(R)evolution of Color Imaging Systems

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Abstract

After an introduction to a number of essentials of color image reproduction in general, the evolutionary development of color information transport and handling in the open system architectures of modern image communication is summarized. Some comments are given on the benefit of using color standards and color management systems but a number of insuperable drawbacks is described as well. Basic remaining problems of device- and observer metamerism have pushed the development of the new technology of multispectral imaging. The potential, structure and state of the art of this revolutionary technology is briefly described together with some more detailed results on the newest development of a complete multispectral imaging system including a 16-channel camera, complex data encoding and a 6-channel display.

Introduction

Thousands of years ago, human beings started producing colored paintings, the first ones on walls or wood, later on papyrus. These very early color reproduction techniques employed pure or mixtures of a few different color pigments and roughly the same methods have continuously been applied up to now in art painting. Just a few hundred years ago, mechanical book printing technologies developed and the evolution of technical color reproduction and color printing began. This process was fundamentally inspired by the finding that a mixture of only three colorants allows the reproduction of a large variety of different colors. The tremendous evolution in color imaging pushed by electronic systems during the last century would not have taken place without the simple possibility of this kind of tristimulus color control.

The simple control by three color components in imaging systems is made feasible by a fundamental feature of human vision: the dominant trichromatic color vision in the cones of the human retina. Any spectral light stimulus striking the human retina gives rise to the generation of only three dominant color signals according to the spectral responsivities of the cones, called the fundamental color matching functions. The three primary color signals, composed of the superposition of spectral light components within the spectral bands of the cones control the complex process of color vision in our brain.

Colors in technical systems are described by the representative of human color vision, the CIE 1931 standard observer. This observer receives tristimulus values CIE XYZ from a spectral stimulus φ_λ according to

$$X = k\int_{380nm}^{780nm}\varphi_\lambda x(\lambda)d\lambda;\quad Y = k\int_{380nm}^{780nm}\varphi_\lambda y(\lambda)d\lambda;\quad Z = k\int_{380nm}^{780nm}\varphi_\lambda z(\lambda)d\lambda; \tag{1}$$

where x(λ), y(λ), z(λ) denote the standard spectral matching functions and k is determined from the normalization of Y = 1 for the spectral stimulus of the illuminant. Due to the integration of spectral components, different spectral stimuli φ_λ may result in the same XYZ values. This effect, called observer metamerism, is the essential basis for today's technical color reproduction systems because it allows to compose the same color values by a color stimulus being different from that of the original. To give an example, the two experimental colors with different spectral reflectances shown in Fig. 1 result in the same XYZ values if viewed under illuminant D65, though, they are composed from different pigments.[1]

Yet, there is a drawback resulting from the use of metamers for color reproduction. The differences between colors of reproduced prints become dependent on the illuminant.[2-4] Considering the examples in Fig. 1, the XYZ values of the two surface colors are roughly the same under illuminant D65 (ΔE94 = 0.17), but they become different under luminescent light of a "D50" tube (ΔE94 = 4.2).

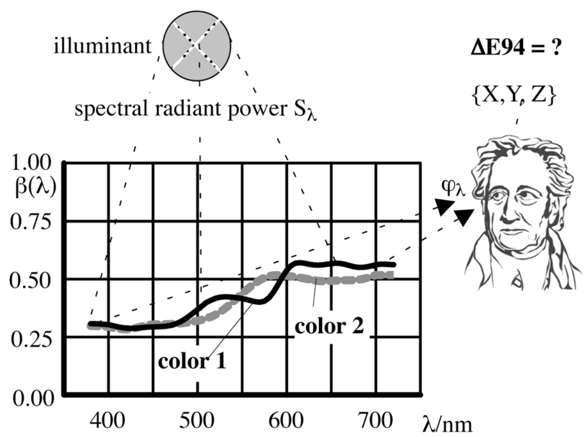

Figure 1. Observer metamerism for two colors given by their spectral reflectances β(λ)

