Visualization of Expanded Printing Gamuts Using 3-Dimensional Convex Hulls

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Abstract: A 3-D convex hull program, Qhull, was applied to data sets consisting of the Neugebauer primaries and selected multicolor traps of 4-, 5- and 6-color printing systems. Program output was plotted as polytopes, curved surface solids or wireframes in CIE Lab space in full color. These produced a 3-D representation of a lithographic printing gamut. Superposition of two or more gamuts affords users full color visual feedback of where, what color and how much color enhancement was brought about by changes of inks or stocks. These techniques provide far more detail than traditional 2-D gamut plots. Quantitative estimates of gamut volumes compared the color reproduction potential of several sets of fluorescent process printing inks. The input of many hundreds of halftone data points from IT8 charts were processed with the same ease as a sparse set of Neugebauer primaries. This produced a more accurate gamut on convex surfaces and some improvement in the accuracy in volumes.

Background

Hallmark Cards has a long history of process printing with 6-color, wide gamut, ink systems. Research into the use of fluorescent colors in Hallmark's 6-color ink systems began in 1960 with imported fluorescent pigments from Germany. Formulation work was done in cooperation with Acme Inks, now INX International, in Chicago. By 1962 Hallmark was commercially printing greeting cards with six process inks, three of which included fluorescent colorants, a fluorescent pink, a fluorescent yellow and a fluorescent magenta. A non-fluorescent light cyan was also used. The blue-shade, process pink aided in printing delicate pastel highlights and pale skin tones. At the midtones a fluorescent magenta was brought into the separation until a full solid of magenta and pink ended the scale. Combining the pink-magenta solid with yellow

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produced brilliant Christmas and Valentine reds. Similarly a pigmented light cyan afforded clean lavenders and light blue tones. Like pink, light cyan gave an extended highlight scale with added tonal gradation. Later a cleaner light cyan was formulated from a dye using chemical processes similar to that used for fluorescent colorants. Fluorescent manufacturers in the United States made major advances in the mid-1960s by encapsulating fluorescent dyes in submicron, organic matrices. Ward (1972) gives a detailed account of the dye chemistry and processing steps in the manufacture of fluorescent colorants for lithography. Microencapsulation produced stronger, more lightfast colorants. These improvements were quickly incorporated into Hallmark's process inks. Later, to improve lightfastness further, non-fluorescent lightfast pigments were combined with magenta and yellow fluorescent colorants. This technique of producing hybrid inks was well documented in the literature of the time (Apps, 1964). After many years of constant refinement, Hallmark Cards in 1999 introduced a new set of 6-color inks in its Warm Wishes line of greeting cards. Known as BigBox Color™, this system contains three fluorescent colors that have greatly expanded our color reproduction capabilities.

To visualize and quantify the improvements of this new colorant system we first employed the commercial software Color3D. With this software printer gamuts can be viewed in 3-D as true color interpolated solid surfaces or as wireframes. In this way two or more gamuts can be viewed simultaneously. In addition to single points, clusters of color points can be projected onto the gamuts to check for their in- and out-of-gamut status. The gamut surfaces are shown in CIE Lab space as curved surface solids. The input data for printer gamuts are entered as the xyY coordinates of the Neugebauer solid primaries for a 4-color printing system – cyan, magenta, yellow, black, red (YM), green (YC), blue (CM), the 3-color black (CMY), and white, the stock. Full appreciation of the 3-D nature of color space is brought about by putting the figures in motion around the L* axis. There are two other axes of motion to set starting points. Thus the gamut can be fully viewed from every angle. One element missing from Color3D is a gamut volume metric.

The basic assumption of the program is that in tristimulus space, CIE XYZ, or in chromaticity space, xyY, these primaries can be connected with straight lines to form a cube-like object. A halftone printing scale of one of the chromatic primary colorants, such as cyan, is depicted as an edge of this object. That edge connects cyan to the white stock point. The locus along this edge is formed by adding the tristimulus light of the paper to the tristimulus light of a solid cyan patch in varying proportions alone the edge. Similarly the line connecting cyan to red is the locus of printing a halftone of magenta over solid cyan. Viewed from the top this produces a hexagonal schematic as seen in Figure 1. When viewed from the bottom the red, green and blue are connected to black by straight lines that represent a halftone of the opponent color over the 2-color trap of a solid pair. The gamut objects in Lab space have curved surfaces because of the non-linear transform from XYZ to Lab.

