Introduction to close-up photography

By reading the following technical notes, you should learn how to use your gear to take close-up pictures, even if you do not own a macro lens.
First, let's define the ***magnification***, or ***reproduction ratio***, ***R***. It is defined as the ratio between the size of the subject on film/sensor and the actual subject size in real life:

$$R = \frac{\text{image size on film/sensor}}{\text{actual subject size}} \qquad [1]$$

Therefore, reproduction ratio indicates how large will be the image on the film/sensor with respect to the actual dimensions of the subject. If we take a picture of a 22 mm diameter coin and if its diameter on the film/sensor is 18.5 mm (see Fig. 1), then the reproduction ratio is

$$R = \frac{18.5}{22} = 0.84 = 1:1.19$$

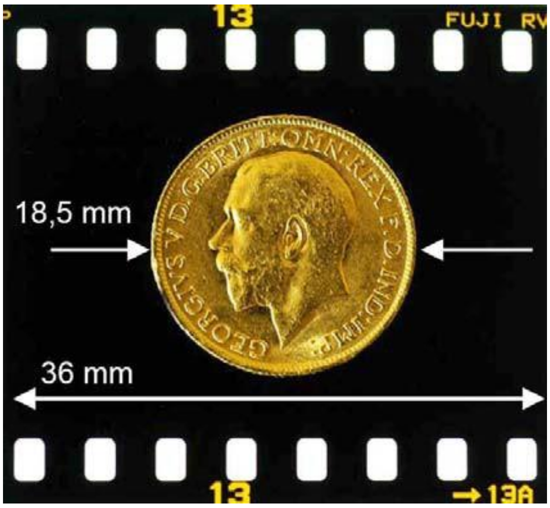

Fig. 1 Image of a 22 mm coin on 24x36 film (R = 18.5:22 = 0.84 X).

For a magnification of 1:10 (= 0.1 X), then the subject size would 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[1]. 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. Consequently, 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 (either macro or not) exhibits the best performance within a certain interval of focus distances;
- 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 borders of the image.

[1] A "normal" (non-macro) 50 mm lens usually focuses at 45 cm. 300 mm lenses focus typically at 2-2.5 meters, although the most recent ones focus closer, at ≈ 1.5 m. A wide-angle lens (i.e., a lens with focal length, *F*, in the 14-35 mm interval) focuses at 20-30 cm.

The laws of geometrical optics tell 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:

$$R = \frac{t}{F} - 1 \qquad [2]$$

Macro lenses usually permit a large increase of t by acting on the focus ring, although macro telephotos sometimes 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). Most modern macro lenses adopt a floating element design; when we rotate the focus ring, not all the glass elements/groups are moved away from the film/sensor plane by the same amount. This implies that the optical scheme of the lens changes and, consequently, the focal length changes too.
Equation [2] 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., $R = 0$ being $t/F = 1$.

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? Let's apply equation [2]. 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, and

$$R = \frac{77.5}{50} - 1 = 0.55 = 1{:}1.8$$

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 focus ring); we know R (= 0.146) and F (50 mm), so we can calculate the overall extension of our 50 mm lens when focused at its minimum focusing distance:

$$t = (R+1) \times F = (0.146+1) \times 50 = 57.3\,\text{mm}.$$

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 PK-13 extension tube) to this value:

$$t' = 57.3 + 27.5 = 84.8\,\text{mm}.$$

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 1:1.8-1:1.44 range. This implies that <u>we cannot focus anymore to infinity</u>, where $R = 0$. **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 considered, the relationship: R = t/F - 1 is not*

rigorous. However, the exact values of R for the Nikkor AI 50/1.8 when coupled to a Nikon PK-13 tube range from 1/1.9 to 1/1.5 (source: Nikon). This fact implies that the simple equation we've used allows calculating *sufficiently* good estimates of the magnification values.
Let us 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 (in the case of telephoto macro lenses it becomes shorter) when we rotate the focusing ring.
Let's consider the AF Sigma 300/4 Apo Tele Macro, which employs floating elements and 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 (reproduction ratio) attainable when a 27.5 mm 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 equation

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

we have two unknown quantities: t and F because, due to the IF mechanism, the "real" (or "effective") 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:

$$D = F \times \left(\frac{1}{R} + R + 2\right), \qquad [3]$$

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 equation [3], we can estimate the "actual" F value when R = 1:3 (= 0.333) and D = 1200 mm (1.2 meters):

