Color

Color

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MIT- EECS

Many slides courtesy of Victor Ostromoukhov and Leonard McMillan

Why is the sky blue part II

- What do you mean exactly by blue?

Admin

- Quiz on Thursday
  - 1 sheet of notes allowed
- Review session tonight 7:30 room 2-136

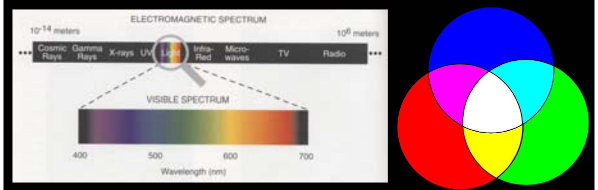
Review of last week

Monte Carlo Recap

- Random rays to sample rendering equation
- No meshing required, no special storage
- No limitation
  - On reflectance
  - On geometry
- Can be noisy (or slow $\frac{1}{\sqrt{n}}$)
- Advanced
  - Irradiance cache
  - Photon map

You believe you know it all

- Color is about spectrum and wavelength
- We can get everything from red, green and blue

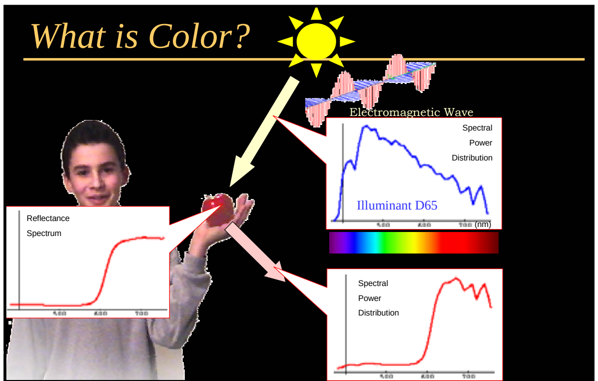


- Well, life is more confusing than that!

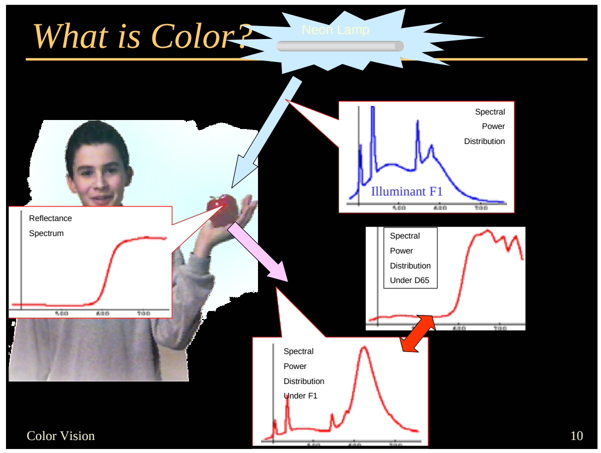
Puzzles about color

- How comes a continuous spectrum ends up as a 3D color space
- Why is violet "close" to red
- Primaries: 3 or 4? Which ones
  - Red, blue, yellow, green
  - Cyan and magenta are not "spontaneous" primaries
- Color mixing
- What is the color of Henry IV's white horse?

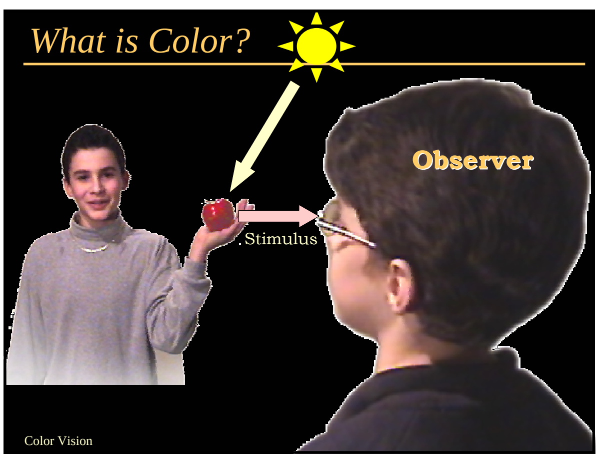
What is Color?



