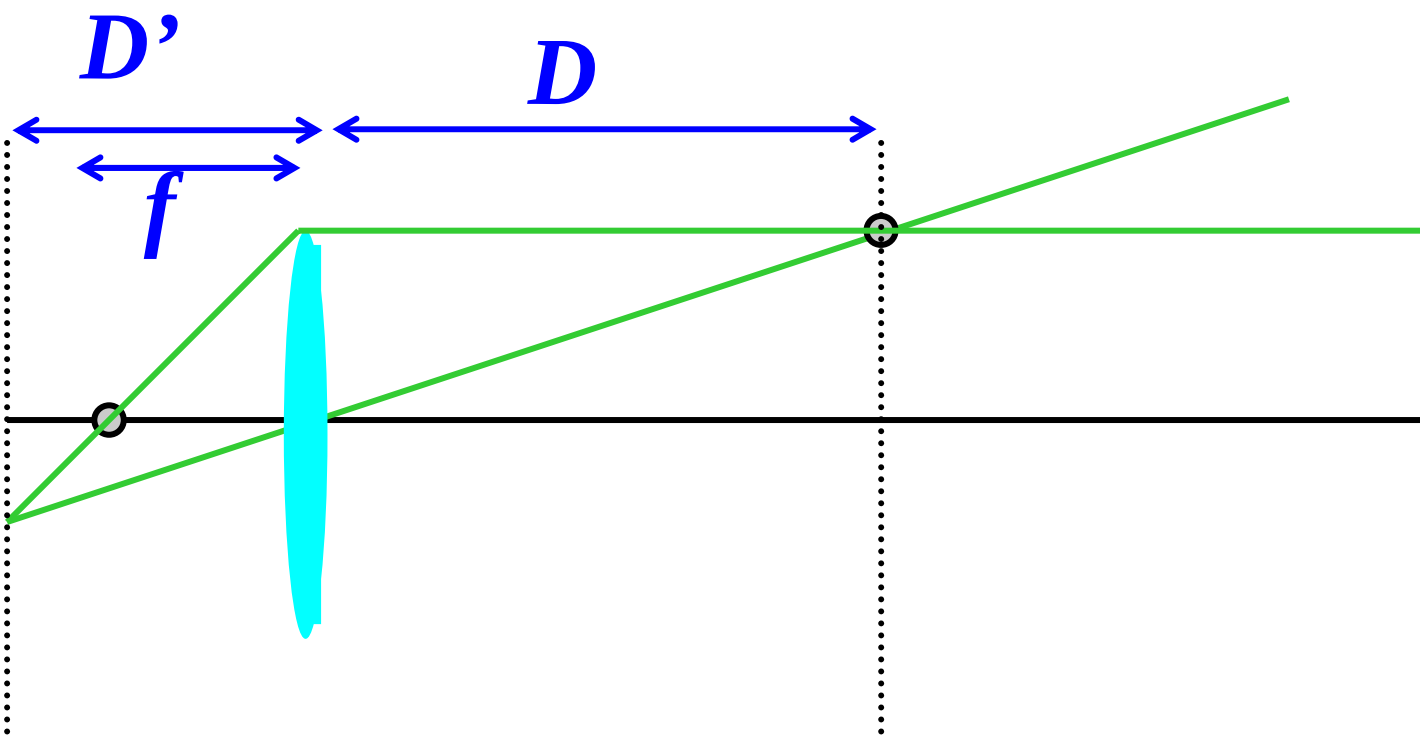
- **http://www.ritsumei.ac.jp/~akitaoka/motion-e.htm**



Focusing

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

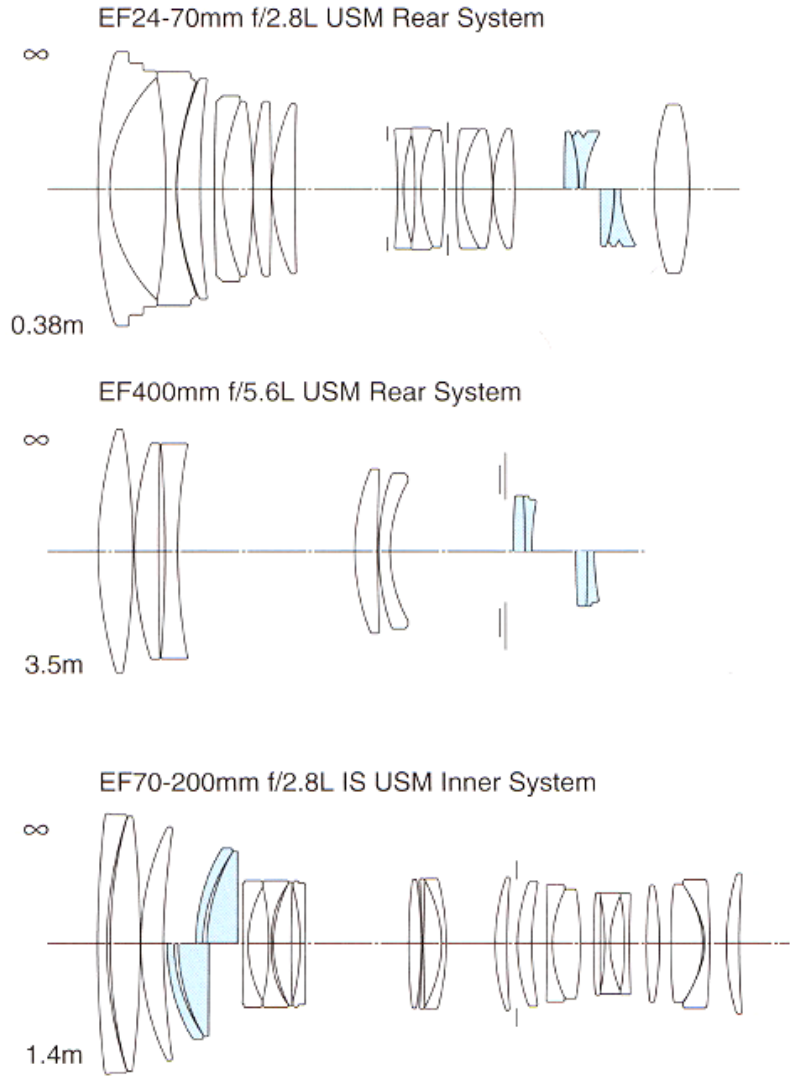
$$\frac{1}{D'} + \frac{1}{D} = \frac{1}{f}$$



In practice, it's a little more complex

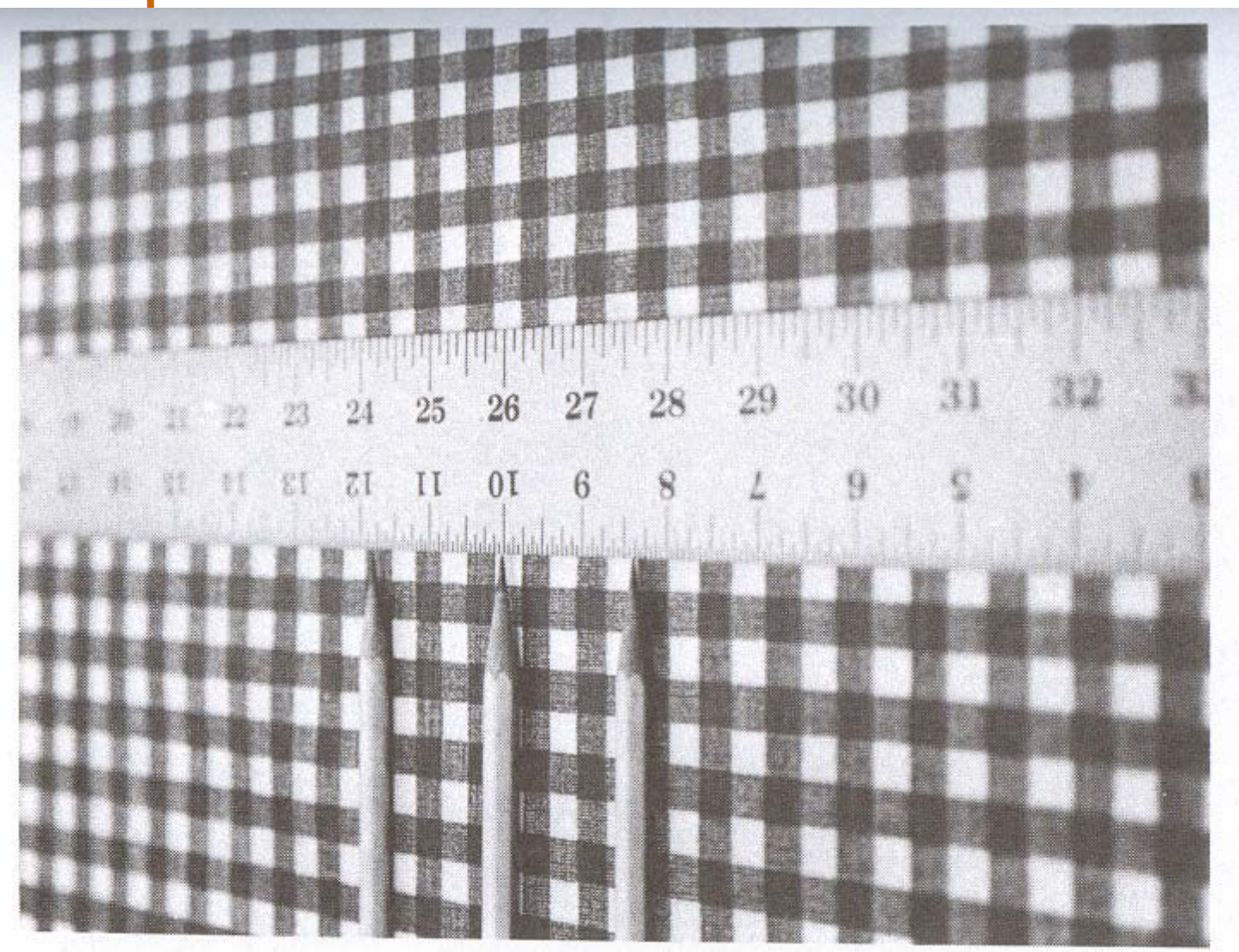
- **Various lens elements can move inside the lens**
  - Here in blue

Figure-29 Rear and Inner Focusing Systems

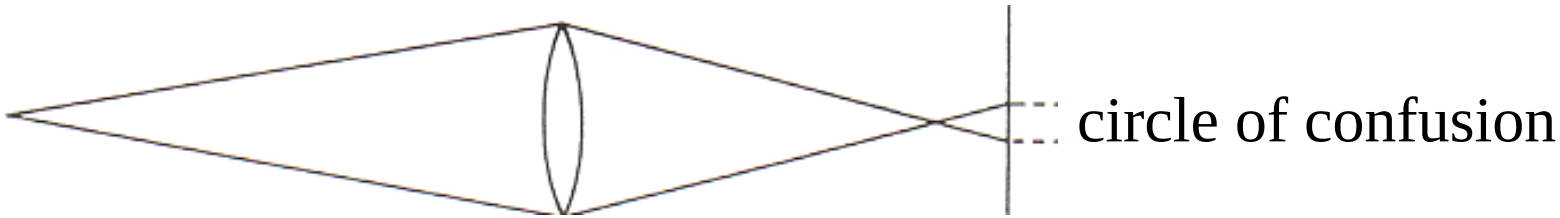


Source: Canon red book.

Defocus & Depth of field


22 23 24 25 26 27 28 29 30 31 32
13 12 11 10 6 8 7 9 5 4

Circle of confusion



From Basic Photographic Materials and Processes, Stroebel et al.

Depth of focus

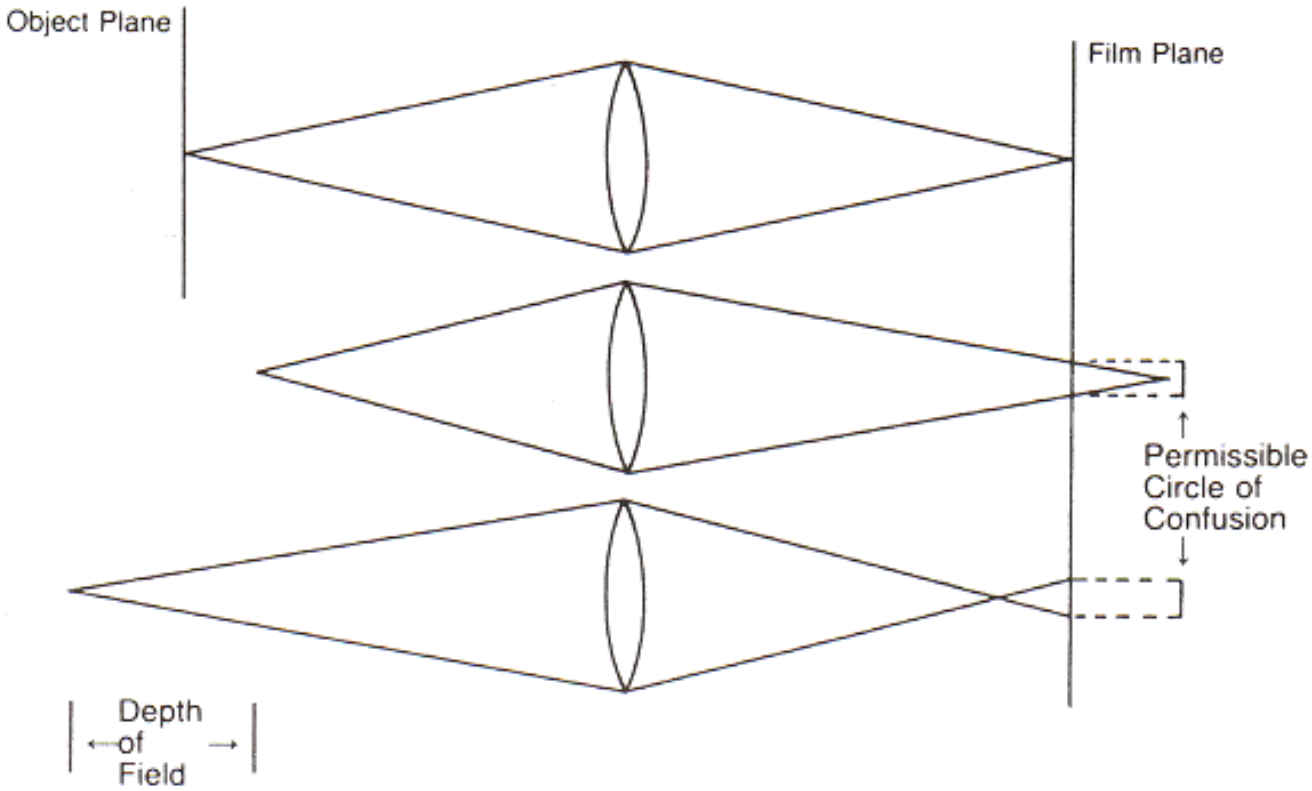


Figure 5–33A Depth of field is the range of distances within which objects are imaged with acceptable sharpness. At the limits, object points are imaged as permissible circles of confusion.

From Basic Photographic Materials and Processes, Stroebel et al.

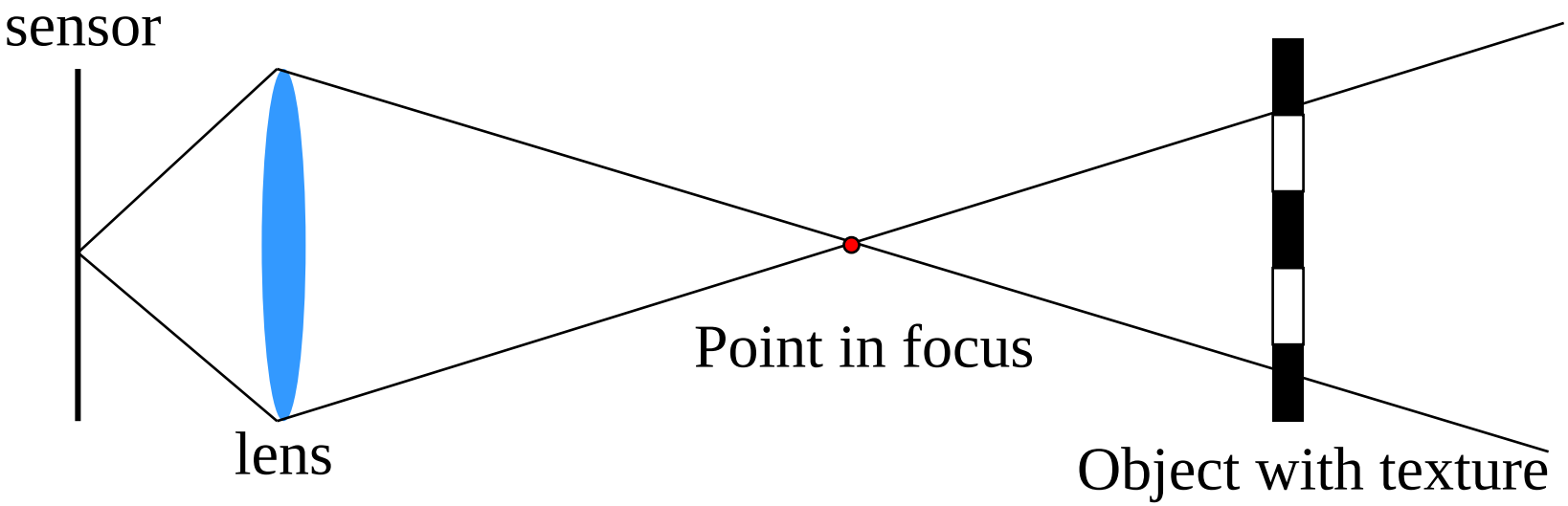
Size of permissible circle?

- **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**

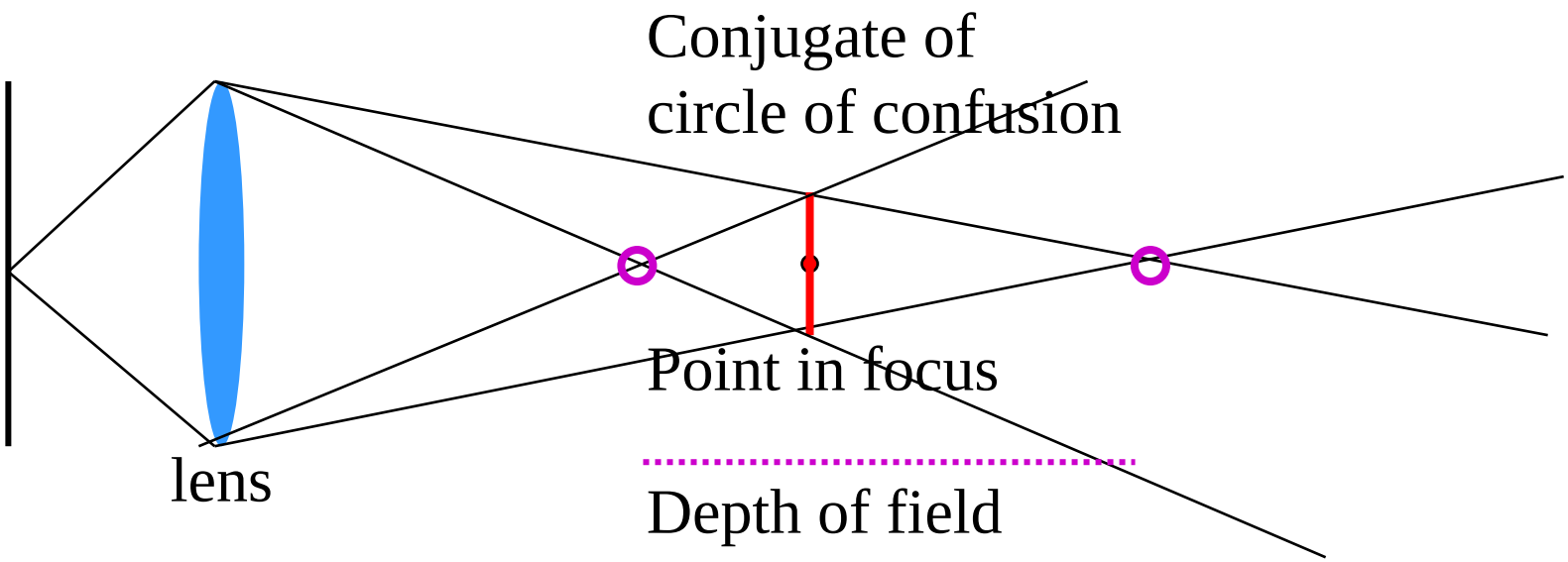
Depth of field: Object space

- **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)



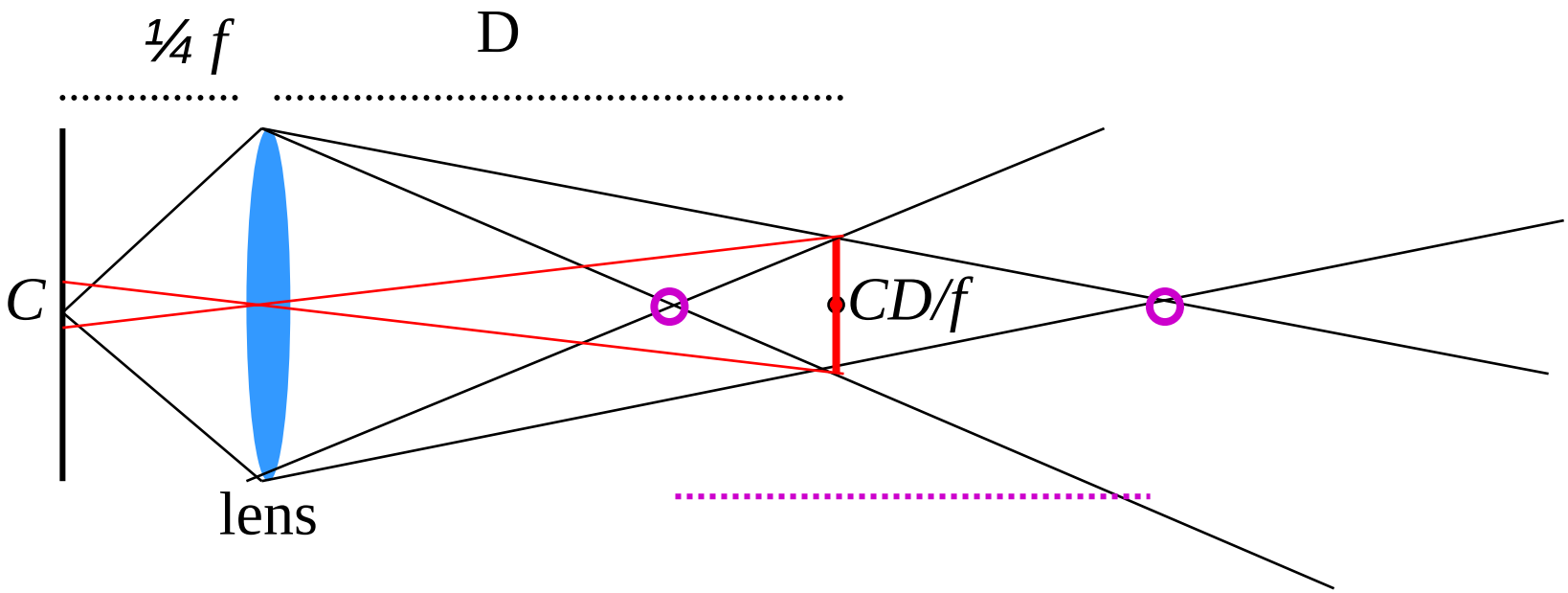
Depth of field: more accurate view

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



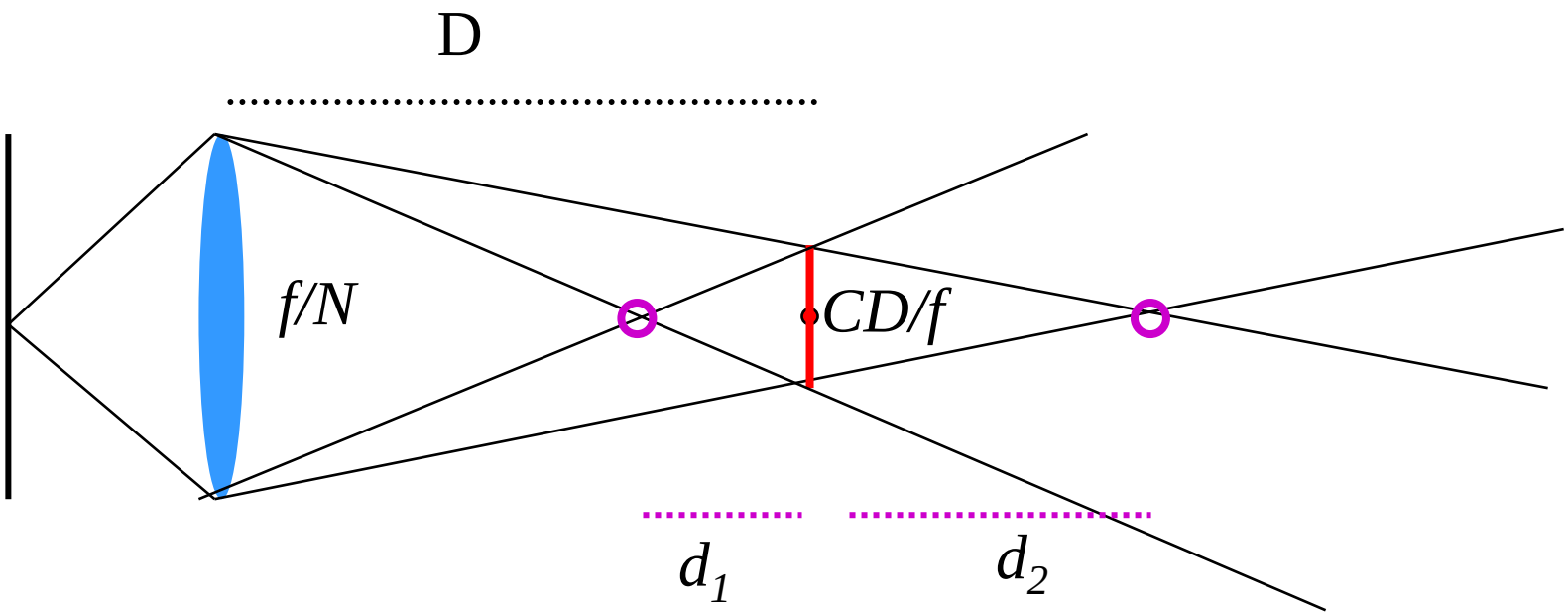
Depth of field: more accurate view

- **Backproject the image onto the plane in focus**
  - Backproject circle of confusion
  - Depends on *magnification factor ¼ f/D*



Deriving depth of field

- **Circle of confusion *C*, magnification *m***
- **Simplification: *m=f/D***
- **Focusing distance D, focal length *f*, aperture *N***
- **As usual, similar triangles**



