Gamut mapping: an overview of the problem

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Introduction

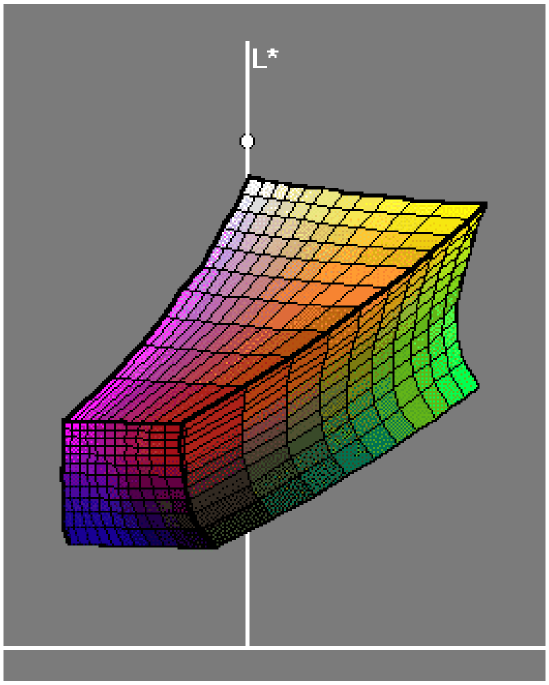
Gamut mapping is a very actual problem in today's color reproduction. For a target device, a gamut mapping algorithm establishes a correspondence between the out of gamut color and the color within the gamut, trying to preserve same color appearance with the original color when that color is rendered on the target device. This problem becomes more and more important with the increasing number of color reproduction devices and cross media image representation. An immediate application of gamut mapping is for creation of color tables of ICC profiles that are used in color management workflow to communicate colors from one device to another. A large number of gamut mapping algorithms is encountered in the literature. This paper does not try to give an overview of these algorithms, despite the fact that few of them are mentioned or discussed. The intention of this paper is more to discuss the factors that influence the gamut mapping and gamut mapping results. Gamut representation and factors to influence the gamut shape size are discussed in the first section. In the second section the influence of the color space is discussed and a linearization procedure for CIELAB is proposed with direct application to gamut mapping problem. In the third section, few gamut mapping algorithms are discussed, in their results are compared with respect to linear mLAB or CIELAB spaces. The immediate application of this analysis is for creation of ICC profiles used to characterize several printing devices.

Gamut representation

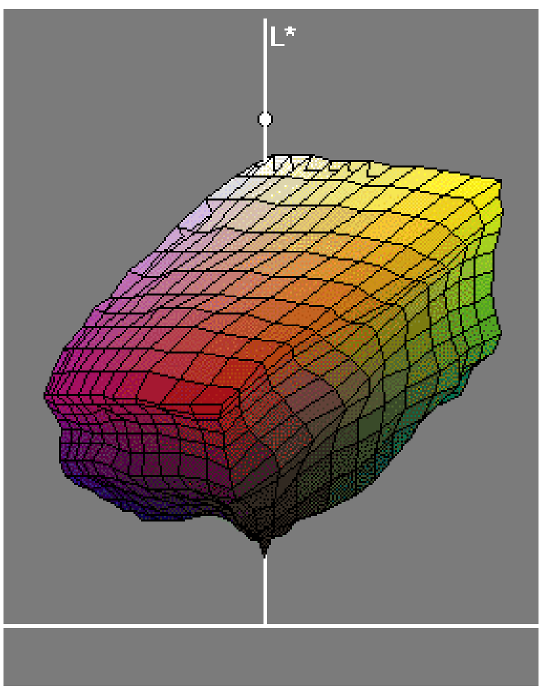
In general, the term "device gamut" or "gamut" refers to all colors that can be rendered or acquired on a device. It is easy to observe that gamut representation is an important factor that influences the final result of gamut mapping procedure. The representation of gamut decides the out of gamut colors, the position and the distance of these colors with respect to gamut surface. These are important elements when the practical gamut mapping procedure is effectively applied. Therefore several factors related to gamut representation should be pointed out.

