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YUV and *luminance* considered harmful

This document is an edited version of Appendix A of my book: Poynton, Charles, *Digital video and HDTV algorithms and interfaces* (San Francisco: Morgan Kaufmann, 2003).

This is a plea for precise terminology in video. The notation *YUV*, and the term *luminance*, are widespread in digital video. In truth, digital video almost never uses *Y'UV* color difference components, and never directly represents the *luminance* of color science. The common terms are almost always wrong. This note explains why. I urge video engineers and computer graphics specialists to use the correct terms, almost always $Y'C_BC_R$ and *luma*.

Cement vs. concrete

I'll demonstrate by analogy why it is important to use correct terms. Next time you're waiting in line for a bus, ask the person next to you in line what building material is used to construct a sidewalk. Chances are that person will answer, "cement."

The correct answer is *concrete*. Cement is calcined lime and clay, in the form of a fine, gray powder. Cement is one ingredient of concrete; the other ingredients are sand, gravel, and water.

In an everyday situation, you need not be precise about which of these terms are used: If you refer to a bridge as being constructed of "cement," people will know what you mean. Lay people are not confused by the term "cement." Interestingly, experts are not confused either. If a bridge superintendent yells out to his foreman, "Get me 500 pounds of cement!" the foreman understands immediately from context whether the superintendent actually wants concrete. However, if you place an order with a building material supplier for 500 pounds of cement, you will certainly not receive 500 pounds of concrete! Lay people have no trouble with the loose nomenclature, and the experts have little trouble. It is the people in the middle who are liable to become confused by loose nomenclature. Worse still, they are liable to use a term without realizing that it is ambiguous or wrong!

True CIE luminance

The principles of color science dictate that true CIE luminance – denoted *Y* – is formed as a weighted sum of linear (tristimulus) *RGB* components. If CIE luminance were transmitted in a video system, the system would conform to the *Principle of Constant Luminance*. But in video we implement an engineering approximation that departs from

$$^{601}Y' = 0.299\,R' + 0.587\,G' + 0.114\,B'$$

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this principle. It was standardized for NTSC in 1953, and remains standard for all contemporary video systems, to form *luma*, denoted *Y'*, as a weighted sum of nonlinear (gamma-corrected) *R'G'B'* components. The nonlinear transfer function is roughly comparable to a square root. To form *luma*, we use the theoretical coefficients of color science, but we use them in a block diagram different from that prescribed by color science: As detailed in my book, in video, gamma correction is applied *before* forming the weighted sum, not after. The "order of operations" is reversed from what you might expect from color science.

The misinterpretation of luminance

Video engineers in the 1950s recognized that the video quantity *Y'* was very different from CIE luminance, and that it needed to be distinguished from luminance. They described it by the phrase *the quantity representative of luminance*. They used the symbol *Y,* but augmented it with a prime to denote the nonlinearity: *Y'*. Obviously the qualifier "quantity representative of" was cumbersome, and over the decades, it was elided. And over time, the prime symbol was elided as well. Unfortunately, no new word was invented to supplement *luminance*, to reinforce the distinction between the color science quantity and the video quantity. Most video engineers nowadays are unfamiliar with color science, and most do not understand the distinction. Engineers today often carelessly use the word *luminance*, and the symbol *Y*, to refer to the weighted sum of nonlinear (gamma-corrected) *R'G'B'* components.

Pritchard, D.H., "U.S. Color Television Fundamentals – A Review," in *SMPTE Journal*, **86**: 819–828 (Nov. 1977).

Smith, A.R., "Color Gamut Transform Pairs," in *Computer Graphics* **12** (2): 12–19 (Aug. 1978, Proc. *SIGGRAPH 78*).

Foley, James D., and Andries van Dam, *Fundamentals of Interactive Computer Graphics* (Reading, Mass.: Addison-Wesley, 1984).

Foley, James D., Andries van Dam, Steven Feiner, and John Hughes, *Computer Graphics: Principles and Practice*, Second Edition (New York: Addison-Wesley, 1990).

The sloppy nomenclature made its way into ostensibly authoritative video references, such as Pritchard's SMPTE paper published in 1977.

The computer graphics pioneer Alvy Ray Smith encountered the word *luminance* in his quest to adapt video principles to computer graphics. Smith apparently correlated the use of the term *luminance* with his knowledge of color science, and understandably – though mistakenly – concluded that video "luminance" and color science luminance were identical. Consequently, video *YIQ* was introduced to computer graphics, having its *Y* component alleged to be identical to CIE luminance.

That incorrect interpretation propagated into authoritative computer graphics textbooks. *Computer Graphics: Principles and Practice*, on page 589, Section 13.3.3, *The YIQ Color Model*, states:

> The *Y* component of YIQ is not yellow but luminance, and is defined to be the same as the CIE **Y** primary.

(The emphasis is in the original. "Yellow" refers to *CMY*, which was mentioned in the immediately preceding section. "CIE **Y** primary" would be more accurately denoted "CIE **Y** component.")

As you have seen, the so-called *Y* component of video – more properly designated with a prime symbol, *Y'* – is *not* the same as CIE luminance. Video *Y'* cannot even be computed from CIE *Y*, unless two other color components are also available. The quoted passage is quite wrong.

About 300,000 copies of various editions and adaptations of *CG:PP* have been printed. Confusion is rampant.

PRATT, WILLIAM K., *Digital Image Processing*, Second Edition (New York: Wiley, 1991). 64.

