CSE 190: Virtual Reality Technologies

LECTURE #4: HUMAN VISUAL SYSTEM

Upcoming Deadlines

Sunday April 11: Deadline for presentation date selection on wiki

Monday April 12: Discussion Project 1

Sunday April 18: Project 1 due

App Presentations

Weijia Zeng

- Virtual Virtual Reality

Tobey Pineda

- Beat Saber

Color Spaces

Color Realism

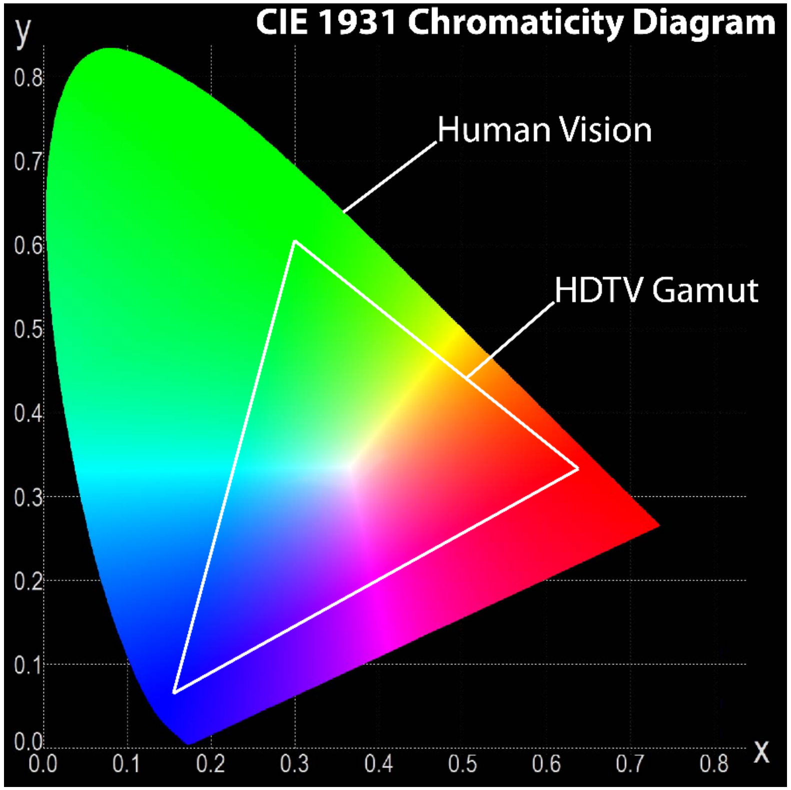
To create compelling virtual worlds we need to render realistic colors.

- Even more important for augmented reality

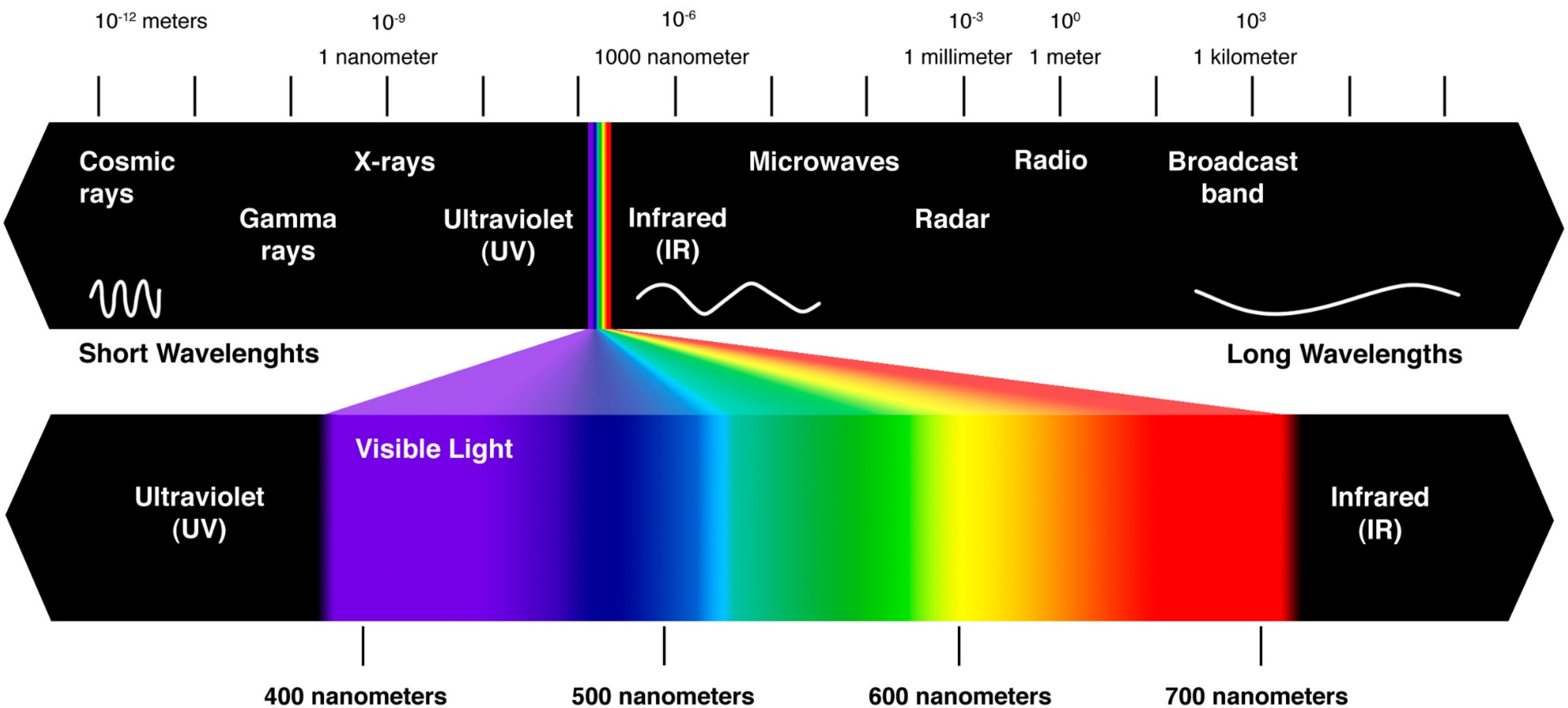
How to measure color realism?

