Chromaticity gamut enhancement by heptatone multi-color printing

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Abstract.

The present paper studies the chromaticity gamut of multi-color printing processes. Heptatone (7-color) printing – the most promising variant of multi-color printing – offers a significantly larger gamut than a conventional CMYK printing process, approaching CRT and film gamuts. The behavior of the process in the device-independent CIE-XYZ and CIE-L*u*v* colorimetric spaces is explored using the compound Neugebauer model developped for this purpose. A simple and straightforward Moiré-free separation process is proposed. The strong point of the proposed separation process is the fact that only 3 different screen layers are needed for *any* odd number of basic colors including black.

1. Introduction

In today's printing industry, the 4-color CMYK (Cyan-Magenta-Yellow-blacK) printing process is the state-of-the art technology. Numerous problems related to color separation, printing device calibration, gray balance and color fidelity of the CMYK printing process have been studied since its invention by Alexander Murray in 1934 ([HUN87], [WYS82], [YUL67], [MOL88]).

Although it proves satisfactory in a majority of cases, this printing process presents an important drawback: its chromaticity gamut is restricted when compared with the gamuts of CRT displays or real dyes. Some saturated colors such as orange, certain reds, violet, purple, blue and certain greens cannot be obtained by conventional CMYK printing.

We propose to extend the printing process by introducing additional basic colors. This contribution modelizes the extension of the CMYK process to 5-color, 7-color and 9-color printing processes. The Heptatone (7-color) process has an excellent chromaticity gamut and is considered as the optimal tradeoff between printing quality and cost.

The modelization of the color behavior of the CMYK printing process is presented in section 3. The modelization tool – the Neugebauer equation – is extended, in section 4, to the multi-color printing process. The results obtained by such a modelization are discussed in section 5. Finally, a scheme for a multi-color separation process is proposed in section 6.

In our study of multi-color printing process gamuts, we used the high-quality Pantone-compatible inks produced by the Swiss company SICPA and printed them on coated paper. Colorimetric measurements were carried out using the Gretag SPM100 photospectrometer.

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For CRT display gamut measurements, we used the Barco calibrated color display, adjusted for an optimal color balance. The measurements were carried out using the Minolta CA-100 CRT Color Analyzer.

2. CMYK printing gamut compared with film and CRT display gamuts

The color gamut of a specific device or process is usually examined in the CIE-XYZ, CIE-L*a*b* or CIE-L*u*v* color spaces [FOL90]. The CIE-XYZ (tri-stimulus) space is an objective device-independent space related to the human visual system by a choice of three basic color-matching functions [WYS82]. Any color visible by the human eye can be represented as a point in the CIE-XYZ color space. A linear transformation relates the CIE-XYZ space to the RGB space of an additive device like a CRT display.

The CIE-XYZ color space is useful for calculation, while the perceptually uniform CIE-L*a*b* or CIE-L*u*v* color spaces are better for qualitative interpretations. A non-linear transformation relates the CIE-XYZ space to the CIE-L*a*b* and the CIE-L*u*v* spaces [WYS82]. Both the CIE-L*a*b* and the CIE-L*u*v* spaces are equally representative of the human perceptual process.

Figure 1 represents a gamut of the CMYK printing process in the CIE-XYZ color space compared with a typical CRT display gamut. The external boundaries of both of these gamuts are influenced by various factors. In the case of a printing process, the major factors are the quality of the inks and of the paper. In the case of a CRT, the quality of phosphors, as well as brightness and color balance will considerably affect the available gamut. As mentioned in [HUN87, p. 139], the color gamut of films is quite close to the gamut of CRTs. The results of a comparison between a printing gamut and a CRT display gamut are the same as those found when comparing printing and films gamuts.

Figure 2 illustrates the comparison of a CMYK printing gamut and a CRT display gamut, in the CIE-L*u*v* color space. The top view (Figure 2a) shows the maximal chromaticity gamut, while the side Blue-Yellow (Figure 2b), Cyan-Red (Figure 2c) and Green-Magenta (Figure 2d) views give a better idea of the Luminance-Chroma repartition in the L*u*v* solid.

A comparison of the CMYK printing gamut with a typical CRT display gamut emphasizes the fact that the latter is significantly larger than the former, both in respect to the maximal chromaticity gamut as well as in respect to its volumic extension in the L*u*v* solid. The difference is especially important in the blue/violet/purple region, and in the turquoise/green/yellow-green region. The orange/red region of the CMYK printing gamut is also underrepresented.

The above-mentioned fact is well known by professionals: well-saturated oranges, purples, blues or greens cannot be obtained using a conventional CMYK printing process. When consulting the Pantone Process Color Imaging Guide [PAN80], it becomes obvious that a conventional CMYK printing process cannot reproduce solid Pantone colors (real dyes) faithfully.

