The Fundamentals of Gamut Mapping: A Survey

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This article aims to give a survey of the fundamentals of gamut mapping by describing the cross-media color reproduction context in which it occurs, by giving definitions of terms used in conjunction with it, by describing its aims and by giving an overview of parameters that influence it. These parameters are primarily the choice of color space used, the category into which a gamut mapping algorithm belongs and whether the approach is image or medium dependent. A succinct summary is then given of the principal trends in gamut mapping studies conducted to date.

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Introduction

Throughout history the art of simulating real life scenes or creating new images altogether on paper, leather, canvas, walls, wood or other materials was superimposed on a trial and error approach to color image reproduction. The situation only began to change in this century with rapid advances in science and technology, which resulted in the development of various color imaging technologies and computing on the one hand and a better understanding of color on the other. As understood today, cross-media color image reproduction is a process, which includes up to four core elements: device characterization color appearance modeling, image enhancement and gamut mapping, which can be combined into a six-stage transform[1] for the reproduction of color images (Fig. 1). This transform is an extension of the five-stage transform[2] where image enhancement and gamut mapping are combined into a single rendering intent dependent gamut-mapping algorithm.

In color reproduction, the description of an original image is initially available in a way specific to the medium in which it is present. To be able to transfer color information between different media, it is first best to describe them in some medium-independent way. To this end, device characterization describes color reproduction media by relating their device-dependent color specification to the characteristics of the resulting visual stimulus in terms of how it excites the eye. However, this alone is not sufficient for color communication, as a given excitation of the eye can result in different color appearances depending on viewing conditions. Further it is necessary to understand the perceptual attributes of a color (e.g., lightness, chroma and hue), as it is these, which need to be communicated rather than some characteristics of stimuli depending only on the receptors in the eye and not on subsequent processing by the visual system. Hence, color appearance models link the description of the stimulus to the perceptual attributes it has when seen in a given environment. These two elements (device characterization and color appearance modeling) would be sufficient for color image reproduction if all media could reproduce the same set of colors and if the reproduction process had no image enhancing intents. As this is often not the case, there is a need for a way of overcoming any differences, that might exist between the sets of colors obtainable on different media, i.e., it is necessary to have an algorithm for mapping between their gamuts (Fig. 2.)—a gamut mapping algorithm (GMA). Finally, there is also a need for allowing for the pursuit of different rendering intents (e.g., accuracy, pleasantness) that results in the inclusion of image enhancement in the color reproduction transform.

In this context, the focus of this article is the gamut mapping stage of the color reproduction transform with the aim of contributing to finding such a solution to the gamut mapping problem, which will give good results

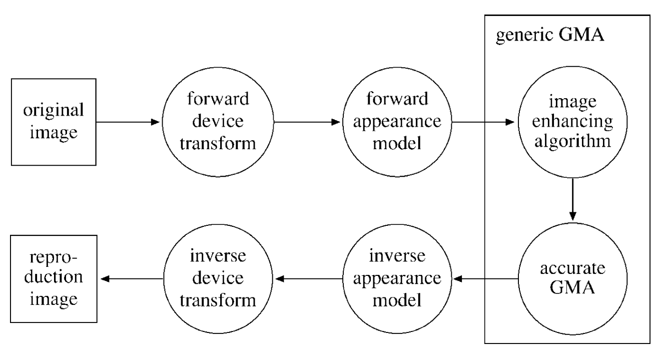

Figure 1. Six-stage color reproduction transform.