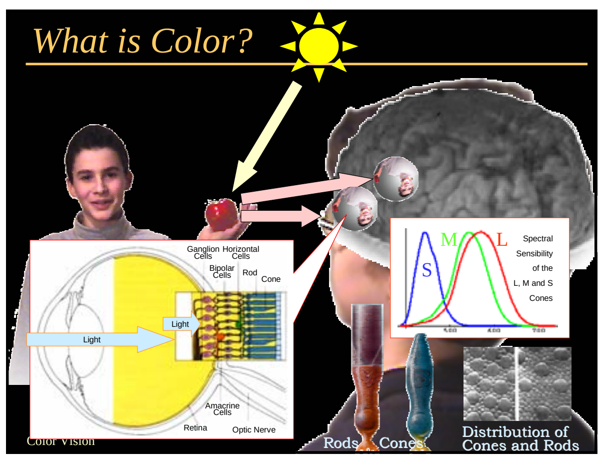
What is Color?



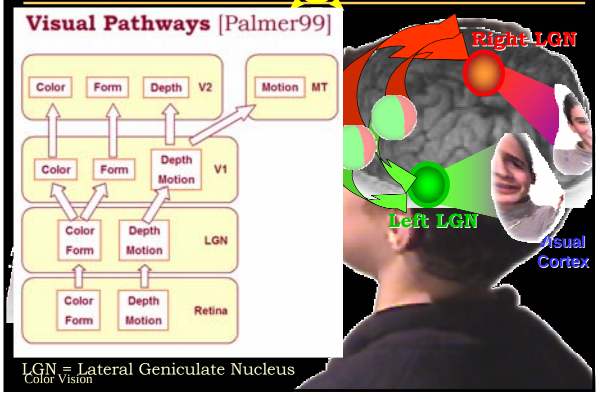
What is Color?



What is Color?



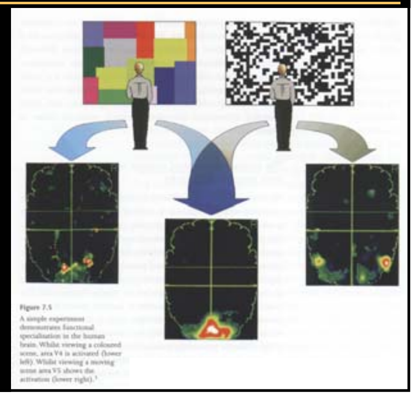
What is Color?



LGN = Lateral Geniculate Nucleus

Areas of the brain

- From [Zeki]

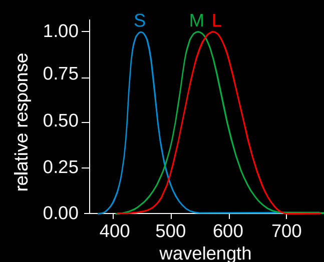


Plan

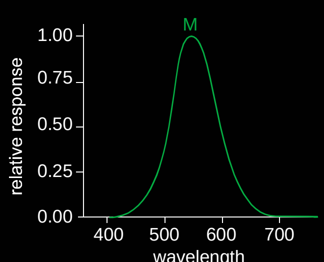
- Color Vision
- Color spaces
- Producing color
- Color effects

