Film Grain, Resolution and Fundamental Film Particles

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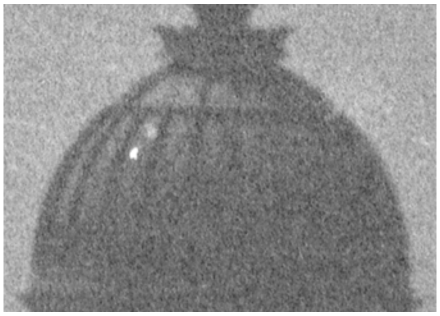
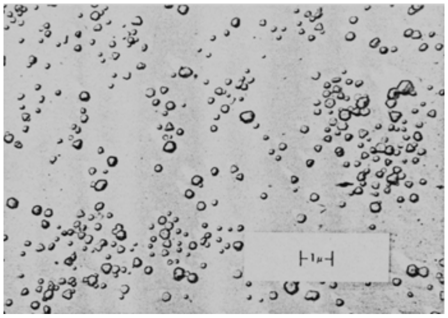
1 Introduction

The purpose of this complex essay is to demonstrate the following:

- **Fundamental film particles (silver particles) are distinct from film grain**
- **Silver particles are an order-of-magnitude smaller than common film grain**
- **Film grain is a perceived property; due to visual clumping of smaller particles through emulsion**
- **Resolution of film is related to the size and distribution of fundamental particles in the emulsion**
- **Film grain limits the ability of the smaller "fundamental particles" to resolve image detail**
- **Imaging film grain is an inadequate method of determining the resolution of a film**





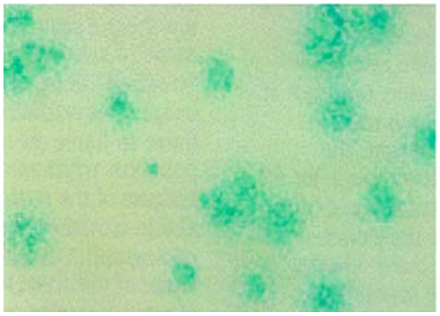


Figure 1 (left) shows a 0.5 mm (horizontal) section of a large format B&W negative scanned at 4800 ppi using a standard flatbed scanning procedure. **Figure 2** (center) from Mees & James (1967) Fig.2-5 shows a micrograph of actual (undeveloped) silver-halide crystal particles (before T-Grain in 1982); most silver particles are much smaller than one micron; average films range from 0.6 um to 0.8 um. **Figure 3** (right) from Kodak H-1 Fig 19b is a very rare Kodak micrograph showing cyan dye clouds in one layer, within color transparency film, at the thin edge of the film.

The term "film grain" is often incorrectly used to describe the "fundamental" particles in a chemical-based photographic image. Fundamental image particles are the smallest particles that form an image: **(a)** silver particles or **(b)** color dye clouds. Film resolution is directly related to the size and distribution of silver particles in an emulsion. Grain is a regular repeating noise pattern larger than the fundamental particles. Some mistake film grain for the image-forming elements in film. Film resolution is diminished by the presence of film grain because it is image noise at a specific frequency well above the terminal resolution of film.

Many Kodak and Fuji “popular” publications, including much of the popular photographic literature (magazines), also make the mistake of referring to fundamental film particles as film grain. This further propagates the imprecise usage of the term.

Film grain is a – perceived – visual phenomenon resulting from the visual accumulation of smaller particles through the thickness of the emulsion layer; see Film Grain, Section 3. Experienced workers explain that different techniques such as **(a)** magnification (through a microscope or loupe), **(b)** enlargement (photographic print) and **(c)** scanning, yield different results for the size of grain. These findings, in themselves, are highly suggestive that film grain is a perceived property, depending on the conditions when perceived.

Size Domain Property	**I-------------------SCALE----------------------I**			**Tool for Evaluating Property**	**What is Measured?**
	Microns	**lp/mm**	**ppi**		
Fundamental Particles	**0.2-2.0**	**5000-500**	**254,000-127,000**	**Microscopy**	**Silver Particles**
Film Resolution*	**6.25***	**80***	**4064***	**MTF Curve**	**Resolving Power**
Film Grain	**10-30**	**50-10**	**2540-1690**	**Image Enlargement**	**Film Grain**
RMS Granularity	**48****	**10****	**528****	**Microdensitometer**	**Noise at 1.0D**
Graininess	**NA**	**NA**	**NA**	**Print Grain Index**	**Random Film Noise**
Human Visual Acuity	**85*****	**6*****	**300*****	**Human Vision**	**Details**

* Applicable to Fuji Velvia RVP capable of 80 lp/mm native resolution.
** Diameter of area used in the RMS Granularity measurement.
*** Based on human not being able to resolve greater than 300 ppi.

Film scanner operators have been trying to eliminate film grain from their scans for years. Film grain obscures the fine detail that silver metal particles (fundamental image particles) are capable of rendering, and, it is visually annoying image noise that becomes more dominant the greater the degree of enlargement. Film grain is a fault of the chemical system.

In an era of 4800-6400 ppi flatbeds, one of the remaining claims to superiority of the drum scanner is its ability to “tune” the capture system to the physical image structure of specific films using two parameters: aperture and pitch. Every activity of the drum scan operator is geared towards eliminating film grain while maintaining resolution. The resulting drum-scanned image is prized when it looks like a digital image, free of film grain.

On the other hand, when printing film using an enlarger (analog technique), operators often use a **grain-magnifying tool** to assure the focus of film. Figure 4 (right) shows a Micro-Sight 12x grain focusing tool. Some operators have assumed that creating sharp “film grain” is the key to achieving image sharpness. However, film grain is not actually sharp because it is made up of numerous smaller particles, which are an order-of-magnitude smaller than the film grain, through the depth of the emulsion. Grain is perceived, rather than being real. In the table above it can be seen that film grain is far larger than the resolving power (MTF Curve) of film: 10-30 microns (um) vs. 6-10 um.

Figure 4

The problems of **(1)** locating a well-focused region of a small piece of film (24 x 36 mm), **(2)** evaluating its degree of focus and then **(3)** focusing that region of the film, explains why **“focusing the grain”** has become a common default for determining image sharpness. Along with the misuse of the term film grain, focusing on the perceived film grain (at the resolution being used for imaging) is a misapplication of imaging resources. Achieving small detail and sharp edges within the image at hand, while avoiding film grain should be the goal of the imaging process, be it on a flatbed, dedicated film or drum scanners.

2 Fundamental Film Particles – Silver-Halide Crystals

The fundamental image particles in chemical-based images are:

- **Silver particles in B&W images**
- **Color dye clouds in color film images (clouds develop from silver particle clumps at center)**

Silver-halide particles (in undeveloped film) average about 0.2 - 2.0 microns (one micron equals one millionth of a meter or, a thousandth of a millimeter). Color dye clouds range from 10 um to 25 um.

- **Silver-halide crystals are 0.2- 2.0 um**
- **Color dye clouds are 10- 25 um**

Human vision is orders-of-magnitude less acute than the size of the silver particles. Even corrected, human vision ranges from 75-100 microns, with an average of 84 um, or 300 dpi. Using a common 10x loupe, humans can image 7.5 to 10 um, which is still too coarse to see individual silver particles, even at a thin edge of an image.

The fundamental image particles (silver), when rescaled into dimensions commonly used for the wavelengths of visible light, range from 200 to 2000 nm (nanometers).

- **1" = 25.4 mm (millimeters)**
- **1" = 25,400 um (microns)**
- **1” = 25,400,000 nm (nanometers)**
- **Microns x 25400 = ppi/dpi**
- **Millimeters x 25.4 = ppi/dpi**

The size domain of visible light is 400-750nm; blue light ranges from 380-450 nm; green light ranges 450-550 nm; and red light ranges 550-750 nm. Ultra-violet light ranges 205-380 nm, while infrared radiation ranges 750-5000 nm. Note that the smallest silver particles (0.2-0.8 microns) are not visible unless clumped into larger agglomerates, because most are smaller than the wavelengths of light. The light microscope has a theoretical maximum resolution of 1000**x** when using a oil immersion objective and condenser, it can resolve particles at 250nm, or 0.25 um.

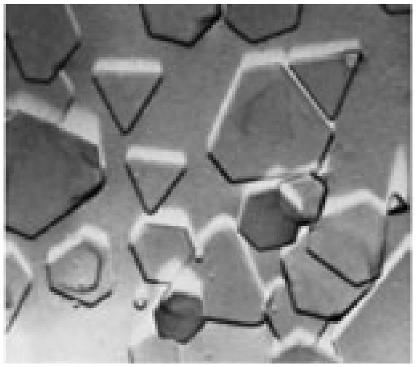


Figure 5: KODAK T-GRAIN emulsion crystals 1982-present, H-1

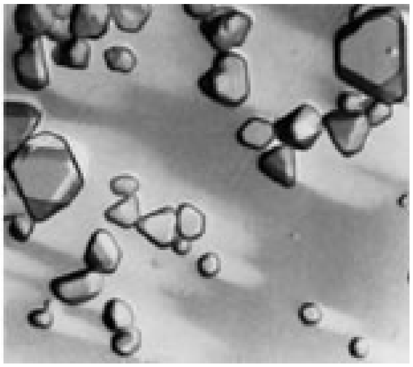


Figure 6: Conventional silver-halide crystals, 1860-1982, H-1

Quote from the Kodak Publication **H-1** (1999):

> “Incorporating T-GRAIN Emulsions into films improves film speed without sacrificing fine grain. The uniquely shaped grains align better than conventional silver crystals, absorbing and transmitting light more effectively. In recent years, [first in Kodacolor VR, 1982] a new type of emulsion KODAK T-GRAIN® was incorporated into some Kodak films. The amount of exposure, which determines the densities of various areas, also affects the graininess of all films. Other factors that affect graininess are different developers and different amounts of development time of black-and-white films. Because the development processes of color films are rigidly fixed, the effect of development [on them] is rarely a factor in their graininess (however, forced processing does cause an increase in graininess). Because many color films are made with emulsion layers of varying graininess levels, increasing the exposure (up to a point) places more of the density in the finer-grained layers, which actually reduces the overall graininess of the observed images.”

Feature Size versus Digital Resolution: Data Table 1

Size	Digital Resolution	Imaging Device
0.1 um	254,000 ppi	SEM/XRD
0.2 um	127,000 ppi	SEM/XRD
0.5 um	50,800 ppi	SEM/XRD
0.8 um	31,750 ppi	SEM/XRD
1.0 um	25,400 ppi	Light Microscope
2.0 um	12,700 ppi	Light Microscope
4.0 um	6,350 ppi	Light Microscope
5.0 um	5,080 ppi	Light Microscope & Scanners
5.3 um	4,800 ppi	Drum or Flatbed Scanners
5.5 um	4,618 ppi	Drum or Flatbed Scanners
6.0 um	4,233 ppi	Drum or Flatbed Scanners
6.34 um	4,000 ppi	Drum or Flatbed Scanners
7.0 um	3,629 ppi	Drum or Flatbed Scanners
8.0 um	3,175 ppi	Drum or Flatbed Scanners
8.5 um	3,000 ppi	Drum or Flatbed Scanners
9.0 um	2,822 ppi	Drum or Flatbed Scanners
10.0 um	2,540 ppi	Drum or Flatbed Scanners
10.5 um	2,400 ppi	Drum or Flatbed Scanners
12.0 um	2,117 ppi	Drum or Flatbed Scanners
13.0 um	1,954 ppi	Drum or Flatbed Scanners
15.0 um	1,693 ppi	Drum or Flatbed Scanners
20.0 um	1,270 ppi	Drum or Flatbed Scanners
21.2 um	1,200 ppi	Drum or Flatbed Scanners
25.0 um	1,016 ppi	Drum or Flatbed Scanners
50.0 um	508 ppi	Drum or Flatbed Scanners
60.0 um	423 ppi	Young Human Eyes
75.0 um	340 ppi	Above Average Human Eyes
85.0 um	300 ppi	Average Human Eyes
100 um	254 ppi	Most Human Eyes
1000 um	25.4 ppi	One Millimeter
1000000 um	NA	One Meter

In ***The Theory of the Photographic Process,*** eds: C.E.K. Mees and J.T. James (1967, 3rd), Chapter 2 by C.R. Berry and R.P. Loveland, pp 38-40 they list the average silver-halide particle sizes for film emulsions such as: high-resolution film, motion picture film, portrait film and high-speed film. The size range is from 0.30 to 1.71 um (microns), about the size of those listed in the Kodak **H-1** publication, 0.2 to 2.0 um.

