The Interaction of Art, Technology and Customers in Picture Making

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ABSTRACT

Human interest in pictures dates back to 14,000 BC. Pictures can be drawn by hand or imaged by optical means. Over time pictures have changed from being rare and unique to ubiquitous and common. They have changed from treasures to transients. This paper summarizes many picture technologies, and discusses their dynamic range, their color and tone scale rendering. This paper discusses the interactions between advances in technology and the interests of its users over time. It is the combination of both technology and society's usage that has shaped imaging since its beginning and continues to do so.

Keywords: HDR

1. INTRODUCTION

Pictures can be paintings, prints, lithographs, silver-halide photographs, video images, digital stills and movies, or phone displays. Pictures are the result of both technology and consumers' use of images. We know of pictures made as long ago as 14,000 BC in the Lascaux Cave paintings. Most images up to the thirteenth century were narratives of objects of interest, without much thought devoted to scene reproduction. With the adoption of Brunelleschi's geometrical perspective in 1400 AD, pictures added more realistic shapes and sizes to the rest of the scene around these objects. With the addition of chiaroscuro, around 1500 AD, the illumination became as important as the objects. As well, chiaroscuro introduced rendering high-dynamic-range scenes in low-dynamic-range media. The advances in Renaissance painting were sponsored by patrons of art, such as the Medicis.

The advance of photo technology since Daguerre and Fox-Talbot (1840s) has been remarkable. Photography has reinvented itself every generation over the last 170 years, and it continues to do so. With the increase in use of photography in the last half of the 18th century, photography moved into the painter's space of scene reproduction, and painters moved elsewhere. However, technology provides a fraction of the story that has controlled the recent history of pictures. The artist-industrialist J.C. LeBlon invented commercial color printing in about 1700, and hand-painted color photographs were common in 1861 when James Clerk Maxwell made the first photographic color separation images using color filters. Color printing preceded its photomechanical implementation by one and one-half centuries. The legacy of making color photographs includes many ingenious cameras, subtractive dye-transfer systems, and additive color films. It was not until the 1940's that the subtractive dye-coupler process became the universal color capture technique. With this highly sophisticated, multilayered film came a universally-used, low-cost, high-volume, product with multi-national corporations as film suppliers, replacing amateur and small business sources.

The digital picture added computation, instant global transmission advantages, and long-term storage problems. Computation allows image processing for high-dynamic range scenes, as well as aesthetic modification. Image processing algorithms possible with digital images can perform tasks that artists used to do. In addition, digital manipulation has become a principle tool of artists. Instant transmission over the internet changed both accessibility and the standards of information content. In 1990 the universally accepted standard for a photograph was the information captured in a 35mm negative, or about 9 megabytes. Today, the typical web image is less than 0.1 megabytes jpeg. Daguerreotypes made in the 1850's are as vibrant today as when they were made. However, digital images are easily lost in media that is easy to use, but is inherently unstable because of obsolescent storage devices and unstable media. The majority of cell phone images have only the lifetime of a telephone call.

The artist, the patron, the dedicated amateur hobbyist, the commercial service provider, and recently multi-national corporations are all image makers. Technology has changed who makes, and who uses pictures. It is the combination of technology and social use that controls the lifetime of an imaging technology, as well as the lifetime of individual images. This talk will describe the details of many advances in imaging technology and how they were replaced by further advances, or by customer preferences.

2. PAINTING

The earliest examples of painting are preserved in rock art. Lascaux cave painting have been dated to 13,000 to 15,000 BC. As best we can tell, these are the artistic expressions of individuals, with possible social implications.

In North America petroglyphs are as old as 3000 BC. Anasazi Indians in Chaco, New Mexico around 1000 AD used a camera-like cave with a small slit so as to project light onto a spiral petroglyph to identify summer solstice, equinox and the cycles of the moon. (Solstice, 2007; Sinclair et al, 1987,1988)

For centuries the picture makers were artists who painted them for themselves, or for noble clients. Pictures were rare; their users were few. Figure 1 shows a thousand year old Sung dynasty scroll. (Ch'in Hsiao-i:1986, 95). The children are seen on a plain background in uniform illumination.

Figure 1 shows a detail of *Children Playing on a Winter Day*, Sung dynasty scroll (960-1297).

In the Italian renaissance, art became more public. Family dynasties such as the Medicis supported public art as today benefactors support public parks. This led to artists' workshops that resembled 20th century research laboratories. These workshops were well funded and well staffed and generated a considerable volume of images available to a wider range of viewers.

The practice of portraying people and objects without an accurate rendition of the surrounding scene and lighting environment changed in the Renaissance. First, Brunelleschi's perspective rendered the geometry of the spatial environment. Later chiaroscuro rendered the high-dynamic-range (HDR) illumination environment.[1] Pre-renaissance paintings render people and scenes in uniform illumination. Leonardo da Vinci is credited with the introduction of chiaroscuro, the painting of light and dark. His portraits of Benois Madonna, in 1478 and Lady with an Ermine, in 1483-1490 capture the illumination as well as the figures. One sees that the illumination comes from a particular direction and that there are highlights and shadows. Caravaggio's paintings, such as *The Musicians*, in 1595-6, portrayed people and illumination with equal importance. In turn Caravaggio influenced several Dutch painter, among them Gerrit van Honthorst (Figure 2).

Figure 2 shows van Honthorst's 1620 painting "The Childhood of Christ". The boy holding the candle has the lightest face. The father, further from the light, is darker. The other children, progressively further from the light are slightly darker.

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[1] Clair-obscur (French) and chiaroscuro (Italian) both mean "light-dark". The two terms are used to denote sharp contrasts of light in paintings, and prints.

Artist's Rendering, Luminance and Appearance

In recent experiments (Figure 2b), we measured the appearance of four identical transparent targets with four levels of illumination in the same scene in a black surround (McCann and Rizzi: 2007). This is the experimental equivalent of van Honthorst's painting. Observers measured appearance by making magnitude estimates (MagEst) between white and black. They were asked to assign 100 to the whitest area and 1 to the blackest areas in the scene.

