Color gamut reduction techniques for printing with custom inks

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ABSTRACT

Printing with custom inks is of interest both for artistic purposes and for printing security documents such as banknotes. However, in order to create designs with only a few custom inks, a general purpose high-quality gamut reduction technique is needed. Most existing gamut mapping techniques map an input gamut such as the gamut of a CRT display into the gamut of an output device such as a CMYK printer. In the present contribution, we are interested in printing with up to three custom inks, which in the general case define a rather narrow color gamut compared with the gamut of standard CMYK printers. The proposed color gamut reduction techniques should work for any combination of custom inks and have a smooth and predictable behavior. When the black ink is available, the lightness levels present in the original image remain nearly identical. Original colors with hues outside the target gamut are projected onto the gray axis or onto desaturated colors. Original colors with hues inside the target gamut hues are rendered as faithful as possible. When the black ink is not available, we map the gray axis G into a colored curve G' connecting in the 3D color space the paper white and the darkest available color formed by the superposition of the 3 inks. The mapped gray axis curve G' is given by the Neugebauer equations when enforcing equal amounts of custom inks. After lightness mapping, hue and saturation mappings are carried out. When the target gamut does not incorporate the gray axis, we divide it into two volumes, one on the desaturated side of the mapped gray axis curve G' and the other on the saturated side of the G' curve. Colors whose hues are not part of the target color gamut are mapped to colors located on the desaturated side of the G' curve. Colors within the set of printable hues remain within the target color gamut and retain as much as possible their original hue and saturation.

Keywords: gamut reduction, artistic imaging, color printing, custom inks.

1. INTRODUCTION

Printing with custom inks[1,2,3] is a widespread technique for protecting documents against anti-counterfeiting attempts. In banknotes for example, designs are often printed with inks of which at least one ink color varies along the length of the banknote, i.e. the ink color is a linear interpolation between two given custom inks. In most banknote designs, the image gamut is severely reduced to the gamut defined by a few custom inks.

In the context of banknote and artistic design, it would be extremely 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 ink.

The problem of color gamut reduction distinguishes itself considerably from the well-known problem of gamut mapping[4,5]. This is especially the case when the gray axis is not part of the reduced target gamut. In addition, we assume that the target gamut does not extend beyond the boundaries of the original gamut, for example the gamut of a CRT monitor. There are however similarities between gamut reduction and gamut mapping. In both cases, it is useful to work in a color space where the lightness is orthogonal to the hue-saturation sections. This allows to first apply a mapping on lightness values and then to map the hues and saturations.

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Let us formulate the gamut reduction problem. Given a reduced gamut given by a few custom inks, create a mapping between an original "full" color gamut, e.g. the color gamut of a CRT monitor and the reduced gamut defined by the 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, the mappings preserving at least to a certain extent the original colors will be preferred. For example, saturated colors located in parts of the color space common to both the input and target gamuts should remain nearly identical and hues of original colors should be preserved as much as possible.

Methods for gamut mapping have been proposed for the cases of one ink and black[6] and for two custom inks[7] (duotone). Both methods try to maintain overall relationships between colors by allowing strong hue and saturation shifts. Our approach consists in mapping colors outside the available target gamut hues as gray or as desaturated “pseudo-gray“ color and colors inside the target gamut hues as close as possible to the original colors.

In the present contribution, we are interested in exploring various gamut reduction techniques. For the sake of simplicity, we consider that the set of available basic colors is determined by the set of custom inks C_1, C_2, C_3 (and C_k if black is available) as well by the combinations of two inks C_{ij} and 3 inks C_{ijk}.

For the sake of the present analysis, we use the Neugebauer equation for computing the color separations and the boundaries of the target gamut[8]. The CIE-Lab space is used for applying the proposed gamut reduction algorithms.

1.1. Lessons learned from the research on gamut mapping

Although gamut reduction differs significantly from gamut mapping, let us see if methods used for gamut mapping can also be used for gamut reduction.

In respect to the clipping[9] of out of gamut colors onto the target gamut boundary, the work by Katoh & Itoh[10] suggests that color differences along the CIE-Lab lightness axis (ΔL^*) have a visual impact twice as large as color differences along the saturation (ΔC^*) and hue (ΔH^*) axes. This may suggest that for gamut reduction, the original lightness range should be mapped in a non-linear manner onto the target lightness range, thus offering the capability of keeping some of the original lightness values unchanged. However, when the target gamut has a relatively small lightness range, one may prefer a linear mapping of the original lightness range onto the target lightness range.

In respect to gamut compression algorithms, Morovic & Luo[5] have shown that gamut mapping algorithms which project out of gamut colors towards a particular point inside the gamut (e.g. $L = 50$ in CIE-Lab)[11] are visually superior to algorithms which separately map the original gamut lightness axis into the target gamut lightness axis and then the saturation of original colors into the saturation of the target gamut[12,13]. However, this superiority may be due to the particular shapes of original (CRT: red, green, blue located far from the lightness axis) and target (printer: cyan, magenta and yellow located far from the lightness axis) gamut boundaries. For this combination of original and target gamut boundaries, out of gamut colors projected radially at constant lightness levels tend to become desaturated.

