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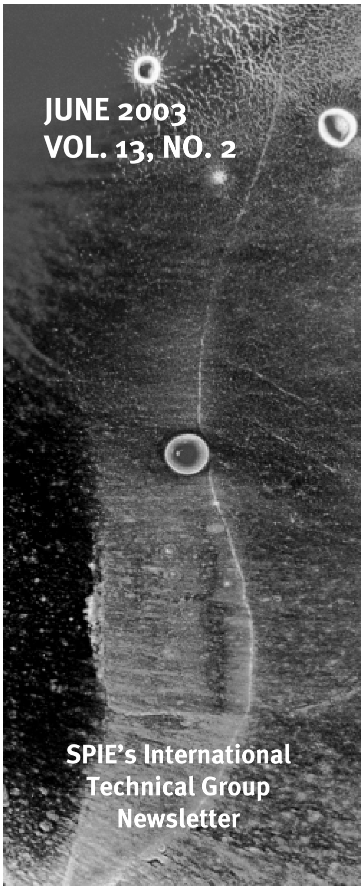

ELECTRONIC IMAGING

Special Issue on:
Gamut Mapping

Guest Editor
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Spatial considerations in gamut mapping

Gamut mapping has been one of the most challenging and active areas of color research.[1,2] The optimal gamut-mapping algorithm (GMA) for a given application depends on input and output gamuts, image content, user intent, and preference. The design of the optimal technique thus commonly involves trade-offs among image attributes such as contrast, luminance detail, vividness, and smoothness.

One might classify GMAs into three basic categories. The first category comprises device-dependent algorithms, wherein the gamut mapping is a function of the input (usually display) and output (usually printer) gamuts. These algorithms are independent of input image content. Most well-known GMAs fall into this category. The second category consists of image-dependent algorithms, wherein the gamut mapping is a function of the input-image statistics and of the output-device gamut. These algorithms are generally expected to perform better than image-independent algorithms since they can adapt to image content[3] at added computational cost. In both these categories, the gamut mapping is a point-wise operation from an input point to an output point in an appropriate 3D color space. Since such operations do not take spatial-neighborhood effects into account, point-wise GMAs are heavily constrained by trade-offs involving preservation of lightness vs. chroma vs. hue. This makes it difficult to develop a common algorithm that achieves high quality for a large variety of images and gamuts.

The third category of GMAs, which is the focus of our work, comprises algorithms that take spatial characteristics into account in addition to color characteristics of the image. With such algorithms, two pixels of the same color in an input image might map to different colors in the output depending on the local characteristics in their respective spatial neighborhood. A few researchers have proposed techniques in this category.[4,5]

We have developed a simple spatial GMA that mitigates the trade-off between luminance and chrominance preservation by incorporating the pixel neighborhood into the mapping. A brief description of the algorithm is presented here: the reader is referred to References 6 and 7 for full details.

Gamut mapping with spatial feedback

Our algorithm is based on the principle that it is more important to preserve luminance at high spatial frequencies, while it is generally desirable to preserve chrominance at low spatial frequencies.

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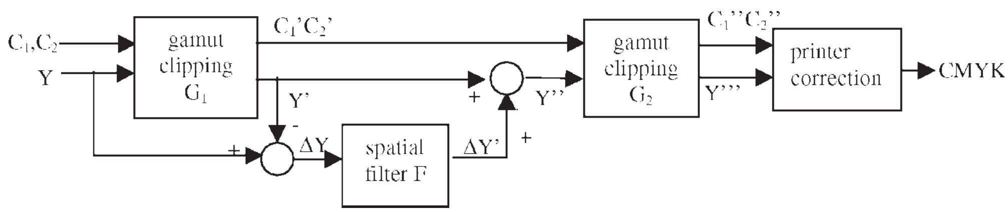

Figure 1. Block diagram of spatial gamut mapping algorithm.

The challenges of gamut mapping

The ability to reproduce color images on various imaging media like computer or television displays, print or projection, is required in an ever-increasing range of contexts. Examples of these are the display of web content on computer monitors, the viewing of DVDs on television screens, the printing of holiday photos, or the projection of business presentations. Furthermore, the images to be reproduced can come from a variety of sources: our environment, data captured with digital cameras, conventional photographs or original artwork in either analog or digital forms.

As the media mentioned above can, and often do, have different ranges (gamuts) of colors that they can achieve, it is frequently the case that some colors cannot be made to match an original exactly. For example, the appearance of some bright green colors that can be displayed on a television in a dark room cannot be achieved in a printed newspaper as the gamuts of these two media do not match. As a result of such gamut mismatches, it is necessary to alter the original colors to ones that a given reproduction medium is capable of achieving. How this replacement, which is frequently referred to as gamut mapping,[1] is to be done to obtain a good reproduction of the original image is a question that still poses many challenges.

Since the first work on gamut mapping appeared in 1978[2] approximately eighty papers[3] have been written on this topic. However, despite this volume of work, there is little consensus on what method of gamut mapping gives the best results (either in terms of accuracy or preference of reproductions) or whether it is even possible to have an algorithm that performs well all the time. Looking at the existing literature in gamut-mapping studies shows a whole host of factors that could have contributed to the differences in the findings of individual studies and the following will be at least a partial list.

