

Color Spaces

A color space is a mathematical representation of a set of colors. The three most popular color models are RGB (used in computer graphics); YIQ, YUV, or YCbCr (used in video systems); and CMYK (used in color printing). However, none of these color spaces are directly related to the intuitive notions of hue, saturation, and brightness. This resulted in the temporary pursuit of other models, such as HSI and HSV, to simplify programming, processing, and end-user manipulation.

All of the color spaces can be derived from the RGB information supplied by devices such as cameras and scanners.

RGB Color Space

The red, green, and blue (RGB) color space is widely used throughout computer graphics. Red, green, and blue are three primary additive colors (individual components are added together to form a desired color) and are represented by a three-dimensional, Cartesian coordinate system (Figure 3.1). The indicated diagonal of the cube, with equal amounts of each primary component, represents various gray levels. Table 3.1 contains the RGB values for 100% amplitude, 100% saturated color bars, a common video test signal.

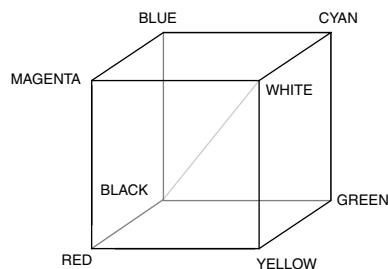


Figure 3.1. The RGB Color Cube.

	Nominal Range	White	Yellow	Cyan	Green	Magenta	Red	Blue	Black
R	0 to 255	255	255	0	0	255	255	0	0
G	0 to 255	255	255	255	255	0	0	0	0
B	0 to 255	255	0	255	0	255	0	255	0

Table 3.1. 100% RGB Color Bars.

The RGB color space is the most prevalent choice for computer graphics because color displays use red, green, and blue to create the desired color. Therefore, the choice of the RGB color space simplifies the architecture and design of the system. Also, a system that is designed using the RGB color space can take advantage of a large number of existing software routines, since this color space has been around for a number of years.

However, RGB is not very efficient when dealing with “real-world” images. All three RGB components need to be of equal bandwidth to generate any color within the RGB color cube. The result of this is a frame buffer that has the same pixel depth and display resolution for each RGB component. Also, processing an image in the RGB color space is usually not the most efficient method. For example, to modify the intensity or color of a given pixel, the three RGB values must be read from the frame buffer, the intensity or color calculated, the desired modifications performed, and the new RGB values calculated and written back to the frame buffer. If the system had access to an image stored directly in the intensity and color format, some processing steps would be faster.

For these and other reasons, many video standards use luma and two color difference signals. The most common are the YUV, YIQ,

and YCbCr color spaces. Although all are related, there are some differences.

YUV Color Space

The YUV color space is used by the PAL (Phase Alternation Line), NTSC (National Television System Committee), and SECAM (Sequentiel Couleur Avec Mémoire or Sequential Color with Memory) composite color video standards. The black-and-white system used only luma (Y) information; color information (U and V) was added in such a way that a black-and-white receiver would still display a normal black-and-white picture. Color receivers decoded the additional color information to display a color picture.

The basic equations to convert between gamma-corrected RGB (notated as $R'G'B'$ and discussed later in this chapter) and YUV are:

$$Y = 0.299R' + 0.587G' + 0.114B'$$

$$U = -0.147R' - 0.289G' + 0.436B' \\ = 0.492 (B' - Y)$$

$$V = 0.615R' - 0.515G' - 0.100B' \\ = 0.877(R' - Y)$$

$$R' = Y + 1.140V$$

$$G' = Y - 0.395U - 0.581V$$

$$B' = Y + 2.032U$$

For digital R'G'B' values with a range of 0–255, Y has a range of 0–255, U a range of 0 to ±112, and V a range of 0 to ±157. These equations are usually scaled to simplify the implementation in an actual NTSC or PAL digital encoder or decoder.

Note that for digital data, 8-bit YUV and R'G'B' data should be saturated at the 0 and 255 levels to avoid underflow and overflow wrap-around problems.

If the full range of (B' – Y) and (R' – Y) had been used, the composite NTSC and PAL levels would have exceeded what the (then current) black-and-white television transmitters and receivers were capable of supporting. Experimentation determined that modulated subcarrier excursions of 20% of the luma (Y) signal excursion could be permitted above white and below black. The scaling factors were then selected so that the maximum level of 75% amplitude, 100% saturation yellow and cyan color bars would be at the white level (100 IRE).

YIQ Color Space

The YIQ color space, further discussed in Chapter 8, is derived from the YUV color space and is optionally used by the NTSC composite color video standard. (The “I” stands for “in-phase” and the “Q” for “quadrature,” which is the modulation method used to transmit the color information.) The basic equations to convert between R'G'B' and YIQ are:

$$Y = 0.299R' + 0.587G' + 0.114B'$$

$$\begin{aligned} I &= 0.596R' - 0.275G' - 0.321B' \\ &= V\cos 33^\circ - U\sin 33^\circ \\ &= 0.736(R' - Y) - 0.268(B' - Y) \end{aligned}$$

$$\begin{aligned} Q &= 0.212R' - 0.523G' + 0.311B' \\ &= V\sin 33^\circ + U\cos 33^\circ \\ &= 0.478(R' - Y) + 0.413(B' - Y) \end{aligned}$$

or, using matrix notation:

$$\begin{bmatrix} I \\ Q \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \cos(33) & \sin(33) \\ -\sin(33) & \cos(33) \end{bmatrix} \begin{bmatrix} U \\ V \end{bmatrix}$$

$$R' = Y + 0.956I + 0.621Q$$

$$G' = Y - 0.272I - 0.647Q$$

$$B' = Y - 1.107I + 1.704Q$$

For digital R'G'B' values with a range of 0–255, Y has a range of 0–255, I has a range of 0 to ±152, and Q has a range of 0 to ±134. I and Q are obtained by rotating the U and V axes 33°. These equations are usually scaled to simplify the implementation in an actual NTSC digital encoder or decoder.

Note that for digital data, 8-bit YIQ and R'G'B' data should be saturated at the 0 and 255 levels to avoid underflow and overflow wrap-around problems.

