Color in Information Display

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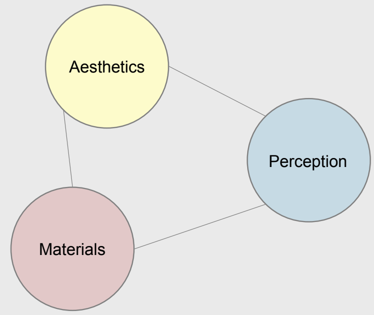
Course Notes on http://www.stonesc.com/Vis05

(Part 2)

Effective Color: Materials



The Craft of Digital Color

Good ideas executed with superb craft"

- *E. R. Tufte*

Good ideas

- Unique, specific examples?
- Or, broadly applicable principles?
- Simple, or subtle and complex?

"Superb craft" means control

What does RGB Mean?

Values used to drive a display

Values encoded in an image

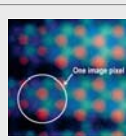
Values captured by a camera or scanner

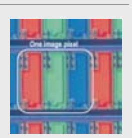
All the same purple?

RGB for Displays

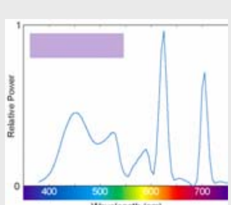
Emissive RGB

- CRT
- LCD
- Plasma
- Projectors





RGB values ⟶ Light

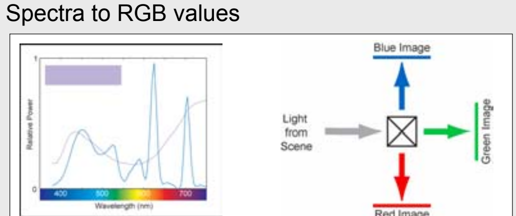


RGB from Cameras

Image capture

- Scanners, cameras
- RGB filters (not cones)

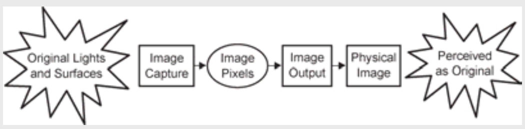
Spectra to RGB values



RGB in Image Encoding

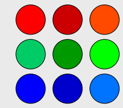
Array of RGB pixels (or equivalent)
- Spatial encoding
- Color/Intensity encoding

Image reproduction
- Link capture and reproduction
- Optimized process

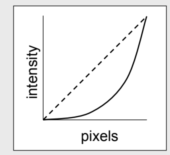


Making RGB Quantitative

Specify primary colors
- Precise hue
- Maximum brightness



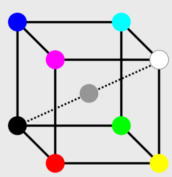
Map numbers (pixels) to intensity
- Linear encodings
- Non-linear encodings
- Both are valid



RGB Color Cube

Three primaries
- RGB lights
- Variable brightness (0..max)
- Add to create color

Characteristics
- Primaries sum to white
- Saturated colors on surface
- Gray scale along diagonal
- Cube bounds color gamut



RGB in XYZ

$R = (1,0,0) = XYZ_R$
$G = (0,1,0) = XYZ_G$
$B = (0,0,1) = XYZ_B$

R,G,B are vectors

Add like vectors
- $(1,1,0) = XYZ_R + XYZ_G$

Scale like vectors
- $(s_1,0,0) = s_2\ XYZ_R$
- if linear intensity encoding, $s_1 = s_2$
- If non-linear, s_2 is different than s_1

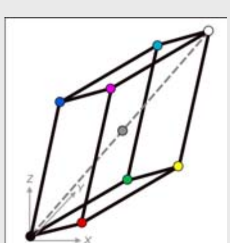
Color Cube in XYZ

Affine transformation (3x3 matrix)

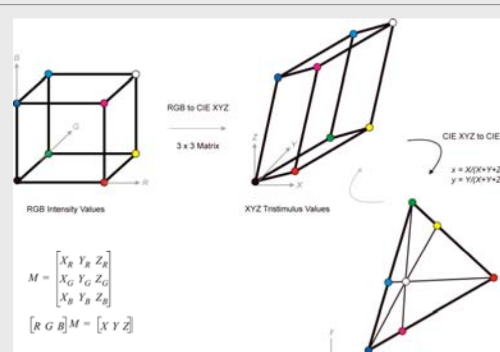
Rectangular parallelepiped

Characteristics
- Primaries sum to white
- Saturated colors on surface
- Gray scale along diagonal
- Bounds color gamut