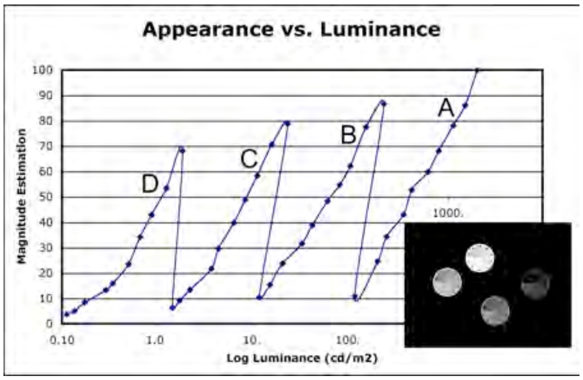

Figure 2b shows the test target in the bottom right. Four identical pie shaped targets with ten different transmissions were mounted on a light box. The top A had no neutral density behind it, B on the left had 1.0; C on the bottom had 2.0; D on the right had 3.0 ND filters. The surround was opaque. In total the target had 40 test areas with a luminance dynamic range of 18,619:1. The graph plots the average of observers' magnitude estimates of the appearance of the 40 test areas vs. luminance.

Average observer estimates are plotted in Figure 2b. The horizontal axis plots luminance measured with a spot photometer (cd/m^2). The vertical axis plots appearance (magnitude estimate value). The top target A has the highest luminance. It generates MagEsts from 100 to 11. The left target B, viewed through a 1.0 ND filter, has uniformly 10 times less luminance than A. It generates MagEsts from 87 to 10. The bottom target C, viewed through a 2.0 ND filter, has uniformly 100 times less luminance than A. It generates MagEsts from 79 to 6. The right target D, viewed through a 3.0 ND filter, has uniformly 1000 times less luminance than A. It generates MagEsts from 68 to 4.

If we look along the horizontal line at MagEst 50, we see that four different luminances (1.06, 8.4, 64 and 414 cd/m^2) generate the same appearance. If we look at luminance 147 cd/m^2 we see that it generated both MagEst = 17 (near black) in A, and MagEst = 87 (near white) in B. Similar examples of near white and near black appearances are found at luminance 15 (B&C), and 1.8 cd/m^2 (B&C).

Magnitude estimates of appearance in complex images do not correlate with luminance.

This Figure 2b experimental data shows great similarity to Gerrit van Honthorst's figures in the painting "Childhood of Christ". Each Scale (A,B,C,D) is the analog for one of the four figures in the painting. As the distance between the candle and the faces grew, the tones rendering the faces got slightly darker. Each person is rendered slightly darker, but the spatial contrasts for each are very similar. Scales A, B, C, and D behave in the same manner. The only differences was that each started and ended a few percent lower in magnitude estimates, despite the substantial decreases in luminance. Figure 2b just assigns numbers to 17th century observations. Chiaroscuro painters did not render luminances; rather they rendered what they saw.

3. PRINTING

Printing is photography's older and bigger brother. Where photography is the technology that gives the individual a record of a scene, printing is technology of efficiently making many copies of a single image. Printing, as the distribution of information to many, was a problem that was addressed earlier and led to much larger commercial markets.

There are reports of cuneiform stone cylinders for making clay tablets as early as 3000 BC. Chinese had paper, ink and relief pillars in the 2nd century AD. Wood block, *Xylography,* has been traced to the 6th century. Paper was found in Asia, the Arab world, and Europe in the 12th century. Gutenberg's press with moveable type printed bibles in 1455. The history of printing is so vast and universal that we will not attempt to present its history; rather we will simply make relevant comparisons when appropriate.

4. PHOTOGRAPHY

Although the photography is a smaller industry than printing, it deals with the interface between light in the world and image capture. Two very interesting subtopics are the study of capture/reproduction of scenes' dynamic range and the capture /reproduction of color. This paper will discuss these topics sequentially in the 19th and 20th centuries.

4.1 The Century of Professional Amateurs

There are so many excellent histories of early photography that it would be foolish to restate the rich and varied history of writing images with light. A particularly good simple summary is found in Mees, *Photography* (1937:1), based on a course of lectures given at the Royal Institution at Christmas, 1936. It summarizes the history from 1727, when Schultze experimented with light-sensitive silver salts, through Thomas Wedgewood's and Sir Humphrey Davy's work on silver nitrates, and through the public and private studies of Niepce, Daguerre and Fox Talbot, including Sir John Herschel's major contribution of hypo, the silver-salt clearing agent. A more detailed history, including ancient Greek references to light sensitive matter and descriptions of camera obscura, can be found in Elder (1932). Other important histories are: Newhall (1982), Scharf (1996), Scharf (2000), Frizot (1998).

In the late 1830's Silver halide photography took a great leap forward from the research on light sensitive material to the development of practical photographic systems. The key advance was Daguerre's discovery of silver development by mercury vapor. In 1839 Daguerre made public disclosure of his technique to the Academie des Sciences, Paris in exchange for a 6,000 franc per annum for life (4,000 francs M. Niepce) from the French government.

One of the early adopters of photography was Samuel Morse, inventor of the telegraph, who bought a daguerreotype camera and obtained a full description of the process. He transferred the technology to United States by teaching the process to American photographers, such as Samuel Broadbent, Albert Southworth, Edward Anthony and Mathew Brady.

In 1844 Brady opened a Gallery in New York featuring family portraits and jewelry. During the American Civil War (1961- 1865) Brady became the portrait maker of the war, the famous generals, politicians and the common soldier.

Photographic jewelry was an early business that flourished in the mid 19th century (West and Abbott, 2005). It became very fashionable in England when Queen Victoria began to wear portraits of Albert prince consort after his death in 1861.

Today's negative-positive photography descends from the experiment of 1835 Fox Talbot's Calotype process. (Scharf, 1996; 2000). In the Daguerreotype the silver plate was developed to a positive image with fuming mercury. With the Fox Talbot's Calotype the silver salts on paper were developed in a water bath to a negative image. This negative, when printed on a second AgCl paper, made the positive print when developed.

In 1851 Scott Archer described a wet collodion process with which photographers made their silver halide negatives at the time of exposure. Landscape photographers carried their darkrooms with them to process negatives in the field (Figure 3).

Figure 3 reproduces a lithograph (Mees (1937) of a photographic camp.

By the 1850s the fascination with making pictures led to societies for the discussion of techniques. An excellent example is the 1854 *Journal of the Photographic Society of London containing The Transactions of the Society and a general Record of Photographic Art and Science.* (Henfrey, 1854). It, along with many other documents in the collection of the Royal Photographic Society of Great Britain, provides a time capsule view of life in the 1850s.

