Color

(some slides from Fredo Durand)

Today's Class

- Readings for this Week
- Mid-Term Presentation
- What is Color?
  - Human Perception
  - Color Blindness & Metamerism
- Color Spaces
  - LMS, RGB, XYZ, HSV, L*a*b*, ….
- Color & Projection in Spatially Augmented Reality

Reading for This Week

- "Tree visualization with Tree-maps: A 2-d space-filling approach", Ben Shneiderman, 1991

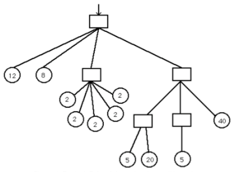


Figure 1: Typical 3-level tree structure with numbers indicating size of each leaf node

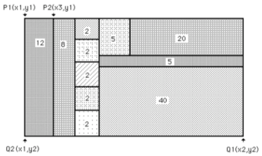
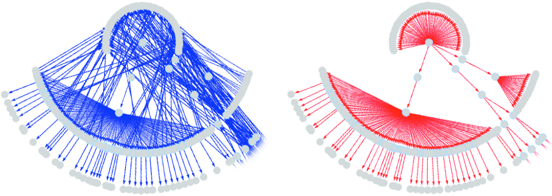


Figure 2: Tree-map of Figure 1

Reading for This Week

- "Heapviz: Interactive Heap Visualization for Program Understanding and Debugging" Aftandilian, Kelley, Gramazio, Ricci, Su, & Guyer, 2010



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Mid-Term Presentations

- 5 minutes per person (10 mins per team of 2)
- Short & polished "Elevator Pitch" style presentation
  - Laptop projection (e.g., powerpoint or live demo), *or*
  - Poster printed
- Revisit & extend a previous assignment
- Teams encouraged (not required)
- Formal peer feedback (incorporated into grade)

Mid-Term Presentations

- What do you need to present?
  - Motivation & audience
  - Technical implementation details (data collection & toolkit usage)
  - Analysis & effectiveness of your results
- Prepare material for both:
  - in class presentation
  - a written document for posting on course webpage

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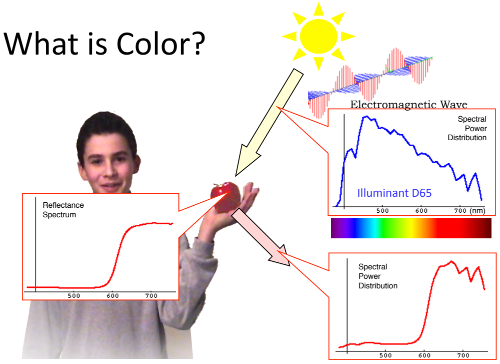
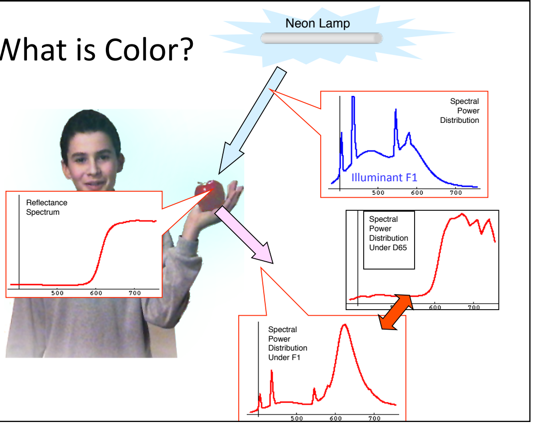
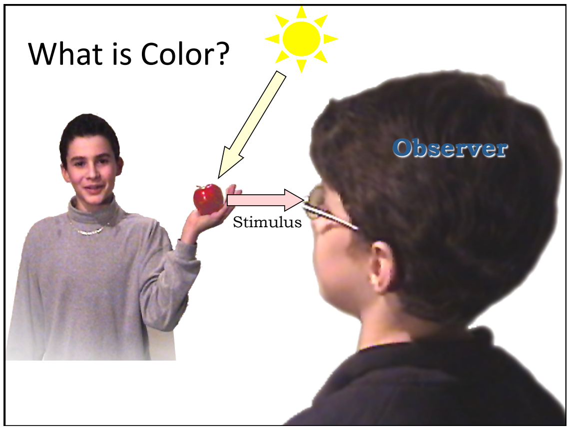
What is Color?