THE SILVER HALIDE GRAINS

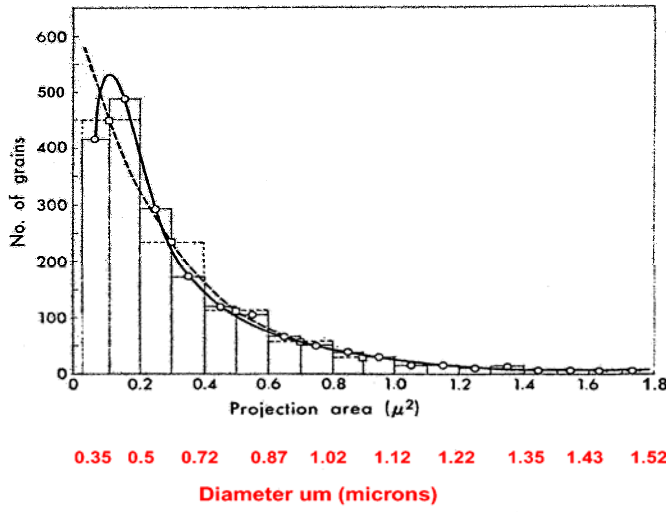


Fig. 2.7. ***Histogram, size-frequency curve, and the effect of the width of the size classes.***

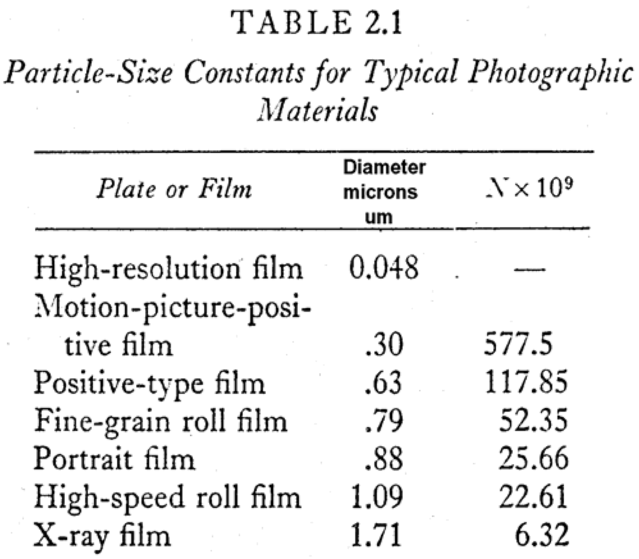


TABLE 2.1

Particle-Size Constants for Typical Photographic Materials

Plate or Film	Diameter microns um	$\mathcal{N} \times 10^9$
High-resolution film	0.048	—
Motion-picture-positive film	.30	577.5
Positive-type film	.63	117.85
Fine-grain roll film	.79	52.35
Portrait film	.88	25.66
High-speed roll film	1.09	22.61
X-ray film	1.71	6.32

Figure 7: Figures are taken from Mees and James (1967) p 39.

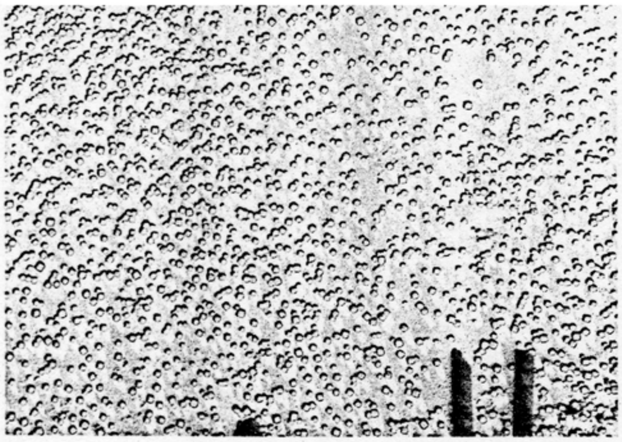


FIG. 2.4. *Preshadowed carbon replicas of small silver bromide crystals of a uniform size precipitated by the double-jet method of Demers. Shadowing angle = 18 degrees. Space between centers of bars = 1 µ.*

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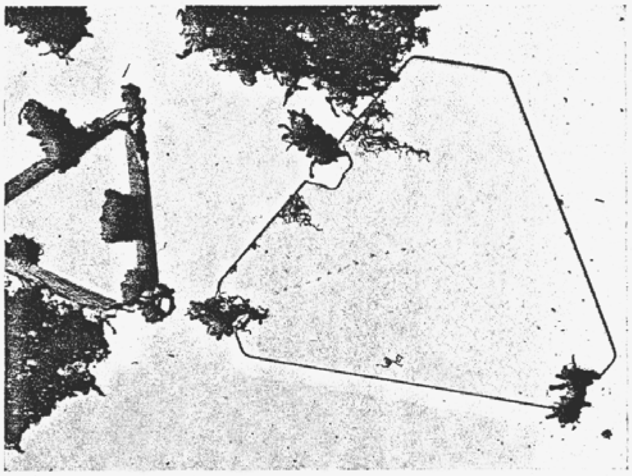


Fig. 1. Electron micrograph (×25,000) showing development centres and the etching out of silver bromide to provide the material for the developed silver.
Photo: R. B. Flint, Research Laboratories, Kodak Ltd.

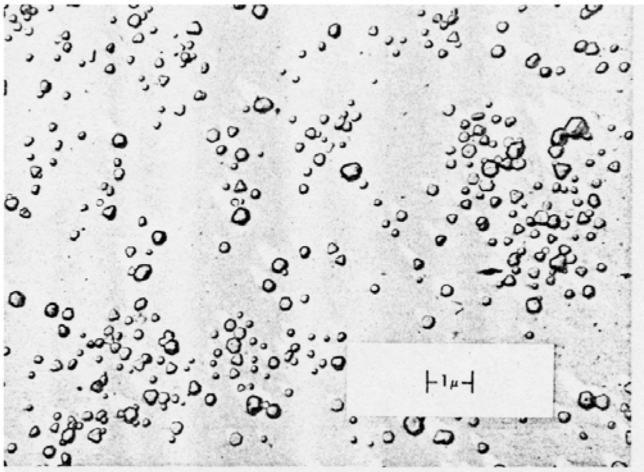


Fig. 2.5 Motion Picture type film emulsion. Size range from 0.2 to 0.6 microns. Bar is 1 micron.

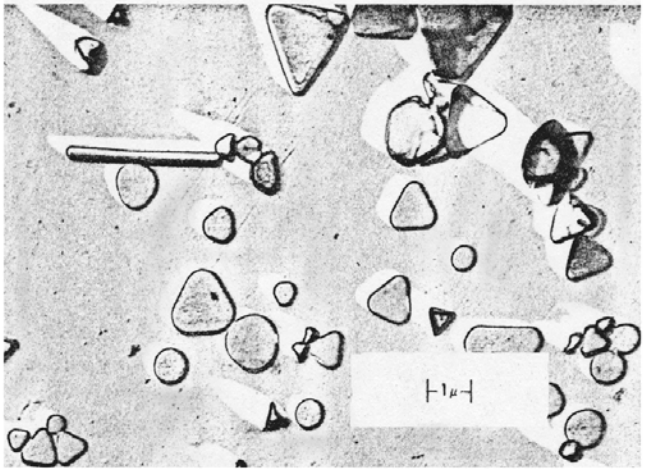
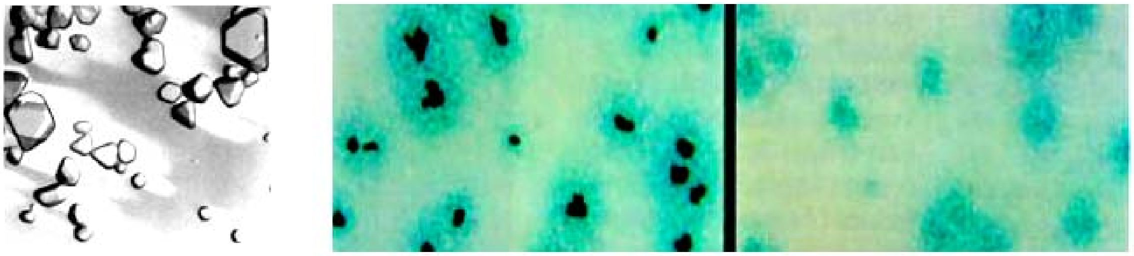


Fig. 2.6 High-Speed negative type emulsion. Grain size from 0.4 to 1.5 microns. Bar is 1 micron.

Figure 8: Images labeled “Figures 2.4, 2.5 and 2.6” are from Mees & James (1967) pp 35-39; the image labeled “Figure 1” is from Baines (1976) p112.

Dye Clouds are the Fundamental Particles in Color Film

Color films have dye clouds (10-25 microns across) that start from silver particle, or clumps, core(s). The dye clouds develop around the silver particle(s), or clumps: see below. Color films have lower resolution than B&W films, because the fundamental particle size is an order-of-magnitude (ten times) larger than in B&W film.



Kodak T Grain Silver Grain & Dye Cloud Dye cloud after full process
(Electron Microscope image of film grain/dye (x600) - Courtesy of Kodak PMI)

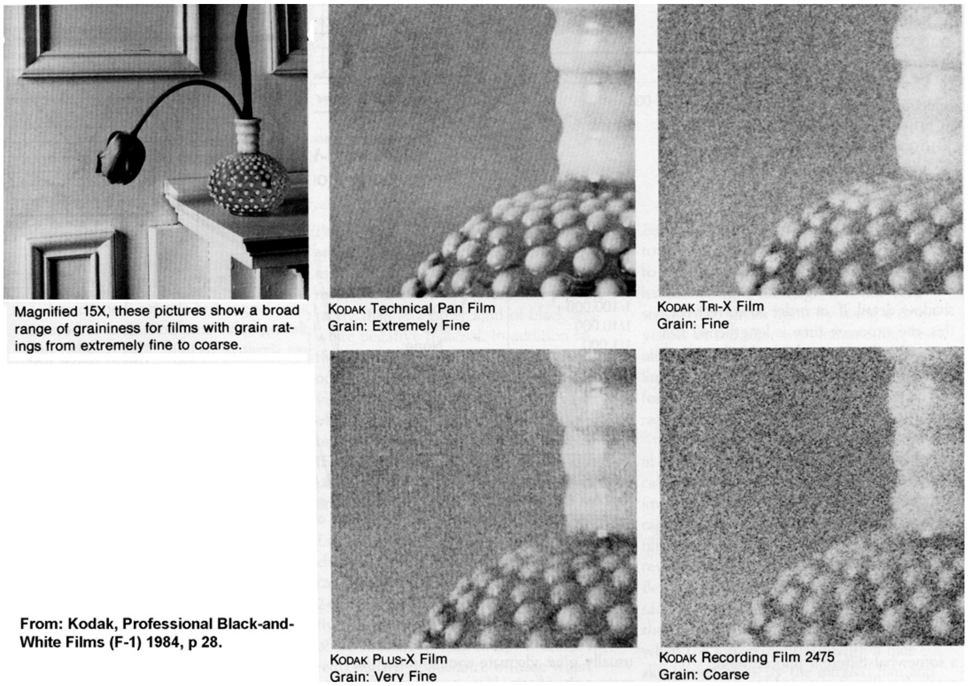
Figure 9: From H-1: The image on the left in a representation of the mix silver particle sizes found in B&W films, before T-Grain. The center image shows cyan dye clouds with silver particle clump(s) centers. On the right, the dye clouds are shown after full development, including a competing dye coupler, which reduces dye cloud size. In actual film, the dye clouds overlap within layers; there are up to 3 layers of the 3 colors of dye clouds (9 layers).

The Kodak **H-1** Publication shows discretely developed dye clouds to be about 6-15 um (microns) across. This assumes that the core silver particle is a clump of smaller particles about 2-5 um across, with the smallest individual silver particle size about 0.5-1.0 um. The images above were made from edges of areas of very faint color, and are probably from the slow film speed type. In areas of greater 0.4 D, individual dye clouds cannot be distinguished. Each color layer group has three different film speeds: (1) a fine grain "slow" layer, (2) a moderate grain "normal" speed layer and (3) a course grain "fast" layer.

3 Film Grain

Film grain is the product of the human eye and brain working in combination when viewing clumps of smaller fundamental image particles, through the full thickness of the emulsion layer. Thus, film grain is "perceived" property rather than an actual "particle." It is, however, real visual phenomenon. Film grain influences the sharpness of a film by acting as a regular noise pattern (unwanted image information) that diminishes the ability to resolve image detail in the size domain of the grain.

Seeing film grain requires enlargement with a loupe, or the use of an enlarged print. Film grain can't be seen by humans without aid of some sort of magnification. The average human can't resolve detail below 85 microns (300 ppi is the resolution limit of humans).



Magnified 15X, these pictures show a broad range of graininess for films with grain ratings from extremely fine to coarse.

KODAK Technical Pan Film
Grain: Extremely Fine

KODAK TRI-X Film
Grain: Fine

KODAK PLUS-X Film
Grain: Very Fine

KODAK Recording Film 2475
Grain: Coarse

From: Kodak, Professional Black-and-White Films (F-1) 1984, p 28.

