Color

Color

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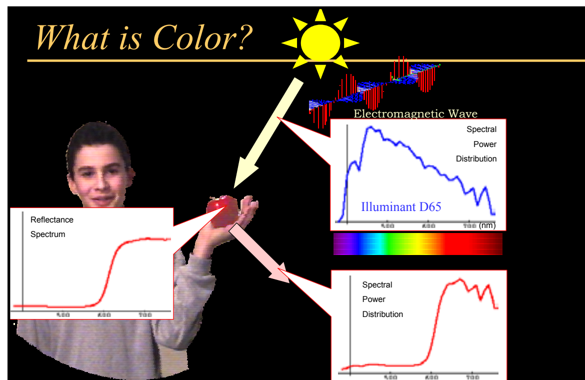
Some slides courtesy of Victor Ostromoukhov and Leonard McMillan

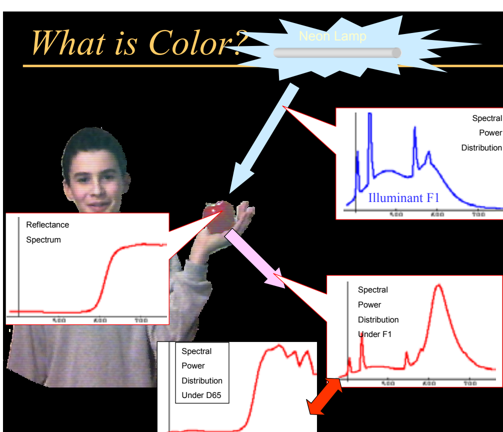
Puzzles

- How comes a continuous spectrum ends into 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?



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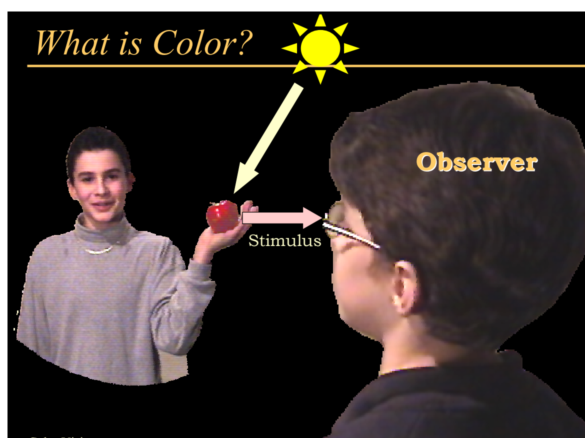
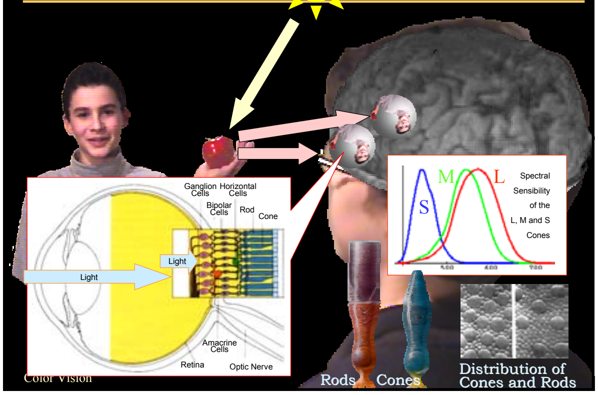
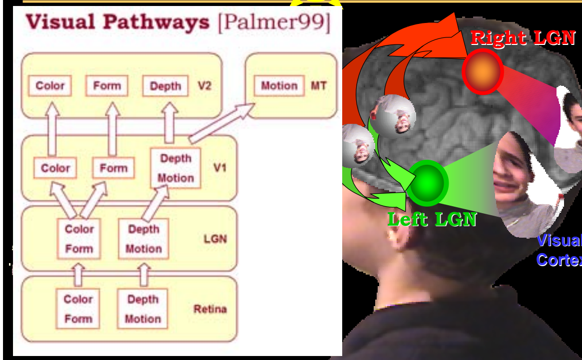


What is Color?



What is Color?



