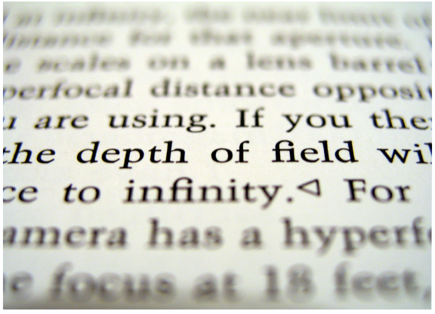
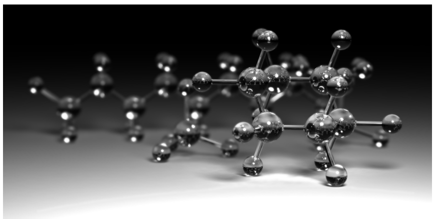
Depth of field

In optics, particularly as it relates to film and photography, **depth of field (DOF)** is the distance between the nearest and farthest objects in a scene that appear acceptably sharp in an image. Although a lens can precisely focus at only one distance at a time, the decrease in sharpness is gradual on each side of the focused distance, so that within the DOF, the unsharpness is imperceptible under normal viewing conditions.



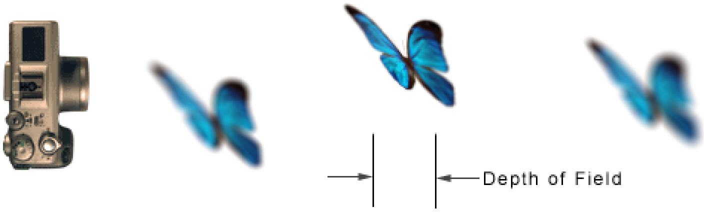
A macro photograph with very shallow depth of field

In some cases, it may be desirable to have the entire image sharp, and a large DOF is appropriate. In other cases, a small DOF may be more effective, emphasizing the subject while de-emphasizing the foreground and background. In cinematography, a large DOF is often called deep focus, and a small DOF is often called shallow focus.



Digital techniques, such as ray tracing, can also render 3D models with shallow depth of field for the same effect.

Circle of confusion criterion for depth of field



The area within the depth of field appears sharp, while the areas in front of and beyond the depth of field appear blurry.

Precise focus is possible at only one distance; at that distance, a point object will produce a point image. [1] At any other distance, a point object is *defocused*, and will produce a blur spot shaped like the aperture, which for the purpose of analysis is usually assumed to be circular. When this circular spot is sufficiently small, it is indistinguishable from a point, and appears to be in focus; it is rendered as “acceptably sharp”. The diameter of the circle increases with distance from the point of focus; the largest circle that is indistinguishable from a point is known as the *acceptable circle of confusion*, or informally, simply as the *circle of confusion*. The acceptable circle of confusion is influenced by visual acuity, viewing conditions, and the amount by which the image is enlarged (Ray 2000, 52–53). The increase of the circle diameter with defocus is gradual, so the limits of depth of field are not hard boundaries between sharp and unsharp.

For a 35 mm motion picture, the image area on the negative is roughly 22 mm by 16 mm (0.87 in by 0.63 in). The limit of tolerable error is usually set at 0.05 mm (0.002 in) diameter. For 16 mm film, where the image area is smaller, the tolerance is stricter, 0.025 mm (0.001 in). Standard depth-of-field tables are constructed on this basis, although generally 35 mm productions set it at 0.025 mm (0.001 in). Note that the acceptable circle of confusion values for these formats are different because of the relative amount of magnification each format will need in order to be projected on a full-sized movie screen. (A table for 35 mm still photography would be somewhat different since more of the film is used for each image and the amount of enlargement is usually much less.)

Object field methods

Traditional depth-of-field formulas and tables assume equal circles of confusion for near and far objects. Some authors, such as Merklinger (1992), [2] have suggested that distant objects often need to be much sharper to be clearly recognizable, whereas closer objects, being larger on the film, do not need to be so sharp. The loss of detail in distant objects may be particularly noticeable with extreme enlargements. Achieving this additional sharpness in distant objects usually requires focusing beyond the hyperfocal distance, sometimes almost at infinity. For example, if photographing a cityscape with a traffic bollard in the foreground, this approach, termed the *object field method* by Merklinger, would recommend focusing very close to infinity, and stopping down to make the bollard sharp enough. With this approach, foreground objects cannot always be made perfectly sharp, but the loss of sharpness in near objects may be acceptable if recognizability of distant objects is paramount.

Other authors (Adams 1980, 51) have taken the opposite position, maintaining that slight unsharpness in foreground objects is usually more disturbing than slight unsharpness in distant parts of a scene.

Moritz von Rohr also used an object field method, but unlike Merklinger, he used the conventional criterion of a maximum circle of confusion diameter in the image plane, leading to unequal front and rear depths of field.

Factors affecting depth of field

Several other factors, such as subject matter, movement, camera-to-subject distance, lens focal length, selected lens *f*-number, format size, and circle of confusion criterion also influence when a given defocus becomes noticeable. The combination of focal length, subject distance, and format size defines magnification at the film / sensor plane.

A 35 mm lens set to *f*/11. The depth-of-field scale (top) indicates that a subject which is anywhere between 1 and 2 meters in front of the camera will be rendered acceptably sharp. If the aperture were set to *f*/22 instead, everything from just over 0.7 meters almost to infinity would appear to be in focus.

DOF is determined by subject magnification at the film / sensor plane and the selected lens aperture or *f*-number. For a given *f*-number, increasing the magnification, either by moving closer to the subject or using a lens of greater focal length, decreases the DOF; decreasing magnification increases DOF. For a given subject magnification, increasing the *f*-number (decreasing the aperture diameter) increases the DOF; decreasing *f*-number decreases DOF.

If the original image is enlarged to make the final image, the circle of confusion in the original image must be smaller than that in the final image by the ratio of enlargement. Cropping an image and enlarging to the same size final image as an uncropped image taken under the same conditions is equivalent to using a smaller format under the same conditions, so the cropped image has less DOF. (Stroebel 1976, 134, 136–37).

When focus is set to the hyperfocal distance, the DOF extends from half the hyperfocal distance to infinity, and the DOF is the largest possible for a given *f*-number.

Relationship of DOF to format size

Out-of-focus highlights have the shape of the lens aperture.

The comparative DOFs of two different format sizes depend on the conditions of the comparison. The DOF for the smaller format can be either more than or less than that for the larger format. In the discussion that follows, it is assumed that the final images from both formats are the same size, are viewed from the same distance, and are judged with the same circle of confusion criterion. (Derivations of the effects of format size are given under Derivation of the DOF formulas.)

"Same picture" for both formats

When the "same picture" is taken in two different format sizes from the same distance at the same *f*-number with lenses that give the same angle of view, and the final images (e.g., in prints, or on a projection screen or electronic display) are the same size, DOF is, to a first approximation, inversely proportional to format size (Stroebel 1976, 139). Though commonly used when comparing formats, the approximation is valid only when the subject distance is large in comparison with the focal length of the larger format and small in comparison with the hyperfocal distance of the smaller format.

Moreover, the larger the format size, the longer a lens will need to be to capture the same framing as a smaller format. In motion pictures, for example, a frame with a 12 degree horizontal field of view will require a 50 mm lens on 16 mm film, a 100 mm lens on 35 mm film, and a 250 mm lens on 65 mm film. Conversely, using the same focal length lens with each of these formats will yield a progressively wider image as the film format gets larger: a 50 mm lens has a horizontal field of view of 12 degrees on 16 mm film, 23.6 degrees on 35 mm film, and 55.6 degrees on 65 mm film. Therefore, because the larger formats require longer lenses than the smaller ones, they will accordingly have a smaller depth of field. Compensations in exposure, framing, or subject distance need to be made in order to make one format look like it was filmed in another format.