Lewis Carroll's Photography

As most people, I first learned of Lewis Carroll from Alice in Wonderland. I later learned that he was an accomplished lecturer in mathematics at Oxford (1856-1881). I still later learned that he was an accomplished photographer. (Gernsheim: 1950). Carroll's diary discusses photography from 1856 to 1880. Figure 4 shows two of his portrait of Alfred Lord Tennyson, and Hallam Tennyson. It is easy to understand that Carroll had the ability to master the skills required, but what I find fascinating is he could find the time to make so many remarkable portraits using 1850s technology.

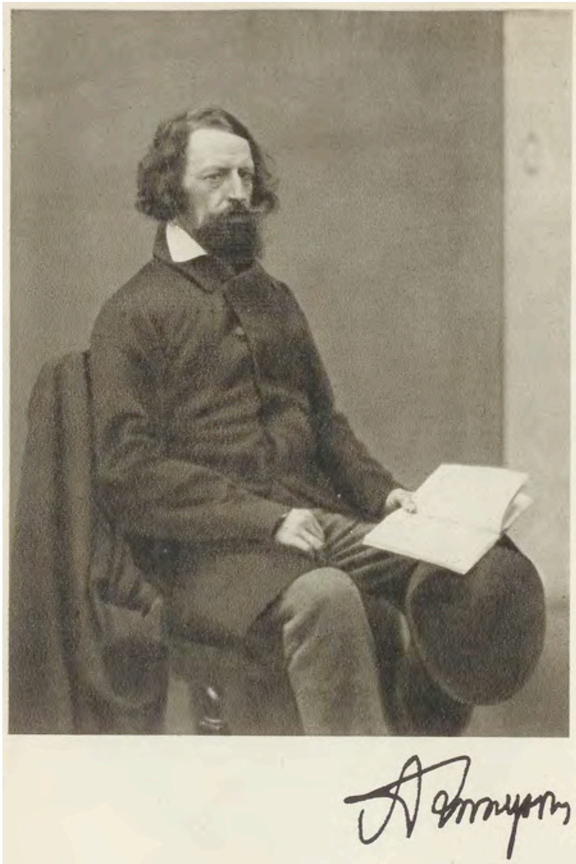

Figure 4a shows Lewis Carroll's portraits of *Alfred Lord Tennyson*, *Poet Laureate, 28th Sept, 1857.*

Figure 4b shows Lewis Carroll's portraits of *Hallam Tennyson, son of Poet Laureate, 28th Sept, 1857.*

H. P. Robinson

Gernsheim (1950:13) reports that Lewis Carol admired the photographs of H. P. Robinson. Robinson's work is remarkable because it remains of great interest today for two completely different reasons. First, it competed directly with painters in the creation of fine art. It went beyond scene reproduction to creating images designed to evoke an emotional response. Second, to be truly competitive, it had to overcome the technical limitations of image rendering. It had to solve all the problems of today's HDR imaging.

In the mid 19th century HDR scenes presented a severe problem for films available at that time. Multiple exposure techniques for rendering HDR scenes go back to the earliest days of negative–positive photography. H.P. Robinson's (1858) composite print "Fading Away" (Figure 5) was made using five differently exposed negatives (Mulligan and Wooters, 1999:360). This dramatic still life was staged using actors.

This multiple negative process is described in detail in Robinson and Abney (1881: 74). The negative capture and positive print is very important to this process. When the photographer developed his negative of the scene exposed for the areas with the most light, the well-exposed areas were darkened with developed silver. The unexposed areas in the negative, corresponding parts of the scene with much less light, were clear glass. That meant that the photographer could take a second, longer exposure to record details in the shadows, develop it and superimpose the two negatives. The shadow details were added through the nearly clear glass of the first negative. This sandwiching of negatives combined with cutting and juxtaposing different negatives of the same scene produced HDR rendition as good as today's digital techniques.

Figure 5 shows H.P. Robinson's 1858 photographic print "Fading Away" made from 5 combined negatives.

Robinson's techniques were empirical. Later in the 1870's and 1880's Hurter and Driffield (1974) established the field of photographic sensitometry. They measured the sensitivity function of silver halide films. C. E. K Mees repeated this work in his thesis at University College London. (Mees, 1956)

Nineteenth century photography started with a few scientists experimenting with light changing matter. It ended with the beginnings of the massive industrialization of photography. Over most of the century photography was developed by thousands of individuals and small groups who painstakingly made each photograph from start to finish. Figure 6 is the frontispiece from Mees (1937), *Coating a gelatin dry plate by hand*. It illustrates beautifully one of many steps needed to make a picture; many of these steps were performed in complete darkness. It also illustrates the commitment of time, facilities and equipment beyond film and camera that were required. By the end of the century there were innumerable small businesses, each in unique niches, finding independent solutions to common problems. There is no better example of the vast diversity of 19th century photography than the search for color photography.

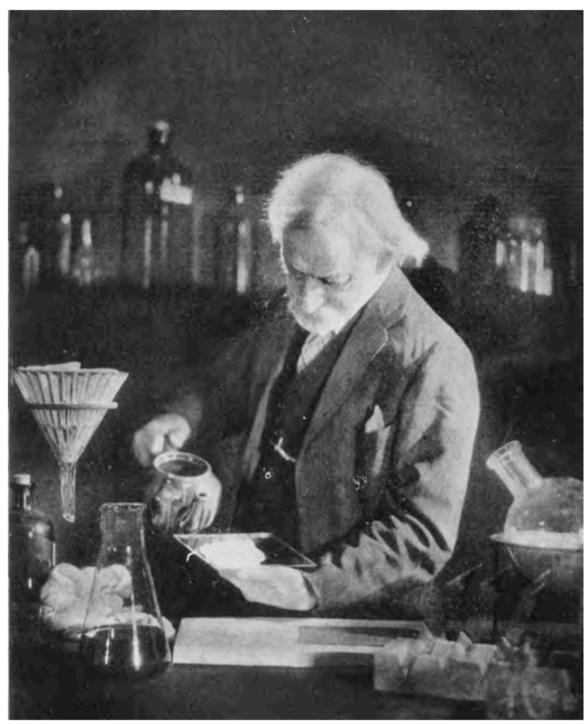

Figure 6 reproduces the photograph *Coating a gelatin dry plate by hand* (Mees, 1937, frontispiece)

Color Photography

All of us are very familiar with the Thomas Young's Bakerian Lecture 1801 at the Royal Society, in which he proposed that human vision is limited to three types of color detectors. We are all also aware of James Clerk Maxwell's, Friday Evening Discourse at the Royal Institution 50 years later, in which he described the invention of color photography using red, green, and blue filters to make three black and white color separation photographs.