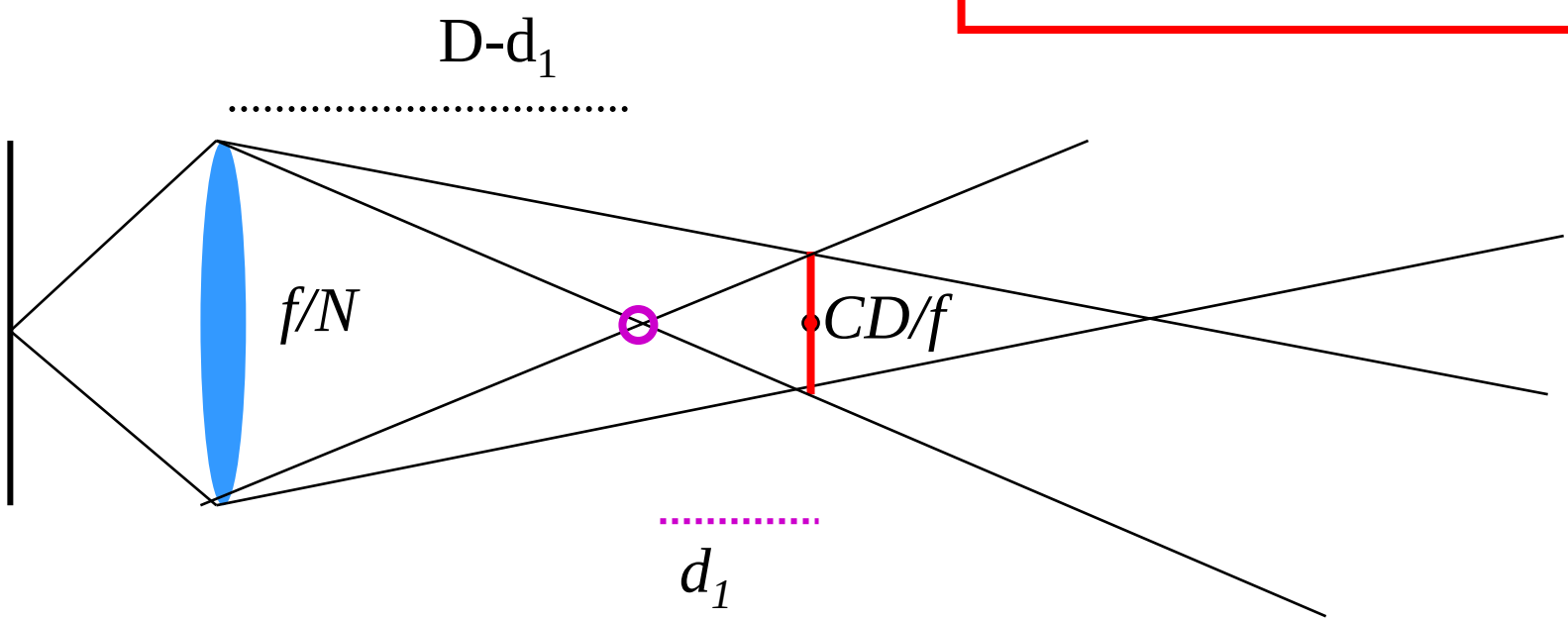
Deriving depth of field

$$\frac{fd_1}{CD} = \frac{D - d_1}{f/N}$$

$$\frac{fd_1}{CD} + \frac{d_1}{f/N} = \frac{D}{f/N}$$

$$d1\frac{f^2/N + CD}{CDf/N} = \frac{D}{f/N}$$

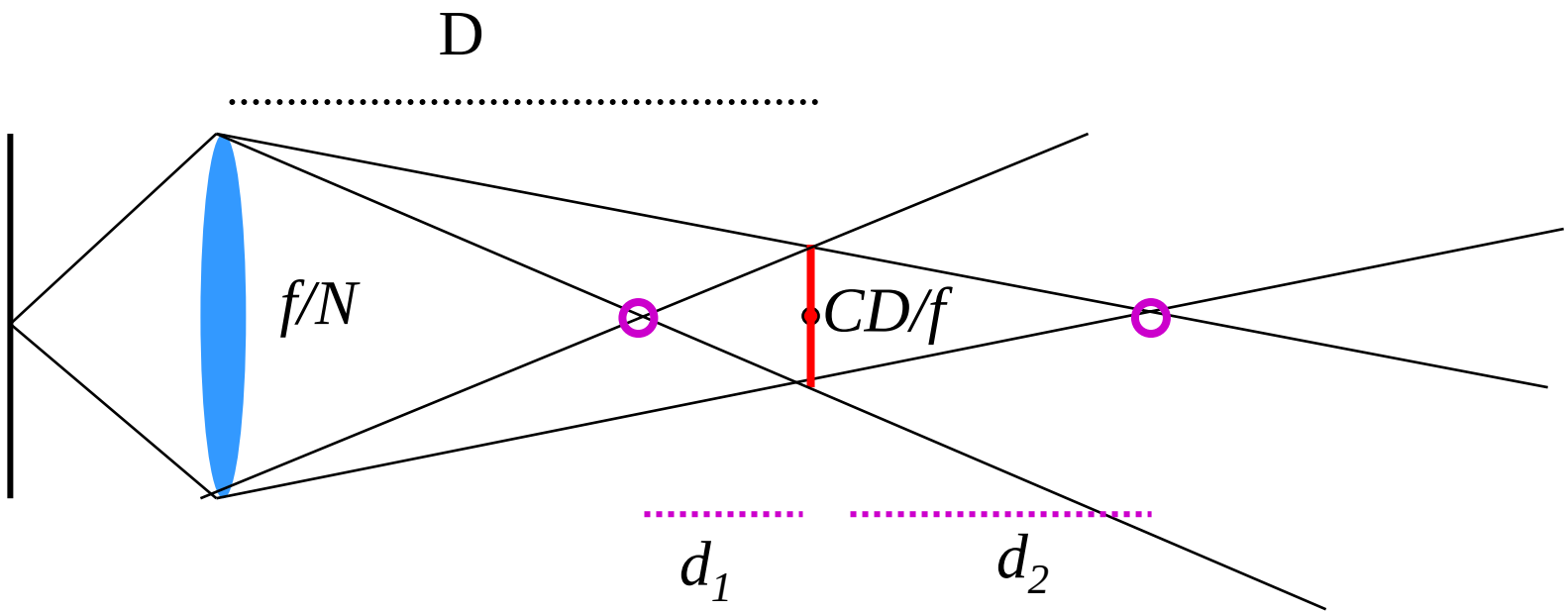
$$d1 = \frac{CD^2}{f^2/N + CD}$$



Deriving depth of field

$$d1 = \frac{NCD^2}{f^2 + NCD} \qquad d2 = \frac{NCD^2}{f^2 - NCD}$$

$$d = d_1 + d_2 = \frac{2NCD^2 f^2}{f^4 - N^2C^2D^2}$$

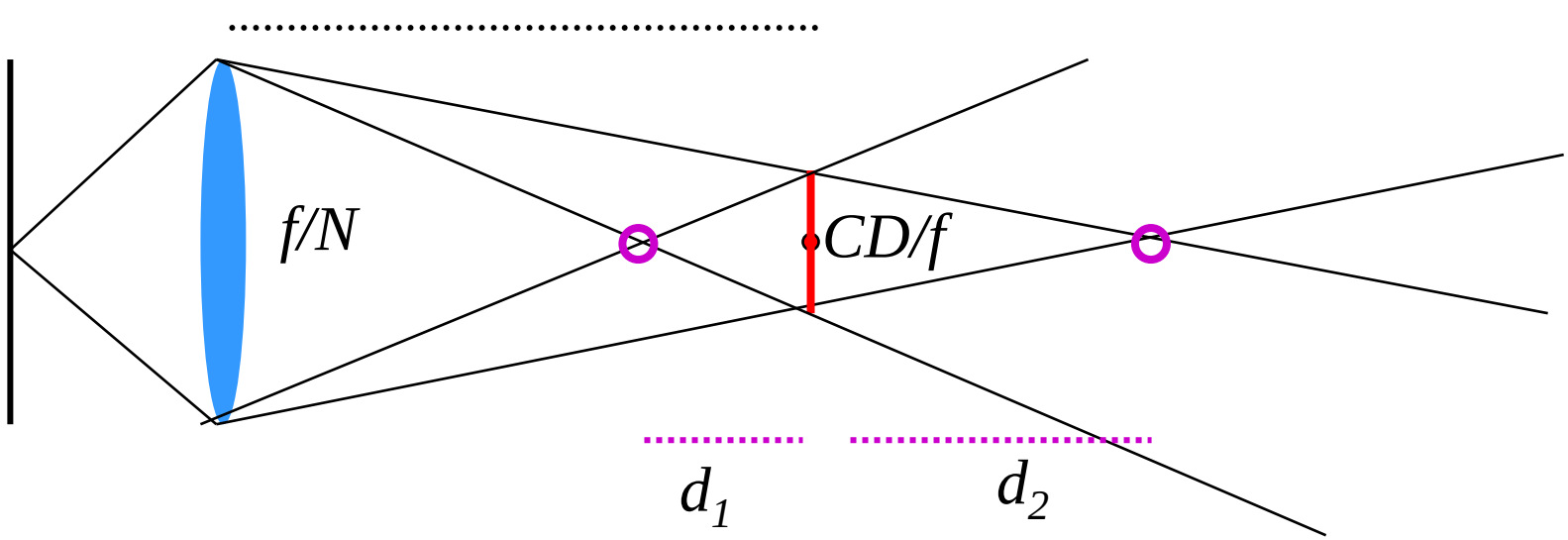


Deriving depth of field

$$d = \frac{2NCD^2 f^2}{f^4 - N^2C^2D^2}$$

$N^2C^2D^2$ term can often be neglected when DoF is small
(conjugate of circle of confusion is smaller than lens aperture)

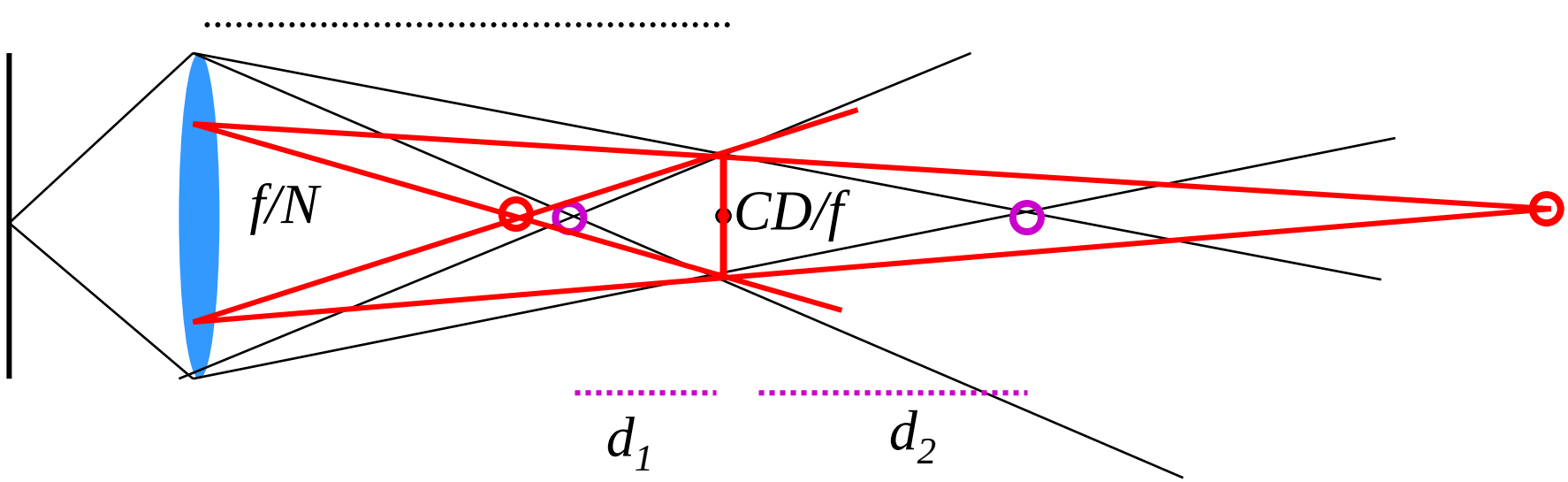
$$d = \frac{2NCD^2}{f^2}$$



Depth of field and aperture

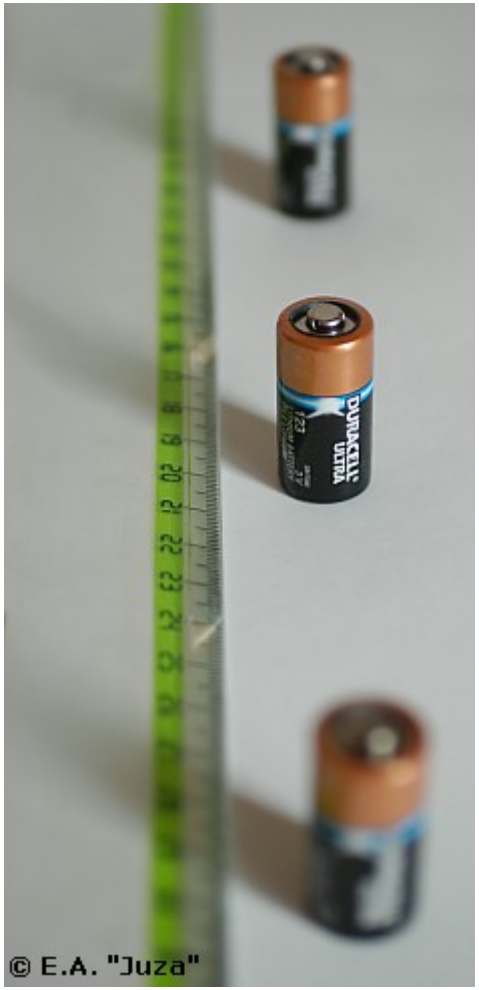
- **Linear: proportional to f number**
- **Recall: big f number N means small physical aperture**

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

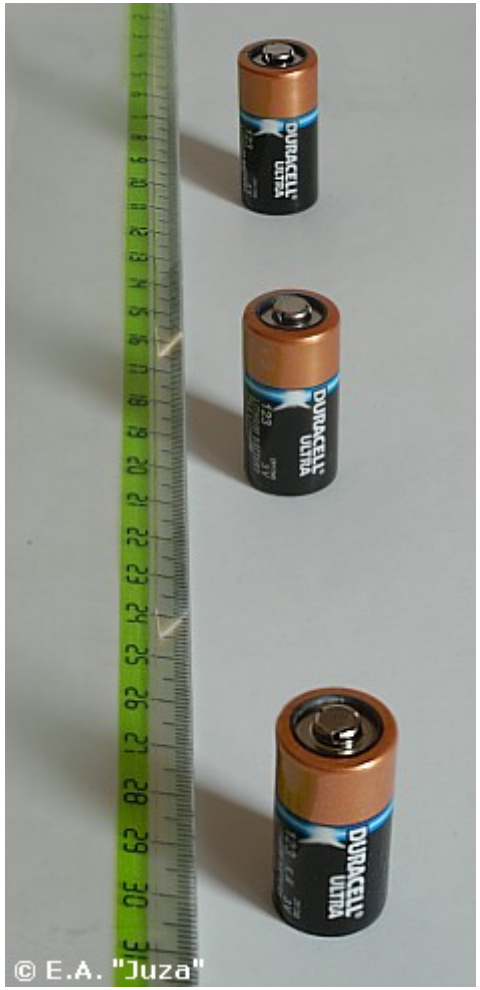


DoF & aperture

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



f/2.8



f/32

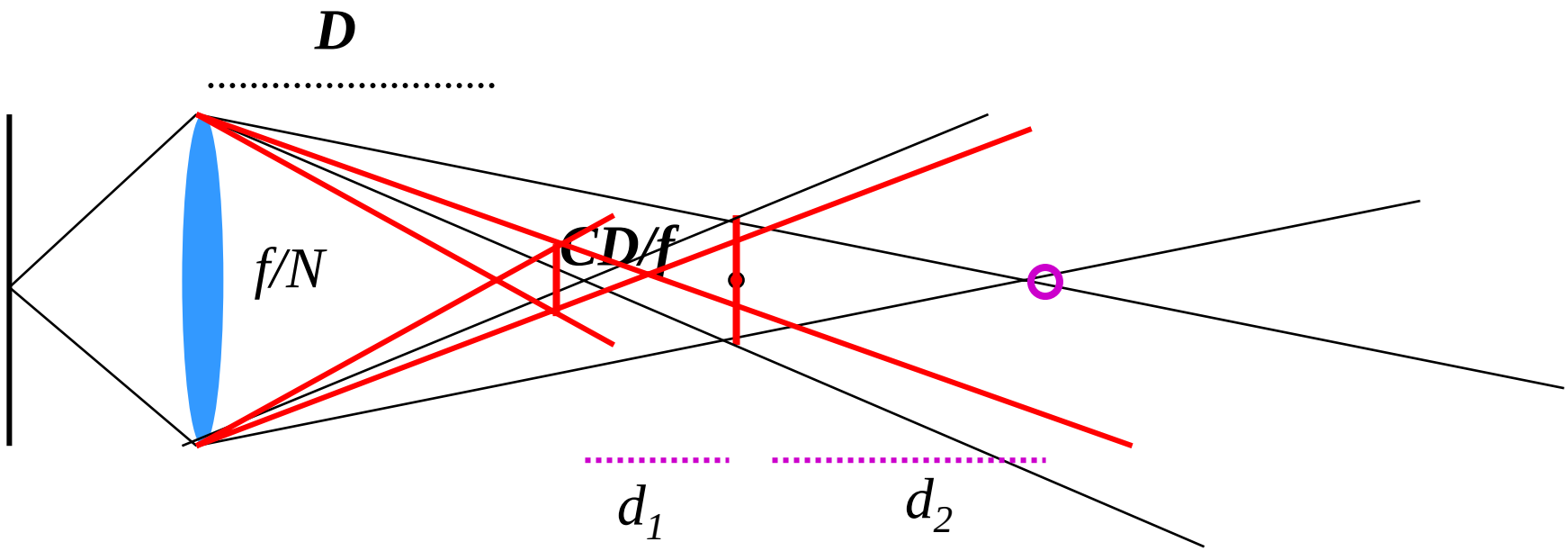
SLR viewfinder & aperture

- **By default, an SLR always shows you the biggest aperture**
- **Brighter image**
- **Shallow depth of field help judge focus**
- **Depth of field preview button:**
  - Stops down to the aperture you have chosen
  - Darker image
  - Larger depth of field

Depth of field and focusing distance

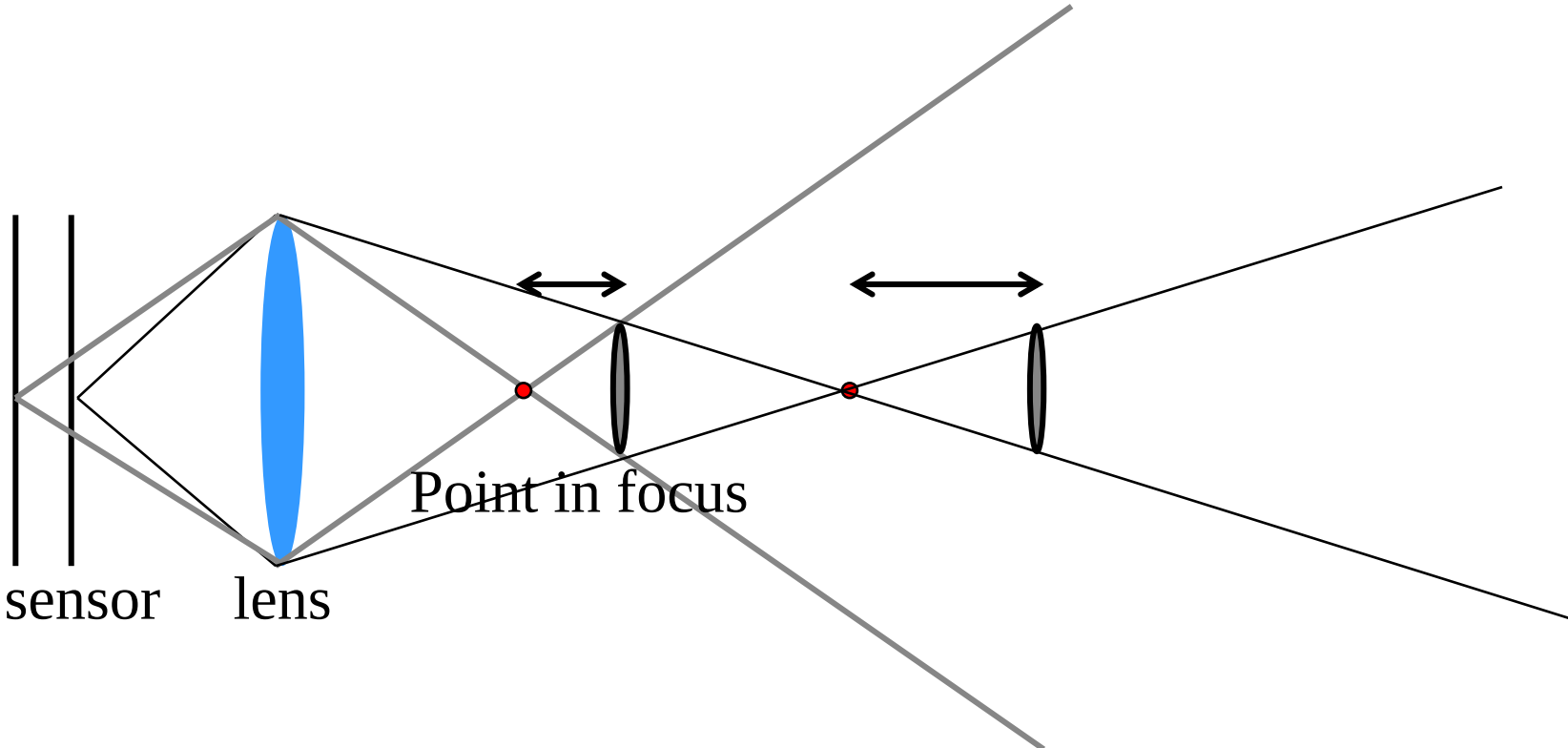
- **Quadratic (bad news for macro) (but careful, our simplifications are not accurate for macro)**

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

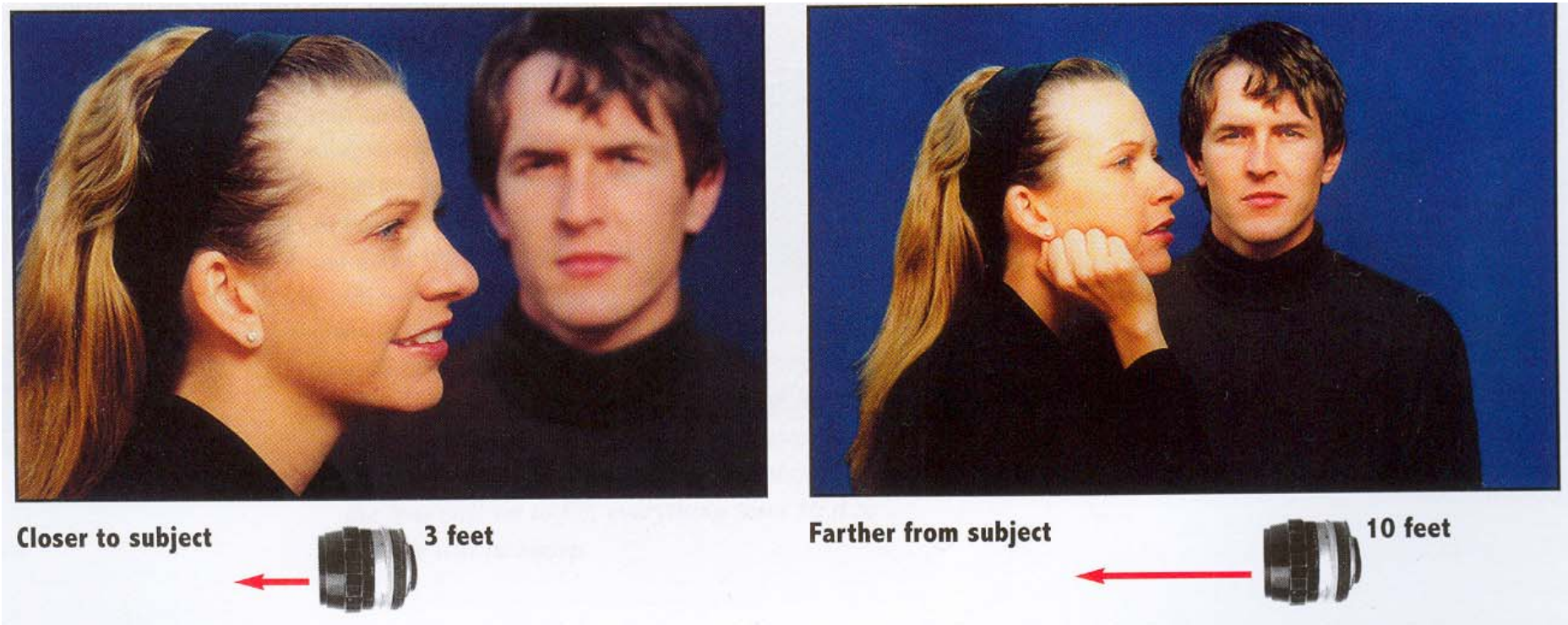


Double cone perspective

- **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.

