Focus and Depth of Field

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Defocus & Depth of field
Depth of field: more accurate view

• Backproject the image onto the plane in focus
  – Backproject circle of confusion
  – Depends on magnification factor $\sim \frac{f}{D}$
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

![Diagram showing the relationships between depth of field, circle of confusion, magnification, and focusing distance.](image)
Deriving depth of field

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

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

\[
d_1 \frac{f^2/N + CD}{CDf/N} = \frac{D}{f/N}
\]

\[
d_1 = \frac{CD^2}{f^2/N + CD}
\]
Deriving depth of field

\[ d_1 = \frac{NCD^2}{f^2 + NCD} \quad d_2 = \frac{NCD^2}{f^2 - NCD} \]

\[ d = d_1 + d_2 = \frac{2NCD^2 f^2}{f^4 - N^2C^2D^2} \]
Deriving depth of field

\[ d = \frac{2NC^2D^2}{f^2} \frac{f^2}{f^4 - N^2C^2D^2} \]

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


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 $\frac{CD}{f}$ becomes bigger than $\frac{f}{N}$
- focus at $D = \frac{f^2}{NC}$ 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
Depth of field & focal length

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

\[ d = \frac{2NC}{f^2} \]

Wide-angle lens

Telephoto lens (2x f), same aperture
DoF & Focal length


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

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
Crazy DoF images

- By Matthias Zwicker
- The focus is between the two sticks

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)
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](http://www.mediachance.com/dvdlab/dof/index.htm)

Depth of Field for different cameras
The coolest depth of field solution

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


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.
Confocal imaging

- Confocal microscopy (invented by Minsky)

![Confocal microscopy diagram](image)

**Figure 2:** The principle of confocal microscopy. (a) Confocal laser scanning micrograph of fluorescently stained Convallaria rhizome (UMIC SUNY/Stonybrook). (b) A reflection mode confocal scanning microscope. An illumination source at $A$ is imaged by an optical system $B$ onto a 3D specimen that sits astride focal plane $C$. The specimen is imaged through a beamsplitter $D$ and a second optical system $E$ onto a detector $F$. A pinhole at $G$ focuses the source on point $J$, which therefore receives light through the full aperture of the illumination system (the lens). However, the illumination received by point $K$ off the focal plane falls off as the square of the distance from this plane, making it dimmer. A second pinhole at $H$ masks out everything but that portion of the image that is focused on $J$ - hence the term confocal. Assuming the specimen scatters light diffusely, and single scattering dominates over multiple scattering, then the amount of light gathered from $K$ will be lower than from $J$, making it even dimmer. By moving the pinholes in tandem, the specimen can be scanned. (c) A reflection mode aperture correlation microscope. The single pinholes have been replaced by matched patterns of pinholes at $G$ and $H$, and the detector has been replaced by an imager at $F$. This system requires no scanning. Instead, a sequence of trials is performed. On each trial, a randomly chosen 1/2 of the points on the focal plane are illuminated. The light falling on $K$ that is attributable to the light focused on $J$ will be lower than the light falling on $J$, as before. $K$ is also illuminated by the light focused on nearby point $L$, but only 1/2 of such points on the focal plane are illuminated at once, so $K$ is still dimmer than $J$.

From Levoy's paper [http://graphics.stanford.edu/papers/confocal/]
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 depth of field is big
Soft focus
Soft focus

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

With soft focus lens  
Without soft focus lens  
source: Hecht Optics

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

From Brinkmann's Art & Science of Digital Compositing
The Bokeh religion
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)
Bokeh

• **Shape of out of focus kernel**


**Fig. 1. Poor Bokeh.** This is a greatly magnified blur circle showing very poor bokeh. Note how the edge is sharply defined and even emphasized for a point that is supposed to be out-of-focus, and that the center is dim.

**Fig 2. Neutral Bokeh.** This is a a technically perfect and evenly illuminated blur circle. This isn't good either for bokeh, because the edge is still well defined. Out-of-focus objects, either points of light or lines, can effectively create reasonably sharp lines in the image due to the edges of the sharp blur circle. This is the blur circle from most modern lenses designed to be "perfect."

**Fig. 3. Good Bokeh.** Here is what we want. This is great for bokeh since the edge is completely undefined. This also is the result of the same spherical aberration, but in the opposite direction, of the poor example seen in Fig. 1. This is where art and engineering start to diverge, since the better looking image is the result of an imperfection. Perfect bokeh demands a Gaussian blur circle distribution, and lenses are designed for the neutral example shown in 2.) above.
The effect of a triangular stop can be seen clearly in this photograph. Note the downwards pointing triangles on the figure in the foreground and the upward pointing triangles on the figure in the background. It all looks rather contrived, but everything you see is 100% natural. The example suggests we should avoid triangular lens stops.
The simple white-on-black test pattern used to determine some of the effects of aperture shape on the out-of-focus images.

