Multi–primary printing

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Abstract

In this keynote the focus is on mapping out the landscape of benefits provided by multi–primary printing and on highlighting some of the major challenges that stand in the way of harnessing its potential. A brief introduction to three and four primary printing and the business needs for multi–primary printing is followed by an enumeration of potential benefits that printing with more than three primaries has. Next some of the key challenges of using larger numbers of primaries are discussed and finally examples are given of future opportunities opened by multi–primary printing.

Introduction

Digital printing is undeniably on the increase and the use of color is becoming responsible for more and more of its output. More than half of the pages prepared for printing being available in electronic form, a growing number of color printers being used and cost–cutting pressures faced by businesses all contribute to growing demand for digital printing, with an estimated 1.14 trillion pages available for digital printing world–wide. Furthermore, of all the digital printing revenue 68% comes from color content and there is a move from black and white to four or more color printing where the latter is expected to reach 75% of printed volume in 2015 (currently at around 45%). There is also a move towards printing with more than just the conventional CMYK primaries with around 10% of printed output being of this kind at present and expected to rise to 15% by 2015. It is worth noting that the worldwide digital print market, which was worth an estimated €32 billion in 2005 is predicted to increase to €125 billion by 2015 and market share is therefore highly desirable here.[1]

From a publishers' and print service providers' perspective the move to higher–quality color content allows for greater added value while in–house color printing provides flexibility, faster response, distributed, decentralized production and lower production cost to its users. Color in the office is also on the increase and delivers greater effectiveness from printed documents. At the high–end of photographic color printing the use of multiple primaries allows for the printing of images that can contain wider ranges of colors and have the permanence of silver halide prints while having all the advantages and new possibilities that digital production facilitates. Photographers get closer to showing the full potential of their images and expressing more completely their vision.

With color printing delivering clear benefits both to print service providers and businesses of any size that use it in–house and with increasing expectations of output quality there is a need to go towards more sophisticated and complex systems to meet and exceed them.

In the above context the focus of this keynote is multi–primary printing both in terms of its many potential benefits and accompanying scientific and engineering challenges. What will be meant here by 'multi–primary' printing is printing were there are more than the three subtractive primaries – cyan, magenta and yellow and what is meant by a primary is a colored material that is deposited onto a substrate in the printing process (e.g. an ink containing pigments or dyes, a toner, a wax, …). Furthermore, the focus here will be on systems where additional chromatic primaries that are not simple dilutions of CMY are used since these open new horizons and pose new complexity.

CMY and CMYK printing

Before looking at multi–primary printing it is worth summing up the key properties of CMY printing and to introduce the changes brought about by a fourth primary – black. The set of ideal CMY primaries is such that each one of them intends to control the response of one of the eye's color receptors – the cones[2] (Fig. 1). Changing the amount of cyan ink, for example, results in changes to the amount of light absorbed in the low–frequency part of the visible electromagnetic spectrum to which the L cone is sensitive and the other two inks equally pair up with the remaining two cone types. A great advantage here is that for each color that can be obtained using a set of CMY primaries there is exactly one combination of C, M and Y amounts that results in it.

