## Appendix C

## An Analysis of Quattron

While 3 primaries based on the CIE colour model have almost universally adopted for active colour reproduction, there are 2 examples where manufacturers of display technology have claimed to have developed colour reproduction based on 4 primaries and 1 example of a manufacturer that has claimed 6 primaries. Both Panasonic Quatrecolor and Sharp Quattron added *yellow* as a primary, and advertised the merits of the respective technology on the basis of improved colour reproduction. Mitsubishi's 6-color *processing* added *yellow*, *cyan* and *magenta*. Both Mitsubishi's 6-colour approach and Panasonic's Quatrecolor are currently obsolete.

Quattron has been criticised for being "just another shameful marketing gimmick" Soneira [2010], on the basis that the addition of a 4'th *yellow* pixel will bring colours the display reproduces outside the bounds of Rec. 709 subset of the CIE colour space while at the same time failing to significantly increase the available colour space.

Note that in our figure, the outer white curve represents the limits of human vision. While the Rec.709 standard is much smaller, it's important to note that the colors between the black triangle and white curve aren't common in nature. Yes, a display can only reproduce the colors that lie inside of the polygon formed by its primary colors, but because yellow falls between the red and green primaries, Sharp's yellow primary would need to lie somewhere outside of the red and green leg of the color triangle. But there isn't much room between the Rec.709 triangle and the human vision curve, is there? For this reason, it's difficult to see why a yellow primary sub-pixel is needed unless Sharp isn't able to put its red and green primaries where they belong. Soneira [2010]

Between 635nm and 535nm, the CIE colour space is approximately linear and therefore predicts that monochromatic colour stimuli within these bounds can be matched with 2 monochromatic primaries. Monochromatic *yellow* is found approximately at the midpoint of this line. Under the CIE colour model all colours within the chromaticity space enclosed by the primaries may be accurately reproduced, and as *yellow* is found on the line be-

tween green and red it may be accurately reproduced if the red and green primaries are monochromatic (which is something recommended by Rec. 2020). The introducing of a yellow primary would therefore serve little or no function, depending on how closely the red and green primaries approach being monochromatic. It should be noted, however, from the colour matching chromaticity diagram that if the space enclosed by 3 primaries were to be maximised the green primary would be placed at approximately maximal y (see Figure C.2) – which is below 520nm. The fact that this cannot be done in practice cannot be derived from the chromaticity diagram. As the spectral distance between the green and red primaries are increased the constituent stimuli will be perceived as increasingly less saturated (increasingly *white*). Under opponency the *red* and *green* primaries are 2 parts of an opponent pair, and therefore green + red = white. While for humans this holds for the opponent pair *blue-yellow*, due to the peculiarities of the human visual system it holds only partially for *red-green*. Nevertheless, this contradicts the underlying assumption of the CIE colour model of linearity between arbitrary primaries. The CIE colour model predicts that colour for any linear segment through the CIE colour space may be reproduced by 2 primaries at the boundaries of the segment. This, however, holds imperfectly within the red-green region. The CIE colour matching chromaticity space is known to be imperfectly linear, but is nevertheless assumed to be so due to the benefits derived from linearity. The non-linearity between the red-green primaries is implicitly acknowledged by the choice of (under the CIE colour model) non-optimal red and green primaries for practical colour reproduction. To reproduce yellow the red and green primaries must be green-yellow and orange, and this reduces the colour space enclosed by the primaries (Rec. 709 being an extreme example, with the gamut reduced to less than half of the colour space mapped by colour matching – see Figure C.2). Proponents of the CIE colour model suggest that the colours lost are 'not very important':

...but be aware that for most applications, gamut size doesn't matter very much. The further out you go in color space, the less frequent the colors appear in nature, so the human eye doesn't notice that they're not quite right except in rare circumstances (like when viewing a full-screen rendering of a very red tulip). Soneira [2010]