However, in the case of custom inks, the target gamut boundary depends on the selected set of inks. But since paper white is part of the target gamut, the target gamut lightness range may be significantly larger than its range of saturation and hue values. This means that target gamuts defined by custom inks tend to be elongated, from paper white to the darkest color formed by the superposition of the available inks. Therefore, for gamut reduction, it makes sense to first map the original lightness axis onto the target lightness axis, and then map original hues and saturations within the mapped constant lightness sections.

Regarding the mapping of original saturation to the target saturation, as proposed by Stone & Wallace[14], we carry out this mapping by a non-linear compression (also called soft compression[15]), i.e. a mapping which tends to preserve some of the original saturation values.

1.2. Color separation and color gamut

The human visual system perceives three attributes of color: lightness, saturation and hue. Gamut mapping is usually performed in a color space that represents these attributes. To obtain the color gamut description of a device, there are two categories of method[16,17,18]. A large set of samples spanning the printable range is measured and empirical methods are used to estimate the gamut boundaries. The second way to define the color gamut is based on an analytical model of the printer that relates color to the amounts of colorants. In the present article, the gamut color of several custom inks can be theoretically represented with two analytical models corresponding to two printing processes.

The first model is based on the MultiColorDithering halftoning method[2,3] where the inks and their superpositions are placed side by side. In that case, the reduced gamut boundary in CIE-XYZ is made of planar triangular faces with vertices representing the inks and their superpositions. The second model is based on the Neugebauer equation[8], where the color gamut boundary comprises curved surfaces. The Neugebauer equation transforms coverages of inks and their superpositions onto CIE-XYZ values.

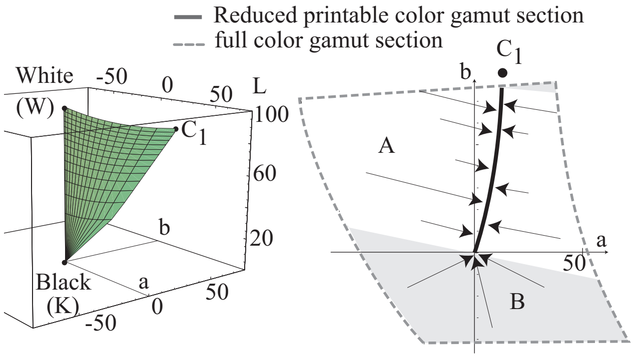
2. GAMUT REDUCTION FOR CUSTOM INKS INCLUDING THE BLACK INK

In this chapter, we assume that the sets of inks includes the black ink. If the paper is white, the original gray axis is nearly identical to the gray axis within the reduced target color gamut. Target lightness levels are very close to original lightness levels.

2.1. One custom ink (C_1) and black

Let us assume that only one single color C_1 is selected by the designer in order to give to his design a monochromatic aspect. The proposed gamut mapping method should map the original colors onto the gamut surface White-C_1-Black. This two-dimensional gamut mapping modifies hue and saturation. The only printable hue is the hue of color C_1. All input colors are projected onto the “triangular” surface formed with vertices corresponding to White, Black and C_1 (Fig. 1a).

Figure 1b shows on the constant lightness slice L=72 (CIE-Lab) the projection of original colors onto the target gamut (continuous bold line).



(a) 3D color gamut target in CIE-Lab.

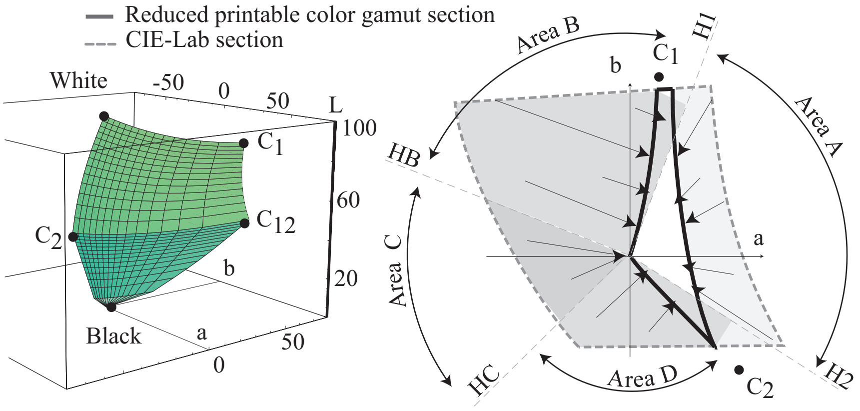
(b) Section L=72, mapping colors into the printable area.

