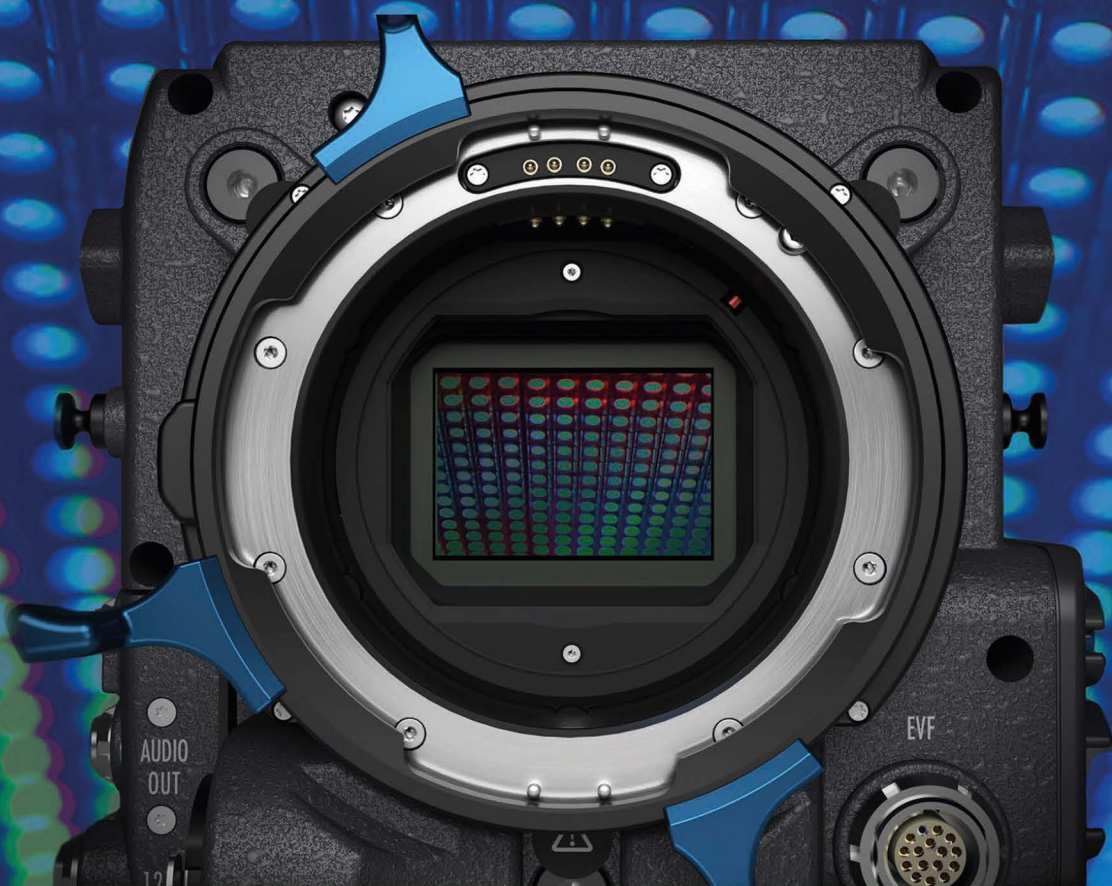


# DIGITAL CINEMATOGRAPHY

SECOND EDITION



FUNDAMENTALS, TOOLS,  
TECHNIQUES, AND WORKFLOWS

A Focal Press Book

DAVID STUMP, ASC

ROUTLEDGE

# *Digital Cinematography*

Today's successful cinematographer must be equal parts artist, technician, and business-person. The cinematographer needs to master the arts of lighting, composition, framing, and other aesthetic considerations, as well as the technology of digital cameras, recorders, and workflows, and must know how to choose the right tools (within their budget) to get the job done. David Stump's *Digital Cinematography* focuses on the tools and technology of the trade, looking at how digital cameras work, the ramifications of choosing one camera versus another, and how those choices help creative cinematographers to tell a story.

This book empowers the reader to correctly choose the appropriate camera and workflow for their project from today's incredibly varied options, as well as understand the ins and outs of implementing those options. Veteran ASC cinematographer David Stump has updated this edition with the latest technology for cameras, lenses, and recorders, as well as included a new section on future cinematographic trends.

Ideal for advanced cinematography students as well as working professionals looking for a resource to stay on top of the latest trends, this book is a must read.

**David Stump**, ASC, has worked on numerous motion pictures and television productions as Director of Photography, as Visual Effects Director of Photography, and as a Visual Effects Supervisor, garnering Emmy nominations and an Academy Award for Scientific and Technical Achievement. A member of the Producer's Guild of America (PGA), the Visual Effects Society (VES), the Society of Motion Picture & Television Engineers (SMPTE), the Academy of Television Arts & Sciences (ATAS), and the Academy of Motion Picture Arts and Sciences (AMPAS), Stump has worked in Digital Visual Effects for over 25 years, since the advent of Computer Generated Images for film. In 2001 he was accepted for full membership into the American Society of Cinematographers, where he is currently chairman of the Camera and Metadata Subcommittees of the ASC Technical Committee.



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# ***Digital Cinematography***

*Fundamentals, Tools, Techniques,  
and Workflows*

**Second Edition**

David Stump ASC

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***This work is dedicated to the memory of my parents,  
David Stump Sr. and Laura Stump,  
who always encouraged my scientific curiosity  
and artistic expression.***

***The most thanks of all go to my wife, Jennifer,  
the greatest contributor of all!***

# *Foreword*

I love shooting film. I love shooting digital. I love analog technology. I love digital technology. I have no agenda for either, and I make my living by knowing and using both effectively. A new era of cinematography has emerged – the era of digital cinematography.

## **What This Book Is About**

This is a book about the tools and technology of digital cinematography. It explains how digital cinematography cameras work, and it will teach the theory and practice of using them.

## **What This Book Is *Not* About**

This book is not about film, television broadcasting, composition, storytelling, screenwriting, lighting or lighting equipment, grip equipment, or how to become a cinematographer. There are plenty of very good books on all of those subjects that are already in publication.

## **Why Should a Cinematographer Read This Book?**

If you want to be a cinematographer in this new age of digital cinematography, you almost can't afford *not* to read it. Today, a director of photography must be three things: first, an artist; second, a technician; and third, a businessman. There are plenty of books written to teach and coach you in the artistry of cinematography, lighting, composition, framing, camera movement ... but very few that give you the information you will need to master the techniques of digital cinema cameras and even fewer to give you an appreciation of the ramifications of the decision you make to use one camera and its resulting workflow over another. Increasingly, cinematographers are being judged by their employers: the studios, the producers, the directors, the editors, and the post producers, on the basis of *all three* of these criteria.

## **Don't Bluff with Buzzwords, *Do Your Homework***

When one considers that there are literally dozens of cameras to choose from to make a movie, television show, commercial, documentary, or video clip, the choice of a camera for any given project can sometimes seem bewildering. The freedom to choose imposes a responsibility on the cinematographer, the responsibility of education. The cinematographer is responsible to his director and his producers to

provide the highest quality that they can afford, and his choice can make the difference between the success or failure of a project. Cinematographers everywhere are now faced with the need to read about, research, and more than anything else, be familiar with the broad spectrum of hardware and techniques available for their work. A cinematographer cannot walk into a meeting with a director or producer and bluff his way through a hardware discussion only to do the minimum research required after the meeting. Workflows vary from one camera to another. Cinematographers are now required to be equal parts artists and technicians, painters and scientists, poets and accountants.

With the proper research under your belt, there will always come the same moment of truth in choosing which camera or recorder or monitor to use for any given project: “What camera should we use?” The cinematographer that has truly done his or her homework and done it well can answer authentically, without an agenda. Educated and informed, he or she can answer the question without having to lean on greater familiarity or comfort level with one camera system or another, answering the question by prescribing the best camera available for the work, and choosing the best quality hardware that the production can afford with the money budgeted.

The cinematographer as an artist must be able to use composition, color, and lighting to evoke emotions and tell a story. In order to succeed he or she must know the tools of lighting, he or she must know the theory and practice of using lenses, he or she must know how to evoke emotions with light and shadow.

But the cinematographer as a technician must also have a deep understanding of the tools and workflows available today. He or she must research and test with every camera available to widen his technical knowledge of the capabilities of the systems available and more importantly, to understand their shortcomings.

The cinematographer as a business person must understand the economic circumstances of filmmaking and become the competent responsible adviser to his or her employer, the producer, the studio, the director; he or she must become the highly qualified expert consultant who knows what the best available tool set for any given production (and the money it has available) might be.

It is always of primary importance to understand the listening into which you are speaking. Producers hire you to create art for them, to be the guardian of the image, to press for quality and beauty at every turn, but they hire you to do that on a budget, and when they get the impression that things are becoming too expensive, their eyes roll back in their heads and they start conferring in hushed tones. Never convince yourself that money is no object – money is the *main* object. Remember that it is called the movie *business*, not the movie *art* or the movie *friends club*. Cinematographers need to be seen to be concerned about saving money, or at least to be concerned about spending it wisely.

To begin, let's dispel a few myths about digital cinematography by saying that you should forget almost *everything* you have *ever* read about digital acquisition in any newspaper or corporate sales brochure, and most of what you read in sponsored blogs. This will allow you to consider this technology without standing in front of the locomotive inertia of sales pitch or the disinformation of journalistic hype. With that in mind, what follows is an outline of the issues that I consider important to success for the future of cinematographers engaging in the relatively new craft of digital cinematography, whether you are a 30 year pro, or a freshman film student.

## As a Cinematographer, You Must Ultimately Serve Three Masters

### *Your Director*

The job will ultimately be awarded to you by the director. Yes, of course the producer and the studio will have a say so in the matter, but if your director wants you on the job, the director will get his or her way. Directors have widely varying styles and interests. I have worked with directors that have little or no interest in camera placement or lens selection, lighting and composition, and I have worked with directors that will say “put the camera right here with a 50mm on it and dolly slowly to over there on this line in the script.” Every director has a different style and focus, and it is up to you to accommodate for each style. One helpful tip is to begin the prep exercise by watching movies together and talking about them as a way to get to a look and style for the project you are doing together. Directors *always* have favorite movies and they *always* have a movie to point to as a way of explaining their wants and expectations. It is up to you to realize those expectations, so you must translate the director’s intent on a scene-by-scene basis to the rest of your crew: your operator(s), your gaffer, your key grip, and your dolly grip(s).

### *Your Producer*

A big part of the Cinematographer’s job is balancing the hopes, dreams, and wishes of your director with the money available to do the job. This is a delicate dance, and ultimately the cinematographer walks a diplomat’s tightrope in balancing what the director wants with what the producer will let you spend to put it on the screen. This part of the job has always been the most stressful to me, but I find it useful to keep in mind that one must at the same time be resourceful and unreasonable. Resourcefulness is always rewarded in the process, and making the effort to save money will buy you favor and credibility with the producer and the studio, but at the same time, being unreasonable in the pursuit of the director’s vision will create a bond that will eventually pay off in loyalty and creativity in the work you share.

### *The Studio*

The producer is your best co-interface with the studio. It is important to remember that someone is putting up a lot of money and taking a lot of risk to make a movie. You have a responsibility to make the best effort to see that risk rewarded. Bring honesty and integrity to your work as a cinematographer. Be open and communicative and the studio can be your friend.

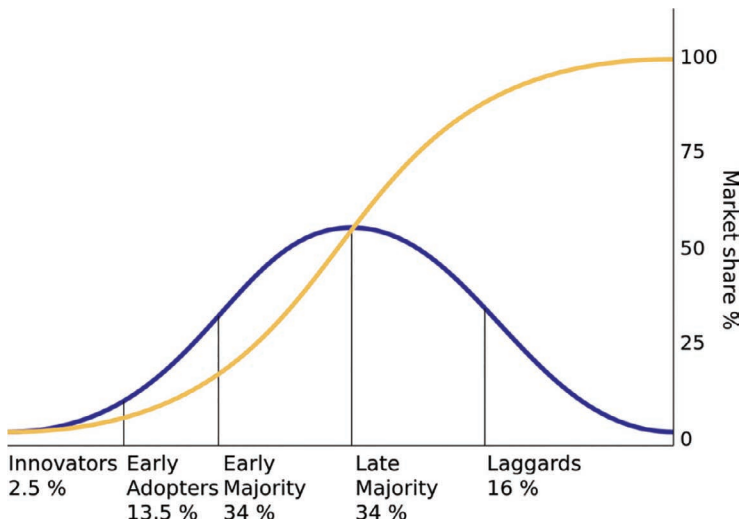
## Look Management

Well color-corrected dailies and look-managed images will embed a familiarity of the eventual desired look in the minds of the director, the producers, the studio, the editors, and everyone involved in a project. This is an *urgently* important first step in arriving at a final look that reflects the cinematographer’s intent! Once the creative team have wed themselves to the look of the dailies, making changes in that look frequently becomes an uphill battle! It often happens that a cinematographer

may not be available for or invited to attend final color correction, so attention to look management during production is a very good step toward assuring the look of the final image.