A study of natural colour reproduction contradicts this assumption, and tulips are a good example to illustrate natural colour reproduction. Tulips (genus Tulipa) displays colour prominently to advertise its reproductive needs and have been cultivated by humans to serve a decorative function in respect of their display of colour. A wide variety of tulip exists, capable of reproducing a broad range of colours. Nevertheless, there is no *blue* tulip. This is because the underlying colour model of the tulip (like that of many flowering plants) expresses absorption of *blue* (the range of short wavelengths). Tulips are therefore naturally *yellow* rather than *red*, and they compete in attracting pollinators by the *purity* and luminance of the *yellow* they are able to reflect from the natural ambient light. This approach to colour reproduction is common in the natural environment and therefore it is very important that colour reproduction is able to match natural *yellow*. For reflective colour reproduction this is achieved by absorbing *blue* and for emissive colour reproduction

this is achieved by combining green, yellow and red light. Under the opponency paradigm green and red subtract (being 2 parts of an opponent pair) leaving only the luminance. The purpose of adding green and red to yellow is therefore to increase the amount of light reflected and thereby increasing perceptual luminance. If colour reproduction is to be achieved without a yellow primary then the green and red primaries may be broadened to fill the spectral gap of the yellow primary. In so doing the red and green primaries become green-yellow and orange (that is, they become impure). Colour reproduction with 3 primaries therefore faces an inherent yellow/red-green contradiction. A contradiction that practical colour reproduction balances by placing the *red* and *green* primaries sufficiently close that when combined will produce a perceptually acceptable *yellow* while at the same time when independent will be perceived as red and green. This will always be an imperfect balance. The role of a *yellow* primary is therefore to break this link between the *red-green* primaries and yellow; allowing perceptually pure primaries at approximately 520nm for green and 630nm for red, while at the same time allowing a pure high luminance natural yellow with green + yellow + red. If the colour information is coded using only 3 primaries, a yellow primary may be driven by the convention R = G. This allows a perceptually accurate and precise transition from *yellow* to red in the same way that natural colour reproduction transitions from *yellow* to *red*.

The addition of a true *yellow* pixel to a 3 primary approach to colour reproduction is to make possible a perceptually pure (fully saturated) green and red primaries while at the same time allowing a natural fully saturated pure yellow. If the red and green primaries have been shifted significantly toward *yellow* (as with Rec. 709, where the green primary is an unsaturated green-yellow and the red primary is orange) there is little to gain by adding a 4'th yellow primary, other than to allow a more fully saturated *yellow*. However, colour spaces such as Rec. 2020, DCI-P3, and Adobe RGB extend the distance of the red and green primaries from yellow and therefore have greater difficulty reproducing a fully saturated *yellow* (see C.3). This perceptual effect is not reflected in the chromaticity diagram, which predicts linearity between the primaries irrespective of the distance the red and green primaries have from yellow. It is an irregularity caused by colour matching operating under the assumption that colour is monochromatic, which holds for all the primaries except yellow (a natural yellow will for at least half of human subjects not match a monochromatic yellow). The addition of a yellow primary therefore allows a colour space (defined under the CIE colour model) to correct for perceptual error in respect of yellow inherent to the CIE colour model, thereby restoring the predicted perceptual linearity between the *red* and *green* primaries.

On this basis, a display technology such as Quattron that employs a *yellow* 4'th primary would be expected to use the 4'th primary to improve the *red* and *green* primaries. Quattron does have 4 colour sub-pixels in the underlying hardware, however, a graph of the spectral response (figure C.1) shows a clear lack of a 4'th primary. The green primary is approximately 100nm wide (twice as broad as the *blue* primary) with a dominant wavelength at approximately 540nm and the *red* primary extends from 580-700nm – most humans have very little perceptual response above 660nm and therefore 580-660nm is perceptually a