- On right: chromaticity diagram of typical HD TV gamut

Goal: understand chromaticity diagrams



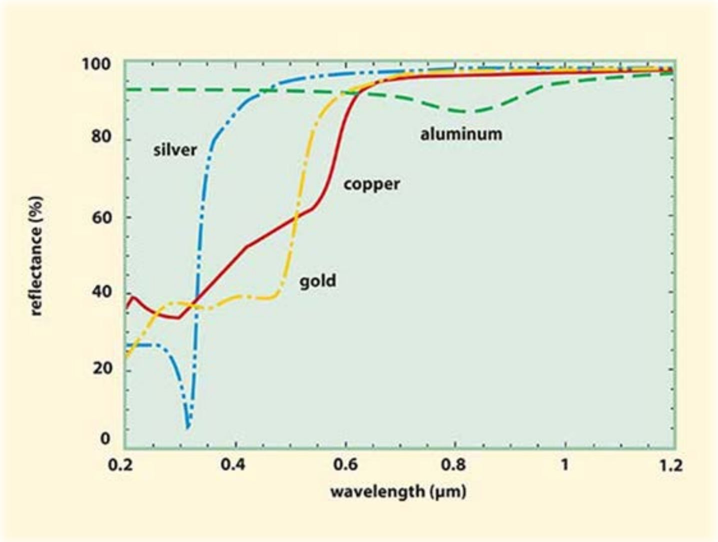
Color Perception



Color Reproduction

How can we store and reproduce colors of objects?

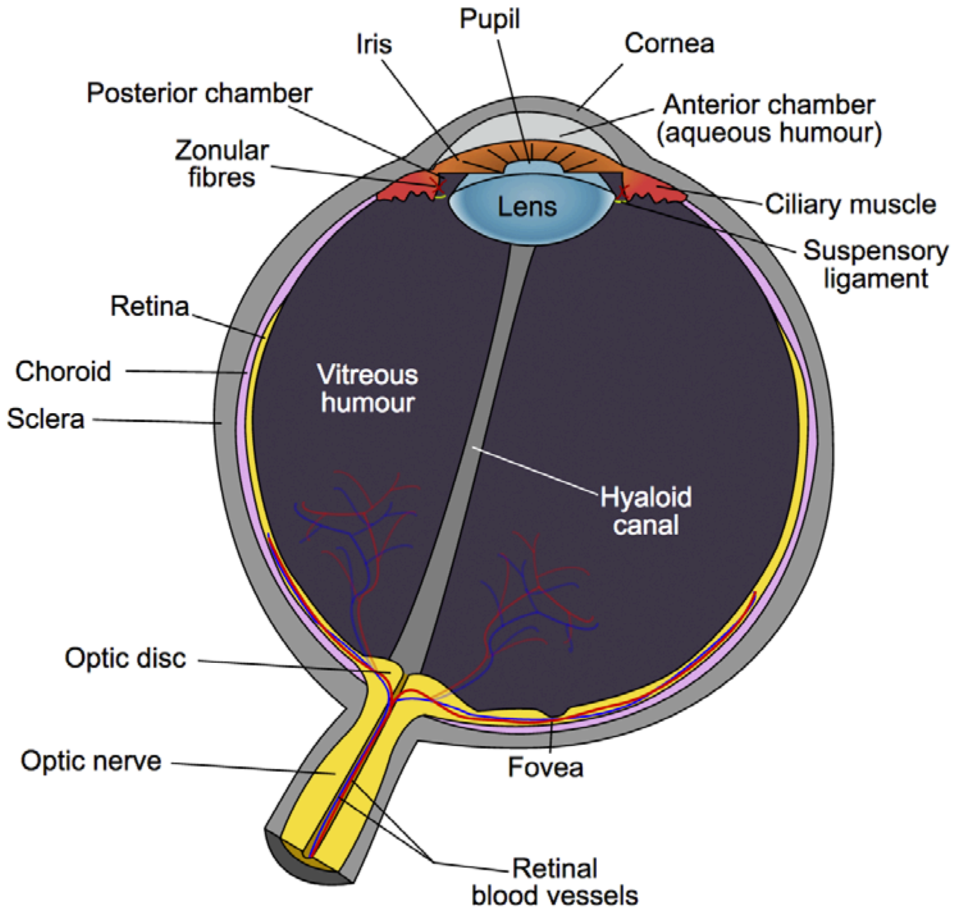
- Naïve approach: store full spectrum



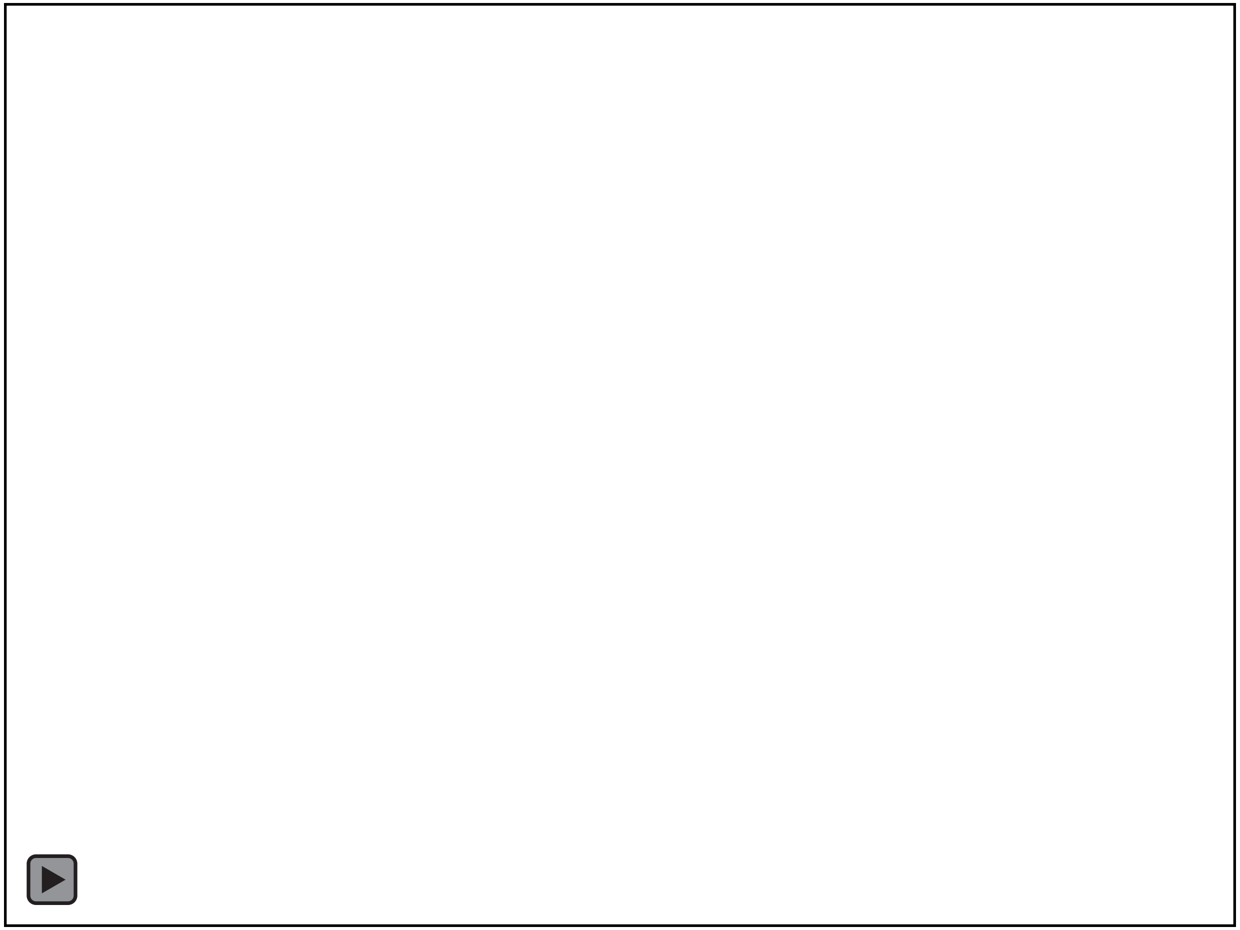
Goal: representation should be as compact as possible