YCbCr Color Space

The YCbCr color space was developed as part of ITU-R BT.601 during the development of a world-wide digital component video standard (discussed in Chapter 4). YCbCr is a scaled and offset version of the YUV color space. Y is

defined to have a nominal 8-bit range of 16–235; Cb and Cr are defined to have a nominal range of 16–240. There are several YCbCr sampling formats, such as 4:4:4, 4:2:2, 4:1:1, and 4:2:0 that are also described.

RGB - YCbCr Equations: SDTV

The basic equations to convert between 8-bit digital R'G'B' data with a 16–235 nominal range and YCbCr are:

$$Y_{601} = 0.299R' + 0.587G' + 0.114B'$$

$$Cb = -0.172R' - 0.339G' + 0.511B' + 128$$

$$Cr = 0.511R' - 0.428G' - 0.083B' + 128$$

$$R' = Y_{601} + 1.371(Cr - 128)$$

$$G' = Y_{601} - 0.698(Cr - 128) - 0.336(Cb - 128)$$

$$B' = Y_{601} + 1.732(Cb - 128)$$

When performing YCbCr to R'G'B' conversion, the resulting R'G'B' values have a nominal range of 16–235, with possible occasional excursions into the 0–15 and 236–255 values. This is due to Y and CbCr occasionally going outside the 16–235 and 16–240 ranges, respectively, due to video processing and noise. Note that 8-bit YCbCr and R'G'B' data should be saturated at the 0 and 255 levels to avoid underflow and overflow wrap-around problems.

Table 3.2 lists the YCbCr values for 75% amplitude, 100% saturated color bars, a common video test signal.

Computer Systems Considerations

If the R'G'B' data has a range of 0–255, as is commonly found in computer systems, the following equations may be more convenient to use:

$$Y_{601} = 0.257R' + 0.504G' + 0.098B' + 16$$

$$Cb = -0.148R' - 0.291G' + 0.439B' + 128$$

$$Cr = 0.439R' - 0.368G' - 0.071B' + 128$$

	Nominal Range	White	Yellow	Cyan	Green	Magenta	Red	Blue	Black
SDTV									
Y	16 to 235	180	162	131	112	84	65	35	16
Cb	16 to 240	128	44	156	72	184	100	212	128
Cr	16 to 240	128	142	44	58	198	212	114	128
HDTV									
Y	16 to 235	180	168	145	133	63	51	28	16
Cb	16 to 240	128	44	147	63	193	109	212	128
Cr	16 to 240	128	136	44	52	204	212	120	128

Table 3.2. 75% YCbCr Color Bars.

$$\begin{aligned}R' &= 1.164(Y_{601} - 16) + 1.596(Cr - 128) \\G' &= 1.164(Y_{601} - 16) - 0.813(Cr - 128) - \\ &\quad 0.391(Cb - 128) \\B' &= 1.164(Y_{601} - 16) + 2.018(Cb - 128)\end{aligned}$$

Note that 8-bit YCbCr and R'G'B' data should be saturated at the 0 and 255 levels to avoid underflow and overflow wrap-around problems.

RGB - YCbCr Equations: HDTV

The basic equations to convert between 8-bit digital R'G'B' data with a 16–235 nominal range and YCbCr are:

$$\begin{aligned}Y_{709} &= 0.213R' + 0.715G' + 0.072B' \\Cb &= -0.117R' - 0.394G' + 0.511B' + 128 \\Cr &= 0.511R' - 0.464G' - 0.047B' + 128\end{aligned}$$

$$\begin{aligned}R' &= Y_{709} + 1.540(Cr - 128) \\G' &= Y_{709} - 0.459(Cr - 128) \\ &\quad - 0.183(Cb - 128) \\B' &= Y_{709} + 1.816(Cb - 128)\end{aligned}$$

When performing YCbCr to R'G'B' conversion, the resulting R'G'B' values have a nominal range of 16–235, with possible occasional excursions into the 0–15 and 236–255 values. This is due to Y and CbCr occasionally going outside the 16–235 and 16–240 ranges, respectively, due to video processing and noise. Note that 8-bit YCbCr and R'G'B' data should be saturated at the 0 and 255 levels to avoid underflow and overflow wrap-around problems.

Table 3.2 lists the YCbCr values for 75% amplitude, 100% saturated color bars, a common video test signal.

Computer Systems Considerations

If the R'G'B' data has a range of 0–255, as is commonly found in computer systems, the following equations may be more convenient to use:

$$\begin{aligned}Y_{709} &= 0.183R' + 0.614G' + 0.062B' + 16 \\Cb &= -0.101R' - 0.338G' + 0.439B' + 128 \\Cr &= 0.439R' - 0.399G' - 0.040B' + 128\end{aligned}$$

$$\begin{aligned}R' &= 1.164(Y_{709} - 16) + 1.793(Cr - 128) \\G' &= 1.164(Y_{709} - 16) - 0.534(Cr - 128) - \\ &\quad 0.213(Cb - 128) \\B' &= 1.164(Y_{709} - 16) + 2.115(Cb - 128)\end{aligned}$$

Note that 8-bit YCbCr and R'G'B' data should be saturated at the 0 and 255 levels to avoid underflow and overflow wrap-around problems.

4:4:4 YCbCr Format

Figure 3.2 illustrates the positioning of YCbCr samples for the 4:4:4 format. Each sample has a Y, a Cb, and a Cr value. Each sample is typically 8 bits (consumer applications) or 10 bits (pro-video applications) per component. Each sample therefore requires 24 bits (or 30 bits for pro-video applications).

4:2:2 YCbCr Format

Figure 3.3 illustrates the positioning of YCbCr samples for the 4:2:2 format. For every two horizontal Y samples, there is one Cb and Cr sample. Each sample is typically 8 bits (consumer applications) or 10 bits (pro-video applications) per component. Each sample therefore requires 16 bits (or 20 bits for pro-video applications), usually formatted as shown in Figure 3.4.

To display 4:2:2 YCbCr data, it is first converted to 4:4:4 YCbCr data, using interpolation to generate the missing Cb and Cr samples.

4:1:1 YCbCr Format

Figure 3.5 illustrates the positioning of YCbCr samples for the 4:1:1 format (also known as YUV12), used in some consumer video and DV video compression applications. For every four horizontal Y samples, there is one Cb and Cr value. Each component is typically 8 bits. Each sample therefore requires 12 bits, usually formatted as shown in Figure 3.6.

