Colour Spaces
in modern multimedia environments
— Convergence after 40 years of colour television

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Traditionally, the ITU-R BT.470 standardized RGB colour space has been used in television production. However, with the introduction of computer-based editing platforms in the early 1990s, other colour spaces such as HCV and CIELab have entered the television environment, along with colour space conversion techniques such as that developed by the ICC. This article presents an overview of the colour spaces and colour management techniques that are used today in the TV production environment.

The first attempts at transmitting colour images were made on 4 September 1940, with the "Field Sequential" technique developed by P.C. Goldmark (CBS). A very helpful factor were the findings of H. Hartridge, a British ophthalmologist, who proved that the eye's resolving power was weaker when processing colour information, compared to brightness information. Thus, the bandwidth for transmitting colour information could be significantly lower, which made the transmission of colour video signals much easier. On 15 December 1953, the first colour television programme was broadcast in the USA by stations belonging to NBC and CBS. The colour transmission system was NTSC (National Television System Committee).

Europe became interested in the technology only in November 1962 and founded the "EBU Ad Hoc Colour Television Group". This Ad Hoc Group met from 3 to 5 January 1963 at the NDR in Hanover, on the initiative of Dr Hans Rindfleisch. At this meeting, a comparison between NTSC and SECAM should have led to a decision on which of the two systems should become the colour TV standard for Europe. However, the PAL colour system was also demonstrated at this meeting (by Mr Walter Bruch of Telefunken) and, in the event, PAL became the system of choice for most of Europe.

Colour space in conventional television broadcasting

During the first 20 years of colour transmission, the standards for production and broadcasting were based on the CCVS-PAL level space which, in turn, is based on the RGB colour space. Capturing of the image source and image processing were based on this standard. It should be noted that the E'_R - E'_G - E'_B colour space was only defined for the phosphorus used for capturing and reproduction (EBU phosphorus). Due to the technical requirements for a better image quality, video signals were edited on the analogue E'_Y - E'_{CB} - E'_{CR} level by the mid 1980s. *Fig. 1* shows the correlation of the E'_R - E'_G - E'_B level space within the E'_Y - E'_{CB} - E'_{CR} cube.

Obviously, it is easy to recognize that processing of video signals within the E'_Y - E'_{CB} - E'_{CR} level space (cube) can also result in signal levels that are outside of the smaller E'_R - E'_G - E'_B cube.

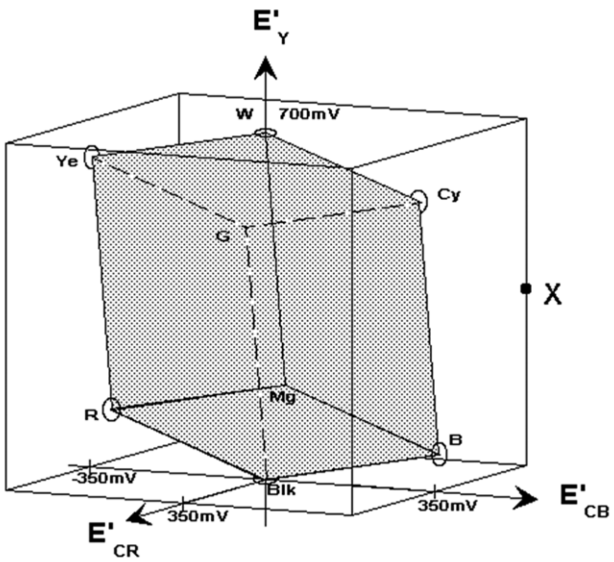

Figure 1
Correlation between the RGB and E'_Y - E'_{CB} - E'_{CR} level spaces

These signal levels represent colours that are illegal for the E'_R - E'_G - E'_B colour space and cannot be fed back into legal E'_R - E'_G - E'_B values without artefacts. The problem of illegal colours surfaced relatively early, but only became significant with digitalization at the E'_Y - E'_{CB} - E'_{CR} component level. In the 1990s, more digital graphics systems were used to produce captions and graphics in this domain. They were also able to generate illegal colours. The relevant equipment at this time was usually developed by manufacturers who had been in the television broadcasting business for a long time, thus taking into account special broadcasting requirements. However, illegal colours could be produced. Images were processed and generated at the E'_Y - E'_{CB} - E'_{CR} component level, based on the RGB colour space. The quality of the image and the colour were controlled on monitors using EBU phosphorus. Until the early 90s, television broadcasting only used the E'_R - E'_G - E'_B and E'_Y - E'_{CB} - E'_{CR} colour spaces, which could be transferred into each other by means of linear matrix equations.

Other colour spaces

With the introduction of computer-based editing platforms, other colour spaces appeared, which could no longer be imported into television linearly. Graphics, images and sequences, which were generated on a computer platform, could only achieve colour-correct reproduction if the colour spaces in question were converted. *Fig. 2* shows the points on the signal path where adjustments to the colour spaces may be needed.

