Something Old, Something New, Something Borrowed, Something Blue

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Abstract: The marriage between traditional graphic arts and electronic imaging faces difficult times. The introduction of colorimetric data and device independence has proven not to be the required elixir. A mapping method involving the original, the display, and the printed output is presented. This mapping method uses a wide gamut RGB space called mRGB. The paper recommends that mRGB be the color management default. Our industry must agree on a single RGB space, if this method or any other is to succeed. This procedure is based on utilizing spectral data to define mRGB. The rendering algorithm has its origins in painting and graphic arts before the age of electronic imaging.

Introduction

During the early development of digital scanning and electronic separations, measurements were limited to density. At that time, spectral measuring devices were too expensive, and the analysis software was best left to experts. The introduction of Colortron™ in 1994 made spectral data and data analysis available at the price of densitometers. Color management and control are no longer limited to density measurement. Since then, spectral data capture has been automated. Measuring the large number of patches required for color management profiles is a fast and easy task.

This paper presents a new color separation algorithm founded on spectral data and uses RGB as a profile connection space. The primaries are chosen to

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provide an integer uniform chromaticity space that spans the gamut of the colorants used in graphic arts and desktop printing. A new separation and gamut-mapping algorithm has been developed that is based on appearance mapping techniques used by painters and graphic artists.
The separation algorithm is at least 10 times faster than current methods. Integer arithmetic performs a table lookup of the amount of colorant. The computational speed is achieved by not having to do floating-point math or interpolation on a three-dimensional grid of points. Changing the separation data in the lookup tables is all that is required to repurpose the image data to a new printer's gamut.

The Marriage

The title of this paper suggests a marriage - a marriage between traditional graphic arts and electronic imaging. In the beginning, electronic imaging served the needs of its partner. Now electronic imaging is trying to change its partner to accept color management and the use of the CIE colorimetry system to produce separations. The attempts of electronic imaging to overcome the empirical limitations of the traditional approach to color are laudable.

Digital processing in the graphic arts started in the mid 70's. These early systems succeeded because they duplicated the analog photographic processing (Yule1965) used to separate films. The mathematical analogy to the workflow of that time allowed separations to be made in terms that were familiar to the separator. The use of density control, masking, bump, and flash exposure were still available as they were in film separations. The electronic scanner and its associated computer made light work of the numerous proofing iterations required to correct an image.

The early relation between the two partners produced reasonable separations. Scanner operators had a set of controls to adjust the separations to the local printing conditions. This process was very vendor- and operator- specific and did not allow separations or files to be shared. The conversion from physical to electronic images made separation easier but did little for communication. The major issue facing the pre-press industry from the 1980s (Johnson 1998) to this day is the transfer of electronic data from pre-press to the printer. There are issues of document format and data description that still need to be resolved. Device independence and file format independence still have not been achieved.

Color management and the recent Portable Document Format (PDF) are positive efforts to solve the workflow issues of moving text and images from pre-press to printer. In spite of these new standards, graphic arts still has to contend with vendor- specific profiles and data formats. Device profiles are embedded in each image to manage the transformation of the image data from input, to display, and, finally, to the printed page. The device profiles, unfortunately, are still vendor specific and prevent a mix of images from different vendors being included in a single document. Preflighting files is essential to catch errors before the file is ripped.

Although graphic arts tried to embrace the new colorimetric transformation process, problems immediately arose. The gamut mapping methods employed by electronic imaging use the CIE L*a*b* color space. This color space is a nonlinear transform of the linear RGB source data. The CIE L*a*b* gamut mappings fail to produce images that have the proper appearance over the range of inks and paper stocks used by graphic arts. The profiles rely on a sparse grid of points to define the gamut volume. Many profiles do not include the neutrals in the grid. The interpolation of the neutrals from the grid does not always result in a true neutral scale. The profiles must be tuned, and it takes many iterations to produce a usable profile. Therefore, there are as many user- and vendor-specific solutions now as there were before the introduction of "device independent color."