Figure 10: Film grain from Kodak H-1, p28

Dye Clouds are Film Grain in Color Film

Dye clouds are the source of film grain in color films. The dye clouds range in size from 10 to 25 microns across, through the thickness of the nine layers of emulsion. Color films have lower resolution than B&W films because the fundamental particle size is an order of magnitude (ten times) larger than in B&W film. Transparency films are said to be grainless because there are no silver particles in the final emulsion, and the dye clouds have indistinct edges. The complexity of the silver-to-dye transition during development, filamentation of dye cloud and the multiple emulsion layers means that only rare “single dye cloud” can be observed, at the edges of transitions, such as in the Kodak (**H-1**, Fig 19a-d) images below.

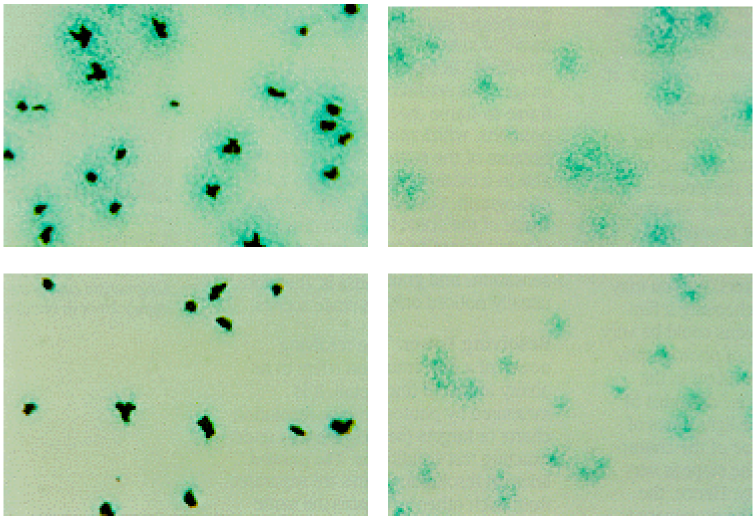


Figure 11: Taken from Kodak H-1 (1998) Figure 19, p25. The above illustrations are 1200X photomicrographs of a special cyan color film layer with incorporated coupler made very thin to permit showing the structure. The upper left picture is the film after color development and shows clumps of metallic silver grains (2-7 um) surrounded by dye clouds (10-25 um). The upper right picture shows another area of the same film after bleaching and fixing with the grain removed. The lower two pictures show the same type of film developed with a color developer containing a completing coupler which reduces the size of the dye clouds; hence, reducing the graininess.

Peter Kraus (2004), familiar to readers of Popular Photography and retired from Ansco/Agfa and Ilford as technical manager, said that color transparencies and negatives have dye clouds about 25um in diameter. Film Grain in a color film is the accumulation of tens, to hundreds, of dye clouds in each of the nine dye layers found in modern color film. See Fuji Film data sheets for depiction of the 9 layers.

Film Grain in Black-and-White Film

Film grain in B&W film is composed of numerous silver particles an order of magnitude smaller than the average film grain size domain -- 15 to 25 microns.

In **Kodak Professional Black-and White Films,** F-5 (1984) p 28:

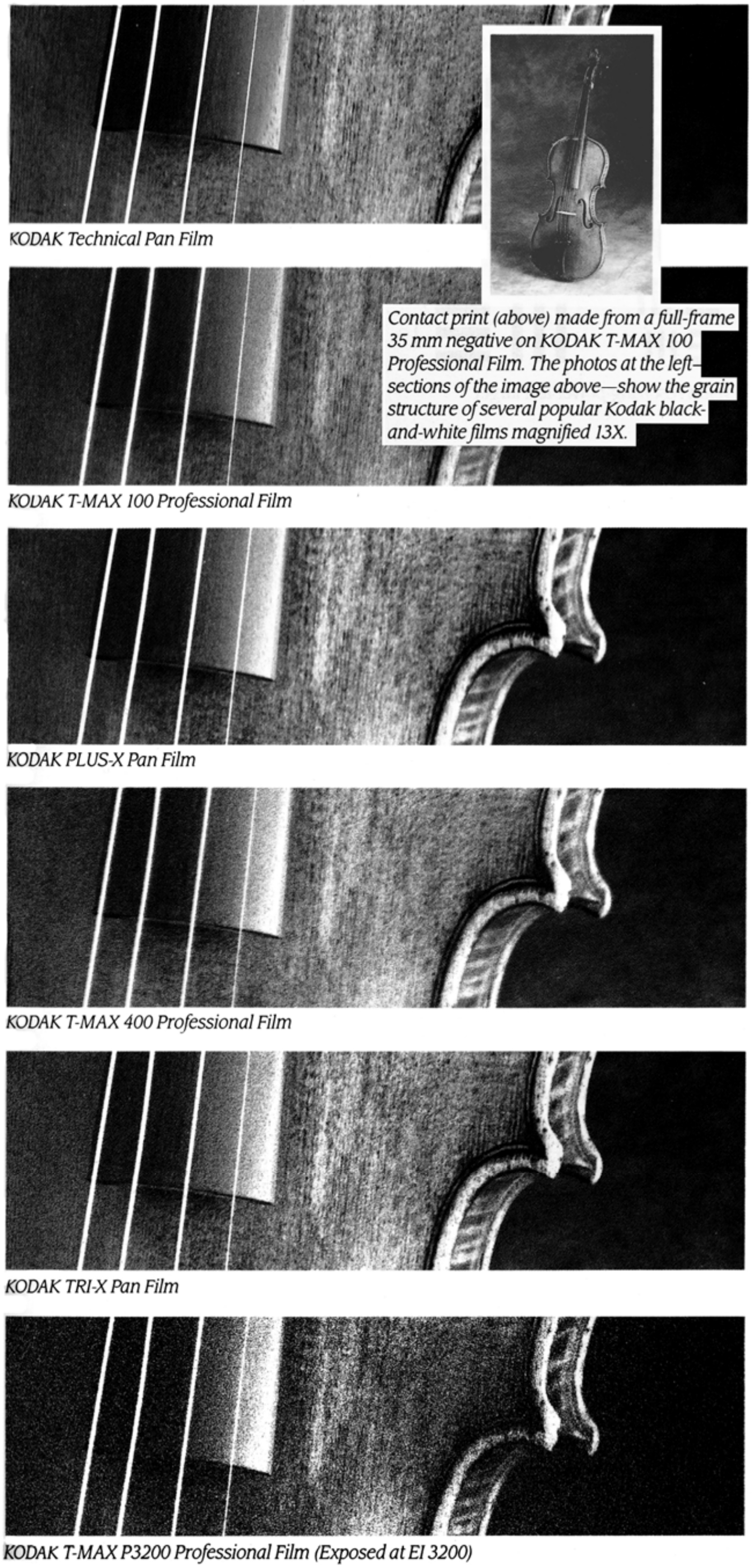
> **“Graininess: The densities in black-and-white negatives are composed of microscopic grains of black metallic silver. By their random placement in the gelatin of the emulsion, there is a statical clumping of the grains that form the familiar granular pattern that becomes visible when a negative is enlarged enough. ”**

And, on p 32:

> **“While commonly called the emulsion, the light-sensitive layer of a film is actually a suspension of silver halide crystals in gelatin. The size and distribution of the crystals, the types of halides of which the crystal are made, their number, how they have been sensitized during manufacture, and the thickness of the emulsion layer, along with many controlling steps in the emulsion and film manufacture, determine such film characteristics as speed, contrast, characteristic curve shape, graininess, resolving power, and optical sensitivity.”**

In Kodak publication on motion picture film Publication **H-1** (1999) p 25:

> **“One might expect a photographic image made up of cyan, magenta, and yellow dye clouds to appear more grainy than the corresponding silver image. In fact, close to its resolution limit** [6 lp/mm, 300 ppi], **the eye sees only brightness differences and does not distinguish color in very small detail. When color films are projected, the “dye-cloud clusters” form groups similar to “silver-grain clusters” in black-and-white films. At high magnifications, these clusters cause the appearance of graininess in the projected screen image.”**



KODAK Technical Pan Film

Contact print (above) made from a full-frame 35 mm negative on KODAK T-MAX 100 Professional Film. The photos at the left–sections of the image above—show the grain structure of several popular Kodak black-and-white films magnified 13X.

KODAK T-MAX 100 Professional Film

KODAK PLUS-X Pan Film

KODAK T-MAX 400 Professional Film

KODAK TRI-X Pan Film

KODAK T-MAX P3200 Professional Film (Exposed at EI 3200)

Figure 12: From **Kodak Professional Black-and White Films** (1998) p 33.

On p 32: **"The densities in black-and-white negatives are composed of microscopic grains of metallic silver. Because the grains are placed randomly in the gelatin emulsion,** [visual] **clumping occurs and forms the familiar granular** [film grain] **pattern that becomes increasingly visible as negatives are enlarged to greater degrees.**

As a rule, the faster the film, the greater the tendency towards graininess. Kodak T-Max Professional films, however, bend this rule. Because these films have Kodak T-Grain Emulsion, they have finer grain than conventional films of comparable speed."

On p 33: **"The type of developer you use affects graininess. A fine grain developer decreases graininess, usually with some loss in speed. Overdevelopment, i.e., using and extended development time, a high temperature, or a highly active developer, increases graininess.**

High density [produced] **by overexposure of a negative also increases *graininess*. Proper exposure and development almost always produce an optimum level of graininess. (Large, even-toned areas in the mid-tones of a photograph will appear more grainy than dark- or light-toned areas or areas that include fine detail.)"**

On p 32: **"The ability of a film to record fine detail is called *definition*, which is a composite of granularity, resolving power, and sharpness. The measurement of this characteristic is called *resolving power* or *resolution.***

The visual effect of unevenness in areas that should be uniform is called *graininess*. An objective measurement of graininess is call *granularity.* [Referred to as RMS Granularity and Noise in this essay]

On p 34: **"The *sharpness* of a film is the subjective perception of good edge distinction between details in a photograph.**

Film manufacturers …measure this using a sine-wave test pattern …recorded on film…and scanned by sensitive measuring equipment. [known as an MTF Curve]

On the previous page are several images of the same subject shot on different films, showing increasing "graininess" in the series, from top to bottom. The images are taken from p 33, in **Kodak Professional Black-and-White Films**, F-5, (1998). The quotes on the right were pulled from pp 32-34, in the same publication.

Cross-Section of Film

While microscopic images of discrete silver particles can be made under special circumstances, the thickness of silver-halide-gelatin emulsion has tens, to hundreds, of silver particle stacked on one another in a small region. Even if human vision was more acute, individual particles could not be resolved because they are too close to each other when observed through the thickness of the emulsion.

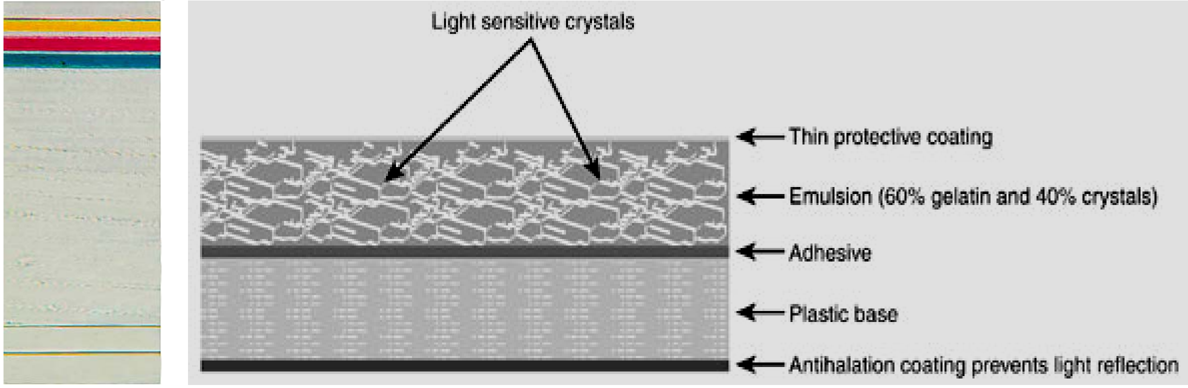


Figure 13: On the left: Figure 46 from Kodak H1, cross-section of a Kodak color negative film, the film is 0.075" thick, each dye layer is 0.003" thick. On the right: is a cross-section diagram from Sams Publication, ***Film Basics for Digital Photographers*** by John Upton, Joseph Ciaglia, Peter Kuhns & Barbara London: Ch 4, June 2004, it can be seen that individual silver particles would be difficult to resolve within the emulsion layer.

Grain Size Variability

Grain size is highly dependent on exposure and development for a specific film. This is noted above in the quotes from Kodak Professional Black-and-White Films, F-5 (1998), p 34.

In general, higher temperature favors larger grain; longer development time favors larger film grain size; and specific developers produced larger or smaller (B&W) grain depending on aggressiveness and pH.

Short exposures use mostly the larger more sensitive silver-halide particles in the film, creating in larger film grain for that exposure. Most films have low, medium and fast sensitivity layers, based mostly on silver-halide particle size. Film grain size, therefore, will vary from image to image but will probably stay within a range, based on the specific film emulsion.

