CSCI 4550/6550 Interactive Visualization

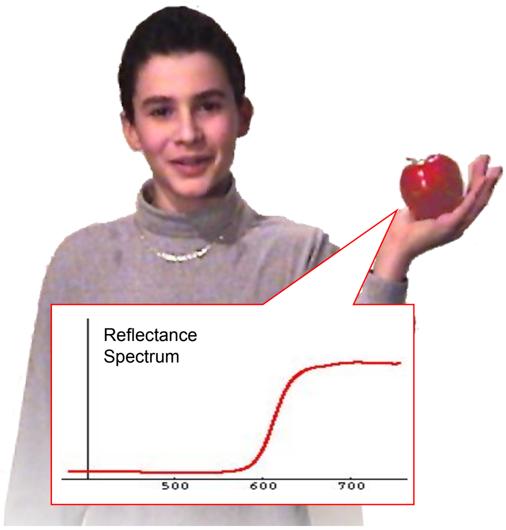
https://www.cs.rpi.edu/~cutler/classes/visualization/S24/

Lecture 7: Human Perception & Color Spaces

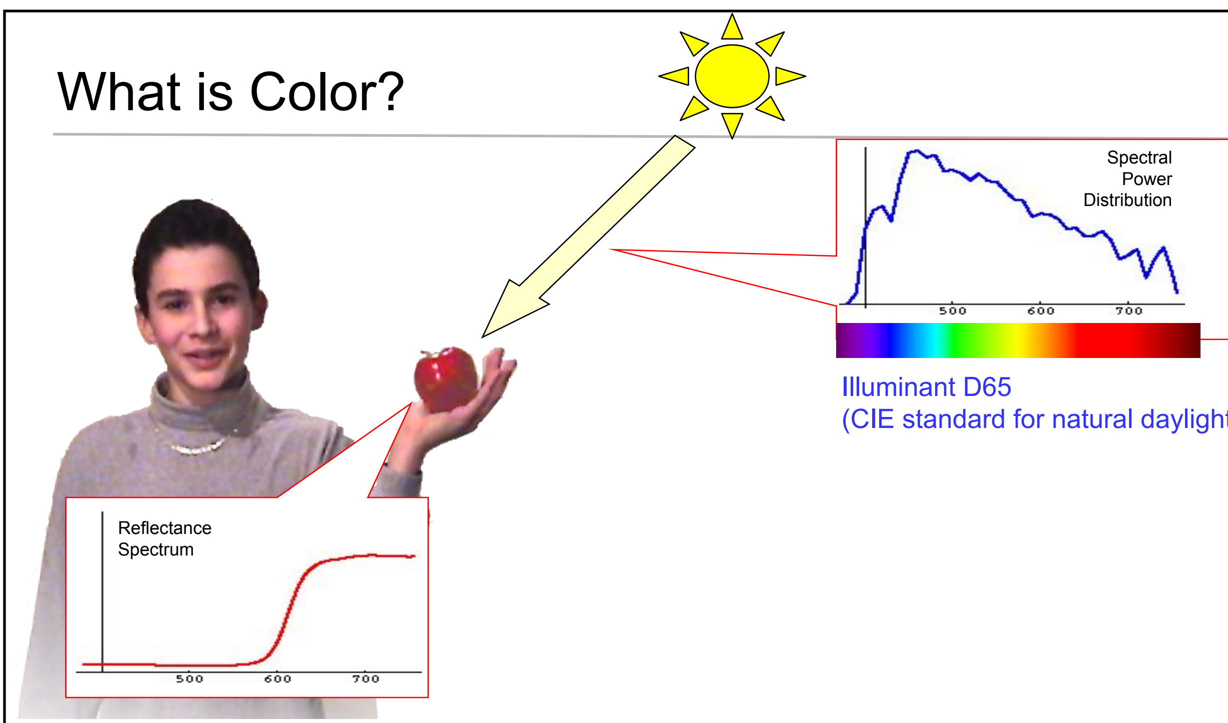
Today

- 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

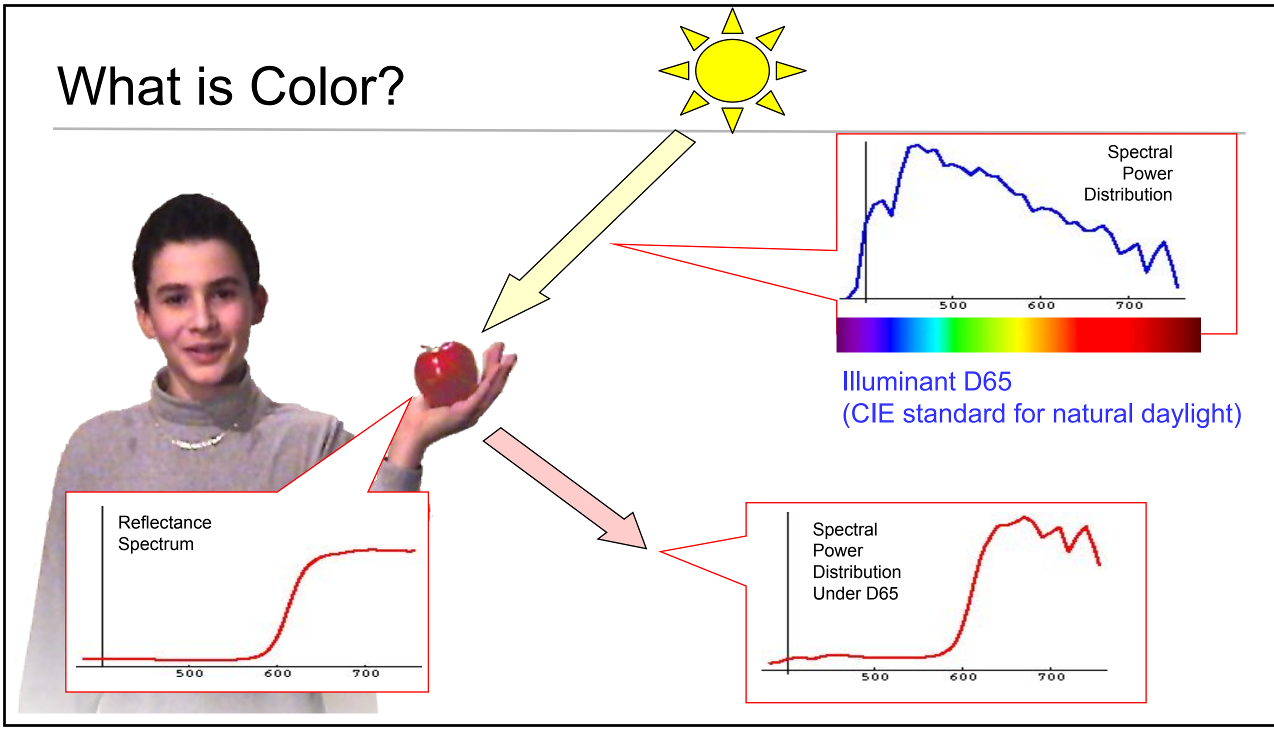
What Color is this Apple? What is Color?

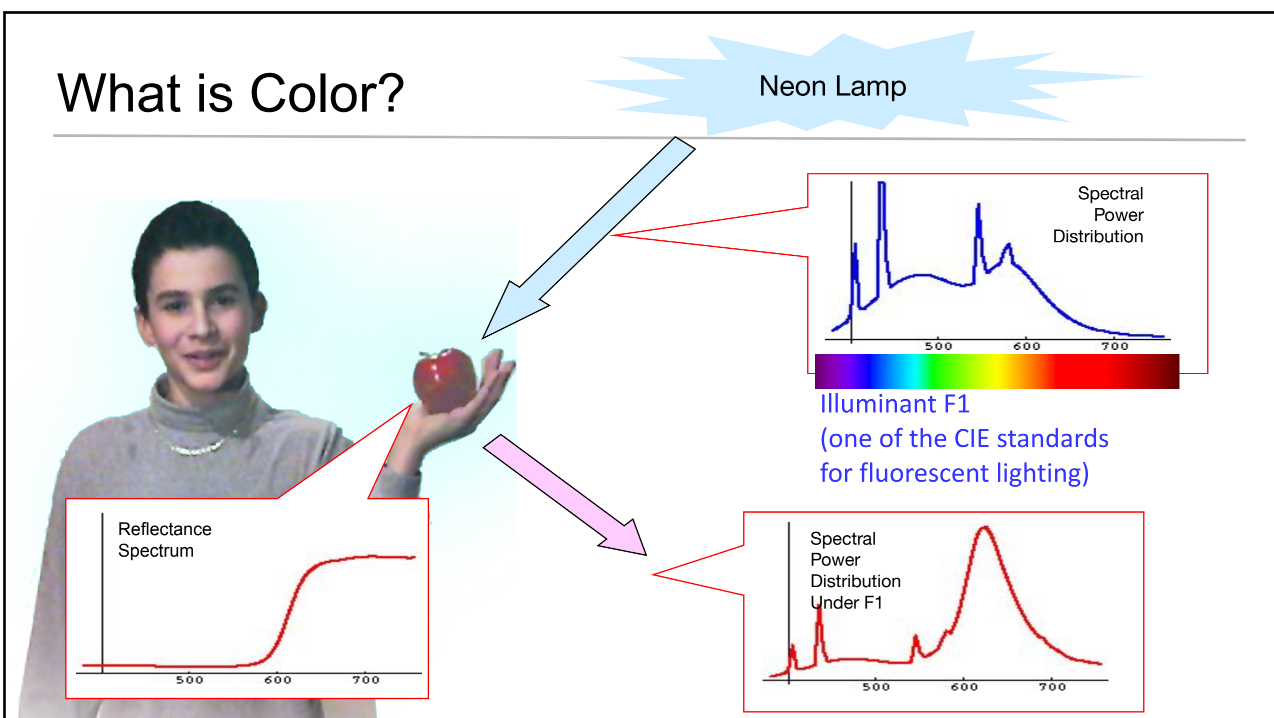


What is Color?



Illuminant D65
(CIE standard for natural daylight)

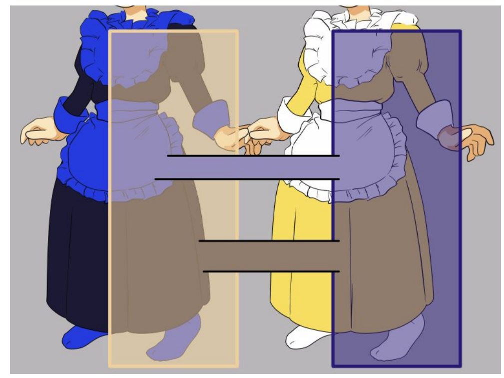

What is Color?
Spectral Power Distribution
500 600 700
Illuminant D65
(CIE standard for natural daylight)
Reflectance Spectrum
500 600 700
Spectral Power Distribution Under D65
500 600 700


What is Color?
Neon Lamp
Spectral Power Distribution
500 600 700
Illuminant F1
(one of the CIE standards
for fluorescent lighting)
Reflectance Spectrum
500 600 700
Spectral Power Distribution Under F1
500 600 700

What Color is the Dress?

