Introduction to colours in ConTEXt MKiV

Luigi Scarso

Abstract

This paper is a short introduction to colours from both theoretical and practical points of view. The last section is devoted to colour in ConTEXt MkIV.

1   Theoretical colours

While light is a well-known physical phenomenon, its interaction with the human body is still a complex subject. An important part of this complexity is due to the eyes being sensitive to a narrow part of the spectrum in a way that is neither uniform nor linear with wavelength; they transmit their signals to the brain by the optic nerves where they are "elaborated" to obtain a stereoscopic colour image.

Leaving out the three-dimensional aspect of vision, the human eye has two groups of specialised cells: the cones, which show three peaks of sensitivity around 420–440 nm ("blue"), 530–540 nm ("green") and 560–580 nm ("red/orange"); and the rods, which show a peak around 490-495 nm and are sensitive to low brightness. The fundamental law is empirical, due to Hermann Graßmann (1809–1877) around 1853 as a result of his experiments with "pure" colour sources. Graßmann was able to measure the same sensation of a colour C as a composition of sensations of 3 primary sources **R**ed, **G**reen and **B**lue weighted between 0 and 100. So, if C_1 and C_2 are two colours such that

$$\begin{aligned} C_1 &= r_1\mathbf{R} + g_1\mathbf{G} + b_1\mathbf{B} \\ C_2 &= r_2\mathbf{R} + g_2\mathbf{G} + b_2\mathbf{B} \end{aligned} \quad (1)$$

then the sensation given by a colour C_3 that is a composition of C_1 and C_2 is

$$\begin{aligned} C_3 &= C_1 + C_2 \\ &= (r_1 + r_2)\mathbf{R} + (g_1 + g_2)\mathbf{G} + (b_1 + b_2)\mathbf{B} \end{aligned} \quad (2)$$

He also found that some colours C_k matched only if combined with a primary source:

$$C_k + r_k\mathbf{R} = g_k\mathbf{G} + b_k\mathbf{B} \quad (3)$$

i.e.

$$C_k = -r_k\mathbf{R} + g_k\mathbf{G} + b_k\mathbf{B} \quad (4)$$

Figure 1 shows a plot of the RGB colour-matching functions similar to those calculated from these experiments; we can see the red component is negative.
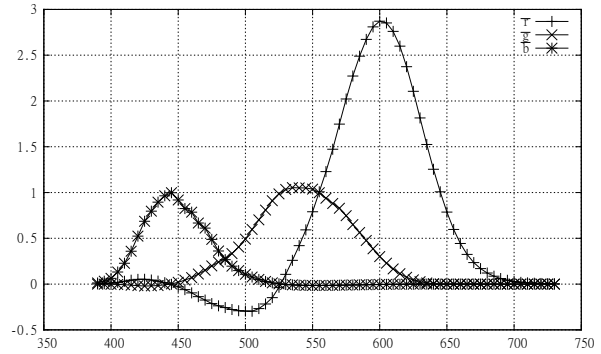

Figure 1: RGB colour-matching functions. X-axis is wavelength λ (nm). These data were obtained with a red primary of $\lambda = 645.16$nm, a green primary of $\lambda = 526.32$nm and a blue primary of $\lambda = 444.44$nm.

Given a colour C with a spectrum $P(\lambda)$ it's possible to calculate the components R, G, B with

$$\begin{aligned} R &= k \int_0^{+\infty} P(\lambda)\overline{r}(\lambda)\mathrm{d}\lambda \\ G &= k \int_0^{+\infty} P(\lambda)\overline{g}(\lambda)\mathrm{d}\lambda \\ B &= k \int_0^{+\infty} P(\lambda)\overline{b}(\lambda)\mathrm{d}\lambda \end{aligned} \quad (5)$$

To avoid calculations with negative numbers and to make use of these data easier, in 1931 the CIE consortium introduced a linear and non-orthogonal transformation $\mathbf{C_{xr}}$ between RGB colour-match space and a new XYZ colour-match space called CIE XYZ 1931 where all values are positive. Hence we have $X = \mathbf{C_{xr}} \cdot \mathbf{R}$ i.e.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.49000 & 0.31000 & 0.20000 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00000 & 0.01000 & 0.99000 \end{bmatrix} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix} \quad (6)$$