To display 4:1:1 YCbCr data, it is first converted to 4:4:4 YCbCr data, using interpolation to generate the missing Cb and Cr samples.

4:2:0 YCbCr Format

Rather than the horizontal-only 2:1 reduction of Cb and Cr used by 4:2:2, 4:2:0 YCbCr implements a 2:1 reduction of Cb and Cr in both the vertical and horizontal directions. It is commonly used for video compression.

As shown in Figures 3.7 through 3.11, there are several 4:2:0 sampling formats. Table 3.3 lists the YCbCr formats for various DV applications.

To display 4:2:0 YCbCr data, it is first converted to 4:4:4 YCbCr data, using interpolation to generate the new Cb and Cr samples.

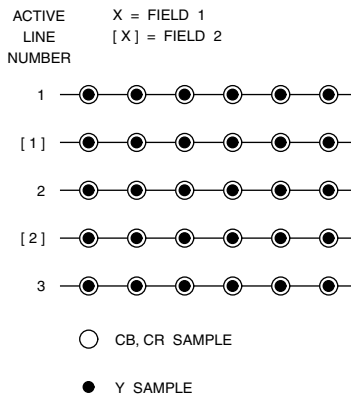


Figure 3.2. 4:4:4 Co-Sited Sampling. The sampling positions on the active scan lines of an interlaced picture.

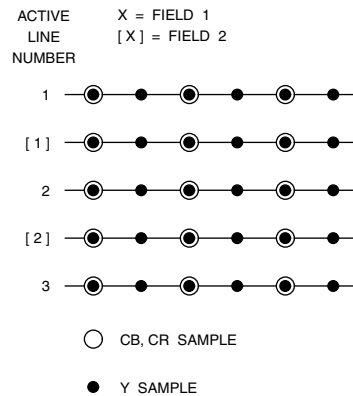


Figure 3.3. 4:2:2 Co-Sited Sampling. The sampling positions on the active scan lines of an interlaced picture.

SAMPLE 0	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4	SAMPLE 5
Y7 - 0	Y7 - 1	Y7 - 2	Y7 - 3	Y7 - 4	Y7 - 5
Y6 - 0	Y6 - 1	Y6 - 2	Y6 - 3	Y6 - 4	Y6 - 5
Y5 - 0	Y5 - 1	Y5 - 2	Y5 - 3	Y5 - 4	Y5 - 5
Y4 - 0	Y4 - 1	Y4 - 2	Y4 - 3	Y4 - 4	Y4 - 5
Y3 - 0	Y3 - 1	Y3 - 2	Y3 - 3	Y3 - 4	Y3 - 5
Y2 - 0	Y2 - 1	Y2 - 2	Y2 - 3	Y2 - 4	Y2 - 5
Y1 - 0	Y1 - 1	Y1 - 2	Y1 - 3	Y1 - 4	Y1 - 5
Y0 - 0	Y0 - 1	Y0 - 2	Y0 - 3	Y0 - 4	Y0 - 5
CB7 - 0	CR7 - 0	CB7 - 2	CR7 - 2	CB7 - 4	CR7 - 4
CB6 - 0	CR6 - 0	CB6 - 2	CR6 - 2	CB6 - 4	CR6 - 4
CB5 - 0	CR5 - 0	CB5 - 2	CR5 - 2	CB5 - 4	CR5 - 4
CB4 - 0	CR4 - 0	CB4 - 2	CR4 - 2	CB4 - 4	CR4 - 4
CB3 - 0	CR3 - 0	CB3 - 2	CR3 - 2	CB3 - 4	CR3 - 4
CB2 - 0	CR2 - 0	CB2 - 2	CR2 - 2	CB2 - 4	CR2 - 4
CB1 - 0	CR1 - 0	CB1 - 2	CR1 - 2	CB1 - 4	CR1 - 4
CB0 - 0	CR0 - 0	CB0 - 2	CR0 - 2	CB0 - 4	CR0 - 4

↑
16 BITS PER SAMPLE
↓

- 0 = SAMPLE 0 DATA
- 1 = SAMPLE 1 DATA
- 2 = SAMPLE 2 DATA
- 3 = SAMPLE 3 DATA
- 4 = SAMPLE 4 DATA

Figure 3.4. 4:2:2 Frame Buffer Formatting.

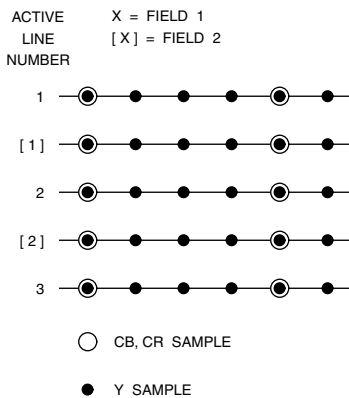


Figure 3.5. 4:1:1 Co-Sited Sampling. The sampling positions on the active scan lines of an interlaced picture.

SAMPLE 0	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4	SAMPLE 5
Y7 - 0	Y7 - 1	Y7 - 2	Y7 - 3	Y7 - 4	Y7 - 5
Y6 - 0	Y6 - 1	Y6 - 2	Y6 - 3	Y6 - 4	Y6 - 5
Y5 - 0	Y5 - 1	Y5 - 2	Y5 - 3	Y5 - 4	Y5 - 5
Y4 - 0	Y4 - 1	Y4 - 2	Y4 - 3	Y4 - 4	Y4 - 5
Y3 - 0	Y3 - 1	Y3 - 2	Y3 - 3	Y3 - 4	Y3 - 5
Y2 - 0	Y2 - 1	Y2 - 2	Y2 - 3	Y2 - 4	Y2 - 5
Y1 - 0	Y1 - 1	Y1 - 2	Y1 - 3	Y1 - 4	Y1 - 5
Y0 - 0	Y0 - 1	Y0 - 2	Y0 - 3	Y0 - 4	Y0 - 5
CB7 - 0	CB5 - 0	CB3 - 0	CB1 - 0	CB7 - 4	CB5 - 4
CB6 - 0	CB4 - 0	CB2 - 0	CB0 - 0	CB6 - 4	CB4 - 4
CR7 - 0	CR5 - 0	CR3 - 0	CR1 - 0	CR7 - 4	CR5 - 4
CR6 - 0	CR4 - 0	CR2 - 0	CR0 - 0	CR6 - 4	CR4 - 4

↑
12 BITS PER SAMPLE
↓

- 0 = SAMPLE 0 DATA
- 1 = SAMPLE 1 DATA
- 2 = SAMPLE 2 DATA
- 3 = SAMPLE 3 DATA
- 4 = SAMPLE 4 DATA

Figure 3.6. 4:1:1 Frame Buffer Formatting.