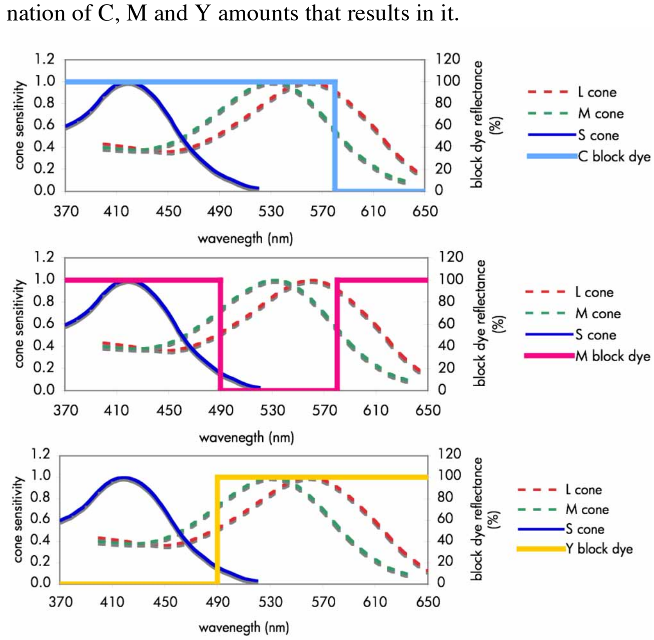

***Figure 1**. Spectral reflectances of ideal CMY primaries (block dyes) and cone sensitivities.*

However, using only CMY inks also has serious shortcomings both for images (where they limit the range of achievable colorfulnesses and lightnesses) and for text and line art (which is often black but has to be printed by combining CMY).

The reason for the limited color range (gamut) of CMY printing is twofold: First, the cones of the human eye have sensitivities that overlap (i.e. there are large wavelength ranges in the electromagnetic spectrum to which more than one cone is sensitive) and three primaries therefore do not allow for an independent control of each cone's responses (Fig. 1) – this is known as *unwanted stimulation*.[2] As a consequence the response to some spectral power distributions cannot be replicated with just three primaries – no matter what those primaries are. Second, actual subtractive color reproduction primaries (as opposed to the ideal ones shown in Fig. 1) have *unwanted absorptions*[2] – i.e. they absorb light even in parts of the spectrum that they are not meant to control (Fig 2).

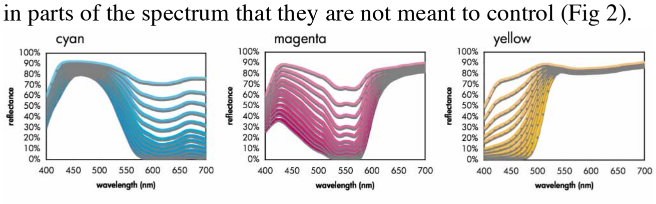

***Figure 2**. Spectral reflectances of actual CMY inks.*

Furthermore, CMY prints are likely to have poor color constancy (i.e. their appearance changes noticeably with changes in the illuminating light source). As a result black ink (K) has been added to the printing ink–sets early on and a list of benefits ensued: increased lightness range, ability to print black line art and text using a single ink, lower cost (amounts of CMY were replaced by a smaller amount of cheaper K ink), potential for better color constancy (using more black allows for prints that change less with changes in lighting). These benefits are not for free though and they introduce two features that become more ample as the number of primaries increases: First, redundancy – the same color can be achieved using multiple, alternative primary combinations (e.g. K=10 and C=M=Y=10 may be equivalent in resulting color on some printing system). Second, likelihood of trade–offs – from among the alternatives some will be better in terms of one attribute and others will excel differently (e.g. K=10 is cheaper and more color constant while C=M=Y=10 is less likely to look grainy). The result is a situation where it is important to identify which print attributes matter and use primaries so that the extent of individual ones is balanced appropriately. Finally, what is an appropriate balance is likely to depend on the print's application (e.g. in photography grain is more objectionable than in technical illustrations).

Multi–Primary Printing Benefits

The most obvious benefit of having more than three chromatic primaries is the increased *color gamut* that this makes possible. The reason for this is that adding carefully chosen new inks to CMY allows for a reduction in unwanted absorptions and therefore the generation of spectra that allow for greater cone response ratios and therefore greater resulting colorfulness. For example, adding a red a green and a blue ink to CMY increases the color gamut on a given paper by 24% in the case shown in Fig. 3.