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

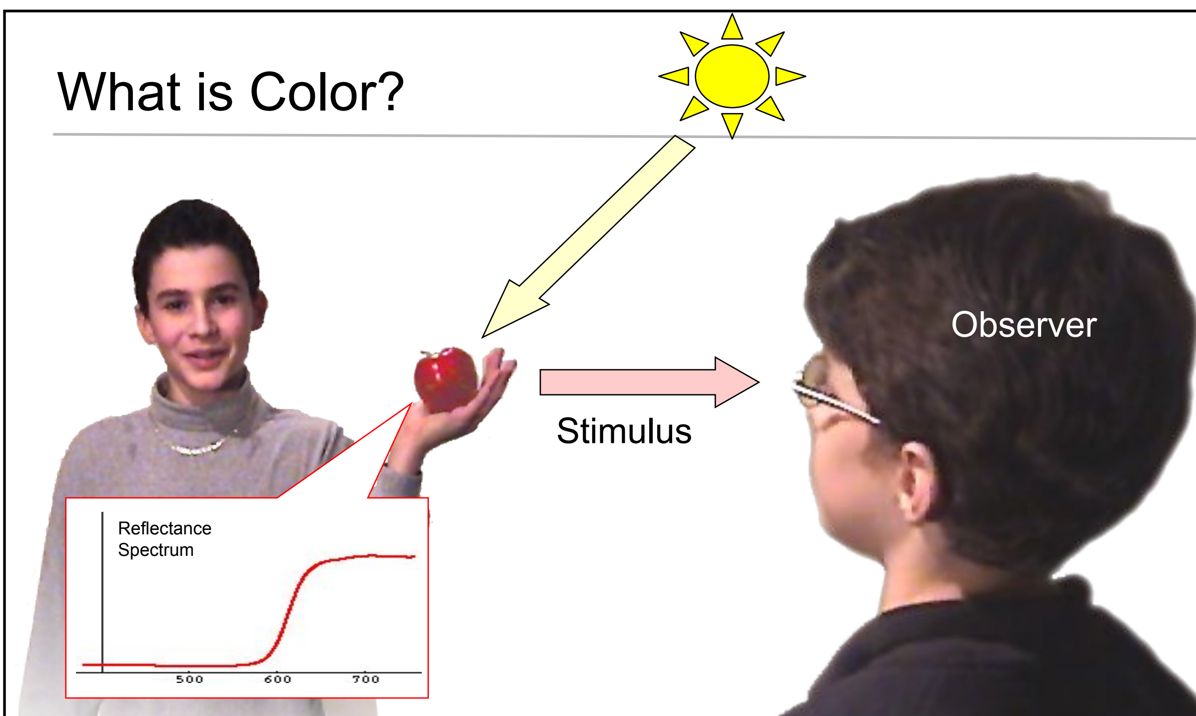
What does the viewer infer about the scene illumination?



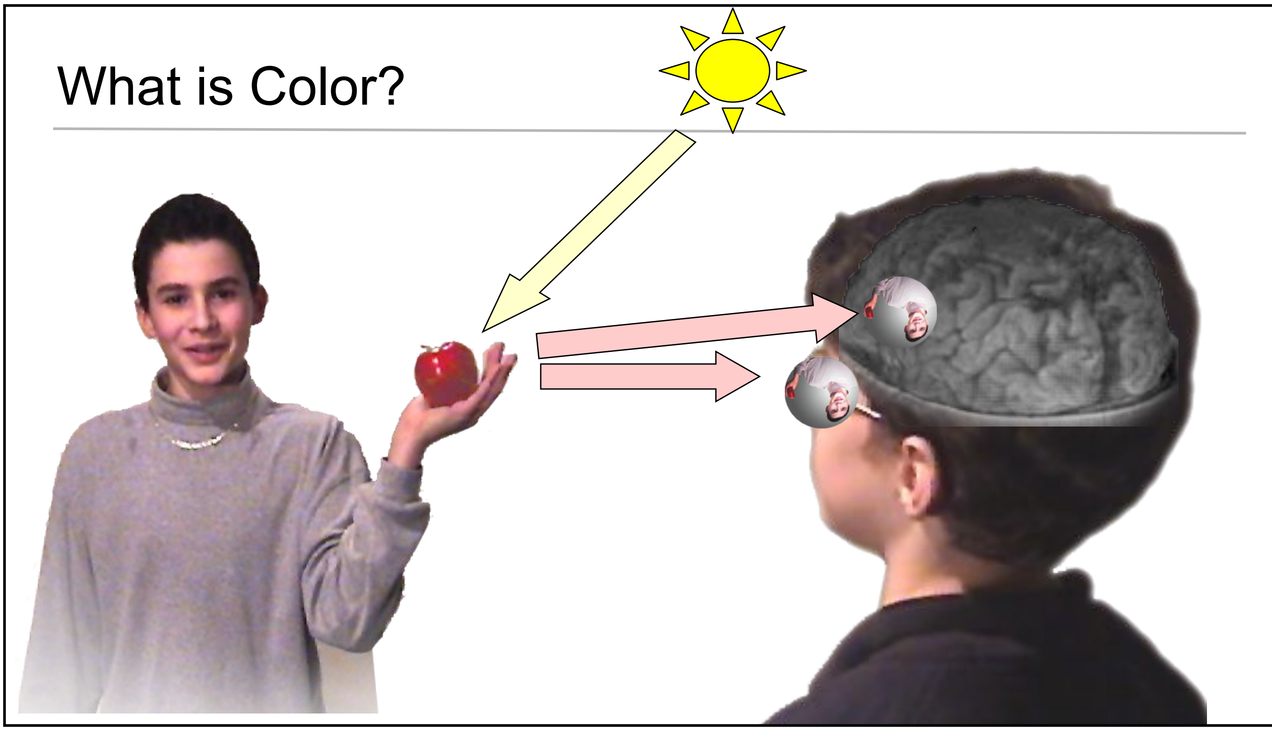
Blue & Black under yellow-tinted illumination?

White & Gold under blue tinted illumination?

What is Color?



What is Color?



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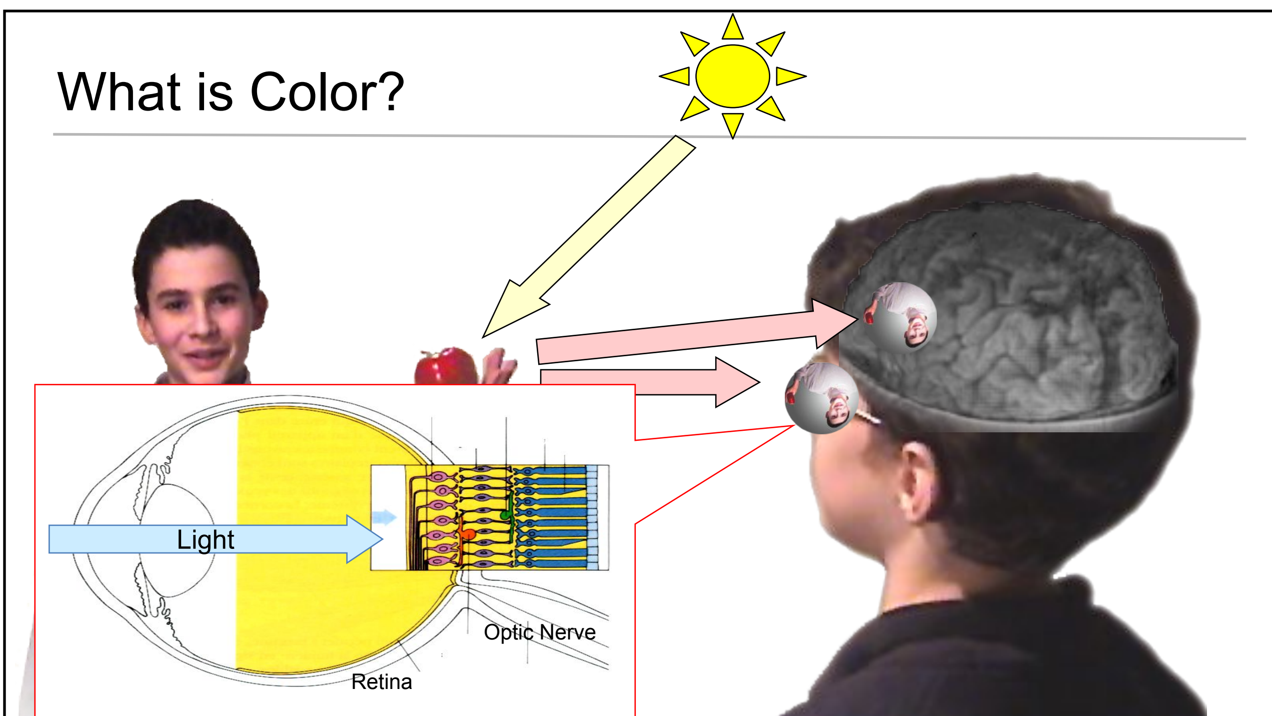
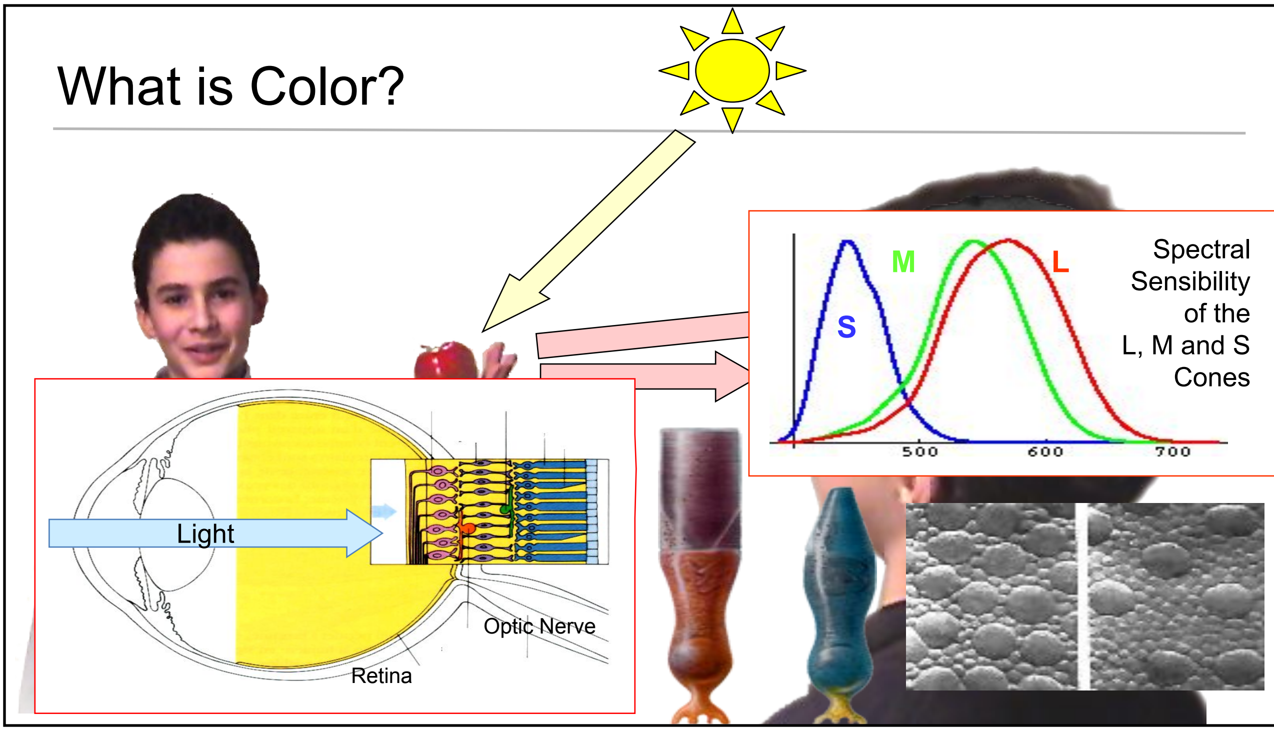
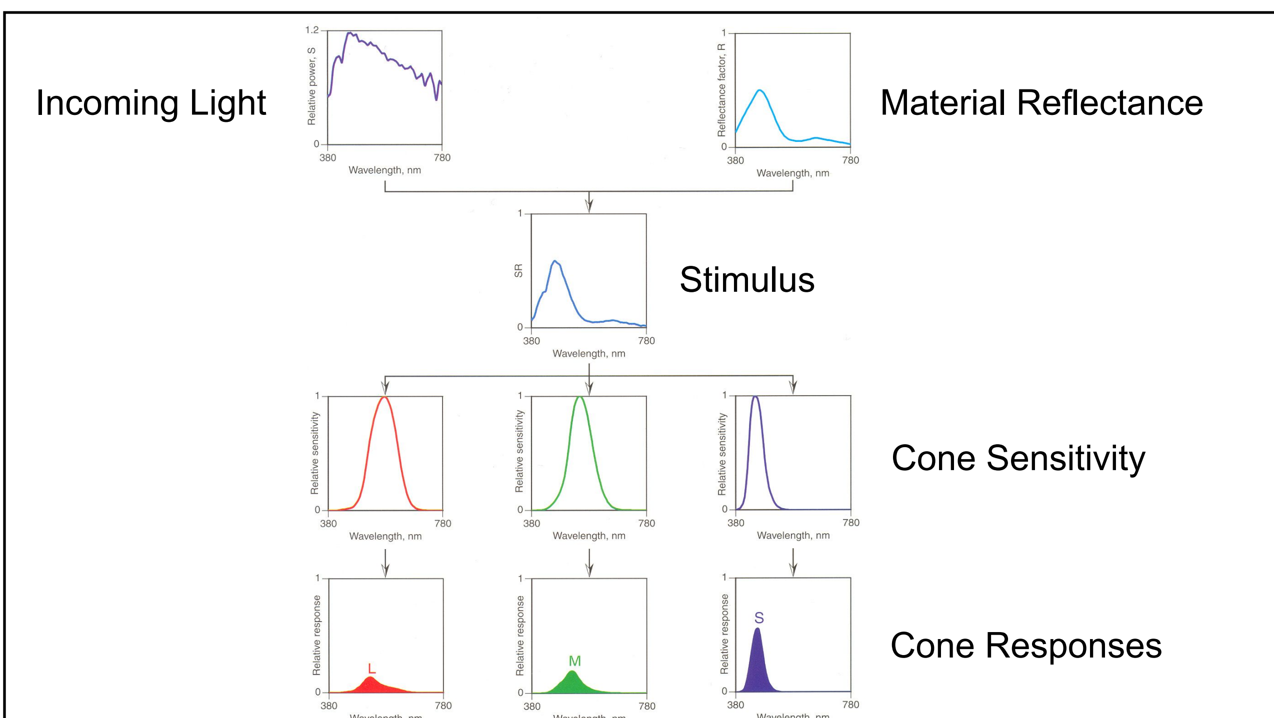
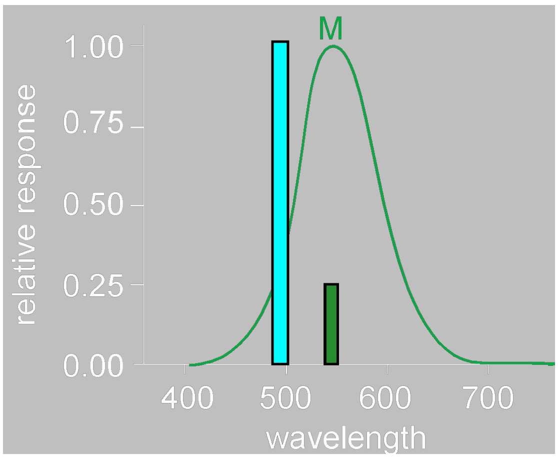