First, the model that is adopted to represent the gamut is essential for the accuracy of the gamut mapping procedure. Analytical gamut representation might be simple and requires few parameters. However the resulted gamut volume does not represent in most cases the non-linearity of the practical devices. On the other hand, empirical models based on 3D LUT and interpolation might require a large data set of measured points but will render more accurately various parts of the gamut that can hide subtle aspects related to color reproduction specific to the modeled device. Figure 1 illustrates the differences between gamut representation based on empirical (a) and analytical model (b) for a color laser printer.

If we focus the discussion toward printing reproduction devices, additional factors must be taken into account for gamut representation. First the reproduction technology can determine different gamut even if printing process runs for same substrate (type of paper). Figure 2 illustrates the gamut differences due to laser and ink jet technologies on plain paper. In case of same reproduction technology, the media influences essentially the gamut of the device as it is illustrated in figure 3 for the case of an ink jet printer running on plain paper and photographic paper. Not only the volume, but the shape of the gamut is significantly different, leading to situations where black region of the gamut is lighter than the blue region of the gamut. This case creates serious problems to gamut mapping procedures and in general to color reproduction process.



(a) analytical gamut representation



(b) empirical gamut representation

Figure 1. Influence of device model on gamut representation

It is important to understand that in case of certain printing devices using 4 (or more) colorants, the gamut may refer to two distinct cases. If the device is forced to print all possible combination of its (4 or more) colorants, the measured color volume is referred as *maximum gamut*. Figure 4 shows sequentially for C, M, Y colorants the influence of black component, generated independently on C, M, Y, in achieving the maximum gamut.