Same focal length for both formats

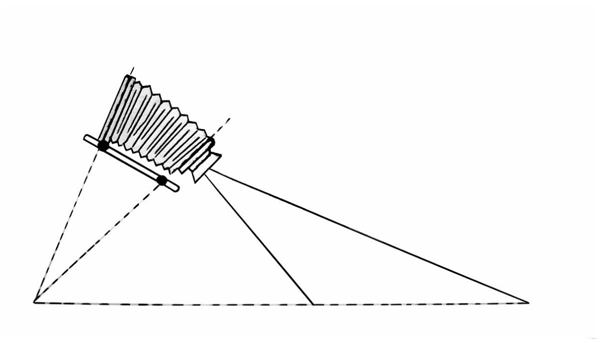
Many small-format digital SLR camera systems allow using many of the same lenses on both full-frame and "cropped format" cameras. If, for the same focal length setting, the subject distance is adjusted to provide the *same field of view* at the subject, at the same *f*-number and final-image size, the smaller format has *greater* DOF, as with the "same picture" comparison above. If pictures are taken from the *same distance* using the same *f*-number, same focal length, and the final images are the same size, the smaller format has *less* DOF. If pictures taken from the same subject distance using the same focal length, are given the *same enlargement*, both final images will have the *same* DOF. The pictures from the two formats will differ because of the different angles of view. If the larger format is cropped to the captured area of the smaller format, the final images will have the same angle of view, have been given the same enlargement, and have the same DOF.

Same DOF for both formats

In many cases, the DOF is fixed by the requirements of the desired image. For a given DOF and field of view, the required *f*-number is proportional to the format size. For example, if a 35 mm camera required *f*/11, a 4×5 camera would require *f*/45 to give the same DOF. For the same ISO speed, the exposure time on the 4×5 would be sixteen times as long; if the 35 camera required 1/250 second, the 4×5 camera would require 1/15 second. The longer exposure time with the larger camera might result in motion blur, especially with windy conditions, a moving subject, or an unsteady camera.

Adjusting the *f*-number to the camera format is equivalent to maintaining the same absolute aperture diameter; when set to the same absolute aperture diameters, both formats have the same DOF.

Camera movements and DOF



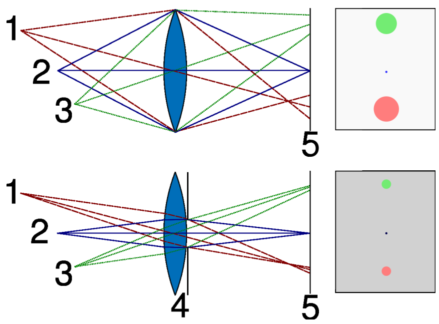
Scheimpflug principle.

When the lens axis is perpendicular to the image plane, as is normally the case, the plane of focus (POF) is parallel to the image plane, and the DOF extends between parallel planes on either side of the POF. When the lens axis is not perpendicular to the image plane, the POF is no longer parallel to the image plane; the ability to rotate the POF is known as the Scheimpflug principle. Rotation of the POF is accomplished with camera movements (tilt, a rotation of the lens about a horizontal axis, or swing, a rotation about a vertical axis). Tilt and swing are available on most view cameras, and are also available with specific lenses on some small- and medium-format cameras.

When the POF is rotated, the near and far limits of DOF are no longer parallel; the DOF becomes wedge-shaped, with the apex of the wedge nearest the camera (Merklinger 1993, 31–32; Tillmanns 1997, 71). With tilt, the height of the DOF increases with distance from the camera; with swing, the width of the DOF increases with distance.

In some cases, rotating the POF can better fit the DOF to the scene, and achieve the required sharpness at a smaller `f`-number. Alternatively, rotating the POF, in combination with a small `f`-number, can minimize the part of an image that is within the DOF.

Effect of lens aperture

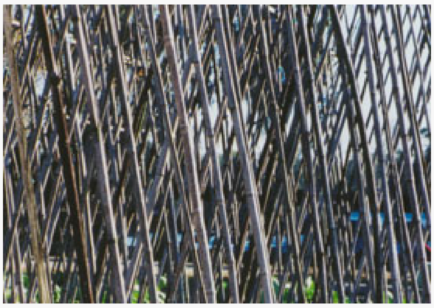


Effect of aperture on blur and DOF. The points in focus (**2**) project points onto the image plane (**5**), but points at different distances (**1** and **3**) project blurred images, or circles of confusion. Decreasing the aperture size (**4**) reduces the size of the blur spots for points not in the focused plane, so that the blurring is imperceptible, and all points are within the DOF.

For a given subject framing and camera position, the DOF is controlled by the lens aperture diameter, which is usually specified as the f-number, the ratio of lens focal length to aperture diameter. Reducing the aperture diameter (increasing the `f`-number) increases the DOF; however, it also reduces the amount of light transmitted, and increases diffraction, placing a practical limit on the extent to which DOF can be increased by reducing the aperture diameter.

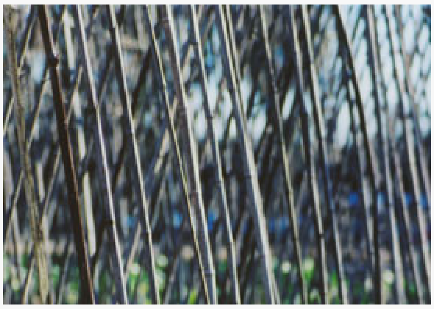
Motion pictures make only limited use of this control; to produce a consistent image quality from shot to shot, cinematographers usually choose a single aperture setting for interiors and another for exteriors, and adjust exposure through the use of camera filters or light levels. Aperture settings are adjusted more frequently in still photography, where variations in depth of field are used to produce a variety of special effects.

DOF with various apertures



f/22

f/8



f/4

f/2.8

Digital techniques affecting DOF

Series of images demonstrating a 6 image focus bracket of a Tachinid fly. First two images illustrate typical DOF of a single image at f/10 while the third image is the composite of 6 images.

The advent of digital technology in photography has provided additional means of controlling the extent of image sharpness; some methods allow extended DOF that would be impossible with traditional techniques, and some allow the DOF to be determined after the image is made.

Focus stacking is a digital image processing technique which combines multiple images taken at different focus distances to give a resulting image with a greater depth of field than any of the individual source images. Available programs for multi-shot DOF enhancement include Adobe Photoshop, Syncroscopy AutoMontage, PhotoAcute Studio, Helicon Focus and CombineZ. Getting sufficient depth of field can be particularly challenging in macro photography. The images to the right illustrate the extended DOF that can be achieved by combining multiple images.

Wavefront coding is a method that convolves rays in such a way that it provides an image where fields are in focus simultaneously with all planes out of focus by a constant amount.

A plenoptic camera uses a microlens array to capture 4D light field information about a scene.

Colour apodisation is a technique combining a modified lens design with image processing to achieve an increased depth of field. The lens is modified such that each colour channel has a different lens aperture. For example the red channel may be f/2.4, green may be f/2.4, whilst the blue channel may be f/5.6. Therefore the blue channel will have a greater depth of field than the other colours. The image processing identifies blurred regions in the red and green channels and in these regions copies the sharper edge data from the blue channel. The result is an image that combines the best features from the different f-numbers, (Kay 2011).

Diffraction and DOF

If the camera position and image framing (i.e., angle of view) have been chosen, the only means of controlling DOF is the lens aperture. Most DOF formulas imply that any arbitrary DOF can be achieved by using a sufficiently large f-number. Because of diffraction, however, this isn't really true. Once a lens is stopped down to where most aberrations are well corrected, stopping down further will decrease sharpness in the plane of focus. At the DOF limits, however, further stopping down decreases the size of the defocus blur spot, and the overall sharpness may still increase. Eventually, the defocus blur spot becomes negligibly small, and further stopping down serves only to decrease sharpness even at DOF limits (Gibson 1975, 64). There is thus a tradeoff between sharpness in the POF and sharpness at the DOF limits. But the sharpness in the POF is always greater than that at the DOF limits; if the blur at the DOF limits is imperceptible, the blur in the POF is imperceptible as well.

For general photography, diffraction at DOF limits typically becomes significant only at fairly large f-numbers; because large f-numbers typically require long exposure times, motion blur may cause greater loss of sharpness than the loss from diffraction. The size of the diffraction blur spot depends on the effective f-number $N\left(1+m\right)$, however, so diffraction is a greater issue in close-up photography, and the tradeoff between DOF and overall sharpness can become quite noticeable (Gibson 1975, 53; Lefkowitz 1979, 84).

Lens DOF scales

Many lenses for small- and medium-format cameras include scales that indicate the DOF for a given focus distance and f-number; the 35 mm lens in the image above is typical. That lens includes distance scales in feet and meters; when a marked distance is set opposite the large white index mark, the focus is set to that distance. The DOF scale below the distance scales includes markings on either side of the index that correspond to f-numbers. When the lens is set to a given f-number, the DOF extends between the distances that align with the f-number markings.