- **Requirement:** any two colors that can be distinguished by humans should have different representations
- **Observation:** any two different colors that cannot be distinguished by humans can have the same representation

Anatomy of the Human Eye

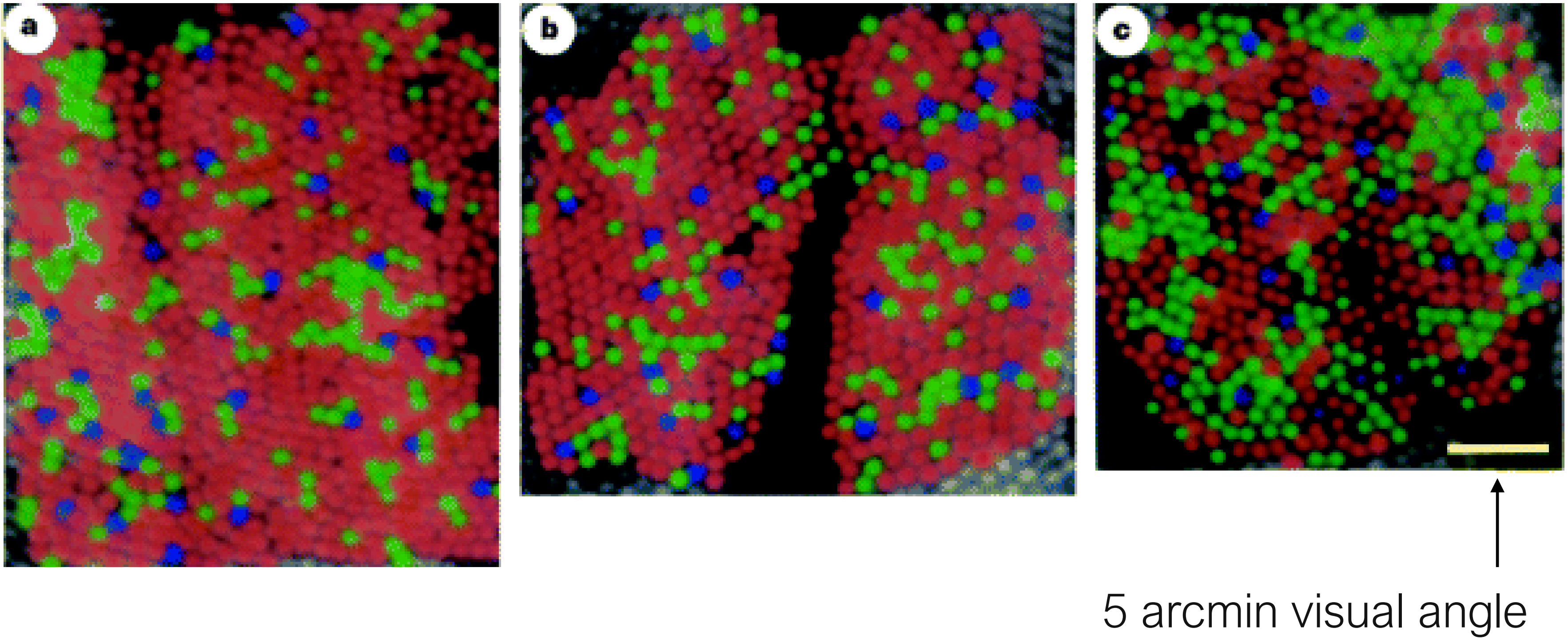


Retina Visualization in VR



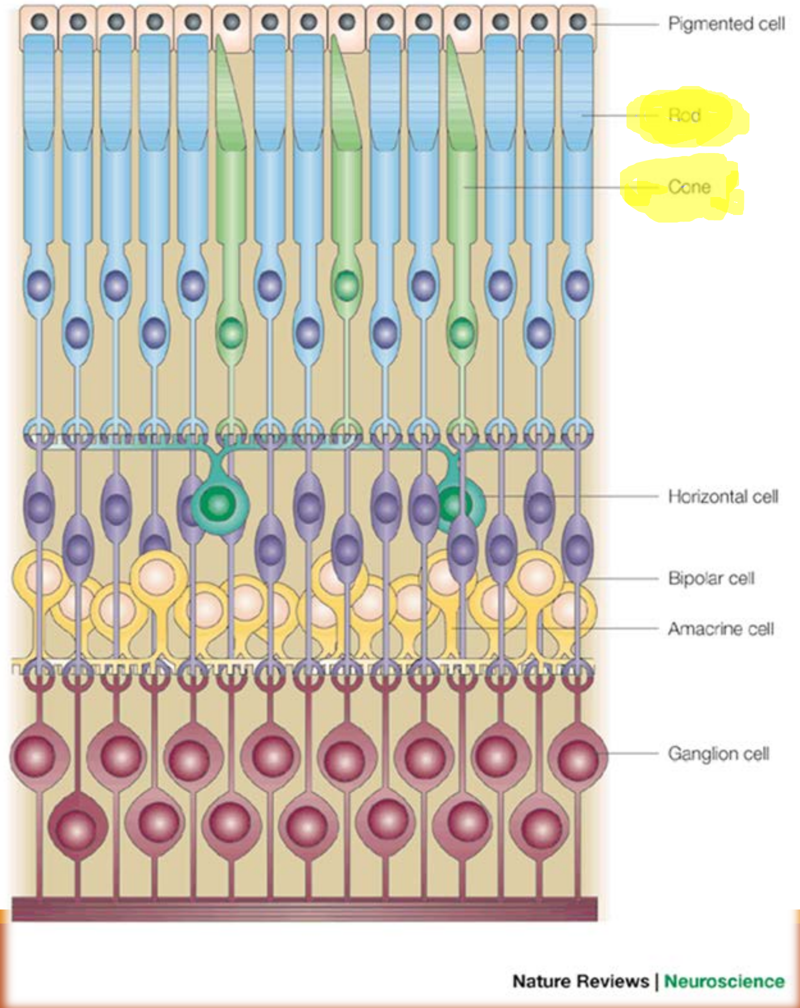
Cones and Rods

Roorda & Williams, 1999, Nature



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

Layers of the Retina



Color Representation

Goal: create minimal set of parameters describing a color sensation.

