Color

(some slides from Fredo Durand)

Elspeth McLean
https://www.elspethmclean.com/stones

Today's Class

- Announcements: Quiz & Final Projects
- Readings for Today
- What is Color?
  - Human Perception
  - Color Blindness & Metamerism
- Color Spaces
  - LMS, RGB, XYZ, HSV, L*a*b*, ….
- Projection in Spatially Augmented Reality

Final Presentation Schedule

9 min (individual)
+1 min questions/setup
16 min (team of 2)
+2 min questions/setup

Tue Apr 18th	*Fri Apr 21st*	*Tue Apr 25th*
2:00 team of 2	2:00 team of 2	2:00 team of 2
2:18 team of 2	2:18 team of 2	2:18 team of 2
2:36 team of 2	2:36 team of 2	2:36 team of 2
2:54 individual	2:54 individual	2:54 individual
3:04 team of 2	3:04 team of 2	3:04 team of 2
3:22 team of 2	3:22 team of 2	3:22 team of 2
3:40 team of 2	3:40 team of 2	3:40 team of 2
3:58 done!	*3:58 done!*	*3:58 done!*

Let me know ASAP if
this doesn't work for you

Final Presentation

- Summarize prior work as necessary
  - You don't need to discuss papers we covered in class
- Be technical:
  - What were the challenges?
  - How did you solve them?
- Live demo / video / lots of images (depends on project)
  - Use plenty of examples (both of success & failure)
- Teams of 2:
  - Both should present & make it clear who did what
- Use your time wisely! Practice! & time yourself!
  - *I will stop you mid-sentence if you run over*

Well-written Research Paper / Report

- Motivation/context/related work
- Accomplishments / contributions of this work
- Clear description of algorithm
  - Sufficiently-detailed to allow work to be reproduced
  - Work is theoretically sound
    (hacks/arbitrary constants discouraged, but must be documented)
- Results
  - well chosen examples
  - clear tables/illustrations/visualizations
  - with descriptive captions!
- Conclusions & Potential Future Work
  - limitations of the method are clearly stated

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Reading for Today:

"Flash Photography Enhancement via Intrinsic Relighting", Eisemann & Durand, SIGGRAPH 2004

no flash
warm ambiance, noisy

flash
flat lighting

combined result:
original lighting, denoised

Reading for Today:

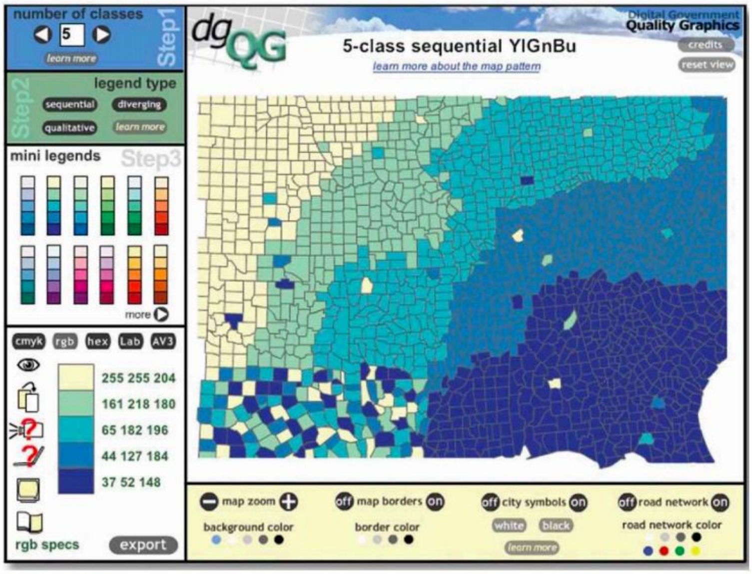
"Real-Time User-Guided Image Colorization with Learned Deep Priors", Zhang, Zhu, Isola, Geng, Lin, Yu, and Efros, SIGGRAPH 2017

Suggested colors

Different possible colorizations

Reading for Today:

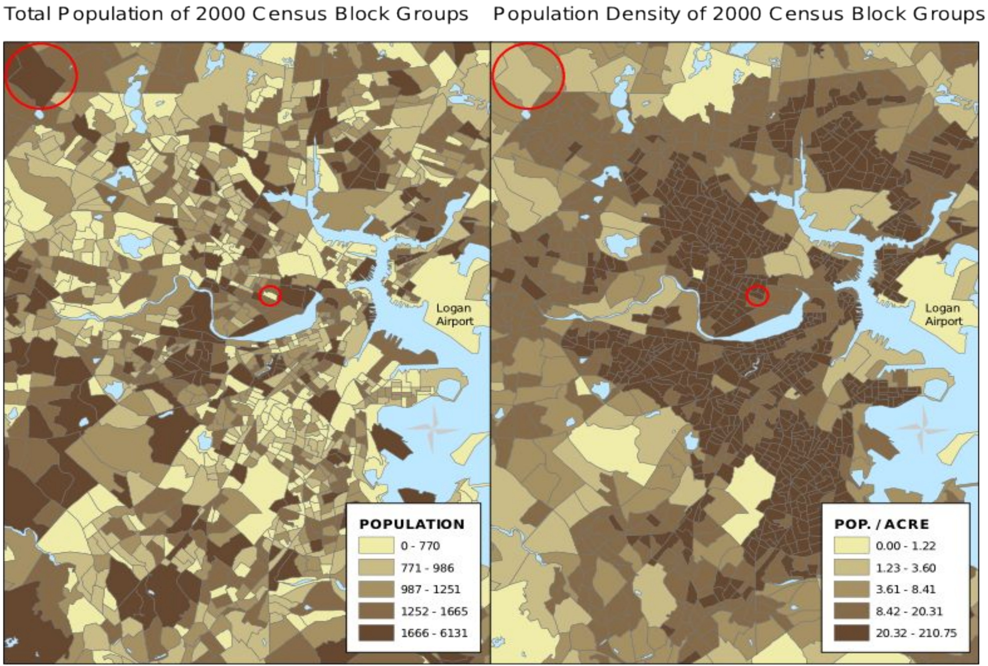
"ColorBrewer.org: An Online Tool for Selecting Colour Schemes for Maps", Harrower & Brewer, The Cartographic Journal, 2003.



5-class sequential YlGnBu

255 255 204
161 218 180
65 182 196
44 127 184
37 52 148

Choropleth map: statistics per area
must be careful about normalization



Total Population of 2000 Census Block Groups

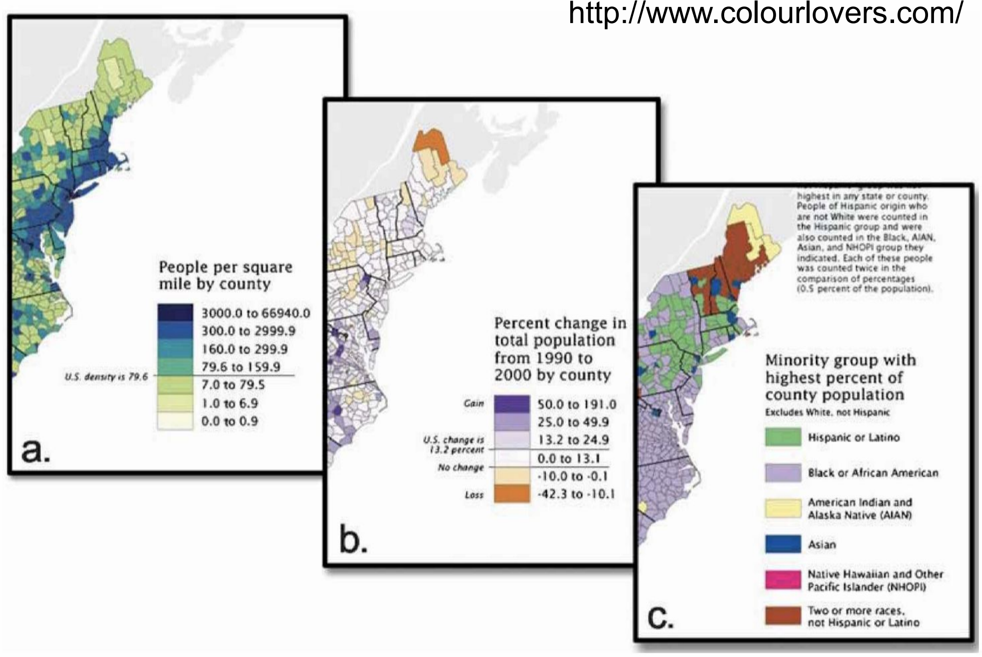
Population Density of 2000 Census Block Groups

