CSE 190: Virtual Reality Technologies

LECTURE #4: COLOR

VR Content Presentations

Tim Hedstrom: Google Cardboard App

- https://itunes.apple.com/us/app/google-cardboard/id987962261?mt=8

Taylor Durrer

- TBD

Christy Ye: Colgate Experiencia 360

- https://www.youtube.com/watch?v=12otR342ijc

Kavin Srithongkham: Zombie Shooter VR

- https://itunes.apple.com/gb/app/zombie-shooter-vr/id935707913?mt=8
- https://youtu.be/JYByhN0fil0?t=46s

Chen Liu: Horizons

- https://play.google.com/store/apps/details?id=com.reactify.HorizonsVR

Announcements

Homework project 1 is due April 21st at 2pm

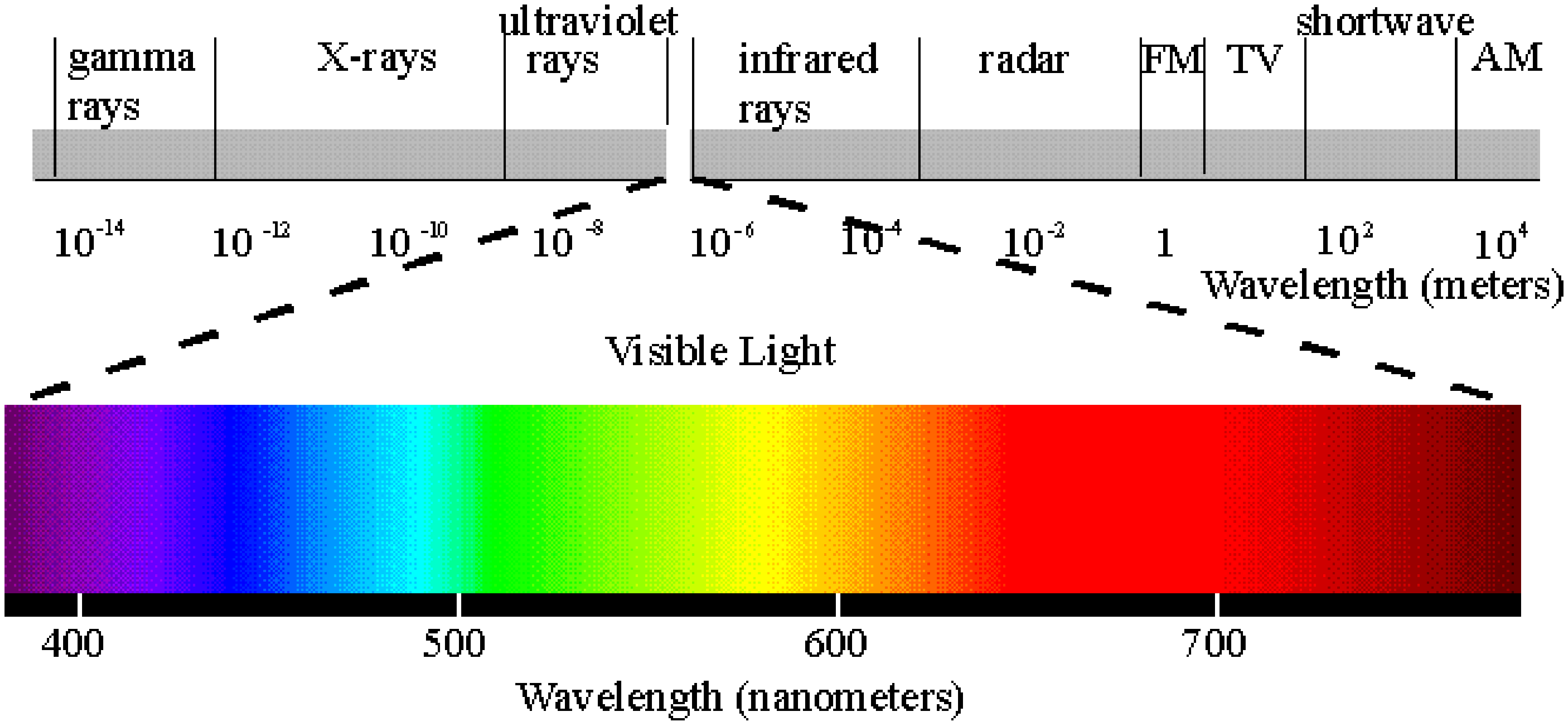
- To be demonstrated in VR lab B210

Disk space issues in lab?

