Color Gamut Quantified
A New Approach to Analyzing Color Gamut

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Abstract
High impact color continues to be a goal of publishers, consumer products companies, and all who use print to communicate their message in an attempt to gain market share and increase sales. As a result, all those involved in the value chain, such as designers, suppliers, and printers, aim to contribute positively towards this goal. As efforts have been made to increase the colorfulness of print, it has been difficult to quantify the size of the color gamut.

Recently, there have been developments by various color management software vendors to provide tools that quantify the size of the color gamut by evaluating ICC profiles. This paper introduces a new color gamut analysis tool developed at Rochester Institute of Technology along with an overview of the other commercially available applications. Using these approaches, case studies will be presented showing gamut differences between various combinations of printing technologies and consumables.

1.0 Introduction
The impact of color on the human visual response system is well understood in all facets of visual communications ranging from television to the various forms of print. At one point each of these was monochromatic, or just “black and white.” Computer monitors have gone from various single-color versions (green, amber, gray, etc.) acting strictly as terminals for interacting with a computer to now high-definition color-managed displays that enable remote soft-proofing and are replacing hard-copy proofing systems.

In packaging, fast moving consumer products companies (CPCs) believe the link between the shelf appeal of the package and sales is very direct and very strong. Gains in market share have been directly tied to enhancements in graphics, design, the use of various visual enhancement features (i.e., holographic films, etc.), and color. To enhance the colorfulness of the printed product, or enlarge the gamut of reproducible colors, colorants (inks) have been focused on as a chief component.

To expand the gamut, multiple approaches have been developed. One approach has simply been to print the process inks (cyan, magenta, yellow, and black) to higher solid ink densities (SID). While this approach does enlarge the gamut to an extent, there are often trade-offs. First, if printed to too high of a density, a color can actually lose chromaticity and result in a smaller gamut. There can also be issues associated with thicker ink film thicknesses, such as drying or curing problems, problems with stability on a printing press, higher cost for the printed product, and others.

Another approach has been to use colorants beyond CMYK. This approach is often referred to as “extended gamut printing.” Here, complementary colors are used to reproduce colors that cyan, magenta, and yellow cannot in combination. One system known as Hexachrome (Reid & Apostol, 2004) utilizes orange and green to accomplish this while another named Opaltone (Opalton, n.d.) utilizes red, green, and blue. In addition to extending the gamut for purposes of colorfulness, both
systems aim at helping to reproduce spot colors, or PMS (Pantone Matching System) colors. This becomes valuable when printers are faced with many individual colors in a job. Instead of printing each color in its own station, the extended gamut approach allows printers to use the six or seven colors in some sort of combination to reproduce the specified colors to minimize the number of required print stations and subsequent manufacturing costs.

Whatever the approach, understanding the impact on the color gamut is important if one wants to characterize and improve it. Even for traditional, non-gamut expanding approaches, it is valuable to understand the color gamut for process control and continuous improvement. Many factors impact the color gamut, such as: inks/ colorants, substrate, other process consumables, color sequence, the type of printing process itself, and others.

2.0 Legacy Approach
Traditional, describing and characterizing color gamuts have been done one of two ways. Both are based on CIE (Commission Internationale de l’Eclairage) colorimetry. While this is not the place for a thorough review of color theory and color spaces, it should be understood that describing color is three-dimensional with the three ordinates being lightness, chromaticity (or saturation), and hue (Figure 1).

One plotting technique utilizes the CIE Chromaticity Diagram (see Figure 2). Here, color is plotted in terms of hue and chromaticity in two dimensions. Lightness is not accounted for in this approach. Color gamuts can be portrayed by plotting multiple points to create an irregular closed shape. This represents the boundary of the particular imaging system in terms of its color gamut and achievable colors. Colors that fall outside of the plot are not reproducible by the system while colors that fall inside the plot can be reproduced.

Figure 2 shows the gamut boundary of an ink-jet printer (the larger plot) along with a gamut boundary of a typical web offset printing press. On one hand, it does show a significant difference between the two devices. However, since color is three-dimensional and this plotting technique only plots in two dimensions (lightness is missing), it is not possible to ascertain which specific colors fall inside or outside the gamut. Other shortcomings include the fact that equal distances on the diagram do not correspond to equal visual differences; the diagram was originally designed to plot the color of light sources as opposed to the color of objects. And lastly, there is no way to quantify the gamut.