The following will present a new "natural appearance" separation algorithm that has the potential for saving the marriage - a promise of a solution to the problems introduced by the current color management systems. Spectral data replaces density controls in the new appearance model. Spectral data defines the appearance of the colorants over the range of illuminants identified for use in the graphic arts. It produces colorimetric definitions of ink trap, chromatic tone, and neutral tone gain. These definitions allow printer variations to be fed back to pre-press. The new method maintains exact hue control in the image. These controls are available because the new separation model uncouples the chroma and the neutral components of the image. This separation model has led to a fast table lookup. The color components of the image are determined by a two-dimensional lookup. This is followed by a one-dimensional lookup of the color and black amounts required for the neutral contribution to the image.

The separation algorithm uses something old – tonal scaling from the graphic arts. A linear RGB uniform color space is something new. The "UCR – GCR" type black model is borrowed from methods employed for centuries by colorists and painters. Finally, something blue is a means of producing long range complex grays that can have different color tones at various tone levels.

Something Old

Graphic arts has dealt with reproduction of images on a wide range of substrates years before the introduction of scanning and color management. Tone scaling has been used to compensate for the difference in the covering power of ink on different substrates. This method has produced excellent images on coated paper and newsprint. Tone scaling has been the clue to a new way to map color gamuts especially those as different as SWOP and newsprint. Figure 1 shows the tone scale used in newsprint compared to SWOP separations. As can be seen on the figure, the dot area in newsprint has been increased to compensate for the covering power of the ink. This technique has its limits and never can compensate completely for the loss of covering power.

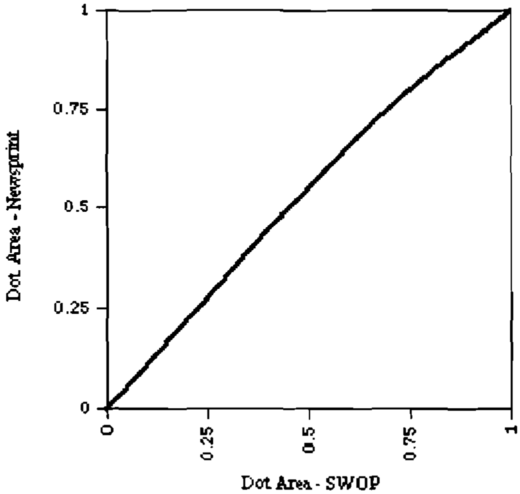


Figure 1. Newsprint Coverage Compensation

The tone scale compensation above 50 percent coverage must be reduced slowly. The form of this compensation follows a saturation growth function given by equation 1,

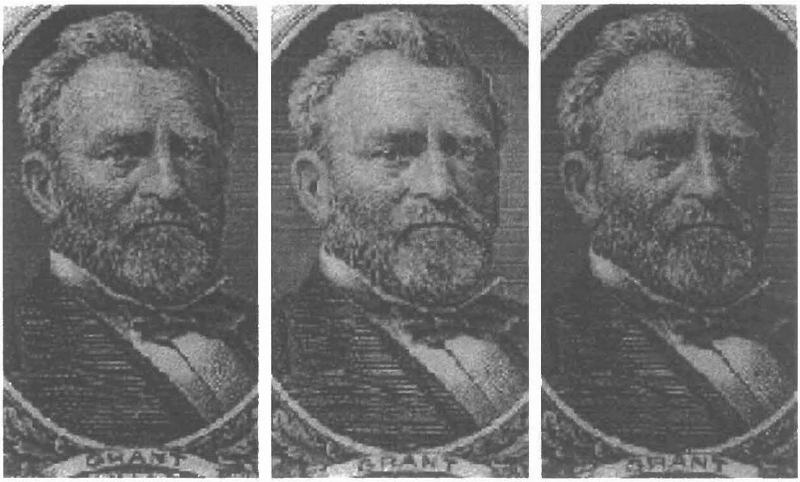
$$O = K_1 * S / (K_2 + S) \qquad (1)$$

where O is the response to the signal S; and K_1 and K_2 are constants chosen to control the rate of saturation.

This form of signal compression is found in the neural response of human vision. Guth (1989) proposed a model that used the saturation growth function to define the complex actions of the human visual system. The current model is an approximation that explains how the visual system adapts when presented with a wide range of brightness.