Cone spectral sensitivity

- Short, Medium and Long wavelength

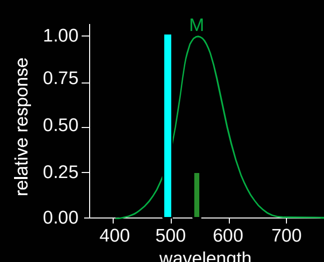


Cones do not “see” colors



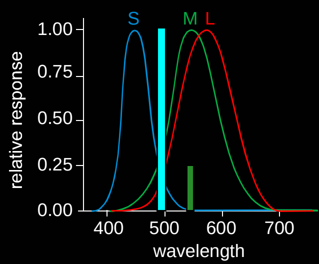
Cones do not “see” colors

- Different wavelength, different intensity
- Same response



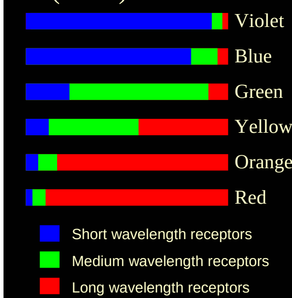
Response comparison

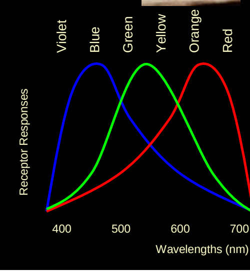
- Different wavelength, different intensity
- But different response for different cones



von Helmholtz 1859: Trichromatic theory

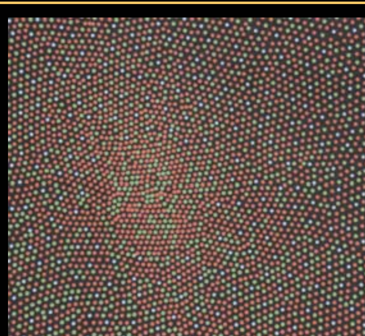
- Colors as relative responses (ratios)





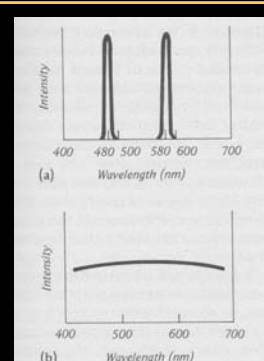
Cones distribution

- In the retina
- LMS 40:20:1
- No S (blue) in retina center



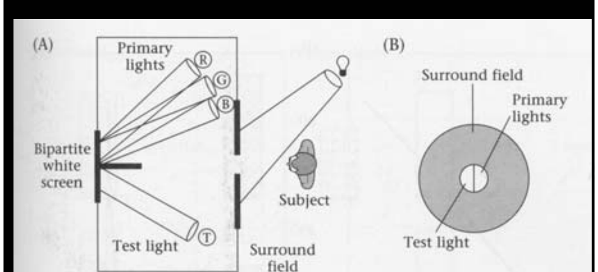
Metamers

- Different spectrum
- Same response



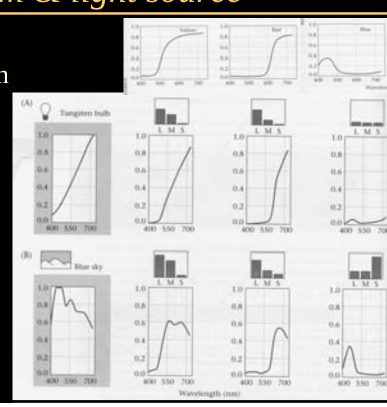
Color matching

- Reproduce the color of a test lamp with the addition of 3 primary lights



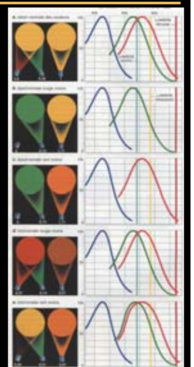
Metamerism & light source

- Metamers under a given light source
- May not be metamers under a different lamp

