WHICH COLOR GAMUT CAN BE ACHIEVED IN MULTICOLOR PRINTING AND IN TELEVISION?

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Abstract

The color gamut in multicolor printing is usually illustrated as hexagon in a chromaticity diagram. However, this neglects the third dimension. In this study the color gamut is calculated as volume in a near visually uniform color space.
In a first part, the color gamut of the theoretical primary colors for multicolor printing is investigated. By variation of the wavelengths of optimum colors the exact spectral values of the best suited primaries can be derived.
The second part deals with the color gamut resulting from the real primaries used in multicolor printing and television. In a comparison, the color gamut which can be achieved with all existing surface colors is calculated. It is shown that multicolor printing is able to render almost 50% of all surface colors.

1. Calculation of the color gamut

Multicolor printing can be considered an additive color mixture system, consisting of 16 elementary colors. For the calculation of the color gamut, only eight elementary colors are relevant:

- Paper White (W)
- Cyan (C)
- Magenta (M)
- Yellow (Y)
- Red (R)
- Green (G)
- Blue (B)
- Black (K)

Black can also be the four-color overlap of Cyan + Magenta + Yellow + Black. As the solid-tone overprint of all four primary colors rarely occurs in the daily practice, the pure Black will be used as corner point of the color solid.
In this case, the color gamut is determined by the volume of a solid having eight corner points which are defined by the color coordinates of the eight elementary colors. In order to calculate the volume of this solid, it has to be assumed that the corners are connected by

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straight lines. This assumption is fulfilled, if the calculation takes place in a color space where additive color mixtures lay on straight lines. Furthermore, the color space should be visually uniform in order to allow a comparison between individual areas of the space.
These conditions are not entirely fulfilled by any color space. However, an acceptable approximation is the CIELUV color space which is nearly uniformly spaced and shows only a slight distortion of the linearity of additive mixtures.

The volume of an octagonal color solid can be best calculated, if it is divided up into rectangular solids called tetrahedrons. This leads to six tetrahedrons being formed by the color coordinates of paper White, Black, of a primary color and of an adjacent secondary color. They have the following corner points:

Yellow	– Red	– Paper White	– Black
Red	– Magenta	– Paper White	– Black
Magenta	– Blue	– Paper White	– Black
Blue	– Cyan	– Paper White	– Black
Cyan	– Green	– Paper White	– Black
Green	– Yellow	– Paper White	– Black

In the CIELUV color space, each corner point has the coordinates L*, u*, v*. The following matrix can be used for the calculation of the volume, if the four corner points are numbered with the subscripts 1, 2, 3 and 4:

$$V = \frac{1}{6} \begin{vmatrix} L^*_1 & u^*_1 & v^*_1 & 1 \\ L^*_2 & u^*_2 & v^*_2 & 1 \\ L^*_3 & u^*_3 & v^*_3 & 1 \\ L^*_4 & u^*_4 & v^*_4 & 1 \end{vmatrix}$$

The result of the calculation is a number which corresponds to the sum of the distinguishable hues, if it is assumed that one unit of a CIELUV coordinate, i.e. one unit ΔE^*_{uv}, corresponds to a just visible color difference.
The description of the color gamut in terms of distinguishable hues is primarily a measure for the volume of the color space. Whether or not it is possible to render this number of hues as distinguishable colors, depends on the other performance criteria of the reproduction process.

2. The color gamut in ideal and real multicolor printing

In ideal multicolor printing, the primary colors must have characteristics permitting to achieve identical color mixtures with both the additive and subtractive process. It can be shown that this is the case, if the primary colors have rectangular spectral curves, the reflectance values at each wavelength being either 100% or 0%. Such colors are called optimal colors. In particular, an ideal primary color should have a reflectance value of 100% in two thirds of the visible spectrum, and 0% in one third of the spectrum. Another condition is that the spectral curves of the primary colors never have a reflectance value of 0% at the same wavelength. This means that the primary colors for ideal multicolor printing can be defined by only two wavelengths λ_1 and λ_2 determining the areas in which the reflectance values are 100% or 0%. In particular, the primary colors must show the following characteristics:

	Area of 100% reflectance (nm)	Area of 0% reflectance (nm)
Cyan	$380-\lambda_2$	λ_2-720
Magenta	$380-\lambda_1, \lambda_2-720$	$\lambda_1-\lambda_2$
Yellow	λ_1-720	$380-\lambda_1$

