Sharpness in the Darkroom

Maximum resolution from corner to corner

The essentials to make the sharpest prints in a darkroom setup are well known and documented in many good photographic texts. It is surprising, therefore, that such simple advice is all too often ignored in the many darkrooms we have visited. Our recommended practices are compiled and explained here, including measured discussion on some of the myths of focusing.

Enlarger Stability

It goes without saying that the enlarger must not wobble during the exposure. Objects can only wobble if they are unnecessarily provoked or not sufficiently constrained. If you have a permanent darkroom setup, our advice is to remove the column from the baseboard and rigidly mount it to the wall, as shown in fig.1.

This isolates the enlarger from floor and table vibrations, and enables vertical column adjustment to level the enlarger head. Wall-mounting brackets are available from some enlarger manufacturers and independent retailers. Alternatively, mount the baseboard column bracket to a rigid wall-mounted shelf, and fix the top of the column to the wall with a homemade bracket. Another benefit from using a wall-mounted enlarger is the ability to lift the column upwards and outwards, so a large printing easel fits under the column for big enlargements. A wall-mounted column must be adjusted using a small spirit level, so that the negative plane is horizontal, both side to side and front to back, as shown in fig.2. Having set up the enlarger, check the rigidity of the setup by observing the stability of the projected image with a grain magnifier.

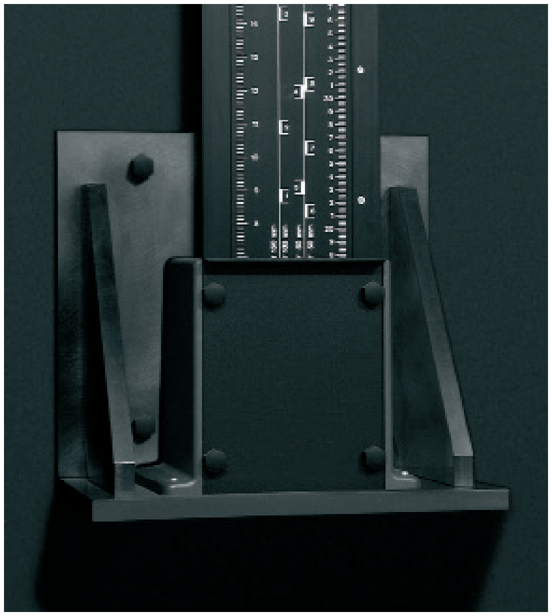


fig.1 (right) This professional Durst L1200 enlarger is wall-mounted through an aluminum bracket, which supports the enlarger's weight and isolates the column from vibration.

fig.2 (far right) A spirit level is used to check the vertical alignment of an LPL enlarger column.

During the exposure, minimize the excitation of the enlarger and baseboard, especially if you are unable to wall-mount the column. If you touch the enlarger, wait for the vibrations to settle down before making an exposure, and then, be careful not to move about or touch the base unit or the table it stands on. Also, if you enjoy listening to music while working in the darkroom, make sure that the speaker boxes are not on the same table as the baseboard. Even heavy outside traffic and nearby railway lines have been known to cause problems. If you have a darkroom timer with a foot switch, use it like a cable release.

Film Flatness

Film does not lie flat naturally. Heat, storage conditions and humidity all affect its natural curl. In the same way that a camera requires the film to be flat, so do enlargers. Glassless negative carriers do not keep the film flat. Fig.3 shows the reflection of a window frame from the film surface, which indicates how difficult it is to keep 35mm film flat in a glassless negative carrier. The problem increases with larger negatives on medium and large-format film.

We cannot rely on the depth of focus to compensate for film unevenness and secure perfect sharpness, because the room for permissible error is just too small (see fig.12). To make matters worse, as the negative warms up in the light path, it pops just as a transparency does in a slide projector. In order to ensure maximum sharpness, the film must be held absolutely flat during projection. We recommend printing the film with the emulsion side down in a negative carrier, which sandwiches the film between two sheets of glass. The extra effort of keeping the four additional glass surfaces dust-free, to avoid unreasonable print spotting, is well worth the results. Nevertheless, to keep unsightly color fringes from forming concentric rings of irregular shape between film and glass (Newton's rings), use a specially etched anti-Newton glass on top of the film, towards the shiny film base. Usually, you can use clear glass on the other, matt emulsion side of the film. However, some films, such as Ilford XP2 and the now discontinued Agfa APX25, have a very smooth emulsion side. With these films, Newton's rings can still occur between the clear glass and emulsion side of the film. If you use this type of film, remove the glass from the bottom altogether, and keep only the anti-Newton glass on top of the film.

Enlarger Alignment

Accurate enlarger alignment is one of the less obvious requirements for sharpness in the darkroom. A misaligned enlarger does not have the baseboard, film and lens planes perfectly parallel. This is evident in the projected image as unequal grain sharpness from one corner to the next. Precise enlarger alignment can be achieved with a simple spirit level, and this method will satisfy all but the most discerning users. However, some enlarger designs prevent convenient spirit level access to film or lens plane, requiring more sophisticated alignment technology.

Using a Spirit Level for Alignment

With the help of a spirit level, the paper, lens and negative planes are adjusted until they are horizontal and as parallel as possible.

1) The easel surface is made horizontal, both back-to-front and side-to-side, either by adjusting the feet or the entire table, possibly using spacers.
2) The wall-mounted column is adjusted vertically, side-to-side and front-to-back, so the negative stage is horizontal front-to-back, as seen in fig.2. In some cases, the customary holes for wall-mounting screws may need to be filed into slots, to enable adjustment of the top and bottom column brackets.
3) Assuming the enlarger head has a tilt feature, adjust it so the negative stage is horizontal, side-to-side. If the head is fixed, then the column will need further adjustment to counteract the error.
4) Lastly, the spirit level is held against the front face of the enlarging lens and the lens stage is leveled, either by the available adjustments or by inserting a spacer into the mechanism.

fig.3 This close-up of a glassless 35mm negative carrier clearly indicates an uneven film surface, seen in the reflection of a nearby window frame.