Another way to state the basic assumption in the model is that the halftones are hard dots. That is, the microdensity of each dot, regardless of its size, is the same and is uniform across its diameter. Rosenberg (1999) has found an exception to our model with stochastic screening. As stochastic dots get smaller they can show higher lightness than larger dots at the same chroma. This produces gamut enhancement. This was traced to non-uniformity of colorant within the single dots. These effects are not taken into account by our model.

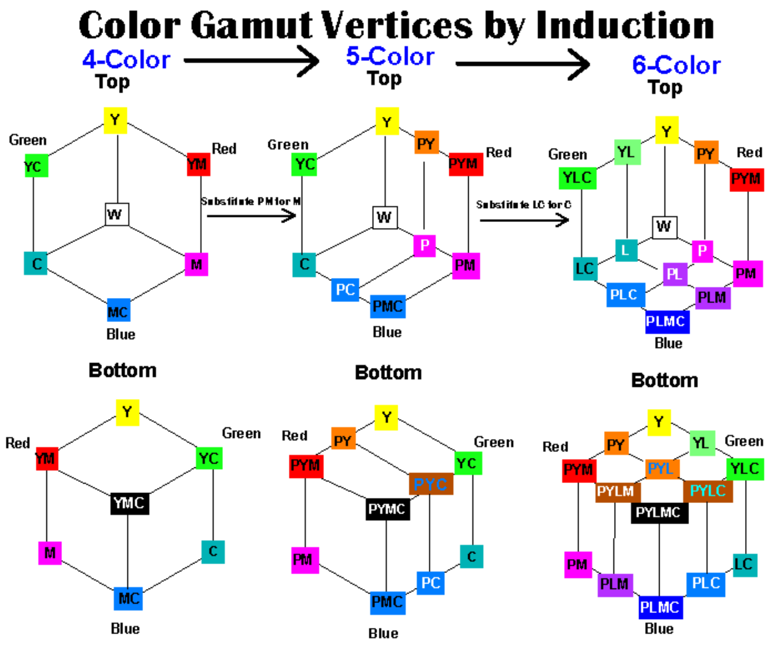


Figure 1 Selection of Vertices for Convex Hull Computations

Mapping a 6-color ink system to the Color3D color cube presented some difficulties. The Hallmark process inks consist of black, cyan, magenta, light cyan, yellow and pink. Hereafter these will be referred to as K, C, M, L, Y and P, respectively, in figures and diagrams. As we add an additional ink, pink, in going to a 5-color system, our magenta chromatic primary becomes PM, the highest chroma magenta printer. By induction everywhere magenta appears in the 4-color schematic, PM appears in the 5-color system. Pink now appears midway between PM and stock. Adding a sixth color, light cyan, produces LC as the highest chromatic cyan. The intermediate traps of our diagram could be ignored if pink lay along the line connecting PM to white paper in XYZ space and light cyan lay on the line connecting LC to white. Unfortunately, this is not the case, complicating matters for a 4-color visualization program like Color3D.

A better means was needed, so a set of gamut visualization and volume metric tools was developed by coupling a 3-D convex hull algorithm from computation geometry with the data visualization tools of MATLAB. A convex hull in 3-D is a mathematical operation similar to shrink wrapping a film around a set of points suspended in space. It produces flat planes as faces. In our study these faces contain or circumscribe all the possible colors that can be produced by an output device, the gamut volume.

Experimental

Printed samples of inks and stock were measured using an X-Rite 938 spectrodensitometer with 0/45 viewing geometry. White stock was used as backing. Measurements were taken in CIE Lab* units using D5000 illuminant and the 1931 observer. The Neugebauer targets for 4-, 5-, and 6-color printing were chosen from the process primaries, the stock (W), and the 2-, 3-, and 4-color traps shown in Figure 1. In all cases the opponent black was forced to be the 4-color trap of CMYK. A total of 26 target patches are needed - 8 for 4-color, 12 for 5-color and 18 for 6-color. Several patches proved to be interior points in the final convex hull solutions. Eight Hallmark lithographic ink systems were characterized as 4-, 5- and 6-color printers by the convex hull method. One 6-color ink system, referred to as Colormaster, contains just one fluorescent colorant, pink. The other system, referred to as BigBox, has three fluorescent inks - pink, magenta and yellow. These two colorant systems are available in ultraviolet and conventionally cured vehicles for coated and uncoated stock.