## Where We Are Now

The “dark days” of the invention and development of digital cameras for cinematography are mostly behind us. We have crossed a tipping point into the era of digital motion picture imaging. We have emerged from the era of the evolution of digital cinematography that suffered from “early adopter syndrome” and we are at the point where single chip Bayer pattern CMOS digital cinema cameras own the greater percentage of the market.



**Figure 0.1** Technology adoption bell curve. Based on Rogers, E. (1962) *Diffusion of Innovations*. Free Press, London, NY, USA, Public Domain, <https://commons.wikimedia.org/w/index.php?curid=8043923>.

With successive groups of consumers adopting a new technology (shown in blue), its market share (yellow) will eventually reach the saturation level. The tools of digital cinematography have spent enough time in the hands of working professionals to mature and evolve. The great news is that it only gets better from here, and the tools seem now not only to meet the capabilities that film gave us, but in some ways to exceed the imaging capabilities of film. That further dictates that we educate ourselves thoroughly on the use of those tools on a daily basis from here on out.

# Understanding Digital Theory

## How Digital Cinema Cameras Work

Cinematography is the art of capturing, recording, and manipulating motion pictures on a medium such as film or a digital image sensor.



Figure 1.1 Making movies.

The discipline that underlies cinematography is the mastery of matching the tonal range of creative scenes in front of the lens to the measured capability of the sensor medium behind the lens in order to artistically capture and record that tonal range.



Figure 1.2 The scene has a tonal range.

## Human Visual Response to Light

Human visual response to the intensity of light is not linear. Human eyes are capable of responding to an enormous range of light intensity, exceeding a minimum-to-maximum intensity variation of over 10-billion-fold, but our vision recognizes light intensity in a way similar to the way film negative records light. Both human vision and film negative respond to a doubling (or halving) in intensity as approximately one stop of change in perceived brightness.

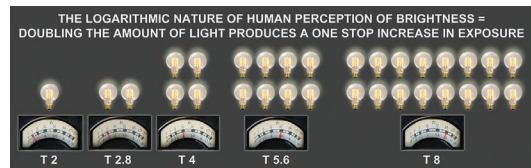


Figure 1.3 A doubling in luminance is perceived as a one stop increase.

Both human vision and exposure of silver halide crystals in film emulsion exposure are similarly nonlinear, and can be approximately modeled either by a logarithm or by a power law function.

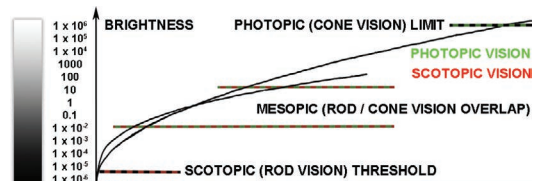
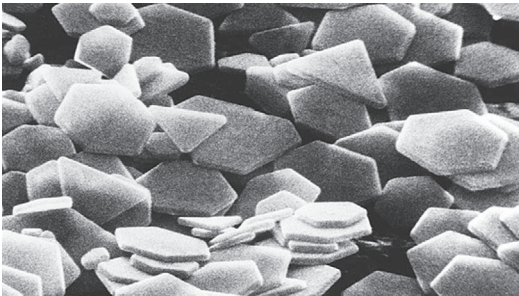


Figure 1.4 Human vision perception of brightness is nonlinear.

Psychophysicist Stanley Smith Steven’s power function laws of psychophysical response to luminous intensity observe that human visual response to brightness is very close to a logarithmic or power function.

**Sensing Light**

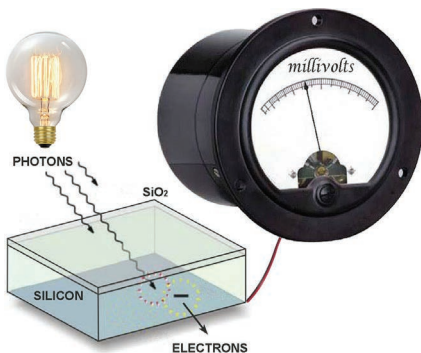
For more than a hundred years, photographic film used light sensitive silver halide crystals to record images.



**Figure 1.5** Silver halide crystals under an electron microscope.

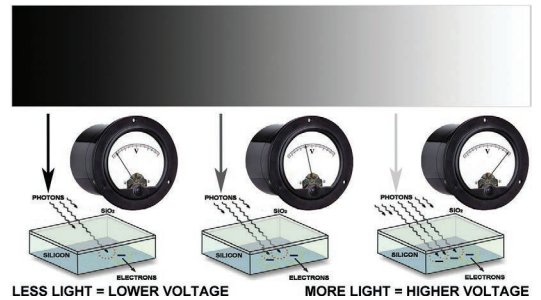
When the exposed silver halide grains were developed and fixed, the crystals were converted to metallic silver, creating the darker areas of film negative. The more light received, the darker the silver halide crystals.

Digital sensors use silicon-based semiconductor devices called photodiodes – essentially microscopic light-controlled valves – which when struck by light allow electrons to pass through. Microscopic photodiodes allow electrons to pass and build up electrical charge when light hits them, and once per frame the camera will count how many electrons were accumulated, drain the charge, and reset the counter to zero.



**Figure 1.6** Photodiodes turn light into voltage.

A digital camera sensor is composed of a grid of photodiodes arranged in rows and columns. Each photodiode allows electrons to build up a charge as light rays from the lens form an image on the sensor grid, which can be measured by the camera. This accumulation of charge is very similar to building up a static charge by walking on carpet with sneakers on a dry day. The more you walk, the more charge you build up. With more light, more charge is built up on each photodiode, and conversely with less light, less charge is built up.



**Figure 1.7** Less light produces lower charge, more light produces higher charge.

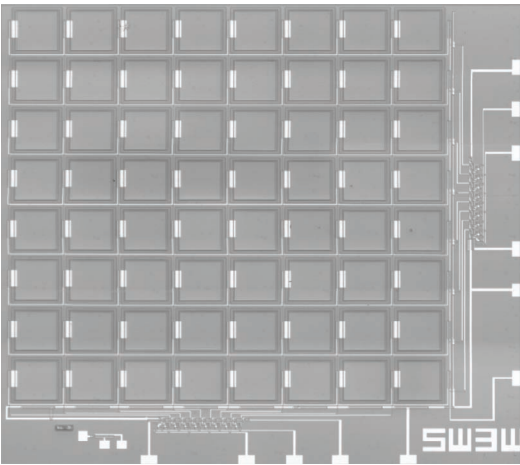
In digital imaging these individual photodiodes are referred to as photosites and their signal product is referred to as sensels). Camera sensors have thousands of rows and columns of photosites that work like independent microscopic light collectors, converting light into voltage on a photosite for photosite, frame for frame basis. This arrangement of photosites is called a raster, a closely spaced rectangular grid of photosites that capture an image.

These rows and columns of photosites are not capable of discriminating color on their own, they are only capable of individually sensing the intensity or power of light hitting them and converting that into voltage. They must be given a means by which color information can be derived. The topic of deriving color from photosites will be addressed later in this chapter.

The number of photosites (usually in the horizontal dimension) is what manufacturers use to give the number of “K” (or thousands of photosites) of a camera. When a camera is said to be “4K,” that means it has *at least* 4096 photosites in the horizontal dimension. As we will see in the next chapter, the number of photosites does not necessarily translate into the effective resolution of the images from a camera, as photosites are not pixels.



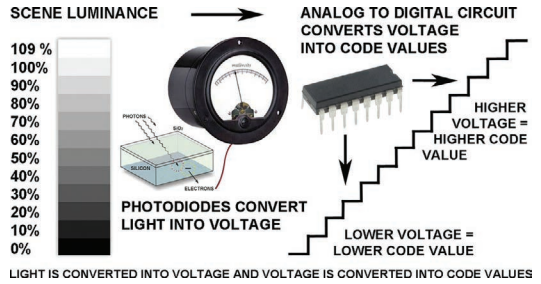
**Figure 1.8** Rows and columns of photosites turn light into electron counts.



**Figure 1.9** Electron microscope view of rows and columns of (monochrome) photosites on a sensor.

### Analog to Digital (A to D) Conversion

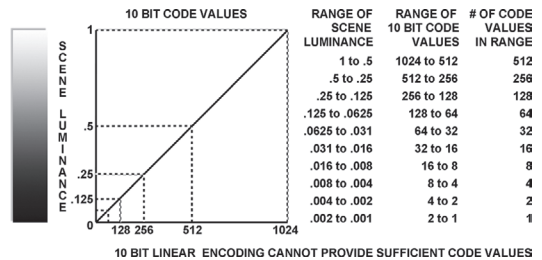
Through the process of analog-to-digital (A to D) conversion, the amount of each photosite’s electric charge is converted by a sampling circuit into binary digits. In digital images, each photosite value is represented by a discrete numerical code value on a frame to frame basis. The process of converting the individual charges from photosites into numerical code values (or samples) is called quantization. The charge built up on each photosite is dumped into the analog-to-digital converter electronics at the end of every frame. A “sample” is a numerical code value that represents this photosite’s accumulated charge that was built up over the exposure time of the frame. Because digital samples are numbers, they can be stored in a computer’s memory and saved to a computer hard drive as data.



**Figure 1.10** Photosites turn light into static electric charge, and A to D conversion turns accumulated charge into digital code numbers.

### Encoding Luminance to Numerical Code Values

Sensor response to light is linear. For twice the amount of light, a photodiode delivers twice the amount of charge. For half the amount of light a photodiode delivers half the amount of charge. If we begin to assign linear numerical code values to linear charges from sensors, we can quickly intuit the issues created by encoding luminance in a linear fashion. This method is inefficient and does not provide enough code values at the dark end of the tone scale.



**Figure 1.11** Linear light encoded in linear code values.

Figure 1.11 shows us a one-to-one linear encoding scheme, where scene luminance is plotted in an arbitrary range from 0 to 1, and encoded into digital code values that are plotted directly as a linear function.

### The Problem with Linear Encoding

The range in relative scene luminance from 1 down to 0.5 covers a one-stop (factor-of-2) difference. In a 10-bit linear encoding scheme, this range is represented by the code values 1024 to

512, so there would be 512 discrete code values assigned to the brightest single stop of light. From 0.5 luminance down to 0.25 luminance is also one stop, but here there are 256 code values available (from code value 512 down to code value 256). From 0.25 luminance down to 0.125 luminance is again only one stop, but here there are 128 code values available (from code value 256 down to 128). From 0.125 luminance down to 0.0625 is also one stop, but here there are only 64 code values assigned (from code value 128 down to 64). The fifth stop down from 1 receives 32 code values, the sixth stop down receives 16 code values, the seventh stop down receives 8 code values, the eighth stop down receives 4 code values, the ninth stop down receives 2 code values and the tenth stop is left to be encoded with one single code value.

If we encoded in a one-to-one linear scheme, we would have more than enough numerical code values to represent the first and brightest stop of luminance, and almost none to represent the bottom toe of the exposure. In a linear encoding, the lower the luminance, the fewer the number of code values available to represent it.

This is why we *do not* encode 10-bit images in a linear scheme. The problem with encoding images this way is that while there are more than sufficient code values to display the brightest stop of light, the lowest six stops are allocated far too few code values to be displayed with any precision at all. The significance of this is that we must very carefully and suitably allocate the number of code values per stop of light in our encoding to make the most efficient and economical use of our available bits.

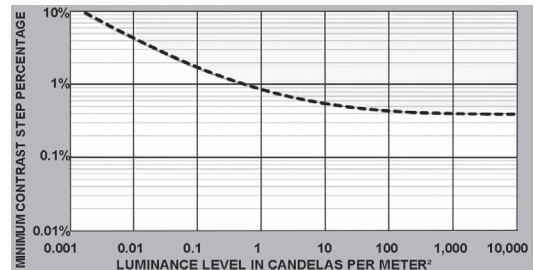
Because human visual response to brightness is very close to a logarithmic or power function, it makes sense to encode digital images from sensors either logarithmically or through a power function for human viewing.

### The Just Noticeable Difference (JND) and Square Root Integral (SQRI)

How many code values (discrete digital luminance steps) must be used in encoding images to ensure that quantizing is never visible in an image over the dynamic range of the camera? The sensitivity of the human visual system to contrast is limited. If two gray levels are close enough in luminance, the difference is indistinguishable to human vision. The ability to discriminate tonal differences varies over the range from dark to bright.

There has been extensive scientific research into how many shades of color humans can distinguish in images. The acknowledged threshold of that ability to distinguish differences in tonal value is described by the concept of the “Just Noticeable Difference,” or “JND.” In imaging, a just-noticeable difference is the amount a color or shade must be changed in order for a difference between two adjacent colors or shades to be noticeable or detectable by human observers at least half the time.

This concept is important to us now because if we employ an encoding scheme that has fewer code values than “Just Noticeable Differences” per stop of light, we can perceive the different shades that make up subtle gradations of color as distinct bands of color. This banding is often referred to as “color aliasing,” which significantly detracts from faithful reproduction of original images, and which detracts from viewing of those images. The number of “Just Noticeable Differences” per stop of light varies dependent on color and luminance, and the eye is more tolerant of greater differences in tone or color at lower luminance levels than at higher luminance levels.



