The Ansel Adams Zone System: HDR capture and range compression by chemical processing

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ABSTRACT

We tend to think of digital imaging and the tools of Photoshop™ as a new phenomenon in imaging. We are also familiar with multiple-exposure HDR techniques intended to capture a wider range of scene information, than conventional film photography. We know about tone-scale adjustments to make better pictures. We tend to think of everyday, consumer, silver-halide photography as a fixed window of scene capture with a limited, standard range of response. This description of photography is certainly true, between 1950 and 2000, for instant films and negatives processed at the drugstore. These systems had fixed dynamic range and fixed tone-scale response to light. All pixels in the film have the same response to light, so the same light exposure from different pixels was rendered as the same film density.

Ansel Adams, along with Fred Archer, formulated the Zone System, staring in 1940. It was earlier than the trillions of consumer photos in the second half of the 20th century, yet it was much more sophisticated than today's digital techniques. This talk will describe the chemical mechanisms of the zone system in the parlance of digital image processing. It will describe the Zone System's chemical techniques for image synthesis. It also discusses dodging and burning techniques to fit the HDR scene into the LDR print. Although current HDR imaging shares some of the Zone System's achievements, it usually does not achieve all of them.

Keywords: Ansel Adams, Zone System, scene visualization, HDR capture,

1.0 INTRODUCTION

If you measure the range of light coming from an Ansel Adams print on a wall in a room, you get a very small ratio of maximum to minimum. For example, the luminance of the white clouds in the center of "Moonrise at Hernandez" is 17.1 cd/m^2; and the black sky is 0.15 cd/m^2. It has a dynamic range of only 114:1. Clearly, an Ansel Adams print does not reproduce scene luminances, pixel by pixel. It renders the artist's intent of what he saw when looking at the scene. How did he do it?

For Ansel Adams there was an orderly and disciplined approach to making photographs. [1-5] First, he visualized the final print that the scene will eventually produce. Second, he measured the scene's dynamic range and the intermediate light coming from key features. Ansel used these scene luminances to determine technique for capturing the scene information in the negative. Third, he used dodging and burning. He used this spatial image processing to modify the scene information captured in the negative, so as to generate the desired rendition consistent with the visualization.

2.0 VISUALIZATION

In Ansel's lectures and in his book" Examples: The Making of 40 Photographs" he described his first use of visualization in making the image "Monolith, The Face of Half Dome", 1927. [7] He had hiked halfway up the plateau above Yosemite Valley with his wife and three friends, carrying his … "Korona 6 1/2 x 8 1/2 view camera with two lenses, two filters, a rather heavy wooden tripod, and twelve Wrattten Panchromatic glass plates." [7] The left image (Figure 1), made from one of Ansel's lecture, slides shows the image taken with a yellow filter. After exposing that negative, Ansel had one negative left. He stopped and visualized how he expected the print to look with the Half Dome against the sky. He "visualized" that the sky would be brighter than the rock and would detract from the image he wanted to make. He decided to take the last negative with a red filter that would render the sky darker than the rock (Figure 1- right). He often said that he ran down the trail to get to the darkroom to see how well his visualization worked.

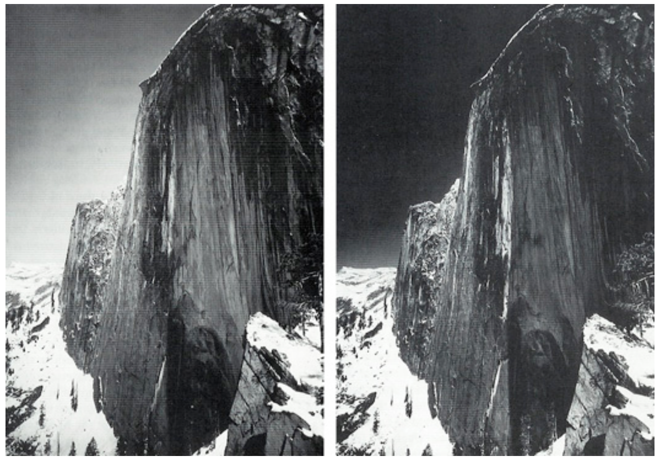

Figure 1 shows pre- and post- visualization made from Ansel's lecture slides.