The use of metamerism is not the only fundament which made technical color reproduction work. The second fundament results from the linearity of the primary color vision process in the cones of the human eye. The "technical eye" in the reproduction chain is a camera or scanner which captures the colors of the image. At first view, analysis by a camera would be expected to work best if - according to human trichromatic color vision- three camera channels with the same spectral responsivities like those of the cones of the retina were used. Due to the strong overlap of two of these functions however, the camera would run into severe problems of electronic noise when separating technical color signals like sRGB to control output devices. This is because noise components always add up even if tristimulus values are subtracted. But correct color analysis can also be realized by three technical sensors with spectral responsivities derived from any linear transform of the color matching functions. This allows optimized separation of spectral responsivities of camera channels and scanners with respect to best electronic signal to noise ratio. However, again a drawback comes in due to the fact that responsivities optimized in this way exhibit negative parts like all color matching functions corresponding to realizable primary colors do (see e.g. the spectral matching curves of the sRGB system in Fig. 2). Since a high signal to noise ratio is the more important feature in image capturing, all present cameras and scanners use an approximation to the positive parts of these curves only. As a result, there occur inevitable errors of color analysis in all our present systems.

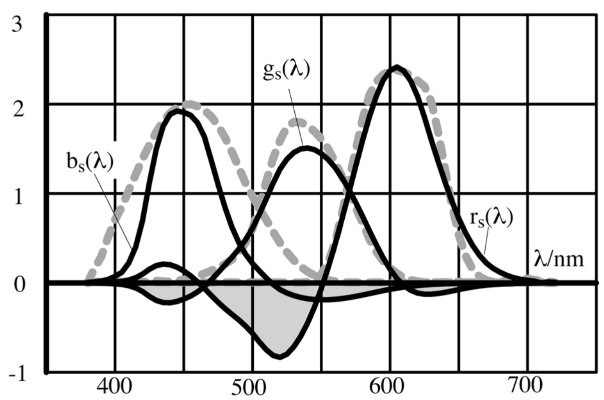

Figure 2. Spectral matching functions of sRGB (solid lines) and typical spectral responsivities of a camera (dashed)

The deviations from color matching functions do also affect the capability of distinction of colors compared to the standard observer. Each image capturing device exhibits its own device metamerism. Color stimuli being metameric to the standard observer are no longer metameric for the image capturing device and there are device metameric colors looking different to an observer.

In addition, there are lots of practical problems. First, the positive parts of spectral matching curves are not met by practical responsivities of sensors (see e.g. the typical set of experimental responsivities of a digital camera given in Fig. 2 by dotted lines). Moreover, displays and printers introduce a lot of trouble by their high degree of nonlinearity of their color transfer functions.

All these problems were not taken very severe in the past because on one hand, it was important to reproduce at least nice colors rather than accurate colors and on the other hand, color reproductions were fabricated in closed printing shops. The closed system architecture with well known system components allowed individual optimizations "by hand" to come to acceptable results.

For the future, we are facing the development of worldwide image communication using a large variety of different color capturing devices on one hand and very different printing and display technologies for image retrieval on the other. As a result, "cross media" image transfer has become a challenge. Moreover, the requirements on accuracy of color reproductions are increasing in many fields of professional and commercial applications. An evolution of traditional tristimulus color imaging systems with the aim to solve the problems mentioned above is therefore going on, but as well, entirely new concepts of color imaging on the basis of multispectral technology are proposed. These systems point to a coming revolution in color imaging technology.

Evolution of Tristimulus Color Imaging Systems: The Step from Closed to Open System Architectures

Closed system architectures for image reproduction have been the dominant technology until 10 years ago. The advantage of this structure is that specific features of all devices in the system can be most efficiently combined to achieve an optimized result of color reproduction. However, color images cannot be transferred into other systems using different components or different system structure.

