Section A

History of HDR Imaging

1

HDR Imaging

1.1 Topics

The chapter lists many disciplines that help us understand High-Dynamic-Range (HDR) imaging. It describes the work of artists, scientists, and engineers that have developed techniques to capture HDR scenes and render them in a wide variety of media. This chapter points out the difference between traditional physics, in which light is always measured at a pixel, and human vision, in which spatial image content is important. In vision it is the relationship between pixels, rather than their individual values, that controls appearance. This turns out to be a central theme for successful HDR imaging and will be discussed throughout the text.

1.2 Introduction

High Dynamic Range (HDR) imaging is a very active area of research today. It uses the advances of digital image processing as its foundation. It is used in camera design, software image processing, digital graphic arts and making movies. Everywhere we turn we see that HDR imaging is replacing conventional photography.

If we want to understand HDR imaging we need an interdisciplinary approach that incorporates the many ways of making images. Further, we need to understand exactly what we mean by conventional photography. This text starts with the history of painting and presents an integrated view of the arts, image science, and technology leading to today's HDR. It ends with a discussion of possibilities for the future.

One of the most important factors in understanding imaging is the careful definition of the goal of the image. This is called *rendering intent*. We might, at first, think that images of scenes have the same goal – copy the scene. As we will see in the text, there are a great many different rendering intents. We could have as our goal:

Reproduce exactly the light from the scene

Match the appearance of the scene

Calculate the surface reflectance of objects in the scene

The Art and Science of HDR Imaging, First Edition. John J. McCann, Alessandro Rizzi.

Calculate the appearance of the scene and print the appearance

Abstract the important features of the scene

Introduce a personal style to the image of a scene

Use the scene for inspiration

Make a pretty picture

It is important to distinguish whether one's goal is to apply skill and craftsmanship to make a personal rendition of a particular scene, or to use science and technology to incorporate a general solution of HDR imaging for all ranges and types of photographic scenes.

The 19th century saw the rapid growth of a cottage industry that required the photographer to make his own plates, take the picture, process the negative, expose the print, develop it, and make it insensitive to light. In the 20th century, the Kodak slogan "You take the picture, we do the rest", changed photography into a major industry. (Chapter 5) It took a great amount of superb scientific research, engineering, and manufacturing development to expand the set of photographers from a devoted few in the 1850s to today's nearly global participation.

There is a parallel in HDR imaging today. In the past few years, we have seen considerable interest in using multiple exposures to capture wide dynamic ranges of scene information, 16 bit quantizations (RAW images), and software tools to recombine the different exposures in a new rendition. These techniques work well for most individual scenes where the photographer uses these tools to make the unique rendition of a particular image. There is a second very important objective, namely to apply art, science, and technology to finding the general solution for using HDR imaging principles for all scenes. That is the goal of this text.

Digital cameras capture scenes using millions of light sensor segments to make *picture elements (pixels)*. We may like to think that the considerable technological advances in 21st century digital imaging make it possible now to accurately reproduce any scene. On further study, we find that imaging remains the best compromise for the rendering intent we have chosen. Despite all the remarkable accomplishments, we cannot capture and reproduce the light in the world exactly. (Section B) With still further study, we find that accurate reproduction is usually not desirable. This is why we need an interdisciplinary study of image making to find the best compromises in rendering the scene.

After all, rendering the high dynamic range of scenes has been a problem since the beginning of scene reproduction. Paintings of scenes date back 160 centuries to colored wall art in the Lascaux caves. Printing has early examples of stone characters for making clay tablets dating back 50 centuries; color wood block plates for printing uniform colors – 14 centuries; perspective in painting – seven centuries; chiaroscuro rendition of apparent illumination – five centuries; and LeBlon's hand-made color-separation printing plates – three centuries – 160 years before James Clerk Maxwell invented the first mechanical color photography.