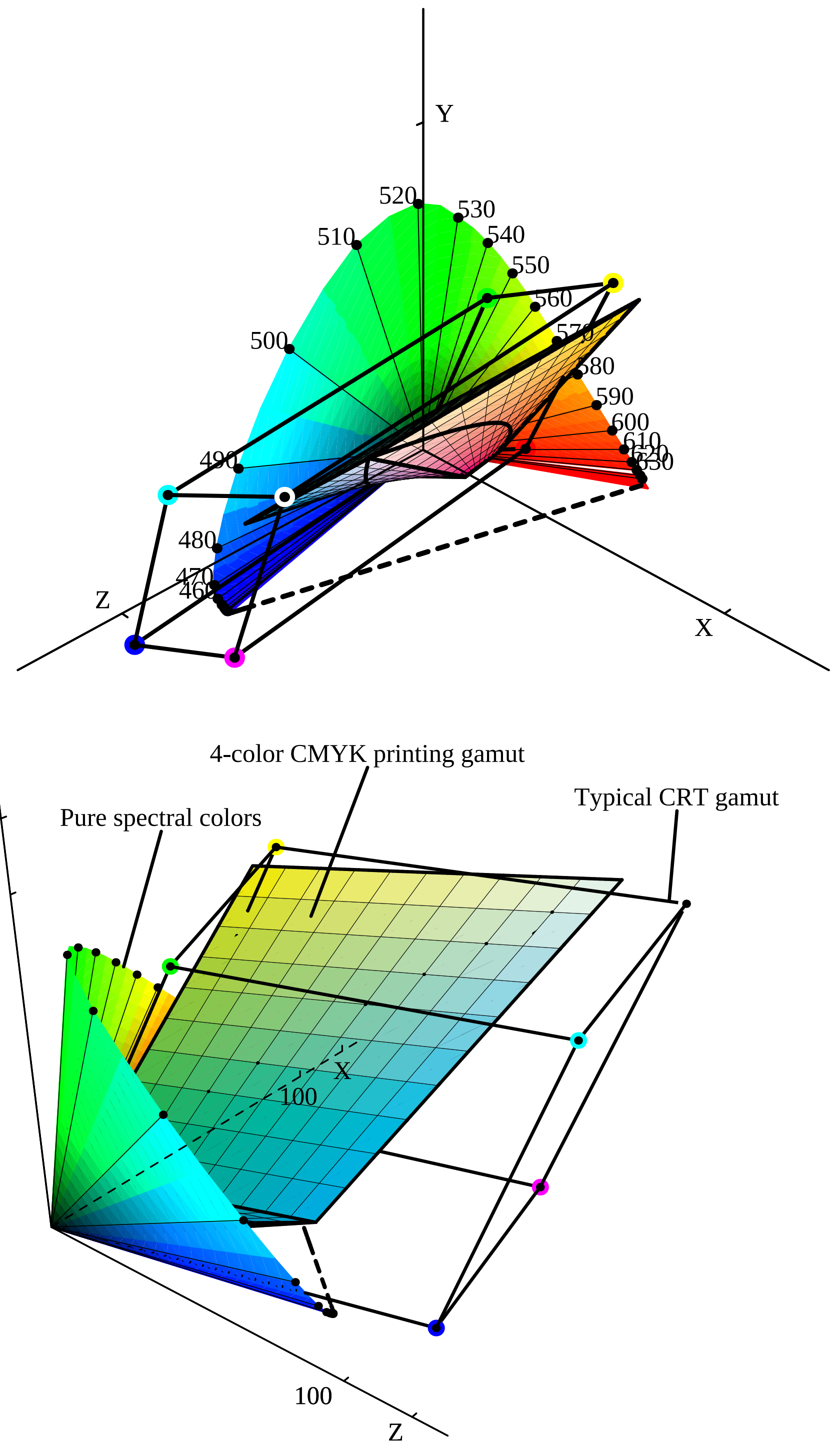


Figure 1. The CMYK printing gamut compared with a typical CRT gamut, in the CIE-XYZ space. The surface of pure spectral colors is limited by the $X + Y + Z = 100$ plane.