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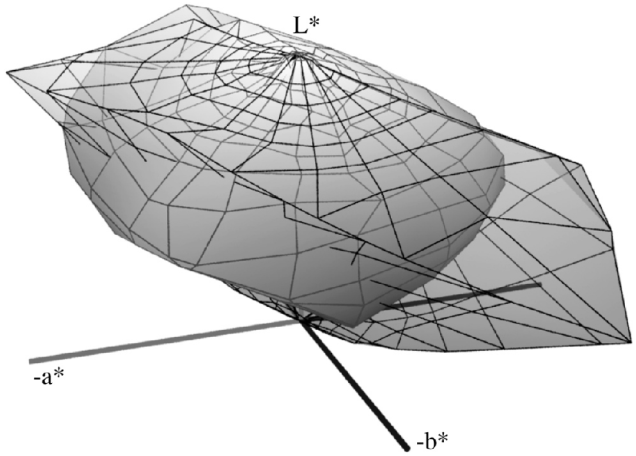

Figure 2. Color gamuts of a printed medium (solid) and a monitor (transparent) in CIELAB.

under a wide range of conditions. Such a solution can in some sense be considered to be universal and could be adopted as a standard.

The importance of having such a solution, which gives good results for a wide range of original images and original and reproduction media combinations is becoming ever more important as the means for color reproduction are becoming more and more wide-spread. This trend implies that color reproduction is no longer a domain of specially-trained experts but is a facility required by a large audience. Hence, it is of importance to provide a transparent and unobtrusive system for color reproduction and any such system will necessarily have to include gamut mapping as an essential feature. In this setting the availability of a universally applicable gamut mapping solution is of paramount importance as potential users would not have the skills for choosing among a number of algorithms intended only for application in specific situations and neither would having to make such a choice be acceptable. Furthermore a universal algorithm is also of use in a professional environment, as it can be used as a default method, which can be supplemented with proprietary gamut mapping algorithms designed for the reproduction of special images or for image reproduction with special intents.

The need for such a universally applicable gamut mapping algorithm has also been recognized by the CIE (Commission Internationale de l'Éclairage) by setting up the Technical Committee 8-03 on Gamut Mapping charged with investigating the issue. Indeed, the authors of this article are its members with the first author being the TC's chairman and this article is an excerpt from the committee's *Survey of Gamut Mapping Algorithms* based primarily on the work of Morovic.[1] In addition to the material published in this article the survey also includes reviews of individual studies on gamut mapping, which can be found at the CIE Division 8 web site—http://www.colour.org/tc8-03/.

The purpose of this article will then be to provide a survey of literature on gamut mapping rather than a detailed critical review of individual studies. To have a better understanding of the state-of-the-art of gamut mapping and hence the context in which a universally applicable gamut mapping algorithm is to be sought, the following areas will therefore be covered: terminology, aims of gamut mapping, methods for finding gamut boundaries, parameters determining the performance of gamut mapping algorithms and the most prevalent trends in gamut mapping studies conducted to date.

Terminology

As with any subject, there is a range of possible interpretations of the basic terms used in gamut mapping as well. Therefore, to avoid misunderstandings, the definitions used by the CIE TC 8-03 on Gamut Mapping will be given next, whereby the definitions of an image were given by Braun and co-workers,[3] those of accuracy and pleasantness by Morovic and Luo[4] and the others by Morovic and Luo:[5]

Image: two-dimensional stimulus containing pictorial or graphical information whereby the original image is the image to which its reproductions are compared in terms of some characteristic (e.g., accuracy).

Color Reproduction Medium: a medium for displaying or capturing color information, e.g., a CRT monitor, a digital camera or a scanner. Note, that in the case of printing, the color reproduction medium is not the printer but the combination of printer, colorants and substrate.

Color Gamut: a range of colors achievable on a given color reproduction medium (or present in an image on that medium) under a given set of viewing conditions—it is a volume in color space (Fig. 2.).

Color Gamut Boundary: a surface determined by a color gamut's extremes.

Gamut Boundary Descriptor (GBD): an overall way of approximately describing a gamut boundary.

Line Gamut Boundary (LGB): the points of intersections between a gamut boundary (as characterized by a GBD) and a given line along which mapping is to be carried out.

***Color Gamut Mapping*:** a method for assigning colors from the reproduction medium to colors from the original medium or image (i.e., a mapping in color space).

***Color Reproduction Intent*:** the desired relationship between color information in original and reproduction media. As a number of solutions to cross-media reproduction problems are possible, various color reproduction intents can be pursued by gamut mapping. The most generic ones of these are accuracy and pleasantness but it is also possible to define others for specific applications (e.g., to provide an accurate reproduction of corporate identity colors while giving pleasant results for others).