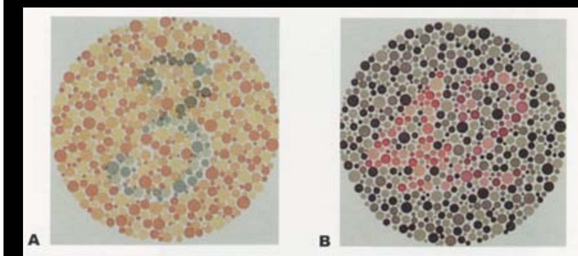


Color blindness

- Dalton
- 8% male, 0.6% female
- Genetic
- Dichromate (2% male)
  - One type of cone missing
  - L (protanope), M (deuteranope), S (tritanope)
- Anomalous trichromat
  - Shifted sensitivity

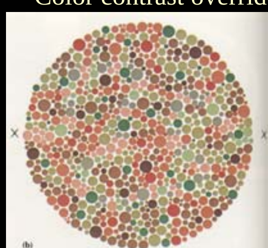


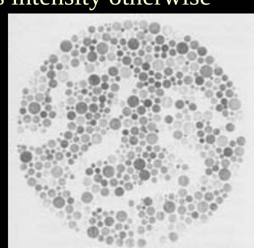
Color blindness test



Color blindness test

- Maze in subtle intensity contrast
- Visible only to color blinds
- Color contrast overrides intensity otherwise





Questions?

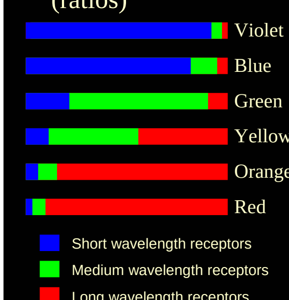
Meryon (a colorblind painter), *Le Vaisseau Fantôme*

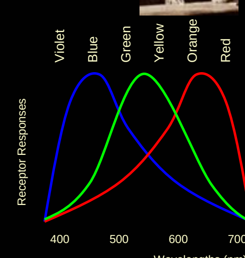
Plan

- Color Vision
  - Cone response, trichromats
  - Opponent theory
  - Higher-level
- Color spaces
- Producing color
- Color effects

Remember von Helmholtz

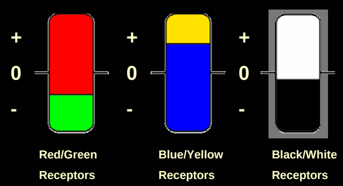
- Colors as relative responses (ratios)





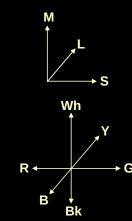
Hering 1874: Opponent Colors

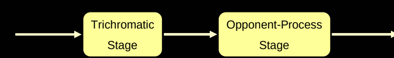
- Hypothesis of 3 types of receptors: Red/Green, Blue/Yellow, Black/White
- Explains well several visual phenomena



Dual Process Theory

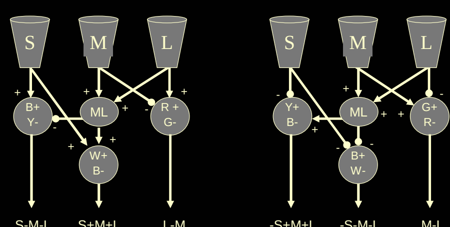
- The input is LMS
- The output has a different parameterization:
  - Light-dark
  - Blue-yellow
  - Red-green





