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Better color conversions for HDR and UHD TV productions

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Abstract. *The introduction of high-dynamic-range (HDR) color spaces and ultra-high-definition's (UHD) wide-color-gamut (WCG) color space in television creates a need to match colors on HDR and WCG displays with colors on conventional high-definition (HD) displays. Many contemporary color conversion methods that apply to conversion from HD to standard definition (SD), and color conversion methods mandated by current television standards, fail to produce a good color match when converting colors from the HDTV color space to HDR or WCG color spaces. This impairs the quality of HDTV contributions to HDR and UHD productions, as well as the quality of distribution of programs originating in HDR or UHD to HDTV viewers. This paper illustrates the color errors caused by the application of several of these conversion methods, and recommends one method, using display-referred colorimetry, for better color matching between narrow-gamut, wide-gamut and high-dynamic-range displays.*

Keywords. High dynamic range; HDR; wide color gamut; Ultra-HD; Rec. 2020; color conversion; BT.1886; display-referred colorimetry

Introduction

This paper recommends a color conversion method for converting high-definition (HD) (or narrow-gamut ultra-high-definition (UHD)) RGB values to wide-gamut UHD and high dynamic range (HDR) RGB values. It details and evaluates several methods for color conversion among HD, standard definition (SD), UHD and HDR color spaces. This includes methods used in practice today, and methods implied by current standards. A first evaluation for conversions from HD to SD is used as a baseline when assessing the methods for converting to UHD and HDR. The method evaluations use colorimetry-based error metrics (International Commission on Illumination [CIE] DeltaE*ab and CIEDE2000) that are independent of the device encoding.

Components of the color conversion methods

All but one of the color conversion methods convert from R'G'B' values in the HD color space to R'G'B' values in SD, UHD or HDR color spaces by applying, in order, a one-dimensional Electro-Optical Transfer Function ($EOTF$), a 3x3 matrix converting from the first linear RGB space via CIE XYZ to the second linear RGB space, and a one-dimensional Opto-Electronic Transfer Function ($OETF$), as shown in the block diagram in Figure 1. The blocks are described below.

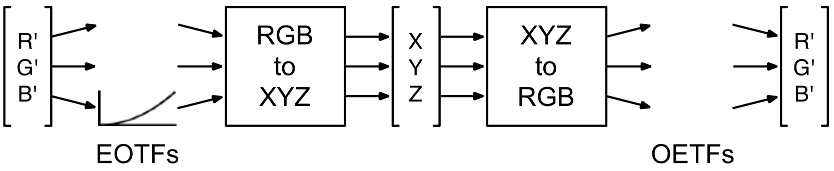

Figure 1. Color conversion block diagram

Color Primaries

The color primaries and white points specified in the HD [1] [2], SD [3], and wide-gamut UHD [4] [5] standards are shown in Table 1. This paper uses 625-line SD (phase alternating line/European Broadcasting Union [PAL/EBU] [6]). Figure 2 shows these color spaces in an xy chromaticity chart.

In lieu of a published HDR standard, this paper uses the primaries of the wide-gamut UHD, and the $EOTF$ defined in SMPTE ST 2084 [7] for HDR.

	HD		SD		UHD & HDR	
	x	y	x	y	x	y
Red	0.640	0.330	0.640	0.330	0.708	0.292
Green	0.300	0.600	0.290	0.600	0.170	0.797
Blue	0.150	0.060	0.150	0.060	0.131	0.046
White	0.3127	0.3290	0.3127	0.3290	0.3127	0.3290

Table 1. xy chromaticities for color primaries and white point for television standards