The first factor that is cited as the source of differences is that some studies test the performance of gamut mapping algorithms (GMAs) by comparing reproductions made using one medium with an original present on another, whereas other studies simulate such medium differences on a display. Experiments using actual differences between media[4-6] tend to report gamut compression and/or linear lightness mapping as outperforming gamut clipping. Simulation, on the other hand,[7-9] more commonly reports better results for clipping and/or knee-function-like compression and nonlinear lightness mapping. The differences between actual and simulated medium differences have also been directly shown to have a very large effect on GMA testing[10] and it is still an open question as to why this is.

Second, the magnitude of gamut differences between the original and reproduction gamut is another factor that might be responsible for differences in findings. Studies with smaller gamut differences are again more likely to favor gamut-clipping approaches, whereas compression performs better when larger gamut differences need to be overcome.

Third, even in a given experiment (i.e. where the type and magnitude of medium difference is fixed) existing algorithms perform very differently for different test images. This can clearly be seen by considering the coefficient of determination (R^2) between GMA performances for individual test images within various experiments, which—for all ten studies published before 2002 that made such data available—was 0.34. Hence, knowing how a GMA performs for one test image gives very little indication of how it will perform for another. A series of experiments was then performed by Pei-Li Sun and myself in which the aim was to establish which image characteristics are responsible for these differences: this work showed that approximately 80% of differences are accounted for by the 3D color histograms of the images.[11] The effects of this difference between GMA performance for different images has also been shown in another study[12] where a large number of fifteen test images were used in the evaluation of GMAs and it was shown that subsets of five test images could be chosen so as to have any of the tested GMAs in the group of best performing algorithms.

What is clear from the above survey of existing gamut-mapping work is that there are still a number of key factors, the effects of which are not well understood and which contribute to the differences in findings of studies carried out to date. As a response to these challenges, the CIE has set up a technical committee (CIE TC 8-03) to attempt a synthesis of existing work and recommend a baseline GMA. Recognizing the heterogeneous nature of existing work, this committee has prepared a set of guidelines for the evaluation of gamut mapping algorithms.[13] The aim of these guidelines is to serve as a platform for conducting such experiments that will be more inter-comparable than existing work on this subject, and will lead to a better understanding of the challenges that gamut mapping poses.

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Image-to-device gamut mapping with compact descriptor

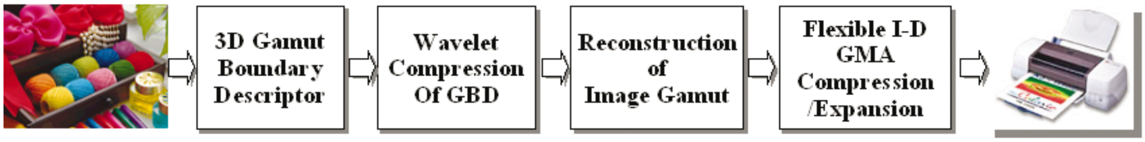
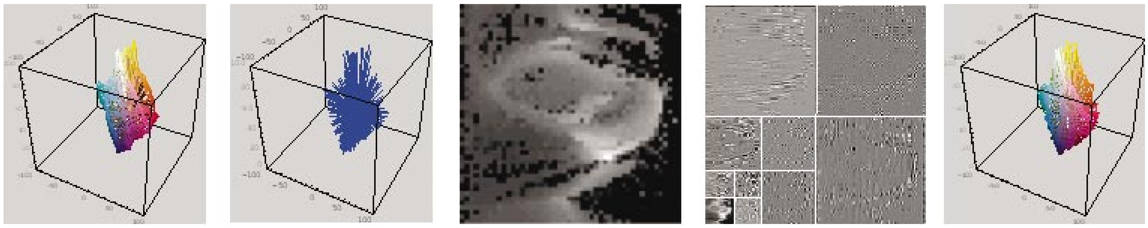
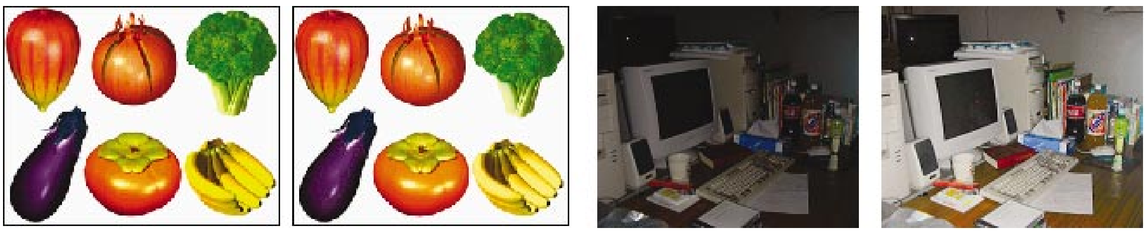


Figure 1. A 3D image-to-device (I-D) gamut-mapping system with a compact gamut descriptor.



(a) Image gamut *(b) Radial vector* *(c) R-image GBD* *(d) Wavelet coding* *(e) Reconstructed from 384 bytes.*

Figure 2. Compact description of the image gamut boundary.



(a) A 2D, conventional, clipping GMA *(b) Our 3D I-D GMA* *(c) Image in dim light* *(d) After gamut expansion for (c)*

Figure 3. The 3D I-D mapping results: (a), (b) are compressed, and (d) is expanded for (c).