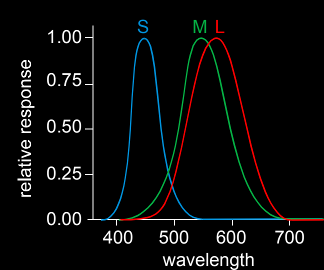
LGN = Lateral Geniculate Nucleus

Plan

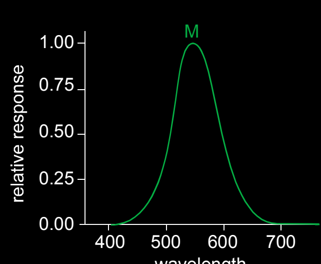
- Color Vision
- Color spaces
- Producing color
- Color effects

Cone spectral sensitivity

- Short, Medium and Long wavelength

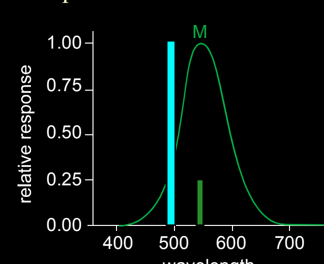


Cones do not "see" colors



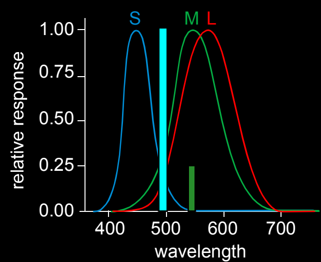
Cones do not "see" colors

- Different wavelength, different intensity
- Same response

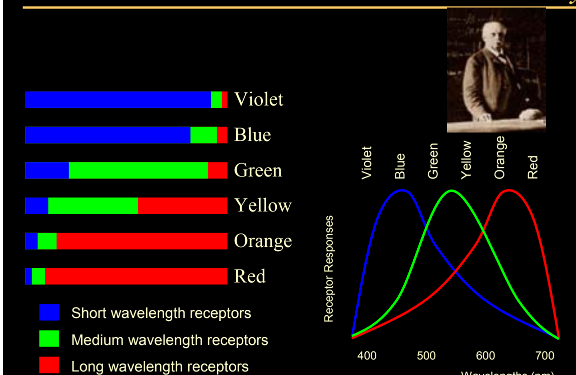


Response comparison

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

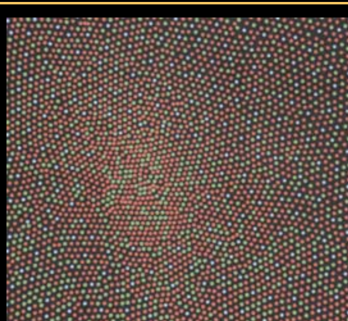


von Helmholtz 1859: Trichromatic theory



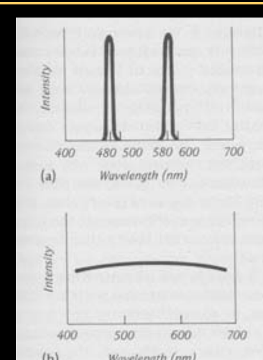
Cones distribution

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



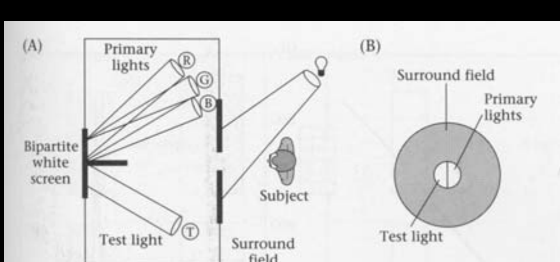
Metamers

- Different spectrum
- Same response



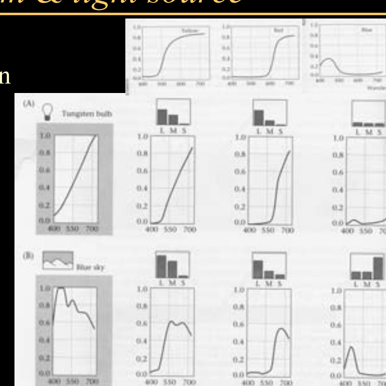
Color matching

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



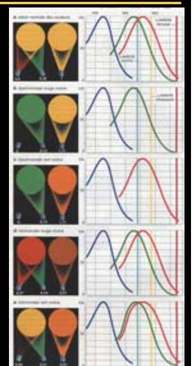
Metamerism & light source

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



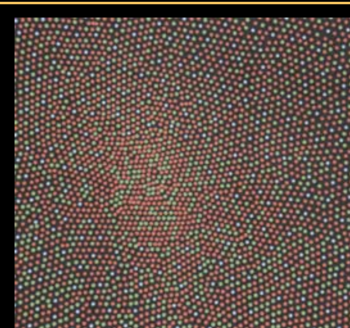
Color blindness

- 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



We are all color blind

- Center of retina
- No S (blue)
- We compensate via gaze movement
- Not well understood