***Accurate Reproduction Intent*:** aims to maximize the degree of similarity between the original image and a reproduction of it as is possible given the constraints of the color reproduction media involved. Note, that the characteristic of accuracy is intrinsically relative (i.e., reproduction *versus* original)

Pleasant Reproduction Intent: aims to maximize the reproduction's correspondence with preconceived ideas of how a given image should look according to an individual whereby this criterion encompasses contrast, lack of artifacts, sharpness, etc. Note, that unlike accuracy, pleasantness is absolute—at least as far as a given observer understands it at a given moment.

Gamut Mapping Aims

On the highest level, the aim of gamut mapping "is to ensure a good correspondence of overall color appearance between the original and the reproduction by compensating for the mismatch in the size, shape and location between the original and reproduction gamuts."[1] As a number of colors are physically not reproducible, it is more advisable to aim for a match of the image's appearance rather than the appearance of individual colors in the image, since the latter can be impossible for some original colors.

One of the difficulties with implementing this aim is that there is as yet no model for quantifying the appearance of complex images and neither is there one for quantifying the difference between them (though S-CIELAB[6] is a step in this direction). In the absence of such a model and of an understanding of whether it could be used effectively in conjunction with gamut mapping, a number of objectives were heuristically arrived at in the past and the following aims were identified by MacDonald[2] to be common to the majority of gamut mapping studies:

- *Preserve gray axis of the image and aim for maximum luminance contrast.* This means a mapping of the original image's white and black points onto the reproduction's white and black points respectively.
- *Reduce the number of out-of-gamut colors.* Ideally all the image's colors should be brought within the reproduction's gamut, however, the exclusion of some extremes is sometimes thought to improve the overall appearance match. This exclusion would mean the use of clipping for the excluded extremes and another method for the remaining colors.
- *Minimize hue shifts.* It is often thought that when colors are reproduced the hue of colors needs to be left unmodified.
- *Increase in saturation is preferred.* As the reproduction gamut is already limited in terms of saturation, at least the available potential should be used to enable the preservation of saturation differences present in the original.

Note that the above list represents assumptions made by some gamut mapping studies whereby the reasons for making these assumptions are in most cases based on experience from traditional color reproduction. Even though experience from traditional color reproduction is of great value, its maxims need to be looked at carefully when used in an environment which enables far more control over color attributes than was previously possible.

A further commonly found aim of gamut mapping was expressed by Stone and co-workers[7] when saying that "the relationship between the colors present was felt to be more important than their precise value." This suggests a move of the what-you-see-is-what-you-get (WYSIWYG) concept onto another level—i.e., it is applied to images rather than individual colors and could therefore be called MetaWYSIWYG.[8] In spite of playing down the importance of a match in the traditional sense, it is still crucial for a color reproduction system to be able to reproduce individual colors accurately—even though some original colors cannot reproduced accurately, their modifications need to be reproduced as such.

Calculating Gamut Boundaries

To fulfill the aim gamut mapping has in a particular color reproduction system, it is first necessary to know the gamut boundaries of the original and reproduction gamuts. An understanding of color reproduction media gamuts has been considered to be of some importance for some time and was investigated by many researchers.[9–14] Knowing the boundaries of the gamuts between which mapping is to be carried out is essential for the majority of GMAs developed to date and can be divided into two separate problems.

