H42: Image RGB to Display Colour XYZ
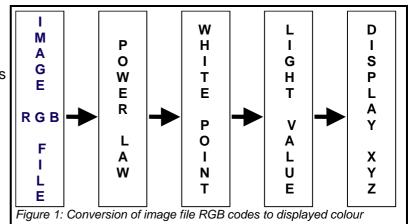
The way in which a CRT or an LCD type of display creates a coloured image is described in another document. The steps in the conversion of the RGB codes in an electronic image file to the brightness (luminance) of the light emitted by the display screen are summarised by the Figure 1.

Figure 1: Conversion of image file RGB codes to displayed colour

Factors involved

The relationships used to model each of the steps are given in the following sections.

RGB Colour codes

The most common level of colour resolution for each picture element (pixel) of a computer display is is 8-bits in each of the R, G and B codes using a total of 24 bits per pixel. This gives 256 levels for each channel (codes 0 to 255) and is sufficient for 16.8 million different R G B codes.
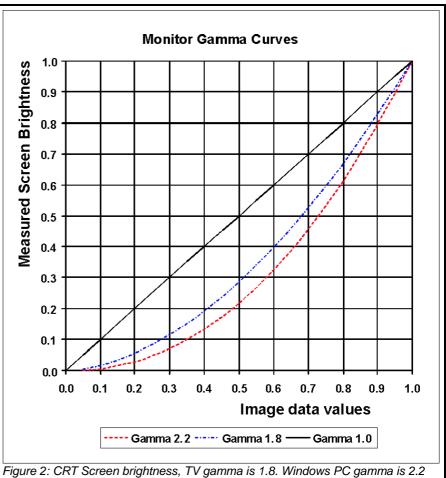
$$256 \times 256 \times 256 = 16.8 \text{ million codes}$$

At first sight, this seems like a huge number of colours, easily able to satisfy the human eye. However the 16.8 million codes, although equally spaced throughout RGB space, are not equally spaced visually.

The colours of neighbouring codes in some areas of RGB colour space are indistinguishable from each other, whilst in other areas the colour difference is easily seen. RGB space is visually non-uniform.

Power law

The non-linearity relationship between the instructions sent to the display system and the intensity of the light output from a display is expressed by a mathematical power-law function. The function describes how much visible radiant energy (lumens, lm) results from the signals sent to the device. The power law exponent has become known as the gamma factor of the display system. The relationship between image data values and screen brightness is illustrated in Figure 2.

Figure 2: CRT Screen brightness, TV gamma is 1.8. Windows PC gamma is 2.2

Under the optimal conditions the following equation is assumed to apply:

$$L = L(W)D^{gamma}$$

L is the luminance (brightness in lumens) of the light emitted by the phosphor dots, L(W) is the maximum luminance of the screen and D is the normalized signal (range 0 to 1) applied to the display.

The standard or default gamma value depends on the type of system, typically

Display gamma = 1.8 for Apple Mac PC systems (and for broadcast TV receivers);

Display gamma = 2.2 for a Microsoft Windows PC monitor

Figure 2 shows the relationship between the normalised pixel data values and the screen brightness for each of these gamma factors.

White point

The white point of a display refers to the characteristics of the light emitted from the screen when the data values are all set to maximum, R = 255, G = 255 and B =255 for example. The nature or "shade" of the white can usually be set in software to suit different applications of the display.

There are four white points in common use for computer displays and they are based on the daylight specification system of the CIE.

The maximum brightness of a display occurs when it is showing white. If this level of brightness is represented as 100 units, then the contributions of the red $L_R(W)$, green $L_G(W)$ and the blue $L_B(W)$ light emitted by the screen to the 100 units depends on the white point setting of the display.

The values for the common white point settings are shown in Table 1.

Note the increasing blueness of the "Daylight" white point as the setting goes from a low colour temperature (D50) to a high colour temperature (D93). The red luminance [$L_R(W)$] decreases while the blue luminance [$L_B(W)$] increases.

Table 1: Relative screen brightness values, at various display white point settings, sum = 100

Colour of light	Brightness (relative units)			
	D50	D65	D75	D93
Red, $L_R(W)$	24.99	21.26	19.76	18.01
Green, $L_G(W)$	69.81	71.52	71.99	72.31
Blue, $L_B(W)$	5.20	7.22	8.26	9.68

The absolute brightness of a display will depend on the settings of the controls of the display, such as the brightness and contrast and the white point. For conventional displays the order of increasing absolute maximum screen brightness is D50, D65, D75 and brightest is the Windows default of D93.

