

Computer Graphics and Image Processing Color II

Part 1 – Lecture 6

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Today's Outline

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

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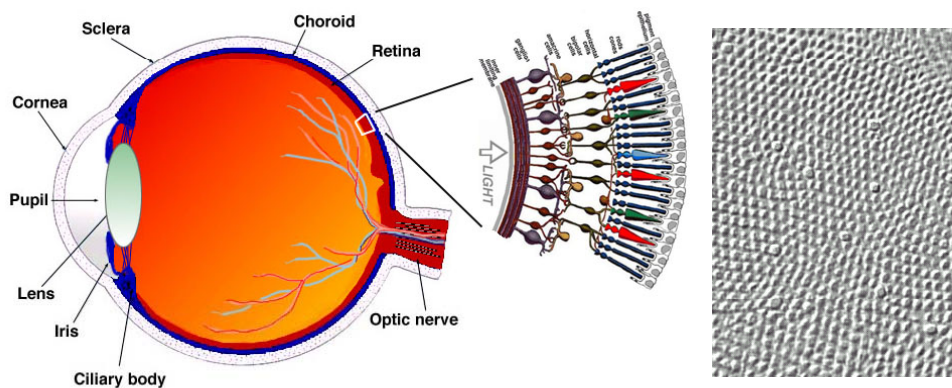


HUMAN PERCEPTION OF COLOR

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The Eye

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



<http://webvision.med.utah.edu/imagesww/fovmoswv.jpeg>

<http://webvision.med.utah.edu/imagesww/Sagschem.jpeg>

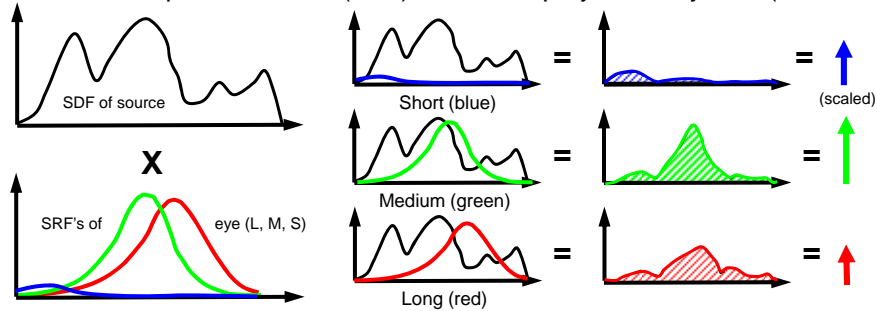
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Seeing Red, Green and Blue

- 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

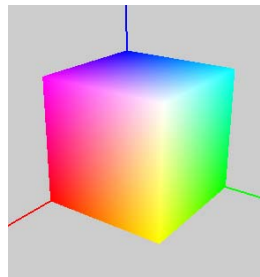
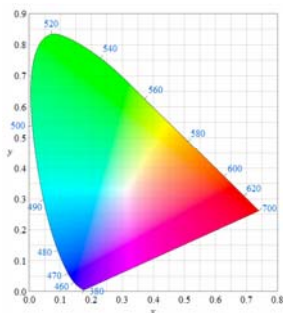
Note: SRF's really L, M, S wave responses (long, medium, short), not R, G, B.

Note: low response of short (blue) is scaled up by vision system (after retina).



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COLOR SPACES



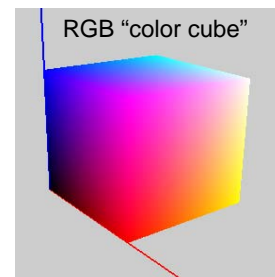
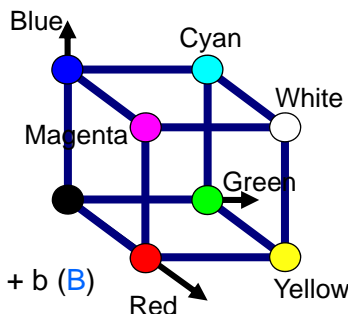
CIE image thanks to Sakurambo

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Color Coordinate Space

- Defines 3 SRFs (**color matching functions**) for some sensing system
- One dimension for each SRF (→ **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

