

Opponent Color Spaces

- Perception of color is usually not best represented in RGB.
- A better model of HVS is the so-call opponent color model
- Opponent color space is has three components:
 - O_1 is luminance component
 - O_2 is the red-green channel

$$O_2 = G - R$$

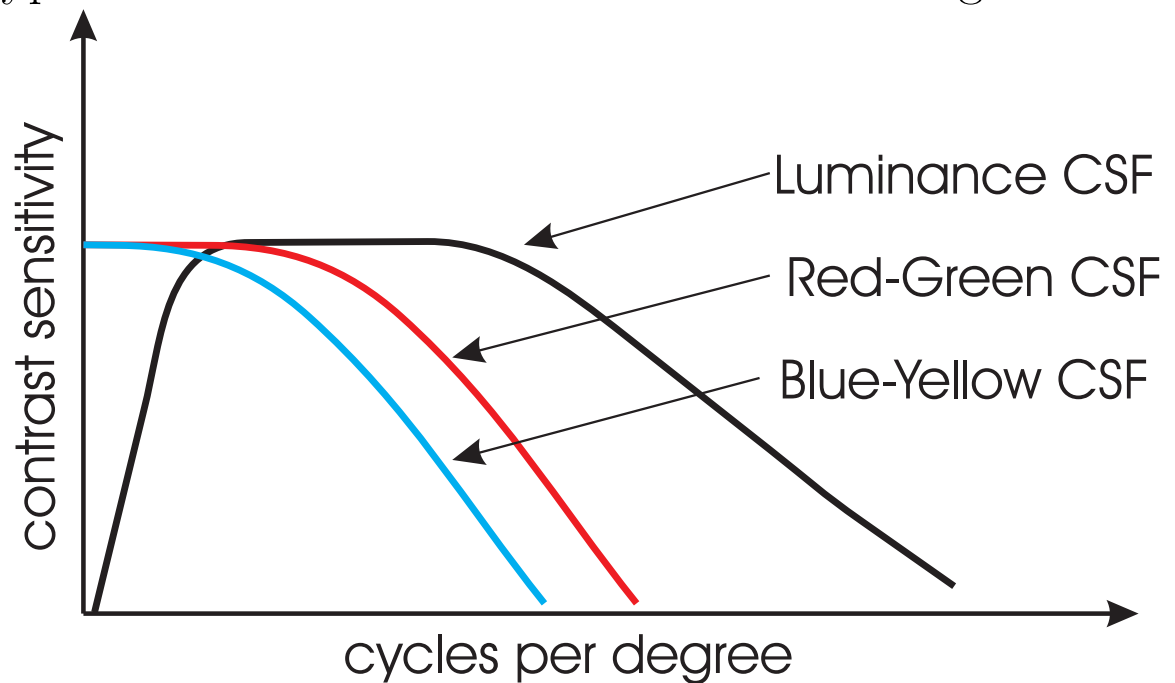
- O_3 is the blue-yellow channel

$$O_3 = B - Y = B - (R + G)$$

- Comments:
 - People don't perceive redish-greens, or bluish-yellows.
 - As we discussed, O_1 is has a bandpass CSF.
 - O_2 and O_3 have low pass CSF's with lower frequency cut-off.

Opponent Channel Contrast Sensitivity Functions (CSF)

- Typical CSF functions looks like the following.



Consequences of Opponent Channel CSF

- Luminance channel is
 - Bandpass function
 - Wide band width \Rightarrow high spatial resolution.
 - Low frequency cut-off \Rightarrow insensitive to average luminance level.
- Chrominance channels are
 - Lowpass function
 - Lower band width \Rightarrow low spatial resolution.
 - Low pass \Rightarrow insensitive to absolute chromaticity (hue and saturation).