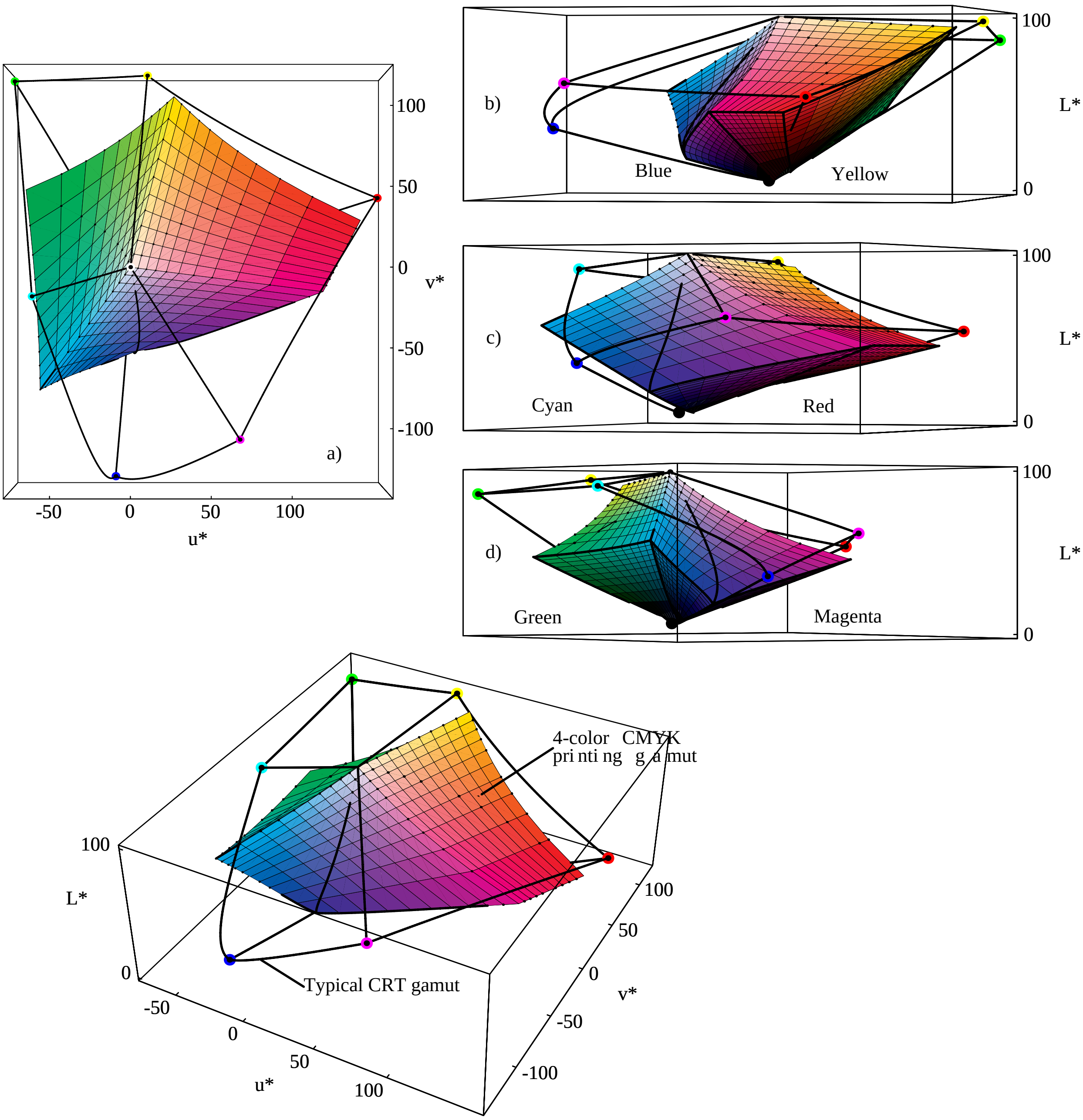


Figure 2. Different views of a typical CRT and the CMYK printing gamuts in the CIE-L*u*v* space.

To conclude, in order to approach the gamut of real dyes or the CRT display gamut, a multi-color process should expand the gamut in three critical directions: blue/violet/purple, turquoise/green/yellow-green and orange/red.

Küppers [KUP85] proposed to solve this problem by introducing additional colors (red, blue, green) to the CMYK printing process. However, his analysis only included the colors which can be produced by linear additive combinations of the basic opaque colors. The separation method he proposed was not adequate for offset printing.

3. Modelizing the color behavior of the CMYK printing process

In 1937, Neugebauer proposed a method of producing colorimetrically accurate reproductions using three basic colors: cyan, magenta and yellow [NEU37]. Neugebauer's work was based on Demichel's equations [RHO89]. According to Demichel-Neugebauer's model, a 3-color halftone process can be considered as an additive system with known colorimetric characteristics of 8 primaries: *white, cyan, magenta, yellow, red* (yellow+magenta), *green* (yellow+cyan), *blue* (cyan+magenta) and *black* (cyan+magenta+yellow). Both Demichel and Neugebauer considered screens oriented at $0° - 30° - 60°$ (conventional photographical screening).