The exchange of color images in a worldwide communication net calls for a system structure with a device independent interface (Fig. 3). Moreover, there still exists a complete confusion regarding definitions of color spaces. For example, most commercial display or printing products use the term "RGB" to specify control or output signals but do not specify how it is defined. A standard for color spaces is therefore an urgent need.

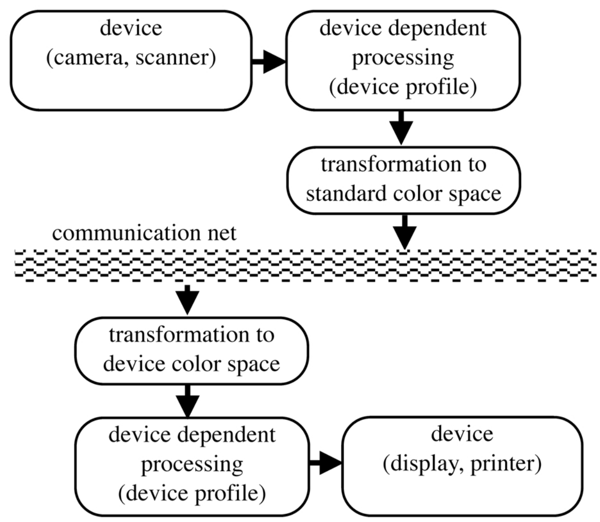

Figure 3. Structure of an open system architecture for image communication

Within the last few years, the standard of sRGB[2] was published. This is not the ideal device independent color space because it is referenced to the primaries of a device (the cathode ray tube ITU-RBT.709-3), but it will help a lot to overcome the confusion between definitions of RGB. Yet, sRGB covers only a small color space with components limited to the range of 0 to 1 (illuminant D65). There is a proposal discussed at present to define an extended 10 bit "esRGB" space with components covering the complete range of optimal colors (Fig. 4). Though the final 10 bit resolution is still quite small - even in view of predistortion[6] - this space will be more appropriate in all applications where colors have to be exchanged between display devices and printers.

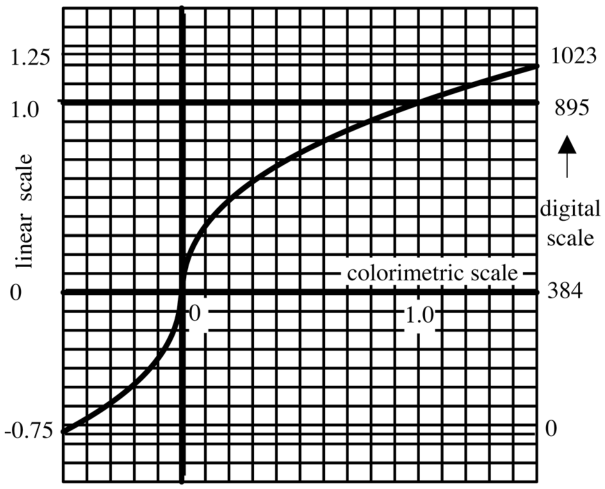

Figure 4. Proposal for the distortion of the components of a 10 bit extended sRGB color space.

The CIE1976 L*a*b* color space is more appropriate. This space is device independent and broadly used in color management systems. The coordinates L*, a* and b* describe an approximation to a perceptually uniform color space and accordingly, the quantization requires less data than colorimetric components like XYZ or sRGB.[3] All natural surface colors are covered by CIELab. However, looking more into the details, the CIELab space is not really perceptually uniform and the search for more uniform spaces is still going on. More complex color spaces considering background and surrounding have been proposed.[4] An interesting color space with coordinates directly representing differences matched to the color difference formula ΔE94 is offered by DIN99.[5] This space describes small color differences very accurately. So, there is still some movement in the field of potential standards. CIELab seems to be the favorite for image communication at present because it is accepted worldwide.