Absolute specification



RGB to XYZ to xy



From *A Field Guide to Digital Color*, © A.K. Peters, 2003

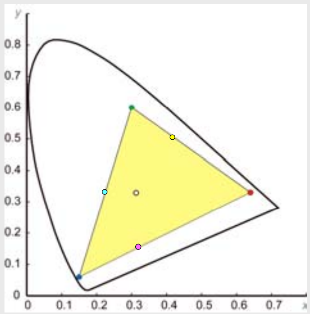
RGB Chromaticity

R,G,B are points

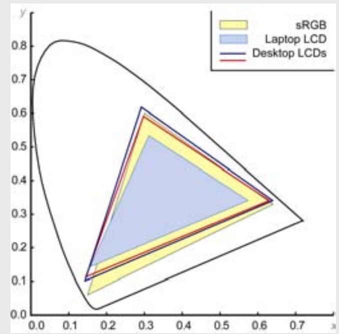
Sum of two colors falls on line between them

Gamut is a triangle

- White/gray/black near center
- Saturated colors on edges



Display Gamuts



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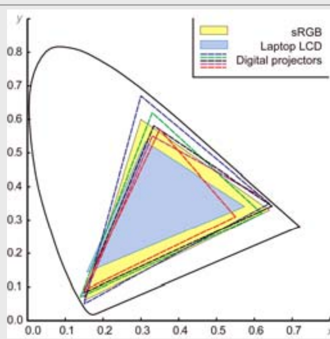
Projector Gamuts



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Pixels to Intensity

Linear

- I = kp (I = intensity, p = pixel value, k is a scalar)
- Best for computation

Non-linear

- $I = kp^{1/\gamma}$
- Perceptually more uniform
- More efficient to encode as pixels
- Best for encoding and display

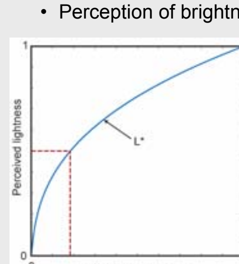
Pixel to Intensity Variation

Intensity Transfer Function (ITF), or “gamma”

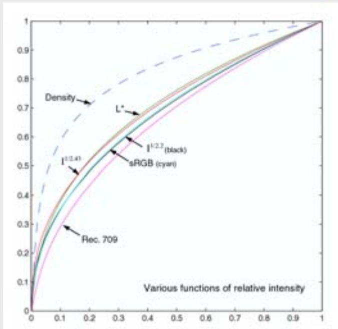
Non-linear Encoding

Perceptually more efficient

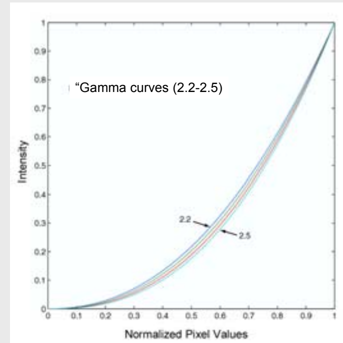
- Perception of brightness is non-linear wrt intensity



Many Non-linear Functions

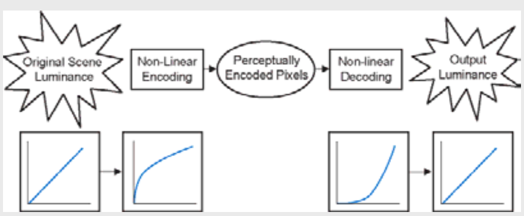


Non-linear Displays

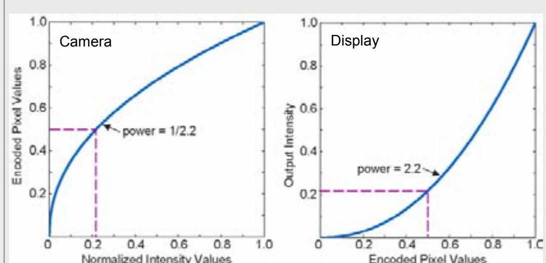


Reproducing Luminance

Encoded pixels are decoded by display



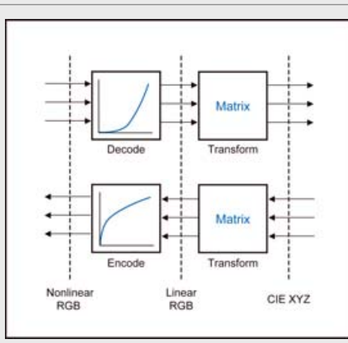
Encode/Decode



"Raw" pixels are perceptually encoded

Non-linear RGB to XYZ

Pixels



XYZ

RGB to XYZ FAQ

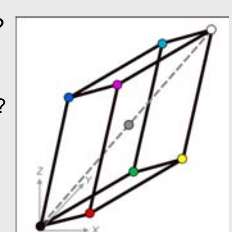
What shape is a non-linear RGB?

