Computer Graphics: Color II

Part 2 – Lecture 11

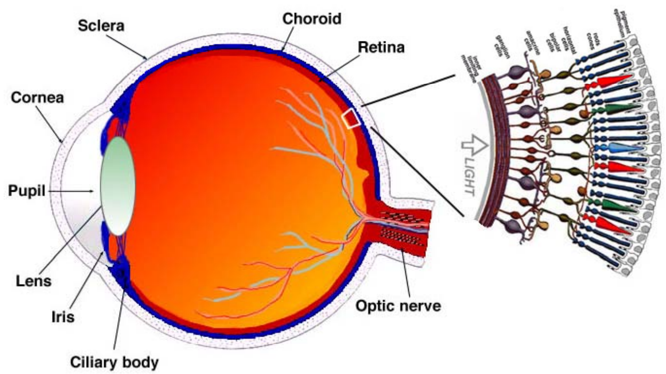
Today's Outline

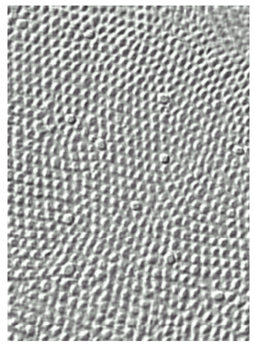
- Recap: Human Perception of Color
- Color Spaces
  - RGB
  - CIE XYZ
  - HLS

HUMAN PERCEPTION OF COLOR

The Eye

- Four types of receptors (sensors): R/G/B cones + rods, each has unique SRF

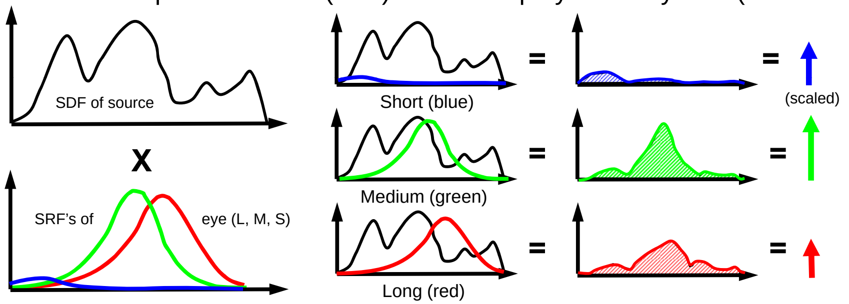


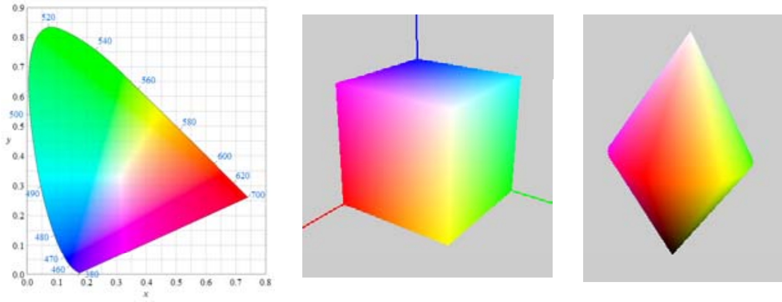


http://webvision.med.utah.edu/imageswv/fovmoswv.jpeg
http://webvision.med.utah.edu/imageswv/Sagschem.jpeg

Seeing Red, Green and Blue

- A cone cell in the retina measures amount of red, green, or blue wavelength energy (3 SRF's). Responds only in bright light.
- SRF of a rod cell covers all wavelengths (measures "gray level" or intensity) Responds in low light, but not in bright light.
- Integral of R, G, or B cone response produces a single value
  Note: SRF's really L, M, S wave responses (long, medium, short), not R, G, B.
  Note: low response of short (blue) is scaled up by vision system (after retina).