Some Practical Consequences of Opponent Color Spaces

- Analog video has less bandwidth in I and Q channels.
- Chrominance components are typically subsampled 2-to-1 in image compression applications.
- Black text on white paper is easy to read. (couples to O_1)
- Yellow text on white paper is difficult to read. (couples to O_3)
- Blue text on black background is difficult to read. (couples to O_3)
- Color variations that do not change O_1 are called “isoluminant”.
- Hue refers to angle of color vector in (O_2, O_3) space.
- Saturation refers to magnitude of color vector in (O_2, O_3) space.

Opponent Color Space of Wandell

- First define the LMS color system which is approximately given by

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.2430 & 0.8560 & -0.0440 \\ -0.3910 & 1.1650 & 0.0870 \\ 0.0100 & -0.0080 & 0.5630 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

- The opponent color space transform is then¹

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ -0.59 & 0.80 & -0.12 \\ -0.34 & -0.11 & 0.93 \end{bmatrix} \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

- We many use these two transforms together with the transform from sRGB to XYZ to compute the following transform.

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} 0.2814 & 0.6938 & 0.0638 \\ -0.0971 & 0.1458 & -0.0250 \\ -0.0930 & -0.2529 & 0.4665 \end{bmatrix} \begin{bmatrix} sR \\ sG \\ sB \end{bmatrix}$$

- Comments:
 - O_1 is luminance component
 - O_2 is referred to as the red-green channel (G-R)
 - O_3 is referred to as the blue-yellow channel (B-Y)
 - Also see the work of Mullen '85² and associated color transforms.³

¹B. A. Wandell, *Foundations of Vision*, Sinauer Associates, Inc., Sunderland MA, 1995.

²K. T. Mullen, "The contrast sensitivity of human color vision to red-green and blue-yellow chromatic gratings," *J. Physiol.*, vol. 359, pp. 381-400, 1985.

³B. W. Kolpatzik and C. A. Bouman, "Optimized Error Diffusion for Image Display," *Journal of Electronic Imaging*, vol. 1, no. 3, pp. 277-292, July 1992.

Paradox?

- Why is blue text on yellow paper is easy to read??
- Shouldn't this be hard to read since it stimulates the yellow-blue color channel?