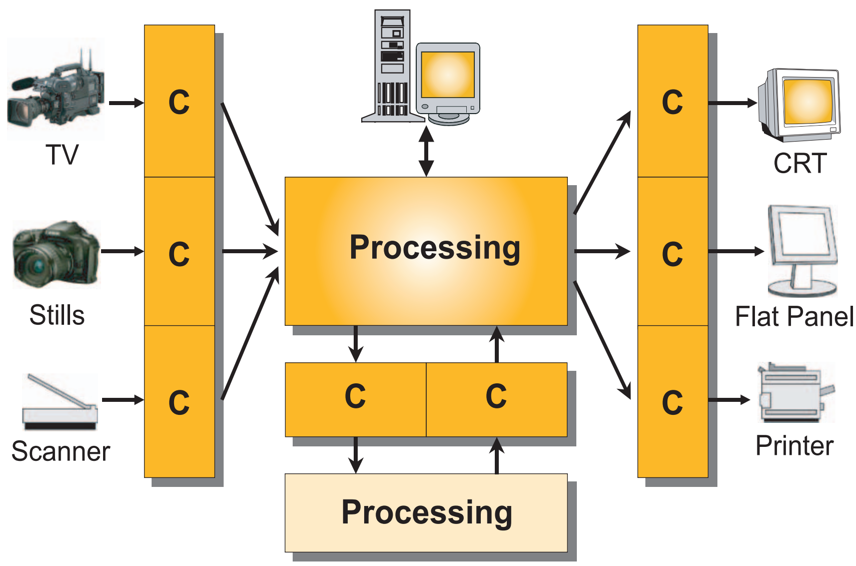

Figure 2
Colour space conversion

If the same phosphorus, e.g. the EBU-defined phosphorus, is used for image capturing and reproduction, a colour conversion is not necessary. Scanners, digital still-picture cameras, flat screens and print media sometimes use different types of phosphorus and thus use different colour spaces. In addition, additive colour mixing (the mixed colour is produced by adding at least two light sources of different wavelengths) is used for reproduction on conventional CRT monitors, while print media use subtractive colour mixing (the mixed colour is produced by filtering different wavelengths from the colour spectrum) *(see Fig. 3)*. The transfer of one into the other is not possible in a linear manner, and sometimes not without artefacts.

In the following sections, a few colour spaces that play an important part in modern production environments are presented.

