CSCI 4530/6530 Advanced Computer Graphics

https://www.cs.rpi.edu/~cutler/classes/advancedgraphics/S25/

Lecture 20: Color

some slides from Fredo Durand

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

For the Birds, Pixar, 2000

Today

- Worksheet: Shadow Techniques
- Readings for Today
- What is Color?
  - Human Perception
  - Color Blindness & Metamerism
- Color Spaces
  - Linear Color Spaces: LMS, RGB, XYZ, HSV
- Projection in Spatially Augmented Reality
  - Human Perception & Perceptual Color Space: L*a*b*
- Readings for Next Time

Readings for Today

- “Modeling and visualization of leaf venation patterns”, Runions, Fuhrer, Lane, Federl, Roggan-Lagan, & Prusinkiewicz, 2007.

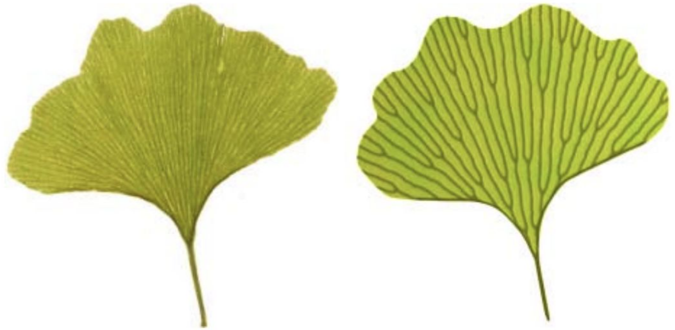


Figure 10: A photograph (left) and a rendered model of ginkgo venation (right).

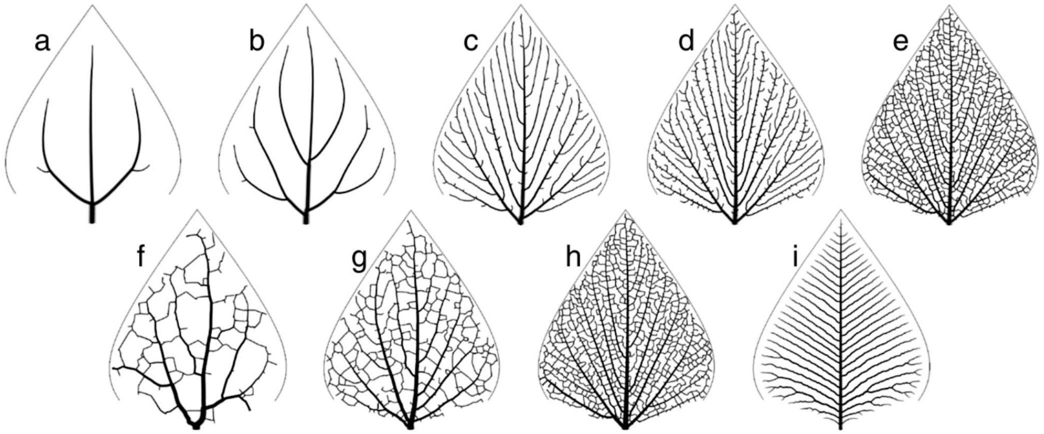


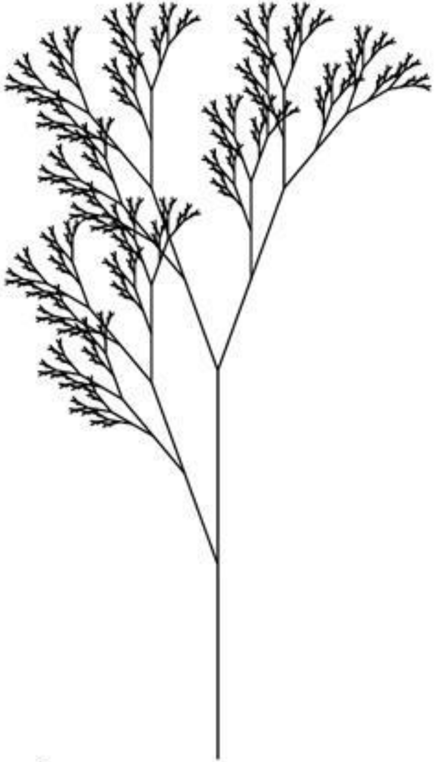
Figure 11: A photograph(left) and a rendered model of lady’s mantle venation (right).

- Interdisciplinary research
- Botanical/biological inspiration
- Leaves are 2D, 2D algorithm makes sense
- Could have been hacked with a texture, refreshing to see effort to correctly model and simulate natural phenomena

L-Systems

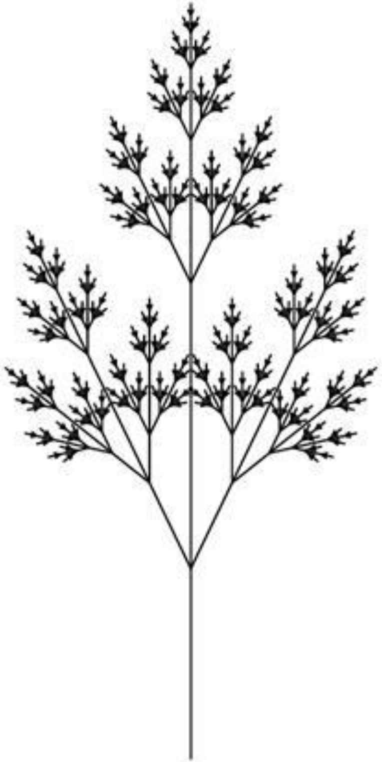
```
alphabet: {a,b}
initiator: a
production rules:
    a -> b
    b -> ba

generations:
    a
    b
    ba
    bab
    babba
    babbabab
    babbababbabba
    babbababbabbababbabab
```

Prusinkiewicz & Lindenmayer,
The Algorithmic Beauty of Plants, 1990
http://algorithmicbotany.org/



d

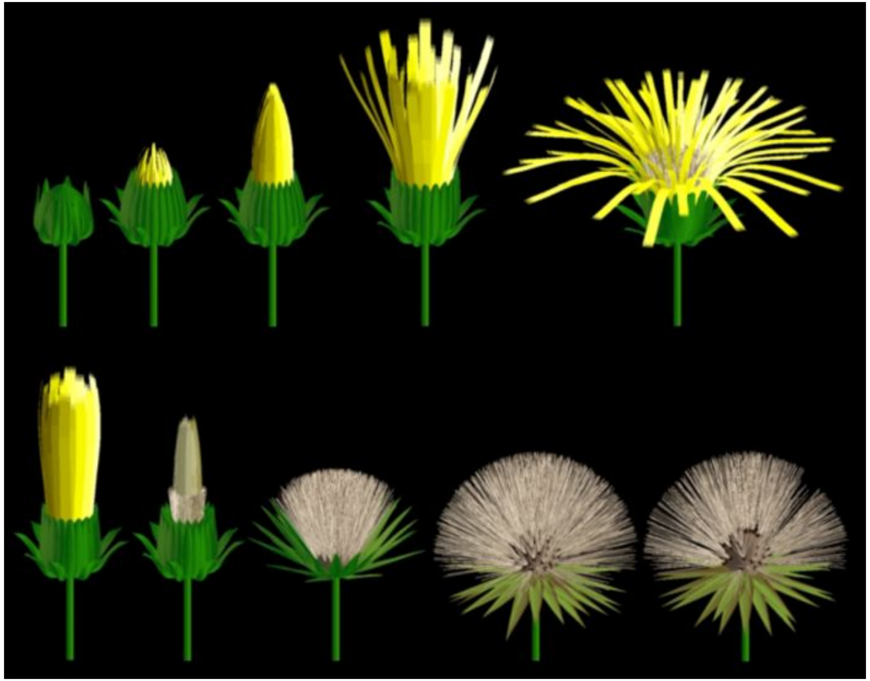
n=7, δ=20°
X
X $\rightarrow$ F[+X]F[-X]+X
F $\rightarrow$ FF



e

n=7, δ=25.7°
X
X $\rightarrow$ F[+X][-X]FX
F $\rightarrow$ FF

L-Systems



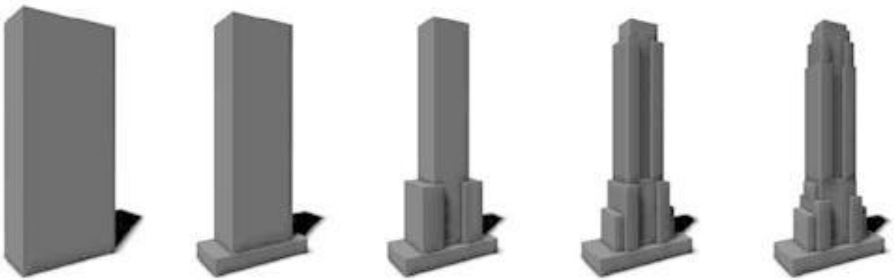
Animation of Plant Development
Prusinkiewicz et al.,
SIGGRAPH 1993

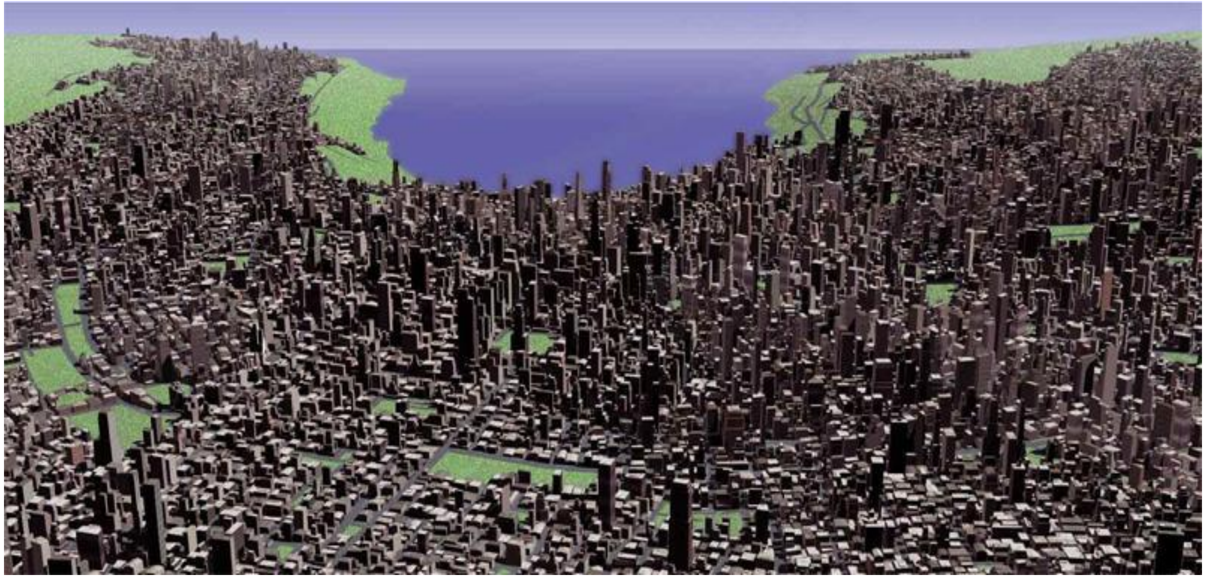
Prusinkiewicz & Lindenmayer,
The Algorithmic Beauty of Plants, 1990
http://algorithmicbotany.org/

“Synthetic Topiary”,
Prusinkiewicz, James, and Mech,
SIGGRAPH 1994

Readings for Today

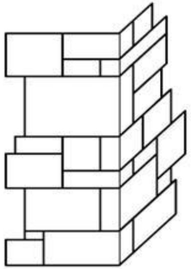
- "Procedural Modeling of Cities", Parish & Müller, SIGGRAPH 2001

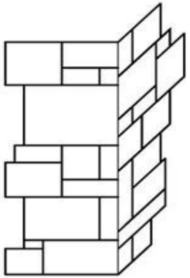




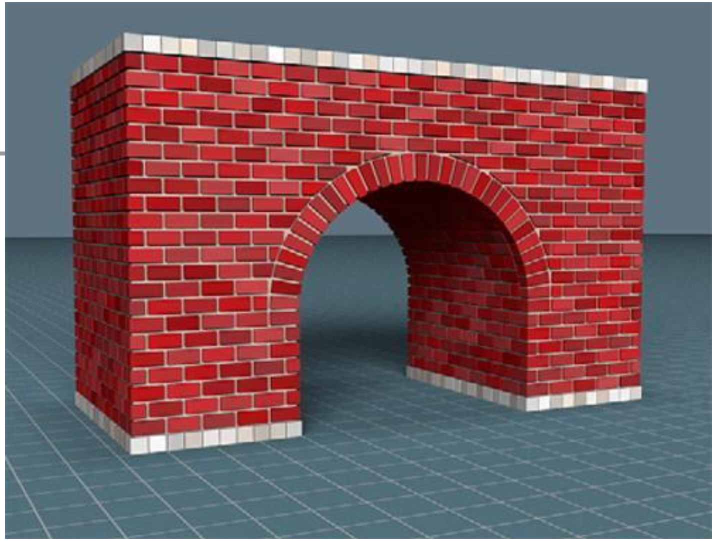
- Details not perfect close up, but good at the scale of a whole city
- City as a living being, e.g., vessels for circulation
- Coarse model, that is refined/sculpted
- Are there limitations on what can be modeled?
    - Older, walkable cities vs. newer, car-focused cities
    - Ancient civilizations, futuristic cities, or alien cities?
- Impressive large, flexible, system
- Thoughtful consideration of runtime and memory efficiency
- Balance between user control and auto-generated content
- Impressive variety from a modest set of rules

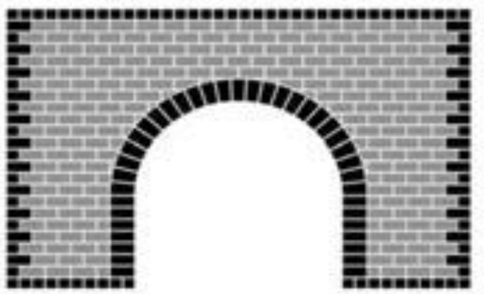
Cellular Texturing

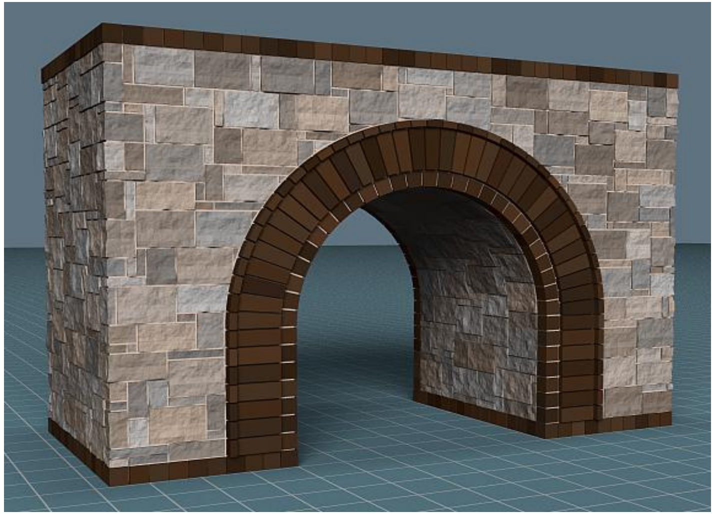

Correct


Incorrect

“Feature-Based
Cellular Texturing for
Architectural Models”,
Legakis, Dorsey, & Gortler,
SIGGRAPH 2001