Better Understanding Opponent Color Spaces

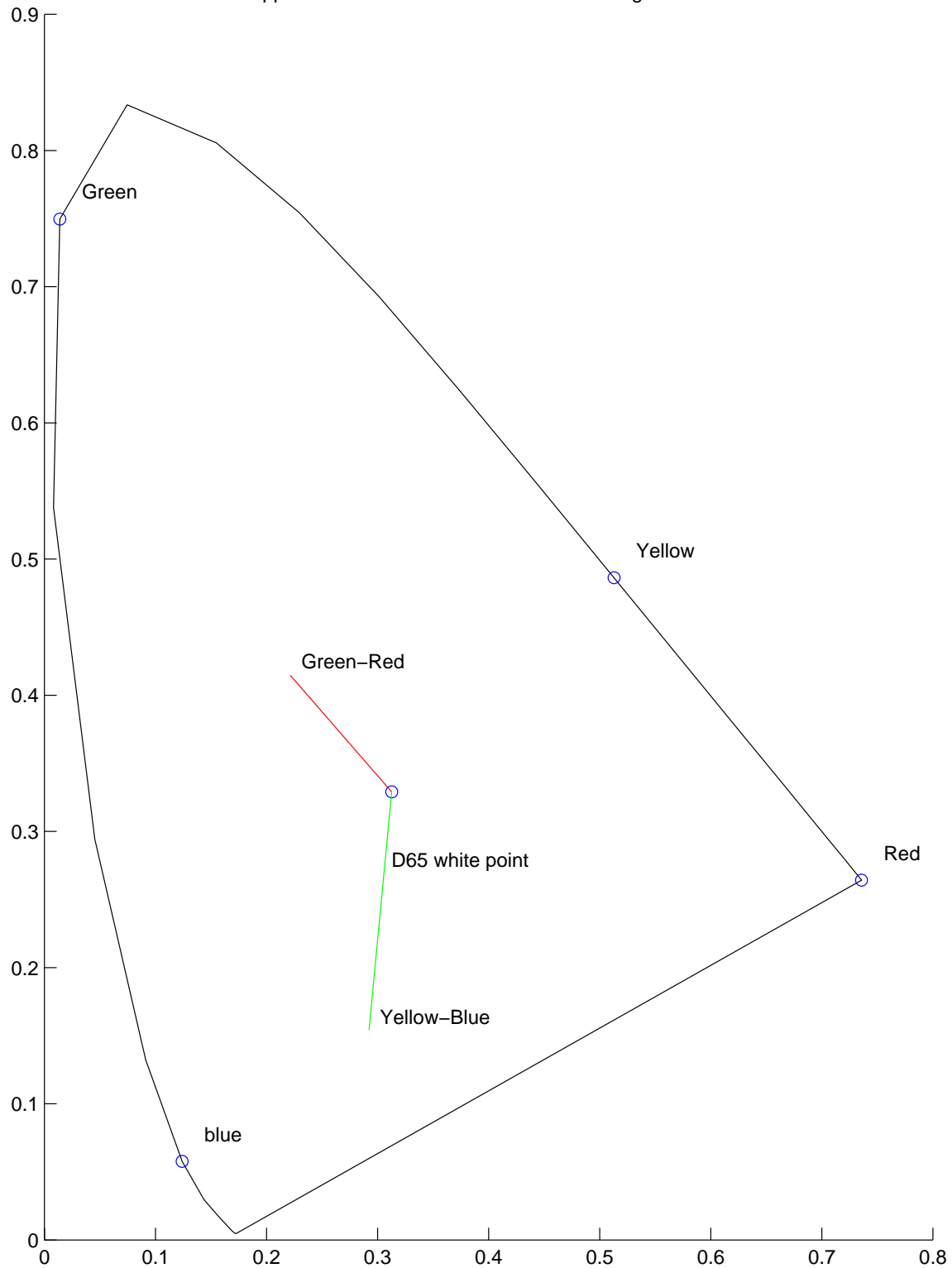
- The XYZ to opponent color transformation is:

$$\begin{aligned} \begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} &= \begin{bmatrix} 0.2430 & 0.8560 & -0.0440 \\ -0.4574 & 0.4279 & 0.0280 \\ -0.0303 & -0.4266 & 0.5290 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \\ &= \begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \end{aligned}$$

- What are v_y , v_{gr} , and v_{by} ?
 - They are row vectors in the XYZ color space.
 - v_{gr} is a vector point from red to green
 - v_{by} is a vector point from yellow to blue
 - They are not orthogonal!

Plots of v_y , v_{gr} , and v_{by}

Opponent Color Directions of Color Matching Functions



Answer to Paradox

- Since v_y , v_{gr} , and v_{by} are not orthogonal

$$\begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} [v_y^t \ v_{gr}^t \ v_{by}^t] \neq \text{identity matrix}$$

- Blue text on yellow background produces and stimulus in the v_{by} space.

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} v_{by}^t = \begin{bmatrix} -0.3958 \\ -0.1539 \\ 0.4627 \end{bmatrix}$$

- This stimulus is not isoluminant!
- Blue is much darker than yellow.

Basis Vectors for Opponent Color Spaces

- The transformation from opponent color space to XYZ is:

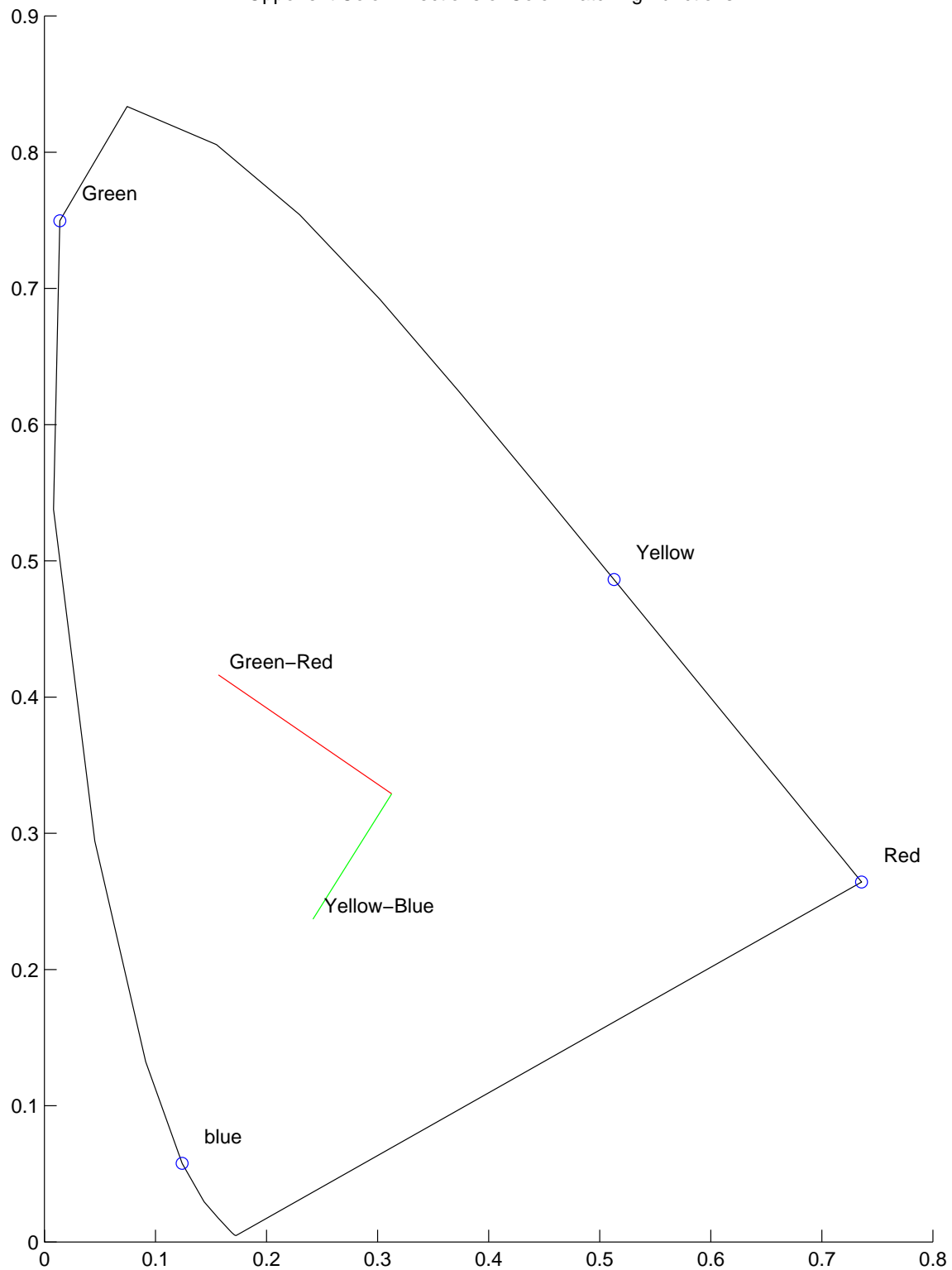
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.9341 & -1.7013 & 0.1677 \\ 0.9450 & 0.4986 & 0.0522 \\ 0.8157 & 0.3047 & 1.9422 \end{bmatrix} \begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix}$$

$$= [c_y \ c_{gr} \ c_{by}] \begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix}$$

- What are c_y , c_{gr} , and c_{by} ?
 - They are column vectors in XYZ space.
 - c_{gr} is a vector which has no luminance component.
 - c_{by} is a vector which has no luminance component.
 - They are orthogonal to the vectors v_y , v_{gr} , and v_{by} .

