# A Multi-Ink Color-Separation Algorithm Maximizing Color Constancy

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## Abstract

Current color-printing technologies may use three or more inks, e.g., CMY, CMYK, CMYKcm, CMYKGO, CMYKRGB. When the number of inks exceeds three, there is the usual color-management one-to-many mapping problem. Because the spectral properties of many modern inks are optimized for maximum color gamut and in some cases, black ink may not be used for pictorial images, many prints have poor color constancy. Changes in lighting dramatically change color balance, particularly for neutrals. An algorithm was developed for multi-ink printing in which the one-to-many mapping problem was overcome by selecting ink combinations with the best color constancy between illuminants F11 and D50. The algorithm was tested using a pigmented-ink inkjet proofing printer. CMYKGO prints color-separated using this algorithm were compared with a generic ICC profile for CMYKcm prints. The CMYK inks were common to both prints. The new algorithm improved color constancy significantly.

## Introduction

Color constancy is the general tendency of the color of an object to remain constant when the level and color of the illumination are changed.[1] It is a result of both physiological and psychological compensations. Upon close inspection, color constancy occurs rather infrequently. The need for color-appearance models in an ICC color-management workflow[2] is indirect evidence that many imaging materials are not color constant.

The color constancy of neutrals has always been a design criterion for photographic dyes since prints are viewed under many different lighting conditions.[3] In graphic arts, color constancy, historically, was not of interest. Rather, metamerism was an issue and resulted in standardized viewing and illumination.[4] Fortunately, most traditionally-printed materials have reasonable color constancy because of the use of spectrally-flat carbon-based black inks and separation algorithms that maximize black ink for neutrals.

Because of the popularity of ink-jet printing technologies, fortuitous color constancy is less commonplace. The practices of only using CMY for pictorial images and using dye-based black inks with long-wavelength reflectance "tails" result in appreciable color inconstancy. As a consequence, in addition to color gamut expansion,[5-7] color constancy should be an ink-design criterion.

In ICC-based color management, we are faced with the usual one-to-many mapping problem. There are usually more inks than colorimetric coordinates. As a consequence, many colors can be matched using more than one combination of inks. For multi-ink printing systems, the algorithms are complex and may involve subdividing either colorimetric or colorant space to achieve greater determinancy.[8-10] Alternatively, a separation strategy can be defined in which the choice of inks and their amounts could be based on maximizing color constancy. This was tested using a pigmented-ink inkjet printer with a CMYKGO ink set (C = cyan, M = magenta, Y = yellow, K = black, G = green, and O = orange) and compared with a CMYKcm ink set (c = light cyan and m = light magenta).

## Algorithm Overview

The goal was to build a color look-up table (CLUT) that converted CIELAB to CMYKGO color separations. First, we developed a spectral printing model, a requirement in order to calculate an object's color constancy. Using this model, we created a large number of virtual samples in six-ink space and calculated tristimulus values for various illuminants and a single standard observer. The sampling goal was to have a sufficient number of virtual samples such that in every region of the output's color gamut, defined in CIELAB for D50, there were multiple color combinations. CIELAB was divided into coarsely-sampled cells and the samples were binned into these cells. For each cell, the most color-constant sample was selected. Non-uniform interpolation was used to populate a finer-sampled grid. To reduce processing time for CIELAB images, linear interpolation was used to create a fully populated 256 x 256 x 256 CLUT.

## Spectral Printing Model

The Yule-Nielsen modified spectral Neugebauer model was first tested, in similar fashion to Taplin and Berns.[11]

Through experimentation, it became clear that to achieve sufficient accuracy for building color profiles, the cellular extension[12,13] was necessary. Thus, we needed $4^6 = 4096$ nodes rather than the usual $2^6 = 64$ for a six ink printer. However, because of maximum ink limitations for the selected substrate, it was not possible to print all of them. An optimization based on research by Balasubramanian[14] was used to statistically predict non-printable colors, find the optimal Yule-Nielsen *n* value, and create one-dimensional LUTs relating digital data with effective dot areas. Six hundred random colors were printed, measured spectrally, and compared with their model predictions. The mean and maximum color differences (D50, 2° observer) were 0.96 and $3.86\Delta E_{00}$, respectively. The mean and maximum RMS spectral errors were 0.8% and 4.5%, respectively.