What is Color?
S
M
L
Spectral Sensibility of the L, M and S Cones
500
600
700
Light
Optic Nerve
Retina


Incoming Light
Relative power, S
1.2
0
380
780
Wavelength, nm
Material Reflectance
Reflectance factor, R
1
0
380
780
Wavelength, nm
Stimulus
SR
1
0
380
780
Wavelength, nm
Cone Sensitivity
Relative sensitivity
Cone Responses
Relative response
L
M
S

Cones do not "See" Colors

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

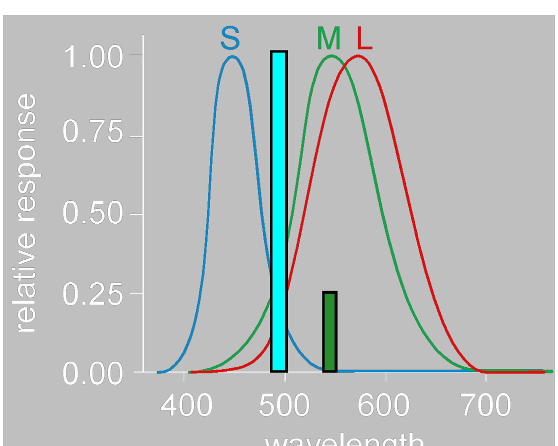


Dim green
Cone M/G: 0.25

Bright cyan
Cone M/G: 0.25

Response Comparison

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



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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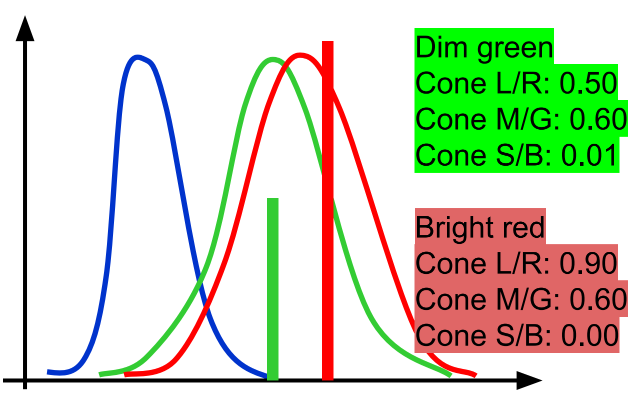
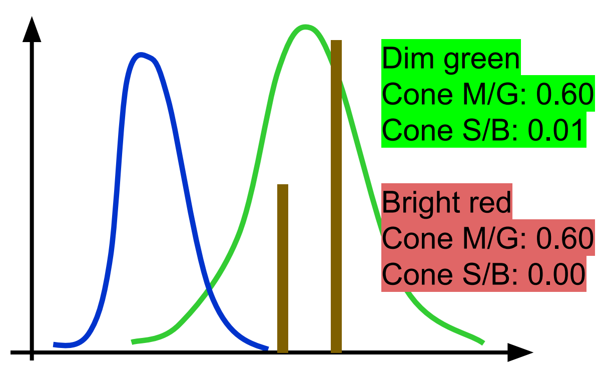
Color Blindness

- 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*

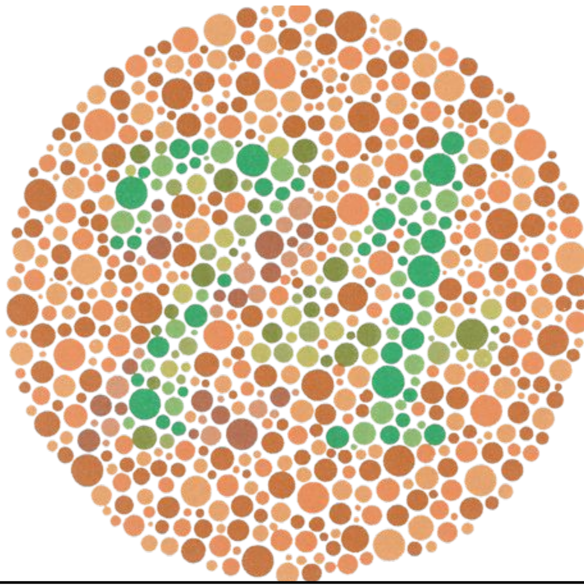


3 cones: Can be differentiated



2 cones: Same responses

Ishihara Color Blindness Test



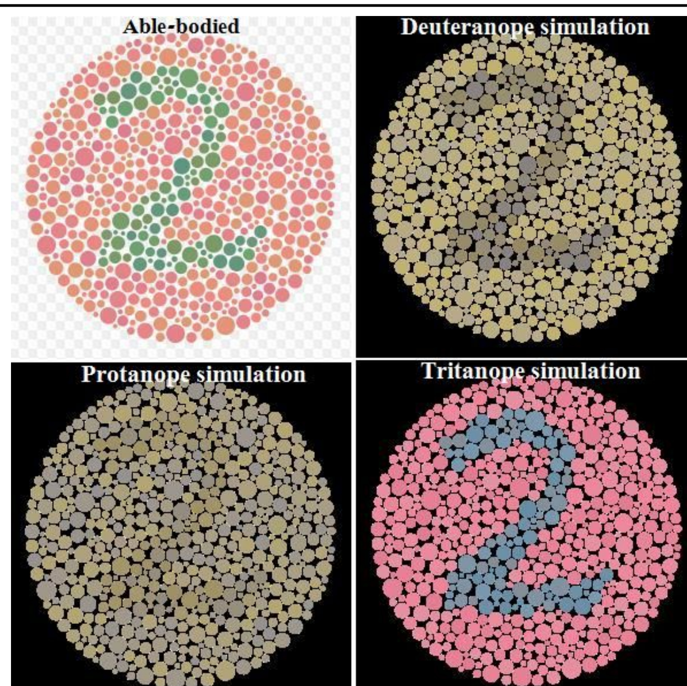
As we have already discussed…
Illumination is very important to proper color perception.