The next potential benefit of multi–primary printing is the reduction of *color inconstancy* (i.e. the change of print appearance with changes in illumination spectral power distribution). While in the CMY case each in–gamut color could be matched using only a single primary combination, the availability of K allowed for greater color constancy for some in–gamut colors. Having additional chromatic primaries further extends this since most in–gamut colors (under a given light source – e.g. D50) can now be matched using an entire set of alternative primary combinations (e.g. for a hypothetical set of primaries C=M=Y=10, K=10, C=R=10, M=G=10 and B=Y=10 all give the same color under D50 but have very different spectral properties). Of those alternatives one will have less color inconstancy than others and, all else being equal, is the one that could be used.

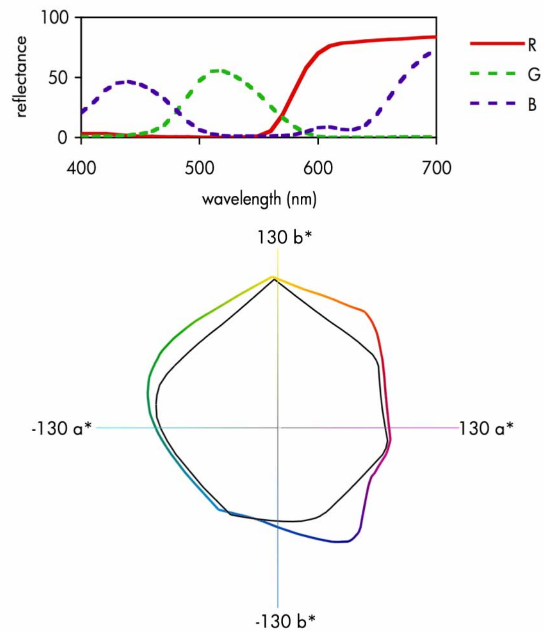

***Figure 3**. Top: spectral reflectances of red, green and blue inks; Bottom: Color gamuts of CMY (black line) versus CMYRGB (colored line) printing in the CIELAB chroma – hue plane.*

Such alternatives also make *spectral reproduction* possible – i.e. given an original it can be that original's spectral reflectance rather than just its color under a specific light source that can be matched. The consequence of such a spectral match would be a reproduction that always looks the same as the original when the two are equally illuminated. In other words it is a reproduction that is free from metamerism.

Having several dilutions of the same colorant material (e.g. two primaries differing in the amount of magenta pigment they contain – i.e. a 'light' and a 'dark' magenta) as primaries also opens the door to *reduced grain* and this is a strategy that has been around for a long time in printing. What this allows is the use of the lighter primary for the reproduction of lighter colors and the darker primary for darker ones. The consequence is lesser visibility of ink dots in lighter colors, which results in smoother, less grainy appearance. While two dilutions of the same ink have been used for a long time more recently the use of four dilutions of black ink has been introduced and allows for a dramatic reduction in grain from inkjet printing. The result is the appearance of continuous tone, photographic quality.

Having more primaries also allows for the use of less colorant volume overall, which has potential cost, drying time and productivity benefits. The reason for this again comes from the availability of alternatives and for at least one of them using less ink than others (e.g. M=Y=10 can be replaced by R=10 in a hypothetical printer, which would result in a halving of the ink mount).

Finally, the availability of RGB colorants in addition to CMY ones makes it possible to print without the need for overprinting the primaries, which is an idea introduced by Küppers.[3] Since a CM overlap can be replaced by a B primary (and analogously for other combinations) the result is a print that has at most the maximum amount of one primary in any one location. The benefits of such printing include the possibility of using opaque primaries, of using less ink and of having a system whose behavior is easier to predict.

Multi–Primary Printing Challenges

All of these advantages are far from being low–hanging fruit. Instead, most of them require making choices from among a combinatorial explosion of alternatives – the same alternatives that are the source of potential benefits – and with multiple, often conflicting, requirements in mind.

