Introduction to close-up photography

By reading the following technical notes, you should learn how to use your gear in order to take close-up pictures, even if you do not own a macro lens.

First of all, let's define the *magnification*, or *reproduction ratio*, ***R***. It is defined as the ratio between the size of the subject on film/sesnor and the actual subject size in real life:

$$R = \frac{\text{size on film (or sensor)}}{\text{actual subject size}}$$

Therefore, reproduction ratio indicates how large will be the image on the film with respect to the actual dimensions of the subject. If we take a picture of a 1 in. diameter coin and if its diameter on the film is 1/2 in., then the reproduction ratio is (1/2)/1 = 1:2 or 0.5 X. For a magnification of 1:10 (= 0.1 X), then the subject size will be ten times larger than the size of the image on film/sensor; or the image on film/sensor is one tenth of the actual size of the subject. In the case of a 1:1 reproduction ratio (= 1 X magnification), the image would be the exact size as the actual subject, hence the term *life-size*. Therefore if an insect is 15 mm long, then the image of the same insect on film will also be 15 mm long. For a larger than life-size magnification, say 10 times the actual size (on film or digital camera sensor!), the reproduction ratio would be 10:1 (10 X).

Common (non-macro) lenses can focus at distances that are more or less 5 to 15 times larger than their focal length value. A "normal" (not macro) 50 mm lens usually focuses at 45 cm. Modern 300 mm lenses focus at 2-2.5 meters (the newest ones focus at 1.5 m). An ultra-wideangle 17 mm lens will focus at 25 cm. This occurrence is simply due to the fact that it is not easy to correct the optical aberrations in an extremely wide range of focusing distances. As a consequence, macro lenses have more complex optical designs and are more expensive than "normal" lenses having the same focal length.

Nevertheless, we should remember that:

- each lens (macro or not) exhibits the best performance within a given focusing distance range;
- good close-up pictures can be taken with most of "normal" lenses (even with zooms) providing that we accept a lack of sharpness, namely at the image corners.

The laws of geometrical optics teaches us that the reproduction ratio, R, increases on increasing the distance, t, between the lens and the film and/or decreasing the focal length, F, according to the following relationship:

$$R = \frac{t}{F} - 1$$

Macro lenses usually permit a large increase of t by acting on the focus helicoid, although macro telephotos often adopt internal focusing (IF) mechanisms which ensure similar results (by reducing F in the previous formula, thus increasing R without any significant modification of t). The above relationship also indicates that $t = F$ when a lens is focused at infinity. In fact, a subject at infinity will be reproduced on the film with a nil size, i.e. $R = 0$ and $t/F = 1$.

Extension tubes

If we own a good quality "normal" lens, we can increase t to focus at shorter distances and to get higher magnification ratios. Let's consider a 50 mm lens which can focus from 45 cm to infinity. The AI Nikkor 50/1.8 has an R value equal to 1/6.84 (= 0.146) at 45 cm. Which are the *R* values we can obtain when this lens is coupled to a Nikon PK-13 (27.5 mm) extension tube? You can click here to know the answer or just apply the above equation. In fact, when focused at infinity, the lens has a *t* value equal to its focal length, 50 mm. With the extension tube, the new value of *t* is *t'* = 50 + 27.5 = 77.5 mm. Therefore

$$R = \frac{77.5}{50} - 1 = 0.55 = 1:1.82$$

At 45 cm, the *t* value of the lens is expected to be a little bit larger than at infinity (you can see the increase of elongation by rotating the focusing ring); we know *R* (= 0.146) and *F* (50 mm), so we can calculate the overall elongation of our 50 mm lens when focused at its minimum focusing distance:

$$t = (R + 1) \times F = (0.146 + 1) \times 50 = 57.3mm$$

As predicted, this *t* value is slightly larger than 50 mm. To get the new *t'* value we have to sum 27.5 mm (the length of the extension tube) to this value:

$$t' = 57.3 + 27.5 = 84.8mm$$

Now we can calculate the new *R* value when the lens is coupled to the PK-13 and focused at its minimum distance:

$$R = \frac{84.8}{50} - 1 = 0.696 = 1:1.44$$

Therefore, with a 27.5 mm long extension tube coupled to a "normal" 50 mm we can take close-up pictures with reproduction ratios in the 1:1.82-1:1.44 range. NOTE: these calculated values have been obtained with a "simple" formula, which holds for single-element lenses. When more complex optical designs (such as those of multi-elements lenses) are concerned, the relationship: *R* = *t/F* - 1 is not rigorous. However, the exact values of *R* for the Nikkor AI 50/1.8 coupled to a Nikon PK-13 tube range from 1/1.9 to 1/1.5 (check out here to know the numbers given by Nikon). This fact implies that the simple equation we used allows to calculate *sufficiently* good estimations of the magnification values.