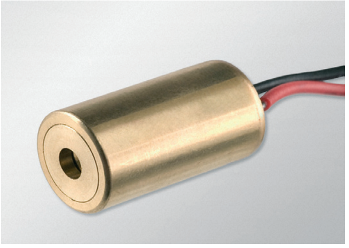


fig.4 A small laser module can be bought from any electronic shop for the price of a few films. To turn it into a self-made laser alignment tool, a housing with a leveling feature has to be made, and the leads have to be connected to a power supply. A detailed technical drawing for a potential implementation is found under 'Tables and Templates' in the appendix.

Constructing a Laser Alignment Tool

A simple laser module can be bought for the cost of a few rolls of film from any good electronic shop (fig.4). With a little ingenuity, it can be fashioned into a useful alignment tool by gluing it into a machined metal cylinder, which in this case was manufactured according to the sketch in fig.5a. Three tapped holes were added to the base of the cylinder to accept small adjustment screws, which assure the laser beam is perfectly vertical when the housing is placed on a horizontal surface. The screws level the laser alignment tool, using the following procedure:

Place the laser alignment tool on the baseboard, and use two heavy objects to form a corner, so that when the alignment tool is rotated, while being pushed into the corner, the center of the laser remains in a fixed position. As the tool is turned, note the position of the laser beam on the ceiling, using some masking tape and a pen. Initially, the laser will trace out a small circle. Turn one or two of the adjustment screws, until the beam aims at the center of this circle. When the adjustment is accurate, the red light spot appears stationary during rotation of the tool. Having calibrated the laser alignment tool, the screw positions can be fixed with a little varnish.

Using a Laser Alignment Tool

If you prefer a professionally made enlarger alignment unit to the self-made variety, we recommend that you check into the 'zig-align' system or the 'Parallel' alignment gage made by Versalab. They can be purchased for the price of a good enlarging lens.

It is sensible to start the laser alignment process with a previously leveled easel and a vertically aligned column. Turn the laser on, making sure to never point it at someone's eyes, and adjust negative and lens stage in sequence as follows, while judging the results according to the instructions in fig.6.

1) Raise the enlarger head to the top of the column and lock it as you would during normal operation. Remove the enlarger lens, and place the laser alignment tool directly beneath the opening just created. Adjust the negative stage until the laser beam's reflection from the negative-carrier glass aims back at the laser exit hole as closely as possible.
2) Return the enlarger lens, and with a filter fitted to its attachment ring or a piece of glass just held against its front surface, adjust the lens stage until the laser beam reflects back on itself, which indicates that it is parallel to the baseboard.

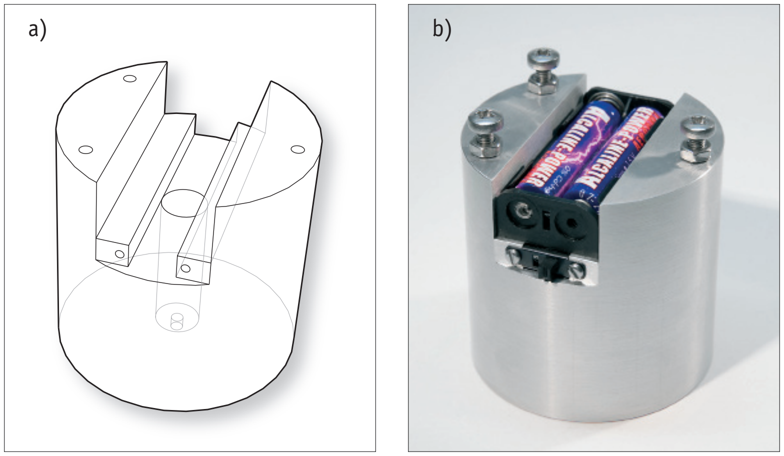


fig.5a&b With some ingenuity and help from a local machine shop, a self-made laser alignment tool is brought from concept to reality. Three adjustable screws level the unit and align the laser module until it projects a perfectly vertical laser beam.

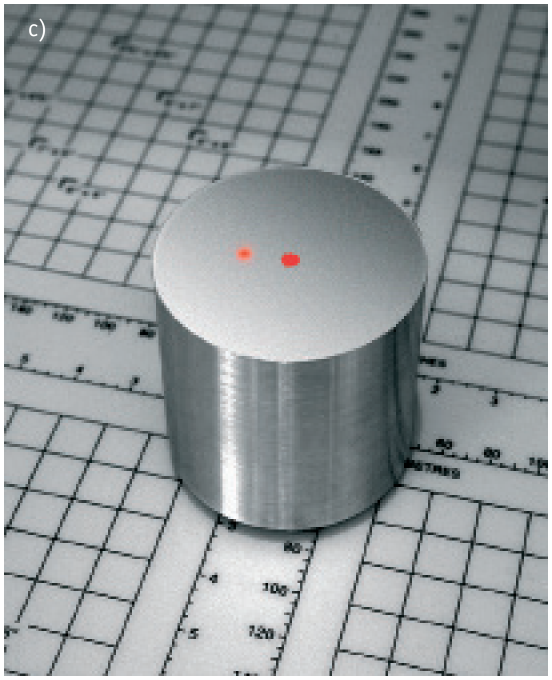


fig.5c The finished laser alignment tool is leveled on the baseboard and placed directly under the enlarger. The laser is then made to reflect off the negative carrier and the lens plane. The location of the reflected laser beam is a measure of misalignment.

Centering the Lens

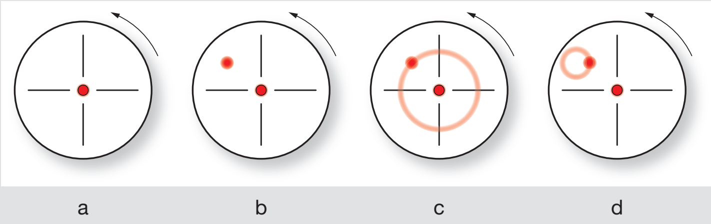
Whichever alignment method you use, it is essential to check that the lens axis is centered in the negative area. To do this, take a fogged negative leader, the same format as your negative carrier, and scratch in two diagonal lines to locate the middle. Center and project this negative on to the easel. Mark the intersection on the easel, and check that this point does not travel across the easel as the head is moved up and down the column. Use the horizontal adjustment mechanism on the lens stage to centralize the lens. After any adjustment, confirm the lens alignment with a spirit level or the laser alignment tool.