3.0 SCENE CAPTURE

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 capture all the information in the scene and that the printing process render this information in the print.

Although the parlance has changed over the years with the transition from silver halide to digital photography, the problem of successfully capturing scene information in an efficient manner remains the same. Discussions of the "range of the scene" in film circles involved techniques to preserve details in the highlights and shadows. Range problems were described as burning out facial skin-tones in the toe of the response function (tone-scale curve), or the lack of definition in the shoulder. Today, the same issues are described as having enough bits to represent the scene.

The discussion becomes very complex when one stops to analyze the limitations of each of the dozens of mechanisms between light coming to the camera, and the light coming from the reproduction to the observers' eyes (Table 1). Each of these steps has independent parameters that could limit the total response of the system.

Process	Device	Film	Digital
Scene			
	Lens	Aperture, # elements, coatings, resolution	Same
	Camera	Volume, surfaces	Same
	Sensor	Resolution, surface, spectral & dynamic ranges	Same
	Sensor processing	Developer, stop bath, hypo, hypo clearing, tone, wash (B&W)	A/D, noise reduction, transfer, de-mosaic, sharpen, color enhance, compress
	Storage	Dry negative	Digital file
	Read storage	Printer	CPU
	Display characteristics	Contact, diffuse / condenser enlarger	Graphics card
	Anticipate display	Paper grade, surface, developer, toning agent	Rendering intent, profile
Reproduction Rendition		Display print	Display device

Table 1 list the processing steps for film and digital imaging systems between scene and print or display.

In today's High-Dynamic Range world, we find imaging formats that can specify scene data over 76 log units. [8] Is this possible? Is this an improvement over silver halide films? How do film and digital systems differ in their dynamic-range performances?

3.1 Tone Scale Curve

The first step in answering these questions is to discuss the terminology of the photographic response function.

For forty years after the inception of practical photography, techniques were based on chemical formulas and visual observations. In the 1870's and 1880's Hurter and Driffield [9] established the field of photographic sensitometry. They measured the response of the AgX film (density) to light exposure. Their first publication, in 1890, describes the characterization of silver halide films as the plots of density vs. exposure. Photographers quickly adopted this practice and it became known as the "H&D curve". English film manufacturers marked their product with H&D ratings. Hurter and Driffield wrote a long series of papers starting in 1881, and continuing through 1903 that studied all aspects of film sensitometry. In 1900, C. E. K Mees became an undergraduate at University College London. He met another student S. E. Sheppard who shared his interested in photography. [10] They repeated Hurter and Driffield's experiments with newer apparatus including an acetylene burner as standard light source. Mees modestly described this undergraduate research by saying: "We made little progress beyond what Hurter and Driffield had put on the record". [10] Nevertheless, it earned them their B.Sc. degree their first scientific article, doctorates in 1906, and a book *Investigations of the Theory of the Photographic Process*. [11]

Also 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'. [12] Just after the introduction of the Brownie, George Eastman went on a different quest, namely the establishment of an industrial 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. Mees's condition was that Eastman buy his present employer Wratten and Wainwright. [10]

Mees, in his 1920 book "The Fundamentals of Photography (first edition) [13] described the reproduction of Light and Shade in (Chapter VII). The description starts by showing the reproduction of a cube using two, three, four, five and six tones (Figure 2). Mees used "*tones"* to explain in simple terms the progression from white to black in a photo. His chapter gives a detailed discussion of how the shape of the photographic *tone-scale* curve affects the photographic print.

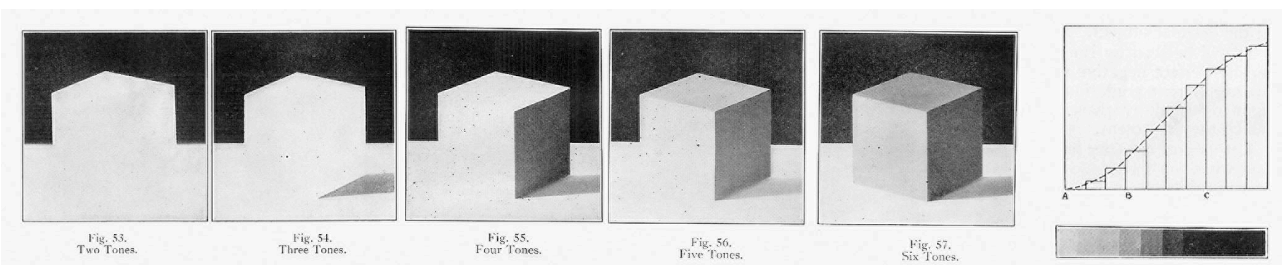

Fig 2 shows illustrations from Mees's chapter "Reproduction of Light and Shade".