RMS Granularity – Measure of Film Noise

RMS Granularity measures the noise in film, because it measures variation in an area of uniform density (usually 1.0D). RMS Granularity is not a measure of "graininess," even though several publications have made this mistake.

RMS Granularity as a measure of the variability of an area of uniform film density using a 48 um aperture <http://www.kodak.com/US/en/motion/support/h1/exposureP.shtml - tgrain>. Root Mean Square (RMS) is the standard deviation of, the Mean, of a range of density measurements, made on film at 1.0 D. It does not measure film grain size, but rather the variability of density at a specific density. Thus, RMS Granularity is a measure of film noise. The 48 um measurement aperture is much larger than actual silver particles so it can only measure the variability of density. In an area of uniform density, this variability is called <u>noise.</u> RMS Granularity numbers range from 5-50; the lower the number the lower the noise in a specific film.

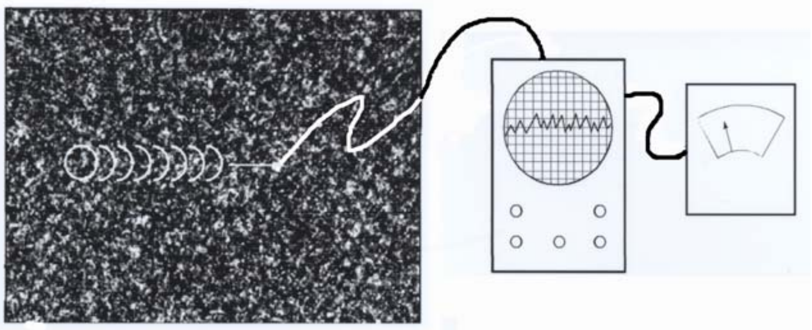


Figure 14: Measuring a RMS Granularity using a 48-micron sample area. Root Mean Square is the Standard Deviation of the Mean of the range of density measurements made on 1.0 D film. Image is from Kodak H-1(1999) p24.

After about 1980, film manufactures began measuring film "granularity" using the RMS Granularity protocol. Kodak slide films have a RMS Granularity of between 8 and 13 and Fuji reversal films have values between 7 and 10. Some color negative films have RMS Granularity rating of 5, quite noise free. However, the negative film must be printed, increasing their final "system" RMS Granularity, markedly.

RMS Granularity of Several Films: Data Table 2

Film Name	RMS Granularity*	Resolution lp/mm @ 30%	Resolution ppi @ 30%
Kodak PORTRA 160NC	NA	73	3708
Kodak ULTRA 100UC	NA	60	3050
Kodak EDUPE	8.7	60	3050
Kodachrome 25	9	50	2540
Kodachrome 64	10	50	2540
Ektachrome 5071 (dup)	9	50	2540
Ektachrome 50	13	40	2030
Ektachrome 64	12	40	2030
Ektachrome 100	11	45	2290
Ektachrome 100GX	8	60	3050
Ektachrome 100plus EPP	11	45	2290
Ektachrome 160	13	35	1780
Fuji Velvia 50 RVP	8	80	4064
Fuji Velvia 100 RVP100F	8	80	3300
Fuji Provia 100F RPD	9	55	2800
Fuji Astra 100 RAP	10	45	2290
Fuji Astra 100F RAP100F	7	65	3300
Fujichrome EI 100	10	45	2290
Average	9.8	64.3	3264

Film Resolution - Sharpness

Film Resolution defines the potential resolving power of a film; Kodak calls this ***sharpness***. Resolution is determined using the MTF Curve, which is found in the film data sheets supplied by manufacturers. However, the MFT curve is measured using a sine wave bar chart printed directly on the film. The actual resolution of film is made on the film through a lens in a camera. Based on the Resolving Power Equation(s) used by both Kodak and Fuji, the actual resolution of a "film-and-camera system" must be decreased by 30-80%, from native resolution. The greater the resolution of the film in a system, the greater the loss of the system resolution, for a specific lens with a given resolving power. This loss of system resolution is due to degradation of the image **(1)** exposed through a lens and **(2)** due to variables in film transport and film processing. This evaluation is covered in great detail in another essay by the author held in EMG Library <http://aic.stanford.edu/sg/emg/library/index.html>, see "Image File Formats: TIFF, JPEG & JPEG2000."

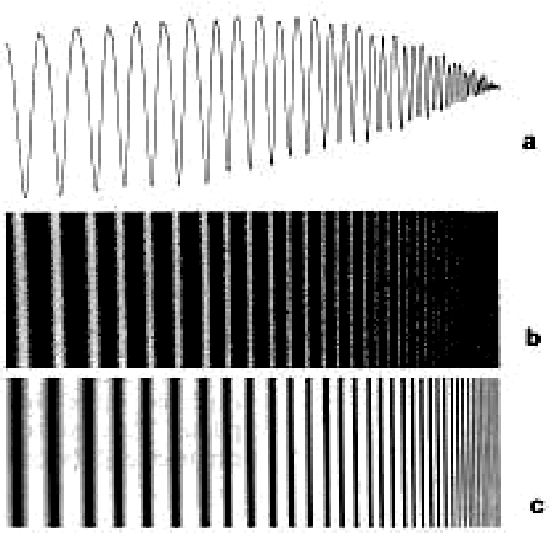


Figure 34
Image (b) of a sinusoidal test object (a) recorded on a photographic emulsion and a microdensitometer tracing (c) of the image.

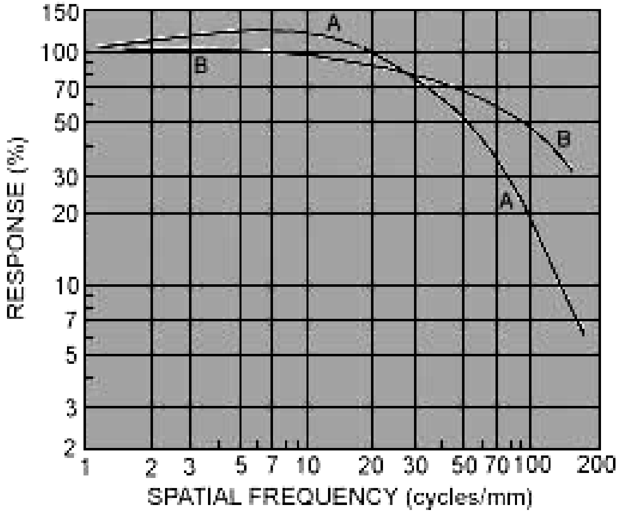
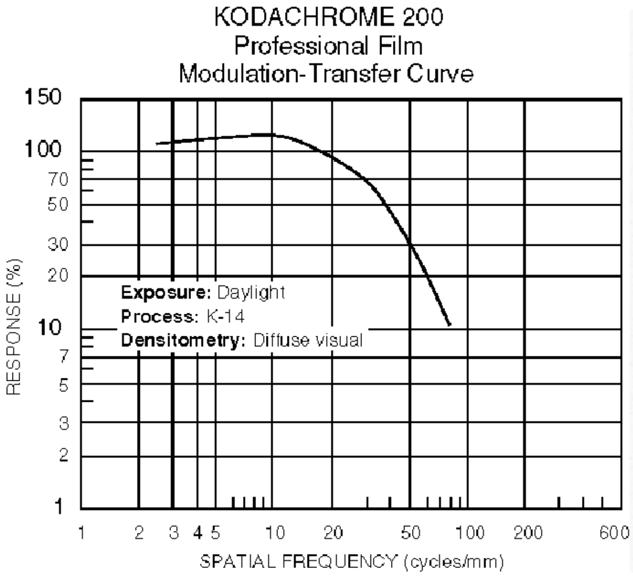


Figure 35
Modulation-transfer curves


KODACHROME 200
Professional Film
Modulation-Transfer Curve

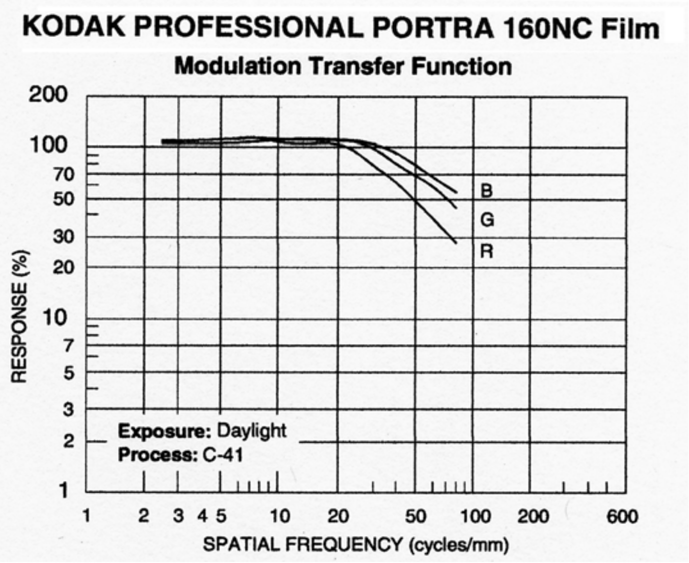

KODAK PROFESSIONAL PORTRA 160NC Film
Modulation Transfer Function

Figure 15: The images internally labeled "Figures 34 & 35" are from Kodak H-1 (1999) p 38. In Fig 35, curve A shows no edge-contrast sharpening while curve B does. In the lower row of graphs, there are two MTF Curves depicting both A & B behavior. Lower row, on the left, MFT Curve for Kodachrome 200 (PKL) from the Kodak data sheet, it shows edge enhancement with a direct-contact MTF value at 30% contrast difference (y axis) of 50-lp/mm. On the right, the MFT Curve from Kodak PORTRA 160NC color negative film that has only slight edge enhancement, with a direct-contact MTF value at 30% contrast difference of 63-lp/mm. Note that the MFT Curves for both films turn downward between 10-30 lp/mm, the influence of film grain on overall film resolution.

The MTF Curve of Kodachrome 200 (PKL) transparency film shows a native resolution of 50-lp/mm, (2540 ppi digital equivalent). Using the Fuji Resolving Power Equation, PKL shot through an excellent 35mm format lens (100 lp/mm lens) will have a final resolution of 33-lp/mm, with a digital equivalent resolution of 1962 ppi. This is a loss of 34% from the native MTF data, due to lens and film related issues. The downturn in the plot line suggests one the film grain size is about 10 lp/mm, or 50 um film grain, and another inflection is at 30 lp/mm, or 17 um film grain.

The Kodak PORTRA 160NC color negative film's MTF Curve shows a resolution of 73-lp/mm for the red dye layer, a digital equivalent resolution of 3708 ppi. The blue and green dye layers have higher contrast but the red dye clouds determine resolution because all the dye layers are seen together (except in an area with the exact red color of the dye) and are degraded by the red layer. When 160NC film resolution is run through the Fuji Resolving Power Equation [EQ2, below], using an excellent 35mm format lens (100 lp/mm lens) it will have a final resolution of 42-lp/mm, a digital equivalent resolution of 2143 ppi. This is a loss of 42% from the native MTF data. The downturn of the MTF plot suggests that the film grain ranges from 20-25 lp/mm, for the various dye layers, 25-20 um film grain.

System Resolving Power Equation

There are many factors rolled onto the equations below. In EQ1, one term (1/r) is for the film and other for the lens. Adding an enlarging lens, will add a third and forth term to the equation; lowering the overall image resolution profoundly.

$$\textbf{EQ1: } 1/R = 1/r_{\text{[film]}} + 1/r_{\text{[camera lens]}} + 1/r_{\text{[enlarging lens]}} + 1/r_{\text{[printing paper]}}$$

The Fuji resolving power equation found in the Fuji Handbook (p102, 1998) is EQ2:

$$\textbf{EQ2: } 1/R_{\text{[system]}} = 1/r_{\text{[film]}} + 1/r_{\text{[lens]}}$$

Where: (1) R = overall resolving power, and (2) r = resolving power of each component

Kodak uses the following equation, EQ3, in its datasheets and handbooks. It is more complicated, and yields almost the same results. It is NOT used below.

$$\textbf{EQ3: } 1/R^2_{\text{[system]}} = 1/r^2_{\text{[film]}} + 1/r^2_{\text{[lens]}}$$

Lens Issues Effecting Resolution

There are at least 7 different types of lens aberrations:

- **Chromatic aberration**
- **Spherical aberration**
- **Coma (uneven magnification)**
- **Astigmatism (non-flat focus)**
- **Flare (external light scattering)**
- **Dispersion (internal light scattering)**
- **Misaligned lens elements**

The center of the lens is generally the sharpest. Resolution declines towards the edge of the image circle. Good modern lenses are not capable of more than 80-140 line-pairs per millimeter (lp/mm) at the center of the lens, and much less, towards the edges. Wide apertures compromise image quality dramatically because the light goes through most of the glass in the lens. Low f-stops (f3.5 to f5.6) in large format lenses are only capable of 10-20 lp/mm at the edges wide open and chromatic aberrations can be extreme, with a rainbow of colors on large high-contrast features near the edges, where the colors focus in different locations.