- Everyone should have at least 500MB quota.
- D: drive has plenty of storage
  - Local drive
  - Not part of user profile
  - Accessible by any user on that PC

Color Spaces

Color Perception



Color Reproduction

How can we reproduce, represent color?

- One option: store full spectrum

Representation should be as compact as possible

Any pair of colors that can be distinguished by humans should have two different representations

Color Spaces

Set of parameters describing a color sensation

“Coordinate system” for colors

Three types of cones, expect three parameters to be sufficient

Why not use L,M,S cone responses?

Color Spaces

Set of parameters describing a color sensation

“Coordinate system” for colors

Three types of cones

- We expect three parameters to be sufficient

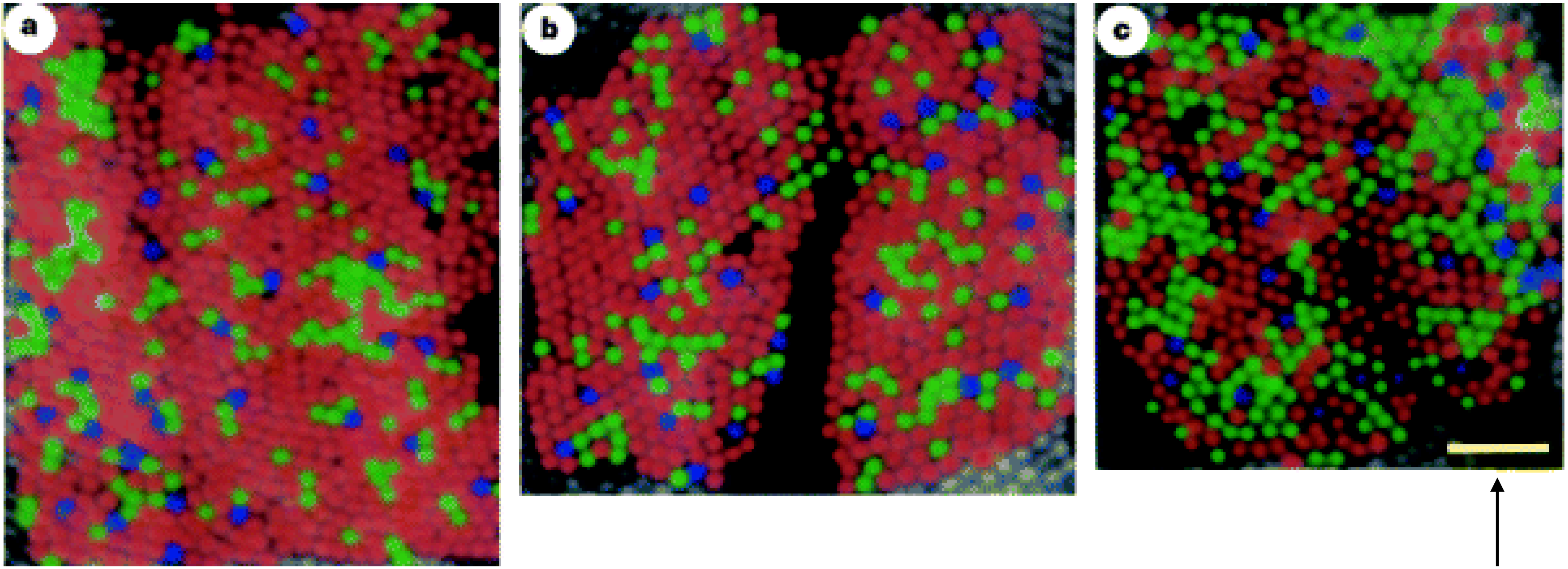
Trichromatic Theory

Claims that any color can be represented as a weighted sum of three primary colors

Proposes red, green, blue as primaries

Developed in 18th and 19th century, before discovery of photoreceptor cells (Thomas Young, Hermann von Helmholtz)

The Retina



5 arcmin visual angle

Roorda & Williams, 1999, Nature

photoreceptors: 3 types of cones (color vision), rods (luminance only, night vision)