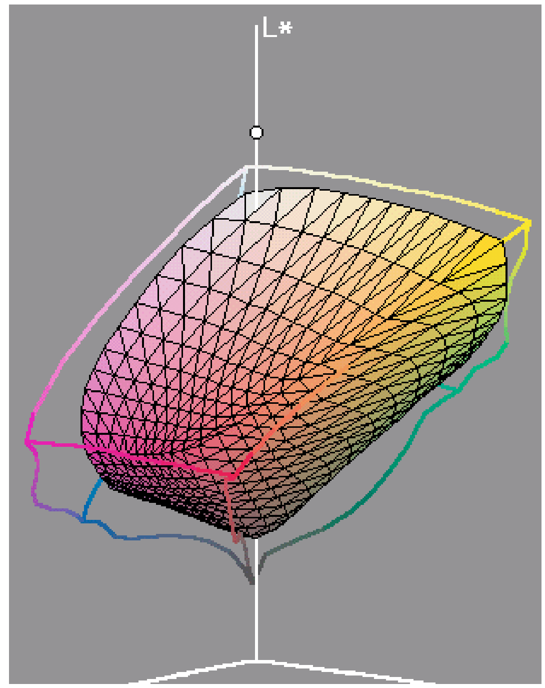


Figure 2. Influence of printing technology on gamut shape

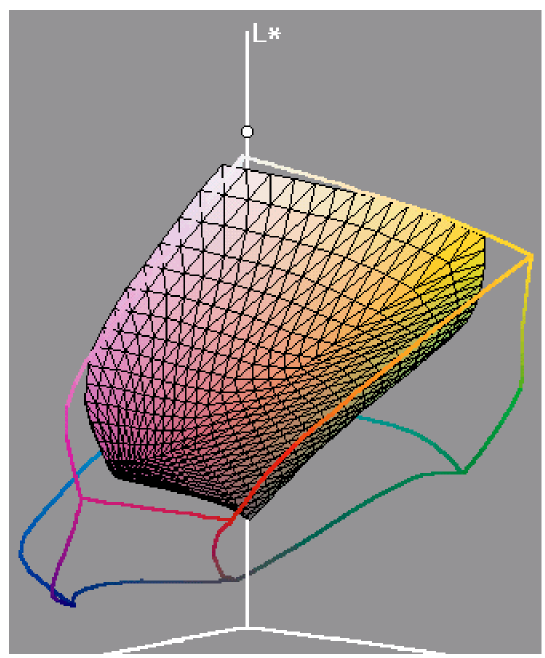
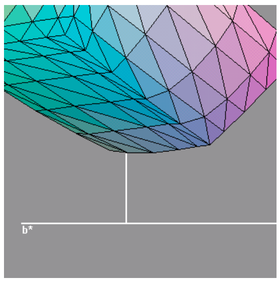
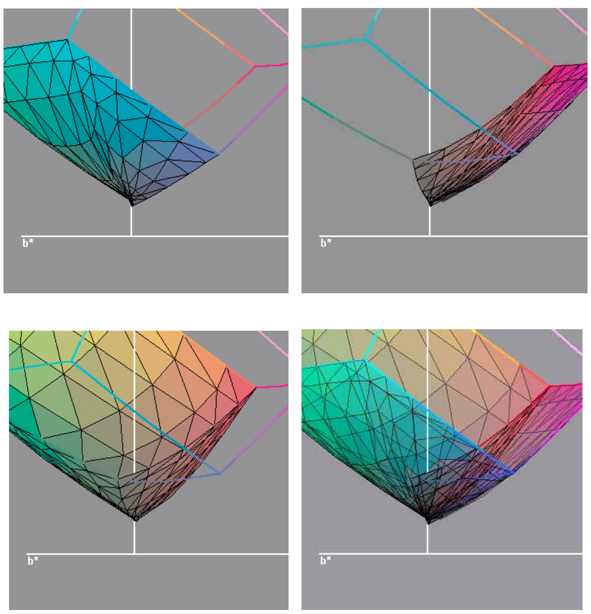


Figure 3. Influence of media on gamut shape and size, and eventually on gamut mapping.

However, if a C, M, Y dependent black generation procedure is used, the resulted gamut may be different. This effect is due to the relationship introduced by the black generation procedure that reduces the number of physical combination of C, M, Y, K colorants form n^4 to n^3 combinations, with possible consequences in the reduction of gamut.



a) detail of CMY gamut



b) detail of gamut improvement due to K addition on C, M , Y region of the gamut

Figure 4. Visualization of optimal gamut

In the real printing devices, the achievement of the optimal gamut with a C, M, Y dependent black generation procedure is one key element in achieving good quality printing results. It also may simplify the gamut mapping procedure and reduces some out of gamut colors. Figure 5 illustrates the gamut reduction due to a poor black generation procedure. In case of smaller gamut, the concave shape of the gamut creates serious problems in choosing a good mapping procedure, while in case of larger gamut this problem does not appear. It is important to note that there are cases when maximum gamut does not necessary conduct to the pleasant feeling of color reproduction. These cases may include the graininess of the image caused by too much black, or a preference for using CMY composite black instead of black ink. In case of black generation, a healthy amount of experience and artistic sense is required in order to optimize the black generation procedure. Additionally, certain media can accept only a limited amount of ink, reducing further the gamut.

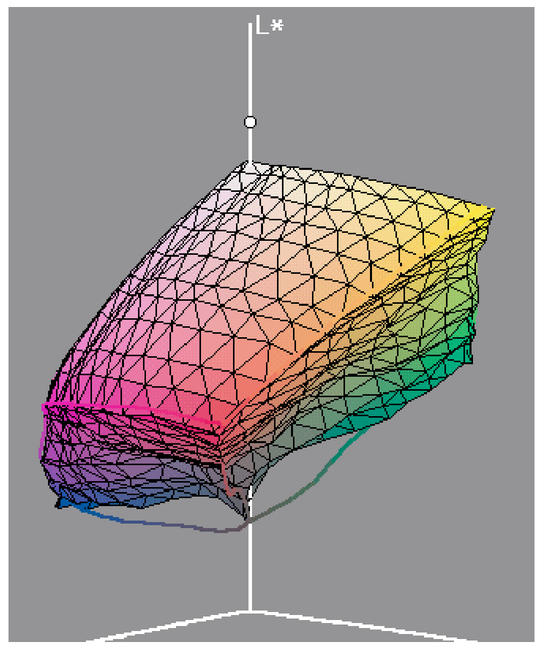


Figure 5. Influence of black generation procedure on gamut shape

Halftoning is another element that influences the device gamut. Figure 6 shows an example of dot-on-dot versus dot-off-dot halftoning and the corresponding gamut variation. The resulted gamut after setting the halftoning procedure, black generation and ink limit constraints is referred in this paper as *effective gamut*. Therefore, careful selection of the mentioned factors is important in achieving a good rendition of colors, close to the optimal gamut. This selection should be performed *before* starting the investigation of any gamut mapping algorithms because it reduces considerably the gamut mapping requirements. It also will reduce the risk of solving by gamut mapping methods, the problems that are not gamut mapping specific and that can be solved much efficiently by acting on the causes that generate these problems.