Detail from the lens shown above. The point half-way between the 1 m and 2 m marks represents approximately 1.3 m.

Zone focusing

When the 35 mm lens above is set to f/11 and focused at approximately 1.3 m, the DOF (a “zone” of acceptable sharpness) extends from 1 m to 2 m. Conversely, the required focus and f-number can be determined from the desired DOF limits by locating the near and far DOF limits on the lens distance scale and setting focus so that the index mark is centered between the near and far distance marks. The required f-number is determined by finding the markings on the DOF scale that are closest to the near and far distance marks (Ray 1994, 315). For the 35 mm lens above, if it were desired for the DOF to extend from 1 m to 2 m, focus would be set so that index mark was centered between the marks for those distances, and the aperture would be set to f/11.

The focus so determined would be about 1.3 m, the approximate harmonic mean of the near and far distances. [3] See the section Focus and *f*-number from DOF limits for additional discussion.

If the marks for the near and far distances fall outside the marks for the largest f-number on the DOF scale, the desired DOF cannot be obtained; for example, with the 35 mm lens above, it is not possible to have the DOF extend from 0.7 m to infinity. The DOF limits can be determined visually, by focusing on the farthest object to be within the DOF and noting the distance mark on the lens distance scale, and repeating the process for the nearest object to be within the DOF.

Some distance scales have markings for only a few distances; for example, the 35 mm lens above shows only 3 ft and 5 ft on its upper scale. Using other distances for DOF limits requires visual interpolation between marked distances. Since the distance scale is nonlinear, accurate interpolation can be difficult. In most cases, English and metric distance markings are not coincident, so using both scales to note focused distances can sometimes lessen the need for interpolation. Many autofocus lenses have smaller distance and DOF scales and fewer markings than do comparable manual-focus lenses, so that determining focus and f-number from the scales on an autofocus lens may be more difficult than with a comparable manual-focus lens. In most cases, determining these settings using the lens DOF scales on an autofocus lens requires that the lens or camera body be set to manual focus. [4]

On a view camera, the focus and f-number can be obtained by measuring the *focus spread* and performing simple calculations. The procedure is described in more detail in the section Focus and f-number from DOF limits. Some view cameras include DOF calculators that indicate focus and f-number without the need for any calculations by the photographer (Tillmanns 1997, 67–68; Ray 2002, 230–31).

Hyperfocal distance

The hyperfocal distance is the nearest focus distance at which the DOF extends to infinity; focusing the camera at the hyperfocal distance results in the largest possible depth of field for a given f-number (Ray 2000, 55). Focusing *beyond* the hyperfocal distance does not increase the far DOF (which already extends to infinity), but it does decrease the DOF in front of the subject, decreasing the total DOF. Some photographers consider this wasting DOF; however, see Object field methods below for a rationale for doing so. Focusing on the hyperfocal distance is a special case of zone focusing in which the far limit of DOF is at infinity.

If the lens includes a DOF scale, the hyperfocal distance can be set by aligning the infinity mark on the distance scale with the mark on the DOF scale corresponding to the f-number to which the lens is set. For example, with the 35 mm lens shown above set to f/11, aligning the infinity mark with the ‘11’ to the left of the index mark on the DOF scale would set the focus to the hyperfocal distance.

Limited DOF: selective focus


At *f*/32, the background competes for the viewer's attention.

Depth of field can be anywhere from a fraction of a millimeter to virtually infinite. In some cases, such as landscapes, it may be desirable to have the entire image sharp, and a large DOF is appropriate. In other cases, artistic considerations may dictate that only a part of the image be in focus, emphasizing the subject while de-emphasizing the background, perhaps giving only a suggestion of the environment (Langford 1973, 81). For example, a common technique in melodramas and horror films is a closeup of a person's face, with someone just behind that person visible but out of focus. A portrait or close-up still photograph might use a small DOF to isolate the subject from a distracting background. The use of limited DOF to emphasize one part of an image is known as *selective focus*, *differential focus* or *shallow focus*.

Although a small DOF implies that other parts of the image will be unsharp, it does not, by itself, determine *how* unsharp those parts will be. The amount of background (or foreground) blur depends on the distance from the plane of focus, so if a background is close to the subject, it may be difficult to blur sufficiently even with a small DOF. In practice, the lens f-number is usually adjusted until the background or foreground is acceptably blurred, often without direct concern for the DOF.

At *f*/5.6, the flowers are isolated from the background.

Sometimes, however, it is desirable to have the entire subject sharp while ensuring that the background is sufficiently unsharp. When the distance between subject and background is fixed, as is the case with many scenes, the DOF and the amount of background blur are not independent. Although it is not always possible to achieve both the desired subject sharpness and the desired background unsharpness, several techniques can be used to increase the separation of subject and background.

At *f*/2.8, the cat is isolated from the background.

For a given scene and subject magnification, the background blur increases with lens focal length. If it is not important that background objects be unrecognizable, background de-emphasis can be increased by using a lens of longer focal length and increasing the subject distance to maintain the same magnification. This technique requires that sufficient space in front of the subject be available; moreover, the perspective of the scene changes because of the different camera position, and this may or may not be acceptable.

The situation is not as simple if it is important that a background object, such as a sign, be unrecognizable. The magnification of background objects also increases with focal length, so with the technique just described, there is little change in the recognizability of background objects. [5] However, a lens of longer focal length may still be of some help; because of the narrower angle of view, a slight change of camera position may suffice to eliminate the distracting object from the field of view.

Although tilt and swing are normally used to maximize the part of the image that is within the DOF, they also can be used, in combination with a small f-number, to give selective focus to a plane that isn't perpendicular to the lens axis. With this technique, it is possible to have objects at greatly different distances from the camera in sharp focus and yet have a very shallow DOF. The effect can be interesting because it differs from what most viewers are accustomed to seeing.

Near:far distribution

The DOF beyond the subject is always greater than the DOF in front of the subject. When the subject is at the hyperfocal distance or beyond, the far DOF is infinite, so the ratio is 1:∞; as the subject distance decreases, near:far DOF ratio increases, approaching unity at high magnification. For large apertures at typical portrait distances, the ratio is still close to 1:1. The oft-cited rule that 1/3 of the DOF is in front of the subject and 2/3 is beyond (a 1:2 ratio) is true only when the subject distance is 1/3 the hyperfocal distance.

Optimal f-number

As a lens is stopped down, the defocus blur at the DOF limits decreases but diffraction blur increases. The presence of these two opposing factors implies a point at which the combined blur spot is minimized (Gibson 1975, 64); at that point, the f-number is optimal for image sharpness. If the final image is viewed under normal conditions (e.g., an 8″×10″ image viewed at 10″), it may suffice to determine the f-number using criteria for minimum required sharpness, and there may be no practical benefit from further reducing the size of the blur spot. But this may not be true if the final image is viewed under more demanding conditions, e.g., a very large final image viewed at normal distance, or a portion of an image enlarged to normal size (Hansma 1996). Hansma also suggests that the final-image size may not be known when a photograph is taken, and obtaining the maximum practicable sharpness allows the decision to make a large final image to be made at a later time.

Determining combined defocus and diffraction

Hansma (1996) and Peterson (1996) have discussed determining the combined effects of defocus and diffraction using a root-square combination of the individual blur spots. Hansma's approach determines the f-number that will give the maximum possible sharpness; Peterson's approach determines the minimum f-number that will give the desired sharpness in the final image, and yields a maximum focus spread for which the desired sharpness can be achieved. [6] In combination, the two methods can be regarded as giving a maximum and minimum f-number for a given situation, with the photographer free to choose any value within the range, as conditions (e.g., potential motion blur) permit. Gibson (1975), 64) gives a similar discussion, additionally considering blurring effects of camera lens aberrations, enlarging lens diffraction and aberrations, the negative emulsion, and the printing paper. [7] Couzin (1982), 1098) gave a formula essentially the same as Hansma's for optimal *f*-number, but did not discuss its derivation.

Hopkins (1955), Stokseth (1969), and Williams and Becklund (1989) have discussed the combined effects using the modulation transfer function. Conrad's Depth of Field in Depth [8] (PDF), and Jacobson's Photographic Lenses Tutorial [9] discuss the use of Hopkins's method specifically in regard to DOF.