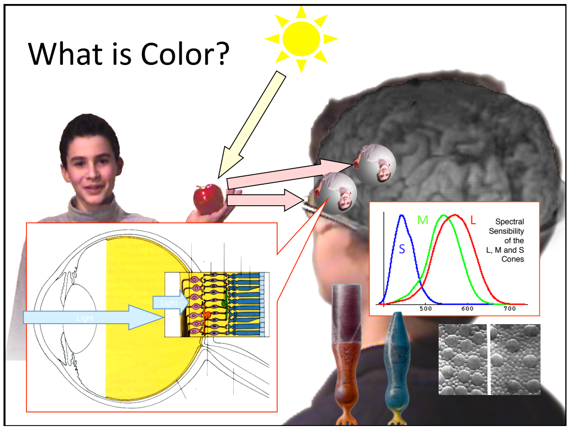
What is Color?

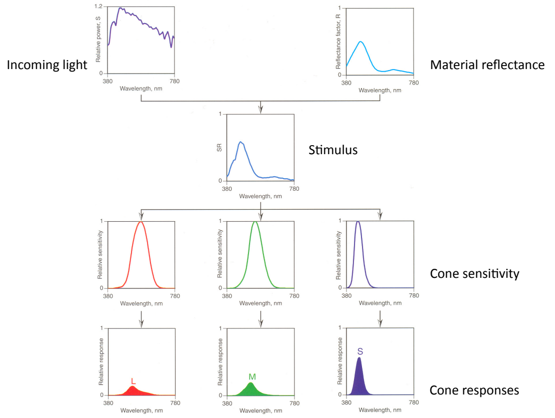


What is Color?



What is Color?





Incoming light

Material reflectance

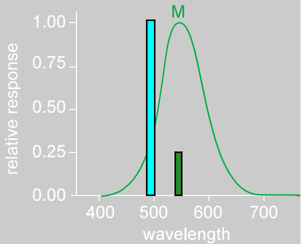
Stimulus

Cone sensitivity

Cone responses

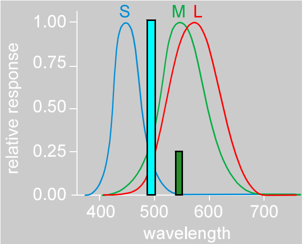
Cones do not “see” colors

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



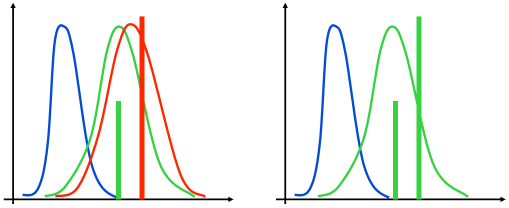
Response Comparison

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



Color Blindness

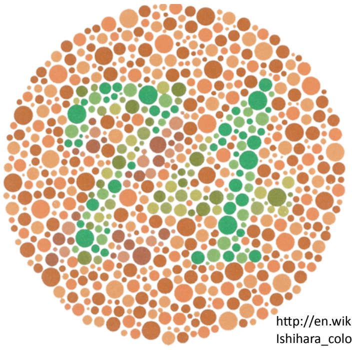
- Classical case: 1 type of cone is missing (e.g. red)
- Now Project onto lower-dim space (2D)
- Makes it impossible to distinguish some spectra



differentiated

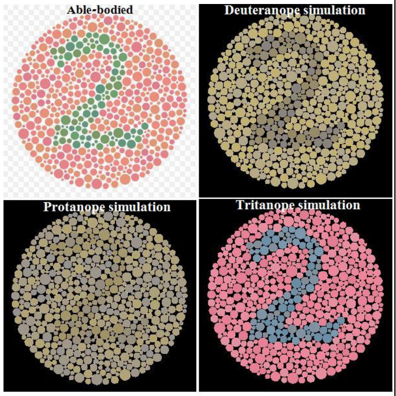
Same responses

Ishihara Color Blindness Test



http://en.wikipedia.org/wiki/ Ishihara_color_test

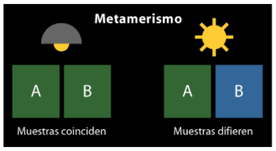
- Deuteranopia: missing green cone
- Protanopia: missing red cone
- Tritanopa: missing blue cone (rare)



http://en.wikipedia.org/wiki/File:Ishihara_compare_1.jpg

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

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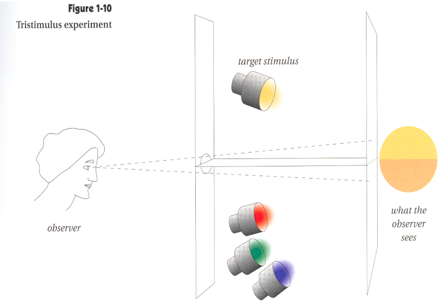
Standard Color Spaces

- 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…

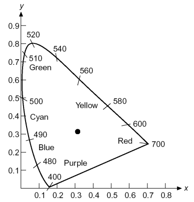
CIE Color Matching Experiments

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.