→ "Coordinate system" for colors

Three types of cones (L,M,S)

→ we expect three parameters to be sufficient (Trichromatic Theory!)

Idea: use L,M,S cone responses!

Tristimulus Experiment

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

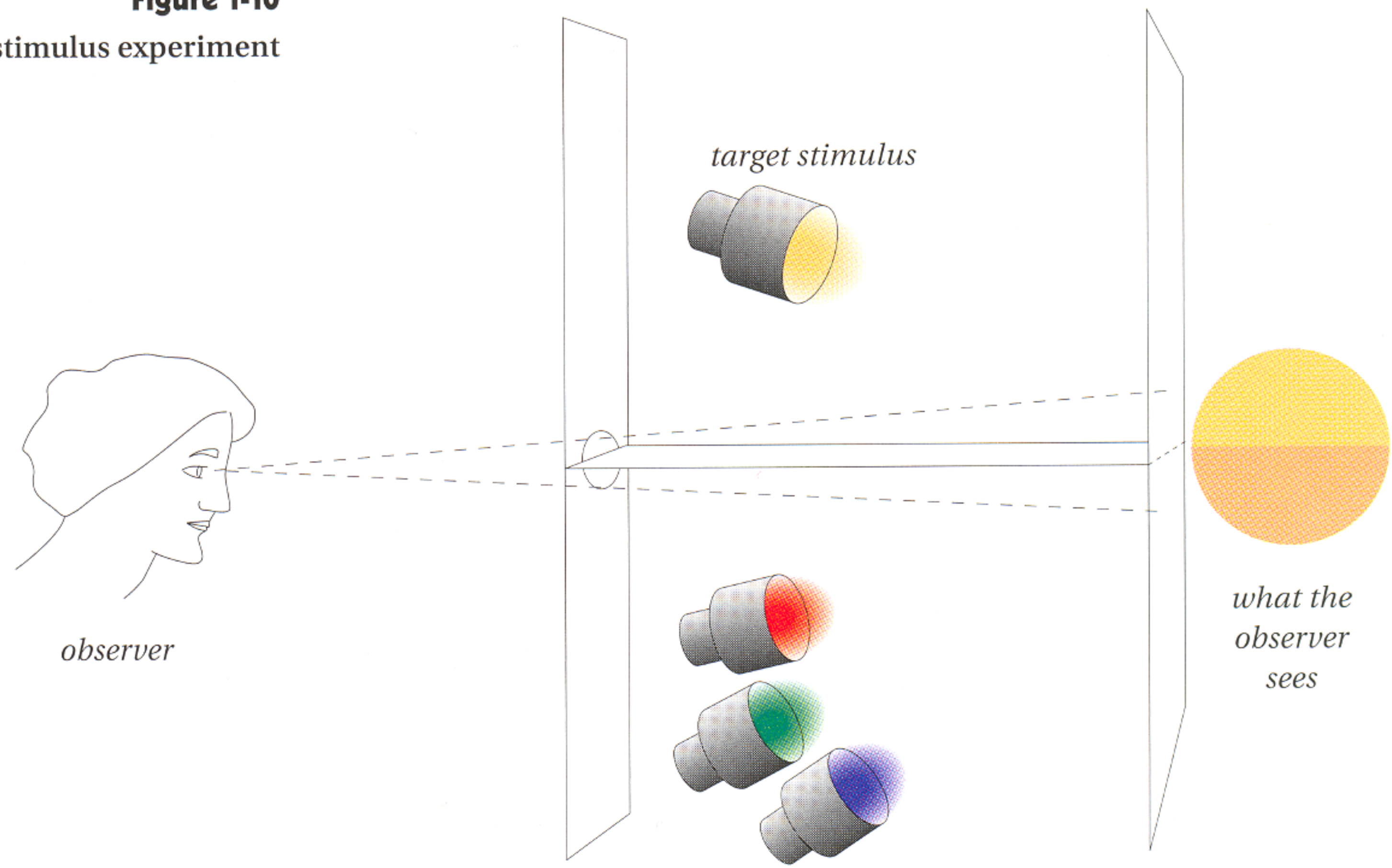
→ tristimulus values

Experimental solution

- First done by CIE (International Commission on Illumination) ca. 1920

Tristimulus Experiment

Figure 1-10
Tristimulus experiment

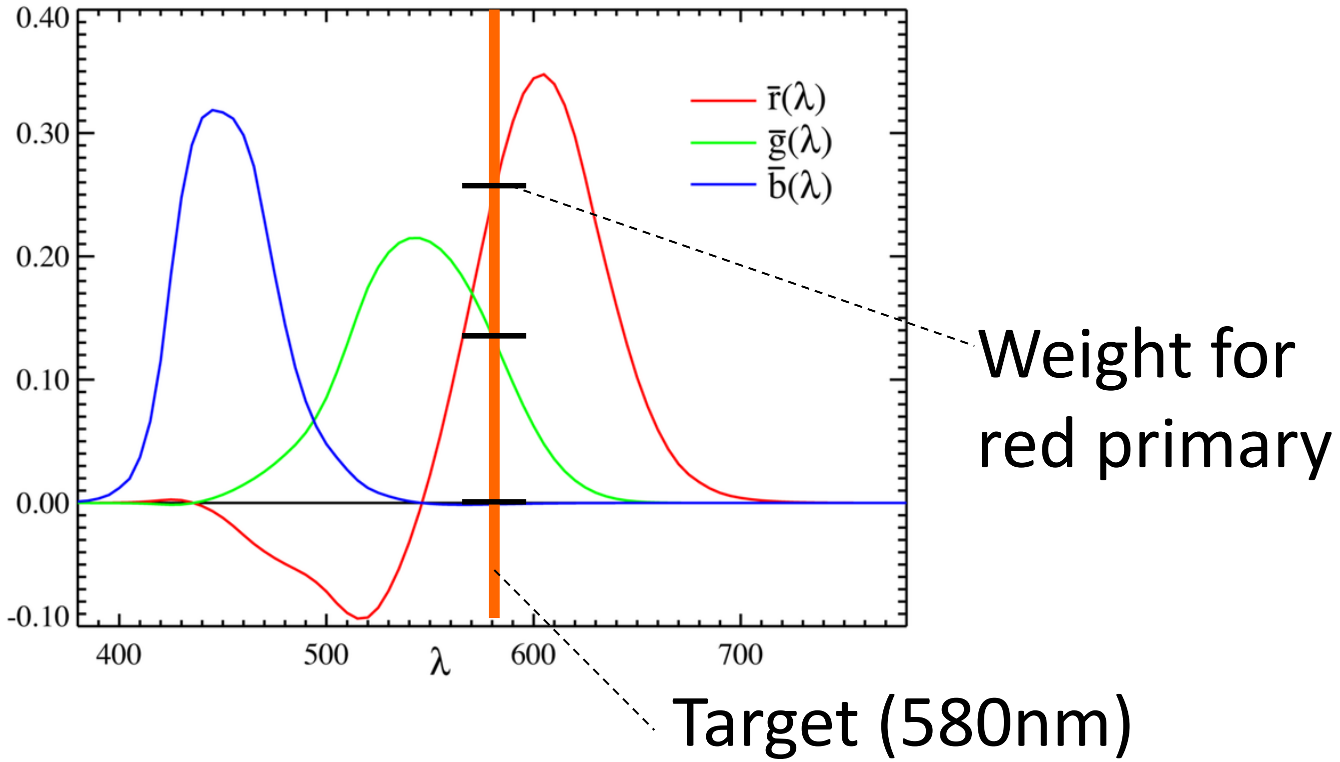


The observer adjusts the intensities of the red, green, and blue lamps until they match the target stimulus on the split screen.