A second approach involves plotting color in the CIELAB color space (Figure 3). Here, colors can be described numerically in three dimensions with L* representing lightness, and a* and b* used to locate a color in the color space so that hue and chromaticity can be calculated and assessed. L* serves as the vertical axis while a* and b* serve as the x-y axes. Often, L* is plotted separately from a* and b*, which are plotted two-dimensionally. Further, C* (chroma) and h° (hue angle) are calculations based on a* and b* to derive colorimetric values for chromaticity and hue. To display the gamut, a hexagonal plot is made utilizing the three
subtractive primary colorants (cyan, magenta, and yellow) along with the overprints of the three (red, green, and blue).

This approach also suffers from the fact that it is only two-dimensional. However, with the L*a*b* coordinates known, calculations can be made of the area of the hexagonal plot and used to compare various conditions, to some level. This approach does not discriminate where the six endpoints fall along the lightness axis. Hence, it is not a valuable calculation. These color space systems are used conceptually to explain terms of normal color descriptors (Field, 1999).

3.0 Newer Approaches

With the advent of color management and ICC profiles, a large sampling of a device's color output can be used to mathematically describe the three-dimensional nature of the device's color output. The steps include:

1. Output of a profiling target (CMYK for hard-copy, RGB for monitors).
2. Color measurement of the target utilizing spectrophotometry. The result is a data set of L*a*b* values for each patch in the profiling target.

The profile represents how that device renders color given a particular input (CMYK or RGB values). Once it has been created, the profile is primarily used to convert image data either from one color space to another (RGB to CMYK or CMYK to RGB) or within a color space (CMYK to CMYK or RGB to RGB). This is how various devices simulate the color output of other devices. For example, computer displays can act as "soft proofing" devices simulating the color output of a printing press.

Another application is to color manage a digital hard-copy proof to a printing press. Using ICC color management allows for color to be managed from image capture, or acquisition (digital camera/scanner), to proofing (soft or hard copy) to final output (printed or displayed).

Profiles also serve in graphically displaying the three-dimensional nature of a device's color gamut as well as enable calculations of the volume of the gamut. Various vendors of color management software (Figure 4 and Figure 5) have this capability. Figure 4 is a screen shot of the same inkjet and web offset profiles that were plotted in the chromaticity diagram. Note how the three-dimensional plot offers much more clarity and insight about the shape and volume of the two device's gamuts.

The software also allows users to rotate and spin the three-dimensional plots so that the gamuts can be viewed from any desired perspective. Additionally, calculations of the gamut's volume are available within the software. However, typically just one number representing the gamut volume is generated as seen in Figure 5. Other than a visual assessment of the plots, there is no way to ascertain where differences in gamuts between devices exist.
4.0 The RIT Gamut Analysis Tool

Identifying a need to understand better where differences can lie in gamuts, Rochester Institute of Technology has developed a tool that utilizes ICC profiles to plot features of gamuts of interest in a unique way. The primary plotting technique uses \( L^* \) / \( C^* \) slices at eight (8) different hue angles, 45-degrees apart, around the entire \( a^*b^* \) plane. Each analysis generates a two-page report (see Appendix) containing the various plots along with tabular data about gamut size for each hue angle and totaled for overall gamut volume.

In the RIT Gamut Analysis Report, the figure on page 31 shows \( L^* \) / \( C^* \) plots of the eight hue angles for the inkjet and web offset printing example. Each of the eight plots shows the following:

- Plots of both conditions of interest
- A plot of a reference condition taken from the ISO 12640-3.4 Draft which represents "real world" colors of very high chroma including natural colors - not necessarily printed.
- Color-coding of the plots corresponding to the hue angle
- A legend for each condition with calculated areas for the \( L^* \) / \( C^* \) slice

To arrive at a quantitative volume of the gamut, each of the eight calculated areas is added together. The resulting value can then be compared to other conditions.

The second page of the report shows a two-dimensional plot of the gamuts in the \( a^*b^* \) plane along with tabular \( L^*a^*b^* \) data for the substrate, the individual CMYK colorants, the overprint colors (RGB) and a 400% patch of CMYK. Additionally, gamut areas for the eight \( L^*C^* \) slices are summarized for the reference and sample conditions along with percentage calculations of the differences of the sample versus the reference and the sample versus the real world condition. Finally, the eight area calculations are summed for a total gamut volume.