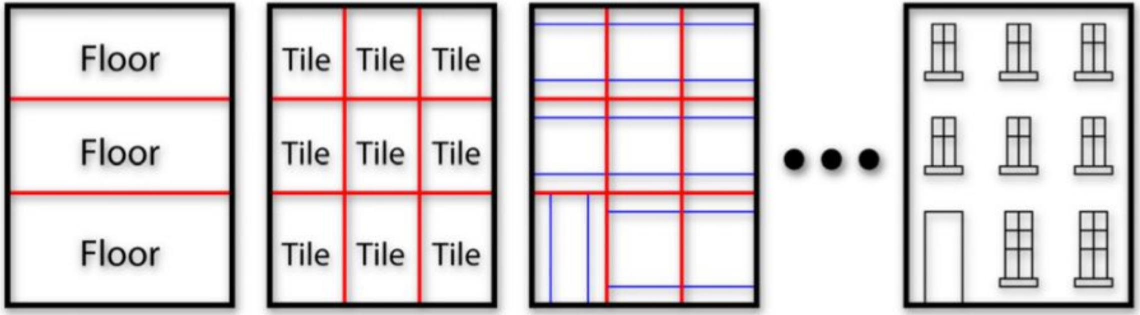






“Procedural Modeling of Buildings”,
Mueller, Wonka, Haegler,
Ulmer & Van Gool,
SIGGRAPH 2006

“Image-based Procedural Modeling of Facades”
Mueller, Zeng,
Wonka, & Van Gool,
SIGGRAPH 2007



Input Photograph

Reconstructed 3D Geometry

Procedural Modeling Advantages

- Small representation
- Generate detail as needed (“infinite”? resolution)
- Great for natural mathematical patterns and man-made engineering and design
- Trivial to make many duplicate objects with small variations

Procedural Modeling Applications

- Entertainment – Gaming
- Education – Studying botanical variation
- Archeological reconstruction
- Realism for Training
- Predicting the future (how will things grow over time)
- Urban planning (preparing for traffic)
- Accommodate for that growth/change

Questions about Procedural Modeling

- Number of rules necessary?
- Cost in human designer time of creating procedural model?
- Re-useability of procedural model?
- Validation
- Can you build a procedural model that produces a specific target?

From a photo of a specific rare wood grain,
can you create a compact procedural model that
creates texture that looks like it came from a
different location of the same/similar tree?

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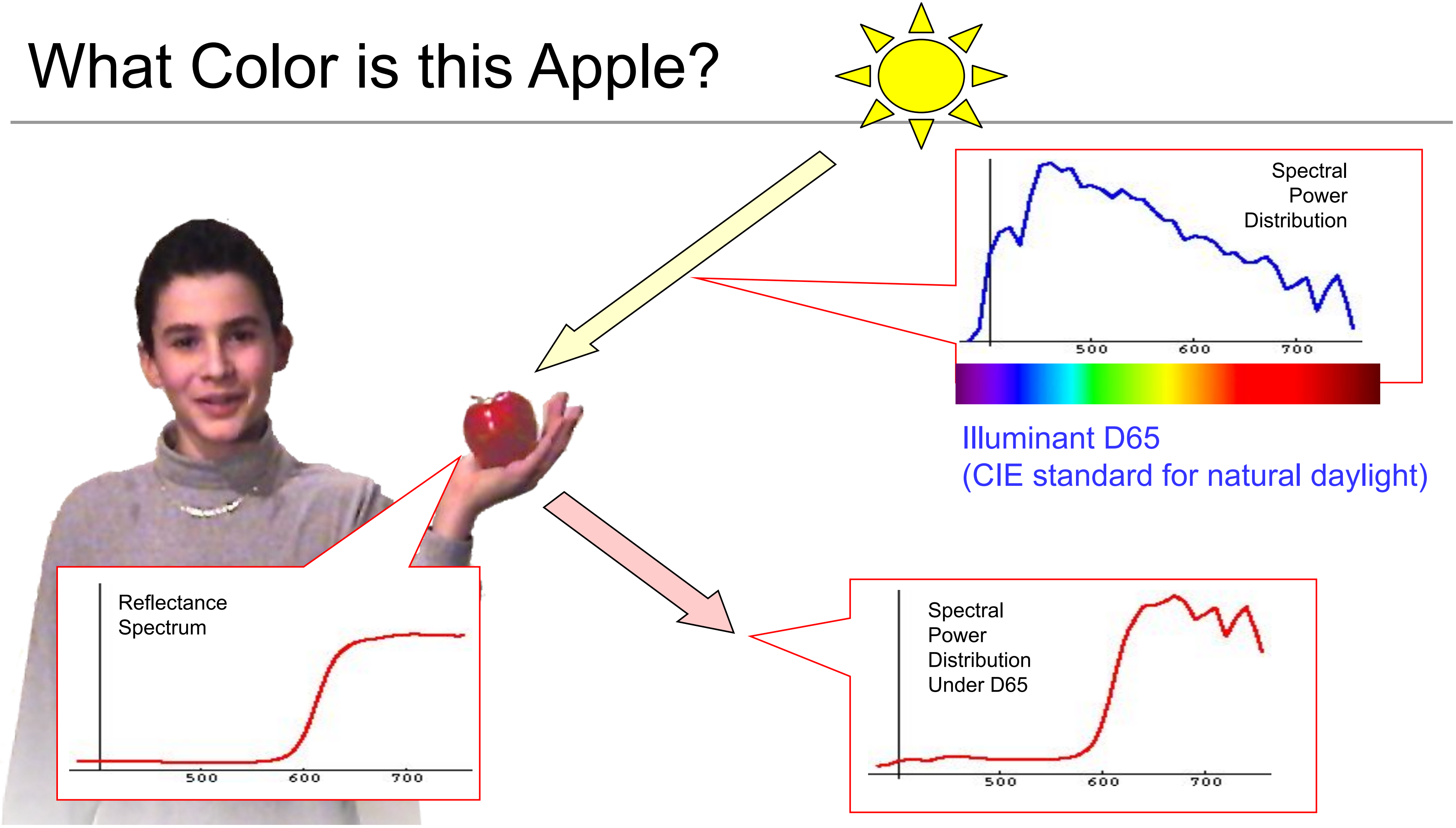
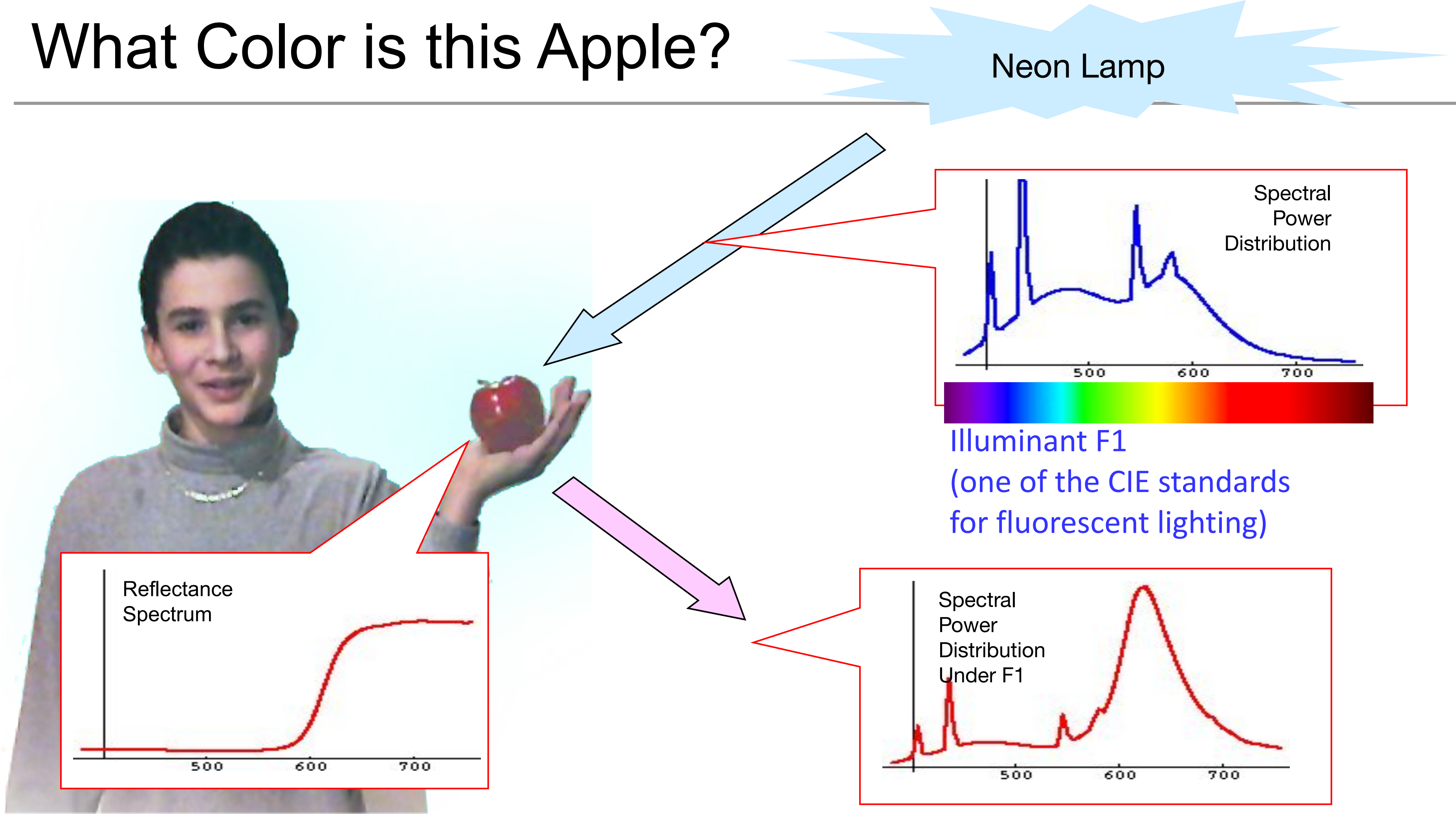
What Color is this Apple?



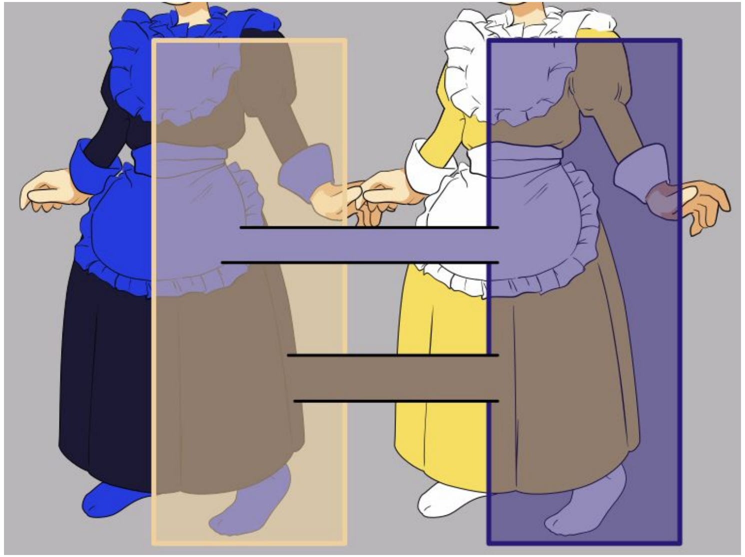
What Color is this Apple?



What Color is this Dress?

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

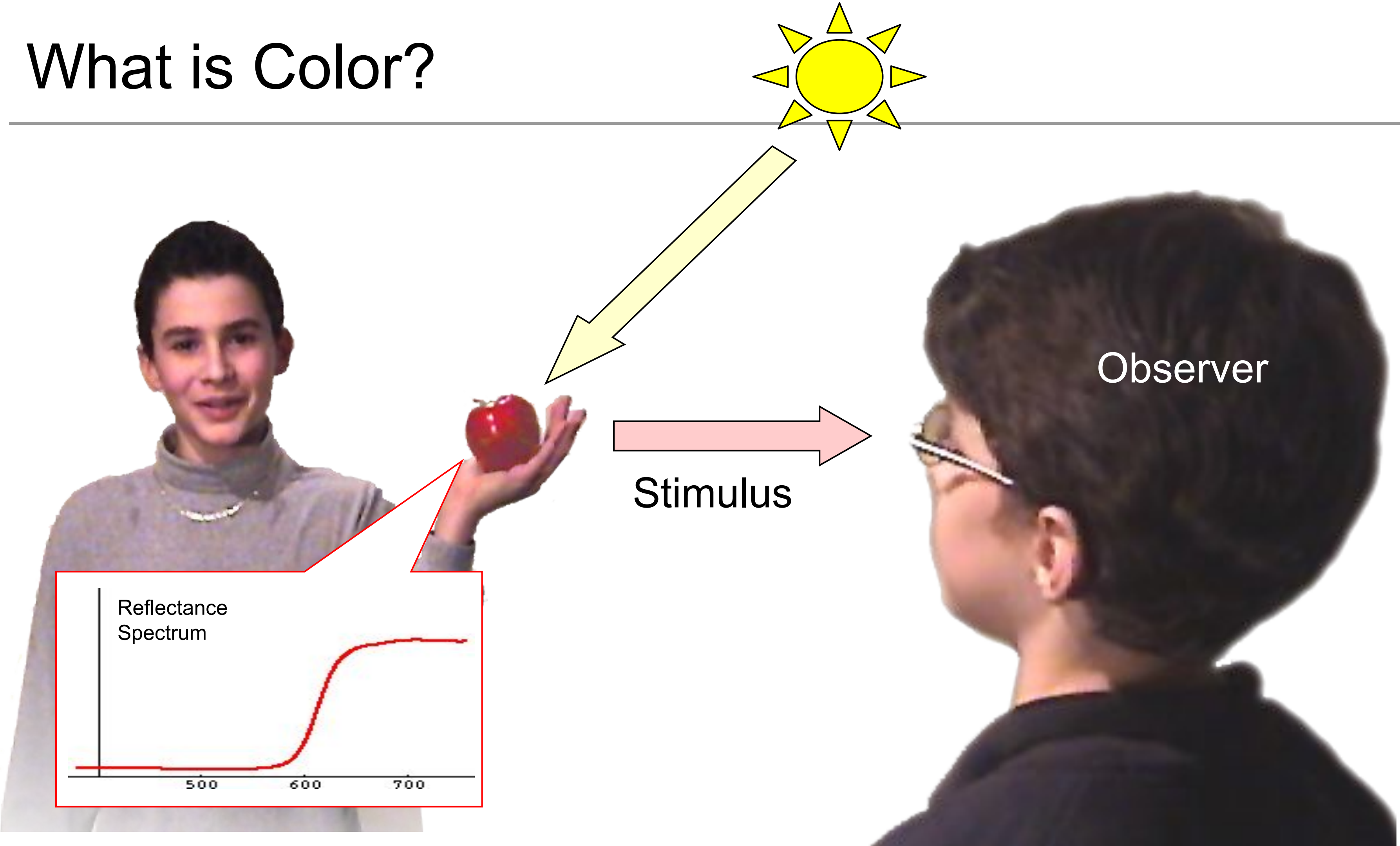
What does the viewer infer about the scene illumination?