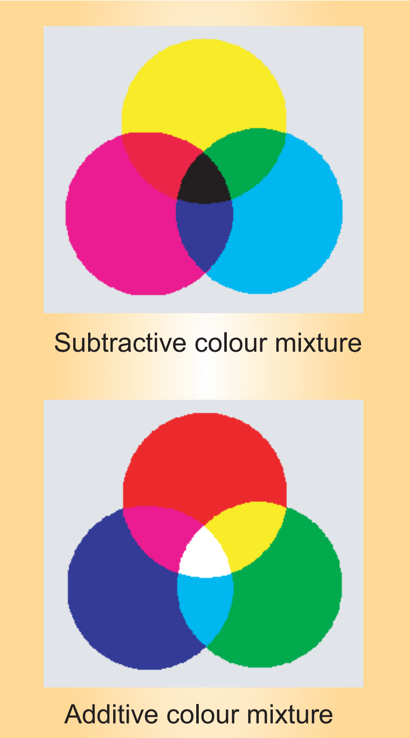

Figure 3
Colour mixing

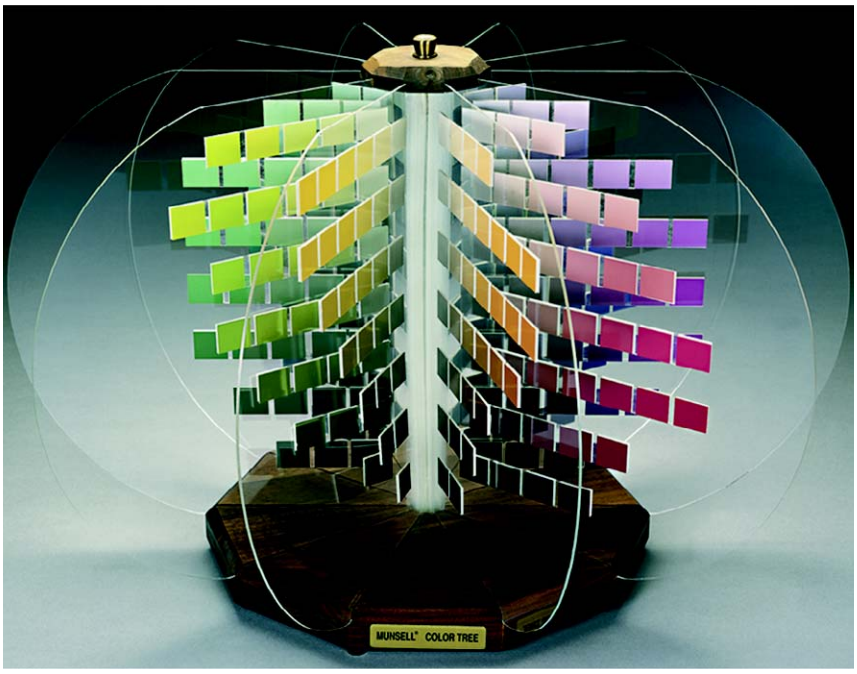

Figure 4
Munsell colour samples

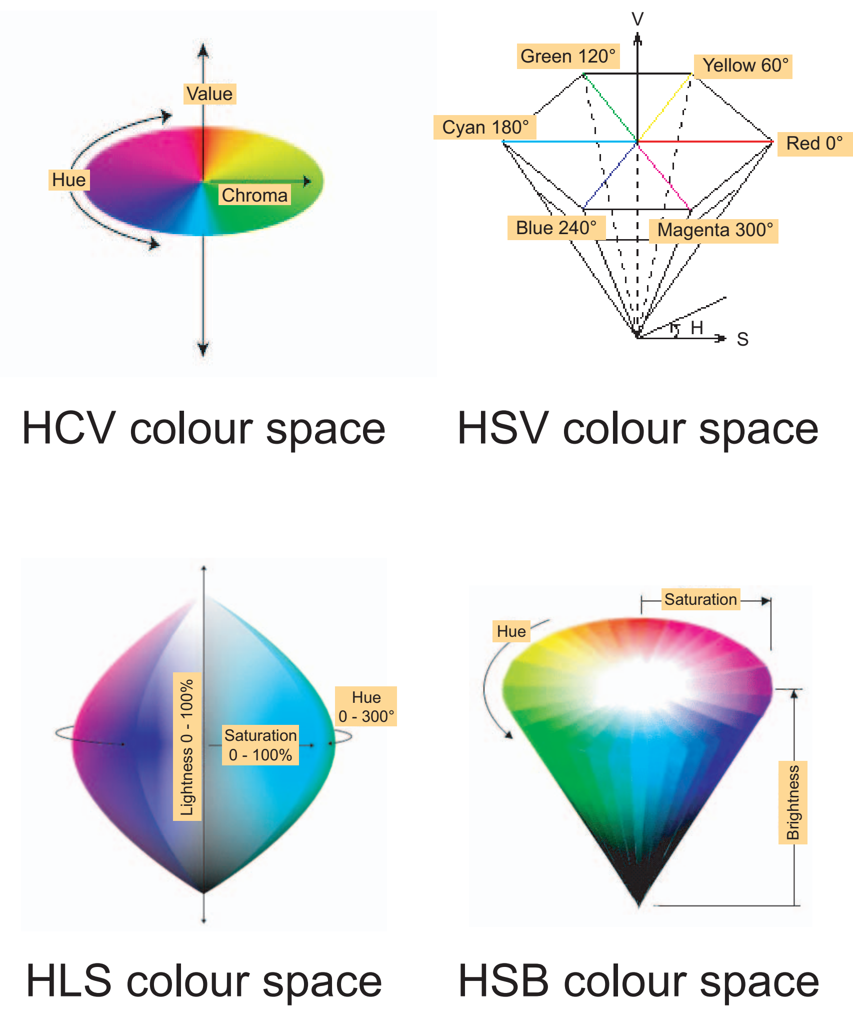

Figure 5
Perceptual colour spaces

Perceptual colour spaces

Computer-based processing platforms often use *perceptual* colour spaces. These colour spaces are adjusted to human perception and are described by ***Hue***, ***Brightness*** and ***Saturation***. In 1915, the painter Albert Henry Munsell (1858 – 1918) developed a collection of colour samples based on the same perceptual difference of colours *(Fig. 4)*.

Based on this collection, a number of perceptual colour spaces have been developed, which take Hue as an axis of the respective colour space model; they are thus very similar. The display of colour in a 3D construction was chosen to arrange the colours in a way that makes the colours comprehensible to the human imagination.

The vertical axis of the two upper models in *Fig. 5* gives a grey scale and is called ***Value*** (V). The distance from the axis equals the saturation and is called ***Chroma*** (C) in the top-left model (not to be confused with the term “chroma” in television). The ***Hue*** reflects the actual spectral gradation (usually given in degrees). ***Saturation*** denotes the intensity of the hues (pale or vivid). Lower saturation places the colour – depending on its brightness – towards white, grey or black. Luminance is a measure of brightness.