Colour values of emitted light

The colour values, in terms of CIE XYZ units, of the light emitted by an electronic display are set by national and by international standards.

The values for the PC monitors and for the PAL (European) type of television displays are virtually the same as those used in the international standard system for RGB codes, sRGB. The defining values are shown in Table 2.

Table 2: The chromaticities of the light emitted by a display

Phosphor	x	y	z
P22 red	0.6400	0.3300	0.0300
P22 green	0.2900	0.6000	0.1100
P22 blue	0.1500	0.0600	0.7900

Remembering that the Y tristimulus value describes the relative luminance of the light, the data given in Table 2 can be used to determine the contributions to the screen X, Y and Z from each type of light emitted by the screen.

Each unit luminance of **red** light will contribute   X = 1.9394,   Y = 1.0000,   Z = 0.0909

Each unit luminance of **green** light will contribute   X = 0.5000,   Y = 1.0000,   Z = 0.1667

Each unit luminance of **blue** light will contribute   X = 2.5000,   Y = 1.0000,   Z = 13.1667

Conversion of R G B to display colour

The steps involved are:

Normalise the digital codes R G B into the range 0 to 1. (R' G' B')

Using the power-law factor for the display system, transform the normalised values to the level of activation of the red, green and blue light emitters. (A_R A_G A_B)

Using the white point setting of the display, determine the luminance of the red, green and blue light emitted by the display. (L_R L_G L_B)

Using the contributions to X, Y and Z of unit luminance of each type of light, determine the XYZ values for the emitted light. (X Y Z)

Re-scale data codes to range from 0 to 1, (R' G' B')

We start by setting V_{max} as the number corresponding to the maximum code that can be given. The digital codes in the image file are then re-scaled from the range (0 to V_{max}), to the range (0 to 1).

For an 8 bit code (24 bit colour), $V_{max} = 2^8 - 1 = 255$

$$R' = \frac{R}{V_{max}} , \qquad G' = \frac{G}{V_{max}} \text{ and } \qquad B' = \frac{B}{V_{max}}$$

Relative brightness of each light source, (A_R A_G A_B)

Apply the display power-law factor

The brightness of the image area relative to the brightness when displaying the white point is obtained by applying the non-linear transformation to the normalised data. The values are in the range 0 to 1 and can thought of as the level of activation of the light emitters in that area of the display (A_R, A_G and A_B).

$$A_R = \left(\frac{R}{V_{max}}\right)^P , \qquad A_G = \left(\frac{G}{V_{max}}\right)^P \text{ and } \qquad A_B = \left(\frac{B}{V_{max}}\right)^P$$

Brightness emitted (L_R L_G L_B)

Take into account the white point settings

Finally the brightness of the red, the green and the blue light emitted from the image area of the screen is determined by multiplying the activation with the white point luminance. The notation L_R L_G and L_B is used to indicate the relative brightness of the red, the green and the blue light emitted by the display respectively.

$$L_R = A_R \cdot L_R(W) , \qquad L_G = A_G \cdot L_G(W) \text{ and } \qquad L_B = A_B \cdot L_B(W)$$

Tristimulus values of the emitted light (X Y Z)

The CIE XYZ tristimulus values for the light emitted by the screen are obtained by summing the contributions to X, Y and Z made by the red, the green and the blue light emitted from the screen.

The colour properties of the light is defined by the display standards, for example the sRGB standard specifies the contributions to X Y and Z of unit brightness of each type of light so that.

$$X = 1.9394\, L_R + 0.5000\, L_G + 2.5000\, L_B$$

$$Y = L_R + L_G + L_B$$

$$Z = 0.0909\, L_R + 0.1667\, L_G + 13.1667\, L_B$$

Colour resolution

The 16.8 million codes, although equally spaced throughout RGB space, are not equally spaced visually. RGB space is non-uniform and the colours of neighbouring codes in some areas of RGB colour space are indistinguishable from each other, whilst in other areas the colour difference is easily seen.

This is illustrated by the data shown in Table 3. The average colour difference of neighbouring RGB codes around the hue circle is shown at five different lightness and chroma levels. The lowest values are for light samples (L* > 80, dE* < 0.60) and the highest values are for dark samples (L* < 25, dE* > 1.0).

Table 3: Colour difference between neighbouring RGB codes for a system with a D65 white point and gamma of 1.80

L*	C*	dE*
80.0	48.0	0.58
50.0	30.0	0.75
25.0	15.0	1.03
10.0	6.0	1.42
5.0	6.0	1.27

Research suggests that at least 10 bits per colour code are required in order for the difference in colour between neighbouring codes to be less than the resolution of the eye, throughout the entire gamut.

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