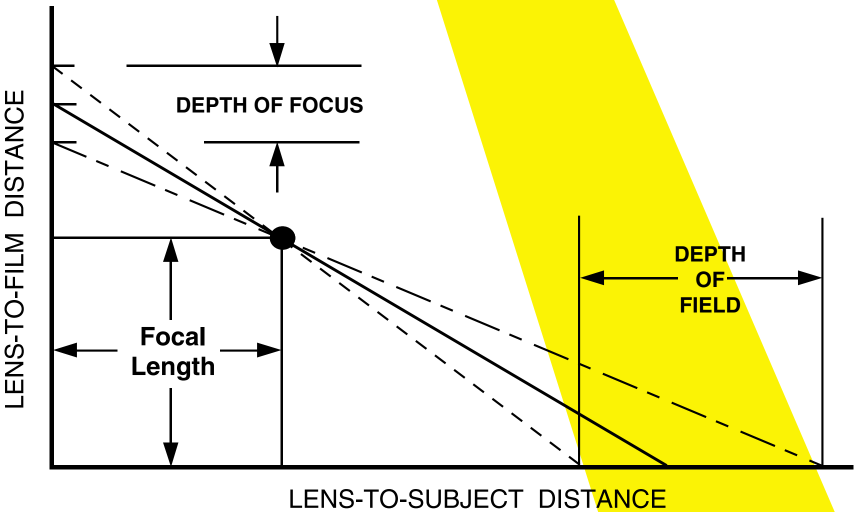
The INs and OUTs of FOCUS

Internet Edition

An Alternative Way to Estimate Depth-of-Field and Sharpness in the Photographic Image



by Harold M. Merklinger

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Published by the author

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http://www.trenholm.org/hmmerk/download.html

Published by the author:

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v 1.0 1 August 1990
v 1.0.2 1 April 1991
v1.03e 1 April 2002
(Internet edition).

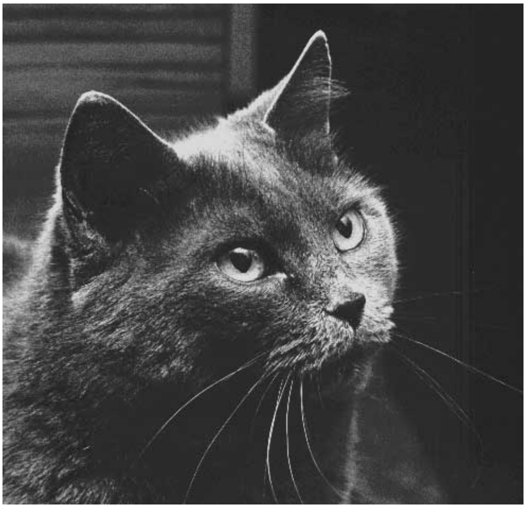
ISBN 0-9695025-0-8

Created in Canada using Adobe Acrobat Distiller, version 3. Note: add 5 to the book page number to get the page number of the electronic document.

ACKNOWLEDGEMENTS

Dedicated to my wife, Barbara, whose idea it was to buy the computer which made this book a realistic proposition for a man who can't spell or type.

CONTENTS



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CHAPTER 1

Depth-of-Field—The Concept

The concept of depth-of-field derives from the observation that not all parts of all photographic images need to be perfectly sharp. Indeed, the physical limitations of lenses, film, and printing media dictate that nothing will in fact be perfectly sharp. This observation, then, brings us to the question: how sharp is sharp enough? Once we establish a standard, the next problem is to discover rules which govern how the standard may be achieved in practice. In applying these rules we learn that there is usually a range of distances for which typical objects will be acceptably well rendered in our photographic image. This range of distances is the depth-of-field. But sometimes, the photographic art form demands that certain images be intentionally blurred. A complete guide to photographic imaging must also help us create a controlled degree of unsharpness. (As an aside, I often think that photography's greatest contribution to the graphic arts is the unsharp image. Prior to the invention of photography, man tended to paint all images sharply—the way the autofocus human eye sees them.)

This booklet is intended to explore concepts of photographic image sharpness and to explain how to control it. After establishing a few definitions and such, we will examine the traditional approach to the subject of depth-of-field and discuss the limitations of this theory. Although almost all books on photography describe this one view of the subject, it should be understood that other quite valid philosophies are also possible. And different philosophies on depth-of-field can provide surprisingly different guidance to the photographer. We will see, for example, that while the traditional rules tell us we must set our lens to f/56 and focus at 2 meters in one situation, a different philosophy might tell us to use f/10 and set the focus on infinity. And while the traditional approach provides us with only pass/fail sharpness criteria, there nevertheless exist simple ways to give good quantitative estimates of image smearing effects. Photographic optics, or lenses, of course affect apparent depth-of-field; we'll examine a number of interrelationships between lens characteristics, depth-of-field, and desired results. We'll also ask the question: Is what you see through your single-lens-reflex camera viewfinder what you get in your picture?

It will be assumed throughout that the reader is familiar with basic photographic principles. You need not have read and understood the many existing treatments of depth-of-field, but I hope you understand how to focus and set the lens opening of an adjustable camera. If you have previously been frustrated with poor definition in your photographs, that experience will be a definite plus: my motivation in writing this booklet was years of trying to understand unacceptable results even though I followed the rules. (I also experienced unexpected successes sometimes when I broke the rules.) The booklet does contain equations. But fear not, the vast majority of these equations only express simple scaling relationships between similar triangles and nothing more than a pencil and the back of an envelope are needed to work things out in most cases.

The next chapter, Chapter 2, will review some of the basic rules of photographic image creation. Chapter 3 will deal with the fundamentals of the traditional approach to the subject of depth-of-field. The traditional method considers only the characteristics of the image. Chapter 4 asks if there are not other factors which should also be considered. Chapter 5 will extend our vision to take into account *what* is being photographed. The following two chapters help to refine our understanding of what happens as an image goes out of focus, and how that the details are affected by such matters as diffraction, depth-of-focus, field curvature and film format. Next, we ask if all this is necessary in the context of the modern single-lens reflex camera which seems to allow the photographer to see the world as his lens does. Chapter 9 adds some general discussion, and Chapter 10 attempts to summarize the results in the form of rules-of-thumb. Chapter 11 provides a very brief summary and, finally, Chapter 12 provides some historical perspective to this study.

The most difficult mathematics is associated with the traditional depth-of-field analysis in Chapter 3. If you don't like maths, you will be forgiven for skipping this chapter.

I hope you will enjoy reading this booklet. Some of the concepts may not be easy, or might seem a bit strange—at first. But in the end, the thing that counts, is that your control over your photography just might improve.

CHAPTER 2

Basic Ideas and Definitions

If we are to come to a common understanding on almost any technical subject, we must all agree on the meaning of certain words. Fortunately for me this is a one-sided conversation and I get to pick the meaning of my words. This chapter is intended to help you understand what my words really mean. After we're finished, please feel free to express any of these ideas in your own words. But that's after we're finished; for now please bear with me.

We'll start by drawing a simplified schematic diagram of a very basic imaging system—a camera plus a single small object. This basic camera and subject are shown in Fig 1.

This diagram is not drawn to scale. It is intended only to help us define and understand many of the technical terms we'll be using. The three most important objects here are the lens, the film and the subject. Light reflecting from the subject radiates in almost all directions, but the only light that matters to the camera is that which falls on the front of the

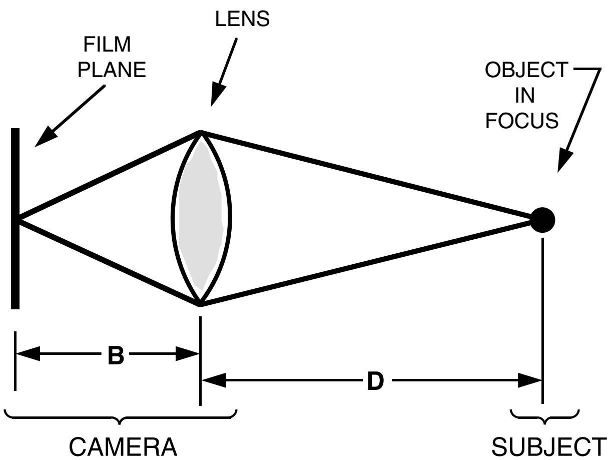


FIGURE 1: *Simplified diagram of Camera and Subject.*

camera lens. This light is focused on the film so that an image of the object is formed directly on the light-sensitive front surface of the film. (The image is actually upside down and backwards, but that will not really matter to us.) The lines drawn from object to outer edges of the lens to the film are intended to represent the outer surfaces of the cones of light which affect the imaging process: the cone in front of the lens has its apex at the object and its base on the front of the lens, the cone behind the lens has its apex at the sharply focused image and its base on the back of the lens. If the image is to be perfectly sharp, there is a mathematical relationship between the lens-to-object and lens-to-film distances and the focal length of the lens. The focal length of the lens is simply defined as the lens-to-film distance which gives a perfect image when the subject is a long, long distance away—as for a star in the night sky, for example. The distinction drawn between an 'object' and a 'subject' is that each object is considered to be sufficiently small that all parts of it are equally well rendered in the image. A subject may be large enough that some parts of it might be sharp while other parts might be out of focus. The subject might be an assembly of objects.

To focus on an object which is close at hand, the lens must be extended—that is, moved further away from the film. Our calculations will be made easier if we use a tiny bit of algebra to represent the situation. We define a few symbols to substitute for the various important distances. We define the lens focal length as **f**. The lens-to-object distance is **D**, and the lens-to-sharp-image distance is **B** (which stands for back-focus distance). Notice that the lens-to-image distance is not always equal to the lens-to-film distance; sometimes we don't focus exactly right

TABLE 1: Basic Definitions

Symbol	Definition
f	Focal length of lens
A	Lens-to-film distance
B	Lens-to-sharp-image distance
D	Lens-to-object distance
E	Lens extension from infinity focus position (**E** = **B-f**)
e	Focus error (equal to **A-B** or **B-A**)
M	Image Magnification (**M** = **A/D**)

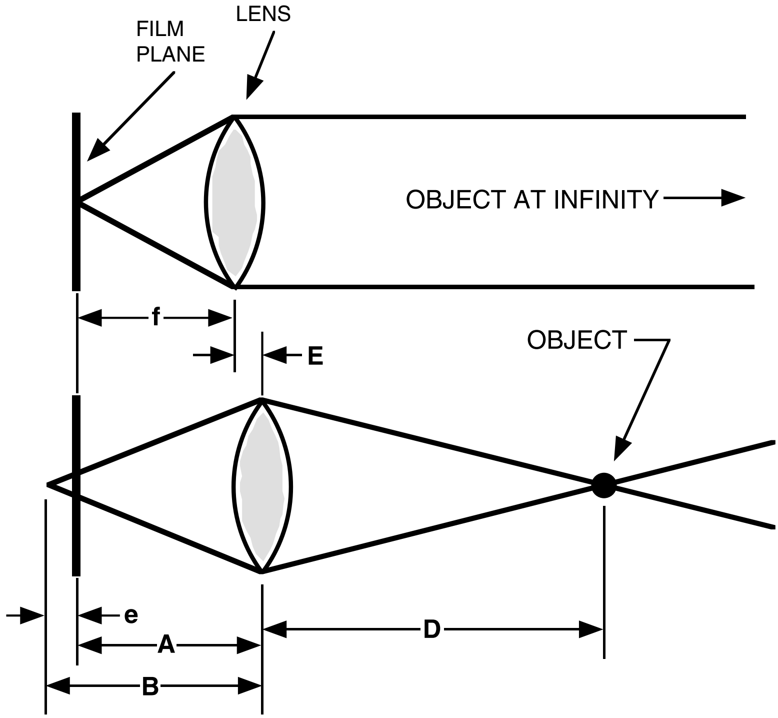


FIGURE 2: *Illustration of the meanings of our basic symbols.*

on target. We'll call the lens-to-film distance **A**, just because A is a letter of the alphabet close to B. The error in focus, the difference between **A** and **B**, we'll call **e** (for error). The distance through which the lens needs to be extended, to compensate for the lens-to-object distance being **D** rather than infinity, we'll call **E** (for extension). Another number that may turn out to be useful is the image magnification, that is, the size of the image expressed as a fraction of the actual size of the real object. The magnification factor, we'll call **M** and it's simply equal to the ratio **A/D**. To make it easier to find these definitions they are listed in Table 1 and illustrated in Figure 2.

Now there is a fundamental law of optics which relates the lens-to-image and lens-to-object distances to the focal length of the lens. This basic lens formula is written like this:

$$\frac{1}{\mathbf{B}} + \frac{1}{\mathbf{D}} = \frac{1}{\mathbf{f}}. \qquad (1)$$

The lens extension **E** needed to focus on an object at a given distance **D** may be determined from the relation above. With some algebra we can obtain:

$$\mathbf{E} = \frac{\mathbf{f}^2}{\mathbf{D - f}}. \tag{2}$$

These formulae can lead to some complicated algebra, but a geometric or graphical solution is also possible. Figure 3 shows how it's done. We draw a dashed line through the center of the lens. This is the lens axis. We also draw two vertical lines: one is drawn one focal length in front of the lens, the other is drawn vertically through the center of the lens. Another horizontal line is drawn exactly one focal length above the lens axis. We put the object directly in front of the lens at distance **D**. To find out where the film should be we draw a straight line from the object through the point, *p*, one focal length above the lens axis and one focal length in front of the lens. Continue drawing the line until it intersects the vertical line drawn through the lens center. The distance from this intersection point, *i*, to the lens axis is equal to **B**. The distance **B** tells us how far behind the lens the film must be if the image is to be in focus. If we were to do this for a number of different distances—a number of different values of **D**, and put tick marks along the vertical line, we would in effect be generating a distance scale to allow us to scale-focus the lens. Figure 3 illustrates how Equation (1) is just telling us something about triangles: It tells us that a right-angle triangle whose perpendicular sides are of lengths **B** and **D** is just a slightly enlarged version of the similar

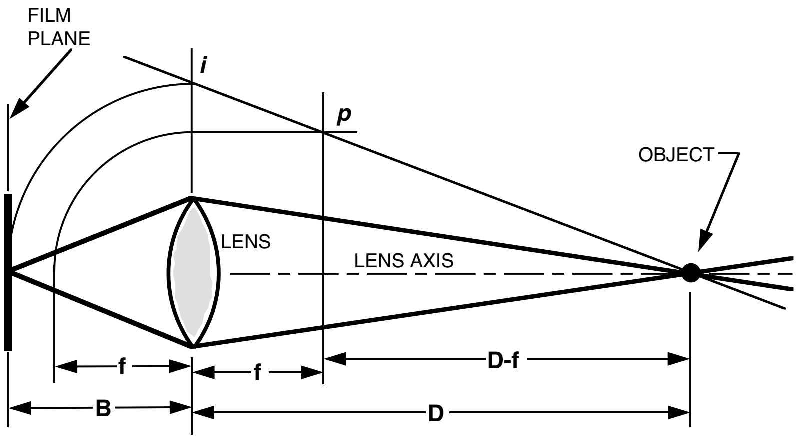


FIGURE 3: *Geometric construction illustrating equation (1).*

triangle whose sides are of lengths **f** and **D-f**. A slight bit of care is needed in applying this, however, because the distance scales on most lenses measure not from the lens but from the film plane. That is, if we define the distance as marked on the lens as **L**, then **L** may be expressed in terms of our other symbols as:

$$\mathbf{L} = \mathbf{D} + \mathbf{E} + \mathbf{f}$$

$$= \mathbf{D} + \mathbf{B}\ . \qquad (3)$$

Strictly speaking the formulae we have and will be using apply only to “thin” lenses. Real lenses especially those made up of several individual elements are “thick” and distances in front of the lens must be measured from the front “nodal point” of the lens and distances from the rear of the lens must be measured from the rear nodal point. Throughout this booklet we will ignore this detail; all lenses will be assumed to be thin.

The worst is just about over. We will continue to use some algebra, but there is usually a simple graphical way to visualise the result as well. Figure 3 can be simplified as shown in Figure 4 by leaving out the drawing of the lens itself and the arcs equating certain of the vertical and horizontal distances.

To use this graph one must know the focal length of the lens, and

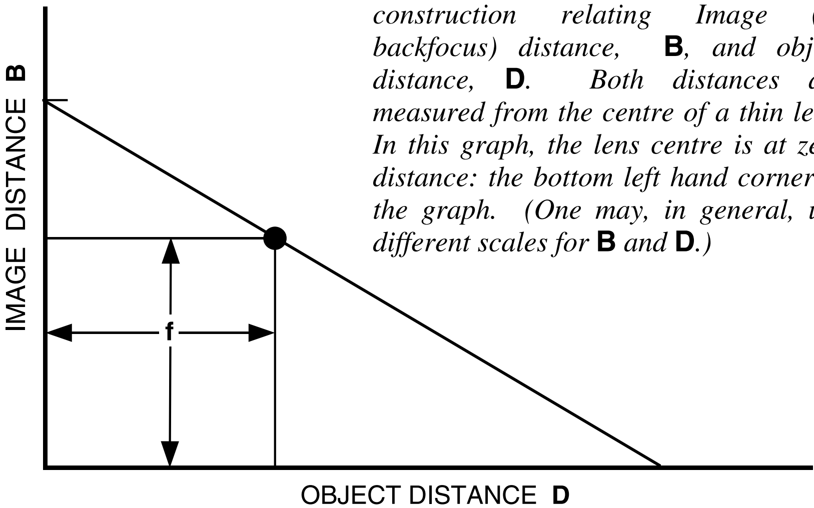


FIGURE 4: *Simplified geometric construction relating Image (or backfocus) distance,* **B***, and object distance,* **D***. Both distances are measured from the centre of a thin lens. In this graph, the lens centre is at zero distance: the bottom left hand corner of the graph. (One may, in general, use different scales for* **B** *and* **D***.)*

either the image distance or the object distance. A "box" one focal length square is drawn in the lower left corner of the graph and a mark is measured off and placed at the known distance—in this case the image distance. A straight line is drawn from this mark through the upper right hand corner of the "box" and continued to intersect the other axis—in this case the object distance axis. Where these lines intersect shows where an object would have to be in order to be in perfect focus. Any straight line which passes through the dot but which does not enter the square box, represents a valid (image producing) solution of Equation 1.