Figure 1. Reduced color gamut with ink C_1 and black in CIE-Lab.

All the color points, which are not in the half-space containing C_1 (area B) are mapped onto the gray axis by keeping their relative lightness values constant. The points located in the other half-space (area A) are orthogonally projected onto the surface, possibly clipped or compressed in case their projection does not intersect surface section W-C_1-K. Colors with hues far from the hue of color C_1 will be therefore more desaturated, i.e. closer to gray than colors with hues close to the hue of C_1.

2.2. Two custom inks (C_1, C_2) and black

The designer may want to reduce the hue range of his design by using only two inks C_1 and C_2, keeping some of the original colors unchanged and mapping other colors onto the limited hue range. The original gray axis remains printable. The only printable hues are located between the hue of ink C_1 and of ink C_2. As shown in Fig. 2, area A is the area where the hues are kept as close as possible to the original. Original colors with hue located outside area A are mapped onto areas at the border of printable area A or onto the gray axis. Printable border areas are located between hue half planes C_1 and H1, and C_2 and H2. H1 and H2 are hues selected by the designer at the border of printable hues.



(a) 3D color gamut target in color space CIE-Lab. (b) Section L=72 (CIE-Lab), mapping colors into the printable area.

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

Area C includes the original points located between the vertical hue half-plane HB perpendicular to the hue plane containing C_1, and the vertical hue half-plane HC perpendicular to the hue plane containing C_2. The original color points in area C are mapped onto the gray axis. Area B is defined between the half-plane of hue C_1 and area C. Likewise, area D is defined between the half plane of hue C_2 and area C. The original points in area B and between the hue half planes of C_1 and H1 are mapped linearly between the hue half planes of C_1 and H1 carrying out an orthogonal projection toward half plane H1. Colors of areas D and between the hue halfplanes C_2 and H2 are linearly mapped into area C_2H2. Their saturation is then reduced to provide space for reproducing original saturated colors mapped into an area of C_2H2 situated beyond the target gamut boundaries.

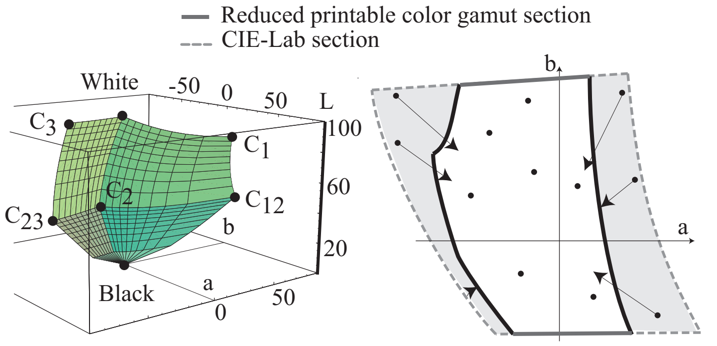
As in the case of one custom ink and black, colors in area B and D with hues far from the target gamut will be more desaturated than colors close to the target gamut hues.

Figures 13 a,b,c show color reproduction examples by color gamut reduction with two custom inks and black. The original cyan dress can not be printed with the chosen sets of custom inks. For the set of inks (b), cyan is projected onto the hue C_{A2}. The cyan dress appears partly as desaturated green, partly as gray. The blue background and yellow are mapped onto the gray axis. For the set of inks (c), both the blue background and the cyan dress are mapped onto the gray axis. Due to the ink C_{B2}, the yellow dress and the faces are closer to the original than when printed with the set of inks (b).

2.3. Three custom inks (C_1, C_2, C_3) and black

Several types of color space coverages may be obtained by three inks and black. Three inks and black may cover all hues (Fig. 3) if the inks are well distributed around the gray axis. In the case of three inks and black covering only part of the hues, we may apply a mapping similar to the one described for two custom inks and black.

For a set of three inks covering all the possible hues, the gamut mapping may be carried out according to one of the well known gamut mapping methods described in the literature[5].



(a) Target color gamut (CIE-Lab). (b) Mapping of colors into the printable area.

Figure 3. Reduced color gamut with three inks (C_1, C_2, C_3) and black.

Figures 13 a,d,e show color reproduction examples by color gamut reduction with three custom inks and the black ink covering only a part of all hues. For the set of inks (d) (set of inks (b) plus C_{A3}), blue and cyan can not be reproduced and are projected onto the hue section C_{A2}. Thanks to C_{A3}, the yellow dress and the faces are closer to the original than when printed with the set of inks (b). For the set of inks (e) (set of inks (c) plus C_{B3}), the cyan dress, the blue background and the green color are projected onto the hue section C_{B3}.