Other applications

Photolithography

In semiconductor photolithography applications, depth of field is extremely important as integrated circuit layout features must be printed with high accuracy at extremely small size. The difficulty is that the wafer surface is not perfectly flat, but may vary by several micrometres. Even this small variation causes some distortion in the projected image, and results in unwanted variations in the resulting pattern. Thus photolithography engineers take extreme measures to maximize the optical depth of field of the photolithography equipment. To minimize this distortion further, semiconductor manufacturers may use chemical mechanical polishing to make the wafer surface even flatter before lithographic patterning.

Ophthalmology and optometry

A person may sometimes experience better vision in daylight than at night because of an increased depth of field due to constriction of the pupil (i.e., miosis).

DOF formulas

The basis of these formulas is given in the section Derivation of the DOF formulas;[10] refer to the diagram in that section for illustration of the quantities discussed below.

Hyperfocal distance

Let f be the lens focal length, N be the lens f-number, and c be the circle of confusion for a given image format. The hyperfocal distance H is given by

$$H \approx \frac{f^2}{Nc}\,.$$

Moderate-to-large distances

Let s be the distance at which the camera is focused (the “subject distance”). When s is large in comparison with the lens focal length, the distance D_{N} from the camera to the near limit of DOF and the distance D_{F} from the camera to the far limit of DOF are

$$D_{\mathrm{N}} \approx \frac{Hs}{H+s}$$

and

$$D_{\mathrm{F}} \approx \frac{Hs}{H-s} \text{ for } s < H .$$

The depth of field $D_{\mathrm{F}} - D_{\mathrm{N}}$ is

$$\mathrm{DOF} \approx \frac{2Hs^2}{H^2 - s^2} \text{ for } s < H .$$

Substituting for H and rearranging, DOF can be expressed as

$$\mathrm{DOF} \approx \frac{2Ncf^2s^2}{f^4 - N^2c^2s^2} .$$

Thus, for a given image format, depth of field is determined by three factors: the focal length of the lens, the `f`-number of the lens opening (the aperture), and the camera-to-subject distance.

When the subject distance is the hyperfocal distance,

$$D_{\mathrm{F}} = \infty$$

and

$$D_{\mathrm{N}} = \frac{H}{2} .$$

For $s \geq H$, the far limit of DOF is at infinity and the DOF is infinite; of course, only objects at or beyond the near limit of DOF will be recorded with acceptable sharpness.

Close-up

When the subject distance s approaches the focal length, using the formulas given above can result in significant errors. For close-up work, the hyperfocal distance has little applicability, and it usually is more convenient to express DOF in terms of image magnification. Let m be the magnification; when the subject distance is small in comparison with the hyperfocal distance,

$$\mathrm{DOF} \approx 2Nc\,\frac{m+1}{m^2}\,,$$

so that for a given magnification, DOF is independent of focal length. Stated otherwise, for the same subject magnification, at the same *f*-number, all focal lengths used on a given image format give approximately the same DOF. This statement is true *only* when the subject distance is small in comparison with the hyperfocal distance, however.

The integrated circuit package, which is in focus in this macro shot, is 2.5 mm higher than the circuit board it is mounted on. In macro photography objects at even small distances from the plane of focus can be unsharp. At *f*/32 every object is within the DOF, whereas the closer to *f*/5 the aperture gets, the fewer the objects that are sharp. There is a tradeoff, however: at *f*/32, the lettering on the IC package is noticeably softer than at *f*/5 because of diffraction. At *f*/5 the small dust particles at the bottom right corner form blur spots in the shape of the aperture stop. The images were taken with a 105 mm *f*/2.8 macro lens.

The discussion thus far has assumed a symmetrical lens for which the entrance and exit pupils coincide with the front and rear nodal planes, and for which the pupil magnification (the ratio of exit pupil diameter to that of the entrance pupil)[11] is unity. Although this assumption usually is reasonable for large-format lenses, it often is invalid for medium- and small-format lenses.

When $s \ll H$, the DOF for an asymmetrical lens is

$$\mathrm{DOF} \approx \frac{2Nc\,(1+m/P)}{m^2}\,,$$

where P is the pupil magnification. When the pupil magnification is unity, this equation reduces to that for a symmetrical lens.

Except for close-up and macro photography, the effect of lens asymmetry is minimal. At unity magnification, however, the errors from neglecting the pupil magnification can be significant. Consider a telephoto lens with $P = 0.5$ and a retrofocus wide-angle lens with $P = 2$, at $m = 1.0$. The asymmetrical-lens formula gives $\mathrm{DOF} = 6Nc$ and $\mathrm{DOF} = 3Nc$, respectively. The symmetrical-lens formula gives $\mathrm{DOF} = 4Nc$ in either case. The errors are −33% and 33%, respectively.

Focus and `f`-number from DOF limits

For given near and far DOF limits D_{N} and D_{F}, the required `f`-number is smallest when focus is set to

$$s = \frac{2D_{\mathrm{N}}D_{\mathrm{F}}}{D_{\mathrm{N}}+D_{\mathrm{F}}}\,,$$

the harmonic mean of the near and far distances. When the subject distance is large in comparison with the lens focal length, the required `f`-number is

$$N \approx \frac{f^2}{c}\,\frac{D_{\mathrm{F}}-D_{\mathrm{N}}}{2D_{\mathrm{N}}D_{\mathrm{F}}}\,.$$

When the far limit of DOF is at infinity,

$$s = 2D_{\mathrm{N}}$$

and

$$N \approx \frac{f^2}{c}\frac{1}{2D_\mathrm{N}}\,.$$

In practice, these settings usually are determined on the image side of the lens, using measurements on the bed or rail with a view camera, or using lens DOF scales on manual-focus lenses for small- and medium-format cameras. If v_N and v_F are the image distances that correspond to the near and far limits of DOF, the required f-number is minimized when the image distance v is

$$v \approx \frac{v_\mathrm{N} + v_\mathrm{F}}{2} = v_\mathrm{F} + \frac{v_\mathrm{N} - v_\mathrm{F}}{2}\,.$$

In practical terms, focus is set to halfway between the near and far image distances. The required f-number is

$$N \approx \frac{v_\mathrm{N} - v_\mathrm{F}}{2c}\,.$$

The image distances are measured from the camera's image plane to the lens's image nodal plane, which is not always easy to locate. In most cases, focus and f-number can be determined with sufficient accuracy using the approximate formulas above, which require only the difference between the near and far image distances; view camera users sometimes refer to the difference $v_\mathrm{N} - v_\mathrm{F}$ as the *focus spread* (Hansma 1996, 55). Most lens DOF scales are based on the same concept.

The focus spread is related to the depth of focus. Ray (2000, 56) gives two definitions of the latter. The first is the tolerance of the position of the image plane for which an object remains acceptably sharp; the second is that the limits of depth of focus are the image-side conjugates of the near and far limits of DOF. With the first definition, focus spread and depth of focus are usually close in value though conceptually different. With the second definition, focus spread and depth of focus are the same.

Foreground and background blur

If a subject is at distance s and the foreground or background is at distance D, let the distance between the subject and the foreground or background be indicated by

$$x_\mathrm{d} = |D - s|\,.$$

The blur disk diameter b of a detail at distance x_d from the subject can be expressed as a function of the subject magnification m_s, focal length f, f-number N or alternatively the diameter of the entrance pupil d (often called the aperture) according to

$$b = \frac{f m_\mathrm{s}}{N}\frac{x_\mathrm{d}}{s \pm x_\mathrm{d}} = d m_\mathrm{s}\frac{x_\mathrm{d}}{D}\,.$$

The minus sign applies to a foreground object, and the plus sign applies to a background object.

The blur increases with the distance from the subject; when $b \le c$, the detail is within the depth of field, and the blur is imperceptible. If the detail is only slightly outside the DOF, the blur may be only barely perceptible.

For a given subject magnification, f-number, and distance from the subject of the foreground or background detail, the degree of detail blur varies with the lens focal length. For a background detail, the blur increases with focal length; for a foreground detail, the blur decreases with focal length. For a given scene, the positions of the subject, foreground, and background usually are fixed, and the distance between subject and the foreground or background remains constant regardless of the camera position; however, to maintain constant magnification, the subject distance must vary if the focal length is changed. For small distance between the foreground or background detail, the effect of focal length is small; for large distance, the effect can be significant. For a reasonably distant background detail, the blur disk diameter is

$$b \approx \frac{f m_\mathrm{s}}{N}\,,$$

depending only on focal length.