Guth showed that the visual system has three channels that mediate perception. They are a lightness – darkness channel, a red – green channel, and a yellow – blue channel. Each channel responds in the manner shown in equation (1).

We hypothesize that the reason tone scale compensation works is that the scaling adds an apparent extra stage of adaptation. The visual system accepts the stimulus and responds to produce a much stronger signal than is present in the image. Figure 2 illustrates the principle being used in a "natural appearance"-gamut-mapping algorithm.

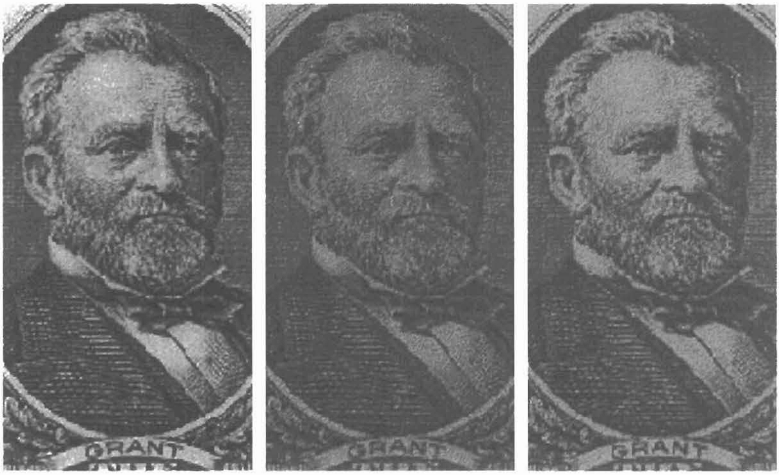


Original | Low Covering Power | Low Covering Power Plus Adaptation

Figure 2. Darkness Saturation Adaptation

In the center image, Grant is degraded to simulate the image being reproduced with ink that has a low covering power. In this example, the maximum coverage yields a black reflectance of only 25 percent. The adapted image on the right has the same grayscale range as the degraded image in the center of the figure. The only difference between the images is that the adaptation function has been applied to the right hand image. The effect of the added adaptation is striking. This is a severe test of the ability to gamut map. Although the recovery is not perfect, there is a noticeable improvement in the appearance of the grayscale range.

The Guth model for the grayscale (luminance) channel of human vision includes both lightness and darkness. Figure 3 shows a degraded image that simulates the image being printed on gray paper using ink with low covering power. The center image has been constrained to a reflectance range of 75 to 25 percent. On the right, adaptation has been applied to both lightness and darkness in this example. The gray scale "natural appearance" expansion used in Figure 3 is seen to work for both branches of the lightness – darkness channel.



Original	Low Brightness Paper Low Covering Power ink	Low Brightness Paper Low Covering Power ink Plus Adaptation

Figure 3. Lightness and Darkness Saturation Adaptation

The next section of this paper explains how the chromatic mechanisms are adapted. A simple linear model of Guth's vision channels is used to produce an approximate uniform color perception space. The channel encoding in this model uses the adaptation function given by equation (1). The degree of adaptation in this channel depends on the covering power of the inks and the brightness of the paper stock.

Something New

The linearized Guth color space, using lightness – darkness, red – green, and yellow – blue vision channels, is the new prize that is being placed in the dowry. The vision model in conjunction with the adaptation scheme presented in the previous section produces a linear transformation between an RGB space and perceived color. What is required to define a working RGB space, and why should the color space be linear?

Let us look at the reasoning for keeping the RGB space linear. Almost all the images brought into the graphic arts start out as CMY dyes on film or paper. The final image is printed on paper using similar CMY colorants. If the gamuts of the input and the output are nearly the same, the relation between the CIE XYZ tristimulus values measured on the original and those measured on the reproduction will be linear. Figure 4 shows that the RGB signals produced by the scanner and the CMY values created for the reproduction are also linearly related. The data shown below are RGB scanned values from a transmissive Kodak Q-60 target and the CMY values produced by the separator. The figure illustrates that the RGB signal values and the CMY dot areas are correlated linearly.

