

Kleijn, Wilson, Watkinson P4 Colour Space – KWW-P4
A new colour gamut for Digital Cinema and UHDTV

=====

By Kommer Kleijn SBC, Peter Wilson HDDC and John Watkinson FAES. Version 3.0 Oct 2026.

Presented at the IMIS “METAMERISM 2026” Conference held at the London Film School on
October 6th 2026.

Contact e-mail: <kwk-p4@kommer.com>

History:

=====

Colour reproduction systems for electronic projection have traditionally used RGB synthesis with either colour phosphors or continuous spectrum lamp sources followed by dichroic separation filters to create trichrome red, green and blue channels. After adding back together these three channels (e.g. when the image input signal is white) then results in a continuous spectrum white light, similar to natural sunlight. The dichroic filters act much like a well designed loudspeaker crossover filter would, where low, mid and high frequencies are split into three channels in a way that no frequencies are lost, when they are put back together again.

This corresponds also with what happens in nature. The sun provides white light with a continuous spectrum of all visible wavelength / frequencies, as does a fire, and colours are created in nature by the dichroic filtering that happens on surfaces. Some light frequencies are more reflected and others are more absorbed by the surface, which gives it its specific colour. The human visual system, which evolved with natural sunlight and fire, is equipped for evaluating all reflective colours, lit by sunlight or fire, with continuous spectra.

However, with the use of dichroic filters in digital projection systems, although well adapted to the human visual system, this technology limited the colour gamut of the rendering to a saturation level approximately comparable to that of BT.709, the standard that was developed for HDTV. This was considered adequate for a long period.

When digital cinema became an option, the cinema industry requested a wider colour gamut, comparable to that of what was possible with a pristine print film, as the film makers community requested the same richness in colour reproduction it had access to with analogue film projection. Analogue film projection, however, is based on subtractive colour synthesis (CMY) allowing for a larger gamut in cyan than a then traditional RGB additive colour system would provide. This is due to the combination of the facts that on one hand the low-frequency (L) cones in our retina's (AKA red cones) and the medium-frequencies (M) cones (AKA green cones) have a large overlap of frequencies for which both react, and on the other hand the low-frequency cones in our retina's (AKA red cones) have an inverse response to spectral cyan light, and the inability of the tri-colour additive RGB colour synthesis projector to produce either spectral cyan light or to create “negative” red light. This limits the projectors ability to create certain tri-stimuli: The inverse (negative) sensitivity of the “L” cones remains unaddressed by tri-chrome RGB additive colour synthesis, while the Cyan layer of subtractive CMY trichrome colour synthesis actually can address it, as reflective colours in nature can as well.

To accommodate the requirements of film makers, and in order to have the film making community accept the transformation from analogue to digital projection, it was decided to heighten the saturation of each of the RGB primaries to enlarge the RGB additive gamut. To achieve this, two notch filters were added in the light path. These notch filters remove part of the spectrum at both the crossover

frequencies, so creating a wider triangle in the CIE1931 colour locus, creating a wider colour gamut, wider than what was seen before in electronic projection. Removing a part of the spectrum allowed to enhance the separation between the tri-stimuli, even without addressing the inverse response of the L cones. The “notched” colour space was called DCI-P3 (Digital Cinema Initiatives - Parameter 3).

However, the addition of the notch filters created “holes” in the light spectrum. Indeed, some light frequencies are now almost absent from the projected light, also when the picture is white. A side effect is that the notch filters also diminish the light efficiency of the projector as the notch filters remove a percentage of light from the flow, and transform it into heat. However, the move towards “notched P3” helped to convince the filmmaking community and, together with other measures, like a new and robust file format and stable projectors without accessible adjustments, this helped to come to an industry agreement to adopt digital distribution and projection, even if P3 does not cover all colours that analogue print film could show. But it came significantly closer.