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

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

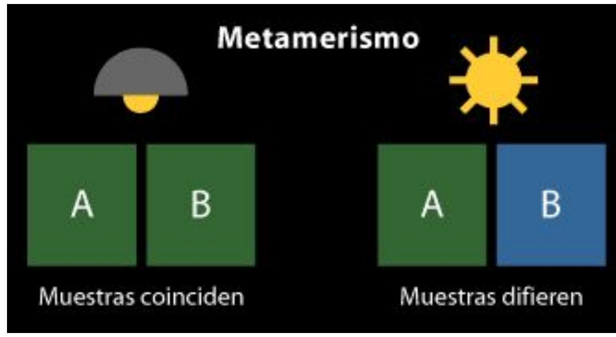
- Deuteranopia: missing medium / green cone
- Protanopia: missing long / red cone
- Tritanopia: (rare) missing short / blue cone

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.
- E.g. the shirt & pants matched in the store lighting, but not outside!

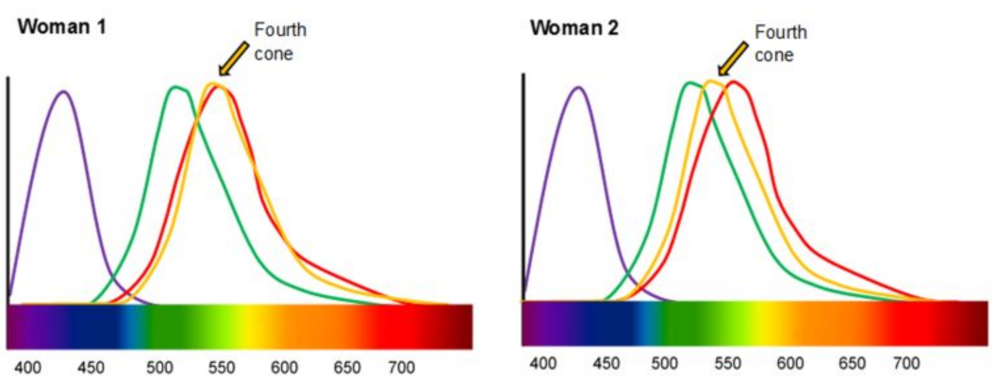


http://gusgsm.com/metamerismo

- 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!



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 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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Reading for Today

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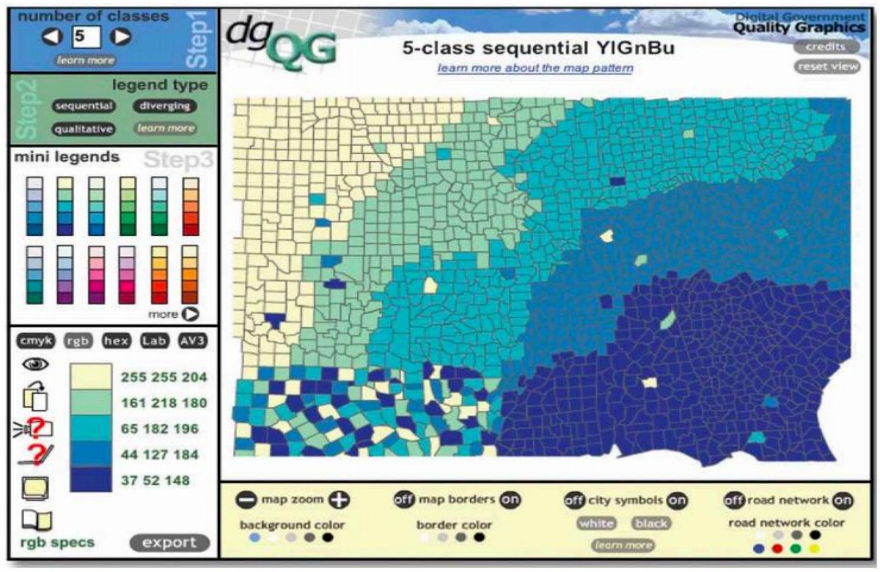
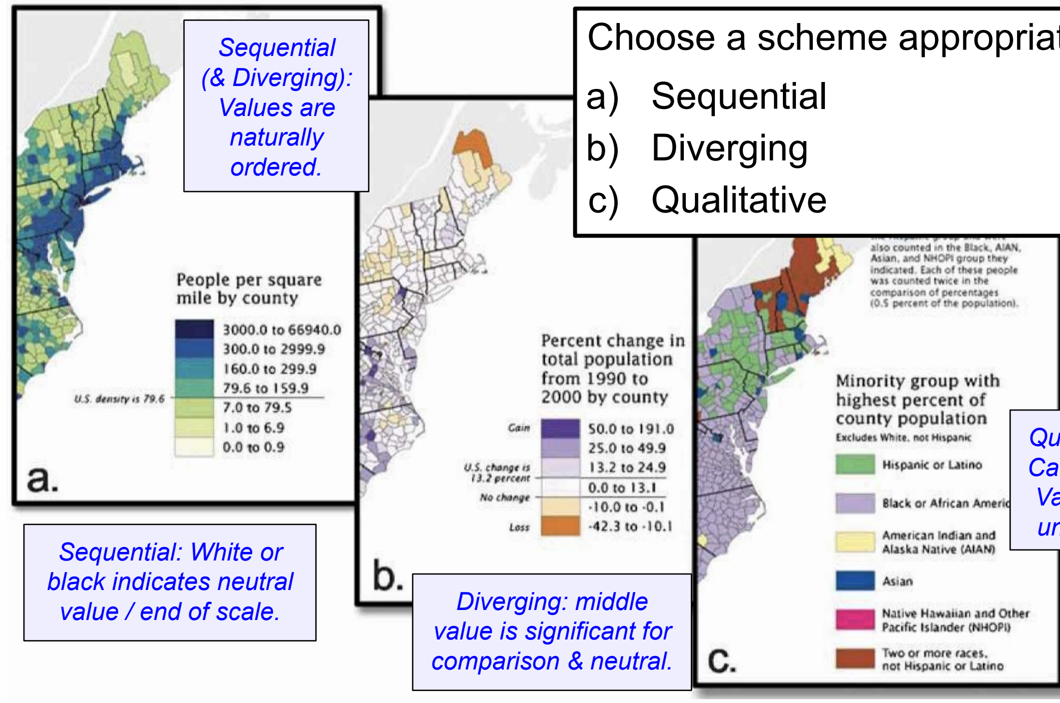


"ColorBrewer.org: An Online Tool for Selecting Colour Schemes for Maps", Harrower & Brewer, The CartographicJournal, 2003.

- 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.

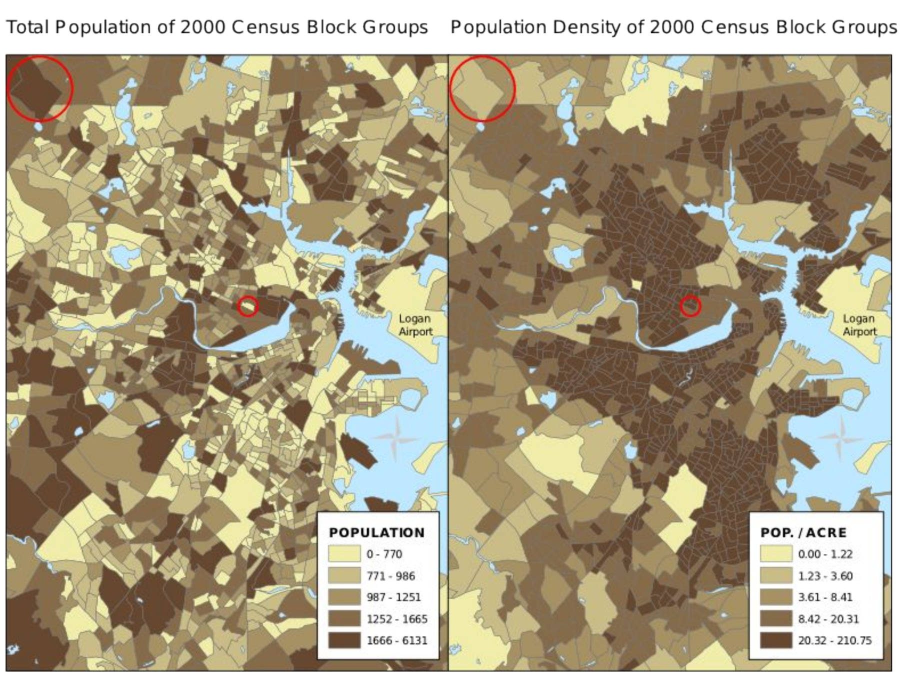
Sequential: White or black indicates neutral value / end of scale.

Diverging: middle value is significant for comparison & neutral.