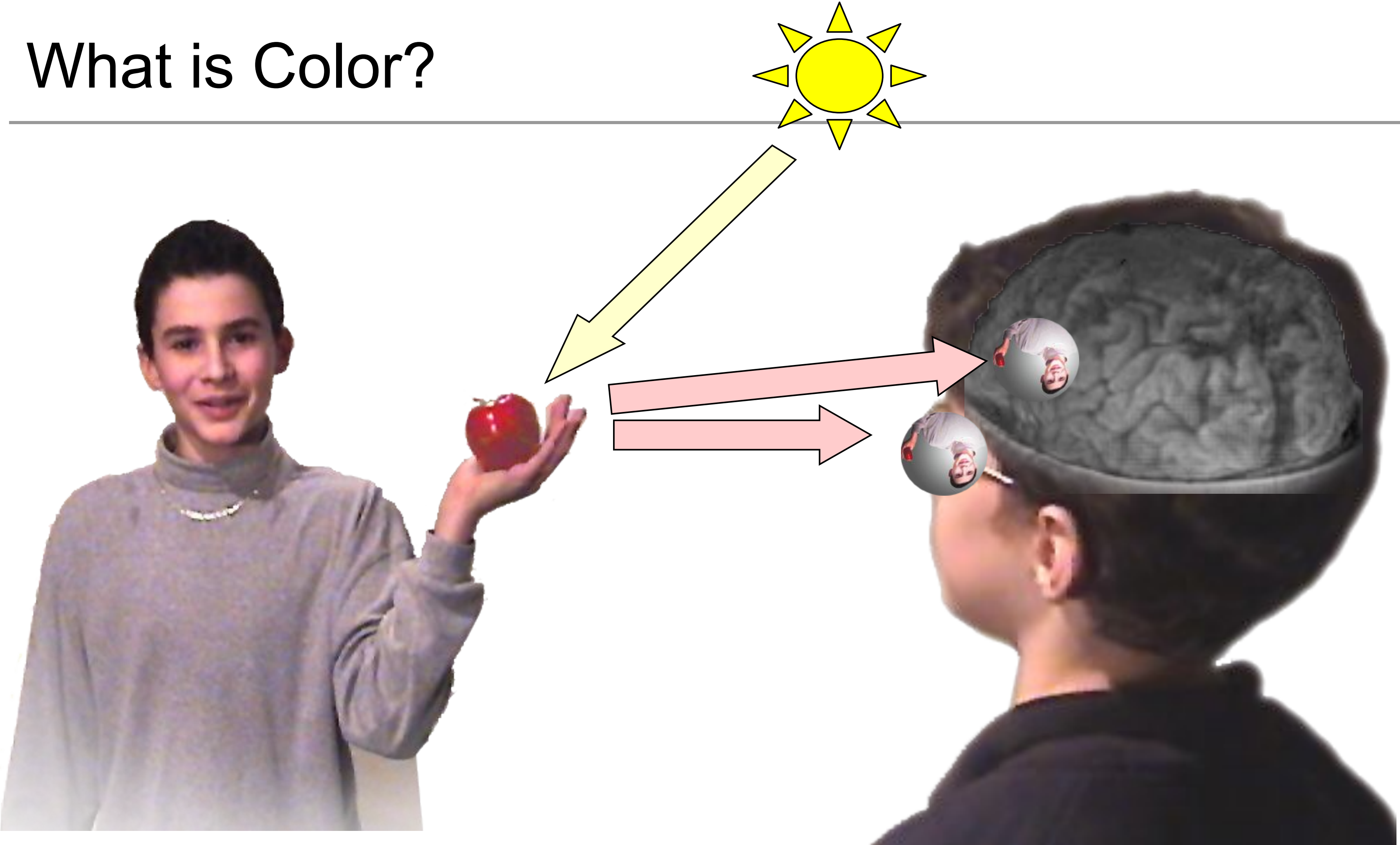
Blue & Black under yellow-tinted illumination?

White & Gold under blue tinted illumination?

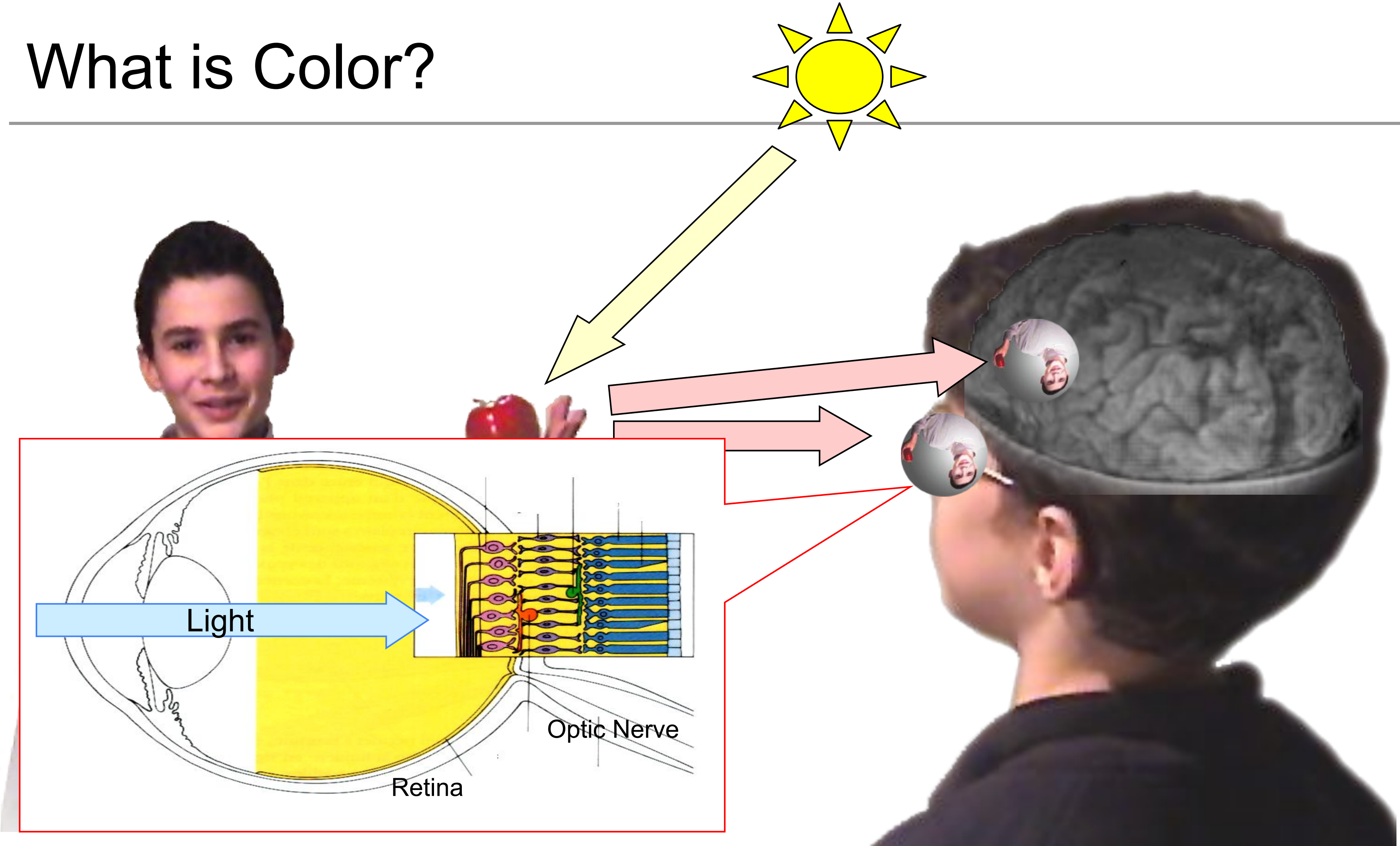
What is Color?



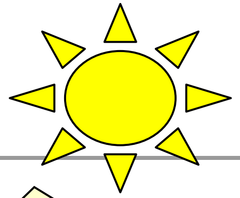
What is Color?

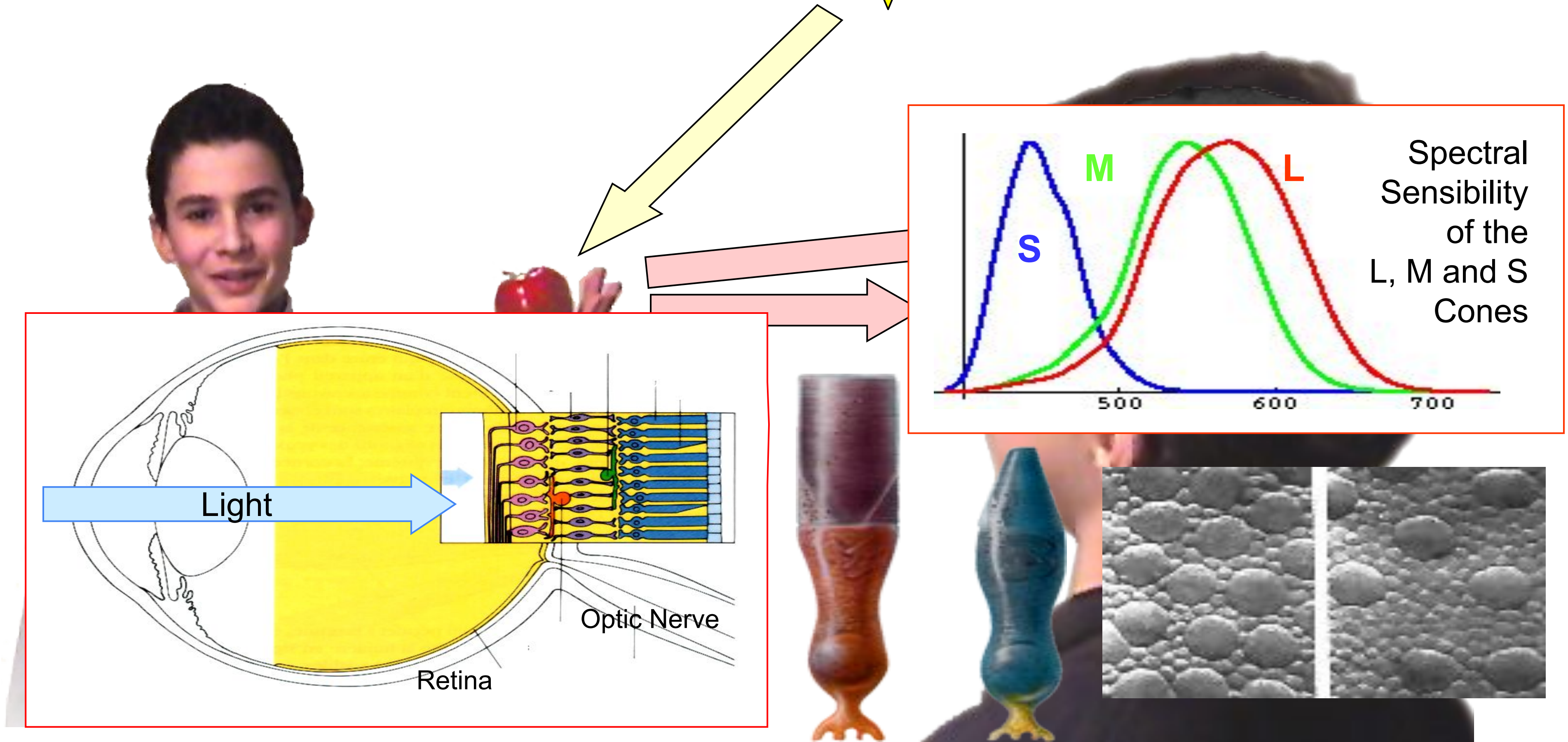


What is Color?



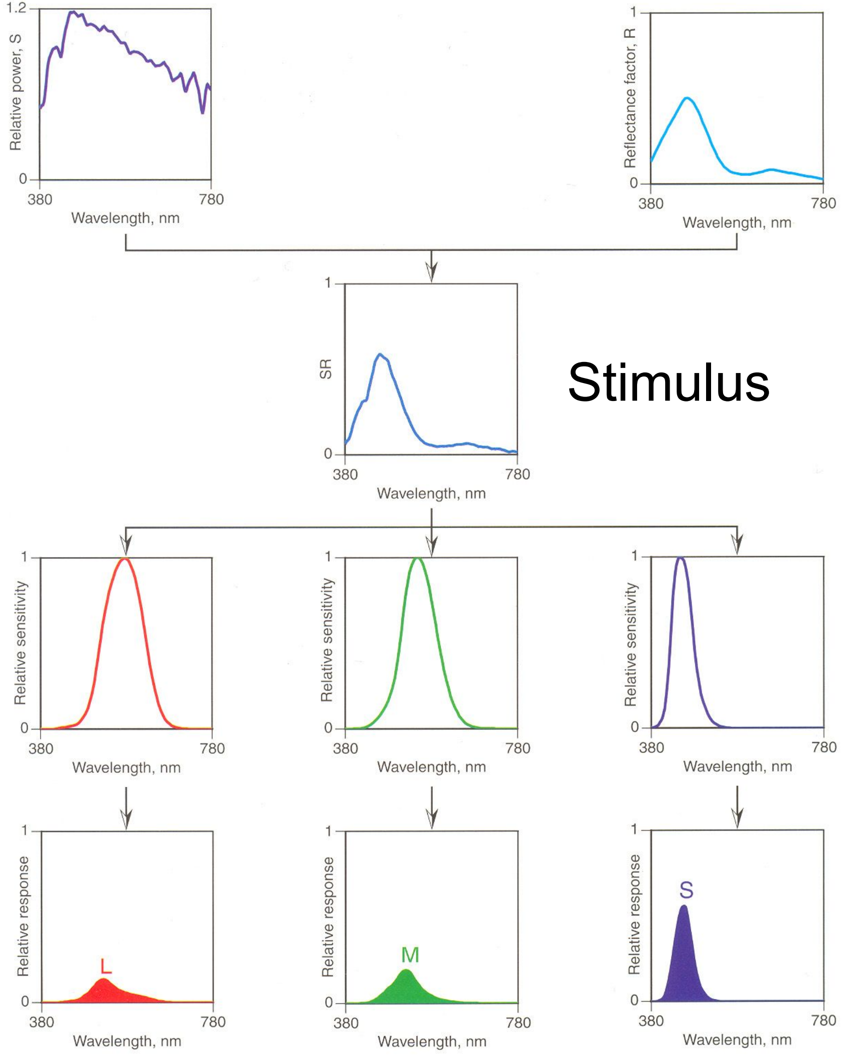
What is Color?





