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 Approximate 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:

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

The Exact Lab Color Space

- XYZ to Lab transform is:

$$\begin{aligned} L &= 116\, f(Y/Y_0) - 16 \\ a &= 500\, [f(X/X_0) - f(Y/Y_0)] \\ b &= 200\, [f(Y/Y_0) - f(Z/Z_0)] \end{aligned}$$

where

$$f(x) = \begin{cases} \frac{1}{3}\left(\frac{116}{24}\right)^2 x + \frac{16}{116} & \text{if } x \leq (24/116)^3 \\ x^{\frac{1}{3}} & \text{if } x > (24/116)^3 \end{cases}$$

- Lab to XYZ transform is:

$$\begin{aligned} Y &= Y_0 f^{-1}\left(\frac{L+16}{116}\right) \\ X &= X_0 f^{-1}\left(\frac{a}{500} + \frac{L+16}{116}\right) \\ Z &= Z_0 f^{-1}\left(\frac{L+16}{116} - \frac{b}{200}\right) \end{aligned}$$

where

$$f^{-1}(v) = \begin{cases} 3\left(\frac{24}{116}\right)^2 \left(v - \frac{16}{116}\right) & \text{if } v \leq \frac{24}{116} \\ v^3 & \text{if } v > \frac{24}{116} \end{cases}$$

- Transition from linear to power-law at $L = 8$ and $7.787 \doteq \frac{1}{3}\left(\frac{116}{24}\right)^2$, $0.008856 \doteq \left(\frac{24}{116}\right)^3$, and $0.1284 \doteq 3\left(\frac{24}{116}\right)^2$.

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 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)[1]
  - Zhang and Wandell ’97 (S-CIELAB color metric)[2]
- Objective:
  - Combine models of spatial frequency response and color space nonuniformities.
  - Particularly important form modeling halftone quality due to high frequency content.

[1] 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.

[2] 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 chrominance where f is in units of cycles/degree. [3]

$$W_y(f) = \begin{cases} \exp\{-0.1761(f - 2.2610)\} & f \geq 2.2610 \\ 1 & f < 2.2610 \end{cases}$$

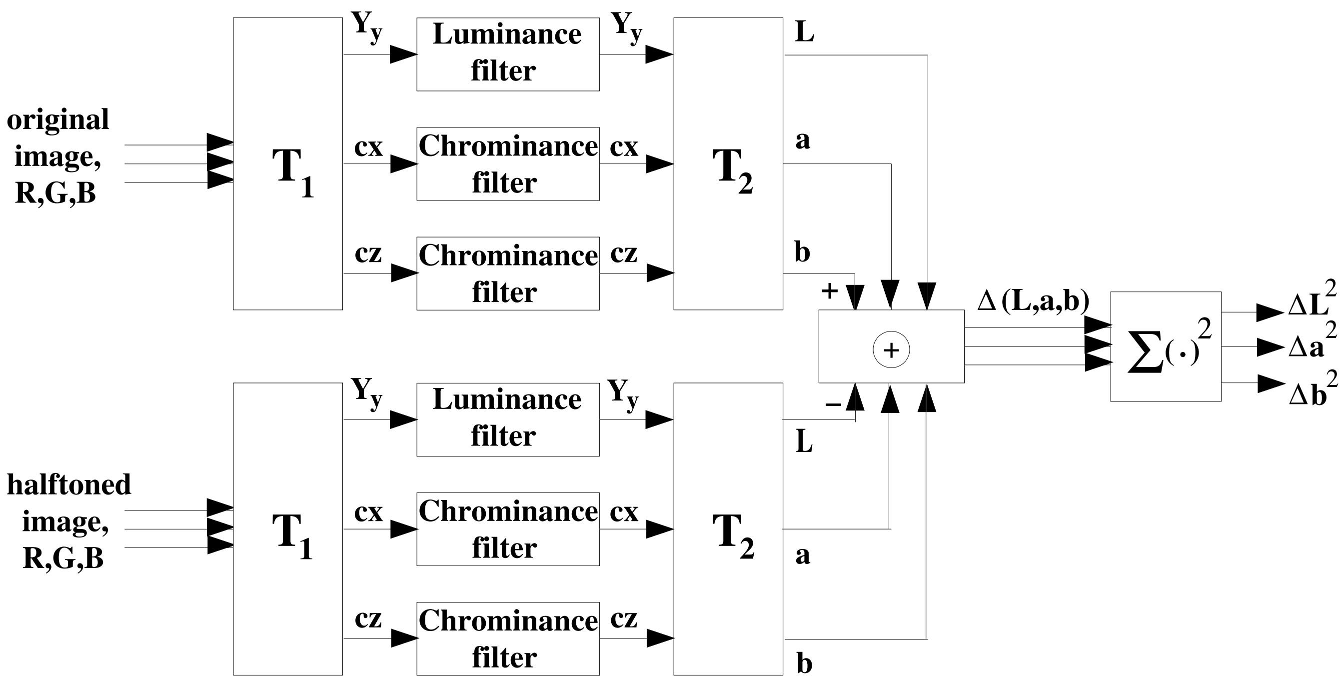
$$W_{cx}(f) = \begin{cases} \exp\{-0.4385(f - 0.2048)\} & f \geq 0.2048 \\ 1 & f < 0.2048 \end{cases}$$

$$W_{cz}(f) = \begin{cases} \exp\{-0.4385(f - 0.2048)\} & f \geq 0.2048 \\ 1 & f < 0.2048 \end{cases}$$

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

[3] Original publication contained a transposition error between the values -0.1761 and -0.4385.

