SIGGRAPH2004

Color in Information Display

Principles, Perception and Models

Maureen Stone, StoneSoup Consulting

A note from SIGGRAPH

- Surveys are online this year
- Linked from courses page
- www.siggraph.org/courses_evaluation

Information Display

- Visualization
- Illustration
- Cartography
- User-interface design
- Multi-scale imaging
- Medical imaging
- …

Goals for this Course

- Introduce design principles (Tufte)
- Relate principles to:
  - Vision and perception
  - Design and aesthetics
  - Digital color models
- Computational tools and models
- Focus on RGB (additive) color
- Relevant research in various fields

A Brief Plug

“Inspiration” for this SIGGRAPH course

All images in notes © A.K. Peters, 2003 unless otherwise noted

Outline

- Tufte’s principles, examples
- Making color quantitative
- Color design & appearance
- Making color robust

Tufte's Principles

- Above all, do no harm *—E. R. Tufte*
- Fundamental uses
  - To label
  - To measure
  - To represent or imitate reality
  - To enliven or decorate

Envisioning Information
Edward R. Tufte

Do No Harm

careful color

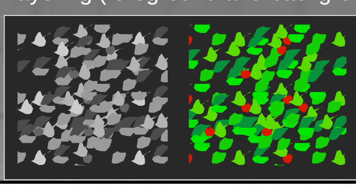
careful color

careful color

careful color

To Label

- Color as a noun
  - Identify (uniqueness and distinctness)
  - Highlighting and emphasis
  - Grouping and segmentation
  - Layering (foreground and background)



Information Visualization
Colin Ware

Count the 7's

13579345978274055
24937916478254137
23876597277103876
19874367259047362
95637283649105676
32543787954836754
56840378465485690

Time proportional to the number of digits

13579345978274055
24937916478254137
23876597277103876
19874367259047362
95637283649105676
32543787954836754
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Time proportional to the number of 7's

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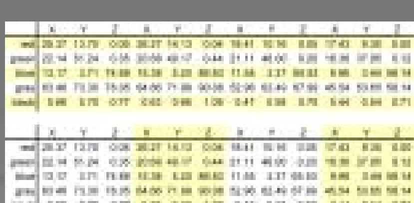
19874367259047362
95637283649105676
32543787954836754
56840378465485690

Both 3's and 7's "Pop out"

- Typically, 5-6 distinct values simultaneously
- Up to 9 under controlled conditions

Grouping, Highlighting



Group rows

Group columns

Perceptual Principles

- "Pop out"
  - Preattentive perceptual process
  - Others: Angle, motion, texture, shape
- Color names
  - Distinct colors have distinct names
  - Basic names (Berlin & Kay)

Perceptual primaries

black
white
gray
red
green
blue
yellow
orange
purple
brown
pink

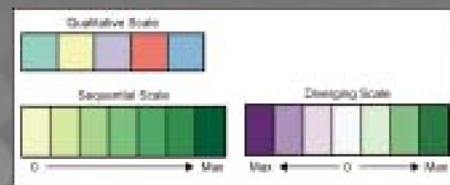
To Measure

- Color as quantity
  - Few intuitive orderings
  - Grayscale, saturation scales
  - Creates clusters of similar values
- Examples
  - Thermometer scales
  - Density plots
  - Thematic maps

"Tilebars" —Marti Hearst

Color Scales

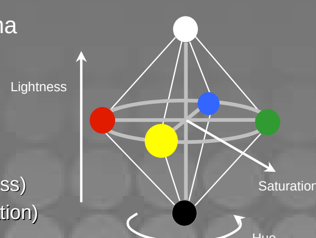
- Path through color space
  - Intensity, density, or saturation
  - NOT hue alone if sequence matters
- Most accurate if quantized



Perceptual Principles

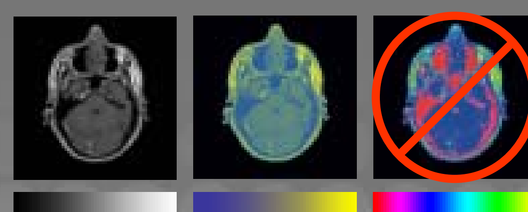
- Perceptual ordering of color
  - Lightness, value
  - Saturation, chroma
  - Hue circle

Low to high ordering
–Dark to light (lightness)
–Vivid to gray (saturation)