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

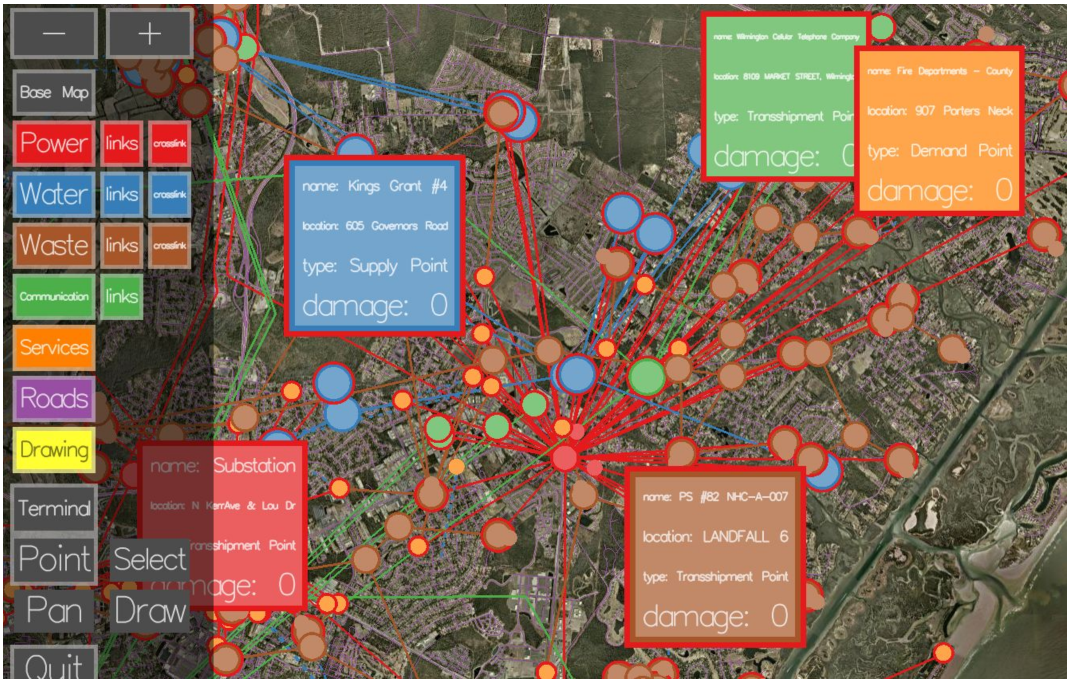
Choose a scheme appropriate for:

- Sequential
- Qualitative
- Diverging

Related online tools:
https://kuler.adobe.com/
http://www.checkman.io/please/
http://paletton.com/
http://colorbrewer2.org/
http://www.colourlovers.com/



Emergency Response Decision Making



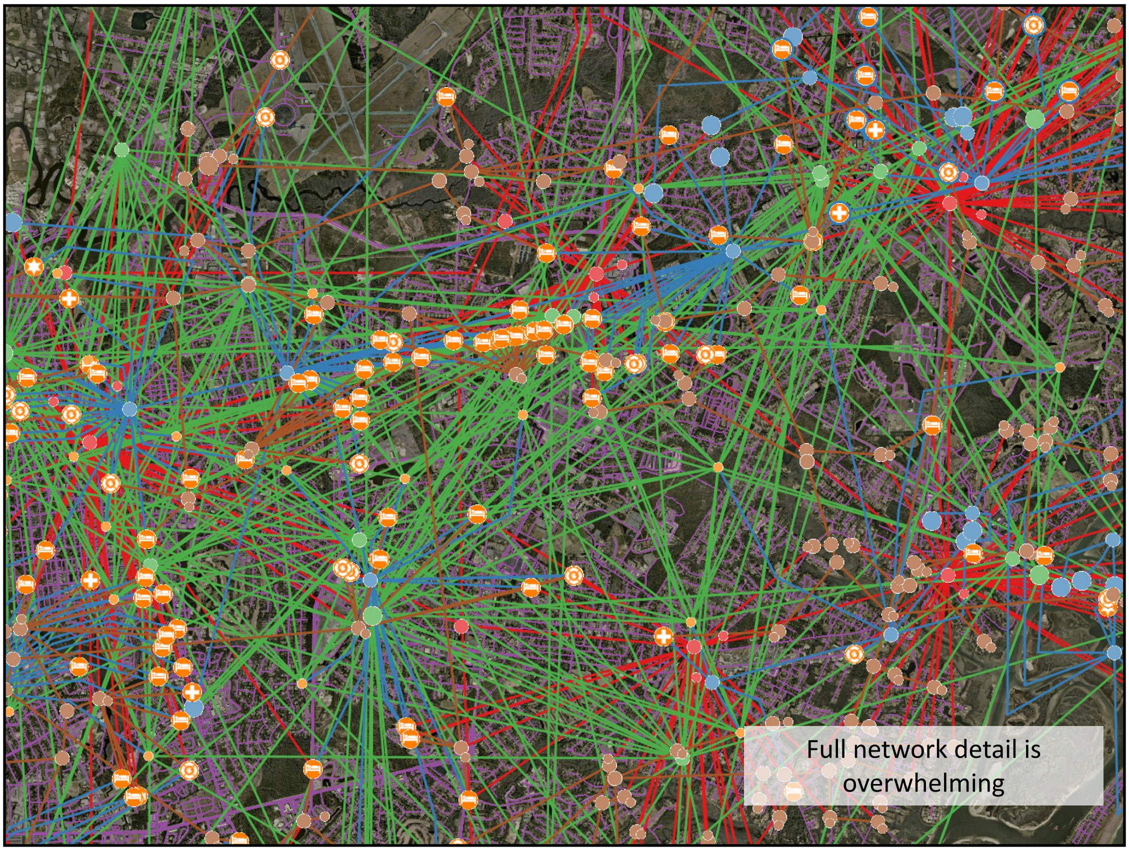
name: Wilmington Cellular Telephone Company
location: 8109 MARKET STREET, Wilmingt
type: Transshipment Poi
damage:

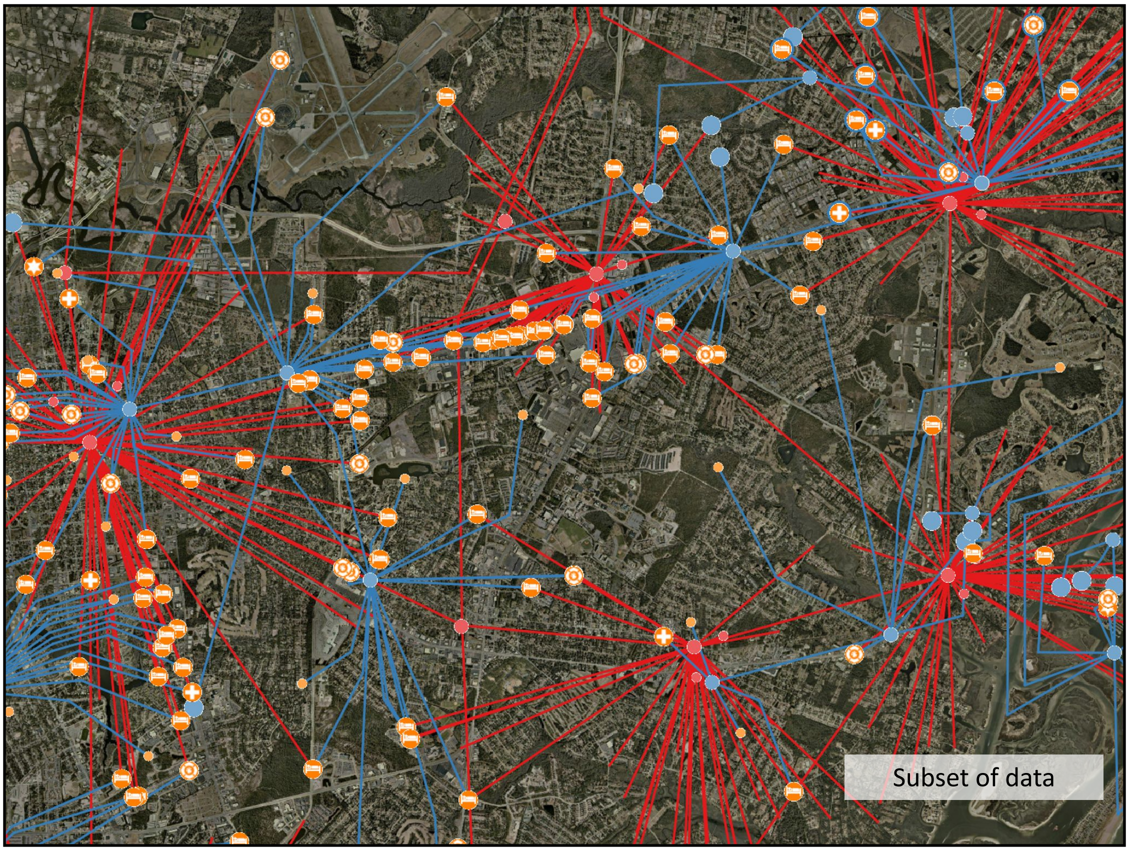
name: Fire Departments – County
location: 907 Porters Neck
type: Demand Point
damage: 0