## Virtual Sample Set

The goal was to create a dataset of ink amounts that well sampled CIELAB and whenever possible, resulted in different ink amounts with similar colorimetry. As a proof of concept, a rather simplistic approach was used. Eleven steps from 0% to 100% area coverage in 10% intervals were defined for each ink. Using the spectral model, $11^6$ = 1,771,561 virtual samples were created and CIELAB coordinates calculated for D50 and the 2° observer.

## Color Inconstancy Index

An index of color inconstancy was calculated, similar to those described in references 1, 15, and 16: Tristimulus values were calculated for illuminants D50 and F11 from their predicted spectral reflectance. Using the CIECAT02 chromatic-adaptation transform,[17] corresponding colors were calculated from each illuminant to D65. The corresponding-color tristimulus values were converted to CIELAB using D65 as the reference white. A weighted CIE94 color difference was calculated with $k_L = k_C = 2$ between the pair of corresponding colors. In this manner, hue inconstancy was penalized twice as much as lightness or chroma inconstancy. This weighted color difference defined the color-inconstancy index, CII.

A CII histogram of the virtual sample set is shown in Figure 1. Many ink combinations have appreciable color inconstancy. As a rule-of-thumb, samples with excellent color constancy have CII values below unity. The only way to change the CII statistics is to change the spectral properties of the inks. Unfortunately, the relationship between spectral properties and color constancy is very complex.[18]

## Sample Binning

CIELAB space was divided into 16 x 16 x 16 cells and each sample was assigned to a cell based on its colorimetric values. As an example, Figure 2 shows the distribution in the a*b* subspace for the slice of cells at L* from 40.0 to 46.7.

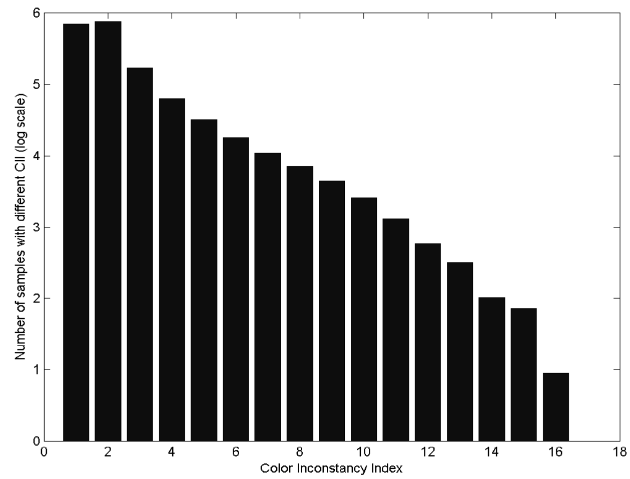


*Figure 1. Color inconstancy index histogram of virtual sample set. Note logarithmic scale.*

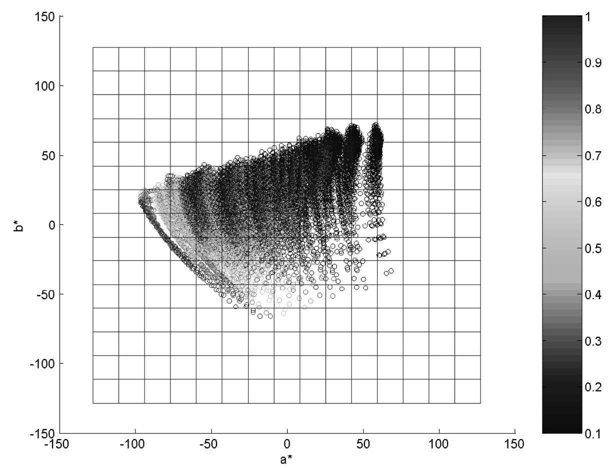


*Figure 2. Sample distribution in the a*b* subspace at L* between 40.0 and 46.7. The color of the datapoints indicates the amount of cyan ink.*

## Selection Criterion

In each cell, different samples representing different ink combinations all achieved nearly the same color. Criteria could be defined in addition to color constancy such as spatial image quality and reproducibility. We limited our criterion to color constancy. We selected the virtual sample within each cell with the smallest CII. A histogram of the selected samples is shown in Figure 3. Compared with Figure 1, the improvement in color constancy is observed.