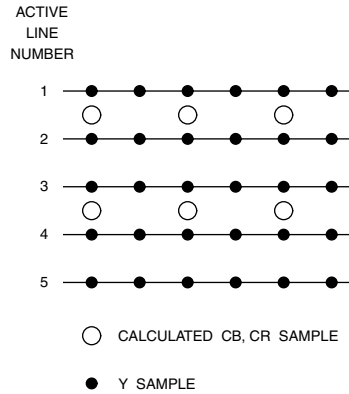
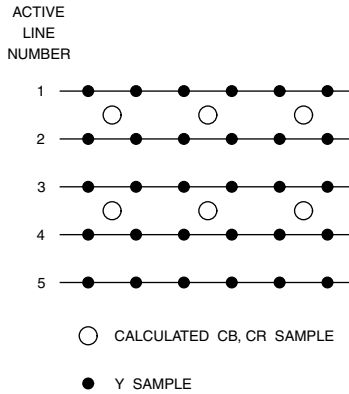


Figure 3.7. 4:2:0 Sampling for H.261, H.263, and MPEG-1. The sampling positions on the active scan lines of a progressive or noninterlaced picture.

Figure 3.8. 4:2:0 Sampling for MPEG-2. The sampling positions on the active scan lines of a progressive or noninterlaced picture.

	SDTV 25 Mbps					SDTV 50 Mbps			HDTV 100 Mbps		MPEG 1, 2	H.261, H.263
	480-Line DV	576-Line DV	480-Line DVCAM	576-Line DVCAM	D-7 (DVCPRO)	DVCPRO 50	Digital Betacam	D-9 (Digital S)	DVCPRO HD	D-9 HD		
4:2:2 Co-Sited						X	X	X	X	X		
4:1:1 Co-Sited	X		X		X							
4:2:0											X	X
4:2:0 Co-Sited		X		X								

Table 3.3. YCbCr Formats for Various DV Applications.

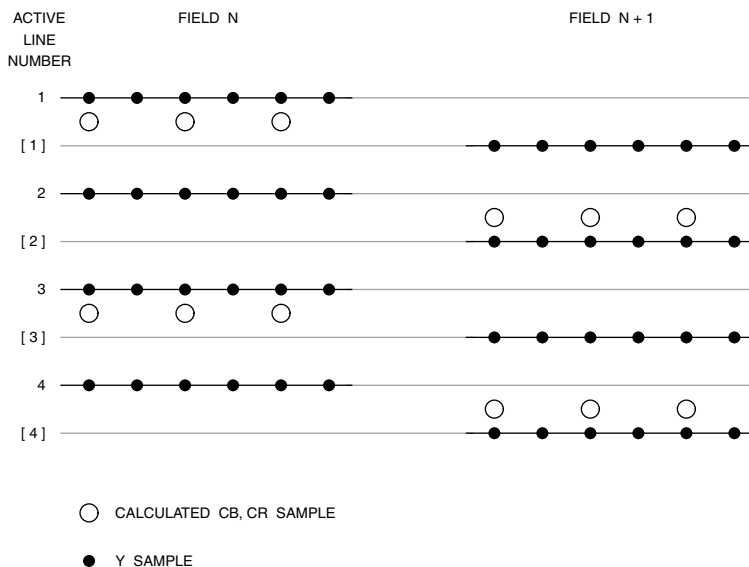


Figure 3.9. 4:2:0 Sampling for MPEG-2. The sampling positions on the active scan lines of an interlaced picture (top_field_first = 1).

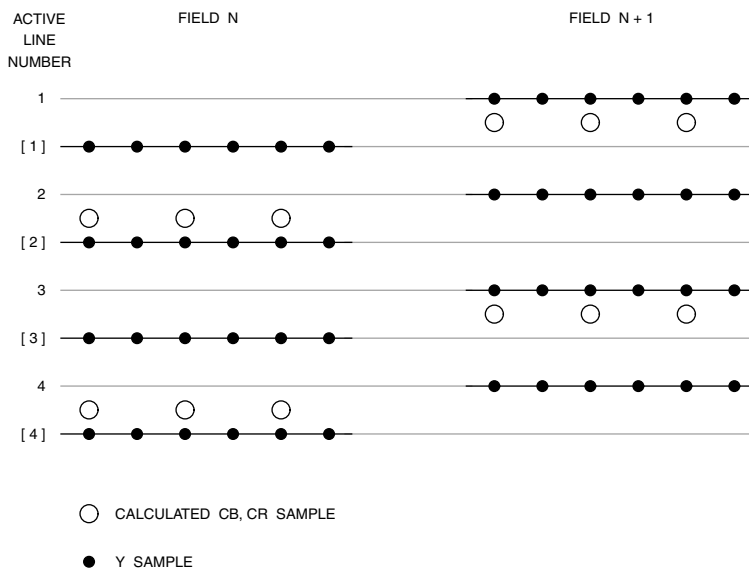


Figure 3.10. 4:2:0 Sampling for MPEG-2. The sampling positions on the active scan lines of an interlaced picture (top_field_first = 0).