Enlarging Lens

It is pointless to use the best camera lens if the print is let down by a poorly performing, cheap enlarging lens. There are many manufacturers of quality optics, Nikon, Schneider and Rodenstock to name but a few, and excellent used Leica and Minolta lenses are available. As with many products, the purchase price is an indicator, but not a guarantee, of the quality of a particular enlarging lens. However, you can minimize the risk by selecting a name-brand, high-quality, six-element, multi-coated lens. This is most likely to ensure high performance in the 4-12x range of enlargements. Nevertheless, several authors have reported that manufacturing tolerances within a brand can vary more than from brand to brand. It is a big advantage, therefore, to buy your lens from an understanding dealer, who lets you check its performance against others.

The optical performance of any lens changes with aperture. Enlarging lenses are no different. An optimum aperture is the best compromise between overall resolution, even illumination and exposure time. For many lenses, the optimum aperture is between f/5.6 and f/11. Keen observation, and some trial and error, will determine your ideal setting for each lens. Having found your ideal setting, try to use this aperture for all your printing, rather than using a constant printing time. After aligning the enlarger, your prints should be grain sharp, in the middle and equally at each corner. At the same time, a print made without a negative in the carrier and printed mid-gray on high-contrast paper should confirm even illumination.

If you use small-format negatives and enlarging lenses in a large-format enlarger, it is critically



To judge the enlarger alignment, rotate the laser and watch the reflected beam. The examples above illustrate how you can tell if the enlarger is out of alignment or if the laser beam is just not perpendicular to the baseboard.

a) The reflected beam stays centered on the target. This indicates that the laser is perpendicular, and the reflecting surface is parallel to the baseboard.
b) The reflected beam is not on center, but it does not move as the laser is rotated. This indicates that the laser is perpendicular, but the reflecting surface is not parallel to the baseboard.
c) The reflected beam is not on center, but it creates a concentric circle around the target as the unit is rotated. This indicates that the laser is not perpendicular, but the reflecting surface is parallel to the baseboard.
d) The reflected beam is not on center and it follows a circular path not centered on the target. This indicates that the laser is not perpendicular, and the reflecting surface is not parallel to the baseboard. If the laser is adjusted closer to perpendicular, the circular path will get smaller until it matches condition ‘b’. If the reflecting surface is aligned to be more parallel to the baseboard, the path of the beam will become concentric with the laser orifice and eventually approaches condition ‘c’.

Good enlarger alignment is indicated by condition ‘a’ and ‘c’.

fig.6 (top) There is an easy way to tell if the enlarger is out of alignment, or if the laser beam is simply not perpendicular to the baseboard.
(text & illustration by Dale H. Marsh)

fig.7 (left) The purchasing price of a particular enlarging lens is an indicator, but not a guarantee, of its quality. However, you can minimize the risk by selecting a name-brand, high-quality, six-element, multi-coated lens.

fig.8 Although this picture of Chris's daughter, Katie, is taken at full aperture with the Fuji 680 and, consequently, has a shallow depth of field, it requires corner-to-corner sharpness to ensure crisp grain over the entire print.

important to place the negative centrally in the negative carrier. The enlarging lens is designed for a certain maximum coverage and the illumination and sharpness degrade quickly outside these boundaries. In our enlargers, we use a film format template, cut from thin black plastic, which we place on the negative carrier's top glass. It was made such that the outer dimensions snugly fit inside the glass frame's inner edges. Once the outer dimensions of the template are trimmed, slightly oversized negative dimensions are centralized and cut out with a sharp knife.

Paper Flatness

Fiber-base papers, and, to some extent, resin-coated papers, suffer from curl and unevenness. We have observed the curl of a piece of paper changing, when placed unrestricted on a flat surface and left to relax for a minute, as it adjusts to the humidity and temperature of its new surroundings. These movements can cause a loss of sharpness, especially towards the borders of the print, as the horizontal creep during the exposure blurs the image. However, a two or four-blade easel holds down the paper satisfactorily. To make borderless prints, simple side restraint easels suffice. If you do not use an easel, attach double-sided, low-tack adhesive tape directly to the baseboard. The tape is applied to the baseboard, and the print is pressed slightly against the tacky surface. This tape has a similar adhesive quality to the one used on 3M 'Post-it' notes, and, although tacky, it does not damage the print when lifted off the baseboard.

However, as long as the paper lies still, there is no need to be overly concerned about paper flatness. Depth of field covers a significant distance at the baseboard, especially with small film formats. An 8x10-inch enlargement, projected at a working aperture of f/8, from a full 35mm, 6x6 and 4x5 negative will have a depth of field of 28, 17 and 9.3 mm, respectively (see fig.12). This should disprove the myth that a single piece of photographic paper, with a thickness of just 10 mil (0.25 mm) and placed under the focus finder, will improve accurate focusing and print sharpness.

Accurate Focusing

Our prints have often been complimented on their excellent sharpness, and yet, our darkroom procedures are common and simple. We just focus the image at full aperture using white light, and then, stop down to the working aperture before printing. Since our results are of high quality, there was really no need to explore other alternatives. Nevertheless, while researching for this book, we uncovered a volume of opinion on numerous effects claiming to cause focusing errors, with considerable disagreement between authors. Out of interest, we have evaluated the significance of some of these effects, including ultraviolet paper sensitivity, focusing with filtered light and focusing at the working aperture.

Ultraviolet Paper Sensitivity

Ultraviolet radiation has a wavelength below 380 nm, and although enlarging lenses transmit this radiation, they are rarely corrected for the chromatic aberration below 400 nm. The data sheets from Agfa, Ilford and Kodak indicate that the spectral sensitivity of their B&W papers extends well into the ultraviolet range.

Consequently, ultraviolet radiation reduces print sharpness, since the paper is sensitive to it, and the lens is not corrected for it. An ultraviolet filter (1A) has a transmittance of only 1% below 380 nm. This filter, placed below the enlarging lens, yields a sharper print but reduces the effective print exposure, if ultraviolet radiation is present in significant quantities.