Plots of c_y , c_{gr} , and c_{by}

Opponent Color Directions of Color Matching Functions



Interpretation of Basis Vectors

- Since c_y , c_{gr} , and c_{by} are orthogonal to v_y , v_{gr} , and v_{by} , we have

$$\begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} [c_y \ c_{gr} \ c_{by}] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

- Therefore, we have that

$$\begin{aligned} \begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} &= \begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} c_{by} \\ &= \begin{bmatrix} 0.2430 & 0.8560 & -0.0440 \\ -0.4574 & 0.4279 & 0.0280 \\ -0.0303 & -0.4266 & 0.5290 \end{bmatrix} \begin{bmatrix} 0.1677 \\ 0.0522 \\ 1.9422 \end{bmatrix} \\ &= \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \end{aligned}$$

- So, c_{by} is an isoluminant color variation.
- Something like a bright saturated blue on a dark red.

Solution to Paradox

- Why is blue text on yellow paper is easy to read??
- Solution:
 - The blue-yellow combination generates the input v_{by} .
 - This input vector stimulates all three opponent channels because it is not orthogonal to c_y , c_{gr} , and c_{by} .
 - In particular, it strongly stimulates c_y because it is **not** iso-luminant.

Perceptually Uniform Color Spaces

- Problem: Small changes in XYZ may result in small or large perceptual changes.
- Solution: Formulate a perceptually uniform color space.
 - Nonlinearly transform color space so that distance is proportional to ones ability to perceive changes in color.
 - Two most common spaces are $L^*a^*b^*$ and Luv .
 - Recently, $L^*a^*b^*$ has come into the most common usage

The Lab Color Space

- Select (X_0, Y_0, Z_0) to be the white point or illuminant, then compute (approximate formula)

$$\begin{aligned}L &= 100(Y/Y_0)^{1/3} \\a &= 500 \left[(X/X_0)^{1/3} - (Y/Y_0)^{1/3} \right] \\b &= 200 \left[(Y/Y_0)^{1/3} - (Z/Z_0)^{1/3} \right]\end{aligned}$$

- Color errors can then be measured as:

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2}$$

Warning: Don't Abuse Lab Space

- Lab color space is designed for low spatial frequencies.
 - It is very good for measuring color differences in objects.
 - It is the standard for measuring paint color.
 - It is good for measuring color accuracy of printers and displays.
- Direct application to images works poorly.
 - Lab does not account for high spatial frequency content of images.
 - Lab formulation ignores different form of CSF for luminance and chrominance spaces.
 - Image coding in Lab space will produce poor results.

Color Image Quality Metrics

- A number of attempts have been made to combine CSF modeling with Lab color space:
 - Kolpatzik and Bouman '95 (YCxCz/Lab color metric)⁴
 - Zhang and Wandell '97 (S-CIELAB color metric)⁵
- Objective:
 - Combine models of spatial frequency response and color space nonuniformities.
 - Particularly important for modeling halftone quality due to high frequency content.

⁴B. W. Kolpatzik and C. A. Bouman, "Optimized Universal Color Palette Design for Error Diffusion," *Journal of Electronic Imaging*, vol. 4, no. 2, pp. 131-143, April 1995.

⁵X. Zhang and B. A. Wandell, "A spatial extension of CIELAB for digital color image reproduction," *Society for Information Display Journal*, 1997.

Image Quality Metric Using YCxCz/Lab

- YCxCz color space is defined as:

$$\begin{aligned} Y_y &= 116(Y/Y_0) \\ c_x &= 500 [(X/X_0) - (Y/Y_0)] \\ c_z &= 200 [(Y/Y_0) - (Z/Z_0)] \end{aligned}$$

- Apply different filters for luminance and chrominance where f is in units of cycles/degree.