CIE colour spaces

In the 1920s, there was a growing desire to define colours objectively, mathematically. The *Commission Internationale d’Eclairage* (CIE) was entrusted with developing a method to make this possible.

In 1928, the mineralogist Siegfried Rösch described a body *(Fig. 6)*, whose surface is constructed of optimum colours. Optimum colours are those among the colours (trichromatic), which are the brightest of the same chromaticity and the most saturated of the same brightness.

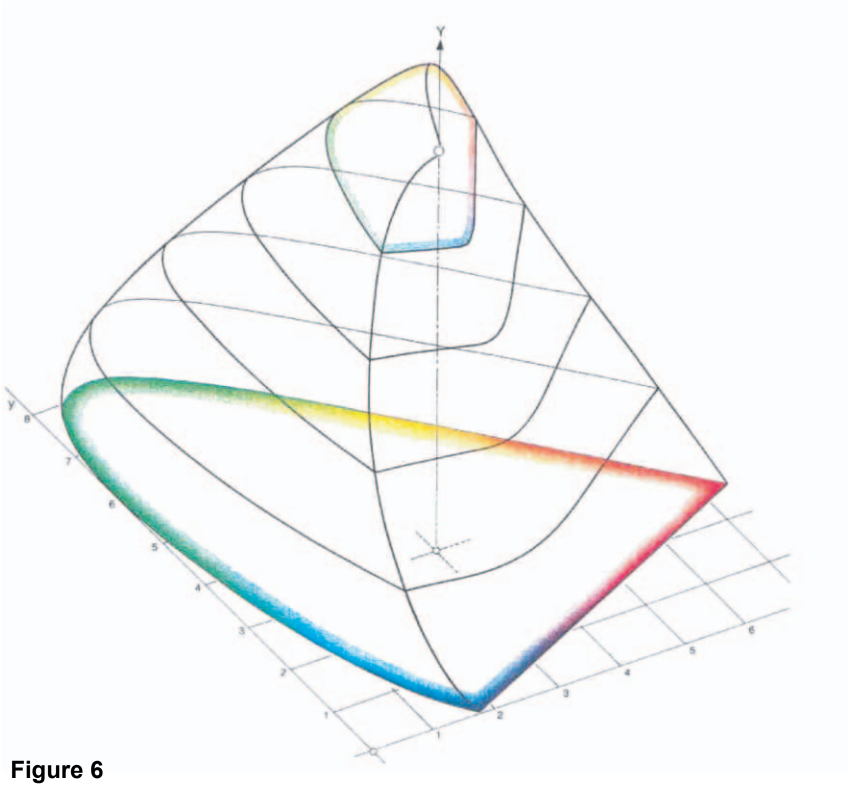

Figure 6
Optimum colour body (Siegfried Rösch)

The base of this body is the diagram published by the CIE in 1931. It was constructed as the result of expansive tests with emmetropes. This diagram enables calculation of the position of every colour in relation to its primary colour. This two-dimensional diagram is only valid for one respective colour temperature, and it is a section of a funnel-shaped body *(Fig. 7)*.

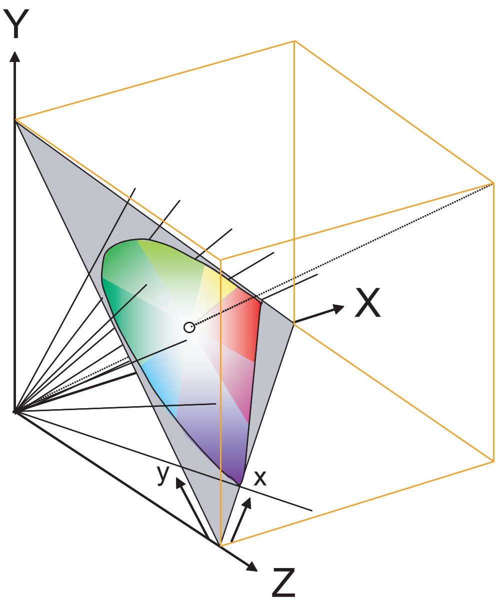

Figure 7
Section from a CIE-1931 diagram

By transforming the triangular face shown in the cube, the CIE diagram of 1931 is derived *(Fig. 8)*.

The advantage of the 2D representation according to CIE lies in the fact that instead of a colour description with three tristimulus values, the description can be made with a statement about hue and saturation i.e. with the two values x and y. The disadvantage is that the diagram is only valid for one spectral brightness and the colour coordination does not correspond well with human colour perception – that means an unequal distribution of the colours within the perceptual colour space. This attribute was described by MacAdam and is called MacAdam ellipses in the CIE-1931 diagram.