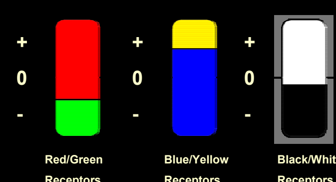


Questions?

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

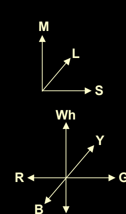
Hering 1874: Opponent Colors

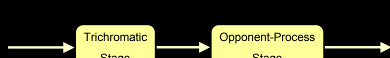
- Hypothesis of 3 types of receptors: Red/Green, Blue/Yellow, Black/White
- Explains well several visual phenomena



Dual Process Theory

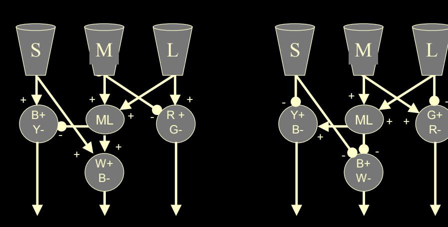
- The input is LMS
- The output has a different parameterization:
  - Light-dark
  - Blue-yellow
  - Red-green





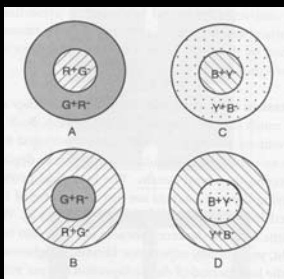
Color opponents wiring

- Sums for brightness
- Differences for color opponents

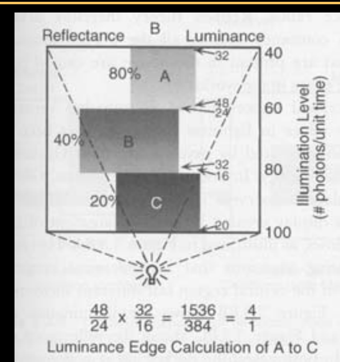


Simultaneous contrast

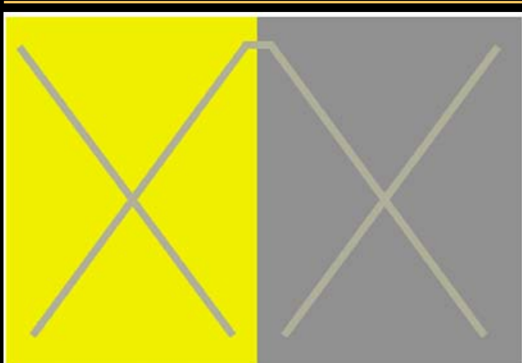
- In color opponent direction
- Center-surround



