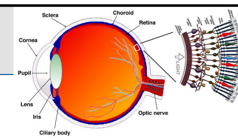
Computational Photography

Lecture 04

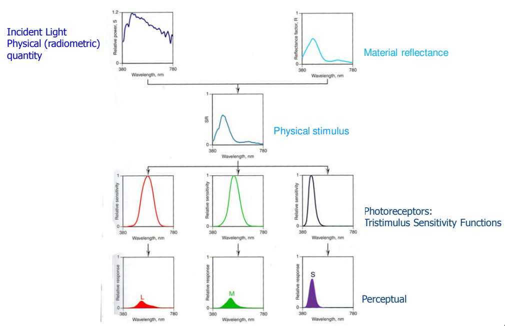
Color Spaces and Color Models

Color

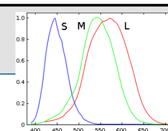


- Sensation (perceptual process) induced by the light that reaches the retina photoreceptors
- The amount and distribution of light that reaches the retina depends on the absorption, scattering, and focusing properties of the eye structures (cornea, crystalline, and fluids – aqueous and vitreous humor)
- Before reaching the retina, light's spectral distribution changes as it interacts with the spectral properties of the scene
- Color = light source * object * observer's sensitivity

Color Perception: the pipeline

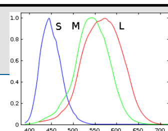


The Human Color Vision



- The **Trichromatic** Color Vision Theory (explains additive colors)
  - **Thomas Young** (1801): Postulated the existence of three types of photoreceptors
  - **Hermann von Helmholtz** (1859): The three types of photoreceptors are more sensitive to the short (S), medium (M), and long (L) wavelengths
- The **Opponent** Color Process (explains after images)
  - **Karl Hering** (1892): It is more efficient for the visual system to record *differences* between the responses of cones, rather than each type of cone's individual response
    - Opponent signals (WB)-(RG)-(YB)

The Human Color Vision



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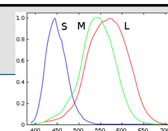
- The **Opponent** Color Process (explains after images)
  - **Karl Hering** (1892): It is more efficient for the visual system to record *differences* between the responses of cones, rather than each type of cone's individual response
    - Individuals with color vision deficiency confuse red/green and yellow/blue

The Human Color Vision



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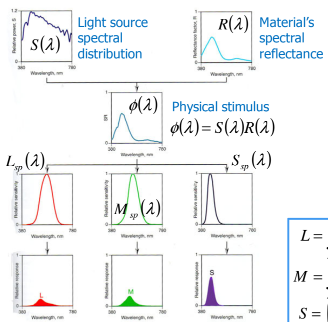
    - Opponent signals (WB)-(RG)-(YB)
- **Stage Theory** (or Zone Theory): currently most accepted
  - **Trichromatic stage** (at the photoreceptors level) followed by an **opponent stage**

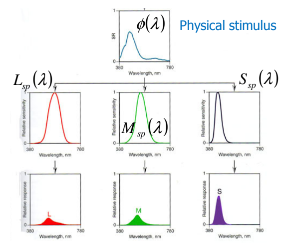
The LMS (Cone) Responses



$$L = \int_\lambda \phi(\lambda) L_{sp}(\lambda) d\lambda$$
$$M = \int_\lambda \phi(\lambda) M_{sp}(\lambda) d\lambda$$
$$S = \int_\lambda \phi(\lambda) S_{sp}(\lambda) d\lambda$$

Equivalent Stimuli

- Any two stimuli with the same three integrated photoreceptor responses will be perceived as equal
  - **Metameric colors**



$$\int_\lambda \phi_1(\lambda) L_{sp}(\lambda) d\lambda = \int_\lambda \phi_2(\lambda) L_{sp}(\lambda) d\lambda$$
$$\int_\lambda \phi_1(\lambda) M_{sp}(\lambda) d\lambda = \int_\lambda \phi_2(\lambda) M_{sp}(\lambda) d\lambda$$
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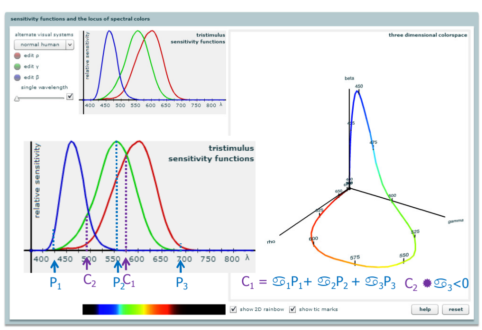
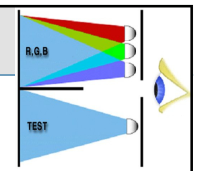
Color Matching



Snapshot from an applet from http://graphics.stanford.edu/courses/cs178/applets/locus.html

