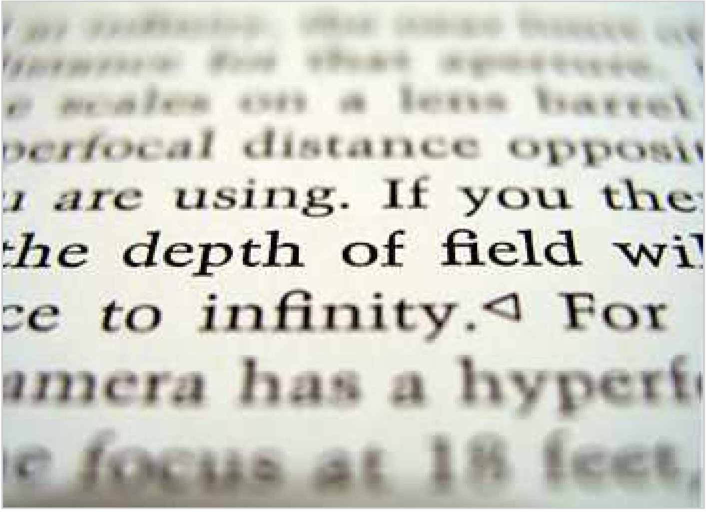
Depth of field

From Wikipedia, the free encyclopedia

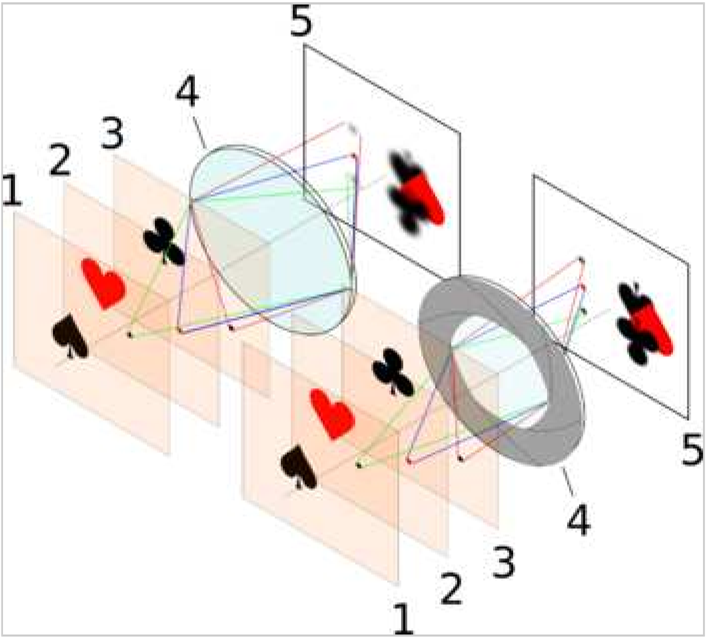
In optics, particularly film and photography, the **depth of field** (DOF) is the distance in front of and beyond the subject that appears to be in focus.

Photography Portal

Contents



A macro photograph with very small depth of field.

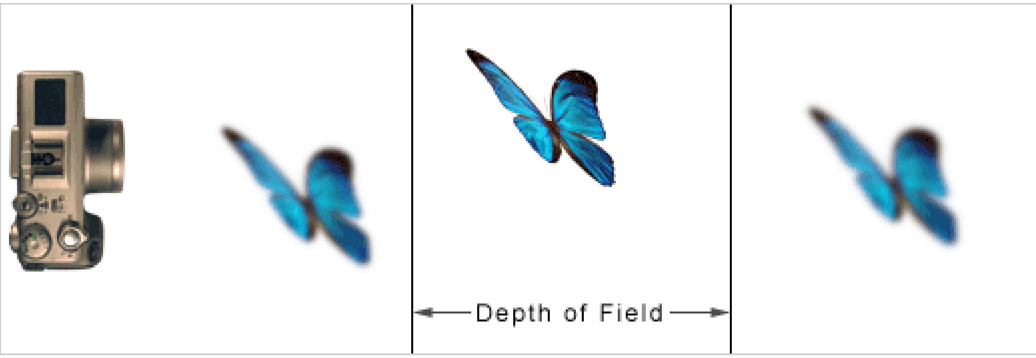


Effect of aperture on blur and DOF. The points in focus (**2**) project points onto the image plane (**5**), but points at different distances (**1** and **3**) project blurred images, or circles of confusion. Decreasing the aperture size (**4**) reduces the size of the blur circles for points not in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

Apparent sharp focus

Precise focus is possible at only one distance; at that distance, a point object will produce a point image. At any other distance, a point object is *defocused*, and will produce a circular image. However, when the circle 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. 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.