Most lenses include something called a diaphragm. This is a device which blocks off some of the light passing through the lens. Usually, the diaphragm leaves a circular opening in the central part of the lens. The purpose of this device is two-fold. First, the presence of the diaphragm restricts the amount of light reaching all portions of the image so that we can control the brightness of the image. Second, the effective diameter of a lens has some effect upon image sharpness. Adjusting the lens diameter allows us some measure of control over sharpness. The common standard, which has come to predominate, describes the effective lens diameter in terms of 'f-numbers'. These are the numbers like 1.4, 2, 2.8, 4, 5.6, 8, 11, 16, 22 and so on that we see on most lenses. An f-number of 8 means that the effective diameter of the lens, the diameter of the hole we can see looking through the *front* of the lens, is equal to one-eighth of the focal length of the lens. A lens having a focal length of 50 millimeters, when stopped down to f-8, will have an effective diameter of 50 divided by 8 or 6.25 millimeters. There are several different ways to denote the effective diameter of a lens; the one I will be using is that using a slash: f/8 means an f-number of 8. This way of writing the f-number serves to remind us that its meaning is to describe the diameter of the lens as a fraction of its focal length. I will introduce two new symbols: **N** (for number) will be used to represent the f-number, and **d** will be used to denote the actual diameter of the lens at the stated f-number. These definitions are repeated in Table 2 and the definitions lead directly to Equation 4:

$$\mathbf{d = f/N.} \tag{4}$$

It must be noted that we will *always* be talking about the *working* f-number or *working* diameter of a lens. The fact that a 50 millimeter lens might have a largest aperture of 25 millimeters or f/2 is of no consequence at all in terms of depth-of-field, if it is stopped down to f/16 or 3.125

TABLE 2: Basic Definitions Continued

Symbol	Definition
f	Focal length of lens
N	Working f-number of the lens
d	Working diameter of the lens

millimeters. Most of the drawings used in this booklet will appear to show a lens being used at its full or largest diameter. This is for convenience in drawing the figures. (It also helps keep down the clutter in the drawings.) It is to be understood that it will always be assumed that the lens is being used at a working diameter of **f/N**, whatever f-number we choose **N** to be.

Another concept needed in our study is a measure of how much an image is blurred by being out of focus. The standard, traditional notion is the circle-of-confusion. Figure 5 helps to explain. If the object is a tiny point source of light—a light shining through a pin-hole, for example—the cone of light falling on the lens will be focused on the image behind (or in front of) the film. If the film is not exactly where the image is—if there is a focus error **e**—the image at the film itself will be a small disk of light, not a point. The small disk-shaped image is called the circle-of-confusion. We'll label the diameter of the circle-of-confusion **c**. The diameter of the circle-of-confusion is proportional to the diameter of

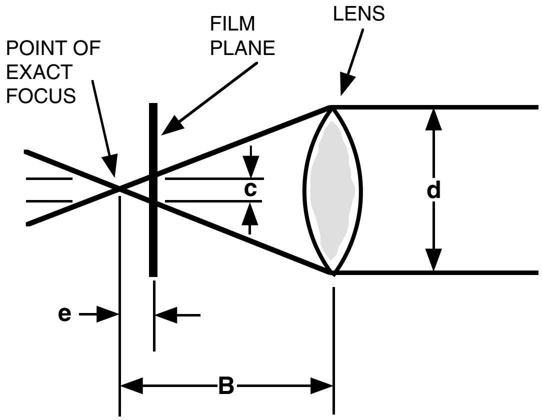


FIGURE 5: *Relationship between diameter of the circle-of-confusion and focus error.*

the lens, **d**, and to the focus error, **e**. From the simple geometry of Figure 5 we can see that:

$$\begin{aligned} \mathbf{c} &= \frac{\mathbf{e}}{\mathbf{B}}\,\mathbf{d} \\ &\approx \frac{\mathbf{e}}{\mathbf{f}}\frac{\mathbf{f}}{\mathbf{N}} = \frac{\mathbf{e}}{\mathbf{N}}. \end{aligned} \tag{5}$$

The wavy equals sign (≈) means "approximately equals". The second part of the equation above is true only when **B** is approximately equal to **f**. **B** will be approximately equal to **f** whenever the lens-to-subject distance is about ten times or more the focal length of the lens. What Equation (5) tells us is that the diameter of the circle-of-confusion is directly proportional to the focus error, **e**, and inversely proportional to **N**, the working f-number of the lens. Notice especially that the effect of focal length is cancelled out, that is, focal length in itself does not need to be used in our calculation of the blurring caused by focus error.

The total allowable focus error 2**g**—a distance **g** either side of the point of exact focus—which may be permitted and still keep the circle-of-confusion, **c**, smaller than some specified limit, **a**, is usually termed the depth-of-focus. We'll discuss this more fully in the next chapter. Note that we will need to be careful to distinguish between **c**, the diameter of the circle-of-confusion which exists under some arbitrary condition and **a**, the *maximum* diameter of the circle-of-confusion which may be permitted. Similarly we must distinguish between **g**, the maximum permissible focus error and **e**, the focus error which exists under some arbitrary condition.

Figure 5 illustrates another example of what I meant about most of our equations dealing with the relationship between similar triangles. Two "triangles" are represented in Fig. 5. The larger one has its apex at the point of exact focus, and its base through the diameter of the lens. The smaller triangle has a "height" of **e**, while the height of the larger triangle is **B**. Because the two triangles are similar (the same shape), the base length-to-height ratio is identical. That is, the ratio of **e** to **c** is the same as the ratio of **B** to **d**. This lets us write:

$$\frac{\mathbf{e}}{\mathbf{c}} = \frac{\mathbf{B}}{\mathbf{d}} \quad \text{or}$$

$$\mathbf{c} = \frac{\mathbf{e}}{\mathbf{B}}\,\mathbf{d}.$$

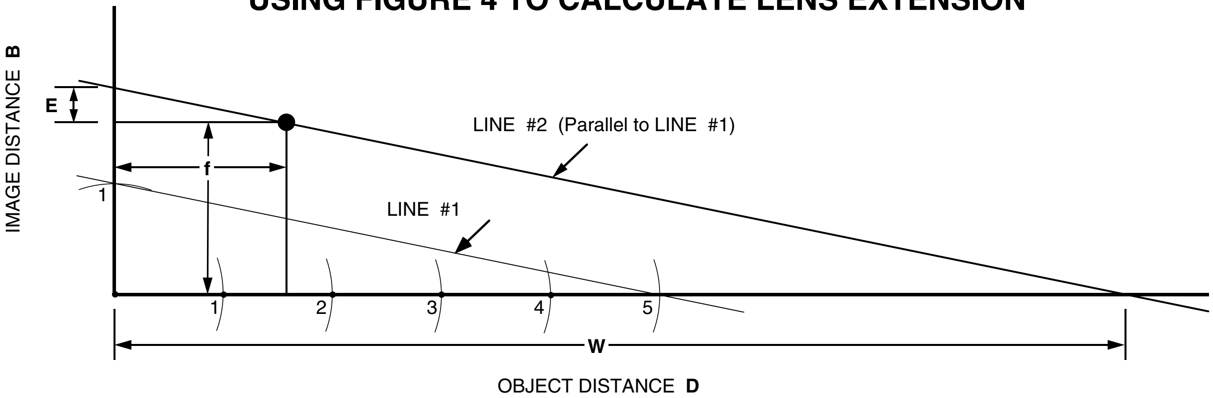
These simple relationships will be used over and over in our examination of depth-of-field.

So there we have it for basic definitions. There will be one or two new definitions as we go along, but I would be getting ahead of myself to introduce them now. In Chapter 3 we'll now have a look at the traditional approach to the estimation of depth-of-field.

An aside: The simple graphic solution of the lens equation demonstrated in Figure 4 is often not very practical to use at normal (pictorial) working distances. But for close-up (macro) photography, it can be quite useful. The image magnification ratio, **M**, determines the slope of the line through the dot. For 1:1 reproduction, the line must be at 45 degrees. For reproduction at one-half magnification, the line must be at 30 degrees to the horizontal so that **B** = **D**/2. For two times magnification, the line must be at 60 degrees so that **B** = 2**D**, and so on (**B** = **MD**). The extra lens extension required, and the working distance in front of the lens can then be read off as the distances between the focal square and where the line through the dot intersects the **B** and **D** axes respectively.

Example: Let's suppose we want to take pictures at a magnification of one-fifth. That is, the image should be one-fifth as large as the real object. Draw a copy of Figure 4 complete with **B** and **D** axes at right angles to one-another and a square having sides equal in length to the focal length of the lens you intend to use. Now take a drawing compass and mark off one unit of distance along the **B** (vertical) axis. (This unit of distance chosen is not important.) Then, without adjusting the compass, mark off five units of distance along the horizontal (**D**) axis. Draw a diagonal line from the point one unit up to the point five units to the right. The line will probably not pass through the upper right corner of the focal square, but that does not matter. Draw a line parallel to the one just drawn, but passing through the upper right corner of the square. Now we have it. The required lens extension may be measured off as the distance between the top of the focal square and where the last line just drawn intersects with the **B** axis. Overleaf is our drawing. Of course, we could use a little geometry or algebra to obtain the result: **E** = **Mf**.

USING FIGURE 4 TO CALCULATE LENS EXTENSION



In this example, we see how Figure 4 can be used to calculate the lens extension needed to permit photography at a reproduction ratio of 1:5. That is, the image is one-fifth the size of the object photographed. LINE #1 is drawn from a point one unit distance up from zero to a point five units to the right of zero. LINE #2 is then drawn parallel to LINE #1 but passing through the large dot. The distance **E** *is the lens extension required. The distance* **W** *is the approximate working distance between lens and subject. Since the triangle with sides* **E** *and* **f** *is similar to the one with sides* **f**+**E** *and* **W**, *we obtain the result* **E** = **Mf**.

CHAPTER 3

The Traditional Approach—The Image

I don't know these things for a fact, but it seems to me that it would be entirely natural for early photographers to have been troubled by the characteristics of their available media (film and paper) and their lenses. The *Leica Handbook* from about 1933 warns the Leica user not to use films which can record lines no thinner than one-tenth of a millimeter; rather one should use newer emulsions capable of supporting "a thickness of outline" of only one-thirtieth of a millimeter. Somewhere I also believe I read in a 1930s book or magazine that the average lens could produce an image spot no smaller than one-twentieth of a millimeter. If we accept such standards as gospel, it would seem pointless to strive for a focus error less than that which would produce a circle-of-confusion of about one-twentieth or one-thirtieth of a millimeter in diameter. And this is just what most treatments of the subject of depth-of-field assume. But films today are capable of much, much better resolution than one-twentieth or one-thirtieth of a millimeter. A good number to use for the best films today is more like one-two-hundredth of a millimeter.

If you read up on the subject of depth-of-field today, you will usually find a rather different rationale for the required image resolution. The human eye is said to be capable of resolving a spot no smaller than one quarter of a millimeter in diameter on a piece of paper 250 millimeters from the eye. If this spot were on an 8 by 10 inch photograph made from a 35 mm negative, the enlargement factor used in making the print would have been about eight. Thus if spots smaller than one-quarter millimeter are unimportant in the print, then spots smaller than one-thirty-second of a millimeter in diameter are unimportant in the negative. The usual standard used in depth-of-field calculations is to permit a circle-of-confusion on the negative no larger than one-thirtieth of a millimeter in diameter.

Near and Far Limits of Depth-of-Field

In the last chapter we saw in Figure 5 how an error in focus leads to a circle-of-confusion in the image. If we should specify how large we may allow the circle-of-confusion to become, this specification may be translated via Equation (5) into an allowable focus error:

$$\mathbf{g} = \mathbf{N}\,\mathbf{a}. \qquad (6)$$

This simply states that the allowable focus error on either side of the point of exact focus is equal to the f-number, **N**, times the maximum permissible diameter of the circle-of-confusion, **a**. If one then assumes that the camera is perfectly aligned and adjusted, we can use Equation (1) to determine the object distances within which our established image quality criterion (the maximum size of the circle-of-confusion) will be met or beyond which it will be exceeded. If the lens is focused at a distance **D** in front of the lens, measured from the front of the lens, the lens-to-film distance will be exactly **B** (based on Figure 2). The depth-of-field will extend from distance $\mathbf{D_1}$ to distance $\mathbf{D_2}$ where the corresponding backfocus distances $\mathbf{B_1}$ and $\mathbf{B_2}$ are equal to **B+g** and **B-g. g** is as defined above in Equation (6). The distance between $\mathbf{B_1}$ and $\mathbf{B_2}$ is the permissible depth-of-focus. Through quite a bit of algebra we can solve Equation (1) to determine $\mathbf{D_1}$ and $\mathbf{D_2}$ in terms of **D**, **N**, and **a**. What we find is:

$$D_1 = \frac{f^2D + gfD - gf^2}{f^2 - gf + gD} \qquad (7)$$

and

$$D_2 = \frac{f^2D - gfD + gf^2}{f^2 + gf - gD}. \qquad (8)$$

Hyperfocal Distance

Equations (7) and (8) can be simplified a bit if we make the substitution:

$$H = f + \frac{f^2}{g}. \qquad (9)$$

The quantity **H** has a special significance, for it turns out to be equal to the inner limit of depth-of-field when the lens is focused at infinity. Using this substitution Equations (7) and (8) become:

$$\mathbf{D_1} = \frac{\mathbf{DH - f^2}}{\mathbf{H + D - 2f}} \approx \frac{\mathbf{DH}}{\mathbf{H + D}} \tag{10}$$

and

$$\mathbf{D_2} = \frac{\mathbf{DH - 2fD + f^2}}{\mathbf{H - D}} \approx \frac{\mathbf{DH}}{\mathbf{H - D}}. \tag{11}$$

The wavy equals sign again means “approximately equals”. The approximate formulae are valid so long as the distance **D** is several times greater than the focal length of the lens. The approximate formulae would not be valid for macro photography. One can now ascertain the truth of the statement just made about **H**. If we set **D** equal to a very large number, Equation (10) tells us that $\mathbf{D_1}$ is equal to **H**. (If we try the same thing with Equation (11), we find that $\mathbf{D_2}$ is equal to **-H**; this is interpreted to mean that the far limit of depth-of-field when the lens is set at infinity is “beyond infinity”.) The distance **H** is usually called the *hyperfocal distance*. Note that it depends not only upon the focal length of the lens but also upon its f-number and upon the allowable circle-of-confusion since **g** = **Na**.

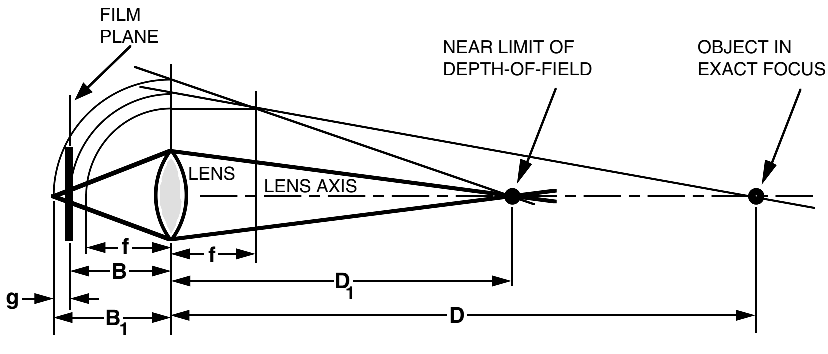


FIGURE 6: *Graphical Representation of Depth-of-field. In this case the lens is focused at its hyperfocal distance* **(D = H)** *and so the outer limit of the depth-of-field* ($\mathbf{D_2}$) *is at infinity.*

A Graphical Solution

Equations (7) and (8) are somewhat complicated—not the sort of thing one can remember easily. A graphical way to illustrate the relationships is shown in Figure 6, and again in somewhat somewhat cleaner form in Figure 7. The hyperfocal distance, **H**, would be the distance, **D**, obtained for an image distance, **B**, equal to **f+g**.

Depth-of-Field Scales

And that is just about all there is to the basics of depth-of-field as it is generally explained. The rest is just a matter of applying the calculations as put forward. Figure 7 helps to explain where the depth-of-field scales on lenses come from. An example of a typical depth-of-field scale is shown in Figure 8. The upper scale is a distance scale generated as suggested in Chapter 2. The lower scale essentially denotes how much focus tolerance we are permitted for any given f-stop.

The first thing to realize is that as one turns the focusing ring of a typical lens, the lens moves in or out by an amount directly proportional to

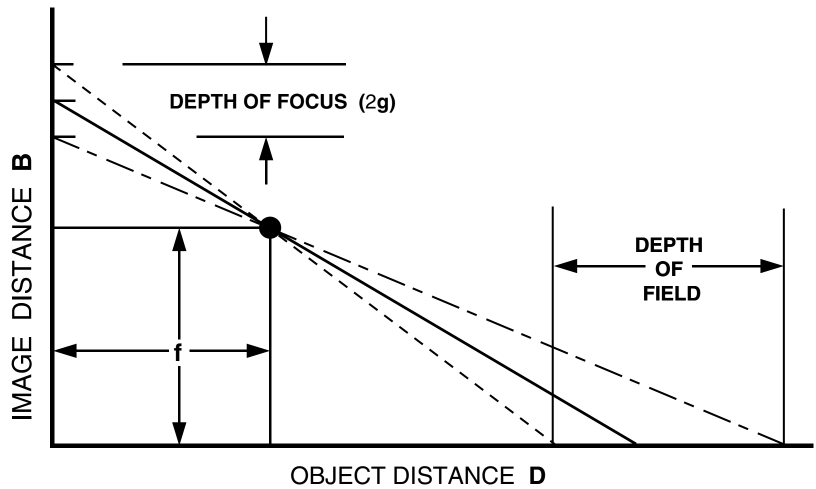


FIGURE 7: *Simplified geometric construction illustrating depth-of-focus and depth-of-field.*

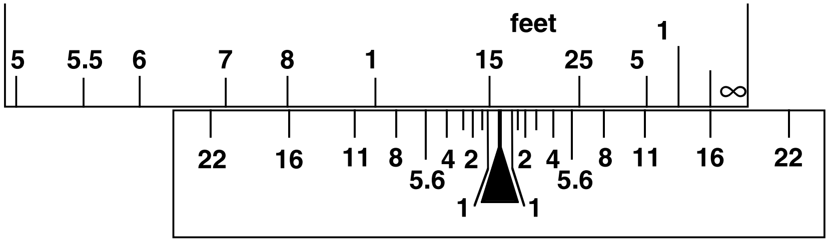


FIGURE 8: *Lens focusing and depth-of-field scales as they might appear on a 50 mm f/1 camera lens. The black triangle in the lower scale is the focus pointer; the other numbers in the lower scale are depth-of-field markers for the standard lens apertures. The upper scale is the standard distance scale.*

the distance through which the focusing ring is moved. If the focusing ring is required to move one inch (measured along its circumference) to move the lens out by one millimeter, then turning the ring through two inches will move the lens by two millimeters and so on. The scale factor which relates how much the lens moves to how much the ring was turned is simply the "pitch" of the helicoid. (A helicoid is a screw thread which translates twisting—or rotation—motion into extension.) And so distance measured along the circumference of the focusing ring is proportional to the movement of the lens along its axis.