In the case of a statistically uniform distribution of colored dots, using the conventional photographical screening, the areas covered by eight primaries can be expressed by the Demichel equations:

$$
\begin{array}{ll}
\text{White} & (1-c)(1-m)(1-y) = f_w \\
\text{Cyan} & c(1-m)(1-y) = f_c \\
\text{Magenta} & (1-c)m(1-y) = f_m \\
\text{Yellow} & (1-c)(1-m)y = f_y \\
\text{Red} & (1-c)my = f_r \\
\text{Green} & c(1-m)y = f_g \\
\text{Blue} & cm(1-y) = f_b \\
\text{Black} & cmy = f_k
\end{array} \qquad (1)
$$

where c, m, y are the areas respectively covered by basic colors *cyan, magenta* and *yellow,.*

If all tri-stimulus $XYZ_w, XYZ_c, XYZ_m, XYZ_y, XYZ_r, XYZ_g, XYZ_b, XYZ_k$ values of a given process are known, the colorimetric value of the resulting color can be calculated using the Neugebauer equation:

$$\overrightarrow{XYZ} = f_w\overrightarrow{XYZ_w} + f_c\overrightarrow{XYZ_c} + f_m\overrightarrow{XYZ_m} + f_y\overrightarrow{XYZ_y} + f_r\overrightarrow{XYZ_r} + f_g\overrightarrow{XYZ_g} + f_b\overrightarrow{XYZ_b} + f_k\overrightarrow{XYZ_k} \qquad (2)$$

Obviously, this equation can be inverted: one can find the values of c, m, y required to obtain a desired XYZ color.

This idea, however neat and clear it may appear, suffers from several drawbacks. In order to obtain the desired accuracy, numerous and complicated corrections are needed. At different times, Yule and Clapper [CLA55], Pobboravski [POB66] and Iwao [IWA73] tried to improve the accuracy of the Neugebauer model. In spite of the complexity of the correction terms, the final result was never absolutely satisfactory. This is the main reason why the Neugebauer equation is not used in today's real-world equipment (i.e. scanners, separation process). The only attempt to build a scanner based on the Neugebauer equation was the Hardy and Wurzburg scanner designed in the early fifties [HUN87].

On the other hand, the ability of the Neugebauer equation to predict the chromaticity of prints was extensively used to modelize printing processes. Kanamori and Kotera [KAN89] modelized the color behavior of a hardcopy process with minimum, mean and maximum dot overlay. Spooner [SPO89] simulated a hypothetical preprocess system using the Neugebauer equation.

4. Compound Neugebauer model

As described in section 2, additional colors have to be introduced in order to expand the gamut of a printing process. So as to facilitate the analysis of the color behavior of a multi-color process, the entire XYZ color space is subdivided into several volumic partitions. This section defines the compound Neugebauer model, a generalized version of the Neugebauer model which was described in the previous section. The compound Neugebauer model is applied to a set of volumic partitions and predicts, within a given partition, the colorimetric behavior as a function of the XYZ values of three basic colors which determine the partition.

Let us start illustrating this compound Neugebauer model by examining the simplest case i.e. printing with two basic colors, C_1 and C_2.

Let a_1 and a_2 be the areas covered by basic colors C_1 and C_2. The printing area will be subdivided into 4 zones or 4 primaries (see Figure 3): $W(white)$, C_1, C_2 and C_{12}. Their areas can be calculated:

$$\begin{array}{ll} \text{primary color } W: & (1-a_1)(1-a_2) = f_w \\ \text{primary color } C_1: & a_1(1-a_2) = f_1 \\ \text{primary color } C_2: & (1-a_1)a_2 = f_2 \\ \text{primary color } C_{12}: & a_1 a_2 = f_{12} \end{array} \tag{3}$$

The colorimetric XYZ value of the resulting color can be calculated when values XYZ_w, XYZ_1, XYZ_2 and XYZ_{12} of the primary W, C_1, C_2 and C_{12} colors are known:

$$\overrightarrow{XYZ} = f_w\overrightarrow{XYZ_w} + f_1\overrightarrow{XYZ_1} + f_2\overrightarrow{XYZ_2} + f_{12}\overrightarrow{XYZ_{12}} \tag{4}$$

When a_1 and a_2 range between 0 and 1, the resulting color locus lies on a curved $WC_1C_{12}C_2$ surface (see Figure 4). In the special case of opaque inks, C_{12} is identical to the last-printed ink (C_1 or C_2).