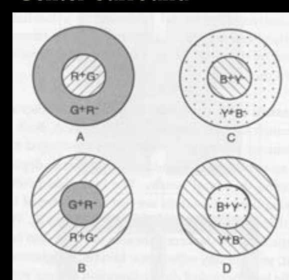
Color opponents wiring

- Sums for brightness
- Differences for color opponents

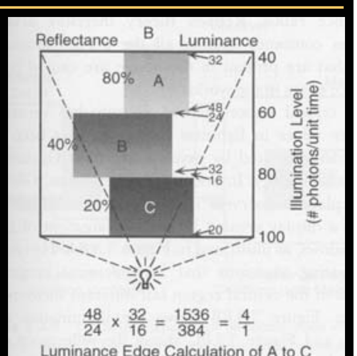


Simultaneous contrast

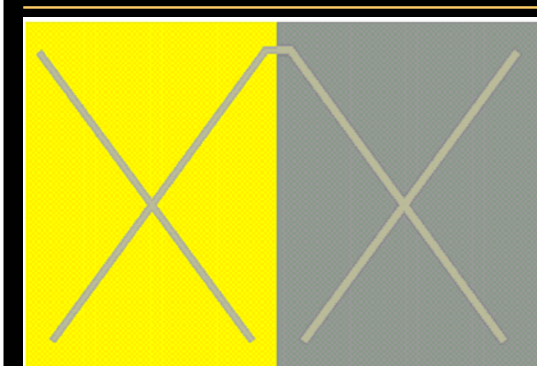
- In color opponent direction
- Center-surround

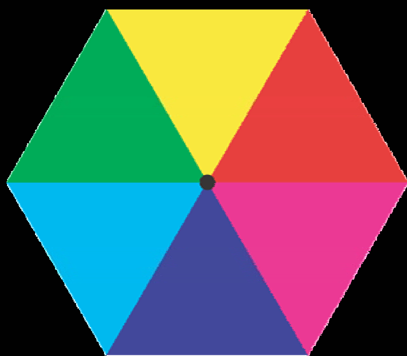


Land Retinex

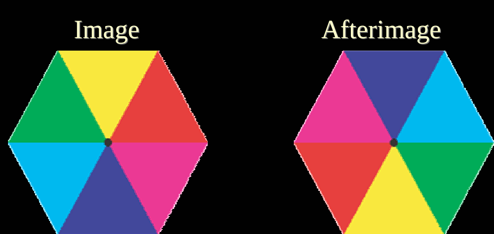


Simultaneous Color Contrast



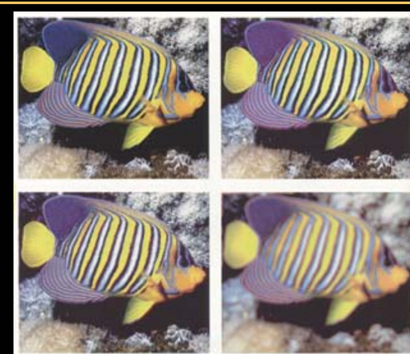


Opponent Colors



Opponents and image compression

- JPG, MPG
- Color opponents instead of RGB
- Compress color more than luminance

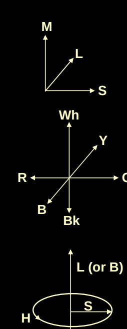


Plan

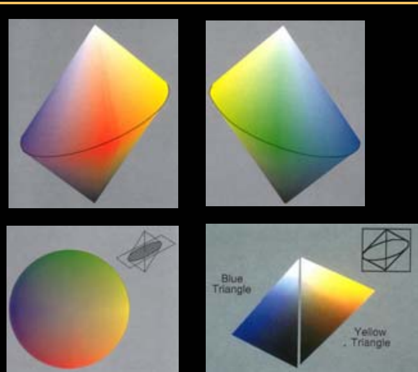
- Color Vision
  - Cone response, trichromats
  - Opponent theory
  - Higher-level
- Color spaces
- Producing color
- Color effects

Color reparameterization

- The input is LMS
- The output has a different parameterization:
  - Light-dark
  - Blue-yellow
  - Red-green
- A later stage may reparameterize:
  - Brightness or Luminance or Value
  - Hue
  - Saturation



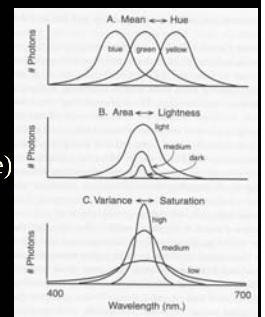
Hue Saturation Value



Hue Saturation Value

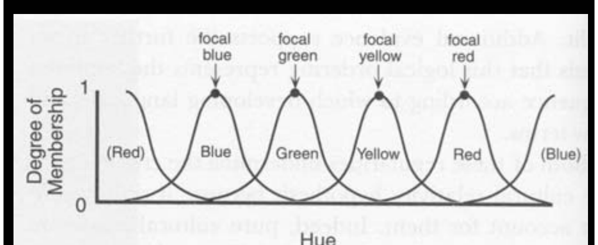
- One interpretation in spectrum space
- Not the only one because of metamerism