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

Now we have an estimate the actual focal length at the minimum focusing distance and, therefore, can calculate the value of t:

$$t = (R+1) \times F = (0.333+1) \times 225 = 300 \text{ mm.}$$

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 - without 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 true macro performance, with a reproduction ratio quite close to half life-size (1:2).
Another question arises. Which is the focusing distance with the extension tube? Equation 3 can provide the answer:

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

Therefore, by using this lens and a 27.5 mm extension tube (PK-13, by Nikon) we can take pictures of shy animals with R ~ 1:2 at about 1 m focusing distance! By adding a good quality 1.4X teleconverter (see Fig. 2), R = 1:1.6 can be achieved at the same distance (0.455 × 1.4 = 0.637 = 1:1.57). In fact, in close-up photography teleconverters increase the magnification. Remember, TCs increase the focal length by the same multiplying factor (1.4X, 1.7X, 2X, etc.) only when the lens is focused "at infinity".

Fig. 2 A telephoto lens (AF Sigma 300 mm f/4 Apo Tele Macro) with extension tube and TC 1.4X.

Let's consider now another example. Fig. 3 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 DX DSLR (sensor size 15.7×23.6 mm). The lens was at its closest focusing distance ($mfd = 50$ cm).

Fig. 3 Life-size image of a millimeter rule taken with APS-C (sensor size 15.7×23.6 mm) reflex camera.

The length of the horizontal size of the picture is, by definition, equal to the longest side of the APS- C sized sensor (approximately 24 mm). Which is the magnification we get by adding 50 mm of extension? We can both calculate and measure the R value. 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, according to Equation 3, $F = D/4 = 500/4 = 125$ mm. Now we have to estimate t: $t = (R + 1) \times F = 2F = 250$ mm. If we add 50 mm extensions, $t' = t + 50 = 300$ mm. Therefore, with 50 mm extension, we get $R = t'/F - 1 = 300/125 - 1 =$ 1.4 X.
Is this a good estimation of the magnification? Is our math too rough? Fig. 4 shows a picture of the same millimeter rule photographed by adding three Nikon extension tubes (PK13 + PK12 + PK11A ≈ 50 mm). The prime lens was focused at the minimum focusing distance.
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 wide 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 %, actually).

Fig. 4 Image at larger magnification of the same millimeter rule as Fig. 3.

Therefore, the use of simplified formulas, which hold for simple/symmetric optical designs, allows to estimate the 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:

$$D = F \times \left(\frac{1}{R} + R + 2\right) = 125 \times \left(1.5 + \frac{1}{1.5} + 2\right) = 521 \text{ mm} \approx 0.5 \text{ m}.$$

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

Let's practice more ...

Let's see know what happens when you use the **AF-S Nikkor 300/4 IF ED** in conjunction with a Nikon **PN-11 extension tube** (52.5 mm). That prime telephoto lens has a minimum focus distance of 1.45 m, with 1:3.7 maximum magnification. The estimated actual focal length at the *mfd* is

$$F = \frac{D}{\left(\frac{1}{R} + R + 2\right)} = \frac{1450}{\left(3.7 + \frac{1}{3.7} + 2\right)} = 243 \text{ mm}.$$

By the knowledge of F, and by using Equation 2, we can estimate the value of t (which we should expect to be close to 300 mm, i.e. the t value at infinity, due to the IF design of the lens):

$$t = (R + 1) \times F = \left(\frac{1}{3.7} + 1\right) \times 243 = 308 \text{ mm}.$$

Now we can evaluate R and D values when we add a PN-11 and with the lens focused at ∞ or at the *mfd*.

1 - Focus at *mfd*

$$R_{mfd} = \frac{t}{F} - 1 = \frac{308 + 52.5}{243} - 1 = 0.486 = 1{:}\,2.1$$

$$D_{mfd} = F \times \left(\frac{1}{R} + R + 2\right) = 243 \times \left(\frac{1}{0.486} + 0.486 + 2\right) = 1104 \text{ mm} \approx 1.1 \text{ m}.$$

2 - Focus to ∞

$$R_{\infty} = \frac{t}{F} - 1 = \frac{300 + 52.5}{300} - 1 = 0.174 = 1{:}\,5.8$$

$$D_{\infty} = F \times \left(\frac{1}{R} + R + 2\right) = 300 \times \left(\frac{1}{0.174} + 0.174 + 2\right) = 2376 \text{ mm} \approx 2.4 \text{ m}.$$

These figures should be valid within ± 10 % uncertainty.

