Color... part 1

(some slides from Fredo Durand)

Today’s Class

• Reading for Today
• What is Color?
  – Human Perception
  – Color Blindness & Metamerism
• Color Spaces
  – LMS, RGB, XYZ, HSV, L*a*b*, ....
• Reading Choice for Tuesday
• Color & Projection in Spatially Augmented Reality
Reading for Today


Choropleth map: statistics per area
must be careful about normalization

Total Population of 2000 Census Block Groups  Population Density of 2000 Census Block Groups

https://en.wikipedia.org/wiki/Choropleth_map#/media/File:Choropleth-density.png
• Color selection is not one size fits all
  – don't always use the same color theme
  – don't always use the default
• Many options in map making programs
  – No guidance about choosing color schemes
  – Don’t tell them what to do, but allow them to explore options
• Standard (cartographic) conventions
  – Variations in lightness are interpreted as ordering
  – Dark equals more, light equals smaller values
  – No more than 7 colors in a choropleth map
    (Legibility vs. information rich tradeoff)
• Just because you can see differences doesn’t mean you can correlate color back to legend
• Important to consider borders & backgrounds

• Choose a scheme appropriate for:
  – sequential, qualitative, or diverging data
  – Diverging data & color schemes is particularly interesting
  – Are there more than 12 classes?
• Would prefer to start with 1 color, then build a scheme around it (like some website color design apps)
• 3 perceptual dimensions of color are hue, saturation and lightness
• cartographers seldom use more than seven classes on a choropleth map
• Idea: Combine colorbrewer.org & “choose the right graph” into one tutorial!
• Unfortunate undergrad who had to evaluate all 385 schemes usability
• User study was not scientific, unsolicited feedback only, possibly biased
• Paper motivation could be stronger
• Online tools:
  https://kuler.adobe.com/
  http://www.checkman.io/please/
  http://paletton.com/
  http://colorbrewer2.org/
  http://www.colourlovers.com/
• Why are color space conversions not identical? Isn’t there a standard?
• Simultaneous Contrast Problem** avoid optical illusion
• Program looks like a(n effective) teaching tool
• Nice emphasis on UI (user interface: how the interface is laid out)/UX (user experience: how the product feels)
• Gradients vs. flat colors?
• Limited # of colors means data will be compressed away
• Writing Comments
  – Read like a user guide not a paper
  – light on technical details
  – Was a justification of a user interface more than an academic paper?
  – Title: Color vs Colour? Pick one
  – Paper seemed intuitive, frequently states the obvious
• Paper a bit dated, but website is still maintained and is current
• Flash praised… why did it (was it forced to) go away?

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Emergency Response Decision Making
Full network detail is overwhelming

Subset of data
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What is Color?

- Reflectance Spectrum
- Spectral Power Distribution
- Illuminant D65 (CIE standard for natural daylight)
What is Color?

Neon Lamp

What color is the dress?

What does the viewer infer about the scene illumination?

Blue & Black under yellow-tinted illumination?
White & Gold under blue tinted illumination?

https://en.wikipedia.org/wiki/The_dress
What is Color?

- Stimulus
- Observer
- Spectral Sensibility of the L, M and S Cones

Light

Retina

Optic Nerve

Amacrine Cells

Ganglion Cells

Horizontal Cells

Bipolar Cells

Rod Cone
Cones do not “see” colors

- Different wavelength, different intensity
- Same response to a single cone
Response Comparison

• Different wavelength, different intensity
• But different response for different cones

![Graph showing response comparison](image)

Dim green
Cone R: 0.20
Cone G: 0.25
Cone B: 0.01

Bright cyan
Cone R: 0.20
Cone G: 0.25
Cone B: 0.25

Color Blindness

• Classical case: 1 type of cone is missing (e.g. red)
• Now Project onto lower-dim space (2D)
• Makes it impossible to distinguish some spectra

![Graph showing color blindness](image)

Dim green
Cone R: 0.50
Cone G: 0.60
Cone B: 0.01

Bright red
Cone R: 0.90
Cone G: 0.60
Cone B: 0.00

Dim green
Cone G: 0.60
Cone B: 0.01

Bright red
Cone G: 0.60
Cone B: 0.00
Ishihara Color Blindness Test

- Deuteranopia: missing green cone
- Protanopia: missing red cone
- Tritanopia: missing blue cone (rare)
Metamerism: Apparent Matching

• When two materials look the same under one lighting condition (a coincidence), but look different under another:

http://gusgsm.com/metamerismo

• Remember that different spectral distribution of input light yield different visual stimuli
• We all experience some color blindness

Tetrachromacy: 4 cones?!