The blur diameter of foreground details is very large if the details are close to the lens.

The magnification of the detail also varies with focal length; for a given detail, the ratio of the blur disk diameter to imaged size of the detail is independent of focal length, depending only on the detail size and its distance from the subject. This ratio can be useful when it is important that the background be recognizable (as usually is the case in evidence or surveillance photography), or unrecognizable (as might be the case for a pictorial photographer using selective focus to isolate the subject from a distracting background). As a general rule, an object is recognizable if the blur disk diameter is one-tenth to one-fifth the size of the object or smaller (Williams 1990, 205),[12] and unrecognizable when the blur disk diameter is the object size or greater.

The effect of focal length on background blur is illustrated in van Walree's article on Depth of field [13].

Practical complications

The distance scales on most medium- and small-format lenses indicate distance from the camera's image plane. Most DOF formulas, including those in this article, use the object distance s from the lens's front nodal plane, which often is not easy to locate. Moreover, for many zoom lenses and internal-focusing non-zoom lenses, the location of the front nodal plane, as well as focal length, changes with subject distance. When the subject distance is large in comparison with the lens focal length, the exact location of the front nodal plane is not critical; the distance is essentially the same whether measured from the front of the lens, the image plane, or the actual nodal plane. The same is not true for close-up photography; at unity magnification, a slight error in the location of the front nodal plane can result in a DOF error greater than the errors from any approximations in the DOF equations.

The asymmetrical lens formulas require knowledge of the pupil magnification, which usually is not specified for medium- and small-format lenses. The pupil magnification can be estimated by looking into the front and rear of the lens and measuring the diameters of the apparent apertures, and computing the ratio of rear diameter to front diameter (Shipman 1977, 144). However, for many zoom lenses and internal-focusing non-zoom lenses, the pupil magnification changes with subject distance, and several measurements may be required.

Limitations

Most DOF formulas, including those discussed in this article, employ several simplifications:

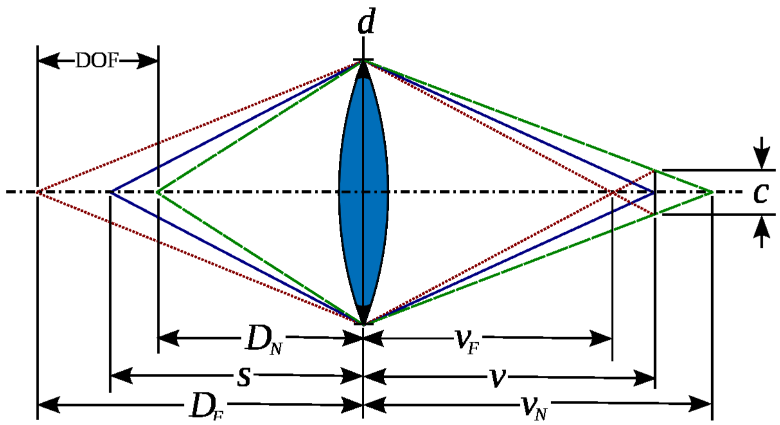
1. Paraxial (Gaussian) optics is assumed, and technically, the formulas are valid only for rays that are infinitesimally close to the lens axis. However, Gaussian optics usually is more than adequate for determining DOF, and non-paraxial formulas are sufficiently complex that requiring their use would make determination of DOF impractical in most cases.
2. Lens aberrations are ignored. Including the effects of aberrations is nearly impossible, because doing so requires knowledge of the specific lens design. Moreover, in well-designed lenses, most aberrations are well corrected, and at least near the optical axis, often are almost negligible when the lens is stopped down 2–3 steps from maximum aperture. Because lenses usually are stopped down at least to this point when DOF is of interest, ignoring aberrations usually is reasonable. Not all aberrations are reduced by stopping down, however, so actual sharpness may be slightly less than predicted by DOF formulas.
3. Diffraction is ignored. DOF formulas imply that any arbitrary DOF can be achieved by using a sufficiently large `f`-number. Because of diffraction, however, this isn't really true, as is discussed further in the section DOF and diffraction.
4. For digital capture with color filter array sensors, demosaicing is ignored. Demosaicing alone would normally decrease sharpness, but the demosaicing algorithm used might also include sharpening.
5. Post-capture manipulation of the image is ignored. Sharpening via techniques such as deconvolution or unsharp mask can increase the apparent sharpness in the final image; conversely, image noise reduction can reduce sharpness.

6. The resolutions of the imaging medium and the display medium are ignored. If the resolution of either medium is of the same order of magnitude as the optical resolution, the sharpness of the final image is reduced, and optical blurring is harder to detect.

The lens designer cannot restrict analysis to Gaussian optics and cannot ignore lens aberrations. However, the requirements of practical photography are less demanding than those of lens design, and despite the simplifications employed in development of most DOF formulas, these formulas have proven useful in determining camera settings that result in acceptably sharp pictures. It should be recognized that DOF limits are not hard boundaries between sharp and unsharp, and that there is little point in determining DOF limits to a precision of many significant figures.

Derivation of the DOF formulas

DOF limits



DOF for symmetrical lens.

A symmetrical lens is illustrated at right. The subject, at distance s, is in focus at image distance v. Point objects at distances D_{F} and D_{N} would be in focus at image distances v_{F} and v_{N}, respectively; at image distance v, they are imaged as blur spots. The depth of field is controlled by the aperture stop diameter d; when the blur spot diameter is equal to the acceptable circle of confusion c, the near and far limits of DOF are at D_{N} and D_{F}. From similar triangles,

$$\frac{v_{\mathrm{N}} - v}{v_{\mathrm{N}}} = \frac{c}{d}$$

and

$$\frac{v - v_{\mathrm{F}}}{v_{\mathrm{F}}} = \frac{c}{d}.$$

It usually is more convenient to work with the lens f-number than the aperture diameter; the f-number N is related to the lens focal length f and the aperture diameter d by

$$N = \frac{f}{d};$$

substitution into the previous equations gives

$$\frac{v_{\mathrm{N}} - v}{v_{\mathrm{N}}} = \frac{v - v_{\mathrm{F}}}{v_{\mathrm{F}}} = \frac{Nc}{f}.$$

Rearranging to solve for v_{N} and v_{F} gives

$$v_{\mathrm{N}} = \frac{fv}{f - Nc}$$

and

$$v_{\mathrm{F}} = \frac{fv}{f + Nc}.$$

The image distance v is related to an object distance s by the thin lens equation

$$\frac{1}{s} + \frac{1}{v} = \frac{1}{f};$$

applying this to v_{N} and v_{F} gives

$$\frac{1}{D_{\mathrm{N}}} + \frac{1}{v_{\mathrm{N}}} = \frac{1}{f}$$

and

$$\frac{1}{D_{\mathrm{F}}} + \frac{1}{v_{\mathrm{F}}} = \frac{1}{f};$$

solving for v, v_{N}, and v_{F} in these three equations, substituting into the two previous equations, and rearranging gives the near and far limits of DOF:

$$D_{\mathrm{N}} = \frac{sf^2}{f^2 + Nc(s-f)}$$

and

$$D_{\mathrm{F}} = \frac{sf^2}{f^2 - Nc(s-f)}.$$

Hyperfocal distance

Solving for the focus distance s and setting the far limit of DOF D_{F} to infinity gives

$$s = H = \frac{f^2}{Nc} + f,$$

where H is the hyperfocal distance. Setting the subject distance to the hyperfocal distance and solving for the near limit of DOF gives

$$D_{\mathrm{N}} = \frac{f^2/(Nc) + f}{2} = \frac{H}{2}.$$

For any practical value of H, the focal length is negligible in comparison, so that

$$H \approx \frac{f^2}{Nc}.$$

Substituting the approximate expression for hyperfocal distance into the formulas for the near and far limits of DOF gives

$$D_{\mathrm{N}} = \frac{Hs}{H + (s-f)}$$

and

$$D_{\mathrm{F}} = \frac{Hs}{H - (s-f)}.$$

Combining, the depth of field $D_{\mathrm{F}} - D_{\mathrm{N}}$ is

$$\mathrm{DOF} = \frac{2Hs(s-f)}{H^2 - (s-f)^2} \text{ for } s < H.$$

Hyperfocal magnification

Magnification m can be expressed as

$$m = \frac{f}{(s-f)};$$

at the hyperfocal distance, the magnification m_{h} then is

$$m_{\mathrm{h}} = \frac{f}{(H-f)}.$$

Substituting $f^2/Nc + f$ for H and simplifying gives

$$m_{\mathrm{h}} = \frac{Nc}{f}.$$

DOF in terms of magnification

It is sometimes convenient to express DOF in terms of magnification m . Substituting

$$s = \frac{m+1}{m} f$$

and

$$s - f = \frac{f}{m}$$

into the formula for DOF and rearranging gives

$$\mathrm{DOF} = \frac{2f(m+1)/m}{(fm)/(Nc) - (Nc)/(fm)},$$

after Larmore (1965), 163).