name: Kings Grant #4
location: 605 Governors Road
type: Supply Point
damage: 0

name: Substation
location: N KerrAve & Lou Dr
type: ransshipment Point
damage: 0

name: PS #82 NHC-A-007
location: LANDFALL 6
type: Transshipment Point
damage: 0


Full network detail is overwhelming


Subset of data

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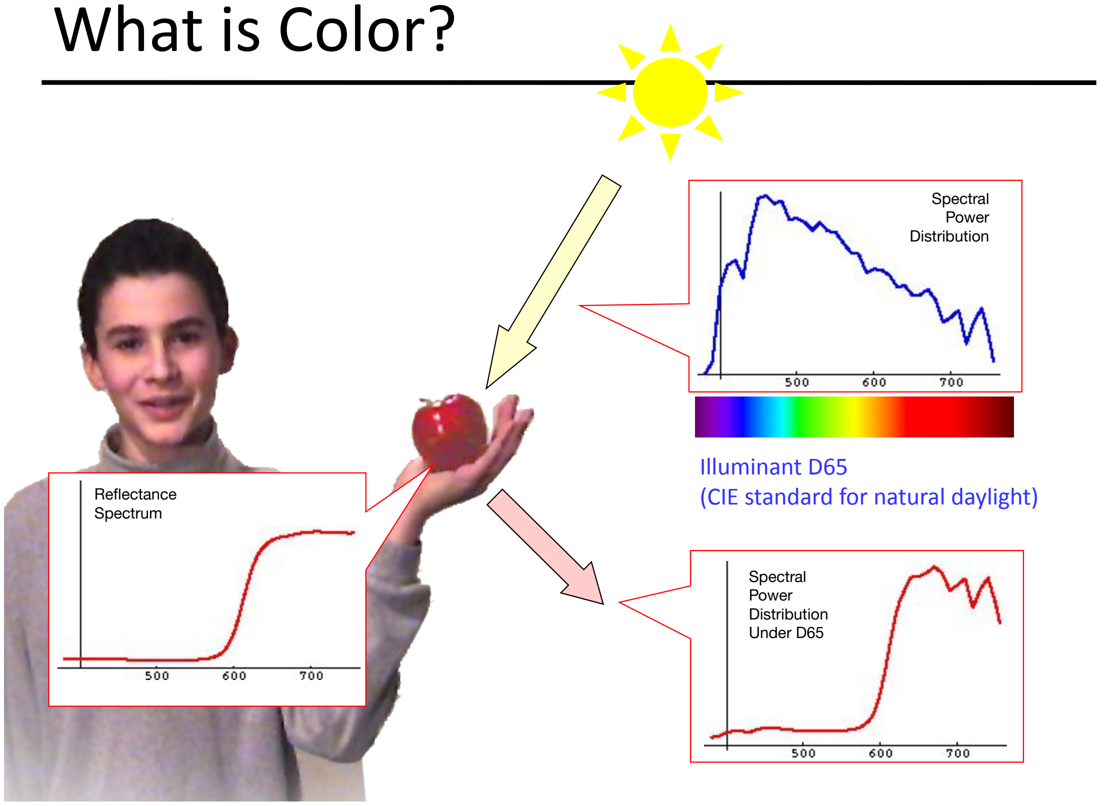
What is Color?

What is Color?



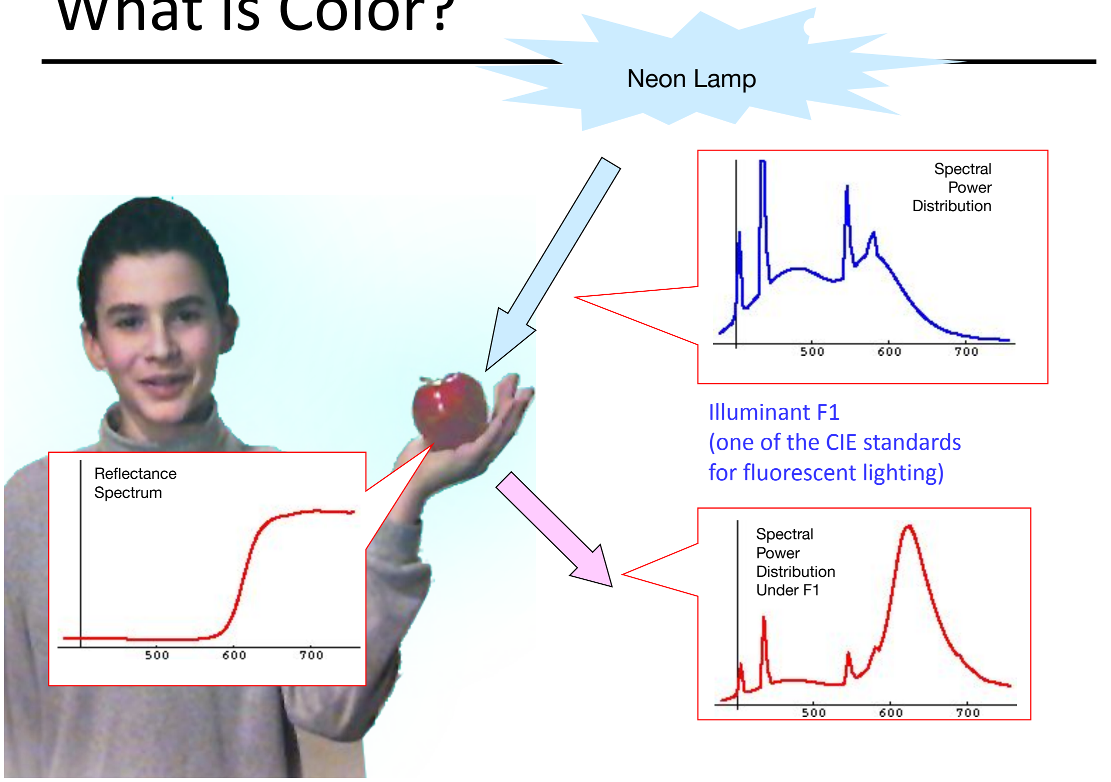
Spectral Power Distribution

Illuminant D65
(CIE standard for natural daylight)

Reflectance Spectrum

Spectral Power Distribution Under D65

What is Color?



Neon Lamp

Spectral Power Distribution

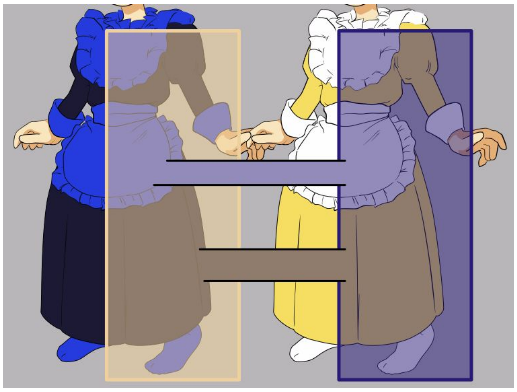
Illuminant F1
(one of the CIE standards
for fluorescent lighting)

Reflectance Spectrum

Spectral Power Distribution Under F1

What color is the dress?

What does the viewer infer about the scene illumination?

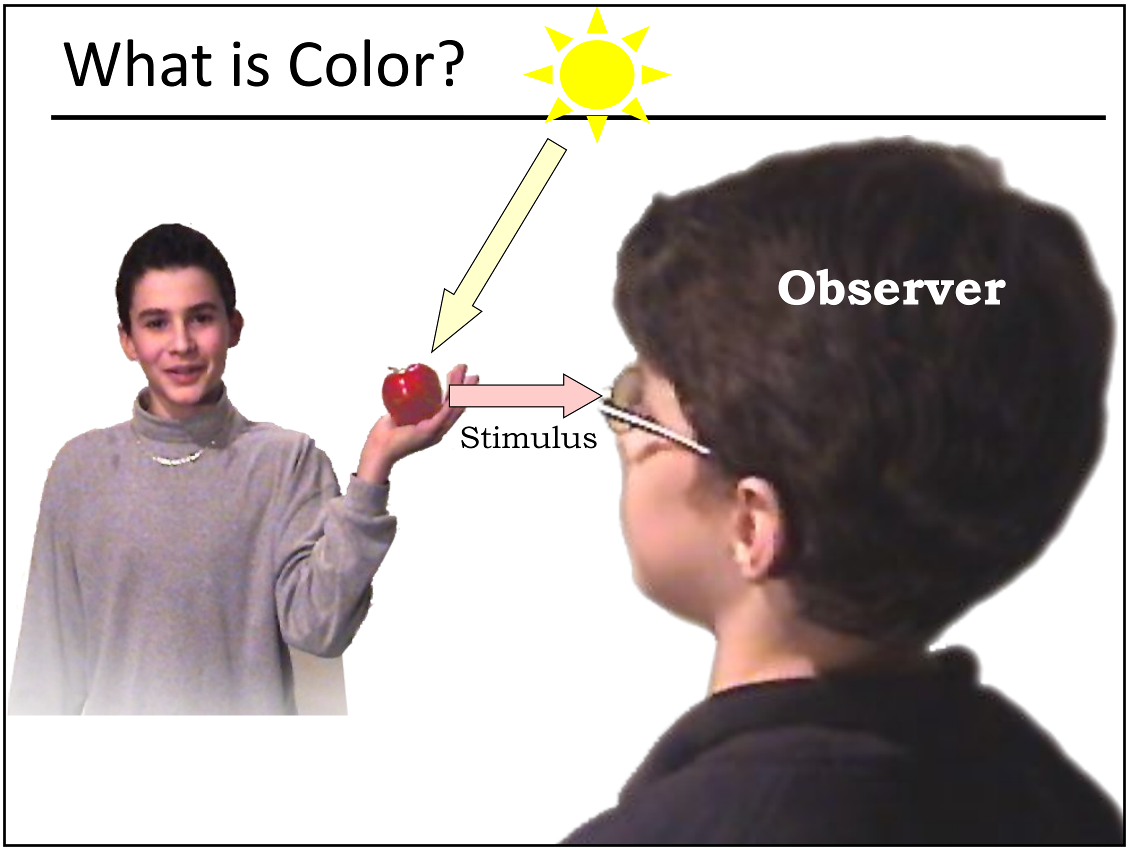


Blue & Black under yellow-tinted illumination?