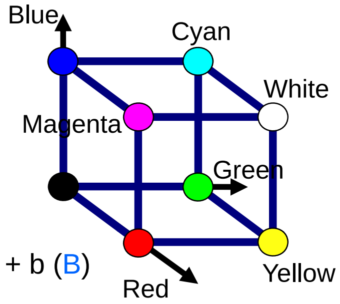


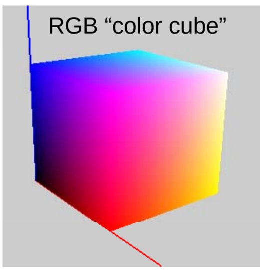
COLOR SPACES

CIE image thanks to Sakurambo

Color Coordinate Space

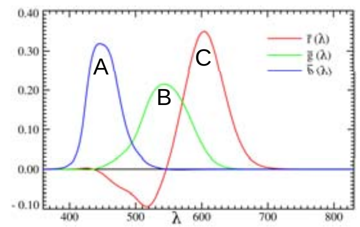
- Defines 3 SRFs (**color matching functions**) for some sensing system
- One dimension for each SRF ($\rightarrow$ **tristimulus color space**)
  - Each dimension represents a **primary color P**
  - Coordinate value = resulting SDF integral normalized to (0, 1)
- Color triple is 3D point defined by **chromaticity values** (c_0, c_1, c_2)
- Example: RGB color space
  - Primaries:
    Red, Green, Blue
    with basis vectors
    R = (0,0,1)
    G = (1,0,0)
    B = (0,1,0)
  - Chromaticity values:
    (r,g,b) = r (R) + g (G) + b (B)





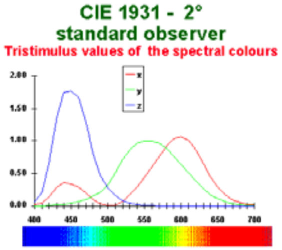
Finding Color Matching Functions

- **Given**: 3 primaries A, B, C
- **Wanted**: 3 SRFs, one for each primary
- **Idea**:
  1. Show light L with pure color of wavelength λ and brightness 1 to test persons
  2. Let them adjust another light P using chromaticities a, b, c until L and P match
  3. Do this with the whole range of wavelengths λ and note down the a, b, c values for each λ
- **Problem**: when using normal, visible colors as primaries, some wavelengths λ need negative chromaticities (because adding colors decreases saturation)

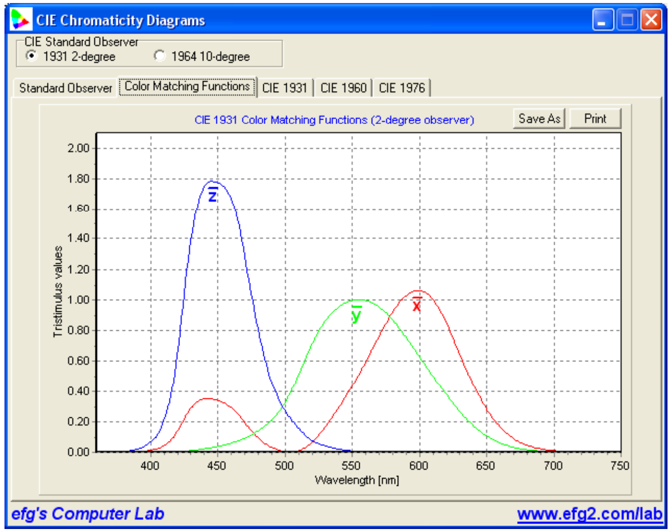


CIE XYZ Colour Space (1931)

- A normalized, standard color space designed by engineers according to requirements:
  - Standard primaries (“R”, “G”, “B”)
  - Only positive chromaticities
  - Equal chromaticities are grays
  - Easy conversion to brightness levels
- Three primaries: X, Y, Z
  - All are “imaginary” (not real colors)
  - SRFs were designed by engineers to meet above requirements
  - Y corresponds to brightness
  - Conversion to RGB is a matrix multiply (linear combination of X,Y,Z = R,G,B and vice versa)