GMAs (gamut mapping algorithms) are essential for color appearance matching across multiple media, and a variety of such algorithms have been developed so far.[1] The first generation of GMAs were designed to work mostly in 2D LC (lightness-chroma) planes,[2] based on the D-D (device-to-device) mapping concept, rather than the I-D (image-to-device) approach. However, the GMA is now advancing from 2D into 3D and D-D into I-D. Well-designed I-D GMAs in 3D color space are expected to produce better color rendition than D-D GMAs. Our laboratory has been working towards a 3D I-D GMA that maps the display image onto the print image seamlessly and preserves continuous gradations.[3]

In general, a conventional GMA is used for gamut compression: to map the image colors with wide gamut on a CRT into the narrow gamut of a printer or copier. However, the source-image gamut may instead be narrower than that of the output device due to poor conditions during image capture or fading after many years of conservation. Sometimes, therefore, gamut *expansion* rather than compression is necessary to improve the appearance of the color in these de-saturated or faded images. As a result, we have been working to design a flexible CMS (color management system) to select compression or expansion automatically according to whether the image gamut is wider or narrower than the device gamut (see Figure 1).

For an effective, flexible 3D I-D GMA, a simple and compact image GBD (gamut boundary descriptor) is indispensable. Generally, the 3D I-D GMA is costly from a computational perspective because the mapping program makes use of image vs. device gamut boundary relations along each mapping line. To date, a variety of GBDs have been developed, but these have mainly been used to describe the device gamut rather than the image gamut. A key factor here is to be able to extract the 3D-image-gamut shell from the random color distributions quickly, and to describe its boundary surface with small number of bits. We have developed a simple and compact GBD that meets this criterion, and which we have called the R- (radial-) image method.[4] The R-image represents a 3D image gamut-shell shape as a 2D monochrome image by finding the maximum radial vectors in the discrete segments divided by constant radial angle step ($\Delta\theta$, $\Delta\varphi$) in CIELAB polar-coordinate space. Each grey-scale pixel in the R-image corresponds to the magnitude of the maximum radial vector in the segment towards the gamut-shell surface from the image color center. It is then relocated at a discrete cell in Cartesian (θ, φ) coordinates (see Figure 2 (a)-(c)).

Because the R-image is a 2D grey-scale image and highly-correlated spatially, it can be compressed by applying conventional picture-coding techniques. For example, the R-image is represented by 48×48 monochrome image and the original GBD takes 2.3K bytes memory. A wavelet-based coding method (JPEG 2000) resulted in much better compression than the DCT-based JPEG. The gamut-shell surfaces were very well restored after having been compressed to just 384 bytes, with the color differences of DE94(rms)=2.6 for standard test image *bride* and DE94(rms)=4.0 for *wool* (see Figure 2 (d), (e)). Since the image GBD must be very compact in terms of memory—1K bytes or less in practice—it may be attached to the source data together with the ICC profile. Thus we can use the image GBD in the 3D I-D GMA. The image gamut-shell shape is quickly reconstructed from the compressed R-image and used for I-D mapping. Image-dependent flexible gamut mapping us-

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Development of the Graphic-Arts Media-Mapping Algorithm

In graphic-arts color reproduction, hard-copy media can have color gamuts that are very different from each other. The challenge undertaken within our project was to test and evaluate methods for reproducing transparency originals on graphic-arts media ranging from gloss-coated to newsprint. Data on which to base a gamut-mapping strategy was obtained from color proofs made by professional pre-press operators, and this data was analyzed to determine the mapping techniques implicitly followed by the operators. This method was based on that used in the earlier CARISMA project.

There was good agreement between the results from the different sites that participated in the study: this allowed a baseline reproduction to be defined. This process was repeated for both gloss-coated and newsprint media. The gamut-mapping algorithm that resulted from the analysis included a nonlinear compression towards a convergence point that was dependent on the lightness and chroma of the color being mapped, as well as the relative boundaries of the original and reproduction media.

In order to compress a given color from the gamut of one medium to another, it is necessary to know the location of the gamut boundaries of the original- and reproduction-media gamuts relative to the color being mapped. A method was developed to determine the color gamut of a hard-copy medium by printing and measuring a test target. This process was used to provide a gamut boundary descriptor for each of the hard-copy media used in the study. A method was also developed to compute the intersection of a gamut boundary with the line of compression from a given color. This was done by locating the nearest coordinates in the gamut-boundary descriptor and finding the intersection by interpolation.

Work was undertaken to modify the existing methods for predicting the appearance of color images in a graphic-arts transparency viewing set-up, where models such as CIECAM97s give a poor prediction of the effect of the dark-surround used when viewing transparencies. After correctly adjusting for the effect on perceived lightness of the dark-surround, all the results were consistent with a rescaling of lightness that was increasingly sigmoidal, with larger differences in the lightness ranges of the original and reproduction media (although not as extreme as some other studies). Algorithms that did not scale the lightness range of the original (or at least the media) into the range of the reproduction media performed badly.

Although preserving hue is often considered a requirement of gamut mapping, the CARISMA data showed that operators, in effect, moved the primary colorants of the original media towards those of the reproduction. This finding was supported by the empirical data, and also in the experimental phases that tested this assumption: a hue shift corresponding to half the difference between the primaries of the two media (intermediate colors being interpolated with the hue angles between the two closest primaries as weights) was preferred for newsprint; clipping in minimum DE was preferred for gloss coated.