Qualitative / Categorical: Values are unordered

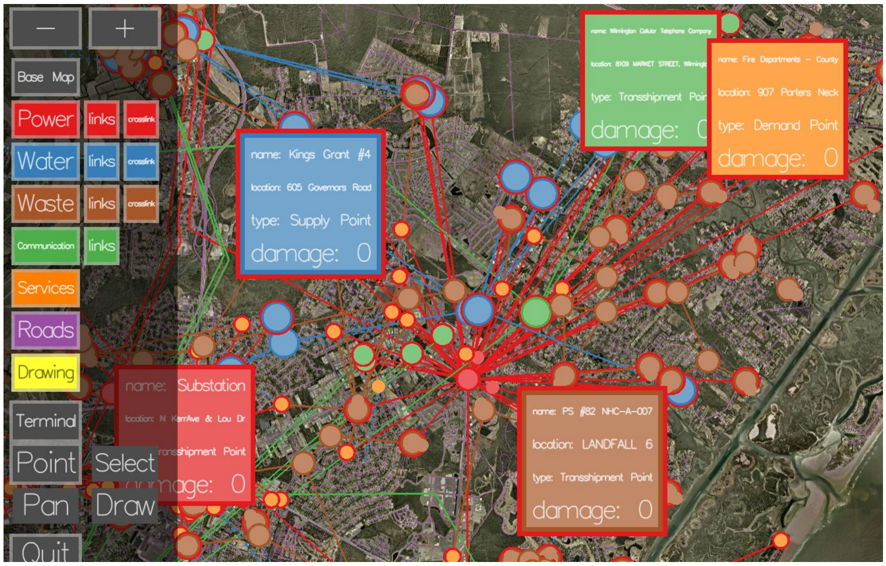
Choropleth map: statistics per area

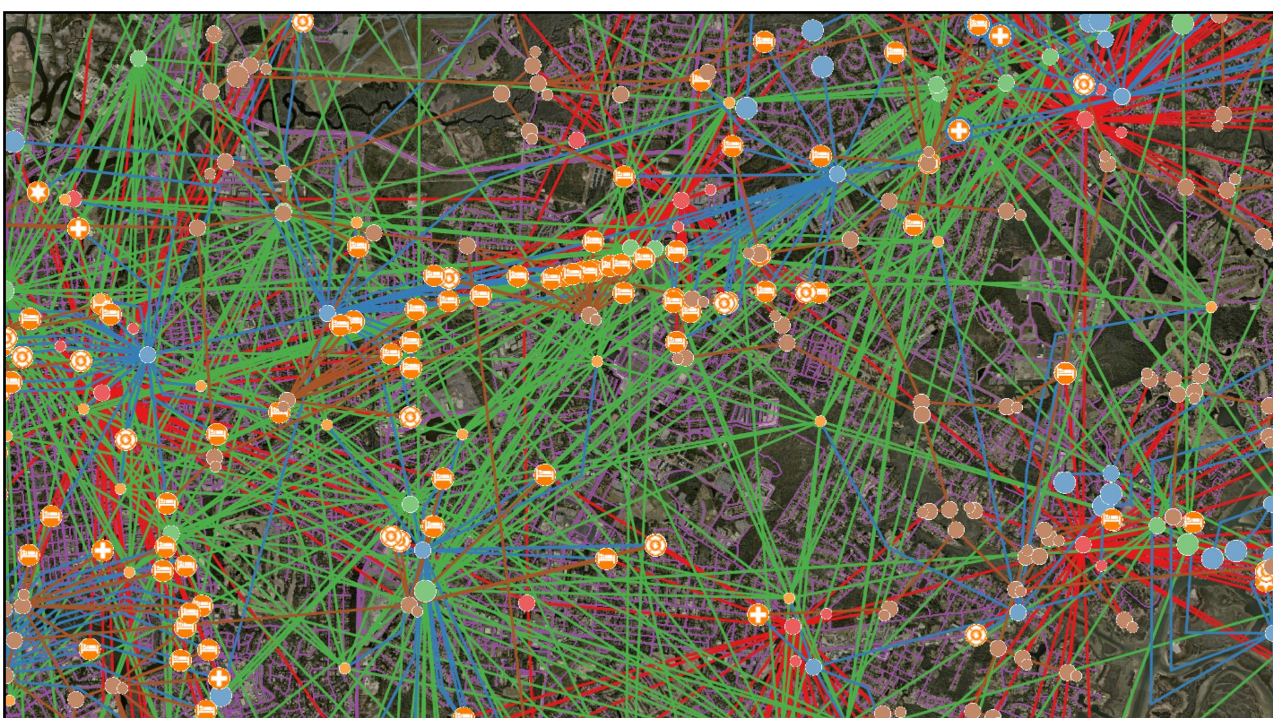
must be careful about normalization



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

Emergency Response Decision Making





Reading for Today

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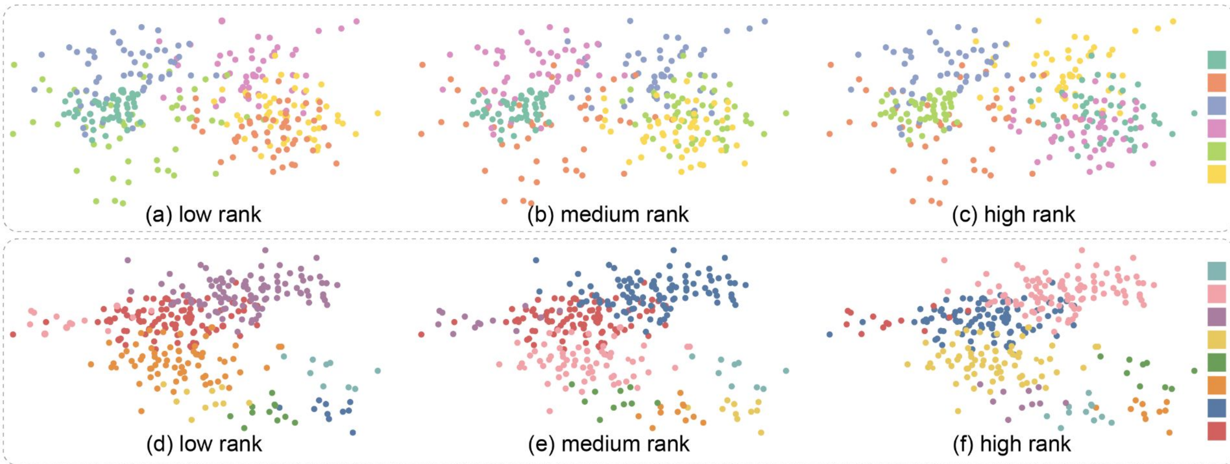

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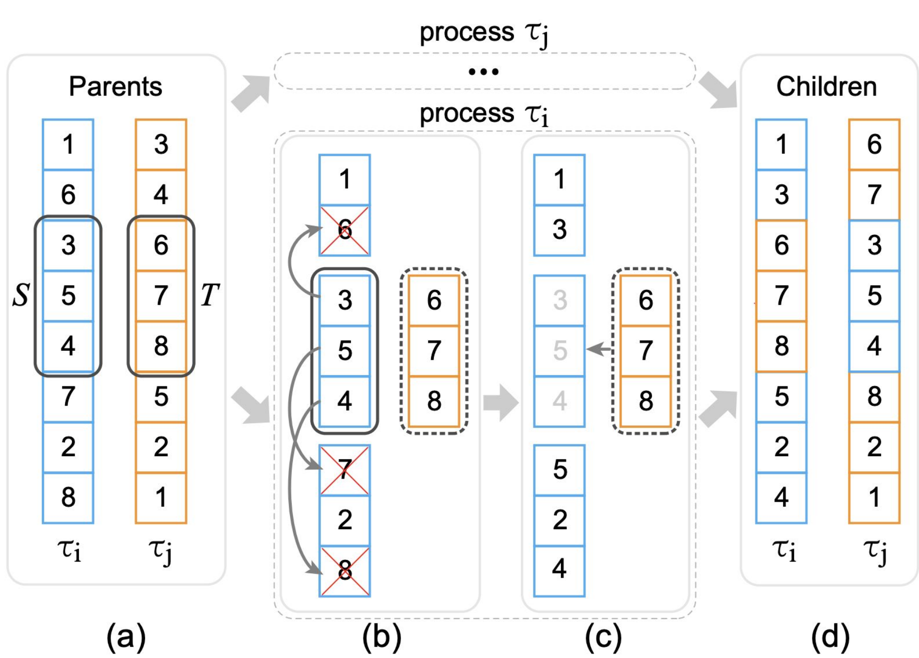
- Multiple studies
  - numerical study, expert study, user study
  - initial pilot study
  - question: color expert vs. classic art background?
- Includes examples of good and bad visualizations
- Maximize color contrast w/ neighboring clusters and w/ background
- Optimize color choice for human perception
- 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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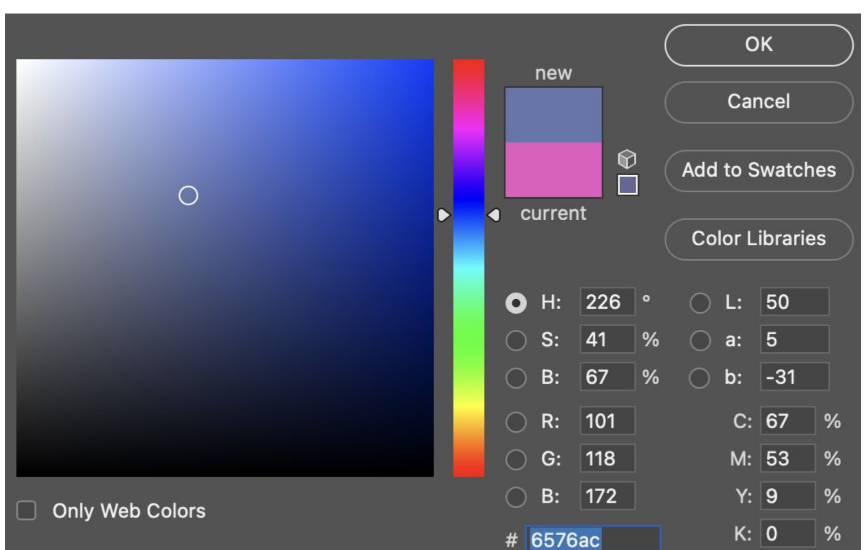
Color Picker in Photoshop

- What are all the different choices?



Standard Color Spaces

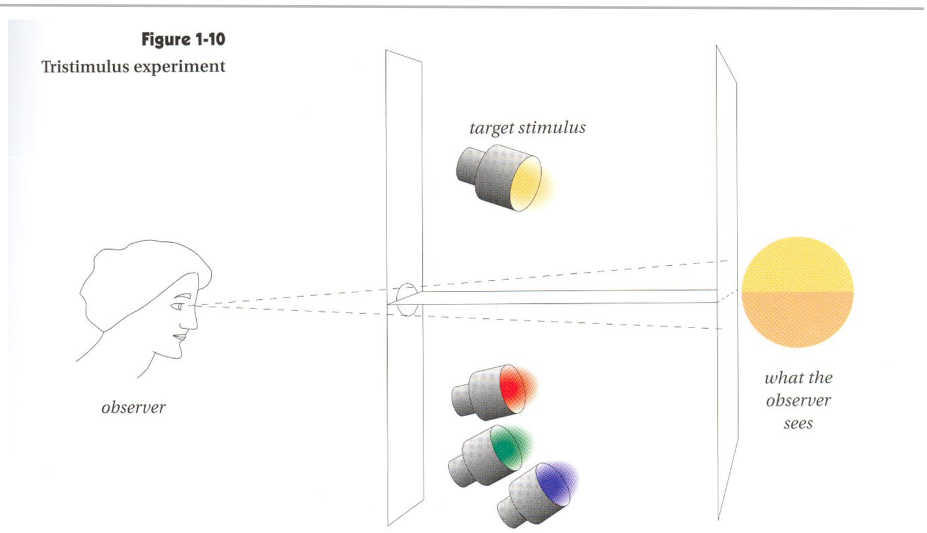
- Colorimetry: Science of color measurement
- Quantitative measurements of colors are crucial in many industries
  - Television, computers, print, paint, luminaires
- Naive digital work uses a vague notion of RGB
  - Unfortunately, RGB is not precisely defined, and depending on your monitor, you might 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



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

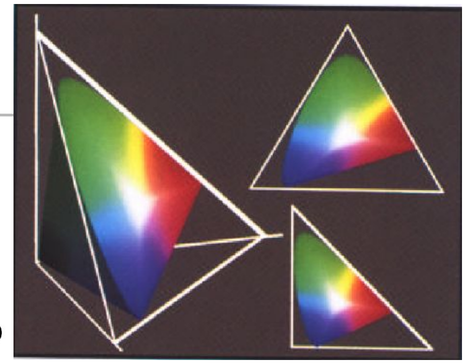
CIE XYZ Color Space

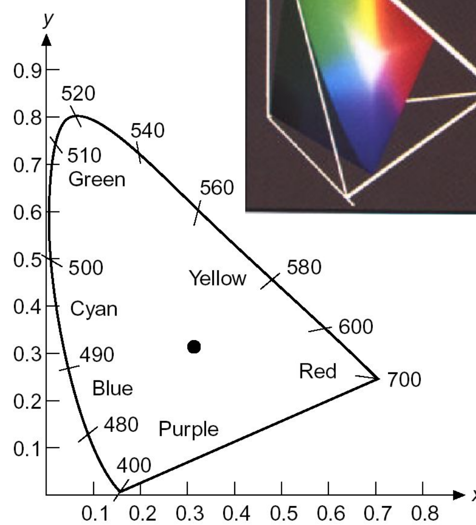
- Can think of X, Y, & Z as 3D coordinates
- Linear transform to/from typical LMS or RGB

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

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

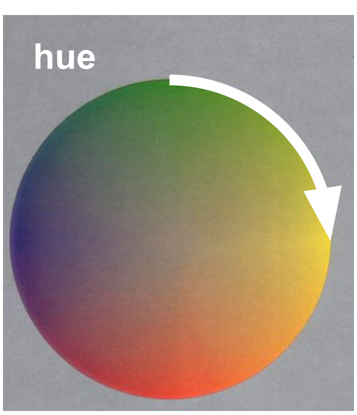
- Note that many points in XYZ do not correspond to visible colors!