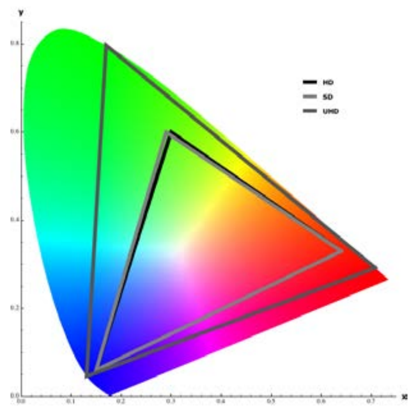

Figure 2. xy chromaticity chart for HD, SD and UHD

Color matrices

For each color space is defined a 3x3 forward matrix MX_i for converting an RGB triplet to a CIE XYZ [8] tristimulus value. This conversion takes the form $XYZ = MX_i \cdot RGB$. The forward matrices MX are calculated from the color primaries and white point using the equation:

$$MX_i = \left[\begin{Bmatrix} r_i \\ g_i \\ b_i \end{Bmatrix} \times \left(\frac{w_i}{w_i.y} \cdot \begin{Bmatrix} r_i \\ g_i \\ b_i \end{Bmatrix}^{-1} \right) \right]^T$$

where

i is one of SD, HD and UHD (HDR uses same matrix as UHD),

r_i, g_i, b_i, and w_i are the xyz triplets for the red, green, blue primaries and the white point of the color space i, $w_i.y$ is the y value of w_i, an xyz value being an xy chromaticity coordinate appended with $z = 1 - x - y$, *and*

· (dot) indicates the matrix product or inner product.

The resulting matrices are

$$MX_{HD} = \begin{Bmatrix} 0.412391 & 0.357584 & 0.180481 \\ 0.212639 & 0.715169 & 0.072192 \\ 0.019331 & 0.119195 & 0.950532 \end{Bmatrix}$$

$$MX_{SD} = \begin{Bmatrix} 0.430554 & 0.341550 & 0.178352 \\ 0.222004 & 0.706655 & 0.071341 \\ 0.020182 & 0.129553 & 0.939322 \end{Bmatrix}$$

$$MX_{UHD} = \begin{Bmatrix} 0.636958 & 0.144617 & 0.168881 \\ 0.2627 & 0.677998 & 0.059302 \\ 0 & 0.028073 & 1.060990 \end{Bmatrix}$$

The matrices for converting from linear RGB values in HD space to linear RGB values in the SD or UHD color space are obtained by combining forward and inverse matrices. The numerical values for the matrices are:

$$M_S = (MX_{SD})^{-1} \cdot MX_{HD} = \begin{Bmatrix} 0.957815 & 0.0421852 & 0 \\ 0 & 1. & 0 \\ 0 & -0.0119341 & 1.01193 \end{Bmatrix}$$

$$M_U = (MX_{UHD})^{-1} \cdot MX_{HD} = \begin{Bmatrix} 0.627404 & 0.329283 & 0.043313 \\ 0.069098 & 0.919540 & 0.011362 \\ 0.016391 & 0.088013 & 0.895595 \end{Bmatrix}$$

Transfer functions

The domain and range are [0,1] for all transfer functions used in this paper.

The current SD, HD and UHD television standards normatively prescribe the same $OETF$, defined in ITU-R Recommendation BT.709, for encoding picture colorimetry into a video signal.

$$\begin{array}{ll} \text{if } Luminance \geq 0.018: & Voltage = 1.099\, Luminance^{0.45} - 0.099 \\ \text{else} & Voltage = 4.500\, Luminance \end{array}$$

ITU-R Recommendation BT.1886 [9], in its simplest form, specifies a gamma of 2.4 as the $EOTF$ of SD, HD and UHD displays.

$$Luminance = Voltage^{2.4}$$

For HDR displays, the $EOTF$ defined in ST 2084 is used.

$$Luminance = \left(\frac{max\left[Voltage^{\frac{1}{m}} - c1, 0 \right]}{c2 - c3\, Voltage^{\frac{1}{m}}} \right)^{\frac{1}{n}}$$

The complete model

The equation for the full conversion is:

$$R'G'B'_{out} = OETF\left(M \cdot EOTF\left(R'G'B'_{HD}\right)\right)$$

where

> $R'G'B'$ values are in the range [0..1],
>
> M is a 3x3 matrix, M_S or M_U for SD and UHD, respectively,
>
> $OETF$ and $EOTF$ are the one-dimensional functions applied to each value in an RGB triplet, and $OETF$ clips the values to the range [0..1].

Color conversion methods

Several methods were evaluated, each using a specified combination of $OETF$, $EOTF$ and matrix.

