

The Impact of Color Management Terminology on Image Quality

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Abstract

The field of color management has been getting an increasing amount of media attention during the past decade or so in addition to focused development efforts by a number of leading imaging companies. Still, there seems to be no one completely satisfied with the results to this point. This paper discusses the impact of several traditional concepts on both end user image quality and the engineering development process to create high quality products. In particular, this paper will address the traditional terms of "white point," "linear," "gamma," "RGB," and "CMYK."

At first glance, it might not seem so obvious why these particular terms can have disastrous effects on image quality. Unfortunately, more often than not, they do. A core source of the confusion is the diversity of technical fields that each of these terms has become fundamental to with conflicting definitions. Several of these fields and their usage of terminology are examined along with explanations of why things worked so well in each individual field until recently.

Another perspective on examining these terms is by asking a series of questions: 1) "what's white?" 2) "what's gray?" 3) "what color is red?" and 4) "what's black?" Each of these questions is examined with respect to multiple color reproduction industries and the terms described above.

The paper concludes with recommendations on usage and a proposal to reduce this confusion.

Introduction

The field of color management has been getting an increasing amount of media attention during the past decade or so in addition to focused development efforts by a number of leading imaging companies. This attention has made it the focus of recent addresses at Seybold Seminars by Steve Jobs of Apple Computer[1] and Bill Gates of Microsoft Corporation.[2] A quick web search turns out thousands of articles and web pages about color management.[3]

Still, there seems to be no one completely satisfied with the results to this point. This is evident when companies like Apple Computer,[4] Canon Information Systems[5] and Eastman Kodak[6] evangelize alternative color management APIs to the native OS-based API suite. It is also evident from numerous articles by industry pundits pointing out the complexities[7] or shortcomings[8] of current solutions along with their fears of any complementary technology.[9] The International Color Consortium itself is struggling to investigate solutions to known problems.[10]

While the state of color management is far beyond where it was ten years ago, it is helpful briefly review some of its evolution in order to provide a reasonable perspective on the complexities of just the communication problem.

Color Management in Open Systems

The field of digital color reproduction is a confluence of several much older industries merging together. Each of these industries has its individual aspects of color reproduction that have evolved within the constraints of its particular production workflows. These industries include broadcast television, motion pictures, slide reproduction, still photography, photofinishing, computer graphics, desktop publishing, paint formulation, presentation graphics, multimedia presentation, graphic arts, textiles and others. Color Science has provided a scientific foundation for all of these industries with varying degrees of significance, but each industry has extended this foundation with empirical results that are specialized to its particular needs. Thus, each of these industries individually encompasses a significant body of knowledge with respect to color reproduction issues. Much has been previously written about the traditional aspects of each field, usually from an analog processing and not a digital processing point of view. In addition, researchers in color science have continued to advance the scientific foundations over the last several decades independently from any of these industries. Unfortunately, until quite recently, most of these efforts have also been independent of modern computer operating systems and digital networks. This has caused significant transition problems between the traditional methods and the constraints imposed by open computing environments and in particular the World Wide Web.

The advent of digital color processing applications in open systems, and in particular the World Wide Web, has begun to force all of these industries into working within open computing environments and with each other. This in turn has created a new technology field - digital color reproduction. This relatively new field has inherited many of the methods and standards from each of its contributing industries. This is in addition to contributions from researchers in the color science community and in combination with the constraints imposed by the various software operating systems, networks, applications and devices that compose the digital computing environment today. The tensions between the traditional industries with each other, and along with the new digital technology, have created an interesting and often conflict-filled new technical environment for digital color reproduction. Most of the current practitioners trace their experience directly to either one of the color or computer industries listed above and many claim authority in setting direction and standards in this new field. Some traditional imaging companies feel threatened by the control of color by operating system venders or other traditional imaging industries. There has been a great reluctance to open up solutions for the betterment of the end-users. This has created an amalgam of solutions for end-users, none of which have fully answered the desire to have transparent, predictable color reproduction and most of which are incompatible with each other.

This chaos and dissention are not new to the color reproduction industry. Adrian Cornwell-Clyne[1] summarized a similar set of conditions in the motion picture industry in 1951 with the following statement, "The public history of 'processes' of colour cinematography is on the whole discouraging and disconcerting, but the reader may be assured that the private history is hardly credible, and will, if ever it be made known, constitute a singular commentary upon the least rational aspects of our society and its culture."