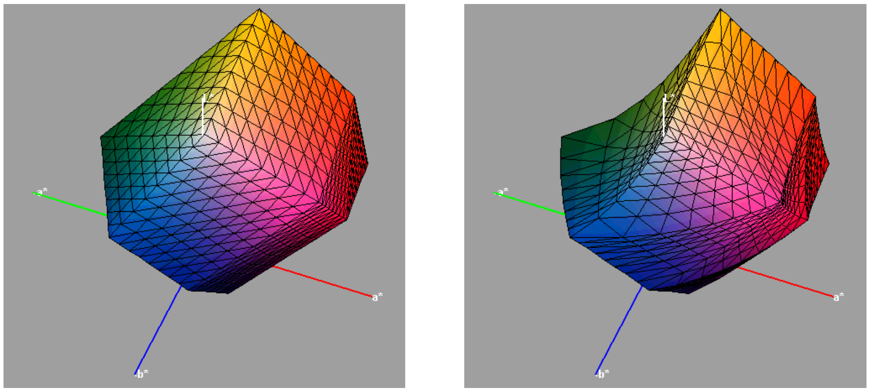
A modified IT8 crosschart was also used as a target. This contained 768 solid and halftone screened patches. These targets were read on a Gretag Spectrolino equipped with a SpectroScan x-y table using the D5000 and the 1931 observer.

For comparison, two samples of Hexachrome® inks were characterized in this study. Pantone's Hexachrome® ink set consists of black, cyan, green, fluorescent magenta, fluorescent yellow and fluorescent orange, K, C, G, M, Y and O respectively. One set of measurements was taken from coated stock crosscharts (a Pantone Hexachrome® Specifier from SNP Cambec in Australia). Seventeen patches were used as input. Besides the primary colors and stock, ten solid traps were measured spectroscopically. These included CM, CG, MO, OY, GY, MY, CY, MOY, CGY, and CMY. The second Pantone sample consisted of thirteen patches that included CM, CY, GY, YM, OM and OY in addition to the primaries and stock. Entitled "Test form for Pantone Hexachrome®", it was printed on 80-pound text Centura Gloss stock and was part of Pantone's product literature.

Treatment of Data

The CIE Lab coordinates of the test charts were imported as text files into MATLAB where a 3-D convex hull was computed and displayed in full color. MATLAB is a matrix-based programming environment with color graphics capabilities. At the heart of its data display resources is its patch command which paints a polygon in 3-D space with color interpolated faces and/or edges in RGB color. With the aid of an Lab to RGB transform, data was rendered in as true a color as possible within the constraints of the computer's CRT gamut. The convex hull in 3-D was found using Qhull, shareware available from the Geometry Center at the University of Minnesota. This program uses the quickhull algorithm to return the triangular faces of the bounded polytope of the problem. The connectivity of vertices is determined fully by Qhull, and it does not necessarily follow the inductive logic used to construct Figure 1. Used in another mode Qhull can return the volume of the geometric solid and the area of its faces. The solid volume can be used as a measure of gamut volume (color reproduction capacity) and carries more information than the traditional 2-D projection of color data onto the CIELAB a*-b* plane. The latter approach, which uses a 2-D convex hull, has been used numerous times in evaluating proofers and ink systems (Shyu, 1999), (Viggiano, 1998), and (Di Bernardo, 1995).

One criticism of 3-D convex hulls in CIE Lab space (Cholewo, 1999) is that points should not be connected by straight lines. Furthermore, the gamut solid is not a polytope with flat faces, but have both concave, convex and saddle-like



(a) a convex hull (b) correctly rendered gamut

Figure 2 Two Renderings of a 5-Color Lithographic Printing Ink Gamut faces. Volume computation could over or underestimate the true volume depending on the geometry of the faces. To visualize this a CMPYK 5-color printing gamut is shown in Figure 2 as a polytope (a) and as gamut solid with curved surfaces (b). In (a) above, the input data in Lab was transformed to XYZ space. The vertices and face connectivity were determined by Qhull. These results were then plotted, connected and painted in Lab space. Qhull returns only triangular faces, of which some can be coplanar with others. Each of these triangles was then tesselated with 64 smaller triangles similar to the original face. This was done to illustrate surface characteristics. In (b) the same operations occurred, but the tesselation was done in XYZ space *before* transforming back to Lab space. This provides a much more accurate rendering of the curved surfaces.

