An Exploration of the Pantone® Hexachrome™ Six-Color System Reproduced by Stochastic Screens

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Abstract

The Pantone® Hexachrome™ color mixing system is a Hi Fi device-dependent space consisting of five chromatic colors and one achromatic color. These six primaries produce a larger gamut of colors than those available from the cyan, magenta, yellow and black (CMYK) device-dependent space of conventional printer's inks. Most images produced by scanners originate in red, green, and blue (RGB) video device space before transformation to Hexachrome space. The Hexachrome color system is described in relation to a typical CMYK device-dependent space and RGB video space. In general the Hexachrome system, like most device—dependent spaces, is non-linear and device dependent.

The reproduction of Hexachrome colors using Icefields® stochastic screens is press-tested and an analysis is made. There are inherent reproduction differences between conventional halftone screens and stochastic screens. This paper assumes that the capability of stochastic screens to improve CMYK reproduction also improves Hi Fi reproduction. A description of the advantages of stochastic reproduction of the Hexachrome Hi Fi color system is given.

Keywords

Hexachrome, RGB color space, CMYK color space, black generation, gray balance, device-dependent space, device-independent color space, chromatic, achromatic, frequency modulation, amplitude modulation, stochastic screening.

Definitions

For purposes of this paper:

Amplitude modulation. The dot diameter increases in direct proportion to a darkening gradient. Dots are aligned in a matrix skewed at an angle.

Frequency modulation. The dot count increases in direct proportion to a darkening gradient. Dots can be positioned in a matrix or in any pattern.

Stochastic screening. Frequency modulated screens in which dots are arranged in a non-deterministic pseudo-chaotic texture in low image frequency areas. In high image frequency areas, dot patterns are structured to reflect the image definition.

Hi Fi Color. Extension of the process-color device-dependent space by the addition of true complementary colors, split primaries, primaries exhibiting uncontaminated spectral curves, or booster colors. Hexachrome adds green, the complement of magenta, and orange, the complement of cyan.

Introduction

General Characteristics of the Hexachrome Device-dependent Space

The addition of Hi Fi colors to the printer's collection of tools allows the printer to reproduce more colors at greater accuracy than possible with the typical CMYK color-gamut. Many Hi Fi color systems use the additive primaries red, green and blue and the subtractive primaries cyan, magenta, yellow and black to recreate the spectrum. There are very few seven-station printing presses in North America. The Pantone® Hexachrome™ system is ideal for a six-station press.

Hexachrome colors can only be described in device-dependent space since they consists of five chromatic inks, most with unique spectral curves. There is no device-independent perceptual Hexachrome model. The Hexachrome color mixing system consists of five primary chromatic colors—yellow, green, cyan, magenta and orange—and achromatic black to darken of gray the colors. These six colors are screened to allow the white of the paper substrate to lighten the colors.

The Hexachrome system is a non-linear color space, consisting of:

- primary hues with spectral curves different from those of true primaries (with the exception of yellow),
- unequal distances between the chromatic primaries,
- different spectral power curves for each primary, resulting in primaries of different brightness
- complementary colors that are not exactly polar opposites on the color wheel.

Brightness is accomplished by screening or adding black according to the observer's logarithmic response to the luminance component of the color. Decreasing or increasing brightness is another non-linear aspect of the Hexachrome system.

Gray Balance Combinations

Achromatic shades in tristimulus color systems are produced by mixing three primaries in equal percentages. In a device-independent CMYK color system, shades of gray are produced by mixing amounts of three primary inks according to ratios that compensate for their impure spectral curves. In the Hexachrome five-chromatic system, shades of gray can be obtained by mixing a primary color with the polar opposite colors of that primary color.

Group 1

Dominant Primary Color	*Polar-Opposite Primary Color Combinations*
Y	CM'
G	MO'
C	OY'
M	GC'
O	CM'

** ' Indicates the minor color of the complementary color ratio.*

When the dominate color is a secondary color, i.e. a mixture of two adjoining primaries, achromatic shades are also produced by the addition of polar opposite colors.

Group 2

Adjoining Primary Colors	*Polar-Opposite Primary Color Combinations*
YG'	CM
GC'	MO
CM'	GY/OY
MO'	GC
OY'	CM

Group 1 can be eliminated by assigning each color adjoining the dominant primary color, i.e. colors indicated with a', the value of 0, therefore there are five combinations of four primaries that result in achromatic tones.