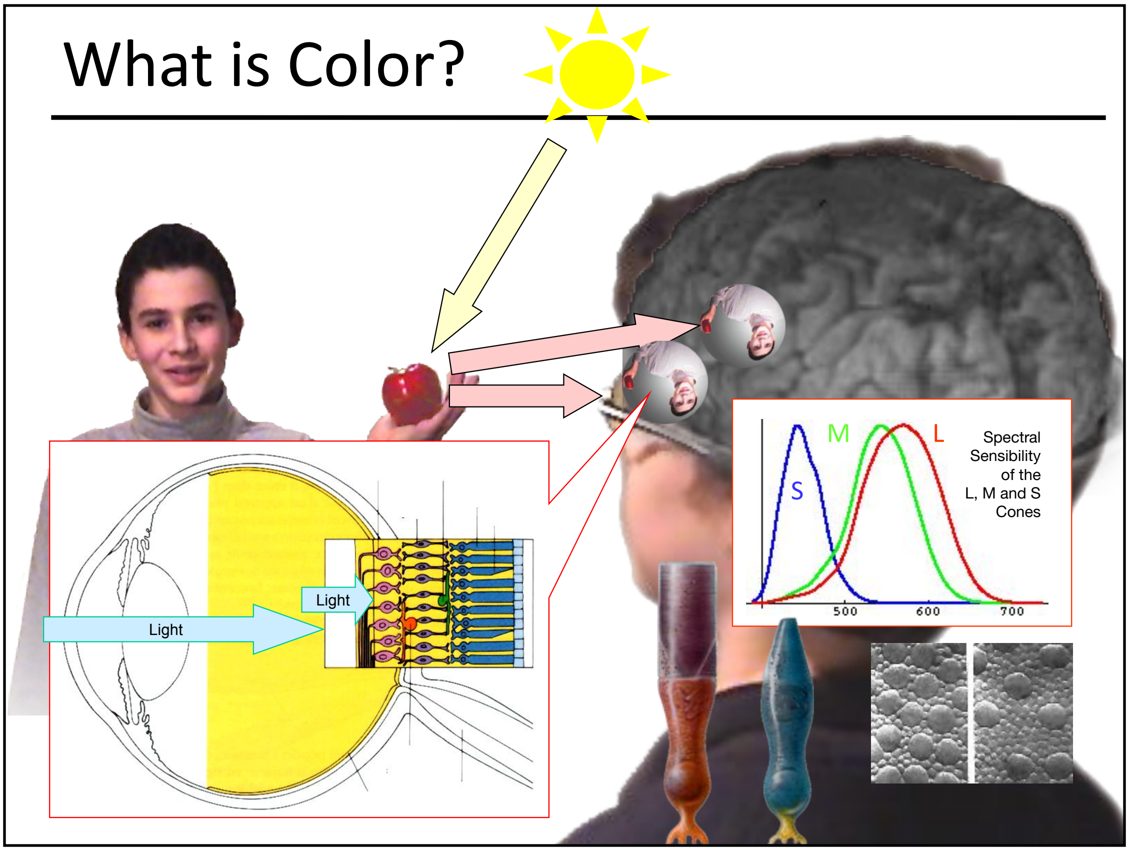
White & Gold under blue tinted illumination?

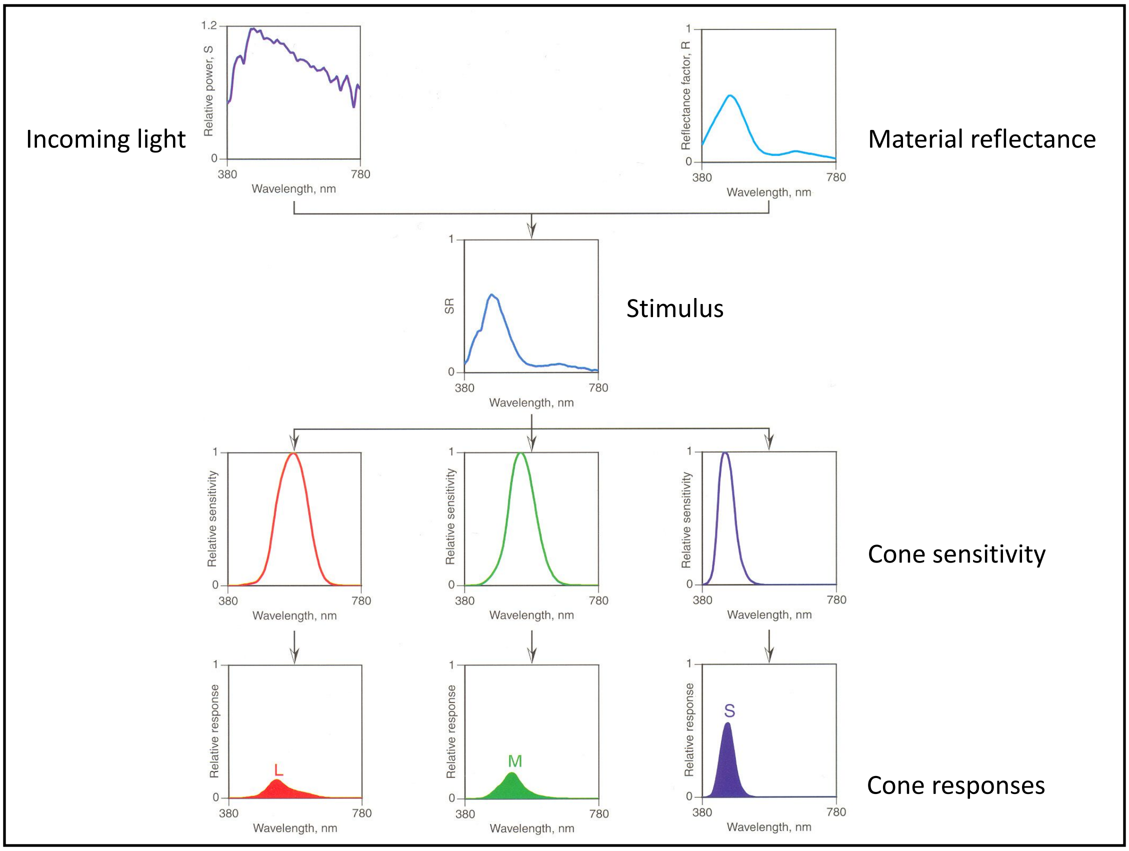
https://en.wikipedia.org/wiki/The_dress

What is Color?



What is Color?