In the proximity of white W, the fourth term $f_{12}\overrightarrow{XYZ_{12}}$ of the equation (4) is negligeably small since, according to (3), $f_{12} = a_1 a_2$. Consequently, in this zone the curved $WC_1C_{12}C_2$ surface is nearly flat, and the resulting color is a linear combination of the $\overrightarrow{WC_1}$ and $\overrightarrow{WC_2}$ vectors weighted by their surface coverage coefficients. In the zone where the $a_1 a_2$ term becomes dominant, i.e. around of C_{12}, surface $WC_1C_{12}C_2$ is curved.

Similarly, in a 3-color printing process (Figure 5), the resulting tri-stimulus XYZ value can be calculated using the compound Neugebauer equation:

$$\overrightarrow{XYZ} = f_w\overrightarrow{XYZ_w} + f_1\overrightarrow{XYZ_1} + f_2\overrightarrow{XYZ_2} + f_3\overrightarrow{XYZ_3} + f_{12}\overrightarrow{XYZ_{12}} + f_{23}\overrightarrow{XYZ_{23}} + f_{31}\overrightarrow{XYZ_{31}} + f_{123}\overrightarrow{XYZ_{123}} \qquad (5)$$

where XYZ_i and XYZ_{ij} are the tri-stimulus values of the corresponding primary colors; the values of f_w, f_i, f_{ij} and f_{123} are calculated based on a_1, a_2 and a_3 surface coverages of the basic colors C_1, C_2 and C_3, as in the case of the Neugebauer equation (1):

primary color W:	$(1-a_1)(1-a_2)(1-a_3) = f_w$	(6)
primary color C_1:	$a_1(1-a_2)(1-a_3) = f_1$	
primary color C_2:	$(1-a_1)a_2(1-a_3) = f_2$	
primary color C_3:	$(1-a_1)(1-a_2)a_3 = f_3$	
primary color C_{12}:	$(1-a_1)a_2a_3 = f_{12}$	
primary color C_{23}:	$a_1(1-a_2)a_3 = f_{23}$	
primary color C_{13}:	$a_1a_2(1-a_3) = f_{13}$	
primary color C_{123}:	$a_1a_2a_3 = f_{123}$	

Unlike in the case of the Neugebauer equation, we don't make any assumption about the inks: any ink with known XYZ_i colorimetric values can be used.

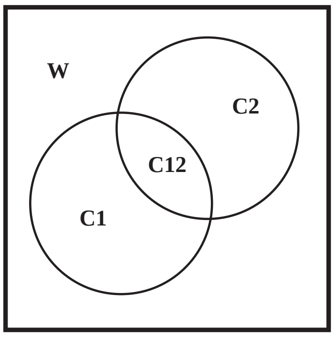


Figure 3. Schematic distribution of 4 primary colors W (white), C_1, C_2 and C_{12}, in the case of 2-color (duotone) printing.

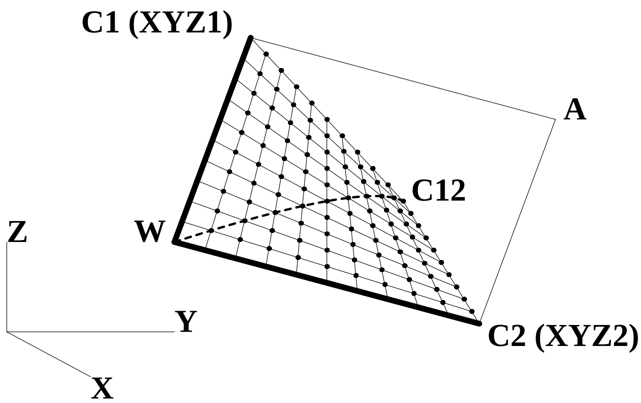


Figure 4. The 2-color (duotone) printing gamut, in the CIE-XYZ space.

When a_1, a_2 and a_3 range between 0 and 1, the resulting XYZ color locus is the volume delimited by surfaces $WC_1C_{12}C_2$, $WC_1C_{13}C_3$, $WC_2C_{23}C_3$, $C_1C_{12}C_{123}C_{13}$, $C_2C_{12}C_{123}C_{23}$ and $C_3C_{13}C_{123}C_{23}$ (see Figure 6a).

As in the case of a 2-color printing process, these surfaces are nearly flat in the proximity of white point W and become curved when the cross-color terms in the equation (5) become dominant.

In the case where C_3 is Black (see Figure 6b), it is generally assumed that $C_3 = C_{13} = C_{23} = C_{123} = K$. The resulting color locus in the CIE-XYZ space is a volume V delimited by four WC_1K, WC_2K, $C_1C_{12}K$, $C_2C_{12}K$ triangles and one curved $WC_1C_{12}C_2$ surface. For any combination of the $\{a_1, a_2, a_k\}$ surface coverages of the basic C_1, C_2, $C_3 = K$ colors, a point XYZ can be calculated according to equations (3,4), and, inversely, for any point inside the volume V, a $\{a_1, a_2, a_k\}$ combination of surface coverages of C_1, C_2 and K basic colors can be found.