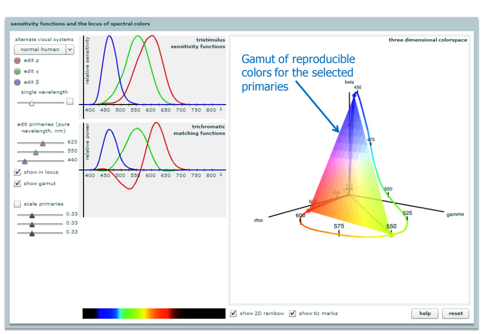
CIE-RGB (1931)

International Commission on Illumination



- **Color Matching Experiment**
  - Defined a standard for color representation
- Subjects should adjust the intensities of three primary light sources to match the test light
- The test light (monochromatic) is changed for the various wavelengths of the visible spectrum and the intensities of the primary light sources were recorded
- Experiments by Wright (10 subj., 1928-29) and Guild (7 subj., 1931)
- **CIE**: Results were combined, averaged and mapped to primaries red (700nm), green (546.1nm), and blue (435.8nm)
  - Resulted in the **CIE-RGB color matching functions**

Color Matching Functions



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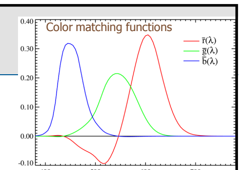
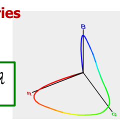
CIE-RGB (1931)

Color Matching Experiment



- The resulting *r(λ)* and *g(λ) color matching functions* have negative values
- Most spectral colors cannot be reproduced by adding the three selected primaries
- The tristimulus values for (any) RGB primaries
  - Amount of the 3 primaries required for color matching Φ(λ)
  - **Color matching functions vary with** choice of **primaries**
  - Integrate the stimulus with the color matching functions

$$R = \int_\lambda \phi(\lambda)\bar{r}(\lambda) d\lambda \quad G = \int_\lambda \phi(\lambda)\bar{g}(\lambda) d\lambda \quad B = \int_\lambda \phi(\lambda)\bar{b}(\lambda) d\lambda$$



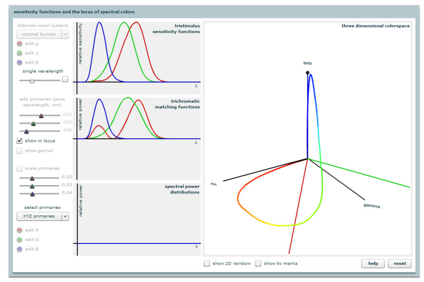
Equivalent Stimuli

- Like for the case of the LMS response, any two stimuli that induce the same integrated tristimulus will be perceived as equal
  - **Metameric colors**

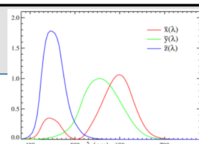
$$\int_\lambda \phi_1(\lambda)\bar{r}(\lambda)d\lambda = \int_\lambda \phi_2(\lambda)\bar{r}(\lambda)d\lambda$$
$$\int_\lambda \phi_1(\lambda)\bar{g}(\lambda)d\lambda = \int_\lambda \phi_2(\lambda)\bar{g}(\lambda)d\lambda$$
$$\int_\lambda \phi_1(\lambda)\bar{b}(\lambda)d\lambda = \int_\lambda \phi_2(\lambda)\bar{b}(\lambda)d\lambda$$

CIE-XYZ (1931)

- Three imaginary primaries (X, Y, Z) that can represent all visible colors as a convex combination



CIE-XYZ (1931)

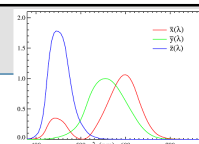


- Three imaginary primaries (X, Y, Z) that can represent all visible colors as a convex combination
- The selected primaries with the following properties:
  - The matching functions are always greater than or equal to zero
  - The *y(λ)* function equals the CIE-1924 luminance function *V(λ)*
  - For achromatic light, *x = y = z*
- The conversion CIE-RGB<->CIE-XYZ is a linear transformation

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.4900 & 0.3100 & 0.2000 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.0000 & 0.0100 & 0.9900 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- Scaling factor normalizes the functions to the same units as CIE *V(λ)*

CIE-XYZ (1931)



- Three imaginary primaries (X, Y, Z) that can represent all visible colors as a convex combination
- The tristimulus values for XYZ primaries

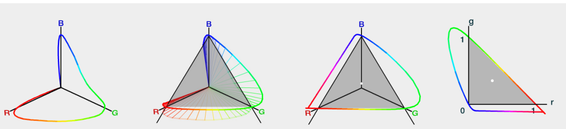
$$X = \int_\lambda \phi(\lambda)\bar{x}(\lambda)d\lambda \quad Y = \int_\lambda \phi(\lambda)\bar{y}(\lambda)d\lambda \quad Z = \int_\lambda \phi(\lambda)\bar{z}(\lambda)d\lambda$$