In practice, the insertion of an ultraviolet filter into the, otherwise unfiltered, light path of a tungsten-halogen enlarger made no detectable difference to an Agfa Multicontrast RC print, neither in print density nor in sharpness. The conclusion that the tungsten bulb emits no significant quantities of ultraviolet radiation was confirmed by the bulb manufacturer's data sheet. A cold cathode head, whose light source uses fluorescent materials, is blue and ultraviolet rich, and therefore poses a greater potential problem. The use of an ultraviolet filter, in this case, may greatly reduce the effective exposure to UV radiation. Unfortunately, each lens, paper and enlarging light system may have its own unique focus error, ranging from minuscule to significant. Comparing two prints made with and without the use of a UV filter will identify whether you need to take corrective actions.

Focusing with Filtered Light

Patrick Gainer wrote an article titled 'Hazards of the Grain Focuser' for *Photo Techniques* Jan/Feb 1997, which explained the chromatic aberrations of the enlarger, an aerial grain focuser and the human eye. His thorough investigation used a simple series of optical experiments to clearly show the inability of the human eye, enlarger lens and the grain focuser to focus at several wavelengths simultaneously.

We repeated these experiments and arrived at similar conclusions. The expectation that optimum focusing occurs only if we focus with contrast filters in place was disproved. We found that focusing with different contrast filtration made little difference to print sharpness, and prints from 10x enlarged negatives could only be distinguished with an 8x loupe. In fact, the ability of any individual to focus consistently is more of an issue than the choice of filtration.

Some grain focusers (fig.9) provide a blue filter to focus only on the wavelength of light most sensitive to the paper. Unfortunately, the human eye is not very sensitive to blue light and the resulting image is dim and difficult to see. In our tests, this method suffered the maximum human focus variability. Patrick Gainer's simple recommendation is to focus without contrast filters in place, and we agree that print focusing is best done with the unfiltered white light of the enlarger. This does not constitute any additional effort, because enlarger light metering must be done without contrast filtration anyway. Nevertheless, critical print sharpness is more likely to be affected by vibration, film flatness and enlarging lens quality than filtration.

Focusing at the Working Aperture

Another popular 'tip' is to focus at the working aperture of the enlarger lens. As the lens is stopped down, the optical aberrations of the lens, and therefore, its sharpness, improves down to the aperture at which the lens performance is diffraction limited. The assumption is that the best focus is obtained with the sharpest projected image. In addition, a low quality lens may suffer from focus-shift, where the focal length of the lens slightly changes with aperture.

A practical test, using any of our high-quality, six-element lenses, showed that there was no repeatable difference between focusing at full aperture or at the working aperture of f/8. However, as with the dark

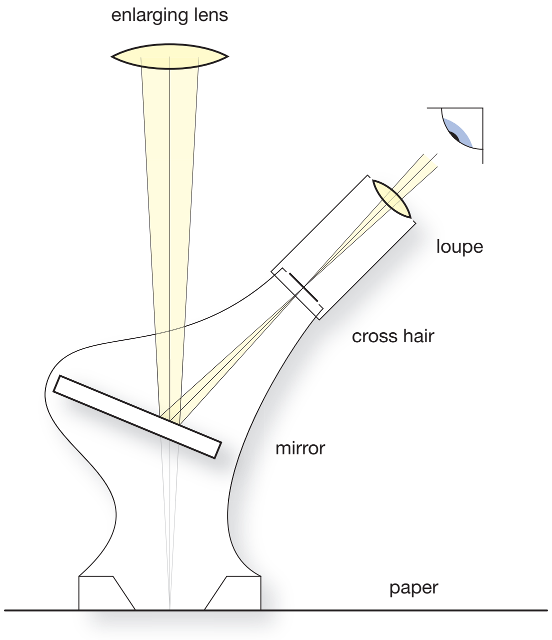
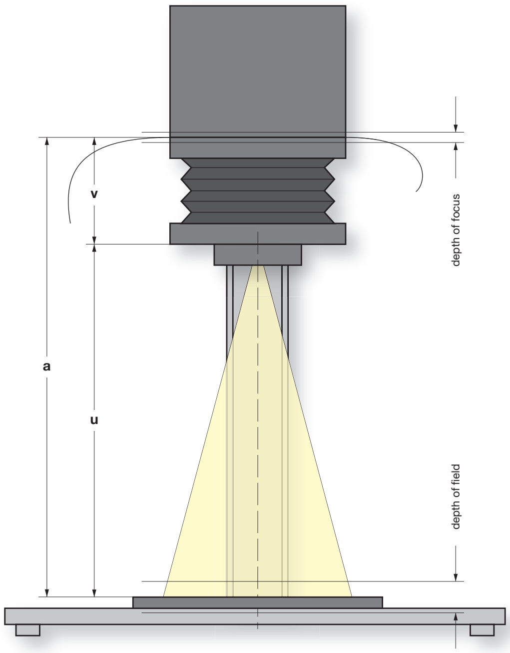


fig.9 Focusing aids compare the aerial image reflected from a mirror with a built-in cross hair. The cross hair is in a fixed position so the length of the light path from negative to cross hair is the same as that from negative to easel. The cross hair is brought into sharp focus by adjusting the loupe, and then, the image is brought into sharp focus by adjusting the enlarger.

fig.10 (right) As there is a zone of reasonable focus surrounding the paper plane, known as the depth of field, there is an equivalent zone of reasonable focus surrounding the negative plane, called the depth of focus.