Hyperfocal distance

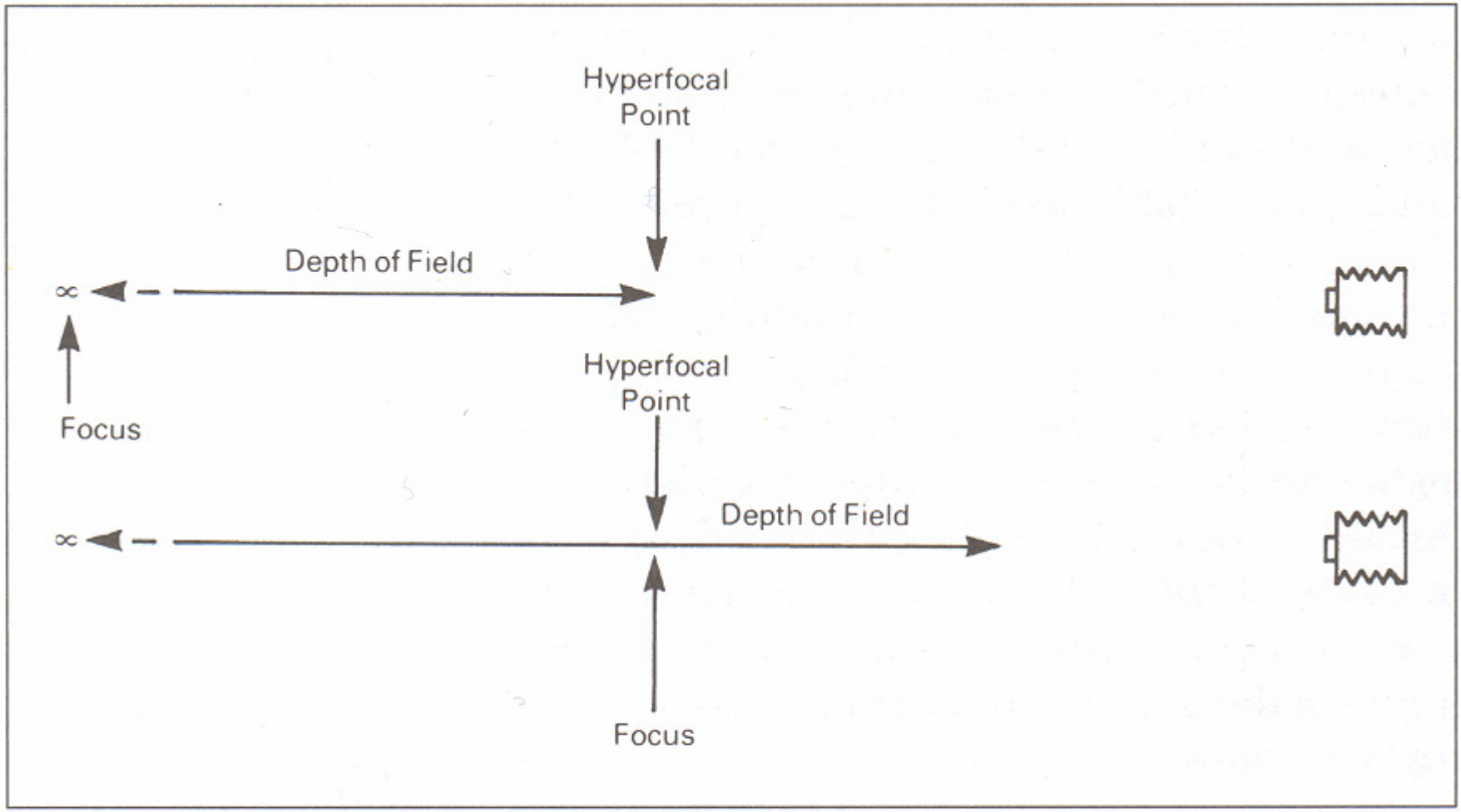


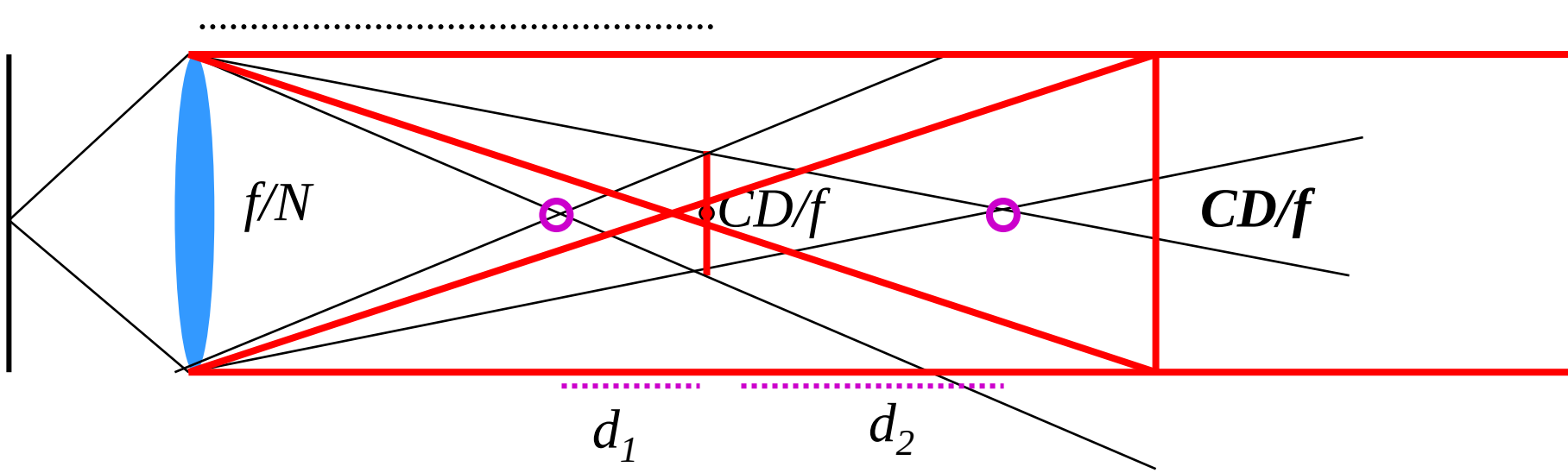
Figure 5–34 The hyperfocal distance is the closest distance that appears sharp when a lens is focused on infinity (top), or the closest distance that can be focused on and have an object at infinity appear sharp (bottom).

From Basic Photographic Materials and Processes, Stroebel et al.

Hyperfocal distance

- **When CD/f becomes bigger than f/N**
- **focus at $D=f^2/NC$ and sharp from D/2 till infinity**
- **Our other simplifications do not work anymore there: the denominator term has to be taken into account in**

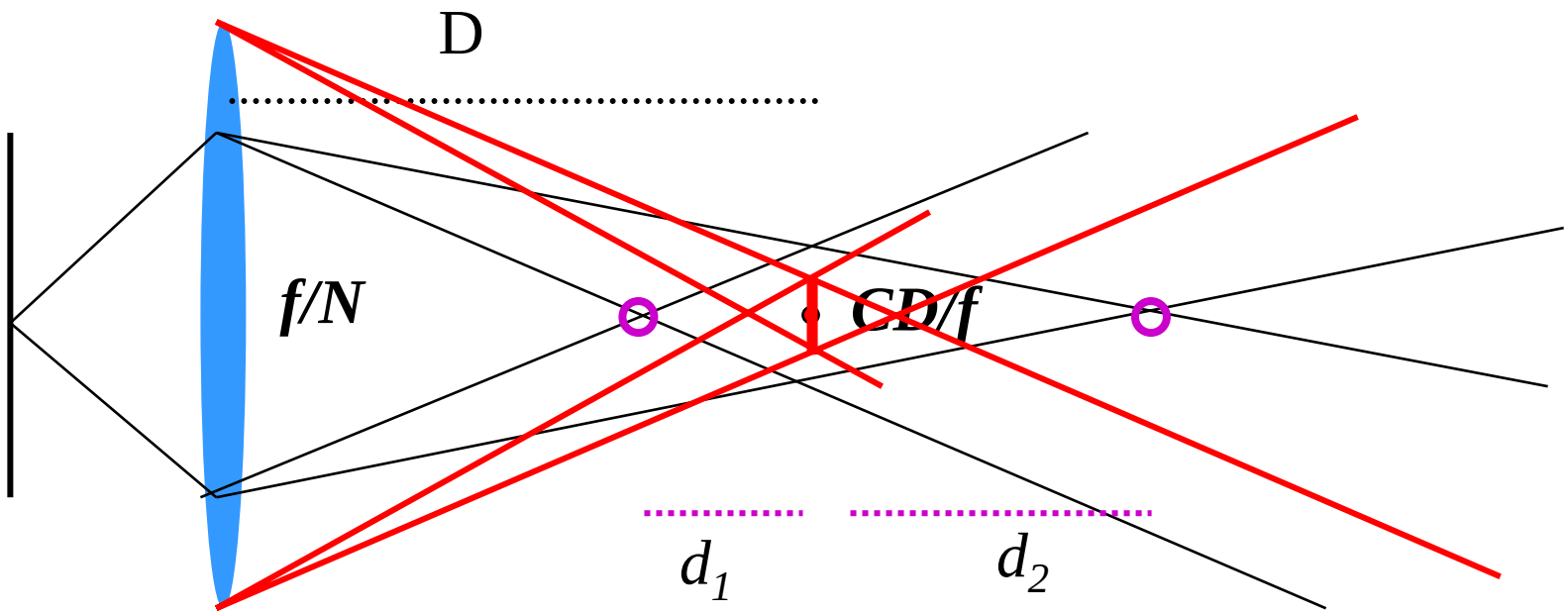
$$d = \frac{2NCD^2 f^2}{f^4 - N^2C^2D^2}$$



Depth of field and focal length

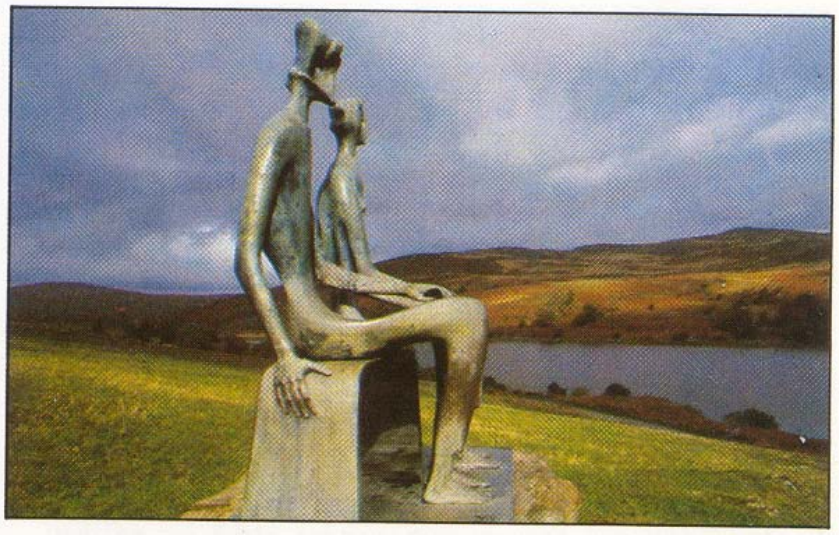
- **Inverse quadratic:**
  the lens gets bigger,
  the magnification is higher

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

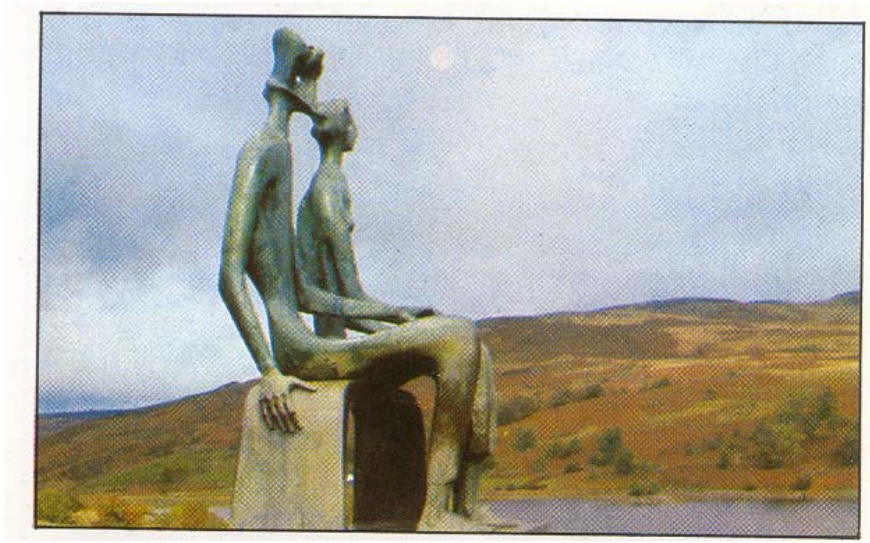


Depth of field & focal length

- **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

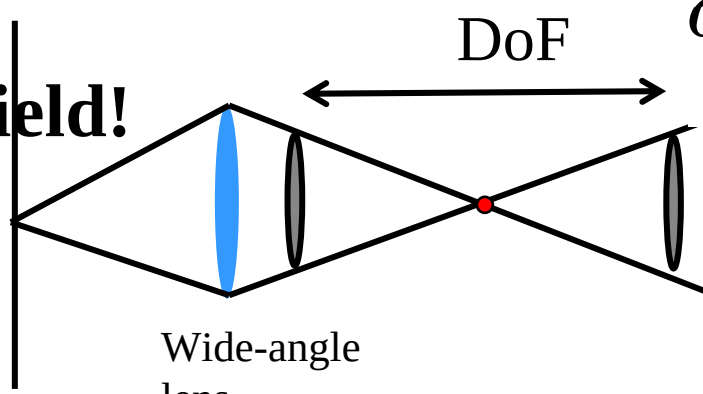


50mm

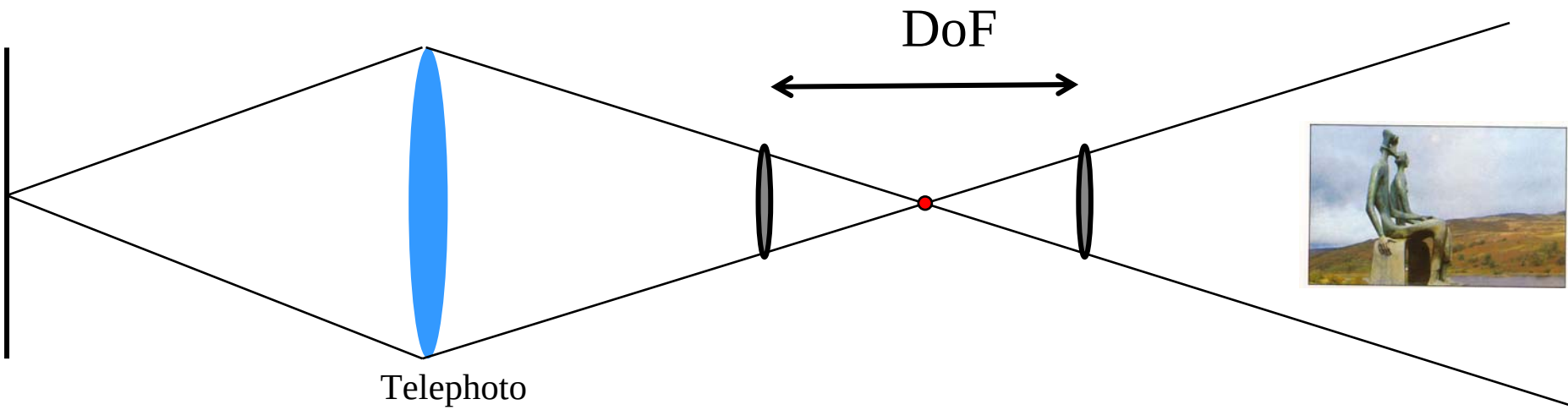
Depth of field & focal length

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

$$d = \frac{2NC'D^2}{f^2}$$



Wide-angle lens



Telephoto lens (2x f), same aperture

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?**

Important conclusion

- **For a given image size and a given f number, the depth of field (in object space) is the same.**
  - The depth of acceptable sharpness is the same
- **But background far far away looks more blurry Because it gets magnified more**
- **Plus, usually, you don't keep magnification constant**

Recap

Effect of parameters

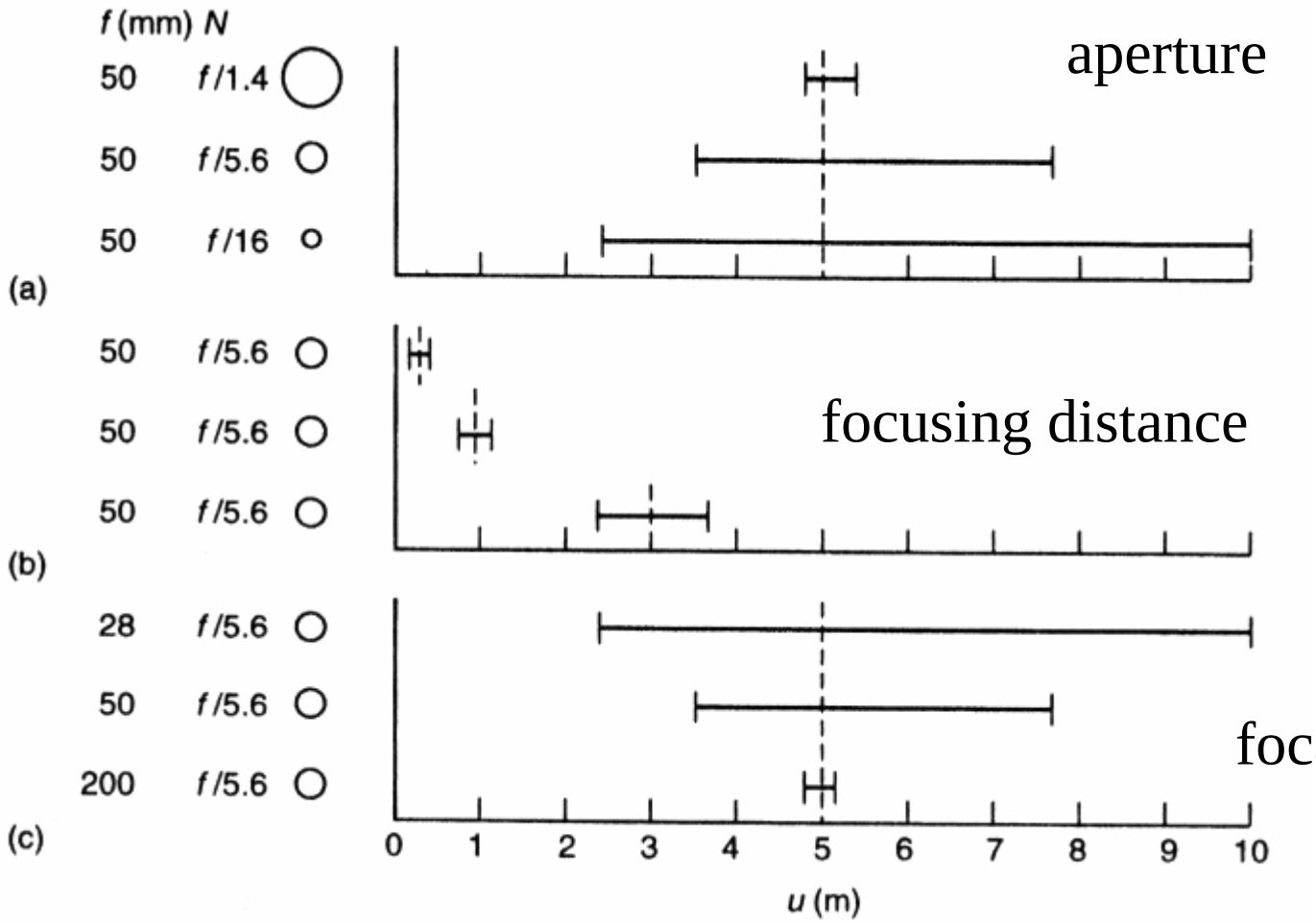
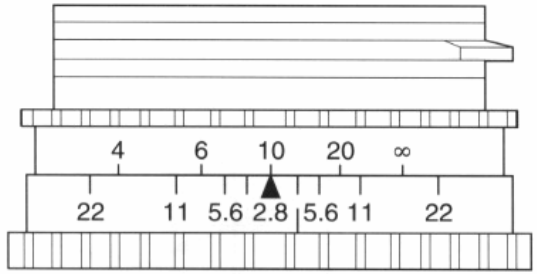


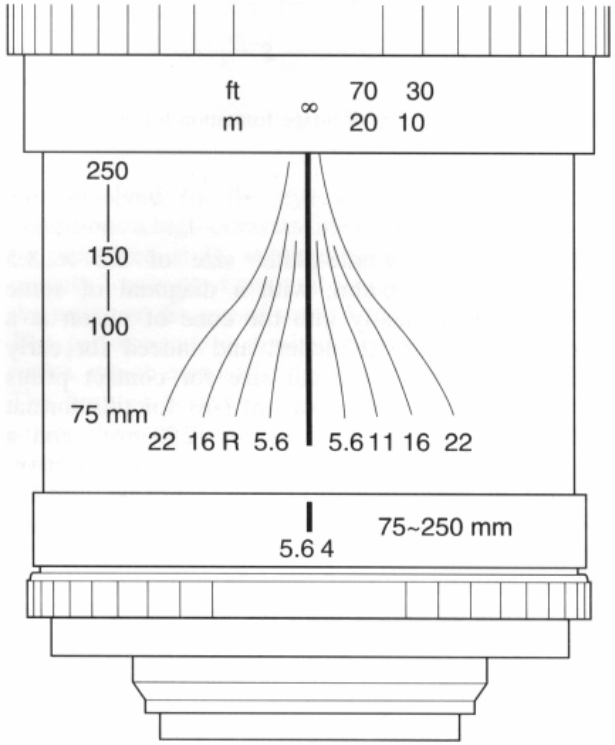
Figure 22.1 Depth of field Effect of the variables focal length (f), f-number (N) and focused distance (u) at constant value for circle of confusion (C). (a) Lens aperture varying from $f/1.4$ to $f/16$ with 50 mm lens focused on 5 m. (b) Focused distance varying from 0.5 to 3 m with 50 mm lens at $f/5.6$. (c) Focal length varying from 28 to 200 mm at $f/5.6$ focused on 5 m.

From applied photographic optics

DoF guides



(a)



(b)

Figure 4.20 Visual indication of depth of field. (a) Depth of field indicator scale. (b) Converging scales on a 75–250 mm *f*/4 zoom lens, including an infrared focus correction mark R

From "The Manual of Photography" Jacobson et al

Is depth of field good or evil?

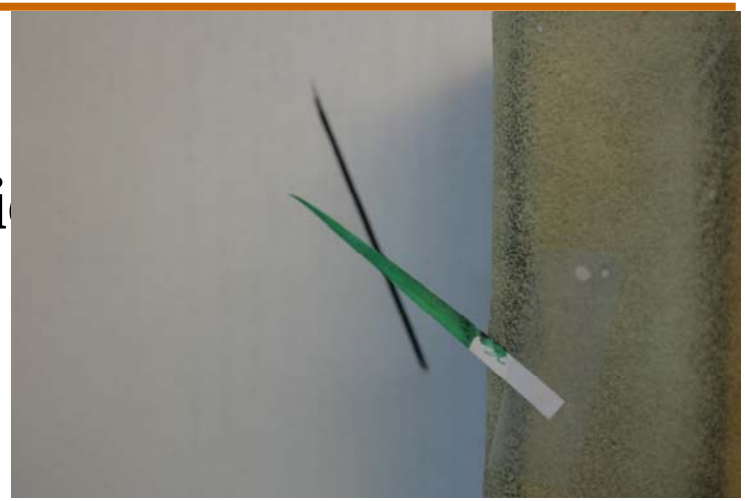
- **It depends, little grasshopper**
- **Want huge DoF: landscape, photojournalists, portrait with environment**
- **Shallow DoF: portrait, wildlife**

Michael Reichman

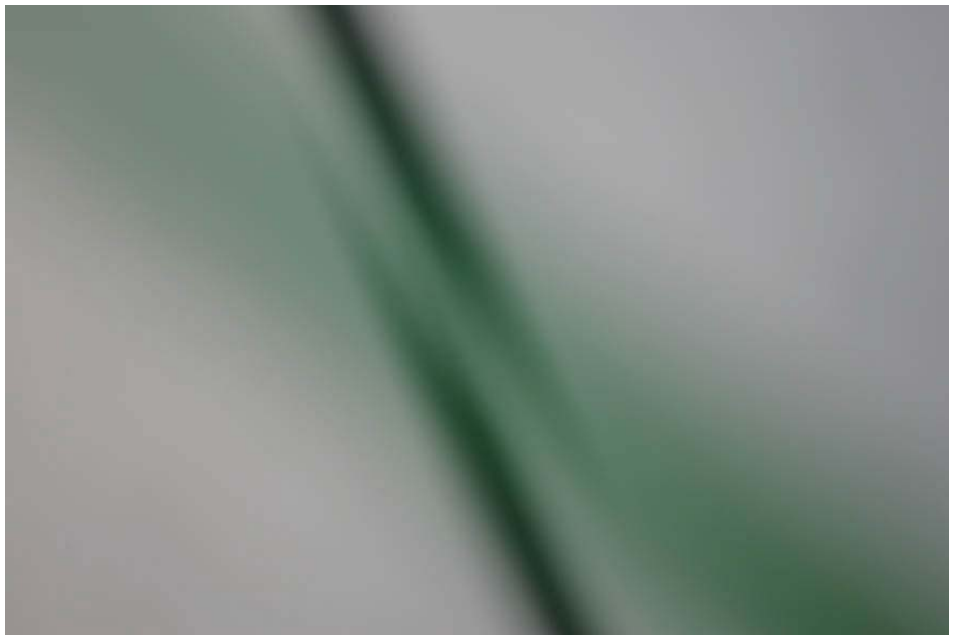
Steve McCurry

Crazy DoF images

- **By Matthias Zwicker**
- **The focus is between the two sti**



Sharp version



Really wide aperture version

Is depth of field a blur?

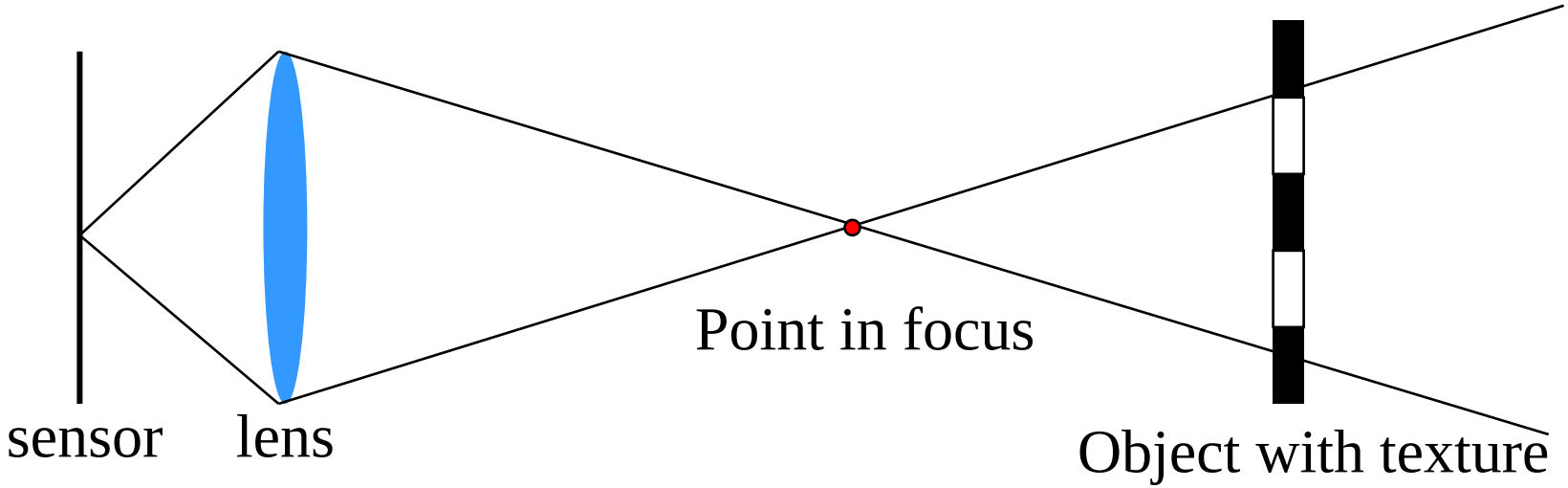
- **Depth of field is NOT a convolution of the image**
- **The circle of confusion varies with depth**
- **There are interesting occlusion effects**
- **(If you really want a convolution, there is one, but in 4D space… more about this in ten days)**