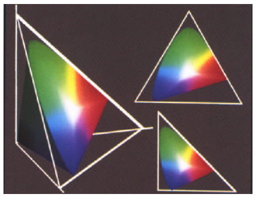
CIE XYZ Color Space



- 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!

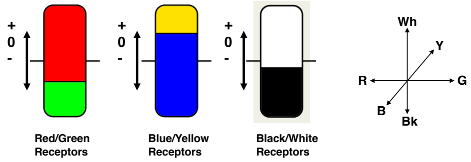
$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 3.24 & -1.54 & -0.50 \\ -0.97 & 1.88 & 0.04 \\ 0.06 & -0.20 & 1.06 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

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



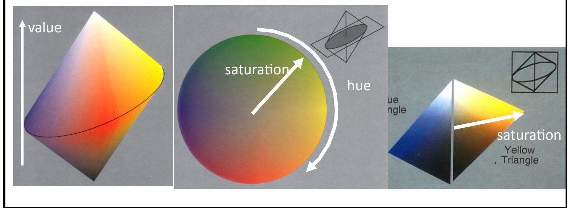
Hering 1874: Opponent Colors

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



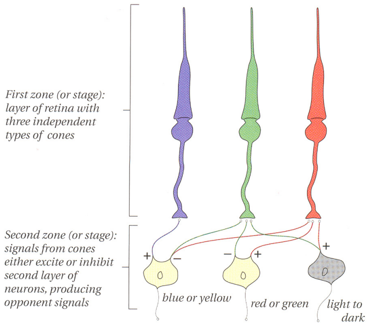
Hue Saturation Value (HSV)

- 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



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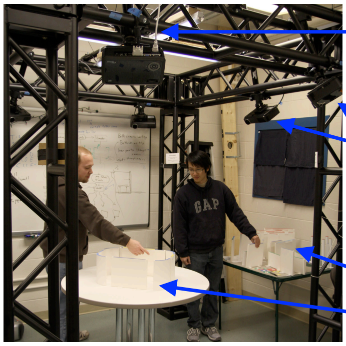
Spatially Augmented Reality (SAR) Projection

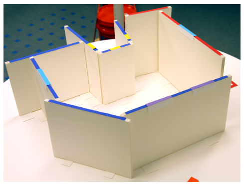


camera detects design geometry

6 projectors augment design

design sketched with foam-core walls

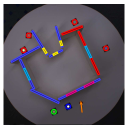
Tangible Interface for Architectural Design



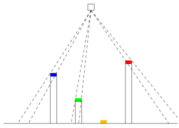
Exterior & interior walls

Tokens for:

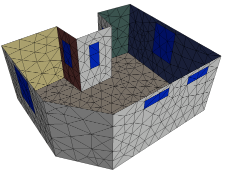
- *Windows*
- *Wall/floor colors*
- *North arrow*



Overhead camera

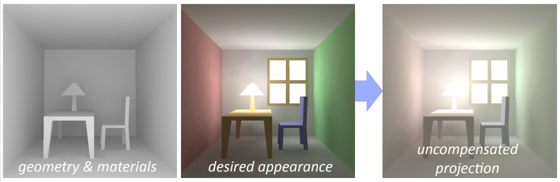


Projection geometry



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

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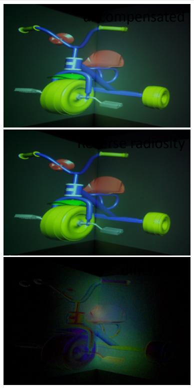
Related Work: Reverse Radiosity

- Forward lighting with radiosity

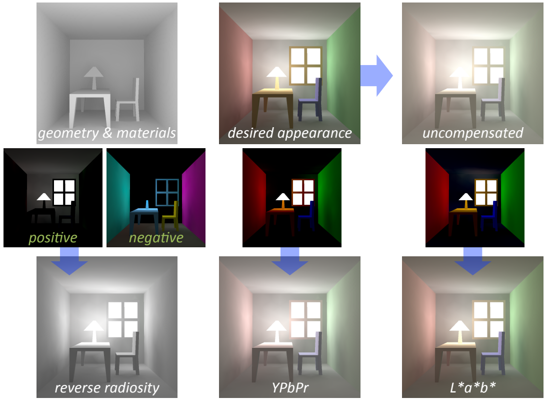
$$\underbrace{B}_{\textit{values for rendering}} = (I - \underbrace{F}_{\textit{form factor matrix}})^{-1} \underbrace{E}_{\textit{direct light}}$$

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

$$\underbrace{E}_{\textit{projection values}} = (I - F)\underbrace{B}_{\textit{desired appearance}}$$