Now, if we put together, side by side, three such volumes whose C_1 and C_2 are Cyan and Magenta, Magenta and Yellow, Yellow and Cyan respectively, we get the complete CMYK gamut in the XYZ space. The resulting process corresponds to the normal CMYK separation with maximal GCR (Gray-Component Replacement). Any color within such a CMYK gamut is obtained by combining only 2 colors with black.

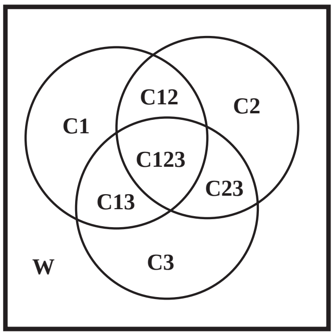
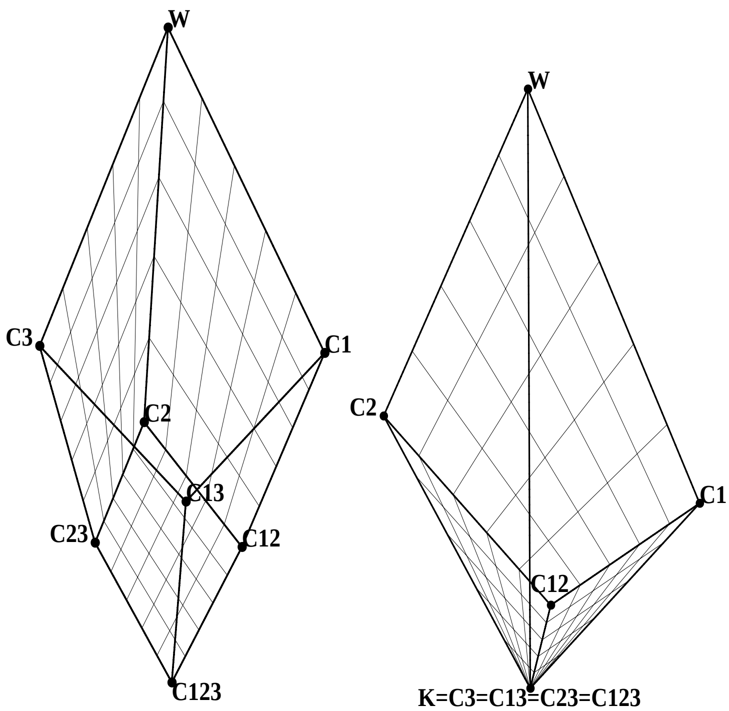


Figure 5. Schematic distribution of 8 primary colors in the case of 3-color printing.



a) b)

Figure 6. 3-color printing gamuts in the CIE-XYZ space.

5. Multi-color printing principles

Let us now increase the number of basic colors up to (2n+1), where n=2,3,... The entire printable gamut is subdivided into 2n partitions instead of 3 partitions in the case of a CMYK printing process (see Figure 7). For each point within a given $C_iC_{i+1}K$ partition, a combination of $\{a_i, a_{i+1}, a_k\}$ surface coverage coefficients can be found after the compound Neugebauer equations (5,6) have been applied to the basic C_i, C_{i+1} and K colors. Since the sum of $2n$ partitions makes up the whole printable gamut, there exists a one-to-one mapping between the colorimetric XYZ values of any printable color and the $\{a_1, a_2, ..., a_{2n}, a_k\}$ set.

Correct gray balance is ensured automatically and no discontinuity in $\{a_1, a_2, ..., a_{2n}\}$ occurs on the boundaries between the partitions.

In *offset printing*, the color image is produced by successively transferring basic colors from screened negative plates to the paper. Each separate color plane is obtained using the conventional *halftone screening* method and is identified by a screen angle/frequency pair. In order to determine the number of different screen angle/frequency pairs needed for multi-color printing, let us consider the Black-White axis projection of the partitioned XYZ gamut, as shown in Figure 7. The problem is reduced to a typical graph coloring problem: how many different labels are needed to label all vertices of a graph composed by all exterior vertices connected to the central point, knowing that two labels belonging to the same edge should be different. For an even number of exterior vertices, only three labels are needed (cases 7b and 7c).