Several other factors, such as subject matter, movement, and the distance of the subject from the camera, also influence when a given defocus becomes noticeable.



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

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.)

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 0.7 meters to infinity would appear to be in focus.

The image format size also will affect the depth of field. 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. What this all means is that because the larger formats require longer lenses than the smaller ones, they will accordingly have a smaller depth of field. Therefore, 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.

Effect of *f*-number

For a given subject framing, the DOF is controlled by the lens f-number. Increasing the *f*-number (reducing the aperture diameter) increases the DOF; however, it also reduces the amount of light transmitted, and increases diffraction, placing a practical limit on the extent to which the aperture size may be reduced. 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.

f/22

f/8

f/4

f/2.8

Above: DOF at various apertures

Camera movements and DOF

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. With tilt, the height of the DOF increases with distance from the camera; with swing, the width of the DOF increases with distance.

Rotating the POF with tilt or swing (or both) can be used either to maximize or minimize the part of an image that is within the DOF.

Limited DOF: selective focus

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 the entire image in focus, 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 closeup 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* or *differential 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.

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*/32, the background is distracting.

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

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

Above: Selective focus

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. 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.

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. 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 refer to this as “wasting DOF”; however, see *The object field method* below. Focusing ahead of the hyperfocal distance increases the DOF ahead of the subject, but decreases DOF beyond the subject, including objects near infinity. Of course, this latter approach may be appropriate for images that do not extend to infinity.

The object field method

Traditional depth-of-field formulae and tables assume equal circles of confusion for near and far objects. Some authors, such as Merklinger (1992),[1] 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.

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.

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; as the subject distance decreases, near:far DOF ratio increases, approaching unity at high magnification. The oft-cited “rule” that 1/3 of the DOF is in front of the subject and 2/3 is beyond is true only when the subject distance is 1/3 the hyperfocal distance.

Depth of field formulae

The basis of these formulae is given in the section Derivation of the DOF formulae;[2] 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

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

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

When the subject distance is the hyperfocal distance,

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

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

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

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

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.

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.

Close-up

When the subject distance *s* approaches the focal length, using the formulae 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,

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

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

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)[3] 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 DOF = 6*Nc* and DOF = 3*Nc*, respectively. The symmetrical-lens formula gives DOF = 4*Nc* in either case. The errors are −33% and 33%, respectively.

Focus and *f*-number

Not all images require that sharpness extend to infinity; for given near and far DOF limits D_N and D_F, the required f-number is smallest when focus is set to

$$s = \frac{2D_N D_F}{D_N + D_F}$$

When the subject distance is large in comparison with the lens focal length, the required *f*-number is

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

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 formulae above, which require only the difference between the near and far image distances; view camera users often refer to the difference $v_{\mathrm{N}} - v_{\mathrm{F}}$ as the *focus spread*. Most lens DOF scales are based on the same concept.

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 focal length, subject magnification, and *f*-number according to

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

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 $b \leq c$, 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 ratio *b* / *c* is independent of camera format; the blur then is in terms of circles of confusion.

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),[4] 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 (http://www.vanwalree.com/optics/dof.html#backgroundblur).

Practical complications

The distance scales on most medium- and small-format lenses indicate distance from the camera's image plane. Most DOF formulae, including those in this article, use the object distance *s* from the lens's object nodal plane, which often is not easy to locate. Moreover, for many zoom lenses and internal-focusing non-zoom lenses, the location of the object 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 object 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 object nodal plane can result in a DOF error greater than the errors from any approximations in the DOF equations.

The asymmetrical lens formulae 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 (rear diameter divided by front diameter).[5] 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 formulae, including those discussed in this article, employ several simplifications:

1. Paraxial (Gaussian) optics is assumed, and technically, the formulae are valid only for rays that are infinitessimally close to the lens axis. However, Gaussian optics usually is more than adequate for determining DOF, and non-paraxial formulae 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 formulae.
3. Diffraction is ignored. DOF formulae imply that any arbitrary DOF can be achieved by using a sufficiently large f-number. Because of diffraction, however, this isn't quite true. Once a lens is stopped down to where most aberrations are well corrected, stopping down further will decrease sharpness in the center of the field. At the DOF limits, however, further stopping down decreases the size of the defocus blur spot, and the overall sharpness may increase. Consequently, choosing an *f*-number sometimes involves a tradeoff between center and edge sharpness, although viewers typically prefer uniform sharpness to slightly greater center

sharpness. The choice, of course, is subjective, and may depend upon the particular image. Eventually, the defocus blur spot becomes negligibly small, and further stopping down serves only to decrease sharpness even at DOF limits. Typically, diffraction at DOF limits becomes significant only at fairly large *f*-numbers; because large *f*-numbers typically require long exposure times, motion blur often causes greater loss of sharpness than does diffraction. Combined defocus and diffraction is discussed in Hansma (1996) and in Conrad's Depth of Field in Depth (http://www.largeformatphotography.info/articles/DoFinDepth.pdf) (PDF) and Jacobson's Photographic Lenses Tutorial (http://www.faqs.org/faqs/rec-photo/lenses/tutorial/).