This analysis technique is very flexible in that it can be used to compare any two conditions, be it different printing processes and/or imaging systems, different ink/colorant systems, different substrates, etc. In the appendix are examples of three analyses illustrating different types of comparisons.

5.0 Summary

With color becoming more and more important in the eyes of purchasers of various forms of printing, be it newspapers, magazines, packaging, or any other printed material, understanding the influence of various consumables with the various printing processes on the final color is vital. Having the ability to quantify the size of the color gamut along with understanding how gamuts are different between various conditions will help all those in the value chain to continuously improve and enhance the colorfulness of print.

6.0 References


Note: It is well known that a step difference in yellow is visually less significant than a step difference in blue. Gamut comparisons in CIELab should therefore be limited to comparing same hue angles only. CIELab is not visually equidistant.
CIELab for special patches

<table>
<thead>
<tr>
<th>Patch</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>88.73</td>
<td>-0.25</td>
<td>3.64</td>
</tr>
<tr>
<td>400% solid</td>
<td>9.08</td>
<td>0.54</td>
<td>1.2</td>
</tr>
<tr>
<td>K    solid</td>
<td>18.62</td>
<td>0.89</td>
<td>1.26</td>
</tr>
<tr>
<td>C    solid</td>
<td>55.87</td>
<td>-37.53</td>
<td>-40.26</td>
</tr>
<tr>
<td>C+Y  solid</td>
<td>51.61</td>
<td>-61.11</td>
<td>26.35</td>
</tr>
<tr>
<td>Y    solid</td>
<td>84.29</td>
<td>-5.93</td>
<td>83.42</td>
</tr>
<tr>
<td>M+Y  solid</td>
<td>46.84</td>
<td>62.85</td>
<td>42.18</td>
</tr>
<tr>
<td>M    solid</td>
<td>47.16</td>
<td>68.56</td>
<td>-3.61</td>
</tr>
<tr>
<td>C+M  solid</td>
<td>26.35</td>
<td>17.96</td>
<td>-41.32</td>
</tr>
</tbody>
</table>

Gamut areas for the 8 L*C* slices:

<table>
<thead>
<tr>
<th>Color</th>
<th>Hue_Angle</th>
<th>SWOP Sample</th>
<th>InkJet Reference</th>
<th>Samp / Ref</th>
<th>Samp / Real World</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow</td>
<td>90</td>
<td>2779</td>
<td>4142</td>
<td>67 %</td>
<td>46 %</td>
</tr>
<tr>
<td>Red</td>
<td>45</td>
<td>2663</td>
<td>3721</td>
<td>72 %</td>
<td>44 %</td>
</tr>
<tr>
<td>Magenta</td>
<td>0</td>
<td>2486</td>
<td>3864</td>
<td>64 %</td>
<td>47 %</td>
</tr>
<tr>
<td>Purple</td>
<td>315</td>
<td>1752</td>
<td>3922</td>
<td>45 %</td>
<td>30 %</td>
</tr>
<tr>
<td>Blue</td>
<td>270</td>
<td>1498</td>
<td>3458</td>
<td>43 %</td>
<td>32 %</td>
</tr>
<tr>
<td>Cyan</td>
<td>225</td>
<td>1916</td>
<td>3673</td>
<td>52 %</td>
<td>43 %</td>
</tr>
<tr>
<td>Emerald</td>
<td>180</td>
<td>1915</td>
<td>3982</td>
<td>48 %</td>
<td>37 %</td>
</tr>
<tr>
<td>Green</td>
<td>135</td>
<td>2454</td>
<td>4036</td>
<td>61 %</td>
<td>41 %</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>17463</td>
<td>30798</td>
<td>57 %</td>
<td>40 %</td>
</tr>
</tbody>
</table>

Note: It is well known that a step difference in yellow is visually less significant than a step difference in blue.
Gamut comparisons in CIELab should therefore be limited to comparing same hue angles only.
CIELab is not visually equidistant. The totals numbers are therefore to be used with great caution.
Real World colors are all the colors that might have to be reproduced as specified by ISO 12640-3.4 draft.