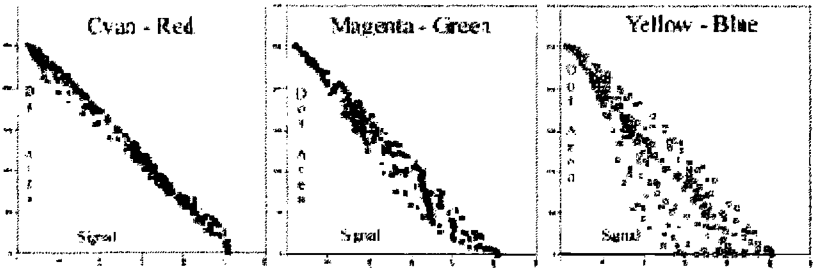


Figure 4. RGB to CMY Linearity

Studies made by McCann and Stokes (1998) on the uniformity of color spaces demonstrated that the CIE L*a*b* (1976) color space did poorly in predicting color differences as compared to the OSA Uniform Color Space and the Colorcurve Space. The hue lines are not straight, which makes gamut compression difficult. In addition, the L*a*b* space is a very nonlinear transform of the original RGB pixel data. Why translate into a nonlinear space, when the input and the reproduction are almost linear transforms of one another?

Another concern facing the color management world is the definition of RGB. There are probably half a dozen RGB spaces in use today. We almost hate to introduce yet another RGB space, but here we go.

The RGB space defined in this paper was derived to yield the best first order approximation of Guth's vision model. The RGB must be chosen to produce the proper channels for his model. Secondly, the primaries must enclose all the colors used in modern marking engines. Finally, an additional constraint was placed on the choice of RGB. We not only want a linear color system, but we also want the calculation of the vision channels to be fast.

The RGB primaries shown on Figure 5 yield the following equations to approximate Guth's vision model,

$$A = (R+G+G+G)/4 \quad (2)$$

$$T = R-G \quad (3)$$

$$D = (R+G-B-B)/2 \quad (4)$$

where A is the Lightness – Darkness channel, T is the Red – Green channel, and D is the Yellow – Blue channel. The RGB primaries used to model Guth's color space are shown on Figure 5.

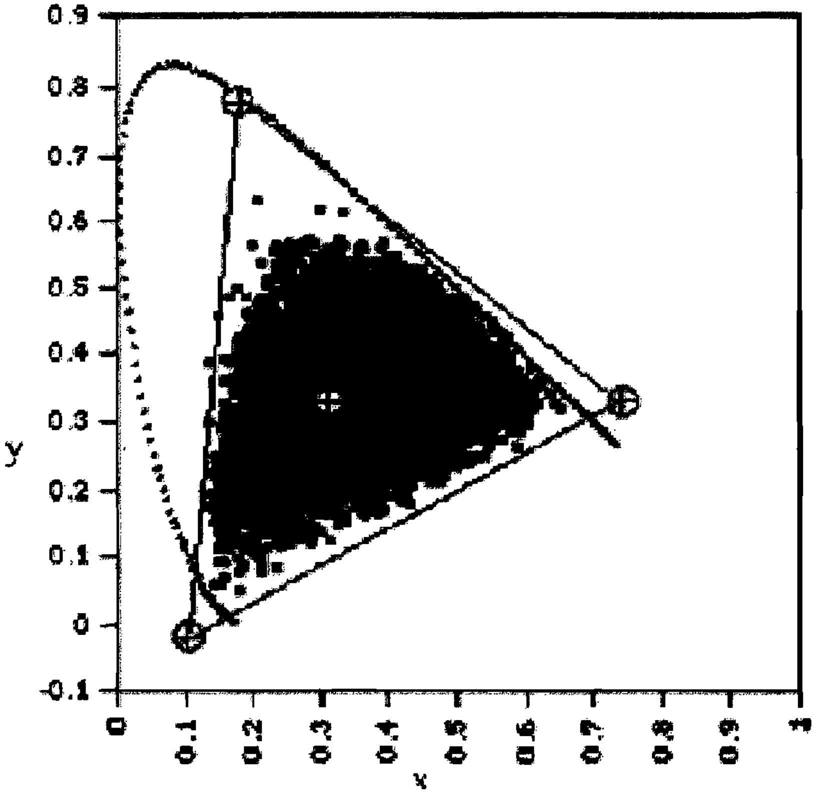


Figure 5. mRGB Primaries

The new RGB primaries will be denoted mRGB to distinguish them from the others that already exist. We chose D65 as the white point for the model given on Figure 5. It works well on displays, and it is closer to the whites of modern papers.