1.3 Replicas and Reproductions

Human vision responds to a narrow band of wavelengths in the electromagnetic spectrum using rod-shaped and three types of cone-shaped cells in the retina. These cells generate three channels of color information that are identified with red, green, and blue light. Figure 1.1 is a three-dimensional cube that represents the *color space* of an image in computer memory. It shows R, G, B axes that combine to make white, red, yellow, green, cyan, blue, magenta, and black.

To understand the underlying problems in scene reproduction, we need to differentiate *replicas* and *reproductions*. A replica is a copy of a painting, by the original's artist, using the same media, or color materials. Replicas use the same media, and have the same physical properties for controlling light.

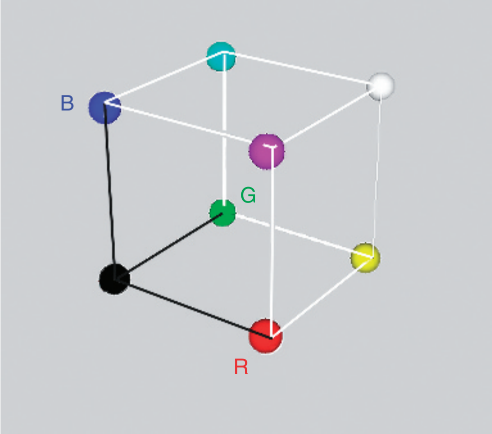

Figure 1.1 A three-dimensional color space with R, G, B axes.

Replicas share the identical color space with the original. Reproductions are copies of original art in different media, such as a computer-screen copy of a painting. The challenge in color reproduction is to capture the information contained in the entire original 3-D color space and to make a copy in a different size and shape reproduction space.

The problem is very similar to moving everything in your house to a new one. The original is one's current house. It is defined by the tools that physics uses to measure light, such as wavelength, and photon count. The *reproduction* house has different dimensions for the length (amount of red), width (amount of green) and height (amount of blue). Reproductions move everything in the old house into the new house, keeping all contents in corresponding rooms, even though the dimensions of the entire house, and each room, are different. Good reproductions are never exact physical copies of the original, because that is not possible. Good reproductions capture the appearance and relationships of objects in the scene. The original and the reproduction have different 3-D color spaces with different sizes and local shapes, because they use different colorants. If the reproduction reproduces the pixels that are in gamut accurately, then the rest of the out-of-gamut pixels make unwanted problems, such as highly visible artifacts. Good reproductions render all the information in the interior of the original's color space, often using different colorimetric colors at corresponding pixels. Reproductions cannot make colorimetric copies of all the pixels in the original because the media are different. The problem with colorimetric reproduction is that it must select the pixels that cannot be reproduced accurately, and do something with them.

1.4 A Choice of Metaphors for HDR Reproduction

Those of us interested in scene reproduction have a choice of two very different paradigms for the process. One paradigm starts with Euclidean geometry that is an essential part of physics and of 19th century psychophysics. The other paradigm starts in the Renaissance and has been amplified by 20th century neurophysiology and image processing.

1.4.1 Pixel-based Reproduction

The first paradigm is the *pixel-based,* or the film photography model. Traditional physics often starts with the Euclidean point. Geometry teaches us about position defined by dimensionless points. Electronic imaging defines picture elements with small, but well defined dimensions, as pixels. Film photography is a triumph of chemistry and materials science using light sensitive crystals that become light-stable images with chemical development. Over the expanse of the sheet of film all pixels have the same response to light, hence the name, *pixel-based* imaging.

Josef Maria Elder's (1905) *History of Photography* describes early Greek and Roman reports of the effects of light on matter, such as cinnabar, indigo blue and rare purple dyes made by exposing snail mucus to light. There were many early silver halide systems prior to 1800 that were the work of notable chemists and physicists. Elder describes the sequence of events leading to Schultze's experiments with silver salts in 1732. In 1737 Hellot, in Paris, made an invisible ink with silver nitrate that turned black with exposure to light (Mees, 1920).