**Figure 1.12** Barten ramp expressing noticeable contrast step percentages as a function of brightness.

A general rule of thumb is that an encoding scheme should allow roughly 60 to 70 code values per stop of light in medium tonal ranges. The optimum distribution of code values per stop of light varies from dark (permitting larger percentage increments of variance in contrast) to bright (demanding smaller percentage increments of variance in contrast), and this distribution varies according to what is referred to as a Barten ramp.<sup>1</sup>

Each photosite is assigned a specific digital red, green, or blue tonal intensity code value. The number of tonal values available is called the color bit depth. The higher the bit depth, the more tonal values available, the fewer the just noticeable color differences. In digital cinema bit depth refers to the

number of digital bits used to encode each color component of a single pixel. A “bit” is a binary digit that can have one of two states. These state values are most commonly represented as either 0 or 1, *true/false*, *yes/no*, *+/-*, or *on/off*. 1-bit color means *on/off*, a binary pair of tones; *black/white*. 10-bit color means 2 to the 10th power bits;  $2^{10} = 1024$  tones per color,  $2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 2 \times 2 = 1024$  tones each for red, green, and blue (RGB). Of the 1024 code values available for encoding color in 10-bit encoding, we reserve the top and bottom 4 bits for other data, so roughly speaking, RGB 30-bit color means we have 1015 values of red, 1015 values of green, and 1015 values of blue available,  $1015 \times 1015 \times 1015 =$  for a total of 1,045,678,375 possible shades of color.

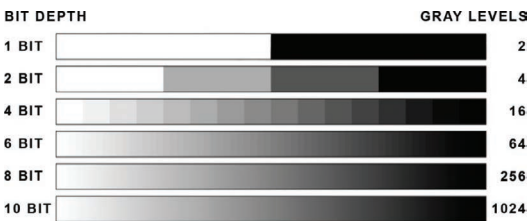


Figure 1.13 Luminance discrimination in bits.

Practical testing of human sensitivity to “just noticeable differences” in display contrast has determined that the minimum quantizing level needed to exceed the threshold of banding visibility in digital cinema is at the very least 10 bits per color (red, green, and blue), encoded logarithmically. A logarithmic scale is a nonlinear scale that quantifies values in orders of magnitude rather than in constant increments.

### Linear vs. Gamma/Logarithmic Encodings

#### Gamma $\gamma$ A Video Power Function

Early television engineers had to solve the problems of the difference between human visual perception of brightness and display output brightness long before digital cinema was invented. Cathode ray tube (CRT) television monitors converted a video signal to light in a nonlinear way, because the CRT electron gun’s intensity (brightness) as a function of applied video voltage is also nonlinear. When a middle gray video signal of 0.5 is fed to a CRT display, the resulting brightness results in a mid-gray of about 22% the intensity of white.



Figure 1.14 Linear light intensity visually compared to gamma corrected intensity.

Their solution was to apply a power multiplier function called gamma to the input signal that approximates the relationship between the encoded luminance in a television system and the actual desired image display luminance. Gamma and other similar multiplier functions such as log encodings are referred to as Opto-Electronic Transfer Functions (or OETFs). The Greek letter Gamma –  $\gamma$  – is used to denote a multiplier that enables efficient coding of linear light for broadcast video recording, transport, and distribution. Gamma is perceived as a change in contrast. Gamma bends the middle tonal values between black and white, while pure black (0.0) and pure white (1.0) are unaffected. Gamma of 1 (unity gamma) means no change, values greater than 1 increase contrast, values less than 1 (fractions) decrease contrast.

Power-law gamma coding is a nonlinear way of encoding used primarily in the RGB video world at 8 bits, and at 10 bits for HDTV as stipulated in Rec 709. The code values for RGB are proportional to the corresponding light coming out of a CRT raised to a power of about 0.45.

For image processing and post production operations such as compositing and CGI, an inverse Opto Electrical Transfer Function (denoted as  $OETF^{-1}$ ) is often used to linearize the data back to radiometric code values.

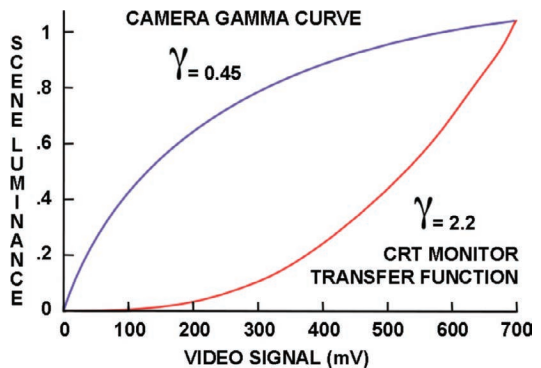
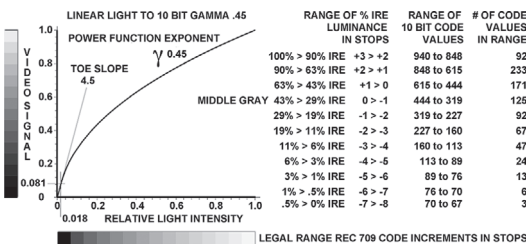


Figure 1.15 Gamma = .45454545 for cameras (blue) and gamma = 2.2 for monitors (red).

To compensate for the application of an encoding gamma function, an Electro Optical Transfer Function such as gamma 2.2, gamma 2.4, gamma 2.6, Perceptual Quantizer (PQ) or Hybrid Log Gamma (HLG) is applied to the signal going to the monitor or projector so that the end-to-end response of the image system is visually linear. In other words, the recorded signal is deliberately gamma distorted so that after it has been equally inversely distorted again by the display device, the viewer sees the correct perceptual tonal scale of brightness.

**ITU-R Recommendation BT.709**

ITU-R recommendation BT.709 specifies a transfer function for HDTV gamma encoding of camera signals. The Rec 709 mathematical gamma transfer function of  $\gamma$  0.45 is a sloped straight-line near zero that blends to a power function so that the overall curve exhibits a continuous slope.



**Figure 1.16** ITU Rec 709 gamma curve for encoding camera signals.

In HD video signals the video signal output voltage of a photosite exposed to 100% diffuse white yields 714 mV or in video engineering terminology, 100 IRE. Overbright white values up to 109% yield up to 785 mV, or 109 IRE. Black level in video signals is set at 53.57 mV or 7.5 IRE. (IRE is a unit used in the measurement of composite video signals. The acronym name is derived from the initials of the Institute of Radio Engineers.)

Most camera manufacturers’ implementations of Rec 709 yield close to the same results when viewed on a monitor or waveform scope. Tonal scales in Rec 709 can be encoded into two different code ranges. Legal range encodes the tonal scale from code values 64 at the low end to 940 at the high end, leaving a -4% margin for underexposure at the toe and a +9% margin for overexposure at the high end. Full (or extended) range encodes the signal from code value 4 at the toe to code value 1019 at the high end, reserving

bits 0 through 3 and bits 1020 through 1023 for video timing reference.

This difference in Rec 709 encodings frequently leads to confusion when transforming from one encoding to the other, and when monitor or projector settings do not match the signal input. Most often legal range is the correct choice for video levels. Choosing incorrectly shows up most visibly in black levels. Excessive black or black clipping usually means that you are looking at full range video on a monitor set up for legal range, and when monitoring legal range on a monitor set up for full range the blacks will look lifted or slightly gray. The choice between Data Level or Video Level is almost always dictated either by the codec you are recording or the codec you’re rendering to, and 90% of codecs are designed for Legal (Video) Levels. Some processing systems make use of all 1024 color code values for processing, but this encoding is not a documented broadcast standard.

**Logarithmic Encoding for Film: a History Lesson**

The Cineon System was created by Eastman Kodak in the early 1990s to solve these same issues of encoding linear light efficiently. The Cineon System was one of the first computer-based end-to-end 4K resolution 10-bit log digital film systems. It was an integrated suite of components – a film scanner, a digital film workstation (with Cineon software for compositing, visual effects work, restoration, and color management) and a film recorder for output back to film. In the late 1980s the Cineon digital film system developed a logarithmic encoding for film scanning. The Cineon log encoding curve became the basis for development of the wide variety of log encodings in digital cameras today.

The Cineon project was responsible for the creation of the Cineon (.cin) 10-bit log file format, designed to handle digital film frames. The Cineon file format became the basis for the later SMPTE standardized Digital Picture Exchange (.dpx) format. The Cineon image file format is very similar to the ANSI/SMPTE DPX file format, and they are for all intents and purposes used interchangeably. Both file formats have variable metadata header (headers contain the data about what the file is and how to use it) lengths and DPX file headers are more flexible, allowing variable image headers to accommodate the needs of different

industries, while the Cineon file format is more specific to digital film.

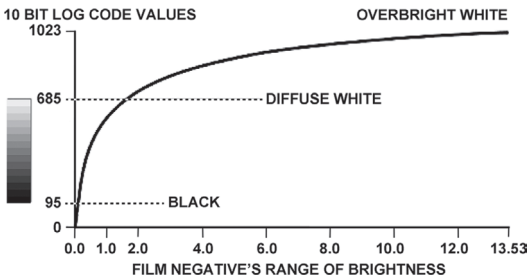


Figure 1.17 Cineon 10-bit log encoding curve.

### 10-Bit Log Cineon/DPX File Format

In a Cineon (.cin) or (.dpx) file, each channel (R, G, B) is encoded with 10 bits, typically in a range from a “black point” at code value 95 to “diffuse white” at code value 685 on the 0–1023 scale of code values. Code value 685 diffuse white is mapped to record a diffuse white reflection, such that rays incident on a white surface are scattered at many angles in a Lambertian reflection, equal in luminance in all directions, rather than at just one angle as in the case of specular reflections.

A “soft clip” was introduced to make the rolloff of whites appear more natural. Values above 685 are reserved for “brighter than white” tones like specular highlights or the sun, and values below 95 are reserved for blacker-than-black information. When negative is “printed up” at the lab to be brighter for artistic reasons or for scene-to-scene color matching, the blacker-than-black information can reveal itself. Similarly, negative can be “printed down” darker, revealing picture information from the over bright detail.

Cineon log film scans capture the entire exposure range of each frame of film and store that range as individual frame 10-bit log Cineon files. Because film negative (like human vision) has a logarithmic response to light, the negative determines the log response curve and the file only needs to faithfully and accurately store the negative's density at each tone level. More encoding values are perceptually useful as exposure to light increases.

Film is measured in logarithmic density units proportional to the negative's optical density. When encoding the exposure latitude of film, we must very carefully and suitably allocate the number of code values per stop of light in our encoding to make the most efficient and economical use of

our bits. If we try to squeeze the range of brightness of film into the full 0 to 1023 code range that would only leave 75 code values for the 0 to 1.0 stop range, the same number of code values as we have allocated to the range from +12 to +13 stop range. Over bright highlights on film do not require the same number of code values, and the human eye cannot discriminate between two over bright film highlights that are close in value at very high brightness levels. Because black is mapped to code value 95, that would leave only a range of 928 code values for the entire remaining exposure range. A scene with very bright highlights can result in values above the Cineon range. Those highlights can be lost in a standard DPX encoding, and that effect is called *clipping*.

The enormous dynamic range of film could not be preserved through the post process without characterizing the response of film with its unique exposure shoulder and toe, and log encoding it, so the Cineon Log encoding curve was devised by Eastman Kodak to preserve the maximum latitude from film scans for digital manipulation into a 10-bit log file. Notice that black is mapped to Cineon code value 95 (out of 1024) instead of 0. The Cineon white code value is 685, which represents 90% of a 100% reflector. In this way, Cineon files store both film Dmin values and Dmax values in order to emulate film's latitude and response characteristics.

### Cineon/DPX Encoding Ranges

Table 1.1 Various Cineon/DPX Encoding Ranges

Cineon / DPX Encoding Ranges		Black Point (out of 1024)	White Point (out of 1024)	Gamma
Encoding Type	Description			
ITU Rec 709	Legal (Video) Range	64	940	2.2
DCI Gamma	Full DCI Range	4	1019	2.6
Print Density	For Use in Film Scans and Film Print Work	95	685	1.66
sRGB	Full Range	0	1023	2.2

## Logarithmic Encoding for Digital Cinema

In the late 1990s into the early 2000s digital cameras began an evolution that would eventually lead them to compete with and displace film. In 1998 SONY's 1920 × 1080 F900 CCD camera with their HDCAM video tape recorders posed a threat to the supremacy of film, but one of the many impediments to its success in the cinema world was Rec 709 color. In June 2000, *Star Wars Episode II – Attack of the Clones* began principal photography shot entirely on a SONY HDW-F900 camera in a Rec 709 workflow with an HDCAM tape deck record solution. Subsequently, the F900 quickly proved insufficient to the giant screen world of cinema, and as the race to develop new and better digital cinema cameras and workflows began, it quickly became apparent that a 4:4:4, 10-bit full bandwidth signal would be essential to the success of any digital camera that wanted to compete in the world of film.