Film Issues Effecting Resolution

The problems with film have been described in detail, in online publications. Achieving crisp focus is the principal problem. However, keeping the film flat in any camera, perpendicular to the lens axis in LF cameras, along with, many hands mixing processing chemicals introduce significant problems. The issues forming an image on film include:

- **Goodness of focus**
- **Trueness of lens axis to film axis**
- **Warp of the film in the film holder or film path**
- **Aperture size (f-stop)**
- **Shutter Speed**
- **Vibration in all phases**

- **Dirt and haze on lens (light scatter)**
- **Film developing variables (exhaustion, impure water or impure chemicals)**
- **Heat and humidity in storage, before and after exposure and processing**
- **Time since exposure, and, possible x-rays exposure during airport screening**

The exposure parameters of shutter speed and f-stop effect sharpness markedly. The f-stops above and below the optimal lens iris opening, f-8, degrade the image noticeably. Slow shutter speeds allow for hand-induced shake during exposure decreasing image sharpness. Fast shutter speeds require longer processing times which enlarges film silver particle size, decreasing film resolution. Mirror travel, and abrupt stops, in SLRs can have a large affect on camera movement (even while on a tripod) when using faster shutter speeds.

Evaluation a System: Camera, Lens and Film

Using the photographic system "Resolving Power Equation" EQ2 (see above) from **FujiFilm Professional Data Guide** AF3-141E (2002) p 129; and the data in the Data Table 3 below, the results are reported in Data Table 4, on the following page.

Selected Film and Lens Resolution Data: Data Table 3

Film	**Resolution**	**1/r** $_{[film]}$	**Film Resolution in ppi Direct Contact at 30% Contrast**
Kodak Ektachrome EKT 160	35 lp/mm	0.0286	1778
Fuji Astia RAP	45 lp/mm	0.022	2286
Kodak ULTRA 400UC	55 lp/mm	0.0182	2794
Kodak ULTRA 100UC	60 lp/mm	0.0167	3048
Kodak PORTRA 160VC	65 lp/mm	0.0154	3302
Kodak PORTRA 160NC	73 lp/mm	0.0136	3708
Fuji Velvia RVP	80 lp/mm	0.0125	4064
Kodak VR100 Color Neg	100 lp/mm	0.0100	5080
Kodak Plus-X	125 lp/mm	0.008	6350
Kodak T-MAX 100	160 lp/mm	0.00625	8128
Lens	**Resolution**	**1/r** $_{[lens]}$	**Lens Cost**
Old lens (1840-1930)	20 lp/mm	0.05	$50-1500
Average lens	40 lp/mm	0.025	$150-500
Good LF lens	60 lp/mm	0.0167	$300-800*
Very Good LF lens	80 lp/mm	0.0125	$1000-3000**
Excellent LF & 35mm lens	100 lp/mm	0.01	$350-5000***
Superior 35 mm lens	120 lp/mm	0.0083	$350-1000**§**
Outstanding 35mm lens	140 lp/mm	0.0071	$350-1000**Δ**
Best Possible 35mm lens	200 lp/mm	0.005	you won't find one
Vapor-ware lens	600 lp/mm	0.00167	you'll hear about it, but can't find one

* Many 35-mm, medium format and large format lenses used at f8, or better lenses used at f11 or f16.

** Schneider APO Symmar 150mm f5.6 lens set at aperture f8.

*** Many second tier lenses at f8.

§ Nikkor & Canon 50mm & 85mm lenses at f8, on a tripod, superior processing, film only, no prints.

Δ Leica or Zeiss 35 mm or medium format lenses.

In Data Table 4, some of the films from the list of the films above are exposed through generic lenses of varying quality (listed directly above) using equation EQ2. The data set assumes random use of f-stop, shutter speeds and point of focus. Fixed cameras, such as 35 mm rangefinders and SLR bodies and medium format (MF), 2¼ x 2¼, or 6 x 6 cm and 2¼ x 2¾, or 6 x 7 cm, have fairly flat film planes and rigidly fixed lens-to-film axis. Note that the film and lens systems described below degrade the overall image dramatically: 21-80%. The higher the native resolution of the film, the more it is degraded by the quality of the lens. When using "120-lp/mm" superior lenses on low-resolution film the image is degraded 23-33%. On high-resolution film, using the same superior lenses will degrade the final image by 40-57%.

Large format (LF) cameras use film holders, which do not have flat film planes; often the film sags at the bottom and the center may have a slight convex warp. The LF lens-to-film axis is never fixed and needs to be aligned for each setup. The Zigalign tool is commonly used to accomplish this critical task. The tilts and swings of view cameras (LF) used in product and architectural photography ignore axis alignment completely. In digital cameras, the capture media (CCD CMOS) is never warped or out of plane unless it was manufactured improperly.

Camera System Resolving Power: Data Table 4

Selected modern films are processed through EQ2, using various classes of lens quality: average (40 lp/mm), good (60 lp/mm), very good (80 lp/mm), excellent (100 lp/mm), superior (120 lp/mm), outstanding (140 lp/mm), best possible lens (200 lp/mm) and mythical lens (600 lp/mm).

ULTRA 100UC	**0.0167 + 0.025 = 0.0417**	**= 24 lp/mm**	**= 1220 ppi**	**60% loss**	**thru 40 lp/mm lens**
ULTRA 100UC	**0.0167 + 0.0167= 0.0334**	**= 30 lp/mm**	**= 1524 ppi**	**50% loss**	**thru 60 lp/mm lens**
ULTRA 100UC	**0.0167 + 0.0125= 0.0294**	**= 34 lp/mm**	**= 1727 ppi**	**43% loss**	**thru 80 lp/mm lens**
ULTRA 100UC	**0.0167 + 0.010 = 0.0267**	**= 37 lp/mm**	**= 1880 ppi**	**38% loss**	**thru 100 lp/mm lens**
ULTRA 100UC	**0.0167 + 0.0083= 0.025**	**= 40 lp/mm**	**= 2032 ppi**	**33% loss**	**thru 120 lp/mm lens**
ULTRA 100UC	**0.0167 + 0.0071= 0.0239**	**= 42 lp/mm**	**= 2126 ppi**	**30% loss**	**thru 140 lp/mm lens**
PORTRA 160NC	**0.0136+ 0.025 = 0.0386**	**= 26 lp/mm**	**= 1316 ppi**	**65% loss**	**thru 40 lp/mm lens**
PORTRA 160NC	**0.0136+ 0.0167 = 0.0303**	**= 33 lp/mm**	**= 1676 ppi**	**54% loss**	**thru 60 lp/mm lens**
PORTRA 160NC	**0.0136+ 0.0125 = 0.0261**	**= 38 lp/mm**	**= 1946 ppi**	**48% loss**	**thru 80 lp/mm lens**
PORTRA 160NC	**0.0136+ 0.010 = 0.0236**	**= 42 lp/mm**	**= 2153 ppi**	**42% loss**	**thru 100 lp/mm lens**
PORTRA 160NC	**0.0136+ 0.0083 = 0.0219**	**= 46 lp/mm**	**= 2320 ppi**	**37% loss**	**thru 120 lp/mm lens**
PORTRA 160NC	**0.0136+ 0.0071 = 0.0207**	**= 48 lp/mm**	**= 2454 ppi**	**34% loss**	**thru 140 lp/mm lens**
Fuji Velvia RVP	**0.0125 + 0.025 = 0.0375**	**= 27 lp/mm**	**= 1372 ppi**	**66% loss**	**thru 40 lp/mm lens**
Fuji Velvia RVP	**0.0125 + 0.0167= 0.0292**	**= 34 lp/mm**	**= 1727 ppi**	**58% loss**	**thru 60 lp/mm lens**
Fuji Velvia RVP	**0.0125 + 0.0125= 0.025**	**= 40 lp/mm**	**= 2032 ppi**	**50% loss**	**thru 80 lp/mm lens**
Fuji Velvia RVP	**0.0125 + 0.010 = 0.0225**	**= 44 lp/mm**	**= 2235 ppi**	**45% loss**	**thru 100 lp/mm lens**
Fuji Velvia RVP	**0.0125 + 0.0083= 0.0208**	**= 48 lp/mm**	**= 2442 ppi**	**40% loss**	**thru 120 lp/mm lens**
Fuji Velvia RVP	**0.0125 + 0.0071= 0.0196**	**= 51 lp/mm**	**= 2592 ppi**	**36% loss**	**thru 140 lp/mm lens**
Kodak Plus-X	**0.008+ 0.025 = 0.033**	**= 30 lp/mm**	**= 1524 ppi**	**76% loss**	**thru 40 lp/mm lens**
Kodak Plus-X	**0.008 + 0.0167 = 0.0247**	**= 40 lp/mm**	**= 2032 ppi**	**68% loss**	**thru 60 lp/mm lens**
Kodak Plus-X	**0.008 + 0.0125 = 0.0205**	**= 49 lp/mm**	**= 2480 ppi**	**61% loss**	**thru 80 lp/mm lens**
Kodak Plus-X	**0.008 + 0.010 = 0.018**	**= 56 lp/mm**	**= 2822 ppi**	**56% loss**	**thru 100 lp/mm lens**
Kodak Plus-X	**0.008 + 0.0083 = 0.0163**	**= 61 lp/mm**	**= 3117 ppi**	**51% loss**	**thru 120 lp/mm lens**
Kodak Plus-X	**0.008 + 0.0071 = 0.0151**	**= 66 lp/mm**	**= 3365 ppi**	**47% loss**	**thru 140 lp/mm lens**
Kodak Plus-X	**0.008 + 0.005 = 0.013**	**= 77 lp/mm**	**= 3912 ppi**	**38% loss**	**thru 200 lp/mm lens**
Kodak T-Max	**0.0063+0.025 = 0.0313**	**= 32 lp/mm**	**= 1623 ppi**	**80%loss**	**thru 40 lp/mm lens**
Kodak T-Max	**0.0063+0.0167 = 0.0217**	**= 43 lp/mm**	**= 2209 ppi**	**73% loss**	**thru 60 lp/mm lens**
Kodak T-Max	**0.0063+0.0125 = 0.0188**	**= 53 lp/mm**	**= 2702 ppi**	**67% loss**	**thru 80 lp/mm lens**
Kodak T-Max	**0.0063+0.010 = 0.015**	**= 61 lp/mm**	**= 3117 ppi**	**62% loss**	**thru 100 lp/mm lens**
Kodak T-Max	**0.0063+0.0083 = 0.0133**	**= 68 lp/mm**	**= 3479 ppi**	**57% loss**	**thru 120 lp/mm lens**
Kodak T-Max	**0.0063+0.0071 = 0.0121**	**= 73 lp/mm**	**= 3708 ppi**	**54% loss**	**thru 140 lp/mm lens**
Kodak T-Max	**0.0063+0.005 = 0.01**	**= 88 lp/mm**	**= 4496 ppi**	**45% loss**	**thru 200 lp/mm lens**
Kodak T-Max	**0.0063+0.00167= 0.00797**	**=125 lp/mm**	**= 6374 ppi**	**21% loss**	**thru 600 lp/mm lens**

Measuring Film Grain

The most common method of evaluating film grain is to enlarge the image until “modulation,” of an area of uniform density, becomes obvious (***The Science of Photography***, Baines, 1976, Ch 18, p 228). The modulation never has sharp edges because it is not made of discrete particles. In an area of 1.0D (dark gray film) the image is made of hundreds of unseen silver particles, side by side and one piled on another through the depth of the film emulsion layer. The “modulation” is film grain.

In Mees & James (1967) they also say the only effective way to measure grain is to enlarge the film photographically until the film grain becomes evident. They warn that the results can be highly variable, based on the capabilities and skills of the people doing the evaluations and recommend using statistics. Training the observers also helps reduce variation in data.

Magnification (by loupe or microscope) is uniformly discouraged as a method because the evaluation is perceptual rather than an objective evaluation of discrete particles of a specific size. All these problems explain why the film manufacturers moved towards using Print Grain Index as a tool for defining film grain.

Print Grain Index

Print Grain Index is a modern tool used to evaluate graininess in an enlargement of color film negatives. Kodak Portra 160NC shows just perceptible film grain at 4.3X enlargement.

The terms Graininess and RMS Granularity are often confused or even used as synonyms in discussions of silver-halide or silver-to-dye-deposit distributions in photographic emulsions. The two terms refer to two distinctly different ways of evaluating film. When a photographic image is viewed with sufficient magnification, the viewer experiences the visual sensation of graininess, a subjective impression of a random round pattern in an image. This pattern can also be measured for its variability of film density (only) using a microdensitometer: this is known as RMS Granularity.

B&W films consist of silver-halide crystals dispersed in gelatin (the emulsion) and coated in a thin layer on a plastic support (the film base). The exposure and development of these silver crystals forms the photographic image. Residual silver (unexposed and undeveloped) is removed by the fixer.