Is black at XYZ = 0,0,0?

Is gray always a straight line?

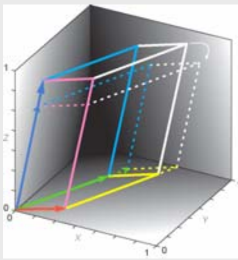
What happens when

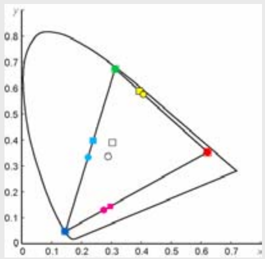
- Brightness, contrast change?
- White point changes?
- Display ages?



White point changes

Change relative amounts of R, G, B





When isn't the Matrix Valid?

Assumptions

- Pixels are spatially independent
- Scaled pixels = scaled spectra (or scaled XYZ)
- Or, scaled pixels = same chromaticity (*xy*)

Common failures

- LCD displays and projectors (small effect)
- DLP projectors with color wheel (RGBW)

Alternative is 3D sampling + interpolation

Tasteful Color

"Good painting, good coloring, is comparable to good cooking. Even a good cooking recipe demands tasting and repeated tasting while it is being followed. And the best tasting still depends on a cook with taste."

Josef Albers

Successful Recipes

"You can think of an RGB or CMYK file as containing, not color, but rather a recipe for color that each device interprets according to its own capabilities. If you give 20 cooks the same recipe, you'll almost certainly get 20 slightly different dishes as a result"

Real World Color Management

Recipe 1

bananas
sugar
egg
butter
baking soda
baking powder
salt
flour

Bake

What is it?

Could you make it?

Recipe 2

3	bananas
1/3	sugar
1	egg
1/3	butter
1	baking soda
1	baking powder
¼	salt
1 ½	flour

Bake at 375 for 15

What is it?

Could you make it?

Banana Muffins

3	bananas
1/3 c	sugar
1	egg
1/3 c	butter
1 t	baking soda
1 t	baking powder
¼ t	salt
1 ½ c	flour

Missing process?

Could you make it?

Bake at 375°F for 15 minutes

Banana Muffins

3	bananas
1/3 c	sugar
1	egg
1/3 c	butter
1 t	baking soda
1 t	baking powder
¼ t	salt
1 ½ c	flour

Mash bananas

Melt butter

Combine bananas, sugar, egg, butter

Combine dry ingredients

Add dry to wet, stir until just mixed

Spoon into muffin tins

Bake at 375°F for 15 minutes

Who needs color management?

RGB to print (classic case)

Mixing RGB from various sources

Creating RGB for various displays

Evaluating RGB color or its application

Transforming from RGB to color models

Color Management

Specify your units
- ICC profiles (CIEXYZ or CIELAB)
- Displays, printers, scanners
- File formats

Specify your process
- Color Management System (CMS)
- Manages profiles
- Performs translations

Types of profiles

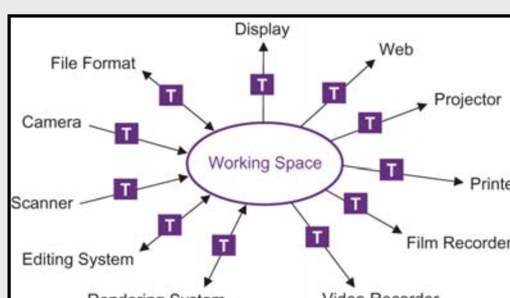
Values used to drive a display (output profile)

Values encoded in an image (image profile)

Values from camera or scanner (input profile)
- Spectra to RGB; not a matrix
- Only colorimetric capture produces tristimulus values
- Otherwise, depends on spectra