Although Mees was exemplary in publishing his fine research in scientific journals, and in supporting published industrial research, he followed the Kodak philosophy of instructing a new kind of customer. He used "tone-scale curve" to replace the then universal term "H&D curve" in his and subsequent Kodak publications. In fact, the terminology is used today in digital high-dynamic-range imaging.

To make a long story short, a tone scale is the equivalent of a one-dimensional lookup table that converts scene luminance to captured image digit. Film and digital systems can be thought of as two step operations: capture the scene and render the print, or display (Table 1). In one case we make a negative film, in the other an array of digits in memory. We will first compare the scene capture performances, and then their renditions.

3.2 Cameras limit Dynamic Range

Film and digital cameras share the same issues imposed by the optics and geometry of cameras. The light falling on the camera image plane is the sum of the desired image of scene luminances and the veiling glare from unwanted reflections from glass and camera surfaces. Glare is negligible in scenes with uniform illumination, but is substantial in scenes with dramatic illumination. Veiling glare determines the dynamic range of light falling on the camera image plane. [15,16]

The differences in amount of veiling glare for film and digital cameras depend on differences in number of glass elements in the lens, coatings, camera volume and sensor surface. Glare is scene and camera dependent. Glare is so large that sensor technologies do not play a role in limiting the dynamic range of almost any scene. [16]

The important distinction in HDR image capture is the difference between recording usable scene information and accurate measurement of the amount of light coming from each object to the camera. It is essential that the image capture step records the detail in the highlights and the shadows. This is the usable information needed for an optimal final print. Adams describes in detail the techniques for exposing and developing negative to, not only capture the usable range, but also to optimize how the scene information is positioned on the tone scale. The Adams "Zone" scale is the same as the "Mees "Tone Scale".

A second very important distinction is the difference between dynamic range and the digital quantization of light levels within that range. The dynamic range of a scene is the ratio of the highest to the lowest amount of light coming from the scene to the camera. It is a ratio of radiances, or luminances. That range is different from the number of bits that are used later in the camera chain to quantize the sensor's response to that light. You can think of the range as the length of a sausage, and the number of bits as the number of sausage slices you choose to have.

3.3 Zone system techniques for HDR scene capture - Interplay of Exposure and Development

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 both development and exposure. The zone system provided the necessary information to select appropriate exposure and processing for each scene's dynamic range.

In chapter 4 of "The Zone System" of the "The Negative" [2], Adams describes exposure and development techniques that control the tone scale of the negative. He says on page 72:

> "It is important to understand that the primary effect of expansion or contraction is in the higher values, with much less alteration of the low values. This fact leads to an important principle underlying exposure and development control: *the low values (shadow areas) are controlled primarily by exposure, while the high values (light areas) are controlled by exposure and development*.