These observations are of significant interest to us as scientists because they were both important advances. Most people walking up and down the streets in Piccadilly, London at those times would have not have understood the value of these events.. The problem was that color photographs were common in 1861. Following lithographic techniques in universal usage for at least a century, a technician simply painted a low-spatial resolution color wash on top a black and white photographs. As well, one can buy today very inexpensive lithographs with hand painted color made at the time of Thomas Young's lecture.

In fact, LeBlon (1980) introduced color printing in Paris about 1700. His three-color Mezzotint process was quite remarkable. He drew multiple-color separation mezzotint plates, assigning the amounts of each ink in each area by visualizing the desired color. Figure 7 shows a magnification of a woman's eye in a print bound into an original copy of Coloritto in the British Art Center, Yale University. One can see the structure of the individual color inks from the multiple colors separations.

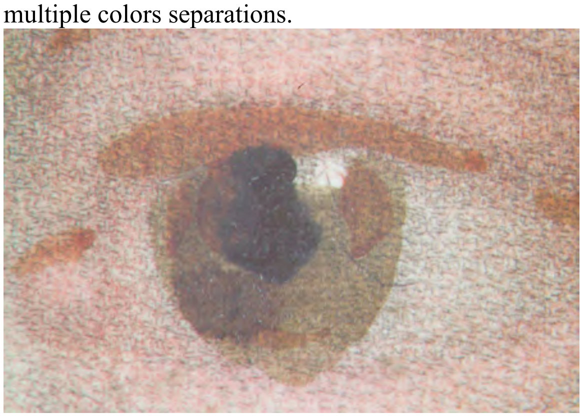

Figure 7 show a magnification of the woman's eye in a color mezzotint.

Fine art color printmaking made remarkable progress in 18th century France as demonstrated in a recent exhibition *Colorful Impressions* at the National Gallery, Washington (Grasselli, 2003).

The commercial interest in color printing had found means to manufacture color prints 160 years before Maxwell worked out the theory of color photography. Making three or four continuous tone printing plates by hand required great skill. Hand coloring of the mechanically printed lithograph was easier. The high level of people's interest made such processes into successful businesses.

Ralph Evans (1961) wrote a Scientific American article for the 100th anniversary of Maxwell's first color photograph of a multicolored ribbon. It added a number of interesting details about the experiment. First, the experiment was performed with blue sensitive silver halide (AgX) emulsions available at that time with little green and no red sensitivity. Ten years after Maxwell's demonstration, Vogel invented color sensitizing dyes that when coated on AgX crystals, made them sensitive to green and red light. Evans suggested that Maxwell's three separation filters had different transmissions and the ribbon had different ultraviolet/blue spectral reflectances. Careful measurements of the sizes of the image made with a simple, non-color-corrected lens suggested that the RGB labeling was switched. Maxwell's color separations simulated the colors of the ribbon, but did not reproduce them. These details are just scientific curiosities, and are not very important. The principle was very important and stimulated a vast number of techniques for making color photographs. Friedman's *Color Photography* provides a detailed description of this field. Wall (1928) describes many color techniques. Coote (1993) and Coe (1987) provide many illustrations of cameras and early color photographs.

One of the most interesting anecdotes of the 1890s is Ives' experiments with "natural color" reproduction. Frederick Ives tried to combine Maxwell's color camera idea with Maxwell's measurements of the color spectral sensitivity curves (Niven: 1965). He proposed that color separations, used to make color reproductions, would have the most "natural color" if the separations had the same spectral sensitivities as humans. He published a book (Ives, 1989) and filed a US patent (Ives, 1990). As described by Friedman:

> *"The Ives disclosure let loose a rather lengthy discussion from which very little seems to have resulted. The poor results that were obtained when using filters for color separation whose transmissions corresponded to color-mixture curves, soon forced the subjective idea of color reproduction into the discard, and the further development of the subject of color photography appears to have proceeded along objective lines."* (Friedman ,1945:13)

Despite a significant investment in the idea of using broad sensitivity functions, Ives abandoned the idea and used narrow-band filters in his 1895 commercial Kromstop color cameras. This assumption, that films should have the same spectral sensitivity as human cone pigments persists today among theoreticians, but not among color imaging manufacturers.

4.2 The Century of Corporate Photography

In 1900 Kodak introduced the Brownie Camera. It cost $1 ($0.15 for film). The ads read 'You press the Button, We do the rest'. (Mees, 1937:29) It was the corporate organization that put advertisements simultaneous in every US town's newspaper that changed photography. It universalized the photographer. Up until then photography was a small industry occupation, or a serious avocation. The new Brownie photographer clicked the shutter, mailed the camera to Kodak, and received by mail their photos and their camera loaded with fresh negatives. All the dangerous chemicals and bulky dark tents were taken away by a large corporation. Eastman introduced convenience into photography.

Just after the introduction of the Brownie, George Eastman went on a different quest, a research lab. It took several years, but in 1912 he persuaded C. E. K. Mees to move from London to Rochester and become Kodak's Director of Research.

20th Century Control of Dynamic Range

Part I- AgX Photography

Mees's *The Fundamentals of Photography*(1920,82) shows an example of a print made with multiple negatives with different exposures (Figure 8).

Over the years the science of silver-halide imaging improved rapidly. Mees established standards for high-dynamic range image capture on the negative, and high-slope rendering on prints (Mees: 1961). Negatives are designed to capture all the information in any scene. The negative response function changes very slowly with change in exposure (low-slope film). This property translates into the fact that negatives capture a wide range of scene luminances. Further, it is relaxes the requirements for cameras to make accurate film exposures. Once the scene is captured and the negative is developed, the final print can be made under optimal conditions at the photofinishing facility. The print paper has a quickly S-shaped nonlinear response to light (high slope). The resulting positive print is higher in contrast than the original scene. The loss of scene detail occurs in this high-contrast print rendering.

Figure 8 shows Mees's combined enlargement from two negatives (Mees, 1920:82).