Thomas Wedgwood and Sir Humphrey Davy (1802) did research on silver halide processes at the Royal Institution, London. At that time Thomas Young was Professor of Natural History there and was writing a book. In Young's famous Bakerian Lecture (1802), he made the suggestion:

> "Now, as it is almost impossible to conceive each sensitive point of the retina to contain an infinite number of particles, each capable of vibrating in perfect unison with every possible undulation, it becomes necessary to suppose the number limited, for instance, to the three principal colours, red, yellow, and blue, . . . : and each sensitive filament of the nerve may consist of three portions, one for each principal colour."

This statement is regarded as the foundation of pixel-based *Colorimetry*. More than 50 years later James Clerk Maxwell performed color matching experiments that are the basis of all CIE color standards. He measured how much long-, middle-, and short-wave light is needed to match any wavelength. Even today, colorimetry calculations limit their input information from the scene to measurements of single pixels.

Analyzing images a pixel at a time could come from Euclidean geometry, the chemical nature of silver halide photography, or the influence of Thomas Young's tricolor hypotheses. It may be a combination of all three. Was Thomas Young influenced by the study of photography by his colleagues at the Royal Institution, Woodward and Davy?

1.4.2 Spatial Reproduction

An alternative paradigm is building images out of *spatial comparisons*. Around 1500, Leonardo da Vinci wrote:

> "Of colours of equal whiteness that will seem most dazzling which is on the darkest background, and black will seem most intense when it is against a background of greater whiteness.
>
> Red also will seem most vivid when against a yellow background, and so in like manner with all the colours when set against those which present the sharpest contrasts." [CA, 184 V.C] (da Vinci, 1939)

Leonardo da Vinci began the study of how appearance is influenced by the content of the image. Experiments by physicists, Otto von Guericke and Count Rumford (1875); writers, von Goethe (1810); chemists, Chevreul (1837); psychologists, Hering (1872); and designers, Albers (1963) amassed a great variety of evidence that appearance was not pixel-based. The rest of the image affected appearance. Perhaps the most compelling argument is that all of the studies of primate neural mechanisms show a series of complex spatial interactions (Hubel & Wiesel, 2005; McCann, 2005). The studies of 20th century psychophysics of Campbell, Gibson, Land, Gilchrist, Adelson, and many others all show that the spatial content of the image controls appearance.

Throughout this text we will compare and contrast the *pixel-based* and *spatial comparisons* paradigms of human vision and scene reproduction.

1.5 Reproduction of Scene Dynamic Range

Some reproductions involve small transformations of the interior of the original's color space, such as a photographic print of an oil painting in uniform illumination. For reflective materials, such as oil paints, and photographic paper, the range of light between white and black is roughly 32:1. Both ranges are limited by the front-surface reflections, rather than the absorption of light behind the surface. Real-life scenes, both indoor and outdoor, are almost always in non-uniform illumination. Illumination introduces a major challenge to reproduction by having an extremely large original color space. On a clear day shadows cast by the sun are 32 times darker than direct sunlight. The 32:1 range of reflectances in a 32:1 range of illumination creates a 1024:1 range of light. Real-life scene reproduction is analogous to moving a castle into a cottage.

Imaging techniques can record scene information over a High Dynamic Range (HDR) of light. The range of captured information is much more than the 32:1 range possible between white and black in a reflective print. In photography, Ansel Adam's Zone System (Chapter 6) provides the logical framework for capturing the wide range of light in natural scenes and rendering them in a smaller dynamic-range print. Adams described a three step process: measuring scene range, adjusting image capture to record the entire scene range, and locally manipulating the print exposure to render the high-range scene into the low-range print. Adams visualized the final image before exposing the negative. He assigned appearances from white to black to image segments. Once the negative recorded all the information, Adams controlled the local print contrast for each part of the image (manually dodging and burning) to render all the desired information in the high dynamic range scene. 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 local contrast control in detail for many of his most famous images. He used chemical and exposure manipulations to spatially control appearances between white and black. Today, we use Photoshop® in digital imaging.