Avoid "The Rainbow"

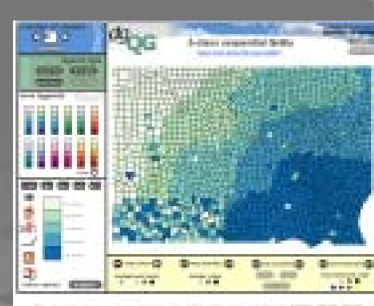
There is no "intuitive" order for Hue



Color Scales

- Long history in graphics and visualization
  - Ware, Robertson et. al, Levkowitz et. al
  - Rheingans
- PRAVADA Color (IBM Research)
  - Rule-based system
  - Includes spatial frequency
- Cartography
  - Cynthia Brewer
  - ColorBrewer

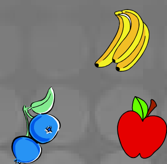
Color Brewer



www.colorbrewer.org

To Represent or Imitate Reality

- Color as representation
  - Key color to real world
  - Iconographic vs. photographic
- Examples
  - Blue for water
  - Green for foliage
  - Red for apples, etc.



Illustrative Color

Gray's *Anatomy of the Human Body*
www.bartleby.com/107/illus520.html

Map of Point Reyes
www.nps.gov

Shape from Shading

- Suggest 3D shape
  - Function only of lightness
  - Tufte: to measure
  - Also imitates reality
- Examples
  - Topo maps
  - Volumetric rendering

Courtesy of the National Park Service

Color and Shading

- Shape is defined by lightness (shading)
- "Color" (hue, saturation) labels

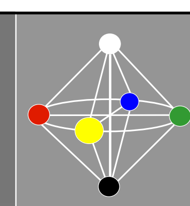
Images Courtesy of TeraRecon, Inc

Simulated Topo Map

Mike Cammarano, Pat Hanrahan, Stanford University

- Color scale
  - Height/depth
  - Land/water
- Shading function
  - Bump mapping
  - NW light
  - Sharpen ridges
- Contour simplification

Perceptual Principles



- Opponent color processing
  - RGB => A, R-G, Y-B
  - Occurs at retina
- Achromatic channel alone defines shape
  - No edge without lightness change
  - No shading with out lightness variation
  - Defines legibility

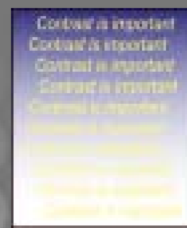
Lightness vs. chroma

Basic image encoding technique

Give less spatial resolution to chroma

Legibility

- Legibility = visible edges
- Outlines, drop shadows add edge contrast

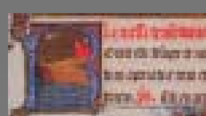


Drop Shadows

Drop Shadow

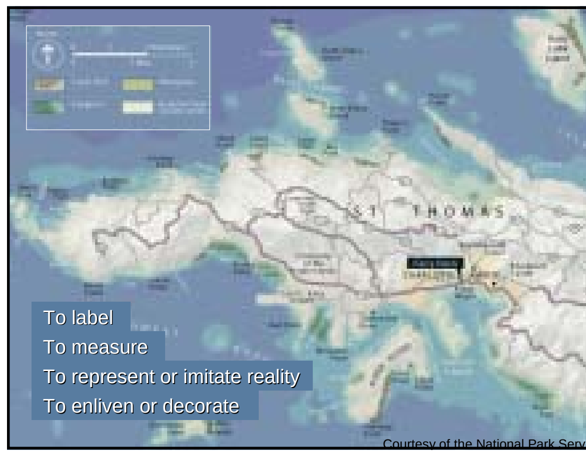
To Enliven or Decorate

- Color as beauty
  - Aesthetic use of color
  - Emotional, personal
- Examples
  - Illustrations, maps
  - Illuminated manuscripts
  - Signs, logos
  - Computer “desktops”



Google

Google



To label
To measure
To represent or imitate reality
To enliven or decorate

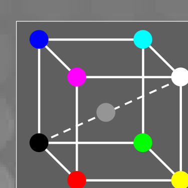
Courtesy of the National Park Servic

Outline

- Tufte’s principles, examples
- Making color quantitative
  - Quantitative RGB
  - Psychophysical metrics (CIE XYZ)
  - Perceptual models
- Color appearance and design
- Making color robust