The Mees 1920 example of multiple exposures was not so much an artistic technique, as it was a demonstration of an improvement in image quality. Mees, as director of Research at Kodak for half a century, led the development of negative films that can capture a greater range of luminances than possible on camera image planes for the vast majority of scenes (McCann and Rizzi: 2007). This film design was the result of extensive photographic research (Mees:1956, 1961). This work led to a *single tone-scale reproduction function*[2] *for color prints.* It was used in all manufacturers' color films for the second half of the twentieth century. Innumerable experiments in measuring users' print preferences led the massive amateur color print market to use a single tone-scale-system response. Even digital camera/printer systems mimicked this function (McCann, 1998b). It is important to note that this tone-scale function is not slope 1.0. It does not accurately reproduce the scene. It compresses the

[2] The term *tone-scale-reproduction function* is used in this paper to describe the system response to light in a camera-image-plane pixel. The term applies to systems such as a silver-halide film in which a particular quantum catch uniquely determines that pixels response.

luminances in both whites and blacks, enhances the mid-tones (increased color saturation) and renders only skin tones accurately. This one *tone-scale-fits-all-scenes* was very successful and became the basis of all color prints made in the second half of the 20th century (See below).

Adams' Zone System

In 1939 Ansel Adams first described the zone system for photographic exposure, development and printing. It described three sets of procedures: first, for measuring scene radiances; second, for controlling negative exposure to capture the entire scene range, and third, spatial control of exposure to render the high-range negative into the low-range print. (Adams, 1981: 47-97).

Adams used a spot photometer to measure the luminances of image segments and assigned them to zones in the scale from white to black in the final photographic print. The zone system imposed the discipline of visualizing the final image by assigning image segments to different final print zones prior to exposing the negative. Adams was a professional performing pianist. He often described the negative as the analog of the musical score and the print as the performance. It was essential that the negative recorded all the information in the scene and that the printing process rendered this information in the print.

Photographic contrast is the rate of change of density vs. exposure. In the negative, the low-zone values are controlled by exposure, and the high-zone values are controlled by development and exposure. The zone system provided the necessary information to select appropriate exposure and processing for each scene's dynamic range.

The final stage was to control the amount of exposure for each local part of the image (dodge and burn) to render all the desired information from a high dynamic range scene into a low-dynamic range print. This process starts with a preliminary test print using uniform exposure. Examination of the print identifies the areas with overexposed whites and underexposed blacks that have lost spatial detail. Dodging refers to holding back exposure from areas that are too dark. Less exposure lightens this local region of the negative-acting print paper and gives better rendition in the blacks. Burning refers to locally increasing the exposure to make an area darker. This is a local spatial manipulation of the image. Not only can these techniques preserve detail in high and low exposures, they can be used to assign a desired tone value to any scene element.

Adams described the dodging and burning process in detail for many of his most famous images. He executed remarkable control in being able to reproducibly manipulate his printing exposures so that the final print was a record of his visualization of his desired image, not a simple record of the radiances from the scene. In fact, Ansel's Zone System process was the 1940's equivalent of an *all-chemical* Photoshop™.

Ansel Adams Zone System combined the chemical achievements of capturing wide ranges of luminances in the negative with dodging and burning to synthesize Adam's aesthetic intent. Controlling exposure and development capture all the desired scene information. Spatial manipulations (dodging and burning) fit the captured range to the limited dynamic range of prints.

Dynamic Range of Scenes

The Jones and Condit (1948) study of 128 outdoor scenes provided two important benchmarks in HDR imaging. First, it compared photographic images (measured camera luminances) and spot photometer measurements from scenes. Second, they devoted a significant portion of the paper to the careful analysis of flare in the image falling on the camera's image plane. The limit of film response to no light exposure is called the fog level of the film. This is the equivalent of the various noise limits in blacks in CCD and CMOS sensors. Jones and Condit showed that the fog limit was significantly lower than the camera flare limit. Although many papers discuss digital camera noise limits, few discuss flare limits. Flare, not sensor signal-to-noise ratios of noise limits, sets the usable dynamic range of cameras.

20th Century Color

Part I- AgX Photography

In the late 19th century color photography used large beam splitting cameras to make three simultaneous color separation images. In the early 20th century these bulky cameras could be replaced by additive color transparent films. They worked on the same principle as our LCD laptop displays. Very small adjacent patches of R, G, and B images viewed at a distance merge into a three-color image, hence the name additive (McCann, 1998a). Friedman and Coe describe a number of successful additive color films.

John Wood's *The Art of the Autochrome* (1993) and Brian Coe's *Color Photography* (1978) display many fine examples of single sheet additive photography.

The disadvantage of these processes was that they had to be illuminated by a bright light and lacked to convenience of color prints. Four color subtractive printing, using yellow, magenta, cyan and black inks, was universally available and more important universally viewable because they were prints. Whites in subtractive color images reflect all incident light. Since additive films remove all the green and blue light to make red; remove all the red and blue light to make green; and remove all the red and green light to make blue, their combination to make white is only one third of the incident light. Subtractive color transparencies are much brighter than additive ones; subtractive colors are essential for prints.

In 1935 Kodak introduced the Kodachrome process that set the standard for all color films for the rest of the 20th century. The project was led by Mannes and Godovsky. Kodachrome was made up of multiple layers of R, G, B emulsions to capture three-color separations in a single layer. The film was processed to form a different color dye image by reacting with the silver in each color separation layer using coupler developers. 'A coupler developer is one that in which the oxidation product of the developing agent combines with a chemical agent in the solution to form an insoluble dye' (Mees, 1937:193).

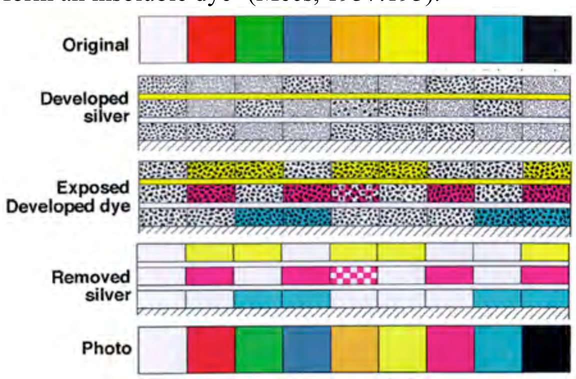

Figure 9a shows the diagram of the Kodachrome process.