4. Post-capture manipulation of the image is ignored. Sharpening via techniques such as deconvolution or unsharp mask can increase the DOF in the final image, particularly when the original image has a large DOF. Conversely, noise reduction can reduce the DOF.
5. For digital capture with color filter array sensors, demosaicing is ignored. Demosaicing alone would normally reduce the DOF, but the demosaicing algorithm used might also include sharpening.

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 formulae, these formulae 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.

DOF vs. format size

To a first approximation, DOF is inversely proportional to format size. More precisely, if photographs with the same final-image size are taken in two different camera formats at the same subject distance with the same field of view and *f*-number, the DOF is, to a first approximation, inversely proportional to the format size. Strictly speaking, this is true only when the subject distance is large in comparison with the focal length and small in comparison with the hyperfocal distance, for both formats, but it nonetheless is generally useful for comparing results obtained from different formats

To maintain the same field of view, the lens focal lengths must be in proportion to the format sizes. Assuming, for purposes of comparison, that the 4×5 format is four times the size of 35 mm format, if a 4×5 camera used a 300 mm lens, a 35 mm camera would need a 75 mm lens for the same field of view. For the same *f*-number, the image made with the 35 mm camera would have four times the DOF of the image made with the 4×5 camera.

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. In windy conditions, the exposure time with the larger camera might allow motion blur. Adjusting the *f*-number to the camera format is equivalent to maintaining the same absolute aperture diameter.

The greater DOF with the smaller format can be either an advantage or a disadvantage, depending on the desired effect. For the same amount of foreground and background blur, a small-format camera requires a smaller *f*-number and allows a shorter exposure time than a large-format camera; however, many point-and-shoot digital cameras cannot provide a very shallow DOF. For example, a point-and-shoot digital camera with a 1/1.8″ sensor (7.18 mm × 5.32 mm) at a normal focal length and *f*/2.8 has the same DOF as a 35 mm camera with a normal lens at *f*/13.

In some cases, camera movements (tilt or swing) can be used to better fit the DOF to the scene, and achieve the required sharpness at a smaller *f*-number.

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, chip makers like IBM are forced to use chemical mechanical polishing machines 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).

Increasing DOF by digital compositing

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 Helicon Focus and CombineZM.

At *f*/11, the DOF in this image of a Wolf Spider is very limited.

Combining 8 exposures, each taken at *f*/11, gives good DOF.

Getting sufficient depth of field can be particularly challenging in macro photography. The images at right illustrate the increase in DOF that can be achieved by combining multiple exposures.

Other digital techniques include wavefront coding and plenoptic cameras.