The position of the wavelengths λ_1 and λ_2 determines the color gamut which can be achieved by the three primary colors.
As to the choice of these wavelengths, H.E.J. Neugebauer carried out investigations as early as in 1935 and found for λ_1 = 489 nm and for λ_2 = 574 nm as being optimal wavelengths. This report deals again with the question which values λ_1 and λ_2 lead to the largest color gamut. For this purpose, the values λ_1 and λ_2 have been varied systematically in intervals of 10 nm as following:

Set of primary colors	λ_1 (nm)	λ_2 (nm)
1	485	575
2	485	585
3	495	565
4	495	575
5	495	585
6	495	595
7	505	575
8	505	585
9	505	595

In order to calculate the color gamut, the secondary colors have also to be known . They are calculated from their spectral values in the same way as the primary colors. For White and Black, the following values have been used:

	White	Black
L*	100	0
u*	0	0
v*	0	0

The calculation of the color gamut for the before mentioned nine sets of ideal primaries yields values between 1.574 million and 1.645 million colors (see table 1). The maximum color gamut was found for the wavelength of $\lambda_1 = 495$ nm and $\lambda_2 = 575$ nm which is in good agreement with the values proposed by Neugebauer.
The calculation shows that the differences between the 9 examined combinations are small. The combination having the smallest color gamut only differs 8% from the maximum gamut.

Tab. 1 Number of colors which can be reproduced by different combinations of optimal primary colors

Set of primaries No	Absorption area (nm) Yellow	Magenta	Cyan	Number of reproducible colors
1	380 - 485	485 - 575	575 - 720	1.591 million
2	380 - 485	485 - 585	585 - 720	1.574
3	380 - 495	495 - 565	565 - 720	1.589
4	380 - 495	495 - 575	575 - 720	1.645
5	380 - 495	495 - 585	585 - 720	1.611
6	380 - 495	495 - 595	595 - 720	1.529
7	380 - 505	505 - 575	575 - 720	1.615
8	380 - 505	505 - 585	585 - 720	1.603
9	380 - 505	505 - 595	595 - 720	1.513

3. The color gamut in real multicolor printing

For real multicolor printing, the color coordinates specified in ISO 2846 (edition 1975) for offset printing have been used. (At the time being, ISO 2846 is under revision. As the foreseeable changes are minor, the present calculation remains representative.)
The number of reproducible colors resulting with offset process inks is 576'000. Compared with the color gamut resulting with the ideal primary colors, this is only 35%. The difference is caused by the fact that color saturation of the real primaries is lower and that the ideal printing process is based on an ideal White and an ideal Black. In real multicolor printing, especially the area of the blue and purple tones is limited compared with the ideal printing process. As alternative to the printing process with three chromatic colors, it can also be asked which color gamut can be achieved, if only two primary colors are printed. A system based on two primary colors requires that the two-color overprint leads to a secondary color being almost achromatic. Colorimetrically spoken, the spectral curves must not overlap each other. Moreover, in order to make the reproduction of bright colors possible, broad-band curves are necessary. Theoretically, the best combination would be a pair of optimal colors having a common wavelength at about 550 nm. This corresponds to a blueish Cyan and an Orange. The two PANTONE colors ORANGE 021C and PROCESS BLUE C are a good approach to the required spectral curves. The color gamut achieved by these colors is determined by a single tetrahedron whose corner points are formed by the two primary colors, the two-color overprint and the paper White. Color measurements on a color chart printed with these two primary colors show that the color gamut comprises some 95'000 colors. Although this is only 16%

of the gamut of the conventional printing process, a number of hues can be rendered which are found in many color originals, such as Blue, Brown or foliage Green.

4. The color gamut in television

In order to calculate the color gamut in television, again the coordinates of the eight corner points in the CIELUV color solid are needed.
These corner points are determined by five primary colors:

- the three phosphors Red, Green and Blue
- White (as an additive mixture of Red + Green + Blue)
- Black (as state of the monitor without stimulation by the phosphors)

For the three phosphors and the White point, standard values are specified for the European and the American television. For Black, theoretically the color coordinates $L^* = u^* = v^* = 0$ can be used. However, a dark screen always shows a certain rest luminance which is typically about 1% of the White.
The result of the color gamut calculation is shown in table 2. As can be seen, about 1.35 million colors can be reproduced with the European television phosphors. Compared to the printing process, this is more than double the color gamut. There are two reasons for that:

- Television phosphors are self-luminous colors and therefore more saturated than the process inks in multicolor printing which are surface colors. More saturated primaries can also produce mixed colors of higher saturation.
- The White of the monitor is considered an absolute White for the calculation, whereas the White in multicolor printing is not identical with the absolute White. A paper not being entirely white reduces the color gamut by about 5%.