In color processes, the initial light sensitive silver particles are removed after development. The dye clouds are center on, and form around, the silver-halide crystals. The original silver-halide crystals, and clumps of crystals, vary in size, shape and sensitivity. Large particles are more sensitive while the smaller, are less sensitive to light.

Silver particles are randomly distributed within an emulsion. Within an area of uniform exposure, some of the silver crystals will be made developable by exposure to light while others will not. Development usually does not change the position of a silver particle.

Randomness is a necessary condition for the perceptual phenomenon of film grain. If the particles were arranged in a regular pattern, such as a halftone dot pattern used in graphic arts, no sensation of graininess would be created. When a halftone is viewed at a magnification sufficient for the dots to be distinguished, the eye notices the regular dot pattern and does not group dots into random patterns, just the existing half-tone pattern. Even though the half-tone dot pattern can be seen, the eye does not perceive graininess because the pattern is regular and not random. At lower magnifications, where the half-tone dots can no longer be resolved, the awareness of half-tone pattern fades away and the image appears smooth, patternless and grainless.

When a random pattern of small dots is viewed with magnification sufficient to resolve the individual dots no pattern can be recognized. When the magnification is decreased so the dots cannot be resolved, they appear to blend together to form a grainy pattern. Further explanations can be found in the Kodak Publication E-58 on graininess and granularity: ***Technical Publication: Print Grain Index*** found at URL <http://www.kodak.com/global/en/professional/support/techPubs/e58/e58.pdf>.

Size of Film Grain: Example

Film grain will be examined using two methods: **(1)** magnification and **(2)** print enlargement.

Size Domains for Magnification and Enlargement Methods: Data Table 5

Sample	Magnification	Method	Estimated Film Grain Size
Unknown B&W film, Fig. 18d	400x	Light Microscope	0.5 um
Unknown B&W film, Fig. 18c	60x	Light Microscope	2.1 um
Unknown B&W film, Fig. 18b	20x	Light Microscope	11.2 um
Portra 160NC	4.3x	Print Enlargement PGI	20.0 um
Unknown B&W film, Fig. 18a	2.5x	Light Microscope	34.0 um
Average Human Visual Acuity	1x	Human Eye	85.0 um
Best Possible Human Acuity	1x	Human Eye	60.0 um

Figure 18c, below, is taken from Kodak **H-1** <http://www.kodak.com/US/en/motion/support/h1/exposureP.shtml - tgrain>. It shows one B&W image at **(a)** 2.5**X**, **(b)** 20**X**, **(c)** 60**X**, **(d)** 400**X** and **(e)** ≈800**X** in an SEM. The absolute limits of resolution for the various magnifications are listed in Data Table 3, above. This is based on the average human visual acuity of 85 um; the best reported visual acuity is 60 um (8 lp/mm) and the worst is 120 um (4 lp/mm).

In the table above the rate of magnification was divided by the average limit of human visual acuity, 85 um, or 6-lp/mm, to yield the smallest estimated particle that could be resolved under ideal circumstances (high-NA objective using oil immersion of objective and Abbe condenser). The light microscope is capable of resolving 0.2 um (microns) using a **(1)** 1.25 NA 100x objective and **(2)** a 1.25 NA Abbe Condenser both with oil immersion.

Figure 16: Images pulled from <http://www.microscope-microscope.org/advanced/numerical-aperture.htm>

Since the silver metal particles after development, in average B&W film, are about 1-2 um, they are just visible in the light microscope at 400**x**.

$$\mathbf{EQ4:}\quad \mathbf{d} = 1.22\cdot\boldsymbol{\lambda} / \mathbf{NA}_{\text{(objective)}} + \mathbf{NA}_{\text{(condenser)}}$$

Where **d** is the distance between two dark particles in microns, **λ** is the wavelength of light, such as green light at 0.55 um (550 nm) and **NA** is the numerical aperture of the lenses being used (objective or condenser). The condenser's NA cannot be greater than the objective's NA. Note that the objective lens is usually magnified by a 10x ocular (eyepiece), resulting in a 60x objective producing 600x magnification at the specimen.

Maximum Resolution of Light Microscope at Average Human Visual Acuity: Data Table 6

Objective	Oil Immersion	NA	Abbe Condenser	NA	Oil Immersion	Resolution (um)
2x	no	0.06	no	0.00	no	11.2
4x	no	0.10	no	0.00	no	6.7
4x	no	0.10	yes	0.10	no	3.4
6x	no	0.16	yes	0.16	no	2.1
10x	no	0.25	yes	0.25	no	1.3
20x	no	0.40	yes	0.40	no	0.83
40x	no	0.65	yes	0.65	no	0.51
50x	yes	0.90	yes	0.90	no	0.37
60x	no	0.75	yes	0.75	no	0.45
100x	no	0.90	yes	0.90	no	0.37
100x	yes	1.25	yes	1.25	yes	0.26

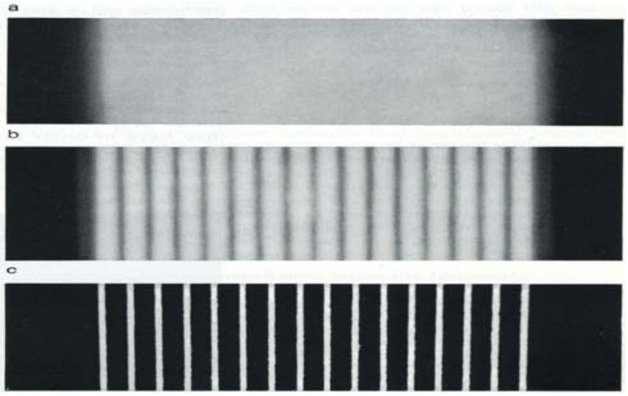


Figure 17

The image on the left (Figure 17) shows the effect of increasing lens resolution, or numerical aperture (NA) for microscope lenses, so that the scatter of light coming from the lighter features, between the black bars, are eliminated as the features are resolved by the lens. The image is taken from **Microscopy from the Very Beginning,** Friedrich K Mollring, Carl Zeiss Publisher, West Germany (1971) p 40.

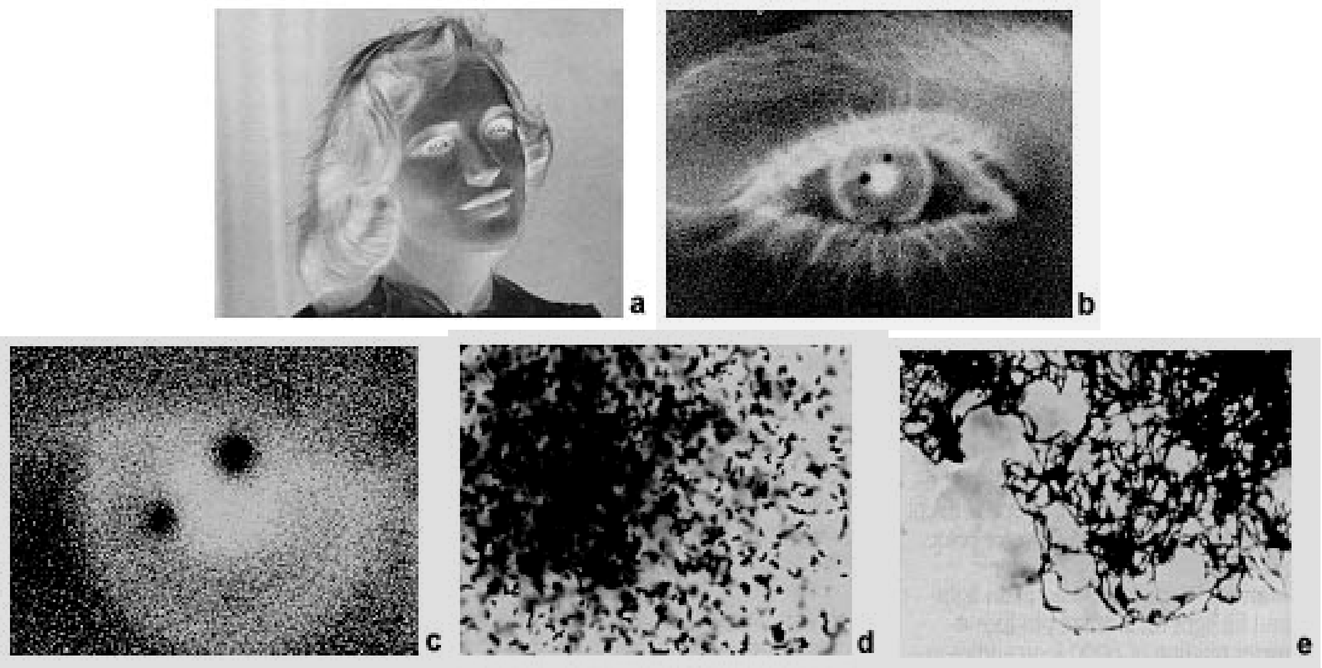


Figure 18: from Kodak **H-1**, Fig. 15: **(a)** a 2.5X enlargement of a negative shows no apparent graininess; **(b)** at 20X some graininess shows; **(c)** when inspected at 60X the individual film grains become distinguishable; **(d)** at 400X magnification, the discrete particles can be seen, note that surface particles are in focus while those deeper in the emulsion are out of focus, the apparent "clumping" of silver grains is actually caused by the overlap of grains at different depths when viewed; **(e)** the makeup of individual grains takes different forms, this image shows filamentary silver enlarged in an electron microscope, when at low magnification filaments appear s a single particle.

Kodak has begun to use Print Grain Index (PGI) to define the degree of usable enlargement for some of its color negative films: PORTRA and ULTRA. The PGI data for Portra 160NC color negative film <http://www.kodak.com/global/en/professional/support/techPubs/e190/e190.pdf> is on page 7 in the PDF; see screen captures below.

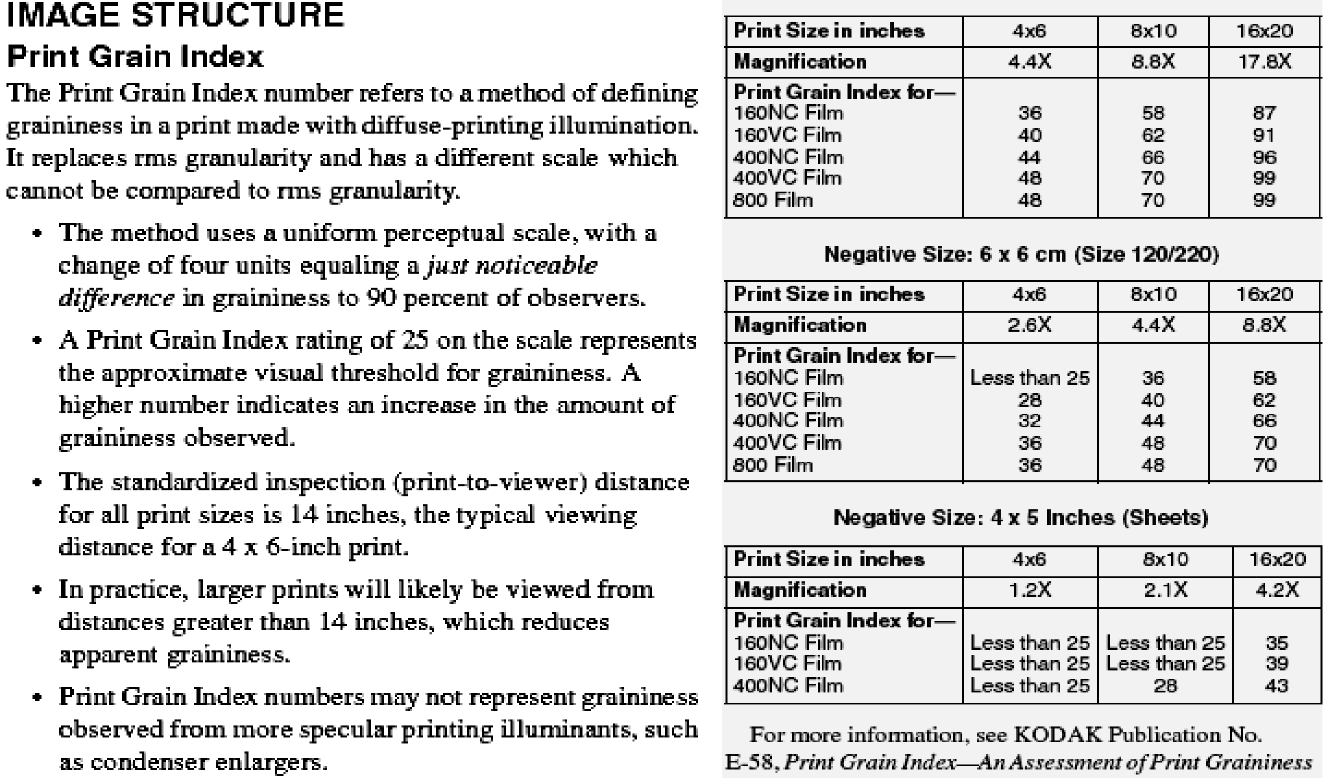


IMAGE STRUCTURE

Print Grain Index

The Print Grain Index number refers to a method of defining graininess in a print made with diffuse-printing illumination. It replaces rms granularity and has a different scale which cannot be compared to rms granularity.

