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
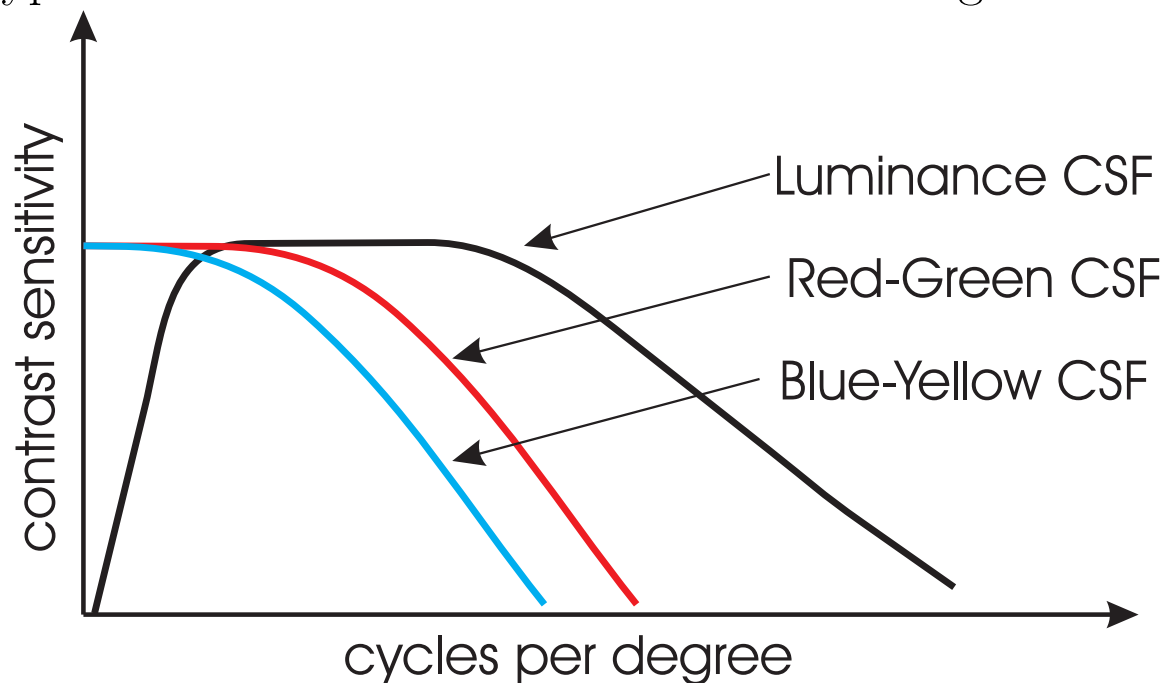 - O_2 is the red-green channel

$$O_2 = G - R$$

  - 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.

- Chromanince channels are

  – Lowpass function

  – Lower band width $\Rightarrow$ low spatial resolution.

  – Low pass $\Rightarrow$ sensitive to absolute chromaticity (hue and saturation).

Some Practical Consequences of Opponent Color Spaces

- Analog video has less bandwidth in I and Q channels.

- Chromanance 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 chnage 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 then[1]

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

- 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 '85[2] and associated color transforms.[3]

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

[2] K. 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.