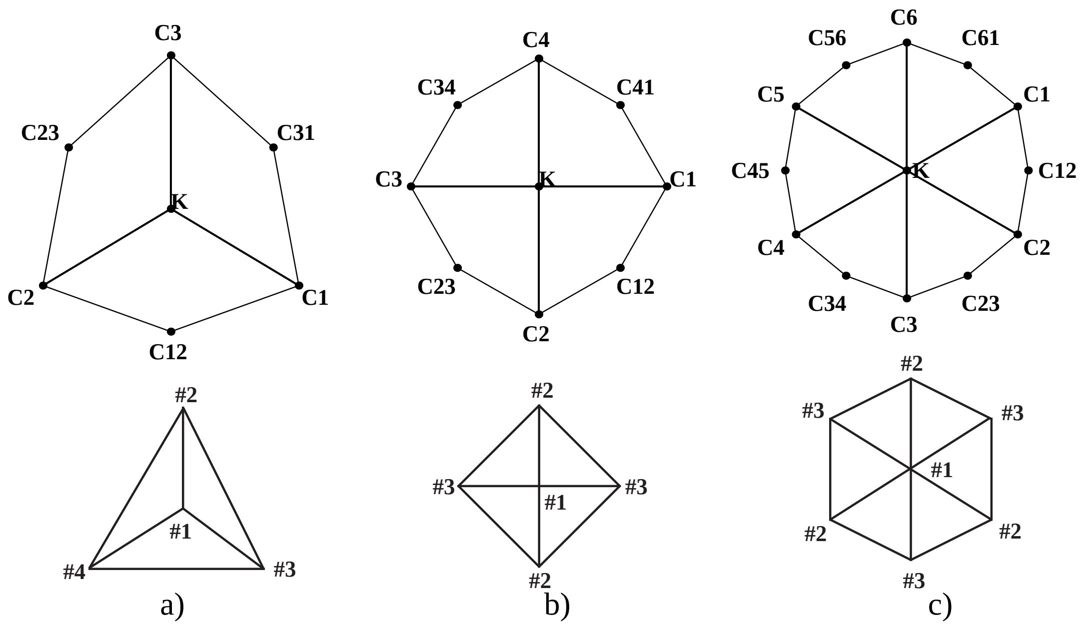


Figure 7. Black-White axis projection of 4-color (a), 5-color (b) and 7-color (c) separation schematic gamuts. The #i label indicates the order number of the screen angle/frequency pair.

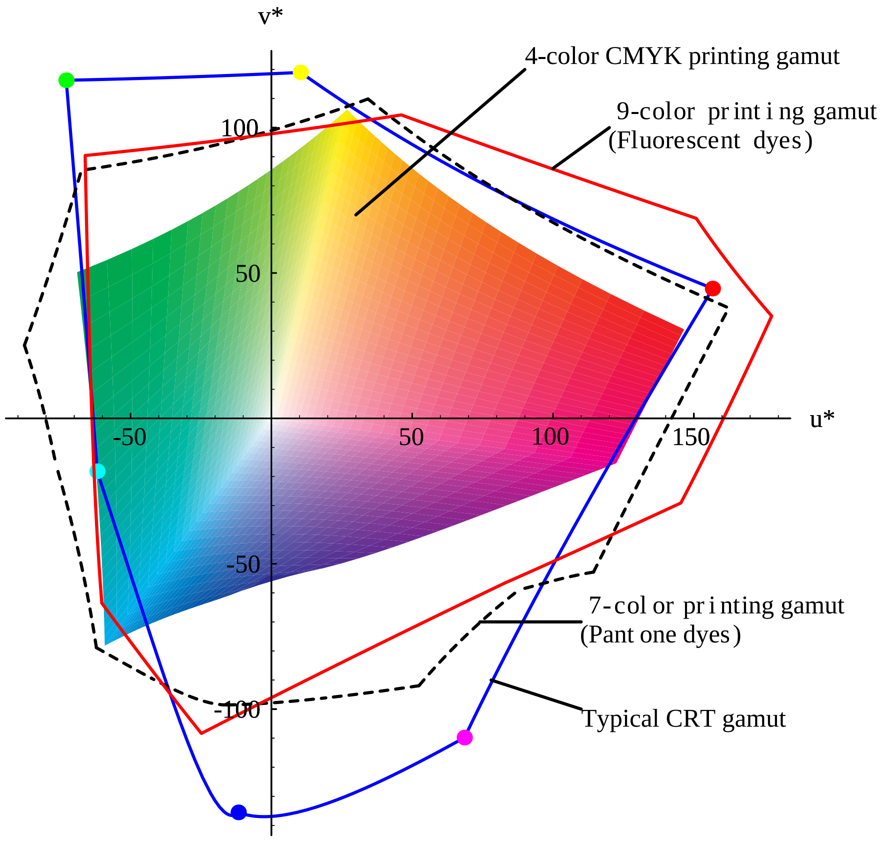


Figure 8. Heptatone (7-color) printing and 9-color printing gamuts compared with the CMYK printing gamut.