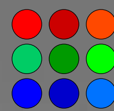
RGB Fundamentals

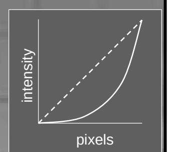
- Three primaries
  - RGB lights
  - Variable brightness (0..max)
  - Add to create color
- Characteristics
  - Primaries sum to white
  - Saturated colors on surface
  - Gray scale along diagonal
  - Cube bounds color gamut



Making RGB Quantitative

- Specify primary colors
  - Precise hue
  - Maximum brightness
- Map numbers (pixels) to intensity
  - Linear encodings
  - Non-linear encodings
  - Both are valid



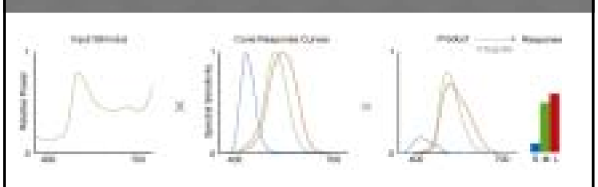


Specify Primary Colors

- CIE Colorimetry
  - Encode spectrum (stimulus) as tristimulus values (CIE XYZ)
  - Two spectra that produce the same tristimulus values "look the same"
- Basis for color measurement
- Similar to cone function in the retina

Retinal Cones

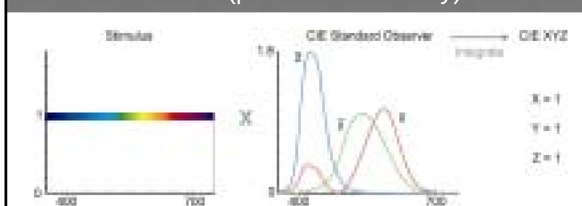
- Encode spectra as three values
- Long, medium and short (LMS)
- 3D vector space



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

CIE Standard "Cones"

- CIE tristimulus values (XYZ)
- 3D vector space (linear xform of cone space)
- Y = luminance (perceived intensity)



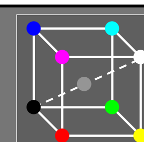
From *A Field Guide to Digital Color*, © A.K. Peters, 2003

RGB in XYZ

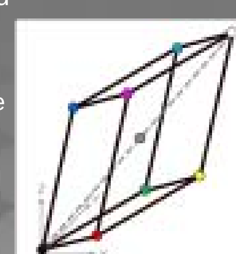
- R,G,B are vectors
- Add like vectors
  - (1,1,0) = $XYZ_R + XYZ_G$
- Scale like vectors
  - $(s_1,0,0) = s_2\, XYZ_R$
  - if linear intensity encoding, $s_1 = s_2$
  - If non-linear, s_2 is different than s_1

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

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



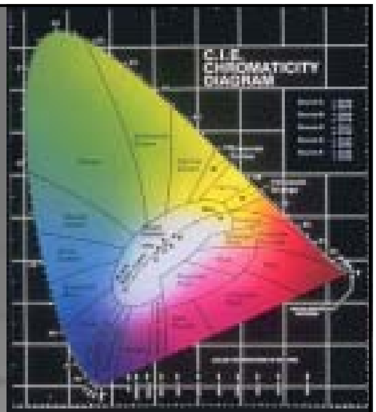
CIE Chromaticity Coordinates

Project X,Y,Z on a plane to separate colorfulness from brightness

$x = X/(X+Y+Z)$
$y = Y/(X+Y+Z)$
$z = Z/(X+Y+Z)$

$1 = x+y+z$

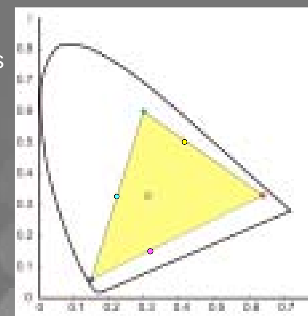
XYZ = xyY



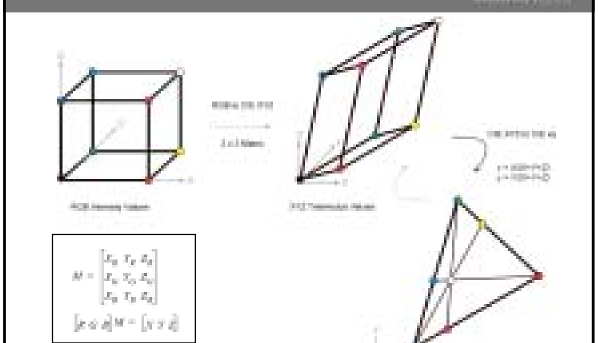
Courtesy of PhotoResearch, Inc.