[3] B. 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?
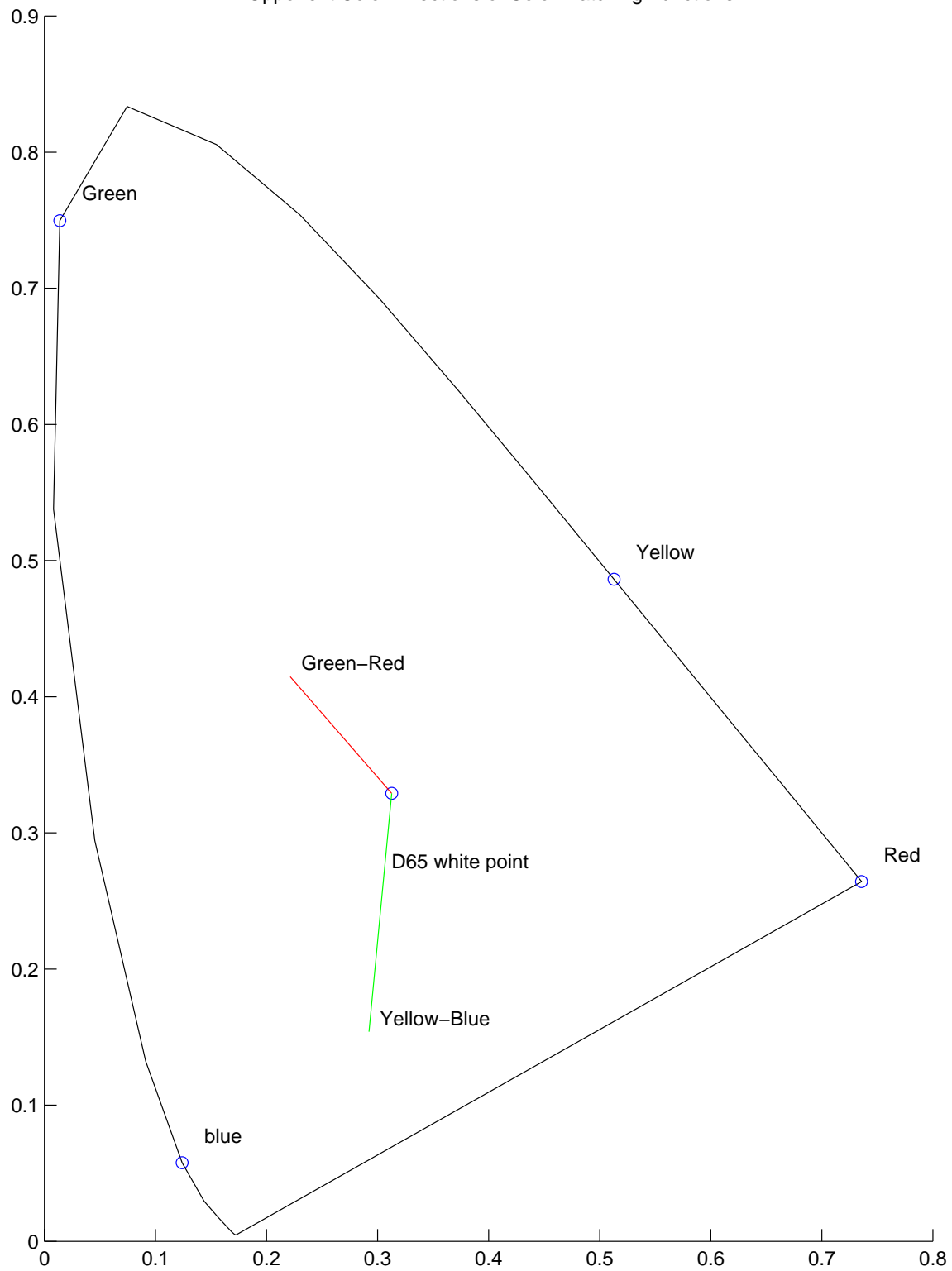
Better Understanding Opponent Color Spaces

- The XYZ to opponent color transformation is:

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

$$
= \begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}
$$

- 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

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

- Blue text on yellow background produces and stimmulus 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 stimmulus is not isoluminant!

- Blue is much darker than yellow.