Incoming Light

Material Reflectance



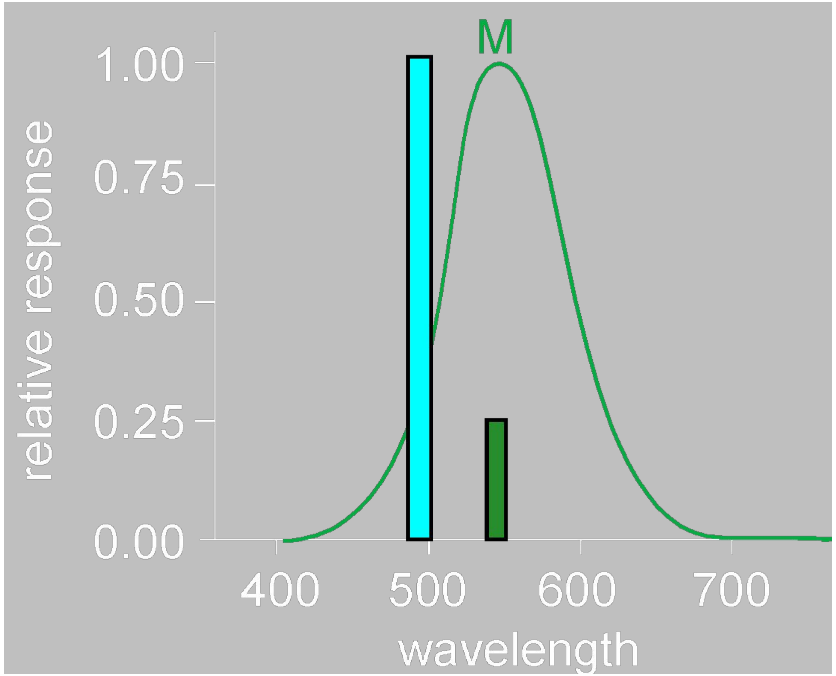
Stimulus

Cone Sensitivity

Cone Responses

Cones do not “See” Colors

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

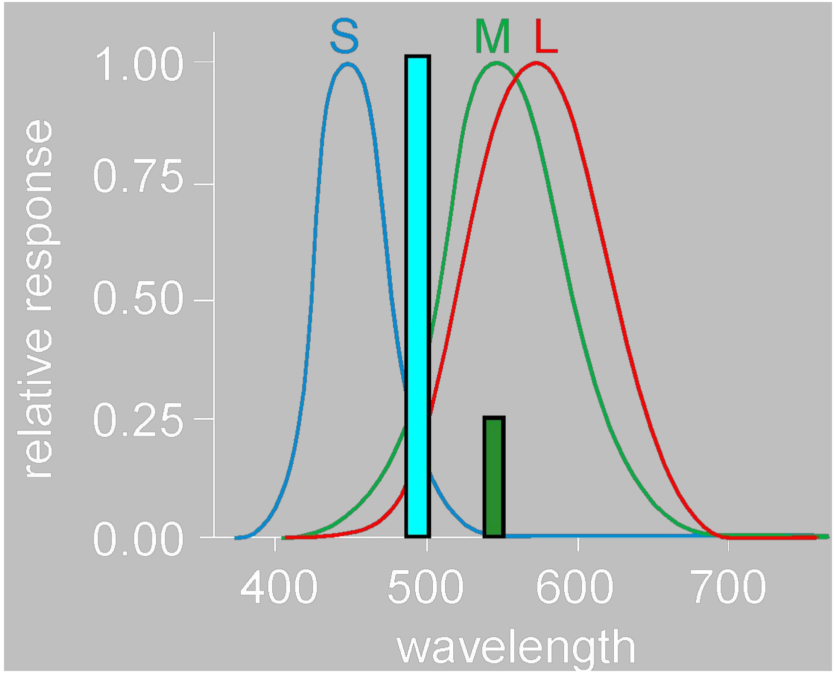


Dim green
Cone M/G: 0.25

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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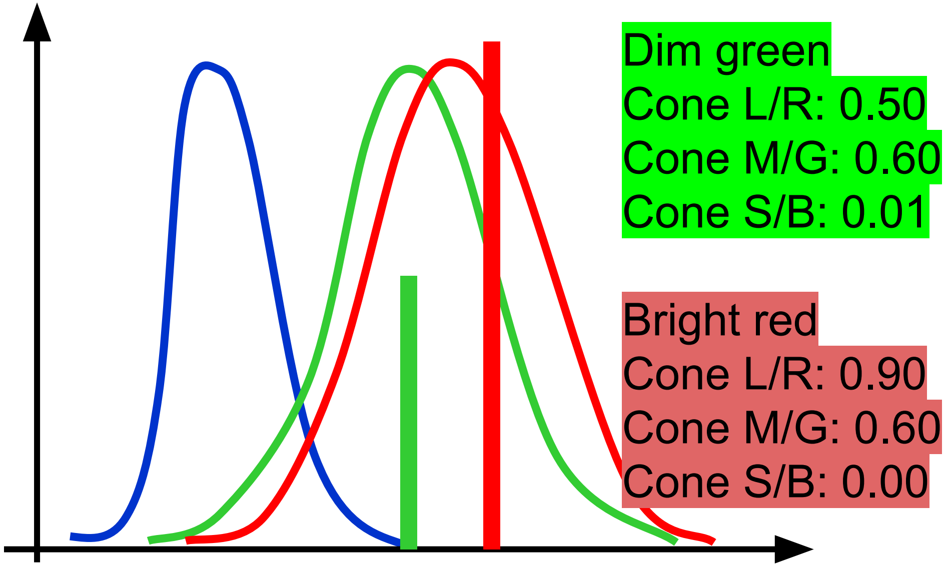
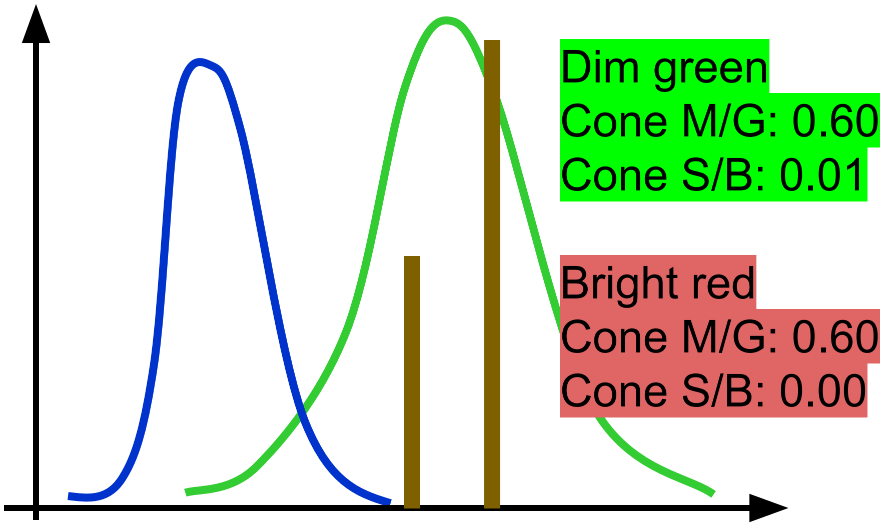
Color Blindness

- 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*

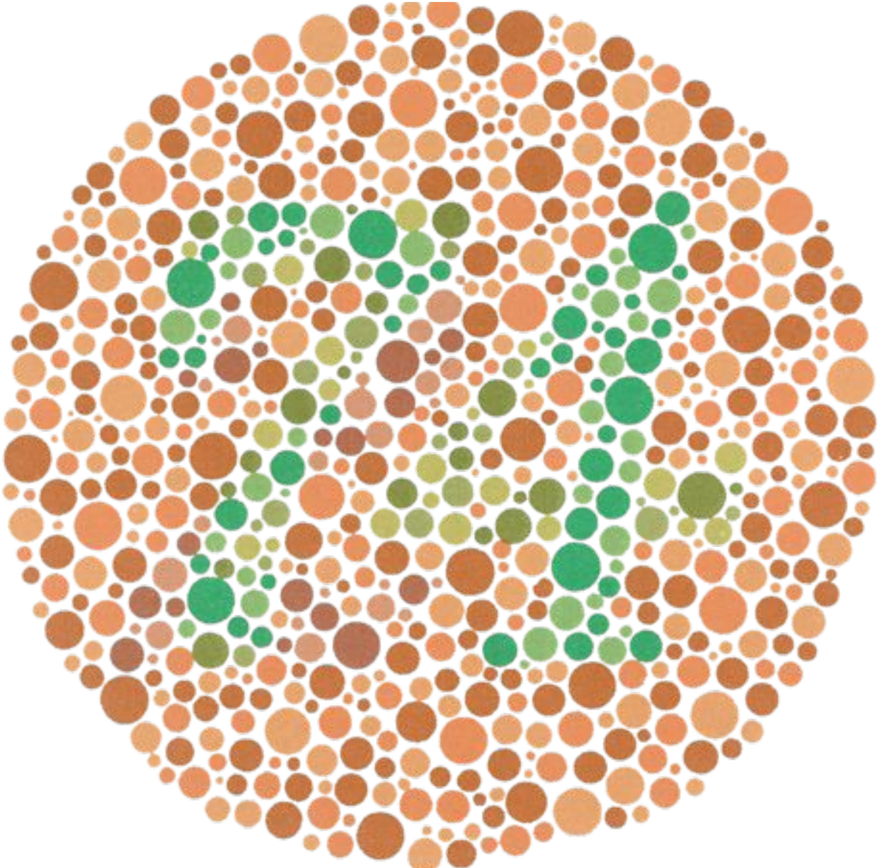


3 cones: Can be differentiated



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 for an accurate diagnoses.

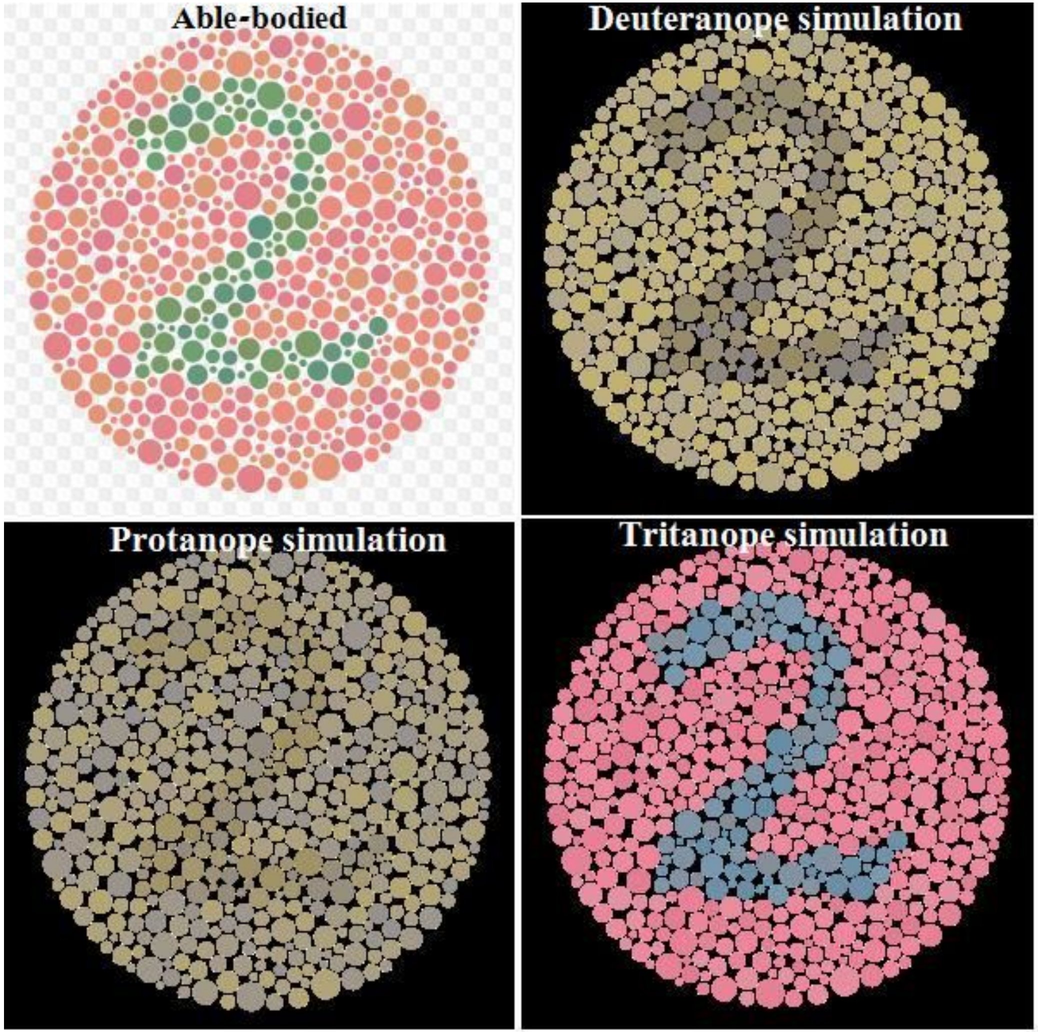
http://en.wikipedia.org/wiki/Ishihara_color_test

- Deuteranopia:
  missing
  medium / green cone

- Protanopia:
  missing
  long / red cone

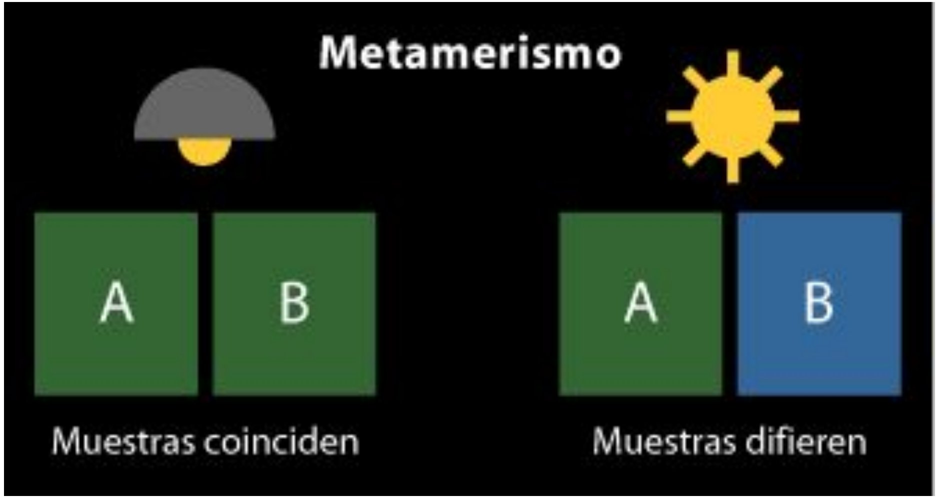
- Tritanopia: (rare)
  missing
  short / blue cone