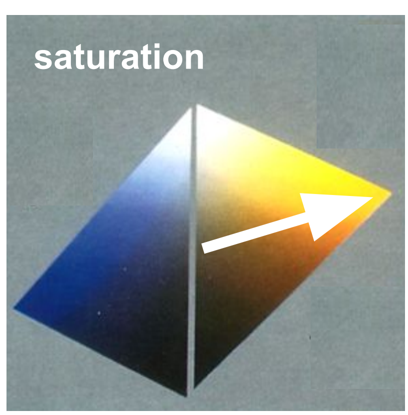


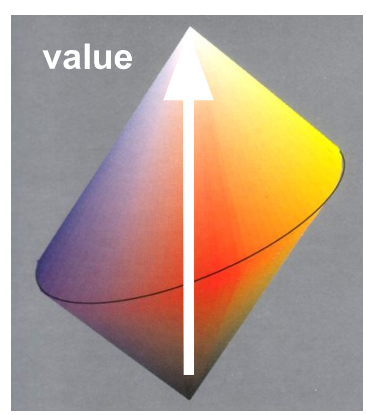


Hue Saturation Value (HSV)

- 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)

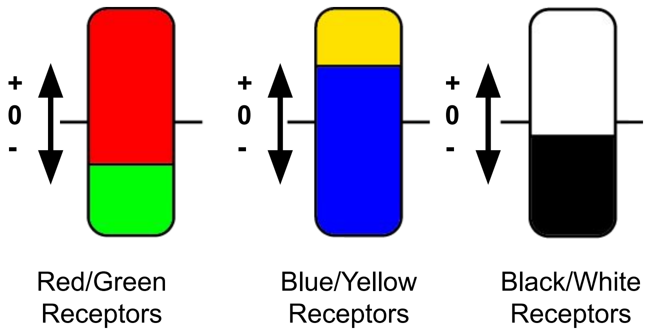


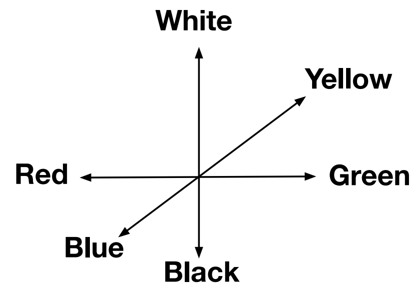




Hering 1874: Opponent Colors

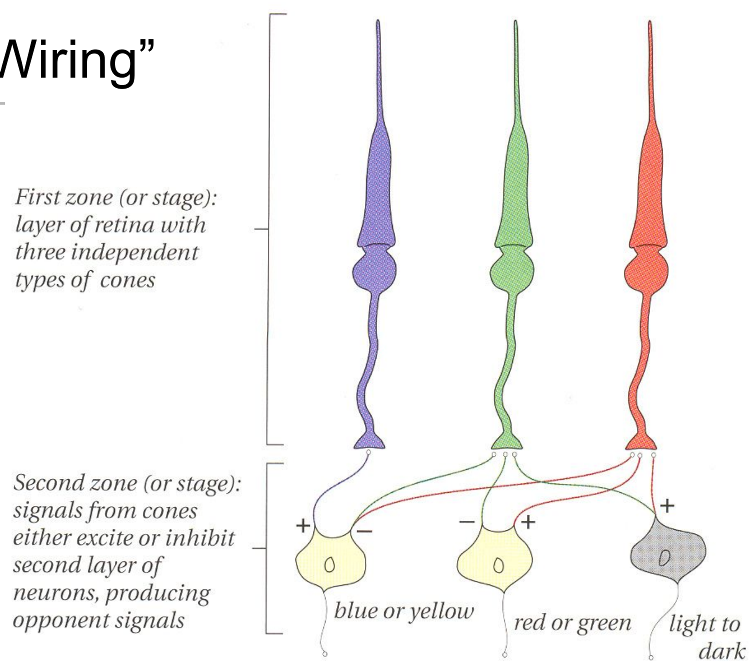
- Hypothesis of 3 types of receptors: Red/Green, Blue/Yellow, Black/White
- Explains well several visual phenomena





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

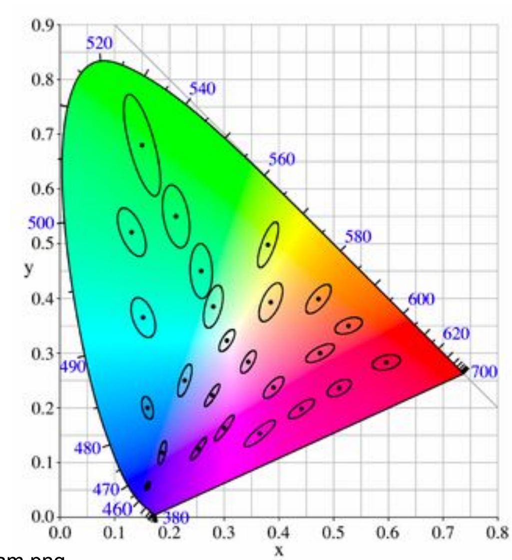


Linear Color Spaces: RGB/XYZ/YPbPr

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

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

- 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]



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

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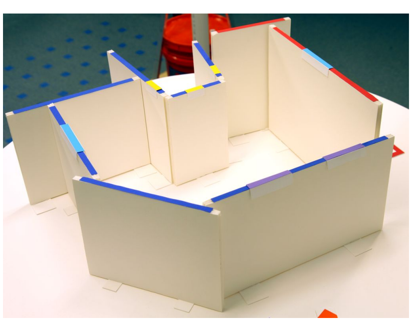
Spatially Augmented Reality (SAR) Projection

camera detects design geometry

6 projectors augment design

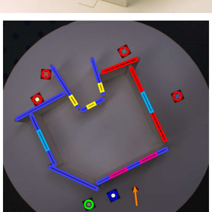
design sketched with foam-core walls

Tangible Interface for Architectural Design

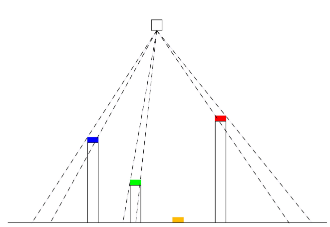


Exterior & interior wall Tokens for:

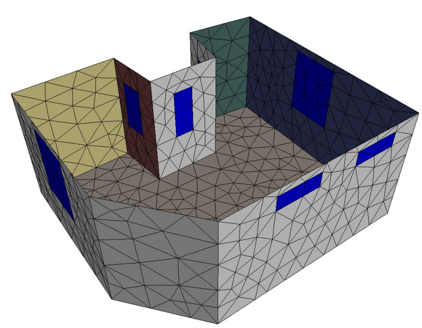
- *Windows*
- *Wall/floor colors*
- *North arrow*