Tristimulus Experiment

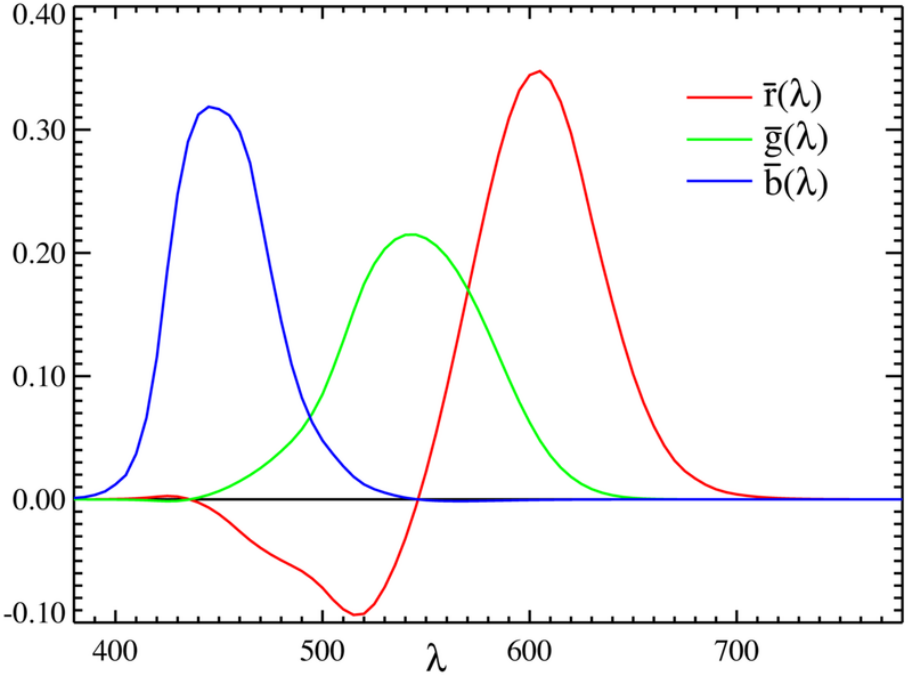
Spectral primary colors were chosen as: blue (435.8nm), green (546.1nm), red (700nm)

Example for target color wavelength of 580nm



Tristimulus Experiment

Matching curves for monochromatic target as measured:



Why negative values?

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

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)

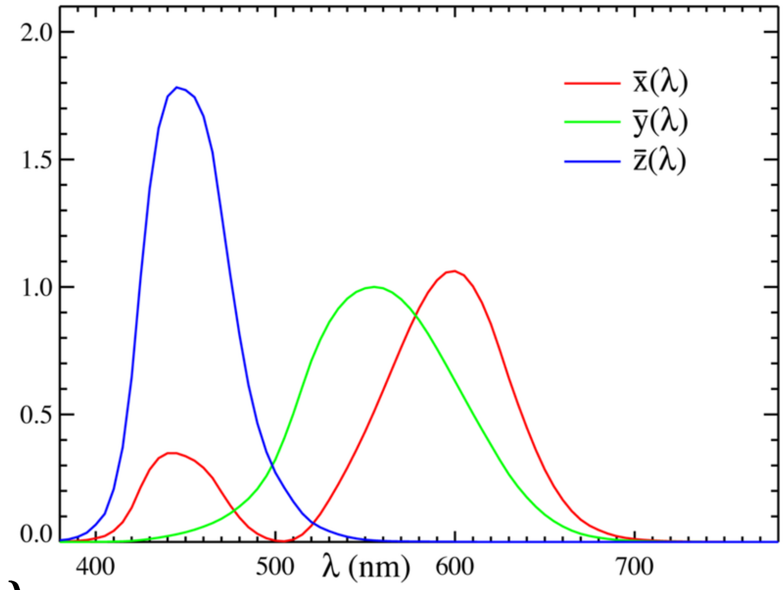
Conversion from CIE RGB to CIE XYZ:

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

CIE XYZ Color Space

Matching curves

No corresponding physical primaries



Tristimulus values

Always positive!