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



Metamerism: Apparent Matching

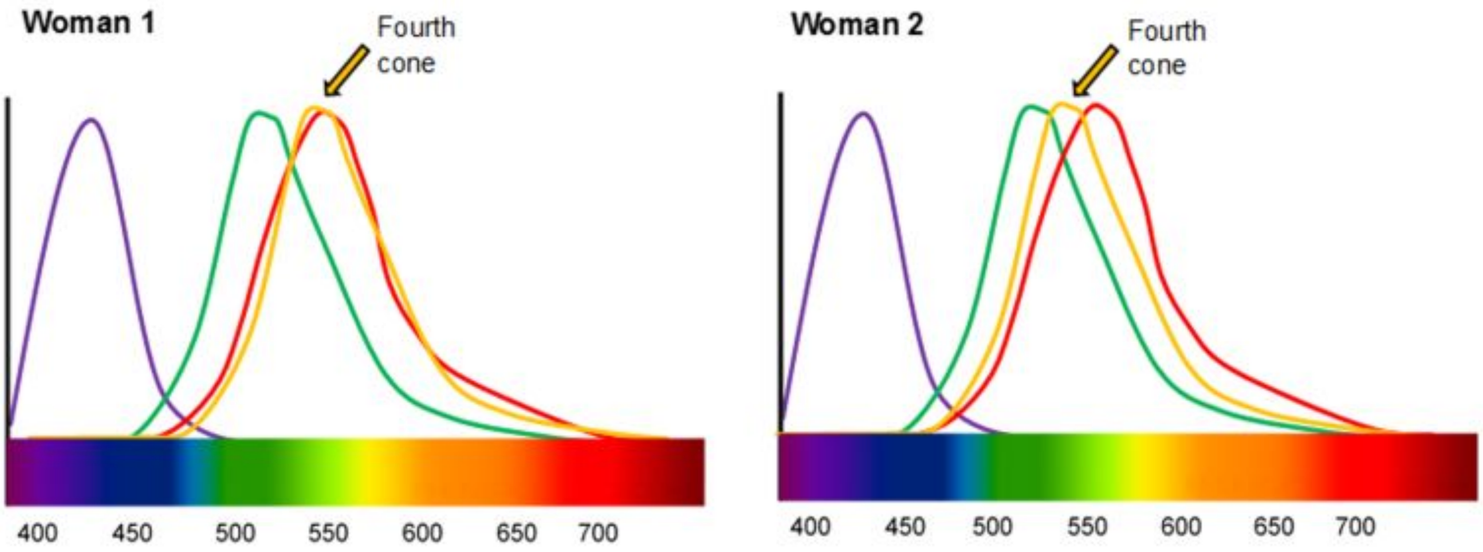
- When two materials look the same under one lighting condition (a coincidence), but look different under another.
- E.g. the shirt & pants matched in the store lighting, but not outside!
- Different spectral distribution of input light yield different visual stimuli
- *We all experience some color blindness*



http://gusgsm.com/metamerismo

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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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

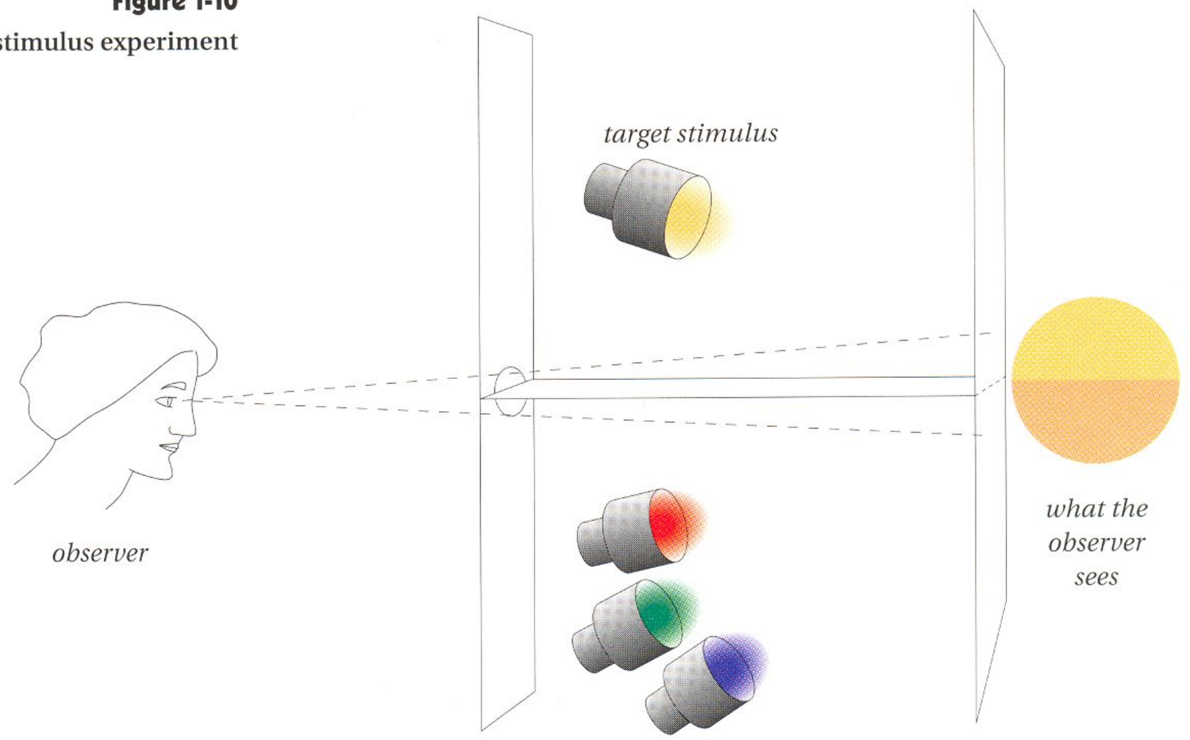
Commission Internationale de l'éclairage (CIE)

a.k.a.

International Commission on Illumination

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.

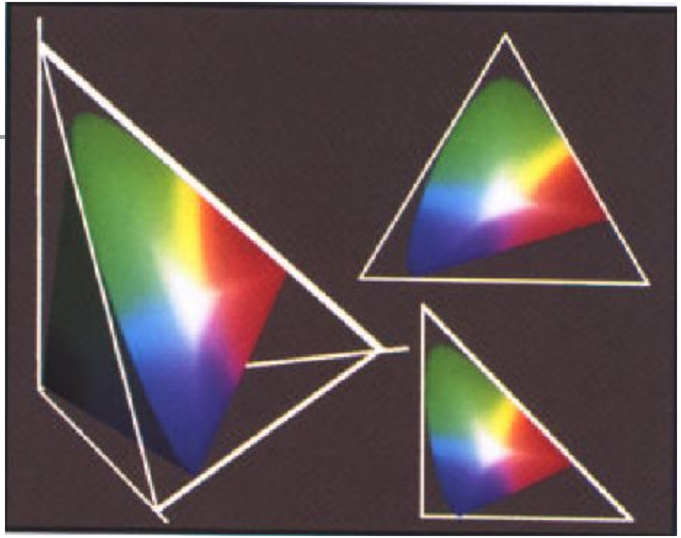
CIE XYZ Color Space

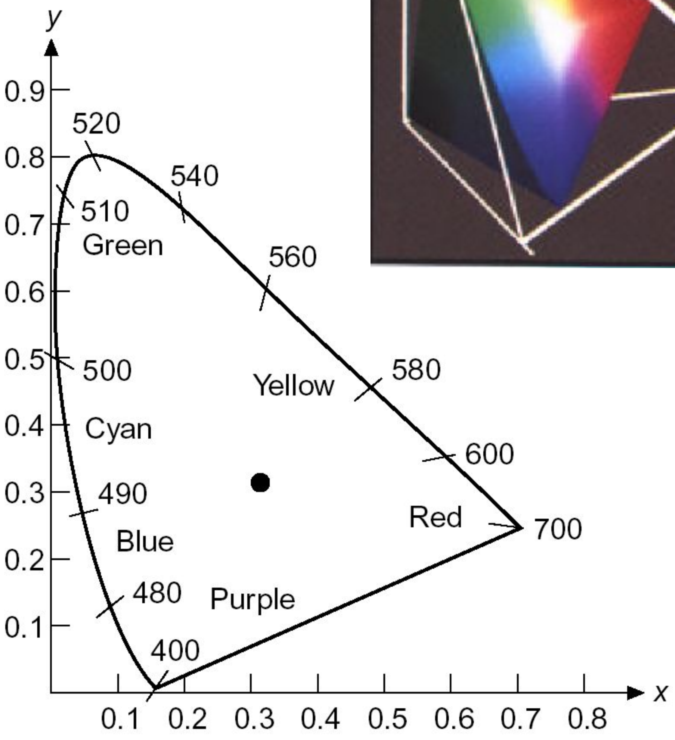
- Can think of X, Y, & Z as 3D coordinates
- Linear transform to/from typical LMS or RGB

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

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

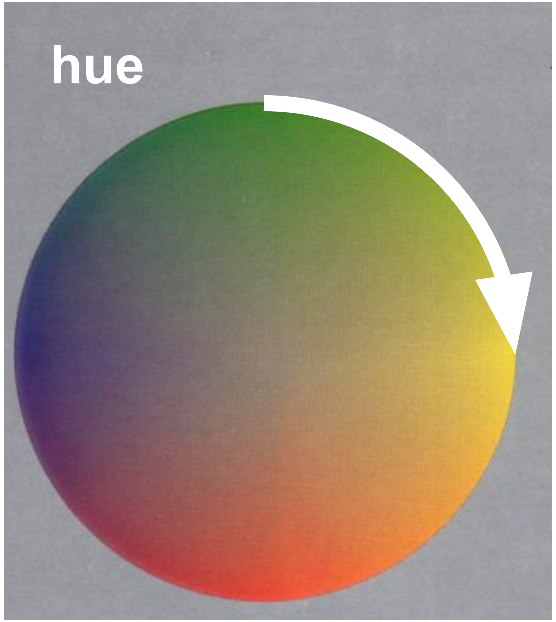
- Note that many points in XYZ do not correspond to visible colors!

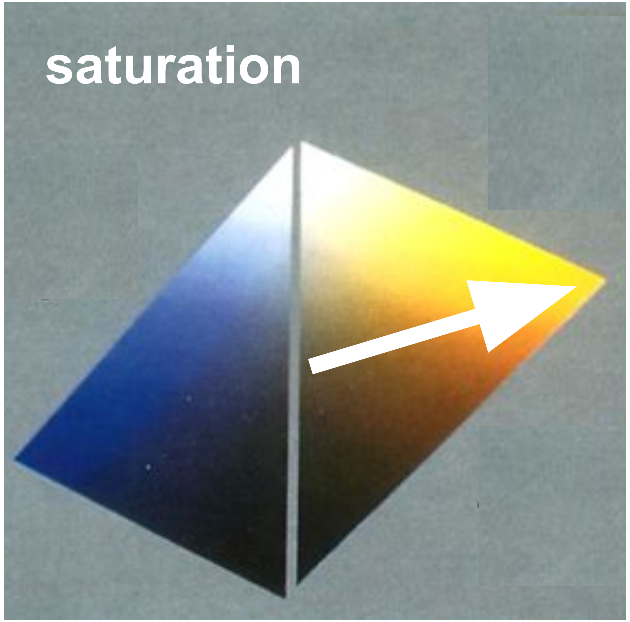


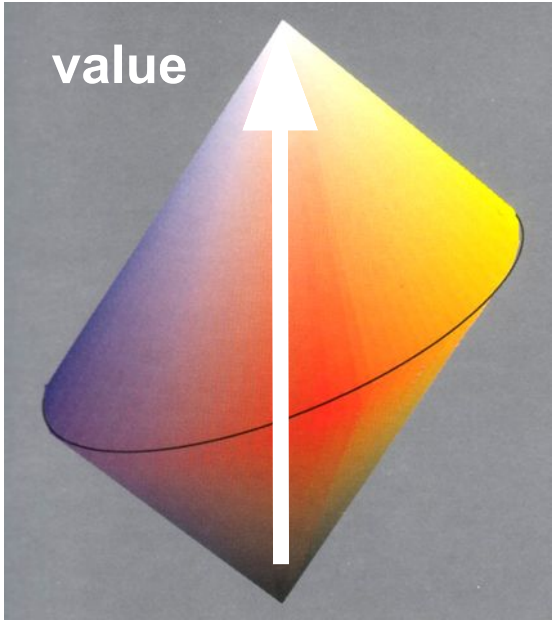


Hue Saturation Value (HSV)

- 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)