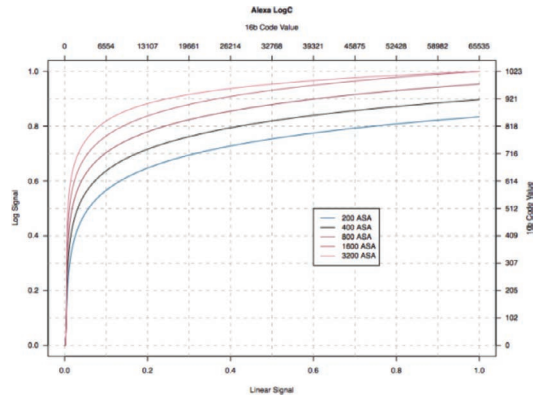
In 2005, the American Society of Cinematographers and the Producer's Guild of America conducted the ASC/PGA Camera Assessment Series, a landmark test of seven digital cameras: ARRI's D-21, Panasonic's AJ-HPX3700, Panavision's Genesis, Red's One, SONY's F23 and F35, and Thomson's Grass Valley Viper shooting alongside an ARRI 435 using four Kodak stocks, two tungsten (Vision2 250T 5217 and Vision3 500T 5219) and two daylight (Vision2 250D 5205 and Vision3 250D 5207). The decision to post the material in a film style digital intermediate dictated that where possible, cameras would record a log encoded signal to emulate the characteristics of film negative, reproducing a wider dynamic range of scene tones within a wider color gamut that is closer to film than a Rec 709 encoding. One direct result of these tests was that the manufacturing community seriously took up the challenge of creating film style log encodings and wider color gamuts that propelled the success of digital cameras into motion picture production.<sup>2</sup>

The proliferation of log encodings in digital cinema cameras is now ubiquitous. Every camera that aspires to be taken seriously in the cinema world now supports its own log workflow. I will briefly cover a few log encodings here, but there will be more on the subject in later chapters.

### ARRI Log C

The Log C curve is a logarithmic encoding of scene tonal values where the relationship between exposure measured in stops and the number of

code values used to encode the signal is constant over a wide range. The overall shape of the Log C curve is similar to the Cineon exposure curve of film negative. Because of fundamental differences between a digital sensor and film negative, the color characteristics are different.



**Figure 1.18** ARRI Log C curves for several ASA settings.

Log C actually is a set of curves for different EI values/ASA ratings. Each curve maps the sensor signal, corresponding to 18% gray scene luminance, to a code value of 400 in a 10-bit signal. A 10-bit signal offers a total code value range of 0 to 1023. The maximum value of the Log C curve depends on the set EI value. The reason is quite simple: when the lens is stopped down, by one stop for example and the EI setting is increased from, say, 800 to 1600, the sensor will capture one stop more highlight information. Since the Log C output represents scene exposure values, the maximum value increases.

### SONY S-Log

S-Log, S-Log2 and S-Log3 are a set of log encoding curves that have been specifically optimized for SONY digital motion picture cameras to maximize the performance of the image sensor. S-Log curves are designed to record and transmit as much of the information recorded by your camera's sensor as possible, to preserve the wide color gamut and dynamic range recorded by the sensor. Using SONY S-Log1 the cinematographer can preserve up to 1000% dynamic range of Rec 709. Using S-Log2, dynamic range increases to 1500%. S-Log3 provides a similar result to S-Log2, but with more detail in the shadows, while extending the dynamic range between mid-tones and highlights.

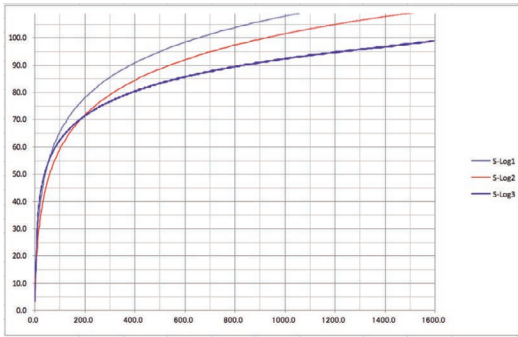


Figure 1.19 SONY S-Log1, 2, and 3 log curves.

S-Log3 is based on Cineon Digital Negative as revised in 2007. The S-Log3 tone curve has no shoulder and reduced toe (with a non-linear curve in shadow area). It is more like a pure log encoding than S-Log2, to provide greater dynamic range in log-based grading.

### Display Referred vs. Scene Referred

What we can learn from the evolution from Rec 709 encoding to log encoding is that the creative intent of cinematography has driven us from a *Display Referred* perceptual coding approach where images are transformed directly into the nonlinear light power of the display being used toward a *Scene Referred* approach where the image data is maintained in a format that as closely as possible represents the original radiometric linear light values, preserving all the color and high dynamic range of the scene.

Log encoding captures the integrity of original images from digital cameras more faithfully than Gamma encoding, storing images in much smaller files for storage and use than radiometrically linear encoding; so for now, log encoding gives us our most effective workflow.

Every manufacturer now understands that characterizing the performance of a new sensor

Table 1.2 Table of log encodings with code values and % IRE levels for waveform monitor reference

Log / Gamma Encoding Function	0.0088% Black -13 stops IRE %	0% Black 10-bit Code Value	18% Gray IRE %	18% Gray 10-bit Code Value	90% White IRE %	90% White 10-bit Code Value
ARRI Log C	3.60%	95	38.4%	400	58.00%	572
Blackmagic 4.6K Film	1.00%	75	41.0%	420	68.00%	664
Blackmagic 4K Film	4.00%	95	38.0%	400	78.00%	743
Blackmagic Film	4.00%	95	38.0%	400	66.00%	642
Canon Log	7.30%	128	32.8%	351	62.80%	614
Canon Log 2	3.60%	95	39.2%	408	58.40%	575
Canon Log 3	7.00%	128	31.3%	351	59.00%	577
Cineon Film Log	3.54%	95	46.0%	481	70.90%	685
DJI D Log	0.00%	64	39.3%	498	86.00%	814
Gamma 2.2	0.00%	64	40.9%	444	100.00%	940
Gamma 2.6	0.00%	64	54.0%	536	100.00%	940
Linear	0.00%	64	18.0%	239	100.00%	940
Panasonic V Log	7.30%	128	42.1%	433	61.00%	602
Rec BT 709	0.00%	64	40.9%	444	101.10%	940
Rec 2100 HLG	0.00%	64	22.0%	260	50.00%	502
RED Log 3 G10	3.40%	94	31.6%	341	49.20%	495
RED Gamma 3	4.00%	95	45.0%	455	77.00%	736
RED Gamma 4	1.00%	72	45.0%	457	81.00%	778
RED Log Film	3.54%	95	46.1%	481	70.90%	685
Sony S Log	3.00%	90	37.6%	394	65.40%	637
Sony S Log 2	3.00%	90	32.3%	347	59.20%	582
Sony S Log 3	3.60%	95	40.6%	420	60.90%	598
sRGB	0.00%	64	48.0%	488	100.00%	940

and writing a log encoding curve to accommodate that unique sensor is one of the keys to a camera's success.

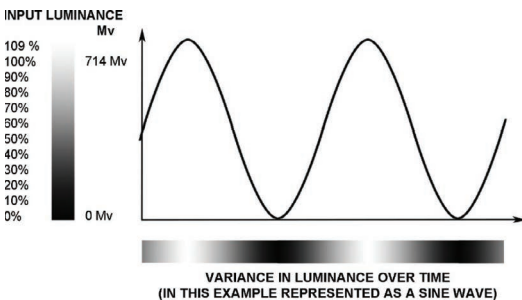
Notice the variations in IRE % and code values from black to middle gray to 90% white from one encoding to another. The decisions that camera manufacturers make in encoding their cameras varies widely. One downstream effect is that post production must have access to accurate de-log profiles for every camera used in order to accurately post produce and color correct their images. It is not unusual for an editorial timeline to include material from half a dozen cameras in one scene, so access to and use of the correct encoding and decoding profiles is imperative.

### Sampling Rate

Now that we have an understanding of how digital encodes gradations of the scene luminance and tonal scale to code values, let's move on to a discussion of how a digital camera samples those tonal scales over time.

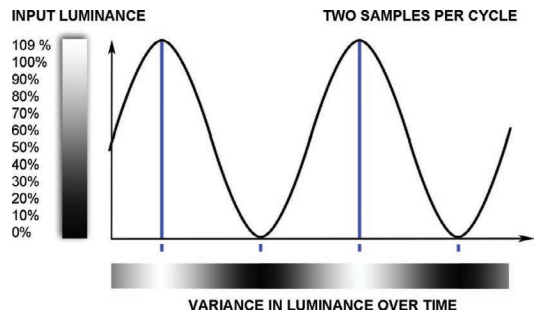
Sampling rate refers to the frequency in megahertz (MHz) at which the analog to digital process in a camera samples analog values from the sensor.

A good way to visualize the process of sampling video is to imagine the analog signal voltage coming from each photosite as a continuous waveform that varies over time. For the sake of this example, I will represent the video signal coming from a photosite with a sine wave varying in luminance from 0 to 100%.



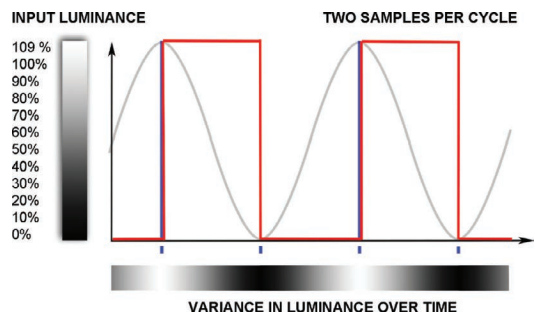
**Figure 1.20** Video signal luminance varies over time.

In this example, the variation of luminance ranges from 1 to 100%, the full dynamic range of the sensor, over time. Now let's study how to slice this analog signal for the purpose of reproducing the original wave shape from our numerical samples. The regular frequency at which we take these samples is referred to as the sampling rate.



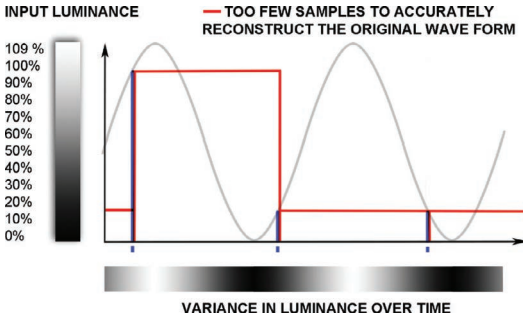
**Figure 1.21** Two samples per cycle of the sine wave.

In order to visualize the sampling of this analog voltage signal, it is useful to imagine the digital samples as slices along those waveforms. In order to create digital video, the samples must be useable to accurately and faithfully reconstruct the original wave form. If there are not enough samples of the analog wave, the reconstructed waveform cannot recreate the original waveform. The more frequently the original wave form is sampled, the more accurate the digital reproduction will be. The code value of each sample endures until it is replaced by a new sample, so digital code values are illustrated as flat top square waves.



**Figure 1.22** Reconstruction from two samples per cycle.

When we try to recreate the original sine wave from just two samples per cycle we can see that the digital representation does not resemble the original waveform. Digital sampling records a code value for each sample, and that value persists until it is replaced by another value. In this example, the only samples available are alternating values for 0 luminance and 100 luminance. This reconstruction is not sufficient to accurately reproduce the original analog video signal. Too few samples cannot serve to reconstruct original analog waveforms.



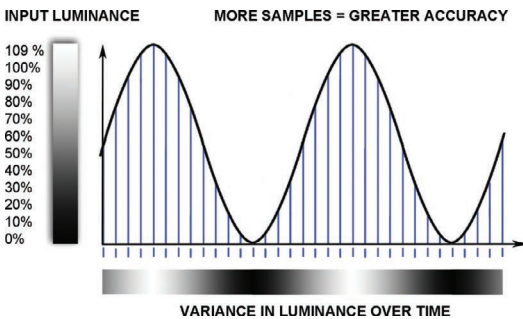
**Figure 1.23** Reconstruction from too few samples fails to reconstruct.

When even fewer samples are taken from the original waveform, the digital reconstruction does not resemble the original wave form in any way. This reconstruction is said to be an “alias” of the original waveform.

### Nyquist Shannon Sampling Theory

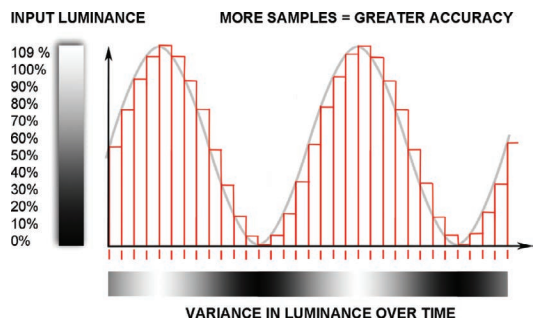
To accurately reconstruct the analog wave forms that form the original picture signal the sampling rate must be more than twice the highest frequency contained in those analog signals.<sup>3</sup>

If the frequency of analog wave forms is sampled at less than two times the highest frequency of the original analog wave form, the digital samples cannot be used to accurately recreate that waveform. Under sampling results in inaccuracies of reconstruction, the original analog waveform cannot be recreated from the under sampled data.



**Figure 1.24** More samples per second (than Figure 1.23) results in greater sampling accuracy.

By sampling at a higher frequency, we can more faithfully reconstruct the original analog wave shape from the digital samples. When represented as digital samples it is much easier to recognize the fidelity of the samples to the original waveform.