- Again, any two stimuli that induce the same integrated tristimulus will be perceived as equal

$$\int_\lambda \phi_1(\lambda)\bar{x}(\lambda)d\lambda = \int_\lambda \phi_2(\lambda)\bar{x}(\lambda)d\lambda$$
$$\int_\lambda \phi_1(\lambda)\bar{y}(\lambda)d\lambda = \int_\lambda \phi_2(\lambda)\bar{y}(\lambda)d\lambda$$
$$\int_\lambda \phi_1(\lambda)\bar{z}(\lambda)d\lambda = \int_\lambda \phi_2(\lambda)\bar{z}(\lambda)d\lambda$$

CIE-RGB Chromaticity Diagram

- Chromaticities of all visible colors using the CIE-RGB primaries



Spectral colors in the CIE-RGB color space

Project the spectral colors onto the R+G+B=1 plane to factor out brightness (lightness)

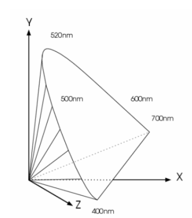
$$r = \frac{R}{R+G+B} \quad g = \frac{G}{R+G+B} \quad b = \frac{B}{R+G+B}$$

Orthographically project r and g onto the RG plane, and align the **R** (now **r**) axis with the horizontal direction

- The chromaticities of most spectral colors cannot be represented
- r and g are called the chromaticity coordinates

CIE-XYZ (1931) Color Solid

- Convex cone containing all colors perceived by humans
  - Represented in the CIE-XYZ color space
  - Spectral colors are at the borders of the solid
  - Colors = chromaticity + brightness (lightness)



CIE-XYZ (1931) Chromaticity Diagram

- Chromaticities of all visible colors using the CIE-XYZ primaries

Spectral colors in the CIE-XYZ color space

Project the spectral colors onto the X+Y+Z=1 plane to factor out brightness (lightness)

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

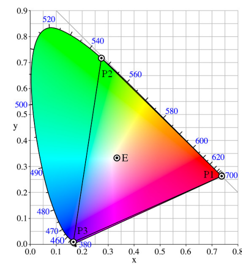
Orthographically project x and y onto the XY plane, and align the **X** (now **x**) axis with the horizontal direction

- The chromaticities of all spectral colors can be represented
- x and y are called the chromaticity coordinates

CIE-XYZ (1931) Chromaticity Diagram

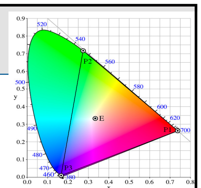
- Chromaticity Coordinates
  - x = X / (X+Y+Z)
  - y = Y / (X+Y+Z)
  - Not the same as color
  - Color representations requires restoring the brightness and is often represented by xyY

$$X = \left(\frac{x}{y}\right)Y = \left(\frac{\frac{X}{X+Y+Z}}{\frac{Y}{X+Y+Z}}\right)Y \qquad z = 1-(x+y) \qquad Z = \left(\frac{z}{y}\right)Y$$



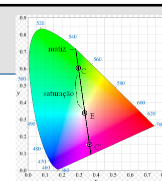
- Chromaticity Diagram
  - The purple line connects the spectral colors red and blue

Properties of the CIE-XYZ CD



- It contains all chromaticies perceived by the human eye
- It is independent of any realizable primary colors
  - Standard for colorimetry
- Given any two chromaticies in the diagram, all chromaticies obtained mixing them fall on the line segment connecting them
- Given three chromaticies, all chromaticies obtained mixing them are in the triangle formed by these three chromaticies
- The *xy* distance between two chromaticies does not correspond to a perceptual distance. Some color spaces have been created with this goal in mind (CIE-L*u*v* and CIE-L*a*b*)

Properties of the CIE-XYZ CD

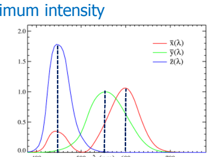


- Consider the line segment passing through the neutral point (E) and a given color (C):
  - The intersection of this line with the border of the diagram defines a hue of color C
  - The ratio between the distances from E to C and from E to the color hue defines the color saturation
  - The color C' symmetric to C with respect to E is C's complementary color (when mixed they produce white)

Mapping from Arbitrary RGB to XYZ

- To map from a monitor with specific RGB primaries, we need (to measure) the XYZ values of such primaries
  - Measure R, G, and B primaries at maximum intensity

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_{red} & X_{green} & X_{blue} \\ Y_{red} & Y_{green} & Y_{blue} \\ Z_{red} & Z_{green} & Z_{blue} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$



