Today

- What is Color?
  - Human Perception
  - Color Blindness & Metamerism
- Readings for Today
- Color Spaces
  - LMS, RGB, XYZ, HSV, $L^*a^*b^*$, ....
- Color & Projection in Spatially Augmented Reality
- Reading Choice for Friday
What Color is this Apple? What is Color?

Reflectance Spectrum

What is Color?

Spectral Power Distribution

Illuminant D65 (CIE standard for natural daylight)
What is Color?

Illuminant D65 (CIE standard for natural daylight)

Reflectance Spectrum

Spectral Power Distribution Under D65

Illuminant F1 (one of the CIE standards for fluorescent lighting)

Neon Lamp

Reflectance Spectrum

Spectral Power Distribution Under F1
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?

What is Color?

Observer

Stimulus

Reflectance Spectrum
What is Color?

Light

Retina

Optic Nerve

Amacrine Cells

Ganglion Cells

Horizontal Cells

Bipolar Cells

Rod

Cone
What is Color?

Spectral Sensibility of the L, M and S Cones

Incoming Light

Material Reflectance

Stimulus

Cone Sensitivity

Cone Responses
Cones do not “See” Colors

- Different wavelength, different intensity
- *May have same response to a single cone*

![Graph showing cone responses to different wavelengths.](image)

**Dim green**
- Cone M/G: 0.25

**Bright cyan**
- Cone M/G: 0.25

Response Comparison

- Different wavelength, different intensity
- *Will have different responses for different cones*

![Graph showing cone responses to different wavelengths.](image)

**Dim green**
- Cone L/R: 0.20
- Cone M/G: 0.25
- Cone S/B: 0.01

**Bright cyan**
- Cone L/R: 0.20
- Cone M/G: 0.25
- Cone S/B: 0.25
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Color Blindness

- Classical case: 1 type of cone is missing (e.g. red)
- Response is projected onto lower-dim space (2D)
- Makes it impossible to distinguish some spectra
As we have already discussed…
Illumination is very important to proper color perception.

This test must be conducted with a calibrated sample and controlled lighting.

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

- When two materials look the same under one lighting condition (a coincidence), but look different under another.
- E.g. the shirt & pants matched in the store lighting, but not outside!
- Different spectral distribution of input light yield different visual stimuli
- We all experience some color blindness

Tetrachromacy: Some People have 4 Cones!?!?

Typically a slight or moderate mutation of the red or green cone. May be detectable by a vision test. Less likely to experience metamerism. But cannot see wavelengths not visible to other humans. Not superhuman vision!
Glasses to “Correct” Colorblindness?

- “Enchroma does not endorse use of the glasses to pass occupational screening tests such as the Ishihara test.”
- Enchroma (and other similar products) is not a cure for color blindness.
- Does not repair missing cones.
- Does not make the eyes more sensitive.
- Filters (selectively darkens) input stimulus.
- Reaction videos are mostly/entirely staged for viral internet marketing.

Debunked by Jonathon, a.k.a., MegaLag
https://www.youtube.com/watch?v=Ppobi8VhWwo&t=0s

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- Good tool for novices - pick the right palette (sequential, diverging, categorical)
  - Why not use continuous gradient rather than discretized values?
- Colorblind aware - good to have this check / assistance! Web accessibility standards
- Respect the difference in target display (monitor, print, etc.)
  - Some dated technology, but still relevant concerns / criteria
- What to do when there is no suggested color palette for situation?
- Only for map area color, no universal recommendation for borders, roads, cities, etc.
  - What to do when we have multiple axes of information to display/overlay?
- Limited palettes, other color choices might be more appropriate for specific datasets
  - Should also consider cultural differences
  - What about individual preference?
- Is this the only color palette tool? No! Was it the first? Probably not!
  - Caution: some palette tools are art/design-focused
- Best paper, well-organized, easier-to-read than other papers this term
Choose a scheme appropriate for:

a) Sequential
b) Diverging
c) Qualitative

Sequential (& Diverging): Values are naturally ordered.