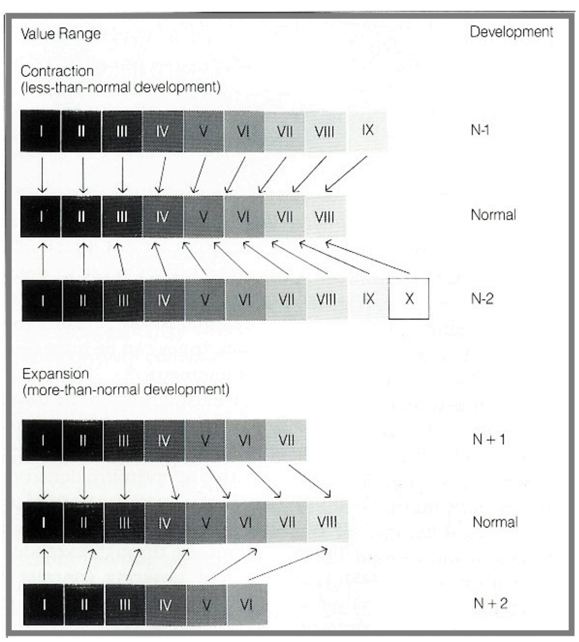

Figure 3 is taken from "The Negative" Figure 4-14. Its caption reads:"*Effect of expansion and contraction*. The arrows suggest the effect at each value of expansion and contraction. For example, a subject area exposed on Zone IX and given N-1 (less time in the developer) results in Value VIII in the final print. Changes in development have the most pronounced effect on high values, an relatively little effect on low values, as shown."[2]

A familiar way to describe the above is to plot the Tone Response (Net Density) vs. Zone in the scene (Figure 4).

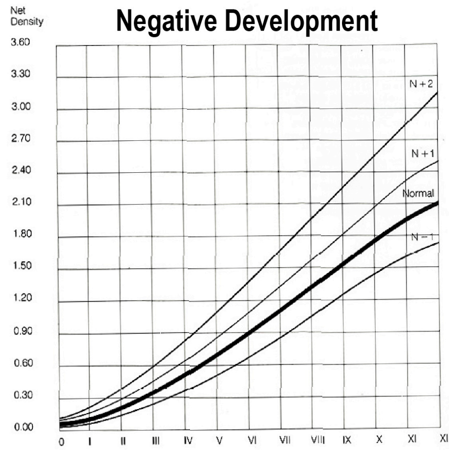

Figure 4 is from Adams [2] (page 247) Film Test Data for Kodak Tri-X Professional

In Figure 4 we see the plots of the negative's density values with under development (N-1), normal, and over development (N+). In this manner, increased exposure and reduced development compresses high-dynamic range scenes into the normal tone-scale range of the negative/positive print system. Alternatively, reduced exposure and increased development expands low-dynamic range scenes into the same system. The range of densities in the negative is the equivalent to the number of gray levels in a digital image. When performing calculations with limited precision one has to be careful not exceed the range possible. With linear digitization of HDR scenes exceeding the limits is easy. However, if one uses logarithmic encoding of HDR scenes, then the range is not limited by the number of bits. The logarithmic encoding is non-linear, so that subtraction of two numbers is the ratio and not the difference. Just as one should optimize the encoding of the range of bits available to perform a calculation, Adams optimized the gray levels in the negative by controlling exposure and determining development before taking the picture. This is equivalent to tuning the A/D converter in a digital camera before exposure.

Figure 5 is based on Adams, "The Print", Test Data [3] (pages 198, 200). It shows the effects of different films and development. It is easy to see their similarity to digital tone scale plots.

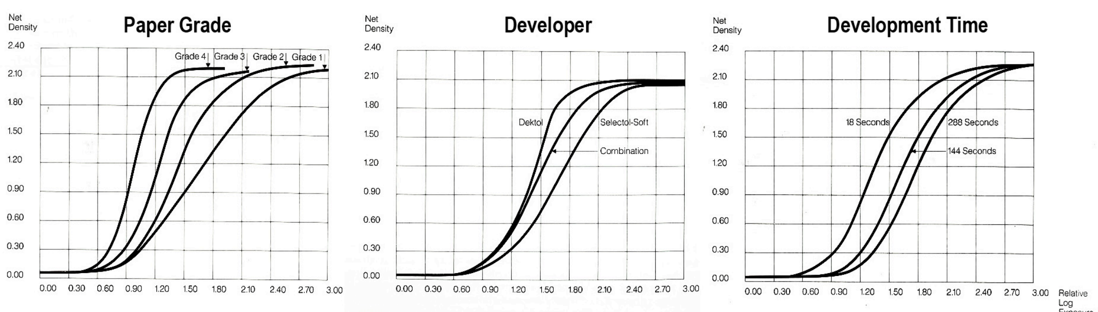

Figure 5 shows tone scale response caused by paper grade, selection of developer and times of print development.