First, it is necessary to compute a gamut boundary descriptor (GBD), i.e., some overall way of approximately describing a gamut. For media gamuts this can be done either directly from specific characterization models—e.g., Kubelka–Munk equations[15] or Neugebauer equations[16]—or using methods which can be applied to any characterization model.[17] Further there are also some methods which can be used for computing the gamuts of images as well as media[18,19] and there have also been some studies that looked more specifically at image gamut calculation.[20,21]

Second, it is also important to be able to find the intersections between the gamut boundary (as computed using the above methods) and a given line along which mapping is to be carried out—the line gamut boundary (LGB). The articles published by Herzog,[22,23] Braun and Fairchild[24] and Morovic and Luo[5,25] describe methods for doing this as well as obtaining the initial gamut boundary descriptor. Note that the first three of these methods are aimed at obtaining the LGB for lines of constant hue and lightness, which are most often used by present GMAs. The last two of the above articles describe methods for finding the gamut boundary along lines of constant spherical coordinates and along any line of constant hue angle respectively. Clearly all these methods can be used to calculate the gamut boundary along any line when iterative techniques are employed.

Gamut Mapping Parameters

Color Space

As can be seen from the definitions of a color gamut and of gamut mapping given earlier, they are both closely associated with color spaces. Most gamut mapping algorithms intend to work with perceptual attributes, i.e., colorfulness, chroma, saturation, brightness, lightness, hue or color names (e.g., red, dark green, orange, etc. whereby each of these would represent a subset of colors represented by a volume in color space) and to make this possible, they are implemented in color spaces which predict them. More specifically, they usually intend to maintain some of a color's perceptual attributes while changing others. If under these circumstances the predictors are imperfect, changes in the predictor of one attribute can also result in changes of another perceptual attribute (e.g., in some cases, if the L*—the predictor of lightness in CIELAB—of a color is changed, its perceived hue or chroma might also change).

In the color spaces that are most often used for gamut mapping—CIELAB and CIELUV[26] and in some cases LLAB[27] or RLAB[28]—there are problems especially with the predictors of hue. In particular there are deficiencies in the uniformity of hue angles in the blue region of CIELAB (e.g., hue angles of around 290°) which can result in changes of perceived hue when only the L* or C* of a color is changed. The performance of the hue predictor in CIECAM97s[29] is somewhat better for this region. More detail on the performance of hue predictors of various color spaces can be found in articles by Hung and Berns[30] and Ebner and Fairchild.[31] Of particular

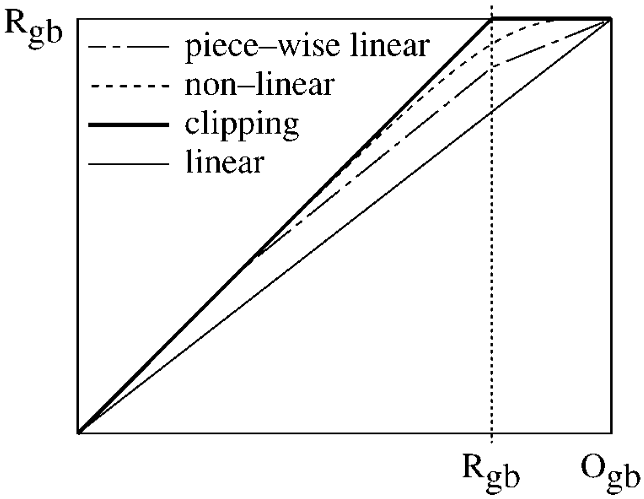

Figure 3. Gamut clipping and compression along a given line (O_{gb} and R_{gb} represent of the original and reproduction gamut boundaries respectively).

interest are also the articles by Ebner and Fairchild,[32] which describes the IPT color space developed so as to have improved hue uniformity, the article by Marcu[33] describing the mLAB space developed for the same reason, the article by McCann[34] discussing some shortcomings of CIELAB and the article by Zeng[35] proposing a gamut mapping solution using different color spaces for different parts of color space.

When implementing or evaluating GMAs, it is important to understand the deficiencies of the color space used for the mapping and not to confuse the color space's predictor with the predicted perceptual attribute (e.g., in CIELAB h_{ab} is not hue and L* is not lightness—they are only their predictors).

Gamut Mapping Categories

Once the necessary gamuts are known in the chosen color space, it is possible to implement a GMA. While there are a wide variety of gamut mapping solutions, many of them can be categorized in terms of the following parameters:

Type of Mapping

Gamut Clipping. Gamut clipping algorithms only change colors which are outside the reproduction gamut either from the very beginning or after lightness compression. For colors outside the reproduction gamut, these algorithms specify a mapping criterion, which is used for finding the point on the reproduction gamut to which a given original color is mapped.