As a consequence there is also a new set of colour-matching functions $\overline{x}(\lambda)$, $\overline{y}(\lambda)$, $\overline{z}(\lambda)$ (see figure 2) so that a colour c with spectrum $P(\lambda)$ has the components X, Y, Z where

$$\begin{aligned} X &= k \int_0^{+\infty} P(\lambda)\overline{x}(\lambda)\mathrm{d}\lambda \\ Y &= k \int_0^{+\infty} P(\lambda)\overline{y}(\lambda)\mathrm{d}\lambda \\ Z &= k \int_0^{+\infty} P(\lambda)\overline{z}(\lambda)\mathrm{d}\lambda \end{aligned} \quad (7)$$

It's easy to show that for a generic spectrum $P(\lambda)$ not null (i.e. a visible colour) we always have $X + Y + Z > 0$ so it makes sense to define x, y, z as
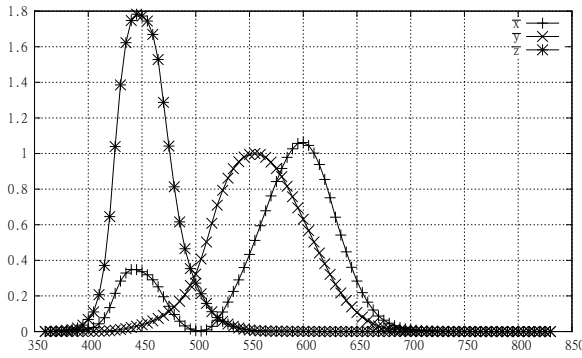
Figure 2: XYZ colour-matching functions per the CIE Consortium, 1931. X-axis is wavelength λ (nm). The CIE used slightly different virtual (i.e. calculated) primary sources from figure 1, namely 435.8nm for blue, 546.1nm for green, and 700.0nm for red. Each source is mathematically a delta (impulsive) function with amplitude +0.0601, +4.5907 and +1.0000.

$$x = \frac{X}{X + Y + Z}$$
$$y = \frac{Y}{X + Y + Z} \qquad (8)$$
$$z = \frac{Z}{X + Y + Z}$$

and hence *for all colours* we have $x + y + z = 1$, $0 \leq x \leq 1$, $0 \leq y \leq 1$, $0 \leq z \leq 1$. This surface is then contained inside the plane $\mathbf{x + y + z - 1 = 0}$ and its vertical projection onto the x-y plane is the *chromaticity diagram* whose peculiar shape is sometimes referred as a horseshoe (see figure 3). It's important to understand that it describes the complete *gamut* of an idealised human eye (it's also referred to as the gamut diagram) and it's *independent* of any particular device: *all the colours that are visible by the human eye are inside the chromaticity diagram.*

This diagram has several properties:

- a flat and uniform power spectrum $E(\lambda)$ has coordinates $x = 1/3, y = 1/3, z = 1/3$. It's called the achromatic point E and corresponds to a white light that can be used as a reference;
- there is no triangle with vertices in the gamut diagram that encloses all of the diagram itself (i.e. there are not three light sources that can produce all visible colours);
- given two points in the gamut (i.e. two real colours) all the colours in the straight line that joins them can be obtained by mixing the start and the end colours;
- given x, y, Y it's possible to calculate X, Y, Z and vice versa, so that the CIE XYZ 1931 colour space is equivalent to the CIE xyY
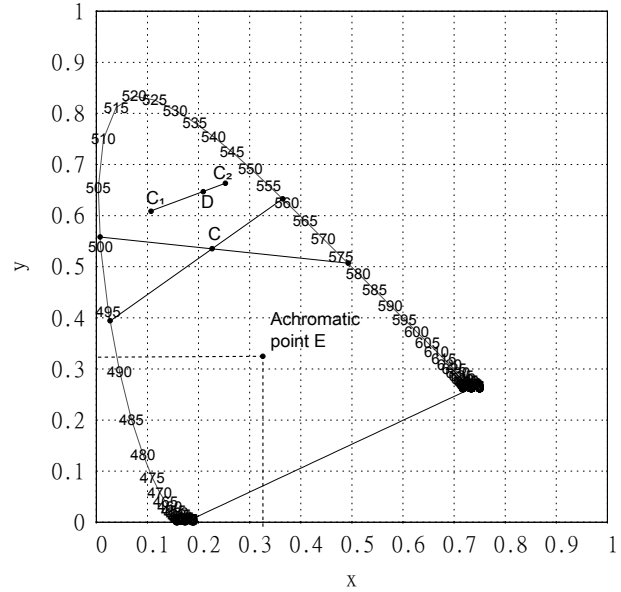