In digital terminology the control of exposure and development is the equivalent of adjusting the quantization of the tone scale. Quantization determines the range of light assigned to each digital level between max and min. Linear quantization is prone to losing information in whites and blacks. Non-linear quantization preserves these details needed for good photography. Ideally we use quantization techniques that are matched to the detail information visible to humans. Appearance tone-scale spacing correlates with the cube root of luminance of the scene, and with the log of luminance on the retina, [17- 20] Human appearance is not a linear function of the amount of light.

Ansel's use of exposure and development of the negative is the way to optimize the use of the negative density range to fit the scene. It is the equivalent of adjusting the quantization scheme in a digital camera to optimize the use of its digit range.

It is possible to record in a single exposure all the usable scene information using film negatives, or wide dynamic range digital sensors. [16] The use of multiple exposures to capture HDR scenes addresses the problem of the use of digits, rather than the range of light from the scene. The different exposures put a single object on different parts of the tone-scale response curve and get different renditions because the tone scale had different quantizations in different parts of the tone curve. Multiple exposures are not necessary if one uses optimal quantizations.

3.4 Compressing the HDR scene into the LDR print and display

Film and digital imaging share an issue in the next step of converting the negative, or digital file for the display. In both cases, the displays respond to specific input information. Each tone or color in the final display is associated with a unique code. In a photographic print there is a specific amount of light that generates an optical density, i.e., 0.5 OD. In an LCD display there is a particular digital code sent to the graphics card to make a particular color, i.e., a specific red.

In photography the tools to render the negative are the exposure, the type of printer (contact, diffuse or projection illumination), the contrast of printing paper (slope/contrast), print development, surface of paper. (Table 1) The photographer has to convert the signal stored in the negative to the desired appearance of the print.

Analogously, there are tools that covert the stored image data into the desired display image. In amateur digital photography, camera, printer and display manufacturers provide profiles [21], or standards to transform the data in memory to the required data to make a density of 0.5 OD, or a specific red.

We have already seen that rendering of HDR scenes is not done by reproducing the luminances of the scene. It is impossible to record the scene accurately because of glare, and even if it were possible it would not provide the artist with an opportunity for applying his rendering intent. So what is the reason that the Zone System and HDR spatial processing make better pictures?

The answer is that the range is less important than how one handles the information between maximum and minimum. It is the encoding of the tone scale values between white and black that controls the quality of the rendition. The limitations we discussed above, namely keeping details in the highlights and shadows has little to do with the range of the sensor. Instead, it has to do with the how one encodes the tone values within the range. The highlights get burned out because the contrast information in the negative is too small for what the print paper needs to render it properly.

A good example of this is found in the evolution of digital camera sensors. The question for digital hardware designers is "How many bits do we need to reproduce all images"? In the early days memory bits were expensive. Then, 256 levels between max and min were sufficient, as long as the tone scale shape was appropriately non-linear. As memory and processing cost plummeted it became possible to use more bits to accomplish the same results. In order to take advantage of the potential of using more information one has to evaluate the real meaning of the data. Camera digits are not scene luminances. They are luminances plus scene-dependent camera glare. [16]

3.5 Tone Scale Compression – A double edged sword

The best example of the limitation of tone-scale processing is Land's Black and White Mondrian. [22]. Here, a black paper and a white paper have the same luminance, because the white is in a shadow. To render what this experiment looks like we need to make a print with a lighter white and a darker black. If we try to improve this image with a new tone scale lookup table we have a problem. White and black have the same digital value. A tone-scale lookup table cannot make the same digit lighter in one part of the scene and darker in another.

