Vignetting

People who arrived on this page through wikipedia, or otherwise wonder about the unorthodox terminology ... the terms "natural", "optical", "artificial", and "mechanical" vignetting, as well as the "cat's eye effect" have all been adopted from Ref. [1].

A photograph or drawing whose edges gradually fade into the surrounding paper is called a vignette. The art of creating such an illustration is a deliberate one. Yet the word vignetting is also used to indicate an unintended darkening of the image corners in a photographic image. There are three different mechanisms which may be responsible. Natural and optical vignetting are inherent to each lens design, while mechanical vignetting is due to the use of improper attachments to the lens. Natural and optical vignetting lead to a gradual transition from a brighter image center to darker corners. At large apertures both phenomena are present and the combined effect is often designated by the term "illumination falloff". Mechanical vignetting can also give rise to gradual falloff, although the usual connotation is one where it causes an abrupt transition with entirely black image corners.

Optical vignetting

Most photographic lenses exhibit optical vignetting to some degree. The effect is strongest when the lens is used wide open and will disappear when the lens is stopped down by a few stops. Together with natural vignetting, optical vignetting causes a gradual darkening of the image towards the corners. This illumination falloff often goes unnoticed but it may become disturbing when the subject has large faces with an even color or brightness. The contrast of the recording medium also plays a role: the higher the contrast, the more pronounced the effect. Figure 1 illustrates optical vignetting for a Carl Zeiss Planar 50/1.4 with an ever exciting subject like a brick wall. At full aperture the image reveals a 'hot spot': a brighter center and a darkening towards the corners (left photograph). When the lens is closed down to f/5.6, the light falloff has disappeared and an evenly illuminated wall remains (right photograph).

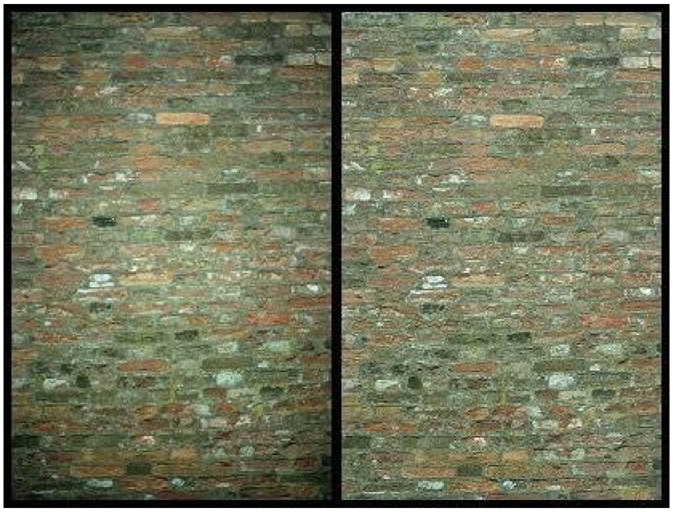

Figure 1. Optical vignetting with a 50/1.4 lens. Left: f/1.4. Right: f/5.6.

Optical vignetting is also known as artificial vignetting. Its origin relates to the simple fact that a lens has a length. Obliquely incident light is confronted with a smaller lens opening that a lens has a length. Obliquely incident light is confronted with a smaller lens opening than light approaching the lens head-on. In Fig. 2 the lens used to photograph the wall in Fig. 1 is shown at two apertures and from two viewpoints. The white openings in the top illustrations denote the entrance pupil, which is the image of the aperture stop seen through all lens elements in front of it and from a position on the optical axis. The entrance pupil is the clear aperture for light that approaches the lens from the front and ends up in the image center.

Figure 2. The Planar 50/1.4 at f/1.4 (left) and f/5.6 (right) seen from the optical axis (top) and from the semifield angle (bottom).

The bottom illustrations show the lens from the semifield angle. Here, the white openings correspond to the clear aperture for light that is heading for the image corner. At f/1.4 the clear aperture is markedly reduced compared to the on-axis case: the entrance pupil is partially shielded by the lens barrel. More precisely, the aperture is delimited by the rims surrounding the front and rear elements. A smaller aperture implies that the lens collects less light for off-axis points than for on-axis points and hence that the image corners will be darker than the image center. At f/5.6 the entrance pupil is much smaller and no longer shielded by the lens barrel. Consequently, obliquely incident light sees the same aperture as normally incident light and there is no optical vignetting.

Cat's eye effect

The consequences of optical vignetting for a subject that is in focus (cf. Fig. 1) is merely a reduced brightness towards the image corners. However, optical vignetting can also have a pronounced effect on out-of-focus parts of the image. Because the shape of an out-of-focus highlight (OOFH) mimics the shape of the clear aperture, the bottom left situation of Fig. 2 leads to the so-called cat's eye effect [1]. Figure 3 evidences the resemblance between the appearance of OOFHs and the aperture shape. With an increasing distance from the optical axis the shape of the OOFH progressively narrows and starts to resemble a cat's eye. The larger the distance from the image center, the narrower the cat's eye becomes.