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



RGB to XYZ to xy



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

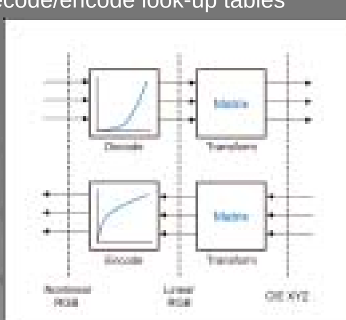
Pixels to Intensity

- 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

Non-linear RGB to XYZ

Add decode/encode look-up tables

pixels



XYZ

Colorimetry for Displays

- Color of primaries
  - Chromaticity usually constant
  - Set by display technology
  - Maximum brightness can vary
- Pixel-to-intensity transfer function
  - Highly variable, must be measured
  - Hardware and software controls
  - CRT "gamma" curve (effectively 2.2)

Summary

- Specify RGB with respect to CIE XYZ
  - Primary colors: xyY or XYZ
  - Psychophysical values (cd/m^2)
- Specify pixel to intensity mapping
  - Linear or non-linear spacing
  - Relative intensity (or luminance)
  - Precision is very important

Applications

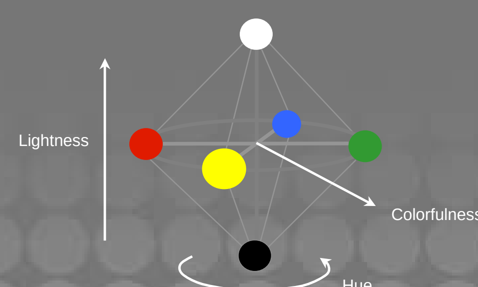
- Linear RGB for computation
  - Lighting simulation
  - Computer graphics
  - Image processing
- Non-linear RGB for encoding and display
  - Image encodings (JPEG, MPEG, etc.)
  - Display technology (CRT "gamma")
  - sRGB ("standard" RGB color space)

Perceptual Color Models

- Tristimulus models (CIE XYZ)
  - Absolute specification
  - Many different values for "white" and "black"
  - Are two colors the same?
- Perceptual models
  - Relative specification
  - Unique values for "white" and "black"
  - How similar are two colors?

*Single colors, neutral background, constant adaptation

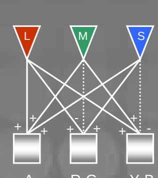
Perceptual Color Spaces



Unique black and white

Opponent Color

- Definition
  - Achromatic axis
  - R vs. G and B vs.Y axis
  - First-level processing
- History
  - Herring, 1878
  - Jameson & Hurvich (1955)



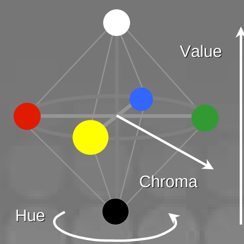
Fairchild, Figure 1-13

Support for Opponent Color

- Unique hues
  - No reddish-green
- Afterimages
  - Red-green, blue-yellow, black-white
- Color vision deficiencies
  - Red-green anomalies *
  - Blue-yellow anomalies

Munsell Color

- Hue, Value, Chroma
  - 5 R 5/10 (bright red)
  - N 8 (light gray)
- Perceptually uniform



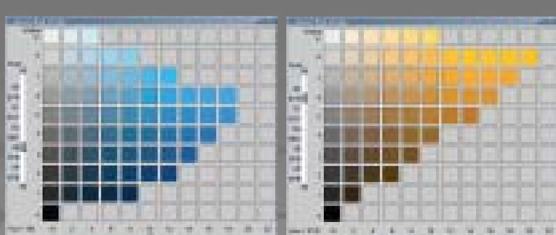
Munsell Renotation System maps between HVC and XYZ

Munsell Atlas

Courtesy Gretag-Macbeth

Interactive Munsell Tool

- From www.munsell.com



CIELAB and CIELUV

- Lightness (L*) plus two color axis (a*, b*)
- Non-linear function of CIE XYZ
- Defined for computing color differences