Device Dependent Color Management

In contrast to closed system architectures, the open system architecture requires a device dependent color correction or transformation to be performed in each device itself. The International Color Committee ICC has developed guidelines how to perform device dependent color management.[6,7] As discussed in the introduction, there are the following basic problems to be considered for image capturing:

1. Spectral responsivities of the sensor elements do not match the color matching functions; negative parts are clipped.
2. Color analysis depends on the light source. Very different light sources have to be considered in scenes, various built-in light sources are used in scanners.
3. Signals generated by the capturing device must be transformed into a standard at the interface.

For the control of displays or printers, the device independent representations of colors have to be transformed into control signals of the individual device in the first step. Secondly, the complex transfer function describing the relation between control signals and produced colors has to be included.

Following the ICC guidelines,[6] necessary information on color transformations are put into a so called device profile (Fig. 5). In the work flow of data processing of a scanner for example, the image data are processed in a color management module (CMM) where the information of the device profile is applied. The profile connection space (PCS) provides a standard at the output to the communication interface.

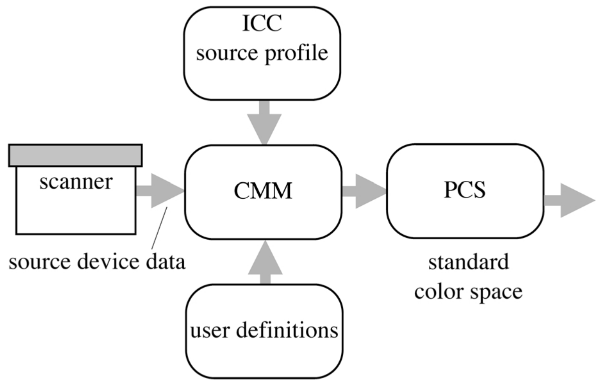

Figure 5. Example of ICC color management work flow for an image source and embedded transformation to a standard

To create a device profile, digital data color targets or physical color targets have been defined by ISO.[7] In Fig. 6, two typical structures of practical profiles are sketched for scanners. The first one uses single channel nonlinear distortion of the three signals of a color sensor followed by a 3 x 3 matrix operation and an optional second nonlinear distortion. Similar structures are used for printers. Nonlinear distortion ensures a stable gray scale whereas the matrix corrects for colors outside the gray scale, e.g. to reproduce at least some original colors correctly like skin color e.g.

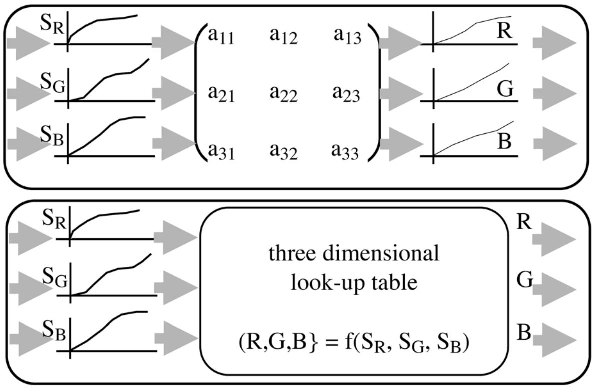

Figure 6. Examples of device profiles for scanners

This profile structure gives some improvement but complete correction of all colors is not possible. More sophisticated is the use of a three dimensional look-up table. Such tables are developed from the measurement of test colors of a target covering a grid within a large area of the color space and the corresponding in- or output signals of the device. Mathematical interpolation and, if required, reversal of the profile is applied to describe the colors corresponding to any quantized combination of in- and output signals of the device.