Figure 5 shows the large number of colorants that were considered in this study. We elected to use a large gamut range that included most colorants. The drawing illustrates that the primaries could be moved inward 15 percent. However, the wide gamut loses little in precision and leaves room for future developments in marking technology.

The ATD tristimulus values are converted to an approximately uniform chromaticity space by defining a lightness correlate, V, as,

$$V = R + (G + G + G) / 2 + B \quad (5)$$

The integer relation given by equation (5) maintains the simplicity of computation used in defining ATD. It should be noted that with 8 bit RGB data, the lightness vector, V, has 892.5 decimal states that will be held as a 16-bit integer. V is not rescaled to 8 bits. Maintaining the full scale of V is essential in the proper "natural adaptation" of lightness. "Natural adaptation", using the 16 bit integer values for V, eliminates the need to use Munsell lightness scaling. The adaptation, as will be seen later, is calculated once and placed in a lookup table. There is no need to process each pixel through a series of cube root calculations to produce a color space.

The chromaticity coordinates, t and d, are given by similar simple computations,

$$t = T / V \quad (6)$$

$$d = D / V \quad (7)$$

The mRGB primaries are not chosen arbitrarily. We are using simple integer formulas to compute a linear approximation to a general vision model researched by Guth. The ATD model is limited to the range of illumination that is typical of viewing conditions in the graphic arts. It assumes a D65 illuminant. The ATD model is restricted to this set of conditions and is not intended to predict the actions of the visual system outside this region. Within the operational range, the ATD system produces accurate predictions of hue, saturation, and lightness.

The chromaticity coordinates, t and d, are a reasonable approximation of a uniform chromaticity space considering all the limitations placed on the calculation. The lightness level 5 data of Munsell are converted to (t, d) coordinates using the binary approximation of Guth's vision model. The results are plotted on Figure 6. The uniformity of the space can be seen by using an affine transformation of the (t, d) coordinates. The transformed data is plotted on the right side of Figure 6 and is an excellent fit to the Munsell data. We have to emphasize that the scaling would be different on different lightness planes. This does not affect the ability of the (t, d) coordinate system to encode chromaticity over the 1000 to 1 range of lightness typical of digital cameras and film scanners.

The Munsell data on Figure 6 in (t, d) coordinates is as uniform as any of the CIE uniform color spaces. Considering the simple approximations made in the definitions of ATD, these results are unexpected. The selection of the mRGB primaries has produced a computationally efficient uniform color space. This is the first principle of "natural adaptation."

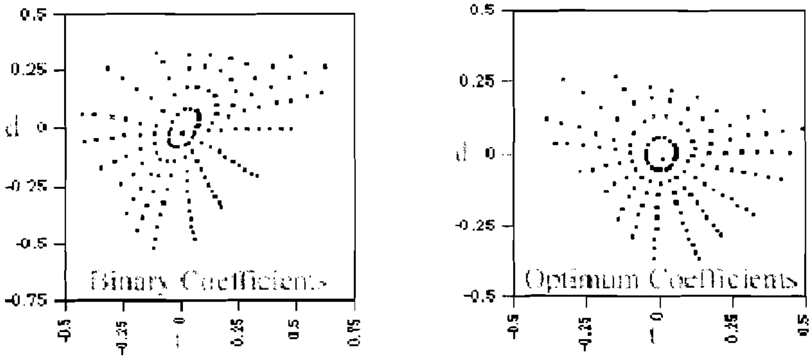


Figure 6. ATD Transform of Munsell Level 5 Color Chips

Something Borrowed

We will use the principle of "natural appearance" to gamut map colorants of different marking engines. We are borrowing the methods of painters and colorists to develop a rendering model for all methods of capture and display. The artists developed an understanding of how to portray their subjects over centuries of trial and error. Their painting techniques use color and black and white pigments to create life like images. They found that it was necessary to separate the use of color from the use of black and white.