Empirical data indicated that colors were compressed towards the achromatic axis towards multiple different convergence points or focal points. A lightness- and chroma-dependent convergence point was developed in which colors close to the neutral axis have an achromatic convergence point of the same lightness, while colors close to the cusp are mapped towards an achromatic convergence point with the same lightness as the cusp.

None of the methods for finding the mapping convergence point was conclusively preferred over the others, and simple convergence-finding methods that preserve the lightness and chroma of the original are the most consistent with the aims of gamut mapping and the experimental results.

Where different methods of compressing towards the convergence point were compared, nonlinear compression was found to perform significantly better than linear compression.

Conclusions

No algorithms were found to perform well on both gloss-coated and newsprint media, which suggests that the performance of many algorithms does not scale well across color gamuts of very different magnitudes. The different experimental stages confirmed that, where the difference between the original and reproduction media gamuts is large, compression gives better results than clipping; while where the differences are small, clipping gives better results. The performance of lightness scaling methods was also affected by the magnitude of gamut difference.

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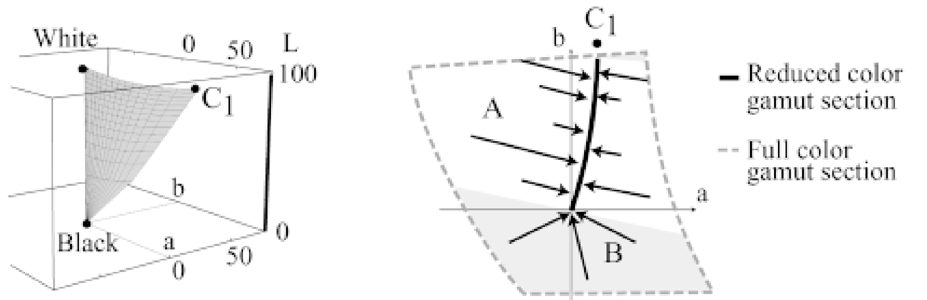
Techniques for color-gamut reduction

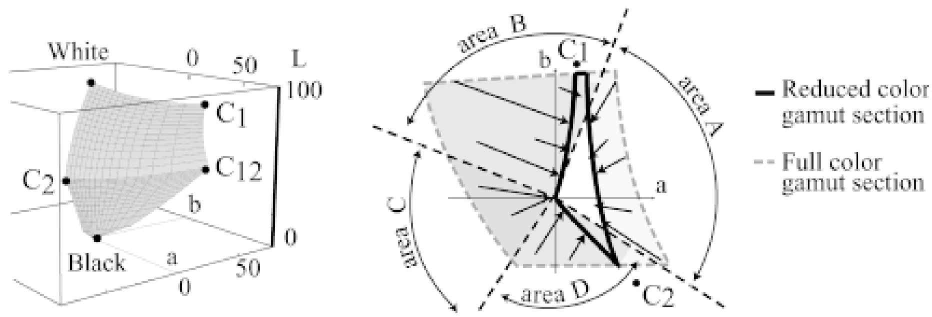
Printing with custom inks[1-3] is a widespread technique for protecting documents against counterfeiting attempts. Banknotes are often printed with a limited set of custom inks. In such banknote designs, the color gamut defined by the custom inks is severely reduced compared with the gamut defined by the standard cyan, magenta and yellow. In the context of banknote and artistic design, it would be very valuable to have a flexible tool able to carry out gamut reduction in order to map a color input image to an image with colors located within the reduced gamut offered by the set of one, two, or three custom inks: generally without the black.

The problem of color-gamut reduction distinguishes itself considerably from the well-known problem of gamut mapping.[4] This is especially the case when the grey axis is not part of the reduced target gamut. The gamut reduction problem consists in creating a mapping between an original “full” color gamut—e.g. the color gamut of a CRT monitor—and the reduced gamut defined by a given set of custom inks. The proposed mapping should preserve color continuity and, whenever possible, smoothness, i.e. a continuous color wedge located in the original color space should be mapped into a continuous color wedge located in the reduced target gamut. In addition, among different possible mappings, those preserving the original colors to at least a certain extent should be preferred. For example, hues of original colors should be preserved as much as possible, and saturated colors located in parts of the color space common to both the input and target gamuts should remain as close as possible.



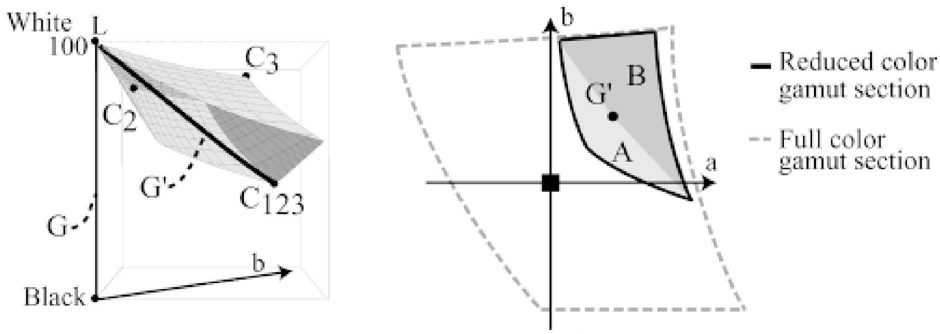
(a) Target gamut (CIE-Lab). (b) Projection of colors into the target gamut.