Tristimulus Experiment

Given arbitrary color, we want to know the weights for the three primaries

Yields tristimulus values

Experimental solution

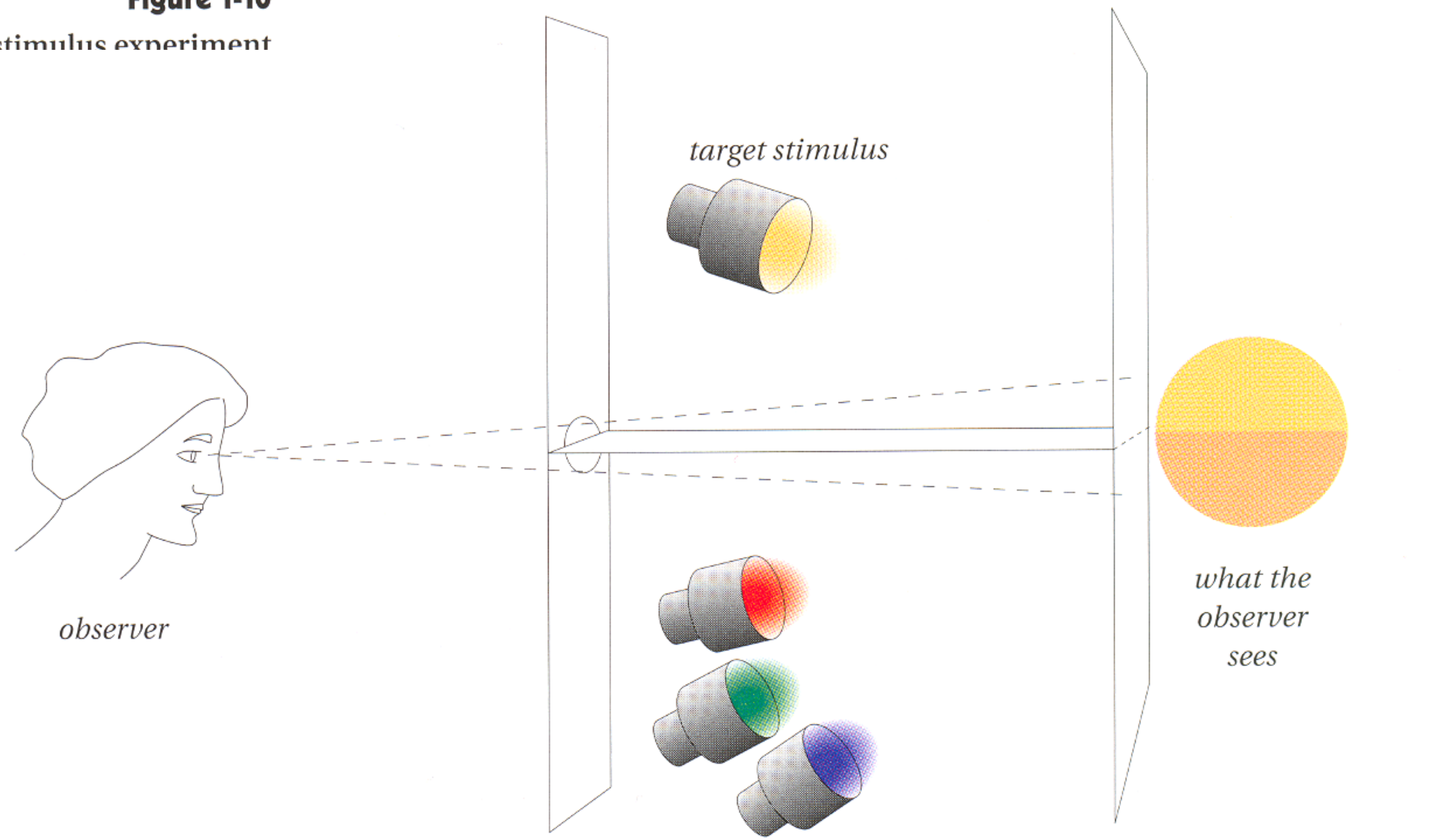
- CIE (Commission Internationale de l’Eclairage, International Commission on Illumination), circa 1920