Incoming light

Material reflectance

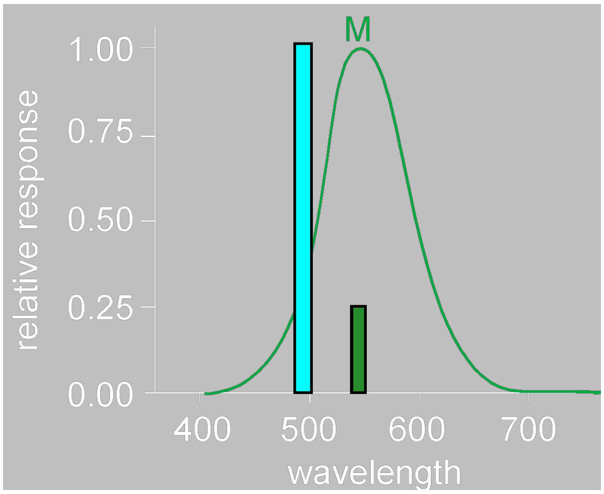
Stimulus

Cone sensitivity

Cone responses

Cones do not “See” Colors

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

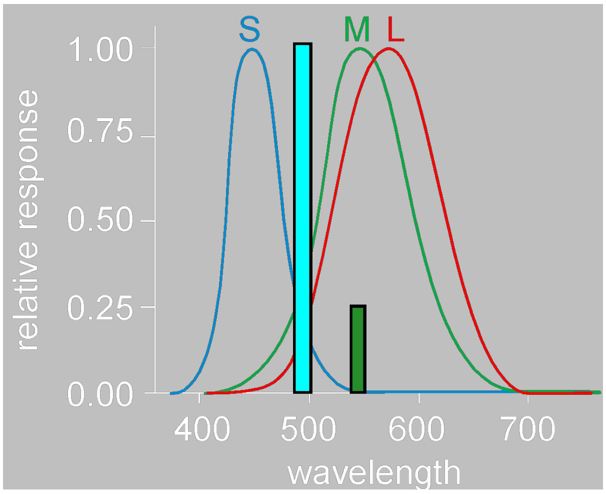


Dim green
Cone G: 0.25

Bright cyan
Cone G: 0.25

Response Comparison

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

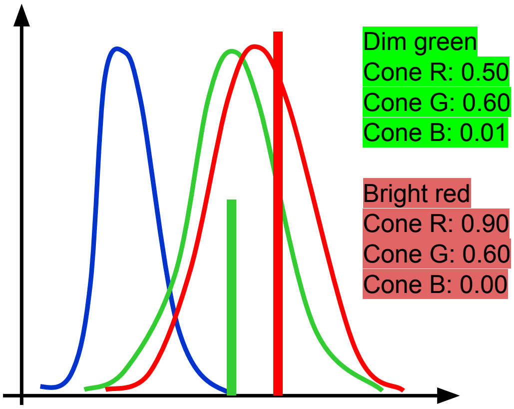


Dim green
Cone R: 0.20
Cone G: 0.25
Cone B: 0.01

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

Color Blindness

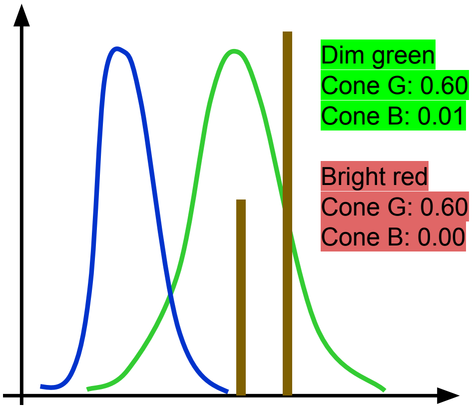
- Classical case: 1 type of cone is missing (e.g. red)
- Now Project onto lower-dim space (2D)
- Makes it impossible to distinguish some spectra



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

3 cones: Can be differentiated

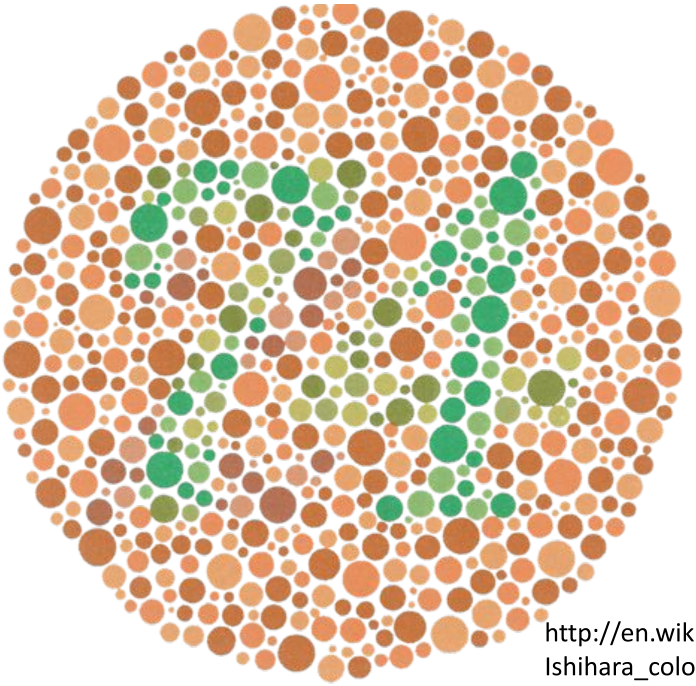


Dim green
Cone G: 0.60
Cone B: 0.01

Bright red
Cone G: 0.60
Cone B: 0.00

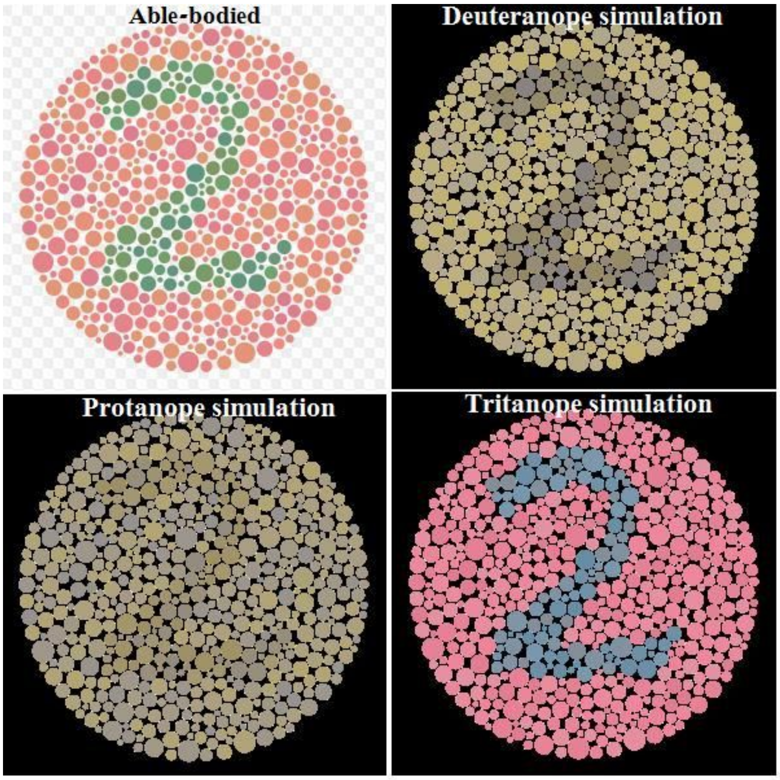
2 cones: Same responses

Ishihara Color Blindness Test



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

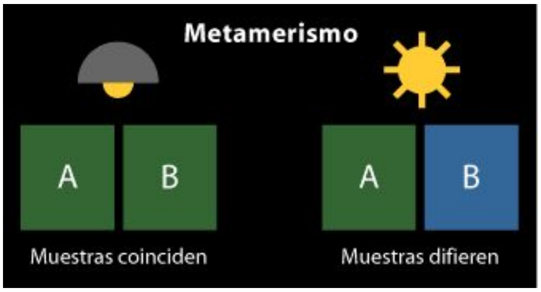
- Deuteranopia: missing green cone
- Protanopia: missing red cone
- Tritanopa: missing blue cone (rare)



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:

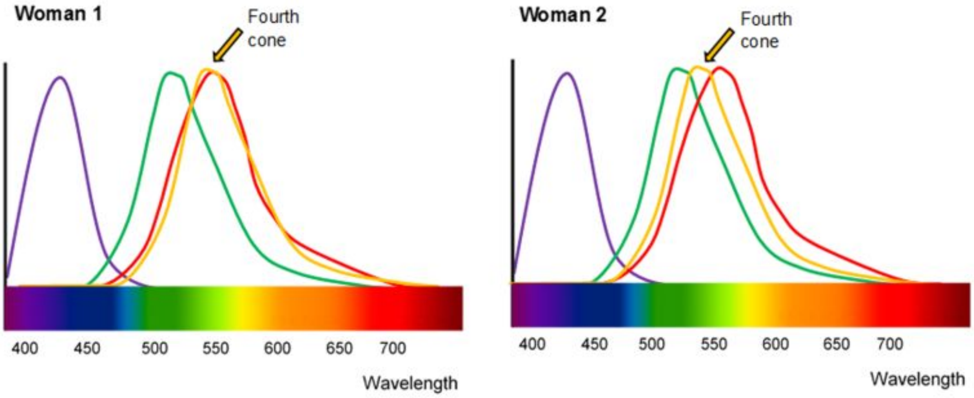


http://gusgsm.com/metamerismo

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

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.



https://theneurosphere.com/2015/12/17/the-mystery-of-tetrachromacy-if-12-of-women-have-four-cone-types-in-their-eyes-why-do-so-few-of-them-actually-see-more-colours/