The introduction of these “spectral holes”, besides the economic disadvantage, also causes visual disadvantages. Indeed, the human visual system relies heavily on “post-processing” as the human eye itself has numerous imperfections that are then compensated for by complex neurological processes. These processes, together with the eyes, form the Human Visual System (AKA HVS) which however relies on the spectrum it has evolved in: A continuous spectrum, containing all light wavelength from 400 to 700 nm and without interruptions or notches. But since the holes created by the P3 notch filters are reasonably small, the visual artefacts that occur because of them have gone largely unnoticed and for those who have noticed them, they have been judged as acceptable, in exchange for the widened

colour gamut and the practical and economic advantages of digital projection.

As a result, the use of the P3 colour space in digital cinema projection has been considered a good compromise and has satisfied the film industry for more than a quarter of a century now.

New problems:

=====

More recently, however, we have seen a number of new developments in digital cinema projection:

Problem 1 – Narrow bandwidth RGB Laser light sources having incompatibilities with the Human Visual System.

Laser diodes have become available with enough power to compete with the Xenon Arc lamps used in cinema projection since almost three quarters of a century. The advantages of laser diodes over Xenon lamps are merely economical: less maintenance, higher efficiency, hence lower power consumption, less cooling needs and quieter operation, and a long life of the laser light source avoiding the uncomfortable lamp replacement operation of Xenon bulbs.

Two main families of laser light source projectors have been introduced to the market:

1a - Laser-phosphor projectors, where laser diodes (any colour, often blue) are used to excite phosphor which then in turn produces spectral light for the projector. This can result in a spectrum similar to that of the Xenon lamp, with undesirable artefacts of a level comparable to that of existing xenon projectors, so to be considered acceptable.

1b - So called “Direct” or “RGB” laser projectors where blue, green and red lasers are used directly without using phosphor. These projectors emit three narrow bandwidth, almost monochrome colours with no spectrum any more at all. As a result,

significantly more and stronger undesirable artefacts occur in the Human Visual System. But the currently standardised (but in fact obsolete) measuring method, intended for evaluating Xenon lamp projectors, incorrectly gives them a clean bill of health. This measuring system was never intended nor evaluated for non-spectral light sources. Among the artefacts are coloured fringes on high contrast content matter, lack of perceived detail on surface structures, a perceived difference in crispiness of the image, laser speckle artefacts and most importantly, metameric failure of perceived colours depending on differences in the age of viewers and genetic differences among viewers. As a result of these metameric failures, viewers in the same room looking at the same screen will experience different colours, and often different from the film maker intention. These artefacts can seriously impact the quality of the movie going experience, even if many viewers may not be able to describe what actually went wrong for them, also as they often do not know what they were supposed to see. But as it can result in a less satisfactory experience, and since satisfaction influences the delay till when the customers return to the box office, the damage caused by these artefacts can damage the success of the cinema industry as a whole. A more detailed description of these RGB laser artefacts can be found in the article series "Laser Illumination in Cinema" by Kommer Kleijn and Peter Wilson, published in "Cinema Technology Magazine", issues "Autumn/Winter 24", "Spring 25", "Summer 25" and "Autumn 25".

Note that these artefacts, except for laser speckle, are in fact already present in the "notch filtered" P3 Xenon lamp projector but to a much lesser degree, and as such have been deemed "acceptable" for 25 years already. Given the huge quantity of content that now exists for the P3 colour gamut, it would seem unwise to propose a reduction in colour space, or any other change that would be incompatible with this large amount of existing P3 content.

Problem 2 - the desire and promotion of "Wider Colour Gamuts" (WCG)

2a. - We must note that the P3 colour space does not cover all reflective colours that occur in nature - those that have been established by Pointer's Gamut, nor does it cover all the colours that a pristine analogue film print can reproduce. Although the P3 colour space can reproduce a number of colours that analogue film print was not capable of rendering, a desire exists for a solution that can reproduce all reflective colours that exist in nature, as defined by the Pointer's Gamut.