Land Retinex



Simultaneous Color Contrast

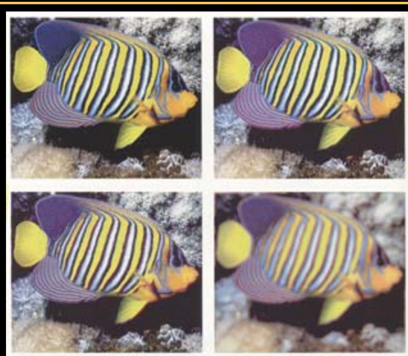


Opponent Colors

Image Afterimage

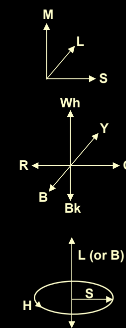
Opponents and image compression

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

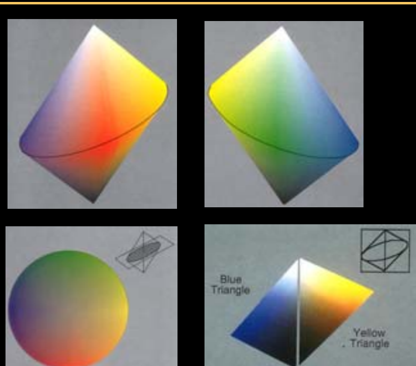


Color reparameterization

- 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



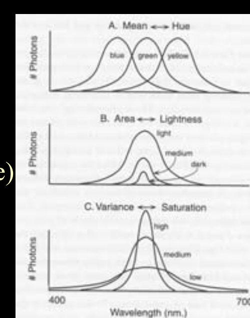
Hue Saturation Value



Hue Saturation Value

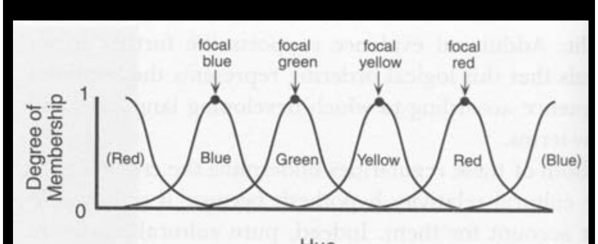
- One interpretation in spectrum space
- Not the only one because of metamerism

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



Color categories

- Prototypes
- Harder to classify colors at boundaries



Questions?


Van Gogh

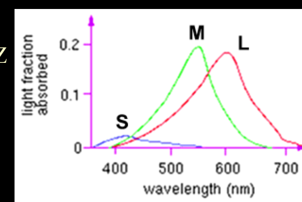

Jawlensky

Plan

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

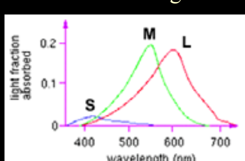
Color response linear subspace

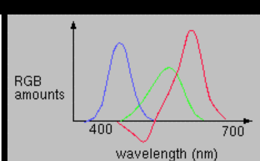
- Project the infinite-D spectrum onto a subspace defined by 3 basis functions
- We can use 3x3 matrices to change the colorspace
  - E.g. LMS to RGB
  - E.g. RGB to CIE XYZ



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

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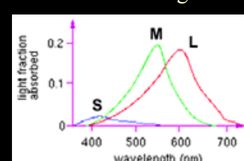
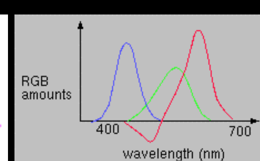
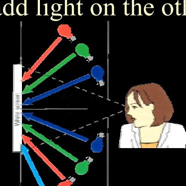




- Second problem: the orthogonal basis is NOT physically realizable

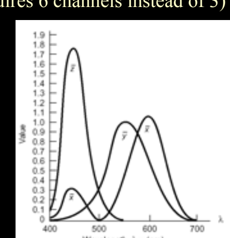
Color Matching Problem

- Some colors can not be produced using only positively weighted primaries
  - Negative values are a problem
  - (e.g. for measurement devices, requires 6 channels instead of 3)
- Solution 1: add light on the other side!



Color Matching Problem

- Some colors can not be produced using only positively weighted primaries
  - Negative values are a problem
  - (e.g. for measurement device, requires 6 channels instead of 3)
- Solution 2: standardize!
- In 1931, the CIE (Commission Internationale de L'Eclairage) defined three new primaries
- Called X, Y , Z,
  - with positive color matching functions

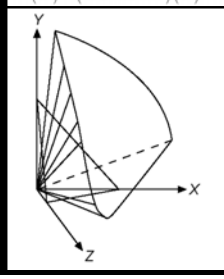


CIE color space

- Can think of X, Y , Z as coordinates
- Odd-shaped cone contains visible colors
  - Note that many points in XYZ do not correspond to visible colors!