The Importance of Terminology

Given the diversity of core technologies contributing to color management solutions, it is extremely important that they communication clearly. Unfortunately, even such basic terms and "white," "black," "linear," "gamma", "rgb," and "cmyk" are typically miscommunicated across industries. The CIE and IEC jointly publish the fundamental reference on color terminology, The International Lighting Vocabulary.[11] Unfortunately, this reference is seldom used effectively and needs continuous updating to keep up with scientific progress in the field, such as the recent adoption of a single color appearance model by the CIE.[12]

Defining White and Black

Dr. Robert Hunt has provided an excellent review[13] of the importance of well-defined terms for "white" and "black." In summary, one must include the viewing conditions that dramatically effect the appearance of the colors. In additional the common viewing condition parameters such as surround, and chromatic adaptation, one must also be careful to describe whether it the white refers to a perfect reflecting diffuser; the targeted media white point or even a self-emissive device.

Similar problems exist for describing black points. While flare or veiling glare is a common physical effect, it is rarely considered in color management systems. When flare is considered, it is rarely with the additional effects of surround and simultaneous contrast which dramatically impact the appearance of the black point.[14]

The ISO 3664 international draft standard on illumination conditions provides some additional progress in specifying viewing conditions for the graphic arts and professional photographers. Unfortunately, it explicitly excludes guidance for cross-media comparisons or viewing conditions that reflect practical home or office conditions.

In summary, seldom do industry practices effectively incorporate enough information to clearly communicate the meanings of "black" and "white" such that they are reproducible by a third party.

Linear With Respect To…

Another difficult, but fundamental term to come to grips with is the color "gray." In addition to the viewing condition problems described above, there is an additional problem describing gray. It is common industry practice to refer to color spaces as linear or non-linear. Unfortunately, there is little description on what this linearity refers to. Poynton aptly points out the degeneration of terminology in the television industry when a single prime indicated the difference.[15] Yet, there is still a fundamental misconception among many engineers on the existence and need for two fundamental classes of color spaces and thus two types of linearity.

These two broad classes of color spaces are used by image creators: we term them "intensity" and "intuitive." The intensity space is "linear with respect to intensity" and is also commonly known as luminance. Physically based modeling is a good example of the first class; computer paint programs are good examples of the second. The intuitive space is "linear with respect to perception" and is also commonly known as lightness. These two classes applications both work on RGB displays, but they use the framebuffer in different ways.

All 3D software algorithms (e.g., polygonal rendering, ray tracing, and radiosity), work in intensity space, because they all attempt to model the physics of the real world. The differences between the algorithms are in the accuracy of the modeling and, consequently, the performance of the algorithms. The most accurate applications work in a luminance/chroma/chroma space and do not convert to an RGB space until the image is ready to be displayed. However such algorithms are very slow and rarely used. Most algorithms that can be accelerated by hardware work in an RGB space. The framebuffer is often used to store both partial and final results. Although interpolation in RGB space yields results that are only rough approximations of what is physically correct, these results are suitable for many applications. In an RGB intensity space, a mid-gray would be represented as approximately (0.18, 0.18, 0.18). This value is then scaled by the size of the framebuffer and stored as an integer approximation. For example, in a thirty-bit framebuffer, that mid-level gray would be represented as (737, 737, 737). Physically based modeling tends to need deeper framebuffers, so that there are enough bits to represent shading in the darker tones. In an 8 bit frame buffer mid-gray would be only (46, 46, 46) leaving only 45 gray levels. Contouring artifacts are occasionally visible in such conditions.

Paint programs, and others, which work in an intuitive space, can use the framebuffer more efficiently. In intuitive space, the mid-level gray is represented as (0.5, 0.5, 0.5). Even on an 8 bit framebuffer this provides 128 shadow tones, which is quite adequate for the display technology in typical viewing environments.

This is not the only reason that such applications work best with mid-gray as the middle digital count. Paint programs often provide color pickers that allow users to directly select RGB values, either through numeric entry or through linear sliders. In both cases, the user will expect the middle intensity to be in the middle of the range of values.

The failure to recognize the difference between these intensity and intuitive spaces has led to great confusion. None of the color standards we examined actually represented their mid-gray as precisely (0.5, 0.5, 0.5). None of the commercial systems sets mid-gray at (0.18, 0.18, 0.18) either. This is one of the reasons that RGB color standards fall short of users' expectations.

In summary, seldom do industry practices effectively incorporate enough information to clearly communicate the meanings of "gray" or "linear."