(red-orange). The red and green primaries therefore overlap, and it may be observed that when a *yellow* stimuli is displayed that there is a dip in the spectral power at the point where the green and red primaries intersect – 575-585nm. The human red sensor (sensitive to long wavelengths) has a peak sensitivity between 564-580nm, and the green (medium) sensor has a peak response between 534-545nm. The Quattron primaries therefore target the *middle* sensor but fail to target the *long* sensor, with a spectral power minima at the sensor's peak sensitivity. This minima point at the intersection between the red and green primaries also suggests that a *yellow* primary is produced by simply combining the *red* and green primaries. If yellow is implemented as red + yellow + green then a lack of an independent yellow primary will reduce a 4'th 'yellow' sub-pixel to equivalency with red and green sub-pixels whose surface area is increased to include that of the 'yellow' sub-pixel. On this basis it may be concluded that Quattron is a "gimmick". It has a yellow sub-pixel but no yellow light to pass through it. Its only function can therefore be to allow more green and red light to pass through, which is equivalent to passing the same light through green and red pixels that are 50% larger. It therefore serves no useful function, as suggested by the critics.



Figure C.1: Spectral response of a common Quattron display. The white response was compared with each of the 4 primaries, given by the respective colored line. All primaries were set to their respective 8-bit RGB maximum, with the exception of *equalized yellow* where G was reduced by 20%. The model tested is LC-40LE811E, which uses LED backlighting.



Figure C.2: Colour gammut of Rec. 709, Rec. 2020, Adobe RGB and DCI-P3 (a digital cinema colour space) mapped onto the CIE 1931 chromaticity diagram. Note that the colour image is an convention used for didactic reasons and not linked the colour model itself.



Figure C.3: Maximal gammut using 3 primaries. The lower yellow line indicates perceptual chromaticity, and upper yellow line indicates a correction by the use of a 4'th primary. With increasing distance between the *red* and *green* primaries the *yellow* 'sags' perceptually. The large circle indicates a region of indecision where a stimuli will either be perceived as *yellow* with either some degree of *green* or some degree of *red* (and with a match with *pure yellow* being impossible). Note that the colour image is an convention used for didactic reasons and not linked the colour model itself.

## References

- Anderson, K. F. (1995). A conversion of wheatstone bridge to current-loop signal conditioning for strain gages. Technical Memorandum 104309, NASA. 27
- Bangert, T. (2008). Trianglevision: A toy visual system. In Kurková, V., Neruda, R., and Koutník, J., editors, Artificial Neural Networks - ICANN 2008, volume 5163 of Lecture Notes in Computer Science (LNCS), pages 937–950. Springer, Berlin/Heidelberg. 5
- CIE, editor (1932). Commission internationale de l'Eclairage proceedings, 1931, Cambridge UK. Cambridge University Press. 2
- CIE (1998). The cie 1997 interim colour appearance model (simple version). Technical report, CIE, Vienna, Austria.
- Conway, B. R. (2003). Colour vision: A clue to hue in v2. *Current Biology*, 13(8):R308–R310. 4
- Conway, B. R. (2009). Color vision, cones, and color-coding in the cortex. *The Neurosci*entist, 15(3):274–290. 6, 9
- Dacey, D. M. (1996). Circuitry for color coding in the primate retina. Proceedings of the National Academy of Sciences, 93(2):582–588.
- Dacey, D. M. (2000). Parallel pathways for spectral coding in primate retina. *Annual Review of Neuroscience*, 23(1):743–775.
- Dacey, D. M. and Packer, O. S. (2003). Colour coding in the primate retina: diverse cell types and cone-specific circuitry. *Current Opinion in Neurobiology*, 13(4):421–427.
- Dartnall, H. J. A., Bowmaker, J. K., and Mollon, J. D. (1983). Human visual pigments: Microspectrophotometric results from the eyes of seven persons. *Proceedings of the Royal Society of London. Series B. Biological Sciences*, 220(1218):115–130. 25
- DeMarco, P., Pokorny, J., and Smith, V. C. (1992). Full-spectrum cone sensitivity functions for x-chromosome-linked anomalous trichromats. J. Opt. Soc. Am. A, 9(9):1465–1476.
- Demarsh, L. E. and Giorgianni, E. J. (1989). Color science for imaging systems. *Physics Today*, 42(9):44–52. 1, 2, 4