Gradient Combinations of Hexachrome Chromatic Colors

Gradients are produced by mixing adjoining primaries. A gradient begins with 100% of one primary and 0% of the adjacent primary. The percentage decreases until the primary color that began at 100% reaches 0%. For example, a gradient that changes from yellow through green to cyan in the CMY space begins with yellow at 100% and cyan at 0%. The midrange green is formed with 50% yellow and cyan. This gradient ends with 0% yellow and 100% cyan. The Hexachrome color system uses three primaries to create the same yellow/green/cyan gradient. There are five gradient combinations: yellow/green/cyan, green/cyan/magenta, cyan/magenta/orange, magenta/orange/yellow, and orange/yellow/green. Most images contain gradients. Grass turns from yellow to blue-green, sunsets from red to yellow, etc.

RGB to Hexachrome Color Transformation Procedures

There are three methods to derive a Hexachrome space from a RGB source image:

1. A color mixing system,
2. A C'M'Y'K' device-dependent space with orange and green booster colors, (' distinguishes Hexachrome primary inks from conventional process color inks),
3. Direct transformation relationship of RGB space to C'M'Y'K'OG device-dependent space.

1. Ink Mixing System

Leonardo da Vinci invented a very simple color mixing system. (This system was later refined by Harald Kueppers.) All the colors in the visible spectrum are the result of mixing two adjoining chromatic colors and then adding the achromatic colors, black or white, to darken or lighten the chromatic color. Leonardo da Vinci used six primary colors – yellow, green, cyan, violet, magenta and red. Each primary is positioned in a circle 60 degrees apart.[1] In his system, a chartreuse green is made by mixing percentages of green and yellow plus a little white. Yellow cannot be mixed with cyan to produce chartreuse since yellow and cyan are not adjoining colors. A color cannot be mixed with its complement to form gray. Gray is produced with the addition of black. The Pantone® Hexachrome™ Color Selector follows this method.

Black is an integral color in this system. All gray shades are available only with the addition of black. Black is not used in a tristimulus color-space such as CMY. According to the CMY substractive color-theory, a neutral color is produced by adding a third color to two adjoining colors, e.g., gray is the result of adding magenta to the two adjoining colors – cyan and yellow. In the CMYK space, black is used to make a truer gray than possible with the mixture of impure CMY inks. Gray balance with only primary colors is not specified in the Pantone® Hexachrome™ Color Selection system.

The da Vinci mixing system is used for reproducing Pantone's numbered color swatches. Find the appropriate color from the Pantone® Color Selector booklet, and look up the percentages of its adjoining color components and the amount of black, or screen, of those colors.

2.C'M'Y'K' with green and orange booster colors

In this case, two maps of colors are made – one map for all the colors that are reproduced by Hexachrome process colors (C'M'Y'K') and another of all the missing colors in the RGB green and orange spectral range. Convert the image's RGB source image to C'M'Y'K' in a conventional manner. Add the orange and green booster colors following the green and orange map to reproduce the missing colors. Adjust the percentages of the mixture to account for variations in tone caused by the addition of green or orange.[2]

This method extends the C'M'Y'K' gamut, but the transition to booster colors is difficult to control. A gradation from yellow through green to cyan is expanded by adding green. The yellow and cyan inks must be reduced where the booster green is added.

3.Transform the RGB image directly to Hexachrome colors

In this case, a table or script is used to convert the image in RGB space directly to Hexachrome primary colors and their mixtures. The RGB color gamut is compressed and adjusted to duplicate the Hexachrome device-dependent space. Black generation is accomplished by producing a brightness plane and removing respective amounts of the gray component from the chromatic colors. Since black is not part of the visual spectrum, all achromatic tones must be created first with the five chromatic color combinations before black generation is considered.[3]

Testing of Hexachrome Ink Performance

The direct color-transformation from RGB to Hexachrome method was selected for press-proof analysis of Hexachrome's performance. The direct-transform procedure allows for better control of gray balance, black generation and total ink percentages.