Scanners are easier than cameras

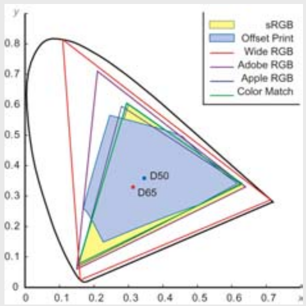
RGB Working Space



Common RGB Spaces

Gamma curve
- 2.2 for PC, Linux
- 1.8 for Mac

Linear for CG
- Rendering space
- Remap for display
- Table look-up



Considerations for RGB

Display-centered
- Easy to see all colors
- Missing some print and film colors
- Non-linear RGB (like sRGB)

Extended RGB
- Covers print, film, and display
- Must gamut map to display
- Non-linear RGB (like AdobeRGB)

Color Management Made Easy

Pick a standard RGB color space
- sRGB for web, displays, desktop printing
- Adobe RGB for film scanning
- Linear RGB for computer graphics

Characterize your display system

Control all (important) transformations

Did Tufte use Color Management?

Designed for print
- Controlled the inks (more than 4)
- Controlled the process
- Only affected by lighting

Similarly
- High quality maps
- Custom display installations
- Graphic arts before digital revolution

Color Management Examples

For the book
- Characterize my display to sRGB
- Get printer's profile
- Use Adobe tools to create CMYK

For SIGGRAPH courses
- Characterize my display to sRGB
- Create PDF tagged with sRGB
- Adjust content for projection

“Calibrated” Projector

Components
- Profile the projector
- Profile my display
- Plug-in for Powerpoint

Edit mode
- Colors are shown using display profile
- Imported images are tagged

Slideshow mode
- Copy of slides are transformed for projection
- LUTs and white point mapped to projector profile

More Examples

Digital photography

- Characterize laptop display
- Profile printer using service
- Use manufacture's scanner profile
- Use ColorSync (or Adobe tools) to manage them all

Digital photography is "killer app" for color management

Market Trends

Digital photography

- Low cost display calibration
- Printer/scanner calibration services
- "Good enough" camera and printer pairings

Home theaters

- Projector and flat panel displays
- Drive to match DVD movies and HDTV
- Trade articles, services, etc.

Characterize Your Display

Visual characterization

- Display primaries from manufacturer
- Visually set "gamma curve"
  - – ColorSync or the Adobe Gamma Tool
- CRT with 2.2 gamma ~ sRGB

Buy a meter and profiling software

- Under $300 for display systems
- www.colormall.com

Hooking to the CMS

Macintosh

- Enable ColorSync
- Set display, working space, etc.

Adobe Tools

- Built into Photoshop, Illustrator, etc.
- Embedded in PSD, PDF, etc.

Hooking to the CMS

Windows ICM

- Piecewise implementation
- Drivers, .icm files
- Many improvements in Longhorn

Other applications, Linux…

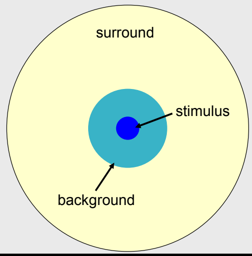
Real World Color Management
B. Fraser, C. Murphy, F. Bunting

Display Characterization Demo

Color Appearance

More than a single color
- Adjacent colors (background)
- Viewing environment (surround)

Appearance effects
- Adaptation
- Simultaneous contrast
- Spatial effects



Color Appearance Models
Mark Fairchild

Image courtesy of John MCann

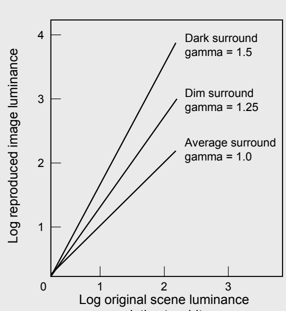
Image courtesy of John MCann

Light/Dark Adaptation

Adjust to overall brightness
- 7 decades of dynamic range
- 100:1 at any particular time

Absolute illumination effects
- Hunt effect
  Higher brightness increases colorfulness
- Stevens effect
  Higher brightness increases contrast

Bartleson & Breneman



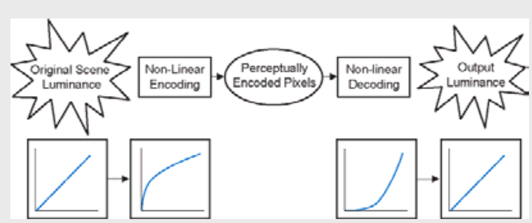
Increase “gamma” of reproduced image as function of the viewing environment

Increases colorfulness and contrast

Standard practice in film and graphic arts

Reproducing Luminance

Goal is not necessarily exact reproduction



Chromatic Adaptation

Change in illumination

Cones "white balance"