Earlier we stated that **g** , the allowable error in focus measured at the film, is equal to **a**, the allowable circle-of-confusion, times **N** , the f-number of the lens. Now, the depth-of-field markers on our depth-of-field scale tell us how much we can turn the focusing ring away from the point of exact focus and still keep the circle-of-confusion within the specified limit. That amount is exactly equivalent to **g** in our formula **g** = **aN**. Or, in other words, the allowable focus error is directly proportional to **a**, the allowable circle-of-confusion, and **N** , the f-number to which the lens is set. This means that the depth-of-focus scale is just a simple ruler. The f/2 mark on the depth-of-field scale is twice as far from the focus pointer (the black triangle in Figure 9) as is the f/1 mark. The f/16 mark is 16 times further away from the focus pointer than is the f/1 mark and so on. If your f/2 lens doesn't show you a mark for f/2, but does show you an f/4 mark, you can judge where the f/2 mark should be: it's half way from the focus pointer to the f/4 mark. The unit in which the 'ruler' measures distance, is the diameter of the allowable circle-of-confusion. If we move the 15 ft mark on the distance scale from the focus pointer to the "8" depth-of-field marker on the right hand side, we have just extended the lens by 8 times the diameter of the circle-of-confusion: 8 thirtieths of a millimeter in the case of a typical 50 mm lens. It's as simple as that! Furthermore, the depth-of-field scale is the same for lenses of all focal lengths. It looks different on different lenses because the pitch of the helicoid is different, but the depth-of-field scale measures the same thing in the same units on all lenses. The distance scale, on the other hand, depends very much upon the focal length of the lens. On a flat-bed camera, the same depth-of-field scale can be used for all lenses. A separate distance scale, however, must be used for each focal length of lens. We'll discuss the nature of the distance scale further in Chapter 7.

There's another useful property of the simple formula discussed in the preceding paragraph. The distance from the focus pointer to the depth-of-field marker for a given f-stop is directly proportional to $\mathbf{a}$, the diameter of the allowable circle of confusion. So, if I don't think 1/30 mm is appropriate and want to use 1/60 mm for the allowable circle-of-confusion, I can just multiply the numbers next to the depth-of-field markers by a factor of two: if I am using f/11 for a working aperture, I should use the f/5.6 markers on the depth-of-field scale (because $2 \times 5.6 \quad 11$). Or, to put it another way, I should stop my lens down by two stops more than the depth-of-field scale says I can.

Let's compare our formulae for depth-of-field with the illustration in Figure 6. The focal length of the lens is 50 mm, and the allowable circle-of-confusion is 1/30 mm. We intend to use the lens at f/16 and desire that our depth-of-field extend from some minimum distance—the smallest it can be—to infinity. The first step is to calculate the hyperfocal distance, H, as defined in Equation (9). We have $\mathbf{f} = 50$ mm, $\mathbf{e} = \mathbf{aN}$, $\mathbf{a} = 1/30$ mm, and $\mathbf{N} = 16$. Thus we have:

$$\begin{aligned} \mathbf{H} &= 50 + \frac{50^2}{16/30} \\ &= 4737.5 \text{ mm.} \end{aligned} \tag{12}$$

Since the scale in Figure 6 is shown in feet, we convert from millimeters to feet, finding that the hyperfocal distance is 15.55 ft. Then, using Equation (10), we find that $\mathbf{D_1}$ is exactly one half of the hyperfocal distance, or 7.77 ft. One more correction: remember the distances we have been working in are measured from the front of the lens whereas the standard distances shown on camera lenses are measured from the film. Therefore we need to add about 50 mm to the calculated distances, obtaining $\mathbf{H/2}$ = (4737.5/2 + 50) mm = 2418.75 mm = 7.94 ft and H = 4737.5 + 50 = 4787.5 mm = 15.7 ft. The small error between this answer and the result shown in Figure 6 is due to two factors: one, in order to focus at 15.7 ft, the lens had to be extended, and so we should have added this slight lens extension in as well; and two, we used the approximate form of Equation (10) rather than the exact form. The far limit of the depth-of-field from Equation (11) is infinity as intended (since $\mathbf{H} = \mathbf{D}$, $\mathbf{D} - \mathbf{H} = 0$, and any number divided by zero is equal to infinity).

Where to Set the Focus

A question which often arises is "If I want the near limit of the depth-of-field to be at **X** and the far limit to be at **Y**, where do I set my focus?" The *Ilford Manual of Photography* (4th edition, 1949) tells us: "Where two objects situated at different distances **X** and **Y** from the camera are to be photographed, and it is required to know at which distance to focus the camera to obtain the best definition on both objects, the point is given by the expression

$$\frac{2\mathbf{XY}}{\mathbf{X}+\mathbf{Y}}.\text{"} \qquad (13)$$

One also frequently encounters a rule instructing one to focus one third of the way through the field. Does this agree with the formula above? The correct answer is: sometimes yes, sometimes no. Using a bit of algebra we can use Equation (13) to find out when the one-third rule is correct. We simply say that the formula, Equation (13), must give us the answer $\mathbf{X}+(\mathbf{Y}-\mathbf{X})/3$—that is, it must say we should focus one third of the way from **X** to **Y** (assuming that **Y** is the distance to the farther object). We find that the resulting equation has two answers. One is that **X** should equal **Y**. That makes sense. When the two objects are the same distance away, we should focus our lens at that distance. The other answer is $\mathbf{Y} = 2\mathbf{X}$. That is, when the farther limit of depth-of-field is at twice the distance from the lens as for the near limit of depth-of-field. Curiously, these two conditions ($\mathbf{Y} = \mathbf{X}$ and $\mathbf{Y} = 2\mathbf{X}$) are the *only* conditions under which the one-third rule applies exactly. Of course, it will apply *approximately* over a slightly greater range of conditions.

Should the size of the Circle-of-Confusion vary with Focal Length?

There is one last item worth mentioning. In some books or articles on the subject of depth-of-field, one may find that the allowable circle-of-confusion is specified as proportional to focal length. That is, while 1/30 mm might be used for a 50 mm lens, 1/15 mm would be used for a 100 mm lens. This scaling used to be done when changing focal length usually meant changing film formats. While a circle-of-confusion of 1/30 mm was appropriate for a 35 mm camera, the negative of the 6×9 cm camera using the 100 mm lens needed to be enlarged only half as much as the 35 mm negative and so 1/15 mm was the allowable circle-of-confusion for the medium format camera. Today, changing focal length usually means changing lenses on the same camera. And if one makes the move from a 35mm camera to medium format, one is usually attempting to improve the image quality as well, so keeping the same circle-of-confusion might well be more appropriate today.

CHAPTER 4

Is the Traditional Approach the Best Approach?

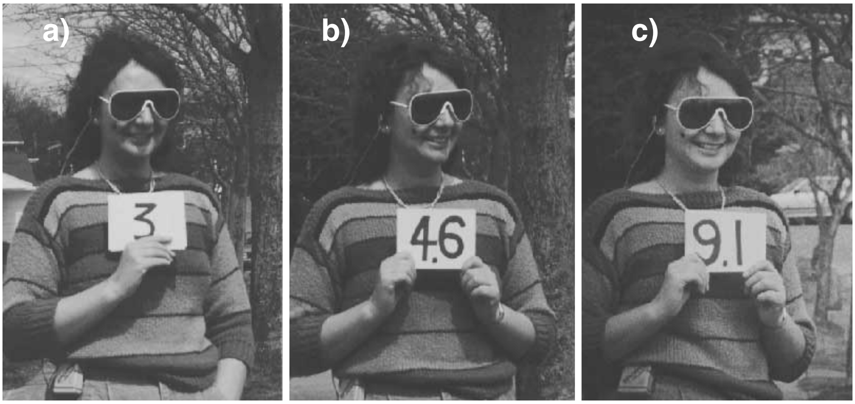
It is my experience as an amateur photographer that the standard rules for depth-of-field do not always satisfy my requirements. In frustration I might say that they never do. There are several factors which seem to evade the traditional reasoning. In general, I have found the results obtained using the time-honoured methods usually yield backgrounds which are on the fuzzy side. And further, I find that objects in the foreground seem to be sharper than I had imagined they would be.

My first attempt to improve my photographs was to use the depth-of-field marker for the next larger aperture than I was really using. The results did not seem to change much, so I then tried using the markers for an aperture two stops larger (lower in f-number). This gave some minor improvement to the fuzzy backgrounds and it did help results match expectations in the foreground as well, but the effect was smaller than I had hoped. What I had failed to realize is that using the depth-of-field markers for the next larger aperture is equivalent to only a 30% reduction in the circle-of-confusion, and using the two-stops-larger markers is equivalent to only a 50% reduction in the assumed circle-of-confusion. I think I was hoping for something like an order-of-magnitude—factor of ten—improvement in background sharpness. Based on information in the last chapter, I now understand that this would have required using the depth-of-field markers for an f-number equal to one-tenth of what I had really ben using. That is, if I had really been using f/11, I should have used the depth-of-field markers for the f/1 aperture! Plainly the allowable depth-of-field for the standard I was hoping to achieve would be almost nil. Yet I was often able to achieve the desired results. Why?

After some thoughts on the matter, I concluded that the traditional depth-of-field calculations were not always appropriate. The traditional rules make no allowance for the characteristics of the subject. How big is it? What is the smallest detail I wish to record? To some extent the human eye and brain working together act as a kind of zoom lens. If we can recognize that the subject is a golf ball, our mental impression of the subject is that it is a sphere a little over an inch in diameter and it has dimples. This is our impression, whether the golf ball is 10 inches away or ten feet away. We do not mentally record 140 times the detail when we view the golf ball ten inches away, than when we see one ten feet away. Yet that is exactly what the traditional depth-of-field rules assume. It is assumed that the desired resolution in linear *image* space is constant. Since a golf ball photographed from ten inches away will be recorded twelve times larger than one ten feet away, the image of the closer ball will actually be recorded with twelve times the linear resolution. This translates into 144 times the actual information content about the golf ball. This is not always what we want. If I can record enough information in the image of the ball at 10 feet, I can probably still tell it's a golf ball even if it is photographed at ten inches with about one-tenth the actual linear image resolution.

In other words, I believe that when I take a picture, there is a certain amount of information that I want recorded in the image, and information content often has more to do with how big the object is than how big the final image is. Objects photographed up close can still be recognized even if they are a little fuzzy. Objects in the distance may need to be very sharply imaged if they are to be recognized at all.

Let's look at an example. I photographed my sister-in-law, June, at a variety of distances with my lens set for maximum depth-of-field. But in the example, I have printed the results so that the image of June is about the same size for each distance. I used a 50 mm lens set at f/8. The hyperfocal distance is thus about 9.1 meters. I focused the lens at this distance for all the photographs. The depth-of-field scale states that the zone of acceptably sharp images extends from 4.6 meters to infinity. Figure 9 shows the results for June at 3 meters, 4.6 meters, 9.1 meters, 18.3 meters, and 49 meters. As you can see I would have no trouble recognizing her at 3 meters—inside the supposed inner limit of acceptable definition—and as far away as 18.3 meters. At 49 meters, I could guess that the subject is probably a woman or a man with long hair and some sort of sun glasses or goggles and that is about it. Although not shown, I also took a picture at a distance of one meter. I had no trouble recognizing her in the image. In fact I think there was probably more information about June in this close-up than there was in any of the other images. Yet she was very much inside the inner limit of depth-of-field. Clearly, for the purposes of recording a recognizable image of June, the traditional rules for depth-of-field do not apply.



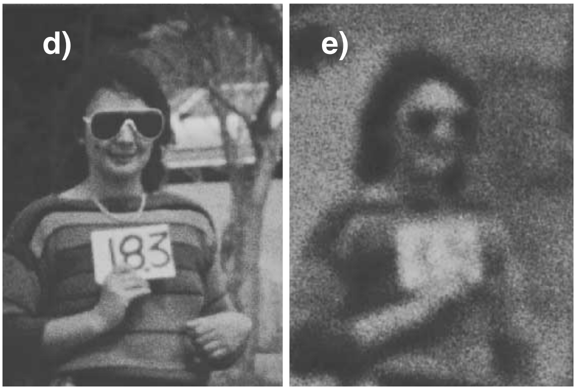


FIGURE 9:
A demonstration of the traditional depth-of-field wisdom. Here we used a 50 mm f/8 lens focused at its hyperfocal distance, 9.1m. June is at distances of 3m, 4.6m, 9.1m, 18.3m, and 49m.

One of the first lessons here is that the traditional approach to depth-of-field specifies the *minimum acceptable* criterion for image quality. And when we focus our lens at its hyperfocal distance, those subjects in the *distance* are *necessarily* defined with this minimum acceptable standard of definition.

I should add that I took similar pictures of June at distances from 1 meter up to 100 meters away, but with the lens focused at infinity throughout. June was quite recognizable out to about 75 meters. And furthermore, even with the lens focused at infinity, she was *still* quite recognizable when photographed from only one meter away.

The next chapter will help us understand these results.

CHAPTER 5

A Different Approach—The Object Field

There is another way to approach the subject of depth-of-field. As a photographer surveying the scene to be photographed, instead of asking what would make all my images look acceptably sharp, I might ask what objects which I see before me will be recorded in this particular image. What will be too small or too out-of-focus to be outlined distinctly? What objects will be resolved? What surface textures will be apparent in the final image? These questions are fundamentally different from that of asking what will achieve a uniform standard of image resolution. And as might be expected, we will not get the same answers or the same advice from our calculations. The results are related, to be sure, but they are not the same. The fundamental difference of which I speak is that we are concentrating our attention on characteristics of the scene to be recorded—the object field—as opposed to the characteristics of the final image. There is a very real distinction to be made here. When we concentrated on the image alone, we did not take into account what was being photographed. We had decided in advance on an across-the-board image quality standard. Maybe the object we were photographing did not require this high standard, or maybe it really needed a higher standard. How would we know? In this chapter, we'll find out how.

The *Disk*-of-Confusion

Suppose that we have a camera with a lens of focal length **f** and that the working diameter of the lens is **d**. The working diameter is the apparent diameter of the lens opening as seen looking into the front of the lens. If the lens has an automatic diaphragm, we assume that it is closed down to its working aperture. The working f-number, **N**, is thus about **f/d**. We focus the lens at distance **D** measured from the front of the lens to whatever object is to be in perfect focus. In essence our lens "sees" the world through cones of rays where the base of a ray cone is the opening of the lens diaphragm, and the apex of the cone is at some point which is in the plane of perfect focus. Beyond the plane of perfect focus, the ray cone expands again. At any distance other than **D**, the lens "sees" the world as if it were made up of disks having a diameter equal to the diameter of the cone at that distance. At a distance **X**, where **X** lies between the lens and the apex of the cone, the diameter of the disk is **d(D-X)/D**. At another distance **Y**, beyond the apex of the cone, the diameter of the disk becomes **d(Y-D)/D**. The size of the disk is directly proportional to the distance either side of the point of exact focus, and to the working diameter of our lens. Any object smaller than the disk will not be resolved. If a small object is bright enough, it may appear as a spot the same size as the disk. If the small object is dark, it may be missed altogether. Any subject larger than the disk will be imaged as though it were made up of a family of disks all of about the same size.

Let's think of it another way. Suppose we have in our camera, located on the film, a very tiny but bright source of light: a very tiny "star". That star will project its light through our camera lens (acting now as a projector). Wherever that starlight falls on a flat surface we will see a disk of light. The size of that disk of light will depend upon where the surface is relative to where the lens is and where it is focused. If the surface happens to be right where the lens is focused, we will see only a tiny bright point of light. A little ways in front of or behind where the lens is focused, we would see a small disk of light. The size of that disk of light obeys the formulae of the previous paragraph. We'll call this disk the *disk*-of-confusion. This *disk*-of-confusion is an exact analog of the circle-of-confusion used in the previous chapter to describe depth-of-field. The *disk* lies in the object field; the circle-of-confusion lies on the film—that is, in the image field.

Figure 10 shows the geometry in graphical form. The lens has working diameter **d** and focal length **f**. It is focused at distance **D** measured from the lens. **S** is the diameter of the *disk*-of-confusion. We'll call the diameter of the disk $\mathbf{S_X}$ if the disk lies between our lens and the point of focus (**X** is less than **D**), or $\mathbf{S_Y}$ if the disk lies beyond the point of focus (**Y** is greater than **D**). The diameter of the circle-of-confusion, **c**, is shown for another object at distance **X** in front of the lens.

Let's go through Figure 10 in detail. An object at distance **D** in front of the lens is focused on the film at distance **B** behind the lens. If **D** is much greater than the focal length, **f**, of the lens, the distance **B** is approximately equal to **f**. A second object at distance **X** in front of the lens, but closer to the lens than the object at **D**, would be focused at the

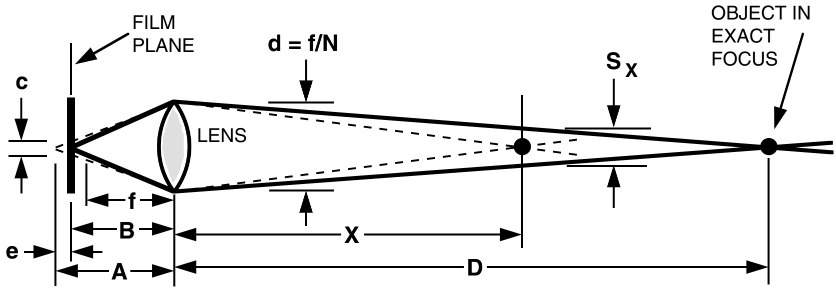


FIGURE 10: *Diagram illustrating how the diameter of the disk-of-confusion depends upon geometry.* $\mathbf{S_X}$ *is the diameter of the disk-of-confusion at distance* **X** *when the lens is focused at distance* **D**.

distance **A** behind the lens and, indeed, a distance **A-B** or **e** behind the film. If the object at **X** were a tiny point of light, the image cast on the film would be a circle of light whose diameter is **c**. By simple geometry we find:

$$\mathbf{c} = \frac{\mathbf{A - B}}{\mathbf{A}}\mathbf{d}. \tag{14}$$

c is the diameter of a circle-of-confusion much as we used in the traditional depth-of-field calculations. Let us now ask the question: what object at distance **X** would be imaged on the film plane as a circle of diameter **c** if the lens were stopped down so as to image the object sharply? The answer is a disk of diameter $\mathbf{S_X}$ where:

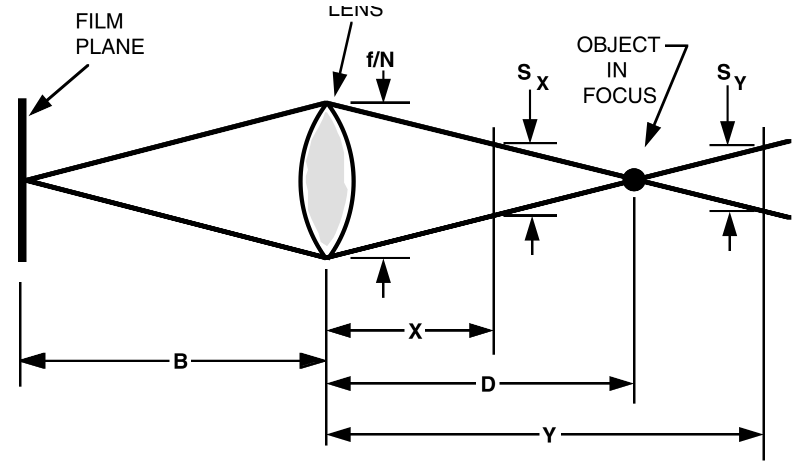
$$\begin{aligned} \mathbf{S_X} &= \mathbf{c}\frac{\mathbf{X}}{\mathbf{B}} \\ &= \frac{\mathbf{A - B}}{\mathbf{A}}\mathbf{d}\frac{\mathbf{X}}{\mathbf{B}}. \end{aligned} \tag{15}$$

The standard lens formula, Equation (1), gives us:

$$\frac{1}{\mathbf{A}} + \frac{1}{\mathbf{X}} = \frac{1}{\mathbf{f}} = \frac{1}{\mathbf{B}} + \frac{1}{\mathbf{D}}. \tag{16}$$

A little algebra gives us:

$$\mathbf{S_X} = \frac{\mathbf{D - X}}{\mathbf{D}}\mathbf{d}. \tag{17}$$



$$S_X = \frac{D - X}{D}\frac{f}{N}, \qquad S_Y = \frac{Y - D}{D}\frac{f}{N}.$$

FIGURE 11: *Simplified version of Fig 10 showing the geometry of Depth-of-Field.*

Similarly, we would find for distances beyond **D**:

$$S_Y = \frac{Y - D}{D} d. \tag{18}$$

Figure 11 extends Figure 10 past the point of exact focus allowing us to see this more clearly. Note that this disk diameter S_X or S_Y is precisely the size of the circle of light which a point of light on the film would cast on a screen at distance **X** or **Y** in front of the lens. Also notice that **D**-**X** and **Y**-**D** are really the same thing: distance from the point of exact focus. A little care is needed with respect to units: we need to ensure that the diameter of the lens and the diameter of the *disk*-of-confusion are measured in the same units (measure both in centimeters, say). Similarly the distance from lens to point or plane of exact focus, and the distance either side of that point must be expressed in the same units (we could use feet for distances even though we are using centimeters for diameters).