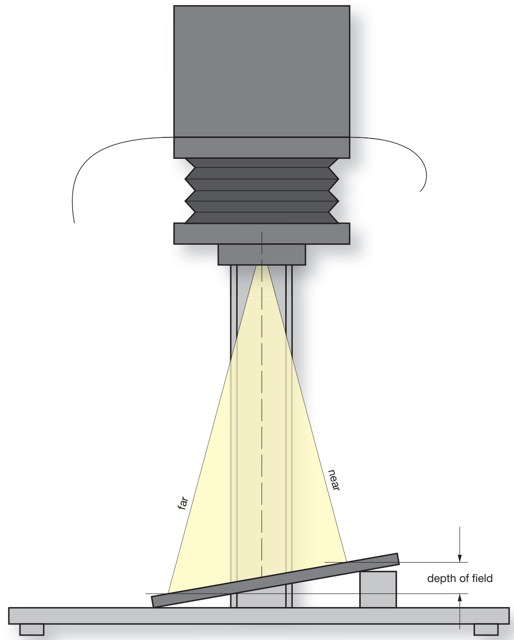


fig.11 (far right) Taking advantage of the depth of field, minor perspective distortions can be corrected through a baseboard lift without losing reasonable sharpness.

format	depth of focus [mm]				depth of field [mm]			
24x36 c = 0.022	4	5.6	8	11	4	5.6	8	11
8x10	0.2	0.3	0.4	0.5	14	20	28	39
11x14	0.2	0.3	0.4	0.5	27	37	53	73
16x20	0.2	0.3	0.4	0.5	53	75	110	150
6x6 c = 0.042	5.6	8	11	16	5.6	8	11	16
8x10	0.6	0.8	1.1	1.6	12	17	23	33
11x14	0.5	0.8	1.1	1.6	22	31	42	62
16x20	0.5	0.7	1.0	1.5	43	62	85	120
4x5 c = 0.089	5.6	8	11	16	5.6	8	11	16
8x10	1.5	2.1	2.9	4.2	6.5	9.3	13	19
11x14	1.3	1.9	2.6	3.8	11	16	22	32
16x20	1.2	1.8	2.4	3.5	22	31	43	62

fig.12 depth of field and focus for several formats and f/stops

blue filter, it was difficult to focus the dim image consistently, and we concluded that it was more likely that this would cause the observer to introduce a focus variability. In addition, any minor focusing errors, still visible at full aperture, are easily lost in the depth of field at smaller working apertures.

Mural Prints

While many of the error mechanisms mentioned above cause little difference to effective print sharpness for small and medium enlargements, mural prints must be considered a special case. Focus and sharpness issues add up, and therefore, critical big enlargements require special care. By all means, conduct your own focus experiments, using different apertures, focus finders and test prints, to establish optimum working conditions. However, take every possible precaution with big enlargements to reduce enlarger vibrations to an absolute minimum.

Depth of Field and Focus

In the chapter 'Sharpness and Depth of Field' we illustrate how, when taking a photograph, the circle of confusion creates zones of reasonable focus around the subject and the film plane, called depth of field and focus, respectively. The sample principle creates similar zones around the negative and the paper plane when the image is projected by the enlarger (fig.10). In each case, the term 'depth of focus' is reserved for the film or negative side of the optical path, whereas the term 'depth of field' is commonly used for the subject or the projection side. The depth of focus ($d_{F'}$) and the depth of field (d_F) can be calculated as:

$$d_{F'} = 2 \cdot c \cdot N \cdot \; 1+\frac{1}{m}$$

$$d_F = 2 \cdot c \cdot N \cdot \; 1+\frac{1}{m} \; \cdot m^2$$

where 'c' is the circle of confusion, 'N' is the aperture of the enlarging lens in f/stops and 'm' is the print magnification of the enlargement. Fig.12 shows typical values, calculated with the equations above.

Both equations assume that the print magnification of the enlargement is already known, and it is good practice to document the printing scale with your printing records. The actual print magnification is simply found by cutting two notches, 1 inch apart, into the negative mask (fig.13) and measuring their projected distance on the baseboard with a ruler.

For the more mathematically inclined, print magnification (m) can also be determined from the basic dimensions of the enlarger setup and calculated as:

$$m = \frac{u}{v} = \frac{u}{f} - 1 = \frac{f}{v - f}$$

$$m > 1 = \frac{\left(\frac{a}{f} - 2\right) + \sqrt{\left(\frac{a}{f} - 2\right)^2 - 4}}{2}$$

$$m < 1 = \frac{\left(\frac{a}{f} - 2\right) - \sqrt{\left(\frac{a}{f} - 2\right)^2 - 4}}{2}$$

where 'u' is the lens-to-paper distance, 'v' is the lens-to-negative distance, 'a' is the total negative-to-paper distance, 'f' is the focal length of the lens, while 'm>1' calculations are meant for enlargements and 'm<1' for reductions. Strictly speaking, lens distances are measured to the nodal plane of the lens, but the center of the lens will suffice as a practical substitute.

For some photographic applications, it may be of interest to adjust the enlarger setup in order to produce a specified print magnification, and, in fact, the equations below are a reverse of the above formulae.

$$u = f \cdot (m + 1) = \frac{a + \sqrt{a^2 - 4 \cdot f \cdot a}}{2}$$

$$v = f \cdot \left(1 + \frac{1}{m}\right) = \frac{a - \sqrt{a^2 - 4 \cdot f \cdot a}}{2}$$

$$a = u + v$$

$$a = \frac{f \cdot (m + 1)^2}{m}$$

During in-camera focusing, the zone around the subject plane (depth of field) is commonly understood as a zone of reasonable sharpness and, therefore, as an extension to what theoretically is only a plane of focus. On the other side of the imaging path, the depth of focus at the camera's film plane is typically considered to be a tolerance band for mechanical focusing inaccuracies. While the former is true, the latter is not entirely the case. As seen in fig.14a, any focus inaccuracy at the film plane will take away from the depth of field, because any deviation from the theoretical film plane position will push subject detail, recorded at the threshold of sharpness, into defined fussiness.

Similar is true when enlarging the negative (fig.14b). Any subject point, captured at the threshold of sharpness, is recorded on the negative as a small fuzzy disc with the same diameter as the circle of confusion. During negative projection, this detail must line up exactly with the theoretical negative plane or the small disc will 'grow' beyond the boundaries of the circle of confusion and into obvious unsharpness.

Nevertheless, just as the depth of field provides a zone of sharpness around the subject plane when recording the subject on film, it also provides a zone of sharpness around the baseboard when projecting the negative with the enlarger. As seen in fig.11, this can be used to tilt the baseboard within limits, without losing reasonable sharpness, and allowing correction of minor perspective distortions in the negative. In practice, the image center is brought into focus at full aperture, and the lens is stopped down until the entire image appears to be in focus. You can use the table in fig.12 to estimate the available depth of field for several formats and apertures.