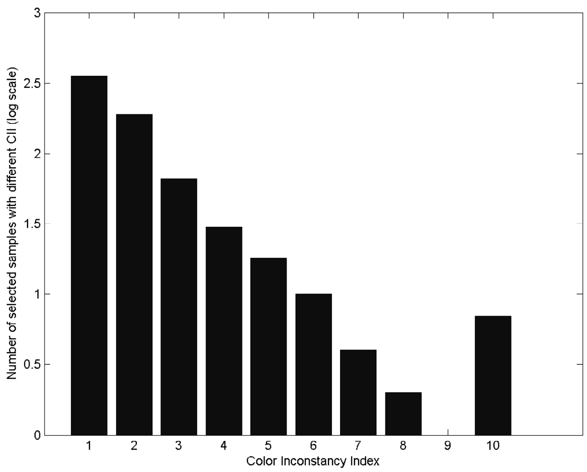


*Figure 3. Color inconstancy index histogram of selected sample set. Note logarithmic scale.*

## Creating a CIELAB to CMYKGO 64 x 64 x 64 Lookup Table with Non-Uniform Interpolation

The selection process left us with a single sample in each cell but a non-regular distribution in CIELAB space. We used a three-dimensional-non-uniform interpolation algorithm for the area coverages in each color plane (CMYKGO) to create a uniformly spaced 64 x 64 x 64 CLUT. To perform the interpolation we used the Matlab function, '*griddata*' that uses Delaunay triangulation.[19, 20]

The result is shown in Figure 4 for the cyan ink at L* = 40. For some regions of CIELAB, oscillations were observed in area coverage, seen in Figure 4 at 20b*. This was likely caused by an insufficient number of samples in a given cell. The oscillation will reduce with improved sampling of the virtual sample set. It is also possible that some type of smoothing will still be necessary, for example, reference 9.

## Color Gamut Mapping

Although the color gamut of our CMYKGO printer is significantly larger than a typical CMYK printer, many perceived colors are still outside of the printable gamut. To populate the CLUT with area coverages for out-of-gamut colors, gamut mapping was necessary. We selected the simple method of $C^*_{ab}$ clipping maintaining $h_{ab}$ and L* for colors within the L* range of the printer. Colors darker or lighter than the six-color gamut were mapped to the darkest and lightest neutral (a* = b* = 0). This is a type of ICC absolute color rendering. Certainly more elegant and elaborate algorithms have been published and it is well known that loci of constant $h_{ab}$ do not have constant perceived hue.

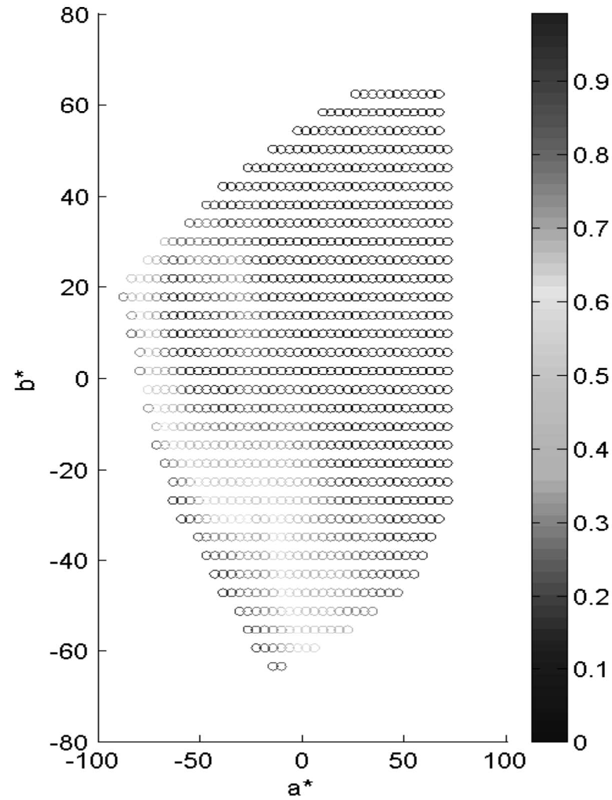


*Figure 4. Sample distribution following non-linear interpolationfor cyan ink at L* = 40,0. The color of the datapoints indicates the amount of cyan ink.*

