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# Do todays digital image sensors out perform photographic film?

The sensors found in todays high end digital cameras are said to produce better resolution and finer tones than film! How are these conclusions reached, and do digital images actually look better than those on film?

With digital capture slowly becoming the norm across the photographic industry, are we actually getting better images or are we sacrificing quality for convenience? This question is not easily answered. Images have different subjective effects on different people and in different environments. In this article I will examine how we compare imaging systems and try to come to some conclusions that are useful to the average working photographer.

## The Technologies

Photographic films still use the same basic process as used by the pioneers. That being that silver halide crystals will form metallic silver when exposed to light. The size of the crystals, the intensity of the light and the duration of the exposure being the main factors effecting the amount of silver produced. Modern emulsions contain specially sensitized materials that are more sensitive and respond to a wider spectrum of light (untreated silver halide responds only to blue light) but the same basic chemistry is at work.

In the case of black and white film, a layer of this emulsion is held between a protective 'super coat' and the films clear base. When the film is exposed to light a 'latent image' is formed in the emulsion layer. As the film is developed this image is amplified chemically to produce a visible negative image.

Colour film is slightly more complicated in that it uses three separate layers of emulsion with differing sensitivities and separated by filters. These each record information for one of the primary colours. The silver is then bleached out of the film during development, leaving behind a coloured dye which forms the negative image for that colour. The three layers combined form a full colour negative image of the subject.

Focusing light though this negative onto more film or photographic paper will then form a positive image, hopefully containing all the tonal information found in the original scene.

Reversal or slide films use a similar process to produce the latent image but it is the unexposed halides that are developed to form the dyes. This produces a positive image in the film that can be used for direct projection.

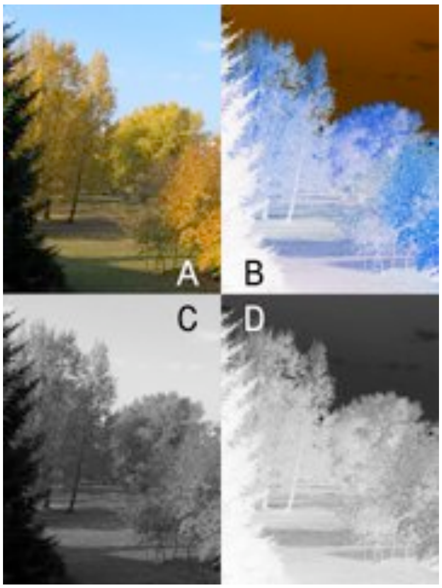

*fig 1.1 Negative images*

## Enter digital

Digital sensors include two basic types, CCDs which were originally developed for analogue video cameras and the more recent and natively digital CMOS sensors. Both are arrays of tiny light sensitive capacitors that each form a separate picture element or pixel. During exposure they each accumulate a charge proportional to the amount of light that falls on them. What happens after exposure depends on the type.

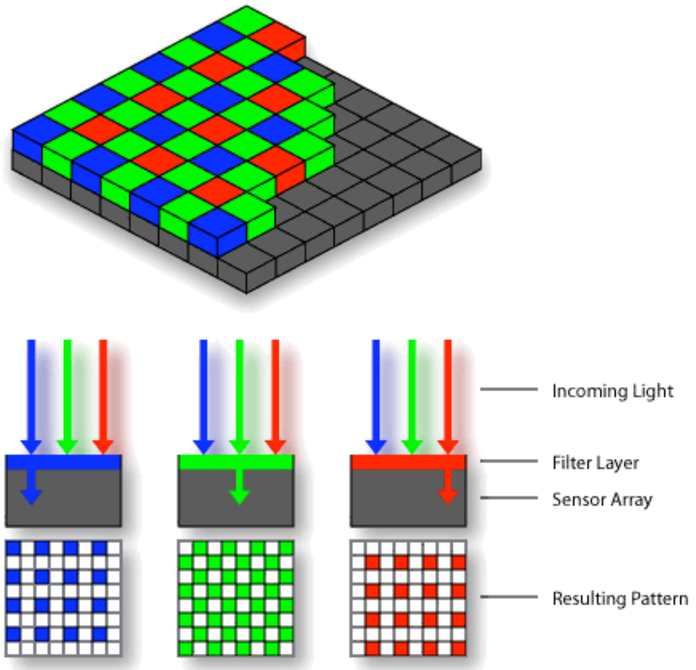

*fig 1.2 Bayer Mask*

CCDs (or charge coupled devices) are specially manufactured so each capacitor passes it's charge to the next in line, while the last one feeds an amplifier circuit. This process is repeated until all the capacitors are empty. The amplifier circuit outputs a voltage which is then converted to a digital value by an analogue to digital converter (ADC).