The neutrals are important in shaping the tone scale of painting. Many painters start by painting the neutrals first. They presented a new concept of adding darkness under and white over the chromatic pigments. They have learned to separate the chromatic part of the image from the lightness – darkness component of the image. Artists know how to compensate for the darkness of each pigment on their palette. They maintain colorfulness in the darkest parts of the image by using the right amount of neutral. The darkness scaling is always based on the reflectance of the pure pigment.

In nature, the shadows are the product of the surface reflectivity and the light falling on the surface. A cloud reduces the light in one part of the scene and, therefore, adds darkness to that part of the scene. Painters mimic the natural actions of nature in the use of black. It is important to realize that the amount of light reduction in the shadow is the same regardless of the reflectivity of the scene elements. The light level of a light yellow patch is reduced by the same amount as a dark green patch. The ratio of darkness levels is the essential element of "natural appearance" reproduction. This is the second principle of "natural adaptation."

The third principle of "natural appearance" is the determination of the maximum lightness of the colorants at the input or capture of the image. The RGB target used in the calibration is shown on Figure 7. The RGB values are chosen to expose the film or paper so that only one or two of the three dyes are developed. These colors are the most luminous that can be produced by the photographic materials and form an umbrella over all the other colors that can be reproduced. The spectral reflection or transmission properties of the developed film or paper are measured before the target is scanned. The spectral values are converted to mRGB for each of the patches shown on Figure 7.

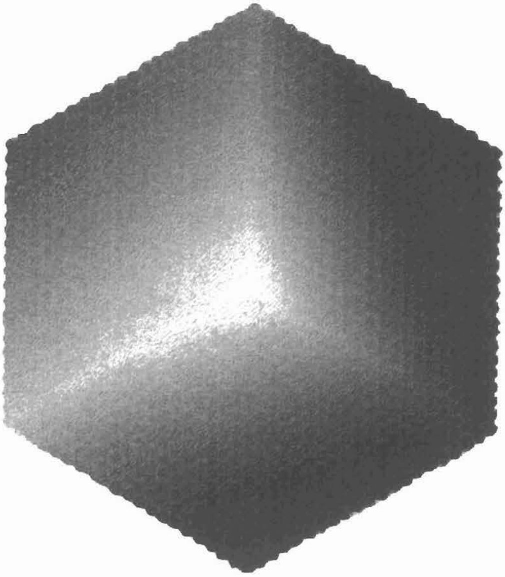


Figure 7. Hexagonal Signal Pattern

The patches are arranged in hexagonal cells. Therefore, there is always a triplet of patches that can be used for interpolation. The conversion of the scanner RGB to mRGB requires a simple 3X3 matrix for each of the triplet cells.The patch layout use on Figure 7 is to help visualize the calibration process. The measurements can be automated by arranging the pacthes in a rectangular array.

The scanner or camera must be linearized for accurate results. A linear scanner response and the mRGB values for the umbella colors are the only parameters required to measure all the colors that lie under the surface of the umbrella. How can this happen?

The ATD color space is a linear colorimetric space. All RGB and ATD tristimulus values with the property given below have the same chromaticity coordinate (t, d),

$$A = c^* A_{top} \qquad R = c^* R_{top} \qquad (8)$$

$$T = c^* T_{top} \quad \text{and} \quad G = c^* G_{top} \qquad (9)$$

$$D = c^* D_{top} \qquad B = c^* B_{top} \qquad (10)$$

where c is a darkness scaling factor, ATD is an arbitrary color, ATD_{top} is the value of a color on the umbrella surface, RGB is the uncalibrated data for the arbitrary color, and RGB_{top} is the calibrated data for the umbrella. All colors that have the same chromaticity are darkness scaled responses of ATD_{top}. Therefore, the umbrella colors completely characterize the scanner.

The calibration can be applied to any input device. All input can be transformed at the time of the scan to mRGB. If this were done, there would be no need for input profiles.

The scanned data can be converted to a new notation, (c, t, d). The term, c, is linearly related to the amount of darkness that is added to the colorants used by the output marking engine. The output engine can be a CRT, an LCD display, a traditional four-color press, or any of the new mulitcolor printers.