9-color printing basic colors:	**Heptatone** printing basic colors:	**CMYK** printing basic colors:
PANTONE 801C	SICPA Process Yellow	SICPA Process Yellow
PANTONE 802C	SICPA Rhodamine Red	SICPA Process Magenta
PANTONE 803C	SICPA Purple	SICPA Process Cyan
PANTONE 804C	SICPA Blue	SICPA Process Black
PANTONE 805C	SICPA Process Cyan	
PANTONE 806C	SICPA Green	
PANTONE 807C	SICPA Process Black	
PANTONE Blue072		
PANTONE Process Black		

Consequently, the total number of different screen layers (angle/frequency pairs) is always *three* in the case of (2n+1)-color printing, while it is *four* in CMYK printing. This fact is crucial for the feasibility of a multi-color separation process. It is already difficult to superimpose 3 screen layers without producing apparent Moiré fringes [AMI91]. Generating more than 3 or 4 Moiré-free screen layers becomes an almost impossible task. Surprisingly, as regards minimizing the Moiré phenomenon, the 5-color and 7-color printing is simpler than conventional 4-color printing.

In order to establish the extended gamut, we measured, for each $C_iC_{i+1}K$ partition, the XYZ_w, XYZ_i, XYZ_{i+1}, $XYZ_{i,i+1}$ and XYZ_k colorimetric values of all W, C_i, C_{i+1}, $C_{i,i+1}$ and K primary colors; the remaining parts of the gamut were computed according to the compound Neugebauer equations (5,6). The gamut obtained with multi-color printing is presented in Figure 8.

The 7-color printing gamut is significantly larger than the CMYK gamut, especially in the blue/violet/purple and turquoise/green/yellow-green zone. In the orange/red region, the increase is also signifacant.

This research was limited to commercially available inks with known characteristics. One could enlarge the printing gamut considerably by using other inks with improved pure and cross-mixture spectra. Fluorescent dyes require the application of an opaque model (see section 4).

6. Separation process for multi-color printing

The previous section describes multi-color separation principles. The entire separation process is schematically presented in Figure 9.

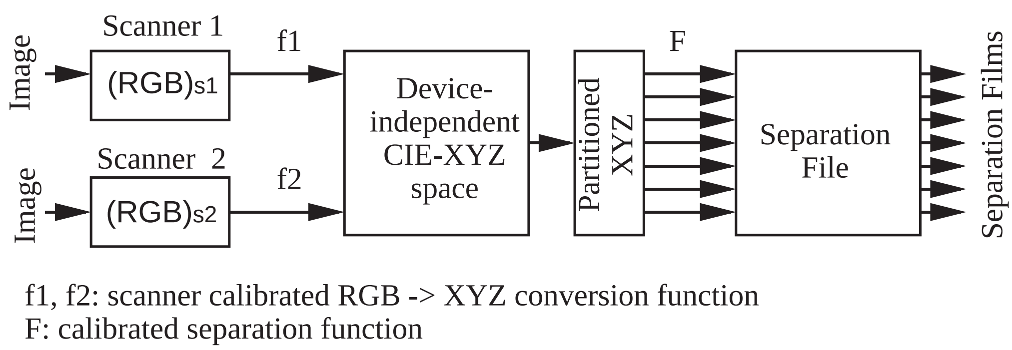


Figure 9. The Heptatone separation process.

Problems of input and output device calibration have been discussed extensively in literature (see [STO88], [LIN89]). We suppose that the simplest way to calibrate both the scanner RGB–>XYZ conversion function f and the output separation function F is the method proposed in [STO88]. A 3-dimensional relationship between the device space and the CIE-XYZ space is established and calibration is achieved using look-up tables and tri-linear interpolation between tabulated values.

Since the Heptatone gamut approaches the film and CRT gamuts, the problem of mapping unprintable colors onto printable colors (*gamut mapping)* is reduced.

7. Conclusions

The proposed modified compound Neugebauer equation can be used successfully for multi-color printing chromatic behavior modelization. For 5-, 7- and any (2n+1)-color printing, the number of different angle/frequency paires required is always 3. This fact makes the Moiré-free multi-color separation process feasible. The separation process for multi-color printing is simple and straightforward.

The Heptatone (7-color) printing process offers a significantly larger gamut than the conventional CMYK printing process, especially in three critical directions (blue/violet/purple, turquoise/green/yellow-green and orange/red), thus approaching the typical CRT display chromaticity gamut. 5-color printing gives a significant gamut enhancement in one direction (i.e. blue/violet/purple).

The Heptatone technology is suitable for high-quality offset printing, as well as for low-resolution color printing devices such as ink-jet or thermal transfer printers.

8. Acknowledgements

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