A Y'C'C'-based method

Method Label = "RGB = RGB"

A common method for HD to SD conversion [10] uses a matrix to convert between Y'C'C' spaces.

$$Y'C'C'_{SD} = M \cdot Y'C'C'_{HD} + o$$

where

$$M = \begin{Bmatrix} 1. & 0.101579 & 0.196076 \\ 0 & 0.989854 & -0.110653 \\ 0 & -0.072453 & 0.983398 \end{Bmatrix},$$

$$o = \left(\begin{Bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{Bmatrix} - M\right) \cdot g, \text{ and}$$

> g is a Y'C'C' code point for a neutral color such as reference black or white.

This is mathematically identical to an assignment in R'G'B' space, $R'G'B'_{SD} = R'G'B'_{HD}$, (using $M = Identity$, $OETF$ = inverse of $EOTF$, and $EOTF = Identity$ in the model).

This method maps each original primary onto the corresponding destination primary. As the standard SD and HD color space encodings are close but not quite identical, this method maps HD green to SD green and introduces a small color shift rotating many colors towards the SD green hue angle.

This color shift has been deemed insignificant for HD to SD conversions [11], which is confirmed here.

This method was not evaluated for HDR, as the peak luminances of the respective encoding ranges are drastically different (100 versus 10,000 cd/m^2).

Standards-compliant conversion method using scene colorimetry

Method Label = "Scene colors"

As the HD, SD, and UHD standards normatively prescribe the 709 curve for encoding picture colorimetry into a video signal, a standards-compliant conversion from one television standard to another will therefore use this $OETF$ for encoding the destination content. For best color matching the inverse of the standard $OETF$ is here used for decoding the source content.

$$EOTF\left(R'G'B'\right) = inverse\ 709\ curve$$

$$OETF\left(RGB\right) = 709\ curve$$

The common color shared between source and destination devices is the color (expressed in CIE XYZ) on a virtual set in front of a virtual camera encoding the picture using the 709 curve. This color is not the same as the color showed in the viewing room. In television systems, this color difference, the system gamma, is the prescribed means by which the colors are enhanced for viewing. The size of the system's color gamut (SD, HD, or UHD) affects the enhancements of non-neutral colors. Thus, while neutral colors are not affected, a large change in gamut can be expected to result in a large color shift in a color conversion of non-neutral colors.

This method was not tested with HDR, as HDR is covered by the next method.

A note on colorimetry

The term scene-referred colorimetry [12] is used to describe the colors in front of the camera, and is distinct from display-referred colorimetry, that is, the colors displayed in the viewing room. As can be inferred from the previous section, (using the inverse camera curve) the standards-based method above uses scene colorimetry (in front of a virtual camera) as the common color.

In practical use, the inverse 709 curve is inadequate for restoring the original scene's true colorimetry, as a typical camera processes the image extensively, such as applying highlight roll-off and gamut compression, before applying a 709-like encoding curve.

A color-savvy desktop video player

Method Label = "Player"

While many desktop video players map video R'G'B' directly to display R'G'B' without any color conversion, one widely used video player [13] supports color conversions based on the video's H.264 [14] video usability information (VUI) parameters (Tables E-3 to E-5 in H.264), which specified the 709 curve. This method uses the 709 curve combined with characteristics obtained from the display's International Color Consortium (ICC) profile. This mismatched pair of transfer functions effectively undoes the system gamma, and users have reported that the playback looks washed out.

$$EOTF\ (R'G'B') = \ inverse\ 709\ curve$$

$$OETF\ (RGB) \ \ = \{R, G, B\}^{\frac{1}{2.4}}$$ or ST 2084 for HDR

A conversion method using display colorimetry

Method Label = "Display colors"

Color conversion can use display-referred colorimetry, converting the HD R'G'B' value to display colorimetry, and then converting the display colorimetry to the target R'G'B value. In this method, the common color shared between source and destination devices is the color (expressed in CIE XYZ) on a reference monitor.

The $EOTF$ and the $OETF$ are as defined for displays: Rec. BT.1886 for the source display, and Rec. BT.1886 or ST 2084 for the target display.

$$EOTF\ (R'G'B') = \{R', G', B'\}^{2.4}$$

$$OETF\ (RGB) \ \ = \{R, G, B\}^{\frac{1}{2.4}}$$ or ST 2084 for HDR

This conversion method is compatible with the use of ST 2084, but violates current SD, HD, and UHD television standards, as it does not use the 709 curve to encode the picture colorimetry.