- The method uses a uniform perceptual scale, with a change of four units equaling a *just noticeable difference* in graininess to 90 percent of observers.
- A Print Grain Index rating of 25 on the scale represents the approximate visual threshold for graininess. A higher number indicates an increase in the amount of graininess observed.
- The standardized inspection (print-to-viewer) distance for all print sizes is 14 inches, the typical viewing distance for a 4 x 6-inch print.
- In practice, larger prints will likely be viewed from distances greater than 14 inches, which reduces apparent graininess.
- Print Grain Index numbers may not represent graininess observed from more specular printing illuminants, such as condenser enlargers.

Negative Size: 24 x 36 mm (Size 135)

Print Size in inches	4x6	8x10	16x20
Magnification	4.4X	8.8X	17.8X
Print Grain Index for—			
160NC Film	36	58	87
160VC Film	40	62	91
400NC Film	44	66	96
400VC Film	48	70	99
800 Film	48	70	99

Negative Size: 6 x 6 cm (Size 120/220)

Print Size in inches	4x6	8x10	16x20
Magnification	2.6X	4.4X	8.8X
Print Grain Index for—			
160NC Film	Less than 25	36	58
160VC Film	28	40	62
400NC Film	32	44	66
400VC Film	36	48	70
800 Film	36	48	70

Negative Size: 4 x 5 Inches (Sheets)

Print Size in inches	4x6	8x10	16x20
Magnification	1.2X	2.1X	4.2X
Print Grain Index for—			
160NC Film	Less than 25	Less than 25	35
160VC Film	Less than 25	Less than 25	39
400NC Film	Less than 25	28	43

For more information, see KODAK Publication No. E-58, *Print Grain Index—An Assessment of Print Graininess*

Figure 19: Taken from Kodak publication E-58 <http://www.kodak.com/global/en/professional/support/techPubs/e190/e190.pdf>.

The data shows that a **4.2x** to **4.4x** enlargement has “just visible” film grain. This 4.4**x** enlargement has a 36 PGI rating (when 25 PGI is just visible). At that magnification, individual dye clouds can’t be distinguished within a region of normal density (0.3 -1.0 D), but only at the edges of very thin regions.

If we assume that the undeveloped silver particle size in Kodak Portra and Ultra color negative films are 0.6 - 0.8 um, the dye clouds would range from 10-25 um. Multiplying 10-25um dye clouds, by 4.3**x**, yields a size range of 43-108 um. The size range has the digital equivalent of 233 ppi to 590 ppi.

The sharpness of the two films are: 73 lp/mm (PORTRA 160NC) and 60 lp/mm (ULTRA 160UC) at 30% contrast, or 3708 and 3048 ppi digital equivalent, native resolution not adjusted for exposure through a lens.

4 Eliminating Film Grain from an Image: Grain is a Regular Noise Pattern

Scanner operators have two operations that are used to approach the goal of eliminating film grain: **(1)** wet mounting and **(2)** scan aperture. Wet mounting can be used with equal effectiveness by flatbed and drum scanner operators to diminish perceived film grain. However, however the wet mounting procedure cannot be used on film scanners (made for just scanning film) because of their physical configuration. Figure 20 below was taken from the ICG website technical paper “A Drum Scanner or a Flatbed” <http://www.icg.ltd.uk/icg/whydrum.htm>.

Drum Scan: Aperture

Aperture is the opening at which the analog PMT (photo-multiplier tube) measures the intensity of light coming from the film. The analog light value measured by the PMT is converted into a digital RGB value in the analog-to-digital converter (A-D), commonly 12-bit native, for most drum scanners.

If the scan aperture is approximately equal to the perceived grain size, (a value determined from the experience of the operator) the noise of the “variations” across individual “film grains” is eliminated when the average density for that region is measured by the PMT.

If the pitch of the image pixels (ppi) is set slightly larger than, or equal to, the aperture size, the uniform density of the light through the aperture is represented by an area of uniform digital image density (D) in the final digital image pixel, on a one-to-one basis. The measured image density for the pixel -- minus the image noise introduced by the variations across the film grain -- is rendered as a uniform RGB value for each individual pixel. This eliminates film grain on the capture level.

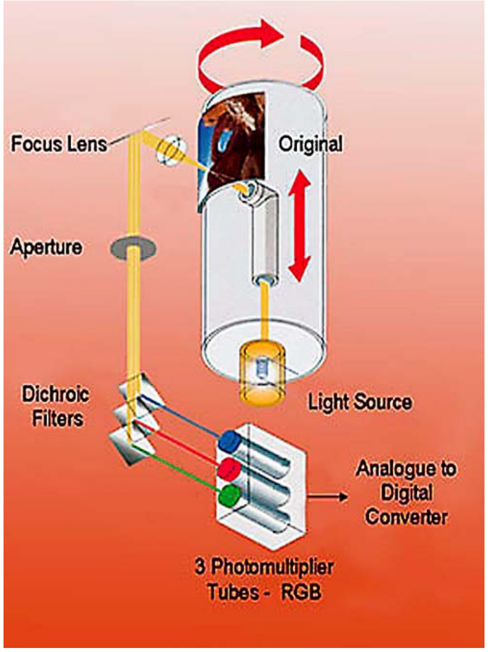


Figure 20: Drum scanner schematic pulled from ICG website.

Each pixel has the same RGB value within that pixel, such as RGB = 128, 128, 128, representing 0.65 D (density), in 24-bit, Gamma 2.2, color space (Adobe RGB 1998).

Often, a drum scanner operator will choose a pixel pitch (ppi) that is much smaller than the aperture. Thus, the uniformly digitized RGB value captured at a fixed aperture is spread over a larger number of pixels, each smaller in area than the size of the original aperture used for capture. An example would be the operator choosing a 12 um aperture (113 um^2 round) because it was an estimation of film grain size, and then using a 5335 ppi pixel pitch (4.75 um square). This setup would yield 5 pixels (22.5 um^2) per aperture area (113 um^2). Each of the 5 pixels is given the RGB value created by the A-D converter from the light intensity measured through the aperture by the PMT. The greater the pixel population, all without the noise from film grain, allows a given image to be enlarged more that the equivalent raw film would be, given its obvious perceived film grain.

Feature Size versus Digital Resolution versus Film Resolution: Data Table 7

Feature Size	Digital Resolution	Film Resolution
0.1 um	254,000 ppi	NA
0.2 um	127,000 ppi	NA
0.5 um	50,800 ppi	NA
0.8 um	31,750 ppi	NA
1.0 um	25,400 ppi	500 lp/mm
2.0 um	12,700 ppi	250 lp/mm
4.0 um	6,350 ppi	125 lp/mm
5.0 um	5,080 ppi	100 lp/mm
5.3 um	4,800 ppi	94 lp/mm
5.5 um	4,618 ppi	91 lp/mm
6.0 um	4,233 ppi	83 lp/mm
6.34 um	4,000 ppi	79 lp/mm
7.0 um	3,629 ppi	71 lp/mm
8.0 um	3,175 ppi	63 lp/mm
8.47 um	3,000 ppi	59 lp/mm
9.0 um	2,822 ppi	56 lp/mm
10.0 um	2,540 ppi	50 lp/mm
10.5 um	2,400 ppi	48 lp/mm
12.0 um	2,117 ppi	42 lp/mm
13.0 um	1,954 ppi	38 lp/mm
15.0 um	1,693 ppi	33 lp/mm
20.0 um	1,270 ppi	25 lp/mm
21.2 um	1,200 ppi	24 lp/mm
25.0 um	1,016 ppi	20 lp/mm
50.0 um	508 ppi	10 lp/mm
60.0 um	423 ppi	8 lp/mm
75.0 um	340 ppi	7 lp/mm
85.0 um	300 ppi	6 lp/mm
100 um	254 ppi	5 lp/mm
1000 um	25.4 ppi	1 lp/mm
1000000 um	One Meter	0.01 lp/mm

In this example, the 35 mm B&W film image (12 um = 2117 x 3176 pixels) would enlarge well to a 7 x 10 print, at the equivalent of 300 dpi or 6 lp/mm. On the other hand, the drum scanned digital version described above could be enlarged to a 16"x 25" print, 5 times larger, with individual pixels printed at 300 dpi, the average human perception.

Balancing aperture and pixel pitch is the art of drum scanning. This sort of graceful lying is common in drum scans. Note that these procedures remain highly prized; based on the high monetary value these scan fetch in the marketplace, even in the presence of flatbed scanners with equal or greater resolution.

Scan Resolution in Flatbed Scanning

The same workflow (increasing number of pixels over the scan pitch) could be followed using a flatbed scanner. However, this is not commonly done because it is seen as padding the actual image resolution.

In an analogous workflow, the 35mm B&W negative would be scanned at 2100 ppi (lets say), which would be equivalent to a 12 um aperture on a drum scanner. The 8-bit B&W file size would be 6.6M pixels, or 2100 x 3150 pixels. In Photoshop the total number of pixels would be increased five times (6.6M x 5 = 33M pixels) using <Image<Image Size< to a 4700 x 7050 pixel image. The process is not exactly the same as drum scanning for many reasons, but the effect is the almost the same.

The major difference is that the lens used in the flatbed scanner must transmit image detail, while the lens in the drum scanner transmits no image detail, just light intensity. Thus the lens in the flatbed scanner is the limiting factor in resolution of the system. This is the same phenomenon found in image capture using a film or digital camera.

The "art" of this process would be to scan at a low enough resolution (1600 to 2200 ppi) to eliminate the perceived film grain, and then enlarge the resulting pixel count in Photoshop, producing directly cloned pixels of small dimensions. If one wanted to print a grainless 16" x 24" image from the 35 mm negative, at the standard 300 dpi, one would need a minimum of 4800 x 7200 pixels (8-bit, B&W, 34 MB file; 24-bit color image would create a 103 MB file; 48-bit color would produce a 206 MB file).

The master pixels would represent film density values, from 11.8 x 11.8um squares [140 um^2] of the film, when scanned at the digital resolution of 2150 ppi. The five pixels [140 um^2⁄28 um^2 = 5 pixels] cloned in Photoshop, from each master pixel, would be 5.3 x 5.3 um square [28 um^2] with a digital resolution of 4800ppi. Each clone would be one-fifth the size of the master, and possess exactly the same RGB value as the master.

Wet Mounting for Film Scanning

The other method of diminishing film grain pioneered by drum scan operators is wet mounting the film in organic solvent. This is also known as wet gate scanning in the world of motion picture film digitization. In both digital capture realms it is known for eliminating scratches in the base and reducing grain by making it look more like it should, soft, because grain is soft due to it diffuse nature.

Figure 21: Scanned by author using both dry (left) and wet mount (right) techniques, at 4800 ppi optical resolution, using 16-bit B&W dynamic range, on an Epson 4990 flatbed. Film grain should look soft because it is perceived through the thickness of the emulsion layer.

In the image above, both scans were made on the same scanner with the same settings, such as **(a)** no sharpening, **(b)** no automatic range or contrast adjustments, **(c)** no color management and **(d)** raw to gamma 2.2 onboard, all at 4800 ppi resolution using 16-bits B&W capture (Epson 4870 flatbed, at its maximum optical resolution).

The difference between the two images is that the image on the left was done in the standard manner (film sitting on the platen, dry) and the one on the right was mounted in Stoddard's solvent on the glass platen, with another layer of Stoddard's solvent and a Mylar sheet as a top layer. Thus, the wet-mounted film was encapsulated in solvent, which eliminates light scattering from the **(1)** surfaces of the film, **(2)** any dust particles or scratches in/on the film and **(3)** minimize scattering from colloidal silver deposits caused by "silvered-out" image silver over time, while also **(4)** minimizing flare, from, **(5)** the diffuse light passing through the film from the traveling light source. Diffuse light (from many directions) is known from film enlarging, to reducing the dominance of film grain.

New Generation of Flatbed Scanners

The Epson 4870 & 4990 uses two-banks of RGB pixel rows (RRGGBB – see top of Figure 22) on the CCD chip. The native resolution of the CCD is 2400ppi. However, the upper row has of each color's pixels is shifted one-half a pixel width. And, each pixel has Individual lenses in the 6-line chip. This technology was pioneered in digital camera technology, where light was gathered from the full area of the pixel rather then the 30-70% area used to gather light with the remaining area being used for localized electronics for the transfer of electrons to the analog to digital converter. The lenses focus light from half the pixel width (2400 ppi) on alternating row of the same colored pixels. In the images below, pulled from the Epson website in Japan, a depiction of the process can be seen, note the half-pixel offset seen in Figure 22. The Epson F-3200 Film Factory (Figs has not been released in the US, it used a 6-line CCD with 1600 ppi native resolution.