The application of color management at a first view seems to solve all problems. Particularly the use of three dimensional profiles seems to provide correct color reproductions. More detailed analysis however shows that mathematical algorithms of commercially available color management software do not work free of errors.[8] Errors in the range of 2 - 6 units of .E94 have rather to be considered. These errors arise from interpolation, reversal of color profiles and quantization depending on the type of mathematical algorithm being applied. A compromise between speed and accuracy has always to be taken into account. Moreover, any profile depends on the type of media at the in- or output, its colorants or pigment characteristics, surface reflection and type of paper. The sensitivity to those parameters is even enlarged by the use of very accurate profiles. For example, the use of a standard input target[7] realized by a photographic image only reproduces colors printed on the same type of photographic paper correctly. Any change to images composed of different colorants leads to noticeable reduction of quality. This problem can only be solved by using a large databank of different profiles, each defined for a specific set of colorants and papers.

Another problem is the handling of colors lying outside the color gamut of a device. Cross media change of color images always causes a loss of color information due to different color gamuts. Colors outside the gamut have to be mapped using a suitable gamut mapping algorithm. A number of gamut mapping algorithms have been published and guidelines are being developed at present within CIE TC8-03, yet, the better solution of enlarging color spaces of all our present devices is still a challenge for the future.

In conclusion, the introduction of the concept of open system architectures combined with standardization and device dependent color management will improve color quality but will not solve many of general problems. Problems of metamerism due to the change of illuminants and problems of differences between observer and device metamerism are not solved as well as the change to different illuminants at cross media color transport without loss. In addition, there is another fact not considered so far, the deviations between color matching functions of human observers. Present color reproduction is optimized for the CIE 1931 standard observer only.

The Revolution: Multispectral Technology

The solution to the fundamental problems of tristimulus reproduction systems is offered by multispectral technology.[9-15] The basic structure of a multispectral imaging system is shown in Fig. 7. A so called multispectral camera captures sequentially a number of spectral image separations representing spectral samples for each pixel of an image. From these samples, spectral stimuli functions are estimated for each pixel of the image and encoded in a multispectral image processor. By taking spectral separations of a white reference sheet in advance, each spectral sample value can be normalized to illuminant E during the process. The result is a device independent representation of spectral stimuli information offered at an open system interface for transfer to any output device. In Fig. 7, the spectral information is reproduced on a multichannel display for example. This display reproduces an approximation to the original spectral stimulus of the colors of each pixel. The process enables the introduction of any spectral illuminant for reproduction without loss of color information or accuracy. Device metamerism effects do not exist anymore and the system is completely free of systematic errors.

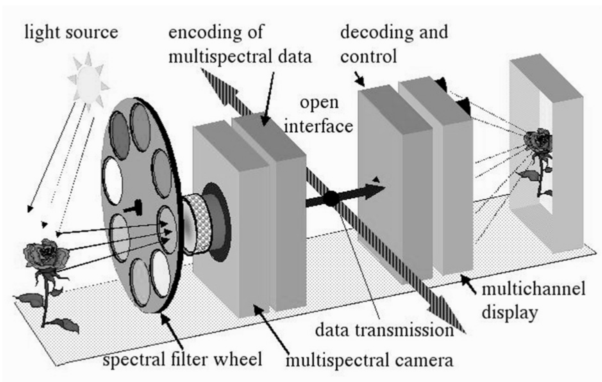

Figure 7. Structure of a multispectral imaging system

The most advanced experimental systems use a black & white image CCD sensor equipped with a filter wheel for image capture. The number of filters and corresponding separations results from a compromise between effort and accuracy of spectral approximation. Detailed studies have shown that a number of 16 channels provides a good compromise for high accuracy color analysis of all kinds of natural, painting or technical colors. The first commercialized systems for up to 3000 x 2000 pixels are equipped with narrow band interference filters. They exhibit maximum absolute color errors of only ΔE94 = 0.8 (10 x 10 pixel averaged) and average color errors of test colors as low as 0.2 assuming the 2° observer.