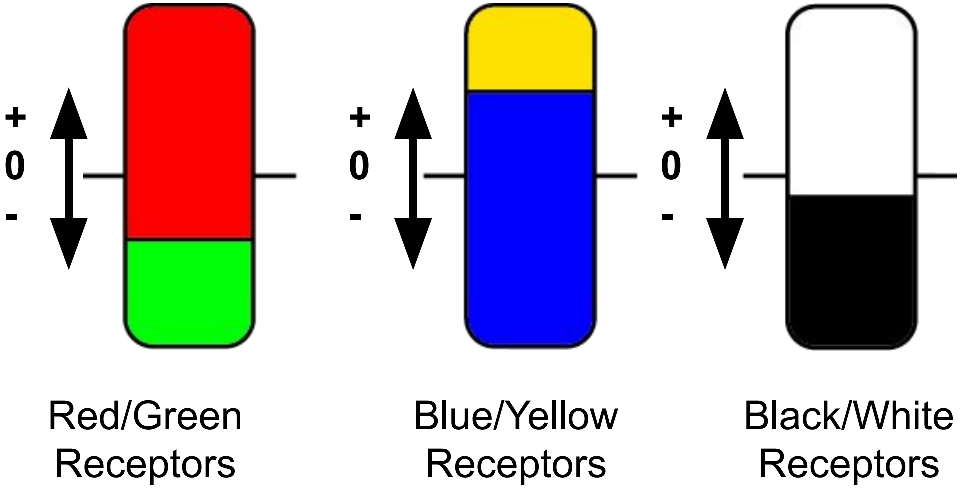


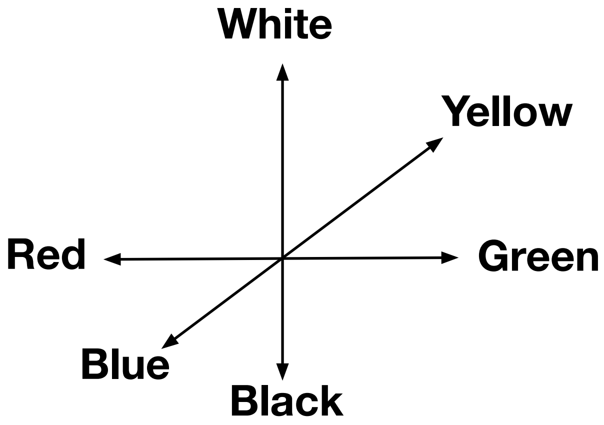




Hering 1874: Opponent Colors

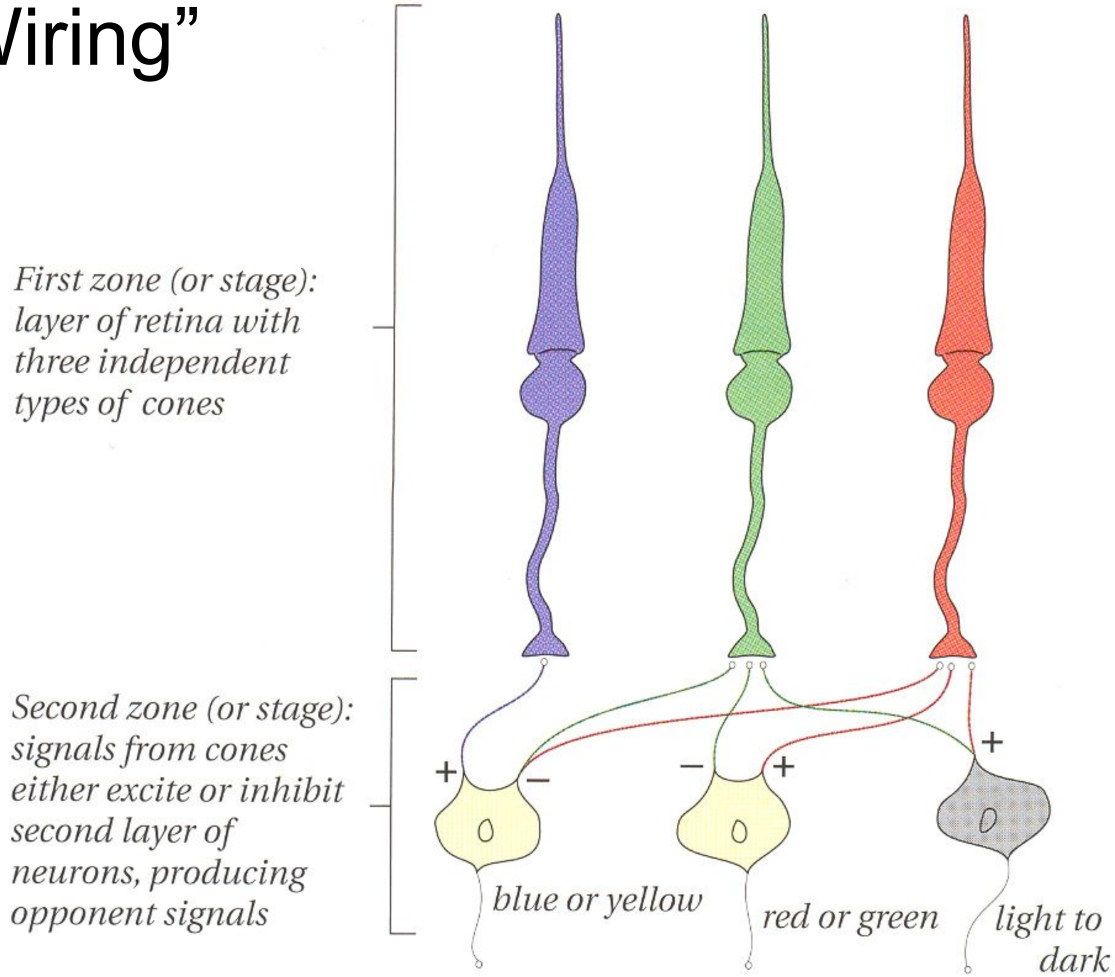
- Hypothesis of 3 types of receptors:
  Red/Green, Blue/Yellow, Black/White
- Explains well several visual phenomena





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

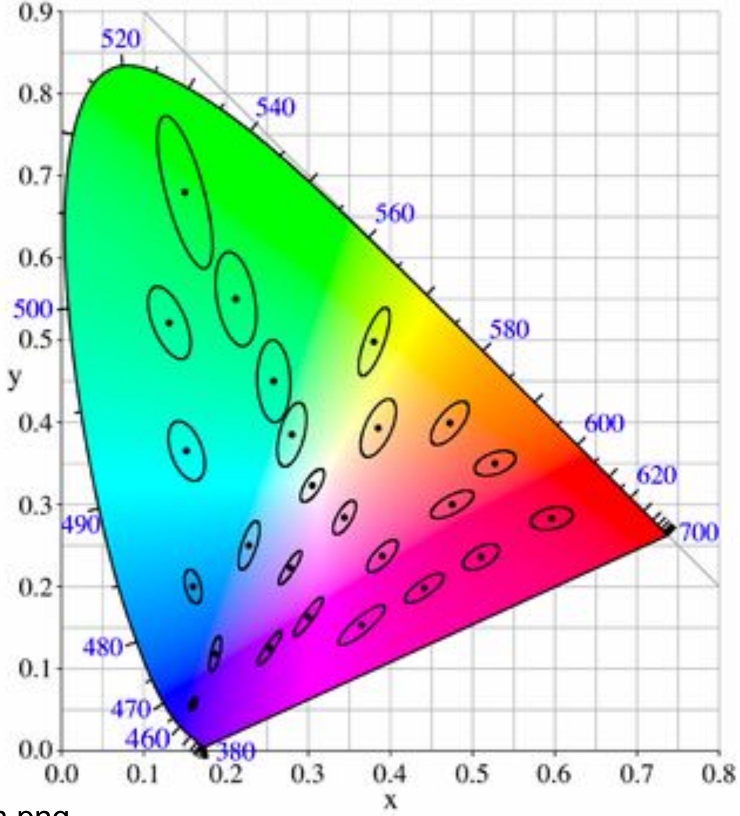


Linear Color Spaces: RGB/XYZ/YPbPr

- 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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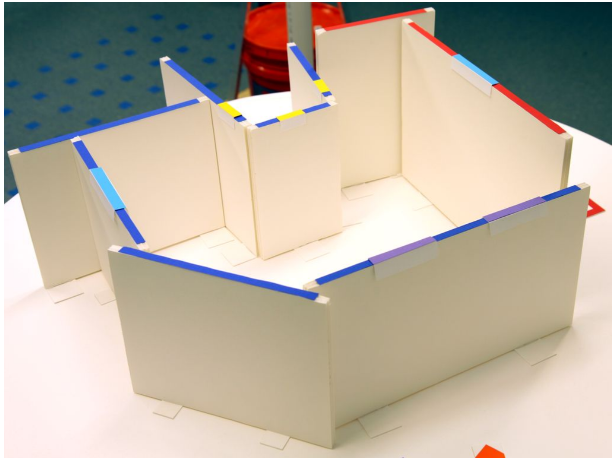
Spatially Augmented Reality (SAR) Projection

camera detects design geometry

6 projectors augment design

design sketched with foam-core walls

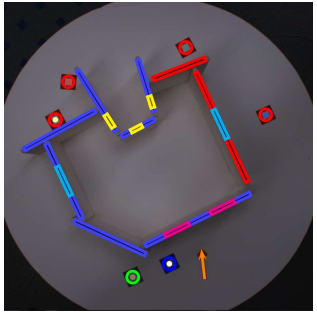
Tangible Interface for Architectural Design



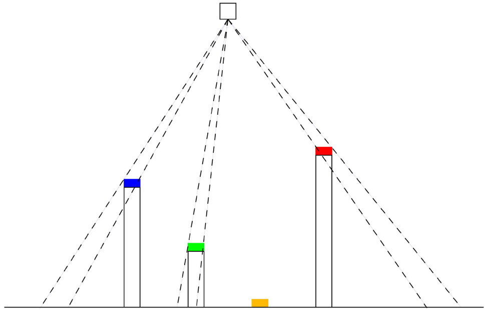
Exterior & interior wall

Tokens for:

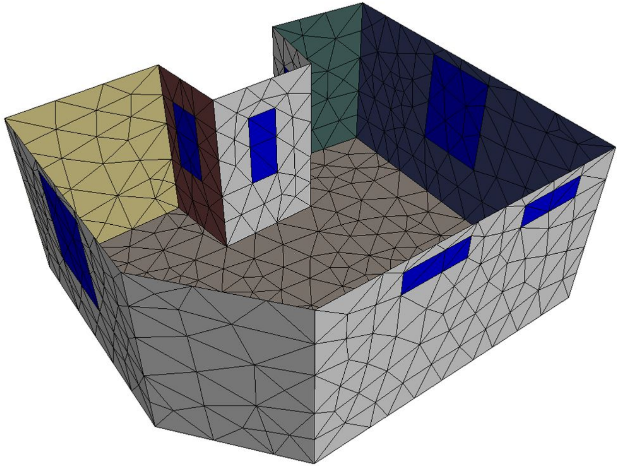
- *Windows*
- *Wall/floor colors*
- *North arrow*



Overhead camera



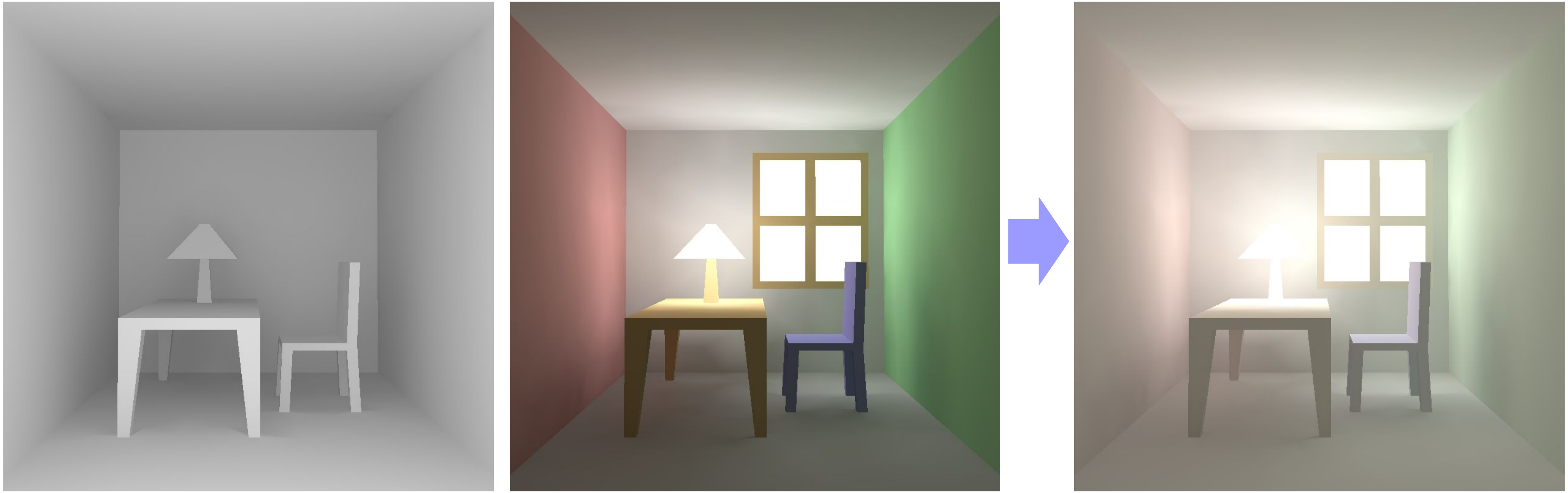
Projection geometry



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

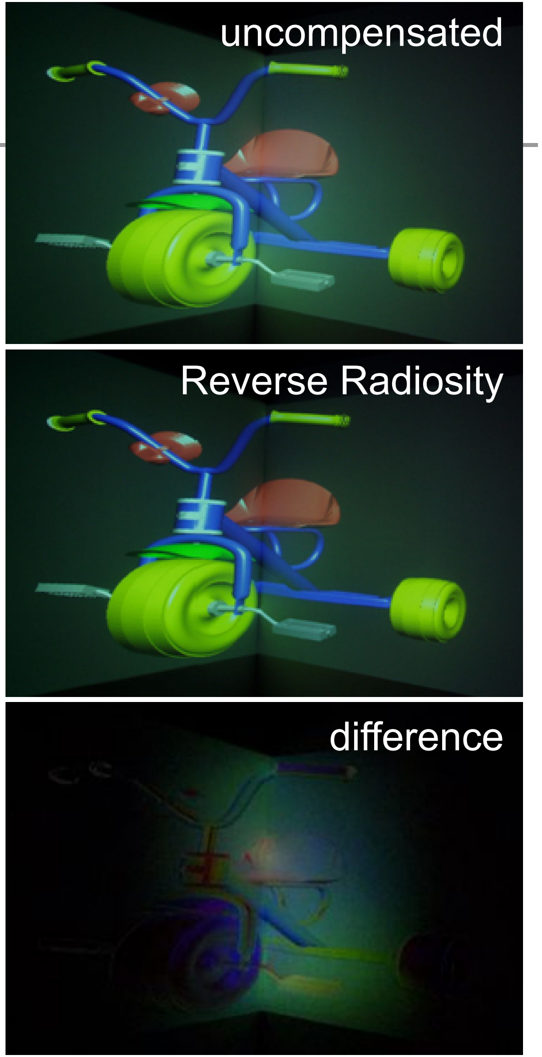
Related Work: Reverse Radiosity

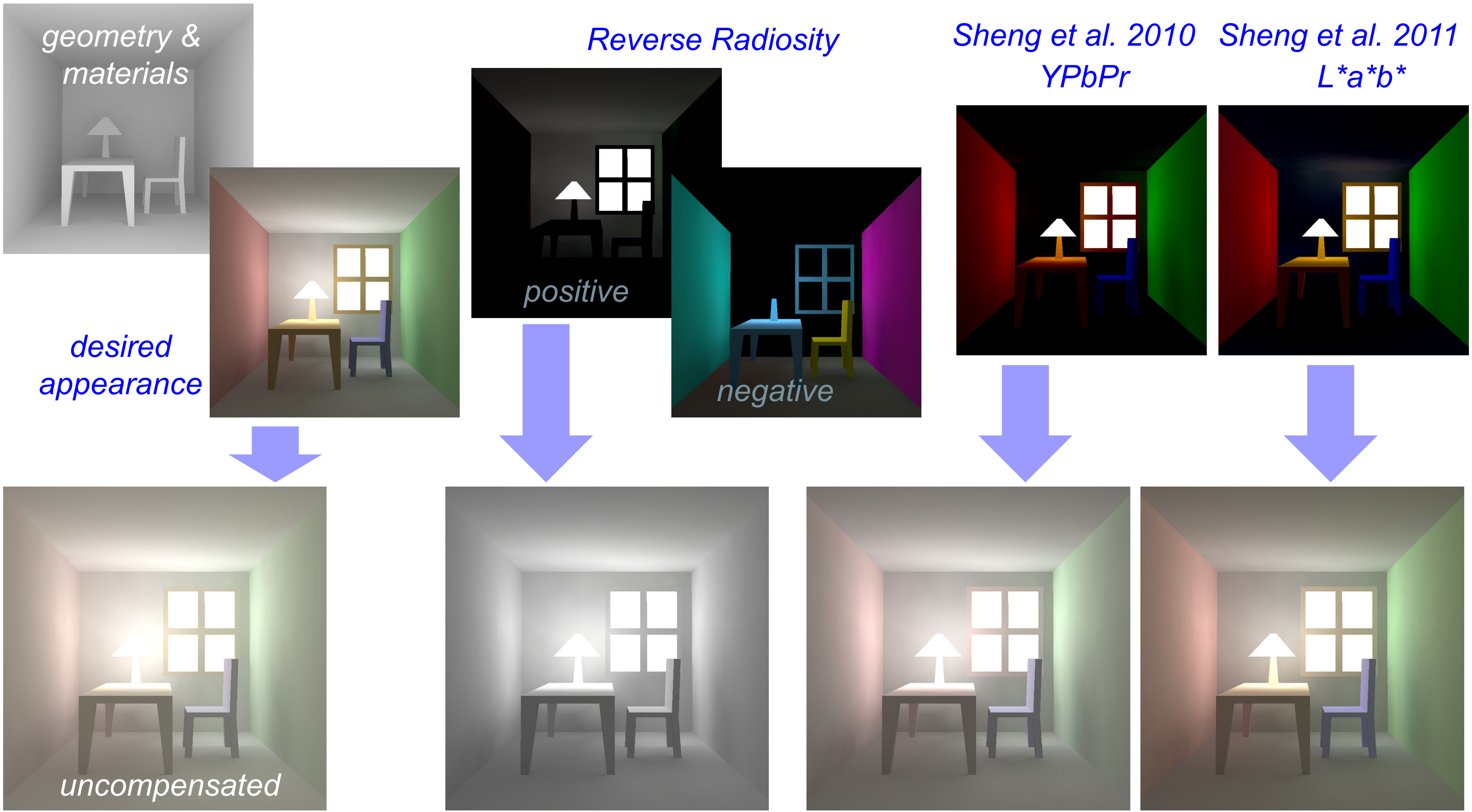
- Forward lighting with radiosity

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

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

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




geometry &
materials
desired
appearance
uncompensated
Reverse Radiosity
positive
negative
Sheng et al. 2010
YPbPr
Sheng et al. 2011
L*a*b*