Here's the test target as photographed with an upwards pointing triangular lens opening and with the film too close to the lens.
Here is a sequence of images of a pin hole illustrating the circle of confusion at four distances behind the Rodenstock Imagon. From left to right, the images were obtained 4 cm in front of the plane of best focus, 2 cm in front, at the plane of best focus and 2 cm behind it. Below the images is a graph showing the brightness of the image along a straight line through the centers of the circles.

Here is a sequence of images of a pin hole illustrating the circle of confusion at seven distances behind the Nikkor-W. The brightness trace below shows that this lens demonstrates a 'bright ring' effect for images behind the plane of sharpest focus, while closer to the lens the trace show nicely rounded corners. The rounded corners can be expected to result in smooth, soft out-of-focus images.
Here's the same scene as used for Figure 2, but this time photographed with the 180/5.6 Nikkor-W, with its standard round opening (at full aperture). We see nice soft highlights in the foreground and a slight ‘bright ring’ effect in the background.

Here's the scene again with the 250 Imagon, using the H=7.7 stop in place. I intended to have two outer rows of sink-strainer holes closed, but there’s slight evidence here that one row of holes was open just a tiny bit.

Nevertheless, the main effects seen here is the ‘bright ring’ out-of-focus highlights in the foreground and the ‘bright core’ highlights in the background.
catadioptric (mirror)

500mm vivitar ($100)
500mm Canon (5k)
Mirror lens
Can be interesting
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 L₁ and L₂ and photocell P. (b) Static system with linear CCD array A. The correlated images at separations d₁ and d₂ correspond to distances u and D respectively. (c) Scanning mirror R to correlate images on twin photocells P₁ and P₂
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

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; M₁, reflex mirror with 30 per cent transmission; M₂, central region with 50 per cent transmission; M₃, 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
Autofocus

- When you half-press the shutter release, the activated AF sensor "looks" at the image projected by the lens from two different directions (each line of pixels in the array looks from the opposite direction of the other) and identifies the phase difference of the light from each direction. In one "look," it calculates the distance and direction the lens must be moved to cancel the phase differences. It then commands the lens to move the appropriate distance and direction and stops. It does not "hunt" for a best focus, nor does it take a second look after the lens has moved (it is an "open loop" system).

If the starting point is so far out of focus that the sensor can't identify a phase difference, the camera racks the lens once forward and once backward to find a detectable difference. If it can't find a detectable difference during that motion, it stops.

Although the camera does not take a "second look" to see if the intended focus has been achieved, the lens does take a "second look" to ensure it has moved the direction and distance commanded by the camera (it is a "closed loop" system). This second look corrects for any slippage or backlash in the lens mechanism, and can often be detected as a small "correction" movement at the end of the longer initial movements.
compute phase difference, deduce distance
Multiple focus sensors

source arthur morris
Lens actuators

Figure-37 Various Lens Actuators

source: canon red book
Photo-16 Ring-type USM

Figure-41 Vibrations Generated by Piezoelectric Ceramic Element

Figure-42 Piezoelectric Ceramic Element Layout (bottom of stator)

source: canon red book
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.janrik.net/ptools/ExtendedFocusPano12/index.html)
- **55 images here**
Scanning: combination in 1 exposure

Macrophotography scanning device. The subject is lit by a fine ray of light with a thickness less than the depth of field; the lens can be used with average apertures that provide maximum sharpness. Mounted on a stand with a headless screw, it is moved forward and backward by a slow and regular movement that is controlled by a motorized micrometer. This device, which can be made by a meticulous handyman, lets you take spectacular shots of large insects with total depth of field.

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

Well, except for diffraction (we did not scale wavelength!)
Fake Depth of Field
Photoshop

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

![Input (sharp layer)](image1)

![Blurred layer](image2)

![Mask of blurry layer](image3)

![Result](image4)
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
Photoshop lens blur

- Filter > Blur > Lens blur

Input

Depth map (painted manually)

Result
Tilt/Shift camera movements
VIEW CAMERA MOVEMENTS

Rise and fall move the front or back of the camera in a flat plane, like opening or closing an ordinary window. Rise moves the front or back up; fall moves the front or back down.

Shift (like rise and fall) also moves the front or back of the camera in a flat plane, but from side to side in a motion like moving a sliding door.

Tilt tips the front or back of the camera forward or backward around a horizontal axis. Nodding your head yes is a tilt of your face.

Swing twists the front or back of the camera around a vertical axis to the left or right. Shaking your head no is a swing of your face.

From Photography, London et al.
CONTROLLING CONVERGING LINES: THE KEY

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.
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.

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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.
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.
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 $\phi$ to satisfy Scheimpflug's rule, locating S within depth-of-field zone $T_2$.
• 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

*Summer dawn beneath Mount Humphreys, Eastern Sierra (California, 2001)*

AA1145 © Galen Rowell • *Unlimited Edition*
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.
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.

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.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:

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)