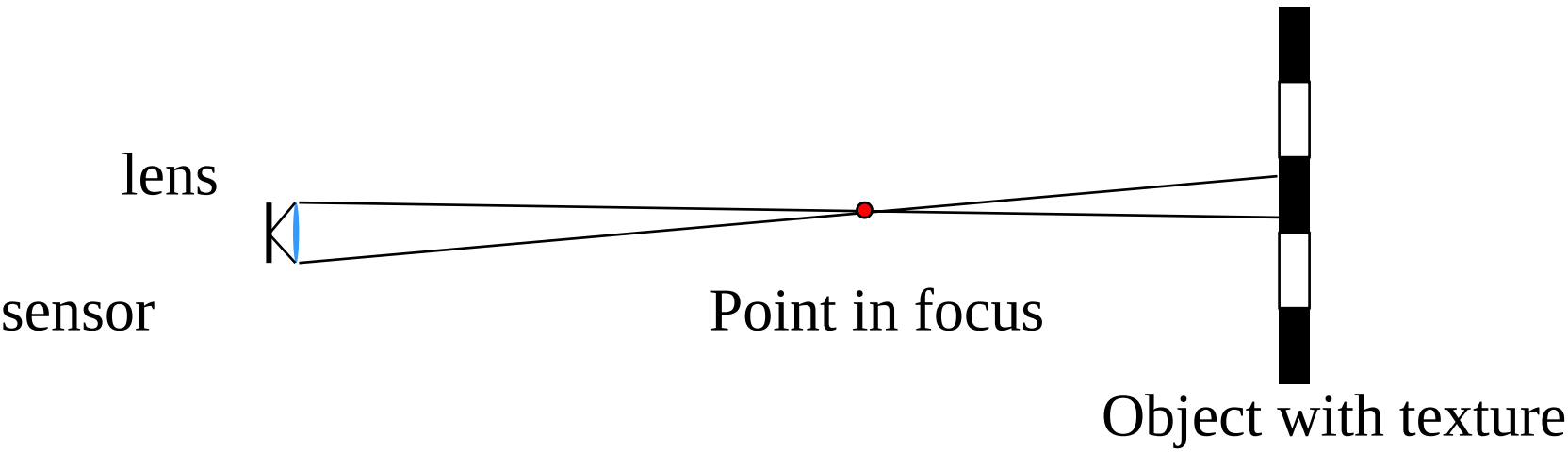
From Macro Photography

Sensor size

Depth of field

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





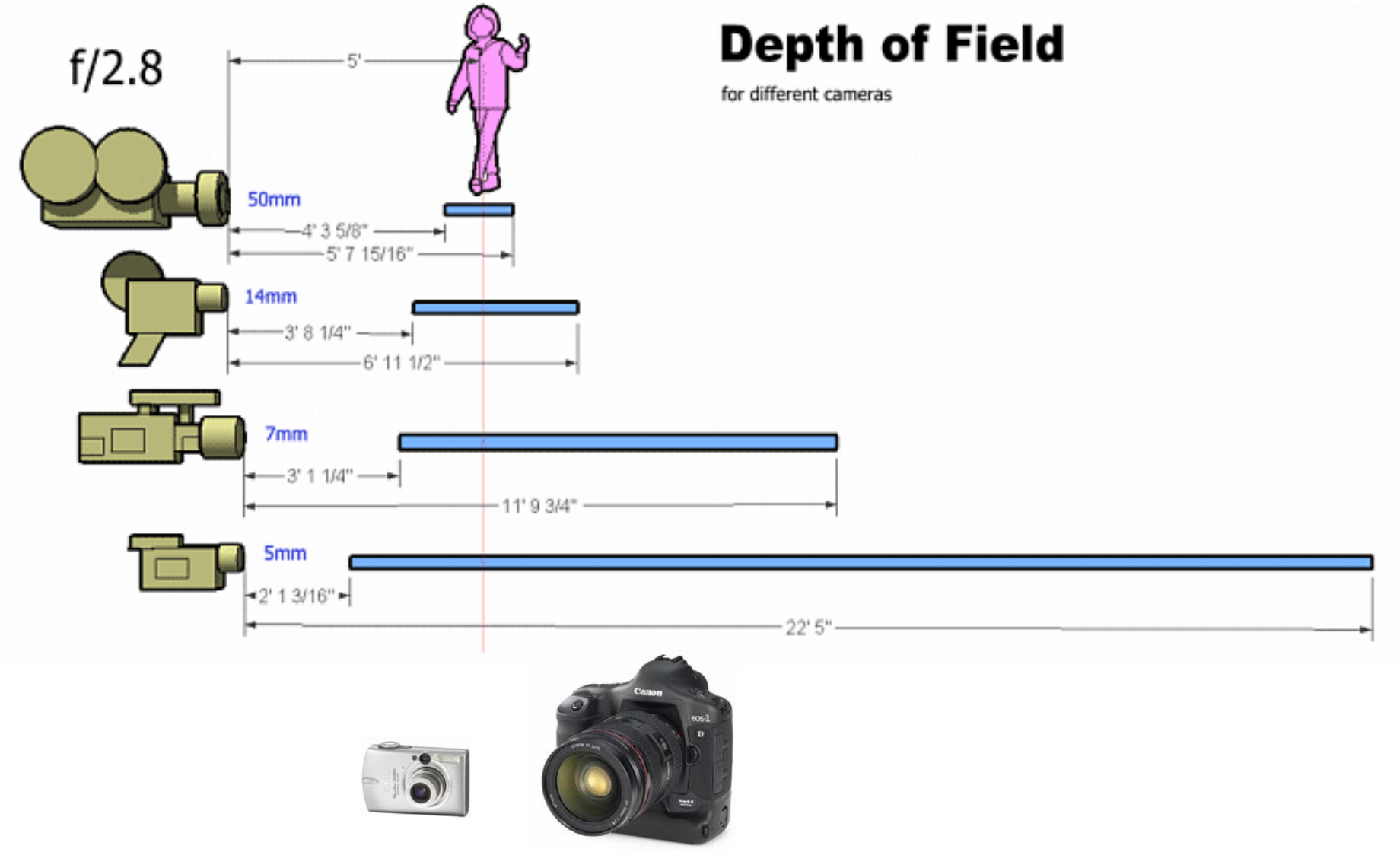
Equation

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

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

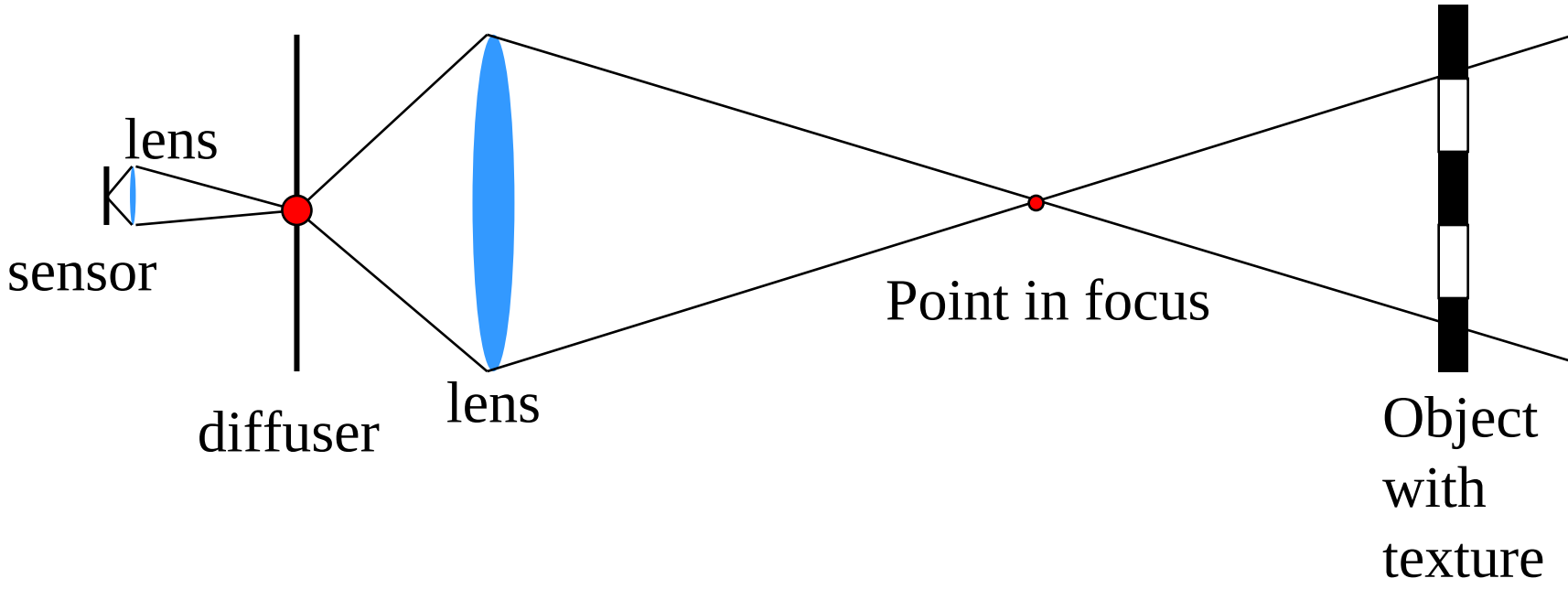
Sensor size

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



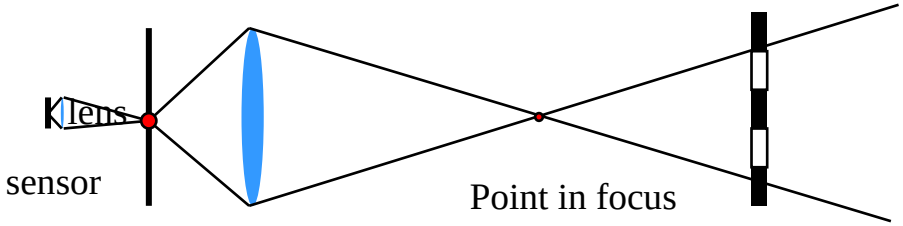
The coolest depth of field solution

- 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



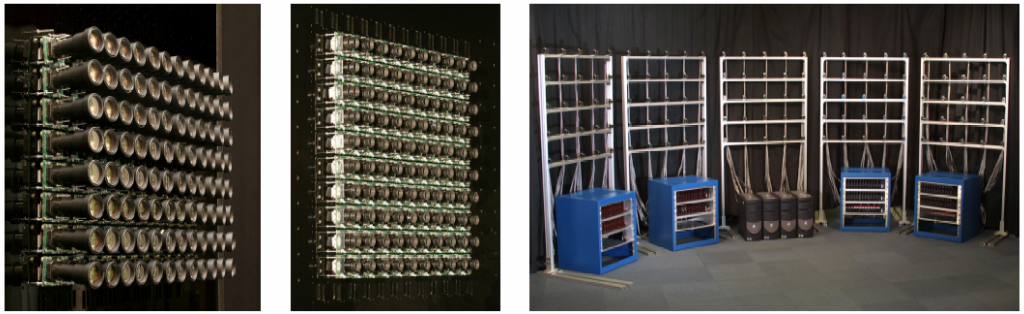
Seeing through occlusion

Seeing beyond occlusion

- **Photo taken through zoo ba**
- **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/)**



(a) (b) (c)

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.

Aperture

Why a bigger aperture

- **To make things blurrier**
  - Depth of field
- **To make things sharper**
  - Diffraction limit

Sharpness & aperture (e.g. for the Canon 50mm f/1.4)

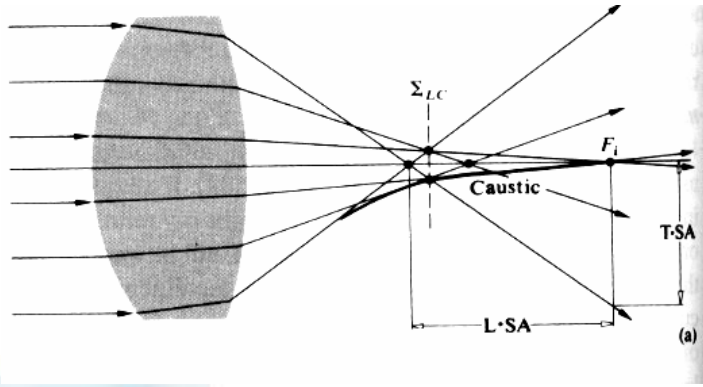
http://www.slrgear.com/reviews/showproduct.php/product/140/sort/2/cat/10/page/3

- **f/1.4: soft (geometrical aberrations), super shallow Dof. Lots of light!**
- **f/2.8 getting really sharp, shallow depth of field**
- **f/5.6: best sharpness**
- **f/16: diffraction kicks in, loses sharpness. But dpoth of field is big**

Soft focus

Soft focus

- **Everything is blurry**
- **Rays do not converge**
- **Some people like it for portrait**



source: Hecht Optics

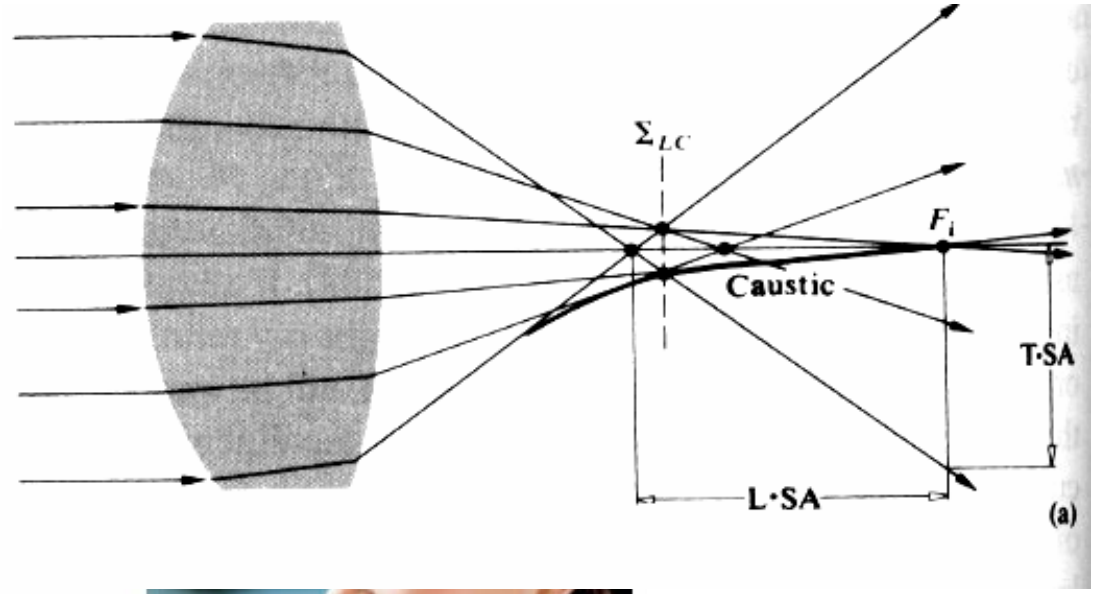
With soft focus lens

Without soft focus lens

Canon red book (Canon 135 f/2.8 soft focus)

Soft focus

- **Remember spherical aberration?**



With soft focus lens

source: Hecht Optics

Soft images

- **Diffuser, grease**
- **Photoshop**
  - Dynamic range issue

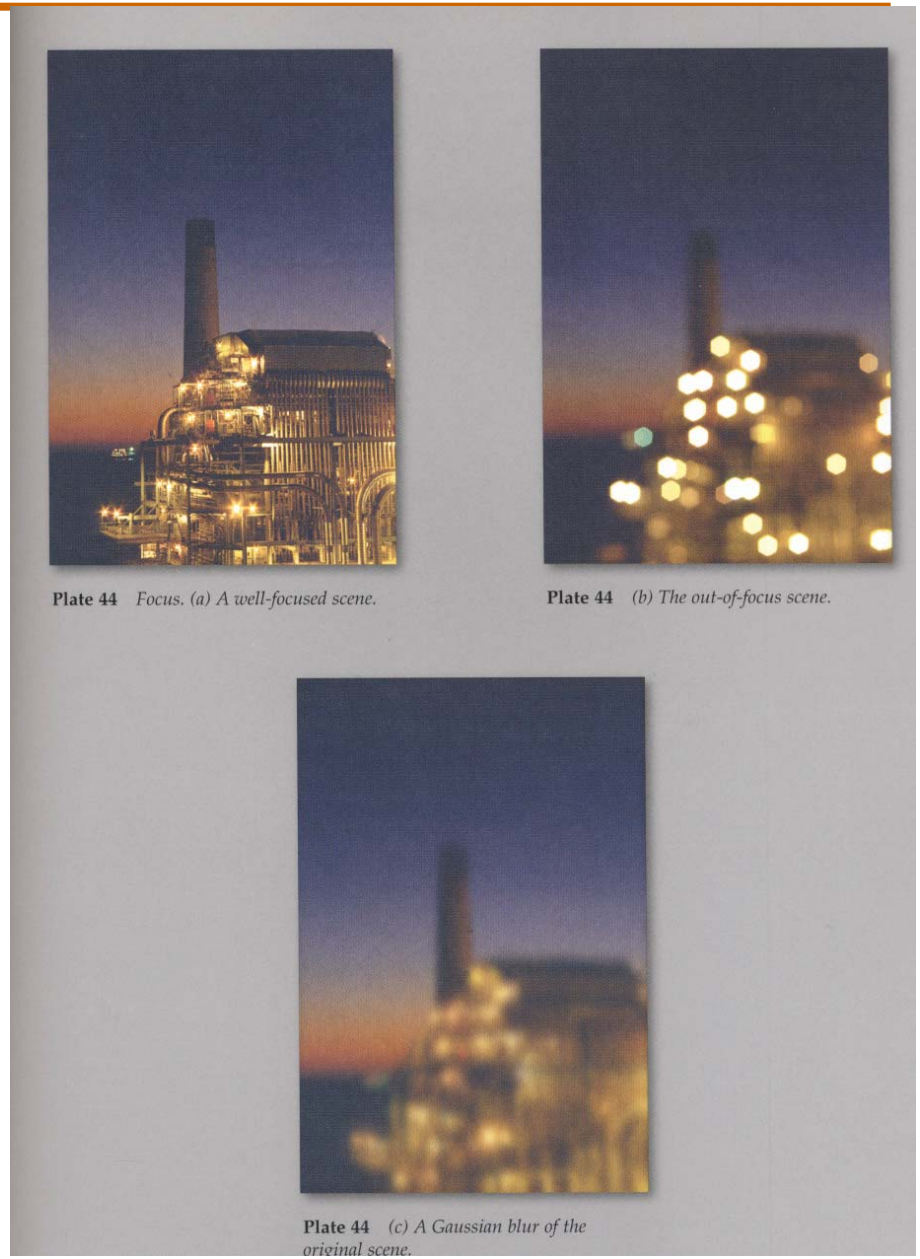


Plate 44 *Focus. (a) A well-focused scene.*

Plate 44 *(b) The out-of-focus scene.*

Plate 44 *(c) A Gaussian blur of the original scene.*

From Brinkmann's Art & Science of Digital Compositing

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/

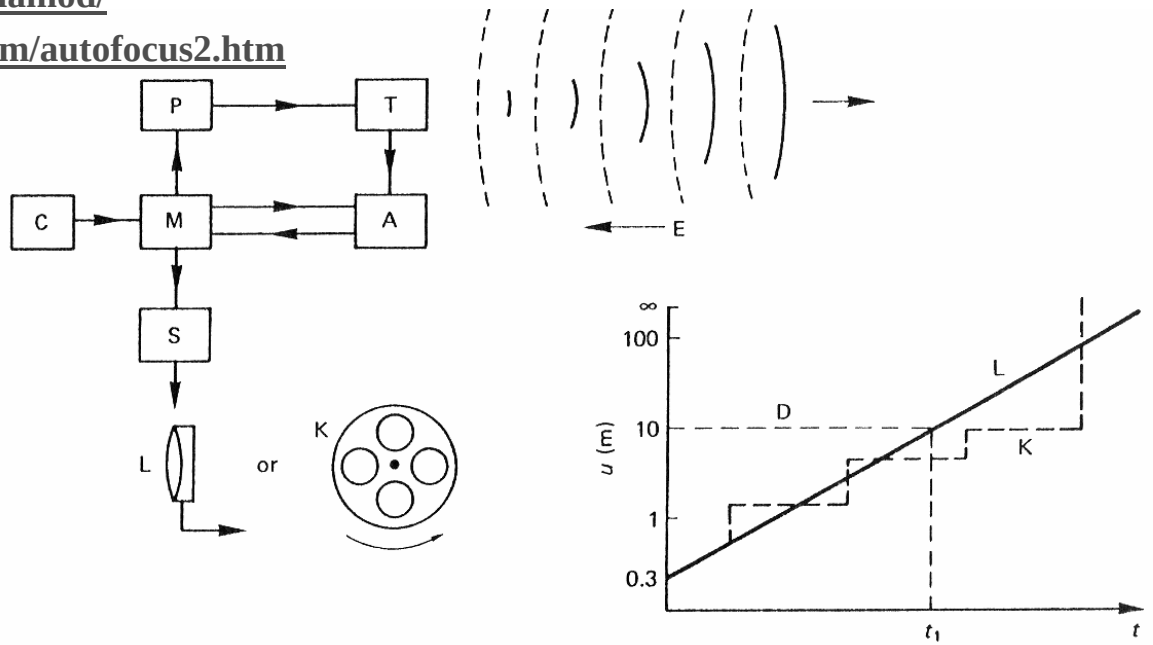
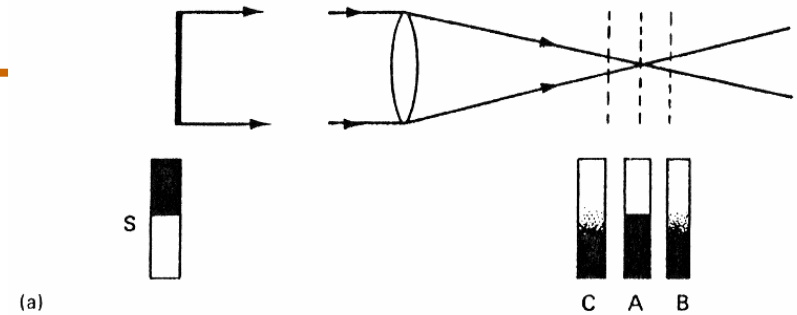
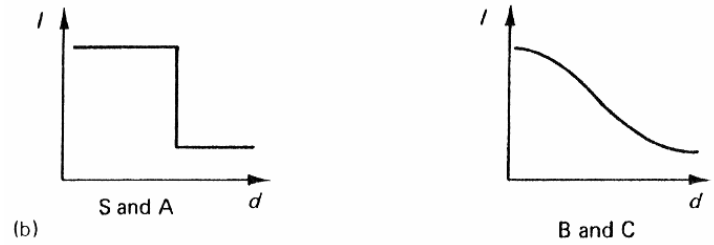


Figure 21.3 Polaroid sonar autofocusing
Ultrasonic pulse emitted by transducer T from power unit P under control of microprocessor M and clock C. Echo E also received by T, digitized by analogue–digital circuitry A, returns to M to control focusing motor S. This halts axial movement of lens L or a rotation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

From Ray's Applied Photographic Optics





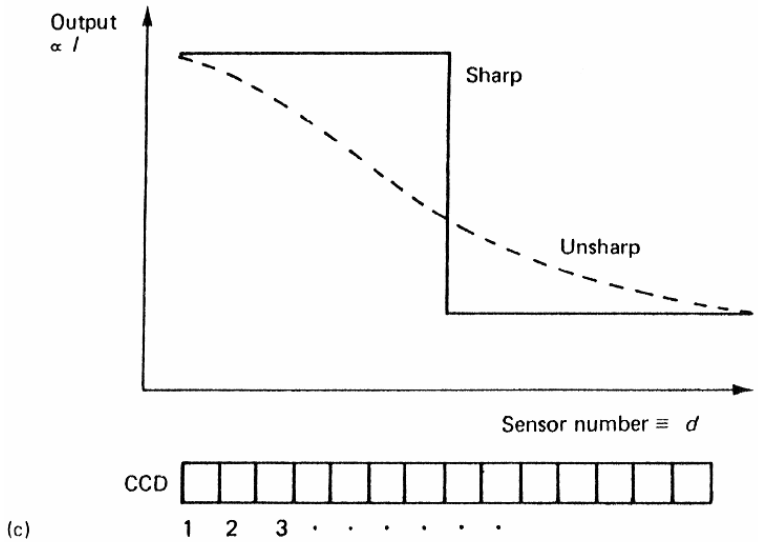


Figure 21.5 Focus detection by a linear CCD array
(a) Subject S imaged in sharp focus at A, but unsharp at C and B. (b) Intensity profiles of S and A and of B and C. (c) Intensity profile as measure of focus determined by linear array of charge coupled devices (CCD) whose output is proportional to intensity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

From Ray's Applied Photographic Optics

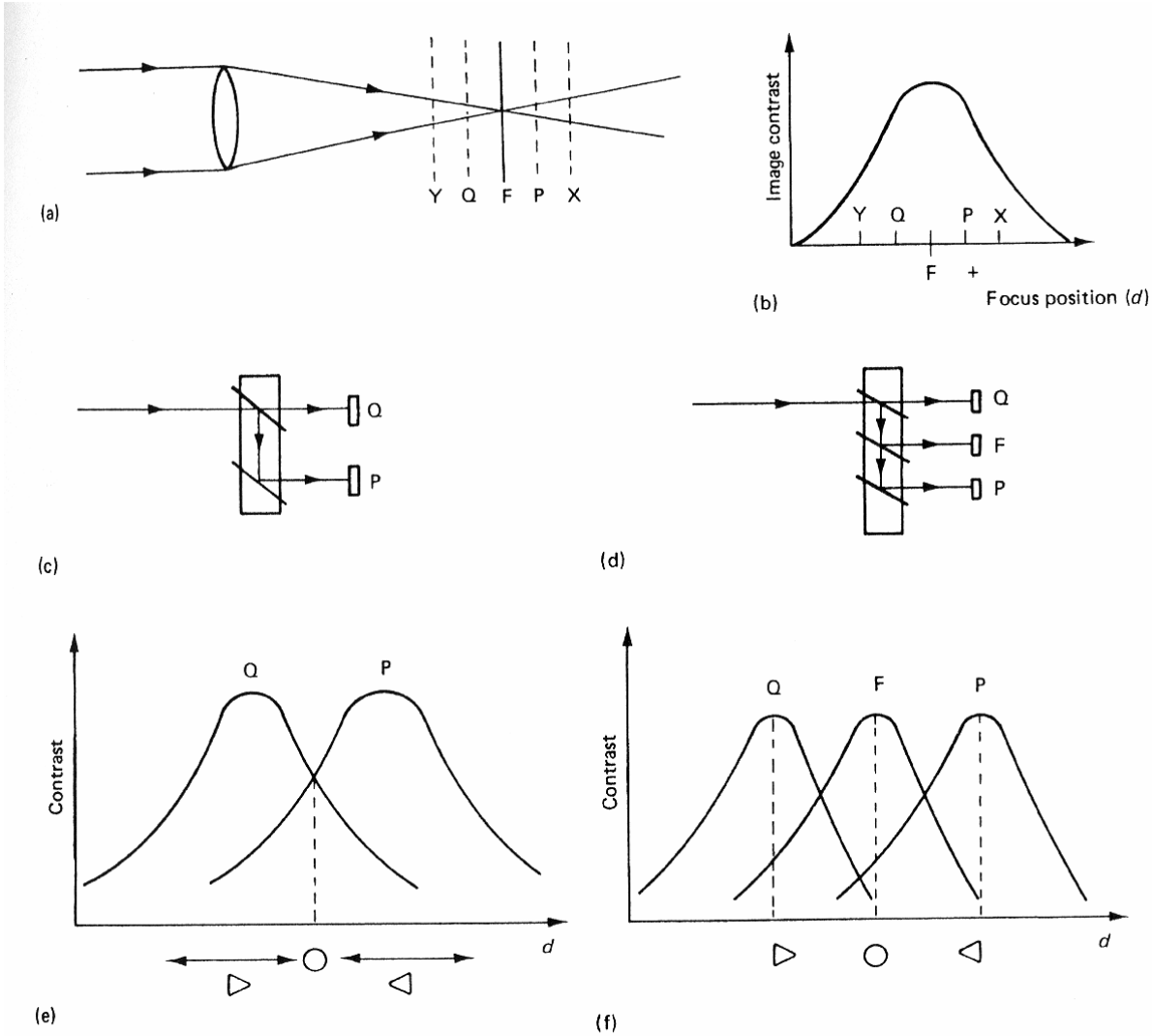
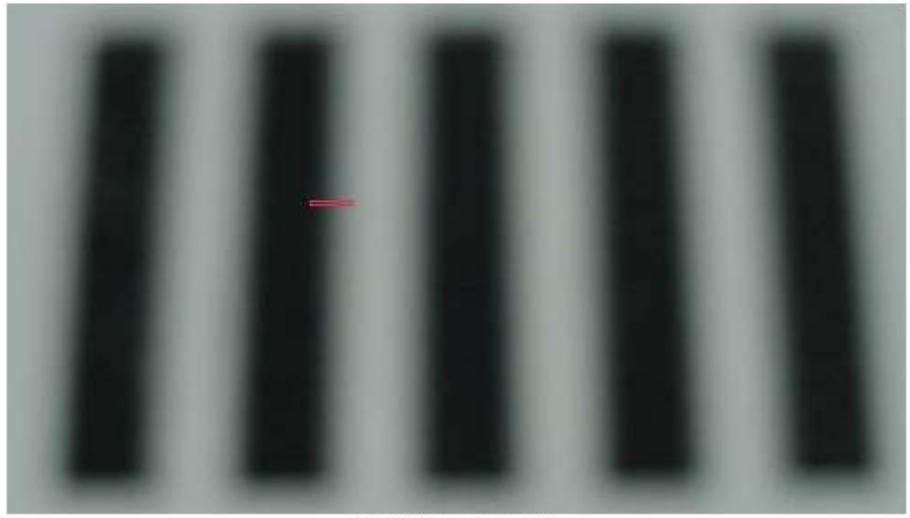