- Scale cone sensitivities
- von Kries
- Also cognitive effects

Creates unique white

From *Color Appearance Models*, fig 8-1

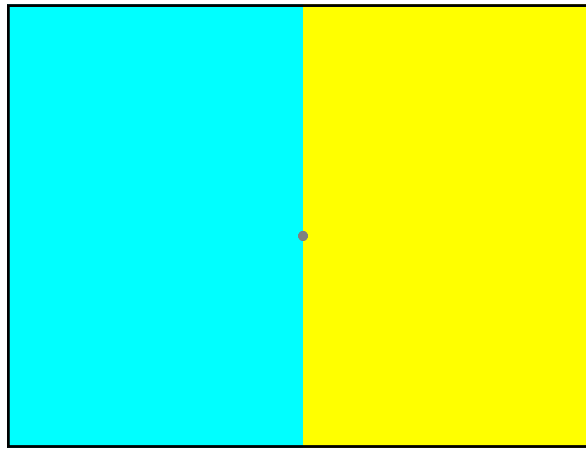


Image courtesy of Mark Fairchild

Chromatic Adaptation

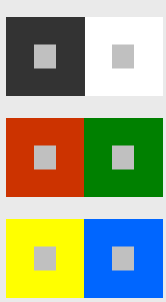
Original image | Overall Purple Tint | Tint Shirt Only

Inspired by Hunt's yellow cushion

Simultaneous Contrast

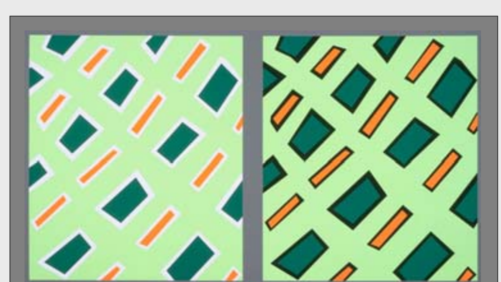
Add Opponent Color

- Dark adds light
- Red adds green
- Blue adds yellow

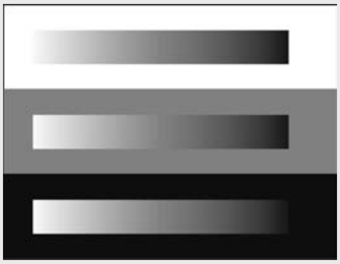


These samples will have both light/dark and hue contrast

Bezold Effect

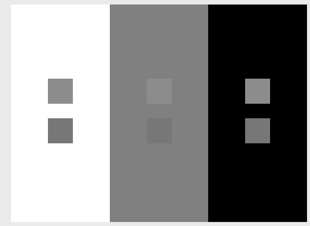


Affects Lightness Scale



Crispening

Perceived difference depends on background

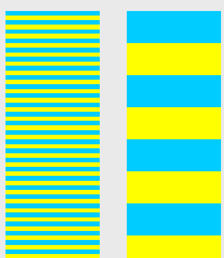


From Fairchild, *Color Appearance Models*

Spreading

Spatial frequency
- The paint chip problem
- Small text, lines, glyphs
- Image colors

Adjacent colors blend



Redrawn from *Foundations of Vision*, fig 6

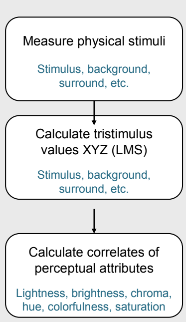
Comparison

From Fairchild, *Color Appearance Models*

Color Appearance Models

From measurements to color appearance

Models
- CIELAB, RLAB, LLAB
- S-CIELAB
- CIECAM97s, CIECAM02
- Hunt
- Nayatani, Guth, ATG



Requirements

CIE TC1-34, Testing Color Appearance Models

Minimum requirements
- Extension of CIE colorimetry
- Predict lightness, chroma and hue
- Chromatic adaptation transform (CAT)

Also in CIECAM97s, CIECAM02
- Absolute illumination
- Background parameters
- Surround (dark, dim or average)
- Degree of adaptation (none to full)

Applications of CAMs

Color reproduction
- Model adaptation across media
- Aid in mapping out-of-gamut colors

Model simultaneous contrast
- Predict confusing color symbols (Brewer)
- Compensate to give equal appearance on different backgrounds (DiCarlo & Sabataitis)

Model color image perception (S-CIELAB)