The color space

The space in which the gamut is represented and the gamut mapping is performed can influence and in many cases can make a difference in achieving a good quality of color reproduction. In this section a correction procedure is described to achieve a better uniformity of CIELAB space that can conduct to better gamut mapping results.

If the color space used for gamut representation is not uniform, the gamut representation may be distorted or certain special loci can only be roughly approximated, with consequences in gamut mapping results, that includes hue shift or bad shadow rendition. Recent studies indicate that the uniform CIELAB and CIELUV color spaces include significant nonlinearities especially in the yellow and blue hue regions [5,6,7,8]. Therefore performing gamut mapping in these spaces may result in a hue shift. The shift is more noticeable in case when distance between the out of gamut color and the gamut is larger, therefore for small gamuts (as in case of plain paper) and for saturated colors. Figure 7 shows a representation of the Munsell rennotation system data (Newhall, Nickerson and Judd). Figure 8 represent the same data but represented in an ideal uniform space that distributes evenly the Munsell data with respect to lightness, chroma and hue.

Determining a uniform color space is extremely important both for gamut mapping and for solving other color related problems. Additionally, it is desirable that the linear color space should not have very different dimensions from the conventional color spaces, in order to be intuitive and practical.

Several achievements toward uniform color spaces are remarkable. Ebner and Fairchild proposed the IPT linear space based on Hung and Berns and their own experimental data that extends beyond the Munsell reflective data set. Ikeda developed the NC-IIIC linear space based on Munsell colors. McCann proposed a 3D LUT mechanism for linearization of CIELAB color space, resulting in the MLAB linear space.

We will describe a similar and independent approach to create a uniform CIELAB based on Munsell rennotation system data (Newhall, Nickerson and Judd. A direct CIELAB to mLAB uniform space was developed. Because our method was specifically designed for gamut mapping based on LUT and tetrahedral interpolation, the reverse transformation was not required. This provided a certain advantage of the gamut mapping that is therefore only affected by the approximation error caused by the direct transformation (CIELAB to mLAB). On the other hand, a complete comparison with other methods that produces uniform equivalent CIELAB space was not carried out because of the lack of data corresponding to the reverse transformation (mLAB to CIELAB). This is a future task of our work.

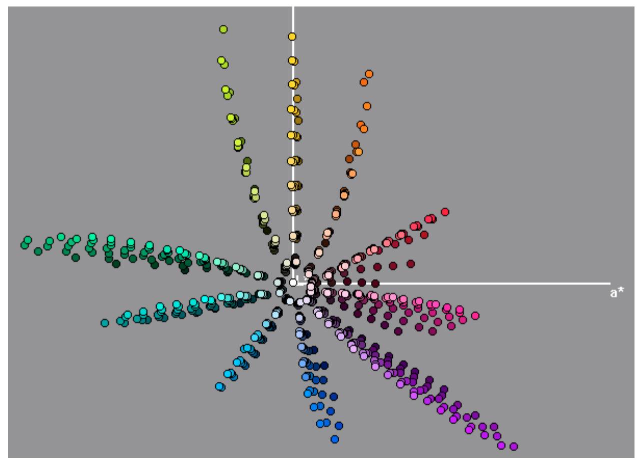


Figure 7. CIELAB visualization of Munsell rennotation system illustrating the hue shift due to chroma and lightness variation