DOF vs. focal length

Multiplying the numerator and denominator of the exact formula above by

$$\frac{Ncm}{f}$$

gives

$$\mathrm{DOF} = \frac{2Nc\,(m+1)}{m^2 - \left(\frac{Nc}{f}\right)^2}.$$

If the *f*-number and circle of confusion are constant, decreasing the focal length f increases the second term in the denominator, decreasing the denominator and increasing the value of the right-hand side, so that a shorter focal length gives greater DOF.

The term in parentheses in the denominator is the hyperfocal magnification m_{h}, so that

$$\mathrm{DOF} = \frac{2Nc\,(m+1)}{m^2 - m_{\mathrm{h}}^2}.$$

A subject distance is decreased, the subject magnification increases, and eventually becomes large in comparison with the hyperfocal magnification. Thus the effect of focal length is greatest near the hyperfocal distance, and decreases as subject distance is decreased. However, the near/far perspective will differ for different focal lengths, so the difference in DOF may not be readily apparent.

When $s \ll H$, $m_{\mathrm{h}}^2 \ll m^2$, and

$$\mathrm{DOF} \approx 2Nc\,\frac{m+1}{m^2},$$

so that for a given magnification, DOF is essentially independent of focal length. Stated otherwise, for the same subject magnification and the same *f*-number, all focal lengths for a given image format give approximately the same DOF. This statement is true only when the subject distance is small in comparison with the hyperfocal distance, however.

Moderate-to-large distances

When the subject distance is large in comparison with the lens focal length,

$$D_{\mathrm{N}} \approx \frac{Hs}{H+s}$$

and

$$D_{\mathrm{F}} \approx \frac{Hs}{H-s} \text{ for } s < H ,$$

so that

$$\mathrm{DOF} \approx \frac{2Hs^2}{H^2 - s^2} \text{ for } s < H .$$

For $s \geq H$, the far limit of DOF is at infinity and the DOF is infinite; of course, only objects at or beyond the near limit of DOF will be recorded with acceptable sharpness.

Close-up

When the subject distance s approaches the lens focal length, the focal length no longer is negligible, and the approximate formulas above cannot be used without introducing significant error. At close distances, the hyperfocal distance has little applicability, and it usually is more convenient to express DOF in terms of magnification. The distance is small in comparison with the hyperfocal distance, so the simplified formula

$$\mathrm{DOF} \approx 2Nc\,\frac{m+1}{m^2} ,$$

can be used with good accuracy. For a given magnification, DOF is independent of focal length.

Near:far DOF ratio

From the “exact” equations for near and far limits of DOF, the DOF in front of the subject is

$$s - D_{\mathrm{N}} = \frac{Ncs(s-f)}{f^2 + Nc(s-f)} ,$$

and the DOF beyond the subject is

$$D_{\mathrm{F}} - s = \frac{Ncs(s-f)}{f^2 - Nc(s-f)} .$$

The near:far DOF ratio is

$$\frac{s - D_{\mathrm{N}}}{D_{\mathrm{F}} - s} = \frac{f^2 - Nc(s-f)}{f^2 + Nc(s-f)} .$$

This ratio is always less than unity; at moderate-to-large subject distances, $f \ll s$, and

$$\frac{s - D_{\mathrm{N}}}{D_{\mathrm{F}} - s} \approx \frac{f^2 - Ncs}{f^2 + Ncs} = \frac{H-s}{H+s} .$$

When the subject is at the hyperfocal distance or beyond, the far DOF is infinite, and the near:far ratio is zero. It’s commonly stated that approximately 1/3 of the DOF is in front of the subject and approximately 2/3 is beyond; however, this is true only when $s \approx H/3$.

At closer subject distances, it’s often more convenient to express the DOF ratio in terms of the magnification

$$m = \frac{f}{s - f}\,;$$

substitution into the “exact” equation for DOF ratio gives

$$\frac{s - D_\mathrm{N}}{D_\mathrm{F} - s} = \frac{m - Nc/f}{m + Nc/f}\,.$$

As magnification increases, the near:far ratio approaches a limiting value of unity.

DOF vs. format size

When the subject distance is much less than hyperfocal, the total DOF is given to good approximation by

$$\mathrm{DOF} \approx 2Nc\,\frac{m+1}{m^2}\,.$$

When additionally the magnification is small compared to unity, the value of m in the numerator can be neglected, and the formula further simplifies to

$$\mathrm{DOF} \approx \frac{2Nc}{m^2}\,.$$

The DOF ratio for two different formats is then

$$\frac{\mathrm{DOF}_2}{\mathrm{DOF}_1} \approx \frac{N_2\,c_2}{N_1\,c_1}\left(\frac{m_1}{m_2}\right)^2\,.$$

Essentially the same approach is described in Stroebel (1976), 136–39).

“Same picture” for both formats

The results of the comparison depend on what is assumed. One approach is to assume that essentially the same picture is taken with each format and enlarged to produce the same size final image, so the subject distance remains the same, the focal length is adjusted to maintain the same angle of view, and to a first approximation, magnification is in direct proportion to some characteristic dimension of each format. If both pictures are enlarged to give the same size final images with the same sharpness criteria, the circle of confusion is also in direct proportion to the format size. Thus if l is the characteristic dimension of the format,

$$\frac{m_2}{m_1} = \frac{c_2}{c_1} = \frac{l_2}{l_1}.$$

With the same *f*-number, the DOF ratio is then

$$\frac{\mathrm{DOF}_2}{\mathrm{DOF}_1} \approx \frac{c_2}{c_1}\left(\frac{m_1}{m_2}\right)^2 = \frac{l_2}{l_1}\left(\frac{l_1}{l_2}\right)^2 = \frac{l_1}{l_2}\,,$$

so the DOF ratio is in inverse proportion to the format size. This ratio is approximate, and breaks down in the macro range of the larger format (the value of m in the numerator is no longer negligible) or as distance approaches the hyperfocal distance for the smaller format (the DOF of the smaller format approaches infinity).

If the formats have approximately the same aspect ratios, the characteristic dimensions can be the format diagonals; if the aspect ratios differ considerably (e.g., 4×5 vs. 6×17), the dimensions must be chosen more carefully, and the DOF comparison may not even be meaningful.

If the DOF is to be the same for both formats the required *f*-number is in direct proportion to the format size:

$$\frac{N_2}{N_1} \approx \frac{c_1}{c_2}\left(\frac{m_2}{m_1}\right)^2 = \frac{l_2}{l_1}\,.$$

Adjusting the *f*-number in proportion to format size is equivalent to using the same absolute aperture diameter for both formats, discussed in detail below in Use of absolute aperture diameter.

Same focal length for both formats

If the same lens focal length is used in both formats, magnifications can be maintained in the ratio of the format sizes by adjusting subject distances; the DOF ratio is the same as that given above, but the images differ because of the different perspectives and angles of view.

If the same DOF is required for each format, an analysis similar to that above shows that the required *f*-number is in direct proportion to the format size.

Another approach is to use the same focal length with both formats at the same subject distance, so the magnification is the same, and with the same *f*-number,

$$\frac{\mathrm{DOF}_2}{\mathrm{DOF}_1} \approx \frac{c_2}{c_1} = \frac{l_2}{l_1},$$

so the DOF ratio is in *direct* proportion to the format size. The perspective is the same for both formats, but because of the different angles of view, the pictures are not the same.