From Principles of Digital Image Synthesis by Andrew Glassner. SF: Morgan Kaufmann Publishers, Fig. 2.4 & 2.5, Page 63 & 64

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

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

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

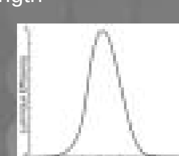
Ratio with reference white

Cube root except near zero

Polar coordinates for hue and chroma

Lightness Scales

- Lightness, brightness, luminance, and L*
  - Lightness is relative, brightness absolute
  - Absolute intensity is light power (cd/m^2)
- Luminance is perceived intensity
  - Luminance varies with wavelength
  - Luminous efficiency function
  - Equivalent to CIE Y



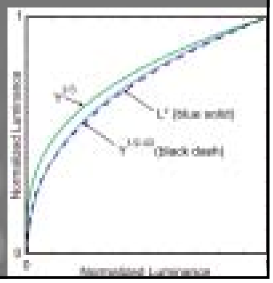
Green and blue lights of equal intensity have different luminance values

The L* Function

L* is a perceptually uniform lightness scale

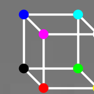
- Combination power + linear functions
- Not 1/3 power
- Best fit is 1/2.43

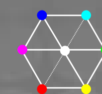
Similar issue in many other non-linear lightness specifications



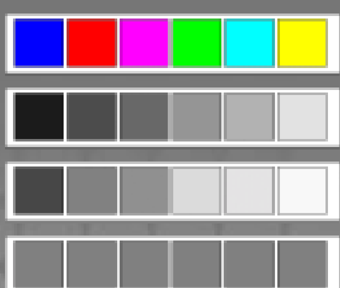
Psuedo-Perceptual Models

- HLS, HSV, HSB
- NOT perceptual models
- Simple renotation of RGB
  - View along gray axis
  - See a hue hexagon
  - L or V is grayscale pixel value
- Cannot predict perceived lightness





L vs. Luminance, L*



Uses for Perceptual Models

- Compute color differences
- Predict legibility, pop-out, color names
- "Intuitive" color selection
- Model for image compression
- Foundation for color appearance

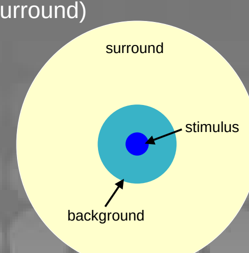
Outline

- Tufte's principles, examples
- Making color quantitative
- Color appearance & design
  - Color appearance and models
  - Color design principles and models
- Making color robust

Color Appearance

- More than a single color
  - Adjacent colors (background)
  - Viewing environment (surround)
- Appearance effects
  - Adaptation
  - Simultaneous contrast
  - Spatial effects

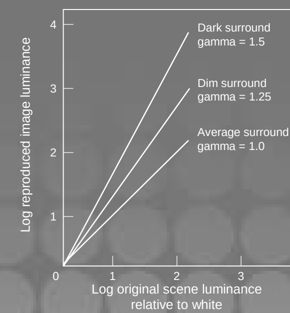
Color Appearance Models
Mark Fairchild



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

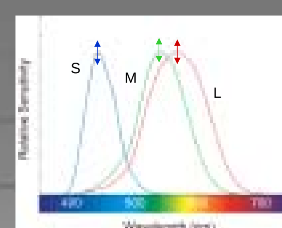
Chromatic Adaptation

- Change in illumination
- Cones "white balance"
  - Scale cone sensitivities
  - von Kries
  - Also cognitive effects
- Creates unique white

From *Color Appearance Models*, fig 8-1

von Kries Adaptation

- Relatively scale the cone response curves
- Linear transformations
  - RGB to XYZ
  - XYZ to LMS
  - Adjust L,M,S
    - Ratio of white (LMS)
    - $\text{white}_2/\text{white}_1$
  - LMS to XYZ to RGB



CIELAB: Wrong von Kries

CIELAB scales XYZ

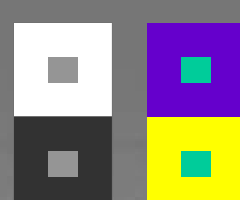
$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \begin{bmatrix} X_{white2}/X_{white1} & 0.0 & 0.0 \\ 0.0 & Y_{white2}/Y_{white1} & 0.0 \\ 0.0 & 0.0 & Z_{white2}/Z_{white1} \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}$$