Figure 21.6 Autofocus using image contrast measurements
(a) Sharp image at F with maximum contrast. (b) Variation of contrast with focus position. (c) and (d) Beamsplitters in equivalent focal planes to compare contrast at Q and P or at Q, F and P using linear CCD arrays. (e) and (f) Double or triple 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

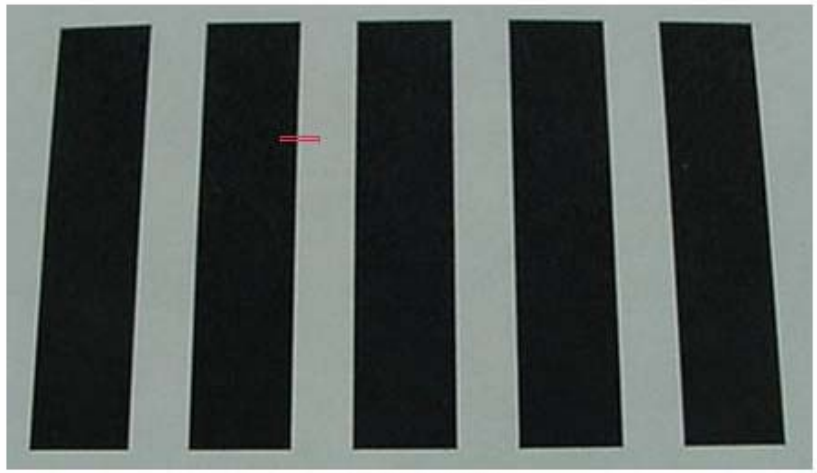
Contrast

- **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**

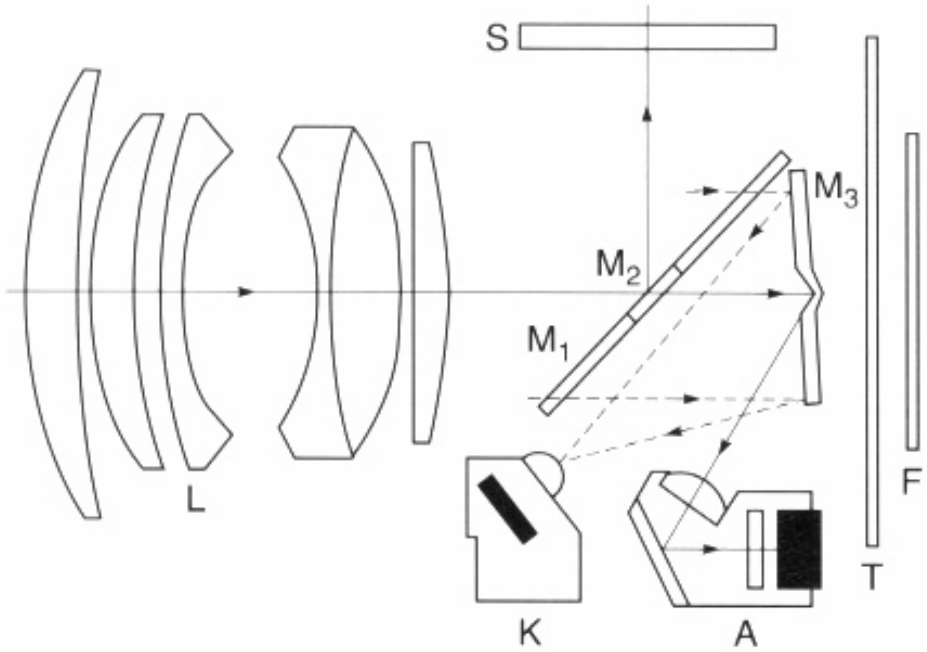
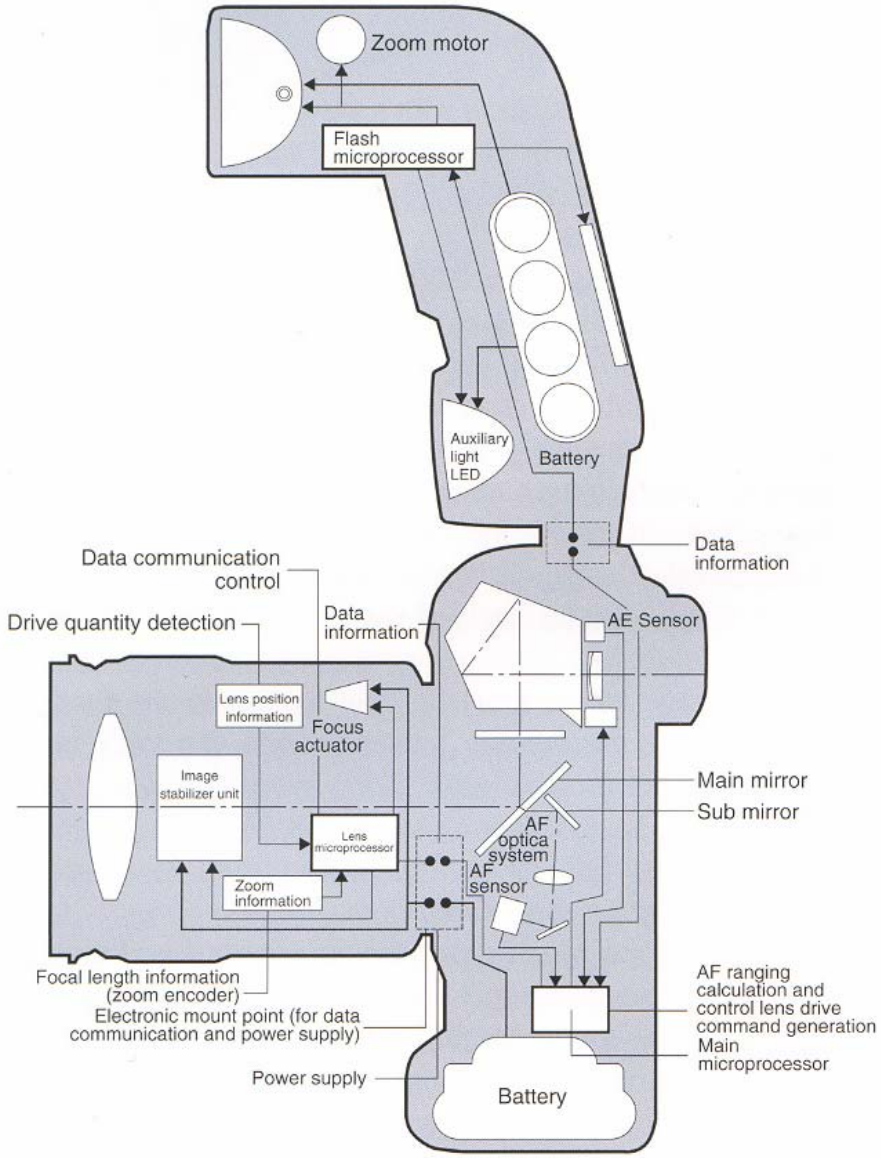


Figure 9.24 Location of autofocus and metering modules. L, camera lens; S, focusing screen; F, film in gate; M_1, reflex mirror with 30 per cent transmission; M_2, central region with 50 per cent transmission; M_3, secondary mirror with two focusing regions; A, autofocus module; K, metering module; spot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

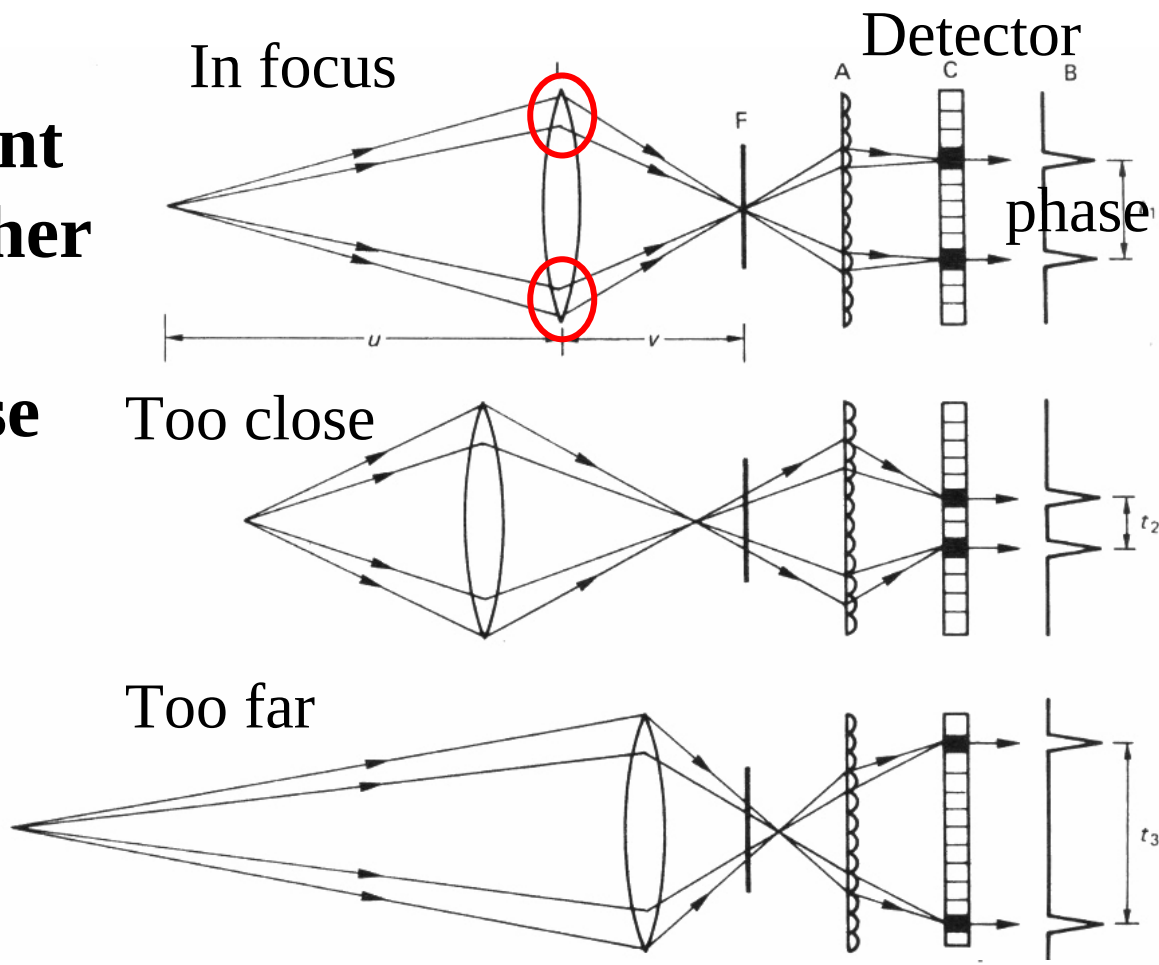


Figure 9.25 Principles of autofocus by phase detection. (a) Subject in focus. (b) Focus in front of subject. (c) Focus beyond subject. Key: L camera lens; F equivalent focal plane; A lenslet array; C CCD linear array; B output signals with time delay t_1 etc.

From The Manual of Photography

Multiple focus sensors

source arthur morris

The Bokeh religion

Bokeh

- http://www.luminous-landscape.com/columns/sm-04-04-

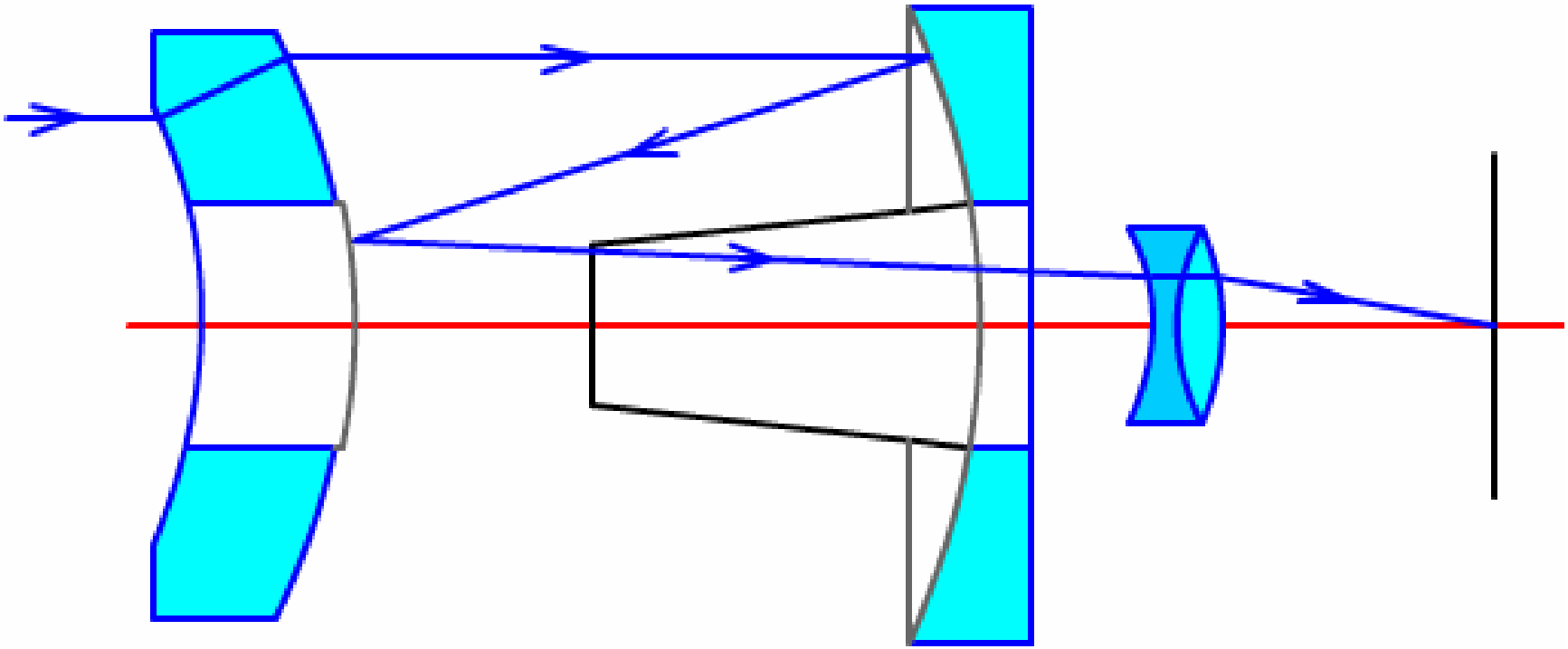
The most obvious way bokeh gets into pictures, of course, is simply as background. In Robert Harrington's cruel but beautiful picture here, for instance, most of the area of the picture is occupied by bokeh, even though it has nothing to do with the subject of the picture. The picture might be as good with a plain white or black background. Still, if you just look at the bokeh as it exists, it's hard to deny that the color and brightness of the out of focus parts contribute to the sense of a certain kind of light, and the feeling of the outdoors.

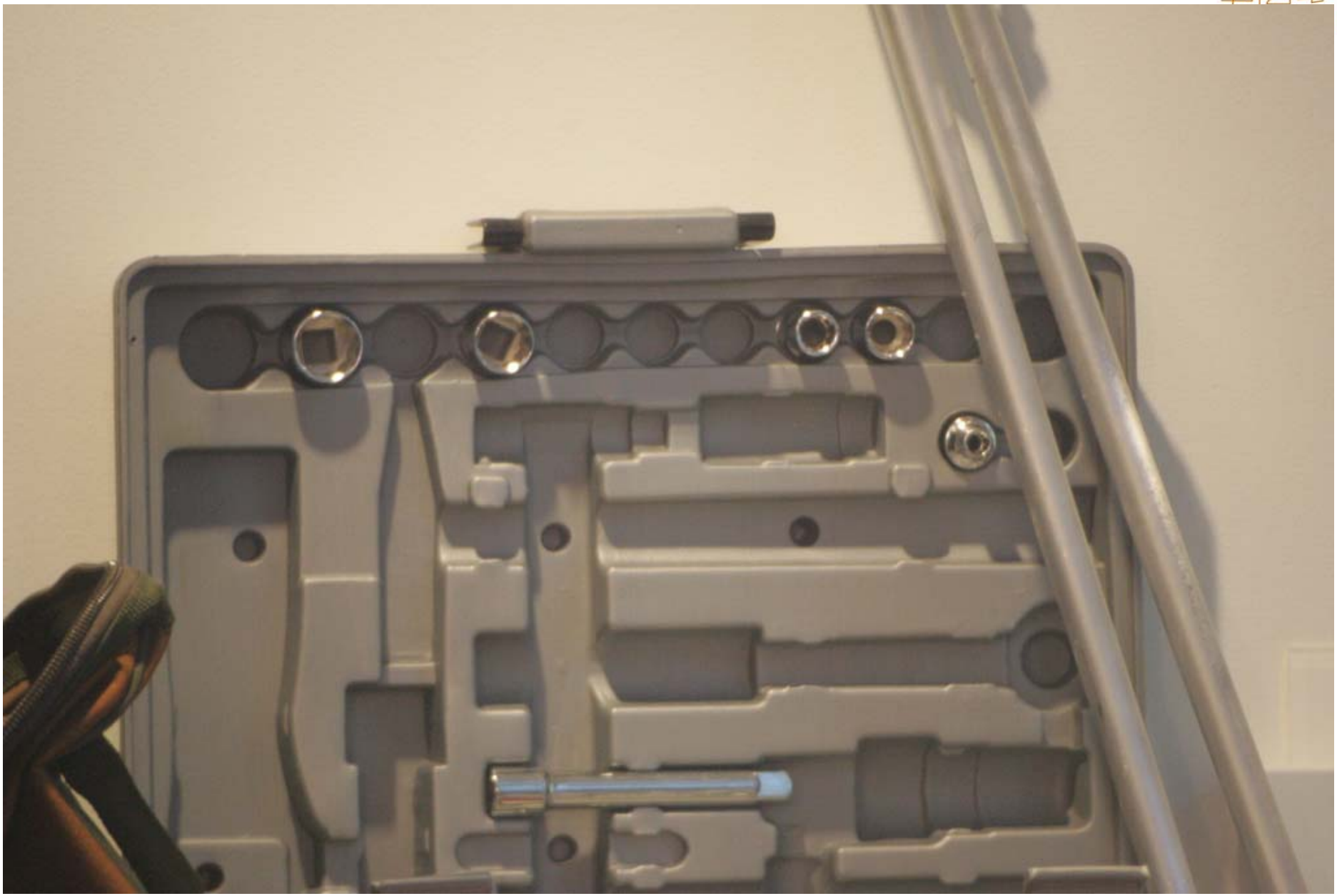
A Distracting Zoom Lens Example of Bad Bokeh

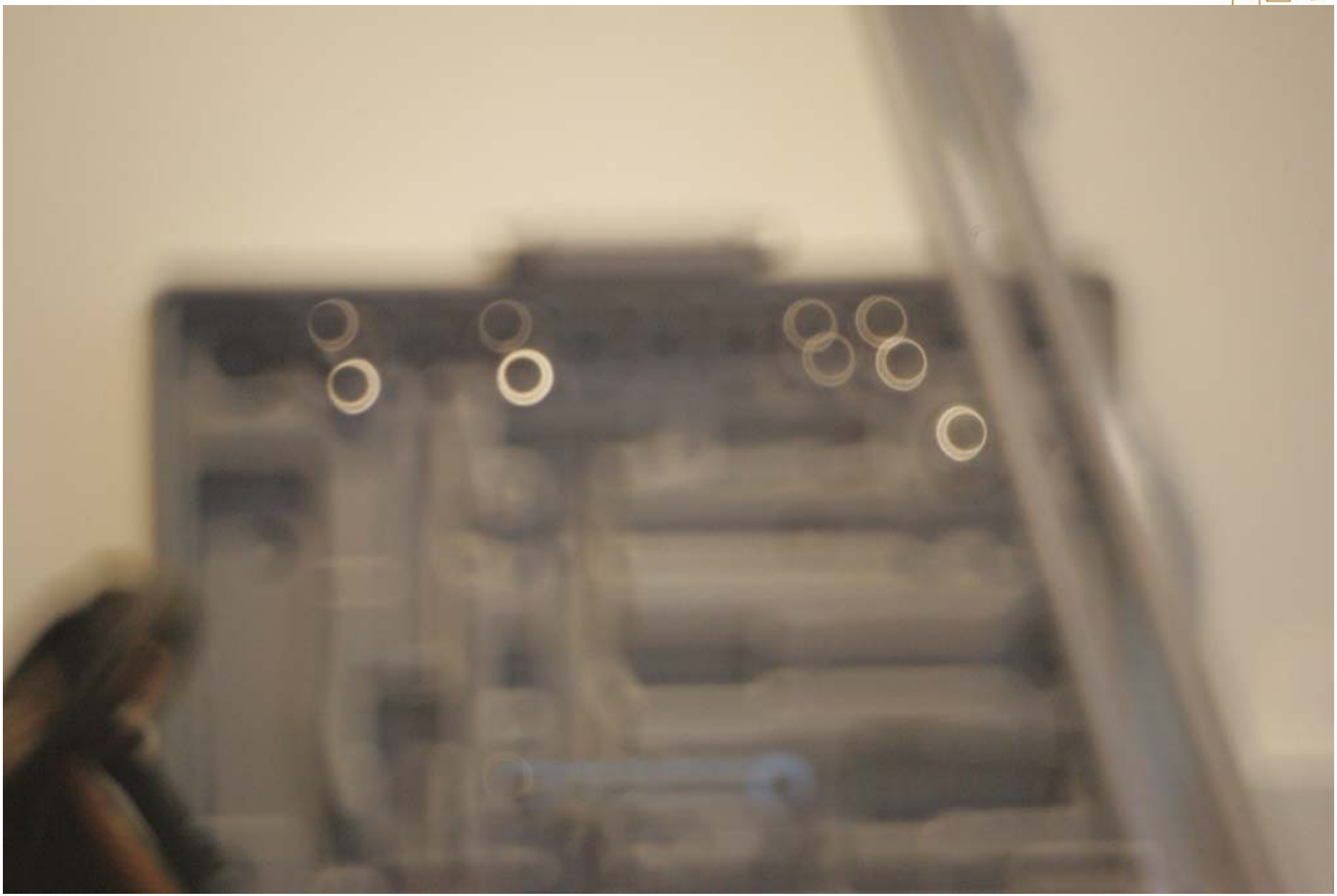
Photo Courtesy of Luis Lopez Penabad - Thank You! (see posting)

catadioptric (mirror)