LMS from XYZ

Better for appearance modeling than XYZ

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Linear transformation, various similar matrices in use

von Kries Adaptation

$L_2M_2S_2$ from $L_1M_1S_1$

Ratio of new/old white ($white_2/white_1$)

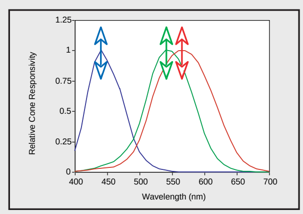
Full adaptation to new illumination

$$L_2 = (L_{white2}/L_{white1})L_1$$

$$M_2 = (M_{white2}/M_{white1})M_1$$

$$S_2 = (S_{white2}/S_{white1})S_1$$

Scale Cone Response



$L_a = k_L L$

$M_a = k_M M$

$S_a = k_S S$

$k_L = 1/L_{white}$, etc.

XYZ_2 from XYZ_1

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = M^{-1} \begin{bmatrix} L_{white2}/L_{white1} & 0.0 & 0.0 \\ 0.0 & M_{white2}/M_{white1} & 0.0 \\ 0.0 & 0.0 & S_{white2}/S_{white1} \end{bmatrix} M \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}$$

Where M is the transformation from XYZ to LMS

CIELAB Equations

Equations for CIE 1976 L*, a*, b* (CIELAB)

$$L^* = 116\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \frac{16}{116}\right]$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{1/3} - \left(\frac{Y}{Y_n}\right)^{1/3}\right]$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{1/3} - \left(\frac{Z}{Z_n}\right)^{1/3}\right]$$

X_n, Y_n, Z_n are the tristimulus values of the reference white.

If $(V/V_n) \le 0.008856$, where V is any of X, Y or Z, replace $\left(\frac{V}{V_n}\right)^{1/3}$ with $\left[7.787\left(\frac{V}{V_n}\right) + \frac{16}{116}\right]$ in the equations above.

Equations for Hue (h_{ab}) and Chroma (C_{ab}^*)

$$h_{ab} = \arctan\left(\frac{b^*}{a^*}\right) \qquad C_{ab}^* = \left[a^{*2} + b^{*2}\right]^{1/2}$$

Ratio with reference white

Cube root except near zero

Polar coordinates for hue and chroma

CIELAB: Wrong von Kries

CIELAB scales XYZ

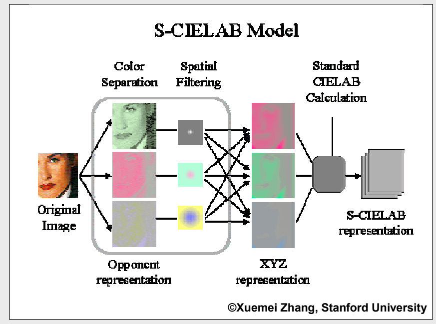
$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \begin{bmatrix} X_{white2}/X_{white1} & 0.0 & 0.0 \\ 0.0 & Y_{white2}/Y_{white1} & 0.0 \\ 0.0 & 0.0 & Z_{white2}/Z_{white1} \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}$$

Von Kries scales LMS

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = M^{-1} \begin{bmatrix} L_{white2}/L_{white1} & 0.0 & 0.0 \\ 0.0 & M_{white2}/M_{white1} & 0.0 \\ 0.0 & 0.0 & S_{white2}/S_{white1} \end{bmatrix} M \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}$$

Where M is the transformation from XYZ to LMS

S-CIELAB (images)



http://white.stanford.edu/~brian/scielab/scielab.html

Display Appearance

Tristimulus characterization
- Relatively easy to accomplish
- But, not a total solution

Want RGB to color appearance
- Robust and reliable color names
- Robust and reliable contrast control
- As robust as print appearance

Visual feedback and simple controls

Appearance Models

Adaptable Color
- Same color, different sizes
- Same color, different backgrounds

Interactive Color
- Does it appear the same?
- User has controls: Zoom, tool tips, etc.

Cross-media rendering
- Maintain encoding
- Names and relationships?

Conclusion

Color in information display
- Tufte's rules
- "Get it right in black and white"

Easier than images
- Fewer colors, larger areas
- Doesn't match a real world scene

Harder than images
- Doesn't match a real world scene
- Critical for information content

Additional Resources

Course notes
- References
- Early copy of slides

My website
- http://www.stonesc.com/Vis05
- Final copy of slides, references

A Field Guide to Digital Color
- A.K. Peters Booth
- Discount for attending this course