Derivation of the DOF formulae

DOF limits

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,

$$\frac{v_N - v}{v_N} = \frac{c}{d}$$

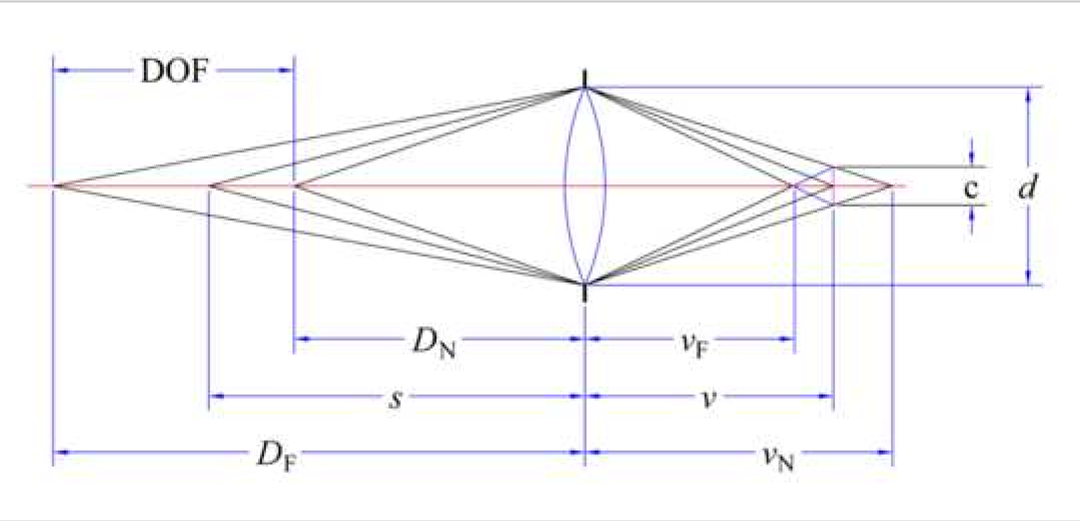
$$\frac{v - v_F}{v_F} = \frac{c}{d}$$

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

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

substituting into the previous equations and rearranging gives

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



DOF for symmetrical lens.

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

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

substituting into the two previous equations and rearranging gives the near and far limits of DOF:

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

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

Hyperfocal distance

Setting the far limit of DOF D_F to infinity and solving for the focus distance s 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 formulae for the near and far limits of DOF gives

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

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

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

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

Moderate-to-large distances

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

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

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

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

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 formulae 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. Substituting

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

and

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

into the formula for DOF and rearranging gives

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

At the hyperfocal distance, the terms in the denominator are equal, and the DOF is infinite. As the subject distance decreases, so does the second term in the denominator; when $s \ll H$, the second term becomes small in comparison with the first, and

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

so that for a given magnification, DOF is independent of focal length. Stated otherwise, for the same subject magnification, 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. Multiplying the numerator and denominator of the exact formula by

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

gives

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

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 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 the subject distance is small in comparison with the hyperfocal distance, the effect of focal length is negligible, and, as noted above, the DOF essentially 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.

Focus and *f*-number

Not all images require that sharpness extend to infinity; 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 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

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

Most discussions of DOF concentrate on the object side of the lens, but the formulae are simpler and the measurements usually easier to make on the image side. 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 minimum when the image distance *v* is

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

The required *f*-number is

$$N = \frac{f^2}{c} \frac{v_\mathrm{N} - v_\mathrm{F}}{v_\mathrm{N} + v_\mathrm{F}}$$

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. In most cases, focus and *f*-number can be determined with sufficient accuracy using the approximate formulae

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

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

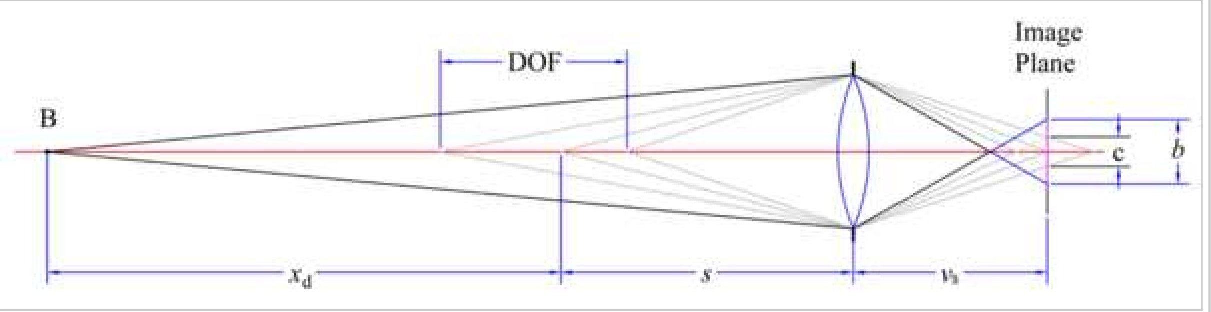
which require only the difference between the near and far image distances; focus is simply set to halfway between the near and far distances. View camera users often refer to the difference $v_N - v_F$ as the *focus spread*; it usually is measured on the bed or focusing rail. On manual-focus small- and medium-format lenses, the focus and *f*-number usually are determined using the lens DOF scales, which often are based on the two equations above.

For close-up photography, the *f*-number is more accurately determined using

$$N \approx \frac{1}{1+m} \frac{v_{\mathrm{N}} - v_{\mathrm{F}}}{2c},$$

where *m* is the magnification.

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

$$b = \frac{f m_{\mathrm{s}}}{N} \frac{D - s}{D}$$

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

$$b = \frac{f m_{\mathrm{s}}}{N} \frac{|D - s|}{D}$$

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

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

then

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

or, in terms of subject distance,

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

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,

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

Differentiating *b* with respect to *f* gives

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

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

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

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

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

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

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

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.