Tristimulus Experiment

Determine tristimulus values for spectral colors experimentally

Figure 1-10

Tristimulus experiment



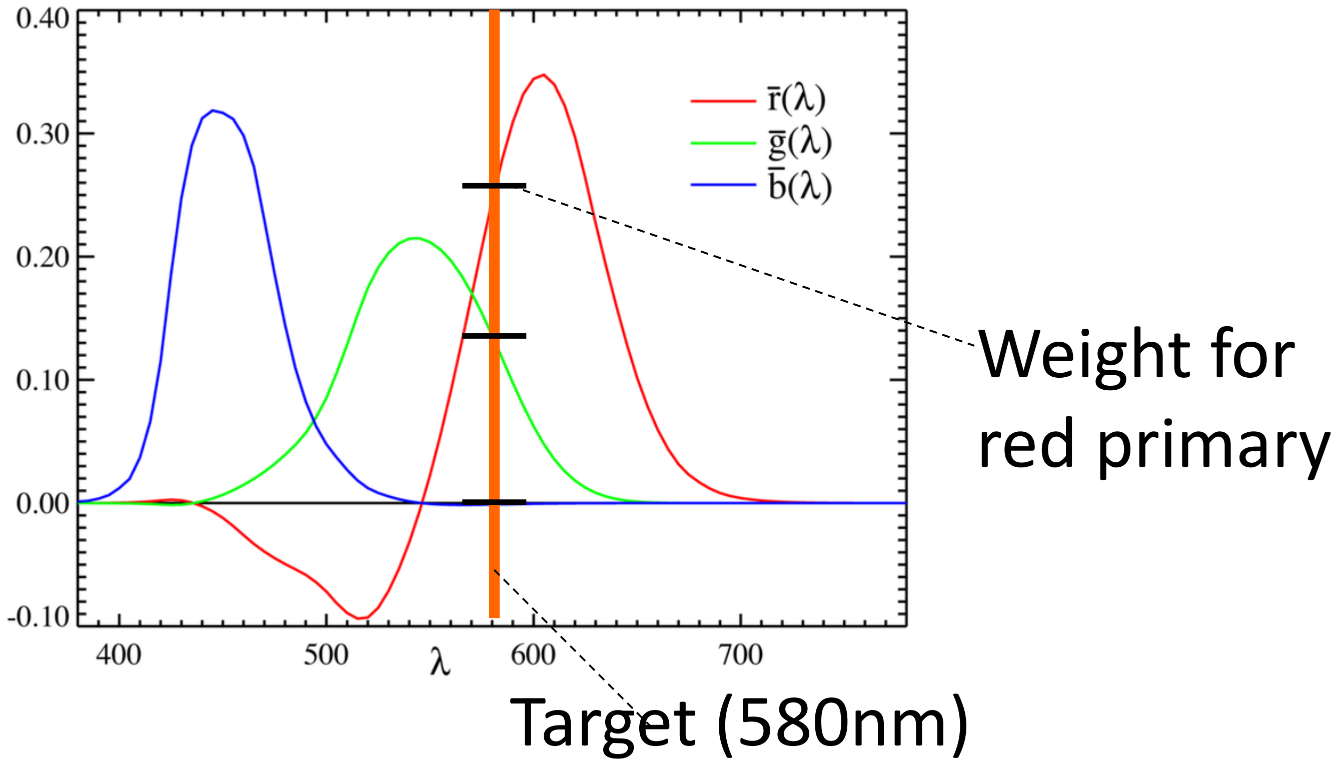
The observer adjusts the intensities of the red, green, and blue lamps until they match the target stimulus on the split screen.

Tristimulus Experiment

Spectral primary colors were chosen

- Blue (435.8nm), green (546.1nm), red (700nm)

Matching curves for monochromatic target



Negative values!

Tristimulus Experiment

Negative values

Some spectral colors could not be matched by primaries in the experiment

"Trick"

- One primary could be added to the source (stimulus)
- Match with the other two
- Weight of primary added to the source is considered negative

Photoreceptor response and matching curves are different!

Tristimulus Values

Matching values for a sum of spectra with small spikes are the same as sum of matching values for the spikes $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$

Monochromatic matching curves

In the limit (spikes are infinitely narrow)

$$R = \int \bar{r}(\lambda) L(\lambda) d\lambda$$
$$G = \int \bar{g}(\lambda) L(\lambda) d\lambda$$
$$B = \int \bar{b}(\lambda) L(\lambda) d\lambda$$

CIE Color Spaces

Matching curves $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$ define CIE RGB color space

- CIE RGB values are color "coordinates"

CIE was not satisfied with range of RGB values for visible colors

Defined CIE XYZ color space

- Most commonly used color space today

CIE XYZ Color Space

Determined coefficients such that

- Y corresponds to an experimentally determined brightness
- No negative values in matching curves
- White is XYZ=(1/3,1/3,1/3)

Linear transformation of CIE RGB:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{b_{21}} \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & 0.20 \\ 0.17697 & 0.81240 & 0.01063 \\ 0.00 & 0.01 & 0.99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