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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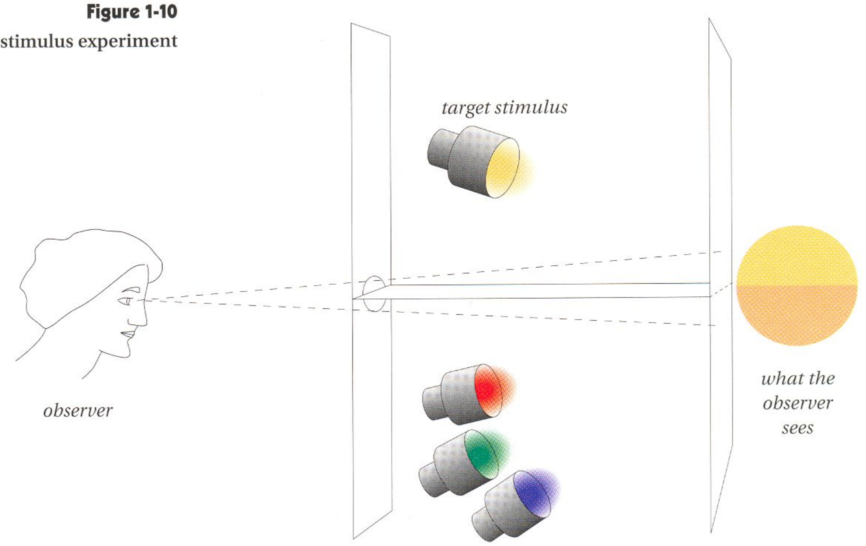
Standard Color Spaces

- 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



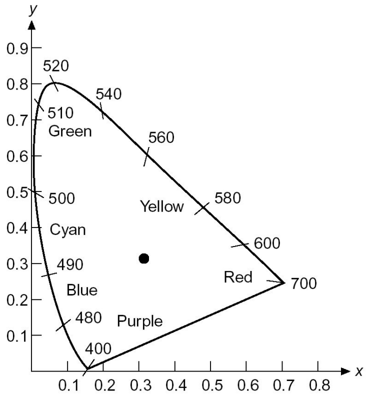
The observer adjusts the intensities of the red, green, and blue lamps until they match the target stimulus on the split screen.

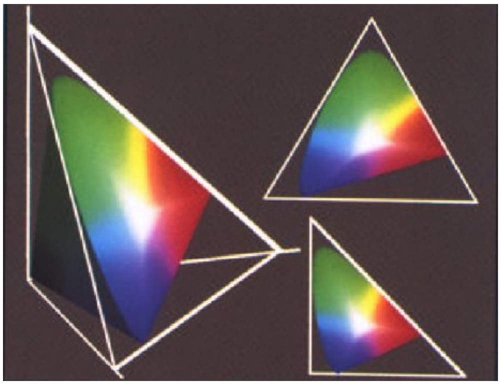
CIE XYZ Color Space

- 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!

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

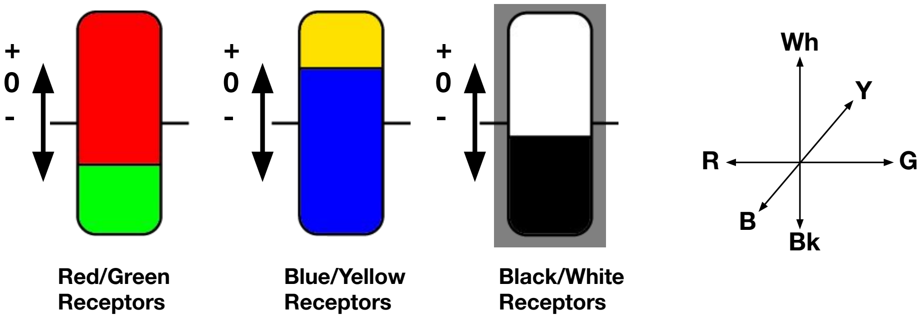
$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0.41 & 0.36 & 0.18 \\ 0.21 & 0.72 & 0.07 \\ 0.02 & 0.12 & 0.95 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$





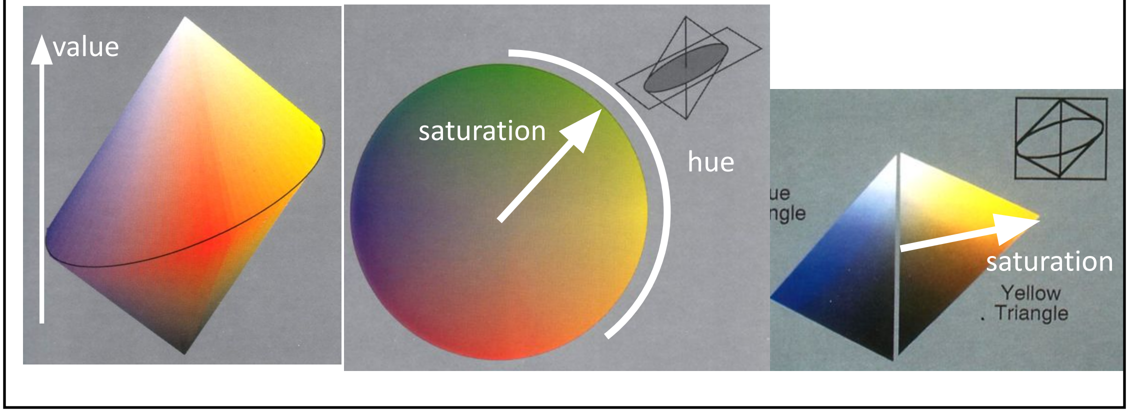
Hering 1874: Opponent Colors

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



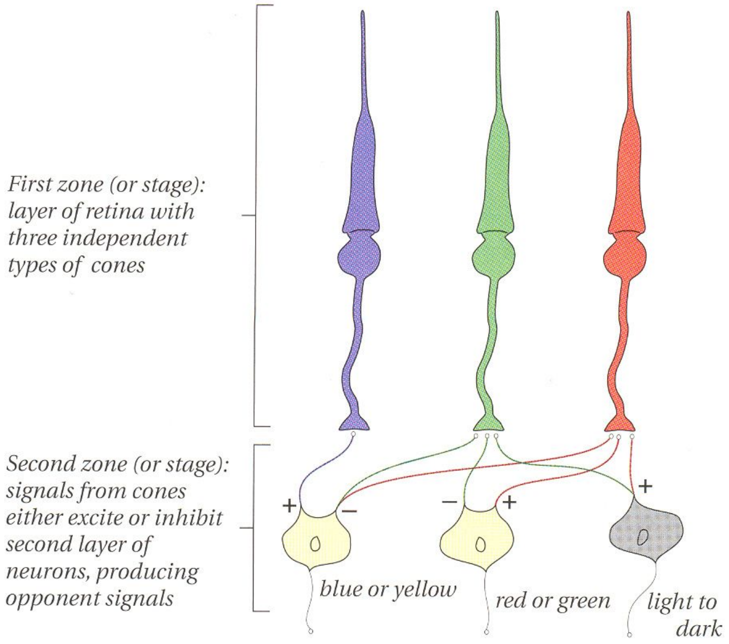
Hue Saturation Value (HSV)

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



Color Opponents “Wiring”

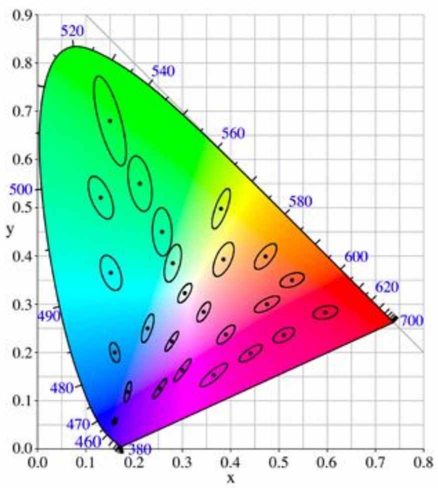
- Sums for bright
- Differences for color oppor
- It’s just a 3x3 matrix to convert HSV from/to LMS, RGB, or XYZ



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]

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



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

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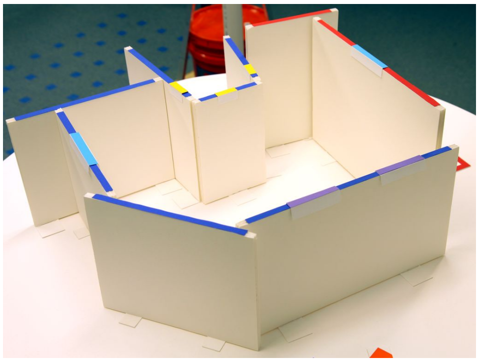
Spatially Augmented Reality (SAR) Projection

camera detects design geometry

6 projectors augment design

design sketched with foam-core walls

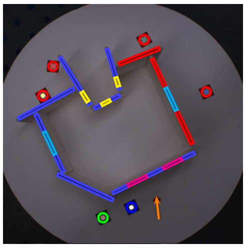
Tangible Interface for Architectural Design



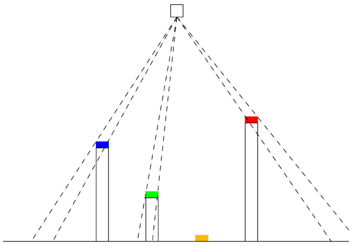
Exterior & interior walls

Tokens for:

