Photographic System Resolution

In music reproduction there is a chain of steps – microphone to tape to amplifier to speakers (skipping a couple). The weakest link limits the fidelity of the system.

The same thing happens in photography as we progress from the lens to the sensor or film and eventually a print or displayed image. The weakest link in that chain limits the ultimate resolution or sharpness.

Photographic resolution can be stated two ways:

- Linear – line pairs per millimeter (lp/mm), line widths per picture height (LW/PH), pixels per mm or pixels per inch (ppi)
- Area – megapixels (MP) or pixels per square millimeter (px/mm^2) or pixels per square inch (px/in^2)

When you double the linear resolution you quadruple the area resolution. But you cannot convert directly from linear to area resolution. It's not that simple.

Linear resolution is used as a measure of edge sharpness – how clearly you can see the hard edges of objects. Area resolution is a measure of how many pixels are contained in the image. It is a measure of how much you can magnify an image before the viewer can see pixilation. That is nominally 300 pixels per inch from a distance of about ten inches (or 300 pixels per foot from a distance of 10 feet, etc.).

It might take a span of several pixels for the viewer to determine whether an edge is sharp or blurred. You can artificially sharpen or soften an edge by changing the acutance at the transition. You can also over-sharpen.

Photographic system resolution can be calculated with one of these formulas:

$$1/Rs^2 = 1/Rl^2 + 1/Rd^2 \quad \text{(digital)}$$
$$1/Rs^2 = 1/Rl^2 + 1/Rf^2 + 1/Re^2 \quad \text{(film)}$$

where all of the terms are in lp/mm:

Rs is the system resolution
Rl is the lens resolution
Rd is the resolution of the digital sensor
Rf is the film resolution
Re is the resolution of the enlarger lens or the scanner

Based on Imatest results, the highest resolution lenses available today for a Nikon full frame (FX) body achieve close to 3200 LW/PH near the center of the image at the optimal aperture. That is 1600 line pairs per picture height over 24 mm or 66.67 lp/mm. Many other good lenses are capable of 55 lp/mm.

Lens and film resolutions are determined using standard targets. But how do we find the resolution of a digital sensor? We should not jump to conclusions. Digital linear resolution may not be what you expect.

We cannot assume that a 24 MP sensor actually delivers 4,000 LW/PH or 83.33 lp/mm (FX) or 125 lp/mm (DX). That is possible only if the alignment of the pattern on the sensor is perfect, the lens is perfect, the Bayer array does not degrade resolution, that the size of the sensor does not matter.

Assume that you could project 4000 lines of alternating black and white lines directly on a 24 MP (4000x6000) sensor. That would be 2000 line pairs or 2000/24=83.33 lp/mm. For that to work the target would need to be perfectly aligned and parallel to the rows of pixels in the sensor with a white line on the odd numbered rows of pixels and the black lines on the even numbered rows. The sensor can record a nice clear resolution of the pattern. Now shift the pattern down by the height of one half pixel. Now each pixel records half of a white line and half of a black line. Every pixel records middle gray and there is no pattern recorded at all.

You could also tilt the pattern with respect to the pixels and get a different issue. You would record a sharp pattern where the lines pass over the center of the pixels and middle gray where they pass between them. You would see a moiré pattern.

Neither scenario would give you a clear resolution of 83.33 lp/mm. But if the projected lines were wider there would be a clearer pattern. The following tables represent a target like the one used in testing lenses or film where 1 represents a white line and 0 represents a black line.

Target pattern = 1 pixel per row

Target value	1	0	1	0	1	0
Pixel #	1	2	3	4	5	6
Monochrom	1	0	1	0	1	0
Bayer[1]	0.5	0.5	0.5	0.5	0.5	

[1] also the Monochrom pattern where the rows are aligned halfway between the pixels

The Monochrom sensor can resolve the target values clearly if they align with the pixel rows but not if they are halfway between the rows. The Bayer array cannot resolve the target values at all.

Target pattern = 1.5 pixels per row

Target value	1		0	1		0
Pixel #	1	2	3	4	5	6
Monochrom	1	0.5	0	1	0.5	0
Bayer[1]	0.75	0.25	0.5	0.75	0.25	

The Monochrom sensor can resolve the target values clearly if they align with the pixel rows but only weakly if they are half way between the rows. The Bayer array can only weakly resolve the target values.

Target pattern = 2 pixels per row

Target value	1		0		1	
Pixel #	1	2	3	4	5	6
Monochrom	1	1	0	0	1	1
Bayer[1]	1	0.5	0	0.5	1	

The Monochrom sensor can resolve the target values clearly if they align with the pixel rows but only partially if they are half way between the rows. The Bayer array can only partially resolve the target values.

For a 24 MP Bayer array there would be only 2000 lines or 1000 line pairs over 24 millimeters. You would know that there is a pattern no matter how much you shifted the lines up and down or tilted the target. It would not be perfectly clear and there could still be a slight moiré pattern if you tilted the alignment but you might be satisfied that a resolution of 41.67 lp/mm could be used in calculating the system resolution. A Monochrom or Foveon sensor would do slightly better since it could assume 1.5 pixels per row instead of 2 – a ratio of 2/1.5=1.333.