Painters have used spatial techniques since the Renaissance to render HDR scenes, and photographers have done so for 160 years. Land and McCann's Retinex algorithm used the initial stage of Adam's wide-range-information capture for its first stage. Instead of using aesthetic rendering, it adopted the goal that image processing should mimic human vision. The Retinex process writes calculated visual sensations onto prints, rather than writing a record of light from the scene. To this aim, Retinex substitutes the original light values at each pixel with ratios of scene information. This approach preserves the content in the original found in the interior of the color space.

Electronic imaging made it possible, and practical, to manipulate images spatially. Automatic spatial processing is not possible in silver-halide photography because film responds locally. Silver grains count the photons. The same quanta catch produces the same film density. Hence, Adams had to manipulate his images by hand. Digital image processing made it possible for each pixel to influence each other pixel (Section F). Details in the shadows are necessary to render objects in shade to humans. The accuracy of their light reproduction is unimportant: the spatial detail of objects in shadows is essential. 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. By preserving the original scene's edges, observers can see details in the shadows that are lost in conventional photography.

The image reproduction industry has developed high-chroma colorants, ingenious tone-scale and spatial-image-processing techniques, so that they can make excellent reproductions. The secret is that they do not reproduce the original's stimulus. What they do is more like reconstructing the furniture for each room so that it has the same spatial relationship with other objects in the new size of room. Good reproductions retain the original's color spatial relationships in the interior of the color space.

1.6 HDR Disciplines

Many disciplines have contributed to our understanding of HDR imaging. Imaging began by painting. The 17th century interest in the physics of light developed the tools that allow us to measure light. Starting around 1800 the science and technology of photography developed photochemical means of recording scenes. Video, digital and computer graphic imaging followed in the 20th century. All of these disciplines are listed in Table 1.1 in blue horizontal rows. The green bars, below, list the different disciplines in understanding human vision. Psychophysics got its beginning in the second half of the 19th century. Its goal was to apply the advances in physical science directly to understanding human sensory mechanisms. It developed the science of colorimetry that measures when two patches of light appear the same.

In the 20th century most of the research in vision emphasized the effects of spatial contents of images. Much of the information from neurophysiology in the 20th century reports on the spatial interaction of neurons. The final section of Table 1.1 lists the disciplines of spatial reproduction in yellow.

1.6.1 Interactions of Light and Matter

Table1.1 lists the disciplines in the first column that are grouped as art (gray); photography (blue); vision (green); and spatial reproduction (yellow).

The stimulus falling on sensors in cameras and vision depends on the interactions of light (*illumination*) and matter (*reflectances)* of objects. For all disciplines, except painting, the image making process begins with counting photons. The physics of photons provides a single description of light: the energy of a photon expressed as the product of Plank's constant and frequency (hν). The sensor's response depends on its spectral sensitivity and the number of photons falling on the sensor. The response, or *quanta catch*, is the measurement principle for all disciplines. Objects in scenes reflect, transmit, and emit variable quantities of light.

1.6.2 Light Sensors

While the physics of light provides us with a singular description across disciplines, the next two columns in Table 1.1 (Sensors, Color Sensors) have different characteristics. Physics uses the narrowest possible spectral band of wavelength for its measurements. Cameras, that depend on short exposures, use broad bands of wavelengths to capture more light. As well, their spectral windows have minimal overlap to improve color separation. Human sensors have extremely broad spectral response with great overlap, making very poor color separations.

1.6.3 Image Processing

We see a major departure in the image processing column. The tradition in the physics of light is that light must be measured as individual pixels. Light is measured by counting the photons captured on each small picture element *(pixel quanta catch)*. All pixels in a photographic film have the same response to the same quant catch.

Human vision is different. Two image segments with identical quanta catch may, or may not, appear the same. Appearance is controlled by spatial interactions. The study of spatial imaging is shown in the

Table 1.1 The disciplines and characteristics that help us understand HDR imaging.