From this angle it appears that a convex hull might grossly overestimate gamut volume. Yet when you view the black axis from the bottom, much of the compression in the yellows and greens is recovered by the bowing out on the bottom half of the gamut. A movie can be constructed in MATLAB to show this curious slumping effect.

A method was devised to compute more correctly the volume of the curved surface gamut (b) in cubic Lab units. Since the vertices in both (a) and (b) are fixed in space, the volume of the (b) gamut is the (a) volume plus or minus the triangular lens corrections for all faces. If the lens is concave one subtracts, and if it is convex, one adds the volume. An individual lens volume is simply the convex hull in Lab of the of the 64 triangles of each curved facet in (b). To determine sign, the midpoint of the triangular face in XYZ was taken and mapped to Lab. This was compared to the midpoint taken of the flat face in (a). Distances were then determined from these points to the Lab point (50, 0, 0), an interior point that can see all the outer surface. If the (b) triangle's center was closer, the volume was subtracted. The existence of saddle-like lens structures complicates this simple approach. A survey showed that 52% of the gamut faces are saddle-like. The convex hull volume of a twisted face would overestimate the true correction volume. To satisfy all possible cases, the convex hull volumes of the 64 subtriangular prisms of each face were computed and then summed to produce the face volume corrections. Twenty-six gamuts from nine ink systems were analyzed. The (b)-type gamuts had +3.2% greater volume than the flat faced convex hulls. Correction factors ranged from –2.9 to 7.4%. In general, the larger the gamut volume, the larger the correction percentage. The three cases where the flat face convex hull had more volume than the curved hull, came from 4-color printers. The average 4-color correction was 1.7%, for 5-color it was 3.8% and 6-color showed 4.8%.

Results and Discussion

The gamut visualization tools were first used to compare the 4-, 5- and 6-color print systems. Figure 3 shows a BigBox 6-color printer superimposed over the 4-color printing system. Both inks were ultraviolet cured on coated stock.

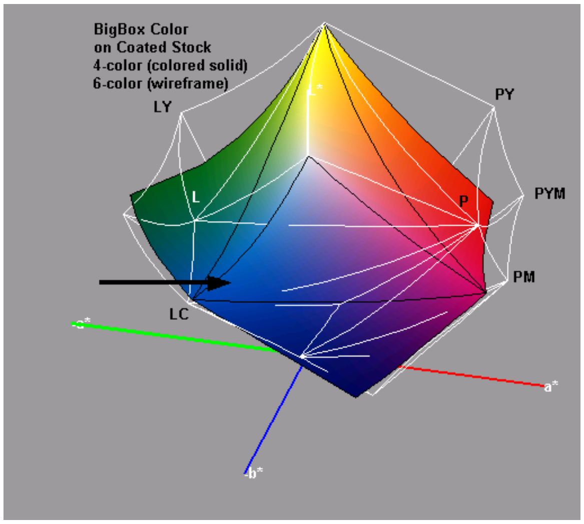


Figure 3 A 50 % Expansion of Gamut by Increasing from 4 to 6 Process Inks

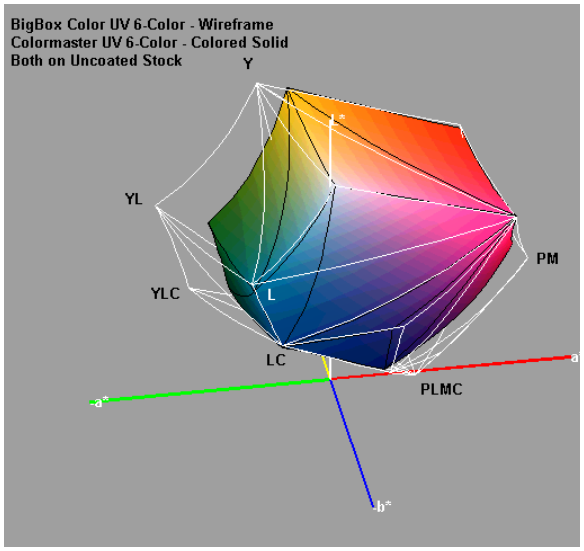


Figure 4 A 25% Expansion of Gamut with Three Versus One Fluorescent Ink

Selected vertices are labeled for clarity. It is clear that the introduction of pink and light cyan adds gamut by elevating the gamut in the L* direction. A 2-D analysis would not pick up this volume because both points, P and L, are interior in a 2-D a*-b* convex hull. The arrow points to an interesting location in color space where the 4-color cyan extends outside the 6-color gamut. This occurs because the 6-color system does not use the cyan ink alone, i.e. without a solid print of light cyan. The 6-color gamut is 50% larger than the 4-color, yet there are a few colors that can be best printed with only four. Gamut volume alone does not tell the full story, and visualization is essential to the analysis.