But the European television phosphors are not in each case more saturated than the primary colors of multicolor printing. As figure 1 shows, the process Cyan and the process Green are outside the color gamut of the European television phosphors. In contrast to this, the phosphors of the American television standard NTSC show a larger color gamut (see figure 2) and allow therefore the reproduction of a higher number of colors, i.e. 1.954 million.
Another question is how many colors are distinguishable in real life. A reliable estimation for this number is 10 million.
It may be surprising that only 6% of all real colors can be reproduced in multicolor printing. It has to be born in mind, however, that a large part of real colors only occurs in form of radiation whose reproduction by a trichromatic process is not very important. The number of colors occuring in form of surface colors is therefore more interesting.
The color gamut of the really existing surface colors can be determined by measuring samples from color order systems which show the highest color saturation. If these colors are plotted in a u'v' diagram, an area is resulting which corresponds to the color gamut of all surface colors (see figure 3). By means of the $L^*u^*v^*$ values, a maximum number of 1.2 million distinguishable surface colors can be calculated. This is slightly more than double of the color gamut in multicolor printing. Outside of the range of multicolor printing are mainly saturated colors in the green, blue and purple tones, but also certain bright colors such as pastel tones.

Tab. 2 **Achievable color gamut in multicolor printing and in television**

	Number of colors			
	Green to Red	**Red to Blue**	**Blue to Green**	**Sum**
European television (EBU Standard)	470'000	572'000	308'000	1'350'000
American television (NTSC Standard)	732'000	702'000	520'000	1'954'000
Ideal multi-color printing	616'000	591'000	438'000	1'645'000
Real multi-color printing (primary colors according to ISO 2846)	277'000	165'000	134'000	576'000
Two-color printing with PANTONE ORANGE 021C and PANTONE PROCESS BLUE C	–	–	–	95'000

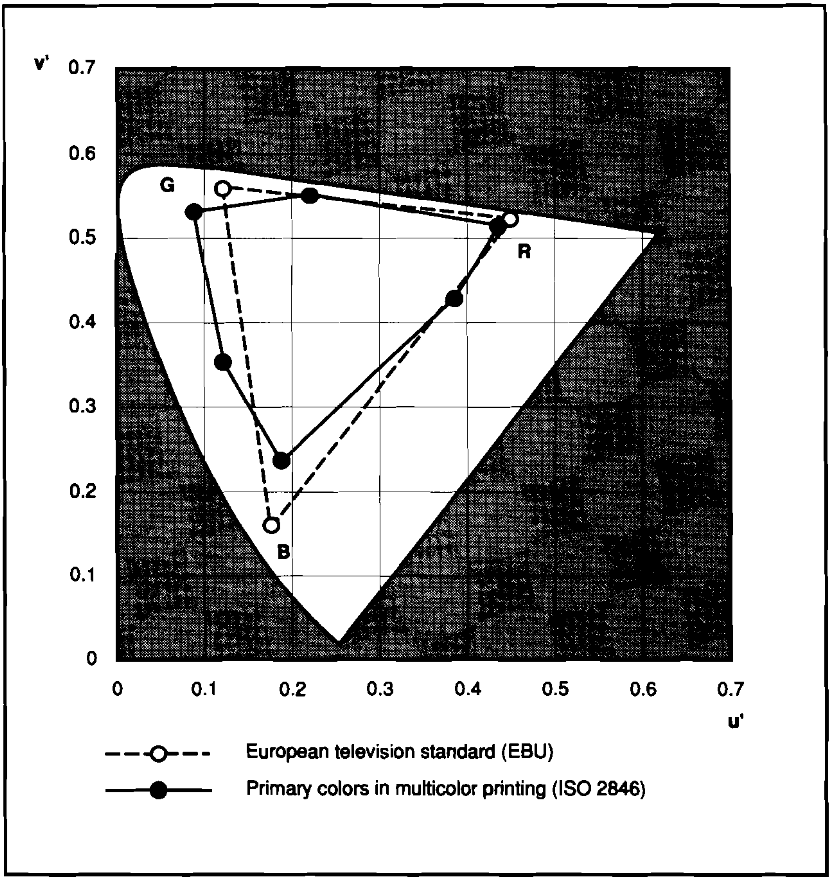

Fig. 1 Comparison of the achievable color gamuts with the phosphors of the European television standard and the process inks in multicolor printing (values for C/2°)