Von Kries scales LMS

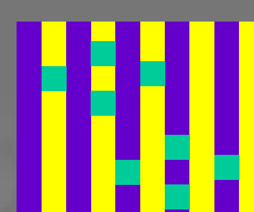
$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = M^{-1} \begin{bmatrix} L_{white2}/L_{white1} & 0.0 & 0.0 \\ 0.0 & M_{white2}/M_{white1} & 0.0 \\ 0.0 & 0.0 & S_{white2}/S_{white1} \end{bmatrix} M \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix}$$

Where M is the transformation from XYZ to LMS

Simultaneous Contrast

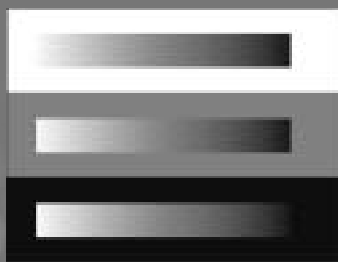


"After image" of surround adds to the color



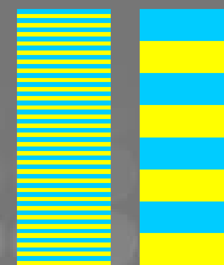
Reality is more complex
Identical patch and surround

Affects Lightness Scale



Effect of Spatial Frequency

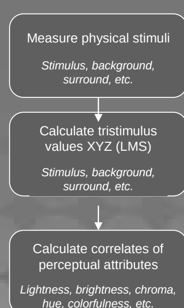
- Smaller = less saturated
- The paint chip problem
- Color image perception



Redrawn from *Foundations of Vision*, fig 6
© Brian Wandell, Stanford University

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

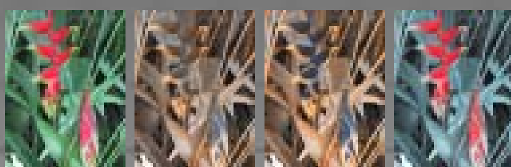
- Color reproduction
  - Model adaptation across media
  - Aid in mapping out-of-gamut colors
- Model simultaneous contrast
  - Predict confusing color symbols (Brewer)
  - Compensate to give equal appearance on different backgrounds (DiCarlo & Sabataitis)
- Model color image perception (S-CIELAB)

Model "Color blindness"

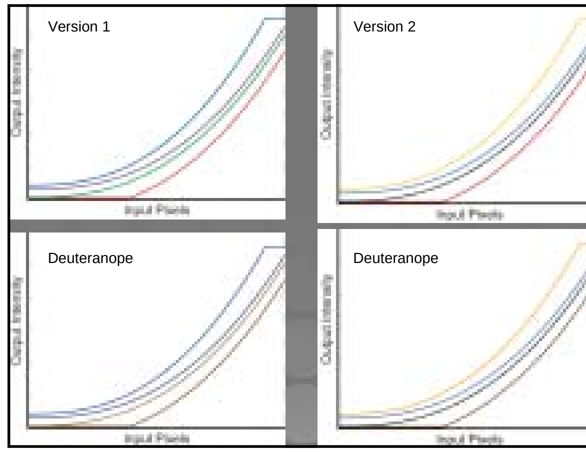
- Flaw in opponent processing
  - Red-green common (deuteranope, protanope)
  - Blue-yellow possible (tritanope)
  - Luminance channel almost "normal"
- Effect is 2D color vision model
  - Flatten color space
  - Can be simulated (Brettel et. al.)
  - Vischeck (www.vischeck.com)

Vischeck

- Simulates color vision deficiencies
- Web service or Photoshop plug-in
- Robert Dougherty and Alex Wade



Deuteranope Protanope Tritanope



Color Design

- Goals
  - Highlight, emphasize
  - Create regions, group
  - Illustrate depth, shape
  - Evoke nature
  - Decorate, make beautiful
- Color harmony

"…successful color combinations, whether these please the eye by using analogous colors, or excite the eye with contrasts." –Wucius Wong

Principles of Color Design
Wucius Wong

Color Design Principles

- Control value (lightness)
  - Ensure legibility
  - Avoid unwanted emphasis
- Use a limited hue palette
  - Control color pop out, color grouping
  - Avoid clutter from too many competing colors
- Use neutral backgrounds
  - Minimize simultaneous contrast