The separation of chroma from darkness using the umbrella concept produces a simple unitary structure for describing color that is not limited to the extant displays and printers. One example is the use of four colors in LCD displays. These devices have to trade off screen brightness for color gamut. The narrow filters required for a wide gamut reduce screen illumination. A solution to this problem is to add a fourth channel, yellow. The additional channel gives the added flexibility of producing both high-screen brightness and a wide color gamut. Other examples of a non-traditional printing solution are the six-color ink jet printers. These printers use a destaturated cyan and magenta ink to improve the rendition of pastels. Hi-Fi color is yet another example of multicolorants required to expand the color gamut. It is, therefore, important to have a color space and a rendering model that has the ability to adopt reproduction methods that do not fit under the simple RGB – CMY trisimulus ageis.

The geometric representation of darkness and the chroma umbrella is shown on Figure 8. The left side of the figure pictures the top of the chroma umbrella. The right panel is a side view showing lines of constant chromaticity, (t, d). The line from the umbrella top surface to the black point is the locus of darkness being added to the color (t, d). The diagram illustrates the new "UCR – GCR" model. The darkness addition is very different from the traditional "UCR – GCR" methods because it takes into account the darkness of the set of colorants at the top of the chroma umbrella. "Natural appearance" does not require that the actual darkness of the umbrella color be known. All that is necessary is to render the ratio of darkness to imitate the actions of the natural lighting falling on the original scene.

The method used in "natural appearance" to add darkness is not that much different from traditional printing. If we go back to the Something Old section of this paper, we find that the newsprint industry has been using a similar approach to adjust for the lack of covering power. Reshaping the tone reproduction to account for the lack of covering power does not maintain the colorimetric accuracy of the image. However it gives the best appearance mapping of the image.

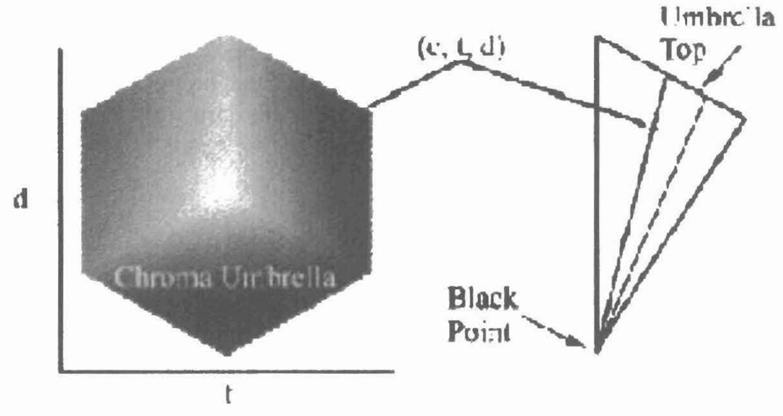


Figure 8. Chroma Umbrella and Darkness Model

The "natural appearance" method of mapping color fits the statement made by Miles Southworth (1992) – "Clean and bright is always right, dark and gray is not the way, and people should not be blue or green". The clean one or two-color overprint colors lie on top of the umbrella. The differences of the covering power and maximum gamut are adjusted by using chromaticity tone scaling of the new gamut to the umbrella gamut. Scaling the umbrella values by the darkness ratio, c, is a meta representation of the original and contains the shadow information required for a "natural appearance" transformation of the image to the new colorant set.

The new form of "UCR – GCR" guarantees that the cleanest and brightest images will result. Since we are taking into account the darkness of every point on the umbrella top, a heavy use of black ink will not muddy colors as it would in a traditional separation. Treating darkness separate from the chromatic part of the image gives us a great deal of flexibility in the choice of black models. It also guarantees the neutrals will be reproduced without unwanted colorcast.

Something Blue

The shadows of nature are blue. Blue blacks are used by artists and printers to enhance the depth and feel of the deep shadows in their images. The "natural appearance" darkness model adds new dimensions to the construction of black. The "UCR – GCR" blacks are based on methods employed when images were mechanically separated. Red, green, and blue optical separations were made to produce the cyan, magenta, yellow halftones. The exposures were adjusted so that the neutrals printed neutral and color went along for the ride. The tradition of the CMYK black models persist although mechanical separations are rarely found today.