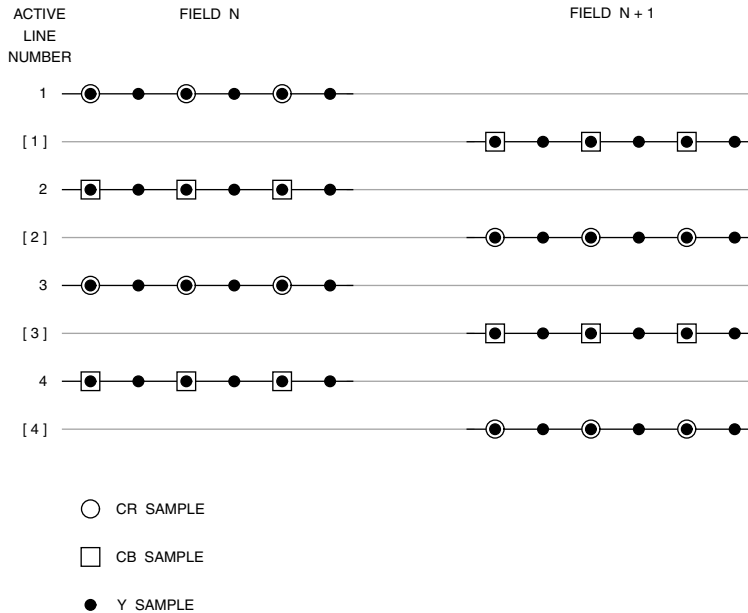


Figure 3.11. 4:2:0 Co-Sited Sampling for 576i DV and DVCAM. The sampling positions on the active scan lines of an interlaced picture.

PhotoYCC Color Space

PhotoYCC (a trademark of Eastman Kodak Company) was developed to encode Photo CD image data. The goal was to develop a display-device-independent color space. For maximum video display efficiency, the color space is based upon ITU-R BT.601 and BT.709.

The encoding process (RGB to PhotoYCC) assumes CIE Standard Illuminant D_{65} and that the spectral sensitivities of the image capture system are proportional to the color-matching functions of the BT.709 reference primaries. The RGB values, unlike those for a computer graphics system, may be negative. PhotoYCC includes colors outside the BT.709 color gamut; these are encoded using negative values.

RGB to PhotoYCC

Linear RGB data (normalized to have values of 0 to 1) is nonlinearly transformed to PhotoYCC as follows:

for $R, G, B \geq 0.018$

$$R' = 1.099 R^{0.45} - 0.099$$

$$G' = 1.099 G^{0.45} - 0.099$$

$$B' = 1.099 B^{0.45} - 0.099$$

for $-0.018 < R, G, B < 0.018$

$$R' = 4.5 R$$

$$G' = 4.5 G$$

$$B' = 4.5 B$$

for R, G, B ≤ -0.018

$$R' = -1.099 |R|^{0.45} - 0.099$$

$$G' = -1.099 |G|^{0.45} - 0.099$$

$$B' = -1.099 |B|^{0.45} - 0.099$$

From R'G'B' with a 0–255 range, a luma and two chrominance signals (C1 and C2) are generated:

$$Y = 0.213R' + 0.419G' + 0.081B'$$

$$C1 = -0.131R' - 0.256G' + 0.387B' + 156$$

$$C2 = 0.373R' - 0.312G' - 0.061B' + 137$$

As an example, a 20% gray value (R, G, and B = 0.2) would be recorded on the PhotoCD disc using the following values:

$$Y = 79$$

$$C1 = 156$$

$$C2 = 137$$

PhotoYCC to RGB

Since PhotoYCC attempts to preserve the dynamic range of film, decoding PhotoYCC images requires the selection of a color space and range appropriate for the output device. Thus, the decoding equations are not always the exact inverse of the encoding equations. The following equations are suitable for generating RGB values for driving a CRT display, and assume a unity relationship between the luma in the encoded image and the displayed image.

$$R' = 0.981Y + 1.315(C2 - 137)$$

$$G' = 0.981Y - 0.311(C1 - 156) - 0.669(C2 - 137)$$

$$B' = 0.981Y + 1.601(C1 - 156)$$

The R'G'B' values should be saturated to a range of 0 to 255. The equations above assume the display uses phosphor chromaticities that are the same as the BT.709 reference primaries, and that the video signal luma (V) and the display luminance (L) have the relationship:

for $V \geq 0.0812$

$$L = ((V + 0.099) / 1.099)^{1/0.45}$$

for $V < 0.0812$

$$L = V / 4.5$$

HSI, HLS, and HSV Color Spaces

The HSI (hue, saturation, intensity) and HSV (hue, saturation, value) color spaces were developed to be more “intuitive” in manipulating color and were designed to approximate the way humans perceive and interpret color. They were developed when colors had to be specified manually, and are rarely used now that users can select colors visually or specify Pantone colors. These color spaces are discussed for “historic” interest. HLS (hue, lightness, saturation) is similar to HSI; the term lightness is used rather than intensity.

The difference between HSI and HSV is the computation of the brightness component (I or V), which determines the distribution and

dynamic range of both the brightness (I or V) and saturation (S). The HSI color space is best for traditional image processing functions such as convolution, equalization, histograms, and so on, which operate by manipulation of the brightness values since I is equally dependent on R, G, and B. The HSV color space is preferred for manipulation of hue and saturation (to shift colors or adjust the amount of color) since it yields a greater dynamic range of saturation.

Figure 3.12 illustrates the single hexcone HSV color model. The top of the hexcone corresponds to $V = 1$, or the maximum intensity colors. The point at the base of the hexcone is black and here $V = 0$. Complementary colors are 180° opposite one another as measured by H, the angle around the vertical axis (V), with red at 0° . The value of S is a ratio, ranging from 0 on the center line vertical axis (V) to 1 on the sides of the hexcone. Any value of S between 0 and 1 may be associated with the point $V = 0$. The point $S = 0, V = 1$ is white. Intermediate values of V for $S = 0$ are the grays. Note that when $S = 0$, the value of H is irrelevant. From an artist's viewpoint, any color with $V = 1, S = 1$ is a pure pigment (whose color is defined by H). Adding white corresponds to decreasing S (without changing V); adding black corresponds to decreasing V (without changing S). Tones are created by decreasing both S and V. Table 3.4 lists the 75% amplitude, 100% saturated HSV color bars.

Figure 3.13 illustrates the double hexcone HSI color model. The top of the hexcone corresponds to $I = 1$, or white. The point at the base of the hexcone is black and here $I = 0$. Complementary colors are 180° opposite one another as measured by H, the angle around the vertical axis (I), with red at 0° (for consistency with the Tektronix convention of blue at 0°). The value of S ranges from 0 on the vertical axis (I) to 1

on the surfaces of the hexcone. The grays all have $S = 0$, but maximum saturation of hues is at $S = 1, I = 0.5$. Table 3.5 lists the 75% amplitude, 100% saturated HSI color bars.