CIE XYZ Color Matching Functions



(X,Y,Z) coordinates of any input SDF are found by multiplying and integrating

This *defines the* (X,Y,Z) *color* of the SDF

CIE Chromaticity Diagram

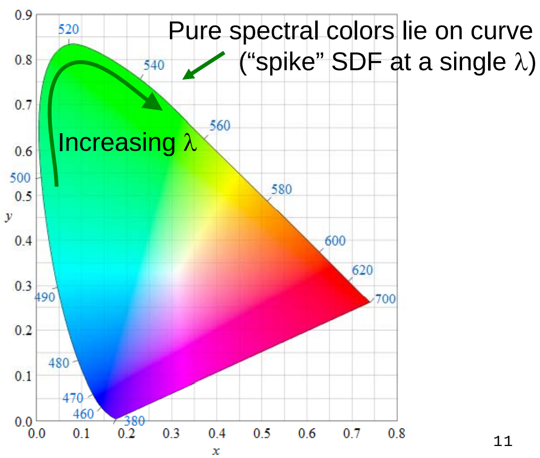
2D Chromaticity Space:

- Projection of 3D XYZ space onto 2D plane X + Y + Z = 1
- Looking only at colors with brightness 1
- 2D coordinates (x,y) defined as:

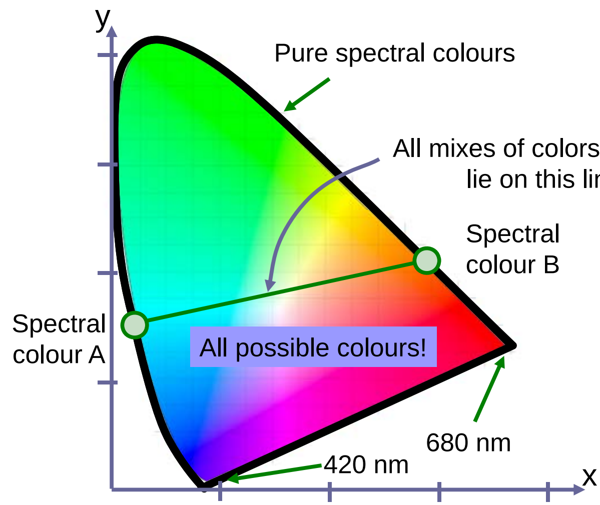
$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

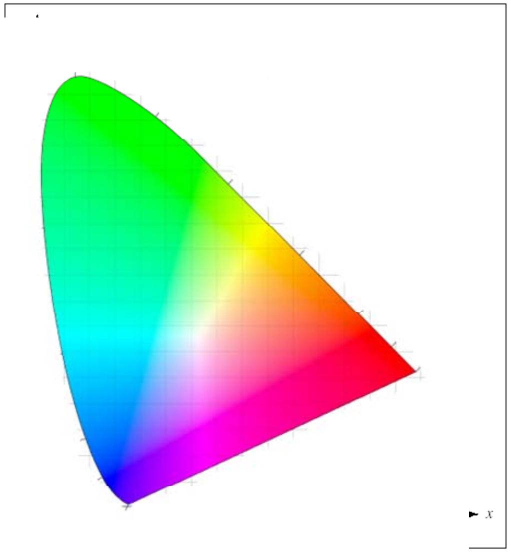
(*x*,*y*) is the chromaticity of the color