- Dominant wavelength (hue)
- Intensity
- Purity (saturation)



Color categories

- Prototypes
- Harder to classify colors at boundaries



Questions?

Plan

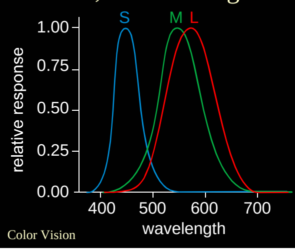
- Color Vision
- Color spaces
- Producing color
- Color effects

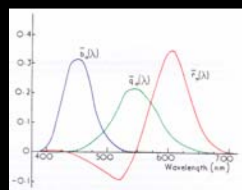
Color spaces

- Human color perception is 3 dimensional
- How should we parameterize this 3D space
- Various constraints/goals
  - Linear parameterization
  - Close to color technology
  - Close to human perception
  - Standard

The root of all evil

- Cone responses are not orthogonal (they overlap)
- To change the M response without changing the L one, we need negative light

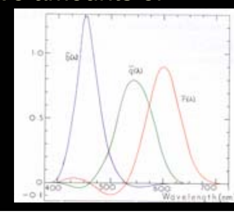




Orthogonal basis (color matching function)

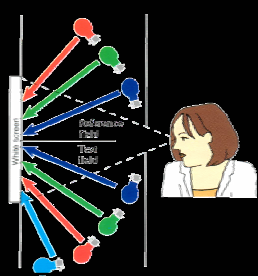
Color Matching Problem

- Some colors cannot be produced using only positively weighted primaries
- E.g. primaries: pure wavelength
  - 650, 530, 460
- Some colors need negative amounts of primaries
- Analysis spectrum has negative lobes



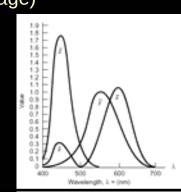
Color Matching Problem

- Some colors cannot be produced using only positively weighted primaries
- Solution: add light on the other side!



Color Matching Problem

- Some colors cannot be produced using only positively weighted primaries
- Some tradeoff must be found between negative lobes in analysis vs. synthesis
- In 1931, the CIE (Commission Internationale de L'Eclairage) defined three new primaries
- Called X, Y , Z,
  - with positive color matching functions

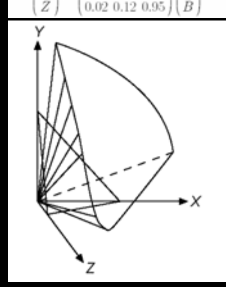


CIE color space

- Can think of X, Y , Z as coordinates
- Linear transform from RGB or LMS

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

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



CIE color space

- Odd-shaped cone contains visible colors
  - Note that many points in XYZ do not correspond to visible colors!

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

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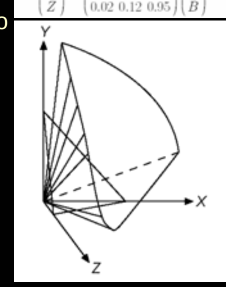