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

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



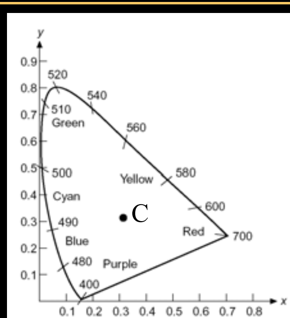
CIE color space

- 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:

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

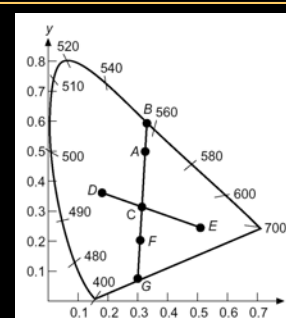
CIE color space

- 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

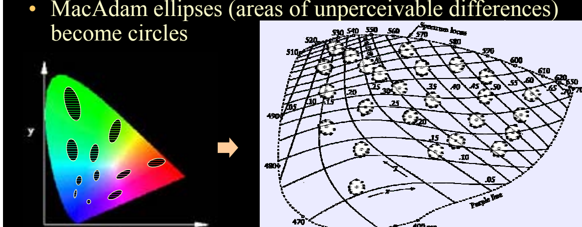
$$\begin{pmatrix}R\\G\\B\end{pmatrix}=\begin{pmatrix}3.24 & -1.54 & -0.50\\-0.97 & 1.88 & 0.04\\0.06 & -0.20 & 1.06\end{pmatrix}\begin{pmatrix}X\\Y\\Z\end{pmatrix}$$

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

- 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.

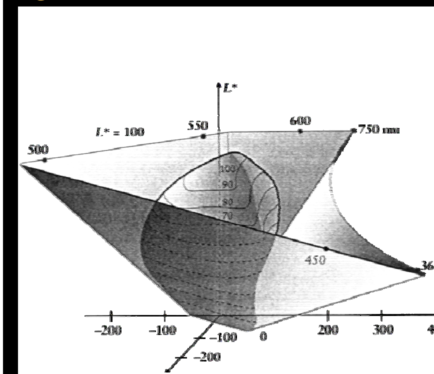
Perceptually Uniform Space: MacAdam

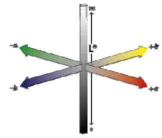
- In color space CIE-XYZ, the perceived distance between colors is not equal everywhere
- In perceptually uniform color space, Euclidean distances reflect perceived differences between colors
- MacAdam ellipses (areas of unperceivable differences) become circles



Source: [Wyszecki and Stiles '82]

CIE-LAB





$$L = 25\left(100\frac{Y}{Y_0}\right)^{1/3} - 16$$

$$a = 500\left[\left(\frac{X}{X_0}\right)^{1/3} - \left(\frac{Y}{Y_0}\right)^{1/3}\right]$$

$$b = 200\left[\left(\frac{Y}{Y_0}\right)^{1/3} - \left(\frac{Z}{Z_0}\right)^{1/3}\right]$$

Source: [Wyszecki and Stiles '82]

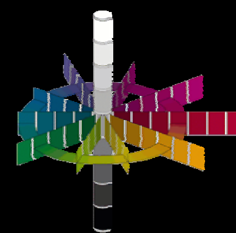
Perceptually Uniform Space Munsell

Hue

Value

Chroma

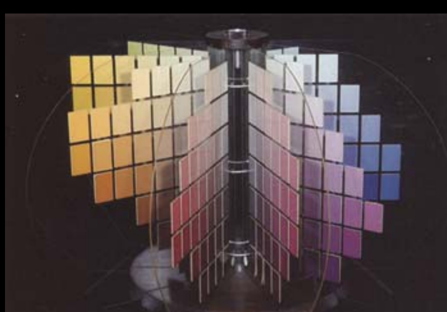
Munsell Color Space



munsell.com

Munsell book of colors

- Perceptually uniform



Questions?

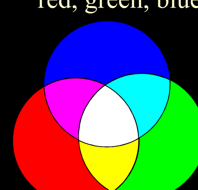
Plan

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

Color synthesis

Additive

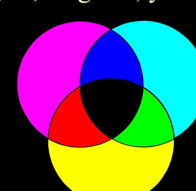
red, green, blue



Add light
(CRT, video projector)

Subtractive

cyan, magenta, yellow



Remove light (e.g. filter)
printer, photos

Color synthesis: a wrong example

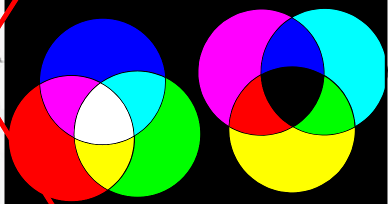
WRONG

Additive

red, green, blue

Subtractive

cyan, magenta, yellow



RIGHT

Device Color Models (Subtractive)

Start with white, remove energy (e.g., w/ ink, filters)

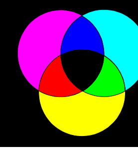
Example: CMY color printer

Cyan ink absorbs red light

Magenta ink absorbs green light

Yellow ink absorbs blue light

C+M+Y absorbs all light: Black!