Figure 4 shows the effects of changing the number of fluorescent printers. Colormaster with one fluorescent pink is compared to BigBox color with three fluorescents. Both printers are 6-color on uncoated stock. The BigBox yellow has a greener hue than that of Colormaster. This greatly enhances reproductions in green areas. The three fluorescents give a 25% larger gamut volume than the standard Colormaster inks in this figure.

Figures 5-7 shows 6-color BigBox conventional cured system superimposed over Pantone's Hexachrome® inks. The samples were printed on different coated

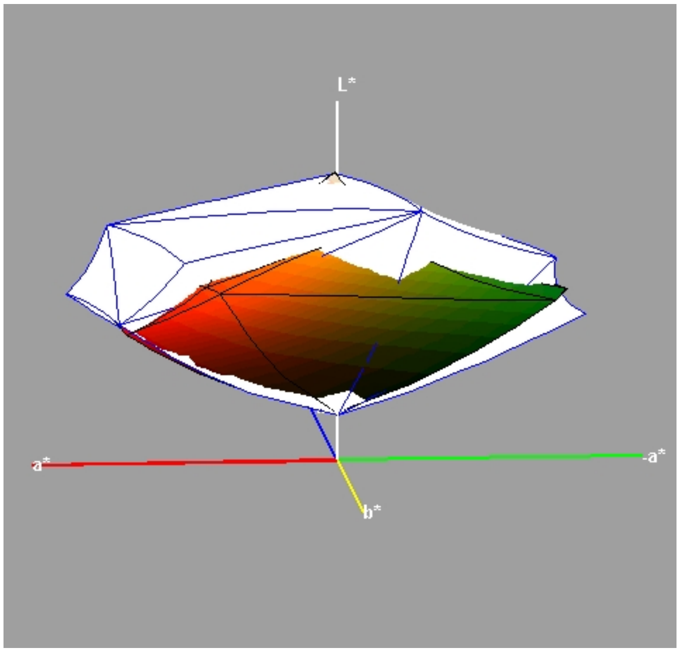


Figure 5 Hexachrome OY and GY Traps
Protruding from the BigBox Gamut (shaded white).

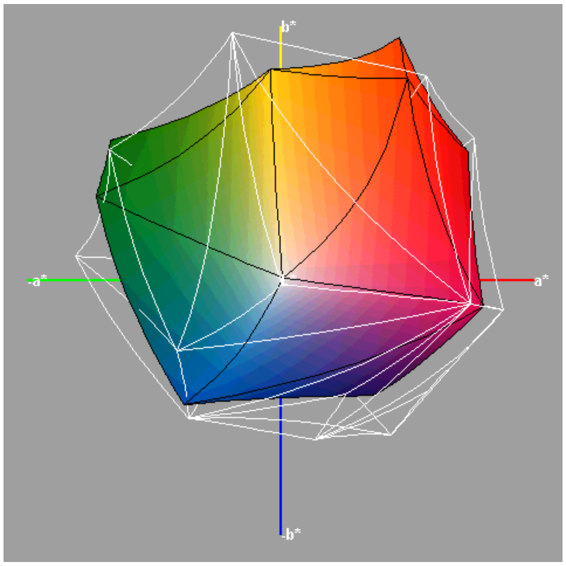


Figure 6 Six-Color BigBox Color™ (wireframe)
Compared to Hexachrome® (interpolated colored solid)