## Creating a 256 x 256 x 256 Color Lookup Table using Linear Interpolation

We extended the 64 x 64 x 64 CLUT to a fully populated 256 x 256 x 256 CLUT in order to improve processing speed when color-separating images encoded in the Adobe Photoshop CIELAB byte encoding scheme. For our implementation, not further optimized for speed, this improved the processing time in Matlab from several hours for a six-megapixel image to several minutes.

## Results and Discussion

The spectral measurements of a GretagMacbeth ColorChecker Color Rendition Chart and a Kodak Gray Scale were used to create a CIELAB TIFF image for D50 and the 2° observer. The image was processed through the color-separation algorithm and printed on the CMYKGO inkjet printer. The image was also printed on an identical model printer with the standard CMYKcm ink set using the manufacturer's generic ICC profile and ICC absolute colorimetric rendering. The CMYK ink set was common to both printers; the same glossy paper was also used.

CIEDE2000 color differences ($\Delta E_{00}$) between the original targets and each printed reproduction were calculated. The CMYKGO profile had much greater accuracy (average $\Delta E_{00}$ = 1.5) than the generic CMYKcm profile (average $\Delta E_{00}$ = 7.3), as expected. Our main research goal was to produce a print with improved color constancy. This comparison is shown in Figure 5. For every color of the ColorChecker and gray scale, the CMYKGO separation using the proposed algorithm achieved a higher level of color constancy than a typical profile. These results have been confirmed visually in a multi-illuminant light booth. In particular, the gray scale maintained its neutral appearance when the lighting was switched between 7500 K filtered tungsten, F2, F11, and 2200 K tungsten.

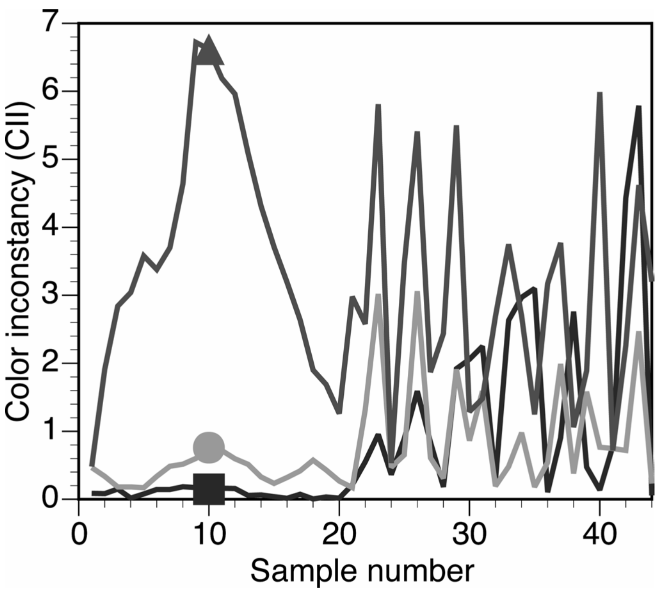


*Figure 5. Color inconstancy comparison between original target (filled square) and reproduction by CMYKcm (filled triangle) and CMYKGO (filled circle) printers. Samples 1 – 20 correspond to the Kodak Gray Scale; samples 21 – 44, the ColorChecker.*

The reflectance spectra from the Kodak Gray Scale #5 and the Orange Yellow Color Checker samples are plotted in Figure 6. Their CII values are listed in Table I. For the neutrals, it is clear that the most spectrally flat sample had the best color constancy. In fact, only object colors with these properties have guaranteed color constancy.[21] The CMYKcm profile did not use black, hence the large spectral selectivity and poor color constancy. When analyzing the Orange Yellow, predicting which sample has the best color constancy based on spectra is not as straightforward. The more complex spectrum of the CMKYGO sample had better color constancy than the original ColorChecker sample. As shown by Berns, *et al.*, the location of the absorption peaks may be the key factor rather than their degree of spectral selectivity.[15] Regardless of the underlying cause, it is clear that the CMYKGO print had improved color constancy compared with both the CMYKcm print and many of the chromatic samples of the ColorChecker.