What all this means is that every point of light on the real object at distance **X** is seen as though it were a disk of diameter S_X. The mathematical term for this is "convolution". The recorded (on-film) image is a sharp image "convolved" with the circle-of-confusion. The resulting image is equivalent to a sharp image of a subject which is the result of convolving the real subject with the *disk*-of-confusion. We'll discuss the concept of convolution a bit more in the next chapter.

The *disk*-of-confusion is about the size of the smallest object which will be recorded distinctly in our image. Smaller objects will be smeared together; larger objects will be outlined clearly—though the edges may be a bit soft.

The size of the *disk*-of-confusion is easily estimated. At half the distance from the camera to the point of exact focus, the disk is half the working diameter of our lens. At twice the distance to the point of focus, the disk is equal to the lens diameter. If we keep Figure 11 in mind, the *disk* size relative to the size of our lens opening is very easily estimated. In using formulae (17) and (18), some care is needed with respect to units, but there is flexibility also. The rules are simple. Again, distances $\mathbf{X}$, $\mathbf{Y}$ and $\mathbf{D}$ must all be expressed in the same units as one another. And diameters $\mathbf{S_X}$, $\mathbf{S_Y}$ and $\mathbf{d}$ must all be in the same units.

And that, really, is almost all there is to estimating the resolution of the subject being photographed. The only things that matter are the working diameter of the lens (size of the lens aperture as seen from the front of the lens), the distance at which the lens is focused, and where the other significant objects are in relation to our lens and the point or plane of exact focus. And the arithmetic is quite simple. If you're like me, you'll find the picture (Figure 11) easy to redraw and to use as a guide to work out the numbers, even if you can't remember the equations.

Examples

We'll now look at two specific examples illustrating how we might apply these new rules. The first example is a special case: what to do when we want everything sharp from here to infinity. The second example will treat a more standard portrait situation.

When a lens is focused at infinity, the *disk*-of-confusion will be of constant diameter, regardless of the distance to the object. The diameter of the *disk*-of-confusion, $\mathbf{S}$, will be equal to $\mathbf{d}$, the working diameter of the lens, at all object distances. We can use this special case to great advantage. If we desire to take photographs of people, we will obtain

FIGURE 12:
June at distances from the camera of 1 m, 3 m, 25 m, 50 m, and 100 m. The 50 mm f/2 Summicron was set at f/8 and focused at infinity for all five shots.

quite recognizable images if the diameter of the *disk*-of-confusion is no greater than about 6 millimeters. Thus if we set our lens opening to 6 millimeters (about f/8 for a 50 mm lens) and set the focus to infinity, we should be able to recognize all the people in our photograph, no matter how close or how far away they are. To test this out, I photographed my sister-in-law, June, at a variety of distances using a Leica M6 loaded with Kodak Technical Pan film. To help test this idea, we applied a black paper dot (mole) 8 mm in diameter to her right cheek. (I could not find any ready-made 6 mm black dots.) Figure 12 shows some of the results. When printing each photograph, I adjusted the degree of enlargement to give about the same final image size. I asked June to walk towards me, starting from a distance of 100 m, stopping at 75 m, 50 m, 25 m, 17 m, 3 m and 1 m. I used a 50 mm, f/2 DR Summicron on a Leica M6 set at f/8 and focused at infinity. I could not in fact see the 'mole' at 100 m. At 75 m, it was questionable whether the dot was there or not, but it did show up clearly at 50 m and closer.

In Figure 12 you can see the results for 100 m, 50 m, 25 m, 3 m and 1 m. I hope you will agree that the basic definition is about the same, except for grain, at all distances up to about 50 m. Before you wax critical of the result at 100 m, please recognize that you are looking at just a small part of a 160× print; that is, a portion of picture that is really 14 ft by 20 ft in size! For reference, the width of the "1" in the image of the "100" sign, on the negative, is about one two-hundredth of a millimeter. The number one two-hundredth of a millimeter is significant, for it is the limit of resolution placed upon a 50 mm f/8 lens by diffraction. It is at least in part diffraction which prevents us from seeing the mole beyond about 50 meters. We'll discuss more about diffraction in Chapter 6. For now, suffice it to say that we must modify our rule a bit by recognizing that, for a 50 mm lens, diffraction effects will usually prevent the resolution of objects smaller than one ten-thousandth of the distance from camera to object.

Just for fun let's see what the conventional rules would tell us to do under similar circumstances. First of all, we would want to set the focus to the hyperfocal distance so that everything from half the hyperfocal distance to infinity is sharp. If half the hyperfocal distance is specified to be 1 meter, then the hyperfocal distance must be 2 meters. What f-stop will give us a hyperfocal distance of 2 meters? The answer is about f/56 (not 5.6, but 56!). This means the lens opening is only about 1 mm in diameter. But does this really work? The truth of the matter is that, neglecting diffraction effects, the diameter of the *disk*-of-confusion will now be 6 mm at a subject distance of only 14 meters. At 50 meters it will be 24 millimeters, or about one inch. That corresponds quite closely with the 27 mm *disk*-of-confusion illustrated by the 49 meter result shown in Figure 9 in the previous chapter. Clearly the results at 50 meters would not be acceptable for the purpose of recognizing someone. One-third of that distance is about all we could permit. The *real* depth-of-field is not 1 meter to infinity, but closer to zero feet to 15 meters. We accomplished our task much more satisfactorily using f/10 and focusing at infinity!

Another interesting exercise is to compare what we gain and what we lose when we focus at infinity instead of the tried-and-true hyperfocal distance. At the inner limit of the conventional depth-of-field the *disk*-of-confusion is half the diameter of the lens opening (because the distance to the inner limit of the depth-of-field is one-half the hyperfocal distance). Thus at the inner limit of depth-of-field the *most* we lose by focusing at infinity is a factor of two in resolution of the subject. On the other hand, for subjects beyond the hyperfocal distance, the story may be quite different. At a subject distance of twice the hyperfocal distance, the *disk*-of-confusion is equal in size to the lens diameter. At this distance either method gives the same result. At three times the hyperfocal distance, the *disk*-of-confusion is twice the lens diameter. At four times the hyperfocal distance, it is three times the lens diameter and so on. At ten times the hyperfocal distance, the *disk*-of-confusion is nine times the lens diameter. Thus, if we are using a good lens, good film, and careful technique, we potentially have a lot to lose in the resolution of distant subjects by focusing the lens at the hyperfocal distance. In practice, by focusing instead at infinity, we will lose a factor of two in subject resolution at the near limit of depth-of-field but gain about a factor of six in the resolution of distant subjects! It's often worth the trade.

Now for our portrait problem: I want to photograph my young niece. It should be a head-and-shoulders portrait. If I use a normal lens, I figure IÆd have to be about 4 feet from the subject to do this. I want to do it in my back yard, but I have another difficulty. The background will be a neighbour's yard, and he's got this 'recreational vehicle' with "PROWLER" written all over it in foot-high letters. I want to make sure that in my photograph the word "PROWLER" can't be read. The 'RV' will be about 60 ft away. Still, I want the portrait to be reasonably sharp; I think I want any of the stripes in her blouse (which are about 1/25 in. in width, to be clearly rendered. I'd guess that I want the zone of sharpness to be at least a foot in depth, front to back. Am I better off using a wide-angle, a normal, or a long-focus lens? What f-stop should I use?

One answer is easy, the other somewhat more difficult. It doesn't matter what lens I use; lenses of all focal lengths will give the same result if set to the same f-stop—provided the working camera-to-subject distance is scaled along with lens focal length. Perspective will be affected by the choice of focal length, but the readability of the letters on the trailer will be the same. Using a long lens will make the letters larger or appear to be closer; using a short lens will make the letters seem farther away and hence smaller. But whether or not I can actually read the word "PROWLER" is determined by the f-number only. To calculate what that f-number should be used to resolve the blouse is easy: it should be about f/6 or *smaller* in diameter. The problem is, to ensure that the letters on the trailer are unreadable, takes f/2.5 or *larger*! So I have an incompatible pair of requirements. Either I have to risk making the blouse fuzzy, or I have to tolerate that word in the background being readable.

To understand how one can arrive at these conclusions, we use the formulae established earlier:

$$\mathbf{S_X} = \frac{\mathbf{D - X}}{\mathbf{D}}\frac{\mathbf{f}}{\mathbf{N}}, \qquad \mathbf{S_Y} = \frac{\mathbf{Y - D}}{\mathbf{D}}\frac{\mathbf{f}}{\mathbf{N}},$$

where **D** is the distance from lens to subject, **f** is the focal length of the lens, **N** is the f-number set on the lens, and **X** is the distance from the lens to the place where we wish to estimate the diameter of the *disk*-of-confusion. $\mathbf{S_X}$ is the diameter of the *disk*-of-confusion at distance **X**.

For the example at hand, dealing first with the requirement to image the stripes of the blouse, we have:

D = 4 ft. (48 in.)

X = 3 ft. 6 in. (42 in.)

f = 2 in., and

$\mathbf{S_X}$ = 1/25 in.

Putting these numbers in the formula, and using a bit of algebra, we get **N** = 6.25; that is, we should use an f-number of 6.25 or greater.

So, if we are using a 2 inch (50 mm) lens we should set it about half way between 5.6 and 8 or to a smaller aperture in order to resolve the stripes on the blouse at a point 6 in. in front of (or behind) the point of exact focus. What if we use a different lens? If we use a lens twice as long, we will need to increase the lens-to-subject distance by a factor of two in order to cover the same area of our subject. If we say **D** = 96 in., **X** = 90 in., **f** = 4 in. and the *disk*-of-confusion stays the same, we get the same answer: **N** = 6.25. In fact, as long as we scale the focal length and the subject distance by the same amount (**D** = 24 times the focal length for this example), we will get exactly the same answer. In other words, if we keep the image-to-subject magnification ratio, **M**, the same, the amount of depth-of-field depends only upon f-number. It doesn't matter whether we use a long lens or a short lens. As long as we keep the subject the same size in our viewfinder, the depth-of-field is governed only by f-number.

Let us now consider the sign in the background. The letters which make up the word are one foot (12 inches) high. We wish the *disk*-of-confusion to be sufficiently large that we cannot read the letters. As a rule-of-thumb, a *disk*-of-confusion equal in diameter to one-fifth of the letter height or smaller will ensure that the letter *can* be read; a *disk*-of-confusion equal in diameter to the letter height will ensure that the letter cannot be read. In between there is a gradual transition from readability to non-readability. There are a number of factors which affect readability, including the style of the letter, the shape of the opening made by the lens diaphragm, the orientation of that shape relative to the letter, the contrast of the letter against its background, and the character of the specific lens in use. Let's assume here that a *disk*-of-confusion 12 inches in diameter is required to ensure we can't read the word. We then apply the formula $\mathbf{S_Y = (Y\text{-}D)f/ND}$, using the following data as input:

$$\mathbf{Y} = 64 \text{ ft. } (768 \text{ in.})$$

$$\mathbf{D} = 48 \text{ in.}$$

$$\mathbf{f} = 2 \text{ in.}$$

$$\mathbf{S_Y} = 12 \text{ in.}$$

Solving for **N**, we obtain $\mathbf{N} = (768\text{-}48)\times 2/(12\times 48) = 2.5$. This means we should use a lens aperture which is larger in diameter than f/2.5.

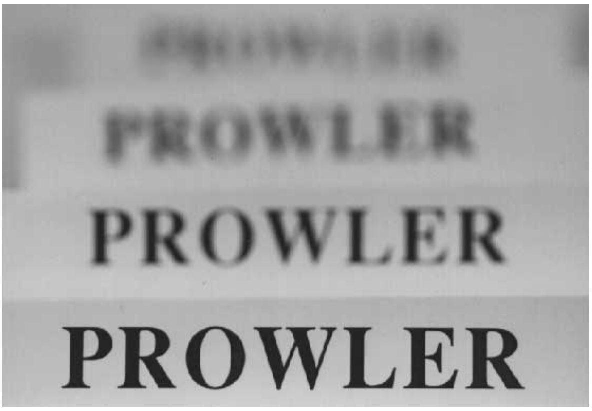
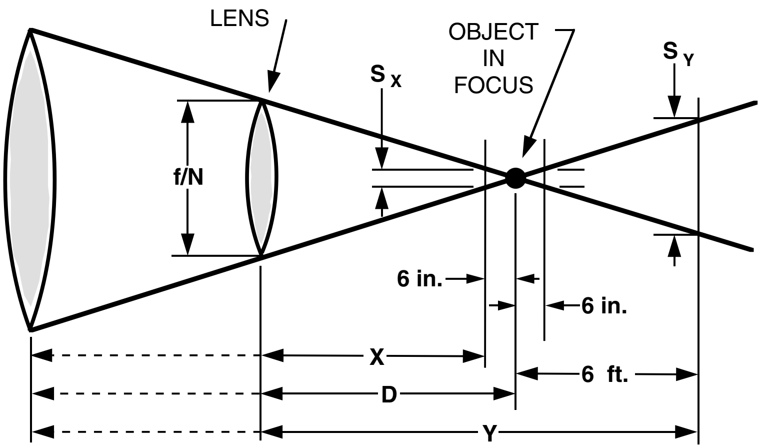


FIGURE 13: *The word "ROWLER" printed on cards placed such that the disk-of-confusion is, top to bottom, equal to 1.0, 0.5 and 0.2 times the height of the letters. The bottom-most word is in focus.*

If we recalculate for lenses of other focal lengths, we will again find that only the f-number matters.

Figure 13 shows a photograph of four cards bearing the word "PROWLER", each card at a different distance. The lens was focused on the nearest card. The remaining three cards were placed so that the *disk*-of-confusion is, respectively, 0.2, 0.5 and 1.0 times the height of the letters. It can be plainly seen that the word is quite readable for the *disk*-of-confusion equal to one-fifth (0.2) the letter height. Even at half the letter height, the word remains readable in this case. When the *disk*-of-confusion equals the letter height, the word can no longer be read, though some of the individual letters might be.

So, in the end we cannot quite do all that we set out to do. There is no f-number which is at the same time larger than 6.25 and smaller than 2.5. A number like f/4 would seem to be a compromise, but we will have to recognize that the stripes in the blouse might be a wee bit fuzzier than we wanted, and the sign in the background might just be readable. The good news is that we can choose any lens that's handy. On the other hand, there's no excuse: "I guess I used the wrong lens."



$$\mathbf{D} = 24\,\mathbf{f}\ ; \quad \mathbf{Y} = \mathbf{D} + 60 \text{ ft.}\ ; \quad \mathbf{S}_{\mathbf{X}} = 1/25 \text{ in.}\ ; \quad \mathbf{D} - \mathbf{X} = 6 \text{ in.}$$

$$\mathbf{f/N} = (\mathbf{D}/6)(1/25) = (24\,\mathbf{f}/6)(1/25) = \mathbf{f}/6.25$$

$$\mathbf{S}_{\mathbf{Y}} = (\mathbf{Y} - \mathbf{D})(1/25)/6 = (60 \times 12)(1/25)/6 = 4.8 \text{ in.}$$

FIGURE 14: *Sketch of Disks-of-Confusion for our outdoor portrait (not to scale).*

I hope these two problems have been instructive in illustrating how we can use simple rules to estimate or control the amount of blurring in our pictures, or to calculate what f-stop and what point of focus will give us the result we want. There's actually no need to write down the formulae we have used here, it's all contained in the sorts of diagrams we've been using. I find it useful to draw a sketch of the situation and use simple geometry to figure out the numbers. The sketch I used to help solve this little problem looked something that shown in Figure 14. Note that Figure 14 is not drawn to scale. The drawing simply helps us to recall how to calculate the various diameters.

Object Field Rules of Thumb

It might help to write down a few preliminary "rules-of-thumb" to help us in our photography. Later, in Chapter 10, we'll add to this list. For now, twelve of them which apply to the object field are as follows:

1. If we want an object to be resolved, we make sure that the *disk*-of-confusion is smaller than the object. If we want to resolve a letter "A" on a sign where the brush strokes forming the letter are one inch wide, we should ensure that the *disk*-of-confusion is no larger than about one inch.

2. If we want an object to be blurred out, we make sure that the *disk*-of-confusion is larger than the object. If we want to ensure that the letter "A" is not readable, we should make sure that the *disk*-of-confusion is about equal to the height or width of the whole letter.

3. Between the point of exact focus and the camera, the *disk*-of-confusion can never be larger than the working diameter of our lens. Beyond twice the distance from lens to point of exact focus, the *disk*-of-confusion grows larger than the lens opening—without limit!

4. If we want *anything* at infinity to be recorded sharply, focus at *infinity*.

5. If we want all objects of, say, 5 millimeters diameter to

be recorded—at whatever distance—we should use a lens aperture of 5 millimeters or smaller and focus no closer than half the distance to the furthest object. (A 5 millimeter aperture corresponds to f/10 for a 50 mm lens.)

6. The zone of acceptable sharpness or resolution of a subject falls *equally* in front of and behind the point of exact focus (*not* 1/3, 2/3!).

7. Stopping down the lens one stop gives us about 40% more depth-of-field; opening the lens one stop gives us about 30% less depth-of-field.

8. Stopping down two stops (to double the f-number) gives us twice the depth-of-field; opening the lens two stops yields half the depth-of-field.

9. To get ten times the depth-of-field requires that we close the lens down by 7(!) stops.

10. Depth-of-field scales linearly with distance from camera to point of exact focus—if we don't change lenses. That is, the zone of acceptable sharpness about the point of exact focus is twice as great if the lens is focused at 20 ft than it would be if the lens were focused at 10 ft.

11. Combining rules 8 and 10: for objects of a particular size, the length of the zone of sharp focus is directly proportional to a) the distance from the camera to the point of exact focus, and b) the working f-number of the lens. To double the depth-of-field, we can either place the objects twice as far away from the camera, or stop the lens down by two stops (double the f-number).