Basis Vectors for Opponent Color Spaces

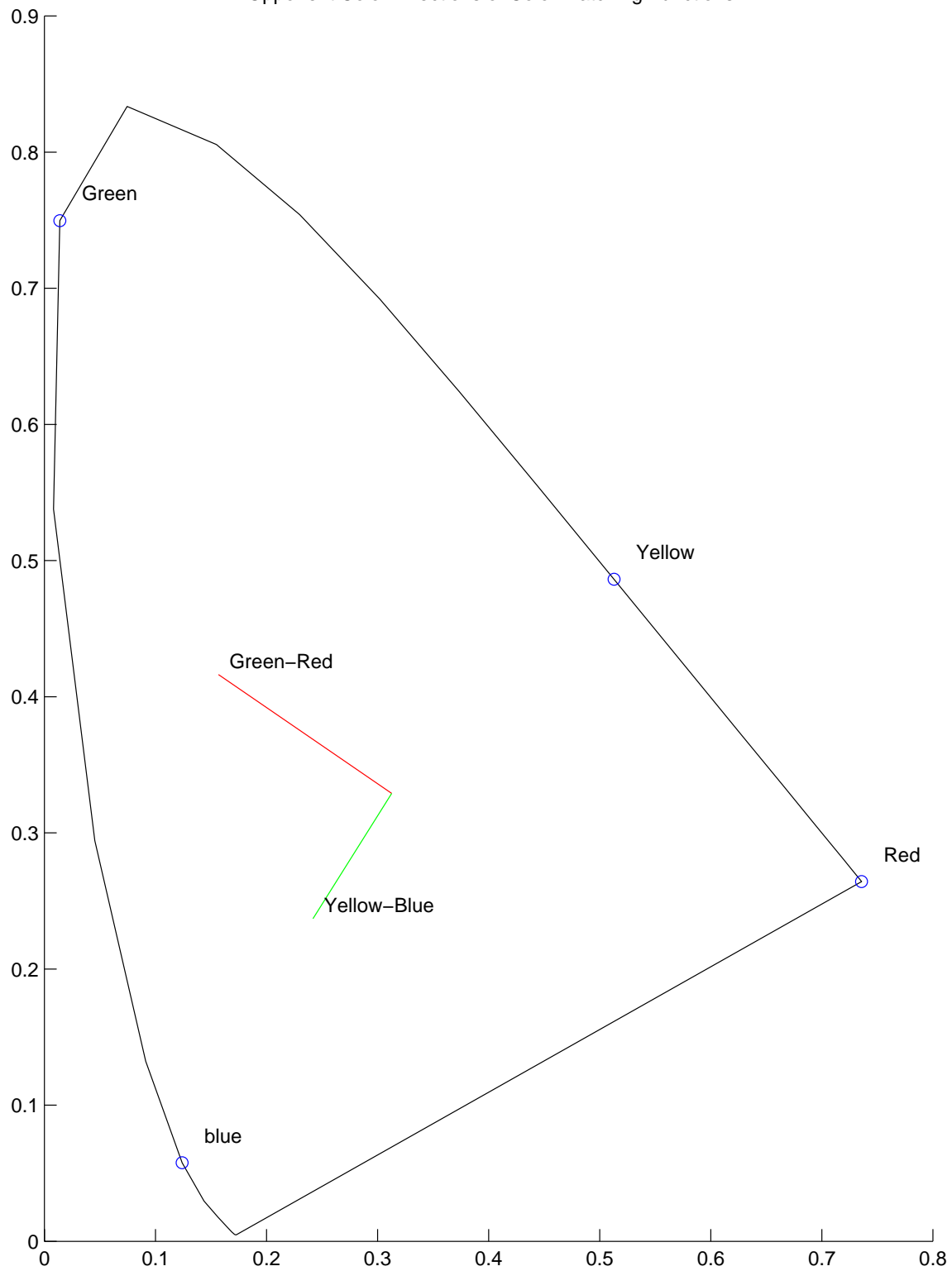- The transformation from opponent color space to XYZ is:

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

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

- 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

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

- Therefore, we have that

$$
\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} v_y \\ v_{gr} \\ v_{by} \end{bmatrix} c_{by}
$$

$$
= \begin{bmatrix} 0.2430 & 0.8560 & -0.0440 \\ -0.4574 & 0.4279 & 0.0280 \\ -0.0303 & -0.4266 & 0.5290 \end{bmatrix} \begin{bmatrix} 0.1677 \\ 0.0522 \\ 1.9422 \end{bmatrix}
$$

$$
= \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}
$$

- 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 chromanance spaces.
  - Image coding in Lab space will produce poor results.