Figure 1. Reduced color gamut with custom ink C_1 and black.



(a) Target gamut (CIE-Lab). (b) Mapping colors into the target gamut.

Figure 2. Reduced color gamut with two custom inks C_1, C_2, and black.



(a) Target gamut with pseudo-gray axis G'. (b) Division of the target gamut into regions A and B.

Figure 3. Reduced color gamut with three custom inks C_1, C_2, and C_3.

Gamut reduction for custom inks including the black ink

If the paper is white and the selected set of inks includes black, the grey axis of the reduced target color gamut is identical or very close to the original grey axis. A linear mapping is adequate for mapping original lightness levels to target lightness levels. When, in addition to black, a single color C_1 is selected in order to give to a design a monochromatic aspect, the proposed gamut mapping method maps the original colors onto the gamut surface *White-*C_1*-Black* (see Figure 1). The points located in area *A* are orthogonally projected onto the surface. Colors with hues far from the hue of color C_1 will therefore be more desaturated, i.e. closer to grey than colors with hues close to that of C_1. All the color points in area *B* are mapped onto the grey axis by keeping their relative lightness values constant.

With two custom inks, printable hues are located between those of inks C_1 and C_2. Area *A* is where the hues are kept as close as possible to the original (Figure 2b). Original colors with hues located in areas *B* and *D* are mapped onto areas at the border of printable area *A* and colors with hue located in area *C* are mapped onto the grey axis. The same method is applicable in the case where three or more custom inks cover less than a 180˚ hue range.

When printing with a set of custom inks not including black, the input color gamut needs to be mapped into a reduced gamut that either does not include the grey axis at all or includes only a part of it. Again, we try to preserve the saturated colors located inside the reduced target gamut as much as possible and map hues

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A multi-resolution spatial gamut-mapping algorithm

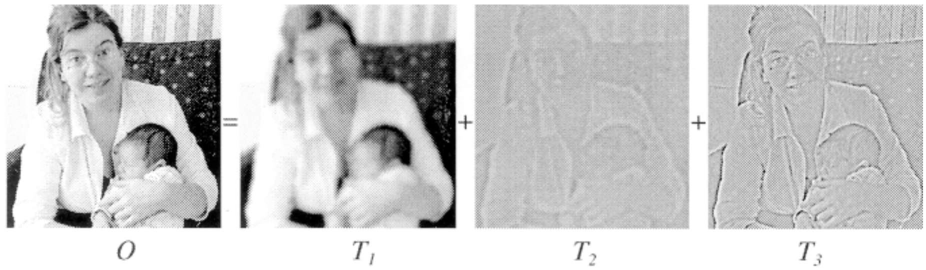

Figure 1. Three-level decomposition of image O (mid-grey represents zero in T_2 and T_3).

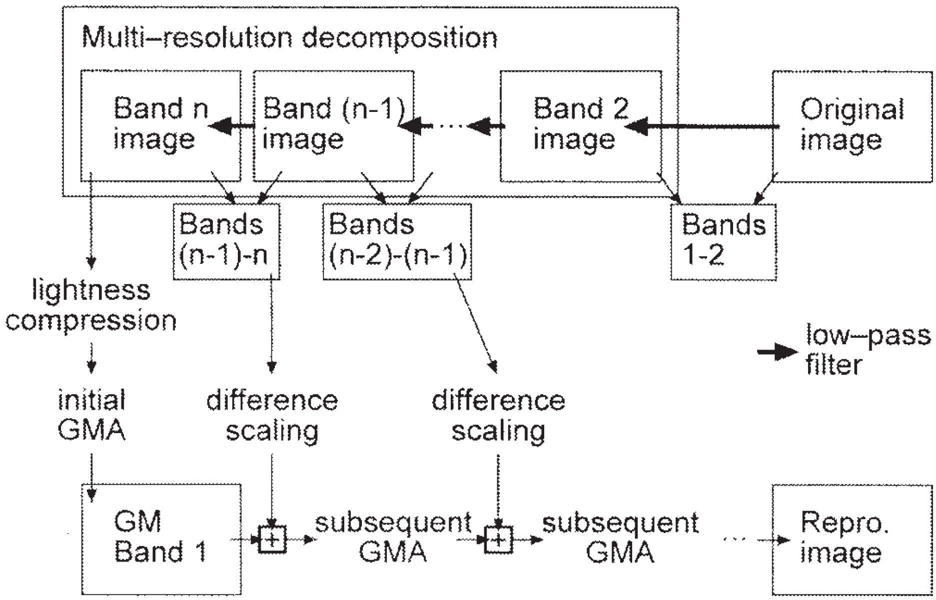

Figure 2. Framework of MSGM algorithm.

Color images have a variety of characteristics, ranging from properties of their colors' distributions to the contents they represent. When reproducing color images across media with different gamuts, it is therefore important to reproduce all of an image's characteristics. For example, original image features—like having individual pixels of certain colors, having predominantly dark colors, having detail in certain parts of the image, or looking natural—all ought to apply to the reproduction as well. Such attention to all image characteristics is particularly important when the reproduction medium has a color gamut that is smaller than the original.