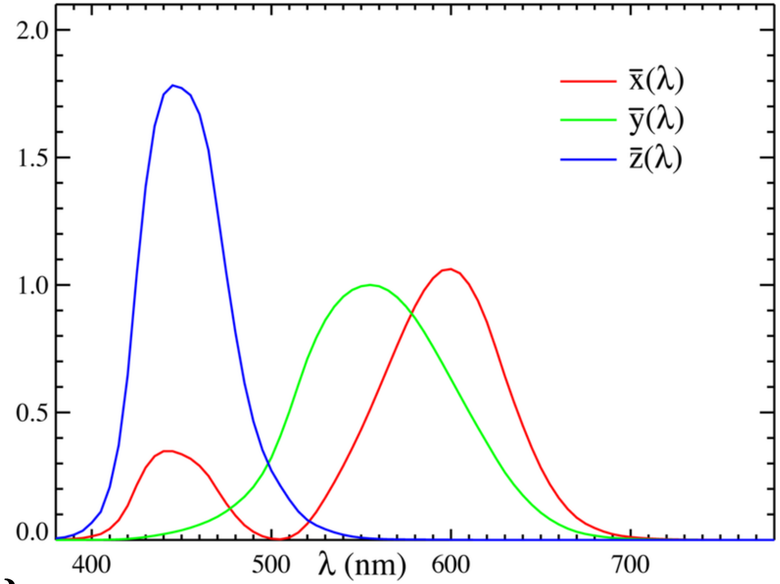
CIE XYZ Color Space

Matching curves

No corresponding physical primaries

Tristimulus values

Always positive!



$$X = \int \bar{x}(\lambda) L(\lambda) d\lambda$$

$$Y = \int \bar{y}(\lambda) L(\lambda) d\lambda$$

$$Z = \int \bar{z}(\lambda) L(\lambda) d\lambda$$

Summary

CIE color spaces are defined by matching curves

- At each wavelength, matching curves give weights of primaries needed to produce color perception of that wavelength
- CIE RGB matching curves determined using tristimulus experiment