CIE Chromaticity Diagram



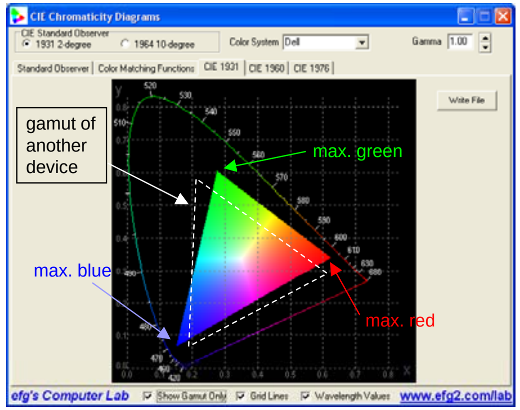
Using the CIE Chromaticity Diagram



- ***w*** is white
- ***e*** and ***f*** are *complementary* colors (→ can be combined to white)
- ***h*** is *dominant wavelength* of ***g***
- ***wg*** / ***wh*** is *saturation* of ***g*** (→ how close in % g is to its pure color)

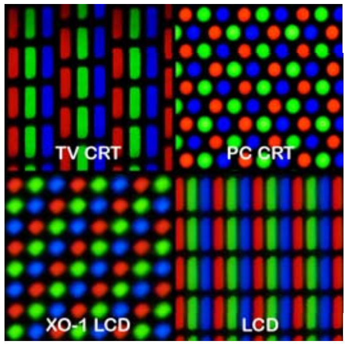
Color Gamut

- Subset of colors that can be represented on a device
- CIE color space can be used to describe color gamut
  1. Measure maximum intensity of each **device primary** in CIE (use filters with SRF's = CIE SRF's)
  2. Convert to (x,y) chromaticity
  3. 2D triangle defines possible device colors (→ color gamut)
- Different devices have different gamuts (→ problem of color conversion)



Additive Color Systems

- Colors are mixed by adding up appropriate amounts of primaries (adding SDF spikes to black)
- Widely used in screens with subpixels that emit R,G,B
- Cones in retina respond to light emitted by each subpixel
- Brain adds the individual cone responses to produce perception of hue, luminance, and saturation



→ **Demo program: ColorMix.exe**
http://www.efg2.com/Lab/Graphics/Colors/ColorMix.htm

Subtractive Color Systems

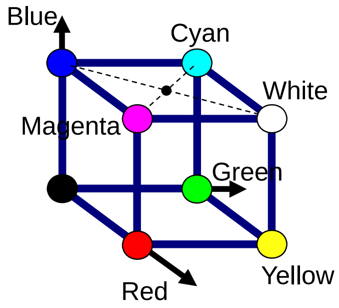
- Colors are mixed by substracting appropriate amounts of colors from white (like using notch SRFs on white)
- White light is reflected or transmitted, and some wavelengths are absorbed (subtracted), e.g. colored glass, printed images
- The colors to substract are the complements of the primaries, e.g. cyan, magenta, yellow (CMY)
  - Cyan absorbs red
  - Magenta absorbs green
  - Yellow absorbs blue

$$(r, g, b) = (1,1,1) - (c, m, y)$$

- CMYK (K = black) often used for 4 colour printers

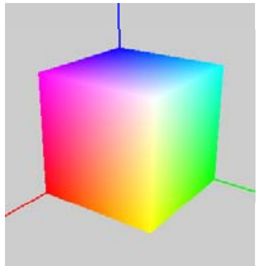
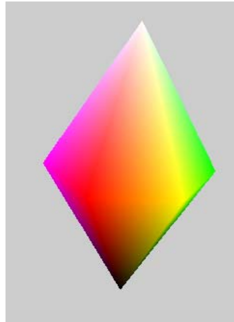
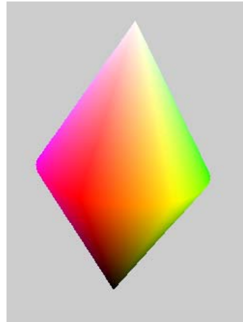
Troubles with RGB

- Difficult to use for color design because selecting a hue sometimes not intuitive, e.g. what combination of RGB do you use to make brown?
  (128, 80, 50) is a good choice. Could you figure that out?
- Not a good color space for interpolating between colors
  - For example,
    ½ blue + ½ white =
    ½ magenta + ½ cyan =
  - Linear interpolation between (r,g,b) chromaticities does not linearly interpolate the saturation or the luminance