Discipline	Light	Matter	Sensor	Color Sensor	Image Processing	Rendition	Chapter
Art	perspective chiaroscuro impressionism	reflection transmission emission	artist's choice	artist's choice	spatial vision	painting etching mezzotint	4
Physics	hv	reflection transmission emission	grease spot photoelectric CCD/CMOS	monochromator filters [very narrow-band]	pixel-based	radiance luminance	2
Photography	hv	reflection transmission emission	silver halide(AgX) orthochromatic panchromatic	sensitizing dye on AgX surface [broad band]	pixel-based	print transparency	5–6
Video & Digital	hv	reflection transmission emission	silicon + filter	filters [broad band]	pixel-based	print display	7
Computer Graphics	hv	reflection transmission emission	artist's choice	artist's choice	pixel-based	print display	8
Psychophysics	hv	reflection transmission emission	luminosity: scotopic/photopic	color match [overlapping bands]	mixed pixel/spatial	metric value	2
Neurophysiology	hv	reflection transmission emission	luminosity: scotopic/photopic	cone sensitivities [extreme overlap]	spatial processing	electric response	7
Spatial Vision	hv	reflection transmission emission	luminosity: scotopic/photopic	cone sensitivities [extreme overlap]	spatial processing	predict vision	14–30
Spatial Reproduction	hv	reflection transmission emission	luminance	filters [broad band]	spatial processing	best reproduction	32–35

stippled boxes at the bottom of the column. (Sections D, E, and F) Electronic imaging removes the pixel-based limitations found in film. Although the sensors count photons, the subsequent electronics can introduce spatial processing, that makes it possible to mimic vision.

1.6.4 Image Rendition

In each discipline there are a variety of rendition techniques that integrate all the properties of capture and processing to make the renditions that can be paintings, prints and displays with a host of different rendering intents.

1.7 Outline of the Text

This text, *The Art and Science of HDR Imaging,* is a survey of all of High Dynamic Range imaging. It involves all the disciplines listed in Table 1.1. For almost all of them, the text will describe a high-level, general review of these disciplines. The last column on the right of Table 1.1 identifies the chapters that discuss the discipline and its role in HDR imaging.

1.7.1 Section A – History of HDR Imaging

The text begins with a discussion of the definitions and tools we need to understand HDR. It describes HDR in natural scenes, painting, and silver-halide photographs. Ansel Adams described the Zone System to capture and reproduce the natural HDR scene in LDR prints. Electronic HDR image processing began to make spatial comparisons in the late 1960s to render HDR scenes and computer graphics came of age in the 1990s with sufficient processing power to manipulate and synthesize illumination. All these fields have made important contributions to understanding HDR.

1.7.2 Section B – Measured Dynamic Ranges

After the historical review, the text includes a number of detailed experiments that drill down to a much deeper level of scientific measurements. These measurements identify the limits that cameras can capture accurately in HDR imaging, as well as the limits of stimuli that humans can detect in images. These in-depth experiments show that the physical limits of cameras and those of human vision correlate with the range of light falling on their sensors. Veiling glare in their optical systems limits the dynamic range of light. These physical limits of high-dynamic-range imaging are highly scene dependent.

1.7.3 Section C – Separating Glare and Contrast

Building on the measurements of what cameras can capture, and what humans can see, we explore the scene-dependent properties of HDR imaging. The first scene-dependent property is the scatter of light in the ocular media. It reduces the contrast of edges depending upon the content of the scene. The second scene-dependent property is spatial comparison, or neural image processing. It increases the apparent contrast of edges depending upon scene content. Although the mechanisms have entirely different physiological causes, and they have very different spatial properties, they tend to cancel each other. The lower the physical contrast of the scene on the retina, due to scatter, the higher the apparent contrast to the observer. These two counteracting spatial mechanisms, *glare* and *neural contras*t play important roles in human vision.

1.7.4 Section D – Scene Content Controls Appearances

Ever since Hipparchus observed the appearance, or stellar magnitude, of stars in the 2nd century BC, many people, in many disciplines, have been studying the relationship of scene appearances with the light from the scene. Vision begins with counting the photons falling on the retina, as photographic films and solid-state detectors do. However, vision is different. Vision compares the quanta catch at one receptor with others at different spatial locations.