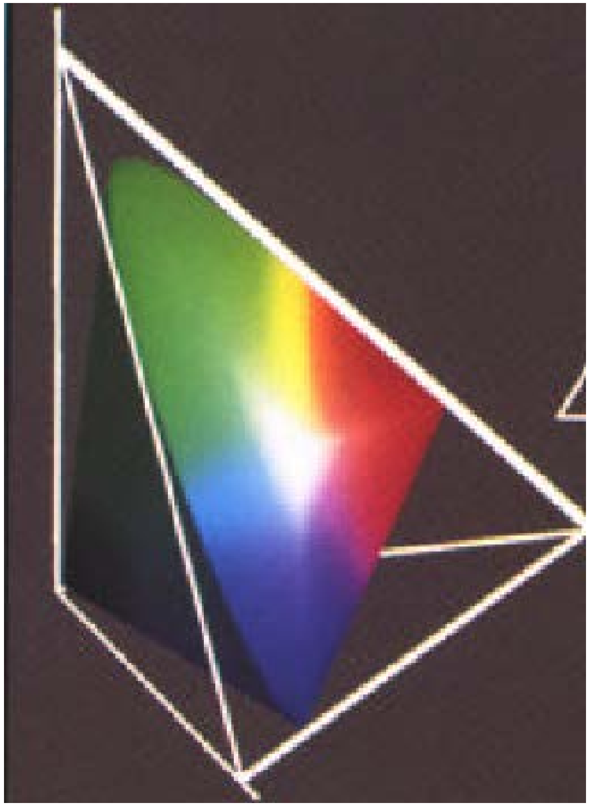
$$X = \int \bar{x}(\lambda) L(\lambda) d\lambda$$
$$Y = \int \bar{y}(\lambda) L(\lambda) d\lambda$$
$$Z = \int \bar{z}(\lambda) L(\lambda) d\lambda$$

3D CIE XYZ Color Space

Visualization

Interpret XYZ as 3D coordinates, plot corresponding color at each point

Many XYZ values are outside of visible color space



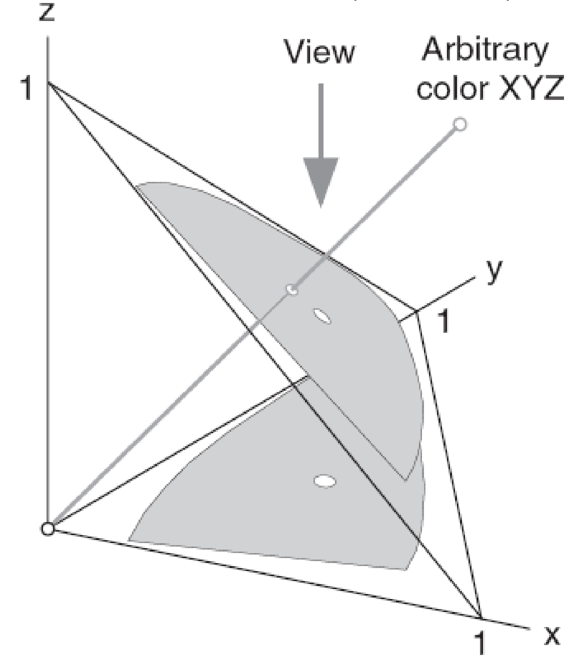
Chromaticity Diagrams

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

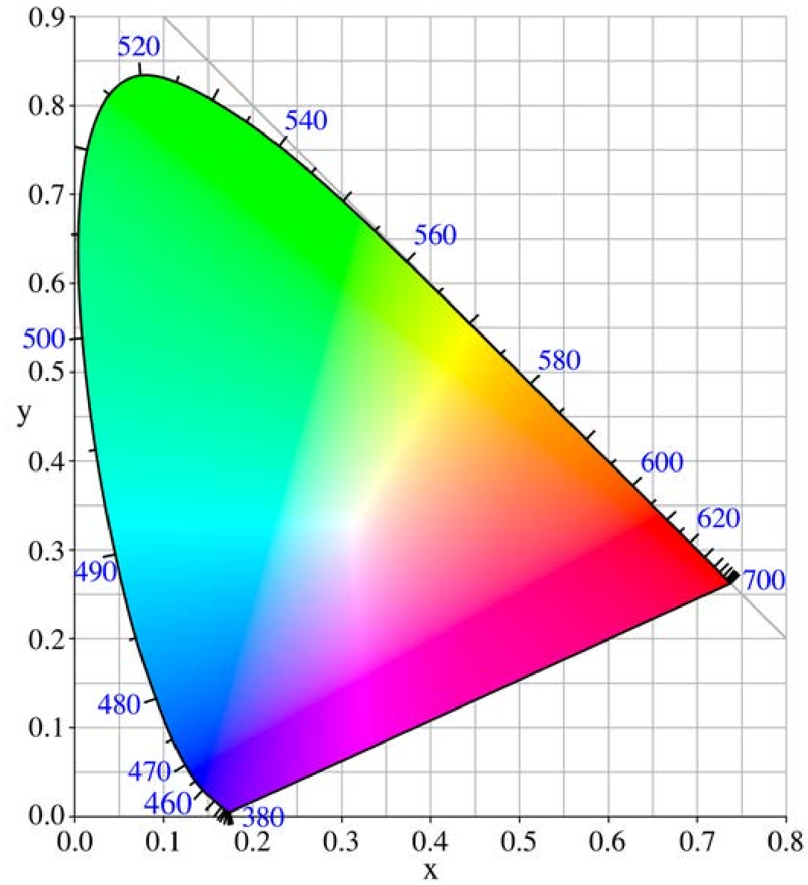
Reconstruct XYZ values from xyY

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

Chromaticity Diagram

Visualizes x,y plane (chromaticities)