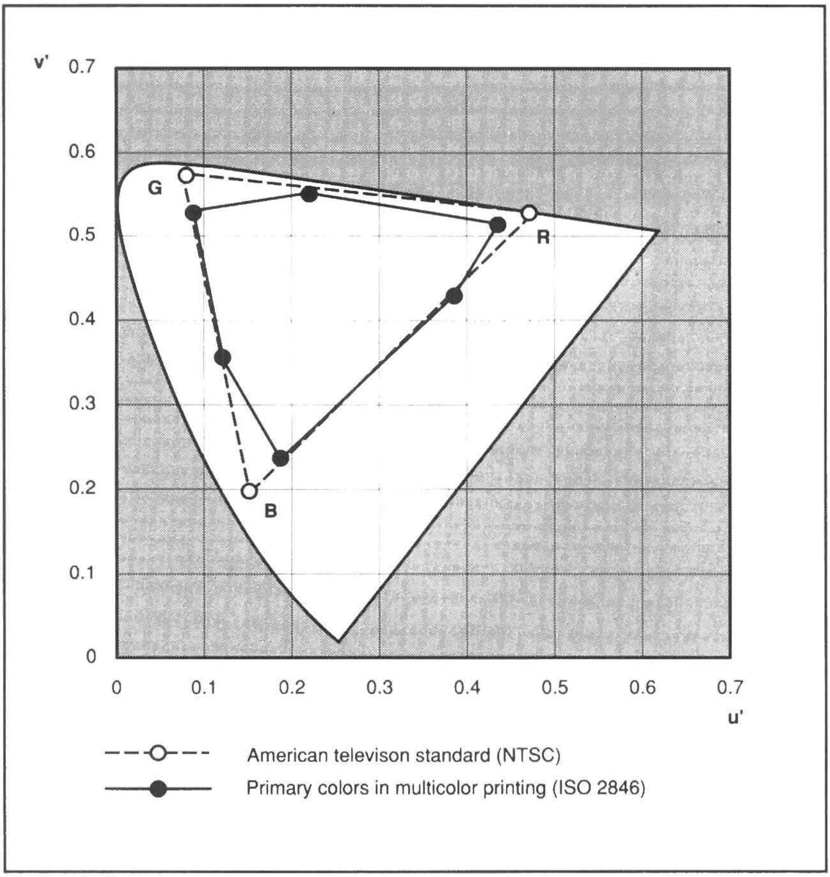

Fig. 2 Comparison of the achievable color gamuts with the phosphors of the American television standard and with the process inks in multicolor printing (values for C/2°)

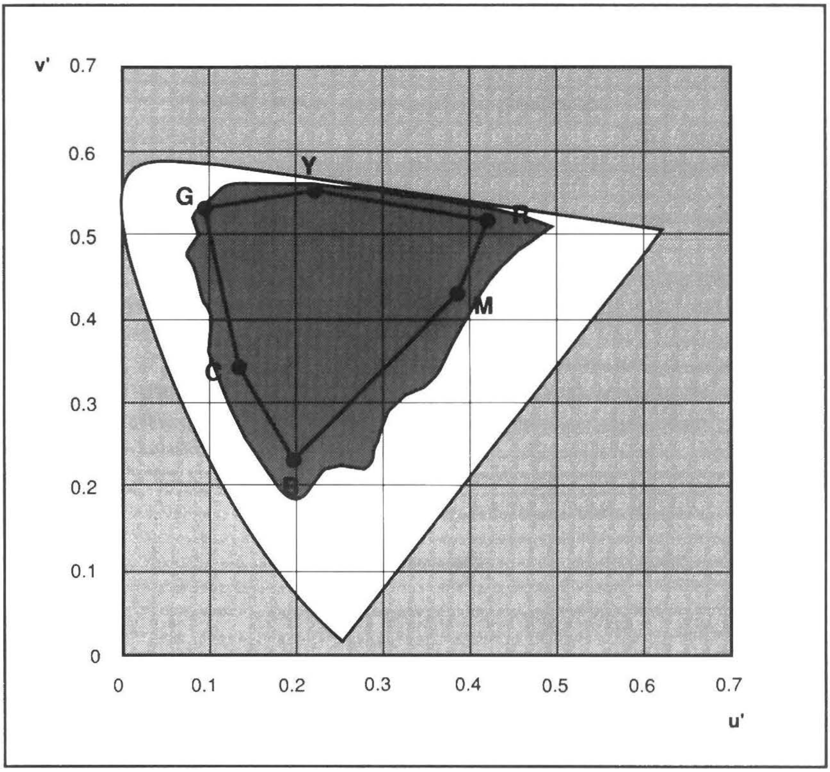

Fig. 3 Color gamut in multicolor printing (ISO 2846) and color gamut of the really existing surface colors (values for C/2°)