Figure 3: CIE xyY 1931 chromaticity diagram. The labels are the wavelengths λ in nm. The point E (the achromatic point) has coordinates $x = \frac{1}{3}, y = \frac{1}{3}$; the colour C can be seen as a result of mixing two different sets of monochromatic lights. Also a colour D can be a mix of the colours C_1 and C_2.

1931 colour space.

But probably the most important thing is that for a given colour, in most cases there are at least two independent sets of monochromatic lights that give the same colour perception when mixed (in figure 3 the two sets are ($\lambda = 495$nm, $\lambda = 569$nm) and ($\lambda = 500$nm, $\lambda = 575$nm)) and this is the best synthesis of the complexity of the human colour perception.

The CIE XYZ 1931 colour-space has several important properties, but an important disadvantage is that it's still difficult to compute the "difference" of two colours. In fact, given $C_1 = X_1, Y_1, Z_1$ and $C_2 = X_2, Y_2, Z_2$ then $\Delta C = \delta_2(C_1, C_2) = \sqrt{(X_1 - X_2)^2 + (Y_1 - Y_2)^2 + (Z_1 - Z_2)^2}$ is not adequate for practical purposes. For an effective Euclidean distance, researchers have found more useful non-linear transformations of the CIE XYZ 1931 colour space; one of the most used led to the CIE $L^*a^*b^*$ 1976 colour-space, with the coordinates L^*, a^*, b^* given by

$$L^* = 116 \cdot \left[f\left(\frac{Y}{Y_n}\right) - 16 \right]$$
$$a^* = 500 \cdot \left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right) \right] \qquad (9)$$
$$b^* = 200 \cdot \left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right) \right]$$

and

$$f(t) = \begin{cases} t^{\frac{1}{3}} & t > \left(\dfrac{6}{29}\right)^3 \\ \dfrac{1}{3}\left(\dfrac{29}{6}\right)^2 t + \dfrac{4}{29} & \text{otherwise} \end{cases} \qquad (10)$$

and X_n, Y_n, Z_n is a reference white point (for example, the achromatic point E mentioned above).

This leads to the important problem of the reference white point. It's clear now that under a monochromatic light the colour perception of a surface is completely different from the perception of the same surface under a "white light" and hence the specification of a "white light" is of extreme importance. It's also appropriate to consider a reference white light that mimics the Sun's daylight, so that we can consider a sort of natural light. Fortunately, physics can help with the well-established concept of *black-body*.

An ideal black-body is an object that absorbs *all* incident electro-magnetic radiations and re-emits them in a characteristic and continuous spectrum. The key point is that this spectrum depends only on the temperature: at room temperature the black-body radiation is mostly infrared wavelengths (invisible to human eyes, which is why the black body looks black), around 2000 K it is red, around 6000 K white and around 10000 K blue.