Chromaticity Diagram

The color gamut perceived by a person with normal vision (the 1931 CIE Standard Observer) is shown in Figure 3.14. The diagram and underlying mathematics were updated in 1960 and 1976; however, the NTSC television system is based on the 1931 specifications.

Color perception was measured by viewing combinations of the three standard CIE (International Commission on Illumination or Commission Internationale de l'Éclairage) primary colors: red with a 700-nm wavelength, green at 546.1 nm, and blue at 435.8 nm. These primary colors, and the other spectrally pure colors resulting from mixing of the primary colors, are located along the curved outer boundary line (called the *spectrum locus*), shown in Figure 3.14.

The ends of the spectrum locus (at red and blue) are connected by a straight line that represents the purples, which are combinations of red and blue. The area within this closed boundary contains all the colors that can be generated by mixing light of different colors. The closer a color is to the boundary, the more saturated it is. Colors within the boundary are perceived as becoming more pastel as the center of the diagram (white) is approached. Each point on the diagram, representing a unique color, may be identified by its x and y coordinates.

In the CIE system, the intensities of red, green, and blue are transformed into what are called the *tristimulus values*, which are represented by the capital letters X, Y, and Z. These

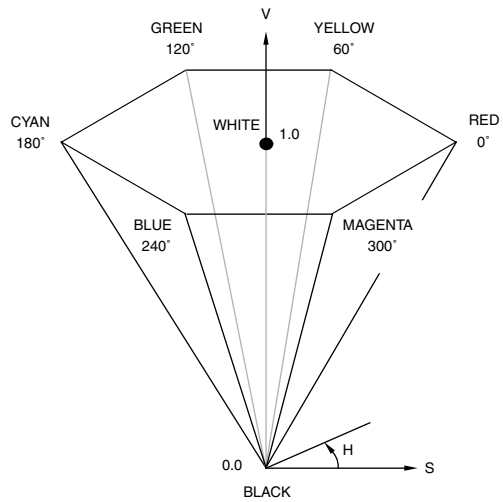


Figure 3.12. Single Hexcone HSV Color Model.

	Nominal Range	White	Yellow	Cyan	Green	Magenta	Red	Blue	Black
H	0° to 360°	-	60°	180°	120°	300°	0°	240°	-
S	0 to 1	0	1	1	1	1	1	1	0
V	0 to 1	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0

Table 3.4. 75% HSV Color Bars.

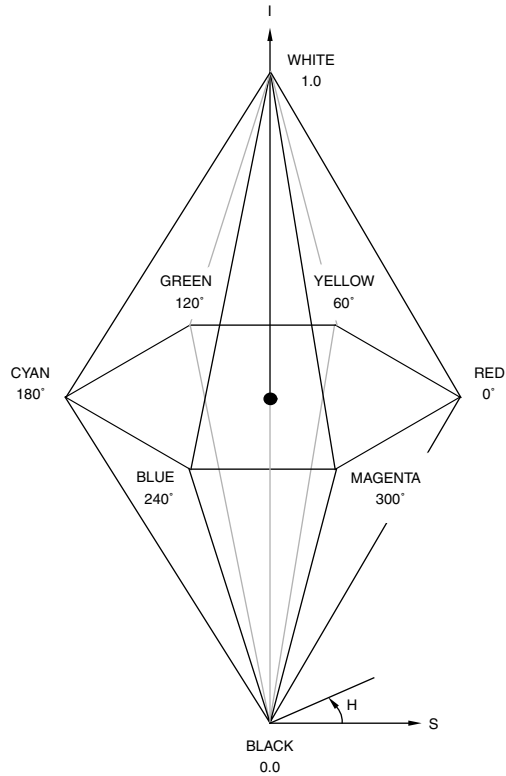


Figure 3.13. Double Hexcone HSI Color Model. For consistency with the HSV model, we have changed from the Tektronix convention of blue at 0° and depict the model as a double hexcone rather than as a double cone.

	Nominal Range	White	Yellow	Cyan	Green	Magenta	Red	Blue	Black
H	0° to 360°	–	60°	180°	120°	300°	0°	240°	–
S	0 to 1	0	1	1	1	1	1	1	0
I	0 to 1	0.75	0.375	0.375	0.375	0.375	0.375	0.375	0

Table 3.5. 75% HSI Color Bars. For consistency with the HSV model, we have changed from the Tektronix convention of blue at 0°.

values represent the relative quantities of the primary colors.

The coordinate axes of Figure 3.14 are derived from the tristimulus values:

$$\begin{aligned}x &= X/(X + Y + Z) \\ &= \text{red}/(\text{red} + \text{green} + \text{blue})\end{aligned}$$

$$\begin{aligned}y &= Y/(X + Y + Z) \\ &= \text{green}/(\text{red} + \text{green} + \text{blue})\end{aligned}$$

$$\begin{aligned}z &= Z/(X + Y + Z) \\ &= \text{blue}/(\text{red} + \text{green} + \text{blue})\end{aligned}$$

The coordinates x , y , and z are called *chromaticity coordinates*, and they always add up to 1. As a result, z can always be expressed in terms of x and y , which means that only x and y are required to specify any color, and the diagram can be two-dimensional.

Typically, a source or display specifies three (x, y) coordinates to define the three primary colors it uses. The triangle formed by the three (x, y) coordinates encloses the gamut of colors that the source or display can reproduce. This is shown in Figure 3.15, which compares the color gamuts of NTSC, PAL, and typical inks and dyes.

Note that no set of three colors can generate all possible colors, which is why television pictures are never completely accurate. For example, a television cannot reproduce monochromatic yellow-green (540 nm) since this color lies outside the triangle formed by red, green, and blue.

In addition, a source or display usually specifies the (x, y) coordinate of the white color used, since pure white is not usually captured or reproduced. White is defined as the color captured or produced when all three primary signals are equal, and it has a subtle shade of color to it. Note that luminance, or brightness information, is not included in the standard

CIE 1931 chromaticity diagram, but is an axis that is orthogonal to the (x, y) plane. The lighter a color is, the more restricted the chromaticity range is.