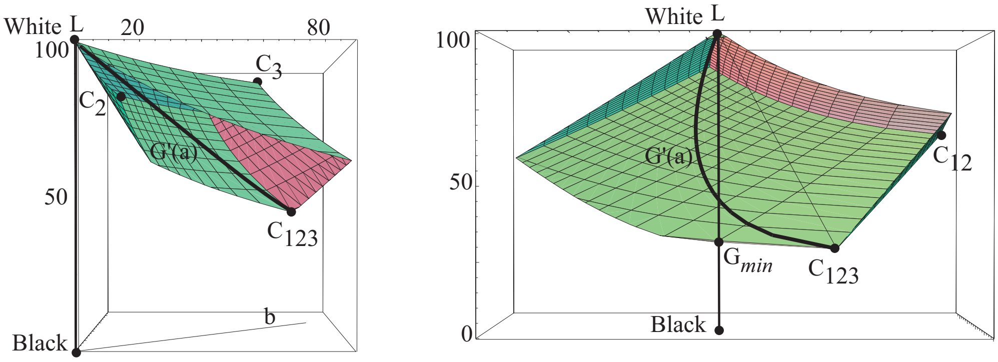
3. GAMUT REDUCTION FOR THREE CUSTOM INKS WITHOUT THE BLACK INK

For printing with a set of custom inks, which does not includes the black ink, a new approach needs to be developed. The full color gamut needs to be mapped into a reduced color gamut, which does not include the gray axis (Fig. 4).

Let us distinguish two cases. In the first case, the reduced target color gamut does not intersect the gray axis (Fig. 4a). In the second case, the target gamut contains a part of the original gray axis (Fig. 4b), i.e., at some lightness levels (point G_{min}), the gray axis is inside the gamut and at other levels, the gray axis is outside the gamut.

3.1. Mapping the gray axis

Since the gray axis cannot be printed with the chosen set of inks, it needs to be mapped onto the target gamut as a continuous smooth curve ensuring that continuous original gray values are mapped into continuous values of lightness, saturation and hue.



(a) Target color gamut that does not include the gray axis.

(b) Target color gamut includes the gray axis.

Figure 4. Two reduced color gamuts sliced following the plane including the gray axis and C_{123}.

The desired curve representing the gray axis in the target gamut connects the paper white to the point with the lowest lightness C_{123}. A smooth curve which by definition remains within the target gamut is the curve representing equal amounts of inks C_1, C_2 and C_3. According to Neugebauer, for amount $0 \le a \le 1$ of inks C_1, C_2 and C_3, we obtain the CIE-XYZ values along this curve:

$$G'(a) = (1-a)^3 . C_{paper} + a\,(1-a)^2 .(C_1+C_2+C_3) + a^2\,(1-a).\,(C_{12}+C_{13}+C_{23}) + a^3 . C_{123},$$

where C_{paper}, C_1, C_2, C_3, C_{12}, C_{13}, C_{23}, C_{123} are the CIE-XYZ tristimulus values of the paper, the inks and their superpositions.

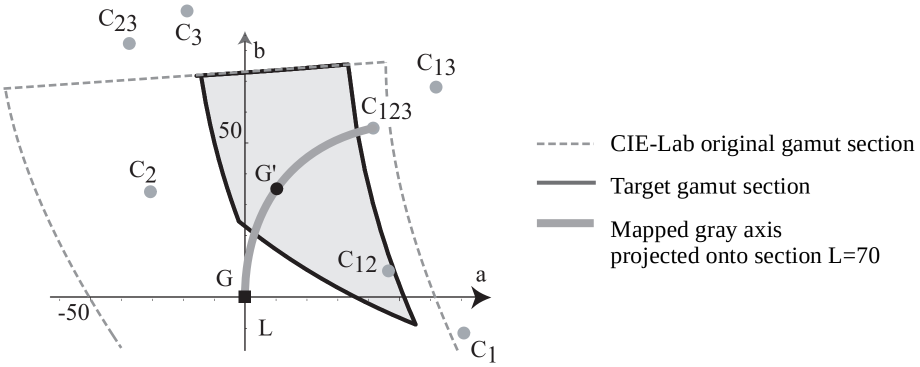


Figure 5. Projection of the equal amounts of inks curve G’(a) onto section L=70 of the CIE-Lab color space.

The equal amounts of inks curve G’(a) is not necessarily included in a constant hue plane. The hue of G’ may progressively change according to the lightness level (Fig. 5).

3.2. Lightness rescaling

The proposed color gamut reduction method should keep as much as possible the original colors. Rescaling in terms of lightness may be based on a linear mapping function (Fig. 6a). However, rescaling according to a non-linear mapping (also called soft compression[15]) may be preferable (Fig. 6b). With linear rescaling, all the points move from their initial position. With smooth non-linear rescaling, we keep as it is a large part of the original lightness range.

For non-linear rescaling, a lightness level L_1 is set, above which the lightness of colors remains unchanged. Points with lightness lower than L_1 are rescaled according to a curve whose tangent at L_1 has the same orientation as the linear portion of the mapping. This curve may be a quadratic Bézier curve. Color reproductions of the original gray axis mapped into 4 different target color gamuts with non-linear and linear lightness rescaling are shown in Fig. 14.