Evaluating the color conversion methods

For each color conversion method, a worst-case (or close to worst case) color shift of a target color, converted from a first to a second display, was determined, and illustrated in a color image.

Evaluation methodology

All color spaces and conversions were simulated, both in Mathematica and using ICC profiles [15] created with the Custom RGB... feature in Adobe Photoshop. The results shown here are from the simulations in Mathematica.

The methods were numerically evaluated using the following set of RGB colors: blue, red, magenta, green, cyan, yellow, and white from 12.5 to 100 IRE in steps of 12.5.

Color differences were calculated as follows, and illustrated in Figure 3:

- onvert a set of $R'G'B'$ triplets from HD to target space using the specified method,

- t the original and the resulting $R'G'B'$ triplets to CIE Lab using the display $EOTF$, the applicable MX matrix, and the D65 white point,
- Calculate the color error metric in Lab space.

The calculated CIE DeltaE*ab [16] metric is the Euclidean distance between two colors in the CIE Lab color space. An alternate metric CIEDE2000 [17] (a.k.a. DeltaE00 or dE00) was also calculated, but it is not recommended for CIE Lab differences $\gg 5$.

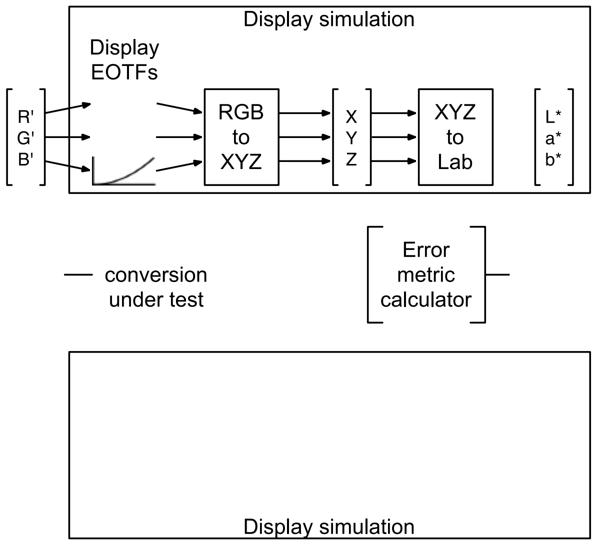

Figure 3. Block diagram for the evaluation process

Converting HD to SD

The methods were first evaluated for color conversions from HD to SD. This provided a baseline for evaluating conversion to UHD. The numerical results are shown in Table 2.

Method Label	*Max dEab*	*Max dE00*	*Color*	*HD color*			*SD color*		
Scene colors	4	1	green	0	100	0	17	100	0
Display colors	3	1	green	0	100	0	27	100	0
RGB = RGB	5	2	green	0	100	0	0	100	0
Player	25	14	green	0	12	0	6	23	0

Table 2. Results for converting to SD

The method with mismatched transfer functions ("Player") has different error characteristics than the other methods. The large errors are at low IRE values, which can be explained by the change of the system gamma. Figure 4 shows plots of the conversion errors in DeltaE*ab and CIEDE2000 (DeltaE00), when applying the method "Player", having a combination of display and scene transfer functions, to primary, secondary and neutral colors converting to SD. The displayed colors indicate the source color. Both plots show a maximum error at slightly below 20 IRE. Note that the error is non-zero for 100 IRE green and yellow, as the green HD primary is outside the SD gamut.

For the remaining methods, the large errors were at or close to 100 IRE. Figure 5 shows plots of the conversion errors in DeltaE*ab and CIEDE2000, when applying the scene colorimetry method ("Scene colors") to primary, secondary and neutral colors converting to SD. The displayed colors indicate the source color. Error values less than 20 are within the tolerances for SD reference monitors [18].