12. If we do change lenses (or zoom) so as to maintain the same image magnification as the camera-to-subject image changes and keep the lens (or lenses) set to the same f-number, the depth of the zone of acceptable sharpness does not change.

If we are using a lens opening which measures less than five or six millimeters (about 1/4 in.) in diameter, and we are photographing people in the mid to far zone (beyond 10 ft, say) with a wide-angle or normal focal length lens Rule 5 states that we can do a lot worse than setting our focus at infinity. We will probably find our pictures to be quite acceptable with the lens focused at infinity. The main difference between the advice given to us in this chapter and that provided by the traditional rules of depth-of-field is that by the rules of this chapter we will tend to focus our lens somewhat deeper into the expected zone of sharpness—and maybe even beyond it!

Working in the Object Space

The intent of this chapter has been to provide the photographer with some simple tools which he or she can use to understand what will or will not be recorded in his or her image. It might at first appear that the process is a bit complicated, but I would point out two things. We are able to estimate the quality of our image in quite some detail, and the mathematics involved is actually much simpler than that used in the conventional depth-of-field calculations. No photographer would think to work out longhand what the conventional depth-of-field is for a zoom lens set at 162 millimeters and f/6.2. Yet using the principles established in this chapter he can, on the back of an envelope, easily estimate whether an object of a particular size at a given distance will be resolved or not.

It might also be pointed out that the two methods of dealing with depth-of-field are entirely consistent with one another. The same laws of optics apply in either case. The primary difference between the two approaches lies in the assumption of what is important. Is it important to resolve 30 dots per millimeter on film, or for key objects in the scene being photographed to show up sharply (or perhaps be blurred out)?

To help understand what we can expect to be in or out of focus, we'll examine the mechanism of image blurring in the next chapter.

CHAPTER 6

Convolution—The Blurring of an Image

The process by which a sharp image becomes blurred, whether by out-of-focus effects or by motion during the exposure, might be called smearing, filtering or convolution. Convolution is the more general mathematical term, and it might also be used for the *de-smearing* or sharpening of an image. The arithmetic can get pretty complicated—so we won't go into that—but it is worth understanding the concept. Understanding convolution might help explain why an out-of-focus image looks as it does.

Convolution is quite simply the process of replacing every small element of one image with another larger image and then adding up the result. If we were to photograph a tiny white speck lying on a black background and if we did not focus accurately, the speck would show up in the image as a small white disk whose diameter is equal to the circle-of-confusion corresponding to the focus error as well as the focal length and diameter of the diaphragm opening of the lens being used. The greater the circle-of-confusion, the larger but dimmer would be the image on the film. If the subject were to consist of not of one, but of two specks, the image would consist of two disks. If the specks were close enough together, the disks would overlap. And where they overlap, the image would be twice as bright. If one of the specks were white but the other gray, one of the disk images would be bright and the other dim.

When we photograph any scene, we can mentally construct the image by supposing that each speck in the image will produce a disk image on the film. Each speck will produce a disk whose diameter corresponds to the focus error, lens opening etc., and whose brightness corresponds directly to the brightness of the speck but inversely to the area of the disk. We build up the complete image by working out the position, brightness and diameter of every disk, each disk corresponding to a speck of the subject we are photographing. The result is a whole jumble of overlapping disks of various brightnesses and diameters. The small bright disks produce sharp images of the objects which are in focus,

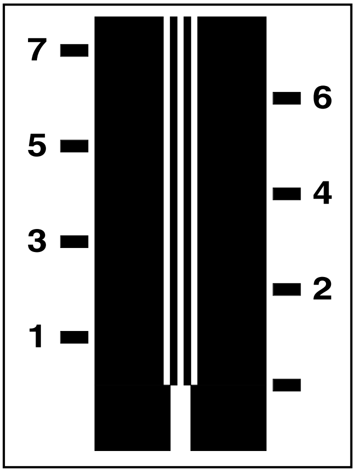


FIGURE 15:
The 'target' which shows three white bars on a black background. The effects of convolution will be shown in graphical form in Fig 16 and in a photograph in Fig 17.

the larger disks produce fuzzy, lower contrast images of those objects which are out-of-focus. The end result is a photograph.

Another essential thing to understand is that the circle-of-confusion is really a circle only when the diaphragm opening is circular. If a lens were to have a triangular diaphragm opening, we would have triangles-of-confusion. The figure-of-confusion is simply a shadow of the lens opening. Whatever shape the lens opening, that will be the shape of the image of a point source on the film. A minor detail here, is that with an opening like a triangle, the out-of-focus triangle-of-confusion would not always be the same way up. For objects closer than the point of exact focus, the triangle would be projected on the film the same way up as the lens opening. Thus when the image is viewed the right way up, the triangle would appear to be upside down—or actually, rotated 180 degrees. For objects beyond the point of exact focus, the triangle-of-confusion would be the right way up in the final image: that is, the same orientation as the lens opening when viewed from behind the camera. However, since most lenses use near-circular lens openings, the effect is usually not very apparent.

Let's look at an example of how convolution works. To make things simple, we'll use three white bars on a black background as the subject we are photographing, and we'll assume that the lens diaphragm opening is square in shape. The square opening means that instead of a *disk*-of-confusion, we will have a *square*-of-confusion. Figure 15 shows

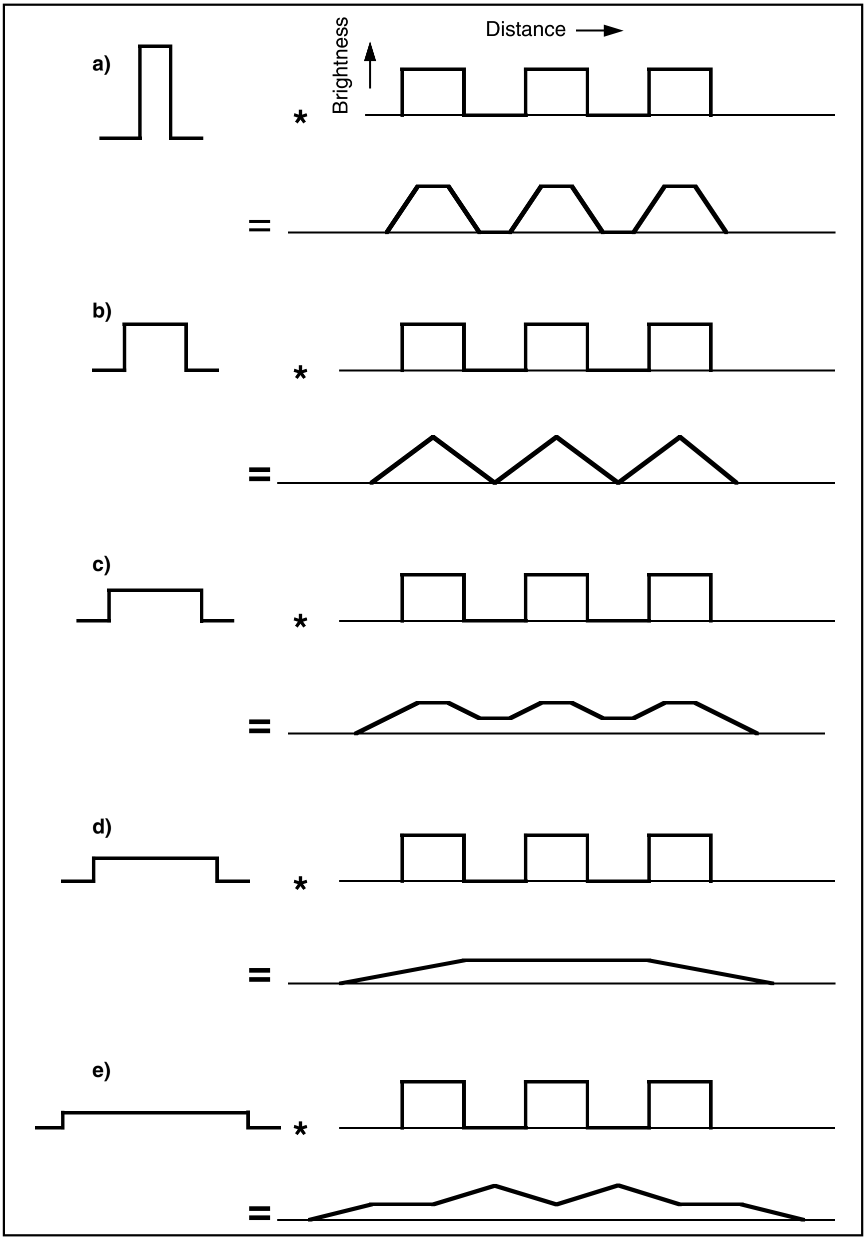


FIGURE 16: *Graphs of brightness against distance illustrating how convolution with squares-of-confusion of increasing size should affect the image of the 'target' shown in Fig 16.*

the subject or target. In Figure 16 I'll try to show what convolution does. We can represent the brightness of the three white bars as a graph of brightness versus distance. In this case we see three square bumps in our brightness graph. Similarly we can represent our *square*-of-confusion as a similar single rectangular bump. The *square*-of-confusion's graph, though, is not necessarily square. If the *square*-of-confusion is small and bright, the bump will be tall and narrow. If the *square*-of-confusion is large (representing a very out-of-focus image) the bump will be low and wide. In Figure 16 a) is shown what happens for a *square*-of-confusion whose width is equal to one-half the width of the white bars. The asterisk (*) is used to denote convolution; the graph which follows the equals sign is the result of the convolution of the one tall half-width bump with the three-bump graph. What we observe is that the brightness of the image of the three white bars still has the same maximum brightness as before, and the black spaces in between are still black. But the edges of the white bars have turned into a gray scale. Note also that the total width of the white bars is now wider than before. In fact the width of each bar is now equal to its original width *plus* the width of the *square*-of-confusion.

If we put our lens more out-of-focus so that the width of the *square*-of-confusion is equal to the width of the white bars, we see the result shown in Figure 16 b). Note the maximum and minimum brightness of the image is the same as before, but only along very narrow strips. Most of the image is now some shade of gray.

Figure 16 c) shows the result when the width of the *square*-of-confusion is equal to one-and-a-half times the width of a single white bar. We still see some evidence of the bars, but the contrast has fallen considerably. We no longer have any pure white anywhere and pure black exists only well away from the group of three white bars.

As the lens is put even more out-of-focus, the contrast continues to drop until the *square*-of-confusion is exactly equal to the distance from the left (or right) side of one white bar to the corresponding side of the next white bar. At this state there is no contrast at all and we cannot distinguish the individual bars in the image at all. The image looks like that of a single 50% gray bar of two-and-a-half times the width of the set of white bars, with a bit of darker gray shading on either side.

If we go a stage farther, something very interesting happens. The contrast starts to increase again. When the *square*-of-confusion is equal to the width of two white bars plus the space between them, the contrast is at a secondary peak, but the *lightest* gray is where *black* in the in-focus image would have been and the *darkest* gray is where the *white* would have been! This is illustrated in Figure 16 e). Our image seems to have switched black for white. Actually a better explanation is that the image is really resolving, not single bars, but *pairs* of bars. And the center of a pair just happens to be where the original black was located. We have not optically made a positive into a negative.

If the *square*-of-confusion were to be made yet larger, the contrast would again fade, and then pick up again—this time with a single light gray stripe where the center white bar is located. Thereafter it is all downhill for contrast, the single gray stripe just would get dimmer and wider. If we were to have more than three bars, however, the cycle would continue on, though the maximum contrast fades with each successive cycle.

Few real lenses have square diaphragm openings, but for these purposes, a square and a circle are not that different. I used a square just to make the mathematics easy. Had I done the calculations for a true circular *disk*-of-confusion, the results in Figure 16 would not have been all that much different. The result graphs would have been smoothed off a bit and that's about all. Do the effects described above really occur in actual photography? Unquestionably, the answer is "yes". I photographed the target shown in Figure 15 with a real camera and lens. I used a 100 mm f/2.8 lens to photograph the target at an oblique angle and got the image shown in Figure 17. The purpose of photographing the target at an oblique angle was to allow me to demonstrate a whole range of sizes for the *disk*-of-confusion at one time. The disk-of-confusion is smallest where the image is in focus, but grows as the bars in the image extend beyond the point of exact focus.

Figure 17 shows some other interesting effects. We know that perspective should cause the bars to diminish in apparent width as they get further away from the lens. In this example, however, the *increasing* width of the bars is due to the convolution effect—the fact that the *disk*-of-confusion is larger for parts of the image farther from the lens—results in the image of the bars actually increasing in size as the bars retreat into the distance! When two objects are convolved with one-another, the size of the result is additive. An object 1 inch by 5 inches convolved with another 2 inches by 3 inches would produce, for example,

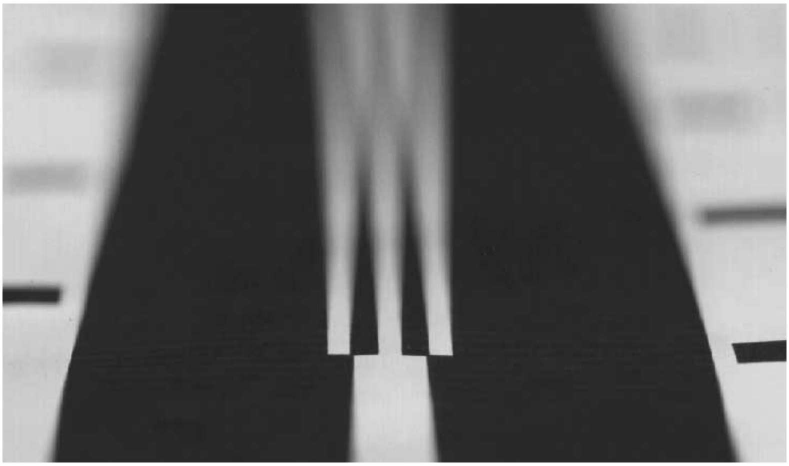


FIGURE 17: *Oblique photograph of the 'target' shown in Fig 15. This shows how an out-of-focus condition can apparently change black into white.*

a result 3 inches (1+2) by 8 inches (5+3). The convolution effect is stronger than the perspective effect in Figure 17. Under circumstances encountered in most pictures and for objects beyond the plane of exact focus, the circle-of-confusion (in the image) stays roughly constant in size as a line in the subject extends towards infinity. Thus the width of a thin line tends not to show the perspective effect in the final image. The *spacing* between lines which are resolved will, however, show the correct perspective. On the near side of the plane of exact focus, the convolution effect enhances the perspective effect. Out-of-focus images are larger than the in-focus images they replace. Also since lens openings are usually round, an out-of-focus image also tends also to be rounder than the real object. As the image of the edge of a coin becomes increasingly out-of-focus, that thin edge will thicken, become oval, and eventually become almost circular—not much different from the out-of-focus image of the face of the coin. Note also how, in Figure 17, the two inner black bars change from black near the bottom of the figure to light gray at the top. This is just as predicted.

Figure 17 also seems to show some apparent additional lines. We started off with three white lines, but at the far end of the target it looks as though we can see four lines. To at least some extent, the additional line is a result of the way the eye sees objects. Look at the result of Figure 16 e) again. At the left side of the result graph, we see that as we move our

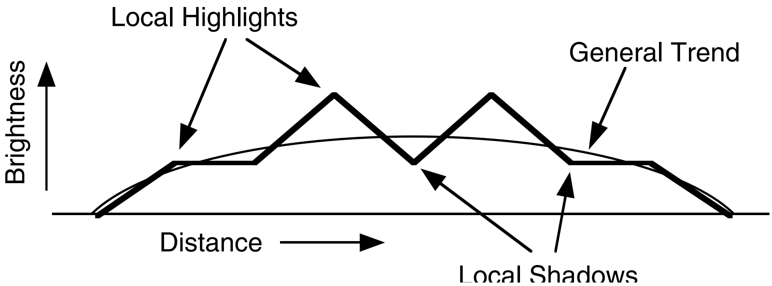
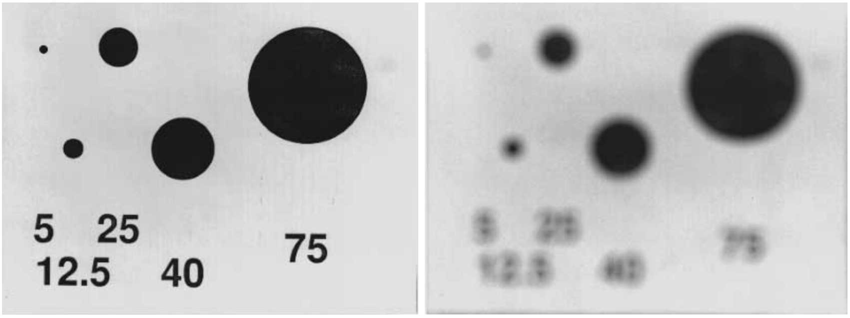


FIGURE 18: *Graph of brightness as a function of distance repeated from Fig 16 e). The thin curved line shows a smoothed curve drawn through the graph traced by the heavier line. 'Peaks' which extend above the smooth curve tend to be interpreted by the eye as being of a lighter shade and those 'valleys' which fall below as a darker shade than surrounding areas even if the 'peaks' and the 'valleys' are actually of the same absolute brightness.*

attention from left to right, brightness begins to increase, then level off at a particular brightness value, and then increase again. The eye tends to see the overall trend—the gradual increase in brightness up to its maximum, and superimpose on that the more subtle changes. Thus the area just before the brightness stops increasing is seen as a local light area, and the area just before the brightness starts to increase again, is seen a local dark area. I try to illustrate this in Figure 18.

When I took the picture shown in Figure 17, I saw through the viewfinder even more lines than appear in the final result. Some of the effects are a result of peculiarities of focusing screens, a subject we will touch on again in Chapter 8.

Let's look at one last example of convolution. Figure 19 (overleaf) shows a photograph of several black dots taken with a 100 mm lens at f/4 (25 mm diameter) and at f/8 (12.5 mm diameter). The sizes of the dots vary from 5 mm to 75 mm. The convolution effect still permits the smaller dots to be detected, but they are gray, not black. The smallest dot is almost undetectable when the lens is set at f/4. But note that the image of the 5 mm dot in this case is just about 25 mm—the same as the *disk*-of-confusion. When the *disk*-of-confusion is exactly equal to the diameter of the black dot, the image shows a true black only in the very center of the dot. (Because a print tends to compress the gray scale, this is even more obvious when looking at the negative than when looking at a



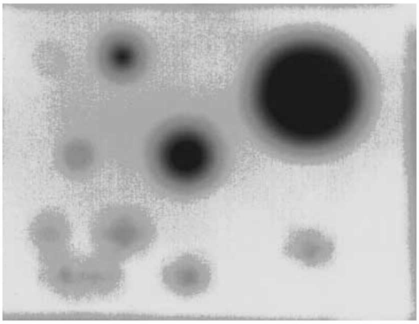


FIGURE 19: *The appearance of black dots of various sizes convolved with a disk-of-confusion. At top left is a sharp print. Above is a photo taken with a disk-of-confusion of 12.5 mm (100 mm lens at f/8, focused at infinity). At left is a similar photo taken with a disk-of-confusion 25 mm in diameter (100 mm, f/4).*

print.) Larger dots show a central black core with a shaded gray ring around them. The diameter of that black core is effectively the diameter of the dot minus the diameter of the *disk*-of-confusion—modified of course by the overall image magnification. If you think the lower illustration in Figure 19 looks a bit strange, you're right. I enhanced the contrast here in order to make the smallest dot show up clearly in the picture. The smallest dot was just barely visible in the original. It was just a very faint, light gray.