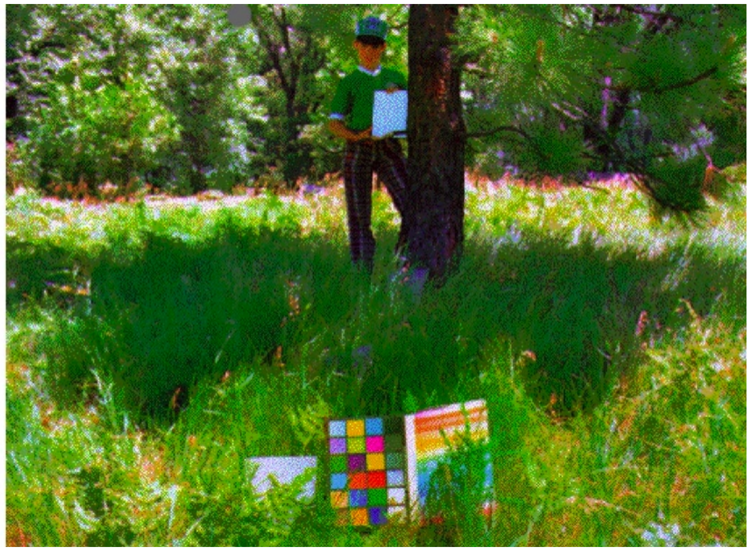

Figure 6 shows (left) a conventional fixed tone-scale photograph, and (right) a Retinex processed print made from a digitize color negative.

Figure 6 shows a 1984 photograph of "John at Yosemite". It was taken at an Ansel Adams photographic workshop in Yosemite. It is a real life example of Land's "Black and White Mondrian" experiment. The white card that John is holding --"White in Shade"—has the same luminance as the black square in the ColorChecker™ in the sun. The left picture in Figure 6 is a conventional photograph taken with a fixed tone scale. The white card in the shade is white and all the squares in the ColorChecker™ are over-exposed white. The picture on the right was captured with a color film negative, scanned to digits with logarithmic spacing, Retinex processed and printed on film paper. [23] The Retinex spatial processing compressed the range of the scene to fit the range of the print. The spatial processing preserved the local edge information. It made the white in the shade lighter and the black in the sun darker. If we simply compressed the captured scene luminances to fit the range of the print, the rendering looks like a foggy day. All the edges will have less contrast.

The challenge is to render one area (digit=128) as white, and another area (digit =128) as black. A digital tone-scale lookup table can make 128 lighter, a different one can make 128 darker. A digital tone-scale lookup cannot make 128 both lighter and darker. The compression of dynamic range has to be a spatial process to be successful.

Tone-scale lookup tables can improve a great many images. They can bring out details in the highlights and shadows. The improvements come from increasing the contrast of small differences in the digital record. Usually these small differences are the result of non-linear tone-scale responses in the camera or display. In effect the tone scale is enhancing the edge information in the improved region. However, enhancement in one region of the tone scale must result in the compression of another region of tones. In order to make the discrimination in the whites better, discrimination between mid-grays, or near blacks, has to be worse.

The only strategy that can compress the dynamic range of a scene for all tonal values, and not lose local contrast, is the introduction of invisible gradients. This is what happens in dodging and burning. It is also what happens in Retinex, ACE, and other spatial image processing. [24, 25]

4.0 ADAMS' PRINTING – "PERFORMING THE SCORE"

Ansel's favorite analogy was that the negative was the musical score and that making the print was the performance. So far in this description of the Zone System we have described all the technical details of making negatives that optimally record the range of light in the scene. We have described Ansel as a skilled recording specialist for light. In making the print Ansel's role changed dramatically. He became the performer of the score in the negative. He became the interpreter of the optimally stored information. The tone-scale functions that he studied and mastered were necessary, but not sufficient to render his visualization of the scene. Spatial manipulation of light projected from the negative onto the print paper was needed to successfully render the visualization. Each scene required a unique spatial intervention.

4.1 Dodging and Burning

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.

Dodging, withholding light from the print paper is often done with a circle of black opaque paper (several inches in diameter) on a wire, or stick. It looks look a lollypop. The lens of the negative enlarger has a small aperture, so as to have a long exposure time. The operator holds the lollypop above the print paper so that the shadow it creates is out of focus. The operator moves the opaque area that removes the light in slow, smooth motions. This moving, out of focus mask makes the area under the lollypop lighter, but leaves no visible image of the lollypop. A brief exposure of a static, in focus mask can be easily seen.

In image processing parlance, dodging introduces gradients in luminance, thus changing the low-spatial frequency content of a portion of the scene. These low-frequency gradients are below visual threshold, and hence not visible. The effect of the reduced light makes the area of interest lighter. The high-spatial-frequency information is unchanged as long as the print paper transfer function is linear. That means that the details, or small features in the area of interest are unchanged. This process does nothing to change the magnitude of the scene edges recorded in the negative. In non-linear portions, such as shadow areas, holding back exposure will make visible the details recorded in the negative but too dense to be seen in the conventional “straight” print.