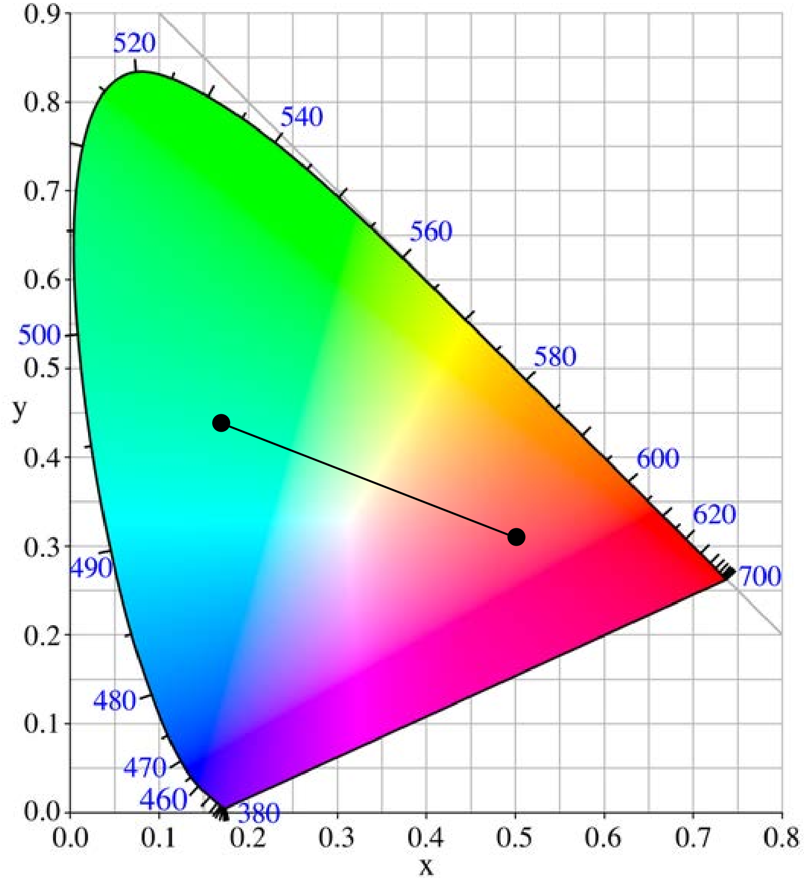
Pure spectral colors on boundary



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

Chromaticity Diagram

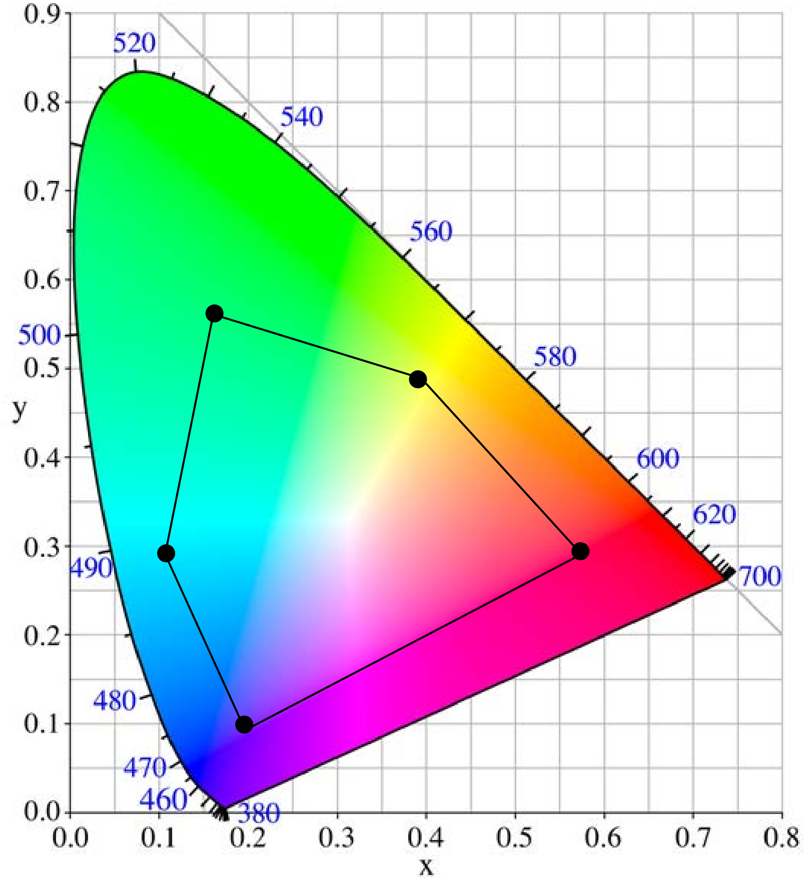
Weighted sum of any two colors lies on line connecting the colors



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

Chromaticity Diagram

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

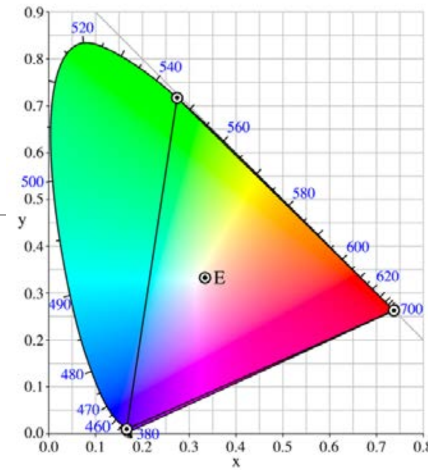


Colors shown do not correspond to colors represented by (x,y) coordinates!

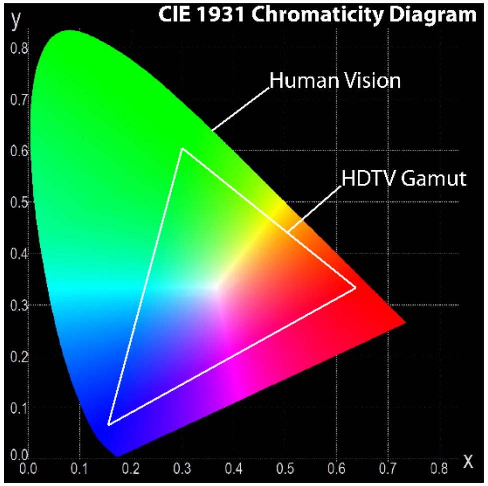
Color Gamut

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 HD TV

Display Gamut

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 there's no way to know!

sRGB

Standard color space, with fixed conversion to CIE XYZ.

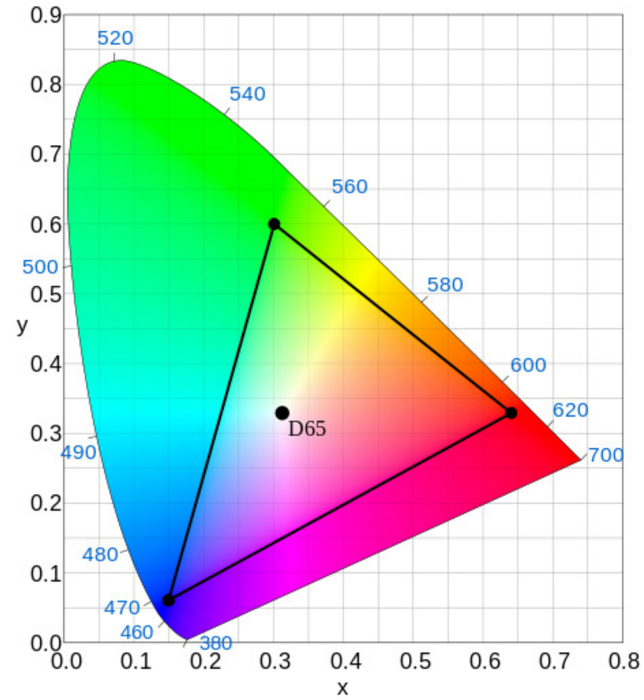
Designed to match RGB values of typical monitor under typical viewing conditions (dimly lit office)

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

sRGB roughly corresponds to 2.2 gamma correction.

sRGB is supported by OpenGL as

- sRGB framebuffers (since OpenGL 3.0)



sRGB color gamut

Color Calibration

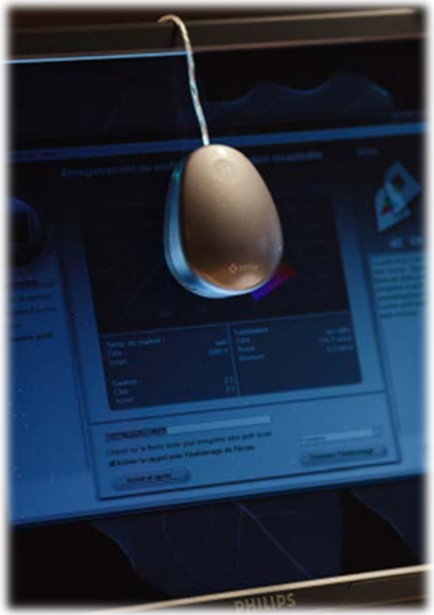
The same RGB values on one monitor will look different than on another

→ Color calibration

Standard for digital publishing, printing, photography.