RGB → CMY conversion

$$\begin{pmatrix} C \\ M \\ Y \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} - \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

Some digital cameras use CMY

CMYK

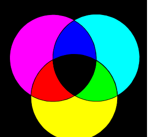
CMY model plus black ink (K)

Saves ink

Higher-quality black

Increases gamut

Conversion not completely trivial



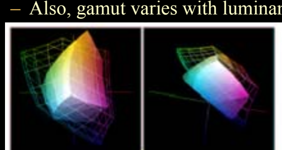
The infamous gamma curve

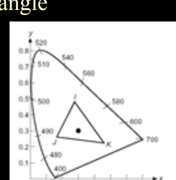
A gamma curve $x \rightarrow x^{\gamma}$ is used for many reasons:

- CRT response
  - The relation between voltage and intensity is non-linear
- Color quantization
  - We do not want a linear color resolution
  - More resolution for darker tones
  - Because we are sensitive to intensity ratios
- Perceptual effect
  - We perceive colors in darker environment less vivid
  - Hunt and Stevens effect
- Contrast reduction

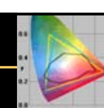
Gamut

- Every device with three primaries can produce only colors inside some (approx.) triangle
  - Convexity!
- This set is called a color gamut
  - (Why can't RGB can't give all visible colors?)
- Usually, nonlinearities warp the triangle
  - Also, gamut varies with luminance





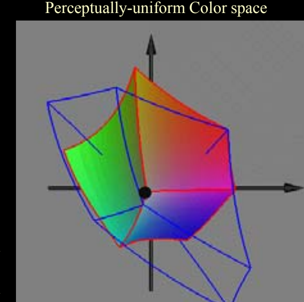
Gamut Mapping



- Color gamut of different processes may be different (e.g. CRT display and 4-color printing process)
- Need to map one 3D color space into another