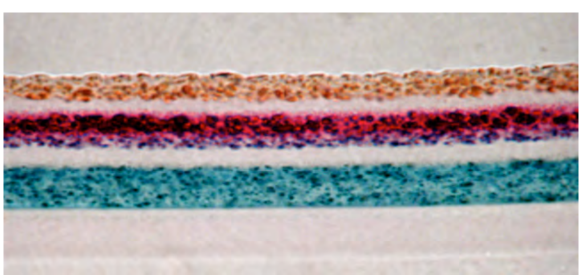

Figure 9b shows M. McCann's cross-section micrograph of a Kodachrome transparency taken by Mannes and Godovsky (from the Jack Naylor Collection). When viewing the slide, light passes from the top through the layers to the observers' eye at the bottom. This cross section is of black area in the photograph and shows the superimposed yellow, magenta and cyan dye layers.

The process was so complex and the processing conditions so exact that only large high volume chemical processing facilities could get satisfactory results. The 19th century professional amateur continued to enjoy his dark room making black and white imagery, but convenient subtractive color processing became the job of large chemical facilities.

20th Century Instant and Electronic Imaging

Many technologies invented in the first half of the 20th century became very successful businesses in the second half. Baird's mechanical television in1925, and Farnsworth's broadcast television in 1927, and Zworykin's all electric camera tube (Iconoscope) in 1929 became the basis of today's television. Carlson first described Xerography in 1937; Land introduced Instant photography in 1947. The color versions followed in 1954, 1955 and 1963, respectively. Here again, the literature is so vast that one should turn to summaries for the many interesting details of the technologies. Hornak's *Encyclopedia of Imaging Science* (2002) describes each technology.

Human Vision is a Spatial Mechanism

Over the past century psychophysical and physiological experiments have provide overwhelming evidence that human vision is a result of spatial processing of receptor information. Hecht and others showed that threshold detection mechanism use pools of retinal receptors. (Davson: 1962). Kuffler (1953) and Barlow (1953) showed that the signal traveling down the optic nerve has spatial-opponent signal processing. In one example, the center of the cell's field of view is excited by light (more spikes per second). The receptors in the surround of the cell's field of view are inhibited by light (fewer spikes per second). The net result is the cell does not respond to uniform light across its field of view and is highly stimulated by edges. It has the greatest response to a white spot in a black surround. Hartline and Ratliff (1958) found spatial processing in the compound eye of Limulus Polyphemus. Dowling (1987) showed pre- and post-synaptic behavior of the retina establishing post-receptor spatial interactions in mammals.

E. H. Land (1964) proposed his Retinex theory, asserting that the three cone types act as sets, where the response was determined by their spatial interactions. The phenomenon of color constancy is best explained by independent long-, middle-, and short-wave spatial interactions. Semir Zeki (1993) found color constant cells in V4 with predicted spatial properties. Hubel and Wiesel (2005) have recounted their study the organization of the primary visual cortex's response to stimuli projected on a screen in front of the animal. In each small region of the cortex they found a three-dimensional array of different representations of the visual field. Each segment of the visual field has columns of cortical cells that report on the left-eye image next to a column for the right-eye image. The cells perpendicular to the left/right eye columns respond to bars of different orientations. The third dimension has cells with different retinal size segments of the field of view. Campbell and colleagues showed that there are independent spatial-frequency channels corresponding to bar detectors of different visual angle. J. J. Gibson (1968), the noted Cornell psychologist, described the importance of bottom-up spatial image processing.

20th Century Control of Dynamic Range

Part II Electronic HDR Rendering

Land (1967: 1428A); Land and McCann (1971:1) demonstrated the first electronic (analog) HDR rendering in his Ives Medal Address to the Optical Society of America. (Figure 10) Here, the intent was to render HDR images using spatial comparisons that mimic human vision. This paper took the ideas of Hans Wallach (1948) that suggested that lightness correlated with spatial ratios and expanded it beyond the restraints of uniform illumination. The idea was that what we see was synthesized from the ratio at an edge multiplied by the ratio at all other edges. This process synthesized an image based on the relationship of all edges in the scene, independent of the luminances of each. The history of the development of this idea is found in Land (1974), in a Friday Evening Discourse to the Royal Institution, London.

Digital Electronic Rendering

The practical embodiment of the principles articulated by Land and McCann needed two technological developments: first, the digital image processing hardware, and second, an efficient algorithmic concept that reduced the enormous number of pixel to pixel comparisons to a practical few, enabling rapid image synthesis. The hardware became commercially available in the early 1970's for the display of digital satellite and medical images. The efficient image processing began with the Frankle and McCann (1983) patent using I^2S image processing hardware with multiresolution software. The explanation of this work and its relation to other multiresolution and pyramid processing is found in the literature (McCann, 2004).

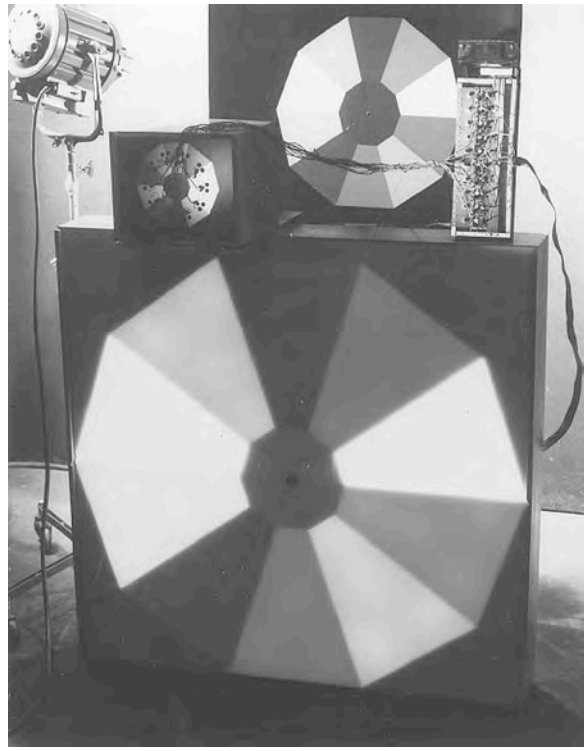

Figure 10 shows Land's Retinex analog image processing demonstration, using spatial comparisons (Land and McCann, 1971).