The fact that as focus is changed, an image can appear to go out-of-focus and then come back partially in-focus again is something I call secondary resolution. And both the real and the psychological effects are part of the phenomenon. What this means in practice is that if we try to put a given object out-of-focus and calculate accordingly, we will sometimes get a surprise—the object is still recognizable. The effect is most often observed with objects that are periodic in structure, that is, they have repeating elements of about the same size. Some good examples are picket fences or chain-link fences. Venetian blinds and window screens are other common examples. Some objects seem stubbornly to resist attempts to make them unrecognizable. The mere fact that the *disk*-of-confusion has a well defined edge means that the convolution of that disk and another object which also has well defined edges will result in an out-of-focus image which has well defined ridges or changes in the gradient of its gray (or colour) shading. In order to make sure that we really achieve an image which is free of such effects it would be necessary to replace the diaphragm with some sort of filter which had a gradual change in density from clear in the middle to black at the edges.

I hope this chapter will help you to understand two things: first that even the out-of-focus image has an understandable structure, and second that this structure can have an important (and sometimes surprising) effect upon your images.

In the next chapter we'll have a look at diffraction effects and how various focus errors can affect our photographs. We'll also look again at the nature of distance scales on lenses and determine that if we could focus past infinity we could turn any lens into a soft-focus lens.

This photograph of Placentia Newfoundland was taken with a 90 mm lens at about f/8. The cannon, the grass, the gravel, and the trees are clearly a bit fuzzy, but we have no difficulty in recognizing them. To have focused the lens on anything other than infinity would have detracted from the main subject: this village built on a sand bar.

CHAPTER 7

Lenses, Films and Formats

Thus far we have talked about depth-of-field as though our camera and lens were perfect. The lens is capable of perfect definition—provided it is correctly focused—and the camera and film geometry are perfectly controlled so that the lens is perfectly focused exactly where we want it to be. Sooner or later reality makes itself evident and we learn that all is not perfect. The diffraction of light prevents perfect lens definition even if the lens is perfectly made. The lens cannot be mounted so as to stay forever in exactly the right place, and even if the lens could, the film cannot. All these effects conspire to prevent the perfect photograph. Yet we have to learn to live within these limitations and to develop working methods which allow us to make acceptable photographs nevertheless.

Diffraction Limits

Light is a wave phenomenon and the physics of such things tells us that waves cannot be perfectly controlled. No matter how hard we try, we cannot get light to focus to an infinitesimally small point. There is a minimum size of disk we can create even with the best lenses that will ever be made. The physical effect is called diffraction. It causes waves to want to spread out, especially if they have passed through a small hole. Diffraction effects limit the ultimate resolving ability of a lens according to its f-number and the wavelength of the light being used to make the exposure. An approximate rule-of-thumb limit on resolving power (independent of lens focal length) for normal circumstances is 200 lines per millimeter at f/8 (or 400 lines per mm at f/4, or 100 lines at f/16, etc.). We can put this in a formula as follows:

$$\text{Resolving Power} \approx \frac{1600}{\mathbf{N}} \text{ lines per millimeter.} \qquad (19)$$

As before, $\mathbf{N}$ is the f-number. If we can resolve 200 lines per millimeter at an f-number of 8, then we can also probably detect the presence or absence of a spot in the image about 1/200 mm in diameter.

We can then work out the diameter of the smallest object we can resolve by multiplying by distance over focal length. In effect we have a minimum diameter for the *disk*-of-confusion which is permitted by diffraction even when the lens is perfectly focused on the object. Again, in formula form, we can write:

$$\mathbf{S_D} \approx \frac{\mathbf{D}}{\mathbf{f}(\text{in mm})} \frac{\mathbf{N}}{1600}$$
$$\approx \frac{\mathbf{D}}{\mathbf{d}(\text{in mm})} \frac{1}{1600}. \tag{20}$$

In this formula the focal length, **f**, or the lens working diameter, **d**, must be expressed in millimeters since resolution was specified in millimeters. The diameter of the *disk*-of-confusion $\mathbf{S_D}$ is measured in the same units as is the distance, **D**, at which the lens is focused. Film, of course, is another limiting factor, but for high quality, slow film such as Ilford Pan F or Kodak Technical Pan, our number of 1/200 mm should be possible to attain. It is worth noting that 200 lines per millimeter in a 35 mm negative corresponds to something like 12 lines per millimeter in a 16×20 in. print. If we can achieve this level of resolution, we can make some outstanding prints.

An important difference exists between the circle-of-confusion produced by diffraction effects and that produced by out-of-focus effects. For the out-of-focus condition, the circle-of-confusion is sharply defined: it has a clearly discernible edge. For an image limited by diffraction, the circle-of-confusion is usually quite fuzzy and indistinct in appearance.

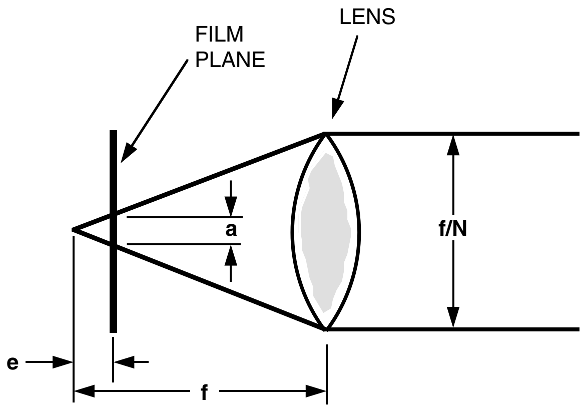


FIGURE 20: *The geometry of Depth-of-Focus.*

While diffraction theory would seem to support the possibility of even greater resolution at apertures larger than f/8, my experience tells me not to count on it. Published lens tests occasionally cite “diffraction limited” performance at f/4 or so, but these results are usually obtained by looking at an aerial image with a microscope. Putting that image on film is a difficult problem which we will address next. In my own lens tests using normal 35 mm cameras, the optimum aperture has nearly always been f/8 or f/11, and 200 lines/mm represents the best-ever resolution I can claim to have observed.

Depth-of-Focus Considerations

What does it require in terms of precision in the lens-to-film distance to approach 1/200 mm resolution? That is, what is the allowable depth-of-focus? With the aid of a very simple diagram we can calculate it.

Figure 20 is just a repeat of Figure 5. We don’t need to worry here about what is going on in front of the lens. Recall that the symbol, **e**, stands for focus error. The ideal camera will focus our image right at the film. What distance **e** could be tolerated if we were to ask that the circle-of-confusion be no larger than the smallest spot we can produce? For this case we set **a,** the largest permissible diameter for the circle-of-confusion, to 1/200 mm. Then simple geometry tells us that

$$\frac{\mathbf{a}}{\mathbf{e}} = \frac{\mathbf{f/N}}{\mathbf{f}}$$

or

$$\begin{aligned} \mathbf{e} &= \mathbf{aN} \\ &= \mathbf{N}/\,200 \text{ mm.} \end{aligned} \tag{21}$$

where **N** denotes the f-number of the lens being used. For **N** = 8, that is with the lens diaphragm set to f/8, we can tolerate an error no greater than 0.04 mm (one twenty-fifth of a millimeter or .0015 inches). For larger lens openings that allowable error gets even smaller: four ten-thousandths of an inch at f/2, for example. My experience has been that for critical work I must use f/8 or a smaller aperture, though preferably no smaller than f/11, with a 35 mm camera. I presume therefore that most 35 mm cameras manage to put the film within about .04 mm of where it belongs. I cannot count on this for *all* camera-film combinations, but it *usually* seems to work out satisfactorily.

Film and Field Curvature

There are at least two other demons ready to foil our attempts at critical photography. These are curvature of field and film curvature. Curvature of field is a property designed into the lens: objects at great distance but a bit off to one side of the lens axis may not be focused at a distance of exactly one focal length behind the lens. The discrepancy between where the true focus is and where the film is supposed to be is the focus error. If we were to examine various parts of the image and somehow force the film into the precise focus, the film would not be flat. It would be curved to some extent and could be a very complex shape indeed. It might look like a part of a sphere, or it might look like the surface of a pond just after a pebble was dropped into it—that is circular ripples centered on the point where the lens axis intersects the film. The other problem is that the film in a real camera wants to take on a slightly curved shape of its own. It seldom happens that the film takes on a shape that agrees with what the lens needs to do its job. Even worse, film usually tends to slowly change its shape—depending upon temperature, humidity, and when the film was last advanced to a new frame. What a critical photographer really needs are lenses each with a perfectly "flat field" and optically ground, glass plates instead of film to hold the light-sensitive emulsion.

Back in the early 1950s one used to read that if one wanted outstanding results, it was necessary to use lenses with *maximum* apertures no larger than f/7.7 for normal film formats and perhaps no larger than f/3.5 for 35 mm cameras. It was said that larger aperture lenses were incapable of critical performance even when stopped down. Today it almost seems that the reverse is true. I have read (and experienced) that larger aperture lenses generally perform better—even stopped down—than lenses of smaller maximum aperture. The explanation, I believe, lies in two areas. First, since the 1950s lens designers have learned how to make large aperture lenses which are near-perfect when stopped down. And second, in order to achieve quality performance at large apertures the image field must be kept very flat. The required flatness of field is, I suspect, usually based on the old 1/30 mm circle-of-confusion requirement. So an f/2 lens would have to hold the image surface flat to within 1/15 millimeters. When the lens is stopped down to f/11, the circle-of-confusion will be no greater than 1/165 mm in diameter at any place on the ideal plane film surface. On the other hand, if an f/4 lens is designed to meet the same maximum aperture criterion, its circle-of-confusion at f/11 will be as large as 1/82 mm. Thus the f/2 lens must have a flatter field and hence is, in principle, capable of putting a nearly diffraction limited image on film throughout the image area, while the f/4 lens will suffer from slightly degraded performance in some regions of the image.

Film Formats

This brings us to another part of the story: what relative performance can be expected for the various film sizes? Well, the depth-of-field, measured in terms of our ability to resolve objects of a given size, is determined by the diameter of the lens opening, regardless of lens focal length. The precision needed at the film plane to resolve *images* of a particular size depends upon f-number. But the image will of course be larger for the longer focal length lens. Depth-of-field considerations then tell us that if one format measures twice the size of another (both in length and in width) and hence needs a normal lens of twice the focal length, the larger format will require that we set our lens two f-stops smaller (same diameter, twice the focal length). This is just another way of saying we can't change the actual diameter of the lens opening. Although we have lost two f-stops, we can get by with twice the graininess in the film and so make up for that light loss by using faster film. We also can 'get by' with half the precision in positioning the lens and film relative to one another and retain the same resolution of the subject. Well, its hard to believe, but that factor of two in allowable geometric tolerance isn't usually enough to accommodate the film curvature problem.

Remember we talked about the film naturally having a tendency to curl. If we suppose that films of all formats are equally "curly", (that is, they tend to have the same radius of curvature) the film that measures twice as large will probably produce a focus error that is not twice as great, but *four* times as great as for the smaller format. To demonstrate this, consider Figure 21.

The curved line is intended to represent a cross section of our curved film which is presumed to be something like a small section of a

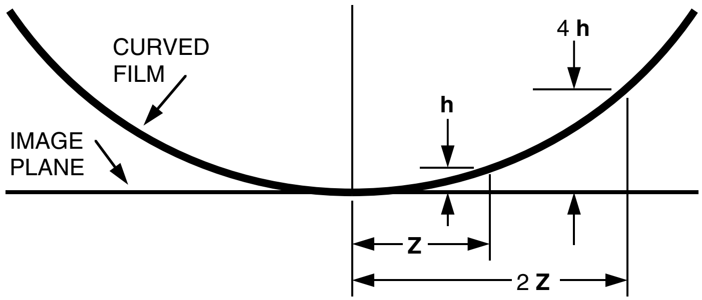


FIGURE 21: *For a fixed radius of film curvature, a film format twice as large will suffer four times the focus error.*

large spherical or cylindrical shell. For small amounts of curvature—and we hope that is the case—the distance between the image plane and the film varies as the square of the distance from the point where the film touches the image plane. In other words, a film format twice as large, requires that one allow for *four* times as much focus error.

Thus while depth-of-field considerations suggest we close down our larger format lens by two stops, film curvature considerations suggest we should close down that longer lens by *four* stops in order to be sure of adequately small focus error. But an f-number four stops smaller, even though we have twice the image magnification, means that diffraction effects will limit the ultimate resolution to only half the resolution of the object that one could have obtained with the *smaller* format. What this means is that we will probably do best by stopping down the larger format lens by about 3 stops and accepting the slight resultant optical degradation. If our 35 mm camera requires f/8 for best performance, we can expect our 6×9 cm roll film camera to need f/22 to be assured of comparable image resolution. We can, of course obtain better image quality with the larger format if we can control the film, that is, keep it flat. And that is exactly why professional photographers use cut film or even plates in critical photography. Cut film, stored flat for most of its life, has a much lesser tendency to curl in the camera. And for a little extra performance we can get film holders which connect to a vacuum pump and hold the film flat by vacuum! The old-fashioned plate, however, remains king where really critical work is necessary.

Depth-of-Focus and Focal Length

We all know that "wide angle lenses have more depth-of-field than normal lenses." Does this mean that wide angle lenses demand less precision in setting the lens-to-film distance? Not on your life. True, the wide angle lens has more depth-of-field for a given f-number. After all, the physical diameter of the shorter focal length lens—for a given f-number—*is* smaller. And, as we have learned, depth-of-field is determined primarily by the effective diameter of the lens being used. But what happens when we experience a focus error due to, say, film curvature? Well, the point of exact focus in the *object* space moves. That is, it is not the main subject which is focused upon, but something either in front of it or behind it. How much does the point of exact focus move? True, for a given fixed standard of resolution at the image plane, images will be degraded by the same amount for lenses of all focal lengths but having the same working aperture. But we may still see some disturbing movement of the plane of exact focus in the object space.

Well, let's suppose we are photographing a person indoors. He is seated in a high backed rocker about 10 feet from our camera. About three feet behind him is a window. Through the window we can see part of the house next door and beyond that the mountains. We use a variety of lenses from 300 mm to 20 mm in focal length. Unknown to us a bit of film is stuck on the film pressure plate of the camera and so the film is actually .2 mm closer to the lens than it is supposed to be. What objects will be in focus? Using the basic lens formula, Equation (1), we obtain the answers shown in the table below. **f** is the focal length of our lens, **D** is the distance from the lens to the object actually in focus. The subject's eyes are at a distance about 3.000 meters (about 10 feet) from our lens.

f	**D**
300 mm	3.016 m
200	3.040 m
100	3.18 m
50	3.91 m
28	12.3 m
25	63 m
20	beyond ∞

From this table we find a number of interesting results. With the 300 mm lens, we focused on the bridge of the subject's nose, but his eyes are in perfect focus. With the 200 mm lens we focused on his eyes, but his ears are perfect. With the 100 mm lens we can see every grain in the wooden back of his rocker. With the 50 mm lens the window is perfect. With the 28, the house next door is just beautiful. With the 25, those mountains aren't bad at all. With the 20, nothing, absolutely nothing is in focus. We have a soft focus effect throughout!

What we see here is that long lenses are actually quite tolerant of errors at the film plane. Short focal length lenses, on the other hand, require absolute precision! Kind of makes that super depth-of-field meaningless if the camera is bent. Other factors can become *more* important than depth-of-field.

More on Distance Scales

Let's turn now, as promised, to an explanation of how the numbers got on the distance scales of lenses. The actual distance, measured along the focusing scale, from the infinity mark to the mark for distance $\mathbf{D}$ is approximately proportional to 1/$\mathbf{D}$. The full formula is

$$\mathbf{E} = \frac{\mathbf{f}^2}{\mathbf{D} - \mathbf{f}} \qquad (22)$$

where $\mathbf{E}$ is the a measure of how far the lens is extended from its infinity position in order to focus properly on an object at a distance $\mathbf{D}$ from the *lens*, and $\mathbf{f}$ is the focal length of the lens. We must take care to express all distances in the same units. We can also express $\mathbf{E}$ in terms of the diameter of the allowable circle-of-confusion, $\mathbf{a}$:

$$\mathbf{E} = \frac{\mathbf{f}^2}{\mathbf{a}(\mathbf{D} - \mathbf{f})} \qquad (23)$$

where $\mathbf{E}$ is now measured in circles-of-confusion just as is the depth-of-field scale. This is a bit more complicated, we have to be able to do division—or do we? The scales in Figure 8 were similar to those on my Leitz DR Summicron. It's a relatively early example; later lenses of the type did not show markers for 50 or 100 feet. Were I to use one of these later lenses, how could I estimate where the 50 and 100 ft markers should be? Well, 50 is twice 25, and 100 is four times 25. Therefore, the 50 ft mark is 1/2 the way from the infinity mark to the 25 ft mark; and the

100 ft mark is 1/4 of the way from the infinity mark to the 25 foot mark. Check it out in Figure 8. This is why conventional wisdom tells us that depth-of-field extends from *half* the hyperfocal distance to infinity. (Note: if you should diligently try to compare the above formula with Fig 8, you will find they do not quite agree. This is because the distance scales on camera lenses measure, not from the lens, but from the film plane. The scale in Fig 8 was calculated using the film plane as the reference. Still, to be really accurate we need also to compensate for the inter-nodal distance of the lens. The formulae get a bit complicated. The formula would be simplest if we could measure object distance from one focal length in front of the lens; then we have just $\mathbf{E = f^2/D}$. Trouble is, the average user doesn't know where a point one focal length in front of the forward nodal point of a lens is exactly.)

The formula for lens extension in the previous paragraph is interesting in another way. The amount of extension needed to focus a lens from infinity to some defined distance scales as the *square* of focal length. A lens *twice* as long in focal length as a normal lens needs to be extended by *four* times as much as a normal lens. Similarly, a lens of *half* the focal length of a normal lens needs only *one-quarter* of the extension. This explains why wide angle lenses hardly seem to move at all in focusing from infinity to a near distance of a meter or so. This scaling relation also applies to depth-of-field. If I want to use the depth-of-field scale on my 50 mm lens to estimate what the conventional depth-of-field would be for a 100 mm lens, all I have to do is imagine that all the distances on the scale are multiplied by four—the factor of four being the square of the ratio of focal lengths.