Let me examine a further example showing which kind of calculations we have to perform when our lens has a floating elements design and, consequently, its focal length changes (usually becomes shorter) when we rotate the focusing ring.

Let's consider the AF Sigma 300/4 Apo Tele Macro, which employs an internal focusing (IF) mechanism. This lens can focus at 1.2 m without any accessory, thus reaching a 1:3 reproduction ratio. Which is the maximum magnification ratio attainable when a PK-13 extension tube is mounted between the lens and the camera body?

Again, when the lens is focused at infinity, *t* = *F* = 300 mm. When the lens is focused at 1.2 m, *R* = 1:3 (0.333 X). We cannot determine, on the basis of the above equations, the value of *t* at the minimum focusing distance. In fact, in the following (simplified) equation

$$t = (R + 1) \times F$$

we have two unknown quantities: *t* and *F* because, due to the IF mechanism, the "real" focal length is expected to shorten. How can we evaluate the focal length of our "300" mm lens when it is focused at 1.2 m?

The following relationship can help us:

$$D = F \times \left(\frac{1}{R} + R + 2 \right)$$

where *D* is the focusing distance (*i.e.* the distance between the film/sensor and the subject), and *F* and *R* are the focal length and the reproduction ratio, respectively.

By using the previous equation, we can estimate the "actual" *F* when *R* = 1:3 (= 0.333) and *D* = 1200 mm (1.2 meters):

$$F = \frac{D}{\left(\frac{1}{R} + R + 2 \right)} = \frac{1200}{\left(\frac{1}{0.333} + 0.333 + 2 \right)} = 225mm$$

Now we know the focal length at the minimum focusing distance and, therefore, we can calculate the value of *t*:

$$t = (R + 1) \times F = (0.333 + 1) \times 225 = 300mm$$

When the AF Sigma 300/4 Apo Tele Macro is coupled to a PK-13 extension tube (whose length is 27.5 mm) and focused at the closest distance (where *t* - withour any further accessory - and *F* are 300 and 225 mm, respectively), we obtain:

$$R = \frac{t}{F} - 1 = \frac{300 + 27.5}{225} - 1 = 0.455 = 1 : 2.2$$

A real macro performance, with a reproduction ratio quite close to half life-size (1:2).

Another question arises. Which is the focusing distance with the tube? The above mentioned relationship can provide the answer.

$$D = F \times \left(\frac{1}{R} + R + 2 \right) = 225 \times \left(2.2 + \frac{1}{2.2} + 2 \right) = 1047mm \cong 1m$$

With this lens and PK-13 we can take pictures of shy animals with R ~ 1:2 at about 1 m focusing distance! By using also a good quality 1.4X teleconverter, *R* = 1:1.6 can be achieved at the same distance (0.455 x 1.4 = 0.637 = 1:1.57). In fact, in close-up photography teleconverters increase the magnification rather than the focal length.

Let's consider now another example. Fig. 1 shows a life-size (1:1) image of a millimeter rule photographed with a Micro-Nikkor AF ED 200 mm f/4 on a Nikon D100 DSLR. The lens was focused at its minimum focusing distance (*mfd* = 50 cm). The length of the horizontal size of the picture is by definition equal to the longest side of the APS-C sized CCD sensor (about 24 mm).