The Scheimpflug Principle

The Austrian cartographer and sea captain Theodore Scheimpflug (1865 - 1911) is credited with the discovery of the optical relationship, which now carries his name. If a camera is adjusted so the film, lens and subject plane intersect in a single line, then everything in the subject plane will be in perfect focus. View cameras can be adjusted to take advantage of the Scheimpflug principle, but cameras with fixed film and lens planes cannot. Therefore, any perspective distortion unavoidably becomes a permanent part of the negative and can only be corrected in the darkroom.

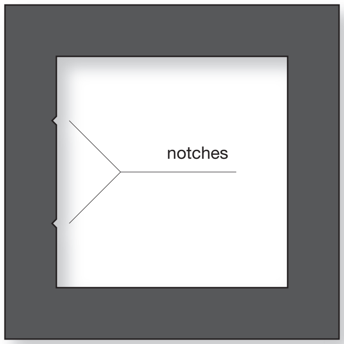


fig.13 The actual print magnification is simply found by cutting two notches, 1 inch apart, into the negative mask and measuring their projected distance on the baseboard with a ruler.

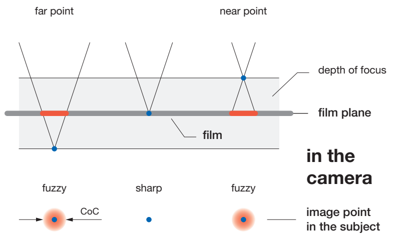


fig.14a Any subject point, captured on film at the threshold of sharpness, is recorded as a reasonably sharp fuzzy disc the size of the CoC.

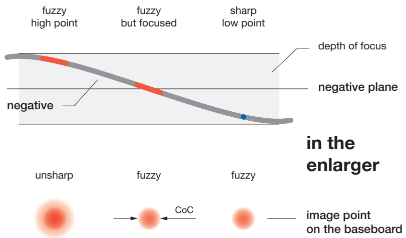


fig.14b Negative detail as large as the CoC must exactly line up with the theoretical negative plane, or it is not resolved in the print. Only perfectly sharp negative detail can benefit from the enlarger's depth of focus.

fig.15 Many enlargers allow only tilting of the lens plane, but with the help of a tilted easel, converging lines can be completely corrected using the Scheimpflug principle. This results into a projection geometry, which is identical to that of a fully adjustable enlarger, as seen in fig.17.

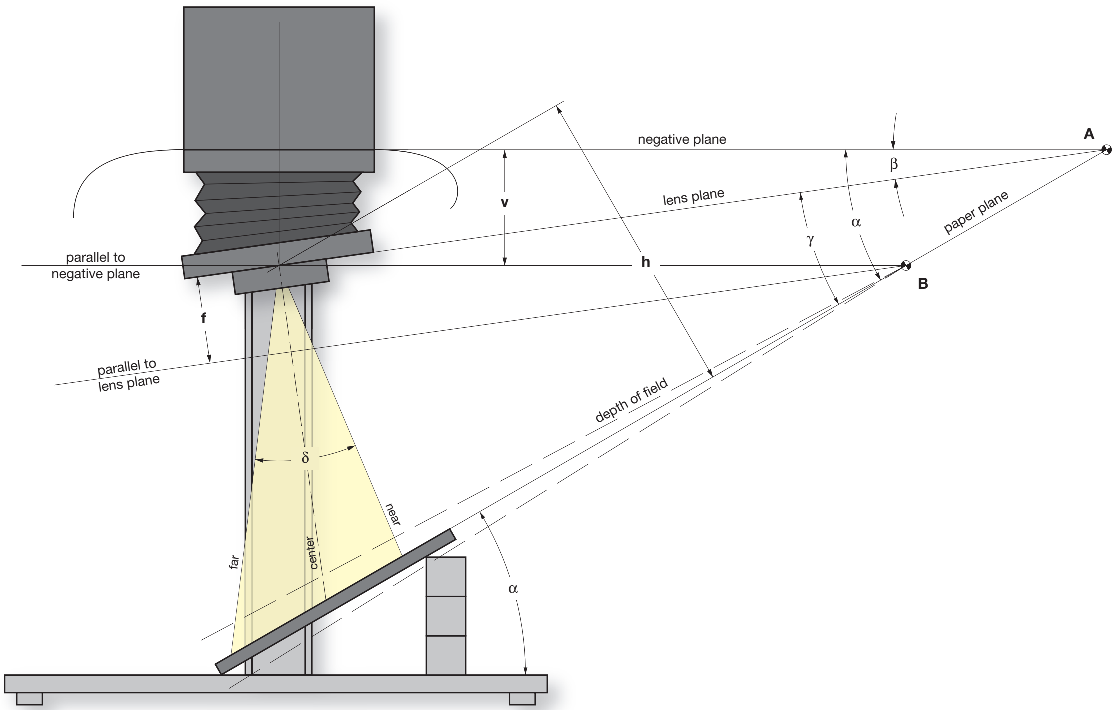


fig.16 This photograph of Ingatestone Church in Essex, UK was taken with a 35mm Canon SLR. In order to get the entire structure into the frame, the camera had to be pointed upwards, creating unwanted, but unavoidable, perspective distortion and converging lines, as seen in the straight print on the left. The corrected print on the right was made from the same negative, but the perspective distortion was corrected until the vertical lines of the church tower appeared to be parallel. In the upper half, the actual print was gradually burned-in to compensate for the exposure loss caused by the head tilt. (images by Paul Robbins)