Overhead camera



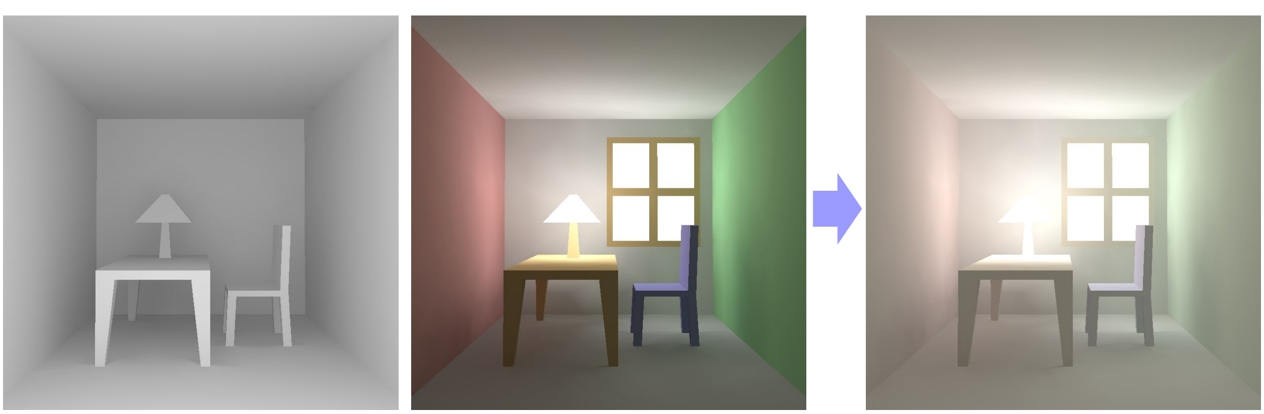
Projection geometry



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

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

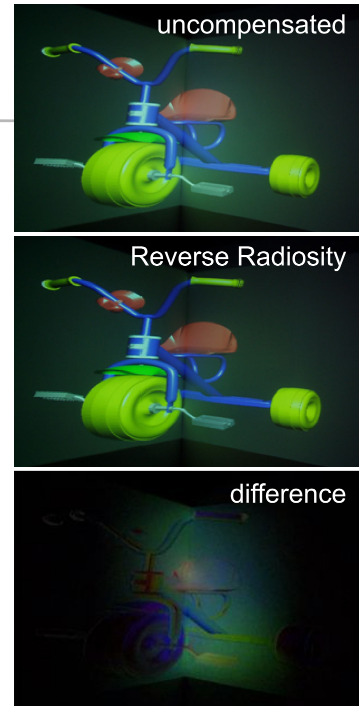
$$B = (I - F)^{-1} E$$

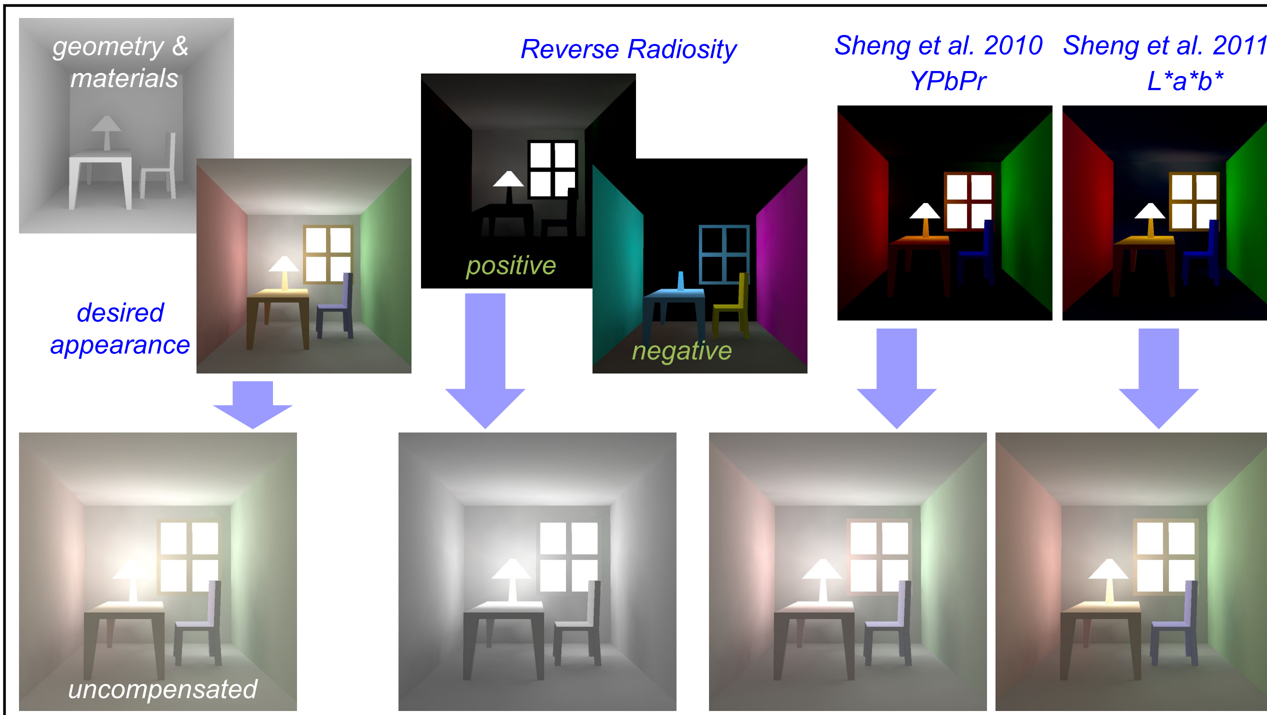
values for rendering *form factor matrix* *direct light*

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

$$E = (I - F) B$$

projection values *desired appearance*





L*a*b*: a Perceptual Color Space

- Designed to match human color perception data

intensity
red-green
yellow-blue

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

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

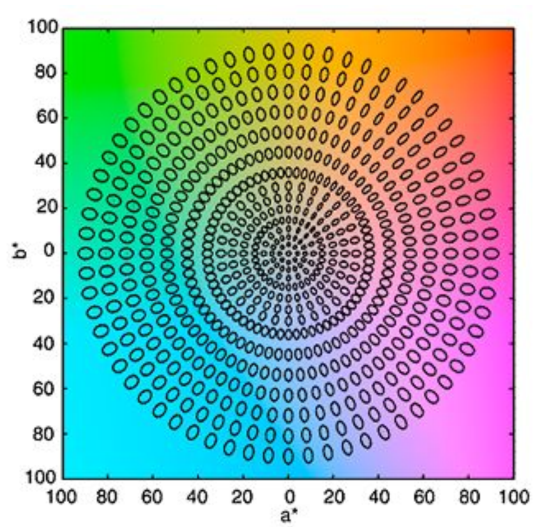
- L*a*b* is *nonlinear*, a challenge for optimization

Quantitative Perceptual Comparison

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

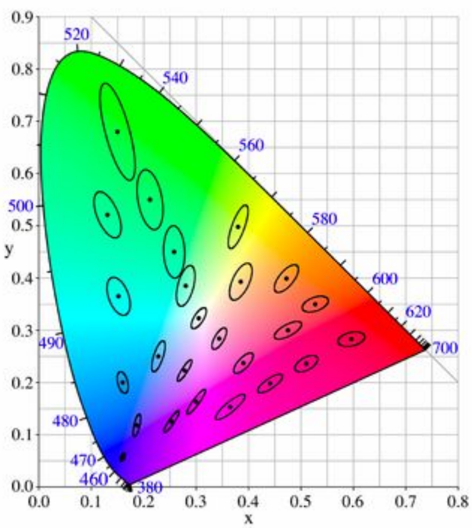
- Where 2.3 ΔE = JND
  "just noticeable difference"

- The MacAdams ellipses
  are more equal size circles
  in L*a*b*

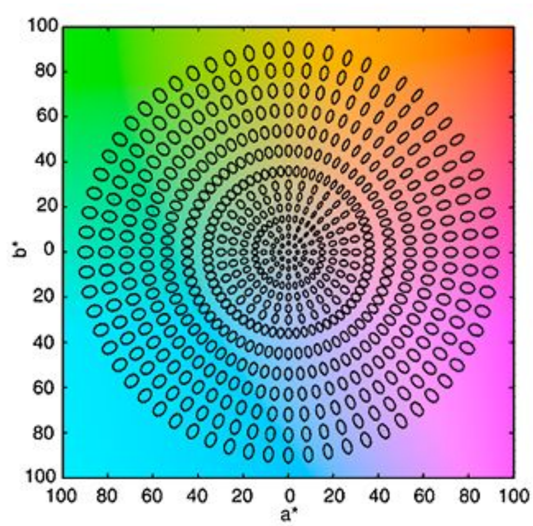


http://w3.kcua.ac.jp/~fujiwara/infosci/ellipses_lab.png

MacAdams Ellipses: XYZ vs. L*a*b*



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



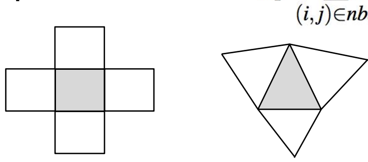
http://w3.kcua.ac.jp/~fujiwara/infosci/ellipses_lab.png

Our Optimization Formulation

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

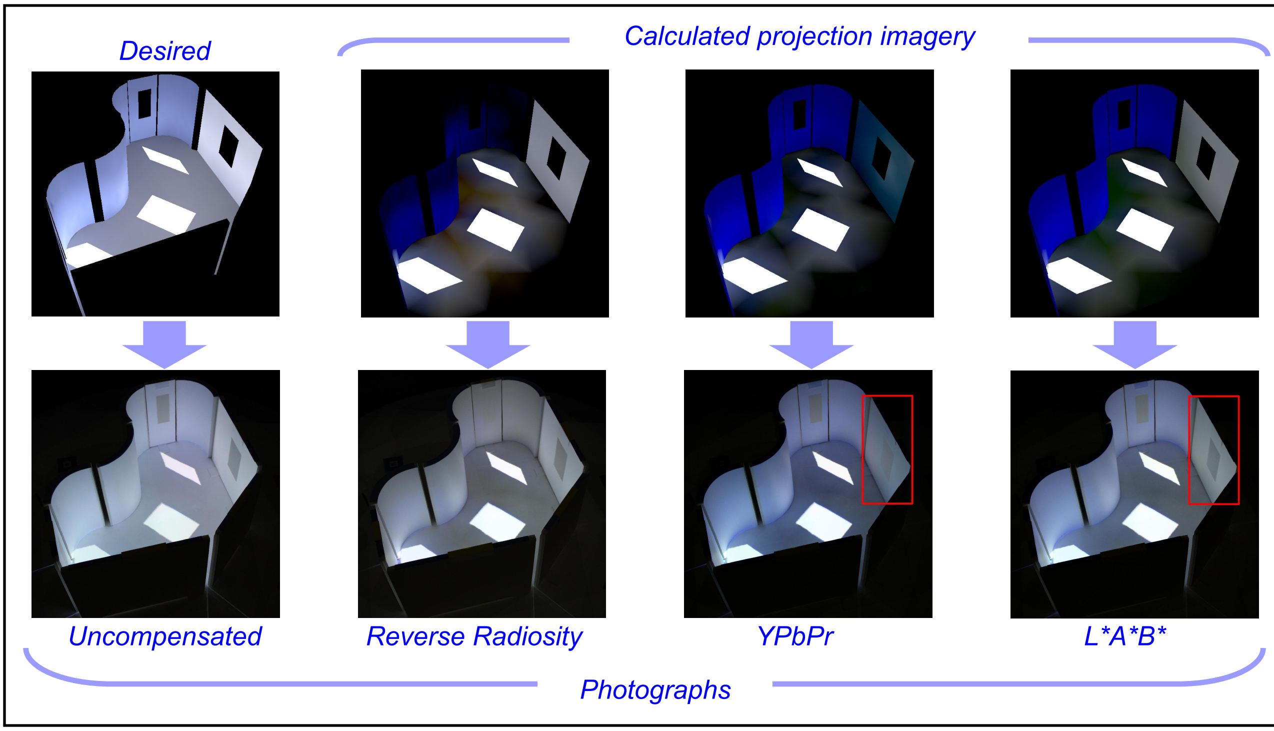
  desired appearance   projection result

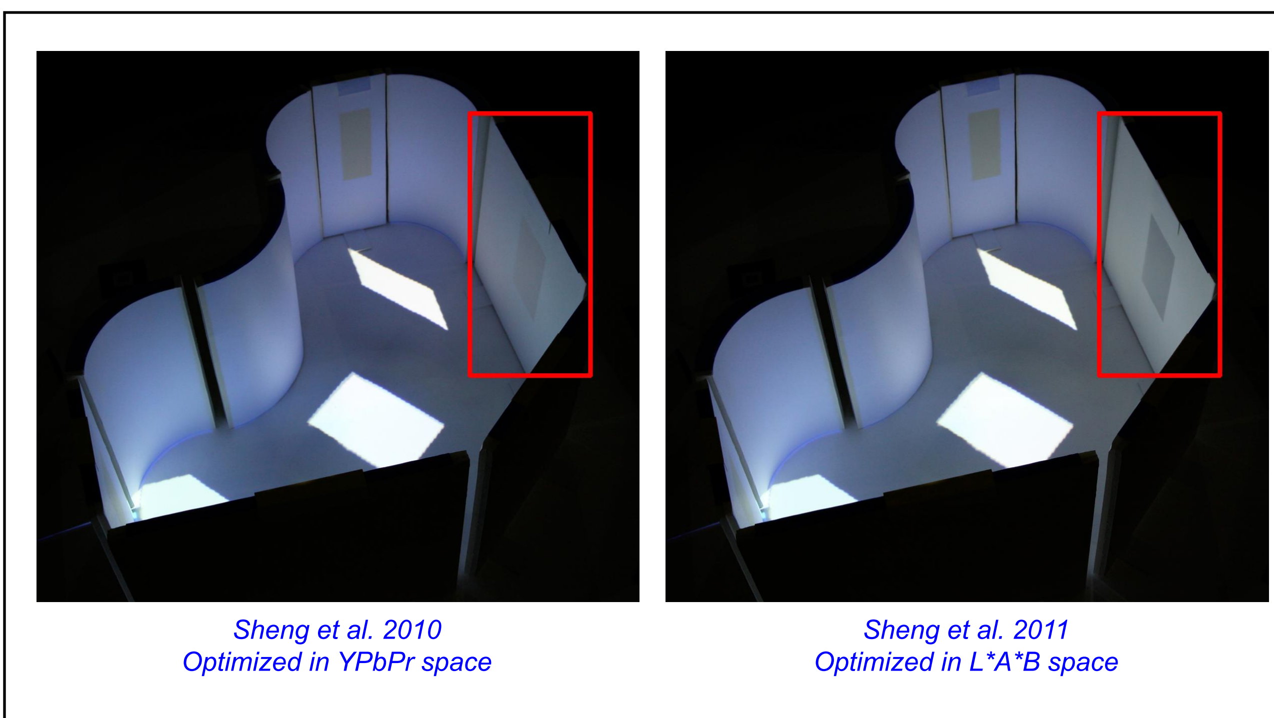
- Spatial Error: $$\phi_{spt} = \sum_{(i,j)\in nbd} [(L_i - L_j) - (L_i' - L_j')]^2 + [(a_i - a_j) - (a_i' - a_j')]^2 + [(b_i - b_j) - (b_i' - b_j')]^2$$