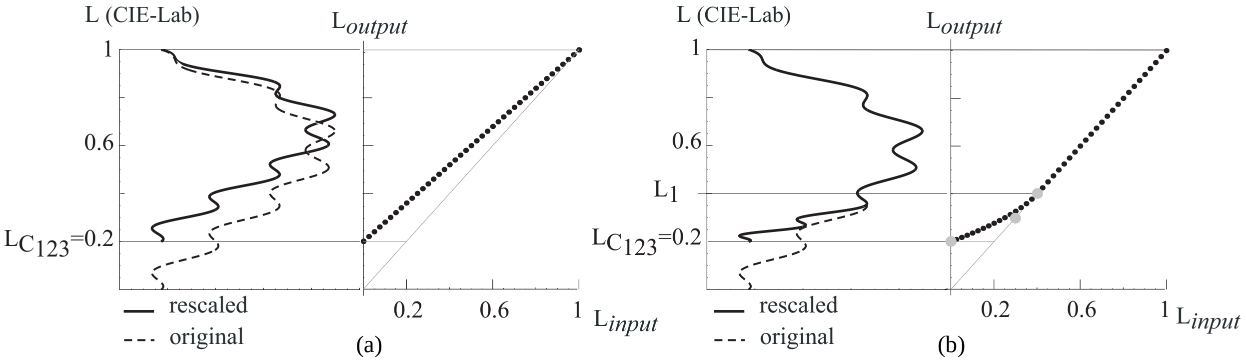
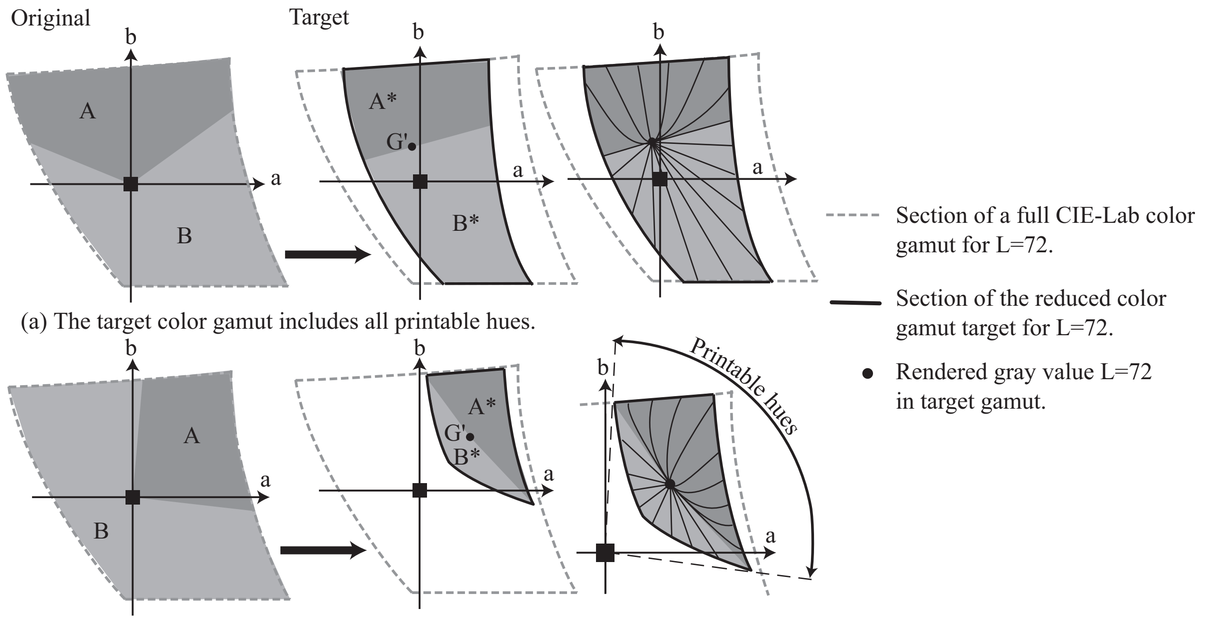


Figure 6. Linear (a) and non-linear (b) mapping of lightness in a hue section.

3.3. Mapping the hues

After mapping of the gray axis and lightness rescaling, hue and saturation need to be mapped. We keep as much as possible the original hues in the printable target color gamut and distribute colors whose hue cannot be printed on the desaturated side of the mapped gray axis G' (Fig. 7b).



(a) The target color gamut includes all printable hues.

(b) The target color gamut does not include all printable hues.

Figure 7. Color gamut reduction with two types of reduced target gamuts.