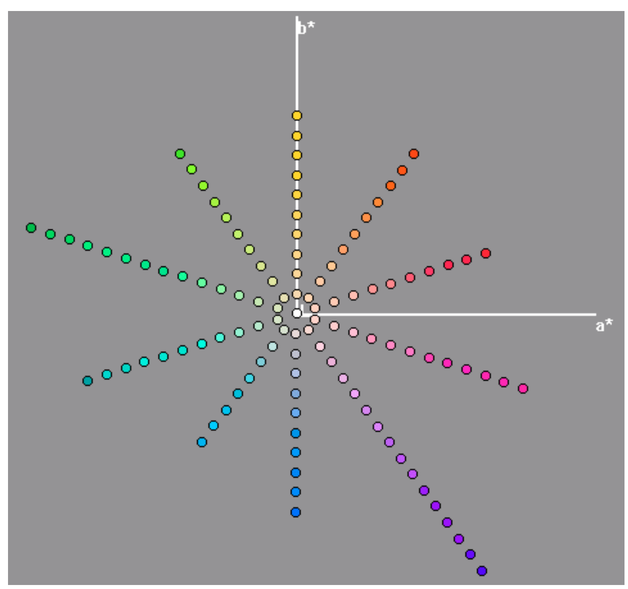


Figure 8. Munsell rennotation system in a CIELAB type coordinate system that is linear in terms of hue, chroma and lightness (mLAB)

An uniform CIELAB space (mLAB)

The derivation of a uniform CIELAB space is based on re-mapping the CIELAB coordinate system based on the constraints imposed by the Munsell renotation system. In the Munsell renotation system the colors progress from top to bottom from light to dark in equal intervals. It also offers under daylight viewing conditions, equally perceived light colors for each row and equally perceived chroma on each column.

The new space, referred here as mLAB, uses also L'a'b' coordinates. It preserves the lightness of CIELAB but remaps the (a*,b*) coordinates into the (a',b') coordinates of mLAB such that the constant angle and chroma intervals in the new space fits constant hue and chroma distances in the chart of the Munsell renotation system.

The data that is used to perform the conversion is collected from [9] table I (6.6.1). This table defines the (x,y,Y) coordinates of the equally spaced samples in lightness (9 intervals), hue (and chroma. An example of 3D representation in CIELAB coordinates of Munsell samples for 5P and 5RP samples is presented in figure 2.

The samples are collected in the ANSI format file for color data representation. A visualization procedure based on the algorithm introduced in detail by Marcu and Abe in [10] is used to check the data integrity and to illustrate once more the CIELAB hue when varying the lightness. The visualization procedure is not essential and any 3D data visualization package (Mathematica, MathLab, etc) or new emerging languages such as VRML can be used.

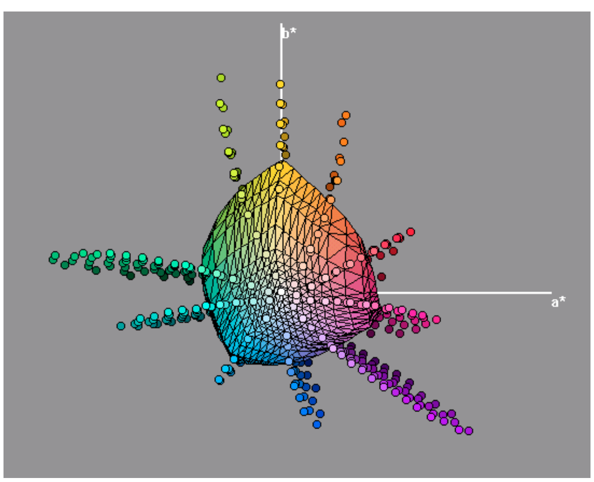


Figure 9. Visualization of an ink jet printer gamut in conventional CIELAB space

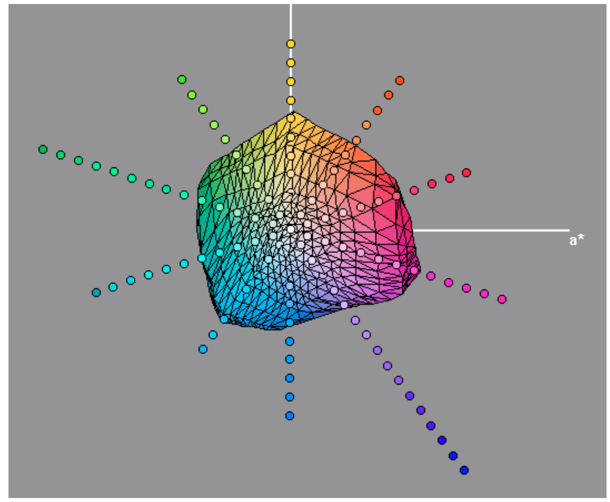


Figure 10. Transformation of the ink jet printer gamut corresponding to the linear mLAB space