**Table I. Color inconstancy indices between illuminants F11 and D50 for the 1931 standard observer for the listed samples.**

| Index | Original | CMYKcm | CMYKGO |
|---|---|---|---|
| Kodak Grayscale 5 | 0.08 | 3.58 | 0.17 |
| ColorChecker Orange Yellow | 4.43 | 2.26 | 0.72 |

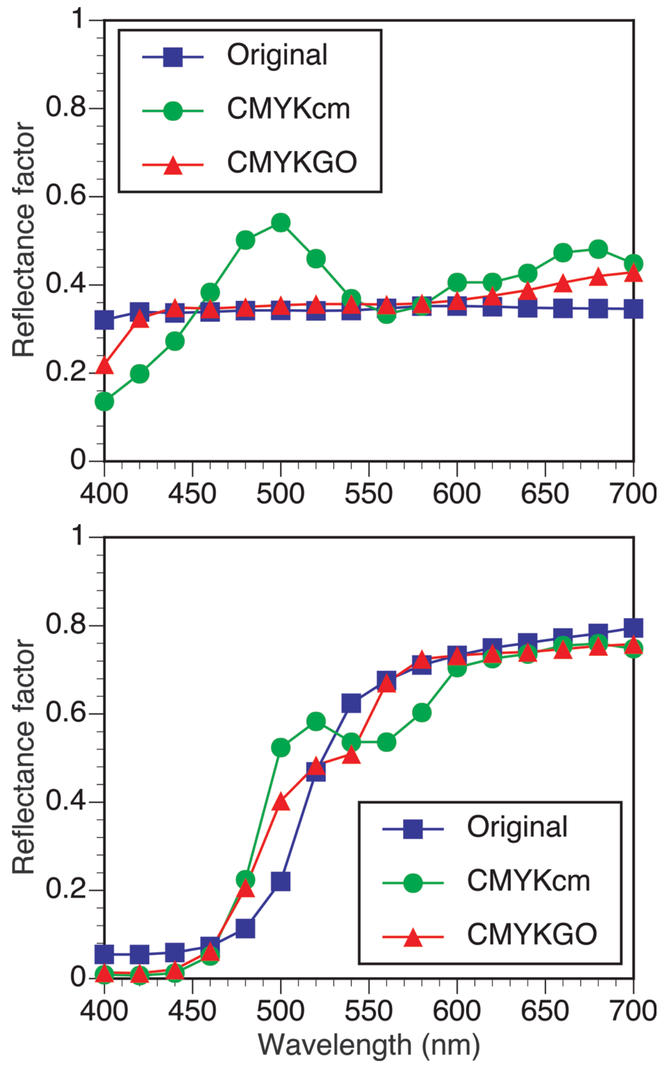


*Figure 6. Reflectance spectra of original and printed reproductions using CMYKGO and CMYKcm ink sets for Kodak Gray Scale Sample 5 (top) and Orange Yellow ColorChecker sample (bottom).*

## Conclusions

An algorithm was developed to deal with the one-to-many mapping problem when building color lookup tables for multi-ink printing. The unique feature of the algorithm is that maximal color constancy was the main selection criterion among ink combinations yielding similar color. The algorithm was tested with spectral data from several targets. The algorithm as implemented can be improved by a better CIELAB distribution of the virtual sample set. Furthermore, one can imagine a number of criteria that can be used as a selection metric, individually or combined, such as graininess, sharpness, maximum black ink amount, print precision, etc. Future research will focus on tradeoffs between these various criteria in terms of print quality. A theoretical analysis is also warranted to understand the inter-relationships between the number of inks, their spectral properties, color constancy, and color gamut.

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## Biography

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