The following diagrams were harvested from the Epson Japanese website <http://www.i-love-epson.co.jp/products/colorio/scanner/f3200/index.htm> and <http://www.i-love-epson.co.jp/products/colorio/scanner/gtx750/index.htm>. While largely in Japanese, there are enough English words used for the diagrams to be understood after some study.

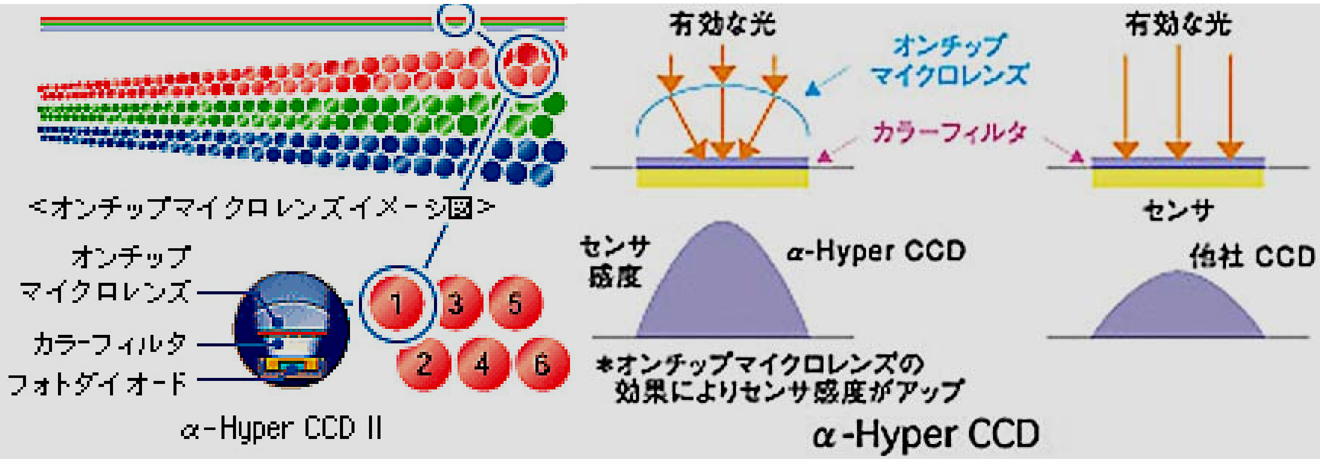


Figure 22: From Epson Japanese F-3200 webpage: (1) shows the new alpha-Hyper CCD II and its cross-section, (2) with the two rows of the same colored pixels offset by half-a-pixel including (3) the microlenses over each individual pixel that collect light at half the pitch of the full array. For the F-3200 the pitch is 1600 ppi; for the GT-X750 (Japan) or 4870/4900 (USA) the pitch is 2400 ppi. The lenses focus image information at twice the density of a single row, because they are offset by a half-pixel width. The center and right diagrams of the top row show how the microlenses collect light and focus it on the active area of the pixel (center) while the image on the right shows the standard CCD configuration where light is focused on the chip by the system's lens. The "active" area on a CCD chip ranges from 30-70% of the full pixel area; the remaining pixel area is reserved for circuitry. The alpha-Hyper CCD has 6 lines of pixels with an "RRGGBB" configuration (top row left diagram) as opposed to the 3 lines of pixels in the normal "RGB" configuration usually found in other (a) flatbed, (b) dedicated film scanners and (c) digital scanning backs used in view cameras (LF).

The following image of a silicon-based sensor and quote is from the ExtremeTech at <http://www.extremetech.com/article2/0,1697,1157576,00.asp>. It shows microlenses over each pixel and a cross-section diagram with microlenses over a silicon array.

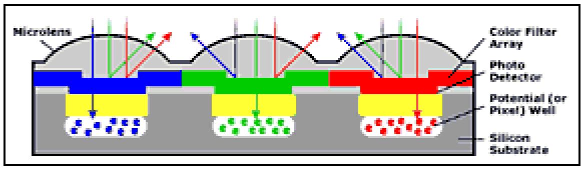


Figure 23: ExtremeTech website, "How Color Is Created: All image sensors are grayscale devices that record the intensity of light from full black to white, with the appropriate intervening gray. To add color to a digital camera image, a layer of color filters is bonded to the silicon using a photolithography process to apply color dyes. Image sensors that have micro lenses will put the color between the micro lens and the photodetector. With scanners that use trilinear CCDs (three adjacent linear CCDs using different colors, typically red, green, and blue) or high-end digital cameras that use three area array image sensors, it's a very simple issue of coating each of the three sensors with a separate color. (Note that some multi-sensor digital cameras use combinations of colors in their filters, rather than the three separate primaries). But for single sensor devices, such as the majority of consumer and prosumer digital still cameras used today, color filter arrays (CFAs) are used."

Kodak sells trilinear arrays, the following CCD being used in BetterLight scanning backs is probably the Kodak KLI-8023 which has 8002 pixels, that are 9um x 9um square, on a sensor that is 2.83" long without the enclosure, and 3.7" with; the URL for the sensor is <http://www.kodak.com/global/en/digital/ccd/products/linear/KLI-8023/specifications.jhtml?id=0.1.6.4.13.4&lc=en>.

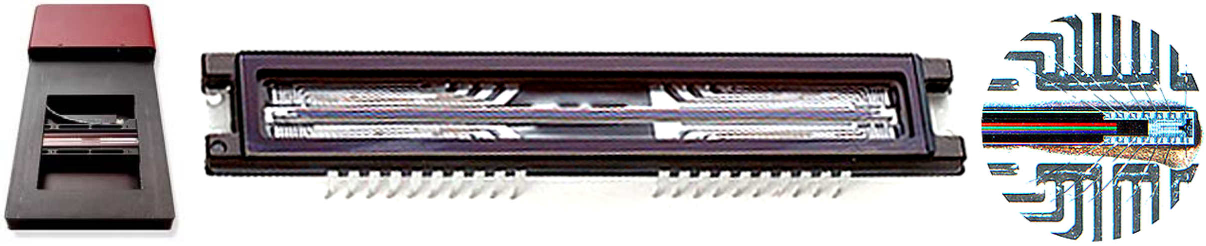


Figure 24: Taken from the BetterLight website (see below), (1) left image shows the scanning-back with the sensor parked mid-scan; (2) the center image shows an enlargement of the trilinear CCD array with "RGB" rows of pixels and (3) on the right, an end of the array is a further enlarged showing the actual red, green and blue bands of pixels.

The following is a quote from Mike Collette's "Scanning backs…How They Work" webpage on the BetterLight website **<**http://www.betterlight.com/how_they_work.html**>:**

> **"The trilinear sensor** is mounted in a ball bearing carriage that glides on a precision track cut into the metal body frame, and is accurately positioned by a matched polymer nut and stainless steel drive screw directly coupled to a high-torque step motor with up to 6400 micro-steps per revolution, for outstanding smoothness at any motor speed. This motor is driven by a dedicated microcontroller that also controls the sensor's exposure and timing, for crystal-accurate synchronization of these important functions."

This design is more solid and accurate than most flatbed scanners, which are also 4-8 times the size but it is basically the same design. Further quoting from the BetterLight webpage:

> **"Within the image sensor, three rows of light-sensitive photodiodes are each covered by a red, green, or blue color filter, making the entire row sensitive to only one primary color.** While Kodak's trilinear sensors use CCD (charge-coupled device) technology like many other digital cameras, in these devices the CCD structures are "blind" (not sensitive to light), and serve only as charge transport "conveyor belts" to carry the individual pixel signals from the photodiodes to an output amplifier for each row. Because there is no need to have the three rows of photodiodes immediately adjacent to each other, a wide CCD structure is positioned adjacent to each row of photodiodes, with the necessary electrical couplings between them. The CCD structure is wider than the photodiode structure so it can carry bigger charge packets (more electrons), which improves dynamic range.
>
> Because of this dual photodiode/CCD structure, these sensors can be reading out three previous rows of color pixel information via the CCD structures while the next three rows of color pixels are being collected in the photodiodes. This allows continuous exposure and readout of the sensor during a scan, without requiring any mechanical shutter. **Better Light scanning backs do not stop and start the scanning mechanism** to allow the data-collection system to "catch up" – instead, the sensor is always moved smoothly and continuously throughout each capture."

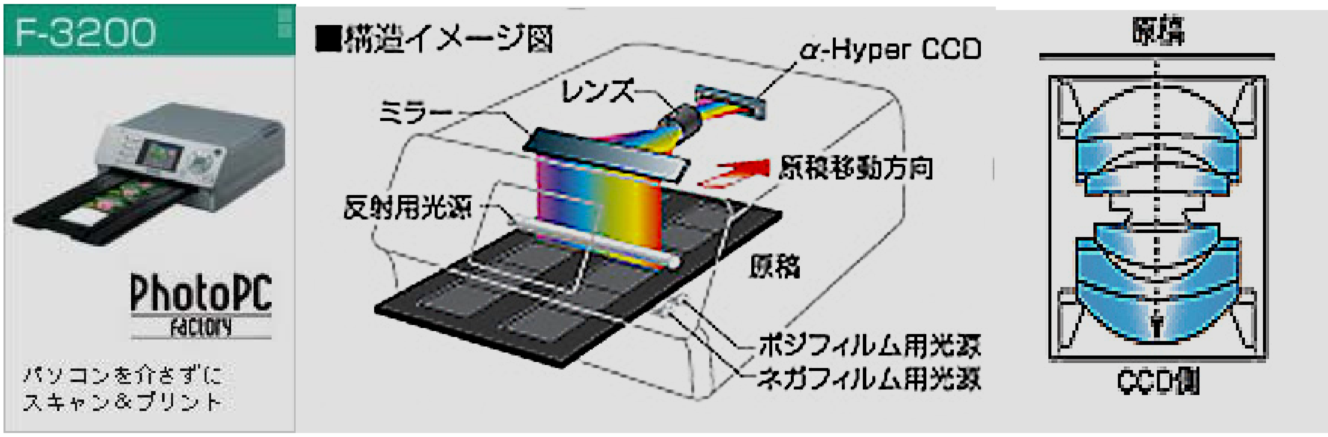


Figure 25: From Epson Japanese F-3200 & GT-X750 webpages: (1) notice that the full width of the "line" being scanned is shaped into an anamorphic image that is focused on the lens, (2) notice the location of the lens between the mirror and the CCD and on the right (3) a typical Epson scanner lens (GT-X750) that has 6 elements in 4 groups, which is a very good optical configuration, especially when the elements are multicoated.

Future Generation of Scanners – Epson Perfection V750-M

The next generation of Epson flatbed scanners is scheduled to be released in May 2006, a quote from the Epson US website:

> “…the Epson Perfection™ V750-M Pro, [is] the first flatbed scanner with ground breaking 6400 dpi resolution and unique fluid mount capabilities for photo studio applications. With amazing 6400 dpi resolution, this powerful performer consistently delivers precision color and detail. An enhanced optical system (High-Pass Optics) consisting of anti-reflective lens coatings and a high-reflection mirror provides the highest level of image quality and helps you achieve faster scans. In addition, the Dual Lens System from Epson optimizes each scan, automatically selecting from two lenses for the desired scan resolution.”

Figure 26: Taken from the Epson Japanese webpage for the GT-X900 (6400 ppi) scanner, said to be released sometime in May'06, in the USA. The image on the left shows the Dual Lens holder and the images on the right show the individual lenses removed from the holder. There design is probably very similar to the lens schematic on the right in Figure 24.

The improvements projected for the GT-X900 (Japan) and the Perfection V750-M seem to be **(1)** better lens coatings, which will reduce flare, **(2)** more efficient moving mirror, **(3)** better overall optics and **(4)** possible CCD improvements over the alpha-Hyper CCD II. Optical components are critical in flatbed scanners because the image being scanned passes through, and is thus modified by, the lens system, which includes the moving mirror that horizontally compresses the image before it is sent to the CCD. The CCD is typically shorter in length than the width of the scan bed; it's usually a third the width. The CCD in the new scanner, at a minimum, will use the alpha-Hyper CCD II technology found in the Epson 4900 & 4870 scanners shown in Figure 22 above.

In addition, the V750-M will be shipped with a wet scanning tray. The use of the word “tray” suggests that the current film holders (seen in the Epson 4870 & 4990 scanners) will fit into the tray. This suggests that the point of best focus will continue to be above the glass plate on the plane of the film in the film holders. A significant improvement would be a manual focus system as seen in part of the Epson's Expression line: the 1680 (8.5"x 11.7") and

1640XL (12.2" x 17.2", tabloid size, now discontinued) and the 10000XL, their current tabloid sized scanner.

Software for Diminishing Film Grain

I have yet to find any software that reduced grain without affecting the image in the size domain of the grain. I'm still looking for better grain removal software, but I'm less hopeful because the problem is not well understood by the software engineers.

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