- http://www.digit-life.com/articles2/rubinar/



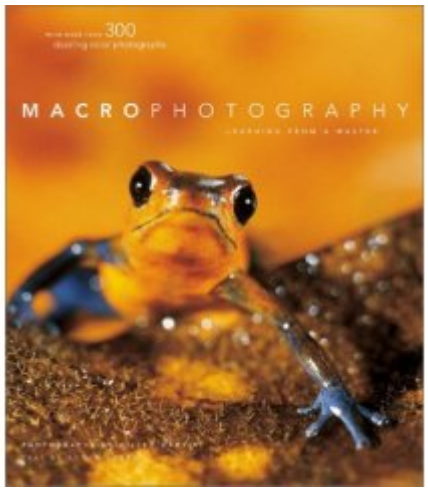




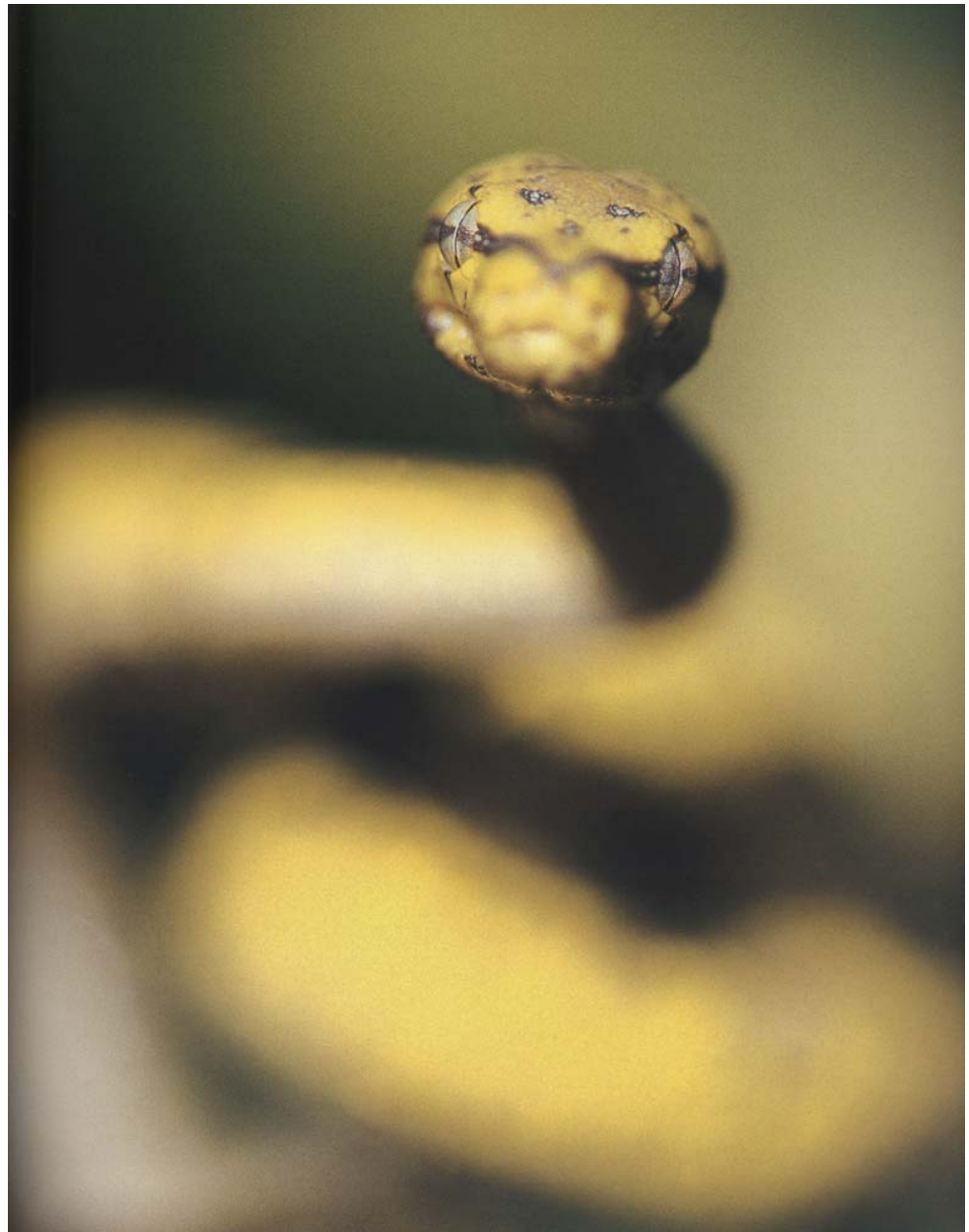
Macro

Macro depth of field is shallow

- **Remember: shallower with smaller focusing distance**



Macrophotography: Learning from a Master



PhotoMontage

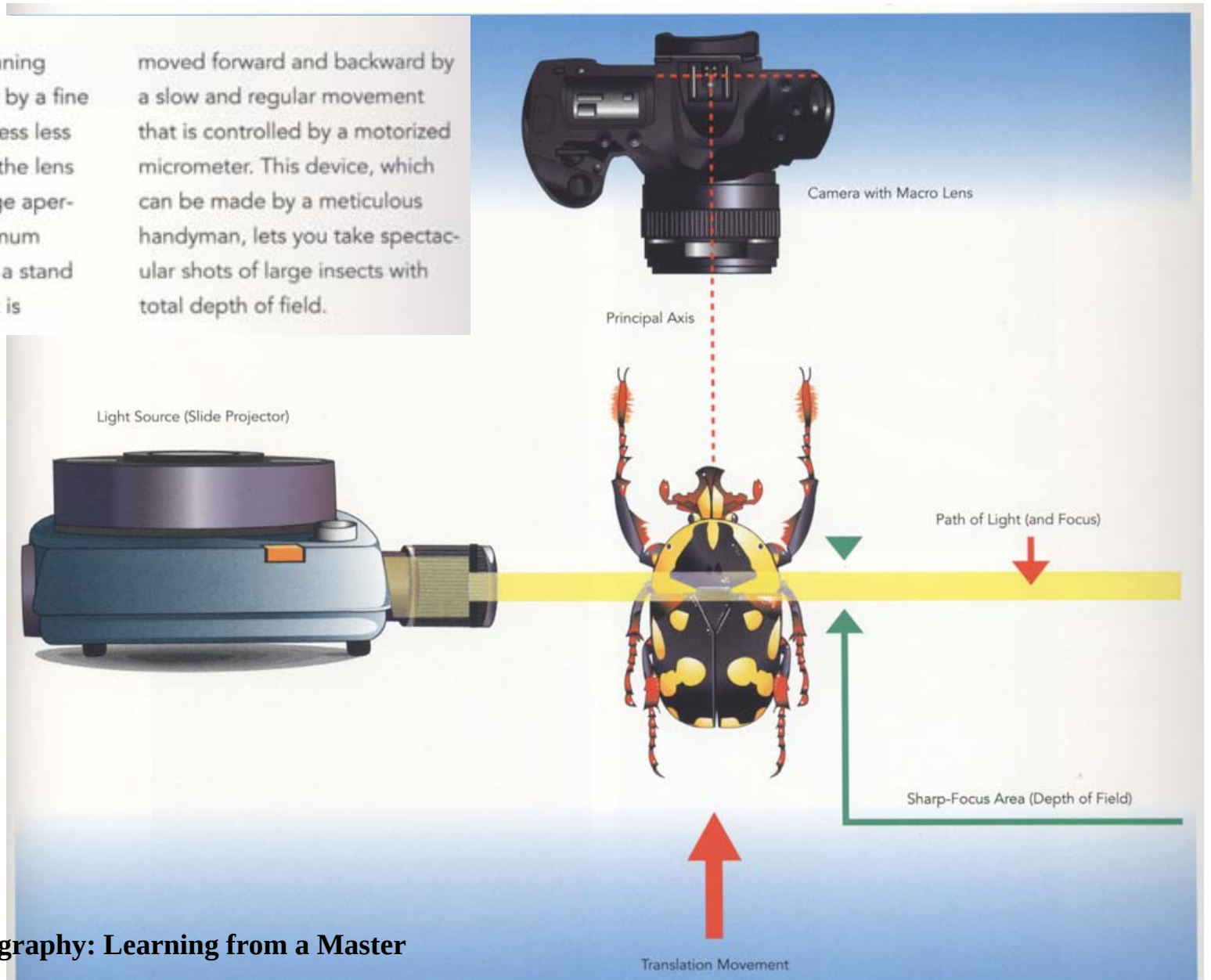
- **Combine multiple photos**

Figure 2 A set of macro photographs of an ant (three of eleven used shown on the left) taken at different focal lengths. We use a global *maximum contrast* image objective to compute the graph-cut composite automatically (top left, with an inset to show detail, and the labeling shown directly below). A small number of remaining artifacts disappear after gradient-domain fusion (top, middle). For comparison we show composites made by Auto-Montage (top, right), by Haeberli's method (bottom, middle), and by Laplacian pyramids (bottom, right). All of these other approaches have artifacts; Haeberli's method creates excessive noise, Auto-Montage fails to attach some hairs to the body, and Laplacian pyramids create halos around some of the hairs.

Macro montage

- http://www.janrik.net/ptools/ExtendedFocusPano12/index.html
- http://www.outbackphoto.com/workflow/wf_72/essay.html
- **55 images here**

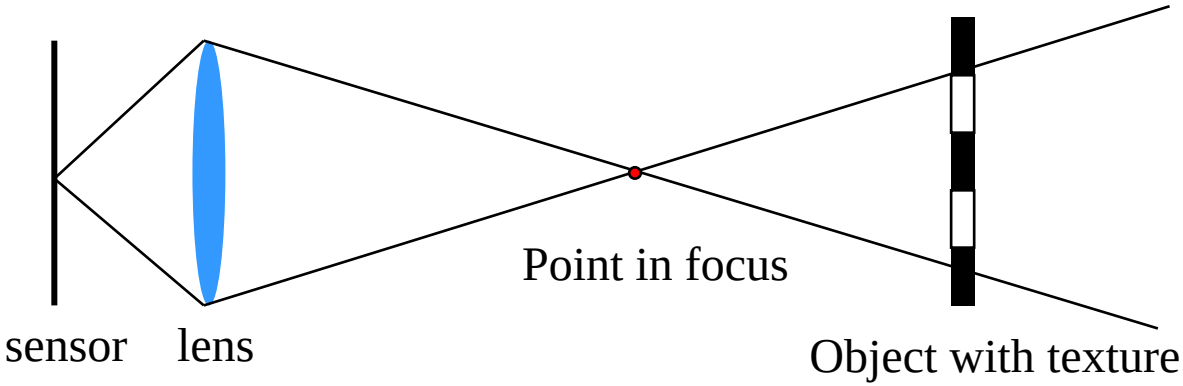
Scanning: combination in 1 exposure

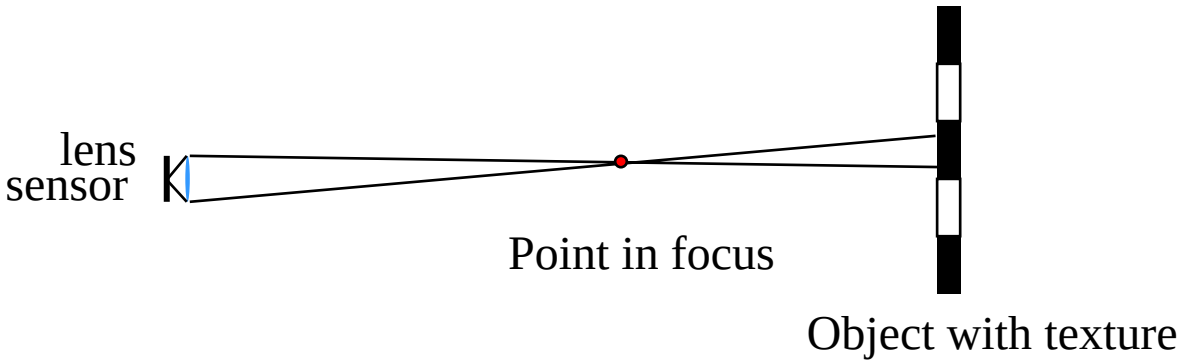


From Macro photography: Learning from a Master

Macro is easy with small sensors

- **1/ minimum focusing distance is way smaller**
- **2/ depth of field is bigger**
- **Summary: you've scaled down the camera, you can take pictures of a scaled-down world**





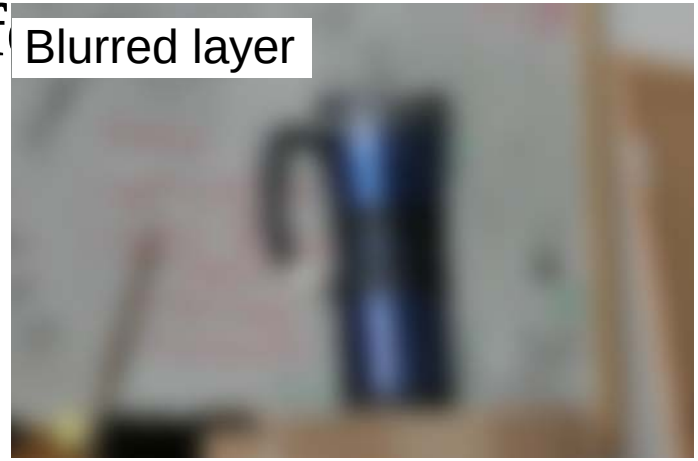
Fake Depth of Field

Photoshop

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

Input (sharp layer)

Blurred layer



Mask of blurry layer)

Result

Photoshop

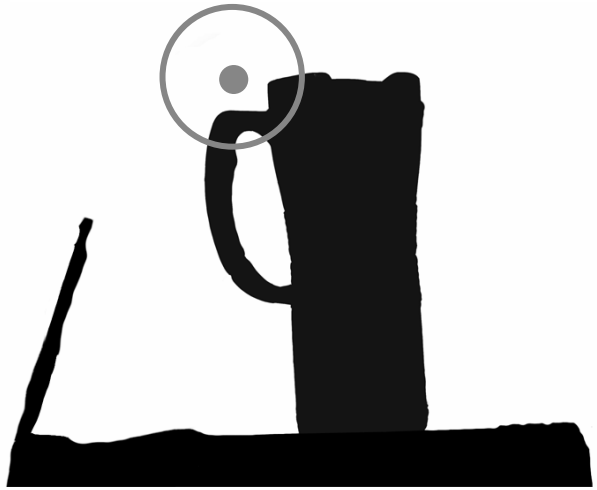
- **Problem: halo around edges**

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)

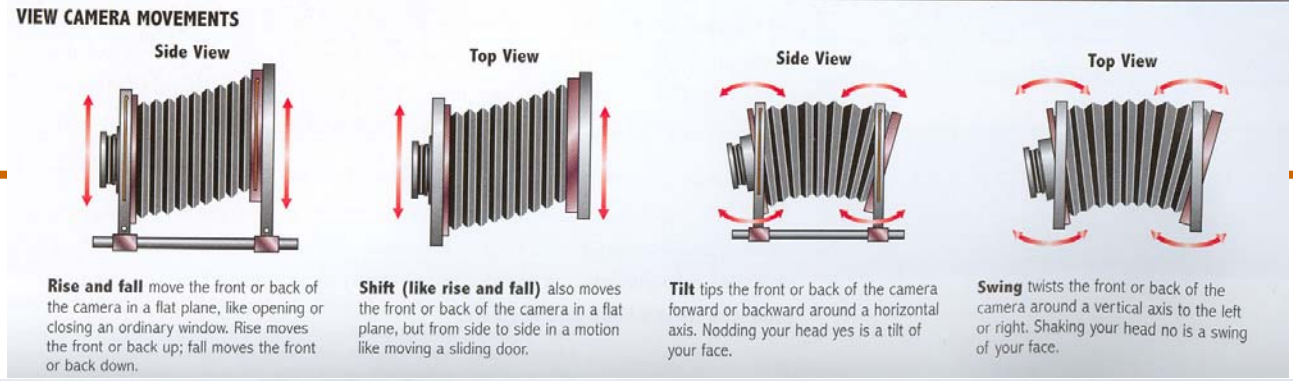


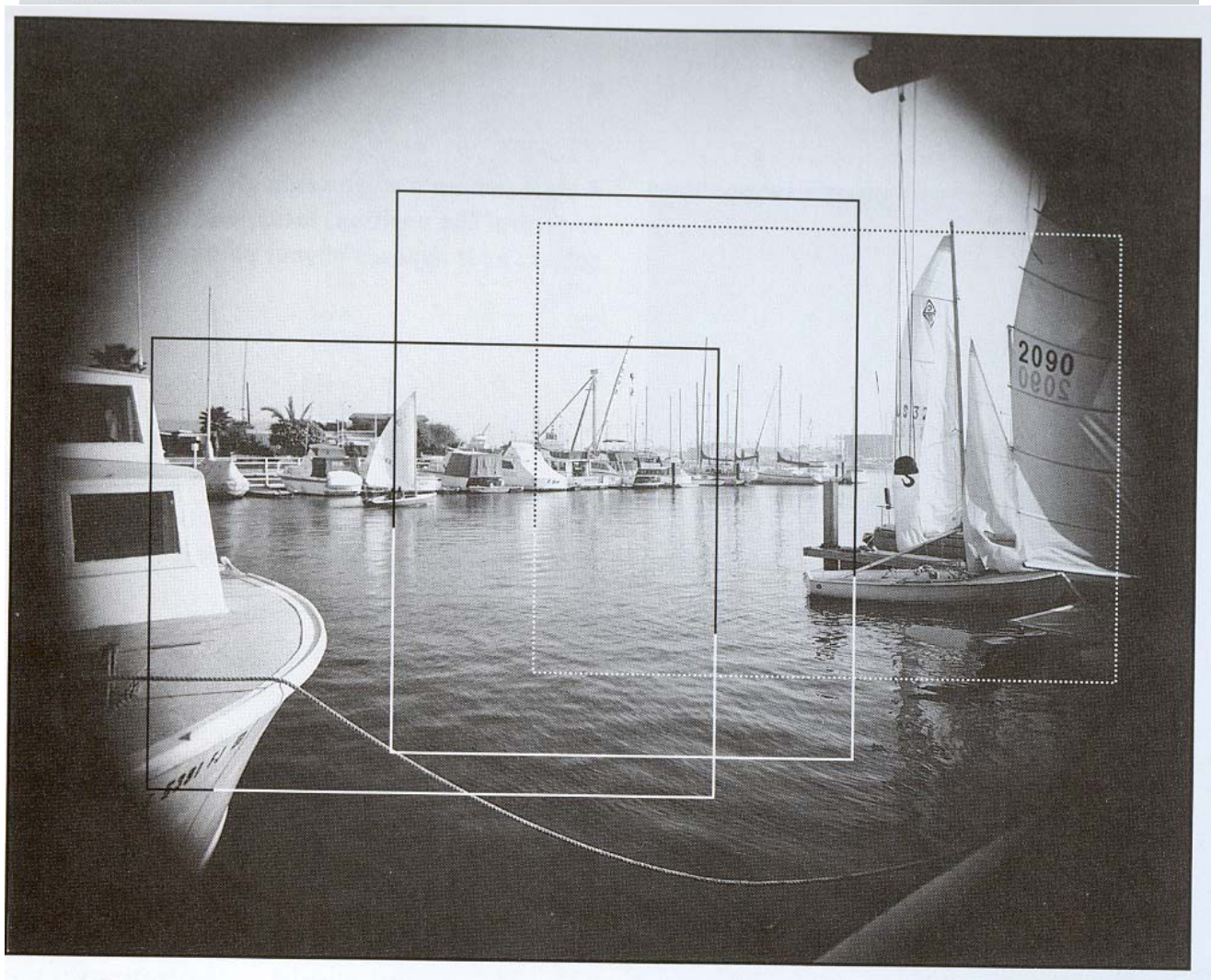
Photoshop lens blur

- **Filter>Blur>Lens blur**

Depth map (painted manually)

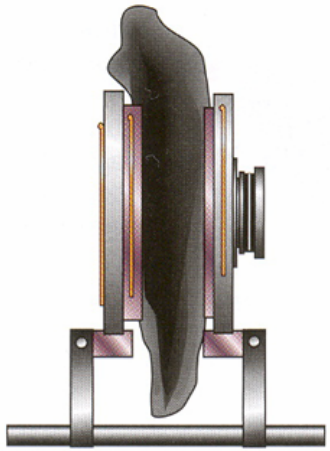
Tilt/Shift camera movements





From Photography, London et al.

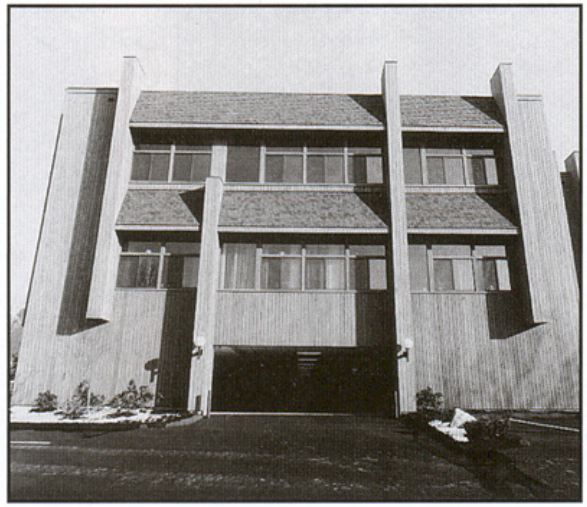
CONTROLLING CONVERGING LINES: THE KEYS

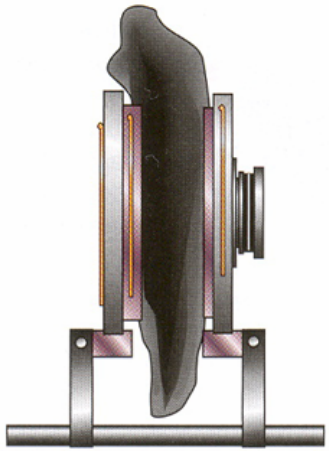


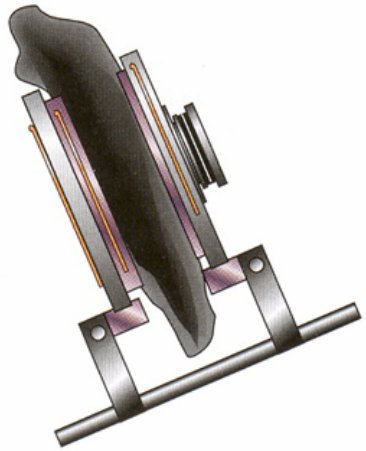
Standing at street level and shooting straight at a building produces too much street and too little building. Sometimes it is possible to move back far enough to show the entire building while keeping the camera level, but this adds even more foreground and usually something gets in the way.

From Photography, London et al.

CONTROLLING CONVERGING LINES: THE KEYSTONE EFFECT





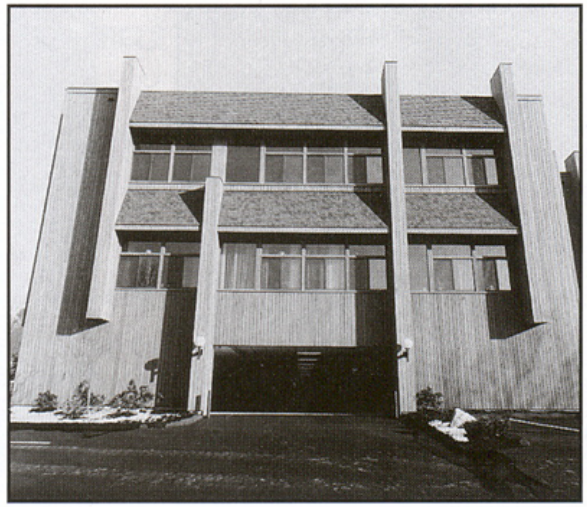


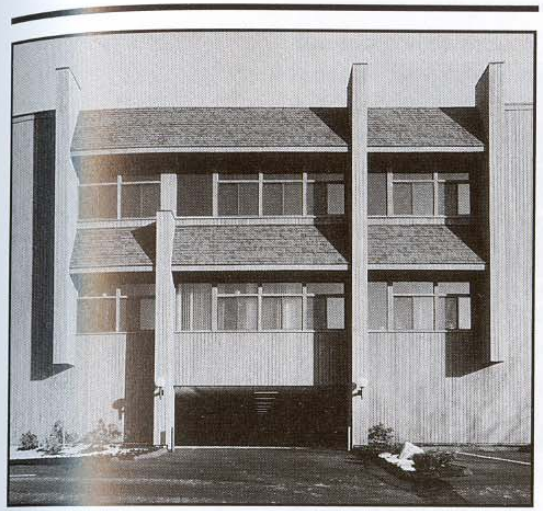
Standing at street level and shooting straight at a building produces too much street and too little building. Sometimes it is possible to move back far enough to show the entire building while keeping the camera level, but this adds even more foreground and usually something gets in the way.

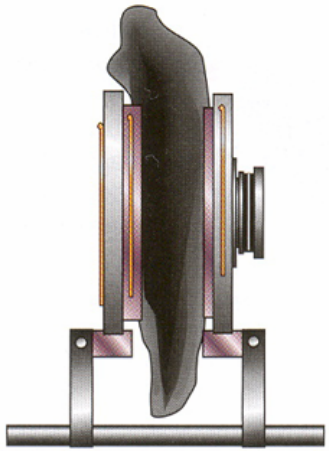
Tilting the whole camera up shows the entire building but distorts its shape. Since the top is farther from the camera than the bottom, it appears smaller; the vertical lines of the building seem to be coming closer together, or converging, near the top. This is named the keystone effect, after the wedge-shaped 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.

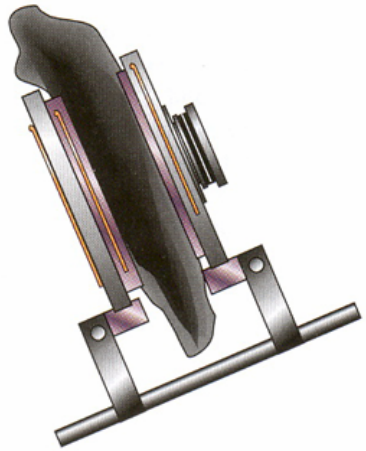
From Photography, London et al.

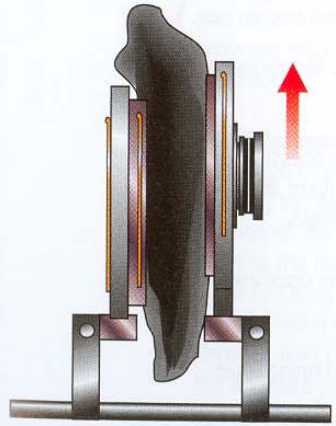
CONTROLLING CONVERGING LINES: THE KEYSTONE EFFECT











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.

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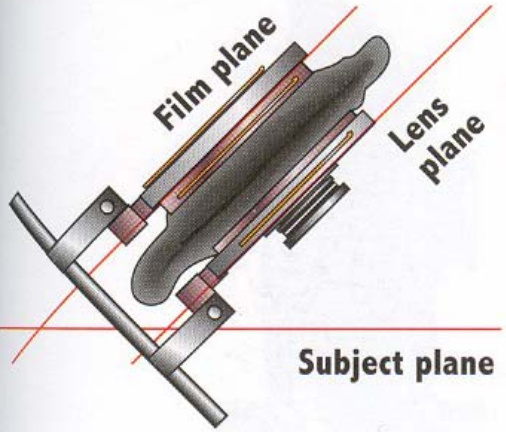
To straighten up the converging vertical lines, keep the camera back parallel to the face of the building. To keep the face of the building in focus, make sure the lens is parallel to the camera back. One way to do this is to level the camera and then use the rising front or falling back movements or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

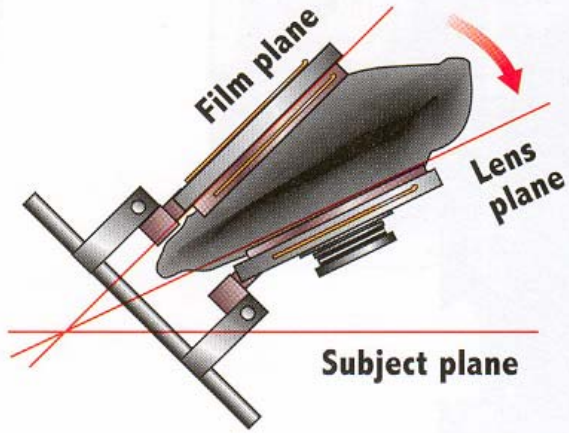
Another solution is to point the camera upward toward the top of the building, then use the tilting movements—first to tilt the back to a vertical position (which squares the shape of the building), then to tilt the lens so it is parallel to the camera back (which brings the face of the building into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

From Photography, London et al.

ADJUSTING THE PLANE OF FOCUS TO MAKE THE ENTIRE SCENE SHARP



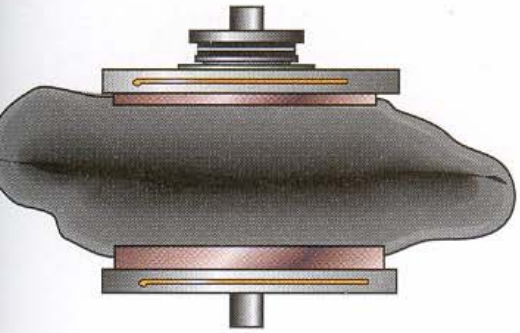
The book is partly out of focus because the lens plane and the film plane are not parallel to the subject plane. Instead of a regular accordion bellows, the diagrams show a bag bellows that can bring camera front and back closer together for use with a short focal-length lens.



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

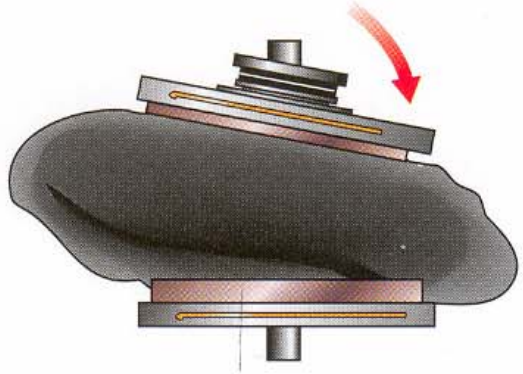
From Photography, London et al.

ADJUSTING THE PLANE OF FOCUS TO MAKE ONLY PART OF THE SCENE SHARP



Top view

Here the photographer wanted just the spilled beans sharp, not those in the foreground and background jars.



A swing of the camera front to the right moves the plane of focus to angle along the receding pile of beans. The photographer opened up the lens to its maximum of f/5.6, which throws the other jars out of focus and directs attention to the beans.

From Photography, London et al.