In order to achieve a more even distribution, the CIE described the CIELUV colour space in 1976. It rectifies the deficiency mentioned above in a way that enables the

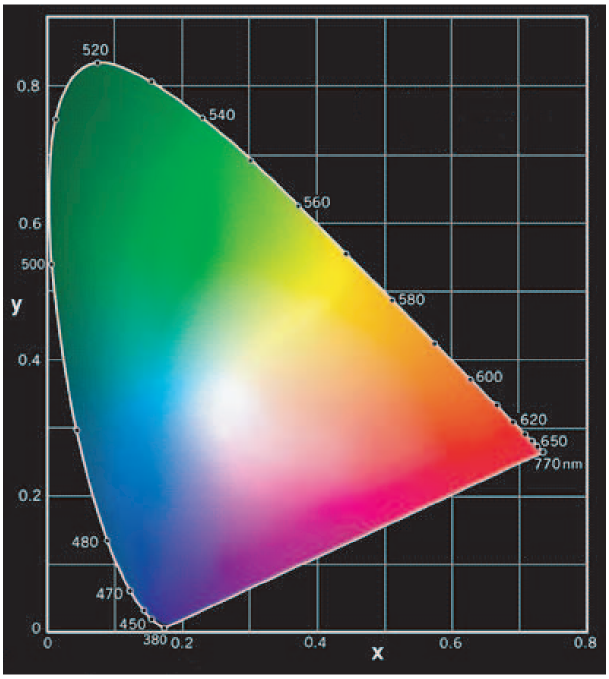

Figure 8
CIE xy diagram

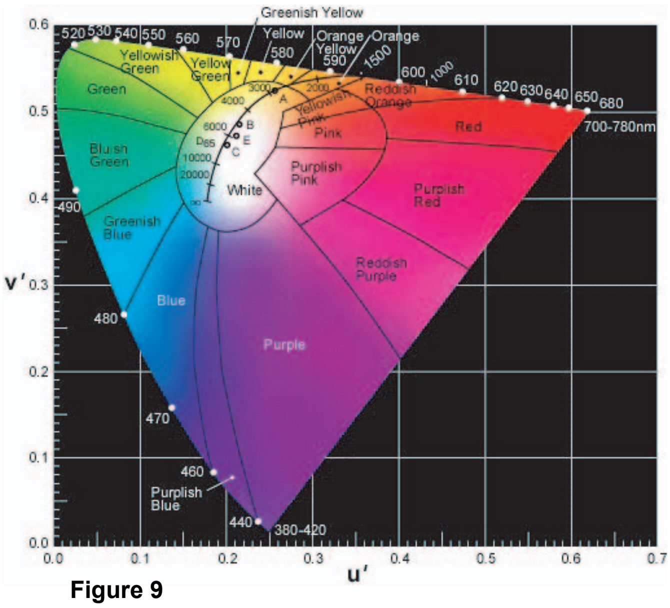

Figure 9
CIE u′v′ diagram

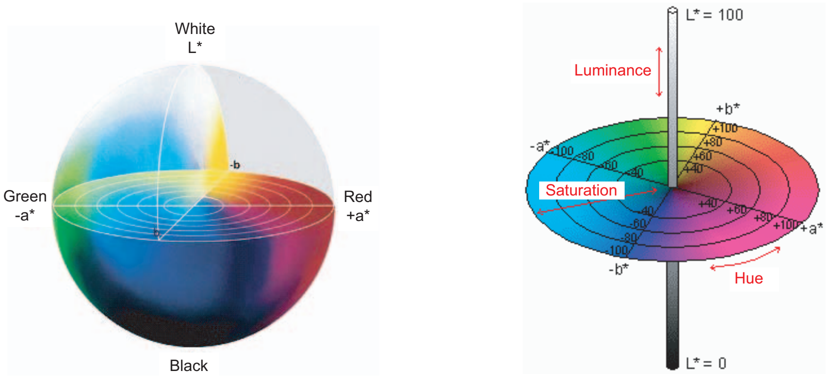

Figure 10
CIELab colour space

human eye to perceive equal distances between colours on the diagram as equal colour differences, independent of their position.

Fig. 9 shows a CIE u′v′ colour space with an even distribution of colour perception. Due to its 2D representation, this colour space is valid only for one particular spectral brightness.

The CIE u′v′ colour space is a good way to display colour metric connections in a perceptual way – for evaluating TV monitors, projectors and the colour quality of image-capturing equipment.

In 1976, the CIE introduced the CIELab colour space *(Fig. 10)*, which combines equal colour perception with a 3D representation.

CIELab is often used as a device-independent colour space for the conversion of different colour spaces (**P**rofile **C**onnection **S**pace; PCS).

Standard and correlation of different colour spaces

The RGB colour space is based on an additive colour mixture with the real primary colours – red, green and blue. In a three-dimensional Cartesian coordinate system, the RGB colour space can be represented as a cube. *Fig. 11* shows the correlation of the CIE-1931 diagram and the cubic RGB colour space.

