Looking at the Depth of Field

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Depth of field is one of those cumbersome but crucial aspects of operating a camera. As a professional scientist I got recently interested in these finer details of operating a film camera. Through numerous books and endless rules of thumbs I finally ended up with the American Cinematographer Manual (ACM), which gave a clear and complete exposition. However, I would suggest it does not precisely contain the answers to the questions a cinematographer would ask oneself faced with a practical problem, although all the information is there: hidden in the tables and the formulae.

The practical questions would be something like: "I have Ned near in a medium shot (MS), and Faye far in full length, or long shot (LS), and both need to be in focus in a single frame. What lens would I use? What is the distance I should focus at optimally?" And "what is the minimal f-stop I can use?" In the case of a tele-lens Ned and Faye would be farther away and farther apart than in the case of a wide-angle lens, if the composition in the frame should be about the same. The focus need to be somewhere in between, but precisely where is hard to recover from the ACM.

With a programmable calculator the answers are easily recovered. However, it would be much nicer if anybody could know the answers instantly with some basic arithmetic. This is possible, with the introduction of one number: x, the shrink factor. The shrink factor is the factor by which Ned needs to be shrunken to fit MS on the negative, and it is the factor by which Faye needs to be shrunken to fit full length on the negative. For 35mm 1.85:1 negative MS is about $x_{\rm N} = 1/100$ and full length is $x_{\rm F} = 1/200$. For a particular negative size these numbers are universal and independent of the lens. One yard is about eighty times the height of a negative frame (0.446" or 11.3mm). This factor x is also the focal length divided by the object distance f/d for a given lens.

For the right composition and the optimal focus Owen, the cinematographer, needs to put Ned at a distance

$$\text{distance}_N = \frac{f}{x_{\rm N}} \tag{1}$$

from the camera lens, Faye at a distance

$$\text{distance}_F = \frac{f}{x_{\rm F}} \quad . \tag{2}$$

Owen should focus at

$$\text{distance}_{\rm focus} = \frac{f}{x_{\rm average}} = \frac{f}{(x_{\rm N} + x_{\rm F})/2} \tag{3}$$

and he should have a minimal f-stop

$$\text{f-stop}_{\rm minimal} = \frac{f(x_{\rm N} - x_{\rm F})}{2s} = 1, 1.4, 2, \cdots 16, 22, 32 \quad . \tag{4}$$

The circle of confusion is s, typically .001" or 0.025mm. No mysteries, no approximations, this is all it takes for a focused composition of your choice. There are two dimensionful numbers in all these equations: the focal length f and the circle of confusion s, one need to use either inches or millimeters for both (1 inch = 25.4mm).

If we return to the example of Owen, with Ned and Faye, and a lens f=25mm, we will find that Ned needs to be at 100 times 25mm, which is 2.5m or 8', Faye at twice that distance, the focus on 133 times 25mm which is 3.33m or 11'. The minimal f-stop number of 25mm times 1/200 times 1/(0.05mm) equals f/2.5. (Look mummy, without calculator!)

If Owen does not have enough light to have both Ned and Faye in focus, he might want to try a shorter lens, since, for example for a f=20mm lens the minimal f-stop is 20mm times 1/200 times 1/(0.05mm) equals f/2.

Clearly the shrink factor is a useful and universal number, that simplifies many of the calculations involving lenses and depth of field. Furthermore, it quantifies what one precisely means with ECU ($x = 1/25$), MCU ($x = 1/50$), MS ($x = 1/100$), LS ($x = 1/200$), ELS ($x = 1/400$), ULS ($x = 1/800$), in relation to the negative format used. For standard 16mm negative (1.33:1 gives .404" $\times$.295") these shrink factors need to be divided by a factor 1.5. However, due to the different aspect ratios and possible video transfer, one might want to redefine the x-factors of the different shots slightly.

One note of caution with respect to the circle of confusion. The typical value of $s = 0.001''$ corresponds to a resolution of 1/440 of the screen height (35mm 1.85:1), which is dangerously close to the resolution of digital video. I would recommend to take one or two f-stops closer. After all I would not have fallen in love with Diane, if I had not seen hair on her skin, thanks to Peter the Cinematographer.

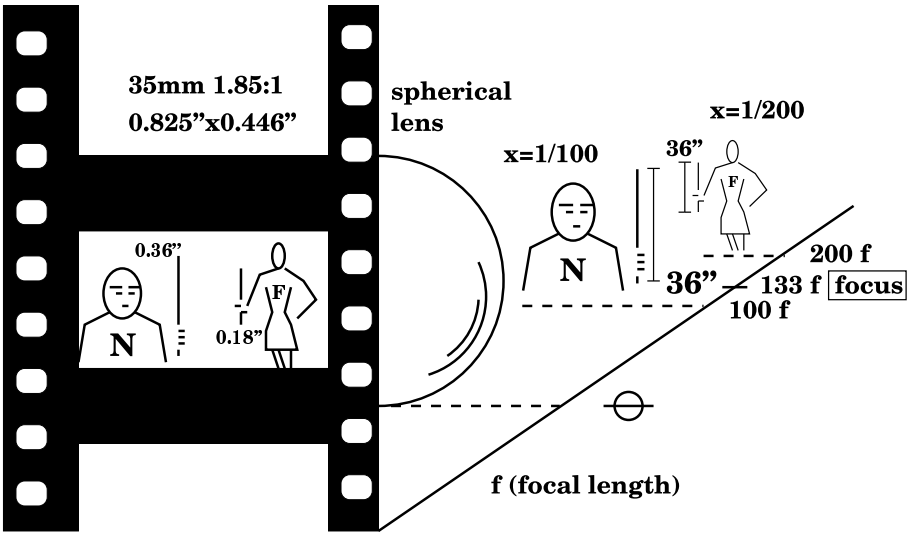

Figure 1: Both Ned and Faye hold up a yardstick. The size of the yardstick on the negative determines the shrink factor, and how far they are from the camera. (The image should be upside down, and Faye is one of those classical beauties who stand six foot tall.)