Color Image Fidelity 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 form modeling halftone quality due to high frequency content.

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[4]B. 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.

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

Image Fidelity Metric Using YCxCz/Lab

- YCxCz color space is defined as:

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

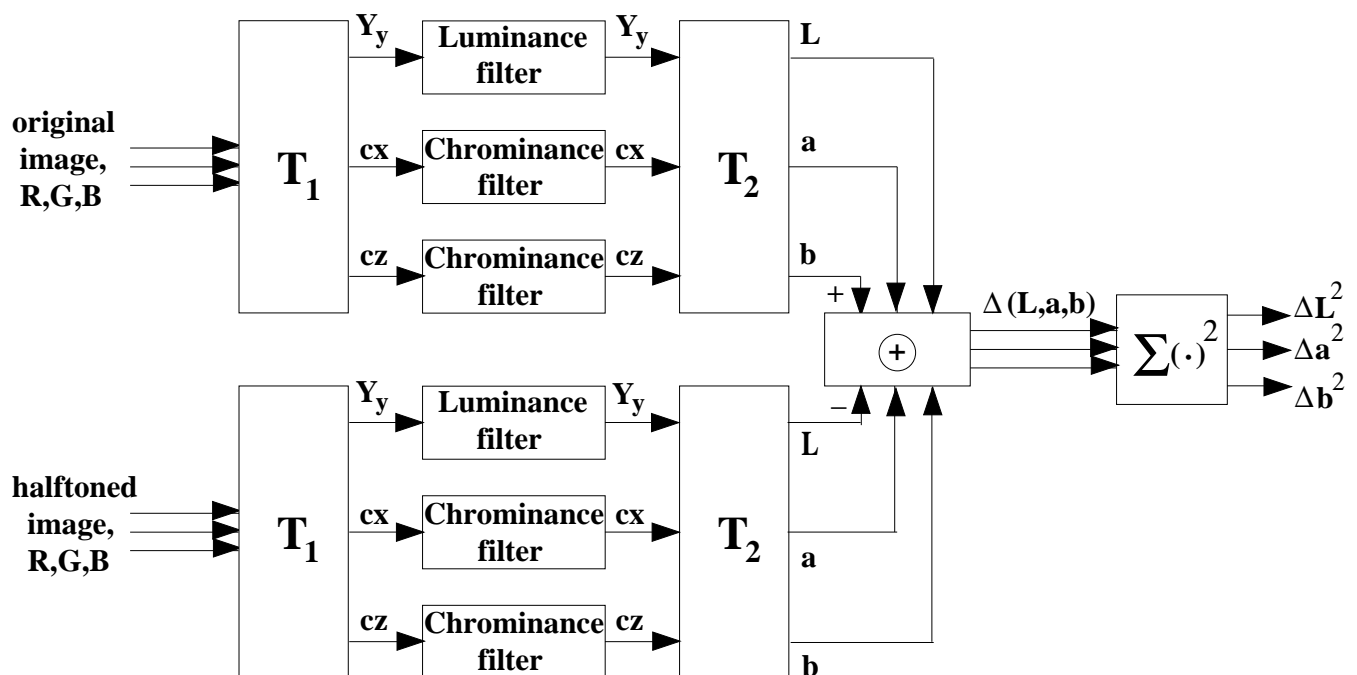- Apply different filters for luminance and chromanance where f is in units of cycles/degree.

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

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

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

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

Flow Diagram for YCxCz/Lab Image Fidelity 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.