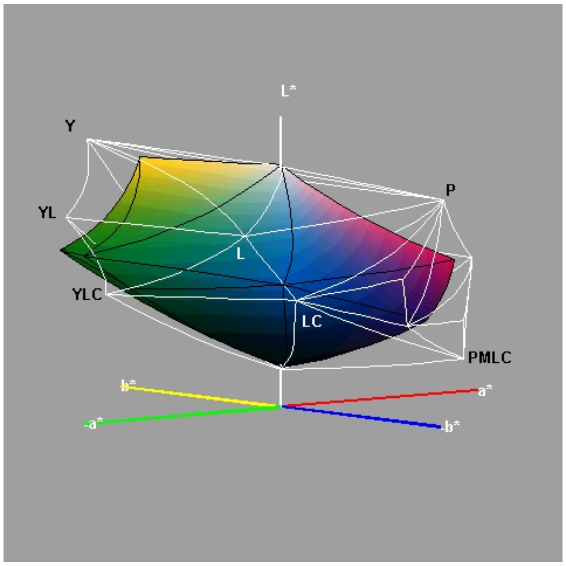


Figure 7 Hidden Gamut Expansion with BigBox Color (wireframe)
versus Hexachrome (interpolated colored solid)

stocks. By making the faces of one gamut opaque white and the other colored, one can clearly visualize the colors of the larger gamut. In Figure 5 the Hexachrome solid traps, OY and GY, extend beyond the BigBox gamut. Despite this, the BigBox color gamut volume is 35% larger. This is not apparent if you use a 2-D view of the a*-b* axes as in Figure 6. The side view in Figure 7 reveals the source of this added volume. It is in the added lightness achieved with the use of the extended primary printers, pink and light cyan, as opposed to added opponent colorants which fill the a*-b* plane. BigBox has more colors in the shadowy blues and purples as well.

All the charts shown thus far were calculated from only solid and solid trap data processed according to the Neugebauer model. The use of halftone crosscharts produces more detail using the same software. Figure 8 used 768 points from two modified IT8 targets as input. Adding more data points only adds more detail to convex surfaces and possibly some improvement in volume accuracy.

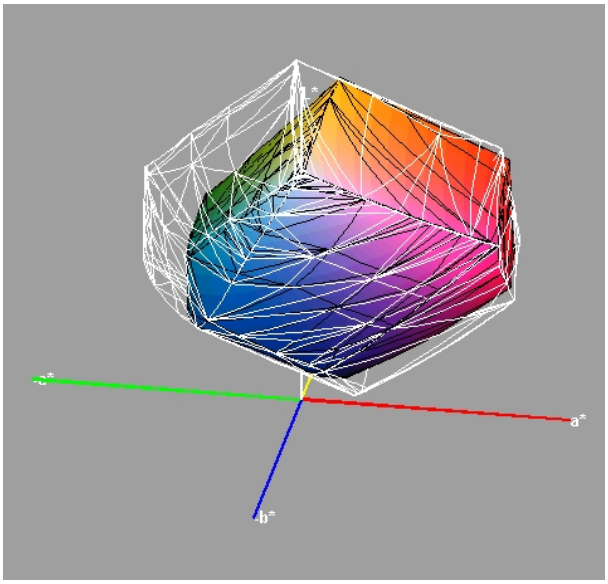


Figure 8 BigBox versus Colormaster from Crosscharts
Both Ultraviolet Cured on Uncoated Stock

If the data are concave in XYZ due to some systems phenomenon, the 3-D hull algorithm will still span the area. Convex hulls then become only good estimates of the geometric volume. One approach to address concave details is to use α-shapes (Cholewo, 1999).