For example, even just determining the *color gamut* of a 12 ink printer requires sampling a 12 dimensional space, which, even at a coarse, uniform sampling of 10 steps per colorant would result in 1 trillion colorant combinations. Even just predicting the color of each of these primary combinations would take decades of computation. Instead it is necessary to use advanced sampling techniques that deliver the correct result without having to sample combinations exhaustively.[4,5]

Harnessing the *color constancy* potential of multi–primary ink sets too is a complex challenge and even though there has been a lot of research in this area[6,7] the current status is one where it is possible to have color constant multi–primary prints, but not ones that also deliver smooth transitions between colors.

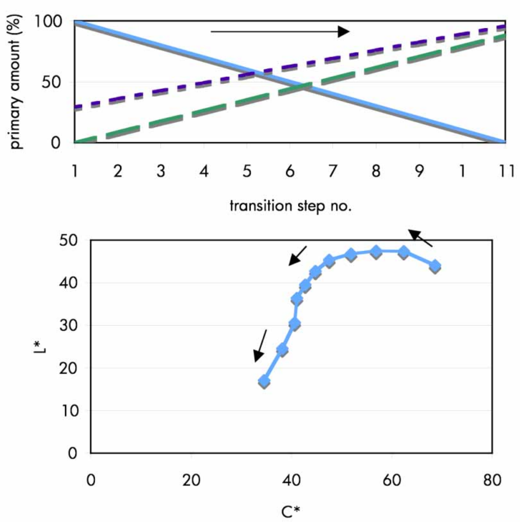

***Figure 4**. Top: Eleven primary combinations with varying amounts of cyan, green and blue ink; Bottom: CIELAB lightness and chroma predictions from their measurements.*

One of the reasons for smooth *transitions* being problematic is the fact that simple linear interpolation between the amounts of two primary vectors where different sets of primaries are non–zero can result in very ill–formed color transitions. For example, Fig. 4 shows the result of transitioning linearly between using cyan at the maximum amount and some blue to using no cyan, blue at the maximum and a lot of green.

Furthermore, primaries additional to CMY (e.g. like the traditional additive RGB primaries) do not behave like CMY in the sense that *secondaries* with them are often nowhere near about half way between the corresponding primaries (Fig. 5). For example, the Y+R secondary is essentially identical to R alone while Y+M is about half–way between the two. Also noteworthy is the fact that secondaries no longer necessarily extend the convex hull of primaries (which they did significantly in the CMY case). For example, the M+B secondary is well inside the primary convex hull. Such imbalance also affects the bit–depth with which primary amounts need to be controlled as a single unit change between one pair of primaries can have very different magnitudes compared to that between another pair.

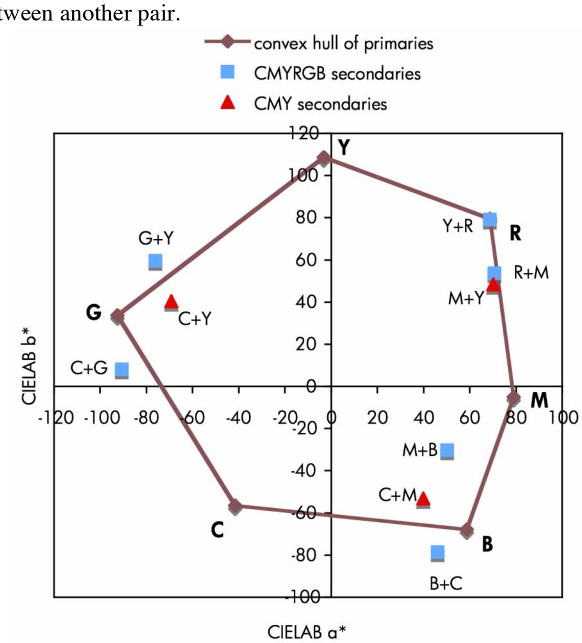

***Figure 5**. Primaries (diamonds), their secondaries (squares) and the secondaries of the CMY primaries (triangles).*

The option of having various *dilutions* of the same colorant also introduces challenges in terms of making meaningful choices. Even though there is a clear trend for the CMYK set of primaries in multi–primary sets this becomes less straight–forward due to their spectral properties.