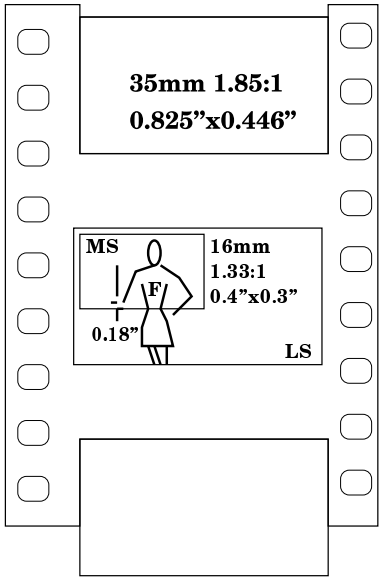

Figure 2: Since the 16mm negative is smaller than 35mm negative, the LS for 35mm yields a MS for 16mm, for the same distance in multiples of focal length ($x = 1/200$).

		ECU	CU	MS	LS	ELS	ULS
		25 f	50 f	100 f	200 f	400 f	800 f
ECU	25 f	0.f	0.4f	0.6f	0.7f	0.75f	0.775f
CU	50 f	0.4f	0.f	0.2f	0.3f	0.35f	0.375f
MS	100 f	0.6f	0.2f	0.f	0.1f	0.15f	0.175f
LS	200 f	0.7f	0.3f	0.1f	0.f	0.05f	0.075f
ELS	400 f	0.75f	0.35f	0.15f	0.05f	0.f	0.025f
ULS	800 f	0.775f	0.375f	0.175f	0.075f	0.025f	0.f

Table 1: The minimal f-stop in terms of the focal length in millimeters (mm), when combining two shots in one frame. The second row and column are the distances of the objects in multiples of the focal length. This table is compiled for 35mm, 1.85:1 negative, with a circle of confusion of 0.025mm. Smaller negatives have smaller circles of confusion, which can be compensated for by taking one or two stops down, every two stops down the circle of confusion is halved. The labeling ECU, CU, MS, LS, ELS, and ULS also have an identical one or two downshift CU → ECU, MS → CU, etc. The boxed numbers are from the example with Ned $x = 1/100$ and Faye $x = 1/200$, which yields a minimal f-stop=2.5 for f=25mm and a minimal f-stop=2 for f=20mm.

		ECU	CU	MS	LS	ELS	ULS
		25 f	50 f	100 f	200 f	400 f	800 f
ECU	25 f	25f	33f	40f	44f	47f	48f
CU	50 f	33f	50f	66f	80f	88f	94f
MS	100 f	40f	66f	100f	133f	160f	177f
LS	200 f	44f	80f	133f	200f	266f	320f
ELS	400 f	47f	88f	160f	266f	400f	533f
ULS	800 f	48f	94f	177f	320f	533f	800f

Table 2: The optimal focus distance in multiples of the focal length, when combining two shots in one frame. The second row and column are the distances of the objects also in multiples of the focal length. The table is universal, except for the labeling ECU, CU, MS, LS, ELS, and ULS, which is associated with 35mm, 1.85:1 negative. Smaller negatives have a downshift CU → ECU, MS → CU, etc. The boxed numbers are from the example with Ned $x = 1/100$ and Faye $x = 1/200$.

$d_N : d_F$	1:1.2	1:1.4	1:2	1:3	1:4	1:5	1:6	1:10	1:15	1:20
d_{focus}	1.09	1.166	1.33	1.5	1.6	1.66	1.71	1.82	1.88	1.9

Table 3: The optimal focus for a ratio of shortest distance and farthest distance expressed in multiples of the shortest distance. Independent of negative or lens. The optimal focus is never beyond twice the shortest distance. The boxed numbers are from the example with Ned $x = 1/100$ and Faye $x = 1/200$.

f-stop\f	15mm	20mm	25mm	30mm	35mm	40mm	45mm	50mm	55mm
1	14'	26'	40'	59'	80'	104'	132'	163'	198'
1.4	10'	18'	28'	41'	56'	74'	93'	115'	140'
2	7'5"	13'	20'	29'	40'	52'	66'	81'	99'
2.8	5'2"	9'4"	14'	20'	28'	37'	46'	57'	70'
4	3'10"	6'7"	10'	14'	20'	26'	33'	40'	49'
5.6	2'7"	4'7"	7'2"	10'	14'	18'	23'	28'	35'
8	1'10"	3'4"	5'1"	7'4"	10'	13'	16'	20'	24'
11	1'4"	2'4"	3'7"	5'2"	7'1"	9'4"	11'	14'	17'
16	10"	1'7"	2'7"	3'7"	5'	6'6"	8'3"	10'	12'

Table 4: The objects between this near-field distance in feet and infinity are in focus for a given lens in mm and f-stop. The optimal focus is twice the near-field distance. The circle of confusion s is again 0.001" or 0.025mm. For example, a f=25mm lens with lighting conditions of f-stop=2.8 allows one to have the depth of field of 14' $-\infty$ (see the boxed number in the table), if one focuses at 28' (2 times 14'). For a comparable result with a 16mm negative, the circle of confusion is about two-third to half, which means that instead of an f-stop=2.8, an f-stop=4 to f-stop=5.6 is required.