The position of the triangle in the CIE-1931 diagram depends on the phosphorus used in the devices. Thus the RGB colour space is a device-dependent colour space. A metrically correct colour representation of video signals is only possible by defining the different types of phosphorus on an exact wave-length spectrum. For the colour television systems used in Europe, the EBU phosphorus was made the standard. *Fig. 12* shows the most significant attributes of the most important colour television systems. The yellow row of the table highlights the attributes of the EBU phosphorus, as defined by ITU-R BT.470.

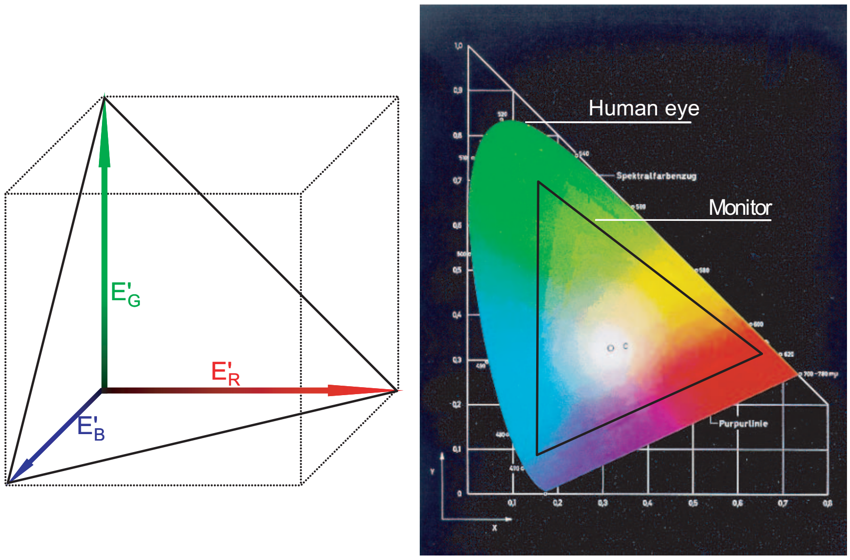

Figure 11
Correlation between RGB cube and CIE xy diagram

The EBU phosphorus is also the basis for the sRGB colour space, developed by Microsoft and HP and standardized under IEC 61966-2-1. In addition to the EBU phosphorus characteristics, the sRGB colour space also takes viewing conditions into consideration, especially external light sources with D50 and 20% reflection.

Standards	Primary colours				
	R	G	B	reference white	Y-matrix
FCC 1953 (NTSC until 1979)	x = 0.674 y = 0.326	x = 0.218 y = 0.712	x = 0.140 y = 0.080	x = 0.310 y = 0.316	$E'_Y = 0.299 \cdot E'_R + 0.587 \cdot E'_G + 0.114 \cdot E'_B$
SMPTE-C SMPTE-RP 145-1999 SMPTE-P22- Phosphore (NTSC since 1979)	x = 0.630 y = 0.340	x = 0.310 y = 0.595	x = 0.155 y = 0.070	x = 0.313 y = 0.329	$E'_Y = 0.299 \cdot E'_R + 0.587 \cdot E'_G + 0.114 \cdot E'_B$
ITU-R BT.470-6 Conventional TV-System PAL G	x = 0.64 y = 0.33	x = 0.29 y = 0.60	x = 0.15 y = 0.06	x = 0.313 y = 0.329	$E'_Y = 0.299 \cdot E'_R + 0.587 \cdot E'_G + 0.114 \cdot E'_B$
IEC 61966-2-1 sRGB The difference to ITU-R BT 709 : Additional definition of the viewing condition: external light sources with D50 and 20% reflection	x = 0.640 y = 0.330	x = 0.300 y = 0.600	x = 0.150 y = 0.060	x = 0.313 y = 0.329	$E'_Y = 0.299 \cdot E'_R + 0.587 \cdot E'_G + 0.114 \cdot E'_B$

Figure 12
Primary colour for different TV standards

Common printing presses, colour printers and film technology all work with subtractive colour mixing. For film technology, the three primary colours – cyan, magenta and yellow – are sufficient. For printing technology, on the other hand, black is usually added; the colour space is then called CMY(K). The CMY(K) colour space can also be represented as a cube.

Just like the RGB colour space, the CMY(K) colour space is device-dependent, because it depends on the colour pigments of the printing products or the colouring agents in the film technology.

Due to the scattering effects of the colour pigments used, the conversion between the colour spaces involved is a non-linear process. In the sphere of the primary colours, the colours of the source colour space cannot be displayed in the target colour space and must be replaced by similar colours. There are different conversion methods, which will be explained in the following section.