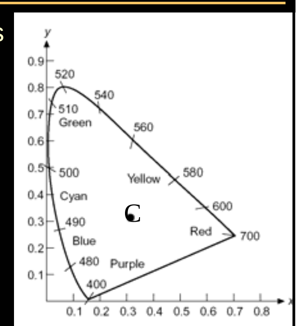
CIE color space

- Objective, quantitative color descriptions
  - Dominant wavelength:
    - Wavelength “seen” (corresponds to Hue)
  - Excitation purity:
    - Saturation, expressed objectively
  - Luminance:
    - Intensity
- Chromaticity (independent of luminance):
  - normalize against X + Y + Z:

$$x = \frac{X}{X+Y+Z};\quad y = \frac{Y}{X+Y+Z};\quad z = \frac{Z}{X+Y+Z}$$

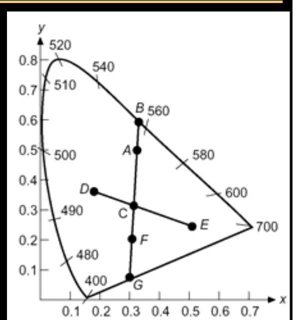
CIE color space

- Spectrally pure colors lie along boundary
- Note that some hues do not correspond to a pure spectrum (purple-violet)
- Standard white light (approximates sunlight) at C



CIE color space

- Match color at some point A
- A is mix of white C, spectral B!
- What is dominant wavelength of A?
- What is excitation purity (%) of A?
  - Move along AC/BC



XYZ vs. RGB

- Linear transform

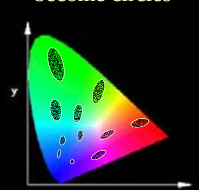
$$\begin{pmatrix}R\\G\\B\end{pmatrix} = \begin{pmatrix}3.24 & -1.54 & -0.50\\ -0.97 & 1.88 & 0.04\\ 0.06 & -0.20 & 1.06\end{pmatrix}\begin{pmatrix}X\\Y\\Z\end{pmatrix}$$

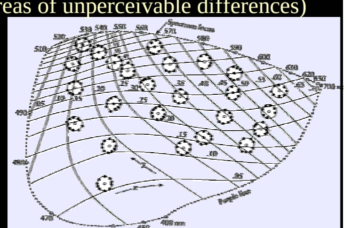
$$\begin{pmatrix}X\\Y\\Z\end{pmatrix} = \begin{pmatrix}0.41 & 0.36 & 0.18\\ 0.21 & 0.72 & 0.07\\ 0.02 & 0.12 & 0.95\end{pmatrix}\begin{pmatrix}R\\G\\B\end{pmatrix}$$

- XYZ is more standardized
- XYZ can reproduce all colors with positive values
- XYZ is not realizable physically !!
  - What happens if you go “off” the diagram
  - In fact, the orthogonal (synthesis) basis of XYZ requires negative values.

Perceptually Uniform Space: MacAdam

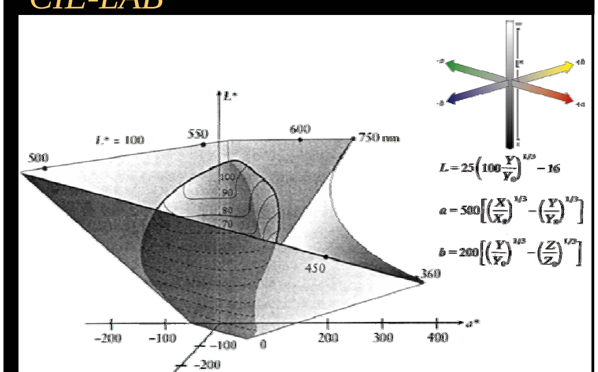
- In color space CIE-XYZ, the perceived distance between colors is not equal everywhere
- In perceptually uniform color space, Euclidean distances reflect perceived differences between colors
- MacAdam ellipses (areas of unperceivable differences) become circles





Source: [Wyszecki and Stiles ’82]

CIE-LAB



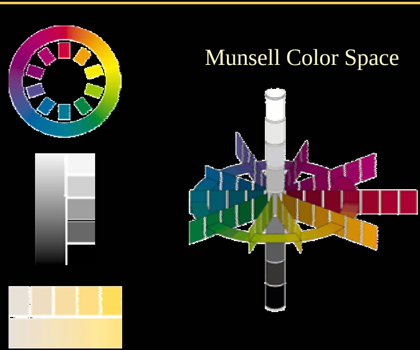
Source: [Wyszecki and Stiles ’82]