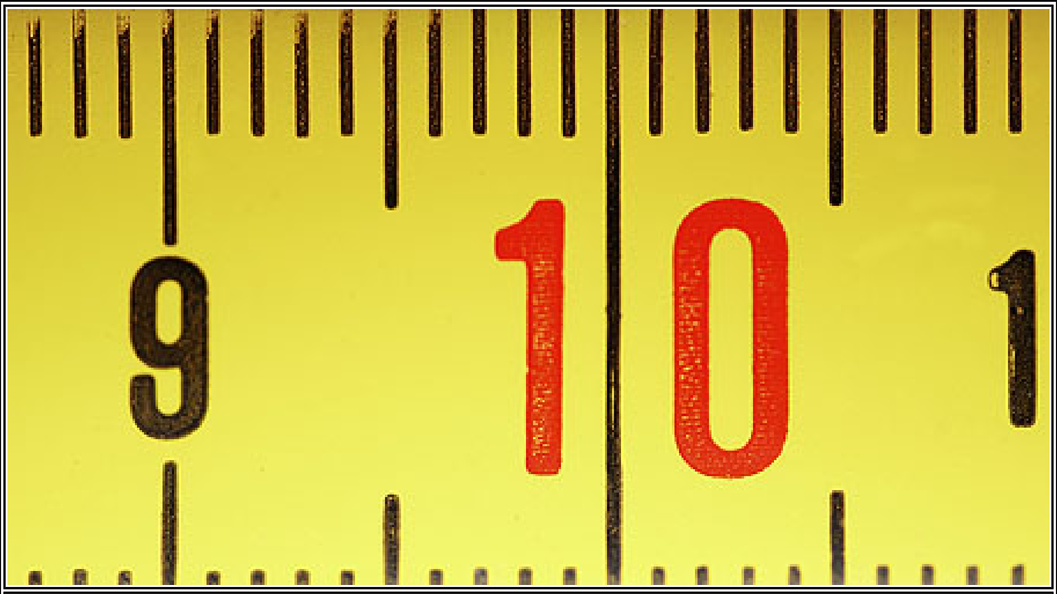

Fig. 1
1:1 image of a millimeter rule (D100 + AF ED Micro-Nikkor 200 mm f/4D)

Which is the magnification we get by adding 49.5 mm of extension tubes? We can calculate the *R* value and we can measure it. I'll do both in the following. To calculate *R*, we need both *t* and *F*. When the lens is focused at the minimum focusing distance (*mfd* = 50 cm), it allows to take life-size images without any accessory. Its focal length @ *mfd* and 1:1 is *F* = *D*/4 = 500/4 = 125 mm. Now we have to estimate *t*: ***t* = (*R* + 1)*F* = 2*F*** = 250 mm. If we add 49.5 mm ext. tubes, ***t' = t + 49.5 = 299.5*** mm. Therefore, with the extension tubes, ***R = t'/F - 1 = 299.5/125 - 1 = 1.4 X***.

Is this a good estimation of the magnification? Fig. 2 shows a picture of the same millimeter rule photographed by adding three Nikon extension tubes (PK13 + PK12 + PK11A = 49.5 mm). The prime lens was focused at the *mfd*.

Fig. 2
Image of the same millimeter rule (D100 + AF ED 200 mm f/4D + ext. tubes)

We have filled the area of an APS-C sensor with a 16 mm long subject. In other words, we have reproduced a 16 mm long subject on a 24 mm long sensor. Magnification can be easily calculated; ***R* = 24/16 = 1.5 X**. The calculated value (1.4 X) differs from the measured one by less than 10 % (6.7 %). Therefore, the use of simple formulas, which hold for symmetric optical designs, allow to estimate magnification with less than 10 % error. Moreover, we can calculate the focusing distance at 1.5 X (i.e. with the extension tubes), and compare this value to the measured one. In fact, I measured a focusing distance around 51-52 cm. The calculated value @ 1.5 X, assuming that the focal length of the

AF Micro-Nikkor 200/4 at the *mfd* is 125 mm, is:

$$D = F \times \left(\frac{1}{R} + R + 2 \right) = 125 \times \left(1.5 \quad + \frac{1}{1.5} + 2 \right) = 521\text{mm}$$

i.e. a value in excellent agreement with the one I measured.

Close-up lenses

A close-up lens reduces the focal length of our objective and increases, consequently, the reproduction ratio.

The optical properties of a close-up lens are defined in terms of its *diopters* and focal length, *F'*. The diopters of a close-up lens are equal to the reciprocal of *F'* (in meters, m). Therefore, a 2 diopters lens has a focal length equal to 1/2 m, or 500 mm. A 1.5 diopter lens has a focal length equal to 1/1.5 m, or 667 mm.

I caught myself looking at the results I obtained using a telezoom plus a close-up lens. In particular, I was successful in taking sharp pictures of dragonflies and butterflies with a discontinued AF Nikkor 75-300/4.5-5.6 zoom equipped with Nikon 5T (focal length, *F'* = 667 mm) or 6T (*F'* = 345 mm) close-up achromatic lenses.

Let's consider a 200 mm lens with a Nikon 4T close-up lens. The focal length, *F'*, of 4T (3 diopters) is 334 mm. The overall focal length, *OFL*, of the coupled lenses is given by the following relationship:

$$OFL = \frac{F \times F'}{F + F'} = \frac{200 \times 334}{200 + 334} = 125mm$$

When the lens if focused at infinity, *t* = *F* = 200 mm; therefore

$$R = \frac{t}{OFL} - 1 = \frac{200}{125} - 1 = 0.6 = 1:1.67$$

This value is also obtained by the *F/F'* ratio. In fact, 200/334 = 0.6.