How can I use this in depth-of-field estimation? I want really sharp pictures using today's materials. And if I'm taking landscapes, I want sharpness from some distance to infinity. Today's films are capable of about seven times the resolution that people usually assume in calculating where to put the depth-of-field markers on their lenses. Using the scales as provided, I set the infinity mark opposite the right-hand depth-of-field marker for the f-stop I intend to use: let's say f/16. The focus pointer points to the hyperfocal distance, about 15 feet. I want the circle-of-confusion to be one-seventh of what was assumed. I can get this by either of two methods. I can set the infinity mark opposite where the f/2.3 marker would be, or, I can refocus from 15 feet to 7 times 15 feet, or 105 feet. And, yes, the revised field of sharp definition will extend from one half of 105, or 52.5 ft, to infinity. But, if you remember what else I have been saying, any object in the near field larger than 50/11 mm (4.5 mm or about one-fifth of an inch) will be clearly visible anyway. That's good enough for most landscapes!

Poor-Man's Soft-Focus Lens

If we focus our lens at infinity, the *disk*-of-confusion is equal in diameter to the diameter of the lens opening (as seen from the front of the lens). We can use this result to achieve a controlled soft-focus effect. For soft-focus portraits, a *disk*-of-confusion of somewhere between 5 millimeters and 1 centimeter can give a pleasing effect. A potential problem, however, is that if the portrait is taken outdoors or in a large room and if there are distracting objects in the background, they will generally give the appearance of being noticeably sharper than the subject. This simple technique will nevertheless be usable if the background is essentially featureless. But there is something else we can do, though it can be difficult to accomplish with most current-day cameras.

What happens if we focus a lens *beyond* the infinity mark? Earlier in this chapter I indicated that this too would deliver a soft-focus effect. It is impossible for any object to be rendered sharply, no matter how far or how close. If we can go back to using the analogy of a tiny source of light located on the film, our lens focused beyond infinity would project a diverging beam of light. The *disk*-of-confusion right in front of the lens is equal in size to the diameter of the lens At greater distances the *disk*-of-confusion just keeps getting bigger. The appropriate formula is:

$$\mathbf{S_Y} = \mathbf{d} + \frac{\mathbf{e'Y}}{\mathbf{f\,N}}. \tag{24}$$

In this equation, $\mathbf{S_Y}$ is the diameter of the *disk*-of-confusion, $\mathbf{d}$ is the working diameter of the lens, $\mathbf{Y}$ is the distance in front of the lens, $\mathbf{f}$ is the focal length of the lens, $\mathbf{N}$ is the set f-number and $\mathbf{e'}$ is the distance by which the lens is set closer to the film than its infinity focus position. In this case $\mathbf{e}$ is given the added dash symbol to indicate that the error is intentional. Strictly speaking Equation (24) is correct only when the intentional focus error $\mathbf{e'}$ is a small fraction of the focal length $\mathbf{f}$ of the lens. It is important to measure $\mathbf{f}$ and $\mathbf{e'}$ in the same units and $\mathbf{S}$, $\mathbf{d}$, and $\mathbf{f}$ in the same units. If we were to use a 50 millimeter lens, we might set it to f/16, retract the lens 1 millimeter closer to the film than the infinity focus position, and pose our subject 2 meters in front of our camera. The diameter of the *disk*-of-confusion is then 50/16 + $1 \times 2000/(50 \times 16)$ = 6.17 millimeters at the subject. But for the background, the *disk*-of-confusion continues to grow larger with increasing distance.

For portrait work the *disk*-of-confusion should probably be in the 5-10 millimeter range. Although this might seem a bit large to record some of the features we wish to see in a portrait, remember that some of the structure in an out-of-focus image will help us record some of that detail. In order to achieve the appropriate size for the *disk*-of-confusion when using the focus-beyond-infinity method, we must necessarily use a small lens opening: 3-5 mm typically. On the one hand this has the practical effect of limiting us to relatively short focal length lenses. On the other hand, we have a method for achieving a soft focus effect with just such small openings. Most ‘conventional’ soft focus lenses require that we use apertures larger than f/8 or f/5.6.

Next, in Chapter 8, I’ll try to explain why one cannot necessarily rely on achieving in the image what one saw on the focusing screen.

Among the potato fields of Prince Edward Island church spires are some of the main obstacles to be avoided by the crop-dusting aircraft. The church spires are thus clearly marked with alternate red and white bands. Taken with a 28 mm lens at f/11, infinity focus provided all the depth-of-field necessary.

CHAPTER 8

Focusing Screens—Can you see the Effect?

Why all the bother about calculating the depth-of-field effect? Can't we just use a view camera or a Single Lens Reflex camera with a depth-of-field preview button to see the effect? Sadly, the answer is no. There are several reasons for this: the nature of focusing screens, contrast effects in imaging media, and just poor viewing conditions when the lens is stopped down.

We'll start with the simplest: viewing conditions. Two things usually happen to the visual SLR viewing image when we stop down the lens. The image becomes darker, so we have greater difficulty seeing it, and the image becomes 'grainy' making it especially difficult to see fine detail. The same is true of the focusing screen of a view camera. While we 'ought' to be able to see the effect, we often just can't see well enough and fine detail gets lost in the grain pattern. At least this is the case when the lens is stopped down to f/8 or smaller.

Modern focusing screens, especially those in modern SLRs have been carefully designed to provide a bright clear image with the typical lens wide open. To achieve this, screen designers have made the screens extremely efficient with working f-stops in the f/2.8 to f/5.6 range. Nearly all the light reaching the screen is relayed to the eye. A consequence of the design is that light arriving at the screen from the outer annulus of a large aperture lens—larger than f/2.8—tends not to be used except when the eye is off the intended viewing axis. If you watch through your SLR viewfinder as you open up the diaphragm from say f/8 to f/5.6 to f/4 and so on to say f/1.4, you will notice that the actual viewing brightness changes little once you have passed f/2. You can confirm that this is not a psychological effect if you have an older SLR with a photo-cell behind the screen and metering system that required stop-down metering. You'll see that the camera meter also fails to show much increase in light as you open up past f/2. The tale of the brighter viewing image provided by f/1.2 lenses is largely wishful thinking, I believe. The viewing image does become more tolerant of eye position, but the brightness really doesn't change much. If the focusing screen can't direct the light from the outer portions of the lens opening, then it also clearly can't show you the true depth-of-field at large lens openings either.

There is another way to prove that the effect seen through the SLR viewfinder is not the true image. Look at the very-out-of-focus image of a small source of light against a dark background—a distant street light at night, for example. Stop the lens down manually to a small (f/8 or so) aperture. If your camera is like mine, you will see the usual large 'circle-of-confusion' shaped just like your diaphragm opening for f-stops of f/4 and smaller. At larger openings I usually see a hexagonal bright core spot about equal in size to the f/4 circle-of-confusion, surrounded by a dimmer annulus which takes the total diameter up to that of the circle-of-confusion corresponding to the set aperture. Furthermore, the position of the brighter core image within the larger circle depends upon where I put my eye. It will tend to be that smaller brighter core image which is noticed by your eye, but it is the larger circle which gets noticed by the film.

As we discussed in Chapter 6, resolving ability is affected by contrast as well as actual image structure. Typical imaging media tend to compress tonal range—that is reduce contrast. Thus, at the extreme bright and dark parts of the image we can expect to observe poorer resolution in these parts of the image than we see with the eye. I have often resolved the letters on the focusing screen image of an out-of-focus neon sign, then found the final print or slide showed only an unreadable blur. The eye could use more of the brightness range than the film/print combination and so managed to read the sign. The final result is offered at much lower contrast and so fails to resolve the letters.

There's another problem I have noted with some lens-screen combinations. Some screens simply don't indicate quite the right focus for particular lenses. At one time I noticed I was having problems with a particular wide angle zoom lens. The pictures simply were not as sharp as I thought they should be. Then I noticed that the camera maker did not recommend the focusing screen I was using for wide angle lenses. I changed the screen and received beautifully sharp pictures in return. In another example I noticed the correct focus on screen did not agree with the distance scale on a particular large aperture 35 mm lens. Careful checking with real film showed that the distance scale on this lens was right. The focusing screen was wrong. Yet tests with the same camera-screen combination gave perfect results with the normal 50 mm lens and with a 35 mm lens of more moderate aperture. I repeated the tests several times as I did not really believe what I was finding. Yet all results were consistent. I can only imagine that this is another example of the effect described earlier where some screens selectively use light coming from a particular zone of the lens opening. And for some lenses that zone is one having significant spherical aberration. Hence the screen tells me the lens is in focus when really, on average, it is not. One thing is for sure: if the screen can't show you when the lens is in correct focus, it certainly will not show you the correct depth-of-field.

One last point is that the resolution capability of the eye is not quite up to that of the best lenses and films. It is usually claimed that the eye can resolve objects equal in size to about 1/1000th or perhaps 1/2000th of the distance to the object. A good camera lens can do about five times better. I normally expect to see detail in my prints which I never saw in the viewfinder. Clearly if I couldn't even see those details, I couldn't judge how sharp they were! An example of a detail I didn't see is given in Figure 12 e): there is a tree branch stretching across in front of June. Because she was 100 meters away at the time, and the tree branch was about 80 meters away, I didn't see it.

So, the lesson of this short chapter is that you cannot necessarily use your SLR viewing screen to obtain an accurate estimate of the final depth-of-field. You might gain a very rough approximation, but the final image will very often look significantly different from what you saw on the focusing screen.

A modern freight locomotive sits in front of the old passenger station at McAdam, New Brunswick. This station once served twenty passenger trains per day. Today it sees two freight trains per day and three passenger trains per week. To have focused on the locomotive, or indeed the hyperfocal distance, would have lowered the contrast and detail in the stonework of the station.

CHAPTER 9

Discussion—Which Method Works?

In this booklet we have considered two basic ways to estimate depth-of-field. One procedure is the tried-and-true method whereby an image standard is described and tables or special scales on the lens are used to establish the bounds of the object field within which the standard will be achieved. A second method has been developed which concentrates attention entirely on the object field, and provides rules to determine which objects will be resolved. Which method works best? There is probably no universal answer. We can in fact use both. I became frustrated with the traditional method and worked out another, but when all is said and done either method can be made to do the job. In this chapter I would like to outline the chain of events which led eventually to this book.

It would be foolish to suggest that the method photographers have been using for countless decades is not up to the job. It is relatively simple, especially in the form of the depth-of-field scale on lenses, and certainly it is easy to use. Yet in my own experience, application of the standard method failed to live up to my expectations. Particularly in street scenes and landscapes where much of the important information is at relatively large distances, those distant objects were just too fuzzy. That observation is what led me to experiment and to think about the problem. All-in-all, the two methods are really much the same. The differences lie in the selection of what is important. So, the two ways of approaching the problem are really complementary. Choose what is important and then select the method. In some cases, close-up photography for example, the two methods give essentially the same result. Where the magnification of all subjects which are in focus is about the same, as in close-up photography or photography using relatively large aperture long focal length lenses, there really is little difference between the methods. The differences become apparent where one is dealing with scenes which show many *similar* objects at *different* magnifications. Here, I find the standard depth-of-field estimation methods don't relate well to the need.

As you might have guessed by now, I like to photograph landscapes and street scenes with important objects extending from very near to very far. Using the standard depth-of-field estimation methods, using the scales provided on the lenses, I consistently got results with the distant objects rather on the fuzzy side and more-than-adequate rendering of the foreground objects.

My first attempts to fix the problem meant applying the standard advice: use the depth-of-field scale for the next-smaller f-number (or next-largest lens opening). I was still not happy. Then I tried using the depth-of-field scale for two stops larger, then three stops larger. I was still unhappy. At this point I decided I would have to do some calculations. Clearly I was demanding more of photography than the 1/30 mm circle-of-confusion was permitting, or even 1/60 mm.

By examining results I was pleased with, I learned that I was expecting about a 1/150 mm spot size on the negative. And I was achieving it—sometimes. Working with the traditional theory, I calculated what this meant. I at first thought it meant I really wanted to specify the permissible circle-of-confusion as 1/150 mm. That is a factor of 5 times smaller than the usual depth-of-field calculations assume. This in turn would mean that when shooting at f/8, instead of using the depth-of-field marks for f/8, I should have been using those for f/8 divided by 5 or f/1.6. But that would make it almost impossible to shoot scenes with *anything* in the foreground—or so I thought. I would have to decide what is important and focus accurately on that. But that conclusion did not square with my experience either.

Experimenting, I learned that with the lens focused at infinity, things up close still seemed to be adequately sharp. More to think about. What did I really mean about the foreground being sharp? I had figured out that I was demanding a 1/150 mm diameter for the circle-of-confusion for objects a long way away, but what did I want up close? Well, for an object 3 feet away, that 1/150 mm diameter for the circle-of-confusion would mean that I would be asking for the resolution of objects no smaller than 20/150 mm or about 1/8 mm (1/200 inches). But those objects I was wanting to be recognizable in the foreground were blades of grass! I didn't care if I could identify individual aphids! Even the 1/30 mm circle-of-confusion, would let me see objects 1/40 in in diameter. I would have been happy with a circle-of-confusion which allowed resolution of objects about 1/16 inch in size, perhaps even 1/8 in, in the foreground.

Life just got complicated. I would have to use calculations for a circle-of-confusion of 1/150 mm for long distances, and for maybe 1/6 mm for the foreground. So it was then I decided to go back to the mathematics, and Chapter 5 of this booklet was the result.

In scenic photography we often do want detailed rendition of large, far-away objects even though they will be very small in the final print. We may wish to distinguish features no more than a foot or so in dimension on a tall, distant building. On the other hand, even the texture of the mortar between bricks can probably be captured with a *disk*-of-confusion of a millimeter or so in diameter. This seems like a worthwhile goal: can we do it?

Let's look at the problem in detail. We are asking for resolution at the object which varies from about 1 millimeter to about 300 millimeters. The objects themselves may be say five feet away for the close objects, or a mile and a half (about 8000 ft.) or more away for the distant ones. I find it generally easier to figure things out in the object space than in the image space, though we can, of course, do it either way.

In the image space, we would say that for a 50 mm lens and for objects 8000 feet away we want a circle-of-confusion 1/150 mm in diameter, while for objects 5 feet away we want a 1/30 mm circle-of-confusion. And we can then attempt to apply this rule by placing the infinity mark on the depth-of-field scale one fifth of the way between the focus pointer and the depth-of-field marker for the f-stop we are using. And the 5 ft mark on the distance scale must be opposite the other marker (for the aperture we are actually using) on the opposite side of the depth-of-field scale. But we have ignored the diffraction limit. This turns out to be another of those impossible problems, unless you have a view camera with back movements. Diffraction considerations require that the lens have a working diameter of 5 millimeters in order to record an object one foot in size at a distance of 8000 ft. And the lens would have to be focused at some distance *beyond* 4000 ft to let us come close to resolving that one foot object. If the lens were focused at 4000 ft, the disk-of-confusion at 8000 ft would be 1 ft. But diffraction also gives us a *disk*-of-confusion of 1 ft. The rules for convolution say in essence that the combined result will be approximately a *disk*-of-confusion 2 ft in diameter.

We really need to focus the lens at about 7000 ft or beyond.

Whatever the case, the *disk*-of-confusion up close will be the diameter of the lens opening: 5 mm. We could compromise and use a lens opening of 2.5 mm (f/20 for a 50 mm lens, or f/10 for a 25 mm lens), thus giving us *disks*-of-confusion of 2.5 mm at 5 ft and 2 ft at 8000 ft. When I examine my photographs I usually find I am quite satisfied with the results I get with a 5 mm *disk*-of-confusion for the foreground objects. It is not critical focus, but it does usually provide enough information about the foreground to make a satisfactory photograph. Focusing closer can help the forground detail, but at a huge price. In this example, I could get a 1 mm *disk*-of-confusion at 5 ft using a 5 mm aperture by focusing the lens at 6.25 ft. But this would cause the *disk*-of-confusion at 8000 ft. to grow to over 60 ft—thirty times my desired standard. The compromise noted above (2.5 mm aperture, focus at 8000 ft) would get me to within a factor of 2.5 or so of my standard at both extremes. Since working out these details, I find I do a lot of photography with the lens simply focused at infinity.

I usually find it easier to work things out in the object space, but really it can be done either way. I hope that the information in this booklet will help you too.

CHAPTER 10

Rules of Thumb

In this chapter, we'll collect in one place a number of the basic concepts relevant to depth-of-field. Several of these were already listed earlier in Chapter 5, but we'll add a few more here.

1. If we want an object to be resolved, we make sure that the *disk*-of-confusion is smaller than the object. If we want to resolve a letter "A" on a sign where the brush strokes forming the letter are one inch wide, we should ensure that the *disk*-of-confusion is no larger than about one inch.

2. If we want an object to be blurred out, we make sure that the *disk*-of-confusion is larger than the object. If we want to ensure that the letter "A" is not readable, we should make sure that the *disk*-of-confusion is about equal to the height or width of the whole letter.

3. Between the point of exact focus and the camera, the *disk*-of-confusion can never be larger than the working diameter of our lens. Beyond twice the distance from lens to point of exact focus, the *disk*-of-confusion grows larger than the lens opening—without limit!

4. If we want *anything* at infinity to be critically sharp, focus at *infinity*.

5. If we want all objects of, say, 5 millimeters diameter to be recorded—at whatever distance—we should use a lens aperture of 5 millimeters or smaller and focus no closer than half the distance to the furthest object. A 5 millimeter aperture corresponds to f/10 for a 50 mm lens, for example.

6. The zone of acceptable delineation of the *subject* falls *equally* in front of and behind the point of exact focus (*not* 1/3, 2/3!).

7. Stopping down the lens one stop gives us about 40% more depth-of-field; opening the lens one stop gives us about 30% less depth-of-field.

8. Stopping down two stops (to double the f-number) gives us twice the depth-of-field; opening the lens two stops (half the previous f-number) yields half the depth-of-field.

9. To get ten times the depth-of-field requires that we close the lens down by 7(!) stops.

10. Depth-of-field scales linearly with distance from camera to point of exact focus—if we don't change lenses. That is, the zone of acceptable sharpness about the point of exact focus is twice as great if the lens is focused at 20 ft than it would be if the lens were focused at 10 ft.

11. Combining rules 8 and 10: for objects of a particular size, the length of the zone of sharp focus is directly proportional to a) the distance from the camera to the point of exact focus, and b) the working f-number of the lens. To double the depth-of-field, we can either place the objects twice as far away from the camera, or stop the lens down by two stops (double the f-number).

12. If we do change lenses (or zoom) to maintain the same image magnification as the camera-to-subject image changes and keep the lens (or lenses) set to the same f-number, the depth of the zone of acceptable sharpness does not change.

13. The size of an out-of-focus image of an object corresponds to the size of the object *plus* the size of the *disk*-of-confusion. And from this there follow the next two points.

14. Out-of-focus images are *larger* than their corresponding (lens stopped down to a pinhole) in-focus size.

15. Out-of-focus images are *rounder* than their in-focus cousins.

16. The human eye can see an object which measures about one thousandth of the distance to that object from the eye—perhaps one two-thousandth if your eyes are good.

17. A good normal focal length lens can resolve objects which measure one five-thousandth of the distance to the objects—perhaps one ten-thousandth if everything is just right.

18. Diffraction places the ultimate upper limit on the resolution of which any lens is capable. The general rule is: the smallest object the lens can resolve is about equal to the distance from lens to object divided by 1600 times the diameter of the lens opening measured in millimeters.