Design Color Models

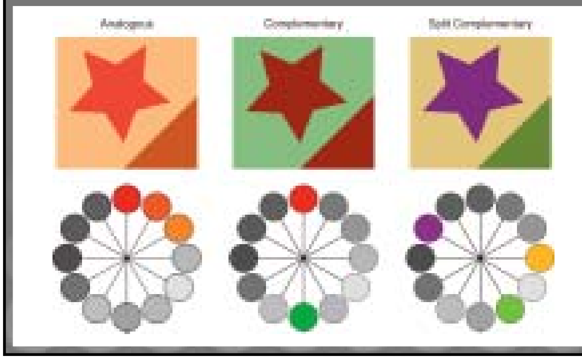
- Hue (color wheel)
  - Red, yellow, blue (primary)
  - Orange, green, purple (secondary)
- Chroma (saturation)
  - Intensity or purity
  - Distance from gray

- Value (lightness)

Modeling Color Design

- Design spaces are perceptual spaces
  - Munsell, OSA, Ostwald
  - Created as design spaces
  - Wong uses Munsell
- Geometric interpretation of color design
  - Color schemes based on hue circle
  - Contrast and analogy as distance
  - Smooth paths for tints, tones and gradations

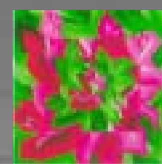
Color Schemes



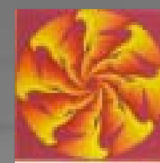
Color Harmony

Apply contrast and analogy to hue, value, chroma

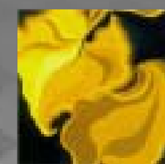
Vary chroma



Contrasting hues



Analogous hues



Vary value

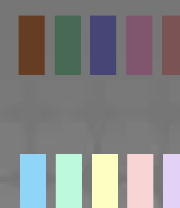
From Wong, *Principles of Color Design*, © 1997, John Wiley & Sons, Inc.

Gradations

- Paths along axis
  - Color to black or white
  - Color to gray
- Media-specific blending
  - RGB blending
  - CMY screens
  - Paint mixture
- Creates slanted or curved paths

Tints and Tones

- Tone or shade
  - Hue + black
  - Decrease saturation and lightness
- Tint
  - Hue + white
  - Decrease saturation, increase lightness



Examples

- Color selection tools
  - Metapalette, Canon Color Advisor (Beretta)
  - Interactive Color Palette Tools (Meier et. al.)
- Color for visualization
  - Ware, Robertson, Levkowitz
  - Rheingans, Brewer, PRAVADA color
  - Healy, Booth (popout and emphasis)
- Color names
  - Kelly & Judd, NBS 1976

Automating Color Selection

- What is color used for?
  - Semantic descriptions, not RGB triples
  - Can be as simple as a name
- Model with perceptual color space
- Accurately display modeled color
  - Display characterization (quantitative RGB)
  - Gamut limitations
  - Color management systems

Outline

- Tufte's principles, examples
- Making color quantitative
- Color appearance & design
- Making color robust
  - Controlling lightness
  - Color gamuts
  - Color management systems

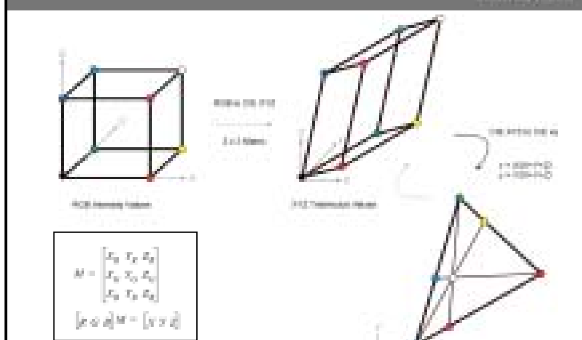
Control Value (Lightness)

- Primary factor in good color design
- Legibility (luminance contrast)
  - 5:1 contrast for legibility (ISO standard)
  - 3:1 minimum legibility
  - 10:1 recommended for small text
- Avoid unwanted emphasis
  - Equal luminance for different hues
- Smooth shading (luminance variation)

Luminance from RGB

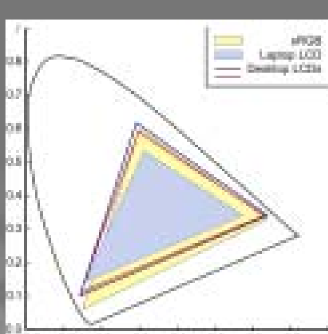
- $Y = rY_R+gY_G+bY_B$ *Not a fixed equation!*
- Y_R,Y_G,Y_B
  - Maximum luminance of primaries
  - Different for different displays
  - Affected by brightness & contrast controls
- r,g,b
  - Relative intensity values (linear)
  - Depends on "gamma curve"