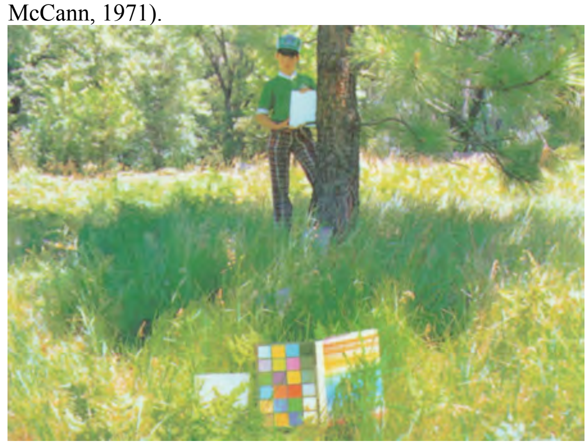

Figure 11 shows an example of an HDR scene processed with spatial comparisons (1978 Frankle and McCann patent application). The illumination on the white card in the shadow is 1/32th that on the black square in the sun. Both the white card in shade and black square in sun have the same luminance. The spatial processing converted equal input digits (~log luminance) into very different output digits, thus rendering the HDR scene into the small range of the reflective print shown here.

Figure 11 shows an example of a very efficient digital, multi-resolution HDR algorithm, using spatial-comparisons first shown in the Annual Meeting of Society of Photographic Scientists and Engineers in 1984. Here, spot photometer readings show that the illumination in the sunlit foreground is

32 times brighter than in the shade under the tree. That means that the sunlit black square has the same scene luminance as the white card in the shade. Prints cannot reproduce 32:1 in sun, plus 32:1 in shade, (dynamic range $32^{\wedge 2}$) because the entire print range is only 32:1 in ambient light. Using the spatial comparison algorithms, described in detail by Frankle and McCann (1983), it is possible to synthesize a new 32:1 image that is a close estimate of what we see.

Land and McCann's Retinex, starting with analog electronics and quickly expanding to digital imagery, used a new approach. It assumed the initial stage of Mees's and Adam's wide range information capture for its first stage. Instead of using Adam's aesthetic rendering, it adopted the goal that image processing should mimic human visual processing. The Retinex process writes calculated visual sensations on print film, rather than a record of scene luminances (McCann, 1988b). To this aim, Retinex substitutes the original pixel luminance values with the results of a spatial computation that takes into account ratios among areas. In computing these spatial relationships the reset step is essential to mimicking vision. It is a powerful non-linear operator that applies the equivalent of a scene-dependent spatial frequency filter (McCann, 2006). Stockham's (1972) spatial filtering of low-spatial frequency image content intended to combine Land's Black and White Mondrian experiments with Fergus Campbell's multi-channel spatial frequency model of vision. This concept was the basis of a great many image processing experiments and algorithms. It differs from the original Retinex algorithm because it lacks the non-linear reset, which locally normalizes images to maxima and generates the equivalent of automatic image-dependent spatial filtering. (McCann, 2006)

The use of multiple exposures in electronic imaging for HDR scene capture was described by Ochi and Yamanaka (1985), Alston et al. (1987), Mann (1993), Mann & Picard (1993) and Debevec & Malik (1997). Debevec and Malik, and subsequent papers had a new and different rendering intent, namely, accurately record the scene luminance. This led to proposals for digital image files covering extended dynamic ranges up to 76 log units (Reinhardt et al, 2006: chapter 3). It also led to the development of Brightside technology (Seetzen, et al, 2004) with a modulated DLP projector illuminating an LCD display. This raised the luminance level of display whites. Raising the luminance of white increases the display's range between white and ambient black. By increasing the range of luminances of the display one can make use of the extended range from HDR capture. There is a simple tautology, namely a display that accurately reproduces all scene radiances must look like a scene.

Recalling Figure 2b is very helpful here. There was no correlation between luminance and appearance in a complex image. Pixel-based global tone scale functions cannot improve the rendition of both the black and the white areas in targets A, B, C, D with the same luminances. Tone-scale adjustments designed to improve the rendering of one luminance region make other luminance regions worse. Land and McCann (1971) made the case that spatial algorithms can automatically perform spatial rendering, doing what Adams did to compress HDR scenes into the limited range of prints. Such spatial rendering is not possible with tone-scale manipulations. By their design, global tone–scale functions have the same effect on all pixels with the same digital input value.

Electronic imaging made it possible and practical to spatially manipulate images. Such spatial processing is not possible with chemistry in silver halide photography[3]. Quanta catch at a pixel determines the system response, namely density of the image. Digital imaging processing, or its equivalent, had to be developed in order for each pixel to be able to influence each other pixel. Digital image processing unchained imaging from being bound to universally responsive pixels. Spatial interactions, by computational means, became technologically possible. Ironically, recent HDR tone-scale processes impose pixel-value-dependent global restrictions on digital systems. Global tone-scale functions rechain *Prometheus unchained*.

Details in the shadows are necessary to render objects in shade to humans. Clearly, the accuracy of their luminance record is unimportant. The spatial relationships of objects in shadows are preserved in multiple exposures. Spatial-comparison image processing has been shown to generate successful rendering of HDR scenes. Such processes make use of the improved differentiation of the scene information. Therefore, one can make the case that improved quantization is key to successful image processing (McCann and Rizzi, 2007).

[3]Silver halide development processes using chemical restrainers can affect local departures from quanta-catch proportionality. These local chemical mechanisms have never been demonstrated over a wide enough spatial region to mimic human vision.

By preserving the original scene's edge information, observers can see details in the shadows that are lost in conventional imaging. Spatial techniques have been used by painters since the Renaissance. Photographers have used multiple exposures and dodging / burning for 160 years.

There have been many different examples of spatial algorithms (McCann (ed.), 2004) used to synthesize improved images from captured image plane luminances. Digital spatial algorithms, such as Frankle and McCann (1983), have been used to display high-range scenes with low-range media. HDR imaging is successful because it preserves local spatial details. This approach has shown considerable success in experimental algorithms (McCann, 2005, 2007) and in commercial products (Sobel, 2004, Eschbach et al. 2004). Figure 12 shows the results of spatial image processing from a single exposure using automatic firmware in an amateur camera.

Figure 12 shows images with and without spatial comparisons, both taken with a commercial HP 945 camera. The pictures are hand-held single-exposure images. The image on the right uses Retinex based *Adaptive Lighting/Digital Flash* camera options. The spatial processing removes the over-exposure of the windows while lightening the red rug, white marble altar, and pews.