This section summarizes many different experiments measuring spatial interactions. This information is helpful in evaluating our thinking about HDR image processing algorithms. If we assume that the best way to render HDR scenes is to mimic human vision, then we need to have a better understanding of how vision works. This section describes the small changes in visual appearance of the maxima with large changes in light. Further, it also describes the large change of appearance with small changes in light from areas darker than the maxima.

1.7.5 Section E – Color HDR

This section reviews the many Color Mondrian experiments using complex scenes made of arbitrary, unrecognizable shapes. These experiments test the validity of pixel-based and spatial comparison color constancy algorithms. It reviews experiments that measure color appearances with particular attention to departures from perfect constancy. As well, it describes the conditions that shut off color constancy in complex images. Finally, it reviews recent experiments 3-D Mondrians using low-dynamic-range and high-dynamic-range illumination. Spatial content of the display plays a major role in color HDR and color constancy.

1.7.6 Section F – HDR Image Processing

The final section of the text describes and compares a large variety of HDR algorithms. One way to categorize these algorithms is to just look at the image information used in the calculation. We will describe in Section F four classes of algorithms based on the scene pixels used in image processing.

The first uses a single pixel in the input image to modify its output pixel. The tone scale approach, inherited from film photography, requires that every scene have a unique adjustment. Even then, the results are less than optimal.

Spatial image processing algorithms, that were impossible with film, are now practical with digital image processing. The output of each pixel can be influenced by the other input pixels from the scene.

The second class of algorithm uses some of the pixels in the input image to modify a pixel. (A pixel is modified by its surrounding pixels).

The third uses all of the input pixels in the image to modify a pixel. An example is using all the scene's image to calculate the spatial frequency representation (Fourier and Cosine transforms); followed by a spatial frequency filter; and retransform of the result to the image domain.

The fourth uses all of the pixels, but uses this information in different ways in different scenes (Retinex and ACE are examples). These scene-dependent algorithms mimic human vision, and will the subject of Section F.

1.8 Summary

The goal of this text is to present an interdisciplinary analysis of HDR imaging. It will review the work of artists, scientists, and engineers that all combine to further our understanding of the best way to reproduce the high-dynamic-range world in a manner appropriate for our human visual system.

1.9 References

Albers J (1963) *Interaction of Color*, New Haven; London, Yale University Press.

Chevreul ME (1839) *De la loi du contraste simultané des couleurs;* (1854) *The Principles of Harmony and Contrast of Colours*, Reinhold. New York, (1967).

da Vinci L (1939) *The Notebooks of Leonardo da Vinci*, MacCurdy E ed, Braziller, New York, 921.

Elder JM (1905) *History of Photography*, trans Epstein E, Dover, New York, 1978.

Hering E (1872) *Outline of a Theory of Light Sense*, trans Hurvich LM & Jameson D, Harvard University Press, Cambridge, 1964.

Hubel D & Wiesel T (2005) *Brain and Visual Perception*, New York: Oxford University Press.

McCann J (2005) Rendering High-Dynamic Range Images: Algorithms that Mimic Human Vision, *Maui: Proc. AMOS Technical Conference*, 19–28.

Mees CEK (1920) *The Fundamentals of Photography*, Eastman Kodak, Rochester.

Rumford, C (1875) *The Complete Works of Count Rumford*, Vol. IV, The American Academy of Arts and Sciences, Boston, Mass., 51–2.

von Goethe JW (1810) *Theory of Colours*, trans. Charles Lock Eastlake, Cambridge, MA: MIT Press, 1982.

Wedgwood T & Davy H (1802) *An Account of a Method of Copying Paintings upon Glass and of Making Profiles by the Agency of Light upon Nitrate of Silver*, J. Royal Institution, London I,170.

Young T (1802) *The Bakerian Lecture. On the Theory of Light and Colour*, Phil. Trans, Royal Society of London, **92**: 12–48.