The CIELAB to mLAB conversion

A color conversion method between the CIELAB and mLAB space is described based on a set of fix points and interpolations.

The CIELAB to mLAB transformation is performed using a tetrahedral interpolation algorithm in CIELAB space [11]. The unknown color is interpolated from four known Munsell colors that determine the minimum tetrahedron that includes the unknown color.

The interpolation tetrahedron can be identified in two ways. The first approach is based on a direct searching procedure. The searching procedure finds the first closed N Munsell values to the unknown color and then checks the inclusion condition for each combination of four colors (from the set of N) determining a tetrahedron. Since the searching procedure can find more than a tetrahedron that includes the unknown color, an additional criterion can be used to select the best tetrahedron (the tetrahedron that will give the smaller interpolation error). We found that the standard deviation of the face angle values of each tetrahedron from the selected candidates can give a good measure of tetrahedron "compactness", and this was correlated with the minimum interpolation error. Even without this criterion, the searching procedure can give acceptable results even if the first tetrahedron to verify the inclusion condition is selected for interpolation. For our experiment N was limited to the closest 15 Munsell colors to the unknown color. This leaves a number of 1365 tetrahedrons to be investigated for each unknown color.

A second approach to decompose the CIELAB space in disjunct and adjacent tetrahedrons. This implies to pre-compute all tetrahedrons determined by the Munsell set and then to use an indexed procedure to find the tetrahedron that includes the unknown color. In either case, once the tetrahedron is identified, the interpolation procedure is performed based on the following set of equations:

$$\boldsymbol{C} = a1.\,\boldsymbol{C}_{m1} + a2.\,\boldsymbol{C}_{m2} + a3.\,\boldsymbol{C}_{m3} + a4.\,\boldsymbol{C}_{m4}, \qquad (1)$$

$$\boldsymbol{C}' = a1.\,\boldsymbol{C}'_{m1} + a2.\,\boldsymbol{C}'_{m2} + a3.\,\boldsymbol{C}'_{m3} + a4.\,\boldsymbol{C}'_{m4} \qquad (2)$$

where $\mathbf{C}_{m1}$, $\mathbf{C}_{m2}$, $\mathbf{C}_{m3}$, $\mathbf{C}_{m4}$ represent the CIELAB vectors of the Munsell set, $\mathbf{C}'_{m1}$, $\mathbf{C}'_{m2}$, $\mathbf{C}'_{m3}$, $\mathbf{C}'_{m4}$ represent the vectors in the mLAB space, a1,a2,a3,a4 represent the baricentric coordinates of the unknown color in the tetrahedron, and C and C' represent the unknown color ant its correspondent in the mLAB. For the reverse conversion the searching procedure is not required due to the regulate structure of the mLAB linear space.

The Munsell renotation system does not cover all the CIELAB values required to fill in for 3D color tables of an ICC profile if CIELAB is used as the PCS. To overcome this problem, the CIEXYZ is selected as PCS and only a subset of values of CIEXYZ corresponding to an area covering all practical CRTs and LCDs devices on the market today is selected for computations. However a "gamut" checking is performed to prove that the limited CIEXYZ space is covered by the samples offered by Munsell renotation system. The equation (1) and (2) are used to verify that none of the colors required to build the XYZ to device or device to XYZ tables of the ICC profile are not left out of the tetrahedrons defined within the Munsell renotation system. More implementation details can be found in [16].