2b. - Colour television has been updated with a new encoding standards. Since the advent of HDTV, the ITU defined a colour space for it, called BT.709. It was based on the then current phosphor materials used in the then current Cathode Ray Tubes (CRT) which were then used for rendering HDTV images. P3 being wider, this made that for about a decade, digital cinema enjoyed a wider colour gamut than television. Another difference between HDTV and digital cinema is the encoding used. HDTV used the same colour space (BT.709) for both encoding and for rendering, as at the time of its conception, on-the-fly colour transformation in the receiver device was economically not a viable option. For digital cinema, however, a mandatory on-the-fly transformation option was adopted, as such had become available also because the rendering device (the digital cinema projector) is a professional device, and not a consumer device. For digital cinema it was decided to use XYZ encoding, an encoding method that is independent from the rendering device or colour space, one that allows to encode any colour the HVS can perceive, not only P3. Then, the XYZ encoding actually encodes what the viewer shall see, and not how to steer the projector channels. This makes the encoding method, and the DCP file format, future proof. The content file contains what the viewer shall see, and each projection system shall transform the colour data in the encoded file

towards the steering signals appropriate for the projection system at hand, often on the fly, in accordance with the specifics of the projector, to obtain that exact visual result.

Then in 2012 the ITU defined a new standard, for UHDTV. As CRT tubes had been abandoned in favour of flat screens, having a range of different rendering technologies, it was time for television to also renew their encoding method. However, in stead of adopting the XYZ colour encoding used in Digital Cinema, ITU kept an RGB type encoding and defined a new RGB encoding standard called BT.2020. BT.2020 is a three parameters RGB encoding that defines three new virtual primaries. These are now so far apart that almost the entire gamut of existing reflected colours (The Pointer's gamut) is inside of this new triangle. Only very few cyan colours are still outside of it. This will allow encoding all but very few existing reflective colours. Note, that the BT.2020 primary colours are not physically realisable, or at least, such was probably not intended. Like with digital cinema, UHD TV sets will have to transform the so encoded colours to the correct steering values for the screen at hand. Similarly to digital cinema, UHDTV set manufacturers now are free to choose the primaries and technologies used for their tiles and transform the encoded colours appropriately on the fly, as transform technologies now have become available at costs also viable for consumer devices.

However, as colour science is not wide spread knowledge, confusion has raised among consumers between the new encoding standard and the rendering of the encoded images. While the new BT.2020 primaries have been chosen for encoding purposes and not for rendering, in the previous standard BT.709 the standard did point to both encoding and rendering primaries. As a result confusion has risen among consumers about a goal to physically implement the BT.2020 primaries as rendering primary colours in devices, while such was possibly never intended.

It may be regretted that ITU did not opt for an XYZ encoding scheme like digital cinema did, because that would have made it clear that the encoded data can not be fed directly as steering signals in rendering, and that a transform is mandatory. Unfortunately, BT.2020 allows for this confusion, and TV and projector manufacturers therefore have received an incentive for creating devices with extremely saturated primaries in order to claim "Close to full BT.2020 rendering". A problem with this is that the BT.2020 encoding primaries are so extremely saturated that they can not be achieved with wide bandwidth spectral light. To embody these primaries physically, this is only possible with narrow bandwidth monochromatic, or almost monochromatic light. Monochromatic light, however, bears incompatibilities with the Human Visual System (HVS) causing important perception artefacts, causing image quality damage.

Subsequently, as achieving BT.2020 rendering has unfortunately become a goal in TV-set design, some TV sets have become capable of reproducing some saturated colours outside of the DCI-P3 gamut. This resulted in rumours that TV would have surpassed Cinema in colour rendering capabilities, and subsequently D-Cinema projector manufacturers use the near BT.2020 reproduction performance of triple monochrome RGB laser projectors also as a sales argument. However, the use of such narrow bandwidth light for primary colours unfortunately causes important artefacts in the Human Visual System that seriously jeopardises perceived viewing quality and viewing comfort. An additional problem is that outdated and inadequate measurement methods are still widely in use which do not take these artefacts into account. As a result, most of these measurements do not reveal these problems and artefacts and projectors are certified as good while in fact yielding a visually degraded result.