Burning is the same process for the opposite direction. It makes the area of interest darker. Here the operator uses a circular hole (several inches in diameter) in a black opaque paper. Again, the image of the circle is out of focus on the print paper. Here the increase in light darkens the area of interest. In the nonlinear highlight areas of the scene this added exposure makes the details in whites more visible.

Adams described the dodging and burning process in detail (pages 102-116) [2] for virtually all of his most famous images. [7] 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 captured all the desired scene information. Spatial manipulations (dodging and burning) fit the captured range to the limited dynamic range of prints.

5.0 APPARENT VS. PHYSICAL CONTRAST

Ansel showed a very powerful example of the difference between actual dynamic range and apparent dynamic range in Polaroid Land Photography (page 148) [6]. He described the pre-exposure technique to see more details in the shadows. As illustrated in Figure 7, the photographer uniformly pre-exposes the film to a very low light level – close to the films threshold response. Then, he exposes the scene whose range far exceeds the film’s range. The response of the film is reproduced in the upper left corner of Figure 7, along with the film’s response to the pre-exposure (lower left). The combined result is shown on the right. The pre-exposure raised the film response to its threshold. Additional amounts of light from the darkest areas in the scene filled in the details in the shadows. This technique adds light everywhere in the image, and hence lowers the actual dynamic range of the film. Nevertheless, it increases the apparent range of the print. This is an excellent example of why preserving local spatial information is the key to successful HDR imaging.

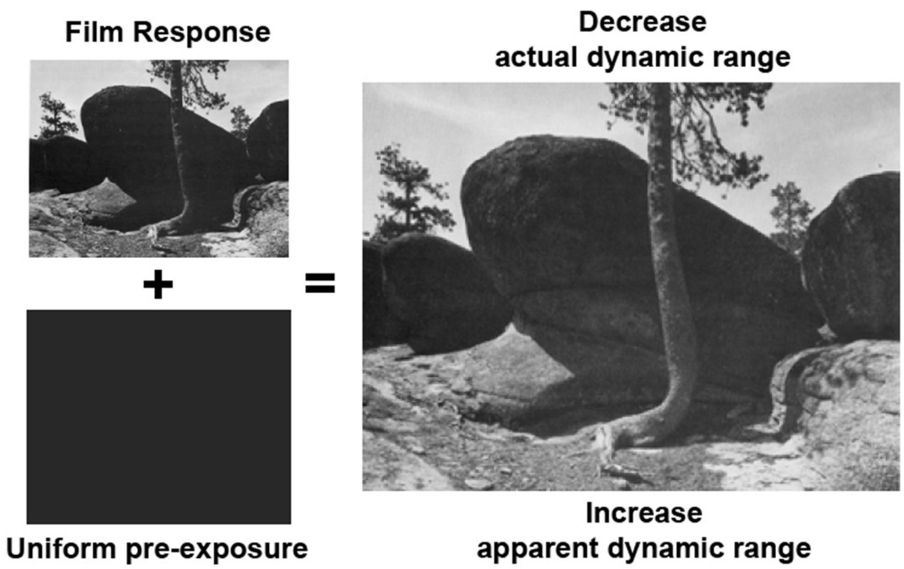

Figure 7 shows the effect of pre-exposing film to increase the apparent range of the print.

6. CONCLUSIONS

There are a great many parallels between the Adam Zone System and HDR photography. The share the same goals and use many parallel techniques. Controlling the capture of useful information and optimizing the storage of the scene information is the first essential part of the process. Recording all the useful information is possible with good single exposure and quantization practice. The rendition of the final image has two components. The stored information needed to be adjusted to fit in the range of the print paper or display device. Meaningful dynamic range compression requires spatial image processing to avoid trading off improvements in one part of the tone scale for degradation in another. Dodging / burning, or Retinex/Ace spatial image processing, reconstruct the image content to preserve local detail while fitting the HDR world into the LDR rendition. Successful HDR imaging synthesizes a new image from the usable light capture to meet the aesthetic rendering intent. This is exactly what Ansel continues to teach us in his technical writings [1-6], and what Ansel and John Sexton show us in their photographs. [26-33]

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