Hence it is possible to specify a temperature that identifies *precisely the spectrum* of a source light that gives a characteristic *perceptual* sensation of a colour, usually referred as *colour temperature T_c*. Nevertheless, the measure of this perception is still subjective, so more precisely the standards talk of *correlated colour temperature (CCT) T_{cp}*. The CIE has specified several of these sources to be used as "white light" only, and not as a general mechanism to define a colour; here is an example of these references sources:

Source	CCT	Note
D50	5003 K	Daylight, horizon light
D55	5503 K	Daylight, midmorning
D65	6504 K	Daylight, noon light
D75	7504 K	Daylight, north sky
E	5454 K	Equal energy
F4	2940 K	Fluorescent, warm white

Of course every source is a point on the chromaticity diagram (figure 3); for example, D50 $= (0.34567, 0.35850)$ and D65 $= (0.31271, 0.32902)$.

2 Practical colours

The colour spaces seen so far are exhaustive and device independent — and *theoretical*. Practical devices always have a gamut that is strictly contained in the CIE xyY 1931 diagram, and in the printing world what matters is the colour of a surface (usually a paper) that is determined by the reflection of the light of a source. Hence there are three effective way to obtain a colour:

Addition. This is how a monitor (CRT or LCD), a *transmitting medium*, works: red, green and blue pixels are side by side (hence not overlapping) and each can emit between 0 (off) and 2^n (express in a convenient unit). For example, if we have $n = 8$ and hence $2^8 = 256$ levels for each pixel, a colour C can have RGB components `(R,G,B)=(0x1C,0x45,0x3B)` or hexadecimal value `0x1C453B`. The colour depth is $8 * 3 = 24$ bits, hence we have max 2^{24} colours (more than 16 million). Some RGB colours can be specified also with 16-bit pixel values (2^{48}, more than $281 \cdot 10^{12}$) or as a real value between 0 and 1 e.g. `(r,g,b)=(0.1,0.2,0.45)`. It's important also to note that digital cameras and scanners store their data as RGB values (so more bits mean more precision for image processing) because most modern consumer transmitting devices share the same basic technical implementations (i.e. they have almost the same gamut).

Subtraction. With an ideally white source (`1.0, 1.0, 1.0`) the reflected colour of a surface (a type of *reflecting media*) can be described as `(r,g,b)=(1-c,1-m,1-y)`, where `(c,m,y)` synthesise the filtered portion of the spectrum of the ideal white light. This is how a digital colour printer works: each dot printed is obtained by an overlapping of 4 dots coloured cyan, magenta, yellow and black (called the *key colour*) where each is between `0.0` (not drawn) and `1.0` (fully drawn); the order of overlapping is also important in industrial printers, and is usually `c,m,y,k`. It's clear that the white colour `r=1.0,b=1.0,g=1.0` is `c=0.0,m=0.0,y=0.0` which means 'don't print anything' or, better, 'show the colour of the surface' which can be different from white (that's why these devices cannot print a white colour on a black paper). The black component is essential to ensure correct colours (for example `(c,m,y)=(1.0,1.0,1.0)` is usually a dark brown) hence a theoretical CMY colour is always translated to a practical CMYK; also common is to express values as real values between `0.0` and `1.0` or in percentages. Another important point is that a CMYK

colour is always defined with reference to white light (e.g. D50) otherwise it makes no practical sense.

Mixing inks. As seen in the colour *D* of figure 3, a colour can be a mixing, on a precise type of paper, of a set of industrial inks (often called spot colours) taken from a de facto standard colour catalogue in a precise quantity. This is how an offset press works; for example, colour PANTONE 567 EC from *Pantone colour bridge coated Euro 1st Edition*. The support is coated paper (can also be uncoated) and the source light is D50. There can also be RGB colour that at least gives an idea of the real colour (in this case 0x1C453B) but this is not always possible: there are inks without any RGB or CMYK representation.