Diverging: middle value is significant for comparison & neutral.

Sequential: White or black indicates neutral value / end of scale.

Qualitative / Categorical: Values are unordered

Choropleth map: statistics per area

Must be careful about normalization

https://en.wikipedia.org/wiki/Choropleth_map#/media/File:Choropleth-density.png
Emergency Response Decision Making

- Multiple studies
  - numerical study, expert study, user study
  - initial pilot study
  - question: color expert vs. classic art background?
- Includes examples of good and bad visualizations
- Maximize color contrast w/ neighboring clusters and w/ background
- Optimize color choice for human perception
- Can we scientifically certify “best” visualization?
Genetic Algorithm

- If you can't figure out a smarter optimization method…

- Encode a potential problem solution as a sequence
  - Each sequence must be same length, with a consistent meaning to the value at each location in the sequence

- Keep a group of your $k$ best-ish solutions

- Try different random variations of that group
  - Swapping random subsequences (crossover)
    - NOTE: This only makes “sense” if neighboring locations in the sequence are related (not fully independent)
  - Randomizing a single location (mutation)
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Color Picker in Photoshop

- What are all the different choices?
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

Commission Internationale de l'éclairage (CIE)

a.k.a. International Commission on Illumination
CIE XYZ Color Space

- Can think of X, Y, & Z as 3D coordinates
- Linear transform to/from typical LMS or RGB

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

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

- Note that many points in XYZ do not correspond to visible colors!

Hue Saturation Value (HSV)

- Hue: dominant color (red, orange, etc)
- Saturation: from gray to vivid color (a.k.a. Chroma)
- Value: from black to white (a.k.a. Brightness, similar to Lightness)
Hering 1874: Opponent Colors

- Hypothesis of 3 types of receptors:
  Red/Green, Blue/Yellow, Black/White
- Explains well several visual phenomena

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

- Can convert between these spaces with a 3x3 matrix multiplication, e.g.:

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

- However, 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]

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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 wall
- 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?

geometry & materials  desired appearance  uncompensated projection
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

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

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

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

\[ E = (I - F)B \]
L*a*b*: a Perceptual Color Space

- Designed to match human color perception data

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

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

- 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*

http://w3.kcuw.ac.jp/~fujiwara/infosci/ellipses_lab.png
MacAdams Ellipses: XYZ vs. L*a*b*

Our Optimization Formulation

- Absolute Error:
  \[ \phi_{abs} = \sum_i A_i [(L_i - L'_{i})^2 + (a_i - a'_{i})^2 + (b_i - b'_{i})^2] \]
  - desired appearance
  - projection result

- Spatial Error:
  \[ \phi_{spt} = \sum_{(i,j)\in nbd} [(L_i - L_{j}) - (L'_{i} - L'_{j})]^2 + [(a_i - a_{j}) - (a'_{i} - a'_{j})]^2 + [(b_i - b_{j}) - (b'_{i} - b'_{j})]^2 \]
  - gradient in desired appearance
  - gradient in projection result

- Complete Objective Function:
  \[ \phi = \alpha \phi_{abs} + (1 - \alpha) \phi_{spt} \]
  - We use \( \alpha = 0.9 \)

- Box constraints:
  minimum & maximum brightness of projector system
  - No negative light!
Desired

Calculated projection imagery

Uncompensated
Reverse Radiosity
YPbPr
L∗A∗B∗

Photographs

Sheng et al. 2010
Optimized in YPbPr space

Sheng et al. 2011
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

Sheng et al. 2011  
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.
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Reading for Friday *pick one*

“Modeling Color Difference for Visualization Design”
Szafir, IEEE TVCG / IEEE VIS 2017
Reading for Friday *pick one*

“Hue-Preserving Color Blending”
Chuang, Weiskopf, and Möller, TVCG 2009

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Reading for Friday *pick one*

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