CMOS (or complementary metal oxide semiconductor) sensors are manufactured using the same process as computer CPUs. Thus they need a voltage converter at each pixel to feed the ADC via more conventional microprocessor wiring. The ADC and other functions are often included on the same chip as the pixel array.

Most sensors of both types achieve colour using a system known as a *bayer mask*. Coloured filters are fitted over the individual pixels making them sensitive to only one of the primary's. For every two green pixels there is one red and one blue, based on the principal that the human eye is most sensitive to green light. At each pixel site information is only recorded for one colour, thus the other two must be interpolated.

Notable exceptions include the Foveon X3 family of sensors, which use multiple layers to capture all three colours for each pixel location, and the 3CCD systems used in many digital video cameras, which employ a prism to split the image in three and have a separate sensor for each colour.

## Defining quality

When we compare the film process with a digital imaging system we are not comparing like for like. The two systems work in very different ways and have different limiting factors. Manufacturers quote various figures to help sell their products but how do they relate to the way we actually perceive image quality? As we will see, what happens at the limits of performance is very different from film to digital.

Grain size on film is responsible for the spacial resolution of the image. Smaller grains can reproduce finer details. However, film contains grains of many different sizes so can resolve details smaller than the largest visible grain structure.

In the digital domain resolution is a product of the number of pixels on the sensor. However, due to the Bayer Mask employed in most sensors, blurring and colour fringing may obscure pixel level detail. So how do we compare the resolution of the two systems?

The modulation transfer function or MTF of a system (see below), measured by photographing a series of black and white lines that get increasingly smaller, is the standard way to compare image resolution. Comparing the MTFs quoted by manufactures, todays high-end digital SLRs clearly out perform 35 mm film and are beginning to rival medium format. However, we have to be a little careful applying this information.

Take for example an oversized print made from a 35-mm negative and a similar print made from a digital image of the same scene. The photographic print has large visible grain and soft details throughout the mid-tone areas but still retains some high contrast details and looks quite pleasing to the eye.

The digital image contains detail not visible in the photographic image but when enlarged to the required size displays pixel artifacts that are subjectively much less pleasant than film grain. Even though the digital image is higher resolution, the photographic image may be subjectively more pleasing after enlargement so the MTF curve does not tell the whole story.

## The curvy line

Comparing the dynamic range of imaging systems is equally complex. If we ignore the effects of the final presentation media, we still have two ranges to consider, the dynamic range of the scene and that of the recorded image.

If we simply compare the dynamic range of the recorded images, then digital comes out a clear winner, with the best systems recording up to 9 stops (with further advances just around the corner) while reversal film will give you 5 to 6. But again this does not tell the whole story.

The characteristic curves (fig.1.5-1.7) show how scene brightness relates to density of the image on film or the voltage generated in the digital sensor. By comparing them we can get a better idea of the differences between the two systems than by looking at the image dynamic range alone.

## Understanding MTF Charts

Put very simply, the MTF chart represents contrast on the vertical axis against fineness of detail on the horizontal. You can see how the contrast retained by the imaging system drops off as the detail gets finer.

The Y-axis, often labeled response, is easy to understand being measured as a percentage of the original contrast. The X-axis is labeled spacial frequency and requires a little more explanation.

Generally measured in cycles per millimeter, spacial frequency, when used in the context of MTF charts, represents the number of black/white line pairs over a given distance measured in the image.

So rather like the frequency response curves used by audio manufacturers, the MTF curve represents the response of an imaging system to differing frequencies, though in this case we are measuring frequency in space as opposed to time.

The plot on the right shows the response of Fujifilm's Provia 100F. You can see that full image contrast is maintained up to about 20 cycles per mm and contrast has dropped to 50% at about 40. This information isn't much use in isolation but when compared against the MTF for other film stocks or digital imaging systems it can give us a good idea of relative resolution.

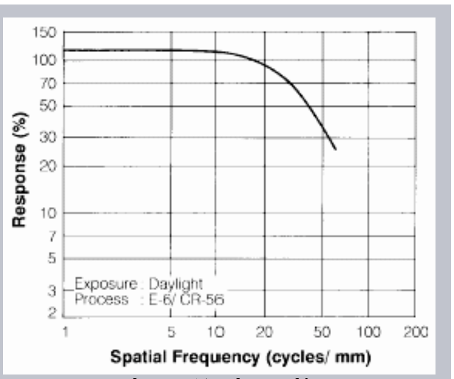

*fig 1.3 MTF for Fujifilm Provia 100F*

The graphic below illustrates the effect on the image. The top half shows the original subject and the bottom half the image on film.