Each distinct color perception has unique coordinates

- CIE RGB values may be negative
- CIE XYZ values are always positive

Chromaticity Diagrams

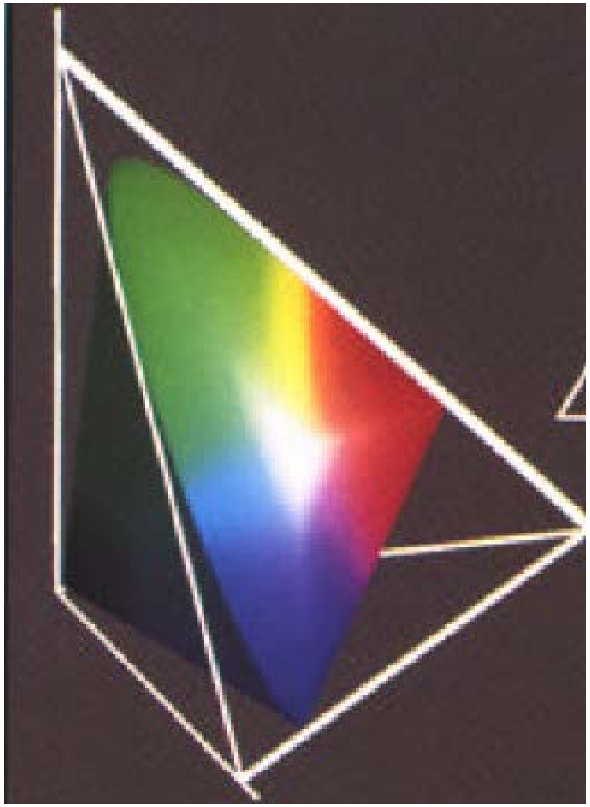
CIE XYZ Color Space

Visualization

Interpret XYZ as 3D coordinates

Plot corresponding color at each point

Many XYZ values do not correspond to visible colors

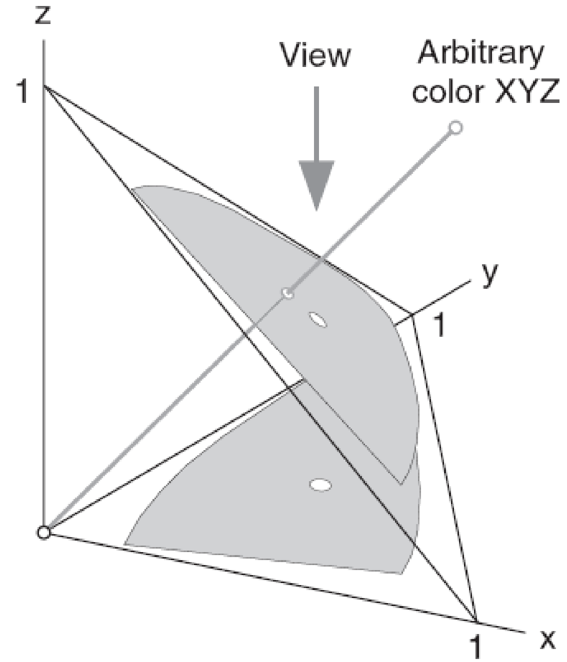


Chromaticity Diagram

Project from CIE XYZ coordinates to 2D for more convenient visualization

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

Drop z-coordinate



Chromaticity Diagram

Factor out luminance (perceived brightness) and chromaticity (hue)

- x,y represent chromaticity of a color

$$x = \frac{X}{X+Y+Z} \quad y = \frac{Y}{X+Y+Z} \quad 0 \leq x, y \leq 1$$

- Y is luminance

CIE xyY color space

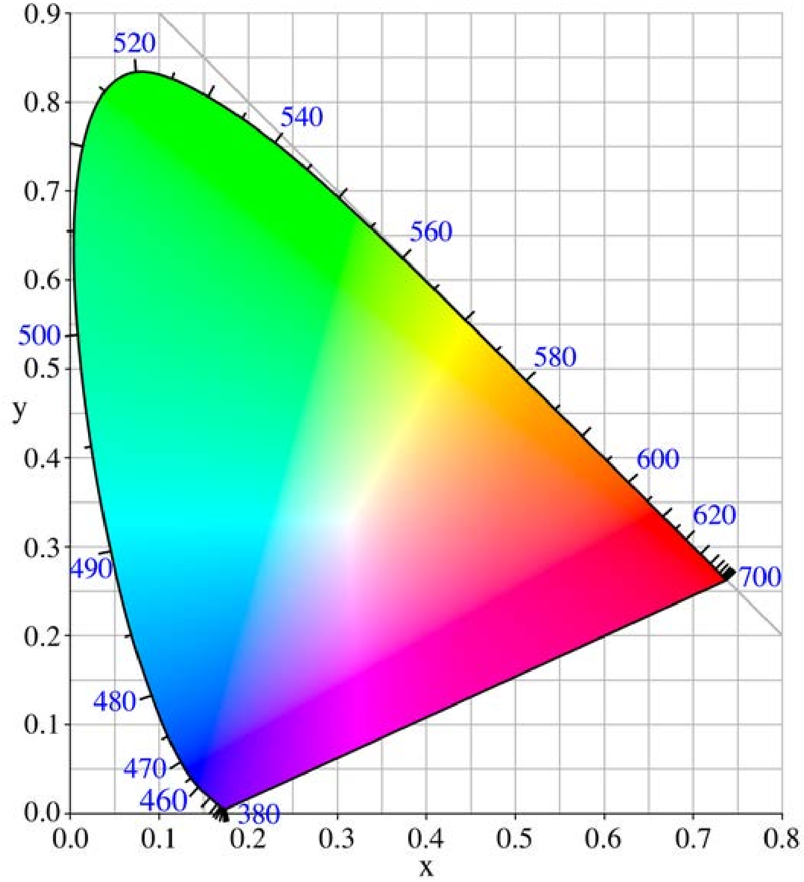
Reconstruct XYZ values from xyY

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

Chromaticity Diagram

Visualizes x,y plane (chromaticities)