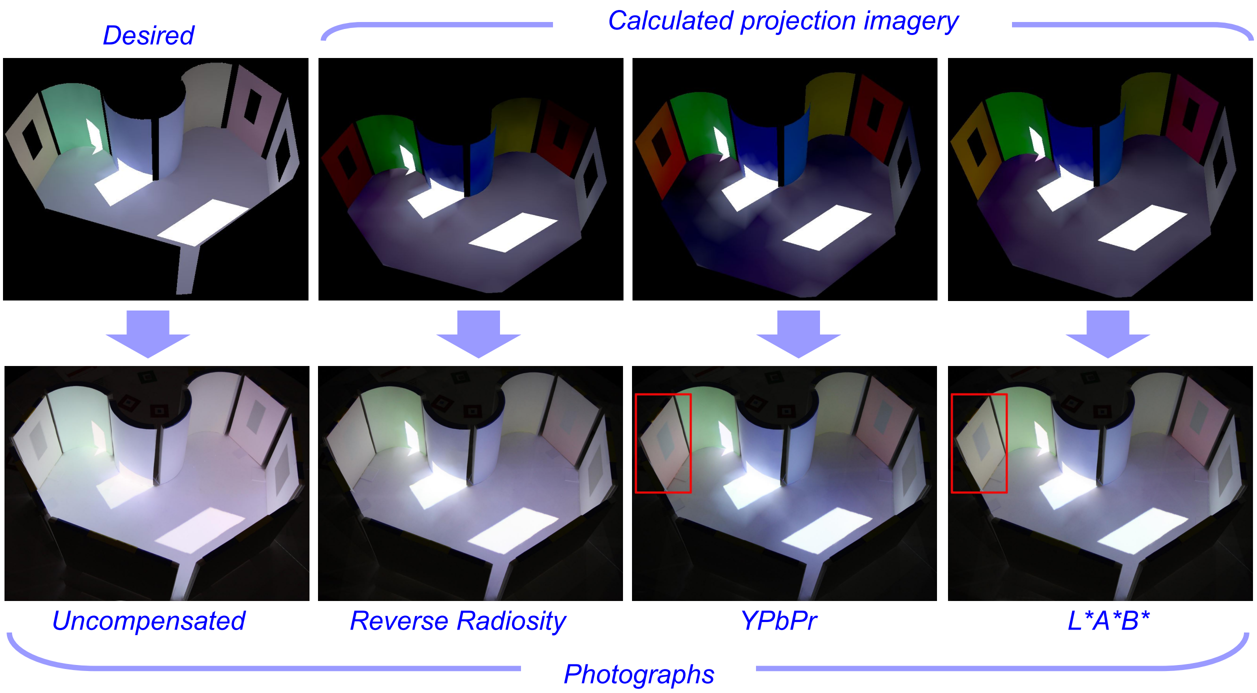


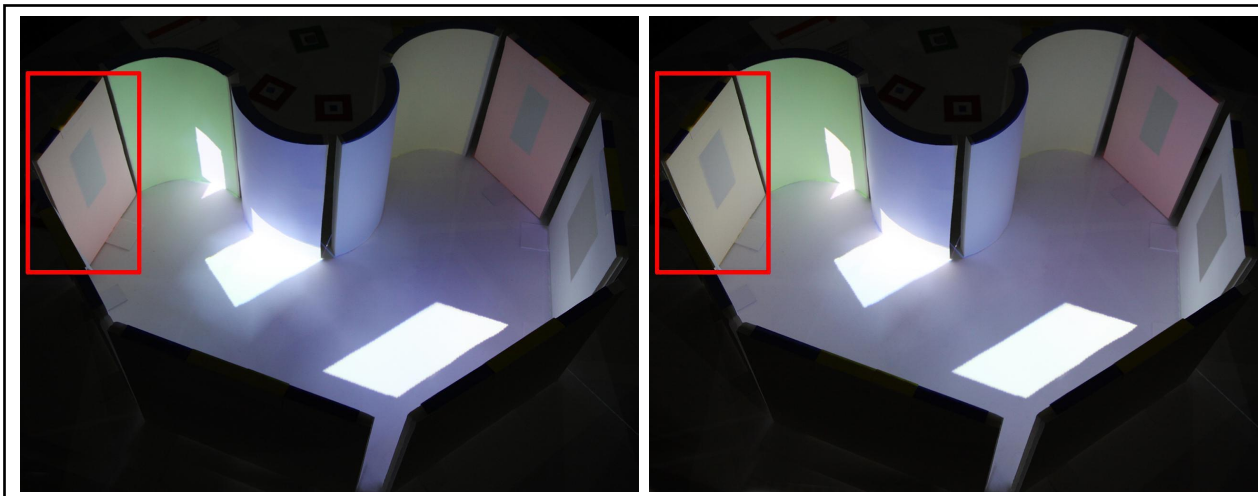
  gradient in desired appearance   gradient in projection result

- Complete Objective Function: $\phi = \alpha\phi_{abs} + (1-\alpha)\phi_{spt}$ *We use α = 0.9*
- Box constraints:
  minimum & maximum brightness of projector system   *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





Sheng et al. 2010
Optimized in YPbPr space

Sheng et al. 2011
*Optimized in L*A*B space*

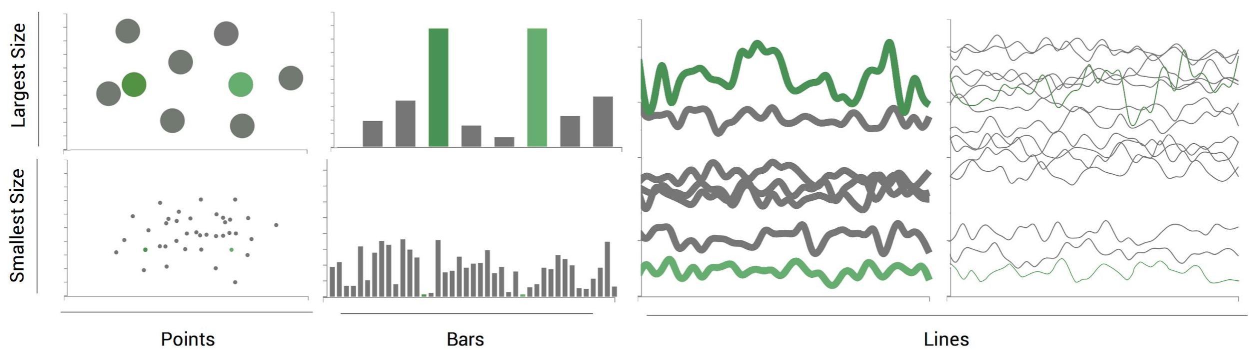
"Perceptual Global Illumination Cancellation in Complex Projection Environments"
Yu Sheng, Barbara Cutler, Chao Chen, and Joshua Nasman
Eurographics Symposium on Rendering (EGSR), June 2011.

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

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

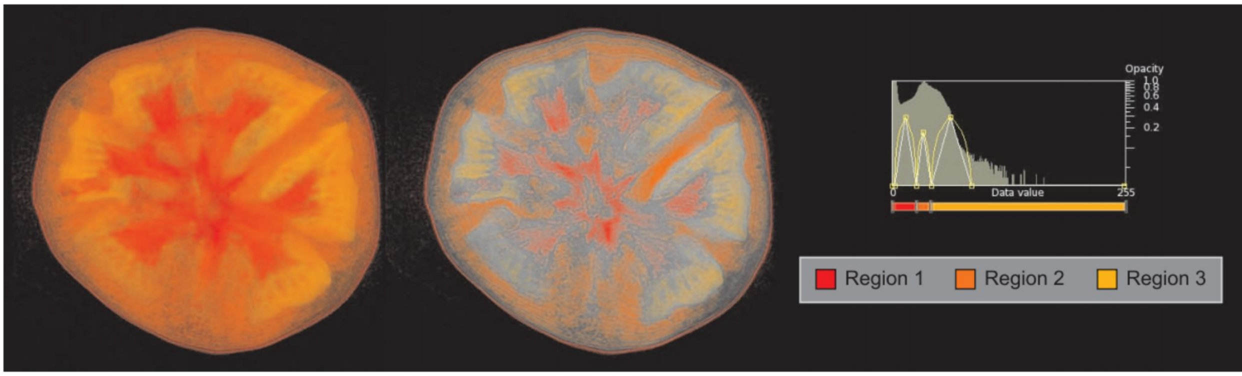


Fig. 1. Volume rendering of a tomato data set using traditional (left) and hue-preserving (middle) color blending. The data histogram, transfer function, and color legend are shown on the right.

Reading for Friday *pick one*

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

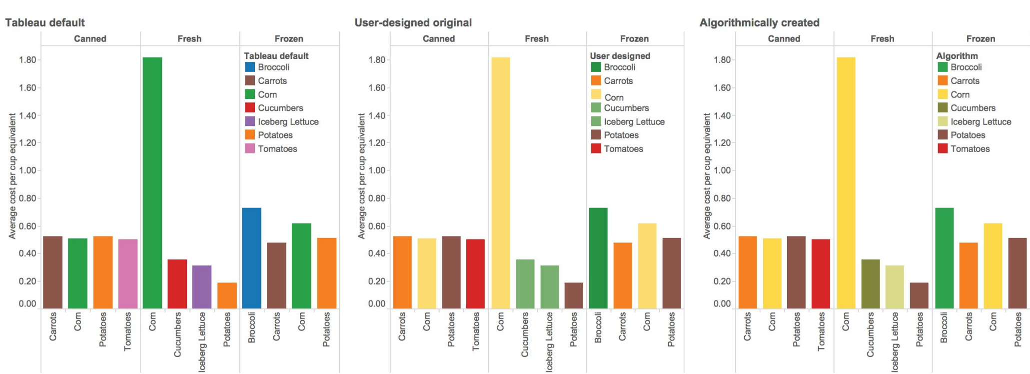


Fig. 1. This visualization was taken from a Tableau Public workbook [11] to illustrate the value of semantic color encoding. Left: The Tableau default colors are perceptually legible, but conflict with the data semantics ('Tomatoes' are pink, 'Corn' is green). Center: The Tableau author matched the colors to the data semantics (red for 'Tomatoes', yellow for 'Corn'), which makes it easier to identify the different types of vegetables in the graph. Right: Our algorithm automatically created a similarly effective result.