L*a*b*: a Perceptual Color Space

- Designed to match human color perception data

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

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

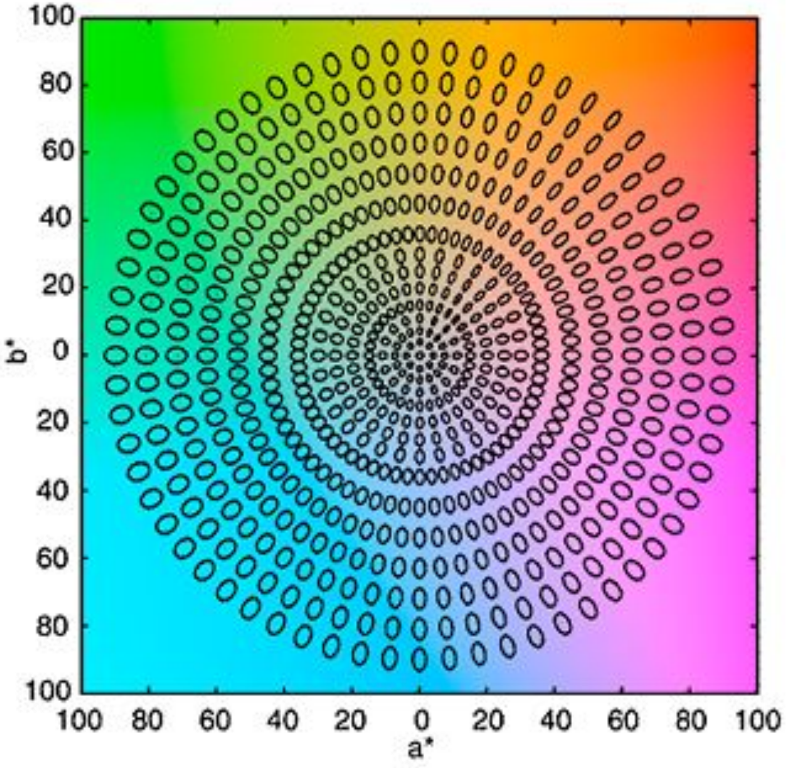
- L*a*b* is *nonlinear*, a challenge for optimization

Quantitative Perceptual Comparison

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

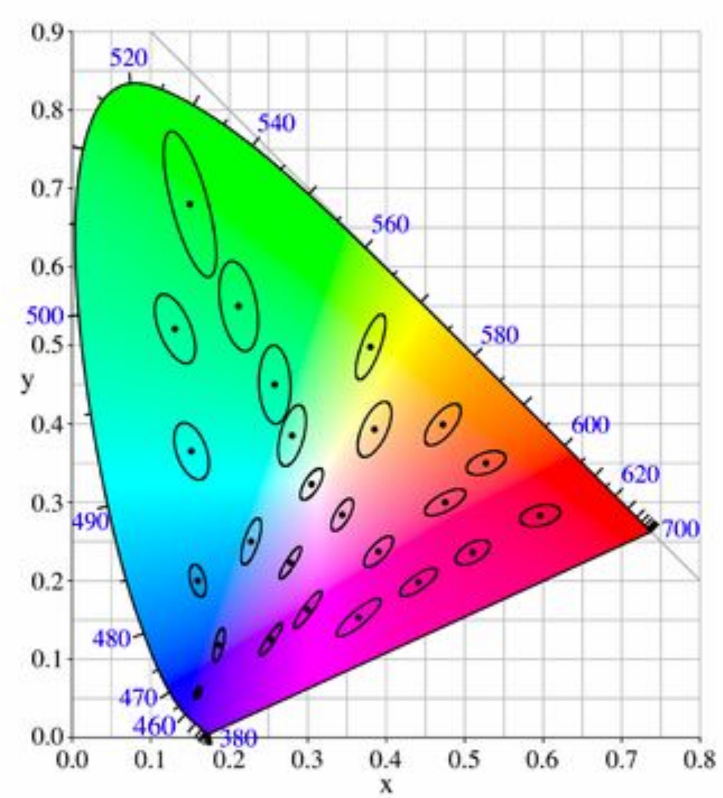
- Where 2.3 ΔE = JND
  "just noticeable difference"

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

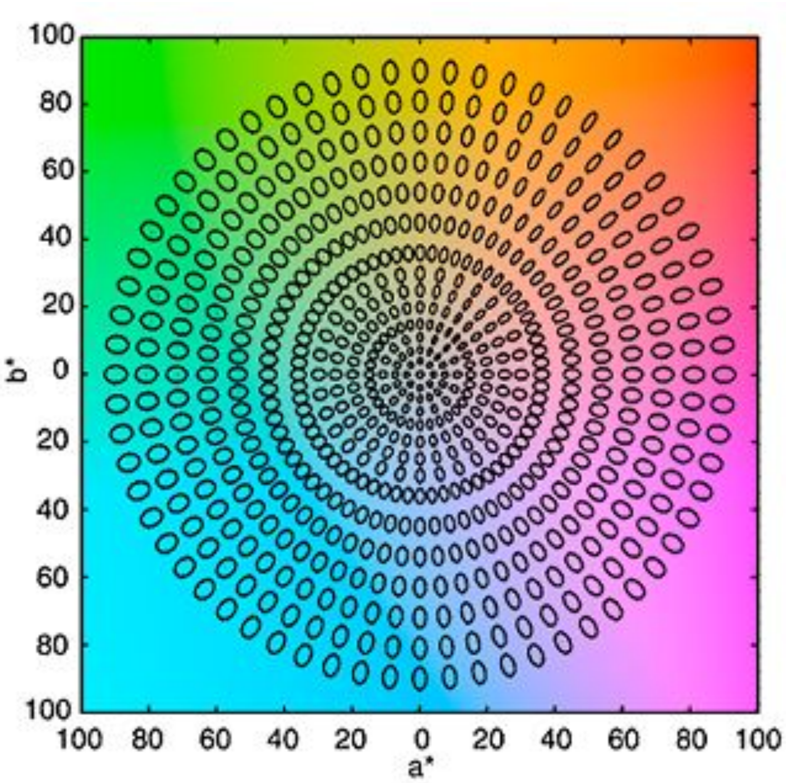


http://w3.kcua.ac.jp/~fujiwara/infosci/ellipses_lab.png

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

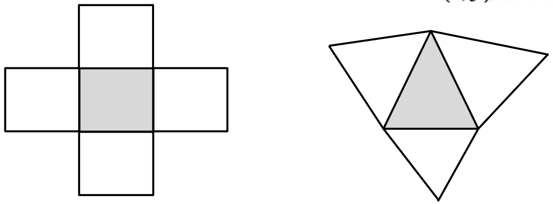
- Absolute Error:

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

desired appearance *projection result*

- Spatial Error:

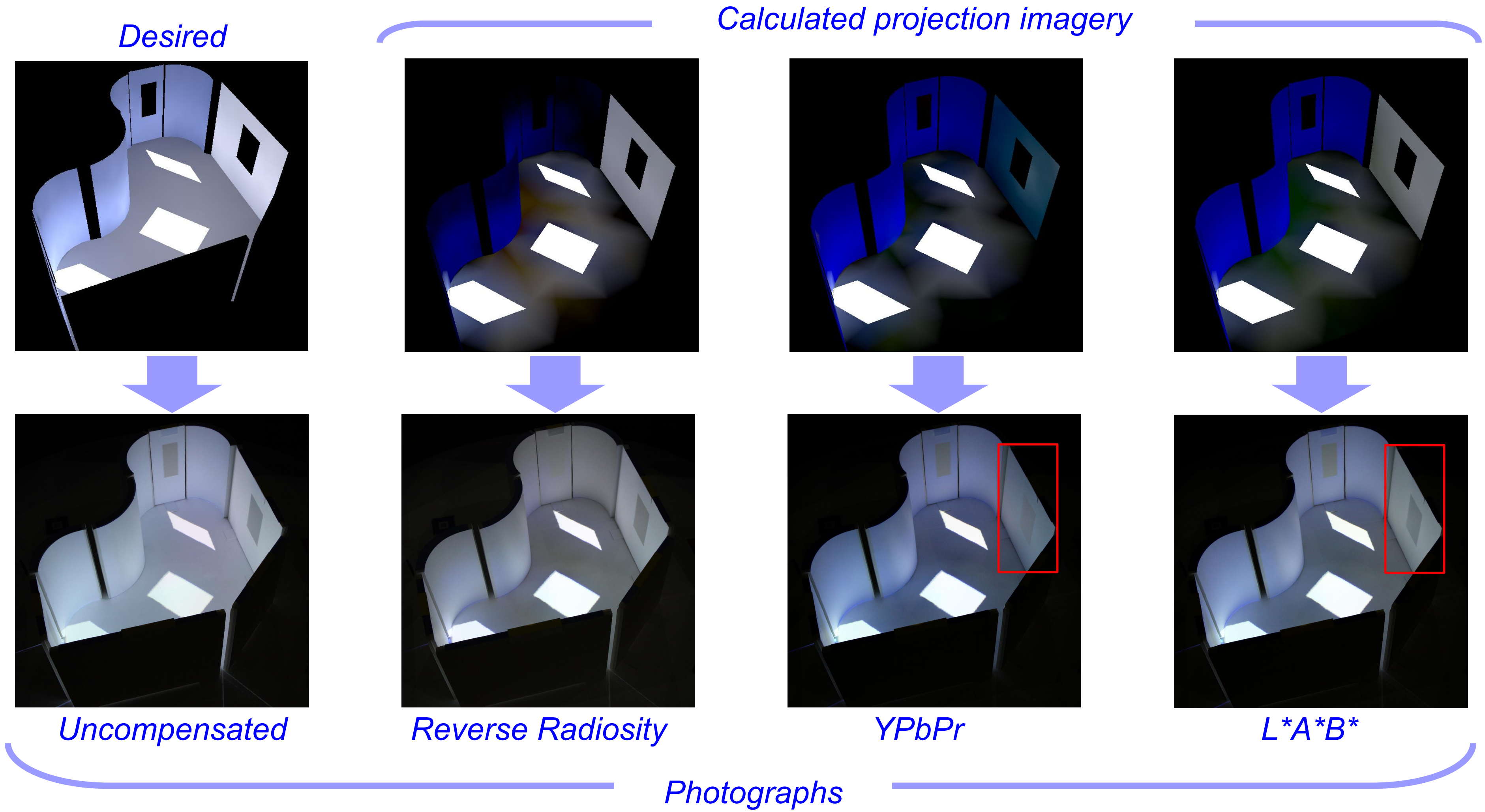
$$\phi_{spt} = \sum_{(i,j)\in nbd} [(L_i - L_j) - (L_i' - L_j')]^2 + [(a_i - a_j) - (a_i' - a_j')]^2 + [(b_i - b_j) - (b_i' - b_j')]^2$$