Scheimpflug's rule

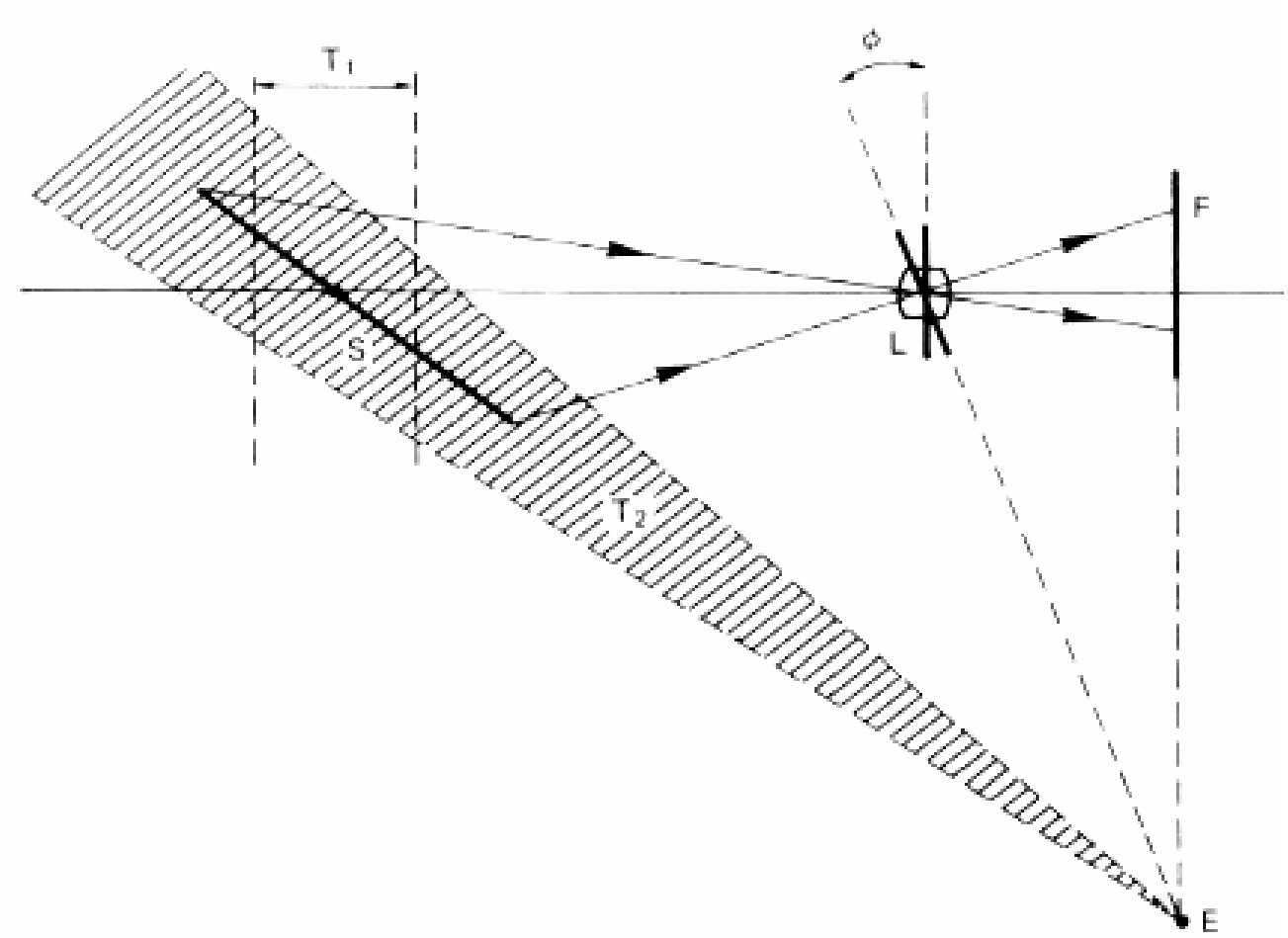
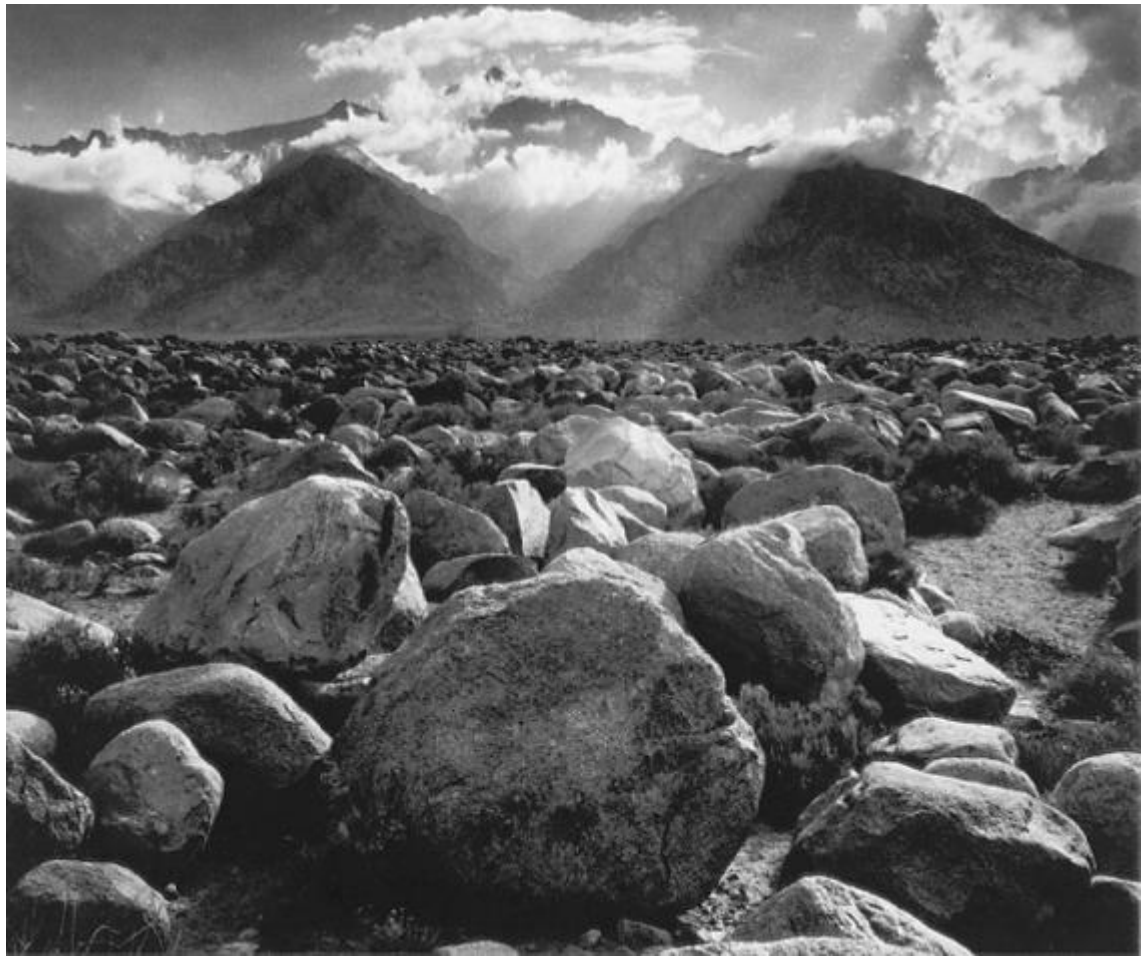


Figure 10.12 Depth of field and camera movements. The inclined subject S is not fully within the depth of field T_1 until lens is rotated through angle ϕ to satisfy Scheimpflug's rule, locating S within depth-of-field zone T_2

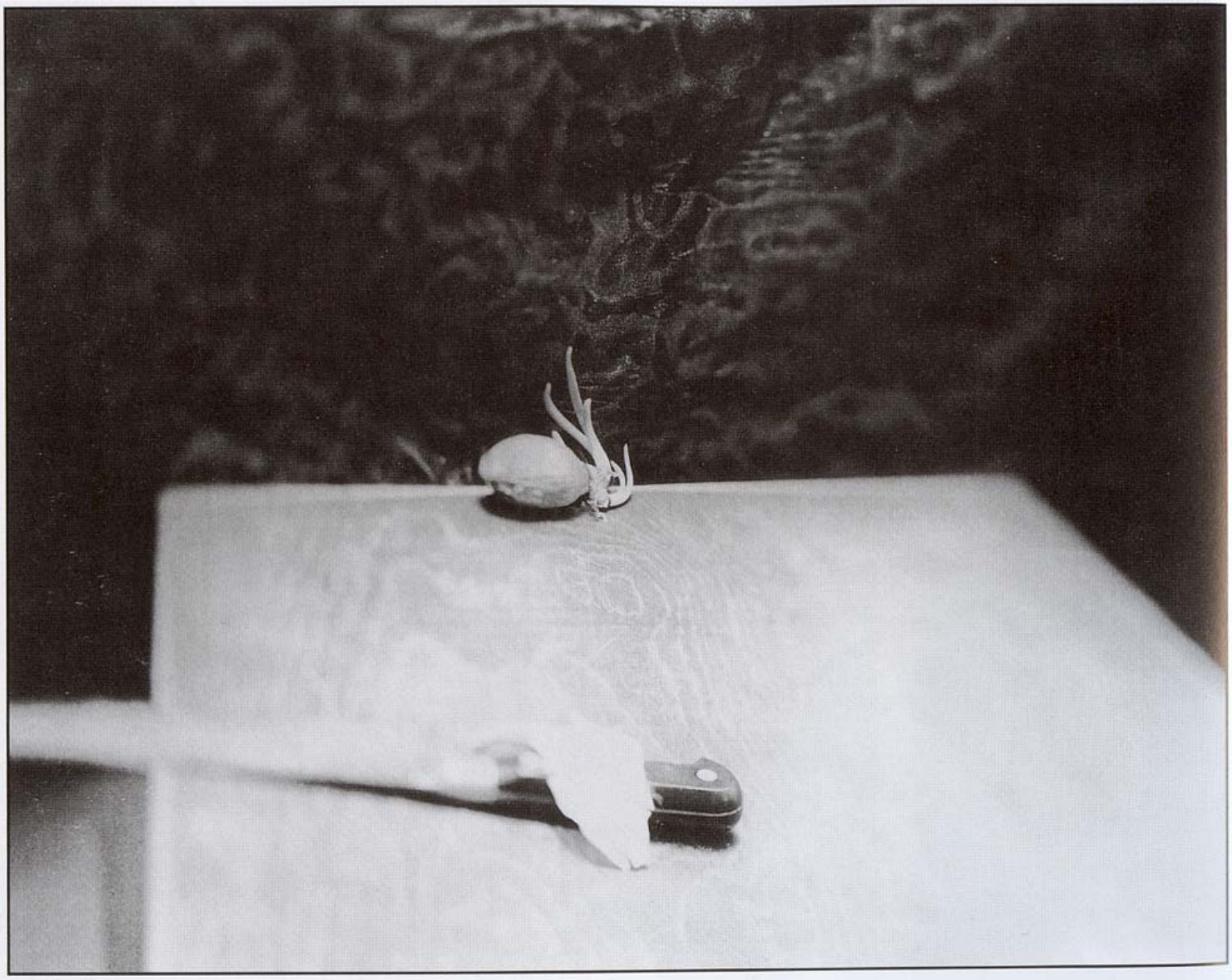
From The Manual of Photography

- **Useful for landscape to get depth of field from foreground to infinity**



Ansel Adams

- **Useful for landscape to get depth of field from foreground to infinity**



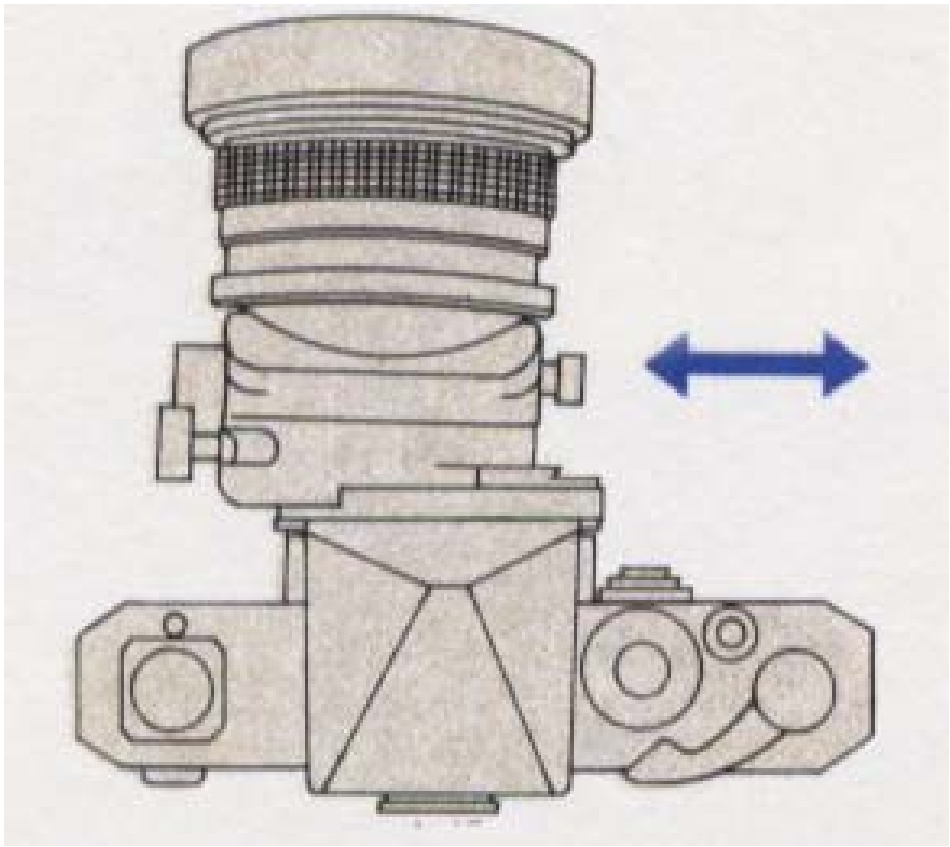
JAN GROOVER Untitled, 1985

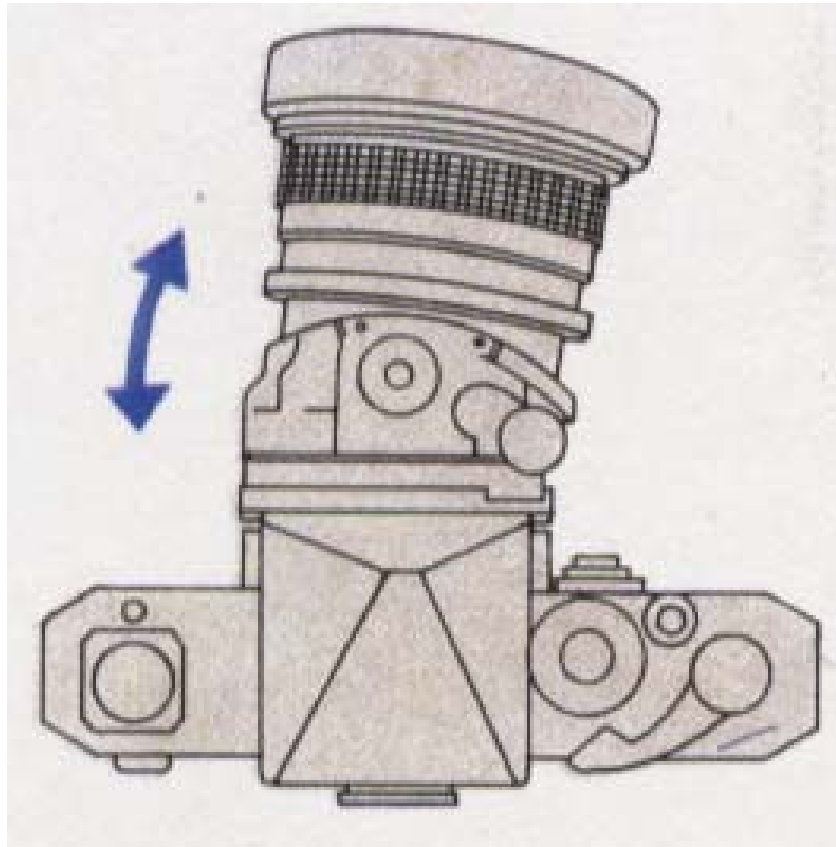
Swinging the camera front to the left or right manipulates the plane of focus. *In this austere still life, the plane of focus is almost at a right angle to the film plane. The objects are commonplace, but the scene is subject to interpretation.*

From Photography, London et al.

Tilt-shift lens

- **35mm SLR version**





Tilt

From Macro photography: Learning from a Master

Olivo Barbieri's model world.

An aqueduct on the periphery of Rome

http://www.metropolismag.com/cda/story.php?artid=1760

Olivo Barbieri's model world.

Paris Hotel and Casino, Las Vegas

http://www.metropolismag.com/cda/story.php?artid=1760

Olivo Barbieri's model world.

Santa Monica Pier, Los Angeles

http://www.metropolismag.com/cda/story.php?artid=1760

Related links

- **By the way, here are a number of links to people doping similar things,**
  http://blog.so-net.ne.jp/photolog/archive/c22183
  http://www.belfastexposed.com/exhibitions/2001/exhimertom.html
  http://www.arte.fi/media/gaal_media.htm
  http://hame.ca/blog3/tiltshift/gallery/
  http://www.flickr.com/groups/tiltshift/
  http://thphotos.com/art-fs.html
  http://www.mo-artgallery.nl/fahlenkampwphr.htm
  many of them inspired by Barbieri
  See in particular
  http://hame.ca/tiltshift.htm
  for many links and info

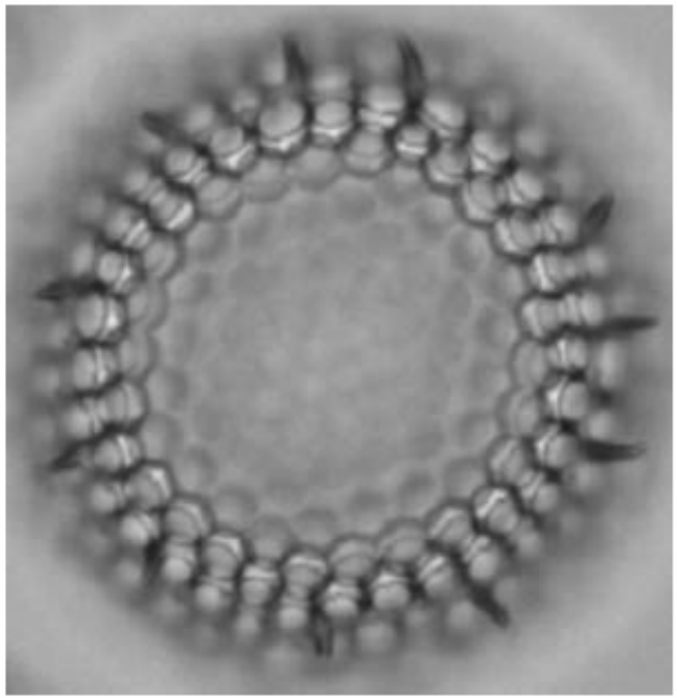
  The lensbaby is a recent popular tool to create related effects:
  http://lensbabies.com/pages/gallery.php?dyer

  And here is an interesting article that tells you how to achieve similar effects with Photoshop
  http://recedinghairline.co.uk/tutorials/fakemodel/
  with interesting reflections about when it works
  (light quality, viewpoint)

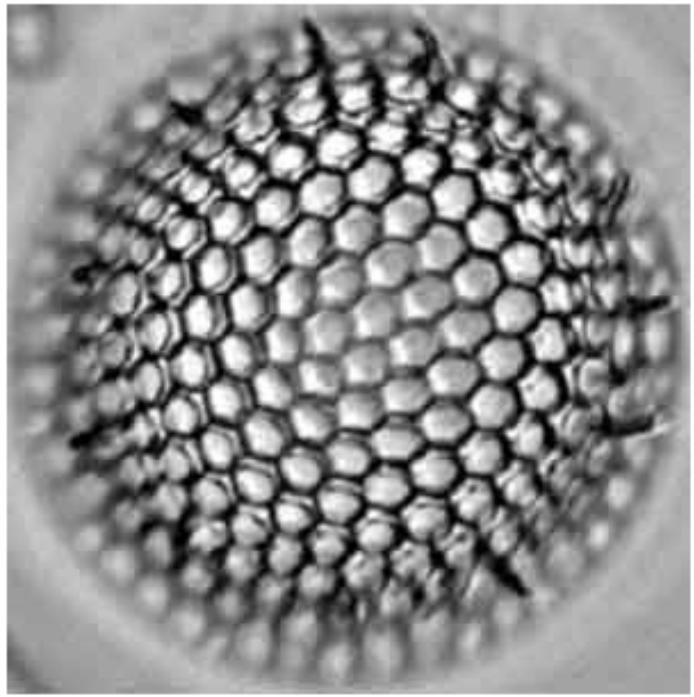
Wavefront coding

Wavefront coding

- **CDM-Optics, U of Colorado, Boulder**
- **The worst title ever: "A New Paradigm for Imaging Systems", Cathey and Dowski, Appl. Optics, 2002**
- **Improve depth of field using weird optics & deconvolution**



Single-cell algae imaged without wavefront coding.



Single-cell algae imaged with wavefront coding.

Wavefront coding

- **Idea: deconvolution to deblur out of focus regions**
- **Convolution = filter (e.g. blur, sharpen)**
- **Sometimes, we can cancel a convolution by another convolution**
  - Like apply sharpen after blur (kind of)
  - This is called deconvolution
- **Best studied in the Fourier domain (of course!)**
  - Convolution = multiplication of spectra
  - Deconvolution = multiplication by inverse spectrum

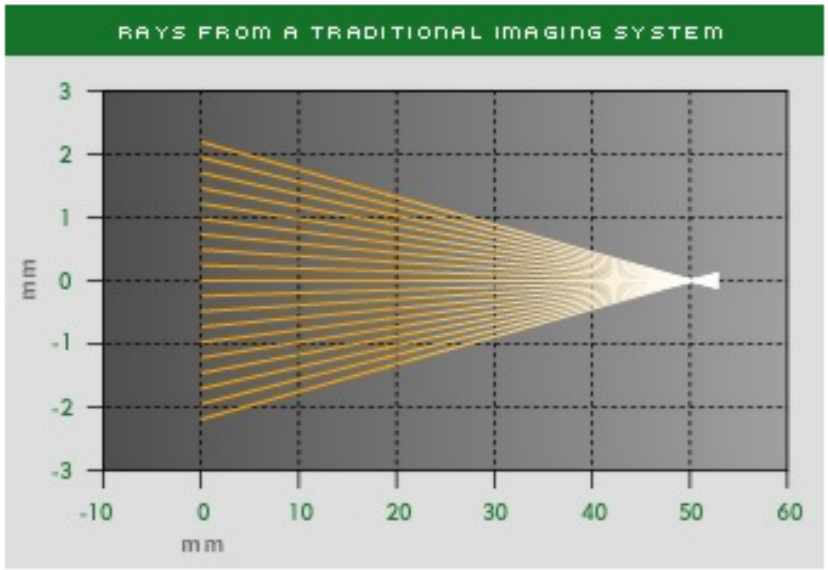
Wavefront coding

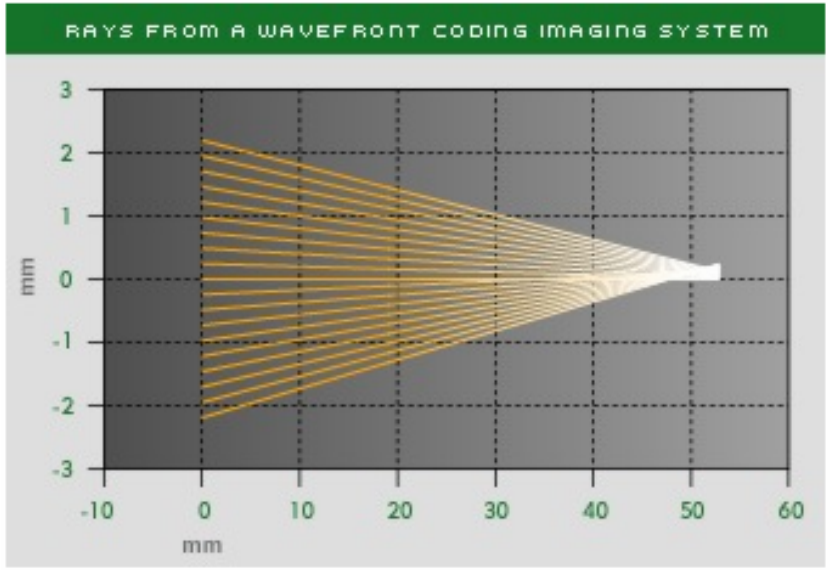
- **Idea: deconvolution to deblur out of focus regions**
- **Problem 1: depth of field blur is not shift-invariant**
  - Depends on depth
  - Blur is not a convolution, hard to use deconvolution
- **Problem 2: Depth of field blur "kills information"**
  - Fourier transform of blurring kernel has lots of zeros
  - Deconvolution is ill-posed

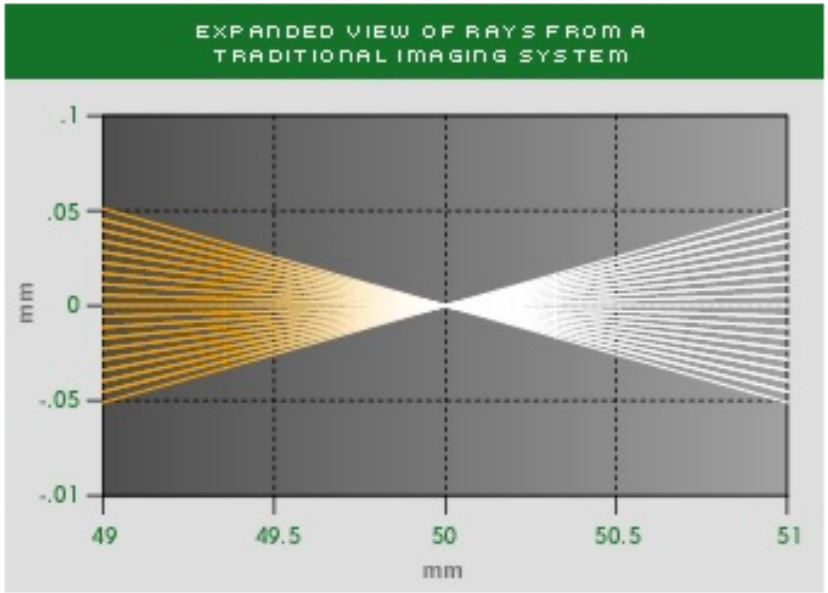
Wavefront coding

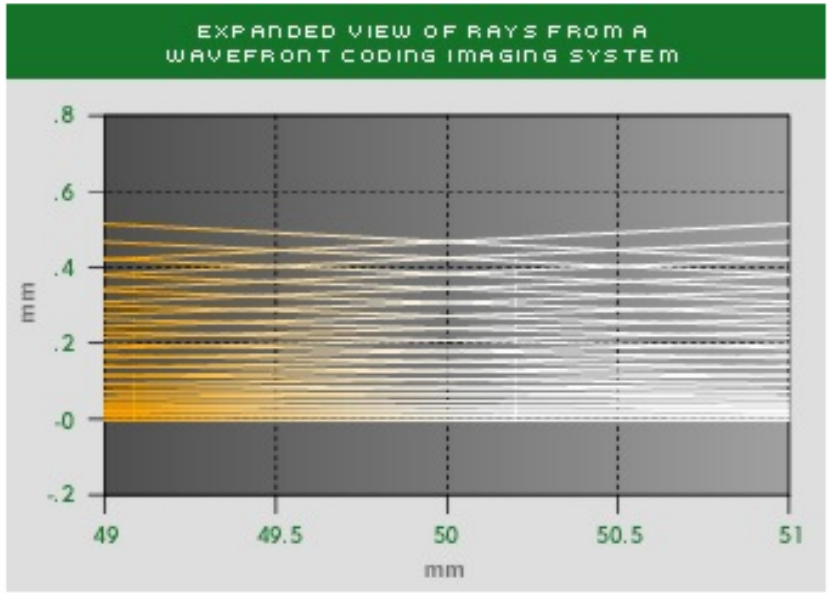
- **Idea: deconvolution to deblur out of focus regions**
- **Problem 1: depth of field blur is not shift-invariant**
- **Problem 2: Depth of field blur "kills information"**
- **Solution: change optical system so that**
  - Rays don't converge anymore
  - Image blur is the same for all depth
  - Blur spectrum does not have too many zeros