Pure spectral colors on boundary



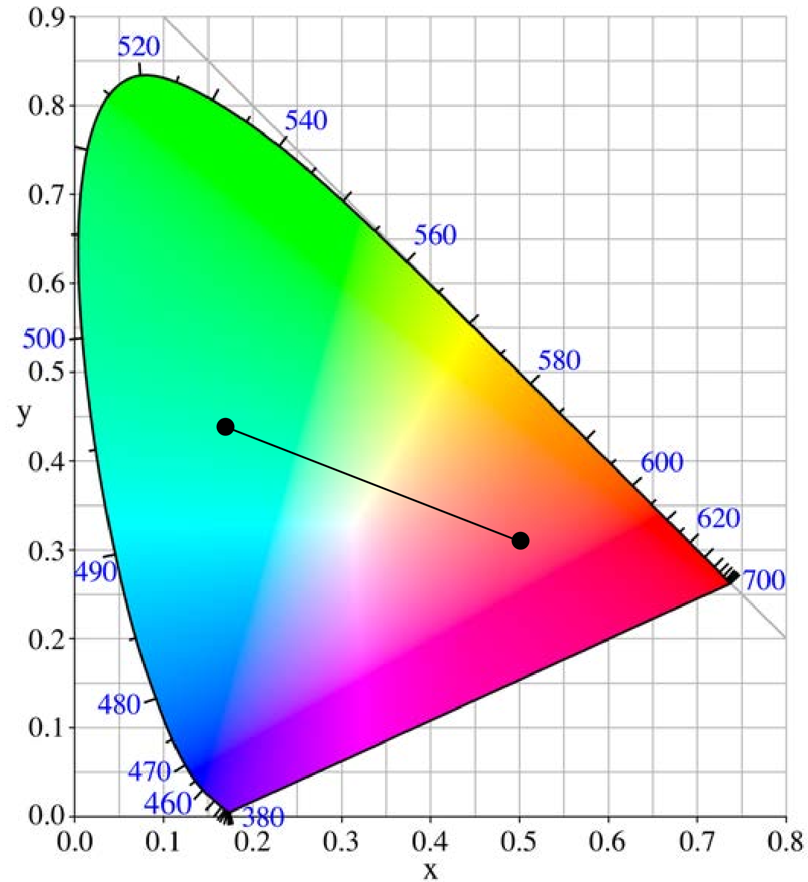
Colors shown do not correspond to colors represented by (x,y) coordinates!

Chromaticity Diagram

Visualizes x,y plane (chromaticities)

Pure spectral colors on boundary

Weighted sum of any two colors lies on line connecting colors



Colors shown do not correspond to colors represented by (x,y) coordinates!

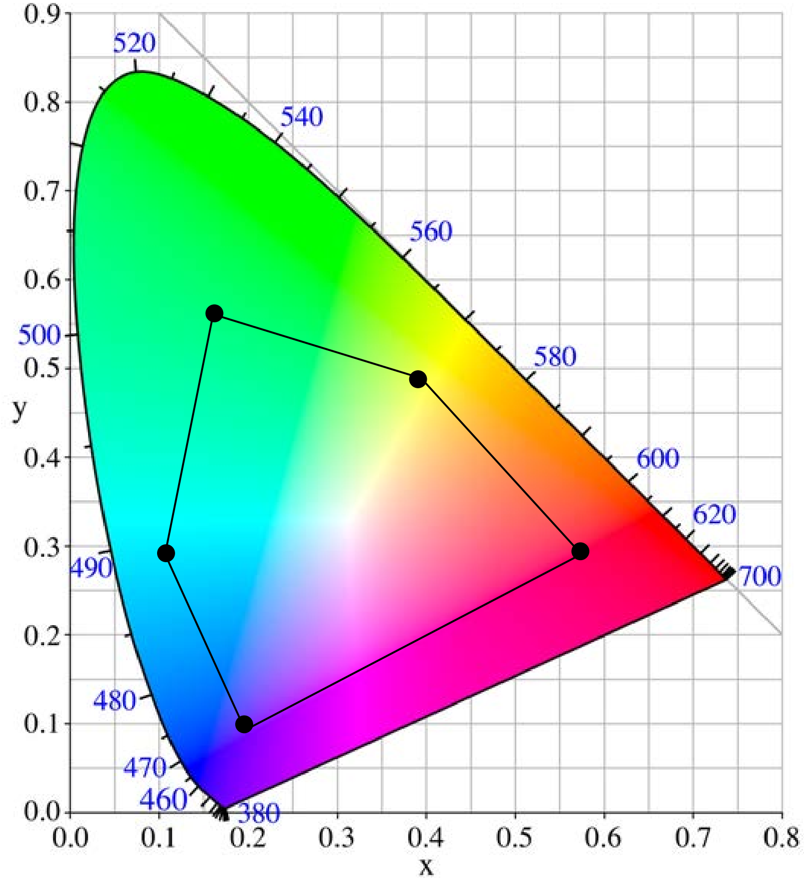
Chromaticity Diagram

Visualizes x,y plane (chromaticities)

Pure spectral colors on boundary

Weighted sum of any two colors lies on line connecting colors

Weighted sum of any number of colors lies in convex hull of colors (gamut)

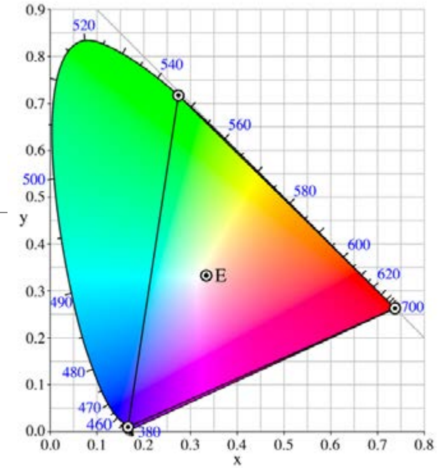


Colors shown do not correspond to colors represented by (x,y) coordinates!