Gamut Compression. Gamut compression algorithms are applied to all colors from the original gamut so as to distribute the differences caused by gamut mismatch across the entire range. Compression is needed when larger differences are to be overcome, as gamut clipping could result in unacceptable loss of variation in out-of-gamut regions under such circumstances.

There are a number of ways how gamut compression can be carried out, whereby it can either be uniform (i.e., determined in the same way for all colors) or non-uniform (having different parameters depending on the attributes of original colors to which they are applied) and the following approaches are the most common (Fig. 3.):

- *linear compression*
- *non-linear compression*
- *piece-wise linear compression*
- *higher-order polynomial compression*
- *combination of different compression methods* (e.g., *soft-clipping* can be a three-part compression method whereby no change is applied to part of the range, clipping to another part and there is a higher-order transition between the two).

Direction of Mapping. It is not only the type of mapping that characterizes a particular gamut mapping approach but also the choice of lines along which the mapping is applied. In most cases gamut mapping is carried out along the following directions (Fig. 4.):

- *lines of constant perceptual attribute predictors* (e.g., constant lightness and hue, constant saturation and hue)
- *lines towards single center-of-gravity* (e.g., compression towards L* = 50 on lightness axis)
- *lines towards variable centers-of-gravity* (e.g., compression towards lightness of cusp on lightness axis)
- *lines towards the nearest color in the reproduction gamut* (e.g., as is the case with minimum ΔE clipping)

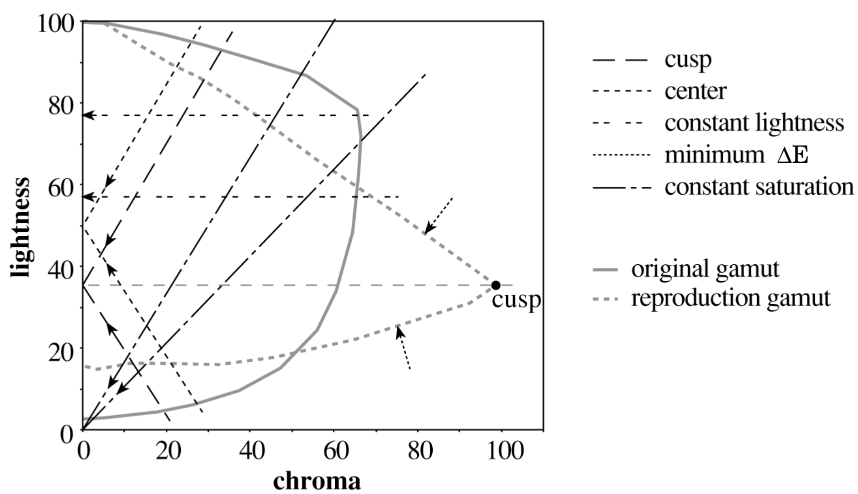

Figure 4. Gamut mapping directions.

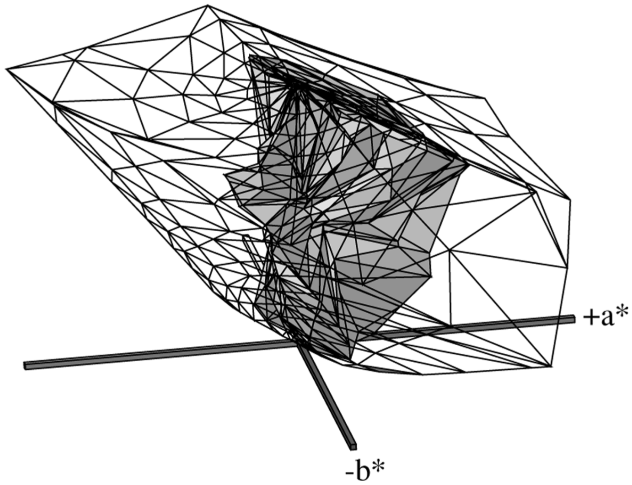

Figure 5. Gamut of CRT (mesh) and MUS image (solid) in CIELAB.