Colour space conversion

For a colour space conversion, it is necessary to describe the source colour space and the target colour space as accurately as possible. In the "profiles", the attributes of a colour space are defined in relation to another, either by a characteristic, a matrix or by a so-called "Look-up table". In order to avoid having to work out a profile for every possible combination of source and target colour space, the target or source colour space of choice is a device-independent "connection space" or **P**rofile **C**onnection **S**pace (PCS). So, only one profile is needed – with the PCS acting as a source or as a target space, as required.

Abbreviations

CCVS	Composite Colour Video Signal	**HSV**	Hue-Saturation-Value (colour space)
CIE	*Commission Internationale d'Eclairage*	**ICC**	International Colour Consortium
CMYK	Cyan-Magenta-Yellow-blacK (colour space)	**NTSC**	National Television System Committee (USA)
HCV	Hue-Chroma-Value (colour space)	**PAL**	Phase Alternation Line
HLS	Hue-Lightness-Saturation (colour space)	**PCS**	Profile Connection Space
HSB	Hue-Saturation-Brightness (colour space)	**RGB**	Red-Green-Blue (colour space)
		SECAM	*Séquentiel couleur à mémoire*

If the target colour space is smaller than the source colour space, the colour space has to be compressed, which can be relevant to the entire colour space or just to parts of it. If the target colour space is larger than the source colour space, the choice is either to keep the colours of the source colour space, or to expand them. Depending on the desired result of the colour space conversion, different *rendering intents* have been defined, which get their own chart entries in the profiles.

The rendering intent defines the desired effect of a colour space conversion. Since colour space conversions cannot be done without artefacts if the target colour space is smaller than the source colour space, a specific rendering intent must be defined. Usually, we can choose between the following three rendering intents.

The ***perception-oriented*** rendering intent optimizes the overall colour impression of the target colour space, so that hue changes are accepted in favour of the overall impression. The ***absolute colour metric*** rendering intent accurately (i.e. exactly) converts colours that are inside the target colour space. Colours that are outside the target colour space are moved to the next representable colour of the target colour space. This does not change the white reference. In contrast to this, however, the ***relative colour metric*** rendering intent may possibly change the white reference of the source colour space into the white reference of the target colour space.

The ICC (International Colour Consortium) developed a method for describing colour spaces and colour space transformations, which is finding increasing acceptance. *Fig. 13* shows ICC colour management as a block diagram.

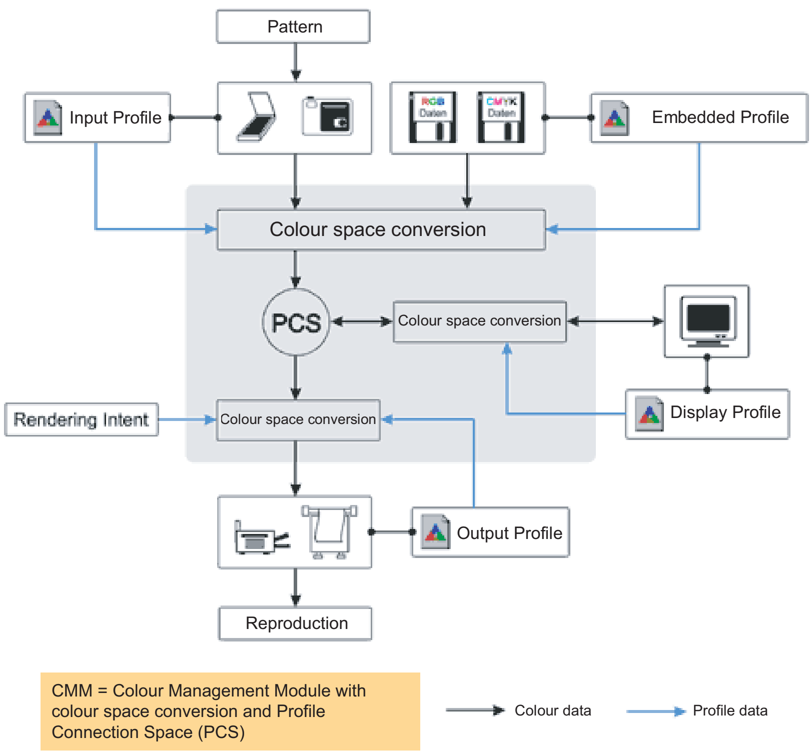

Figure 13
ICCview colour management system

As the diagram shows, the incoming content is transferred to the PCS via a colour space transformation. For reproduction with printers or monitors using the PCS, another colour space transformation must be conducted. Every colour space transformation has its respective profile and rendering intent.

In order to compare colour spaces, the ICC developed a program for comparing two colour spaces in three dimensions (http://www.iccview.de). This program offers the opportunity to visualise in advance the colours that cannot be displayed in another colour space and which must therefore be brought to the target colour space according to the rendering intent.