Gamma

One attempt to resolve the "linear" terminology problem is with the term "gamma." Unfortunately, the term is not used consistently. This inconsistency greatly adds to the level of confusion. Katoh and Deguchi[16] recently published an excellent review on CRT characteristics in which they defined seven different, but useful gamma terms just within CRT devices. In this same paper, they pointed out how gamma is commonly used across incompatible modeling equations. This misuse has lead to many common myths about the default "gamma" of CRTs being 2.4 or 2.5 or 2.8 or 1.8.

In summary, seldom do industry practices effectively incorporate enough information to clearly communicate the meaning of "gamma."

Defining RGB

It is common place to communicate colors as RGB values and think that this is meaningful. For example, a value of 255,0,0 is supposed to represent red, but what "red" is this. Is it an orangish-red, a dark-blood red, a pinkish red or what? Given the current RGB standards and incompatible RGB devices, it is impossible to answer this question. A representative, but by not means exhaustive, list is shown below. In addition to the obvious incompatibilities between the standards used in different individual technologies, there are several separate technological areas for which multiple incompatible RGB standards are defined (broadcast television, vision research, robotics, and operating system defaults). Just within the field of broadcast television standards, there is often ambiguity within a single RGB space as to whether it is gamma-corrected or not.

Finally, many standards (GKS, VRML, GIF, etc.) do not provide any definition of RGB at all, but assume that there is one ubiquitous and unambiguous RGB space, which further exacerbates the problem. A file in one of these standard formats could be in any of the color spaces in Table 1 below and these represent only a small sample of the RGB color spaces in common practice across industries. This ambiguity in the controlling color space can potentially be costly and even life threatening. If that sounds extreme, consider the effects of misinterpretation of color information in the fields of web-based catalog shopping and telemedicine. A customer ordering the wrong color jacket and shipping it back can cost the vendor money; A doctor misdiagnosing a problem could cost the patient his life. In color as in all things, miscommunication can be expense and fatal.

If one considers a CMY space to be a simple inversion of an RGB space, which is done amazingly often in practice, this greatly increases the number of conflicting definitions by adding the numerous incompatible densitometry standards (A, M, T, to name only a few).

SMPTE RP 145[17]	JPEG[18]	SRGB[19]
EBU 3213[20]	NTSC 1953[21]	VRML[22]
MICROSOFT[23]	APPLE[24]	SGI[25]
ISO/TC130[26]	SONY[27]	CGATS[28]
BFD[29]	ITU-R BT.601[30]	ITU-R BT.709[31]
Smith & Porkony[32]	CIE 1931[33]	CIE 1964[34]

In summary, seldom do industry practices effectively incorporate enough information to clearly communicate the meaning of "rgb."

Defining CMYK

A very similar problem to that described above exists when communicating color with CMYK. It is interesting to note that the term "cyan" is a relatively recent one for the graphic arts and was adopted explicitly to avoid confusion with "blue.[35]" Even if one indicated that they are using SWOP cmyk, there is still not enough information for reproducible communication. Some of the critical missing pieces include typical viewing condition information, color appearance models and the underlying models or equations of some of the parameters. McDowell has published an excellent review of the progress of current CMYK standards.[36] One of the more provocative proposals is the concept of reference printing conditions. This proposal is conceptual similar to the sRGB standard for RGB devices, but instead provides a series of standard CMYK color spaces.

In summary, seldom do industry practices effectively incorporate enough information to clearly communicate the meaning of "cmyk."

Who Decides What is "right?"

We examined how various common color terms are confusing and miscommunicated. It is reasonable to ask why aren't there already well-defined standards would provide definitions for all of this. Until recently, it was difficult to see how any of the current standards organizations could solve this problem. Currently, the organizational structures of the major standards bodies seem to be almost incompatible with each other by design. Some seem based on horizontal technologies across systems (CIE), some seem based on vertical technologies (ISO), some seem to have a matrix structure (JTC1) and some are in transition between structures (IEC). These different approaches while all potentially valid and useful, lead to inevitable overlap of charters and responsibilities. Cooperation via the liaison procedures is often only a matter of exchanging documents, not true joint efforts. Some joint efforts are tactical collaborations for closed-loop color reproduction systems. Unfortunately their impact can be felt far beyond their written scope, again leading to confusion in the industry on which standard to follow. This approach is at odds with producing a cross-technology standard that is compatible with most industry practices; a strong requirement of the computer based industries.

The IEC has until recently been focused on hardware, in particular connectors and not the firmware that is an integral part of the hardware design in electronics. With the advent of IEC/TC100, this focus seems to be shifting to a much broader systems approach, but again, cooperation with other relevant bodies is still to be determined, although a strong emphasis on industry consortia is being considered.