It is also important to understand the fundamental interconnectedness of mapping type, mapping direction and the color space in which gamut mapping is carried out, as choices in any one of the former two influence each other and they are both influenced by the latter (e.g., hue shifts in the blue region of CIELAB might give good results due to the color space's hue non-uniformity[25]).

Image versus Medium Gamuts

When gamut compression is used, there arises a question as to which gamuts to map between. This is the case as the original gamut can be seen as either the gamut of the original medium or the gamut of the original image (i.e., a subset of the original medium's gamut (Fig. 5)). For current gamut clipping methods this is not an issue as it is sufficient to know the reproduction gamut to which any irreproducible colors from the original are mapped.

To make as few changes to the original image as possible, it is more reasonable to use the image gamut as the original gamut since this means that colors are only modified when necessary. Indeed there are a number of experimental studies that support the idea that the use of image gamuts gives preferred reproductions.[36–39]

If, on the other hand, media gamuts are used, a given image could be modified to allow for colors which are not present in it (e.g., when the medium gamut is used an image's colors are changed even if all of them are in the reproduction gamut to begin with). However, there is a practical advantage to mapping between media gamuts as lookup tables (LUTs) can be calculated from them and then used for transforming an image without knowing its individual gamut.

Trends in Gamut Mapping Studies

As already mentioned, the present article is based on a *Survey of Gamut Mapping Algorithms* of the CIE TC 8–03 on Gamut Mapping. That survey includes reviews of 57 individual articles published between 1977 and the first quarter of 1999 and this section is a summary of its findings as well as of articles published before the end of 2000. The reviews showed that a wide variety of gamut mapping strategies have been proposed and in some cases also evaluated in the past. What will be attempted here is an identification of the more prevalent approaches and those that seem to be particularly promising or inductive of future work.

First, one of the most noticeable trends in the reviewed gamut mapping work is the agreement among different studies that image-dependent methods are preferred over medium-dependent methods, which is in some sense supported by a number of sources.[36–44] At the same time, however, there is some work that suggests that while determining gamut mapping on an image-dependent basis gives better results, it is not an image's gamut that determines how it ought to be gamut mapped.[20]

Second, there is significant number of studies where clipping is given preference over compression[36–38,45–55] whereby this is done implicitly in some cases. In some of these articles minimum ΔE clipping is used by default and in others clipping algorithms are proposed without reference to compression. In addition, there is a also good number of articles among the above which have arrived at the preference of clipping by means of well-designed psychophysical experiments.[36–38, 52, 53] The exception to this trend is the article by Morovic and Luo,[56] where clipping performed significantly worse than compression. A possible explanation of this is that, in all the former cases the relationship between original and reproduction gamuts was either artificial, relatively small (when compared with gamut differences between the media in Morovic and Luo[56]) or there was no lightness difference between them and therefore it was sufficient to use clipping. For overcoming larger gamut differences, however, it seems to be advantageous to use compression. The verification of this hypothesis would be of particular use to arriving at a universal GMA.

Third, while the vast majority of algorithms published before 1999 start with uniform overall lightness compression, there are a number of solutions that propose other mappings. The earliest of these is the work of Ito and Katoh[57] where no initial lightness mapping is applied and both lightness and chroma differences are overcome in a single step. The GMAs proposed by Morovic and Luo[5,25,56,58,59] again either have no initial lightness mapping (for the SLIN or CUSP GMAs) or map lightness in a chroma-dependent way (GCUSP) whereby maintaining more of the chroma of more chromatic colors. Braun and Fairchild[60–64] then suggest the use of sigmoidal lightness mapping which gives more weight to the middle than to the extremes of the lightness range whereby preserving more overall contrast. Finally Kang and co-workers[65,66] suggest lightness clipping and Braun and co-workers[53] suggest a luminance compression using an inverted power function in a linear RGB color space for the purposes of pleasing color reproduction. Which of these is the best solution again seems to depend on gamut difference and requires further verification.