Figure 3. The cat's eye effect. The rectangular area indicated by the dotted white line is shown enlarged at the bottom. (Photograph by Peter Boehmer.)

The cat's eye effect is readily observed in an SLR viewfinder. Just inspect distant street lights with the lens set at close-focus. By judging the narrowness of the cat's eye with an OOFH in the image corner it is possible to estimate the amount of optical vignetting. If the lens is stopped down the aperture where optical vignetting disappears may also be visually found. For instance, the Planar 50/1.4 is almost completely cured at f/2.8.

Optical vignetting tends to be stronger in wideangle lenses and large aperture lenses, but the effect can be noticed with most photographic lenses. Zoom lenses are often saddled with a fair amount of optical vignetting. Oversized front or rear elements help to reduce this type of vignetting and are frequently applied in wideangle lens designs. At any rate, the given speed of a lens always refers to the on-axis case; the full aperture for off-axis objects is smaller.

Natural vignetting

Natural vignetting, more properly termed natural light falloff, is inherent to each lens design and becomes more troublesome for wideangle lenses. It is associated with the famous $\cos^4$ law of illumination falloff. Contrary to popular belief, the argument for this law is not measured in object space but in image space. It is measured at the rear end of the lens as the angle at which the light impinges upon the film.

To illustrate natural vignetting and to point out differences between lens designs at the same time, I consider two examples. While rangefinder wideangle lenses tend to be better corrected than their retrofocus competitors, in particular for curvilinear distortion and lateral color, they also have the disadvantage of persistent light fall-off. Two contemporary wideangle designs are shown in Fig. 4: the Carl Zeiss Distagon 21/2.8 and the Carl Zeiss Biogon 21/2.8. The top design is an asymmetrical retrofocus lens for Contax SLR cameras (and all that to give way to the mirror!), the bottom lens is a symmetrical design for use on the Contax G rangefinder cameras. The black bars indicate the actual position of the variable leaf diaphragm (the aperture stop), the red bars indicate the exit pupil, which is the image of the aperture stop that an observer sees when he looks into the lens from the rear. The exit pupil serves to illuminate the film and delineates the light cone received by a point on the film (Fig. 5).

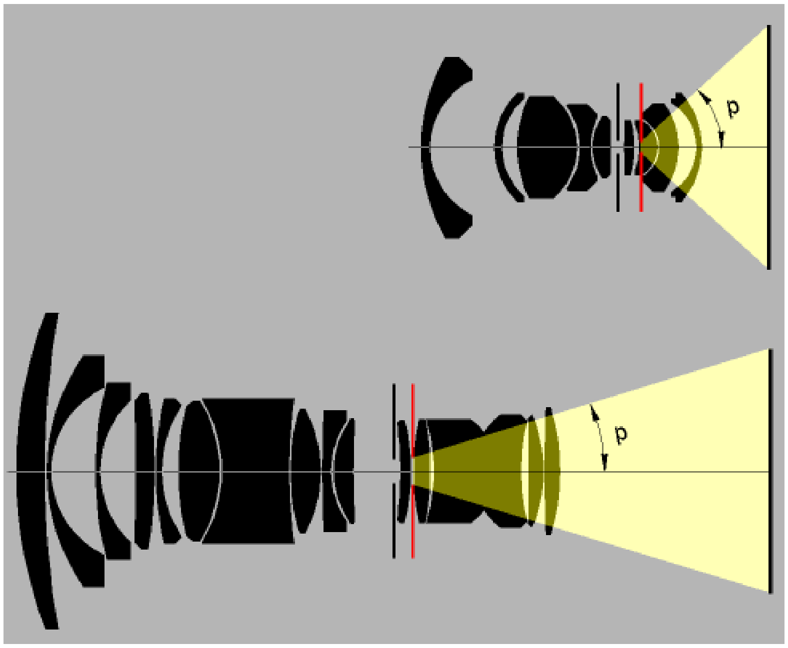

Figure 4. Image illumination in relation to the position of the exit pupil for two 21/2.8 lenses. Top: the retrofocus Distagon 21/2.8 design. Bottom: the Biogon 21/2.8 rangefinder design. The angle *b* differs between the designs.

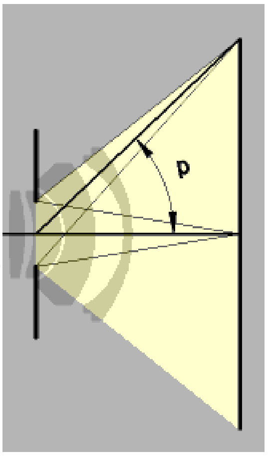

Figure 5. The $\cos^4$ law explained for the Biogon.