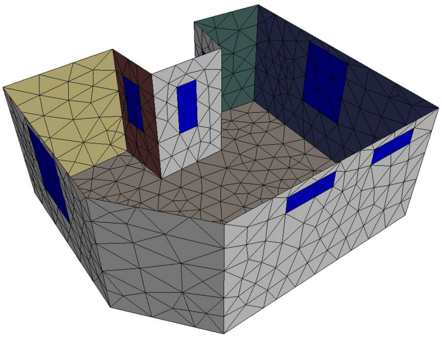
- *Windows*
- *Wall/floor colors*
- *North arrow*



Overhead camera

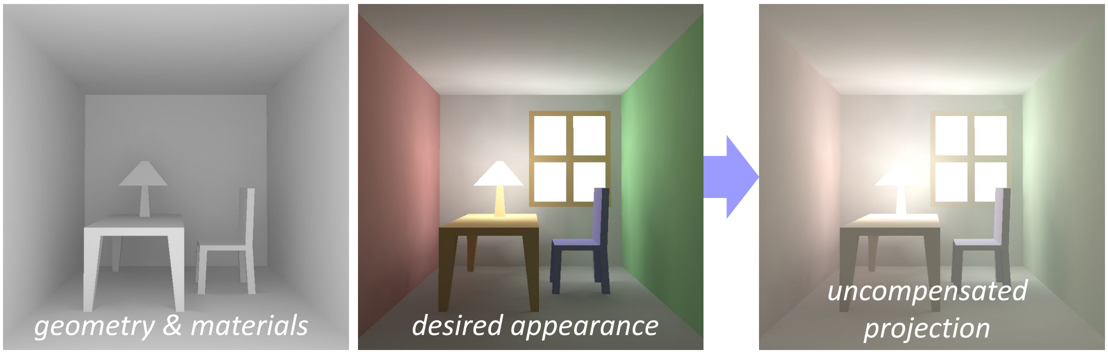


Projection geometry



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

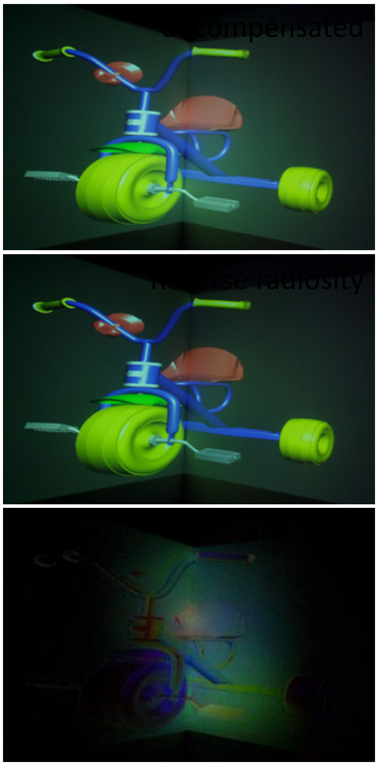
Forward lighting with radiosity

$$\underset{\substack{\nearrow \\ \textit{values for} \\ \textit{rendering}}}{B} = \underset{\substack{\uparrow \\ \textit{form factor} \\ \textit{matrix}}}{(I - F)^{-1}} \underset{\substack{\nwarrow \\ \textit{direct} \\ \textit{light}}}{E}$$

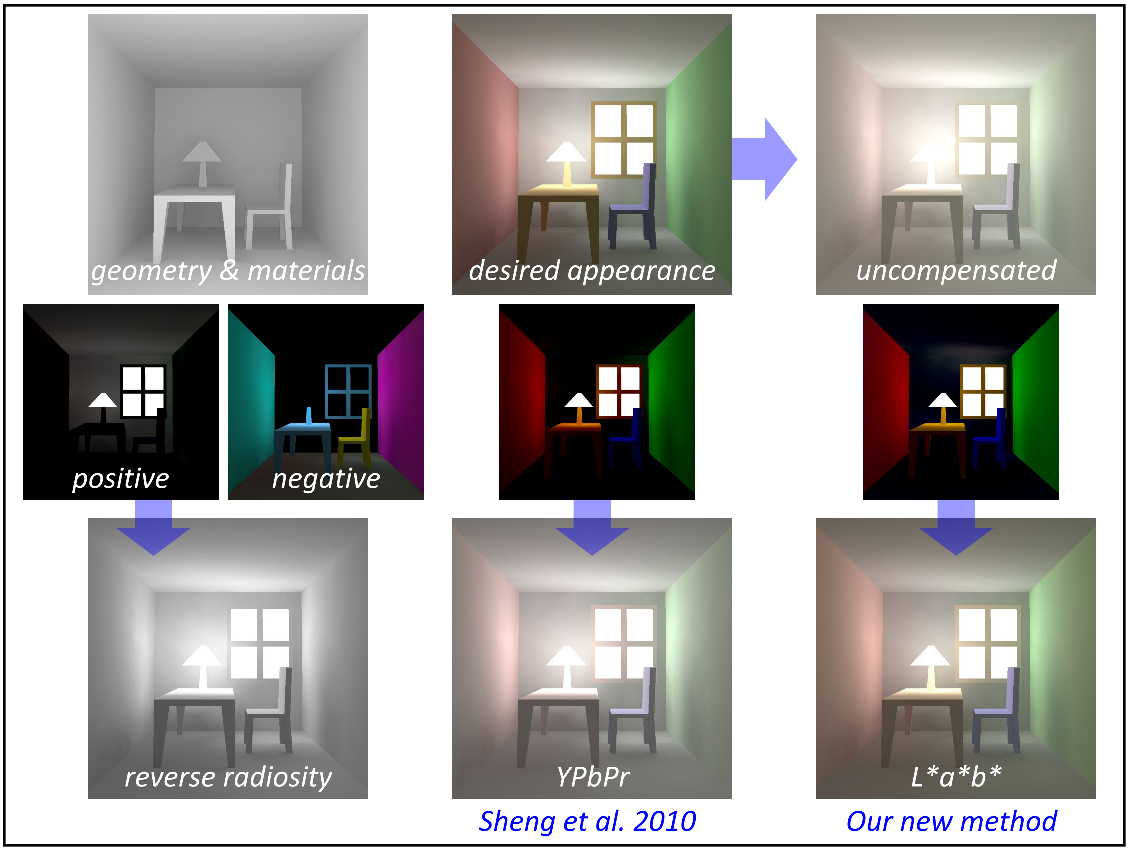
Inverse lighting with radiosity:
Reverse Radiosity (RR)

- [Bimber et al. 2006]

$$\underset{\substack{\nearrow \\ \textit{projection values}}}{E} = (I - F)\underset{\substack{\nwarrow \\ \textit{desired appearance}}}{B}$$



Bimber et al. 2006



L*a*b*: a perceptual color space

Designed to match human color perception data

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

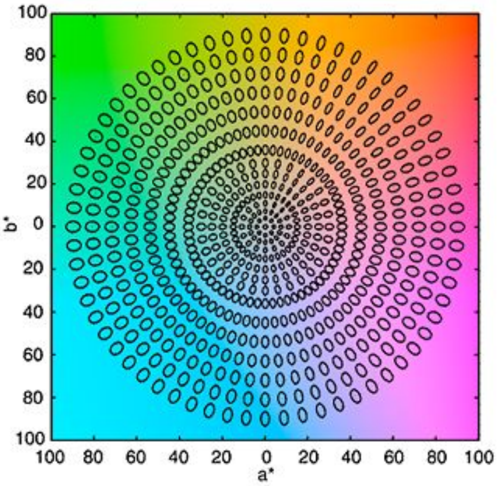
$$h(t) = \begin{cases} t^{\frac{1}{3}} & t > (6/29)^3 \\ \frac{1}{3}(\frac{29}{6})^2 t + \frac{4}{29} & \text{Otherwise} \end{cases}$$

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

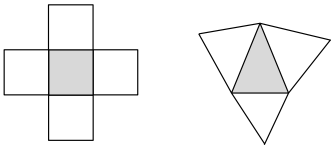
Our Optimization Formulation

Absolute Error:

desired appearance *projection result*

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

Spatial Error:



$$\phi_{spt} = \sum_{(i,j)\in nbd} [(L_i - L_j) - (L_i' - L_j')]^2 + [(a_i - a_j) - (a_i' - a_j')]^2 + [(b_i - b_j) - (b_i' - b_j')]^2$$