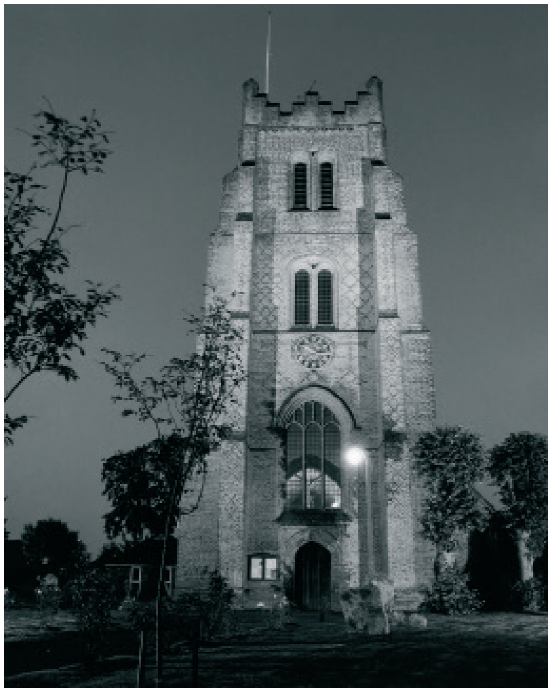


fig.16a converging lines not corrected

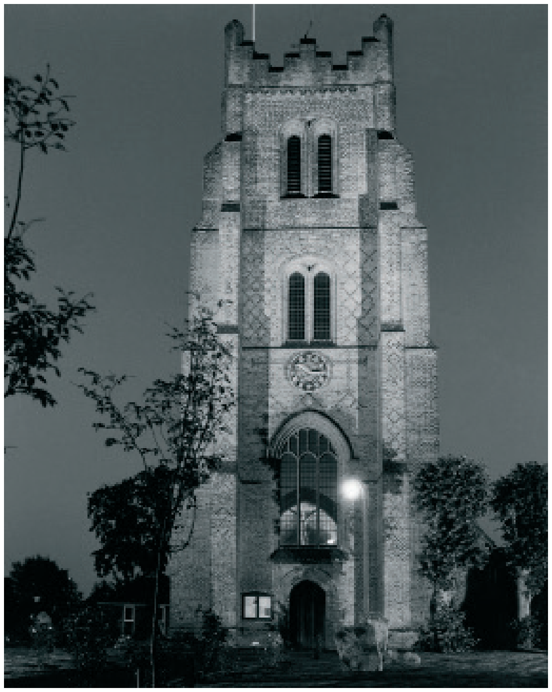


fig.16b converging lines corrected

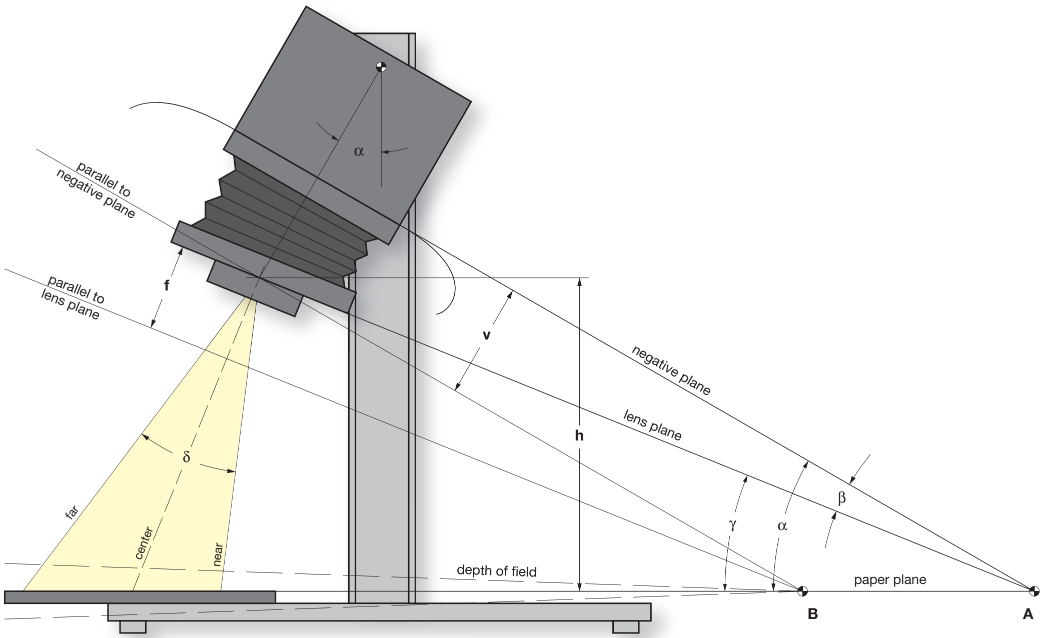


fig.17 Professional enlargers feature full 'Scheimpflug' correction capabilities similar to view cameras. If such an enlarger is adjusted so the negative, lens and paper planes intersect in a single line, then the entire image will be in perfect focus. This technique eliminates perspective distortions, also called converging lines, at the printing stage. The setup involves a three-step process and may require some exposure correction on the 'near' and 'far' side.

β	f = 50 mm					
h \ α	5	10	15	20	25	30
200	1.2	2.5	3.7	4.9	6.0	7.1
300	0.8	1.7	2.5	3.3	4.0	4.8
400	0.6	1.2	1.9	2.4	3.0	3.6
500	0.5	1.0	1.5	2.0	2.4	2.9
600	0.4	0.8	1.2	1.6	2.0	2.4
700	0.4	0.7	1.1	1.4	1.7	2.0
800	0.3	0.6	0.9	1.2	1.5	1.8
900	0.3	0.6	0.8	1.1	1.3	1.6
1,000	0.2	0.5	0.7	1.0	1.2	1.4

β	f = 80 mm					
h \ α	5	10	15	20	25	30
200	2.0	4.0	5.9	7.8	9.6	11
300	1.3	2.7	3.9	5.2	6.4	7.6
400	1.0	2.0	3.0	3.9	4.8	5.7
500	0.8	1.6	2.4	3.1	3.9	4.6
600	0.7	1.3	2.0	2.6	3.2	3.8
700	0.6	1.1	1.7	2.2	2.8	3.3
800	0.5	1.0	1.5	2.0	2.4	2.9
900	0.4	0.9	1.3	1.7	2.2	2.5
1,000	0.4	0.8	1.2	1.6	1.9	2.3