CIE-LAB

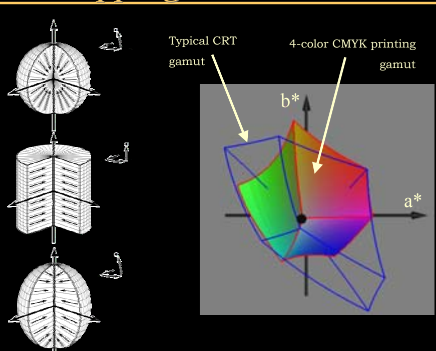
Perceptually-uniform Color space



Typical CRT gamut

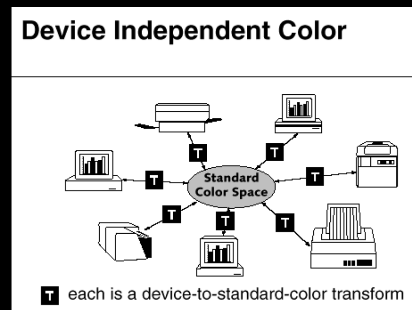
4-color printing gamut

Gamut Mapping



Gamut mapping is a morphing of 3D color space according to adopted scheme

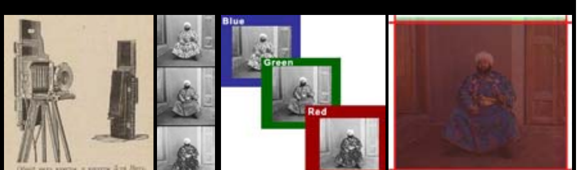
ICC



http://www.color.org/

Playtime: Prokudin-Gorskii

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



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

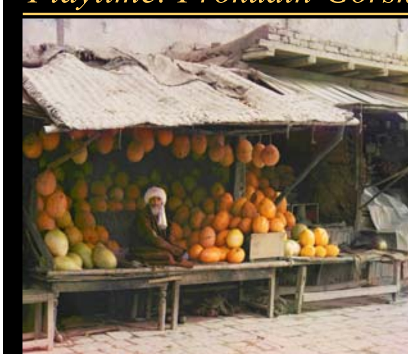
Playtime: Prokudin-Gorskii

- Digital restoration

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

Playtime: Prokudin-Gorskii

Playtime: Prokudin-Gorskii



Playtime: Prokudin-Gorskii

Questions

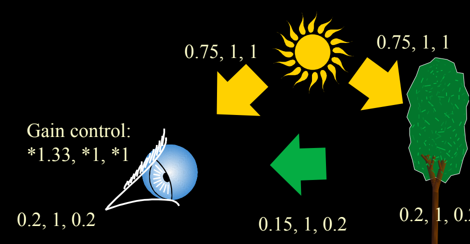
Lippman spectral color reproduction

Plan

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

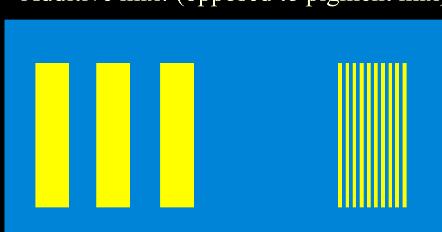
Chromatic adaptation

- Von Kries adaptation
- Different gain control on L, M, S



Spreading

- Optical mix when spatial frequency increases
- But before fusion frequency
- Additive mix! (opposed to pigment mix)



Crispening

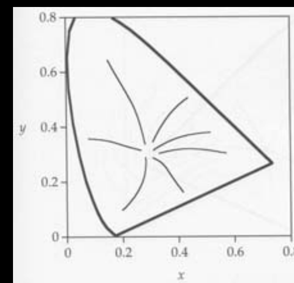
- Increased sensitivity

Hunt and Stevens effect

- Stevens effect
  - Contrast increases with luminance
- Bartleson-Breneman effect
  - Image contrast changes with surround
  - A dark surround decreases contrast (make the black of the image look less deep)
- Hunt effect
  - Colorfulness increases with luminance
- Hence the need for gamma correction

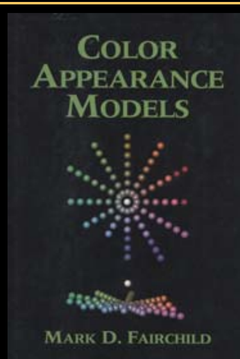
Abney Effect

- Hue changes with the addition of pure white



Color appearance models

- Predict the appearance of a color depending on
  - Objective stimulus
  - Surrounding, context



Color terms (Fairchild 1998

- Color
- Hue
- Brightness vs. lightness
- Colorfulness and Chroma
- Saturation
- Unrelated and related colors

Color

- chromatic and achromatic content. This attribute can be described by chromatic color names such as yellow, orange, brown, red, pink, green, blue, purple, etc., or by achromatic color names such as white, gray, black, etc., and qualified by bright, dim, light, dark, etc., or by combinations of such names.
- Note: Perceived color depends on the spectral distribution of the color stimulus, on the size, shape, structure, and surround of the stimulus area, on the state of adaptation of the observer's visual system, and on the observer's experience of the prevailing and similar situations of observations.

Related and Unrelated Colors

- Unrelated Color
  - Color perceived to belong to an area or object seen in isolation from other colors.
- Related Color
  - Color perceived to belong to an area or object seen in relation to other colors.

Hue

- Hue
  - Attribute of a visual sensation according to which an area appears be similar to one of the perceived colors: red, yellow, green, and blue, or to a combination of two of them.
- Achromatic Color
  - Perceived color devoid of hue.
- Chromatic Color
  - Perceived color possessing a hue.

Brightness vs. Lightness

- Brightness
  - Attribute of a visual sensation according to which an area appears to emit more or less light.
- Lightness:
  - The brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting.

Colorfulness & Chroma

- Colorfulness
  - Attribute of a visual sensation according to which the perceived color of an area appears to be more or less chromatic.
- Chroma:
  - Colorfulness of an area judged as a proportion of the brightness of a similarly illuminated area that appears white or highly transmitting.

Saturation

- Colorfulness of an area judged in proportion to its brightness.

Questions?

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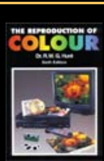

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