19. For best resolution, film flatness typically limits the physically largest (numerically smallest f-number) aperture we can use reliably to about f/8 for 35 mm cameras. And it gets worse than that (we must use even smaller apertures) for larger formats using roll film.

20. The usual depth-of-field scale is calculated for a 1/30 mm circle-of-confusion. Typical 35 mm films and lenses are capable of delivering a 1/150 mm standard. To convert an existing depth-of-field scale to a new (higher, more demanding) standard, all we have to do is multiply the numbers on the depth-of-field scale by the improvement factor we desire. To go for that five-fold possible improvement, multiply all the numbers by 5: Instead of f/2, read f/10. Alternatively, divide the f-number you are actually using by 5 and look for that spot on the existing depth-of-field scale: if you are using f/11, look for the f/2.2 depth-of-field mark. And,

if you wish, you can use different standards for the far limit of depth-of-field and for the near limit.

21. We can also easily estimate the revised hyperfocal distance from existing depth-of-field scales. Suppose we wish to use a figure of 1/150 mm for the diameter of the circle-of-confusion but the scale on our lens is based upon the 1/30 mm figure. Place the infinity mark over the depth-of-field marker for the aperture in use, and read off the standard hyperfocal distance at the focus pointer. Multiply that distance by five—that's our new hyperfocal distance.

22. If we are using the standard depth-of-field scales (or scales modified as suggested in 20.) *and* focusing the lens at its hyperfocal distance, the *disk*-of-confusion at the near limit of the depth-of-field will be one-half the diameter of the lens opening. A further result of this is that the actual definition of objects can get worse by *no more than* a factor-of-two, between the supposed inner limit of depth-of-field and right in front of the camera! Take care, however, to note that this last rule applies *only* if one chose to focus at the hyperfocal distance.

23. A gentle repeat reminder: when you focus at the hyperfocal distance, you are *guaranteeing* that subjects in the distance will be resolved *no better than* your specified *minimum* standard. In order to improve upon this, you must focus beyond the hyperfocal distance.

CHAPTER 11

Summary

There have been countless articles written on the subject of depth-of-field. This booklet has provided yet another. It has been my hope to provide the advanced photographer with a method of dealing critically with this subject in an understandable and useful way. Nothing could be much handier than the depth-of-field scales that are provided on almost all lenses. Unfortunately it all gets a bit complicated when we try to adjust that system to the specific needs of a particular photograph. A different way of treating the problem results in a system which, though not quite as simple, still can be handled with a sketch and a simple four-function calculator—or even pencil and paper. We can even use the method to mentally visualize the result before the picture is taken, and then adjust matters if the result is not what we are really trying to achieve.

Along the way I have also tried to offer a bit of insight on how lenses behave: how the blurred image relates to the lens and how long and short lenses place different demands on the camera and the photographer. The shape of the lens diaphragm affects the appearance of the out-of-focus image; long lenses require careful focusing by the photographer; and short lenses demand mechanical precision in the camera body and lens mount. *All* lenses can benefit from flat-field design and from flatness of the light-sensitive emulsion. In the end, we can achieve results which well exceed the commonly used 1/30 mm circle-of-confusion.

The traditional depth-of-field philosophy usually ends with the advice: to maximize depth-of-field, choose a moderately small lens opening, set the focus to the hyperfocal distance, and shoot. My parting advice would be a little different. For typical normal and wide-angle lenses, especially lenses having focal lengths less than about 50 mm no matter what the camera format, set the lens opening to somewhere in the 2 mm to 5 mm range, set the focus at infinity, and shoot. For lens openings larger than 5 mm, and for longer lenses that tends to mean all normal working f-stops, focus on what is critically important. The same is true of close-up photography no matter what the lens. But if you are taking scenic pictures with an 8×10 in. view camera on a tripod, and with a 300 mm lens, f/64 is not at all a bad choice (as a number of famous photographers have noted).

Halifax City Hall. Even though the 20 mm f/8 lens was focused at infinity, the detail of the wall by my left elbow is more than acceptably sharp. Focusing closer would have lowered the contrast in the central area of this picture.

CHAPTER 12

Historical Notes and Bibliography

Historical Notes

The earliest reference I have cited, an early version of the *Ilford Manual of Photography* by Bothamley (about 1906), contains essentially no reference to depth-of-field. The entire topic is summarized as follows: “Focus, in the first place, upon the principal object, and then try the effect of smaller and smaller stops (if you are using an iris diaphragm, slowly rotate the ring so that the aperture gradually closes) until all the remaining parts of the picture are sufficiently well defined to avoid any blurring or fuzziness. Excessively small stops destroy the roundness and atmosphere of the picture, beside necessitating longer exposures, but if enlargements or lantern slides are to be made from the negative, a stop must be sufficiently small to give good definition throughout the picture. Architectural subjects, especially with elaborate detail, usually require smaller stops than landscapes, unless the detail lies pretty much in one plane.” To put this in perspective, it should be appreciated that this book was written at a stage in the development of photography when advice such as the following was also appropriate: “A *shutter* will be required if rapid exposures are to be given, ...”

My personal library then skips to the year 1933 where we see a fairly well developed traditional theory on the subject of depth-of-field in the *Leica Handbook* by Vith. By this time depth-of-field tables and even depth-of-field scales were to be found on certain cameras. The book notes that earlier Leica lenses lacking depth-of-field rings may be retrofitted. More importantly for my purposes, the text states “The desired sharpness of definition of 1/250 of an inch thickness of outline obtainable with negatives that can only be used for direct contact prints is quite inadequate for our purposes. We require a thickness of outline up to 1/750th of an inch and are able to obtain such sharpness of definition only by means of the new fine grained films, and in that event it is quite easy to realize our aim if we only take full advantage of the Elmar lens of the Leica.” I interpret this quotation to state that ordinary films of the day were capable of recording detail no smaller than 1/10 of a millimeter. The best films of the day were capable of recording detail on a scale of about 1/30 millimeter. Hence Leitz had perfect justification for using a figure of 1/30 mm for the circle-of-confusion in their calculations.

Rudolf Kingslake, then Head of the Lens Design Department at Kodak, states in *The Complete Photographer* (1942-1949) that he was frequently asked at what aperture a lens produces its best definition. His response was as follows: "The answer is that the further it is stopped down, the better it is likely to be until about f/22, after which diffraction of light at the lens aperture tends to *enlarge* the image point as the lens aperture is further reduced." Another article by H.W. Zieler in the same book gives the corresponding diameter of the circle-of-confusion for an f/22 lens as, you guessed it, 1/30 millimeter. Zieler also notes that the resolving power of the human eye permits it to resolve objects of a diameter between 1/2000 and 1/1000 of the distance to the object, depending upon variations in individual eye sight. He further notes that this corresponds to a $4\times$ to $8\times$ enlargement of a 1/30 mm image when the print is viewed at 10 inches. (Both of these authors admit that better results might be obtained under exceptional circumstances. A third author, Walter E. Burton, notes that the Zeiss f/6.3 Tessar and the f/7.7 Kodak Anastigmat produce their best results wide open.)

It all fits then. The best films, the best lenses and the best eyes all conspire to support the 1/30 mm standardization for the diameter of the circle-of-confusion—at least when using 8×10 in. prints from 35 mm negatives and viewed at a distance of 10 inches. This of course applies to the period 1933 to about 1950.

G. H. Cook of Taylor, Taylor and Hobson, in his 1950 Leica Photography article on camera lenses, notes two or three interesting items. The first is that "...the modern trend is to balance the aberrations so that performance is as good as it can be at full aperture, even if that arrangement is not best for lower apertures." This statement supports another from the same era I recall reading (though I am not able to relocate) which stated that no lens with a maximum aperture larger than f/7.7 could be expected to produce really critical results at *any* aperture. Cook then goes on to show how an f/2 lens which is allowed to have only one distance scale might have its best aperture at f/8, but if one is allowed to readjust the focus at each f-stop, one might obtain the best results at f/2.8. In other words, the true focal length of real lenses is a function of working f-number (because of spherical aberration). Cook's third point, and one we shall not pursue further as it just complicates life too much, is that the lens focusing position for best definition might further depend upon subject contrast! The point about the focal length being a function of working f-number is important in our study of depth-of-field because it means that the depth-of-field scale on lenses *should not* really be symmetrical (as they are on every lens I have ever seen)!

Every discussion of the subject of depth-of-field concentrates on the circle-of-confusion at the film surface. Or rather, every discussion but one. Rudolf Kingslake in his article on "Camera Optics" in the 15th Edition of the *Leica Manual*, does mention the size of the smallest object which can be photographed at any distance as a function of f-stop. By his formula, the smallest object which could be resolved by a 50 mm f/10 lens would have a diameter equal to 1/5000th of the distance to the object. The number I have used in my analysis is 1/10,000th of the distance. (Similar discrepancies will be found from article to article on diffraction limitations and resolution ability. The answer one gets depends on the assumptions one makes: colour of light, criteria for resolution, contrast required etc. Factors of two in the limit of resolution are somewhat difficult to distinguish. Factors of six or seven are easy.) I know of no extension of this concept to the more general concept of depth-of-field I have described in this book. I am not an optics man by profession, however, and such a treatment may well exist. I would be interested in learning of any such prior work.

The Popular Photography article on normal lenses by Norman Goldberg contains a useful database of information on typical standards for longitudinal colour aberration and for spherical aberration. A typical red-blue spread in position of the best focus is about .08 mm—or ± .04 millimeter about the mean focus position. This is sufficient to be a source of trouble at apertures larger than about f/8. My estimate for the film position problem is about the same. Spherical aberration appears to be somewhat better with typical lenses: the typical focus shift on stopping down is about ± .02 millimeters, though values as high as ± .06 millimeters are shown to exist. I believe these figures support my notion that critical imaging requires stopping down to f/8 or so with 35 mm cameras—or luck. The good news is that we can still do a lot better than a 1/30 mm circle-of-confusion these days: perhaps even a factor-of-7 better.

The remaining references were consulted mainly for their descriptions of the usual depth-of-field calculations. This they do in somewhat more detail than I have done. For more information on the traditional approach to this subject I would advise that these or any of many other technical works on photography should be consulted. Blaker's *Applied Depth of Field* provides a particularly complete treatment of the topic.

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INDEX **(Add 5 to get the e-page no.)**

ADDENDUM

I have been persuaded to include a little information about myself, the preparation of this book, and the photographs contained. I hope the following will prove useful.

About the Author

Harold Merklinger is an avid amateur photographer and camera collector. His interest in photography began when, at the age of eight, his sister received a camera as a Christmas present. The following year he received his own camera, an Ansco Craftsman kit-camera. Within a year he had won first and third prizes at a local hobby fair. He took up darkroom work at age 12 and soon thereafter began using 35 mm cameras. At age 18 he bought his first Leica with his earnings from photography. He considered taking up photography as a profession, but decided he could probably better afford photography if he weren't a photographer. Instead he took up science, obtaining a Ph.D. in Electrical Engineering and Nonlinear Acoustics at the University of Birmingham (UK) in 1971. He was elected a Fellow of the Acoustical Society of America in 1981 and is currently the Head of the Underwater Acoustics Section at the Defence Research Establishment Atlantic in Dartmouth, Nova Scotia, Canada. Though born in the United States of America, he has spent most of his life in Canada.

About the Book

This book was produced almost entirely on an Apple Macintosh SE personal computer. The manuscript was prepared using Microsoft Word, version 4. Line drawings were prepared in a variety of drawing programs including MacDraw, MacDraw II, SuperPaint 2 and Canvas versions 2.0 and 2.1. Final Encapsulated PostScript (EPS) drawing files were produced by Canvas Separator. Half-tones were scanned on a Canon IX-30F flatbed scanner and processed mostly in Digital Darkroom 2, though some minor changes were done in ImageStudio 1.0 or DesignStudio. Final preparation of half-tones and the cover was done on a Linotronic L300 imagesetter. The cover itself was drawn in Canvas 2.1, translated to EPS by Canvas Separator, and imported into DesignStudio 1.0.1 for final adjustments. Page layout was done with DesignStudio; text and line drawings were then printed (20% enlarged) on a 300 dot per inch QMS PS-810 laserprinter.

About the Photographs

Page iv:	Leica M5 with Visoflex III and short mount 135/2.8 Elmarit between f/5.6 and f/8, bounce flash, Kodak Tri-X.
Pages 23 and 30:	Original exposures with Leica M6 with DR-Summicron 50/2 at f/8. Natural illumination on hazy day. Kodak Technical Pan film, 1/125 sec, developed as recommended in Technidol-LC. For the higher magnifications, enlargement was done in three stages. Original negative to enlarged positive using Canon F-1 with bellows and Canon 20/3.5 macro lens, Ilford Pan-F developed in Kodak Microdol-X diluted 1:3. Second stage (enlarged negative) as for first stage except Kodak T-Max 100 film was used and a Canon FD 50/3.5 macro lens was used instead of the 20 mm lens in some cases. The third stage was standard enlargement onto Ilford Ilfobrom paper.
Page 34:	Minolta MAXXUM 7000 with 100/2.8 macro lens at f/4. Studio flash with umbrella and Ilford Pan-F.
Pages 44 and 46:	Leica R4 and 100/2.8 Apo-Macro-Elmarit-R on Kodak T-Max 100. Natural outdoor light with (manual) exposure adjusted to permit f-stop indicated (f/2.8 for the photo on page 44).
Page 48:	Leitz-Minolta CL with 90/4 Elmar-C at f/8, Fuji HR-400 film exposed at ISO 200 (original in colour).
Page 64:	Leica M4-P, 28/2.8 Elmarit-M, Ilford Pan-F, f/8, light yellow filter.
Page 74:	Canon New F-1, Canon FD 20-35/3.5L zoom at 20 mm, f/8, Kodak T-Max 100, light yellow filter.
Page 79:	Canon EOS-1, Canon EF 100-300/5.6L zoom, Kodak T-Max 100, program flash.

All black and white films except Technical Pan were developed in Kodak Microdol-X, diluted 1:3.

Depth-of-Field for View Cameras

Since *The INs and OUTs of FOCUS* was published, several readers have asked if the same methods can be applied to view cameras. The short answer is “yes”. The methods I have described for estimating resolution and depth-of-field are equally applicable to view cameras, but there are one or two things which must be considered carefully.

For those who may not be familiar with view cameras, what makes these cameras different is that the lens axis is not necessarily perpendicular to the film plane. By tilting or swinging the lens, the plane of exact focus is skewed. The effect is used to obtain greater apparent depth-of-field than would otherwise be possible. In effect, the camera can be focused simultaneously on both near and distant objects, provided the objects are not located on a line passing through the camera lens, that is, not one directly behind the other.

The conventional concept of depth-of-field based on image resolution leads to a very complex analysis for view cameras, and I will not even attempt to describe it here. Suffice it to say, the little depth-of-field calculators one sees on some view cameras are correct provided the focusing motion of the camera back moves the back in a direction nearly perpendicular to the film plane. The same condition applies to depth-of-field gauges which have been offered for sale. If the film is strongly tilted with respect to the direction of the focusing motion, the calculations will be inaccurate. This is because the actual movement of the film perpendicular to the film plane will be less than the linear

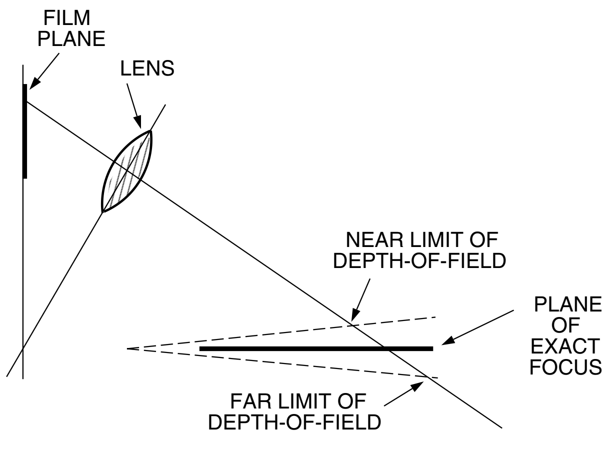

FIGURE 22: *Limits of Depth-of-Field for view cameras using traditional methods.*

motion of the camera back in this case. As an approximation, the depth-of-field along any ray from lens to subject will be just about the values calculated or provided in tables for a normal camera focused at the distance from lens to plane of exact focus measured along that ray. But of course, the distance from lens to plane of exact focus will vary from ray to ray. Thus one has a great many calculations to do. Figure 22 shows the general scheme of things.

For the object field method, things work just as described in this book: the depth-of-field for a given size of disk-of-confusion is as provided in Equation (18): $(\mathbf{Y}\text{-}\mathbf{D})$ and $(\mathbf{D}\text{-}\mathbf{X})$ are equal to $\mathbf{SD/d}$, where $\mathbf{S}$ is either $\mathbf{S_X}$ or $\mathbf{S_Y}$. Please note, however, that $\mathbf{D}$ is always measured *perpendicular* to the plane of exact focus! This is just as it was before, but for normal cameras, measuring perpendicular to the plane of exact focus is the same as measuring along the lens axis. For view cameras the plane of exact focus is not necessarily perpendicular to the lens axis! Figure 23 shows the geometry for this view of depth-of-field.

Comparing Figures 22 and 23, it is clear that the two depth-of-field philosophies give quite conceptually different answers for the size and shape of the in-focus zone. For the conventional depth-of-field theory the zone of sharp focus is wedge-shaped. For the object field method, the zone of sharp focus is uniform in thickness. The apparent differences are entirely due to the assumptions made: for the conventional method, image resolution is the criterion, whereas for the object field method, resolution of the subject is the concern. What makes the difference is, of course, that image magnification is not constant everywhere along the plane of sharp focus for view cameras—as it is for normal cameras.

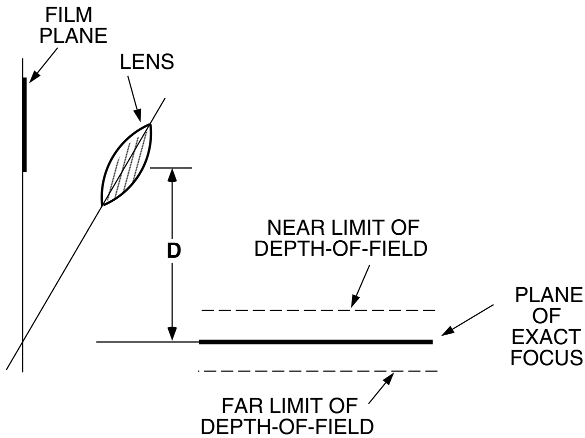

FIGURE 23: *Boundaries of Depth-of-Field estimated using the object field method. Note that* **D** *is measured in a direction perpendicular to the plane of exact focus.*

The INs and OUTs of FOCUS is a book for the advanced photographer who wishes to take advantage of today's high performance materials and lenses.

Mastery over the imaging process is the goal: Limitations due to diffraction, focal length, f-stop, curvature of field, and film curl are weighed against what is possible.

If you have been frustrated by a seeming inability to consistently obtain super-sharp images, this may be the book for you. The reader is taken beyond the traditional concept of depth-of-field to learn how to control precisely what will (or will not) be recorded in the image.

This book contains information you have not read in any other popular book on photography.