Again, we can evaluate the focusing distance:

$$D = F \times \left(\frac{1}{R} + R + 2 \right) = 125 \times \left(1.67 + \frac{1}{1.67} + 2 \right) = 534mm$$

If we attach the same close-up lens to a 105 mm, focused at infinity, we get

$$OFL = \frac{F \times F'}{F + F'} = \frac{105 \times 334}{105 + 334} = 80mm$$

and

$$R = \frac{t}{OFL} - 1 = \frac{105}{80} - 1 = 0.313 = 1:3.2$$

If we use a Nikon 3T close-up lens (*F'* = 667 mm) we get:

$$OFL = \frac{F \times F'}{F + F'} = \frac{105 \times 667}{105 + 667} = 91mm$$

and

$$R = \frac{t}{OFL} - 1 = \frac{105}{91} - 1 = 0.154 = 1:6.5$$

Therefore, the following general rule holds:

The more powerful the close-up lens (*i.e.* the shorter its focal length) and the longer the focal length of the prime lens, the larger the reproduction ratio.

As a further example, I have calculated the reproduction ratios that can be obtained by coupling a Canon 500 D achromat (2 diopters, *F'* = 500 mm) to 1) the AF ED 80-200/2.8 D zoom and 2) the AF Sigma 300/4 Apo Tele Macro. The results are summarised in the following table:

lens	focusing distance (*m*)	focal length (*mm*)	OFL (*mm*) with 500 D	*t* (*mm*)	*R***
80-200	∞	**80**	**69**	**80**	**1:6.3**
80-200	∞	**105**	**87**	**105**	**1:4.8**
80-200	∞	**135**	**106**	**135**	**1:3.7**
80-200	∞	**200**	**143**	**200**	**1:2.5**
300/4	∞	**300**	**188**	**300**	**1:1.7**
300/4	**1.2**	***225 ****	**155**	**300**	**1:1.1**

*** due to floating elements design and IF mechanics; ** when the lens is focused at infinity, *R* is given by the *F/F'* ratio.**

In the "*Extension tubes*" section we took close-up pictures of a millimeter rule with an AF ED Micro-Nikkor 200 mm f/4D at the *mfd*. With 49.5 mm extension tubes we got 1.5 X magnification (and we calculated 1.4 X magnification using simple equations). We'll try to perform now a similar comparison between calculated and measured magnification values when close-up lenses are employed to increase the life-size magnification of a macro lens.

Question: which is the magnification we get using a Nikon 5T close-up lens (1.5 diopters, 667 mm focal length) on a Micro-Nikkor AF ED 200 mm f/4D macro lens **focused at its *mfd*** ?

The overall focal length of the 200 (at *mfd*) + 5T combo is:

$$OFL = \frac{F \times F'}{F + F'} = \frac{125 \times 667}{125 + 667} = 105mm$$

The *t* estimated value remains the same as previously calculated: ***t* = *250* mm**. Therefore, the reproduction ratio is easily obtained: ***R* = *t*/*F* - *1* = *250*/*105* - *1*** = **1.38 X**. What about the *true* value of the magnification? Fig. 3 shows the same millimeter rule of Fig. 1, but photographed with a 5T close-up lens coupled to the AF Micro-Nikkor focused at the *mfd*:

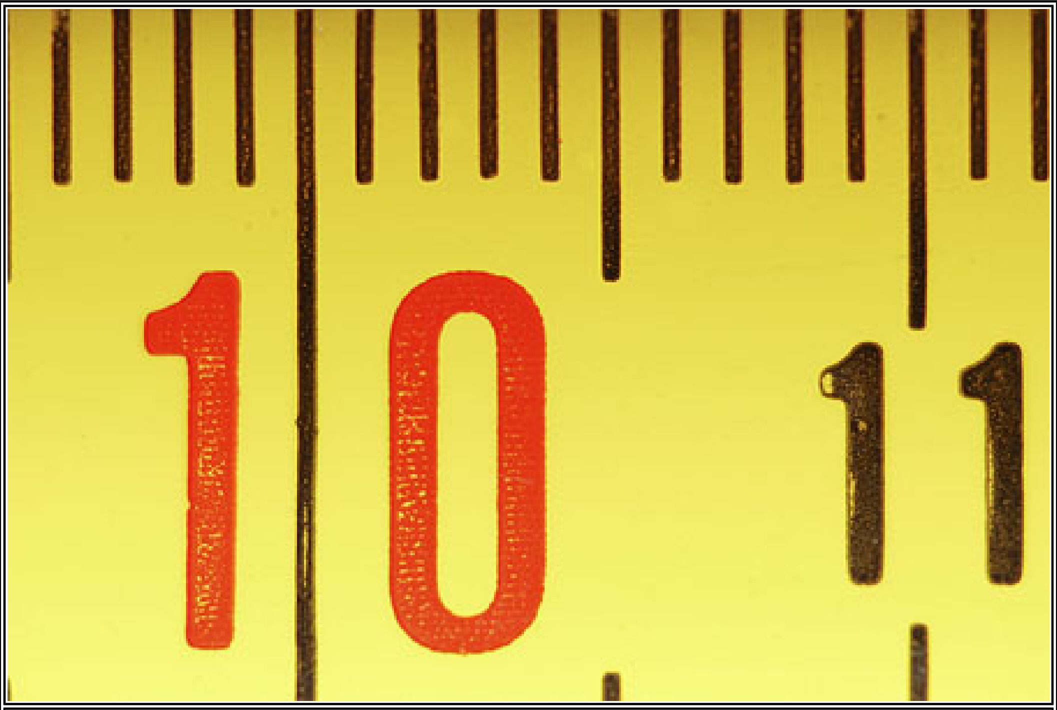

Fig. 3
Image of the millimeter rule (D100 + AF ED 200 mm f/4D + 5T)

The magnification is 24/17 = **1.41 X**. Therefore, the calculated value of magnification (1.38 X) is in excellent agreement with the true (measured) one, being the difference a mere 2.3 %.

Depth of Field (DOF)

The depth of field depends on the following quantities:

- the reproduction ratio (*R*);
- the aperture (*f*);
- the diameter (*d*) of the circle of confusion.

Therefore, when somebody says "the DOF of wideangles is larger than telephotos", don't believe him (her). As a matter of fact, the above sentence is correct if the distance between the film and the subject is the same. In this case, the size of the image on film is larger when a telephoto lens is used. Consequently, the reproduction ratio is larger and DOF is smaller. But if we shoot a butterfly and obtain the same size of the subject on the film, the DOF is also the same independently of the focal length. The only difference in taking close-up pictures with a 50 mm or a 200 mm lens will be the angle of view (AOV). The quantitative relationship which correlates DOF with the above quantities is:

$$DOF = \frac{d \cdot 2 \cdot f \cdot (R+1)}{R^2}$$

Usually, 1/30 mm is considered to be an acceptable size of the circle of confusion; the above relationship can therefore be written as

$$DOF = \frac{2 \cdot f \cdot (R+1)}{30 \cdot R^2}$$

In this case, DOF is in mm. The following table gives DOF as a function of the reproduction ratio and the aperture.

DOF (in *mm*) as a function of the aperture and the reproduction ratio (*R*)

R	*aperture*			
	8	*11*	*16*	*22*
1:5	16	22	32	44
1:4	10.6	14	20	29
1:3	7.3	10	15	20
1:2	3.2	4.5	6.4	8.8
1:1.4	1.8	2.5	3.6	4.9
1:1	1.1	1.5	2.1	2.9
1.4:1	0.65	0.90	1.3	1.8
2:1	0.4	0.5	0.8	1.0

Angle of View (AOV)

The angle of view, α, depends on the focal length, *F* (mm), and the reproduction ratio, *R*:

$$\alpha = 2 \cdot \mathrm{arctg} \frac{d}{2 \cdot F(1+R)}$$

In the above equation, ***d*** is the diagonal (mm) of the picture (43.27 mm in the case of 24x36).

At infinity, *R* = 0 and the angle of view depends on the focal length only:

$$\alpha = 2 \cdot \mathrm{arctg} \frac{d}{2 \cdot F}$$

The following table shows the variation of the AOV with the focal length and the reproduction ratio:

AOV as a function of the focal length and the reproduction ratio (*R*)

R	*AOV*			
	50 mm	*90 mm*	*105 mm*	*180 mm*
0	47°	27°	23°	14°
1:5	40°	23°	19°	11°
1:3	36°	20°	18°	10°
1:2	32°	18°	16°	9°
1:1	24°	14°	12°	7°

The data show that at 1:1 the angle of view is one half of the one at infinity. It is worth noting that this is true when the focal length of the lens does not change with the focusing distance. In the case of modern macro lenses, however, the floating elements' design causes a decrease of *F* at the near limit. For example, at the minimum focusing distance, the actual focal length of the AF Micro-Nikkor 70-180 is around 90 mm when the zoom ring is set at 180 mm. As a consequence, the angle of view *increases* when the lens is focused at close distances. In fact, the AOV at infinity is 14° and it is 16° at 0.75 X (*R* = 1:1.33).

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