β	f = 105 mm					
h \ α	5	10	15	20	25	30
200	2.6	5.2	7.7	10	13	15
300	1.7	3.5	5.2	6.8	8.4	10
400	1.3	2.6	3.9	5.1	6.3	7.5
500	1.0	2.1	3.1	4.1	5.1	6.0
600	0.9	1.7	2.6	3.4	4.2	5.0
700	0.7	1.5	2.2	2.9	3.6	4.3
800	0.7	1.3	1.9	2.6	3.2	3.8
900	0.6	1.2	1.7	2.3	2.8	3.3
1,000	0.5	1.0	1.6	2.1	2.5	3.0

β	f = 150 mm					
h \ α	5	10	15	20	25	30
200	3.7	7.4	11	14	18	21
300	2.5	5.0	7.4	9.7	12	14
400	1.9	3.7	5.5	7.3	9.0	11
500	1.5	3.0	4.4	5.9	7.2	8.5
600	1.2	2.5	3.7	4.9	6.0	7.1
700	1.1	2.1	3.2	4.2	5.2	6.1
800	0.9	1.9	2.8	3.7	4.5	5.4
900	0.8	1.7	2.5	3.3	4.0	4.8
1,000	0.7	1.5	2.2	2.9	3.6	4.3

1/12 f/stop	δ = 40°					
γ = α–β	5	10	15	20	25	30
far	+1	+2	+4	+5	+6	+8
near	-1	-2	-3	-4	-5	-7
total	2	4	7	9	12	15

1/12 f/stop	δ = 45°					
γ = α–β	5	10	15	20	25	30
far	+1	+3	+4	+6	+7	+9
near	-1	-2	-4	-5	-6	-7
total	2	5	8	11	14	17

1/12 f/stop	δ = 50°					
γ = α–β	5	10	15	20	25	30
far	+1	+3	+5	+6	+8	+11
near	-1	-3	-4	-5	-7	-8
total	2	6	9	12	15	19

1/12 f/stop	δ = 55°					
γ = α–β	5	10	15	20	25	30
far	+2	+3	+5	+7	+10	+12
near	-2	-3	-5	-6	-8	-9
total	3	6	10	13	17	21

fig.18 These two tables aid in determining the initial lens tilt 'β' (top) and exposure correction according to the angle between lens and paper 'γ' (bottom). Measure the lens to paper distance 'h' and the head tilt 'α'. Find the lens tilt 'β' for your focal length in the top table. Calculate the angle between lens and paper from $\gamma = \alpha - \beta$, and use the bottom table to find the exposure correction, relative to the centerline, in 1/12-stop increments for the near and the far side of projection, depending on your enlarging lens' angle of coverage 'δ'.

Some enlargers are equipped to fully support the Scheimpflug principle. If the enlarger is adjusted so the negative, lens and paper plane intersect in a single line, then the entire projected image will be in perfect focus. In the same manner as view cameras, this technique is used to eliminate perspective distortions, also known as converging lines (fig.16). A professional setup (fig.17) permits tilting of negative and lens plane independently and involves a three-step process.

1) Raise the enlarger head to 'h' to get the desired print size and focus.
2) Tilt the enlarger head to 'α' until the perspective distortion is eliminated and, otherwise, converging lines appear parallel. Refocus the image center, and estimate the location 'A' of the theoretical intersection between negative plane and paper plane.
3) Now, use fig.18 to estimate and adjust the angle of the lens plane to 'β' until it also intersects at 'A'. Check with a focusing aid, and make the necessary correction to the lens plane until corner-to-corner focus is achieved.

It takes a bit of experience to get the last step correct, but estimating the initial lens plane adjustment can be made easier using the top table in fig.18. Unfortunately, this leaves yet another problem. The distance between negative and paper is greater on the far side than it is on the near side. This gradually increases the magnification towards the far side and corrects the perspective distortion, but it also creates uneven paper illumination. Depending on the angle between lens and paper (γ = α–β), and the coverage of the lens, this difference of illumination may be significant and easily visible in the final print. A gradual burning down from the near towards the far side will correct for the light loss. A test strip will determine the amount of exposure correction required, or you can use the bottom table in fig.18 as a starting point.

Unfortunately, few enlargers feature the flexibility to adjust negative and lens plane independently, but many allow tilting of the lens plane, as seen in fig.15. In this case, tilt the easel, while the negative is projected onto the paper, until the converging lines appear to be parallel. This will throw the image out of focus, but tilting the lens plane will correct it. Correct lens tilt and focus until the entire image is in perfect focus. At that point, the projection geometry is identical to that of a fully adjustable enlarger, with the same need for exposure correction. This setup is less convenient than the enlarger adjustments in fig.17, and precise easel tilt is not always possible, but it is still a big help in correcting converging lines.

Exposure Height and Exposure Correction

Whenever the enlarger head is raised or lowered, and the negative magnification is changed, print exposure must be corrected. In 'Tables and Templates', you will find a chart to determine the magnification of your enlargement and another to estimate the exposure compensation required to accommodate a change in enlarger height. Strictly speaking, projected print exposures fail to follow the inverse-square law, but they follow the inverse square of the lens-to-paper distance if the paper reciprocity failure is ignored, in which case, a new theoretical exposure time (t_2) is given by:

$$\frac{t_2}{t_1} = \left(\frac{u_2}{u_1}\right)^2 = \left(\frac{m_2+1}{m_1+1}\right)^2$$

$$t_2 = t_1 \cdot \left(\frac{u_2}{u_1}\right)^2$$

$$t_2 = t_1 \cdot \left(\frac{m_2+1}{m_1+1}\right)^2$$

where 'u_1' and 'u_2' are the old and new lens-to-paper distances, 'm_1' and 'm_2' are the old and new magnifications, and 't_1' is the old exposure time.

Both charts in the appendix illustrate the optical relationships and eliminate the need for any calculations. Of course, if you are using a darkroom meter to measure print exposures anyway, you probably never need the charts or the math to ascertain a new exposure time when changing the enlarger height.

A Sharper Image

The recommendations in this chapter have covered all fundamental variables of print sharpness, as they exist in the darkroom. A well-aligned, stable and undisturbed enlarger, holding a flat negative and projecting it with a well-focused, high-quality lens, at its optimum aperture setting, onto motionless flat paper, will result in the sharpest print possible.