**Figure 1.25** More samples results in greater accuracy of reconstruction.

Samples must be taken at a high enough frequency to enable accurate reproduction of the original analog wave forms in order to recreate the picture that the camera originally photographed from digitally recorded and stored data. The more samples per cycle, the greater the accuracy in reproduction of the original wave form.

When a waveform is grossly under sampled reconstruction becomes impossible because the resulting reconstructed wave form bears no resemblance to the original. In this case we call the inaccurate reconstruction an “alias” of the original. If, theoretically, we increased the sampling frequency to approach infinitely high frequency, the width of each sample would approach zero, and we could theoretically increase the accuracy of our reconstruction of the analog phenomenon being sampled to approaching 100% precision. This solution is not practical, as it would result in enormous files sizes for each image, so the number of samples per picture becomes an economic compromise.

There were two factors that determined the sampling rate for digital video. The first factor was this concept that sampling had to happen at a high enough frequency to reproduce the original analog signal. The second factor was that any new digital broadcast system design had to fit within the framework of the existing legacy analog broadcast system.

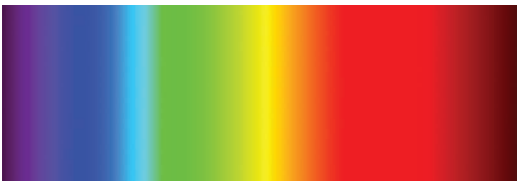
All of this data from sensors must be conveyed per pixel, per frame, per second in real time from the sensor to the record media or broadcast/display system. Data rate is the amount of digital information (bits) that is conveyed or recorded per unit of time, expressed as bits per second (bit/s) or megabits per second (Mb/s) that makes up the digital video signal or recording stream. The photosite count of the sensor, times the bit depth, times the frame rate (plus some bits for metadata and timing signals) equals the bits per second output. The higher the bit rate, the more

data being transmitted, and the higher the quality of the video signal.

In  $1920 \times 1080$  4:2:2 HD broadcast video, the sample rate was set at 74.25 MHz for luminance (Y) and 37.125 MHz for the blue (Cb) chrominance, and red (Cr) chrominance components. The bit rate of a standard  $1920 \times 1080$  RGB video signal is approximately calculated as the number of samples per second times the number of bits per sample. The number of samples per second is the number of samples per picture times the number of pictures per second. A  $1920 \times 1080$  10-bit RGB signal frequency is 74.25 MHz. As the number of pixels increases, so does the bit rate. Ultra High Definition TV cameras have twice as many samples ( $3840 \times 2160$ ) in both the horizontal and vertical dimensions, so the sampling rate for UHD TV is four times the sampling rate of High Definition television. In non-broadcast digital cinema cameras, sampling rates run much higher and are no longer related to the original analog broadcast system sampling rates.

## Color

Rows and columns of photosites are not capable of discriminating color on their own, they are only capable of individually sensing the intensity or power of light hitting them. They must be given a means by which color information can be derived.

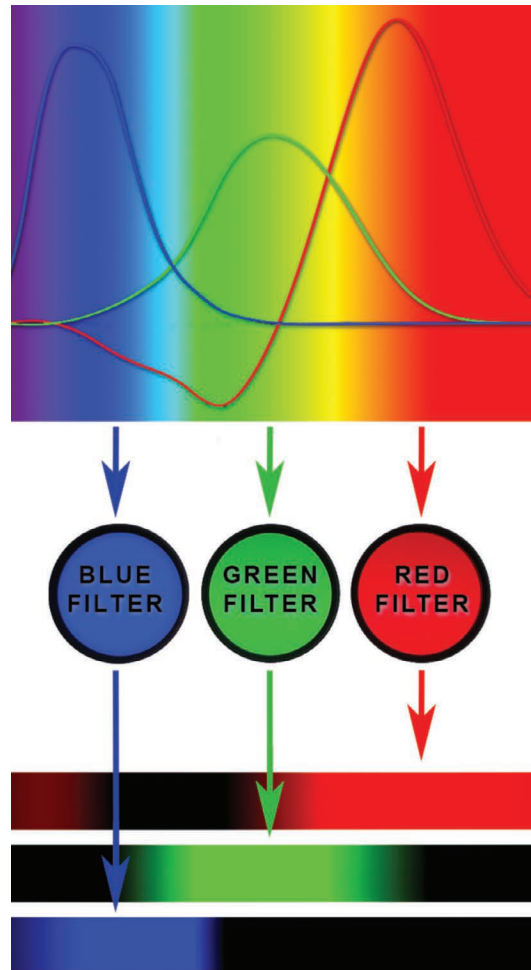


**Figure 1.26** The human visible spectrum.

The perception of color in human beings begins with specialized retinal cells in our eyes – called cone cells – that contain pigments with different spectral sensitivities. In human eyes, there are three types of cones sensitive to three different spectra, resulting in what is called trichromatic vision. These cones are called short (S), medium (M), and long (L) cones, and although the three types do not correspond precisely to red, green, and blue, they give us the RGB color model, which is (for human beings) a convenient means for visually representing color in images.

In order to understand how color photography works, it is important to understand how

visible light gets separated by color filters into the three primary colors (red, green, and blue) that we use to reproduce images.



**Figure 1.27** Visible light divided into its RGB components.

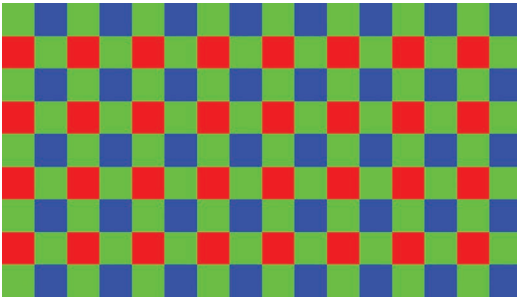
Similar to the way the pigments in the three types of cones on our retinas filter light into red, green, and blue, photographic filters can be used to separate light into its primary colors.

## Bayer Pattern CMOS Sensors

Almost all cameras currently in use for digital cinematography employ a single chip monoplanar Complementary Metal Oxide Semiconductor (CMOS) image sensor. The rows and columns of photosites on a CMOS sensor are covered by a painted on transparent Color Filter Array (CFA) composed of a regular repeating pattern of

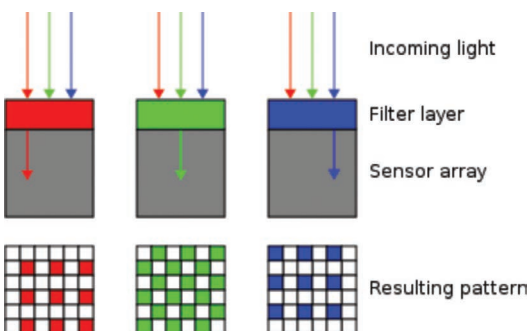
microscopic red, green, and blue filters. Each photosite can only capture light of one of the primary colors, while rejecting light of the other two primary colors.

Just like on the human retina, the individual red, green, and blue color separation filters are microscopic in size. This color filter array is arranged in a pattern commonly called a Bayer pattern, named after its inventor, Dr. Bryce Bayer of Eastman Kodak.<sup>4</sup>



**Figure 1.28** Enlarged section of a Bayer pattern color filter array.

The light falling on such an array of photosites is largely wasted. A green photosite can only collect the green light that falls on it; red and blue light are blocked. A red photosite can only collect the red light that falls on it; green and blue are rejected, and a blue photosite can only collect the blue light that falls on it, rejecting red and green light.



**Figure 1.29** Filtered red, green, and blue light landing on non cosited photosites.

In summary, a Bayer pattern sensor is composed of thousands of rows and columns of adjacent, non cosited photosites covered by a color filter array arranged in a repeating pattern of red, green, and blue filters. By this method, a Bayer pattern sensor discretely samples each of the three primary colors from adjacent photosites for use in

interpolating one RGB color for each photosite with the assistance of its neighboring photosites. These *photosites* are not yet tricolor *RGB pixels*.



**Figure 1.30** A Bayer pattern sensor is comprised of rows of red, green, and blue filtered photosites.

### Color in the Digital Realm: What Are Pixels?

The word **pixel** is a contraction of *pix* (for “pictures”) and *el* (for “element”).

A pixel is the smallest, addressable three color (RGB) element in a digital imaging device. The address of a pixel corresponds to its physical coordinates on a sensor or screen.

The word **sensel** is a contraction of *sens* (for “sensor”) and *el* (for “element”).

A sensel is the signal value from one single monochrome photon collecting element on a sensor. In other words, a sensel value is the electrical signal value product of a photosite. On a Bayer pattern sensor, individual photosites can only sense one color: either red only, or green only, or blue only, and as such, sensels and/or photosites) are NOT pixels.

Pixels are full color RGB samples of an original image. More pixels provide a more accurate representation of the original image. The color and tonal intensity of a pixel is variable. In digital motion picture cinematography systems, any unique color is typically represented by 10-bit log digital code values for each of the three component intensities of red, green, and blue.

### Color Bit Depth

Color bit depth refers to the number of gradations of tricolor RGB brightness value or tonal range, and describes the amount of color information stored in each pixel. As we increase bit depth, we increase the number of colors that can be represented. In a 10-bit RGB image, each color channel (red, green, and blue) carries  $2^{10} = 1024$  variations of color. Excluding reserved bits from code values 0–4 and

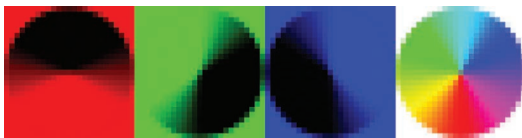
1019–1023, that enables up to 1,045,678,375 colors per RGB pixel.



**Figure 1.31** Only pixels contain RGB (red, green, and blue) information.

### Photosites Are NOT Pixels!

One of the most important distinctions we can make when talking about digital cinema cameras is that photosites are *not* pixels. It is important to note here that if a camera manufacturer advertises that a sensor is 4K, the cinematographer must dig deeper to learn whether that means 4K photosites or 4K pixels. In this book, the author may also use these terms ambiguously where citing a manufacturer's usage. 4K of photosites does not necessarily produce 4K pictures with 4K of real world resolution.



**Figure 1.32** Red, green, and blue photosites combine to create RGB pixels.

RGB pixels must be created from RAW Bayer images by mathematically interpolating samples from adjacent, non co-sited, red only, green only, and blue only photosites. This mathematical combining of values is called deBayering. The mathematical processes of deBayering average adjacent photosites in a wide variety of ways, and the process also averages effective real world resolution as well. This subject will be covered in more depth in Chapter 2.

### Color Bit Depth: How Many Crayons in the Box?

Higher color bit depth gives you more shades of color – it's like having more crayons in your coloring box.\*



**Figure 1.33** Fewer colors to choose from reduces the accuracy with which subtle graduations in colors can be reproduced.



**Figure 1.34** More colors to choose from means that subtler graduations of color can be reproduced.

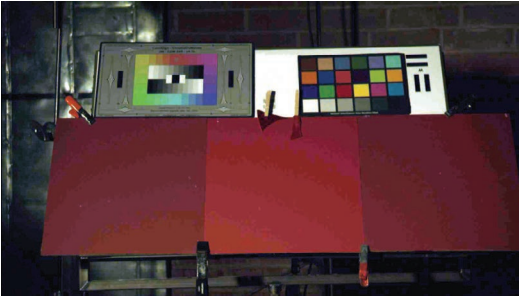
As we learned earlier, bit depth refers to the number of digital bits used to store the tonal scale or color information of each pixel as a digital representation of the analog world. The higher the bit depth the more shades or range of colors in an image, and accordingly, the bigger the file size for that image.

### The Math of Color Sampling

If we take enough samples often enough, and divide each of those samples into enough discrete

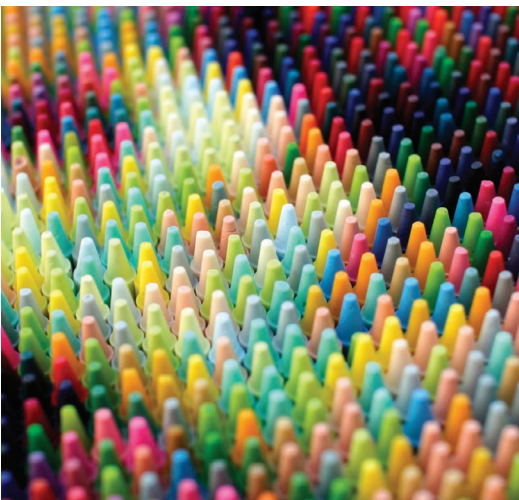
\* Quote attributed to Scott Billups

colors, we can reproduce our pictures more accurately.



**Figure 1.35** Low color bit depth results in color aliasing – notice the banding in the RED cards!

Insufficient color bit depth (too few discrete colors) results in color aliasing, which looks like distinct separate bands of red shades across this image instead of a subtle gradation of color. Higher color bit depth means the more discrete colors the encoding of each color channel (red, green, or blue) divides the tonal scale into, the less banding in subtle gradations of color can be seen. More crayons in the box means less difference between the colors of the crayons from one to the next.