The chromaticities and reference white (CIE illuminate C) for the 1953 NTSC standard are:

$$R: \quad x_r = 0.67 \quad y_r = 0.33$$

$$G: \quad x_g = 0.21 \quad y_g = 0.71$$

$$B: \quad x_b = 0.14 \quad y_b = 0.08$$

$$\text{white: } x_w = 0.3101 \quad y_w = 0.3162$$

Modern NTSC systems use a different set of RGB phosphors, resulting in slightly different chromaticities of the RGB primaries and reference white (CIE illuminate D₆₅):

$$R: \quad x_r = 0.630 \quad y_r = 0.340$$

$$G: \quad x_g = 0.310 \quad y_g = 0.595$$

$$B: \quad x_b = 0.155 \quad y_b = 0.070$$

$$\text{white: } x_w = 0.3127 \quad y_w = 0.3290$$

As illustrated in Figure 3.15, the color accuracy of television receivers has declined in order to increase the brightness.

The chromaticities and reference white (CIE illuminate D₆₅) for PAL and SECAM are:

$$R: \quad x_r = 0.64 \quad y_r = 0.33$$

$$G: \quad x_g = 0.29 \quad y_g = 0.60$$

$$B: \quad x_b = 0.15 \quad y_b = 0.06$$

$$\text{white: } x_w = 0.3127 \quad y_w = 0.3290$$

The chromaticities and reference white (CIE illuminate D₆₅) for HDTV are based on BT.709:

R: $x_r = 0.64$ $y_r = 0.33$

G: $x_g = 0.30$ $y_g = 0.60$

B: $x_b = 0.15$ $y_b = 0.06$

white: $x_w = 0.3127$ $y_w = 0.3290$

Non-RGB Color Space Considerations

When processing information in a non-RGB color space (such as YIQ, YUV, or YCbCr), care must be taken that combinations of values are not created that result in the generation of invalid RGB colors. The term invalid refers to RGB components outside the normalized RGB limits of (1, 1, 1).

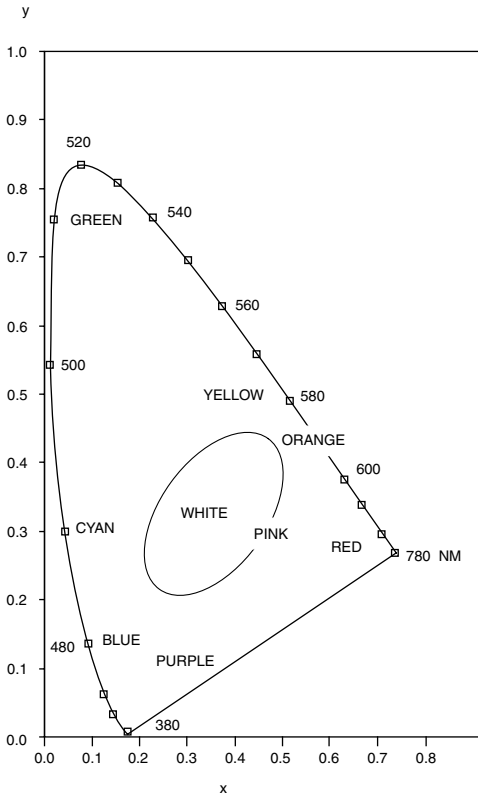


Figure 3.14. CIE 1931 Chromaticity Diagram Showing Various Color Regions.

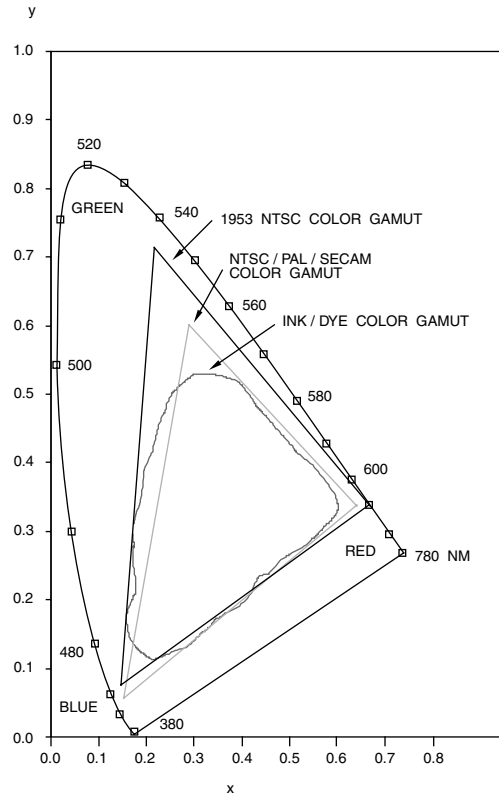


Figure 3.15. CIE 1931 Chromaticity Diagram Showing Various Color Gamuts.

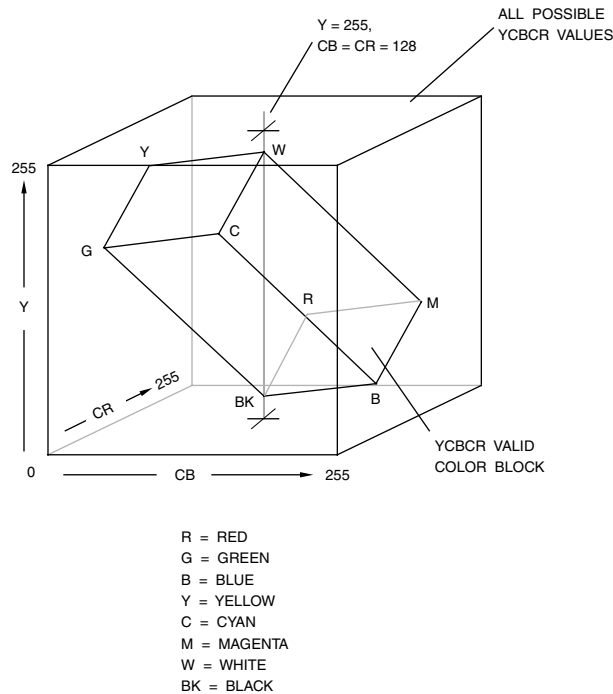


Figure 3.16. RGB Limits Transformed into 3-D YCbCr Space.