Fourth, the preservation of hue (or hue angle) is also a point which occurs in all but the following articles[25,39,58,67,68] and the articles where minimum ΔE clipping is used. A related issue is also the preservation of hue names which the work of Motomura[69–71] has particularly focused on.

Fifth, there are a number of articles which suggest the use of different mapping methods for different parts of color space.[25,35,39,52,54,55,57,58,67,68,72–75]

Sixth, regarding the direction of mapping the approaches tried most frequently involve mapping along lines that are constant in some perceptual attributes (e.g., lightness and hue for the LLIN algorithm[1]), lines that converge on a single point (e.g., the point on the lightness axis having the lightness of the cusp as is the case for GCUSP[1]), lines that have the same slope,[77] lines that are determined by smallest color difference,[78–80] lines that are curved[81,82] or lines that are determined by corresponding distances along the original and reproduction boundaries.[83]

In terms of gamut clipping, the method proposed by Katoh and Ito[49] seems to be a good solution, not least because of its simplicity and good correlation with the results of the experimental study of Ebner and Fairchild.[51] In addition the relative importance of $L \geq h > C$ used in this model is also confirmed by Wei *et al.*[39] Recently, Ito and Katoh[84] have published a more extensive investigation of minimum color difference gamut clipping and have recommended the use of ΔE_{94}[85] in CIELUV and ΔE_{BFD}[86] in CIELAB. More recently a gamut clipping solution that aims to preserve spatial luminance or lightness variation has also been proposed[87] and it too seems to be a promising approach well worth further evaluation.

In terms of gamut compression algorithms, there is a degree of inhomogeneity between the various proposals, whereby the GCUSP algorithm proposed by Morovic and Luo[25] and the GMA using sigmoidal lightness compression and proposed by Braun and Fairchild[60–64] seem most promising. Of these GCUSP has been most extensively tested and found to perform well for various printed media as well as both in the CIELAB and CIECAM97s color spaces.[59] In addition to its accuracy it has also been found that reproductions made with it are pleasant when the original images are pleasant.[4] The sigmoidal lightness compression algorithm, on the other hand has under some conditions been shown to perform better than GCUSP and has been tested independently as well.[20] However, due to the variation in results of gamut compression studies, more work is needed for seeing what algorithm is best suited for a default solution.

Finally, there are some articles describing interesting approaches, which either rely on a more satisfactory solution of other problems before they can become effective (e.g., Nakauchi and co-workers,[42,43] which uses an image difference model) or which are meant for specific applications (e.g., Braun and co-workers,[88] which is specifically for business graphics).

Most of the techniques reviewed here were closely related to CRT and printed media. In this context, other methods were also tried to reduce the gamut mismatch problem by using more than four inks, in which case the gamut of the printed medium is increased. However, it was suggested that some of these systems do not actually provide significant improvements[89] and therefore do not diminish the need for gamut mapping. Attempts have also been made to obtain exact color matches (i.e., relative luminances, CIE chromaticities and absolute luminances are identical) between CRT and print,[90] however, this means that only colors from the overlap of the two gamuts can be used. Due to this intensive focus on CRT to print mapping in the past, it would be very useful to conduct studies that use different media combinations, like transparency to CRT or print, in future.

Gamut mapping is also of importance in other fields and, as an example, proprietary solutions have been devised for the ray tracing of prisms and rainbows[91] and for the joining together—sometimes referred to as seamless welding—of several images (e.g., for panoramic pictures).[92]

Conclusions

Arriving at a universally applicable gamut mapping algorithm is an aim shared by many researchers and industrialists working in this area and the purpose of this article was to make the common basis arrived at by the members of the CIE TC 8–03 on Gamut Mapping more widely available. The terminology, parameters influencing gamut mapping and view of past research presented here are those of the technical committee and are important prerequisites for effective cooperation on the development of future, generally acceptable solutions.

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