Often it is only a slight mutation of the red or green cone (left diagram), and thus not be easily detectable by a vision test or enable enhanced color vision.

Glasses to “correct” Colorblindness?

- Enchroma is not a cure for color blindness.
- Results vary depending on the type and extent of color vision deficiency.
- Enchroma does not endorse use of the glasses to pass occupational screening tests such as the Ishihara test.

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Standard Color Spaces

• Colorimetry: Science of color measurement
• Quantitative measurements of colors are crucial in many industries
  – Television, computers, print, paint, luminaires
• Naive digital work uses a vague notion of RGB
  – Unfortunately, RGB is not precisely defined, and depending on your monitor, you might get something different
• We need a principled color space…

CIE Color Matching Experiments

Figure 1-10
Tristimulus experiment

The observer adjusts the intensities of the red, green, and blue lamps until they match the target stimulus on the split screen.
CIE XYZ Color Space

- Can think of $X$, $Y$, $Z$ as coordinates
- Linear transform from typical LMS or RGB
- Note that many points in XYZ do not correspond to visible colors!

\[
\begin{pmatrix}
R \\
G \\
B
\end{pmatrix} =
\begin{pmatrix}
3.24 & -1.54 & -0.50 \\
-0.97 & 1.88 & 0.04 \\
0.06 & -0.20 & 1.06
\end{pmatrix}
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix}
\]

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix} =
\begin{pmatrix}
0.41 & 0.36 & 0.18 \\
0.21 & 0.72 & 0.07 \\
0.02 & 0.12 & 0.95
\end{pmatrix}
\begin{pmatrix}
R \\
G \\
B
\end{pmatrix}
\]

Hering 1874: Opponent Colors

- Hypothesis of 3 types of receptors: Red/Green, Blue/Yellow, Black/White
- Explains well several visual phenomena
**Hue Saturation Value (HSV)**

- Value: from black to white
- Hue: dominant color (red, orange, etc)
- Saturation: from gray to vivid color

**Color Opponents “Wiring”**

- Sums for brightness
- Differences for color opponents
- It’s just a 3x3 matrix to convert HSV from/to LMS, RGB, or XYZ
Linear Color Spaces: RGB/XYZ/YPbPr

- Equal steps in linear color spaces do not correspond to equal differences for human perception
- MacAdam ellipses visualize the lack of perceptual uniformity [MacAdam 1942]

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
= 
\begin{bmatrix}
0.4124 & 0.3576 & 0.1805 \\
0.2126 & 0.7152 & 0.0722 \\
0.0193 & 0.1192 & 0.9505
\end{bmatrix}
\begin{bmatrix}
R_{\text{Linear}} \\
G_{\text{Linear}} \\
B_{\text{Linear}}
\end{bmatrix}
\]


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Reading for Tuesday: (choose one)

“Modeling Color Difference for Visualization Design”
Szafir, IEEE TVCG / IEEE VIS 2017

Reading for Tuesday: (choose one)

“Hue-Preserving Color Blending”
Chuang, Weiskopf, and Möller, TVCG 2009
Reading for Tuesday: *(choose one)*

“A Linguistic Approach to Categorical Color Assignment for Data Visualization”, Setlur and Stone, IEEE InfoVis 2015

Homework Assignment 5: Experimenting with Color

- Revisit an earlier assignment/data/toolkit
  - Make a non-color-related improvement to this visualization
- Prepare many versions of the same visualization experimenting with different color palettes, e.g.:
  - Shades of grey
  - Black & white
  - Cool vs. warm tones
  - Bold/saturated vs. pastel
  - Colorblind aware
  - Light vs dark background and/or color negation
  - Etc.