Given this challenge, it is worth looking at the properties of existing cross-media reproduction solutions to see whether they adequately address it. As most parts of cross-media reproduction workflows are descriptive (e.g. device characterization and color-appearance modelling), the work of preserving image characteristics beyond individual pixel colors falls to the gamut-mapping algorithm (GMA). Looking at existing solutions,[1] it can be seen that the majority of them perform transformations that are determined only by factors derived from the original and reproduction media and a given original pixel's color. Hence these algorithms focus on colors of individual pixels and transform them without explicitly taking into account other image characteristics, or at most taking into account the original image's color gamut. Therefore, when such algorithms are also intended for the reproduction of other image characteristics, their reproduction is dealt with indirectly.

An important improvement as compared with such pixel-color-only approaches is the GMA proposed by Braun and Fairchild,[2] which analyses an original image's lightness histogram and adjusts its behavior accordingly. While this type of method deals well with the distribution of original lightnesses, there is still significant room for improvement by addressing further important image characteristics. The most obvious candidate for a next step is to improve the reproduction of an original's spatial properties.

Over the years, a handful of gamut-mapping algorithms has already been proposed with the aim of explicitly dealing with this important characteristic.[3-8] Here, an alternative spatial gamut-mapping algorithm, operating in a multi-resolution and full-color way, is proposed. The reason for using more than just two bands in the multi-resolution decomposition is that relationships in images can be considered not only between an a pixel and a neighbourhood of fixed area but also between neighbourhoods of different areas. An example decomposition of an image *O* is shown in Figure 1. Where T_1 is the lowest resolution band and T_2 and T_3 are difference images between bands of successively higher resolutions. Furthermore, differences between bands of the multi-resolution image representation can be computed in terms of all three dimensions of a color space, rather than only in terms of lightness, as has previously been the case.[3,7,8] This allows for dealing with local changes not only in lightness but also in chroma and hue.

Based on these concepts, a multi-resolution and full-color spatial gamut-mapping algorithm (MSGM) is proposed here. Its aim is to maintain an original image's overall color appearance as well as spatial variation as much as is possible within the limits of a reproduction medium's gamut. This will be attempted by taking an original and first computing a multi-resolution decomposition of it. Then the lowest-resolution band will be gamut-mapped and the difference between the lowest and next higher bands from the original decomposition will be added to it. The result will again be gamut-mapped and the process will be repeated until all bands from the original decomposition are incorporated again into the gamut-mapped image (see Figure 2).

A psychophysical experiment evaluating the performance of this algorithm in comparison with other spatial and non-spatial methods was conducted and its results showed that this method is in the top group of GMAs overall. Furthermore, it has the advantage that it performs better than other methods for images that— on average—are reproduced inaccurately, while for images that are reproduced accurately by all algorithms it is not very different from the mean. Further details of this algo-

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Spatial considerations in gamut mapping

Continued from cover.

The technique tightly couples the spatial and color transformations in a corrective feedback mechanism, resulting in a robust framework for gamut mapping. A block diagram of the proposed algorithm is shown in Figure 1.

Let us define G_1 as a point-wise gamut-clipping algorithm that emphasizes preservation of chroma over luminance. Let G_2 be another point-wise gamut clipping algorithm that emphasizes preservation of luminance over chroma. First G_1 is applied to the input colors, and an error image ΔY is computed between the luminances of the input signal Y and gamut-mapped signal Y'. A spatial filter F is applied to the error image, resulting in image $\Delta Y'$. Here, F has high-pass frequency characteristics, i.e. it preserves the high spatial frequencies while suppressing the low spatial frequency components of the signal ΔY. The error image, which comprises only the high frequency errors introduced by gamut mapping, is then added back to the gamut-mapped signal Y' to yield signal Y''. The feedback step may move some pixel colors ($Y'' C_1' C_2'$) out of the gamut, so a second gamut mapping operation G_2 is applied to limit all colors to the intended gamut. The proposed algorithm exhibits the following characteristics:

- If a region in the image is completely within the gamut, then both G_1 and G_2 are identity functions; hence this region of the image is unaltered.
- If a region in the image is outside the gamut, and is smoothly varying (i.e. of low frequency), the overall mapping in this region is predominantly G_1.
- If a region in the image is outside the gamut, and contains high frequency detail, then the overall mapping is predominantly G_2.

In summary, the proposed scheme leads to the preservation of the characteristics of G_1 in low spatial frequencies and those of G_2 in high spatial frequencies. Hence the strengths of both algorithms are exploited in the appropriate spatial frequency bands, and the trade-offs that one must face with point-wise algorithms are significantly mitigated.

The optimal selection of G_1 and G_2 and the spatial filter F depends on many factors: these include image characteristics, device characteristics, rendering intent, and preference. In the initial phase of our research, G_1 was chosen to map out-of-gamut colors to the nearest surface point of the same hue. This mapping generally favors preservation of chroma over luminance. For G_2, the cusp-clipping algorithm[1] was chosen: this tends to emphasize luminance over chroma preservation, especially for points close to the gamut surface. Finally, a simple linear high-pass filter was chosen for F that produces satisfactory results with a relatively low computational overhead. The algorithm has been shown to offer superior performance to standard GMAs in psychophysical experiments.[7]

We believe the proposed technique represents an important direction in gamut mapping; namely the use of spatial information. Future work involves further optimization of the algorithm parameters and automatic adaptation of these parameters to global and local image content.