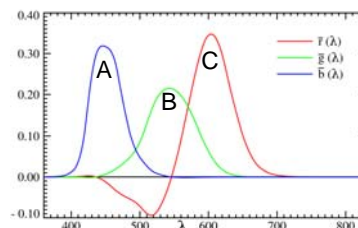
- Primaries:
 - Red, Green, Blue
 - with basis vectors
 - $R = (0,0,1)$
 - $G = (1,0,0)$
 - $B = (0,1,0)$
- Chromaticity values:
 - $(r,g,b) = r(R) + g(G) + b(B)$



Finding Color Matching Functions

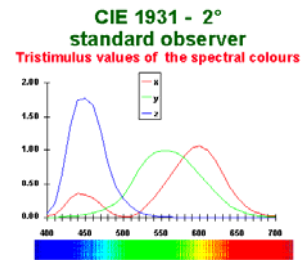
- **Given:** 3 primaries A, B, C
- **Wanted:** 3 SRFs, one for each primary
- **Idea:**
 1. Show light L with pure color of wavelength λ and brightness 1 to test persons
 2. Let them adjust another light P using chromaticities a, b, c until L and P match
 3. Do this with the whole range of wavelengths 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)



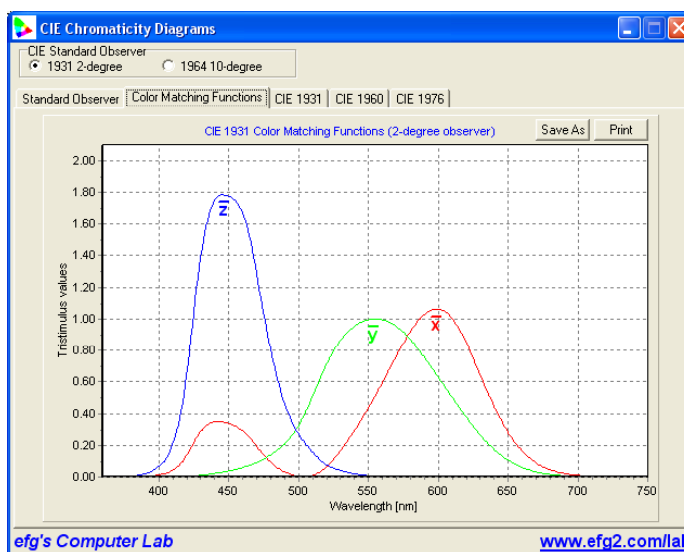
CIE XYZ Color Space (1931)

- 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)



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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

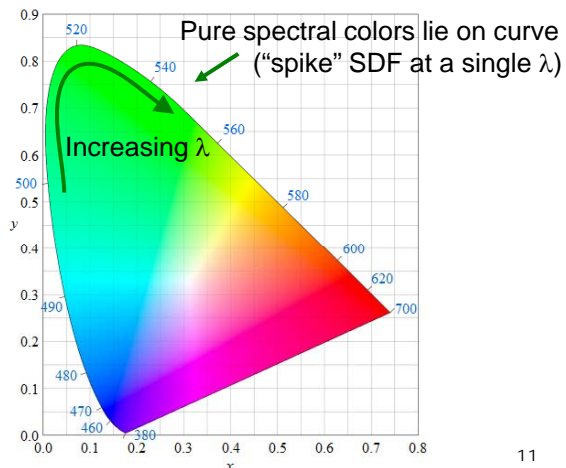
2D Chromaticity Space:

- 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:

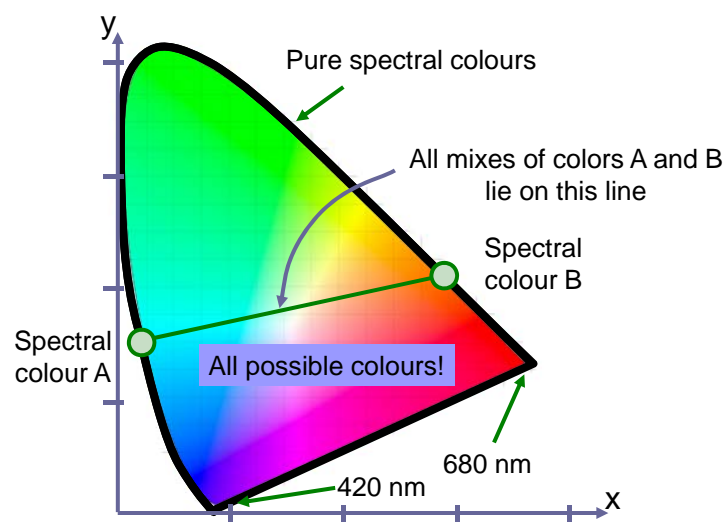
$$x = \frac{X}{X + Y + Z}$$

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

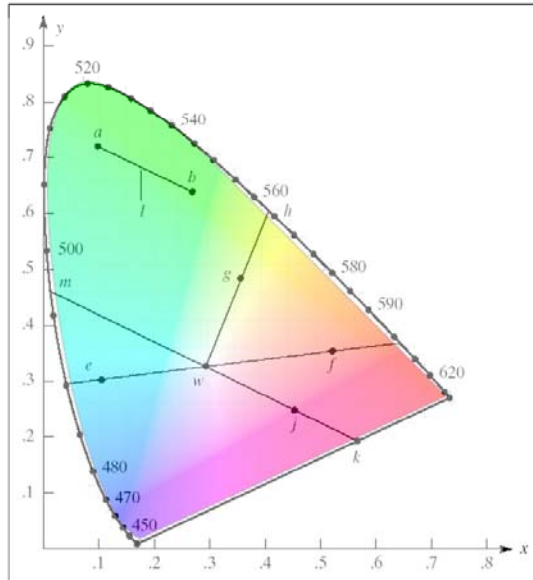
(x,y) is the chromaticity of the color



CIE Chromaticity Diagram



Using the CIE Chromaticity Diagram

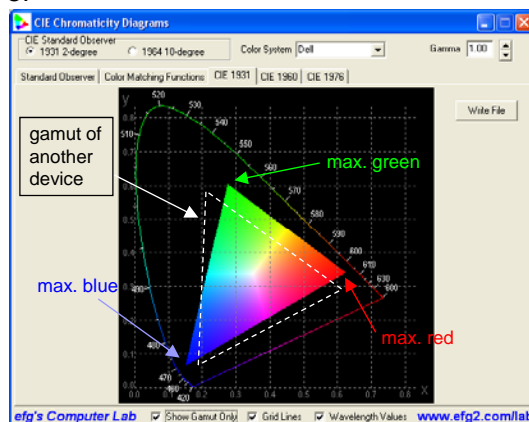


- **w** is white
- **e** and **f** are complementary colors (→ can be combined to white)
- **h** is dominant wavelength of **g**
- **wg / wh** is saturation of **g** (→ how close in % **g** is to its pure color)

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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)



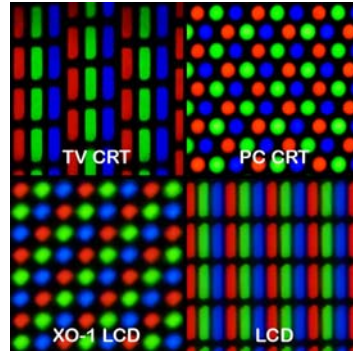
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Additive Color Systems

- 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>



Top image thanks to Pengo

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Subtractive Color Systems







- Colors are mixed by subtracting 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 subtract are the complements of the primaries, e.g. cyan, magenta, yellow (CMY)
 - Cyan absorbs red
 - Magenta absorbs green
 - Yellow absorbs blue
- CMYK (K = black) often used for 4 colour printers