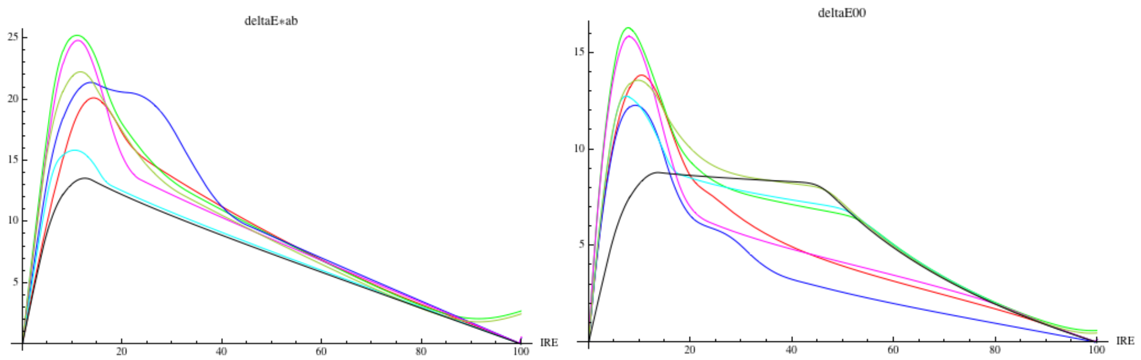

Figure 4. DeltaE*ab and CIEDE2000 results for converting primary, secondary and neutral color ramps (0-100 IRE) from HD to SD using display and scene transfer functions ("Player").

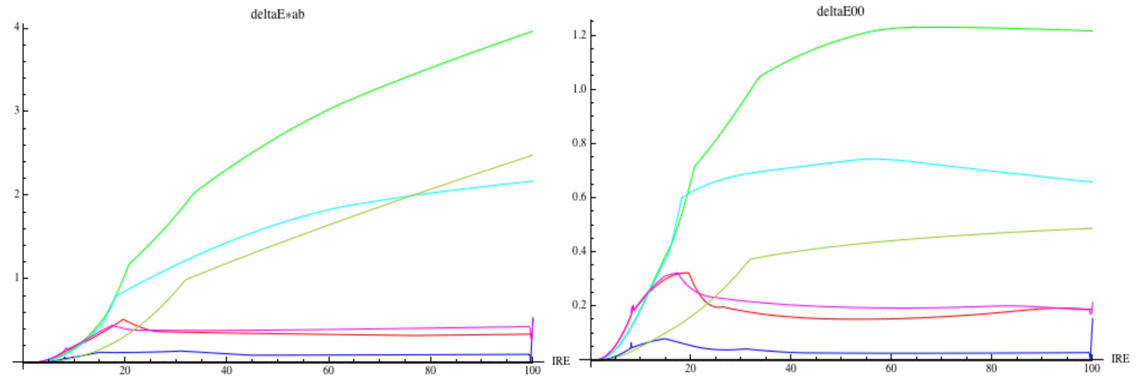

Figure 5. DeltaE*ab and CIEDE2000 results for converting primary, secondary and neutral color ramps (0-100 IRE) from HD to SD using scene colorimetry ("Scene colors").

Converting HD to UHD & HDR

The methods were next evaluated for color conversions from HD to UHD and HDR. The numerical results are shown in Table 3.

Method Label	*Max dEab*	*Max dE00*	*Color*	*HD color*			*UHD color*		
Scene colors	17	3	green	0	100	0	57	96	27
Display colors	0	0	-	-	-	-	-	-	-
RGB = RGB	86	12	green	0	100	0	0	100	0
Player	25	14	green	0	12	0	14	22	8

Table 3. Results for converting to UHD

For HDR, only the methods "Player" and "Display colors" were evaluated. The results are not reported separately as they were identical to the UHD results. The HDR and UHD methods differ only in the $OETF$. When the method $OETF$ and the second display's $EOTF$ are complementary, (see Figure 3), they cancel out each other and the remaining model is then identical for HDR and UHD.

The method with mismatched transfer functions ("Player") again has different error characteristics than the other methods. The large errors are at low IRE values, which can be explained by the change of the system gamma. The results are very similar to the SD results, with the maximum error at slightly below 20 IRE.