Cropping

Cropping an image and enlarging to the same size final image as an uncropped image taken under the same conditions is equivalent to using a smaller format; the cropped image requires greater enlargement and consequently has a smaller circle of confusion. The cropped image has less DOF than the uncropped image.

Use of absolute aperture diameter

The aperture diameter is normally given in terms of the *f*-number because all lenses set to the same *f*-number give approximately the same image illuminance (Ray 2002, 130), simplifying exposure settings. In deriving the basic DOF equations, the substitution of f/N for the absolute aperture diameter d can be omitted, giving the DOF in terms of the absolute aperture diameter:

$$\mathrm{DOF} = \frac{2s}{(dm)/c - c/(dm)},$$

after Larmore (1965), 163). When the subject distance s is small in comparison with the hyperfocal distance, the second term in the denominator can be neglected, leading to

$$\mathrm{DOF} \approx \frac{2sc}{dm}.$$

With the same subject distance and angle of view for both formats, $s_2 = s_1$, and

$$\frac{\mathrm{DOF}_2}{\mathrm{DOF}_1} \approx \frac{c_2}{c_1}\frac{d_1}{d_2}\frac{m_1}{m_2} = \frac{l_2}{l_1}\frac{d_1}{d_2}\frac{l_1}{l_2} = \frac{d_1}{d_2},$$

so the DOFs are in inverse proportion to the absolute aperture diameters. When the diameters are the same, the two formats have the same DOF. Von Rohr (1906) made this same observation, saying "At this point it will be sufficient to note that all these formulae involve quantities relating exclusively to the entrance-pupil and its position with respect to the object-point, whereas the focal length of the transforming system does not enter into them." Lyon's Depth of Field Outside the Box [14] describes an approach very similar to that of von Rohr.

Using the same absolute aperture diameter for both formats with the "same picture" criterion is equivalent to adjusting the *f*-number in proportion to the format sizes, discussed above under "Same picture" for both formats

Focus and f-number from DOF limits

Object-side relationships

The equations for the DOF limits can be combined to eliminate Nc and solve for the subject distance. For given near and far DOF limits D_{N} and D_{F}, the subject distance is

$$s = \frac{2 D_{\mathrm{N}} D_{\mathrm{F}}}{D_{\mathrm{N}} + D_{\mathrm{F}}} \, ,$$

the harmonic mean of the near and far distances. The equations for DOF limits also can be combined to eliminate s and solve for the required f-number, giving

$$N = \frac{f^2}{c} \frac{D_{\mathrm{F}} - D_{\mathrm{N}}}{D_{\mathrm{F}}(D_{\mathrm{N}} - f) + D_{\mathrm{N}}(D_{\mathrm{F}} - f)} \, .$$

When the subject distance is large in comparison with the lens focal length, this simplifies to

$$N \approx \frac{f^2}{c} \frac{D_{\mathrm{F}} - D_{\mathrm{N}}}{2 D_{\mathrm{N}} D_{\mathrm{F}}} \, .$$

When the far limit of DOF is at infinity, the equations for s and N give indeterminate results. But if all terms in the numerator and denominator on the right-hand side of the equation for s are divided by D_{F}, it is seen that when D_{F} is at infinity,

$$s = 2 D_{\mathrm{N}} \, .$$

Similarly, if all terms in the numerator and denominator on the right-hand side of the equation for N are divided by D_{F}, it is seen that when D_{F} is at infinity,

$$N = \frac{f^2}{c} \frac{1}{2 D_{\mathrm{N}} - f} \approx \frac{f^2}{c} \frac{1}{2 D_{\mathrm{N}}} \, .$$

Image-side relationships

Most discussions of DOF concentrate on the object side of the lens, but the formulas are simpler and the measurements usually easier to make on the image side. If the basic image-side equations

$$\frac{v_{\mathrm{N}} - v}{v_{\mathrm{N}}} = \frac{Nc}{f}$$

and

$$\frac{v - v_{\mathrm{F}}}{v_{\mathrm{F}}} = \frac{Nc}{f}$$

are combined and solved for the image distance v, the result is

$$v = \frac{2 v_{\mathrm{N}} v_{\mathrm{F}}}{v_{\mathrm{N}} + v_{\mathrm{F}}} \, ,$$

the harmonic mean of the near and far image distances. The basic image-side equations can also be combined and solved for N, giving

$$N = \frac{f}{c} \frac{v_{\mathrm{N}} - v_{\mathrm{F}}}{v_{\mathrm{N}} + v_{\mathrm{F}}} \, .$$

The image distances are measured from the camera's image plane to the lens's image nodal plane, which is not always easy to locate. The harmonic mean is always less than the arithmentic mean, but when the difference between the near and far image distances is reasonably small, the two means are close to equal, and focus can be set with sufficient accuracy using

$$v \approx \frac{v_{\mathrm{N}} + v_{\mathrm{F}}}{2} = v_{\mathrm{F}} + \frac{v_{\mathrm{N}} - v_{\mathrm{F}}}{2} \, .$$

This formula requires only the *difference* $v_N - v_F$ between the near and far image distances. View camera users often refer to this difference as the *focus spread*; it usually is measured on the bed or focusing rail. Focus is simply set to halfway between the near and far image distances.

Substituting $v_N + v_F = 2v$ into the equation for N and rearranging gives

$$N \approx \frac{f}{v} \frac{v_N - v_F}{2c}.$$

One variant of the thin-lens equation is $v = (m+1) f$, where m is the magnification; substituting this into the equation for N gives

$$N \approx \frac{1}{1+m} \frac{v_N - v_F}{2c}.$$

At moderate-to-large subject distances, m is small compared to unity, and the f-number can often be determined with sufficient accuracy using

$$N \approx \frac{v_N - v_F}{2c}.$$

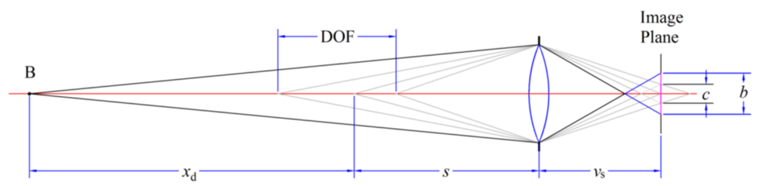
For close-up photography, the magnification cannot be ignored, and the f-number should be determined using the first approximate formula.

As with the approximate formula for v, the approximate formulas for N require only the focus spread $v_N - v_F$ rather than the absolute image distances.

When the far limit of DOF is at infinity, $v_F = f$.

On manual-focus small- and medium-format lenses, the focus and f-number usually are determined using the lens DOF scales, which often are based on the approximate equations above.

Foreground and background blur



Defocus blur for background object at B.

If the equation for the far limit of DOF is solved for c, and the far distance replaced by an arbitrary distance D, the blur disk diameter b at that distance is

$$b = \frac{f m_s}{N} \frac{D - s}{D}.$$

When the background is at the far limit of DOF, the blur disk diameter is equal to the circle of confusion c, and the blur is just imperceptible. The diameter of the background blur disk increases with the distance to the background. A similar relationship holds for the foreground; the general expression for a defocused object at distance D is

$$b = \frac{f m_s}{N} \frac{|D - s|}{D}.$$

For a given scene, the distance between the subject and a foreground or background object is usually fixed; let that distance be represented by

$$x_d = |D - s|;$$

then

$$b = \frac{f m_s}{N} \frac{x_d}{D}.$$

or, in terms of subject distance,

$$b = \frac{f m_s}{N} \frac{x_d}{s \pm x_d},$$

with the minus sign used for foreground objects and the plus sign used for background objects. For a relatively distant background object,

$$b \approx \frac{f m_\mathrm{s}}{N}.$$

In terms of subject magnification, the subject distance is

$$s = \frac{m_\mathrm{s} + 1}{m_\mathrm{s}} f,$$

so that, for a given f-number and subject magnification,

$$b = \frac{f m_\mathrm{s}}{N} \frac{x_\mathrm{d}}{\frac{m_\mathrm{s}+1}{m_\mathrm{s}} f \pm x_\mathrm{d}} = \frac{f m_\mathrm{s}^2}{N} \frac{x_\mathrm{d}}{(m_\mathrm{s} + 1) f \pm m_\mathrm{s} x_\mathrm{d}}.$$

Differentiating b with respect to f gives

$$\frac{\mathrm{d}b}{\mathrm{d}f} = \frac{\pm m_\mathrm{s}^3 x_\mathrm{d}^2}{N \left[(m_\mathrm{s} + 1) f \pm m_\mathrm{s} x_\mathrm{d}\right]^2}.$$

With the plus sign, the derivative is everywhere positive, so that for a background object, the blur disk size increases with focal length. With the minus sign, the derivative is everywhere negative, so that for a foreground object, the blur disk size decreases with focal length.