Proposed solutions:

=====

\$1. A new Colour Gamut for Digital Cinema and UHDTV: KWW-P4

=====

The proposed solution is a new Colour Gamut definition that would be applicable to Digital Cinema projectors, digital cinema direct-view screens, and UHDTV television-sets, called KWW-P4 (Kleijn, Wilson, Watkinson, Parameter 4). The proposed colour gamut will not use narrow bandwidth primaries and should not cause more HVS artefacts than P3 does. Like XYZ encoding and BT.2020 encoding it will also include all colours of the Pointer's gamut but unlike P3 it will be capable of reproducing all colours of the Pointer's Gamut, and unlike REC.2020, it will do so without the need for narrow bandwidth primaries that create undesired artefacts. It also will be compatible with both the existing encoding methods: it is compatible with the actually used DCP XYZ encoding and also with the UHDTV BT.2020 encoding. It is also backwards compatible with existing P3, BT.709 and BT.601 content, and also with most BT.2020 content: All of pointer's gamut colours encoded in BT.2020 will be rendered and many colours outside pointer's gamut as well. It additionally will embrace future "KWW-P4" content with additional colours that neither P3 or BT.2020 have been able to contain, outside P3 and/or BT.2020, including colours inside the Pointer's Gamut as well as some outside of it.

Important is the realisation that both the D-cinema encoding techniques (D-cinema XYZ) and the UHDTV BT.2020 both require an "on-the-fly" colour transform hardware in every rendering device and that this fact allows for adding a fourth colour channel to the colour rendering engine without the need for a fourth channel in the encoding, or in the file format or in the transmission channel, or in cameras. Cameras, in fact, already can record all colours of the Pointer's Gamut, eventually new software updates may be

needed to encode the newly reproducible colours.

We feel that it may have been the prospect of the burden of a fourth transmission channel, and/or fourth capture channel that has previously withheld designers from adding a fourth primary colour to rendering methods.

However, we must realise that with the on-the-fly transforms that are in use today, we can now look at these aspects separately. A fourth primary colour in rendering can now be considered without the need for adding a channel to the encoding, capture or transmission. We consider this realisation as one of the main new ideas that this new colour space brings. The other being the realisation that the HVS can detect/sense a fourth colour (Cyan), which is addressed by natural colours in nature and also by analogue film using YMC colour synthesis, but not by RGB systems. Combining these two discoveries resulted in proposing KWW-P4.

KWW-P4 proposes to add a fourth colour to rendering, and to rendering only. In projectors this will cause the burden of an additional a fourth modulator and additional optics, or an additional projector, while for direct view cinema screens and televisions additional LED's or pixels will be needed. The latter may be less complex to realise. For the second KWW-P4 flavour (KWW-P4 ready) it can also be considered to add an additional single colour projector to an existing P3 Phosphor laser projector or to a P3 Xenon projector.

The additional colour will be cyan. By adding a spectral Cyan channel, KWW-P4 will allow for a complete colour gamut, fully covering the Pointer gamut, and without a need for narrow bandwidth light, and thus without creating additional artefacts in the HVS and also without a need to modify encoding or transmission, remaining compatible with existing standards.

Two flavours of KWW-P4 are proposed:

A full version and a reduced version that would allow for easier transition. They might be called “Full KWW-P4” and “KWW-P4 ready”

\$1.1: “KWW-P4” or “Full KWW-P4”

“Full KWW-P4” uses a fourth colour for rendering, without a need for a fourth channel in the media files, transmission or capture. The primary colours for RED and BLUE are close to the ones used for REC.2020. However, we propose to generate these spectrally and not monochromatic. For RED and BLUE we think such is possible while staying relatively close to the REC.2020 RED and BLUE primaries. They have been moved slightly inwards: RED: $X=0.675$, $Y=0.3$ / BLUE: $X=0.155$, $Y=0.05$. The third primary colour will be the GREEN colour, exactly the same as is defined for the actual P3 standard: $X=0.265$, $Y=0.69$. This colour can also be created as a spectral colour. The FOURTH colour will be CYAN. It should also be created with spectral light and is situated on the co-ordinates of $X=0.4$ and $Y=0.1$ on the CIE193 chart. These 4 primaries should allow to render all colours of Pointer’s gamut without the need for narrow bandwidth light.