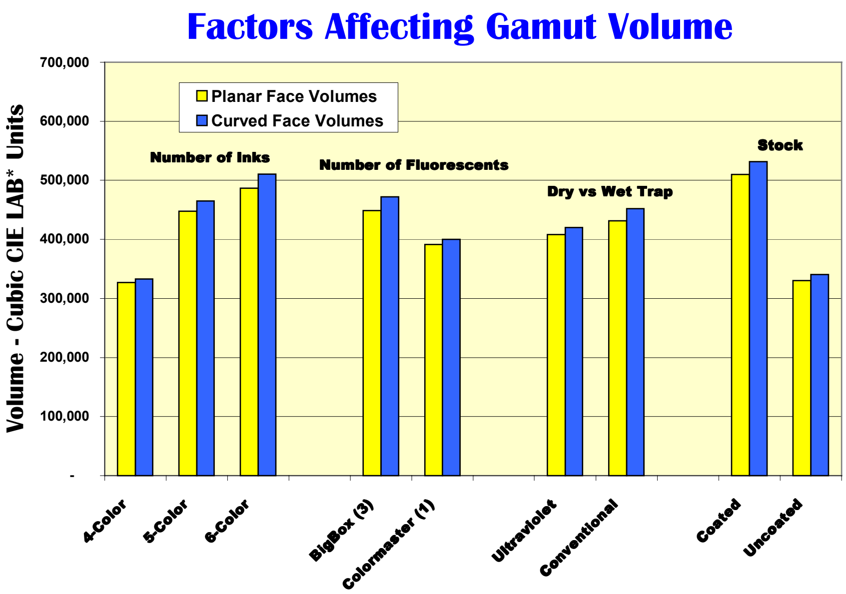


Figure 9 Gamut Volume as a Function of Printing System Variables

The Appendix contains printing gamut volume data from nine ink systems. A summary chart in Figure 9 illustrates several factors affecting the printing gamut volumes of the Hallmark ink systems such as the number of inks being printed, the number of fluorescent colors printed, the curing mechanism, which is really wet versus dry trap, and the type of stock. The type of stock has the largest effect on gamut volume. This is followed closely by the difference between 4-, 5- and 6-color printing. The number of fluorescents is third. Finally is the difference between the ultraviolet and conventional inks. The difference in the latter factor is purposely minimized to simplify the number of color reproduction profiles needed for prepress.

Conclusions

Three-dimensional convex hulls can be used to construct a geometric solid for visualizing the printing gamut of an output device in full color. Overlapping two such hulls can be used to show improvements or advantages of one printer over another. Volume calculations provide a metric for quantifying these results. A method was demonstrated to compute the true volume of curved surface gamuts in Lab space. Such tools have potential applications in the study of ink/paper interactions, in process ink development, and in lightfastness studies. Last but not least, gamut visualization is an essential cornerstone to gamut mapping, the art of reconciling differences in source gamut with device output gamut.

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Appendix

Calculated Gamut Volumes Using a Planar Face Model and a Curved Face Model

Ink Family	Cure	Stock	Colors	Planar Vol*	Curved Vol*	%ΔVol
Colormaster	Conventional	Coated	4-Color	394,460	393,336	-0.28%
Colormaster	Conventional	Coated	5-Color	523,497	534,827	2.16%
Colormaster	Conventional	Coated	6-Color	545,297	577,532	5.91%
Colormaster	Conventional	Uncoated	4-Color	208,021	210,659	1.27%
Colormaster	Conventional	Uncoated	5-Color	328,194	338,013	2.99%
Colormaster	Conventional	Uncoated	6-Color	366,221	382,883	4.55%
Colormaster	Ultraviolet	Coated	4-Color	376,774	373,246	-0.94%
Colormaster	Ultraviolet	Coated	5-Color	506,858	517,049	2.01%
Colormaster	Ultraviolet	Coated	6-Color	539,522	571,194	5.87%
Colormaster	Ultraviolet	Uncoated	4-Color	207,647	201,653	-2.89%
Colormaster	Ultraviolet	Uncoated	5-Color	337,346	337,319	-0.01%
Colormaster	Ultraviolet	Uncoated	6-Color	363,108	364,141	0.28%
BigBox	Conventional	Coated	4-Color	493,212	516,965	4.82%
BigBox	Conventional	Coated	5-Color	622,556	660,454	6.09%
BigBox	Conventional	Coated	6-Color	659,081	700,785	6.33%
BigBox	Conventional	Uncoated	4-Color	260,554	277,682	6.57%
BigBox	Conventional	Uncoated	5-Color	369,027	396,297	7.39%
BigBox	Conventional	Uncoated	6-Color	410,039	437,947	6.81%
BigBox	Ultraviolet	Coated	4-Color	394,399	404,929	2.67%
BigBox	Ultraviolet	Coated	5-Color	502,491	531,997	5.87%
BigBox	Ultraviolet	Coated	6-Color	564,762	597,113	5.73%
BigBox	Ultraviolet	Uncoated	4-Color	277,248	284,038	2.45%
BigBox	Ultraviolet	Uncoated	5-Color	389,098	403,935	3.81%
BigBox	Ultraviolet	Uncoated	6-Color	444,427	455,927	2.59%
Hexachrome	Ultraviolet	Coated	6-Color	484,841	488,841	0.83%
Hexachrome	Conventional	Coated	6-Color	487,119	488,127	0.21%

Units of volume in all cases are cubic CIE Lab Units

Corrections Summary

Mean	3.20%
StdDev	2.83%
Min	-2.89%
Max	7.39%