The magnification of the defocused object also varies with focal length; the magnification of the defocused object is

$$m_\mathrm{d} = \frac{v_\mathrm{s}}{D} = \frac{(m_\mathrm{s} + 1) f}{D},$$

where v_s is the image distance of the subject. For a defocused object with some characteristic dimension y, the imaged size of that object is

$$m_\mathrm{d} y = \frac{(m_\mathrm{s} + 1) f y}{D}.$$

The ratio of the blur disk size to the imaged size of that object then is

$$\frac{b}{m_\mathrm{d} y} = \frac{m_\mathrm{s}}{m_\mathrm{s} + 1} \frac{x_\mathrm{d}}{N y},$$

so for a given defocused object, the ratio of the blur disk diameter to object size is independent of focal length, and depends only on the object size and its distance from the subject.

Asymmetrical lenses

This discussion thus far has assumed a symmetrical lens for which the entrance and exit pupils coincide with the object and image nodal planes, and for which the pupil magnification is unity. Although this assumption usually is reasonable for large-format lenses, it often is invalid for medium- and small-format lenses.

For an asymmetrical lens, the DOF ahead of the subject distance and the DOF beyond the subject distance are given by[15]

$$\mathrm{DOF_N} = \frac{Nc(1 + m/P)}{m^2[1 + (Nc)/(fm)]}$$

and

$$\mathrm{DOF_F} = \frac{Nc(1 + m/P)}{m^2[1 - (Nc)/(fm)]},$$

where P is the pupil magnification.

Combining gives the total DOF:

$$\mathrm{DOF} = \frac{2f(1/m + 1/P)}{(fm)/(Nc) - (Nc)/(fm)}\,.$$

When $s \ll H$, the second term in the denominator becomes small in comparison with the first, and (Shipman 1977, 147)

$$\mathrm{DOF} \approx \frac{2Nc(1 + m/P)}{m^2}\,.$$

When the pupil magnification is unity, the equations for asymmetrical lenses reduce to those given earlier for symmetrical lenses.

Effect of lens asymmetry

Except for close-up and macro photography, the effect of lens asymmetry is minimal. A slight rearrangement of the last equation gives

$$\mathrm{DOF} \approx \frac{2Nc}{m}\left(\frac{1}{m} + \frac{1}{P}\right)\,.$$

As magnification decreases, the $1/P$ term becomes smaller in comparison with the $1/m$ term, and eventually the effect of pupil magnification becomes negligible.

Notes

[1] Strictly, because of lens aberrations and diffraction, a point object in precise focus is imaged not as a point but rather as a small spot, often called the *least circle of confusion*. For most treatments of DOF, including this article, the assumption of a point is sufficient.

[2] Englander describes a similar approach in his paper Apparent Depth of Field: Practical Use in Landscape Photography (http://www.englander-workshops.com/documents/depth.pdf). (PDF); Conrad discusses this approach, under Different Circles of Confusion for Near and Far Limits of Depth of Field, and The Object Field Method, in Depth of Field in Depth (http://www.largeformatphotography.info/articles/DoFinDepth.pdf) (PDF)

[3] The focus distance to have the DOF extend between given near and far object distances is the harmonic mean of the *object conjugates*. Most helicoid-focused lenses are marked with image plane–to–subject distances, so the focus determined from the lens distance scale is not exactly the harmonic mean of the marked near and far distances.

[4] Higher-end models in the Canon EOS line of cameras included a feature called depth-of-field AE (DEP) that set focus and `f`-number from user-determined near and far points in much the same manner as using DOF scales on manual-focus lenses (Canon Inc. 2000, 61–62). The feature has not been included on models introduced after April 2004.

[5] Using the object field method, Merklinger (1992), 32–35) describes a situation in which a portrait subject is to be sharp but a distracting sign in the background is to be unrecognizable. He concludes that with the subject and background distances fixed, no `f`-number will achieve both objectives, and that using a lens of different focal length will make no difference in the result.

[6] Peterson does not give a closed-form expression for the minimum `f`-number, though such an expression obtains from simple algebraic manipulation of his Equation 3.

[7] The analytical section at the end of Gibson (1975) was originally published as "Magnification and Depth of Detail in Photomacrography" in the *Journal of the Photographic Society of America*, Vol. 26, No. 6, June 1960.

[8] http://www.largeformatphotography.info/articles/DoFinDepth.pdf

[9] http://www.faqs.org/faqs/rec-photo/lenses/tutorial/

[10] Derivations of DOF formulas are given in many texts, including Larmore (1965), 161–166), Ray (2000, 53–56), and Ray (2002), 217–220). Complete derivations also are given in Conrad's Depth of Field in Depth (http://www.largeformatphotography.info/articles/DoFinDepth.pdf) (PDF) and van Walree's Derivation of the DOF equations (http://toothwalker.org/optics/dofderivation.html).

[11] A well-illustrated discussion of pupils and pupil magnification that assumes minimal knowledge of optics and mathematics is given in Shipman (1977), 144–147).

[12] Williams gives the criteria for object recognition in terms of the system resolution. When resolution is limited by defocus blur, as in the context of DOF, the resolution is the blur disk diameter; when resolution is limited by diffraction, the resolution is the radius of the Airy disk, according to the Rayleigh criterion.

[13] http://toothwalker.org/optics/dof.html#backgroundblur

[14] http://www.dicklyon.com/tech/Photography/DepthOfField-Lyon.pdf

[15] This is discussed in Jacobson's Photographic Lenses Tutorial (http://www.faqs.org/faqs/rec-photo/lenses/tutorial/), and complete derivations are given in Conrad's Depth of Field in Depth (http://www.largeformatphotography.info/articles/DoFinDepth.pdf) (PDF) and van Walree's Derivation of the DOF quations (http://toothwalker.org/optics/dofderivation.html).

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- Andrew Kay, Jonathan Mather, and Harry Walton, "Extended depth of field by colored apodization", Optics Letters, Vol. 36, Issue 23, pp. 4614-4616 (2011).

Further reading

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External links

- Depth of field explained (http://www.naturessecretlarder.co.uk/wildlife-photography-tutorials/depth-of-field-explained.htm)
- DoF (depth of field) calculator Multiline depth of field/hyperfocal distance/circle of confusion calculator with all parameters configurable. Provides two calculation methods: direct (camera+lens+distance+aperture=dof) and 'reversed' (camera+lens+object size+desired dof=distance/aperture) (http://www.altersky.com/photo/dof)
- Carl Zeiss Depth of Field and Bokeh (http://www.zeiss.de/C12567A8003B8B6F/EmbedTitelIntern/CLN_35_Bokeh_EN/$File/CLN35_Bokeh_en.pdf). *Camera Lens News* #35. April 2010. Accessed 2010-04-13.
- Jeff Conrad's Depth of Field in Depth (http://www.largeformatphotography.info/articles/DoFinDepth.pdf) (PDF). Includes derivations of most DoF formulas
- Doug Kerr's Depth of Field in Film and Digital Cameras (http://dougkerr.net/pumpkin/articles/Depth_of_Field.pdf)
- Rik Littlefield's An Introduction to Extended Depth of Field Digital Photography (http://www.janrik.net/insects/ExtendedDOF/LepSocNewsFinal/EDOF_NewsLepSoc_2005summer.htm)
- Dick Lyon's Depth of Field Outside the Box (http://www.dicklyon.com/tech/Photography/DepthOfField-Lyon.pdf) (PDF). A format-independent look at DOF
- Stanford University CS 178 interactive Flash applet (http://graphics.stanford.edu/courses/cs178/applets/dof.html) on depth of field, with formula and geometric construction.
- Paul van Walree's Depth of field (http://toothwalker.org/optics/dof.html).
- Paul van Walree's DOF with Pupil Magnification (http://toothwalker.org/optics/dofderivation.html). Includes derivation

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