Digital imaging opens new horizons for the creation of blacks. "Natural appearance" has made the chromatic part of the image orthogonal to the neutral part of the image. The components of the neutral scale can be selected to control the appearance of the image. Figure 9 illustrates the structure of the black model. The first column is the black ink table. That is followed the tables of the color primaries, $P_1, P_2, \ldots P_n$.

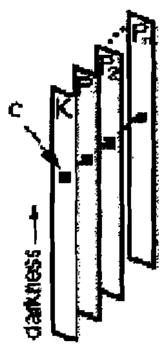


Figure 9. Black Model Structure

The number of colors used in the creation of blacks is not limited to CMYK and can be extended to any set of primaries; $P_1, P_2, \ldots P_n$ and K. Cyan, orange, and black can be combined to produce very dense blacks when printing with six colors. The components can be chosen to create special effects such as warm highlights and cool blacks without considering of the effects on tonal balance.

There are 893 states in the black table. The table is addressed by the darkness ratio, c. Dot areas stored at a given address are elements of a multi-tone neutral. The multi-tone neutral spans the 893 levels of the table. The table is structured to include the darkness adaptation required to compensate for covering power. The darkness model can also incorporate the color of the substrate into the black model. The dense table of darkness values obviates the need to use CIE L*a*b* to encode the darkness steps.

One unexpected advantage of the "natural appearance" is the handling of keyness. We have found that the combination of adaptation and the long gray scale eliminate the need to consider the original tone scale. The darkness ratio model maintains appearance as we transfer the image from stage to stage in the reproduction process.

Summary

The computer and graphic arts industries must agree on an RGB space. Many extant methods can produce input device profiles for mapping raw RGB values to a colorimetric based RGB space. A large number of RGB spaces are in use today. The plethora of spaces is confounding efforts to move toward true device independence and a workflow that does not require tags or profiles.

The theme of this paper is that the adoption of a single RGB space removes at least one profile in the imaging chain. We show that one choice, mRGB, leads to a linear – uniform chromaticity space, ATD. The ATD space is designed to use integer arithmetic. The combination of very few equations and integer mathematics produces a computationally efficient image-processing algorithm. The speed increase is estimated to be 10 to 15 times alternative floating-point algorithms.

A study of the techniques of artist and colorist led to a non-metric – vision based gamut mapping technique. The ATD color space is channel based. It has three channels; lightness – darkness, red – green, and yellow – blue. The channels are independent. We find that the channels respond to a form of signal conditioning that imitates the channel's light adapting capabilities. We add a small amount saturation adaptation to the images. The visual channels respond by producing signals more intense than if no correction is used.

The ATD channels are independent. Therefore, the lightness – darkness channel can be separated from the chromatic channel. We are using the "natural appearance" methods employed by painters and colorists to define a new "UCR – GCR" black model. The "natural appearance" model applies an amount of darkness that is the ratio between the black point and the darkness associated with the brightest color that can be produced using one or two colorants. The darkness ratio established at the input stage is invariant. Hence, the input becomes an invariant meta-color space.

Gamut mapping the meta-space to any other colorant system is accomplished by using the saturation growth adaptation of the new colorants to the meta-colorants. This is accomplished by storing the color data in a two-dimensional array. The array is indexed by the (t, d) chromaticity of the meta-color space. Each (t, d) coordinate has the colorant amounts required to reproduce the exact hue and the adapted saturation required to approximate the meta-color. The darkness ratio, c, indexes the black components of the model. The addition of the color and the black components produces the dot values used in rendering the meta-color.

The "natural appearance" gamut mapping has the advantage of mapping all colorant systems from a single model. The gamut stretching is done in the tables. Documents do not need output profiles. There is only one meta-color space profile and it is defined at the time of input. For the first time, once an image is scanned the data never needs to be repurposed. The document has a single definition and can be output on any device.

This paper has created a full dowry that should restore the marriage of graphic arts and electronic imaging. Each element added; something old, something new, something borrowed, and something blue, will enable graphic arts to embrace device independence. The replenished dowry has produced a simpler and more productive workflow.

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