In order to keep the continuity between hues, mapped hue lines on a given lightness section have to gather to the corresponding point of the mapped gray axis G'. We define two areas for the mapping (Fig. 7). Area A of the original color gamut is mapped onto the area A* of the target color gamut. In this area, we keep as much as possible the original hues and saturations. When the target color gamut incorporates all printable hues, color points in area B may be printed with their original hue and possibly a saturation close to the original saturation as shown in Fig. 7a. However when the target gamut does not contain all hues at all lightness levels, some hues cannot be reproduced (Fig. 7b). In order to partition the target gamut into areas A* and B*, we draw a line through G’ perpendicular to GG’, yielding intersection points A and B with the reduced target gamut (Fig. 8). To ensure the continuity of colors mapped into the A* and B* spaces, all lines linking points in area A* and G should intersect segment [BG’] or [G’A]. For example, in Fig. 8, line GC does not intersect segment [BG’]. In that case, segment [BG’] must be replaced by [CG’] in order to form the final boundary of area A*. The curves (e.g. curve G’E) used for the mapping of hue lines from area A to area A* are constructed according to Fig. 8. The control points D of quadratic Bézier splines are located on segments [G’A] or [G’C].

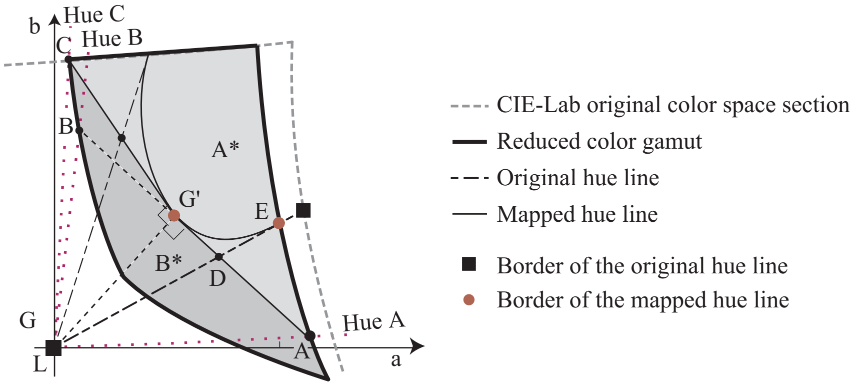
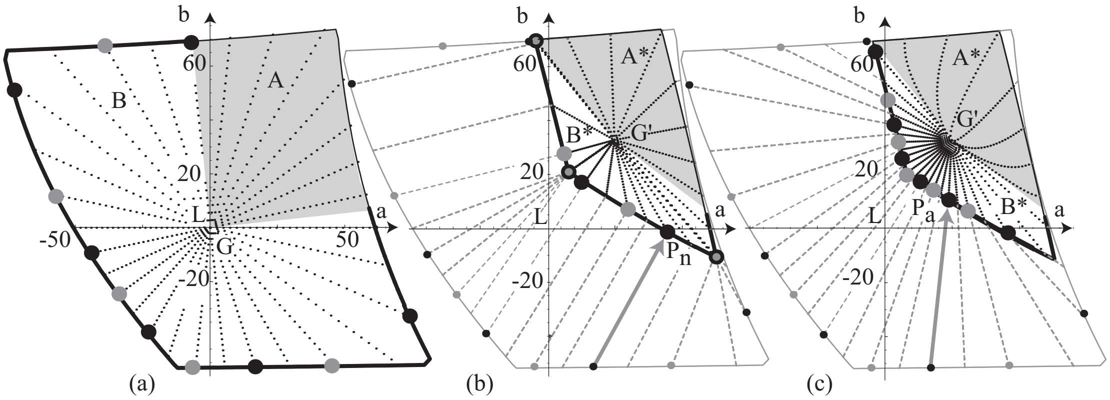


Figure 8. Mapping original hue lines into curves in the target gamut.

For mapping the most saturated original colors of each hue, i.e. the original color gamut boundary (Fig. 9a), we define two projection methods. The first method (Fig. 9b) maps each point of the full color gamut boundary into the nearest target gamut boundary point (P_n) in term of Δ E (CIE-Lab). The second method (Fig. 9c) maps all points of the original color gamut boundary whose hues are printable (external boundary of A), to the most saturated locations of the same hue on the reduced gamut boundary. Other points are distributed on the external boundary of B* (P_a) according to their original angular distribution within area B relative to G onto a similar angular distribution within area B* relative to G’ (Fig. 9c). This second mapping method enables each original color to be distinguishable when printed with the chosen set of custom inks. However, the first mapping method renders colors closer to the original colors.



(a) (b) (c)

Figure 9. Mapping of the original color gamut boundary points (a) onto the reduced target gamut according to (b) the closest point and according to (c) their angular distribution.

Figure 10 shows the mapping of area A of the original color space onto the target gamut. By using curves (Fig. 10a) instead of straight lines (Figs. 10 b,c), original colors at high saturation are rendered more accurately.