Practical colour management

As mentioned before, the traditional field of television broadcasting has no use for colour space transformations. Only when devices with "foreign" colour spaces are used, is a colour space conversion necessary. *Fig. 14* takes this fact into account.

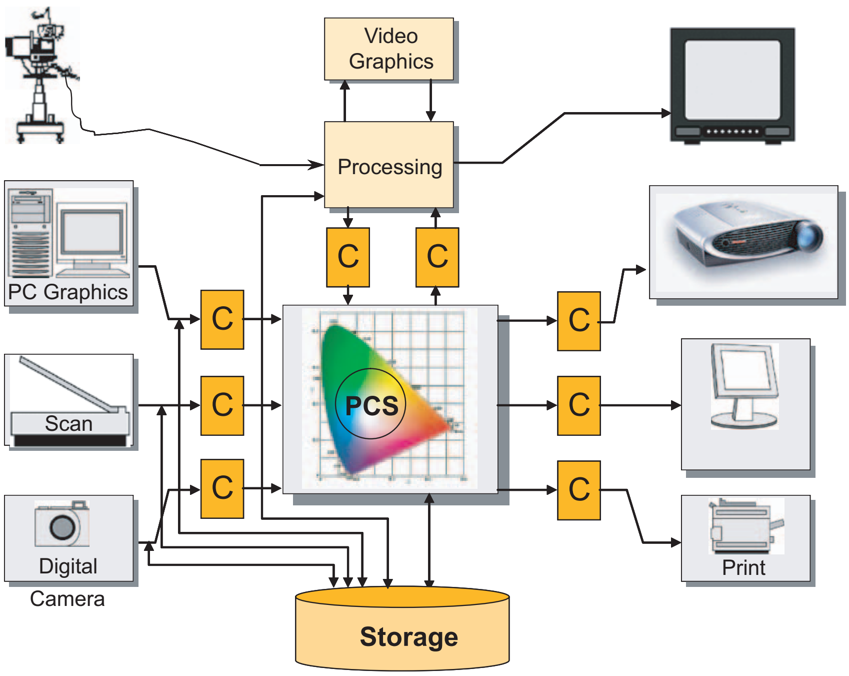

Figure 14
Colour management system recommended by an expert group out of the public broadcaster in Germany

If non-broadcast sources and sinks have to be integrated into a television studio environment, then also their colour spaces must be converted. The same holds true if content from the television studios is to be processed with PC-based graphics systems. As already explained, a PCS can achieve this task economically and it can only be reached through the use of profiles. Unfortunately, the necessary profiles are not always provided by the manufacturers. Usually, the manufacturers provide standard profiles but they are not sufficient for a correct conversion. If profiles are not available, they have to be produced by means of calibration and subsequent profiling. Commercial equipment that is currently available for profile production is limited to test charts and profiling software for digital cameras, scanners, computer monitors and printers. Software for the profiling of video equipment (film scanners, exposure systems, video cameras etc.) is still scarce.

For input devices (scanners, digital cameras), manufacturers use a standard pattern (slides or positives, depending on the device), in order to determine deviations from a reference database. With these deviations, a colour profile can be verified.

Printers can be profiled by printing out test image files, measuring the printouts photometrically and comparing them with reference values. This profile takes the printing technique, paper quality, inks and application into account.

The most precise way of profiling TV monitors can be achieved with a spectral photometer and profiling software. The profiling software shows a number of different colours that have been measured with a spectral photometer and compared with the reference data. The software then creates the monitor profile – also taking into account the features of the graphics card.

Conclusions

As *Fig. 14* shows, extensive colour management is only necessary when the production environment uses devices which were not specifically developed for television broadcasting and which use colour spaces other than the ITU-R BT.470 standardized RGB colour space. If the basic principles outlined in this article are not followed, it can lead to significant colour errors which will be difficult to correct at a subsequent stage in the broadcast chain.

Although the end user cannot normally recognize small errors in colour reproduction (because a reference colour source is not available to him/her), it is absolutely necessary to deliver the colours

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Mr Gierlinger chairs different working groups dealing with acceptance guidelines for different frequently-used broadcast products such as VTRs and Non-Linear Editing systems. He is member of a working group comprised of measurement and service department leaders from the public broadcasters of Germany. He is also a member of the SMPTE and is particularly engaged in picture quality evaluation.

as accurately as possible – with minimal variation from the well thought-out colour schemes designed by the production staff. Commercials in particular must be transmitted in the exact colours intended – to enable product recognition and advertising effects – because the consumers already have the colour references in the product itself.

Practical work has shown that, with correct colour management, even critical colours – such as terracotta gold – can be printed with a colour-managed printer, can be used as a studio background and can appear as terracotta gold again on the consumer's television set.