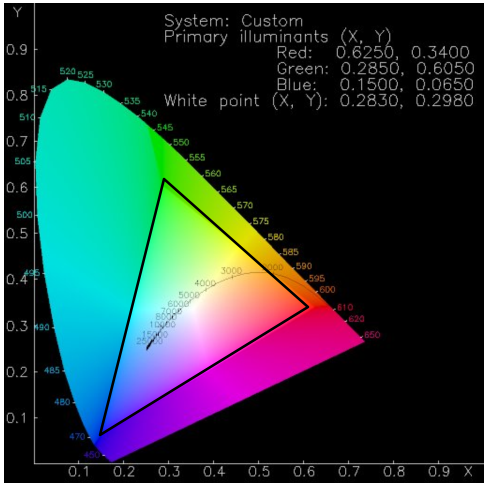
Gamut

Any device based on three primaries can only produce colors within the triangle spanned by the primaries

Points outside gamut correspond to negative weights of primaries



Gamut of CIE RGB primaries



Gamut of typical CRT monitor

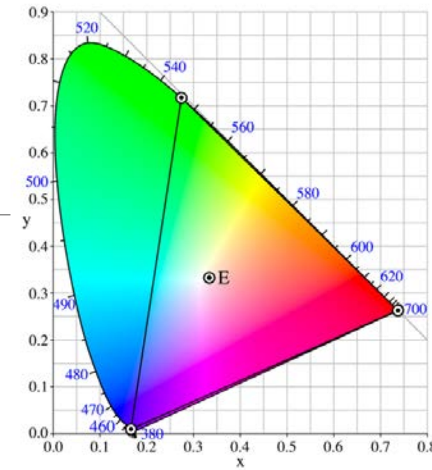
RGB Monitors

Given red, green, blue (RBG) values, what color will your monitor produce?

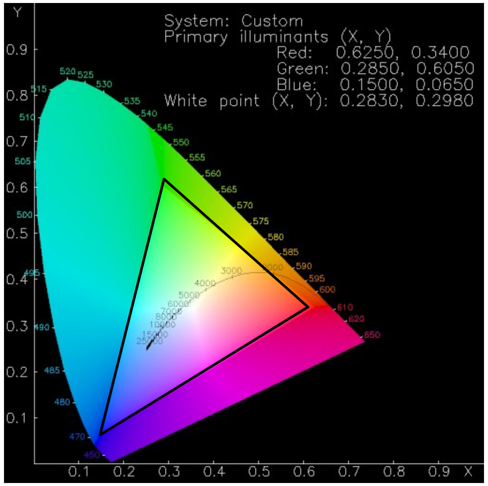
- I.e., what are the CIE XYZ or CIE RGB coordinates of the displayed color?
- How are OpenGL RGB values related to CIE XYZ, CIE RGB?

Often you don't know!

- OpenGL RGB ≠ CIE XYZ, CIE RGB



Gamut of CIE RGB primaries



Gamut of typical CRT monitor

sRGB

Standard color space, with standard conversion to CIE XYZ

Designed to match RGB values of typical monitor under typical viewing conditions (dimly lit office)

- If no calibration information available, it is best to interpret RGB values as sRGB

sRGB roughly corresponds to 2.2 gamma correction

sRGB is supported by OpenGL as

- sRGB textures (since OpenGL 2.1)
- sRGB framebuffers (since OpenGL 3.0)

Conclusions

Color reproduction on consumer monitors is less than perfect

- The same RGB values on one monitor look different than on another
- Given a color in CIE XYZ coordinates, consumer systems do not reliably produce that color

Need color calibration

- But no selling point for consumers
- Standard for digital publishing, printing, photography

Display calibration

Further Reading

Wikipedia pages

- http://en.wikipedia.org/wiki/CIE_1931_color_space
- http://en.wikipedia.org/wiki/CIELAB

More details:

- CIE Color Space:
  - http://docs-hoffmann.de/ciexyz29082000.pdf