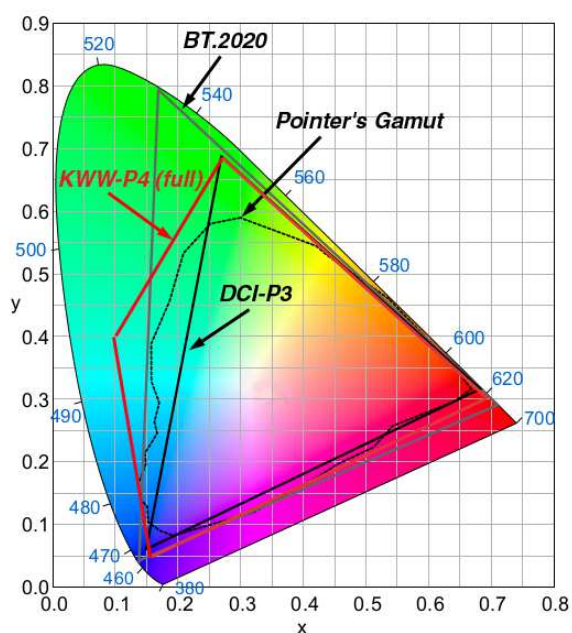


Figure 1: KWW-P4 (full)

\$1.2 KWW-P4 ready

“KWW-P4 ready” would be a slightly reduced version with the goal to ease transition. Now, for the GREEN, RED and BLUE primaries it would use the exact same colours as is defined for actual P3. Only the fourth colour, CYAN would be added with the with the co-ordinates of $X=0.4$ and $Y=0.1$ on the CIE1931 XY locus chart. This “KWW-P4 ready” colour gamut will contain most of the pointer gamut colours but not all. However, it can be created by adding a fourth channel to an existing system or set-up, for example by adding an additional projector to an existing phosphor laser system or even to a Xenon projector.

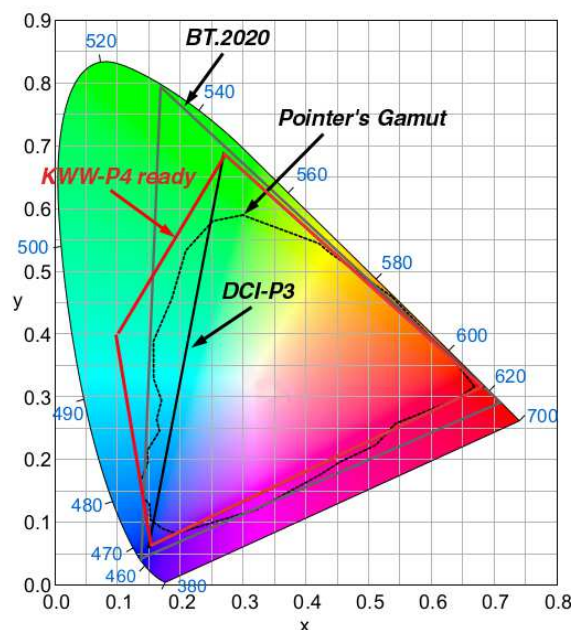


Figure 2: KWW-P4 ready

Additional note:

When KWW-P4 would be applied to screens intended for rendering of REC.2020 encoded contents (like television sets), then (at the discretion of the display maker) a CYAN channel on the $X=0.4$ and $Y=0.15$ position on the CIE1931 XY locus chart would actually be sufficient as the additional colours created by the $Y=0.1$ position (in stead of $Y=0.15$) can’t be encoded in the REC.2020 encoding standard.