Bimber et al. 2006



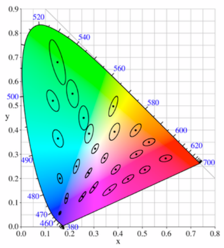
Sheng et al. 2010

Our new method

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]

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



http://en.wikipedia.org/wiki/File:CIExy1931_MacAdam.png

L*a*b*: a perceptual color space

Designed to match human color perception data

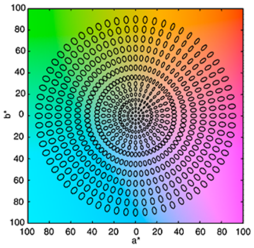
$$\begin{array}{r} \textit{intensity} \\ \textit{red-green} \\ \textit{yellow-blue} \end{array} \begin{bmatrix} L \\ a \\ b \end{bmatrix} = \begin{bmatrix} 116h(\frac{Y}{Y_n}) - 16 \\ 500\left(h(\frac{X}{X_n}) - h(\frac{Y}{Y_n})\right) \\ 200\left(h(\frac{Y}{Y_n}) - h(\frac{Z}{Z_n})\right) \end{bmatrix}$$

$$h(t) = \begin{cases} t^{\frac{1}{3}} & t > (6/29)^3 \\ \frac{1}{3}(\frac{29}{6})^2 t + \frac{4}{29} & \text{Otherwise} \end{cases}$$

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 ΔE = JND (just noticeable difference)
- The MacAdams ellipses are more equal size circles in L*a*b*



http://w3.kcua.ac.jp/~fujiwara/infosci/ellipses_lab.png

Our Optimization Formulation

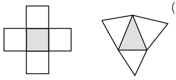
Absolute Error:

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

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

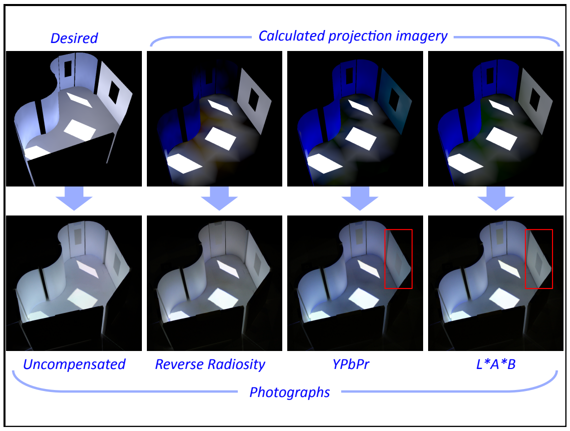
gradient in projection result

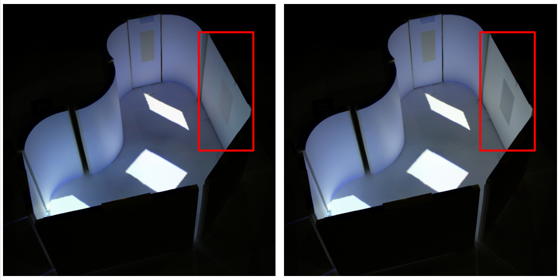
Complete Objective Function: $\phi = \alpha\phi_{abs} + (1 - \alpha)\phi_{spt}$

We use α = 0.9

Box constraints:

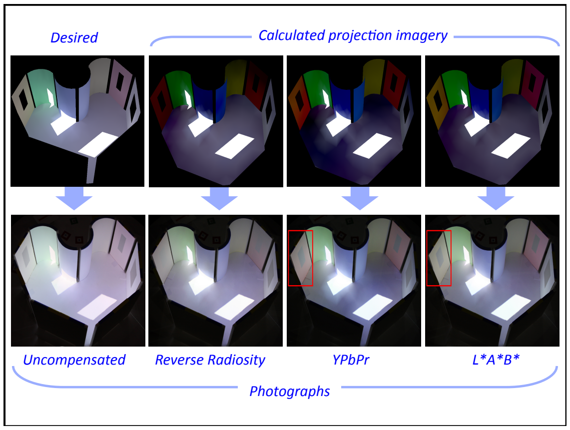
minimum & maximum brightness of projector system

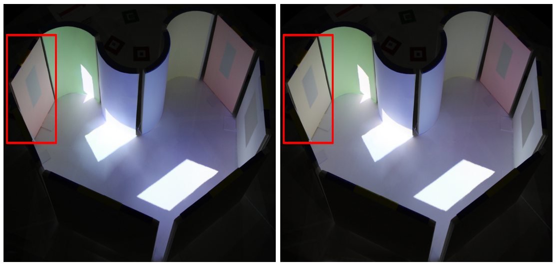




Sheng et al. 2010
Optimized in YPbPr space

New method
Optimized in L*A*B space





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.