For the remaining methods, the large errors were at or close to 100 IRE. Figure 6 shows plots of the conversion errors in DeltaE*ab and CIEDE2000, when applying the scene colorimetry method ("Scene colors") to primary, secondary and neutral colors converting to UHD. The displayed colors indicate the source color. No gamut clipping occurred when converting from HD to UHD or HDR as the HD gamut is fully enclosed in the UHD and HDR gamuts.

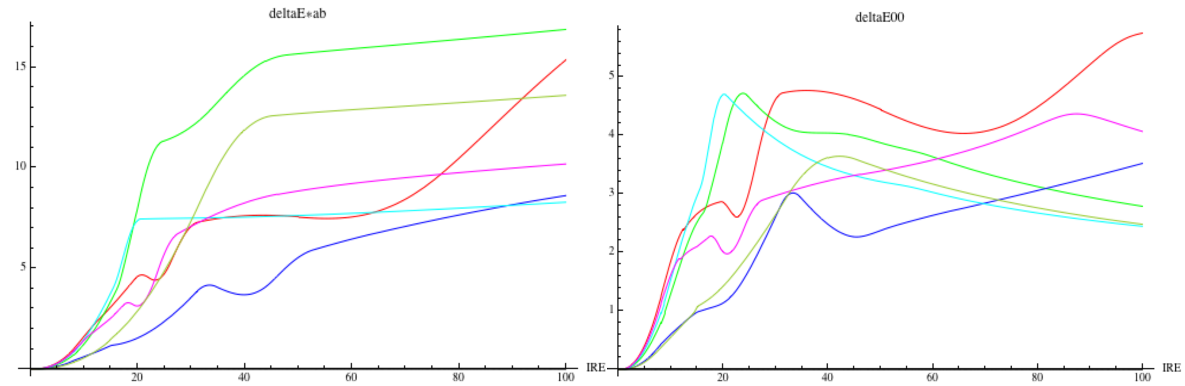

Figure 6. DeltaE*ab and CIEDE2000 results for converting primary, secondary and neutral color ramps (0-100 IRE) from HD to UHD using scene colorimetry ("Scene colors").

Visualizing the color differences

A set of RGB colors was selected and composed into an image strip. The colors included blue, red, magenta, green, cyan, yellow, and white at 25, 50, 75, 100 IRE. The methods were applied to this image strip. The images included in the paper have been desaturated for distribution.