A digital sensor with a Bayer array contains separate pixels for red, green and blue. Half of the pixels are green and the other half are either red or blue. For example, a 24 MP sensor has 12 MP of green, 6 MP red and 6 MP blue. To further confuse the issue, a row of pixels are either RGRGRG or GBGBGB while a column of pixels are RGBGRGBG – the patterns are not symmetrical.

Film, especially black and white film, can have much higher resolution than a sensor – 80 to 160 lp/mm is common. Kodak Tmax claims 125 lp/mm for Tmax 100. Adox claims 800 lp/mm for CMS 20 II but that's for a very high contrast image. Film is not the weakest link, especially with larger formats that have lower lens resolution.

Will the film be printed using an enlarger lens or will it be scanned? Either way we need to consider the resolution of the final step, Re, to see how much the enlarger lens or the scanner degrades the image.

An enlarger lens is special in that it is designed to perform well over a short distance, like a macro lens. It is reasonable to assume that it can do as well as the best camera lens. A resolution of 60 lp/mm may be a good estimate for FX. Enlarger lenses for formats larger than FX are comparable to the best camera lenses for the same format but they will likely not be the weakest link.

An Epson V750 flatbed scanner has been reported by ScanDig to have an optical resolution of about 2300 ppi – pixels per inch (2300/25.4mm per inch= 90.55 pixels per millimeter, 45.28 lp/mm). That's not as good as a superior lens and it would be the weakest optical link for a 24x36mm image. Even if you use the scanner at a higher ppi setting you can't get better *optical* resolution, just bigger files. However, for medium or large format files 45.28 lp/mm is probably equal to or better than the camera or enlarger lens's resolution.

ScanDig states that the Nikon Coolscan 9000 has an optical resolution of 4,000 ppi (4000/25.4 = 157.48 pixels per millimeter or 78.74 lp/mm). That's better than an enlarger or camera lens but still low enough to affect the total resolution for 35mm film. For medium format film that resolution is probably high enough that the scanner will not degrade the system resolution.

ScanDig also reports that the Hasselblad Flextight X5 drum scanner can scan 35mm film at 6300 ppi (landscape) or 8000 ppi (portrait). That's 124.02 lp/mm and 157.48 lp/mm respectively and the camera lens remains the weakest link. Medium format film can be scanned at 3200 ppi (62.99 lp/mm) and 4x5 sheets at 2040 ppi (40.16 lp/mm) but those resolutions might still be as good as or better than the camera's lens resolution. Note that the V750 flatbed appears to have a higher resolution than the Flextight for 4x5 film.

Disclaimer

Results below are based on reasonable assumptions but they should be taken with a grain of salt. Film resolution is measured differently and it may be slightly different from what is assumed in this analysis. In the accompanying spreadsheet the reader can easily substitute different values to see the effects.

Examples

Here are some results for digital cameras. Note that the last column, LW/PH, tells us how much total linear detail the image can clearly resolve.

Combination			System Resolution (Rs)	
Lens lp/mm	Body MP	Format	lp/mm	LW/PH
50	24	FX	32.09	1540
50	24	DX	39.05	1250
50	45.7	FX	37.69	1809
50	24 Monochrom	FX	37.16	1784
66.67	24	FX	35.44	1701
66.67	24	DX	45.60	1459
66.67	45.7	FX	43.48	2087
48	50 medium format	33x44mm	30.58	2216

No digital sensor achieves a system resolution close to that of the lens alone.

Film at 100 lp/mm with enlarger:

Combination			System Resolution (Rs)	
Camera lens lp/mm	Enlarger lens lp/mm	Format	lp/mm	LW/PH
50	60	24x36mm	35.86	1721
48	45	57x57mm	31.19	3556
30	30	4x5	20.75	3984

Film at 100 lp/mm scanned:

Combination			System Resolution (Rs)	
Lens lp/mm	Scan resolution	Format	lp/mm	LW/PH
50	6300	24x36mm	42.07	2019
50	4000	24x36mm	38.89	1867
50	2300	24x36mm	31.82	1527
45	4000	57x57mm	37.92	4323
45	3200	57x57mm	35.67	4066
45	2300	57x57mm	31.28	3566
40	2300	4x5	24.26	4658
40	2300	8x10	24.26	9316

Film resolution

Film	lp/mm	Source
Tmax 100	125	Kodak
Tmax 400	100	Kodak
Pan F+	150	Ilford*
FP4+	110	Ilford*
HP5+	100	Ilford*
Delta 100	160	Ilford*
Delta 400	145	Ilford*
Delta 3200	100	Ilford*
XP2 Super	110	Ilford*
SFX 200	80	Ilford*
Fuji Velvia 50	80	Fuji
Fuji Neopan Acros	100	Fuji
Adox CMS 20 II	up to 800	Adox

* Unconfirmed

References

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7. Several Lens Reviews in Photography Life report Imatest resolution in LW/PH.