Another interesting solution has been realized by a multispectral camera equipped with nonmechanical filters based on LCD electrooptic control.[12]

Spectral encoding typically uses the expansion of spectral functions into a number of basis functions. The weights of the basis functions approximating the spectral functions by superposition are called the multispectral values V_i. The basis functions are estimated from a large number of test spectra and optimized with respect to minimum color error, e.g. using principal component analysis (PCA).[16-20,1,10]

To make the multispectral data compatible to conventional tristimulus color reproduction, it has been proposed to choose the first three basis functions as linear transform of the color matching functions.[20] By this way, a so called compatible multispectral data format has been defined (Fig. 8). The first three components of this data set are tristimulus values (XYZ or RGB e.g.). They can be picked out of the data set if conventional color reproduction devices will be controlled from multispectral information only. The complete set of data including the first three components describes spectral information. A further step uses nonlinear encoding of multispectral values to realize efficient quantization of the components. In this step, even L*a*b* values can be used for the compatible part of the data set.[1,21] Still more advanced methods use combined spectral and spatial image encoding.[22]

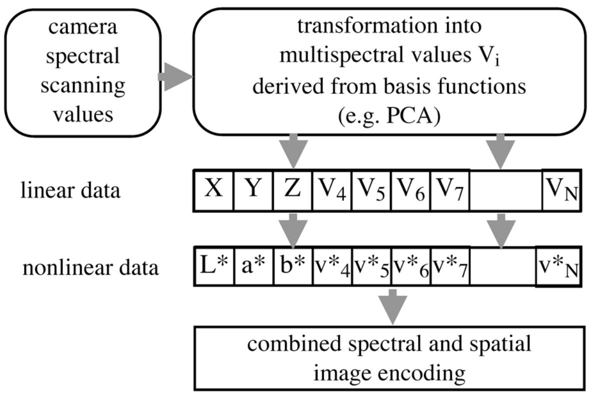

Figure 8. Encoding of multispectral data into the "tristimulus compatible" linear and nonlinear data format

The number of multispectral values in the data set is derived from color error studies. Maximum or average errors of a large number of test spectra are used therefore. Not only the standard observer is considered but also a variety of observers exhibiting different color matching functions to minimize observer metamerism.[20] The required accuracy also depends on the spectral illuminant considered for reproduction. If this is a smooth illuminant, excellent results with maximum color errors ΔE94 < 1 will be achieved with only 9 multispectral values. If non-uniform illuminants like luminescent lamps have to be applied, 12 multispectral values should be used.

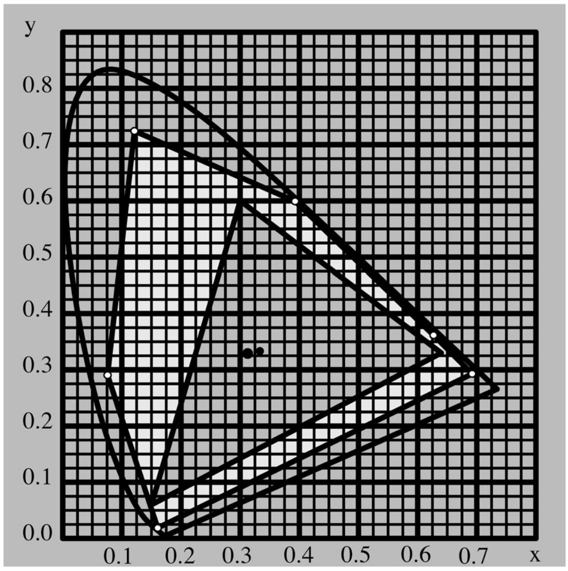

Figure 9. 6-primary display in the xy-color table and comparison with sRGB color space (inner triangle)