The mapping of area B of the original gamut into area B* of the reduced target gamut may be carried out by three different methods. We may map the original hue line (1) along a Bézier curve linking G’ and P_n (nearest point on target gamut) with P_a (point on target gamut according to angular distribution) as control point (Fig. 10a), (2) along a straight line linking G' and P_n (Fig. 10b), or (3) along a line linking G' and the point P_a (Fig. 10c). According to the second method, several original hue line are possibly mapped into a single hue line. Mapping hue lines along curves (first method) allows to distinguish between neighboring hues.

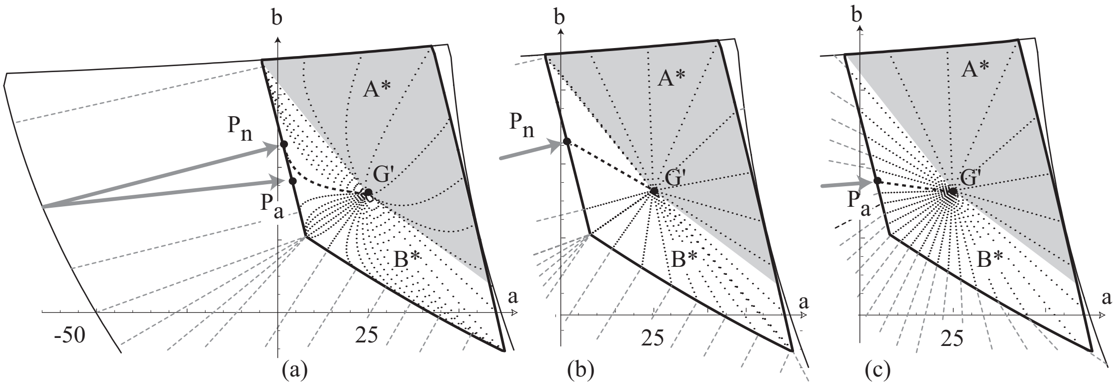


Figure 10. Mapping of hue lines (a) with curves in both areas A* and B*, (b) with lines linking the nearest target boundary color and G', and (c) with lines distributed according to an angular distribution.

3.4. Saturation mapping

After establishing the mapping of hue lines between original and reduced target gamut, let us propose both a linear and a non-linear saturation mapping method.

3.4.1 Linear saturation mapping

The definition of area A ensures that for each hue, a point exists on the reduced target gamut boundary. However, area A* is defined differently, depending if a linear or a non-linear mapping is chosen. For linear mapping, area A* is defined as explained in Sec. 3.3 (Fig. 8). Saturation values are mapped along successive positions of the curve representing the mapped hue line.

3.4.2 Non-linear saturation mapping

For applying non-linear saturation mapping, area A* must ensure that each of its color points has a larger saturation than the saturation of G' (Fig. 12a). The saturation of G' corresponds to *MinSat* (Fig. 11) and the saturation of the most saturated mapped point E corresponds to *MaxSat*. With non-linear saturation mapping, we would like to keep the rendered points as close as possible to the original points. We define three different saturation rescaling segments. At high saturation, a non-linear mapping between input saturation and output saturation preserves as much as possible high saturation levels (Fig. 11). At intermediate saturation levels, linear saturation mapping is applied. Low saturations are compressed into a limited range by a non-linear mapping. Non-linear saturation mapping can be applied to colors in area A (Fig. 12b). In area B, it is not possible to remain close to the original saturation values. However, in order to ensure continuity at the boundaries of areas A* and B*, we also apply non-linear saturation mapping in area B* (Fig. 12b). This tends to map saturated colors located outside the target gamut hues to colors closer to gray.

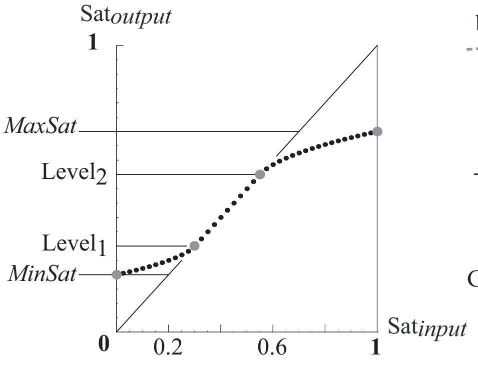


Figure 11. Saturation rescaling.

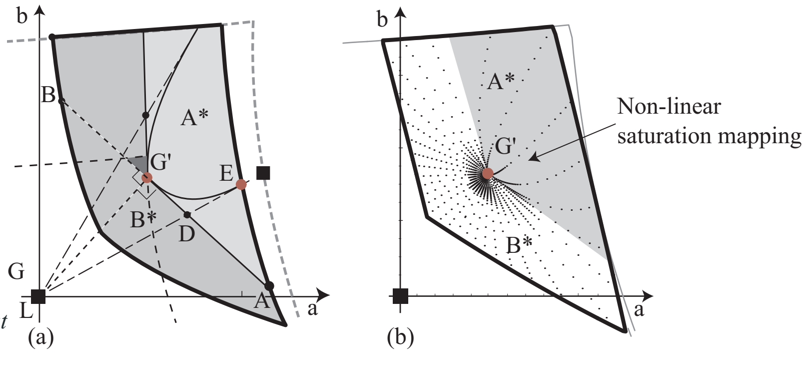


Figure 12. Example of target color gamut division for non-linear saturation mapping.