- DeValois, R. L. and DeValois, K. K. (1993). A multi-stage color model. *Vision Research*, 33(8):1053–1065. 3
- Dipert, B. (2010). Display-technology advancements: Change is the only constant. *EDN*, pages 24–33.
- Douma, M. and WebExhibits (2008). Cause of color / curator, michael douma. Retrieved August 13, 2012. 49
- Fairchild, M. D. (2004). Color Appearance Models: CIECAM02 and Beyond. In *The 12th Color Imaging Conference*. IS&T.
- Feisner, E. A. (2006). *Colour*. Laurence King, London, England.
- Goethe, J. W. v. (1840). *Theory of Colours*. John Murray, London, England. Translated by Charles Lock Eastlake.
- Goldsmith, T. and Butler, B. (2005). Color vision of the budgerigar (*Melopsittacus undulatus*): hue matches, tetrachromacy, and intensity discrimination. Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology, 191(10):933– 951. 5
- Goldsmith, T. H. (2006). What Birds See. Scientific American, 295(1):68-75. 5, 7, 17, 19
- Greenwood, V. (2012). The Humans With Super Human Vision. Published online, Retrieved August 13, 2012. 1, 31, 32
- Hart, N., Partridge, J., Bennett, A., and Cuthill, I. (2000). Visual pigments, cone oil droplets and ocular media in four species of estrildid finch. *Journal of Comparative Physiology A: Neuroethology, Sensory, Neural, and Behavioral Physiology*, 186(7):681–694.
- Hunt, R. W. (1995). *The Reproduction of Colour*. Fountain Press, Kingston-upon-Thames, England. 1, 49
- Hurvich, L. M. (1997). Chromatic and achromatic response functions. In Byrne, A. and Hilbert, D. R., editors, *Readings on Color: The Science of Color*, pages 67–91. MIT Press. 27
- Hurvich, L. M. and Jameson, D. (1957). An opponent-process theory of color vision. *Psychological Review*, 64(6, Part 1):384–404. 3
- ITU (2002). ITU-R BT.709-5: Parameter values for the HDTV standards for production and international programme exchange. Technical report, ITU, Geneva, Switzerland.
- ITU (2011). ITU-R BT.601-7: Studio encoding parameters of digital television for standard 4:3 and wide screen 16:9 aspect ratios. Technical report, ITU, Geneva, Switzerland.
- Jordan, G. and Mollon, J. (1992). Do tetrachromatic women exist? Invest. Ophthal. & Vis. Sci., 33:754. 1