An inverse procedure was not required for gamut mapping. It can be observed that the gamut mapping procedure finds the weights of the mapped color as function of the gamut data set in mLAB. For this set, the corresponding CIELAB colors are known from the direct transformation. Therefore the inverse transformation is simply reduced to compute the equation (1) with the weights from gamut mapping procedure performed in mLAB space and the known CIELAB colors defining the gamut.

The mapping procedure in the mLAB space can use the same mapping functions as the constant angle mapping in CIELAB space. The difference now is that the L'a'b' values of a color in mLAB space really represent the perceptual constant hue and chroma according to the definition of the Munsell renotation system. Therefore the proposed method combines the advantage of color specification of the CIELAB space with the advantage of the uniform perceptual color specification in the Munsell renotation system and does not restrict the applicability of any gamut mapping procedures available for CIELAB. An example of gamut representation for an ink jet printer gamut in CIELAB space is carried out in figure 9, while the same gamut in the uniform mLAB space is presented in figure 10.

Gamut mapping procedures

Gamut mapping procedures can be classified in different ways. Recent studies offer complete description and systematic comparisons between most important techniques. For a very documented review of the gamut mapping techniques please see reference [13] and [14]. Ito and Katoh classifies the gamut mapping techniques in three groups [13]:

- 1D mapping (chroma mapping);
- 2D (constant hue section mapping);
- 3D (minimum distance mapping).

This classification makes a lot of sense and enables the reader to navigate intuitively and easily through the vast reference list of available today, sensing the novelty and the value of one technique over another. Additionally, for the 3D mapping procedures, the authors investigate 6 color difference formulae showing the advantages and disadvantages of using each one of them. Additional classifications of gamut mapping algorithms can be done based on soft/hard clipping, linear/nonlinear compression, sequential/simultaneous mapping order, image/device dependent-independent mapping [17].

In this section, we limited the discussion to only 5 mapping methods corresponding to the 2D mapping in Ito and Kato classification. Our analysis extends the results presented in [16] for comparison between the gamut mapping in Munsell constant hue section versus the one performed in CIELAB constant hue angle, base don the following strategies:

(a)-constant lightness;

(b)-constant saturation;

(c)- mapping to the closest color of the gamut

(d)-mapping to a defined center of the gamut;

(e) mapping to a variable achromatic point;

These procedures are briefly described in the figure 11, 12 and 13. It can be noted that the 2D description of these procedures really represents constant perceptual hue sections in the mLAB space.

In figure 12, the method (d) clips the out of gamut colors on the gamut surface toward the gravity center of the destination gamut. The gravity center, Cg, is selected on the achromatic axis at 50% between the black and white achromatic axis of the destination gamut.

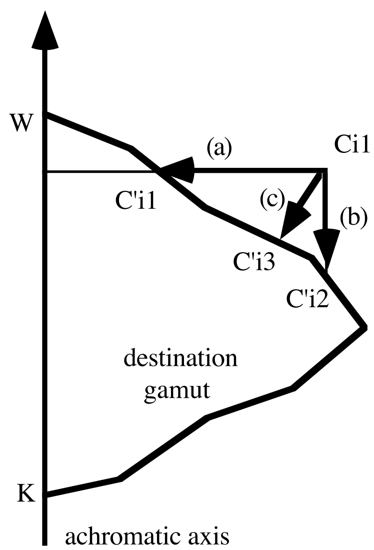


Figure 11. Gamut mapping based on constant lightness (a), constant saturation (b), and on combination of (a) and (b)