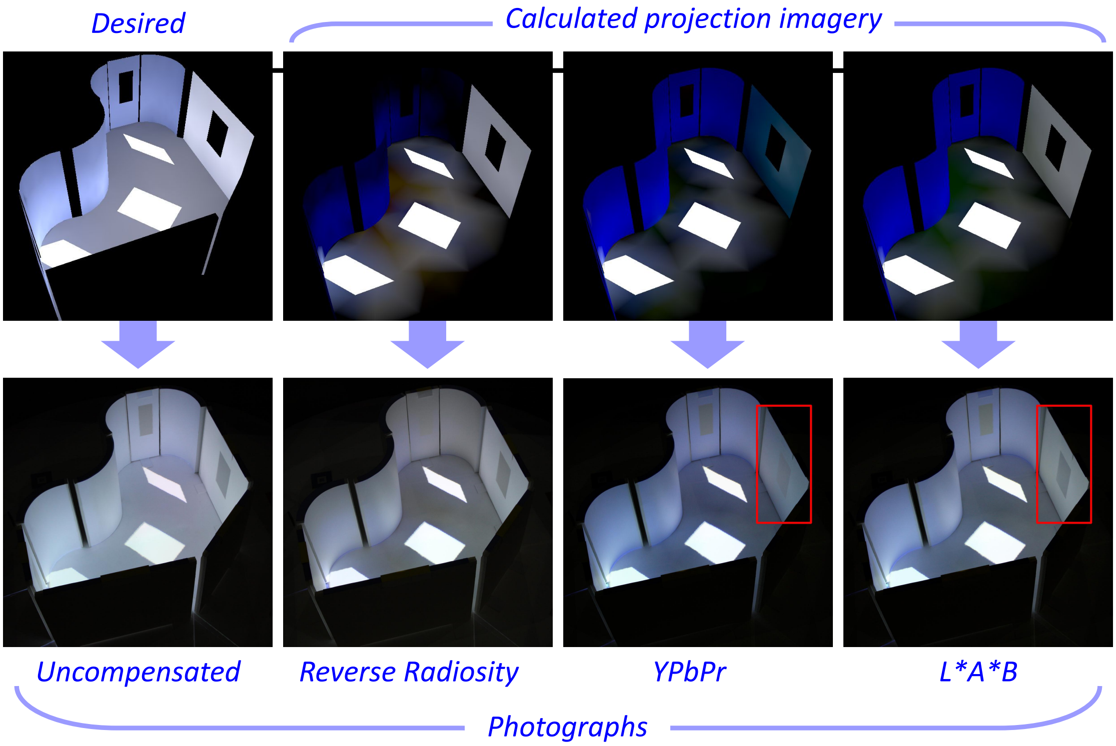
gradient in desired appearance *gradient in projection result*

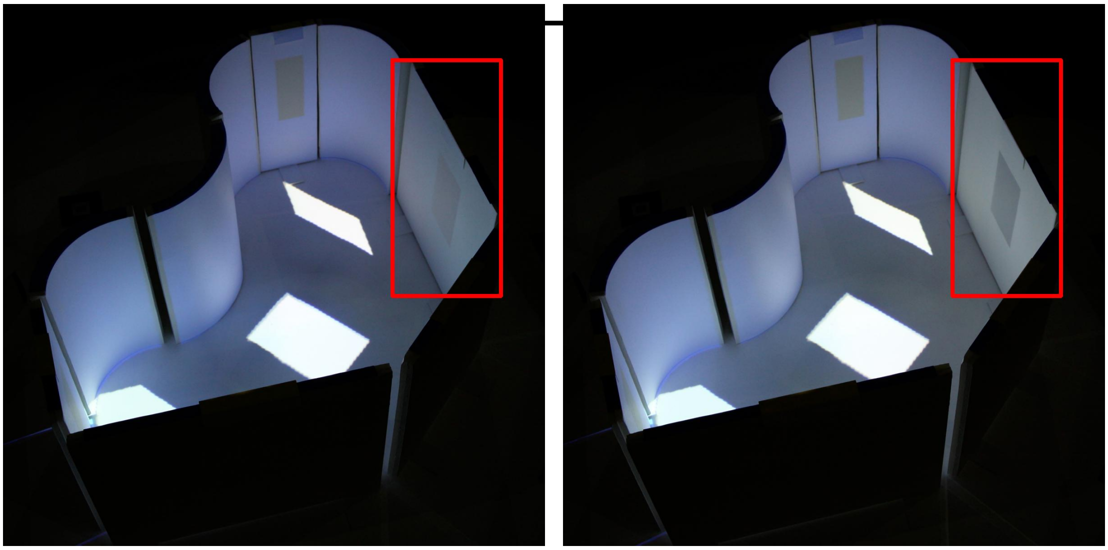
Complete Objective Function: $\phi = \alpha\phi_{abs} + (1-\alpha)\phi_{spt}$

We use α = 0.9

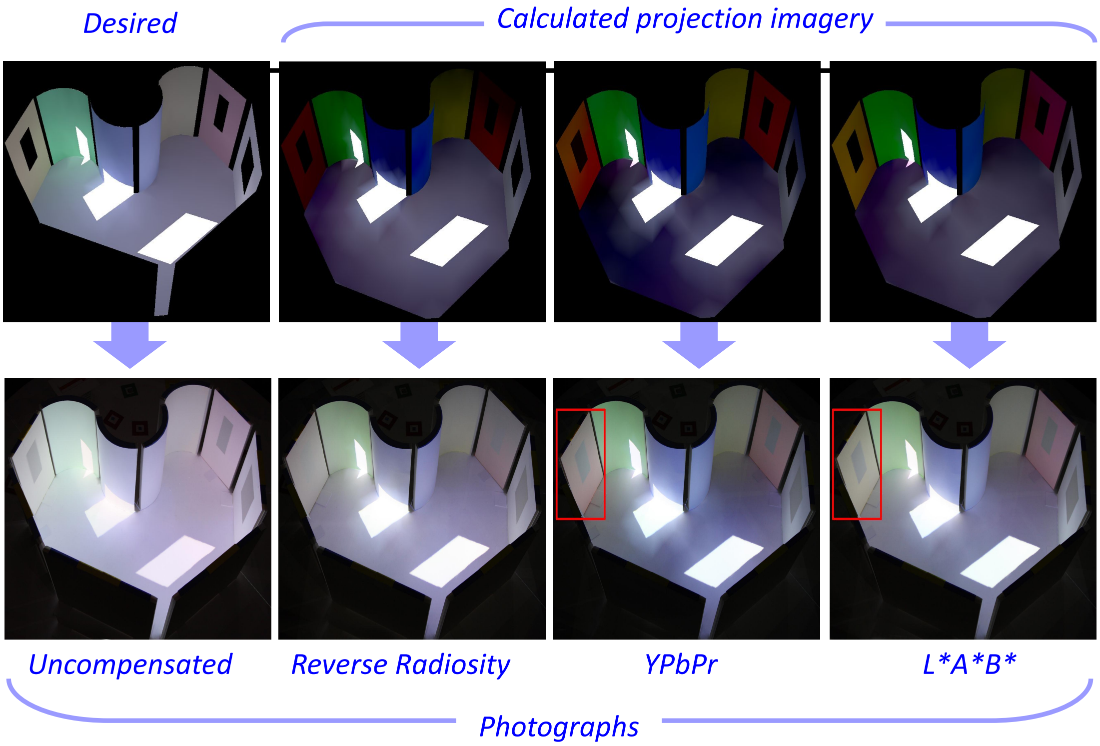
Box constraints:

minimum & maximum brightness of projector system




Sheng et al. 2010
Optimized in YPbPr space

New method
Optimized in L*A*B space



Desired

Calculated projection imagery

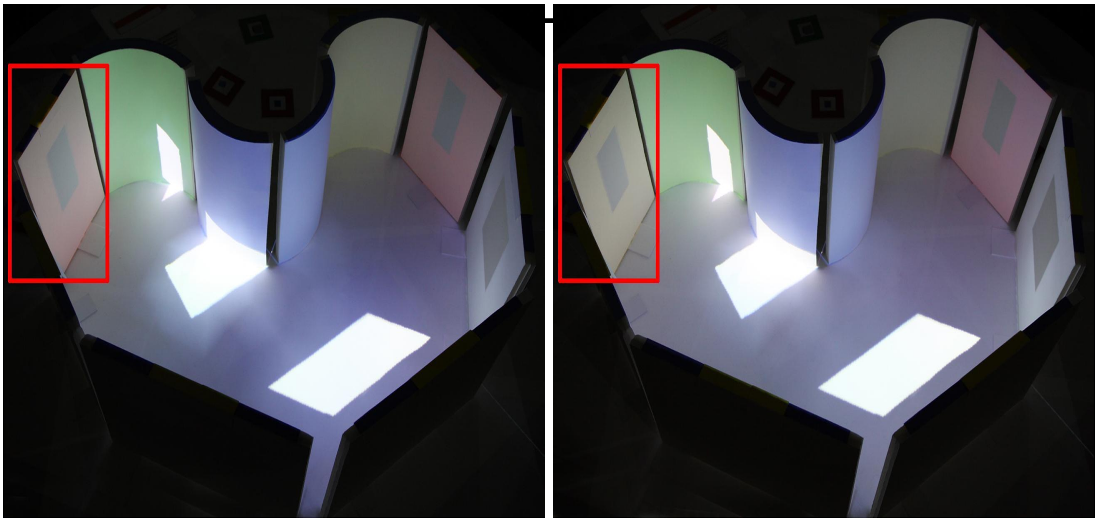
Uncompensated

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.