- Lennie, P. (2000). Color vision: Putting it together. *Current Biology*, 10(16):R589–R591. 1, 4, 5
- Lennie, P. and D'Zmura, M. (1988). Mechanisms of color vision. Critical Reviews in Neurobiology, 3(4):333–400. 13
- Livingstone, M. and Hubel, D. (1988). Segregation of form, color, movement, and depth: anatomy, physiology, and perception. *Science*, 240(4853):740–749. 31
- Lotto, R. B. and Purves, D. (2000). An empirical explanation of color contrast. *Proceedings* of the National Academy of Sciences, 97(23):12834–12839. 9
- Lowengard, S. (2006). *The Creation of Color in Eighteenth-Century Europe*. Gutenberg(e), Columbia University Press.
- MacAdam, D. L. (1985). *Color Measurement: Theme and Variations*. Springer, Berlin, Germany. 49, 51, 53
- Mancuso, K., Mauck, M. C., Kuchenbecker, J. A., Neitz, M., and Neitz, J. (2010). A multi-stage color model revisited: Implications for a gene therapy cure for red-green colorblindness. In Anderson, R. E., Hollyfield, J. G., LaVail, M. M., and Mandal, M. N. A., editors, *Retinal Degenerative Diseases*, volume 664 of *Advances in Experimental Medicine and Biology*, pages 631–638. Springer, New York. 3
- McCamy, C. S. (1998). On the number of discernible colors. *Color Research & Application*, 23(5):337–337. 32
- Mollon, J. (1989). "Tho' she kneel'd in that place where they grew..." The uses and origins of primate colour vision. *J Exp Biol*, 146:21–38. 6
- Moroney, N., Fairchild, M. D., Hunt, R. W. G., Li, C., Luo, M. R., and Newman, T. (2002). The CIECAM02 color appearance model. In *The 10th Color Imaging Conference: Color Science and Engineering Systems, Technologies, Applications*, volume 10, pages 23–27, Scottsdale, Arizona. IS&T.
- Nathans, J. (1989). The Genes for Color Vision. Scientific American, 260(1):42–49.
- Neitz, J., Carroll, J., and Neitz, M. (2001). Color vision: Almost reason enough for having eyes. *Opt. Photon. News*, 12(1):26–33.
- Neitz, J., Geist, T., and Jacobs, G. H. (1989). Color vision in the dog. Visual Neuroscience, 3(2):119–125. 7
- Neitz, J. and Neitz, M. (2008). Colour vision: The wonder of hue. *Current Biology*, 18(16):R700–R702. 3, 4, 22
- PerkinElmer, Inc. (2009). ACULED VHL Product Note. Retrieved August 13, 2012.

- Poynton, C. (2003a). Digital Video and HDTV Algorithms and Interfaces. Morgan Kaufmann, San Francisco, CA. 32, 41, 42, 51, 52, 53, 54
- Poynton, C. A. (1993). "Gamma" and Its Disguises: The Nonlinear Mappings of Intensity in Perception, CRTs, Film, and Video. *SMPTE Journal*, 102(12):1099–1108. 27, 28, 29, 31
- Poynton, C. A. (2003b). YUV and luminance considered harmful. In *Digital Video and HDTV Algorithms and Interfaces*, pages 595–600. Morgan Kaufmann, San Francisco, CA. 28
- Ribe, N. and Steinle, F. (2002). Exploratory experimentation: Goethe, Land, and Color Theory. *Physics Today*, 55(7):43–49.
- Rieke, F. and Baylor, D. A. (1998). Single-photon detection by rod cells of the retina. *Rev. Mod. Phys.*, 70:1027–1036. 28
- Shepard, R. N. (1997). The perceptual organization of colors: An adaptation to regularities of the terrestrial world? In Byrne, A. and Hilbert, D. R., editors, *Readings on Color: The Science of Color*, pages 311–356. MIT Press.
- Shepard, R. N. and Cooper, L. A. (1992). Representation of colors in the blind, color-blind, and normally sighted. *Psychological Science*, 3(2):97–104. 16
- Solomon, S. G. and Lennie, P. (2007). The machinery of colour vision. *Nat Rev Neurosci*, 8(4):276–286. 4, 5, 6
- Soneira, R. (2010). Display Myths:: shattered. Maximum PC, pages 45-51. 87, 88
- Sun, X., Chang, Y., Ye, Y., Ma, Z., Liang, Y., Li, T., Jiang, N., Xing, W., and Luo, L. (2012). The effect of dietary pigments on the coloration of japanese ornamental carp (koi, cyprinus carpio I.). Aquaculture, 342-343(0):62–68.
- Thornton, W. A. (1999). Spectral sensitivities of the normal human visual system, colormatching functions and their principles, and how and why the two sets should coincide. *Color Research & Application*, 24(2):139–156. 2
- Valberg, A. (2001). Unique hues: an old problem for a new generation. *Vision Research*, 41(13):1645–1657.
- Vorobyev, M. (2006). Evolution of colour vision: The story of lost visual pigments. *Perception*, 35:168. 5
- Wyszecki, G. and Stiles, W. S. (1967). Color Science: Concepts and Methods, Quantitative Data and Formulas. John Wiley & Sons, New York. 49