For example, given that RGB has a normalized value of (1, 1, 1), the resulting YCbCr value is (235, 128, 128). If Cb and Cr are manipulated to generate a YCbCr value of (235, 64, 73), the corresponding RGB normalized value becomes (0.6, 1.29, 0.56)—note that the green value exceeds the normalized value of 1.

From this illustration it is obvious that there are many combinations of Y, Cb, and Cr that result in invalid RGB values; these YCbCr values must be processed so as to generate valid RGB values. Figure 3.16 shows the RGB normalized limits transformed into the YCbCr color space.

Best results are obtained using a constant luma and constant hue approach—Y is not

altered while Cb and Cr are limited to the maximum valid values having the same hue as the invalid color prior to limiting. The constant hue principle corresponds to moving invalid CbCr combinations directly towards the CbCr origin (128, 128), until they lie on the surface of the valid YCbCr color block.

When converting to the RGB color space from a non-RGB color space, care must be taken to include saturation logic to ensure overflow and underflow wrap-around conditions do not occur due to the finite precision of digital circuitry. 8-bit RGB values less than 0 must be set to 0, and values greater than 255 must be set to 255.

Gamma Correction

The transfer function of most displays produces an intensity that is proportional to some power (referred to as gamma) of the signal amplitude. As a result, high-intensity ranges are expanded and low-intensity ranges are compressed (see Figure 3.17). This is an advantage in combatting noise, as the eye is approximately equally sensitive to equally relative intensity changes. By “gamma correcting” the video signals before display, the intensity output of the display is roughly linear (the gray line in Figure 3.17), and transmission-induced noise is reduced.

To minimize noise in the darker areas of the image, modern video systems limit the gain of the curve in the black region. This technique limits the gain close to black and stretches the remainder of the curve to maintain function and tangent continuity.

Although video standards assume a display gamma of about 2.2, a gamma of about 2.4 is more realistic for CRT displays. However, this difference improves the viewing in dimly lit environments, such as the home. More accurate viewing in brightly lit environments may be accomplished by applying another gamma factor of about 1.09 ($2.4/2.2$).

Early NTSC Systems

Early NTSC systems assumed a simple transform at the display, with a gamma of 2.2. RGB values are normalized to have a range of 0 to 1:

$$R = R'^{2.2}$$

$$G = G'^{2.2}$$

$$B = B'^{2.2}$$

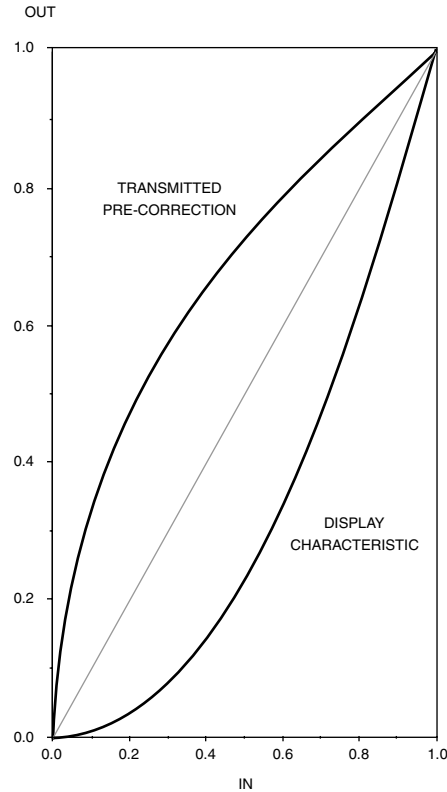


Figure 3.17. Effect of Gamma.

To compensate for the nonlinear display, linear RGB data was “gamma-corrected” prior to transmission by the inverse transform. RGB values are normalized to have a range of 0 to 1:

$$R' = R^{1/2.2}$$

$$G' = G^{1/2.2}$$

$$B' = B^{1/2.2}$$

Early PAL and SECAM Systems

Most early PAL and SECAM systems assumed a simple transform at the display, with a gamma of 2.8. RGB values are normalized to have a range of 0 to 1:

$$R = R^{2.8}$$

$$G = G^{2.8}$$

$$B = B^{2.8}$$

To compensate for the nonlinear display, linear RGB data was “gamma-corrected” prior to transmission by the inverse transform. RGB values are normalized to have a range of 0 to 1:

$$R' = R^{1/2.8}$$

$$G' = G^{1/2.8}$$

$$B' = B^{1/2.8}$$

Current Systems

Current NTSC and HDTV systems assume the following transform at the display, with a gamma of [1/0.45]. RGB values are normalized to have a range of 0 to 1:

for $(R', G', B') < 0.0812$

$$R = R' / 4.5$$

$$G = G' / 4.5$$

$$B = B' / 4.5$$

for $(R', G', B') \geq 0.0812$

$$R = ((R' + 0.099) / 1.099)^{1/0.45}$$

$$G = ((G' + 0.099) / 1.099)^{1/0.45}$$

$$B = ((B' + 0.099) / 1.099)^{1/0.45}$$

To compensate for the nonlinear display, linear RGB data is “gamma-corrected” prior to transmission by the inverse transform. RGB values are normalized to have a range of 0 to 1:

for $R, G, B < 0.018$

$$R' = 4.5 R$$

$$G' = 4.5 G$$

$$B' = 4.5 B$$

for $R, G, B \geq 0.018$

$$R' = 1.099 R^{0.45} - 0.099$$

$$G' = 1.099 G^{0.45} - 0.099$$

$$B' = 1.099 B^{0.45} - 0.099$$

Although most PAL and SECAM standards specify a gamma of 2.8, a value of [1/0.45] is now commonly used. Thus, these equations are now also used for PAL and SECAM systems.

Non-CRT Displays

Many non-CRT displays have a different gamma than that used for video. To simplify interfacing, the display drive electronics are usually designed to present a standard CRT transform, with a gamma of [1/0.45]. The display drive electronics then compensate for the actual gamma of the display device.

Constant Luminance Problem

Due to the wrong order of the gamma and matrix operations, the U and V (or Cb and Cr) signals also contribute to the luminance (Y) signal. This causes an error in the perceived luminance when the amplitude of U and V is not correct. This may be due to bandwidth-limiting U and V or a non-nominal setting of the U and V gain (color saturation).

For low color frequencies, there is no problem. For high color frequencies, U and V disappear and consequently R', G', and B' degrade to be equal to (only) Y.

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