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Image-to-device gamut mapping with compact descriptor

Continued from page 3.

ing the image GBD on the user side is our final goal.

Also at the user side, the 3D I-D GMA is easily performed by a direct pixel-to-pixel comparison between the R-image of the source image and the user output device. By taking the 3D density plot of the R-image and comparing its volume with that of output device,[5] we can decide whether gamut compression or expansion is more appropriate. In the case of gamut expansion, the source-image colors are moved towards the device-gamut-shell surface along the mapping line with reference to the image-vs.-device-gamut boundaries. The desaturated images are therefore transformed to vivid colors (see Figure 3). We expect the device-independent but image-dependent CMS will emerge in the coming color-media age.

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Gamut mapping for more colorful prints

Continued from page 12.

ally designed on a display device such as a CRT screen, which has a relatively large gamut. The designer of the image may have no knowledge of either the intended output media type or the viewing conditions under which the output will be judged. As a result, the design intention may be poorly fulfilled due to gamut differences between the CRT used by the designer and that of the printer. Color accuracy in chroma and lightness is difficult to define for a business graphic image. If a gamut-mapping algorithm maps the original colors to corresponding colors of maximal chroma while preserving contrast, it may actually fulfill the initial goal of the designer. Also, when a reproduction device has some portion of the gamut that is larger than the initial CRT gamut used for designing the image, it may be desirable to allow these colors to be used in the printed image. Following the above arguments, we propose gamut mapping to maximize color use for business graphics printing. One method is given in the following two key steps.

Step 1: Uniformly map the display gamut to that of the printer on the equal hue plane with the aim of using every color the printer can print. Figure 1 shows point *A* in the display gamut mapped to the Point *A'* in the printer gamut. Determination of *A'* can be achieved in various ways. We propose the use of center of gravity *C* and *C'*, apex point *P* and *P'* as references and perform the uniform mapping with,

$$\begin{cases} \angle ACP \equiv \angle A'C'P' \\ \dfrac{\overline{CA}}{\overline{CB}} \equiv \dfrac{\overline{C'A'}}{\overline{C'B'}} \end{cases} \qquad 2.$$

where *B* is the interception of line *CA* with the CRT gamut boundary, and *B'* is determined in the same way.

Step 2: Enhance chroma along *A'P'* to *A"* with reference point *N'* on the neutral axis with the following function (as shown in Figure 2).

$$\overline{A''P'} = \overline{A'P'}\left(1 - e^{\left[\frac{\overline{N'A'}}{\beta\,\overline{N'P'}}\right]^{\alpha}}\right) \qquad 3.$$

where α and β are the factors controlling the amount of color enhancement (α=2,4,6, …).

Mapping to a darker color makes a print more colorful

The specification and realization of gamut-mapping goals rely on the classification of various color attributes represented by the CIE attribute correlates, namely, L^*, C^*_{ab}, and h_{ab}. It is well known that these predictors crudely represent their actual perceptual counterparts. Even for the three perceptual attributes, they may not be actually perceived as definitively as specified in the Munsell system.[3] These facts can be problematic for gamut mapping. For example, one important quality aspect of color image reproduction is the chromaticity, colorfulness or vividness of the reproduced highly-chromatic colors. Vividness, colorfulness, and chromaticity correspond to the *CIE* C^*_{ab}. Therefore, mapping algorithms can aim to favor higher C^*_{ab} for highly-chromatic colors along with fulfilling other mapping goals. The question is, when choosing a lightness mapping scheme, what should be the guideline to achieve a more colorful color?

To determine the effect of CIE lightness (L^*) on the perceived colorfulness, we produced four groups (red, green, blue and yellow) of highly-chromatic color samples with an inkjet printer. Each group consisted of nine samples of the same CIELAB hues but with small variations of L^* and C^*_{ab}. A paired-comparison experiment was then conducted using 50 observers. We found that L^* significantly contributed to the perceived colorfulness for this set of samples.[4]

A colorfulness scale is constructed to combine the effects of C^*_{ab} and L^* on the perceived colorfulness by using,

$$C_{\text{Colorfulness}} = C_0' + 0.1C'\left[1 + \frac{C'}{L^*}\right]^3 \qquad 4.$$

where *C'* is,

$$C' = \frac{\ln(1 + 0.045C^*_{ab})}{0.045} \qquad 5.$$

The relationship described by Equation 4 indicates that we can achieve a more colorful mapping for the highly-chromatic colors (both inside and outside of the printer gamut) by reducing the L^* of these colors.

One implementation is to reduce L^* in a preamp adjustment as shown in Figure 3. *A'* is determined by,

$$\overline{AA'} = \beta\left[\frac{\overline{N'A'}}{\overline{NP}}\right]^{\alpha} \qquad 6.$$

where *P* is the apex of the L^*C^* gamut and α and β are coefficients controlling the lightness reduction amount. This mapping technique has proven to be effective for making prints more colorful.