Close-up lenses

A close-up lens is a sort of filter that reduces the focal length of our objective and increases, consequently, the reproduction ratio (see Equation 2). 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 ½ 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 telephoto zoom plus a close-up lens. I was successful in taking sharp pictures of dragonflies and butterflies with a 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.

The overall focal length, *OFL*, of the lens+filter combination is given by the following relationship:

$$OFL = \frac{F \times F'}{F + F'}.$$

Let's consider a 200 mm lens with a Nikon 4T close-up lens. The focal length, F', of 4T (2.9 diopters) is 1000/2.9 = 345 mm. Therefore

$$OFL = \frac{F \times F'}{F + F'} = \frac{200 \times 345}{200 + 345} = 126.6 \text{ mm}.$$

When the lens if focused <u>to infinity</u>, $t = F = 200$ mm; therefore

$$R = \frac{t}{OFL} - 1 = \frac{200}{126.6} - 1 = 0.58 = 1{:}1.7.$$

This magnification value is also given by the *F/F'* ratio. In fact, 200/345 = 0.58.
Again, we can evaluate the focusing distance:

$$\mathrm{D} = 127 \times \left(\frac{1}{0.58} + 0.58 + 2\right) = 546 \text{ mm} \approx 0.5 \text{ m}.$$

If we attach the same close-up lens to a 105 mm, with focus set to infinity, we obtain

$$OFL = \frac{F \times F'}{F + F'} = \frac{105 \times 345}{105 + 345} = 80.5 \text{ mm}$$

and

$$R = \frac{t}{OFL} - 1 = \frac{105}{80.5} - 1 = 0.304 = 1{:}3.3.$$

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

$$OFL = \frac{F \times F'}{F + F'} = \frac{105 \times 667}{105 + 667} = 90.7 \text{ mm}$$

and

$$R = \frac{t}{OFL} - 1 = \frac{105}{90.7} - 1 = 0.157 = 1{:}6.3.$$

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 (two-element close-up filter, $F' = 500$ mm) to the AF ED 80-200/2.8 D zoom and the AF Sigma 300/4 Apo Tele Macro. The results are summarized in the following table:

lens	Focus distance (m)	Focal length (mm)	*OFL* (mm) with 500D	*t* (mm)	R**	
80-200	∞	80	69	80	1:6.3	0.16
80-200	∞	105	87	105	1:4.8	0.21
80-200	∞	135	106	135	1:3.7	0.27
80-200	∞	200	143	200	1:2.5	0.40
300/4	∞	300	188	300	1:1.7	0.60
300/4	1.2	225*	155	300	1:1.1	0.91

* due to floating elements design of the AF Sigma 300/4 Apo Macro;
** 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 a Micro-Nikkor AF ED 200 mm f/4D at the *mfd*. With 50 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 maximum magnification of a macro lens. Question: which is the magnification we'll obtain by 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 the *mfd*? The overall focal length of the 200 (at *mfd*) + 5T combo is:

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

The estimated t value remains the same calculated previously: $t = 250$ mm. Therefore, the reproduction ratio is easily obtained: $R = t/F - 1 = 250/105 - 1 =$ 1.38 X. What about the *true* magnification? Fig. 5 shows the same millimeter rule as Fig. 3, but photographed with a 5T close-up lens coupled to the AF Micro-Nikkor 200/4 focused at the *mfd*:

Fig. 5 Image of the millimeter rule (APS-C reflex + AF ED Micro-Nikkor 200 mm f/4D + Nikon 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 (i.e., measured) one, being the difference a mere 2.3 %.

Depth of Field (DoF)

Depth of field refers to the range of perceived sharpness in any image, extending from a point in front of the subject to a point behind it. In "normal" photography of subjects at medium distances, the zone of acceptable sharpness extends roughly from one-third in front of the main point of focus, to two-thirds behind it. However, as the magnification of the subject increases, these relative proportions change. In close-up photography, the distances in front of and behind the main point of focus become equal, and we should focus on a point halfway into the subject.
Moreover, in close-up photography depth of field is easier to calculate being dependent on the following quantities only:

- the reproduction ratio, R;
- the aperture, f;
- the diameter, δ, of the circle of confusion.

Therefore, when somebody says "the DoF of a 50 macro is larger than the DoF of a 200 macro lens", don't believe him/her. As a matter of fact, the quoted sentence is correct when 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/sensor, the DoF is the same independently of the focal length of the lens we've used[2].