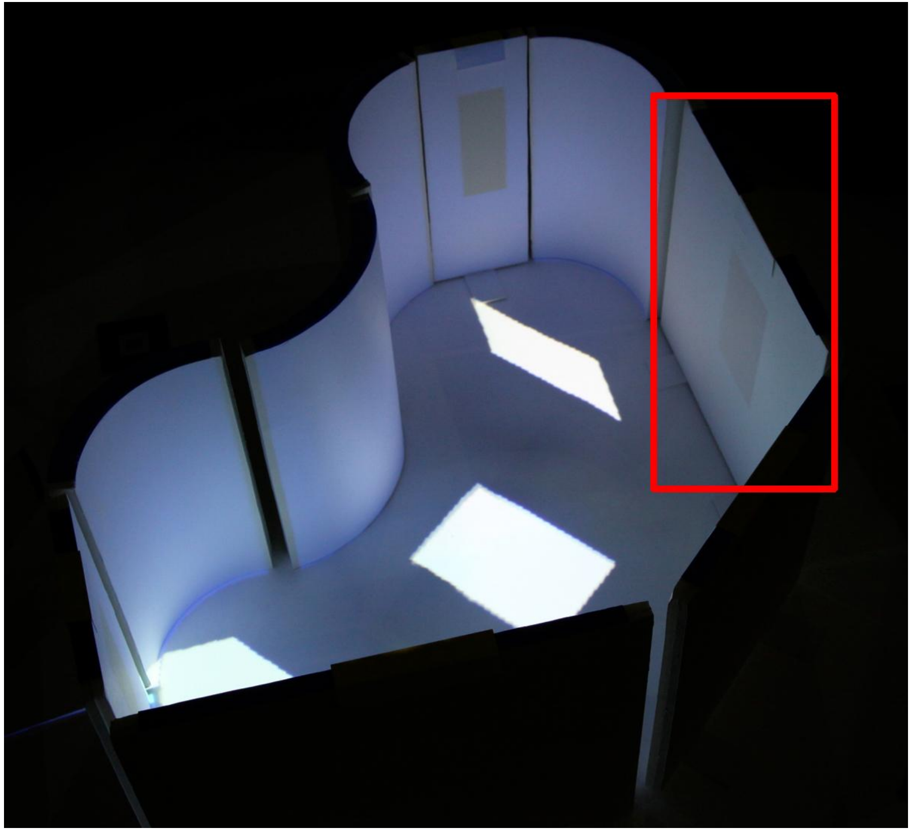


gradient in desired appearance *gradient in projection result*

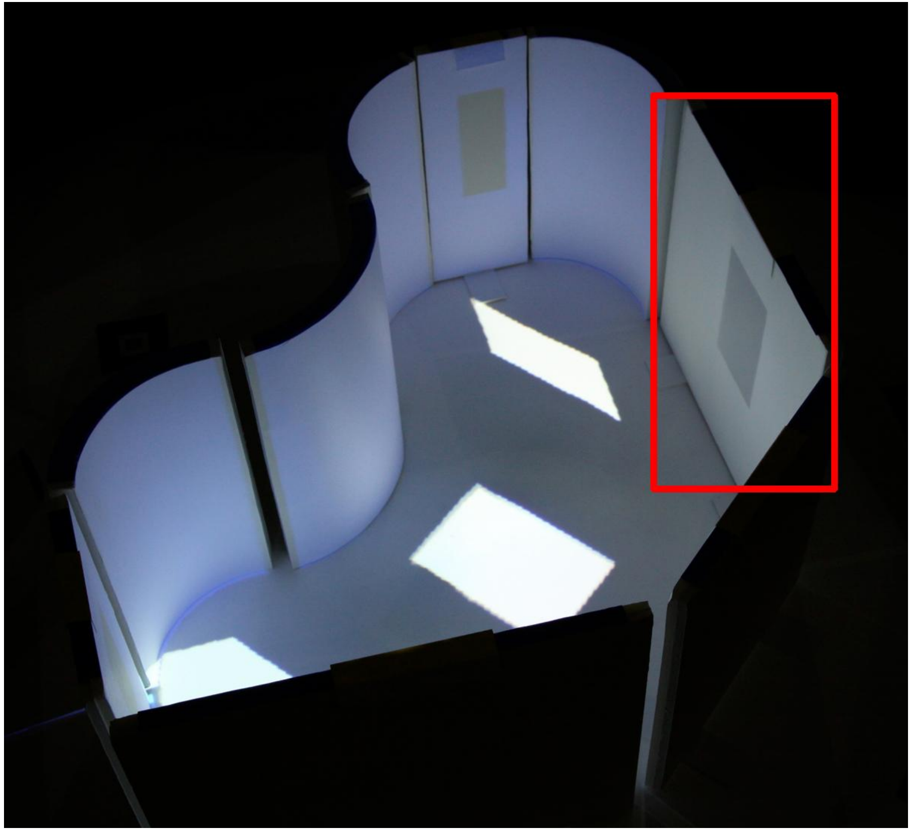
- Complete Objective Function: $\phi = \alpha\phi_{abs} + (1-\alpha)\phi_{spt}$ *We use α = 0.9*
- Box constraints:

minimum & maximum brightness of projector system *No negative light!*

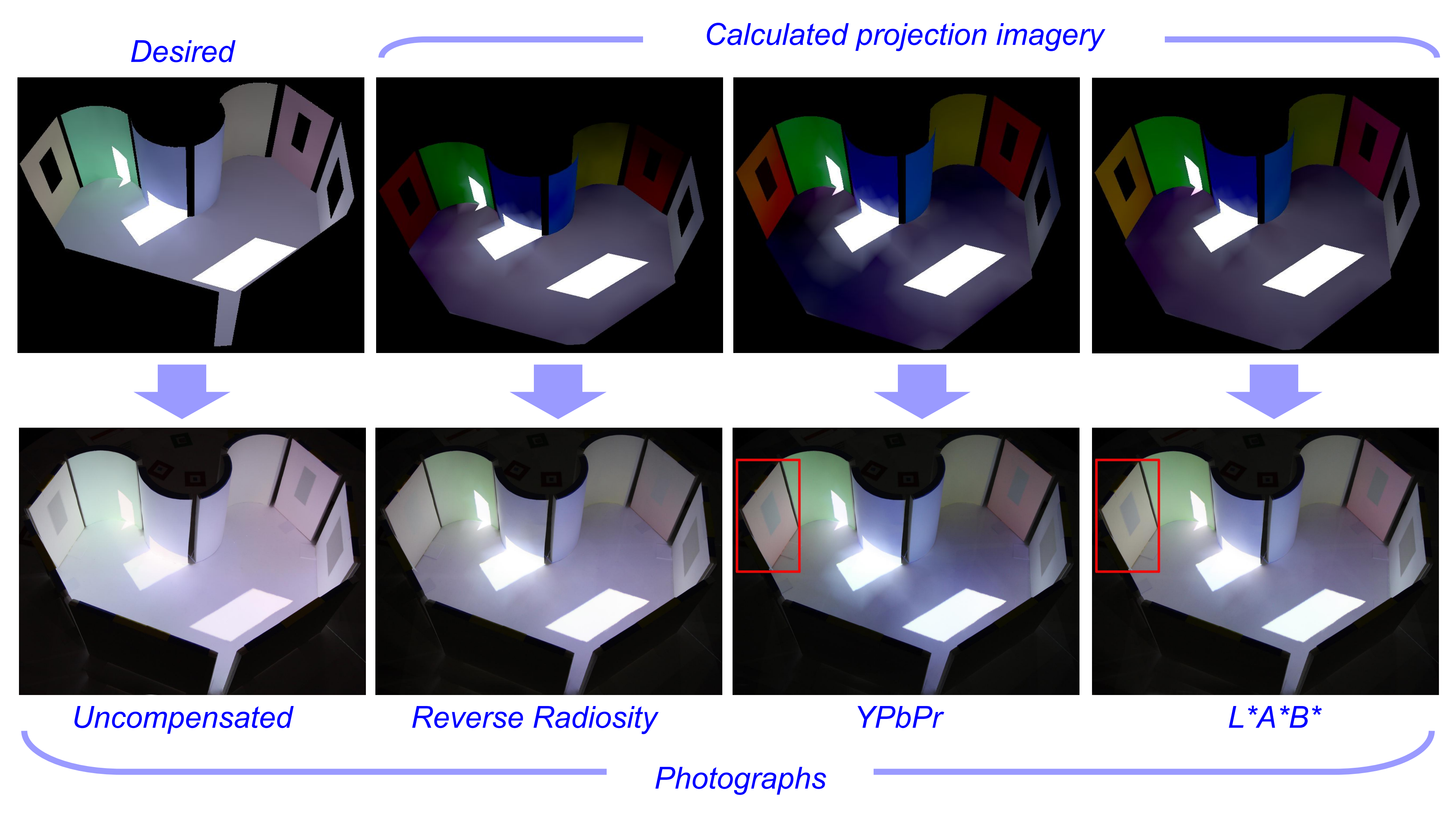

Desired
Calculated projection imagery
Uncompensated
Reverse Radiosity
YPbPr
L*A*B*
Photographs

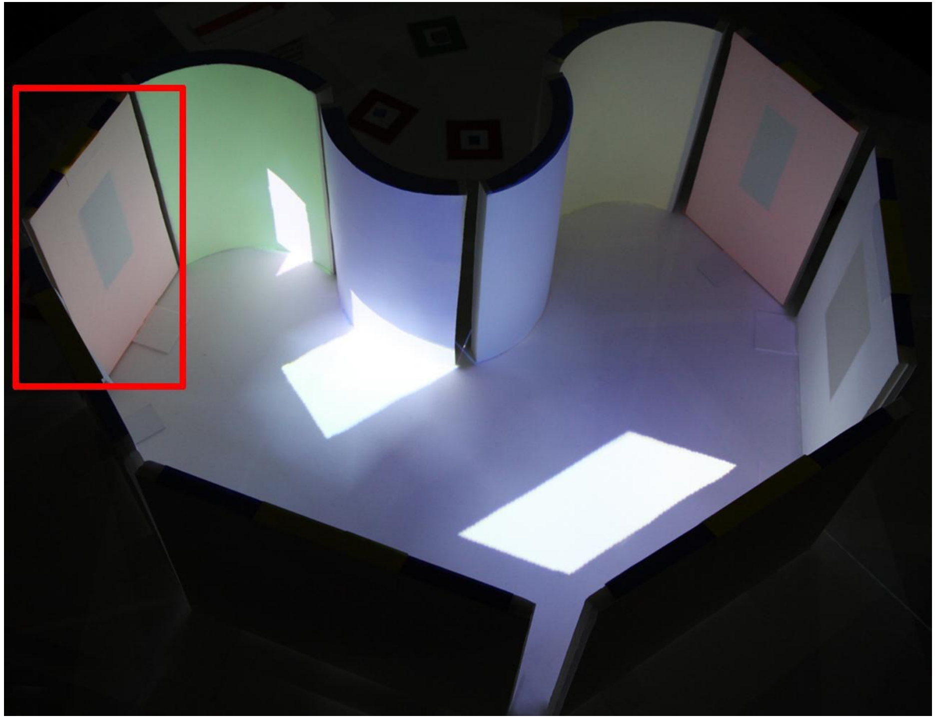


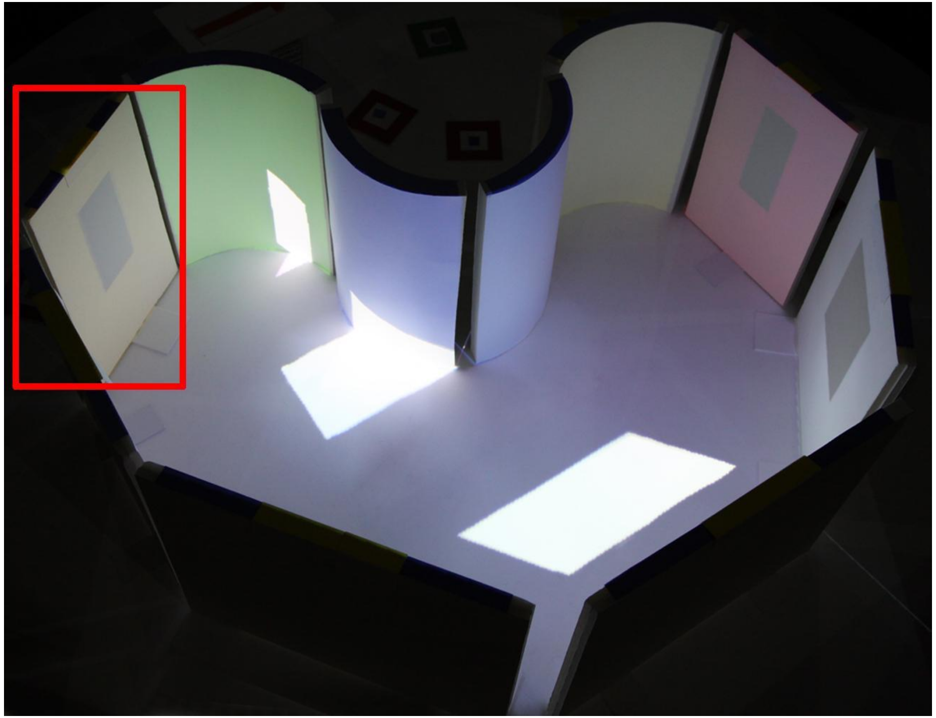
Sheng et al. 2010
Optimized in YPbPr space



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


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*

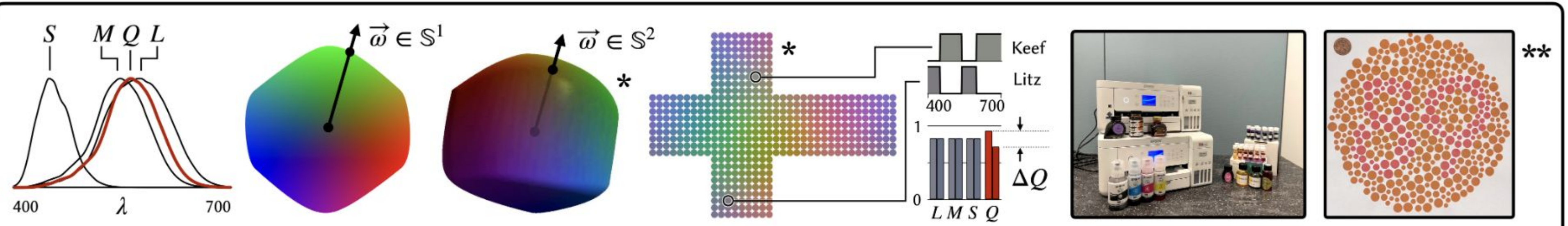
"Perceptual Global Illumination Cancellation in Complex Projection Environments"
Yu Sheng, Barbara Cutler, Chao Chen, and Joshua Nasman
Eurographics Symposium on Rendering (EGSR), June 2011.

Today

- Worksheet: Shadow Techniques
- Readings for Today
- What is Color?
  - Human Perception
  - Color Blindness & Metamerism
- Color Spaces
  - Linear Color Spaces: LMS, RGB, XYZ, HSV
- Projection in Spatially Augmented Reality
  - Human Perception & Perceptual Color Space: L*a*b*
- Readings for Next Time

Readings for Next Time *(pick one)*

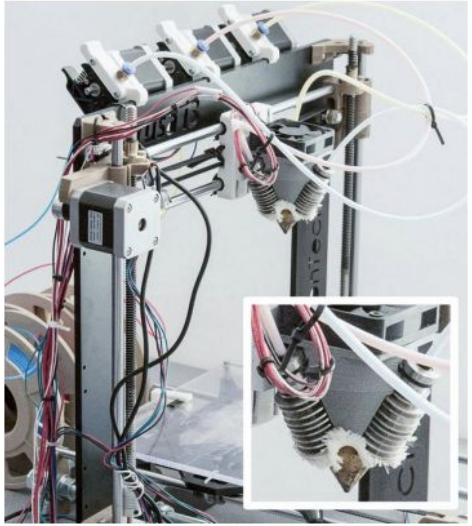
- "Theory of Human Tetrachromatic Color Experience and Printing"
  Lee, Jennings, Srivastava, & Ng,, ACM TOG 2024

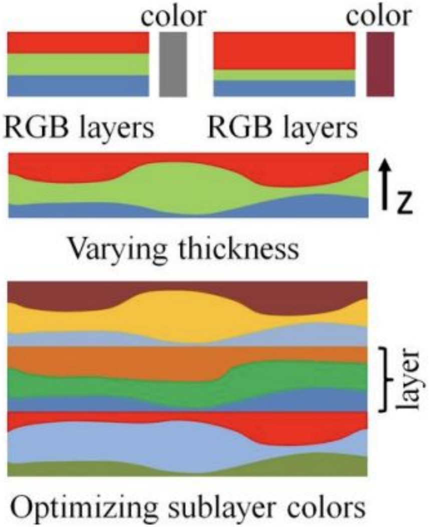


A: Human Tetrachromatic Spectral Response Functions
B: Regular Trichromatic Chromaticities + Hues
C: Tetrachromatic Chromaticities + Hues
D: Tetrachromatic Hue Sphere, Flattened, and Keef/Litz Hues
E: Keef/Litz Reflectances and ΔQ
F: Prototyping Platform for Tetrachromatic Printers
G: Photo of Example Tetrachromatic Print; Color Test

Readings for Next Time *(pick one)*

- "Colored Fused Filament Fabrication",
  Song, Martinez, Bedell, Vennin, & Lefebvre, ACM TOG 2019





Readings for Next Time *(pick one)*

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

no flash
warm ambiance, noisy

flash
flat lighting

combined result
original lighting, denoised