Ray version


RAYS FROM A TRADITIONAL IMAGING SYSTEM
3
2
1
0
-1
-2
-3
mm
-10
0
10
20
30
40
50
60
mm


RAYS FROM A WAVEFRONT CODING IMAGING SYSTEM
3
2
1
0
-1
-2
-3
mm
-10
0
10
20
30
40
50
60
mm


EXPANDED VIEW OF RAYS FROM A TRADITIONAL IMAGING SYSTEM
.1
.05
0
-.05
-.01
mm
49
49.5
50
50.5
51
mm


EXPANDED VIEW OF RAYS FROM A WAVEFRONT CODING IMAGING SYSTEM
.8
.6
.4
.2
-0
-.2
mm
49
49.5
50
50.5
51
mm

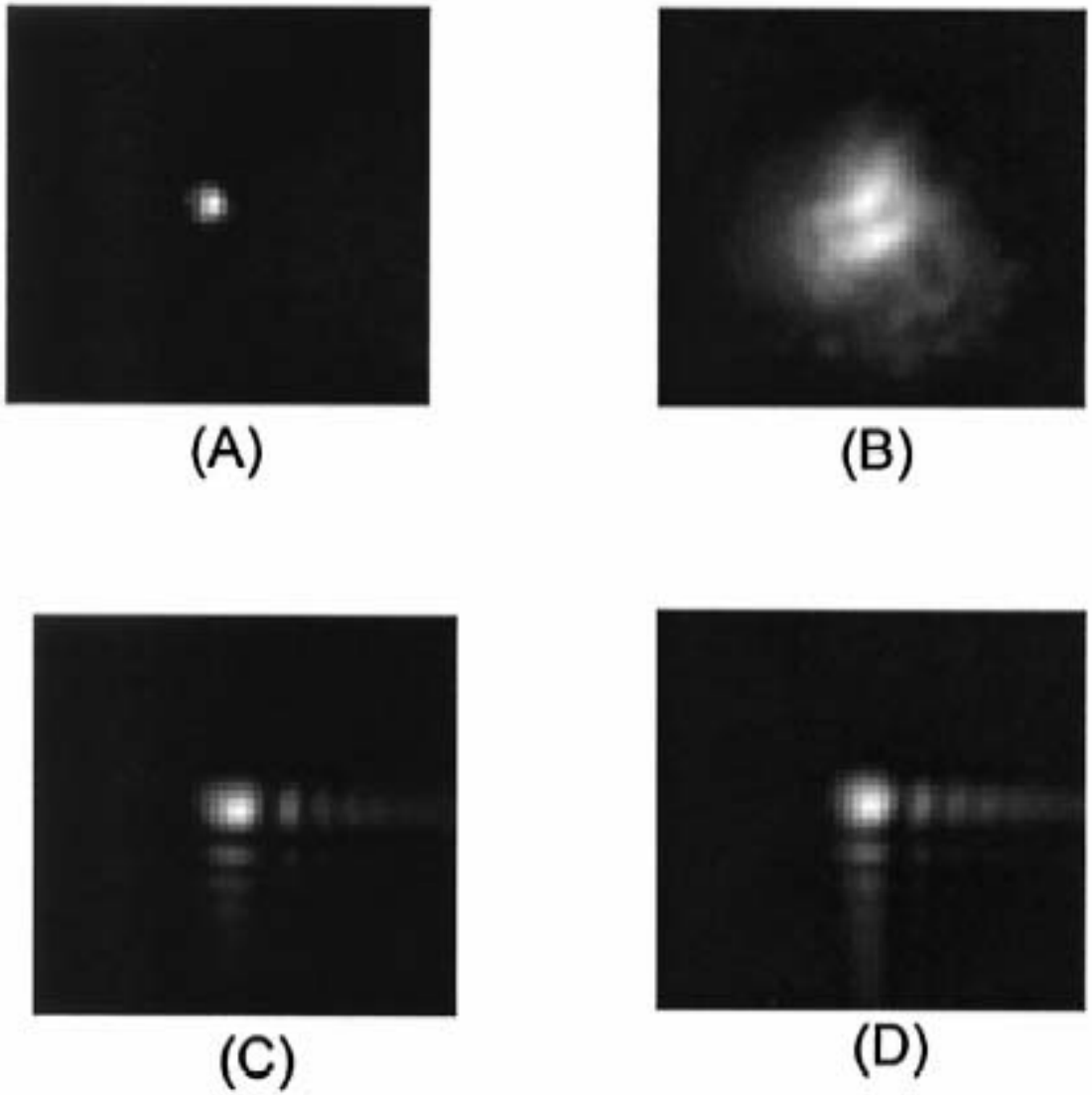


Fig. 3. PSFs associated with the rays of Fig. 2. The PSFs for a normal system are shown for (A) in focus and (B) out of focus. The PSFs for a coded system are shown (C) in the normal region of focus and (D) in the out-of-focus region.

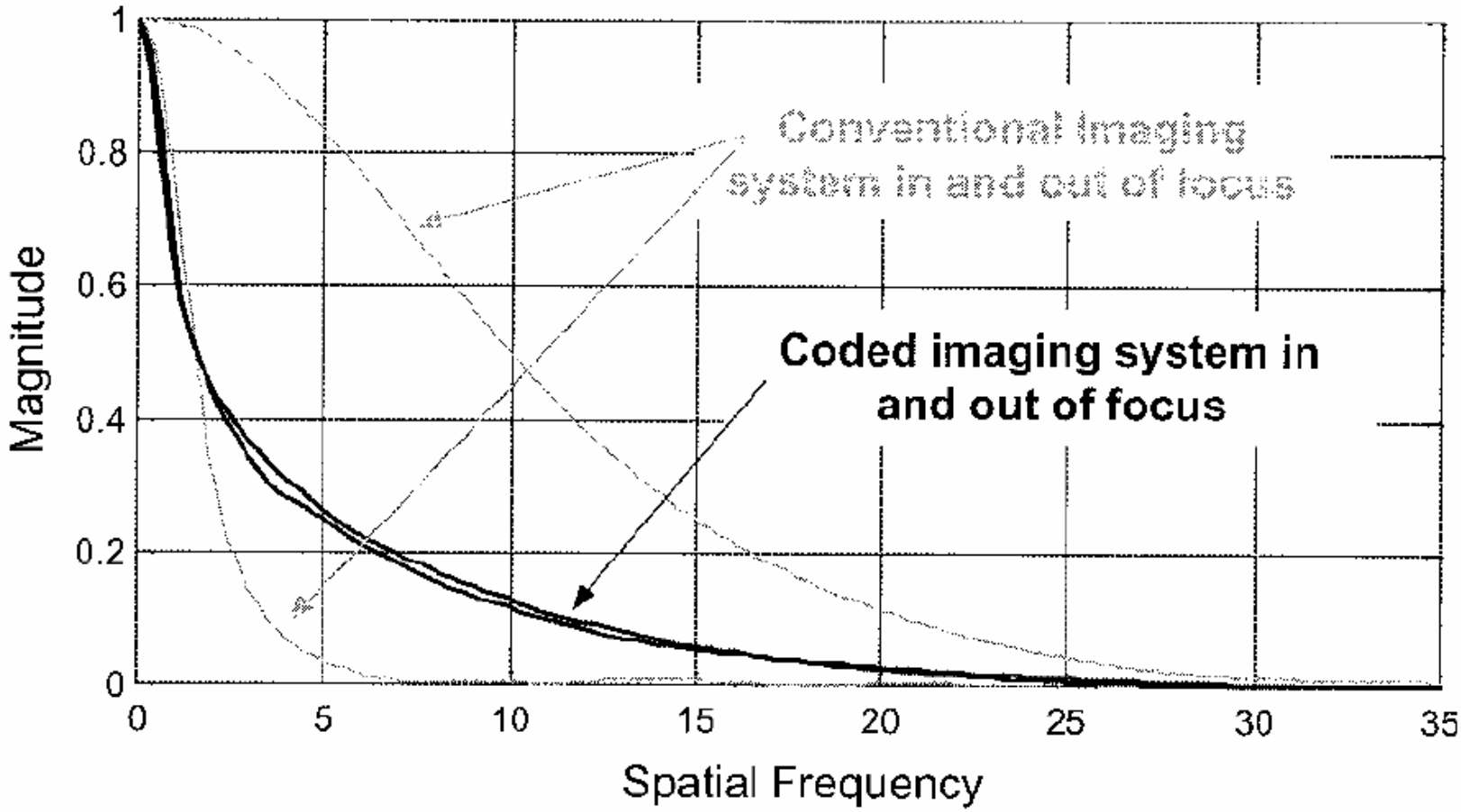


Fig. 5. MTFs corresponding with the PSFs of Fig. 3 for a conventional image in and out of focus and a coded image for the same misfocus values.

Traditional Optical System Image

Intermediate Extended Depth of Field Image

Stopped Down Traditional System Image

Final Wavefront Coded™ Image

Other application

- **Single-image depth sensing**
- **Optimize optical system so that blur depends A LOT on depth**

Important take-home idea

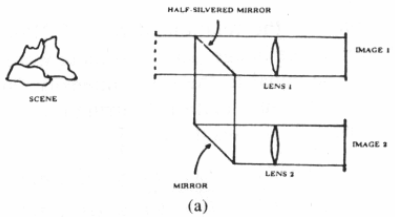
Coded imaging

- **What the sensor records is not the image we want, it's been coded (kind of like in cryptography)**
- **Image processing decodes it**

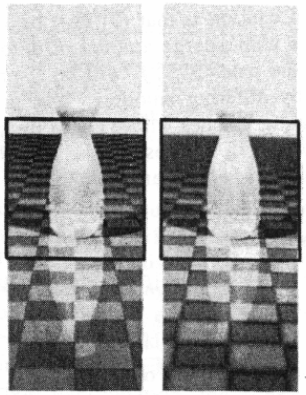
Defocus from focus/defocus

Depth from defocus

- **Pentland 87**

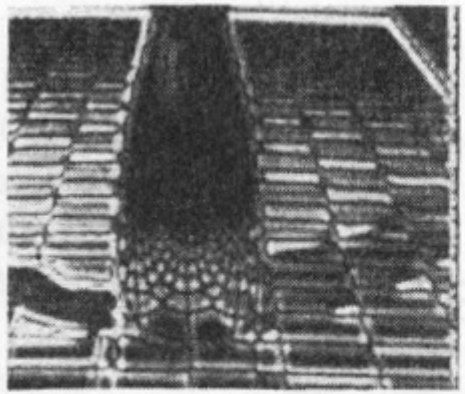


(a)

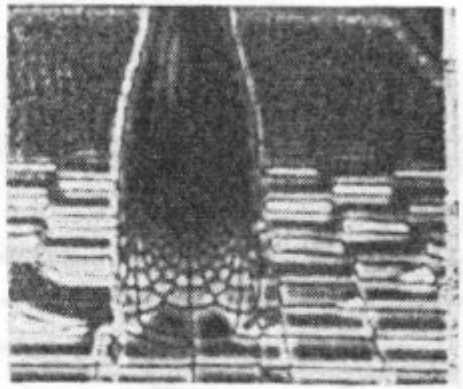


(b) (c)

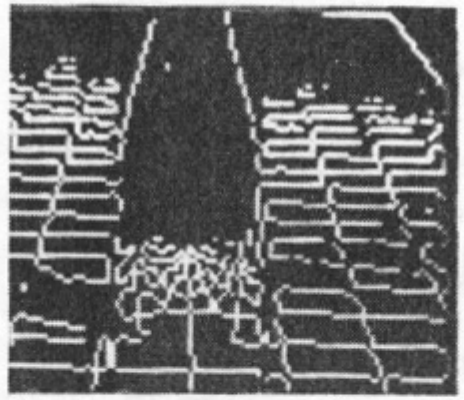
Fig. 1. Images identical except for depth of field. (a) Production: the light from a single view is split into two identical images and directed through two lens systems with different aperture size. Alternatively, one can vary the aperture between alternate frames from a standard video or CCD camera. In either case the two resulting images are identical except for depth of field, as shown in (b) and (c). These images are of a mirrored bottle on a checkered plain, redigitized from [14].



(a)



(b)



(c)

Fig. 5. (a) and (b) show the normalized high-frequency content of Fig. 2(b) and (c), respectively. (c) shows the focal disparity map (analogous to a stereo disparity map) obtained by comparing (a) and (b); brightness is proportional to depth.

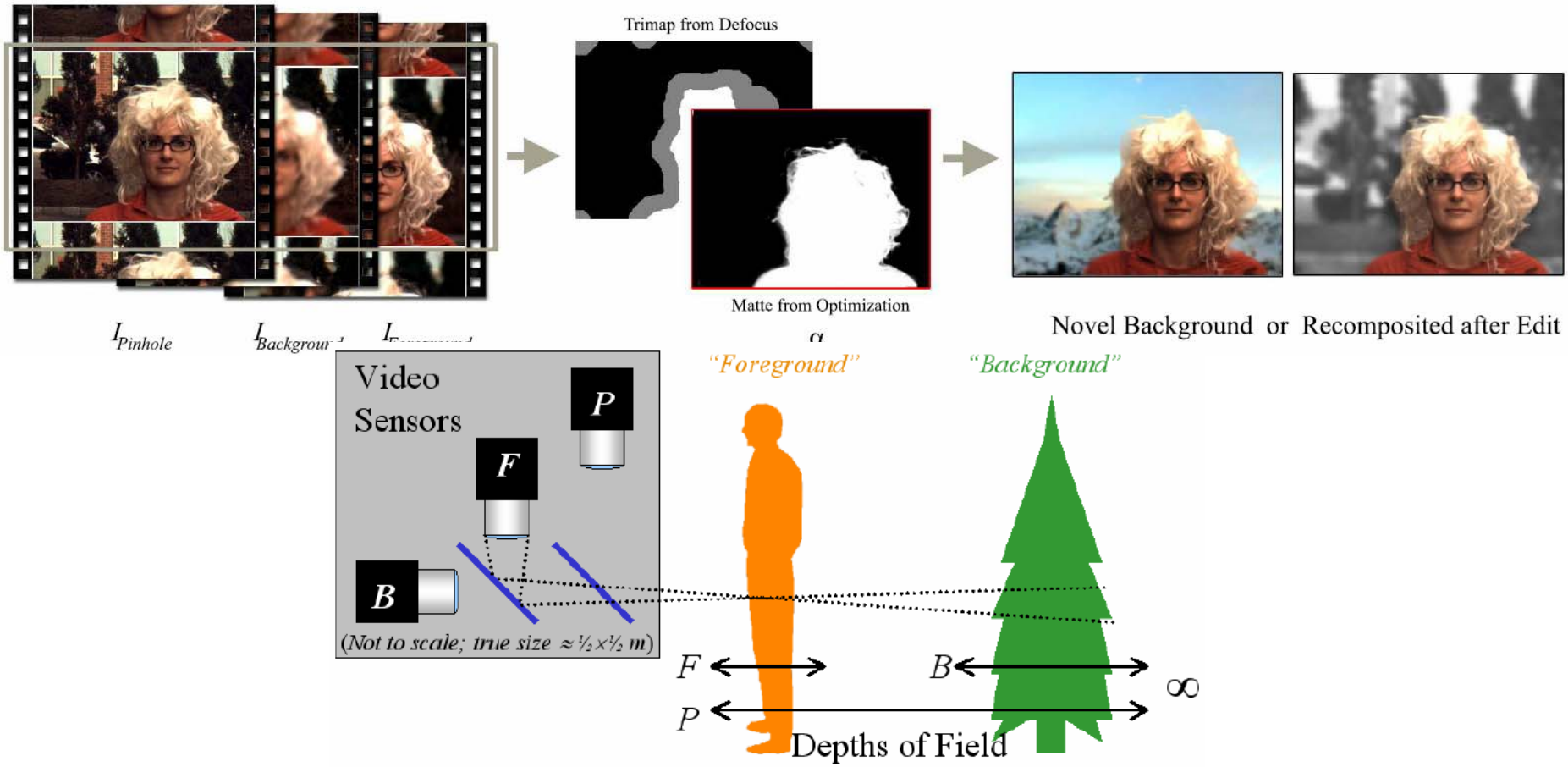
Depth from focus

- http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?isNumber=5032&arNumber=196282&isnumber=5032&arnumber=196282
- http://www.ri.cmu.edu/pub_files/pub1/xiong_yalin_1993_1/xiong_yalin_1993_1.pdf

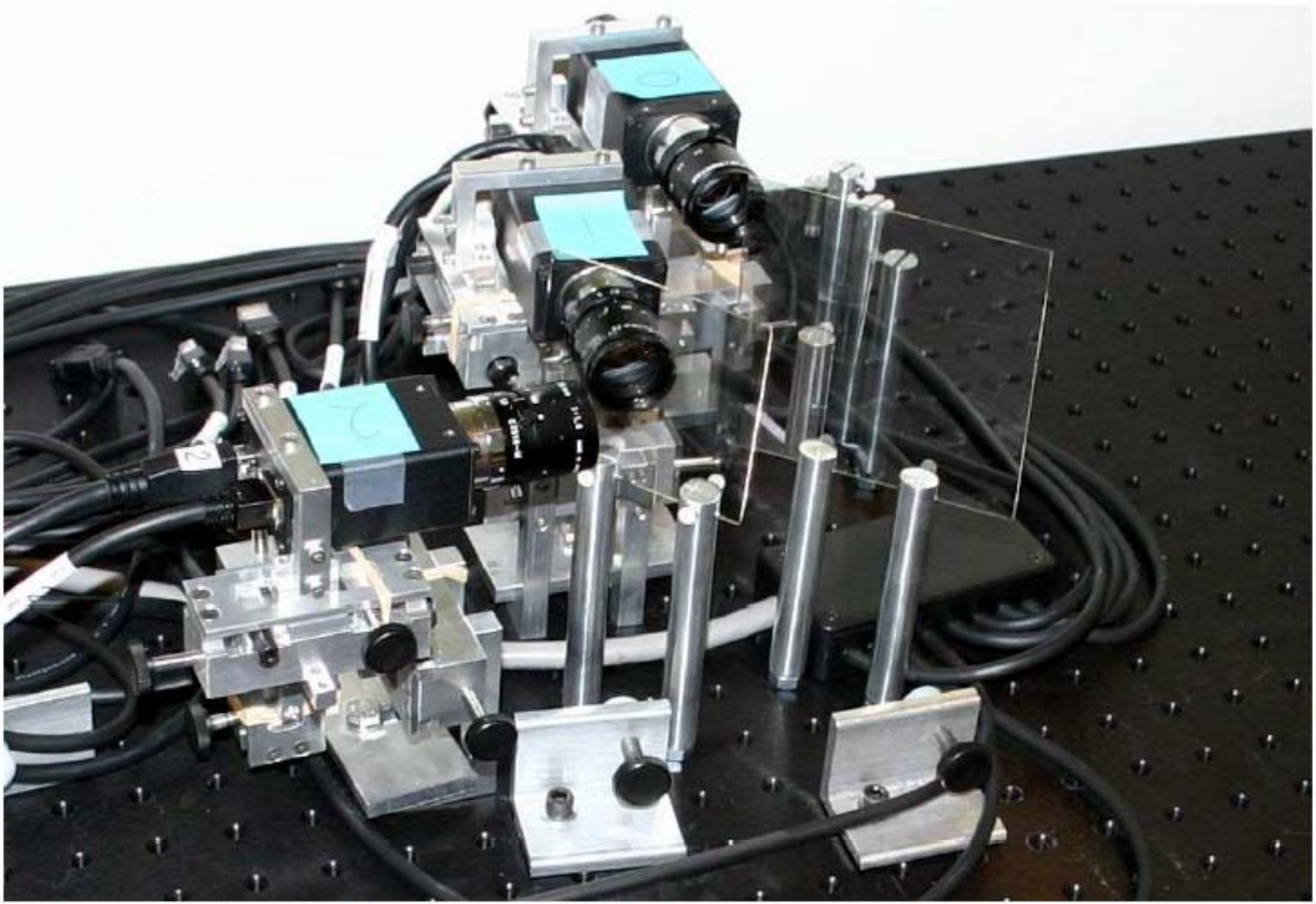
Defocus matting

Defocus Matting

- **With Morgan McGuire, Wojciech Matusik, Hanspeter Pfister, John “Spike” Hughes**
- **Data-rich: use 3 streams with different focus**

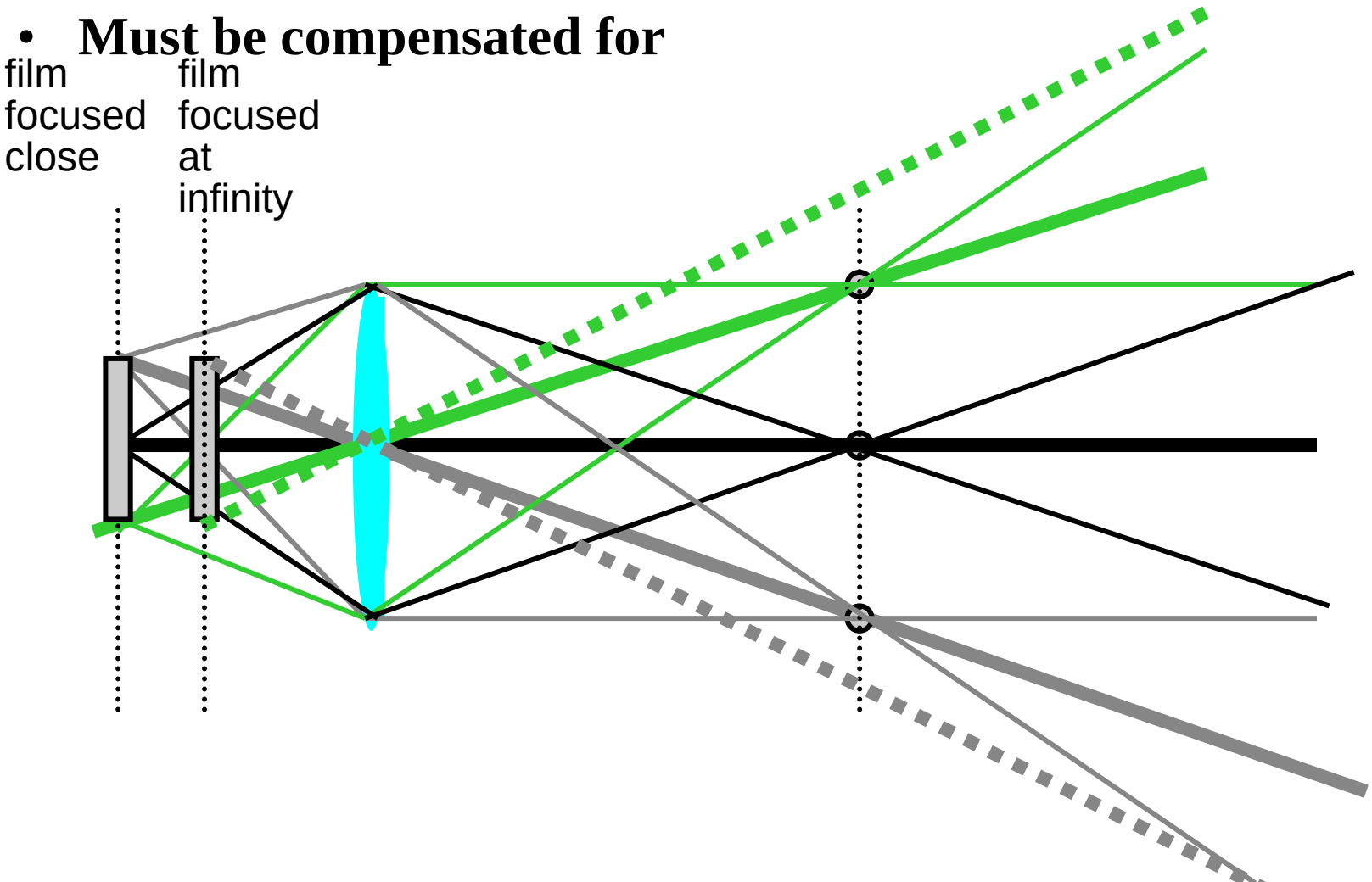


Morgan's crazy camera



But recall: field of view & focusing

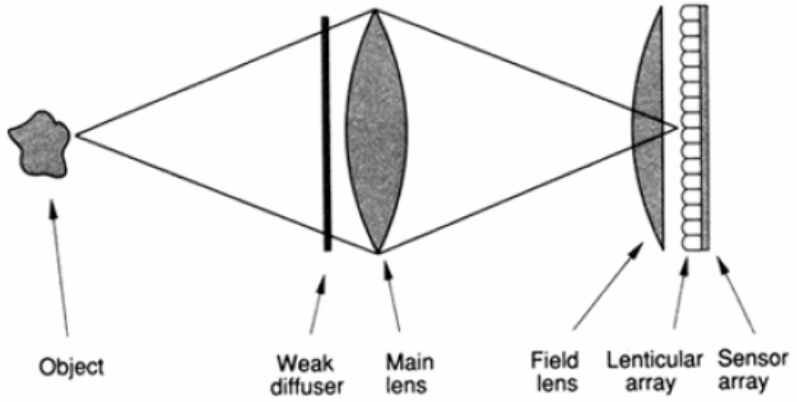
- **What happens to the field of view when one focuses closer?**
  - It's reduced
- **Must be compensated for**

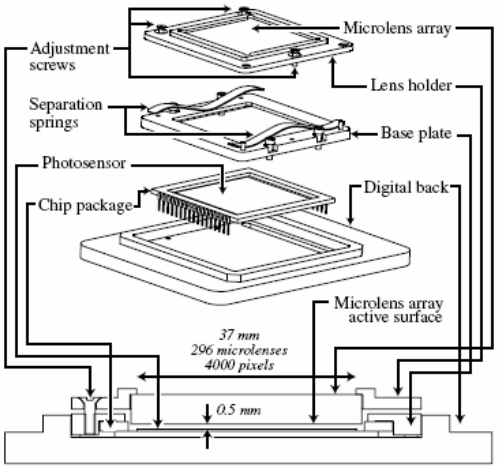


Plenoptic camera refocusing

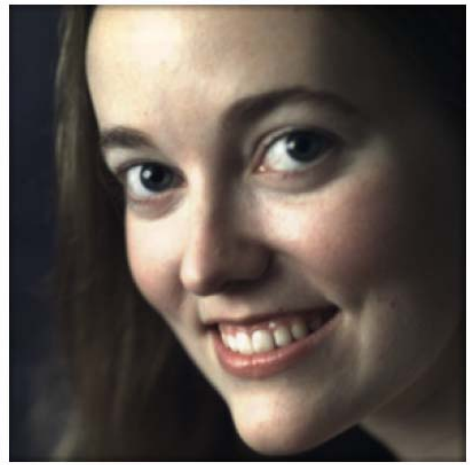
Plenoptic/light field cameras

- **Lipmann 1908**
- **Adelson and Wang, 19**





Ng et al. for



Links

DoF

- **http://www.cs.mtu.edu/~shene/DigiCam/User-Guide/950/depth-of-field.html**
- **http://en.wikipedia.org/wiki/Depth_of_field**
- **http://www.luminous-landscape.com/tutorials/dof2.shtml**
- **http://www.cambridgeincolour.com/tutorials/depth-of-field.htm**
- **http://www.dofmaster.com/dof_imagesize.html**
- **http://www.vanwalree.com/optics/dofderivation.html**
- **http://www.janrik.net/insects/ExtendedDOF/LepSocNewsFinal/EDOF_NewsLepSoc_2005summer.htm**
- **http://www.mir.com.my/rb/photography/fototech/htmls/depth.html**
- **http://www.luminous-landscape.com/tutorials/understanding-series/dof.shtml**
- **http://www.normankoren.com/Tutorials/MTF6.html**
- **http://www.photo.net/learn/optics/dofdigital/**
- **http://www.juzaphoto.com/eng/articles/depth_of_field.htm**
- **DoF calculators**
  - http://www.dofmaster.com/dofjs.html
  - http://www.dof.pcraft.com/dof.cgi

AF

- **http://www.juzaphoto.com/eng/articles/how_autofocus_works.htm**
- **http://en.wikipedia.org/wiki/Autofocus**
- **http://electronics.howstuffworks.com/autofocus.htm**