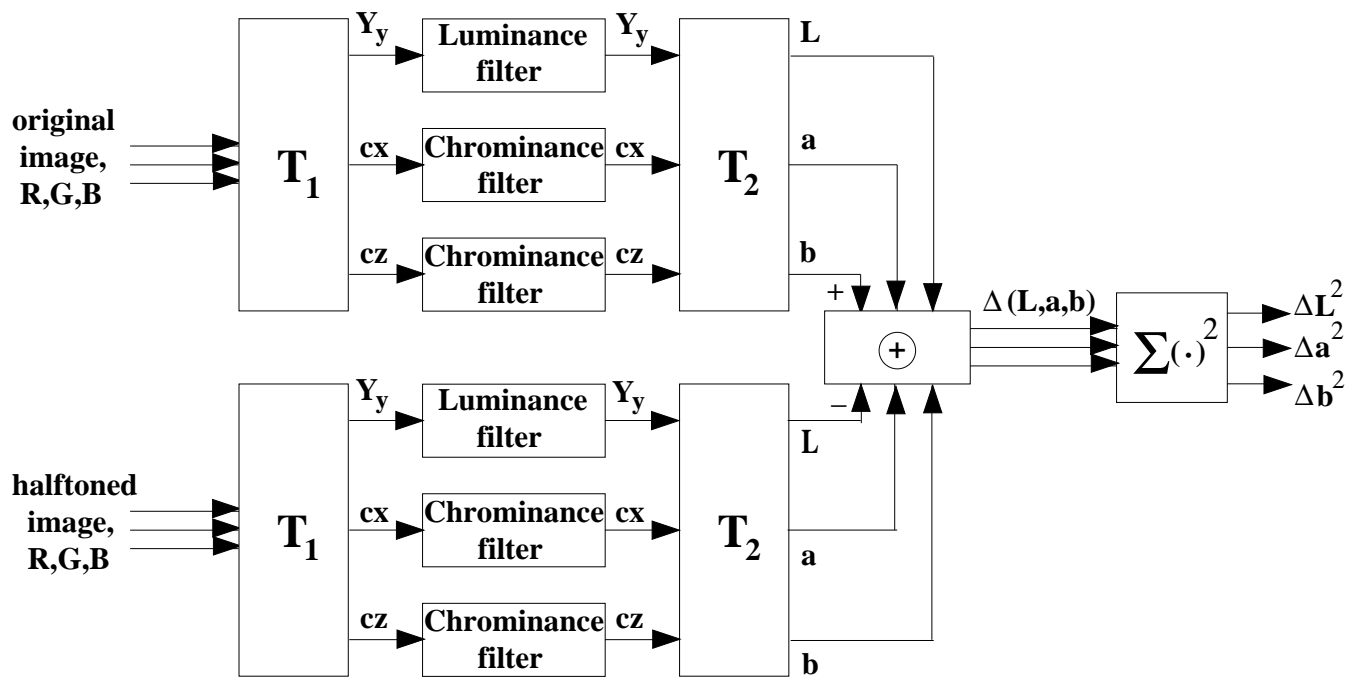
$$W_y(f) = \begin{cases} \exp \{-0.4385(f - 2.2610)\} & f \geq 2.2610 \\ 1 & f < 2.2610 \end{cases}$$

$$W_{cx}(f) = \begin{cases} \exp \{-0.1761(f - 0.2048)\} & f \geq 0.2048 \\ 1 & f < 0.2048 \end{cases}$$

$$W_{cz}(f) = \begin{cases} \exp \{-0.1761(f - 0.2048)\} & f \geq 0.2048 \\ 1 & f < 0.2048 \end{cases}$$

- Then transform filtered YCxCz image components to Lab and compute ΔE .

Flow Diagram for YCxCz/Lab Image Quality Metric



- Low pass filters are applied in linear domain \Rightarrow more accurate for color matching of halftones.
- Nonlinear Lab transformation accounts for perceptual nonuniformities of color space.