The ISO is organized by vertical technologies such as photography (TC42), cinemaphotography (TC-36), graphic arts (TC-130), and does not have any display-centric TCs. This vertical organization precludes the development of broad, cross-industry solutions. Traditionally, these TCs are focused on high-end, professional standards, sometimes to the detriment of the consumer market needs.

The ITU functions as a giant technical committee focused on telecommunications (ITU-T) and receivers (ITU-R), in particular, broadcast television. It is actually a part of the United Nations and structurally independent of ISO, CIE and IEC. Their focus has the same weakness in lack of cooperation and broad cross-technology vision, as does the ISO. Focusing on one specific field is a good way to make progress within that industry, but does not provide the broad vision needed to solve cross-industry and cross-technology problems.

The JTC1, seemingly designed for "joint technical" efforts, has historically lacked a firm connection to industry needs. This was dramatically illustrated by the ODA and GACDI architectures, which were developed completely independently of the computer industry that would have to implement this massive endeavor. While there was industry involvement in these efforts, operating system vendors, who drive architectural changes in computer systems, were not heavily involved.

The CIE would appear to be the ideal body for broad color standards, but its organizational structure and bylaws are completely incompatible with modern technological developments. The CIE is organized to move at a much more deliberate pace. That pace is suitable to standardization in industries where change happens slowly. But in the technology-driven fields of today products cycles from development to obsolescence can occur in less than three years.

Industry consortia or collaborations have recently made significant impact in color management standards as witnessed by the broad adoption of the ICC and sRGB efforts. Yet, narrow proprietary concerns and questionable intellectual property issues plague these relatively informal bodies. Finally, individual companies with a majority market share occasionally establish de facto standards in sheer frustration with the entire standards processes described here. These efforts are often conceived with little input from other experts in the field and suffer from significant technical flaws that must be painfully addressed in the open market.

Each of these bodies and their technical committees depends on the volunteer efforts of experts in the industry. Unfortunately with color management, this expertise is rarely available for such unselfishness without some assurance of reasonable progress. Finally, many of the experts in narrow technical committees are committed to advancing only the needs of their particular field and have little experience in other markets. Yet, some solution must be found or all of the markets will be limited by their inability to unambiguously communicate color across technological boundaries.

Until recently, the CIE has made little effort to actively solicit interested parties in developing color management standards within this august body. This is changing dramatically with the recent efforts to form a CIE Imaging Division that will address industry application issues from a broad color perspective. Ideally, all other application-based color standards activities would migrate to this body. This would provide "one stop shopping" for companies interested in color management across industries and provide a convenient liaison body for standards that need color support. While appearing a logical step from the industry standpoint, it remains to be seen if the ISO, IEC, ITU or JTC1 are willing to give up any of their "turf" for the good of the end users.

Suggestions

Below is a list of suggestions to that have been found useful in resolving the terminology problems discussed in this paper.

1. Do not provide parameter values without the underlying equations or models. Without including the underlying equations or models, even by reference, parameter values are misleading at best.
2. To help clarify the meanings of white and black, the appropriate viewing conditions should be included and include all of the required parameters in the CIECAM97s viewing conditions such as surround, luminance level, etc. The amount and methods for flare and simultaneous contrast compensation is also required.
3. Do not use the term "linear" without completing the phrase "linear with respect to…"
4. Do not use the term "gamma" without clarify adjectives. One suggestion is to use more generic terms such as "simple exponential curve gamma" and "complex exponential curve gamma" to describe differences in some CRT modeling equations.

5. Do not refer to RGB colors without referring to a very well defined RGB standard such as sRGB[19] that includes a reference viewing condition, observer, device and color appearance model.
6. Do not refer to CMYK colors without referring to a very well defined CMYK standard that includes a reference viewing condition, observer, device and color appearance model.
7. Encourage that all imaging application color standards be developed within the CIE in the future and encourage your national standards bodies to support this transition.

This all might sound overwhelming, but there does exist a mechanism to make it much simpler. This would be to refer to either standard or device ICC profiles when describing many of these terms. While not yet perfect, the ICC is attempting to provide clear, unambiguous communication standards for color management. It would also be beneficial if the CIE provided guidelines that either adopted these suggestions or improved upon them as a part of their new imaging division.

Acknowledgments

I would like to acknowledge Todd Newman of Canon Information Systems for his significant contributions to this paper and also to my colleagues at Hewlett-Packard Company, Mary Nielsen, Bob Sobol and Gary Dispoto for their insight and advice on these topics.

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