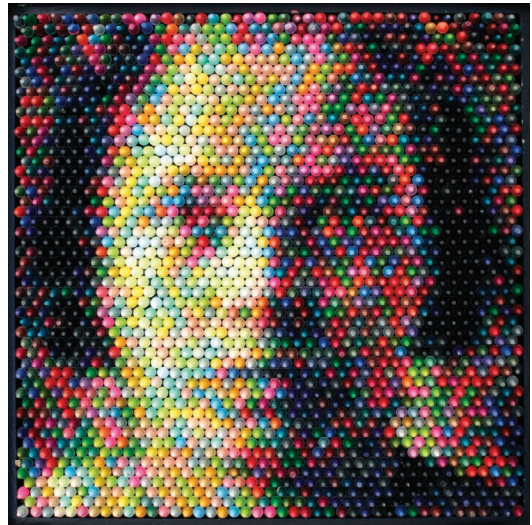
**Figure 1.36** With more colors to choose from we can make more beautiful pictures.

Source: detail from True Color Series – “Girl 1” crayon art courtesy of artist Christian Faur – [www.christianfaur.com/](http://www.christianfaur.com/).

### The More Crayons, the Prettier the Pictures

If we take enough samples often enough, and divide each of those samples into enough discrete colors, we can reproduce our pictures more accurately.

Sampling color bit depth is the maximum number of color tonal bits each sample’s RGB components can use to reconstruct pictures from digital samples. DPX file systems used in digital cinema operate in 30-bit color, which means 10 bits (logarithmic encoded) per channel of red, green, and blue. Of those 1024 code values available for encoding each color we reserve the top and bottom 4 bits for other data, so roughly speaking, RGB 30-bit color means we have 1015 values of red, 1015 values of green, and 1015 values of blue available,  $1015 \times 1015 \times 1015 =$  for a total of 1,045,678,375 possible shades of color.



**Figure 1.37** More colors to choose from means prettier pictures.

Source: “Girl 1” crayon art courtesy of artist Christian Faur – [www.christianfaur.com/](http://www.christianfaur.com/).

The more we oversample analog signals, the more accurately we can recreate those original signals from our digital samples. The tradeoff comes in storage space. If we excessively oversample, then the size of media storage of our images is increased, so the tradeoff is economic. Some degree of oversampling is beneficial to the quality of the images, but excessive oversampling wastes resources and slows processing.

### ACES

There is much effort being given to refining a new file format as the eventual future of digital cinema, and there are research and development efforts under way to implement a 16-bit half float file coding for image manipulation purposes. Floating point math carries code values as exponents rather

than as integers, which makes the process reversible without the decimation (rounding errors) inherent in integer mathematics. The Academy of Motion Picture Arts and Sciences (ACES – Academy Color Encoding System) project is an attempt to create a ubiquitous 16-bit half float motion picture file format that will serve our industry all the way from color correction through archive. 16-bit sampling quantizes to 2 to the 16th power or 65,536, code values (65,536 shades of red, 65,536 shades of green, and 65,536 shades of blue) which provides much more accuracy and subtlety of color shading.

This is especially important when working with wide-gamut color spaces where most of the more common colors are located relatively close together, or in digital intermediate, and where a large number of digital transform algorithms are used consecutively. At this time, ACES version 2.0 is under construction, and the Academy of Motion Picture Arts and Sciences have put in motion an initiative to put ACES into the public domain through an open source project called the Academy Software Foundation. These efforts will be covered more deeply in later chapters of this book.

## Notes

1. Researcher Peter G. J. Barten has developed and refined a number of equations for understanding human visual capabilities in this realm. He defines a metric for describing perceived image quality that is based on the square root of the normalized modulation of the picture. He calls this metric the SQRI or square root integral. He observes experiments where comparable image contrast was varied in steps of one “Just Noticeable Difference” (or JND); the minimum amount of contrast change that is detectable more than 50% of the time in test subjects, and his tests show a very close correlation to the results of real world testing. Detection of “Just Noticeable Differences” depends on many factors, resolution, luminance, refresh rate, and others, and the number of “JNDs” per stop of light varies dependent on color and luminance, but humans are quite sensitive to these differences in contrast. For a scholarly look at human vision and our ability to distinguish subtle differences in contrast please read *Contrast Sensitivity of the Human Eye and Its Effects on Image Quality* by Peter G. J. Barten.
2. [https://theasc.com/ac\\_magazine/June2009/CASPart1/page1.html](https://theasc.com/ac_magazine/June2009/CASPart1/page1.html); [https://theasc.com/ac\\_magazine/September2009/CASPart2/page1.html](https://theasc.com/ac_magazine/September2009/CASPart2/page1.html).
3. The Nyquist–Shannon sampling theorem provides a condition for the sampling and reconstruction of a band-limited signal. When reconstruction is done using the Whittaker–Shannon interpolation formula, the Nyquist criterion is a necessary condition to avoid aliasing. Basically, the theorem states that if samples are taken at a slower rate than twice the highest frequency limit, then there will be some signals that cannot be correctly reconstructed. The minimum required bandwidth sampling frequency theorem was implied by the work of Harry Nyquist in 1928, in which he showed that up to  $2 \times B$  independent pulse samples could be sent through a system of bandwidth  $B$ . Nyquist did not consider the problem of actual sampling and reconstruction of continuous signals. The Shannon sampling theorem was an extension of Nyquist’s work that proved that analog frequencies could be reconstructed from samples.
4. Bryce E. Bayer was the American scientist who invented the Bayer Color Filter Array, which is used in most modern digital cameras. In 1975, while working for Eastman Kodak, Bayer filed a patent application and received U.S. patent number 3,971,065. The filter employs what is called the “Bayer Pattern,” a checkerboard-like arrangement of red, green, and blue photosites on a square grid of photosites that allows digital cameras to capture color images. Half of the photosites collect green light, and the others are evenly divided between red and blue light. The patent application described the filter as “a sensing array for color imaging” that “includes individual luminance- and chrominance-sensitive elements that are intermixed so that each type of element occurs in a repeated pattern with luminance elements dominating the array.”

# Camera Sensors, DeBayering, Sensitivity, and Noise

## The Practical Differences between Film and Digital Sensors



Figure 2.1 Cinematography is now film *and* digital.

The single best piece of advice that I can offer with regard to the difference between exposing film and exposing digital is this: it's okay and sometimes desirable to slightly overexpose film, but it's not okay or advisable to overexpose digital unless that overexposure is EXACTLY what you want!

Cinematographers have widely varying methodologies for determining an exposure, some simple, some convoluted. Film negative has enormous exposure latitude and is very forgiving of a wide variety of exposure techniques.

Modern digital cinema cameras are now achieving wide latitude too. The difference between digital video cameras with a Rec 709 heritage and limited ability to capture dynamic range and digital cinema cameras with a filmic heritage is quickly widening.



Figure 2.2 Spectra light meter.

Digital is like reversal (or auto positive) film stocks. There can sometimes be very little margin for error in exposure, especially at the high end of the tonal scale, and once a photosite reaches full light well capacity (or clip) it cannot continue to record any more detail. When using film negative one could always “print down” a bit to save some detail in excessively bright areas, and this can frequently save an overexposed area in the frame. The same overexposure in digital traditionally could not be corrected. The attempt to “print down” overexposed highlights usually did not result in any detail regained, but rather, a similar amount of highlight detail, just rendered at a lower gray level.

The real distinction to be understood here is the difference between HD broadcast type cameras that render internally and produce a display-ready output, which is like shooting on slide film, and digital cinema cameras producing an output in log or raw format that needs an additional step to be display-ready, which is more like shooting on negative film.

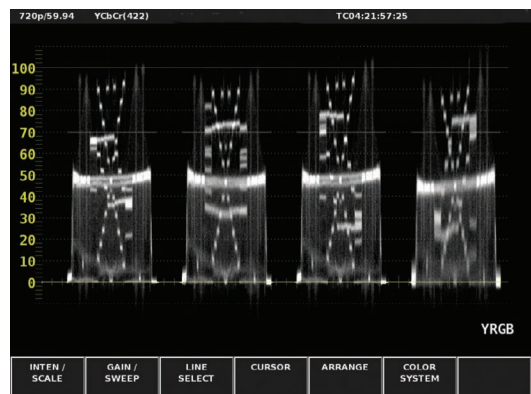


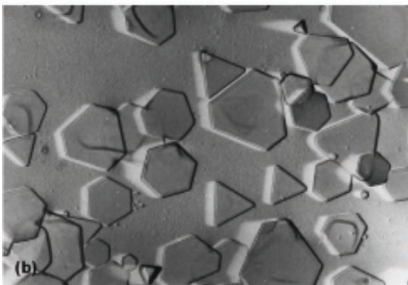
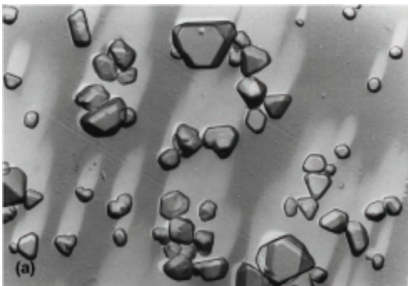
Figure 2.3 Digital exposure tools.



**Figure 2.4** Overexposed sky with clipped exposure in clouds.



**Figure 2.5** The same image color corrected to lower levels (note that the clipped areas do not gain any detail by “printing down” the image).

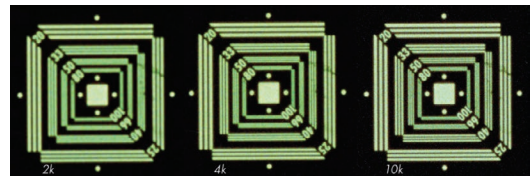


**Figure 2.6** Film grains as photographed by an electron microscope

Source: reproduced with permission of AccessScience (www.AccessScience.com), ©McGraw-Hill Education.

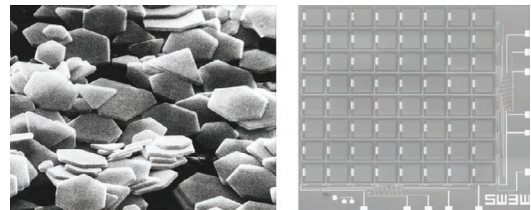
A good rule of thumb in digital work has traditionally been that at the bright end of the exposure range, digital cameras are not WYSIWYG (what you see is what you get) but rather WYSIAYG (what you see is *all* you get). When a photosite reaches 100% saturation it is said to be at “full well capacity” or “clip,” and any picture detail that arrives above that “clip” level is lost (overexposed) forever! This happens when photosites reach their maximum electrical charge level and cannot produce any additional voltage from more photon arrivals.

Film has a random pattern of different sized grains that (depending on the sensitivity of the particular film stock) can achieve very high resolution.



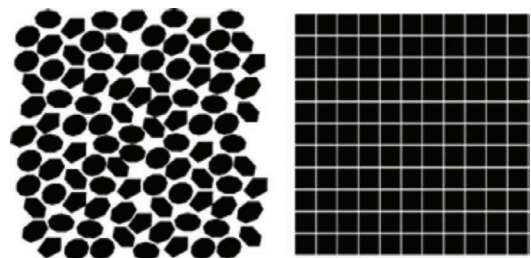
**Figure 2.7** Film scanned at various resolutions.

Scanning film at resolutions higher than 4K (such as up to 10K) yields very well resolved grain.



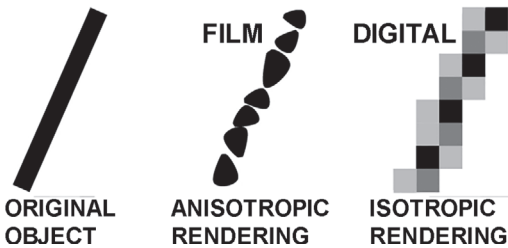
**Figure 2.8** Silver halide film grains compared to a sensor grid pattern.

Source: Silver Halide Photo Copyright (c) 2013 Kodak. Used with permission; Sensor Photo Micrograph Elsevier Science Direct Used with permission www.sciencedirect.com/science/article/pii/S0924424702003928.



**Figure 2.9** How film emulsion and digital sensors see differently.

Digital sensors have an exact grid of discrete photosites. Their resolution is very predictable and can be calculated as the result of several mathematical factors; sensor type; CCD vs. CMOS, Bayer pattern sensor vs. 3-chip sensor, deBayer algorithm, photosite count, optical low pass filter and recording workflow all figure into the resolution equation (as we will soon learn).

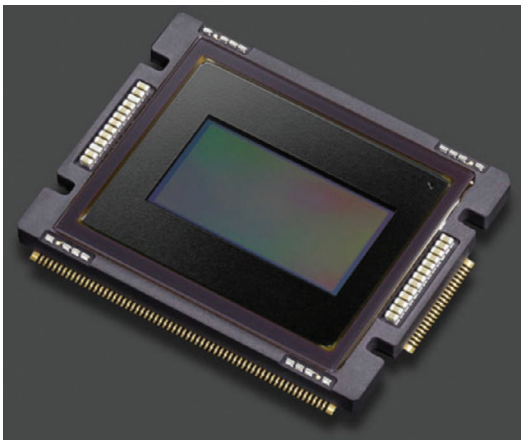


**Figure 2.10** Isotropic and anisotropic renderings of a real-world object.

As a result, digital reproduces real world images in a more isotropic way. A photosite array has isotropic spacing because the shape and space between any two adjacent photosites is the same along each axis, x and y.