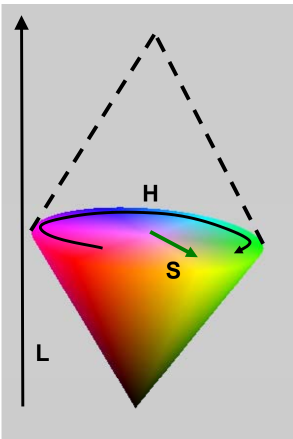


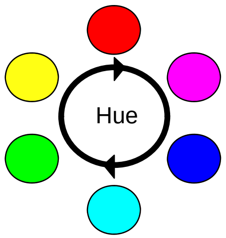
HLS Color Space

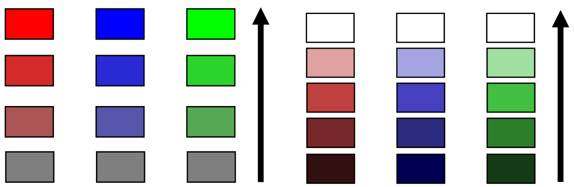
- Hue, Lightness, Saturation
- Based on transformation of RGB cube
  → double "hexcone"→ double cone

HLS Color Space





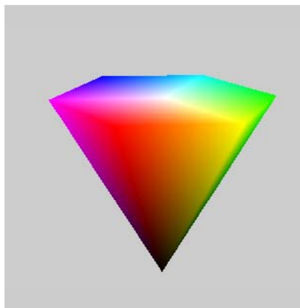
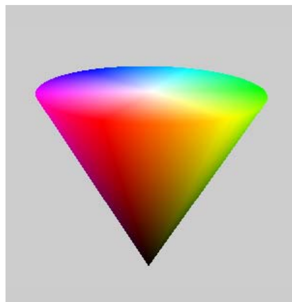
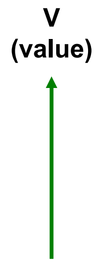


Saturation
(lightness = 50%)

Lightness
(saturation = 50%)

HSV Color Space

- Hue, Saturation, Value (similar to Lightness)
- Only single cone:
  at the top all colors are brightest

Colour interpolation: RGB vs HLS

- Linear interpolation between 2 RGB colours in RGB space:
  $C_0 = (r_0, g_0, b_0) \Rightarrow C_1 = (r_1, g_1, b_1)$
  - $r(t) = r_0 + t\,(r_1 - r_0)$, $g(t) = g_0 + t\,(g_1 - g_0)$, $b(t) = b_0 + t\,(b_1 - b_0)$
    $0 <= t <= 1$
  - **Problem**: saturation and luminance are not linearly interpolated. Interpolation may correctly vary from one hue to another, but S and L may vary in strange ways!
- Linear interpolation between 2 HLS colours in HLS space:
  $C_0 = (h_0, l_0, s_0) \Rightarrow C_1 = (h_1, l_1, s_1)$
  - $h(t) = h_0 + t\,(h_1 - h_0)$, $l(t) = l_0 + t\,(l_1 - lg_0)$, $s(t) = s_0 + t\,(s_1 - s_0)$
    $0 <= t <= 1$
  - All 3 components (HLS) linearly interpolated
  - **Solution**: Convert C_0, C_1 to HLS; interpolate in HLS, convert results back to RGB

SUMMARY

Summary

1. Colors can be represented using a 3D color space
2. RGB: easy to use for additive color mixing, but limited gamut
3. CIE can represent all visible colors
4. HSL can linearly interpolate properly between hue, saturation and lightness

References:
- Color Description: Hill, Chapter 11.2
- CIE Color Model: Hill, Chapter 11.3
- Other Color Spaces: Hill, Chapter 11.4

Quiz

1. What is a color coordinate space?
2. Name an advantage of the CIE color model.
3. What is a color gamut?
4. What are the disadvantages of RGB?