When *spectral color reproduction* is the aim (which is one of the potential benefits of multi–primary printing) it is also necessary to determine how to deal with original spectra that cannot be matched using a given set of primaries. This aspect of the process is called *spectral gamut mapping* and its understanding is still in its infancy.[8,9]

Having multiple primaries in printing systems where amplitude–modulated *halftoning* is used introduces further challenges since only three halftones can be superimposed without moiré artifacts (CMYK printing already has this issue and only gets away with ignoring it since it has a very light ink – Yellow – whose dots are not very visible and whose halftones' interference with other colorants' halftones is not objectionable). In a multi–primary system though there are more than three colorants that have significant dot visibility and this needs to be taken into account at the color separation stage and may impose limitations.[10]

Papers or other printing substrates each have a limit to how much colorant (e.g. ink, toner, etc.) they can hold before it either stops adhering to the substrate, deforms the surface, spreads on it excessively or soaks it to the extent that it disintegrates. As a consequence of this limit, only colorant combinations that are below it are valid and this adds further challenge to solving all of the above problems.

Even though multi–primary printers are most directly controlled using a device color space[11] that has as many dimensions as there are primaries (e.g. 4 for a CMYK printer, 7 for an CMYKRGB printer, etc.), there is often a need for addressing their output as CMYK or RGB. In other words, it is often necessary to build color separations from a virtual CMYK or RGB to a printer's native device color space. The reason for this is ease of integration into existing workflows and use with existing process control or ICC profiling tools. Otherwise these would either need to be updated for every new primary combination or need to be able to deal with arbitrary ones – both of which is currently impractical. Furthermore it is often unnecessary to have more than a three–dimensional (e.g. RGB) way of addressing a printer since the vast majority of content is defined in a three–dimensional way (either directly or even when it is in CMYK form, its printing involves the contents transformation into CIELAB, which has three dimensions). A challenge here is then to have more than one such virtual device color space – typically RGB and CMYK – available simultaneously and for the two to give consistent results (i.e. addressing the printer in one way or the other giving similar results).

Finally it is worth pointing out that these complex multi–primary printing systems benefit greatly from having the means of embedded spectral reflectance measurement as this helps make output from them more stable and predictable. These abilities to self–calibrate and self–profile result in easier and faster integration of the printer into existing workflows and in greater flexibility of using them to print onto a wider range of substrates. An example of a printer that has an embedded spectrophotometer and the ability to self–calibrate and self–profile is the *HP Designjet Z* series.

Future Opportunities

In addition to the great benefits that multi–primary printing systems deliver by themselves, there are future opportunities that arise from spectral color reproduction in systems where capture, editing and printing are done in a multi–primary way. What this will enable is color reproduction that does not suffer from today's metamerism limitations and will result in prints that look like the originals they represent under any light source as well as for viewers with deficient color vision. While this will certainly bring new challenges (e.g. bandwidth, editing user interface, etc.), there are already cases where such approaches deliver benefits. For example, multi–primary video capture, transmission and finally display allow for remote diagnosis in dermatology, endoscopy and pathology[12] and spectral color reproduction allows for previewing of fabric designs without having to commit to their costly and lengthy prototyping as fabrics.[13]

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Ján Morovič received a Ph.D. in color science from the Colour & Imaging Institute of the University of Derby (UK) in 1998, where he subsequently lectured in digital color reproduction. Since 2003 he has been a senior color scientist at Hewlett–Packard in Barcelona, Spain, where he worked on technologies including HP CMYK Plus, HP Professional PANTONE Emulation and the multi–color separation algorithms of the twelve–ink HP Designjet Z3100 printer. He also chaired the CIE's Technical Committee 8–03 on Gamut Mapping.