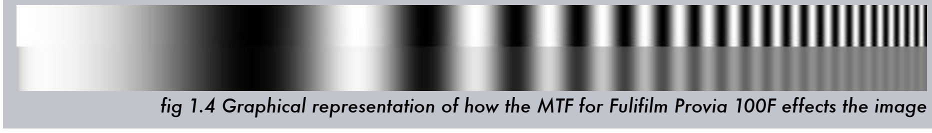

*fig 1.4 Graphical representation of how the MTF for Fulifilm Provia 100F effects the image*

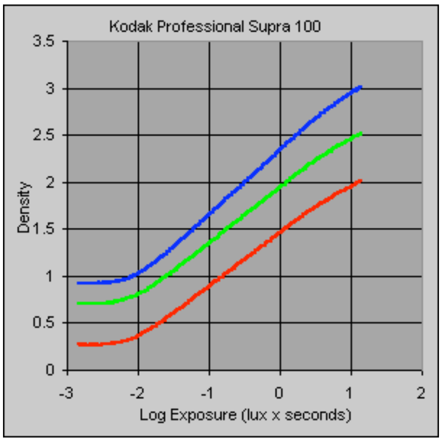

*fig 1.5 Negative film*

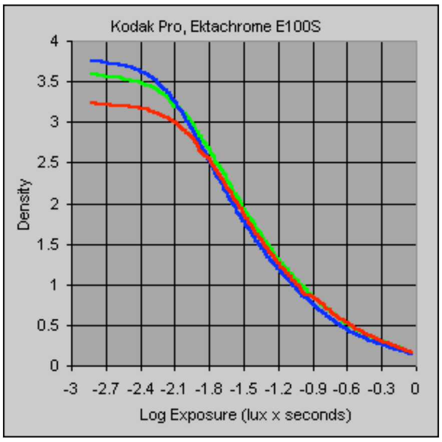

*fig 1.6 Reversal film*

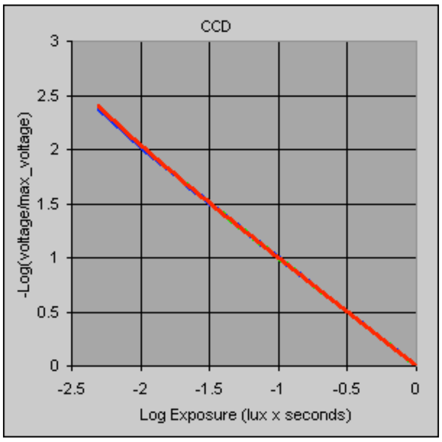

*fig 1.7 CCD*

Negative film (fig.1.5) captures a wide range of subject brightness (up to 11 stops in monochrome) but compresses this into a smaller range on the negative. As we can see from the response curve, it is also non-linear in the highlights and shadows. This will have the effect of compressing the highlights and loosing shadow detail. Though it means some subtlety of tone is lost and contrast is reduced, this makes negative films, especially black and white films, ideal for high contrast situations.

Digital and reversal films both record the scene contrast pretty directly but as the curves show, the response at the extremes is quite different.

Digital systems (fig.1.7) are inherently linear, a brightness increase or one stop in the scene produces an increase of one stop in the recorded image, no matter if we are in the mid-tones, highlights or shadows. This linear relationship is maintained until a digital maximum is reached, at which point no brighter area can be recorded and the information is clipped (recorded as white). The opposite happens at the black end of the tonal range.

Reversal film (fig.1.3) on the other hand is only linear in the mid-tones, with response falling off gradually in the shadows and the highlights. So though the mid-tone portion of a scene is represented faithfully the highlights and shadows are compressed. Images taken on reversal film often look more punchy and saturated as a result.

So though digital again seems to have the numerical advantage, film has certain characteristics that make it more pleasing or more practical in certain situations. However, photographic film is a mature medium where as digital image capture is still a fairly young technology, with much refinement still to come.

Fujifilm's latest D-SLR, the Finepix S3 Pro, has a CCD which boasts an expanded dynamic range and claims to simulate the response of either negative or reversal film. Looking at the audio and video industries, where features designed to simulate the response of analogue media are almost ubiquitous, does the S3 heralds the beginning of a trend for 'film simulation' modes and sensors designed to be 'more film-like'?