Thus, every media has its own colour space (i.e. a specific gamut, a subset of the CIE XYZ 1931 diagram) and a way to walk between them is given by a *ICC colour profile*, which is a map between the specific gamut of the device and a standard colour space called the *Profile Connection Space*, that is in turn based on CIE XYZ 1931 with default source light D50. The key point is that this PCS colour space is device-independent, making it possible to compare two different device-dependent colour spaces, and also to specify a 'colour rendering style' of the device-dependent colour space to match the desired result. These 'styles', called *rendering intent*, are *absolute colorimetric*, *relative colorimetric*, *perceptual* and *saturation*. From ICC specifications, "the colorimetric rendering intents operate directly on measured colorimetric values, though possibly with correction for chromatic adaptation when the measured values were not calculated for the D50 PCS illuminant. The other rendering intents (perceptual and saturation) operate on colorimetric values which are corrected in an as-needed fashion to account for any differences between devices, media, and viewing conditions".

Here is a short list of ICC profiles:

- sRGB_v4_ICC_preference.icc: RGB colour space. The profile of most of LCDs, scanners and digital cameras;
- ISOcoated_v2_eci_300.icc: CMYK colour space. To be used for machine-finished glossy or matte coated papers. It's considered a more or less standard profile (Europe);
- UncoatedFOGRA29.icc: CMYK colour space. To be used for uncoated papers (Europe);
- GRACoL2006_Coated1v2.icc: CMYK colour space. To be used for machine-finished glossy or matte coated papers (USA).

A very useful program to explore the colour profiles is transicc from little cms, a C library also useful in implementing a colour management system. Here is a simple example on how to convert a red RGB colour C_0 to the equivalent CMYK C_1; note the ICC profiles and the -t0 option that means the rendering intent is 'perceptual':

```
# transicc.exe -isRGB_v4_ICC_preference.icc
    -oISOcoated_v2_300_eci.icc -v3 -t0
LittleCMS ColorSpace conversion calculator ...
Profile:
 sRGB v4 ICC preference perceptual intent beta
Output profile:
 ISO Coated v2 300% (ECI)
...
Enter values, 'q' to quit
R? 255
G? 0
B? 0
C=0.6210 M=99.6170 Y=89.6544 K=2.6841
[PCS] Lab=(48.3055,86.7471,68.7393)
XYZ=(37.1789,17.0361,0.7712)
```

It's worth observing that the theoretical CMYK colour $C_2 = (0, 1.0, 1.0, 0)$ has the coordinates [PCS] Lab=(49.4726,65.9508,52.1581) and thus $\Delta E^* = \sqrt{(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2} = 26.623$ while two colours are regarded as identical if $\Delta E^* < 2.8$.

3 Colours in ConTEXt

The PDF Reference describes three families of colour spaces:

1. the *device colour spaces*: DeviceGray, DeviceRGB, DeviceCMYK;
2. the *CIE base colour spaces*: Lab, ICCBased, CalGray, CalRB;
3. the *specials*: Pattern, Indexed, Separation, DeviceN.

In ConTEXt MkIV it's possible to define a device colour space with the \setupcolors and \definecolor macros, as in

```
\setupcolors[state=start,rgb=yes,cmyk=yes]
\definecolor[BlueGRAY][s=0.1]
\definecolor[BlueRGB][r=.1,g=.1,b=1]
\definecolor[BlueCMYK][c=0.9,m=.0.909,y=0,k=0]
\definecolor[Blue][r=.1,g=.1,b=1,
    c=0.9,m=.0.909,y=0,k=0]
```

Then we can use it by its name as in \color[Blue] {I'm blue}. The GRAY colour space is the last resort, and the RGB colour space has precedence over CMYK, so Blue is an RGB colour; if we use rgb=no,cmyk=yes, then Blue is the inverted CMYK colour (1-r,1-g,1-b), not the one specified (the same for rgb=yes,cmyk=no), and with

`rgb=no,cmyk=no` all colours are converted to GRAY. So, we should pay attention to the colour definitions.

ConTEXt MkIV also manages colour transparency: in

```
\definecolor[BlueTrs][r=.1,g=.1,b=1,t=0.7,
                     a=normal]
```

the key `t` specifies a solid colour with `t=1.0` or full transparency with `t=0.0`, while the key `a` is the transparency alternative method (there are 13 alternatives). Still today transparency must be used with care because printing is not reliable (some printers simply reject PDFs with these colours even if solid).