Flow Diagram for YCxCz/Lab Image Fidelity Metric



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

Image Fidelity Metric Using Linearized CIELab

- YCxCz can be used as the basis of a linearized fidelity metric [4] [5]
- Why use YCxCz opponent color space?
  - Aligned with Lab
  - Linear structure makes it suitable for halftoning
  - Image fidelity can be measured using a quadratic norm
- Strategy
  - Transform to YCxCz
  - Filter each channel with a different filter
  - Compute sum of squared error over all three channels and all pixels
- Monga, Geisler, and Evans found this space to work best among four possible choices. [6]

[4] T. J. Flohr, B. W. Kolpatzik, R. Balasubramanian, D. A. Carrara, C. A. Bouman, and J. P. Allebach, "Model based color image quantization," *Proc. SPIE Human Vision, Visual Processing, and Digital Display IV,* vol. 1913, pp. 270-281, 1993.

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

[6] V. Monga, W. S. Geisler, and B. L. Evans, "Linear, Color-Separable, Human Visual System Models for Vector Error Diffusion Halftoning," *IEEE Signal Processing Letters,* vol. 10, no. 4, pp 93-97, April 2003.

Luminance Spatial Filter for Linearized CIELab

- Luminance filter hybrid of Näsänen and Sullivan models
  - Define adjusted spatial frequency (cycles/degree)

$$\tilde{f} = \frac{\| f \|}{s(\Theta)},$$

where $\| f \| = \sqrt{f_1^2 + f_2^2}$ and

$$s(\Theta) = \frac{1 - 0.7}{2} \cos(4\Theta) + \frac{1 + 0.7}{2}.$$

The angle Θ is defined as

$$\Theta = \arctan(\frac{f_1}{f_2})$$

  - Then the luminance filter is given by

$$W(\tilde{f}) = aL^b \exp\left(\frac{-\tilde{f}}{c\ln(L) + d}\right),$$

where $L = 11.0cd/m^2$ (assumed average luminance of display), $a = 131.6$, $b = 0.3188$, $c = 0.525$, $d = 3.91$.

Chrominance Spatial Filter for Linearized CIELab

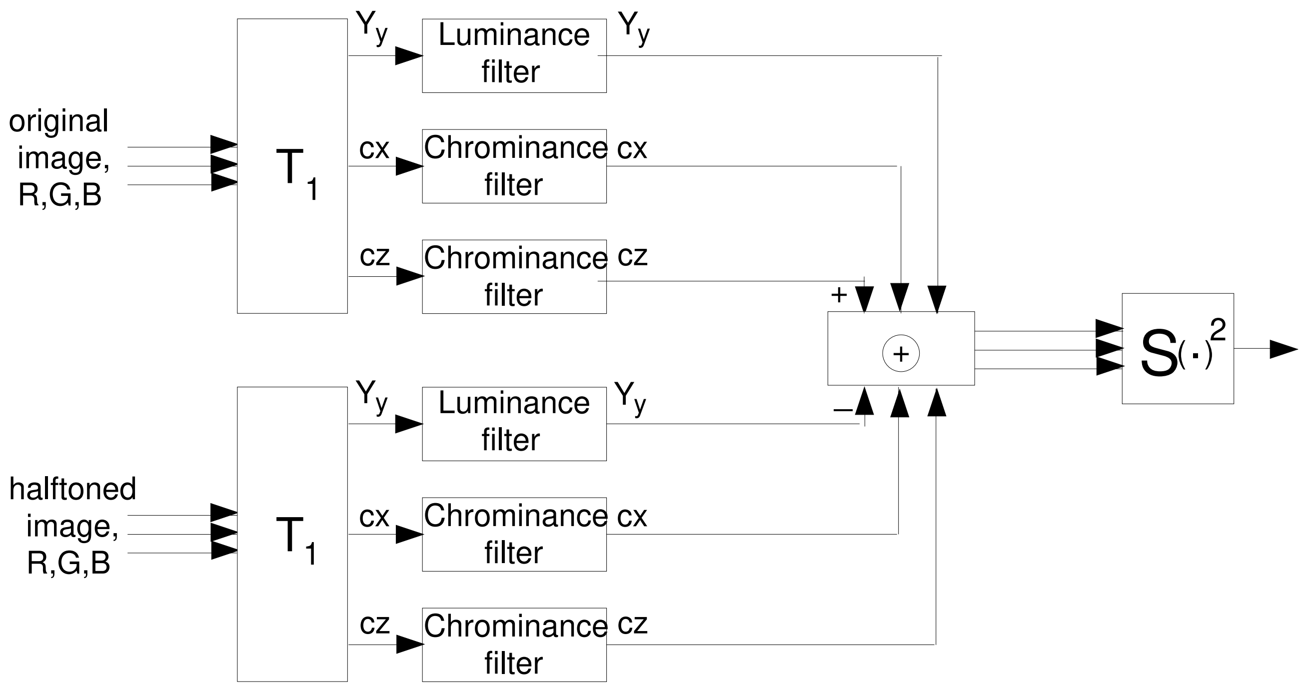
- Chrominance filter based on Mullen data [7]

$$W(f) = A \exp(-\alpha \parallel f \parallel).$$

where $\alpha = 0.419$ and $A = 100$.

[7] K. T. Mullen, "The Contrast Sensitivity of Human Color Vision to Red-Green and Blue-Yellow Chromatic Gratings," *J. Physiol. 359, 1985, pp. 38 1- 400.*

Flow Diagam for Lineared CIELab Fidelity Metric



- Low pass filters are applied in linear domain $\Rightarrow$ more accurate for color matching of halftones.
- Sum is computed over all pixels and all three color channels.
- Quadratic form of metric makes it very useful