The error also propagated into the digital image processing community. A widely used book in that field states:

> N.T.S.C. formulated a color coordinate system for transmission composed of three tristimulus values *YIQ*. The *Y* tristimulus value is the luminance of a color.

The video quantities are certainly *not* tristimulus values, which are, by CIE's definition, proportional to intensity.

Loose nomenclature on the part of video engineers has misled a generation of digital image processing, computer software, and computer hardware engineers.

The enshrining of luma

I campaigned for adoption of the term *luma* to designate the nonlinear video quantity. The term had no pre-existing meaning, and by virtue of its being different from *luminance*, it invites readers from other domains to investigate fully before drawing conclusions about its relationship with luminance.

With the help of Fred Kolb, my campaign succeeded: In 1993, SMPTE adopted Engineering Guideline EG 28, *Annotated Glossary of Essential Terms for Electronic Production*. EG 28 defines the term *luma*, and clarifies the two conflicting interpretations of the term *luminance*. While a SMPTE EG is not quite a SMPTE "Standard," at long last the term has received official recognition. There's no longer any excuse for sloppy use of the term *luminance* by the authors of video engineering papers.

It is a shame that today's SMPTE and ITU-R standards for digital video persist in using the incorrect word *luminance,* without ever mentioning the ambiguity – even conflict – with the CIE standards of color science.

Color difference scale factors

To represent color, luma is accompanied by two *color difference* – or *chroma* – components, universally based on *blue minus luma* and *red minus luma*, where blue, red, and luma have all been subject to gamma correction: *B′–Y′* and *R′–Y′*. Different scale factors are applied to the basic *B′–Y′* and *R′–Y′* components for different applications. $Y'P_BP_R$ scale factors are optimized for component analog video. $Y'C_BC_R$ scale factors are optimized for component digital video such as 4:2:2 studio video, JPEG, and MPEG. Kodak's PhotoYCC ($Y'C_1C_2$) uses scale factors optimized to record the gamut of film colors. *Y′UV* and *Y′IQ* use scale factors optimized to form composite NTSC and PAL video.

When I say *NTSC* and *PAL*, I refer to color encoding, not scanning: I do not mean 525/59.94 and 625/50.

ITU-R Rec. BT.601, *Studio encoding parameters of digital television for standard 4:3 and wide-screen 16:9 aspect ratios* (Geneva: ITU).

$Y'C_BC_R$ scaling as defined by Rec. 601 is appropriate for component digital video. $Y'C_BC_R$ chroma is almost always subsampled using one of three schemes: 4:2:2, or 4:2:0, or 4:1:1.

Y'UV scaling is properly used only as an intermediate step in the formation of composite NTSC or PAL video signals. *Y'UV* scaling is not appropriate when the components are kept separate. However, the *Y'UV* nomenclature is now used rather loosely, and sometimes – particularly in computing – it denotes *any* scaling of *B'–Y'* and *R'–Y'*.

Digital disk recorders (DDRs) are generally able to transfer files across Ethernet. Abekas introduced the convention of using an extension "**.**yuv" for these files. But the scale factors – in Abekas equipment, at least – actually correspond to $Y'C_BC_R$. Use of the "**.**yuv"" extension reinforces the misleading *YUV* nomenclature.

Chroma components are properly ordered *B'–Y'* then *R'–Y'*, or C_B then C_R. Blue is associated with *U*, and red with *V*. *U* and *V* are in alphabetic order.

Subsampling is properly performed only on component digital video, that is, on $Y'C_BC_R$. Subsampling is inappropriate for *Y'UV*. If you see a system described as *Y'UV 4:2:2,* you have a dilemma. Perhaps the person who wrote the description is unfamiliar with the principles of component video, and the scale factors actually implemented in the equipment (or the software) are correct. But you must allow for the possibility that the engineers who designed or implemented the system used the wrong scale factors! If the wrong equations were used, then color accuracy will suffer; however, this can be difficult to diagnose.

HAMILTON, ERIC, *JPEG File Interchange Format*, Version 1.02 (Milpitas, Calif.: C-Cube Microsystems, 1992).

Proper $Y'C_BC_R$ scaling is usual in Motion-JPEG, and in MPEG. However, the $Y'C_BC_R$ scaling used in stillframe JPEG/JFIF in computer applications usually uses "full-range"" (or "full-swing"") luma and chroma excursions, without any headroom or footroom. The chroma excursion is $^{254}/_{255}$ of the luma excursion. The scaling is almost exactly that of $Y'P_BP_R$, but is unfortunately described as $Y'C_BC_R$: Now even $Y'C_BC_R$ is ambiguous! I am hopeful that proper $Y'C_BC_R$ scaling will be incorporated into the next revision of JFIF, so that compressed stillframe and motion imagery in computing can be combined without suffering a conversion process.

Except for very limited use in the encoding and decoding of composite $4f_{SC}$ (or loosely, "D-2") studio video, *Y'IQ* coding is obsolete.

Conclusion: A plea

Using the term *luminance* for video *Y'* is tantamount to using the word *cement* instead of *concrete* to describe the main construction material of a bridge. Lay people don't care, and experts can live with it, but people in the middle – in this case, the programmers and engineers who are reimplementing video technology in the computer domain – are liable to draw the wrong conclusions from careless use of terms. Users suffer from this, because the exchange of images is compromised.

I urge video engineers and computer graphics specialists to avoid *YUV* and *luminance*, and to use the correct terms, $Y'C_BC_R$ and *luma*. ■