According to the saturation mapping shown in Fig. 11, $Level_2$ and $Level_1$ can be defined as percentages of the full saturation output range. The non-linear high saturation range defined by $Level_2$ may be a useful parameter for increasing or decreasing the overall saturation of gamut reduced images.

Color reproductions of a hue line according to a linear and a non-linear saturation mapping are shown in Fig. 15. With non-linear saturation mapping, the range where original saturations and mapped saturations remain very close can be controlled by the designer.

3.5 Image reproduction example

Figures 16 a,b,c show the same image rendered with different sets of 3 custom inks, without black. The darkest printable color with the first set of inks, C_{a123}, is not black but a dark brown. The strongly reduced target gamut does not cover even a small part of the gray axis. As shown on the top-right wedge, most green and blue hues can not be reproduced. Fig. 16a shows the best compromise obtained with the presented mapping method. Faces, white, yellow and brown colors are rendered close to the original colors. All other colors are rendered in brown tones which represent the gray axis mapped into the target gamut.

Fig. 16b shows the image mapped into a larger target gamut. All the hues are printable. Faces, yellow and brown objects are rendered close to the original colors whereas other colors tend to be desaturated. Original colors close to black are rendered with colors close to C_{b123} (e.g. dark background).

The third gamut reduced image (Fig. 16c) is rendered with a set of inks whose colors are close to magenta, cyan and yellow. All rendered colors are close to the original colors.

4. CONCLUSION AND PERSPECTIVES

This paper proposes methods for mapping an original full color gamut into a reduced target color gamut. Gamut reduction differs from gamut mapping mainly by the fact that the target color gamut may not include the gray axis. Various methods for color gamut reduction have been proposed. The methods we introduce depend on the choice of the custom inks and on the presence or absence of the black ink. In the case of 3 inks without black, the original gray axis is mapped along a curve defined by equal amounts of the chosen inks.

When the target gamut does not incorporate the gray axis, we divide it into two volumes, one on the desaturated side of the mapped gray axis curve G' and the other on the saturated side of the G' curve. Colors whose hues are not part of the target color gamut are mapped to colors located on the desaturated side of the G' curve. Colors within the set of printable hues remain within the target color gamut and retain as much as possible their original hue and saturation.

On constant lightness slices, we map the original hue lines located on the saturated side of the G' curve along curves connecting the most saturated colors with the mapped gray point. The mapping of original hue lines onto these curvilinear hue trajectories allows to retain as much as possible their original hues. A non-linear saturation mapping also allows to retain as much as possible the original saturation values.

Once integrated into an interactive software package, gamut reduction may become a valuable tool for creating designs to be printed with a limited set of custom inks. In addition, it may be very useful for designing banknotes where the color of a custom ink varies according to its horizontal or vertical position.

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APPENDIX

Original and gamut reduced images are given at: http://diwww.epfl.ch/w3lsp/publications/colour/

Additional information such as the CIE-XYZ values of the custom inks and their combinations is also given in order to allow other researchers to compare their gamut reduction algorithms with our methods.

Figure 13. Original image (a) mapped into 4 different target color gamuts: two custom inks and black (b),(c); three custom inks and black (d),(e).

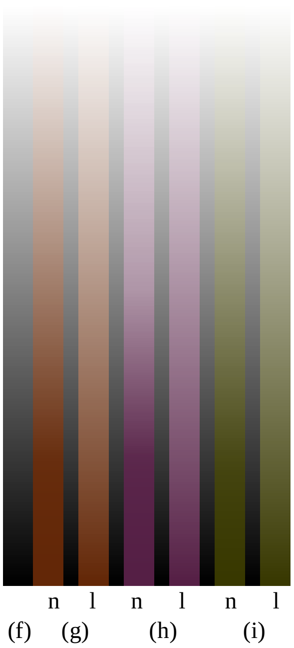

Figure 14. Gray axis (f) mapped into 3 different target gamuts according to (n) non-linear and (l) linear lightness rescaling.

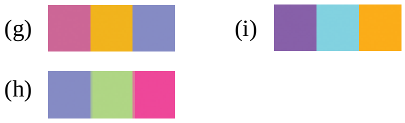

Figure 15. Original hue line (within the disks) obtained by (a) a linear saturation mapping, (b) a non-linear saturation mapping.

Figure 16. Original image (outside the disks) mapped onto 3 different reduced target gamuts (inside the disks).