Film renders images in a more anisotropic way, systemically different for every orientation or size of the original object. Anisotropy is the property of being directionally dependent, which implies different properties in different directions.

### Sensor Size Has an Effect on the Image We See



**Figure 2.11** A typical digital sensor.

The desire to work with a sensor the size of a 35mm film frame is a strong force driving

development in this area, and many of the issues of digital cinema revolve around the very basic differences between sensor technologies.

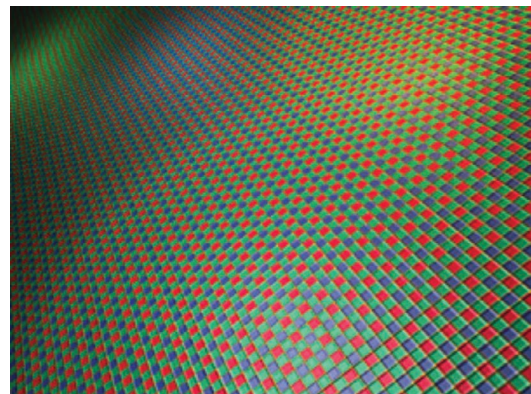


**Figure 2.12** There is a *huge* supply of good 35mm film lenses in the world.

A great deal of effort has been expended on the development of single chip 35mm and Super 35mm sensors for digital cinema because there is a great demand to use existing cinema lenses to acquire images on digital cameras and because film makers prefer the depth of field characteristics of the 35mm format for aesthetic reasons. Gathering the image using a single chip camera with a sensor the size of a 35mm film frame means that we can use existing cinema lenses, without many of the problems digital camera builders encountered designing 3-chip CCD television cameras around the inherent chromatic aberration of prismatic color separation.

Generally speaking, single sensor cameras render images with the same depth of field and image characteristics that we have become accustomed to in a hundred years of filmic experience.

### Bayer Pattern Sensors



**Figure 2.13** Bayer pattern color filter array.

Digital motion picture camera sensor design has moved away from CCD (Charge Coupled Device) technology to CMOS (Complimentary Metal Oxide Semiconductor) technology, partly because of improvements in CMOS capabilities, and partly because of the cost to manufacture. The Bayer pattern mosaic sensor employs a color filter array pattern for arranging *non co-sited* (side by side) RGB color filters over a square grid of adjacent photo sensors on a monoplanar chip. CMOS' particular arrangement of color filters is used in most single-chip sensors in digital motion picture cameras, camcorders, and scanners to create a color image. This filter pattern is composed of 50% green, 25% red, and 25% blue photosites, and is also frequently called GRBG, RGBG, or BGGR based on a repeating 2×2 pattern which begins at the upper left-hand side. There are two green photosites for each red and blue photosite. Because green is the source channel for luminance in digital pictures, this color ratio makes sense in the design of a single plane sensor. This pattern constitutes an orthogonal sampling lattice, with photosite order numbering from left to right, top to bottom. There are many other color filter array patterns and sensor types in use for other purposes in other devices, but for now we will limit the discussion to the patterns and sensor types most commonly used in digital cinema cameras.

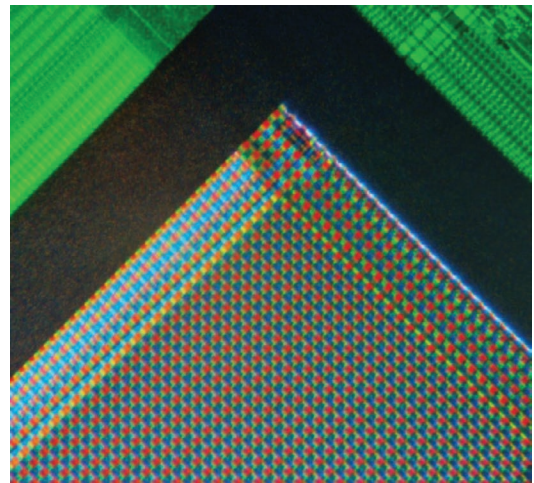


**Figure 2.14** Bayer pattern color filter array.

Because of the human visual system, a minimum of three color planes are required

to represent a full color digital image. The spectral response of these planes usually corresponds to the sensitivities of cones in the human eye.

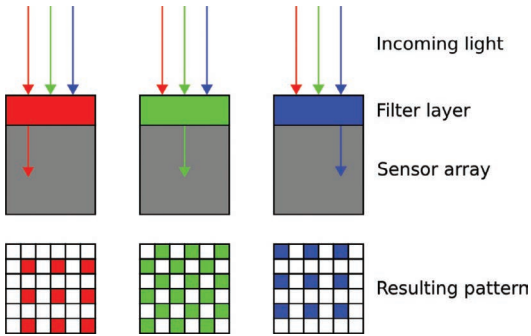
A typical camera sensor detects light intensity but no color information. Most digital cinema cameras use a single light sensor together with a Color Filter Array (CFA). The CFA allows only one color of light to reach the sensor at each photosite. The result is a mosaic image, where a pixel location captures either red, green or blue light. The Bayer pattern is the most commonly used CFA design. (B. E. Bayer, "Color imaging array," U.S. Patent 3,971,065, 1976.)<sup>1</sup>



**Figure 2.15** Closeup view of a Bayer pattern sensor.

The convenience of this single chip sensor method of gathering images comes with a price. A Bayer pattern array lays out a red, a blue, and (usually) two green photosites side by side in offset rows to achieve an average color and luminance sample of the image. Because all three colors are recorded by separate and non-co-sited photosites, the resulting images initially contain color sampling errors that result from the difference between the light sampled or not sampled by each photosite.

To reiterate, the light falling on a Bayer pattern array is largely wasted. A green photosite can only collect the green light that falls on it, red and blue light are blocked. A red photosite can only collect the red light that falls on it, green and blue are rejected; and a blue photosite can only collect the blue light that falls on it, rejecting red and green light.



**Figure 2.16** Filtered red, green, and blue light landing on non co-sited photosites.

The white squares in each color record represent sites where there is no color information. Values will be synthesized and assigned to those areas by a process of interpolation. A Bayer pattern sensor discretely samples and records each of the three primary colors from adjacent photosites for use in later interpolating one RGB color for each photosite on the sensor with the assistance of its neighboring photosites. These *photosites* are not yet tricolor *RGB pixels*.

## RAW File Formats

A camera RAW image file contains minimally processed image data from a Bayer pattern image sensor in a digital motion picture camera. RAW files are not yet ready to be viewed or edited until the image is processed by a RAW converter into a usable image file format. There are dozens of raw formats in use by different manufacturers of digital image capture equipment.

A RAW digital image usually holds a wider dynamic range and color gamut than the resulting deBayered frame it will parent; the purpose of RAW image formats is to save, with minimum loss, the data obtained from the sensor. Raw image formats are intended to capture the scene-referred radiometric characteristics of the scene, the physical information about the light intensity and color of the scene, at the highest level of the camera sensor's performance.

RAW files contain a file header which conveys the byte ordering of the file, a file identifier, and an offset into the main file data, camera sensor size, and color profile map of the Bayer pattern Color Filter Array (CFA) required to assign discreet colors to the sensor image data. They also contain image metadata required including exposure settings, camera and lens model, date, time, and place, authoring information, and an image thumbnail (a JPEG or

other temp conversion of the image), which is used to view the file on the camera's viewfinder.

## DeBayering (De Mosaicing) RAW Bayer Pattern Images



**Figure 2.17** A typical RAW Bayer pattern image before color assignment.

Photosites in this Bayer pattern arrangement cannot be said to be pixels, as they only carry RAW monochrome tonal values until they are assigned colors in either red only, green only, or blue only, corresponding to the dye color covering each individual photosite. Once each photosite has been told whether it is a red, green, or blue photosite, the image then consists of discrete red only, blue only and green only values, which look like this:



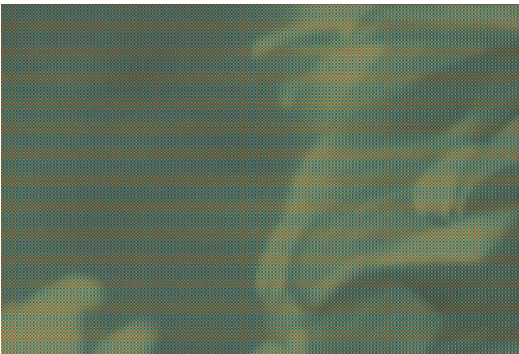
**Figure 2.18** RGB Bayer image before deBayering.



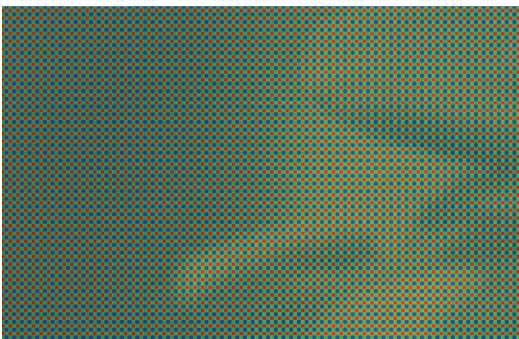
**Figure 2.19** The same image after deBayering.

The process of “deBayering” interprets from adjacent discreet red or green or blue photosites to create RGB pixels that attempt to accurately reconstruct the scene. We will learn more about this process.

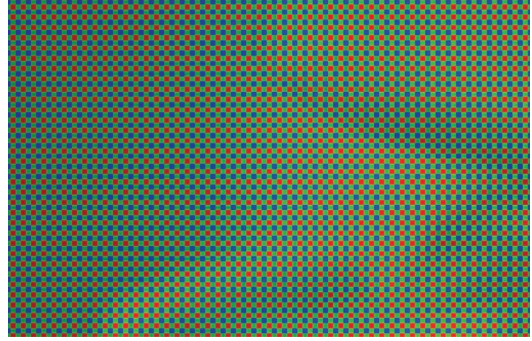
If we take a closer look at the image we can gain some insight into the imaging process before and after deBayering.



**Figure 2.20** Bayer image (not yet deBayered).



**Figure 2.21** Bayer image magnified.



**Figure 2.22** Very close on a Bayer pattern image before deBayering

Close examination of the image reveals that it is still constructed of individual photosites values that all fall on either a red tonal scale, a green tonal scale or a blue tonal scale.

None of the camera original photosites yet contains full RGB information; as a result, their digital code values can be stored as a value one third the size of an RGB pixel. Raw images are generally about one third the size of RGB images.

The process of de mosaicking these images is called de Bayering, a mathematical operation that interpolates the missing color data for each photosite in the array from surrounding known data in order to synthesize a full color RGB pixel at every photosite location on the imager.



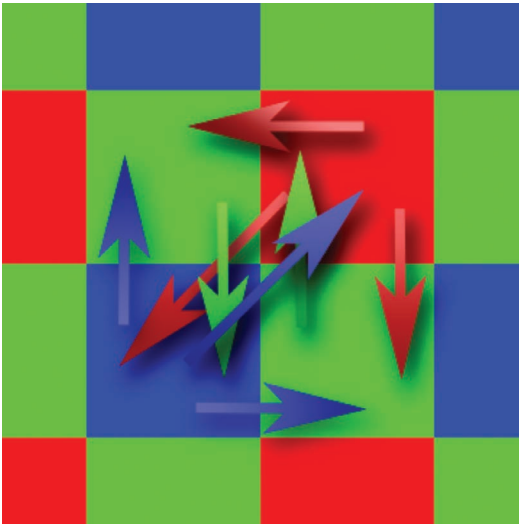
**Figure 2.23** The same image after deBayering.

### **De Bayering Algorithms**

A variety of deBayer reconstruction processes are used to mathematically generate and assign full color RGB values to all of these single color value photosites based on color information shared and interpreted from neighboring photosites. There are numerous mathematical algorithms for interpolating missing color information for red only, blue only, and green only photosites, and each algorithm can deliver different aesthetic results. I will summarize a few (of the many) here.

### Nearest Neighbor

The simplest of all interpolation algorithms is a nearest neighbor interpolation. Using a  $2 \times 2$  neighborhood from the Bayer pattern, missing color values are interpolated by simply adopting the nearest sampled value.

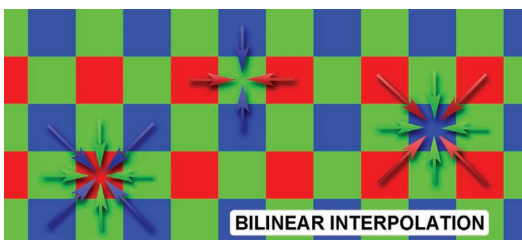


**Figure 2.24** “Nearest neighbor” DeBayering.

The sampled blue and red values in a  $2 \times 2$  neighborhood are used at the three remaining locations. The sampled green values can be shared in either a vertical or horizontal direction to fill in color values for the photosites without green information.

### Bilinear Interpolation

Another simple interpolation algorithm is bilinear interpolation. A  $3 \times 3$  neighborhood is taken from the CFA and missing color values are calculated by averaging nearby values.