Whereas the exit pupil of the rangefinder lens is separated from the film by approximately its focal length, the exit pupil of the retrofocus design is pushed away from the film with the glass. Thus, from the yellow cones illuminating the film, the angle *b* is significantly larger for the Biogon than for the Distagon. It is this angle that is most important for the $\cos^4$ law. An enlargement of the Biogon rear end is found in Fig. 5. Two cones are indicated, one to illuminate a point on the optical axis (image center) and one to illuminate an off-axis point (image corner). Compared with the image center, the corner illumination is less for three reasons. First, there is a $\cos^2(b)$ factor due to the inverse square law: the light has a longer way to travel to the image corner. Second, the pupil seen by the off-axis point is not round but elliptical and has a smaller area than the round pupil seen by the image center. This yields another $\cos(b)$ factor. Note however that this cosine factor is approximate. It needs refinement when the pupil diameter is not small compared to its distance from the film [2]. Third, while the light hits the image center at normal incidence, it strikes the image corner at the angle *b*. This yields another $\cos(b)$ factor. The last effect relates to Lambert's law and can be compared with a late afternoon sun which heats the earth less than the sun at noon because the same beam of sunlight is spread over a larger area. The combined effect of all cosine factors is a $\cos^4$ illumination falloff towards the image corners.

It is remarked that the $\cos^4$ law is not truly a law but rather a combination of cosine factors which may or may not be all present in a given situation.

Although the $\cos^4$ law is indeed better applied to image space than object space, for many (but not all) lenses good agreement between theory and practice is actually found by taking one cosine in object space and three cosines in image space. The single cosine in object space then accounts for the amount of light collected by the lens. If one presumes that all collected light is also projected on the film (conservation of energy), this one cosine replaces the second of the abovementioned factors. The resulting $\cos^4$ law then reads $\cos(a)*\cos^3(b)$, where *a* denotes the angle in object space. Significant departures from this law arise when lens designers use the Slyusarev effect [1] to increase the apparent size of law arise when lens designers use the Slyusarev effect [1] to increase the apparent size of one or both pupils for off-axis points. This may result in a dramatic improvement of the image illumination.

The angle *a* is the same for both 21-mm lenses, but since the angle *b* differs between the Distagon and the Biogon it is expected that the image illumination will differ between the two lenses. Indeed, there is a considerable difference: Fig. 6.

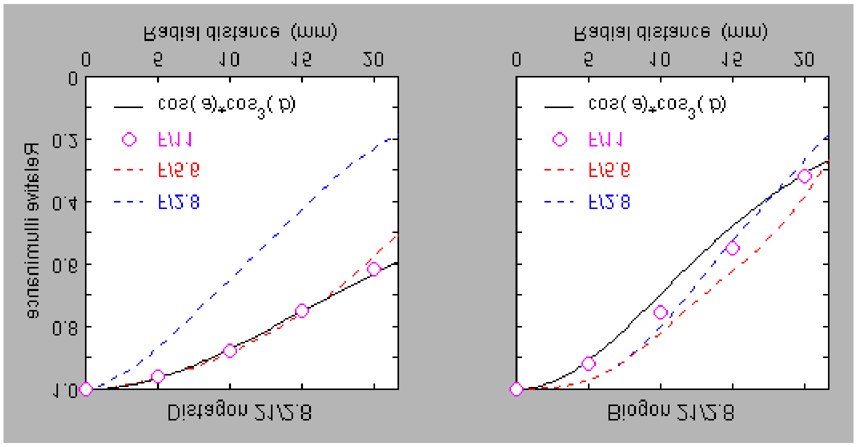

Figure 6. Illumination charts for the Distagon 21/2.8 and the Biogon 21/2.8 (Zeiss data).

In an illumination chart the curves are given relative to the image center. I.e, the image center illuminance is 1.0 and the illuminance at other points is given as a fraction relative to the image center. At full aperture both designs have a corner illuminance of 0.2, which means that the image center receives five times the amount of light the image corner receives. This will certainly be noticed in photographs which include a blue sky or the brick wall of Fig. 1. Upon stopping down the lenses, the Distagon image illumination improves drastically. At f/11 the corner is only 0.8 stops darker than the center. The Biogon illumination however does not improve that much, the corner illumination remaining 1.8 stops behind the center. A full-stop difference remains between the corner illuminations of the two designs. The difference is that the Distagon suffers mostly from optical vignetting at full aperture and benefits from a smaller aperture. The Biogon on the other hand suffers primarily from natural vignetting, which is not cured by a smaller aperture. Figure 6 also shows the $\cos^4$ curves for both designs. There is an excellent match for the Distagon at small apertures. By contrast, the Biogon illuminance is close to its $\cos^4$ curve at all apertures.