Framed area and DoF (in *mm*) as a function of aperture and reproduction ratio, *R*, for both APS-C (approximately 16×24 mm) and full-frame (24×36 mm) cameras.

R	24×36 Framed area (cm)	APS-C Framed area (cm)	**DoF** (*mm*) at various apertures (f)							
			8		**11**		**16**		**22**	
			24x36	APS-C	24x36	APS-C	24x36	APS-C	24x36	APS-C
1:5	12 × 18	8 × 12	16	10.6	22	15	32	21	44	29
1:4	9.6 × 14.4	6.4 × 9.6	10.6	7.1	14	9.3	20	13	29	19
1:3	7.2 × 10.8	4.8 × 7.2	7.3	4.9	10	6.7	15	10	20	13
1:2	4.8 × 7.2	3.2 × 4.8	3.2	2.1	4.5	3	6.4	4.3	8.8	5.9
1:1.4	3.4 × 5.0	2.3 × 3.4	1.8	1.2	2.5	1.7	3.6	2.4	4.9	3.3
1:1	2.4 × 3.6	1.6 × 2.4	1.1	0.73	1.5	1	2.1	1.4	2.9	1.9
1.4:1	1.7 × 2.6	1.1 × 1.7	0.65	0.43	0.9	0.6	1.3	0.9	1.8	1.2
2:1	1.2 × 1.8	0.8 × 1.2	0.4	0.27	0.5	0.3	0.8	0.5	1.0	0.67

The only difference in taking close-up pictures with a 50 mm or a 200 mm lens will be the angle of view (AoV, see next section). The quantitative relationship which correlates DoF with the above-mentioned quantities (i.e., R, f and δ) is:

[2] To calculate exactly the DoF, we should take into account the lens asymmetry, which is defined by the pupil magnification, *P*. If we consider *P*, we discover that telephoto lenses provide a slightly larger DOF than wide-angles! However, on a first approximation, and from a practical point of view, we can neglect the effect of *P*.

$$\mathrm{DoF} = \frac{\delta \times 2 \times f \times (R+1)}{R^2}. \quad [4]$$

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

$$\mathrm{DoF} = \frac{2 \times f \times (R+1)}{30 \times R^2}. \quad [5]$$

In this equation, DoF is given in mm.
The table above reports framed area and DoF values as a function of reproduction ratio, aperture, and sensor size (full-frame, 24×36 mm, or APS-C, 16×24 mm).

Angle of View (AoV)

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

$$\alpha = 2 \times \mathrm{arctg}\frac{x}{2 \times F \times (1 + R/P)}. \quad [6]$$

In Equation 6, x is the diagonal (mm) of the sensor/film (43.27 mm in the case of 24x36), and P is the pupil magnification, which measures the lens asymmetry[3]. If we assume that our lens has a symmetric design (this holds for 50-60 mm macro lenses), then

$$\alpha = 2 \times \mathrm{arctg}\frac{x}{2 \times F \times (1+R)}. \quad [7]$$

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

$$\alpha = 2 \times \mathrm{arctg}\frac{x}{2 \times F}. \quad [8]$$

The following table shows the variation of the AoV with the focal length and the reproduction ratio (assuming $P = 1$).

AoV as a function of focal length, reproduction ratio (R) and sensor size (24×36 or APS-C)

R	Angle of View (**AoV**), α							
	50 mm		90 mm		105 mm		180 mm	
	24×36	**APS-C**	**24×36**	**APS-C**	**24×36**	**APS-C**	**24×36**	**APS-C**
0 (focus to ∞)	47°	31°	27°	18°	23°	15°	14°	8.9°
1:10	43°	29°	25°	16°	21°	14°	12°	8.1°
1:5	39°	26°	23°	15°	19°	13°	11°	7.4°
1:3	36°	24°	20°	13°	17°	11°	10°	6.7°
1:2	32°	21°	18°	12°	16°	10°	9.1°	5.9°
1:1	24°	16°	14°	8.9°	12°	7.6°	6.8°	4.5°

The data show that at 1:1 the angle of view is about one half of that 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. Consequently, *i)* the angle of view does not change significantly when the lens is focused at close distances and *ii)* the set aperture remains constant from infinity to the closest focusing distance.

[3] $P = 1$ for symmetric design lenses, $P < 1$ for telephotos, $P > 1$ for wide-angle lenses designed for reflex cameras (i.e., wide-angles with retrofocus design).