Red photosites have 4 Blue neighbors and 4 Green neighbors	Green photosites have 2 Red neighbors and 2 Blue neighbors	Blue photosites have 4 Red neighbors and 4 Green neighbors
Red photosite assumes Blue Value as average of 4 Blue neighbors and Green value as average of 4 Green neighbors	Green photosite assumes Red Value as an average of 2 Red neighbors and Blue value as average of 2 Blue neighbors	Blue photosite assumes Red Value as an average of 4 Red neighbors and Green value as average of 4 Green neighbors

**Figure 2.25** How bilinear “deBayering” works.

This interpolation method performs well in smooth areas where the colors change slowly from one to the next. When utilized along edges where color changes occur abruptly, false color and zipper artifacts are introduced, sometimes resulting in a poor image quality.

The simplest demosaicking methods interpolate each color channel separately. One such technique is bilinear interpolation, which uses the average of the surrounding photosites. In bilinear interpolation, each missing green value is calculated as the average of the four surrounding green values, and each missing red or blue value is calculated as the average of the two nearest neighbors or four nearest neighbors, depending on the position relative to the edge. Other standard interpolation methods, such as cubic spline interpolation, can be used to slightly improve the performance when processing each color channel separately.

The problem with methods that interpolate the color channels independently is that they usually fail at sharp edges in images, resulting in objectionable color artifacts.

To minimize the problems caused by simple channel independent methods that interpolate the color planes separately, adaptive demosaicking algorithms have been developed which utilize the correlation between the color channels.

Advanced demosaicking algorithms put a lot of computational effort into reconstructing high frequency detail in the red and blue color channels. If the image is compressed afterwards, it will often be converted to YCbCr 4:2:0 format. In this format, the chroma channels (Cb, Cr) are down-sampled by a factor of two in both the horizontal and vertical directions, resulting in a loss of the high frequency color information.<sup>2</sup>

### Cubic Interpolation

Cubic interpolation is similar in nature to linear interpolation. Cubic interpolation suffers from the same artifacts as linear interpolation, but to a lesser degree. The expanded  $7 \times 7$  neighborhood reduces the appearance of these artifacts, but they are still present in the final image.

### High Quality Linear Interpolation

High quality linear interpolation improves linear interpolation by exploiting interchannel correlations between the different color channels. A  $5 \times 5$  neighborhood is used, wherein the nearby photosites of the corresponding color channel are averaged and then added to a correction term calculated from information in a different color channel. Despite a modest increase in the number of computations performed compared to

the linear and cubic interpolations, this method outperforms many more complicated, nonlinear methods, with greatly reduced edge artifacts.

### *Smooth Hue Transition Interpolation*

The key assumption of high quality linear interpolation is that hue is smoothly changing across an object's surface. The false color artifacts of linear and other methods of interpolation result when hue changes abruptly, such as near an edge. In this case, hue is defined as the ratio between color channels, in particular the ratio between red/blue and green.

### *Pattern Recognition Interpolation*

Thus far, all of the interpolation algorithms cited have flaws estimating colors on or around edges. In an attempt to counteract this defect, pattern recognition interpolation describes a way to classify and interpolate three different edge types in the green color plane. Once the green plane is interpolated, the red and blue color planes are interpolated using the smooth hue transition interpolation described previously. The first step in this procedure is to find the average of the four neighboring green photosites, and classify the neighbors as either high or low in comparison to this average. This photosite is then defined as an edge if three neighbor photosites share the same classification. If not, then the photosite can either be a part of a corner or a stripe. If two adjacent neighbor photosites have the same classification, then the photosite is a corner. If two opposite pixels have the same classification, then the photosite is a stripe.

### *Adaptive Color Plane Interpolation*

Up to this point, the interpolation of the green color plane has occurred using only information from the green samples from the CFA data. However, certain assumptions can be made regarding the correlation between the color planes. One well-known assumption is that the color planes are perfectly correlated in a small enough neighborhood. It works well to interpolate missing photosite values along edges, rather than across them. In order to utilize the edge detection capability of adaptive color plane deBayering, it is useful to consider many directions. In some methods, as many as 12 directions are considered in which all the G information in a 5×5 neighborhood is used.

## **Resolution in Bayer Pattern Cameras**

It is a bit disingenuous to cite a camera's resolution as the resolution of the final image created demosaicking. The deBayering process is a

process of *averaging* or *interpolating* color values across the sensor, and decimation of resolution is inherent in that averaging. It is *not* accurate to cite the resolution of a sensor as the number of photosites. Photosites are *not* RGB pixels. The real world resulting effective resolution of deBayered images depends on the deBayer algorithm used. For this reason, it makes no sense to assess a Bayer pattern camera's resolution in terms of photosite count. Any given deBayer algorithm can produce the same number of RGB pixels from the same original raw image, so the real question is what is the efficiency of the deBayer algorithm employed in terms of resolution delivered?

Depending on the deBayer math used, the resulting color information can vary in real world measurable spatial resolution, most often less than the photosite count of the sensor. Depending on the math used, the effective output spatial resolution can be expressed as a percentage of the Bayer sensor photosite count. The most widely used methods of deBayering usually result in from 66% to 80% of the photosite count of the sensor, and higher with some algorithms. It is possible to deBayer to higher pixel counts, but the methods that result in higher measurable real world spatial resolution are mathematically intensive, usually not real-time.

## **Converting Raw Images to RGB Images**

Converting a raw image to an RGB image takes a fair amount of image processing. It includes much more than just deBayering. This processing also bakes in a look in the image.

In a video or JPEG workflow, this processing is done entirely in the camera.

In a raw image workflow, most of the image processing is done in post. As post gets the original sensor data, post can apply and reapply different looks without the loss of quality that would occur should you drastically edit a video image in post.

The image processing often includes the following steps in the order shown below:

### ***Dead Pixel Removal***

The values of dead or stuck photosites are restored through interpolation with the nearest good same-color photosites.

### ***Noise Reduction***

Noise reduction is an early stage in the image pipeline. This assures that later non-linear stages produce results that are more predictable without sporadically amplifying the noise. Beware that too much noise reduction can destroy image detail.

### **Linearization**

The sensor's response to light is rarely truly linear. Many sensors have a soft knee, a slightly reduced sensitivity above 70%. The linearization step restores this to a linear signal.

### **Black Level Subtraction**

The signal recorded by unexposed photosites is rarely zero. Non-light sources such as thermal noise and electrical interference within the sensor can generate a small signal.

The average level of this black signal can be calculated and then subtracted from the image. After the subtraction, on average the unexposed photosites will have a value of zero. Due to sensor noise, some photosites may now get negative values. These values must be retained, as clipping to zero can result in visible artifacts such as blotchy shadows.

### **Demosaic to RGB**

The demosaicking stage restores the RGB image pixels from the color-filtered photosites. Bayer (RG/GB) is the most common layout for the color filter mosaic, but since other color filter layouts are in use, the general name for this process is demosaicking, (often loosely referred to as deBayering).

The demosaicking algorithm varies from vendor to vendor, and the most advanced methods are protected by patents or trade secrets.

Here we can only give a sampling of the available algorithms:

#### *Nearest Neighbor of Same Color*

The very crude nearest neighbor method fills in the missing color values from a nearest photosite of the desired color. While the method is fast, the results are inferior. Sharp edges will show severe color bleed. For Bayer patterns, the effective image resolution is half the photosite resolution, as that's the spacing of the red and blue samples. This method can be acceptable when the image is downsampled to the effective (meaning eventual output) resolution.

#### *Averaging Same Colors*

A missing color value can be calculated by averaging the colors of the surrounding photosites of the desired color. This method is slower than the nearest neighbor method, and the results usually are slightly better, although edges get jaggies instead of color bleeds. For Bayer patterns, the effective image resolution is yet again half of the photosite resolution. Unfortunately, this method is very common, as it is very easy to implement.

### *Using All Photosites*

The better methods use all available colors and photosites for restoring each color. Just like in the eye, the spectral curves of the different color filters are designed to overlap. It is rare to find a color on set that registers in only one set of color filters. And almost all natural objects have wide spectral reflectance curves. The extreme exceptions would be laser lights. Thus, all objects provide details in all photosites, and the advanced methods utilize this using all photosites to calculate each color plane. The effective image resolution is now *the same as* the photosite resolution. As these methods often detect gradients, they may be more sensitive to image noise.

We now have an RGB image in the color space of camera RGB, and we can now apply the processing steps that require RGB pixels.

### **Lens corrections**

When the lens characteristics, including the focal length for a zoom, are well known, lens artifacts such as barrel distortion and chromatic aberration can be reduced by applying the appropriate geometric counter-distortions.

### **Cropping**

Next, the image is cropped. The demosaicking methods can produce artifacts in the edge pixels, so these are cropped off. The cropping can also set the desired aspect ratio, such as 2.39:1, 16:9, or 4:3.

### **Scaling**

The RGB image can be scaled up or down to the desired image-sampling rate, such as  $1920 \times 1080$ . This must be done with methods that don't introduce moirés or discard image details. Upsampling will not provide more image detail, but may be needed to fit a specific workflow, such as HD.

### **White Balance**

In the white-balance step, the RGB values read off a gray card are used to scale the RGB channels to equal values for gray. This can be as simple as just dividing with the gray card RGB values, or more advanced, taking into account chromatic adaptation, and applying a matrix.

This step is easily combined with the color conversion step for better overall performance.

This step may also include clipping overexposed pixels to the max neutral value. If not all three channels are clipped, then advanced methods may also try to restore the actual exposure values.

### Color Conversion

In this step, the camera RGB values are converted to a more useful RGB color space, such as Rec 709 or ACES. This is commonly done by applying a matrix multiplication.

The matrix needs to include chromatic adaptation, which compensates between the color temperature on set, and the color temperature of the new color space, so that colors look natural in their new color space.

If this image were being prepared to go into a post workflow such as ACES, we would stop here. If instead we were preparing HD footage, the following steps would be applied.

### Color Enhancements

Some video and still-camera workflows automatically apply selective color enhancements such as improving skin tones, or sky colors.

### Toning Curve

As the world as seen by the camera looks flat, a toning curve is applied to add contrast.

### Gamma Curve

If the outgoing data format is gamma encoded, such as Rec 709, a gamma curve is applied.

### Clip to Fewer Bits

The data up to this stage has often been carried at large bit depth, such as 12, 16, or 32 bits. At this point the least significant excess bits need to be discarded.

### Lossy Compression

Finally, a lossy compression may be applied to get down to a target data rate, such as 250 Mbit/s for digital cinema.

### Cinema DNG Format

Raw image formats were first introduced in the still camera market in the late 1990s. The combination of high quality raw images and powerful image editors such as Photoshop provided powerful tools for image creation, superior to using JPEG files. By 2007, at least 80% of all professional still photographers shot raw images.

In the early days, every camera vendor created its own raw file format. This resulted in a proliferation of multiple file formats for every application to support. In 2011, there were over 150 unique formats. Interestingly the vast majority of these

proprietary file formats are actually good old TIFF under the hood, sometimes with proprietary metadata tags such as color encoding.

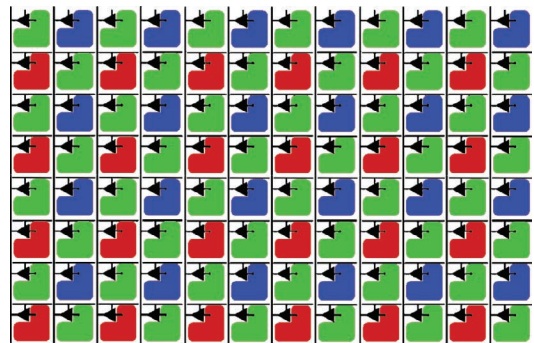
To stem the tide of proprietary formats, in 2005 Adobe introduced its own raw format, called DNG. Adobe's DNG (also based on TIFF) eliminated the need for proprietary formats by including a superset of the features found in all of the proprietary raw formats, plus options for more metadata, all fully documented and usable freely, without NDAs or license fees, including a free software library. The DNG format is now used by hundreds of camera and software vendors, excluding only the few camera manufacturers who have a business interest in using their own proprietary formats.

All known raw files can be converted to DNG without loss of data, and many publishers convert their various raw files to DNG for archiving to assure that the images will be readable in the future when the original camera format is eventually abandoned.

A few years after the digital revolution changed the nature of still photography, the digital cinema market went through the same turmoil. At one point, there were over 60 different raw formats, a large number of those coming from a single camera manufacturer. A group of camera and software vendors realized where the proliferation of proprietary formats was leading, and at NAB in 2008, under the leadership of Adobe, the Cinema DNG initiative was formed. The Cinema DNG format is DNG extended with metadata unique to motion picture production (such as time code).<sup>3</sup>

### On Board Image Processing

In a CMOS sensor, each photosite has its own adjacent photon charge-to-voltage conversion. The sensor often also includes onboard analog to digital converters, so that the chip itself outputs digital bits.



BAYER PATTERN CMOS SENSOR WITH PROCESSING CIRCUITRY AT PHOTOSITES

**Figure 2.26** CMOS charge to voltage circuitry lives at each photosite.