- Analytically, this corresponds to

$$\begin{array}{lll} X_{red} = \int_\lambda \phi_{red}(\lambda)\bar{x}(\lambda)d\lambda & X_{green} = \int_\lambda \phi_{green}(\lambda)\bar{x}(\lambda)d\lambda & X_{blue} = \int_\lambda \phi_{blue}(\lambda)\bar{x}(\lambda)d\lambda \\ Y_{red} = \int_\lambda \phi_{red}(\lambda)\bar{y}(\lambda)d\lambda & Y_{green} = \int_\lambda \phi_{green}(\lambda)\bar{y}(\lambda)d\lambda & Y_{blue} = \int_\lambda \phi_{blue}(\lambda)\bar{y}(\lambda)d\lambda \\ Z_{red} = \int_\lambda \phi_{red}(\lambda)\bar{z}(\lambda)d\lambda & Z_{green} = \int_\lambda \phi_{green}(\lambda)\bar{z}(\lambda)d\lambda & Z_{blue} = \int_\lambda \phi_{blue}(\lambda)\bar{z}(\lambda)d\lambda \end{array}$$

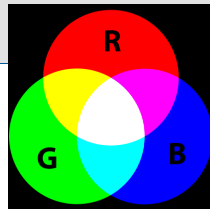
Mapping from Arbitrary RGB to XYZ

- If the specific RGB primaries are not known it is a reasonable assumption to use the sRGB primaries
  - sRGB: standard RGB for color management and for the Internet
  - The primary set for HDTV (ITU-R BT-709/2)
- Mapping from CIE-XYZ to sRGB

$$\begin{bmatrix} sR \\ sG \\ sB \end{bmatrix} = \begin{bmatrix} 3.2410 & -1.5374 & -0.4986 \\ -0.9692 & 1.8760 & 0.0416 \\ 0.0556 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

  - Expects XYZ tristimulus values in the [0-1] range
  - The sRGB primary set has a much more limited color gamut than XYZ
- Mapping from sRGB to CIE-XYZ: inverse of the above matrix

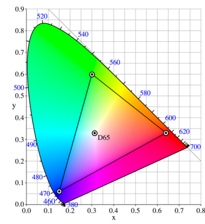
RGB Color Model



- Additive color model that uses red (R), green (G), and blue (B) as primary colors
- Most popular color model, used in color monitors
- There are several color spaces based on this model: sRGB, Adobe RGB, Adobe Wide Gamut RGB
  - A color space is defined through the specification of three primary colors and the reference white

sRGB Color Space

- Standard RGB (sRGB) is the standard color space for monitors, digital cameras, scanners, and for digial images in general
- Created by HP and Microsoft
- Uses 3 primaries defined in ITU-R BT.709-2, and D65 as reference white

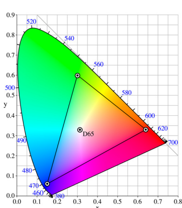


$$\begin{bmatrix} R_{linear} \\ G_{linear} \\ B_{linear} \end{bmatrix} = \begin{bmatrix} 3.2410 & -1.5374 & -0.4986 \\ -0.9692 & 1.8760 & 0.0416 \\ 0.0556 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

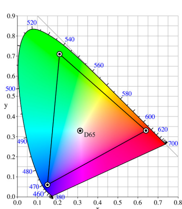
$$C_{srgb} = \begin{cases} 12.92\, C_{linear}, & C_{linear} \leq 0.0031308 \\ 1.055\, C_{linear}^{1/2.4} - 0.055 & C_{linear} > 0.0031308 \end{cases}$$

C represents each one the R, G, and B color channels.

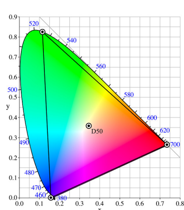
Comparison among RGB Color Spaces



sRGB



Adobe RGB
50% of the visible colors

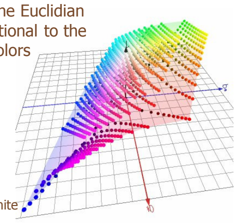


Adobe Wide Gamut RGB
78% of the visible colors

CIE-L*a*b* (1976)

- Uses a lightness channel (L*) and two opponent channels: red-green (a*) and yellow-blue (b*)
  - Based on the second stage of the human visual system
- Approximately perceptually uniform: the Euclidian distance between two colors is proportional to the perceptual distances between these colors

$$L^* = 116\, f(Y/Y_n) - 16$$
$$a^* = 500[\, f(X/X_n) - f(Y/Y_n)]$$
$$b^* = 200[\, f(Y/Y_n) - f(Z/Z_n)]$$
$$f(t) = \begin{cases} t^{1/3} & t > 0{,}008856 \\ 7{,}787t + 16/116 & \end{cases}$$



Xn, Yn, and Zn are the coord. of the XYZ reference white