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Techniques for color-gamut reduction

Continued from page 5.

outside it onto de-saturated pseudo-grey colors. Since the grey axis cannot be printed with the chosen set of inks, we map it onto the target gamut as a continuous smooth curve ensuring that continuous original grey values are mapped into continuous values of lightness, saturation and hue. A smooth curve, which by definition remains within the target gamut, is the curve representing equal coverage of inks C_1, C_2 and C_3. With this pseudo-grey axis, we divide the target gamut into two distinct regions: one on its de-saturated side (area *A*, Figure 3b) and one on its saturated (area *B*, Figure 3b). Input gamut colors with hues that are not part of the target gamut are mapped into colors located on the de-saturated side of the pseudo-grey axis. Colors within the set of printable hues remain within the target color gamut and retain their original hue and saturation as much as possible.

More information and images illustrating our results can be found at:
http://diwww.epfl.ch/w3lsp/research/colour/

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A multi-resolution spatial gamut-mapping algorithm

Continued from page 6.

rithm and its evaluation can be found elsewhere.[9]

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Gamut mapping for more colorful prints

When two competing digital printers are compared against each other in print quality, color is often one of the most critical factors. Differences in color are a direct result of the algorithms used and the goal set in the gamut-mapping process. Here we describe our work in three aspects of gamut mapping. First, we describe our findings on potential large errors when paired comparison-based scaling methods are used to evaluate gamut-mapping algorithms. Second, we present an algorithm that maximizes the use of color for business graphics. In the third part, we explore the discrepancy between CIE metrics and perceptual attributes. We apply the findings to gamut mapping and achieve more colorful prints by mapping high-chroma colors with reduced lightness.

Error estimation in perceived image-quality measurement

The commonly-used scaling technique for gamut-mapping evaluation is the method of paired comparison. Given paired-comparison data, scaled values can be derived based on statistical modeling. The Thurstone and Bradley-Terry models are popular examples of this.[1] However, little has been reported in regard to the inherent theoretical precision. A paired-comparison test can be time-consuming and costly. There is always the tendency to use a relatively smaller number of observers. This may introduce large scaling or measurement errors that can make the scaling test inconclusive, and even misleading, if interpreted incorrectly.

In the Thurstone model, the derivation of the scaled values involves the solution of a set of equations that join the proportion of choices of all the possible stimulus pairs. An analytical approach for error estimation is difficult. Using a form of Monte-Carlo simulation, we investigated the scaling error for various combinations of a number of samples (stimuli) and a number of observers (sampling size).[2] The errors are presented in the form of average standard deviation of the scaled values. For a typical scaled value-difference range of 2, corresponding to a highest proportion of choice value of 97.7%, the fitted equation (standard errors) is,

$$\sigma(n, N) = \frac{2.5}{N^{0.46} n^{0.61}} \qquad 1.$$

where n is the number of samples compared and N is the number of observers. The simulation proves paired comparison-based scaling methods can have surprisingly large errors on the derived scaled values for smaller N and n. We have further confirmed the error estimation by bootstrapping a set of paired comparison data.

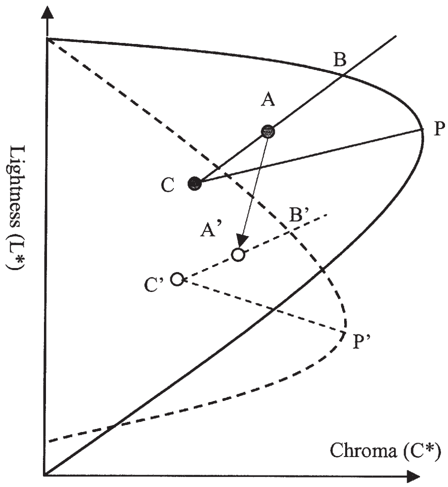

Figure 1. Step 1: Mapping A to A'. Solid lines represent the display gamut; broken lines represent the printer gamut.

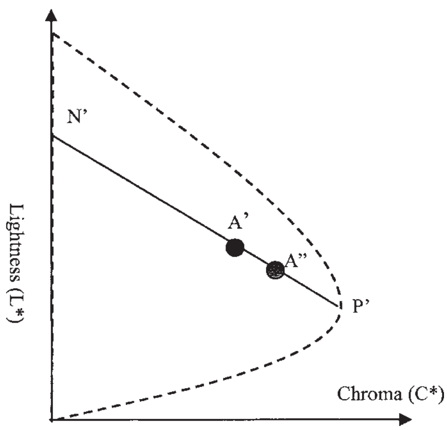

Figure 2. Step 2: Color enhancement along A'P' to A".

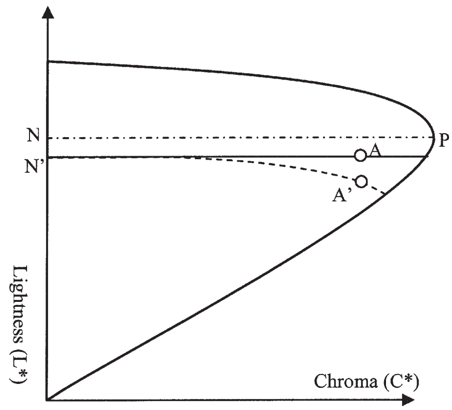

Figure 3. Pre-mapping lightness adjustment for colorfulness.

Gamut mapping for maximal use of color in business graphics

When a graphical image is created, it is usu-

Continues on page 8.

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