Figure 7. Original image strip

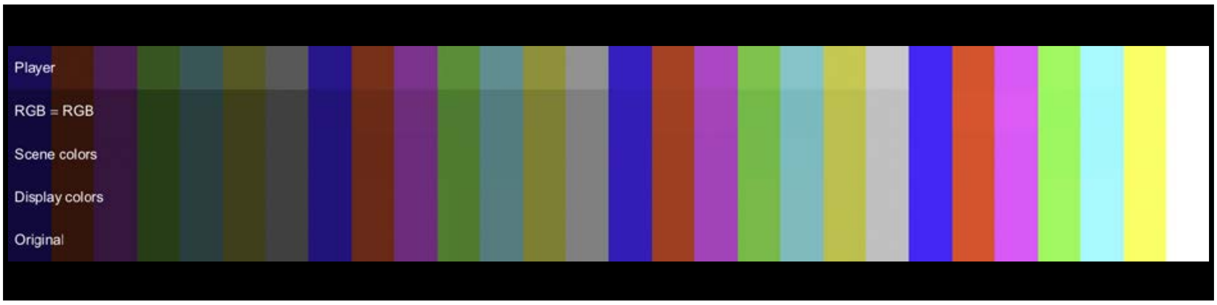

Figure 8. Strip converted from HD to SD and original strip

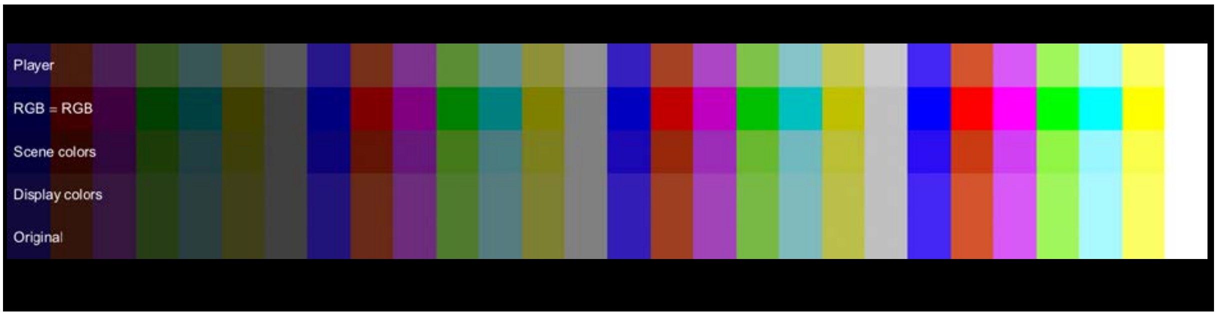

Figure 9. Strip converted from HD to UHD and HDR and original strip

Figure 7 to Figure 9 show the original strip, the conversion to SD and the conversion to UHD. Some observations include:

- The Player strip is much lighter than the center strips, because it changed system gamma.
- In SD, Figure 8, the center strips appear almost identical, as expected from the low conversion errors.
- In UHD, Figure 9, the center strips are dissimilar, with the "Display colors" strip being most similar to the original, yet again as expected from the conversion errors.

Summary of results

Table 4 summarizes the findings. For each method and use case, the table shows its max dEab (DeltaE*ab) and dE00 (CIEDE2000) errors.

A pass-fail limit was set at 5 dEab. This limit is the largest error of the RGB = RGB method for SD, a method that has been considered acceptable when converting from HD to SD.

For UHD and HDR, only the method using display colorimetry ("Display colors") passes, highlighted in bold in the table. Thus, of the methods evaluated here, this is the recommended method for converting to UHD and HDR. In Figure 9 the other methods show visible differences.

	Method characteristics			*Converting from HD gamut to SD*			*Converting from HD gamut to UHD & HDR*		
Method Label	*EOTF*	*OETF*	*Matrix*	*Max dEab*	*Max dE00*	*Approval*	*Max dEab*	*Max dE00*	*Approval*
*Scene colors **	Inverse 709	709 curve	MS or MU	4	1	Pass	17	3	Fail
Display colors	**Gamma 2.4**	**Inverse gamma 2.4**	**MS or MU**	**3**	**1**	**Pass**	**0**	**0**	**Pass**
*RGB = RGB **	Identity	Identity	Identity	5	2	Pass	86	12	Fail
Player	Inverse 709	Inverse gamma 2.4	MS or MU	25	14	Fail	25	14	Fail
* Not evaluated for HDR display									

Table 4. Summary of results

Conclusion and further work

Current practice, proven successful in converting HD colors to SD, is not best practice for color conversion from HD to UHD or HDR, because it introduces large color errors. Instead, display colorimetry (Rec. BT.1886 or SMPTE ST 2084) should be used for color conversions to wide-gamut UHD and HDR. The 709 curve, while acceptable for HD to SD conversions, should not be used for conversion to wide-gamut UHD or HDR. Mismatched $EOTF$ and $OETF$ pairs should not be used for any color conversion for television, because they change the system gamma.

Compliant use of the recommended "Display colors" method would require an update of the television and codec standards, as the recommended method uses an encoding function (inverse of Rec. BT.1886) other than the method prescribed by television standards, and current video compression standards such as ITU-T Rec. H.264 (Table E-4 therein) and ITU-T Rec. H.265 [19] (Table E-4 therein) cannot indicate the use of the recommended encoding function (inverse of Rec. BT.1886).

About the author

Lars Borg is a Principal Scientist in Digital Video and Audio Engineering at Adobe. Borg, who joined Adobe in 1989, develops solutions and standards in the areas of high dynamic range, wide color gamut, Ultra-High Definition TV, digital cinema, digital imaging, color processing, color management, video compression, metadata, and holds over 40 patents in related areas. Borg was a key contributor developing the Academy Color Encoding System, created the CinemaDNG format, is active in SMPTE standards committees, and is the chairman of a SMPTE group on Dynamic Metadata for Color Transforms. Borg holds an M.S. in electrical engineering from Royal Institute of Technology, Stockholm, Sweden.

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