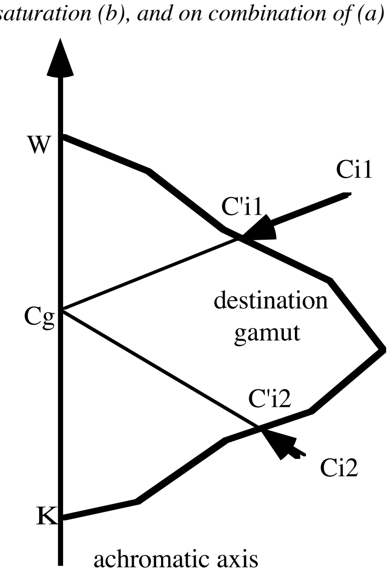
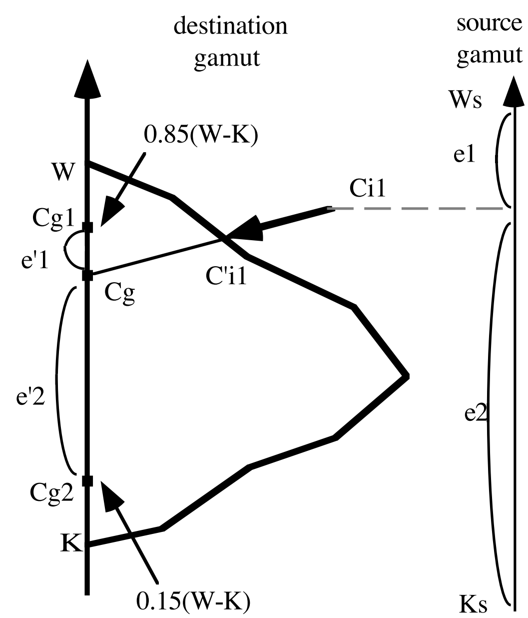


Figure 12. Gamut mapping to the gamut center (method (d))

In figure 13, the gamut mapping (e) uses a variable achromatic point, Cg , that can migrate between two fix points, Cg1 and Cg2, of the achromatic axis of the destination gamut. The points Cg1 and Cg2 are fix and are selected empirically lower than the lighter and higher than the darker points of the destination gamut (15% in our experiment). The position of the center Cg between the fix points Cg1 and Cg2 is determined based on the luminance level of the color to be mapped, Ci1, in the source gamut. This position is determined with respect to the whiter and darker points of the source gamut and is described by the ratio e1/e2 on the achromatic axis of the source gamut. The center Cg is selected between Cg1 and Cg2 such that the ratio e'1 / e'2 = e1 / e2 as it is illustrated in figure 13.



Cg is chosen such that: e1 / e2 = e'1 / e'2 ;

Figure13. Gamut mapping to a variable achromatic point (method (e)).

The gamut mapping experiment was used for a profile of the Color Style Writer 6500 printer. The samples are a mixture of SCID data (bitmaps) and graphic data (vectors). The printed samples were viewed in a light booth, under D50 illuminant. The original image was displayed on a calibrated CRT monitor (AppleVision 850 display, 1.8 gamma with D50 white point).

The comparison was carried out in two directions. First the CIELAB and mLAB color spaces were investigated with respect to the 5 gamut mapping procedures (a)~(e). It was observed visually that in all 5 cases, the mLAB space conduct to a better mapping in blue and yellow regions of the space regardless of gamut mapping procedure. This was an expected result because in the uniform mLAB space the straight lines correspond to perceptual constant hue and the hue shift will be reduced.

Second the comparison was carried out between the investigated gamut mapping procedures. It was found that lightness mapping preserves the best the tonal rendition of images that contribute to the naturalness sensation of gamut mapping. However for yellow and blue regions, the lightness mapping reduce significantly the saturation and therefore the some improvements were required. The procedure to a variable achromatic point was selected to provide the best trade of the preservation of saturation for all hues and preservation of details in shadow regions.

Conclusion

This paper presents few aspects related to gamut mapping, gamut representation, color space influence. An uniform mLAB color space was presented as an extension of the CIELAB color space. The uniform mLAB space was found to improve gamut mapping compared with the CIELAB space. The mLAB uniform space does not cover all possible CIELAB colors. However the mLAB can be extended for new data set that goes beyond the Munsell renotation sytem if this set is available.

Not many gamut mapping techniques were investigated. However, the analysis proves that the mLAB gamut mapping is preferred against CIELAB constant hue angle mapping. It also appears that the mapping to a variable achromatic point (e) is most preferred procedure against preserving lightness or saturation, mapping to the center of the gamut or to the closest gamut color procedures.

This study will be extended to investigation of the full conversion between the mLAB and CIELAB space, and to extension of the conversion based on other data set when available. Further work should also be carried on evaluation of other gamut mapping techniques.

Acknowledgement

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