Hexachrome Gamut

Hexachrome's ink characteristics were compared to RGB and CMYK characteristics using Hue, Saturation, Lightness (HSL) data derived from RGB equivalents of Pantone numbered swatches. RGB equivalents of Pantone® Hexachrome™ swatches were provided by Pantone, Inc. The RGB coordinates were converted to HSL color space using the Apple Color Picker. *(Figure 1)*

The RGB transformations expressed in percentages were:

Primary	*Red*	*Green*	*Blue*
Yellow:	100%	90%	0%
Orange:	100%	40%	9%
Magenta:	88%	15%	42%
Cyan:	7%	47%	67%
Green:	0%	64%	20%
Black:	12%	10%	8%

The Apple Color Picker conversions to HSL color space were:

Primary	*Hue angle*	*Saturation*	*Lightness*
Yellow:	54°	100.00%	50.00%
Orange:	20°	100.00%	54.50%
Magenta:	338°	75.25%	51.50%
Cyan:	200°	81.08%	37.00%
Green:	139°	100.00%	32.00%
Black:	30°	20.01%	10.00%

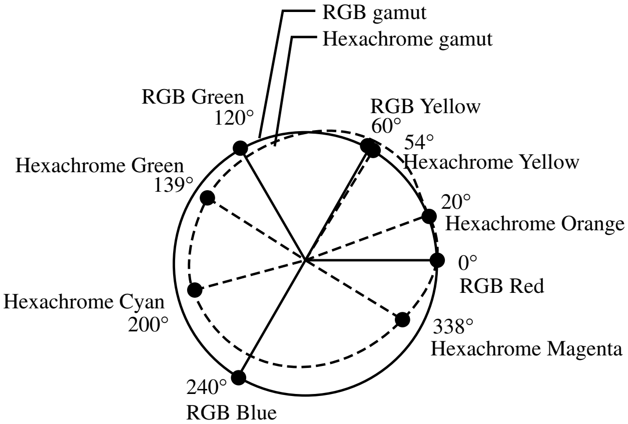


Figure 1. HSL Color Wheel

There are as many CMYK gamuts as there are color printers. The following HSL space coordinates represent a general CMYK device-dependent space based on Pantone's process CMYK primaries converted to HSL space by the Apple Color Picker.

The RGB transformations expressed in percentages are:

Primary	*Red*	*Green*	*Blue*
Yellow:	100%	93%	0%
Magenta:	88%	90%	41%
Cyan:	0%	64%	89%
Black:	0%	0%	0%

The Apple Color Picker conversions to HSL space are:

Primary	Hue angle	Saturation	Lightness
Yellow:	56°	100.00%	50.00%
Magenta:	336°	77.78%	49.50%
Cyan:	196°	100.00%	44.50%
Black:	0°	0%	0%

A modified HSL wheel demonstrates Hexachrome, RGB and CMYK gamut size differences. *(Figure 2)*

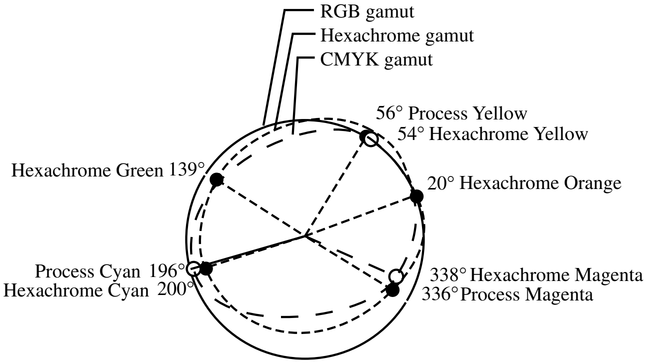
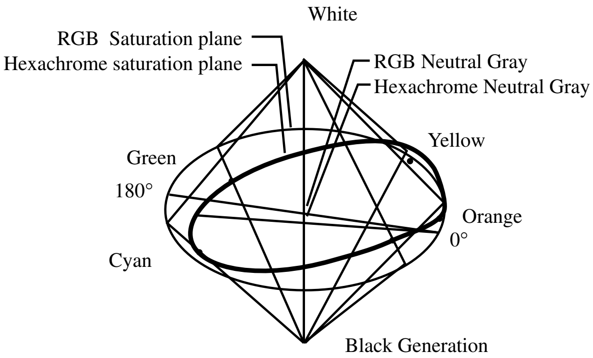


Figure 2. HSL Color Wheel

The HSL hue angles demonstrate that the Hexachrome primaries are not symmetrical around the color circle. Any secondary color's distance between two adjoining primaries is non-linear. The number of colors available between major axes, or primary degree angles, vary with the distance of degree of separation.