For spot colours (the Separation special colour space) things are a bit more complex: we must ensure that the tint is exactly specified by its name (case and spaces matter!) and associated with a CMYK reference colour for a low-quality print (just to see it), hence the two-steps definition:

```
\setupcolors[state=start,rgb=no,cmyk=yes,
            spot=yes,overprint=yes]
\definecolor[Pantone294][c=1,m=.56,y=0,k=.18]
\definespotcolor[BlueSPOT][Pantone294]
            [p=1,e=PANTONE 294 CV]
```

The `overprint=yes` setting ensures that black overprinting the spot colour will not knock out the colour.

As of August 2010, ConTEXt MkIV has started to support the CIE based colour space ICCBased for RGB, CMYK and GRAY (only) and limited to the entire document (not for single object colour). An ICC profile must first be registered into the `color-profiles.xml` file by filling these fields (the function colors.iccprofiles (filename, verbose) in `colo-icc.lua` can help here):

filename: the file name of the ICC profile;

colorspace: the colour space of the profile;

class: the device class of the profile (`prtr` for printer, `mntr` monitor, `scnr` scanner, `spac` space);

id: identifier of the measured data (not for the profile) on which the profile relies; e.g. FOGRA39;

info: (optional) descriptive text about the profile;

checksum: md5 checksum of the profile;

version: version number of the profile in hex;

url: url where the profile can be downloaded;

outputcondition: (optional) information about print technology, paper type and weight.

The profiles for RGB, CMYK and GRAY colour spaces can be set for the entire document with

```
\setupcolors[state=start,rgb=yes,cmyk=yes]
\setupbackend[profile={sRGB_v4_ICC_preference.icc,
    default_cmyk.icc, default_gray.icc}]
```

Supporting ICCBased colour spaces is part of wide support for PDF/X specifications, a subset of full PDF focused on achieving more reliability in exchanging PDF files by enforcing restrictions; for example, fonts must all be included. All PDF/X-* are formalized in ISO standard 15930. The specifications currently under development for ConTEXt MkIV are PDF/X-1a:2001, PDF/X-1a:2003, PDF/X-3:2002, PDF/X-3:2003, PDF/X-4, and PDF/X-4p, where X-1* is more restrictive than X-4*. The latest, PDF/X-5, is left out.

To enable a format we again use `\setupbackend`:

```
\setupbackend[format=PDF/X-4,
profile={sRGB_v4_ICC_preference.icc,
default_cmyk.icc, default_gray.icc},intent=
{ISO Coated v2 300\letterpercent\space (ECI)}]
```

Here we specify in `profile` the ICC profiles of the colour's document, while in `intent` we specify the ICC profile of the intended output, a coated paper in this case. This is a feature of PDF/X-4; PDF/X-1a:2003 permits only CMYK and spot colours.

As final note, it's important to understand that PDF/X is a complex subject and ConTEXt MkIV is not a preflight tool. A PDF made with inclusion of other PDFs as images are particularly fragile: it is easy to do with ConTEXt, but can easily lead to an invalid PDF; for example if the included PDF does not have all its fonts embedded, or contains an RGB colour, or a transparency that is prohibited by the format chosen. So it's better to have a preflight tool for checking, and at present only commercial tools are reliable (yes, room for improvements here).

4 Reference information

- General information: `http://en.wikipedia.org/wiki/International_Commission_on_Illumination`
- A useful link for theoretical information: `http://www.fho-emden.de/~hoffmann/howww41a.html`
- The diagrams were traced with data from: `http://cvrl.ioo.ucl.ac.uk`
- ICC information: `http://www.color.org`
- Useful PDF/X information at the site of the Ghent PDF Workgroup: `http://www.gwg.org`
- Implementation of PDF/X in ConTEXt MkIV: `http://wiki.contextgarden.net/PDFX`
- More information about colours in ConTEXt: `http://wiki.contextgarden.net/Colors`, `http://wiki.contextgarden.net/Reference/en/definecolor`

⋄ Luigi Scarso
luigi.scarso (at) gmail dot com