RGB Gamuts

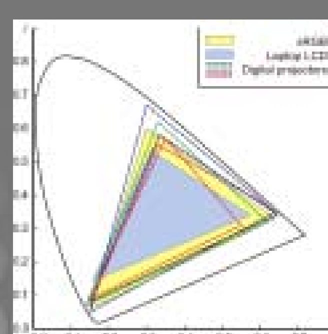


From *A Field Guide to Digital Color*, © A.K. Peters, 2003

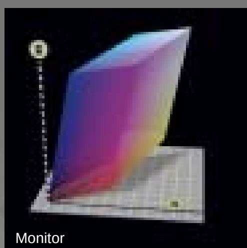
Display Gamuts

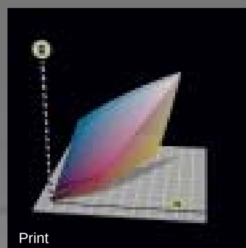


Projector Gamuts



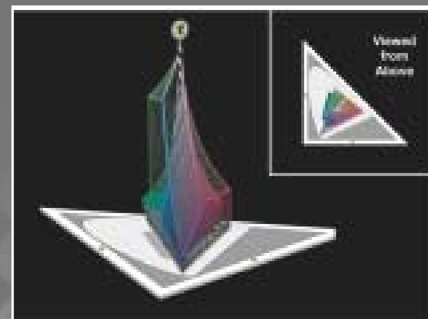
Monitor & Print in XYZ





Images by Bruce Lindbloom

Monitor & Print in xyY



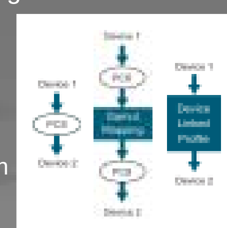
Images by Bruce Lindbloom

Color Management

- Cross-media color reproduction
  - Characterize media (as in RGB to XYZ)
  - Characterize image encoding
  - Map (images) from one medium to another
- Color Management Systems
  - Profiles specify color (ICC standard)
  - CMS "engine" implements the transformations

Process

- Characterize devices, images
- Map through PCS
- Gamut mapping
  - Redefine black/white
  - Map out-of-gamut colors
  - Appearance transformation
- Scan-display-print focus



Device-Independent Color

- Profiles (P) & Profile Connection Space (CIELAB)

User-Center View

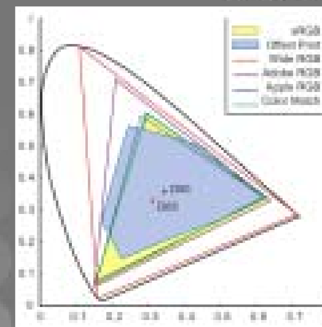
- Standard RGB working space

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)

Common RGB Spaces

- Gamma curve
  - 2.2 for PC
  - 1.8 for Mac
- Linear for CG
  - Rendering space
  - Remap for display
  - Table look-up



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

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
  - Flat panels have different primaries
- Buy a meter and profiling software
  - Under $500 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.
- Windows ICM
  - Piecewise implementation
  - Drivers, .icm files

Color Management Made Easier

- Active feedback, such as cameras
  - Projection display systems
  - Majumder & Stevens, Raskar
- Cost-effective RGB characterization
  - For information content, not psychophysics
  - Model effect of common variations
- Color management for information display
  - RGB to RGB gamut mapping
  - Illustrations rather than images

Robust Color

- Depends on quantitative color
  - Design in perceptual space
  - RGB to XYZ to display
  - Color management can help
- Robust design
  - Reads well in gray scale
  - Minimizes red-green coding
  - Duplicated by shape, texture, etc.

Outline

- Tufte's principles, examples
- Making color quantitative
- Color design & appearance
- Making color robust
- Additional resources

Additional Resources

- Course notes
  - References
  - Early copy of slides
- http://www.stonesc.com
  - Final copy of slides, references
  - Wait one week
- *A Field Guide to Digital Color*
  - A.K. Peters Booth
  - Discount for attending this course