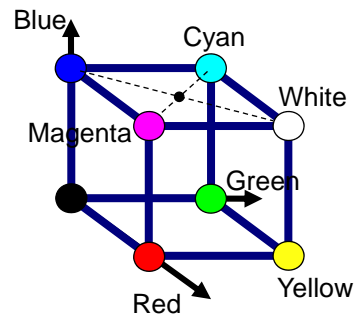


$$(r, g, b) = (1, 1, 1) - (c, m, y)$$

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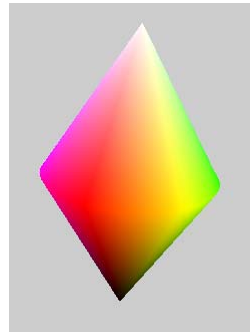
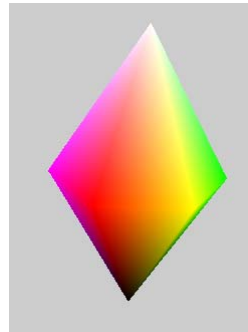
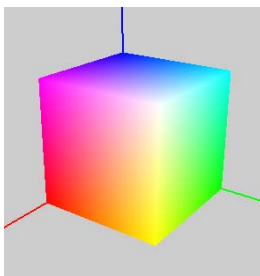
Troubles with RGB

- 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,
 $\frac{1}{2}$ blue  + $\frac{1}{2}$ white  = 
 $\frac{1}{2}$ magenta  + $\frac{1}{2}$ cyan  = 
 - Linear interpolation between (r,g,b) chromaticities does not linearly interpolate the saturation or the luminance

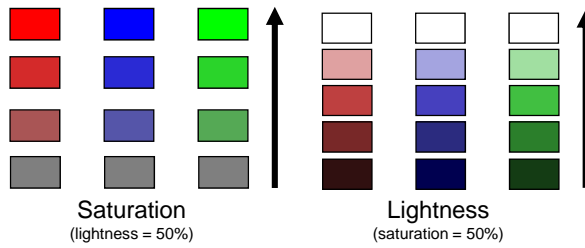
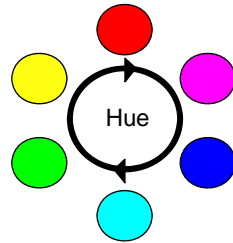
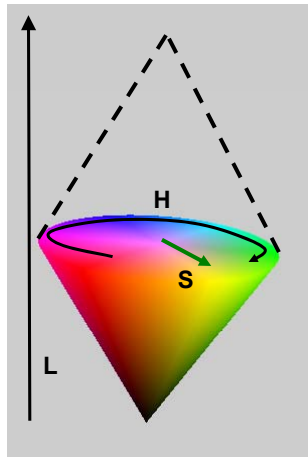


HLS Color Space

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

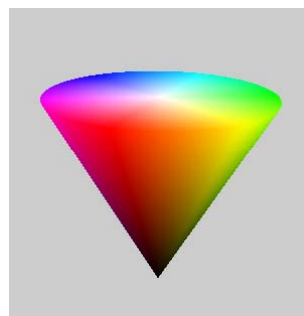
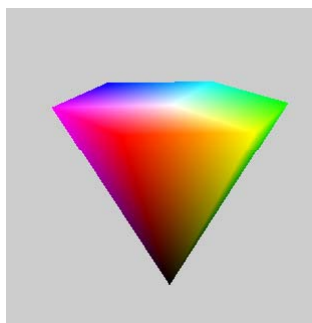


HLS Color Space



HSV Color Space

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



V
(value)
↑

Colour interpolation: RGB vs HLS

- Linear interpolation between 2 RGB colors in RGB space:
 $C_0 = (r_0, g_0, b_0) \Rightarrow C_1 = (r_1, g_1, b_1)$
 - $r(t) = r_0 + t(r_1 - r_0)$, $g(t) = g_0 + t(g_1 - g_0)$, $b(t) = b_0 + t(b_1 - b_0)$
 $0 \leq t \leq 1$
 - **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 colors in HLS space:
 $C_0 = (h_0, l_0, s_0) \Rightarrow C_1 = (h_1, l_1, s_1)$
 - $h(t) = h_0 + t(h_1 - h_0)$, $l(t) = l_0 + t(l_1 - l_0)$, $s(t) = s_0 + t(s_1 - s_0)$
 $0 \leq t \leq 1$
 - 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

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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?

YELLOW BLUE ORANGE
BLACK RED GREEN
PURPLE YELLOW RED
ORANGE GREEN BLACK
BLUE RED PURPLE
GREEN BLUE ORANGE

Say the color of the word (not the word itself)

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