- Analyze the effectiveness of the color scheme for each visualization.
  - How well does it convey the message? Or mislead the viewer?
- Compare the visualizations to each other.
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Spatially Augmented Reality (SAR) Projection

camera detects design geometry
6 projectors augment design
design sketched with foam-core walls
Tangible Interface for Architectural Design

Exterior & interior walls

Tokens for:
- Windows
- Wall/floor colors
- North arrow

Overhead camera  Projection geometry  Inferred design
Motivation:

Can we do a better job reproducing the desired appearance?

Related Work: Radiometric Compensation

- Minimize artifacts caused by light modulation with local surface [Bimber et al. 2005; Nayar et al. 2003; Grundhöffer & Bimber 2008]
- Does not consider global light inter-reflection

Grundhöffer & Bimber 2008
Our Problem Statement

• Known scene geometry
• Known surface reflectances, all ideal diffuse
• Fixed, calibrated projectors
• Given:
  Desired target surface appearance (texture)
  for each physical surface
• Solve for:
  Projection texture for each physical surface that
  most faithfully reproduces the desired appearance

Related Work: Reverse Radiosity

• Forward lighting with radiosity

\[ B = (I - F)^{-1}E \]

Values for rendering form factor matrix direct light

• Inverse lighting with radiosity: Reverse Radiosity (RR)
  – [Bimber et al. 2006]

\[ E = (I - F)B \]

Projection values desired appearance

Bimber et al. 2006
L*a*b*: a perceptual color space

Designed to match human color perception data

\[
\begin{bmatrix}
L \\
a \\
b
\end{bmatrix} = \begin{bmatrix}
116h\left(\frac{Y}{Y_n}\right) - 16 \\
500\left(h\left(\frac{X}{X_n}\right) - h\left(\frac{Y}{Y_n}\right)\right) \\
200\left(h\left(\frac{Y}{Y_n}\right) - h\left(\frac{Z}{Z_n}\right)\right)
\end{bmatrix}
\]

\[
h(t) = \begin{cases} 
  t^{\frac{1}{3}} & t \leq (6/29)^3 \\
  \frac{1}{3}\left(\frac{29}{6}\right)^2t + \frac{4}{29} & \text{Otherwise}
\end{cases}
\]

L*a*b* is nonlinear, a challenge for optimization
Quantitative Perceptual Comparison

\[ \Delta E = \sqrt{(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2} \]

• Where 2.3 \( \Delta E \) = JND (just noticeable difference)
• The MacAdams ellipses are more equal size circles in \( L^*a^*b^* \)

Our Optimization Formulation

Absolute Error:
\[ \phi_{abs} = \frac{\sum_i A_i [(L_i - L'_i)^2 + (a_i - a'_i)^2 + (b_i - b'_i)^2]}{A_{avg}} \]

Spatial Error:
\[ \phi_{spatial} = \sum_{(i,j) \in nbd} [(L_i - L_j) - (L'_i - L'_j)]^2 + [(a_i - a_j) - (a'_i - a'_j)]^2 + [(b_i - b_j) - (b'_i - b'_j)]^2 \]

Complete Objective Function:
\[ \phi = \alpha \phi_{abs} + (1 - \alpha) \phi_{spatial} \]

We use \( \alpha = 0.9 \)

Box constraints:
minimum & maximum brightness of projector system
Desired

Calculated projection imagery

Uncompensated
Reverse Radiosity
YPbPr
L*A*B
Photographs

Sheng et al. 2010
Optimized in YPbPr space

New method
Optimized in L*A*B space
Desired Calculated projection imagery

Uncompensated Reverse Radiosity YPbPr L*A*B*

Photographs

Sheng et al. 2010
Optimized in YPbPr space

New method
Optimized in L*A*B space

“Perceptual Global Illumination Cancellation in Complex Projection Environments”
Yu Sheng, Barbara Cutler, Chao Chen, and Joshua Nasman
Eurographics Symposium on Rendering (EGSR), June 2011.