20th Century Color

Part II- Electronic Imaging

In September, 1981 Aiko Morita, Chairman of Sony Corp. gave a press conference at the Plaza Hotel in New York City announcing Mavica, the first digital camera (Time 1971). He took a color digital still picture, displayed it on television and then the picture transmitted across the room to a second computer. He also made a thermal print. The camera was a machine shop prototype, not a production camera. The transmission took many minutes to cross the room and the color saturation of the print was very poor compared to AgX prints. Nevertheless, this presentation changed imaging. Immediately following that press conference all imaging companies began to spend more than 50% of their research budgets on digital imaging.

That year, IBM announced the first PC. In 1984 Apple introduced the MAC. These digital technologies have expanded to the point of crowding out AgX photography. Digital printing replaced optical print by the end of the 20th century. Even high-resolution Ektachrome transparency AgX films are printed with digital printers today. In addition to color film printers there are electrographic in 1955, Inkjet in 1976, Thermal 1980 and Vaught's and Endo's Thermal Inkjet in 1987 (McCann: 1998a; Hornak, 2002),

7. CELLUAR DIGITAL IMAGING

Photography is in the middle of another massive change caused by technology and the lives of its users. Digital cameras have been added to the feature set of most new cellular phones. The techniques of today's electronics manufacturing makes it very difficult to add or subtract features from a mass-produced product. It is far simpler to include all features in a device and make the user ignore the ones not wanted than to make, market and train users to select what they want. The world is well on the way to universal cell phone usage, and that includes a camera available at all times, whether or not it is wanted. That creates an enormous problem for camera manufacturers. If every one has been given a camera by their cell phone makers, how do they sell cameras? The only cost for this camera is the time to learn to use it and the problem of what to do with the images.

The use of cell phone images is interesting. The price is nil, the convenience is very high, and the quality ranges from poor to good enough. Even at these low resolutions and high compression, the storage and transmission costs of images, still and video, are much higher than for audio. The cell phone is not the photo album. It seems unreasonable to spend much more time to put the image somewhere than to make it. And when I put it somewhere, how will I find it?

8. ARCHIVAL IMAGES

Daguerreotype images developed in fuming mercury are remarkably stable. With only reasonable care they are as vibrant today as the day they were made.

Black and white silver halide prints have a life expectancy of hundreds of years. Color films are somewhat more likely to fade. Electronic prints vary from unstable thermal images to stable pigmented dyes. Nevertheless, the trend is unmistakable. The more recent the technology, the less archival are its images. In the majority of uses this is not a problem. The image stability meets the users' needs. Ironically, the more convenient the process is, the less valuable the result. It is so easy to take a picture automatically that it is difficult to devote attention to the composition, lighting and perspective of the image. We are far more likely to take the instantaneous picture and see if it is good enough. Great convenience makes it harder to make pictures that are as good as they can be.

9. DISCUSSION

This paper is brief and selective survey of picture making technology, with a few passing references to its older sibling printing. The two hundred year history began as the work of a very few who formed small groups of like-minded colleagues. As the number and size of these groups grew they spawned hundreds of cottage industries that prospered in small niche markets. The user of photography began with a few chemists, spread to devoted amateurs and a small number of professionals. Gernsheim (1950:5) report that London had 3 professional photographers in 1841, 51 in Great Britain in 1851 and 534 in 1861. He comments that this list of register photographers " is certainly an understatement, since it does not take account of the legion of petty dabblers, or the thousands of employees engaged in the trade".

By 1900 the mature small photographic business exploded by expansion of the number of users. Kodak and many other large corporations improved the performance, convenience and quality of pictures taken by completely amateur photographers. These improvements came from research and development sponsored by large corporations, in turn supported by massive growth in usage.

Today's imaging technology is breathtakingly beautiful. The displays are very bright; the prints are clean and sharp. The colors are fully saturated. The process is instantaneous. The availability is global. Who could possibly complain?

The unique property 21st century imaging is becoming increasingly democratic and less individualistic. Today's cell phone has in it CMOS sensors, digital image processing, storage, display and transmission functions, each the results of sizable development teams. It is not possible to build any of these devices in a small lab. It is the result of large teams making tiny modular components integrated into a single device. The more universal the device is, the larger the market, the greater the profit, the more successful the endeavor. But, what would H.R. Robinson think about replacing his AgX film and camera with a cell phone? Color would be an advantage, but he, as Ansel Adams, might be uncomfortable with the assigned fixed color rendering of the scene. Multiple exposure techniques might emulate those he developed in the 1850s, but the dynamic range of light on camera's image plane is limited by veiling glare (McCann and Rizzi, 2007). Glare is dependent on camera size and aperture so that the cell phone's small, fast lenses will limit dynamic range more than his old cameras. Multiple exposures give improved quantization of details, but do not affect the camera&scenes' veiling glare limit. Robinson could use Photoshop to fuse and manipulate his multiple exposures. That certainly would be an advantage over cutting and fitting glass plates by hand.

Are there concerns about the development of future technology? An interesting example is the perpetual debate between marketing managers and engineers about the number of pixels. The best pixels have large areas, to capture many photons, and improve signal-to-noise ratios. The problem is that resolution and cost both increase with the number of pixels in a sensor. If not limited by cost, we could have large arrays of large area pixels capable of capturing the entire dynamic range of light falling on the camera image plane. But, cost is a very big problem. Then, for the same size sensor, we have to compromise between resolution (number of pixels) and dynamic range (area of each pixel).

Think back to the debates in the 1980s between AgX film/camera engineers and digital camera engineers, both competing for R&D dollars from perplexed managers and marketing strategists. These debates happen in all imaging companies. The simplest take-home-message at the time for the AgX proponent was that digital was inferior because it had such poor resolution. It took 15 to 20 years for digital resolution in amateur cameras to be equivalent to AgX. In those years the marketing managers and the public have all 'learned' the popular misconception that image quality depends almost exclusively on the number of pixels. Engineers are now confronted with the difficult task of raising the level of the discussion to re-evaluating the trade-offs between resolution and dynamic range. Number of pixels does not determine image quality.

In a cell phone the cost and size of: the camera chamber, the sensor, and the lens all work against capturing the same range of light as a 35mm camera and negative. The range of illumination from nighttime campfires to sunny beaches also makes the problem difficult. If one's glass is half-empty, the 21st century may replace the convenient 20th century pictures with still more convenient, but lower quality images. If one's glass is half-full the appreciation and need for quality in photography will lead us along a path, so far unanticipated, to many new advances in picture taking. That is what has happened in the past. We will have to wait to see, or better yet, participate in the development of pictures in the 21st century.

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