Mechanical vignetting

When mechanical extensions to a lens protrude into its field of view, the image corners receive less light than they would in the absence of the extension and vignetting occurs. The extension can be too long a lens hood, stacked filters, or a combination. The hood and/or filters obscure the entrance pupil from obliquely incident light and the remedy is obvious: use proper accessories. A single, thick filter can already vignette a wideangle lens so it pays to check on vignetting behavior before filters and lens hoods are purchased.

Figure 7. A typical case of mechanical vignetting. (Distagon 28/2 @ f/11 + Contax metal hood #3)

Figure 7 illustrates a typical case of mechanical vignetting. The image was taken with the Distagon 28/2 equipped with Contax metal hood #3, which is simply too long for this lens. A graphical explanation is given in Fig. 8. With the Distagon used at f/11 and infinity, an image corner relies for its illumination on the orange ray pencil, which comes from infinity heading towards the entrance pupil (in red). The angle with the optical axis is the semifield angle, which amounts to 37 degrees. In the absence of a hood the oblique ray pencil has full access to the entrance pupil, but in the presence of the hood the entrance pupil is invisible to this pencil. The pupil is eclipsed by the hood and the image corner receives no light at all. A comprehensive discussion on mechanical vignetting is found on the lens hood page.

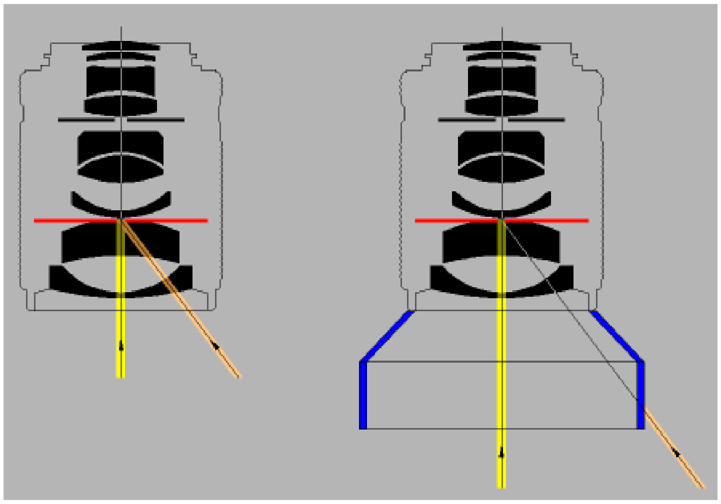

Figure 8. The Distagon 28/2 without and with Contax metal hood #3. The oblique ray pencil is blocked when the hood is attached.

Note that Fig. 8 does not show refraction of the pencils. For mechanical vignetting it suffices to consider the entrance pupil and obstructions in front of the lens. Refraction is indirectly taken into account by the position and size of the entrance pupil (Zeiss data). However, the pencils are drawn correctly outside the lens.

Remedies

Three causes of dark image corners have passed in review. Optical vignetting is due to the dimensions of the lens: off-axis object points are confronted with a smaller aperture than a point on the optical axis. The remedy is to stop down the lens. The darkening noticed at full aperture already improves greatly when the lens opening is decreased by one stop. A

complete cure often requires two or three stops—depending on the design. The darkening that remains at small apertures is due to natural vignetting. Natural vignetting is not cured by stopping down the lens. Lenses which strongly suffer from natural vignetting benefit from a gradual gray filter which is dark in the center and brighter towards the corner. Finally, mechanical vignetting is due to extensions attached to a lens. The image corners may become completely black and the photographer can only blame himself as he should use proper accessories.
All types of vignetting are at their worst with the lens focussed at infinity. At close focus the field of view decreases and the size of the image circle increases. The vignetted area is pushed outward with the image circle and when the focus is close enough the optical or mechanical vignetting will be outside the film frame (or digital sensor). As a matter of fact, it is optical vignetting that determines the size of the image circle in the first place. Natural vignetting improves too, since the exit pupil moves away from the film (at least, with most lens designs).

It should be mentioned that vignetting is not always a bad thing. A lens designer can deliberately introduce vignetting in favor of a better control of aberrations, sacrificing field coverage for overall contrast and sharpness. Moreover, the vignetting effect can be used artistically to draw the attention away from the image periphery and to emphasize the subject.

References

[1] Sidney F. Ray, Applied photographic optics, 3rd ed., Focal Press (2002).
[2] Warren J. Smith, Modern optical engineering, 3rd ed., McGraw-Hill (2000).

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