In the audio world tape simulation has been around for some time. Though it never sounds quite like tape, it can produce very pleasing results, with the best systems introducing non-linearities in the analogue domain before quantization. Is this a glimpse into the future of digital photography?

## Noise and Grain

We have already discussed film gain in the context of resolution but it also effects image perception in other ways. It is seen in an image as interference or information not in the original scene that has been introduced by the system, we refer to this as noise. In digital systems noise is introduced by random mistakes in the electronics and quantization errors, where the actual tone is between two digital levels and is rounded up or down as a result.

The signal to noise ratio is used to measure how much the noise interferes with image quality. But as before straight numerical comparison is not really sufficient here. Film grain is visible in most images but is random in form and not that subjectively unpleasant. Film can also resolve details smaller than the visible grain, or below the noise floor. In the digital domain noise is generally smaller and less obvious but it is fairly unpleasant to look at and very little information is retained from below it.

Films vary greatly but reversal films tend to have less grain than negatives and the lower the ISO the better. Images taken on slow reversal films such as Fujifilm Velvia 50 have very low noise rivaling the best digital images. Digital systems tend to have very good noise performance at low ISO settings but fairly poor at high. Some good general rules are CCDs are less noisy than CMOS (debatable these days) and larger pixels produce less noise than smaller ones. However, with big pixels we start to run into problems with aliasing according to Nyquist theorem (see below).

## Colour

The last major factor, and possibly the hardest to quantify, is colour reproduction. The colour accuracy of the best colour reversal films is very high and it could be argued that digital is yet to achieve such good flesh tones or highly saturated colours without loss of graduation. But digital systems improve very quickly and if we consider the chain through to the final print then perhaps the boot is on the other foot.

Colour management of digital systems offers the photographer effortless, repeatable colour accuracy right through to output. Combined with tomorrows sensors I cannot see film retaining any advantage here for long.

### *Nyquist Sampling Theorem*

Also known as the Nyquist-Shannon theorem, it is employed when converting any analogue signal into digital. It states that the sampling frequency (in the case of digital images, the number of pixels in a given space) must be twice the highest frequency in the original signal (detail in the image formed by the lens).

$$2f_H < f_s$$

$f_H$ is the signal bandwidth

$f_s$ is the sampling frequency

The highest frequency recoverable at any given sampling frequency is called the Nyquist frequency. Any frequencies in the source greater than Nyquist will cause aliasing in the digital signal. That is they will be recorded as distortion, most often visible as moire patterns and colour artifacts in digital images.

In digital cameras with small pixels this is rarely a problem as the lens does not resolve any information above Nyquist (it operates as an anti-aliasing filter). With bigger pixels and better lenses we can resolve details well above Nyquist and so aliasing becomes a problem. There is not a lot we can do about this without sacrificing resolution as sharp (high Q) filters are virtually impossible in optical systems. This may be one of the ultimate limiting factors of digital image quality.

## So which is best?

How does this help the working photographer decide which system to use? They have different merits and different disadvantages, which may or may not be important on a particular shoot. But I think it is safe to say that neither system has a clear technical advantage at the moment. The choice is another part of the photographers creative responsibility and another commercial tool.

Both systems still have their place in the photographic industry, as they do in the motion picture industry, and I believe they will do so for the foreseeable future. So don't believe those who tell you the latest digital systems out perform film across the board. But equally don't believe those who say film is always going to look better. The answer lies somewhere in the quagmire between.

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*2005*

## Shannon Information Capacity

Claude Shannon's capacity theorem describes the information capacity of any communication channel based on the bandwidth and signal to noise ratio.

$$C = BW \log_2(SNR+1)$$

$C$ is the information capacity
$BW$ is the bandwidth
$SNR$ is the signal to noise ratio

If we consider images as a communication channel we can apply this to imaging systems, The frequency at which the MTF curve falls below 50% becomes the bandwidth and the signal to noise ratio is the difference in decibels between the level at which clipping occurs and the level of noise when no signal is present.

However, as we have seen, defining both signal to noise ratio and clipping level in photographic systems is far from easy. So when comparing digital with photographic systems we must take the results of Shannon capacity comparisons with a pinch of salt.

Shannon capacity theorem was derived in the context of digital communications so is ideally suited to comparing digital systems against one another. If we are careful to define clipping threshold and noise level we can also use it to compare photographic systems.

Comparisons made between the two will always be subject to subjective assessments. Measurements made in the two systems would need to be weighted to take into account their differing subjective effects. The shoulder of the photographic curve will also have to be accounted for so the digital vs film comparison will never be entirely free from subjective interpretation.

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