Perceptually Uniform Space Munsell

Hue

Value

Chroma



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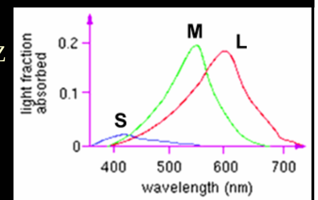
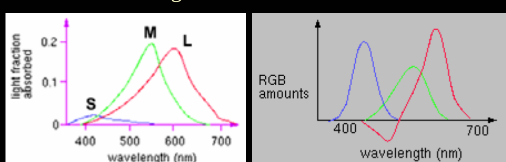
Color response linear subspace

- Project the infinite-D spectrum onto a subspace defined by 3 basis functions
- We can use 3x3 matrices to change the colorspace
  - E.g. LMS to RGB
  - E.g. RGB to CIE XYZ



Color response and RGB or LMS

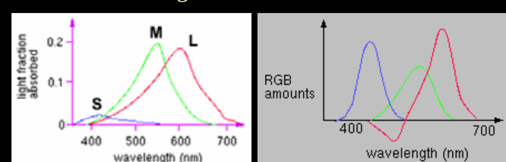
- Project the infinite-D spectrum onto a subspace defined by 3 basis functions
- Small problem: this basis is NOT orthogonal
- What does orthogonal mean in our case?



- Second problem: the orthogonal basis is NOT physically realizable

Color response and RGB or LMS

- Project the infinite-D spectrum onto a subspace defined by 3 basis functions
- Small problem: this basis is NOT orthogonal
- What does orthogonal mean in our case?



- Second problem: the orthogonal basis is NOT physically realizable

Munsell book of colors

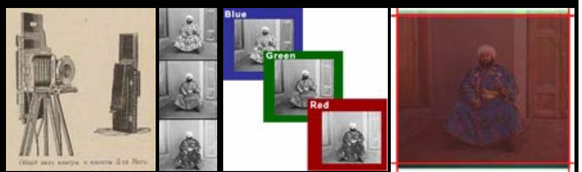
- Perceptually uniform

Questions

Lippman spectral color reproduction

Playtime: Prokudin-Gorskii

- Russia circa 1900
- One camera, move the film with filters to get 3 exposures



http://www.loc.gov/exhibits/empire/

Color Vision 67

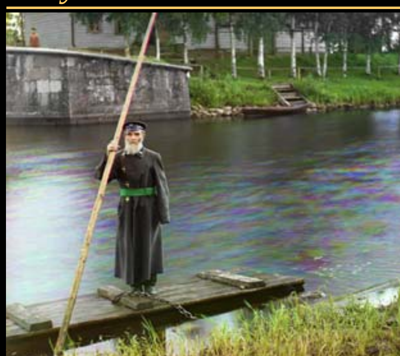
Playtime: Prokudin-Gorskii

- Digital restoration

http://www.loc.gov/exhibits/empire/

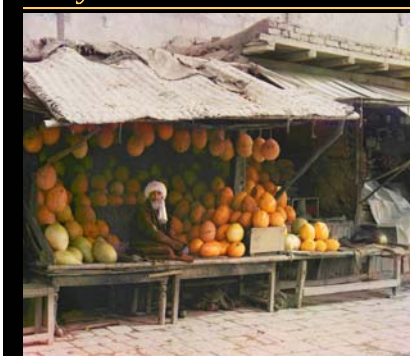
Color Vision 68

Playtime: Prokudin-Gorskii



Color Vision 69

Playtime: Prokudin-Gorskii



Color Vision 70

Playtime: Prokudin-Gorskii

Color Vision 71

Second part on Tuesday

Color Vision 72