The effect of focal length on background blur is illustrated in van Walree's article on Depth of field (http://www.vanwalree.com/optics/dof.html).

Asymmetrical lenses

The 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[6]

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

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

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

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

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. ^ 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)
2. ^ Derivations of DOF formulae are given in many texts, including Larmore (1965) and Ray (2002). 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://www.pinnipedia.org/optics/dofderivation.html).
3. ^ A well-illustrated discussion of pupils and pupil magnification that assumes minimal knowledge of optics and mathematics is given in Shipman (1977).
4. ^ 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.
5. ^ The procedure for estimating pupil magnification is described in detail in Shipman (1977).
6. ^ 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://www.pinnipedia.org/optics/dofderivation.html).

References

- Hansma, Paul K. 1996. View Camera Focusing in Practice. *Photo Techniques,* March/April 1996, 54–57. Available as GIF images on the Large Format page (http://www.largeformatphotography.info/).
- Langford, Michael J. 1973. *Basic Photography*. 3rd ed. Garden City, NY: Amphoto. ISBN 0-8174-0640-9
- Larmore, Lewis. 1965. *Introduction to Photographic Principles*. 2nd ed. New York: Dover Publications, Inc.
- Merklinger, Harold M. 1992. *The INs and OUTs of FOCUS*. v. 1.0.3. Bedford, Nova Scotia: Seaboard Printing Limited. Version 1.03e available in PDF at http://www.trenholm.org/hmmerk/. ISBN 0-9695025-0-8
- Ray, Sidney F. 2002. *Applied Photographic Optics* (http://books.elsevier.com/us/focalbooks/us/subindex.asp?isbn=0240515404). 3rd ed. Oxford: Focal Press. ISBN 0-240-51540-4
- Shipman, Carl. 1977. *SLR Photographers Handbook.* Tucson: H.P. Books. ISBN 0-912656-59-X
- Williams, John B. 1990. *Image Clarity: High-Resolution Photography*. Boston: Focal Press. ISBN 0-240-80033-8

Further reading

- Hummel, Rob (editor). 2001. *American Cinematographer Manual.* 8th ed. Hollywood: ASC Press. ISBN 0-935578-15-3

See also

- Angle of view
- Bokeh
- Circle of confusion
- Deep focus
- Depth-of-field adapter
- Depth of focus
- Frazier lens (very deep DOF)
- Hyperfocal distance

- Perspective distortion
- Shallow focus
- Tilted plane focus (rotation of the POF)

External links

- Cambridge in Colour tutorial Depth of Field (http://www.cambridgeincolour.com/tutorials/depth-of-field.htm): illustrations and terminology for photographers
- Depth of field calculator (http://www.dofmaster.com/dofjs.html)
- Depth of Field explanation and comparison photographs (http://www.kevinwilley.com/l3_topic02.htm)
- Depth of Field—the Third Dimension (http://photospot2004.blogspot.com/2004/07/depth-of-field-third-dimension.html)
- Luminous Landscape demonstration that all focal lengths have approximately the same depth of field (http://www.luminous-landscape.com/tutorials/dof2.shtml) when *f*-number and subject image size are maintained
- Explanation of why “all focal lengths have approximately the same depth of field” (http://www.dofmaster.com/dof_imagesize.html) only under certain conditions
- Jeff Conrad's Depth of Field in Depth (http://www.largeformatphotography.info/articles/DoFinDepth.pdf) (PDF). Includes derivations of most DoF formulae
- Joe Englander's Apparent Depth of Field: Practical Use in Landscape Photography (http://www.englander-workshops.com/documents/depth.pdf) (PDF). Alternative criteria for circle of confusion
- David Jacobson's Photographic Lenses Tutorial (http://www.faqs.org/faqs/rec-photo/lenses/tutorial/)
- Rik Littlefield's An Introduction to Extended Depth of Field Digital Photography (http://www.janrik.net/insects/ExtendedDOF/LepSocNewsFinal/EDOF_NewsLepSoc_2005summer.htm)
- Paul van Walree's Depth of field (http://www.vanwalree.com/optics/dof.html).
- Paul van Walree's DOF with Pupil Magnification (http://www.vanwalree.com/optics/dofderivation.html). Includes derivation
- CombineZ—free software for increasing DoF of digital photos by combining differently focused versions of the same shot (http://www.hadleyweb.pwp.blueyonder.co.uk/CZM/combinezm.htm)
- Justin Snodgrass's Depth of Field Explained Video (http://snodart.com/tutorials.php).

Retrieved from "http://en.wikipedia.org/wiki/Depth_of_field"

Categories: Geometrical optics | Science of photography