The resulting gamut chart indicates that many secondary colors formed by magenta and cyan, i.e., those colors associated with saturated violet, are missing. Green and cyan lack brightness. Adding white to these tones does not result in brighter inks but in pastel shades of green and cyan.

The Hexachrome gamut is larger than the CMYK gamut. The increased purity of the inks, and the fluorescent component of yellow, orange and magenta inks, extend the gamut by increasing the number of secondary colors and providing greater spectral power distribution. *(Figure 3)*



Hue, Saturation, Lightness Color Space

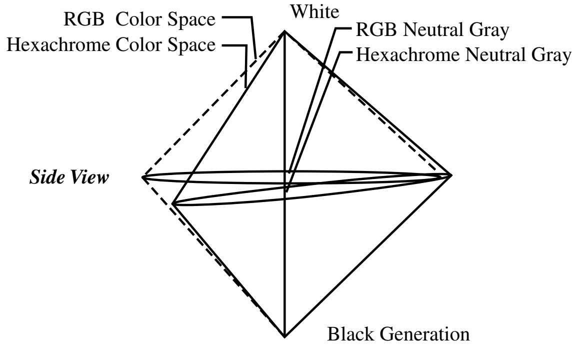


Figure 3. HSL Color Space

Hexachrome Ink Densities

Two test forms were printed. The first test form was printed from negative film in Canada and from positive film in Japan. *(Figure 4)* This test form included C'M'Y' and C'M'Y'K' gray balance patches, color patches composed of two and three adjoining primaries, with and without black, and complementary color combinations. The screen percentage ratios were according to ISO SCID standards and of equal percentages. Dot-gain compensation was computed during the stochastic screening conversion process. A second test form consisting of only the C'M'Y'K' colors was printed in the United States (Not reproduced for this paper).

Icefields® stochastic screening software was selected because of its:
excellent dot offset,

- linear dot-gain throughout all gray levels,
- accurate frequency modulation,
- high detail in shadow areas,
- easy dot-gain compensation interface, and
- ease of the dot diameter selection to meet the dot size needs of the various imagesetters and printing presses at the three locations.

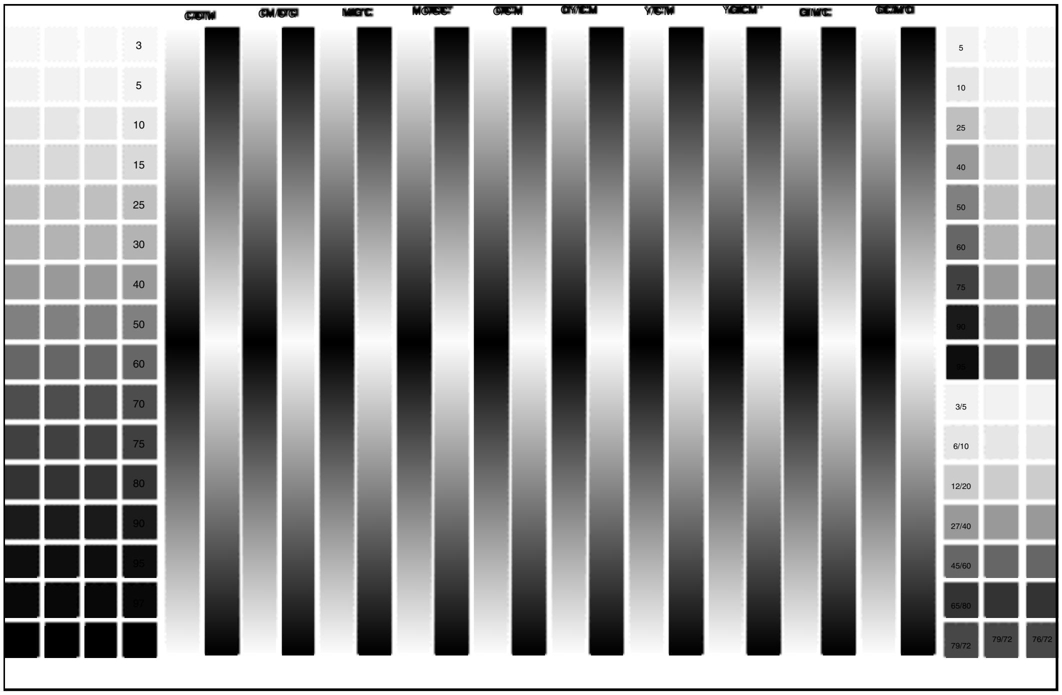


Figure 4. Test Form

At the Canadian press site, the following ink densities were used:

Orange (using the magenta filter)	1.4
Green (using the cyan filter)	1.4
Cyan	1.6
Magenta	1.2
Yellow	0.9
Black	1.7

The Japanese press site used the following ink densities:

Orange (using the magenta filter)	1.6
Green (using the cyan filter)	1.6
Cyan	2.0
Magenta	1.6
Yellow	1.2
Black	2.0

The color printing sequence for the Canadian company was yellow, orange, magenta, green, cyan and black. In Japan the ink order was orange, yellow, magenta, green, cyan and black. The inks were not perfectly transparent and trapping yellow on top of orange resulted in brighter secondary colors.

At the Canadian printing press, ink densities were adjusted until the C'M'Y' gray-balance colors appeared gray to trained observers. These ink densities are used as standard densities for Hexachrome reproduction at sites using Icefields® technology.

The density differences between the Japanese and Canadian tests indicate that Hexachrome yellow reflects more light than process yellow causing the C'M'Y' and the C'M'Y'K' gray balance to have a warm color cast. The greater density of the Japanese test also resulted in greater saturation and dot-gain.

The second test form, printed in the USA, compared halftone with stochastic screened photos and test patches. The test form was the result of a conventional RGB to CMYK transformation. Four pieces of film containing halftone and stochastic variations of each image were produced. Dot-gain of the stochastic screens matched the halftone dot-gain. Ink densities of the halftoned images were set at SWOP halftone reproduction standards.[4]

The halftone gray balance shifted to a brown cast, but the stochastic screens held the neutral gray tones. A warm color cast in the images was apparent in the halftone screen reproduction. As expected, the C'M'Y'K' reproduction was warmer and reds were brighter, when compared to the same image reproduced from the same plates using conventional process inks.

Stochastic Screening Color Reproduction Characteristics

Anecdotal observations comparing stochastic with halftone screens suggest that the following characteristics of stochastic screens may benefit the reproduction of images using Hexachrome colors.

Stochastic Dot Perimeter Gain

Proper dot-gain control results in diminished visual grain, control of saturated colors and elimination of stochastic screen's larger optical gain.

Dot perimeter measurements indicate that a stochastic screen, in the 0% to 50% gray range composed of dots of the same diameter and number as a halftone screen, exhibits less dot-gain by perimeter movement. The clustering of the stochastic dots accounts for the lower dot-gain. Stochastic screens, consisting of smaller diameter dots and of greater number, exhibit greater gain than halftone screens. Even though the dots are smaller, and hence their perimeters shorter, the dots are more numerous and the larger number of dots results in greater gain.[5] Dot-gain resulting from light scatter through the film emulsion, (modulation transfer function), may be greater.[6] *(Figure 5)*

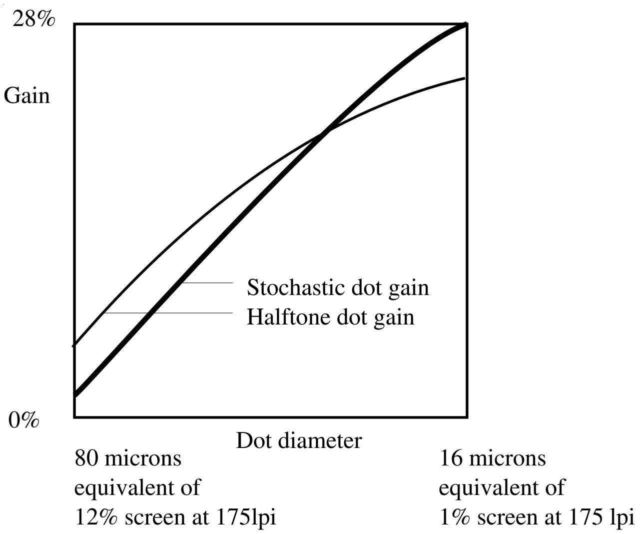


Figure 5. Physical Dot-Gain at 50%

Optical Dot-gain

The pattern of dots affects light reflection and light absorption. Amplitude modulated screens reflect light in an organized manner. Irregular frequency-modulated screens introduce noise into the reflected light. Fourier analysis suggests that the even-spaced halftone dots allow light to retain some of its coherence. Light reflected in the same manner with irregular stochastic adds noise to the reflection pattern disturbing the coherence of the reflected light and increasing optical gain. *(Figure 6)* The additional colors of the Hexachrome system my increase optical dot-gain.