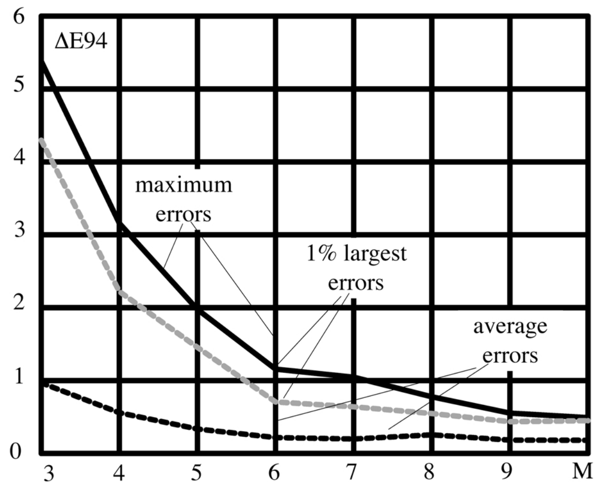

Figure 10. Simulated color reproduction errors ΔE94 of a multichannel display as a function of the number M of channels (lines), and errors of a 6-channel display from experimental characteristics (points)

Multispectral image reproduction by multichannel displays is the aim of a number of developments.[23,24,20] Experimental systems are realized in the laboratory. They are composed of two LCD or DMD beamers each equipped with narrow band color filters to provide six narrow band lights. The advantage of these devices compared with tristimulus displays is not only the potential to reduce observer metamerism, but also to provide an increased color gamut. The gamut of an experimental 6-primary display compared to sRGB is shown in Fig. 9. The control of channels of a multichannel display from spectral input information has to be theoretically optimized with respect to minimum observer metamerism. Figure 10 shows a typical simulation for a number of 3 to 10 channels and the results for experimental data of a six channel display. The control is optimized by stochastic optimization with respect to smallest color errors calculated from 24 color matching functions of human observers and 384 different test spectra.

Investigations into multispectral printing have been published in Refs. 25 and 26. The control of at least 6 or 9 colors in a multispectral printer will be much more complicated due to the nonlinear characteristics of printing processes.

Conclusions

Conventional color imaging based on tristimulus color information transport has experienced a tremendous evolution during the past centuries. This development was forced by the requirement for open system architectures with the development of worldwide image communication on one hand and the progress of image capture, display and printing technology on the other. A number of systematic drawbacks rooted in the tristimulus technology of today limits the quality and constancy of color reproduction but the introduction of color management systems is going to improve the final quality remarkably, though some limitations remain unsolved in principle. There is the phenomenon of metamerism which is the fundament of tristimulus reproduction technology on one hand, but introduces unsolvable problems in view of high quality color discrimination under different illuminants and in view of the problems of different color matching functions of real observers on the other. An important step to solve those problems is offered by multispectral technology which is based on the transport of color stimuli rather than tristimulus values. This revolutionary technology requires much more effort, yet, the progress of electronic technology helps more and more to make color stimuli transport from image capture to the destination as well as multispectral display realizable. First multispectral systems are going to be commercialized and multispectral display and printing has become a topic of research and development. Color reproduction accuracy is the highest available at present and there is no doubt that this technology is ready to replace conventional systems.

Another important problem of color reproduction, the area of color appearance, has not yet been taken into account in this paper. Only the problem of reproducing the "physical part" of color information in original documents or scenes has been discussed. Color appearance problems have certainly to be considered as well in the future, but anyway, color appearance phenomena can only be taken into account and help to improve the appearance of reproduced color images if at least systems will be available to transport the physical content of colors in images completely without systematic errors.

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Biography

Bernhard Hill received his diploma and Dr.-degree in Electrical Engineering from the Aachen University of Technology. In 1969, he joined the Philips Research Laboratory Hamburg, Germany and started research in the field of laser beam deflection, laser recording and holography. He became head of the optics group in 1974 and developed erasable magnetooptic memory technology and optical printing devices. In 1984, he changed to the Aachen University of Technology. He is now focused on color management, gamut mapping and multispectral imaging. From 1990 to 1994, he was manager and dean of the faculty. He is member of IS&T, SID, VDE and vice president of the german color society DfwG, and he is the german representative in CIE - Division 8.