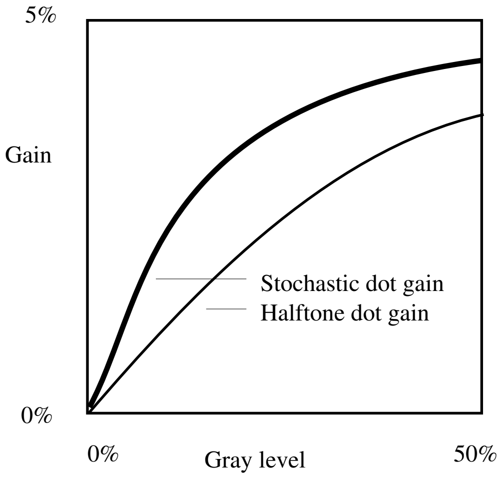


Figure 6. Optical Dot-Gain at 50%

Optical and Physical Mixing Characteristics of Stochastic Screens.

The pattern of dots in a stochastic screen minimizes the optical mix of primary colors normally associated with halftone rosettes. The pattern maximizes physical mixing or trapping of primary pigments. Secondary colors resulting from physically mixing inks may produce different spectral frequencies than secondary colors resulting from the optical mix of the same percentages of the same primary colors. The physical mixing of primary colors may result in the production of a greater number of secondary colors than the optical mixing of halftone dots in rosette patterns.

A visual comparison of ink mixing at highlight, quarter tone, midtone three-quarter tone and shadow tone indicates:

- In shadow and three-quarter tone areas the irregular positions of white areas, or voids, cause greater fill-in due to the larger area of ink around the voids than in similar halftone screens.
- In the midtones, the irregular dot positions cause greater areas of ink to be mixed with previously applied ink. This process is called wet trapping
- The halftone screen's rosette pattern at quarter tones prevents ink trapping, and secondary colors are the result of optical mixing. Stochastic screen's clusters trap more ink in the quarter tones resulting in less optical mixing.
- Secondary colors in the highlights for both halftone and stochastic screens are the result of optical mixing.

Inks that are physically mixed may create a better gray balance and a larger gamut if those inks contain amounts of true pigments and are transparent. Pantone's ink formulation produce a purer yellow, orange and magenta. Stochastic screening of Hexachrome's purer colors may result in a fuller color gamut in the quarter-, mid-, three quarter- and full-tones.

Gray Balance

The physical mixing of colors in stochastic screens may produce a better gray balance than possible with optical mixing. Stochastic screening of Hexachrome colors benefit from:

- improved gray balance over halftone.
- smaller variations in dot-gain result in better control of color cast.
- a substitution of achromatic black beginning at darker percentages.

Definition in Saturated Colors

Greater saturation of color, without dot-gain, extends the color gamut. Stochastic screens produce shadow tones with fewer voids than halftone screens, therefore the lower dot count increases saturation. Hexachrome colors exhibit greater saturation without loss of image definition.

The Perception of Stochastic Granularity

The perception of grain is controlled by the darkness of the color used, the frequency of image data, size of the individual dots, and the accuracy of the transformation.

In high-frequency image areas, the pattern of dots is structured by the image detail. Dot structures consistent with the image detail contain little grain. Dot patterns that reflect image detail structure add another level of communication of visual information. Dot structures place color more precisely than halftone dot matrices and hence color fidelity is greater.[7]

The physical mixing of inks appears to diminish graininess. The physical mix of primaries may form truer shades of secondary colors than does halftone's optical mix. If truer secondary colors is the result of mixing primary pigments, then it follows that there are more secondary colors in stochastic screens. Secondary colors behave according to a combination of subtractive and additive color theory.8 It remains to be tested if the greater additive color response in stochastic screens results in more accurate spectral transmission curves. Mixing of more than three Hexachrome colors may display less granularity.

A Recommended RGB to Hexachrome Transformation Procedure

The use of RGB video space as the origination color space solves many color-correction problems. Metameric differences, white point, color correction and negative spectral curves are a few of the problems solved during the production of the RGB image.

The image is converted to Hexachrome space by following a color-transformation management procedure. A common procedure follows:

1. The RGB gamut is compressed to match the Hexachrome gamut. A perceptual map of the remaining colors changes the RGB gamut to conform to the Hexachrome gamut.
2. Black generation and gamma considerations further distort the RGB image.
3. A direct conversion from RGB color space to Hexachrome device-dependent space is made. *(Figure 7)*
4. Black generation is applied.

Conclusion

Stochastic reproduction of Hexachrome colors has several advantages over halftone reproduction.

Gray-balance is achieved with the combination of two primaries and two polar-opposite primary colors plus black. Gray-balance achieved by stochastic screens does not suffer from moiré. Gray-balance produced by trapping of stochastic dots may be more accurate and more tolerant of dot-gain variations.

Total ink percentage is easier to control. Black does not need to be generated until about the 70% level compared to about the 40% level with halftone. Printers using Hexachrome are using a relatively high-cost system of color reproduction, and the economic reasons for black generation are not applicable.

Hexachrome also improves stochastic reproduction. The combination of five colors to form neutral-gray areas may reduce multiplicative grain in flat areas.[9]

k density is a measure of the ability of ink to absorb light. Ink density is only one element in dot-gain control. Dot-gain is controlled on the press by adjustments to blanket pressure, ink viscosity, water repel, and ink density. However, darkness and saturation of a color directly relate to dot-gain, hence the tolerance to dot-gain variations is an asset. It appears that stochastic screens are more tolerant to dot-gain variations than are halftone screens. The smaller stochastic dots exhibit smaller perimeter movements than does a halftone dot. Hexachrome inks may be more tolerant of dot-gain density variations.

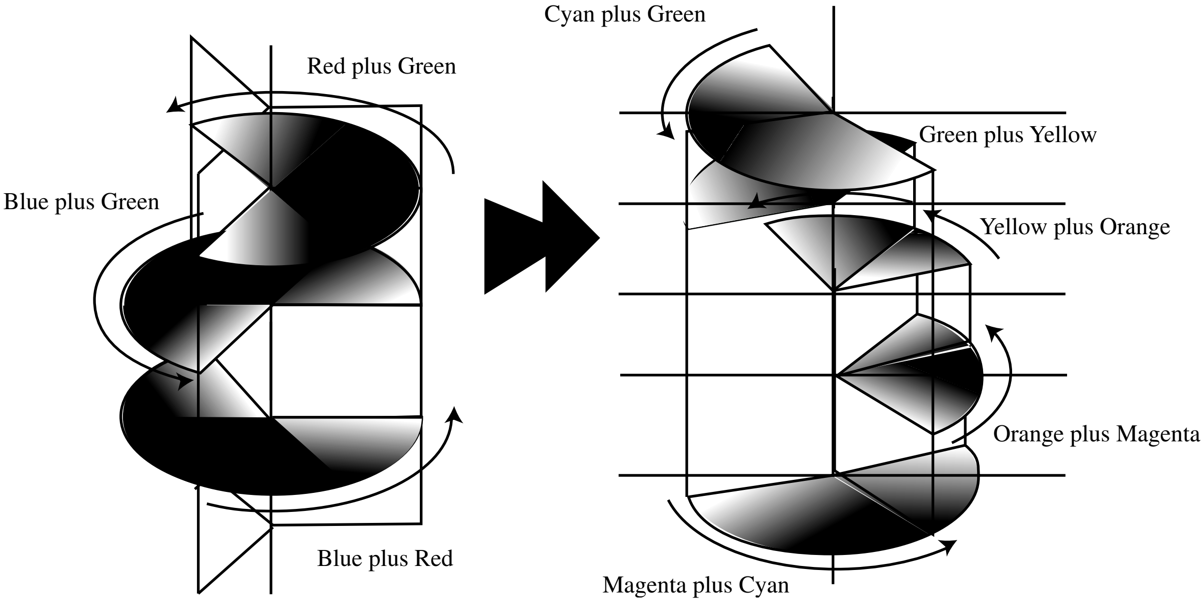


Figure 7. Color Space Conversion

Stochastic screens may increase Hexachrome's gamut by extending saturation and more accurately mixing secondary colors.

Hexachrome colors may exhibit less chroma-shift due to dot-gain variations with stochastic screens.

Disadvantages may include greater dot-gain, greater optical dot-gain and greater graininess in highlight areas.

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