Will become critical for photo-realistic AR.

But: not important to most consumers as long as colors on screen do not have to match any others.



Display Calibration

Human Visual System

Overview

Color Representation

Field of View

Spatial Resolution

Temporal Resolution

Dynamic Range

Accommodation Range

Colors

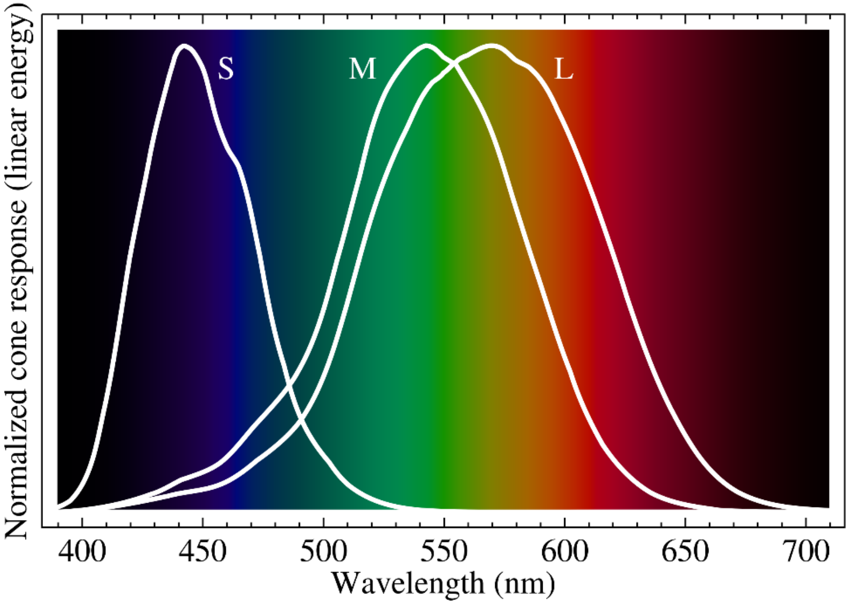
How many colors can the human eye distinguish?

About 10 million

But not evenly distributed in red, green and blue

32 bits can store 2 billion colors

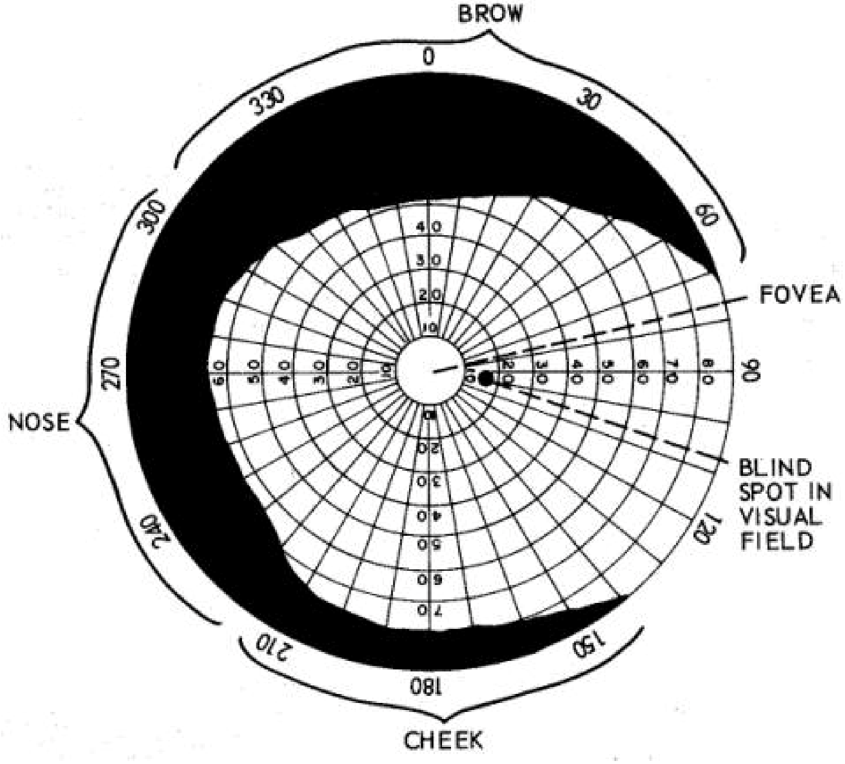
→ 32 bits storage per pixel

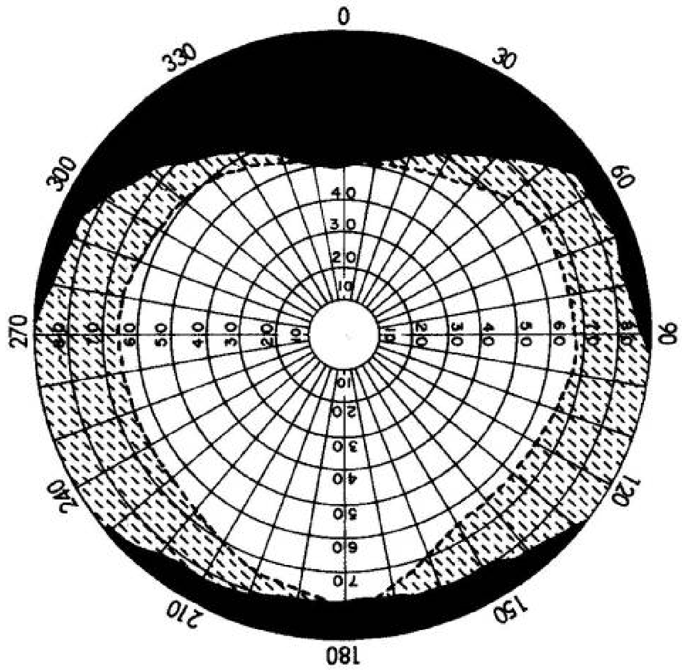


Field of View

Monocular visual field

Binocular visual field





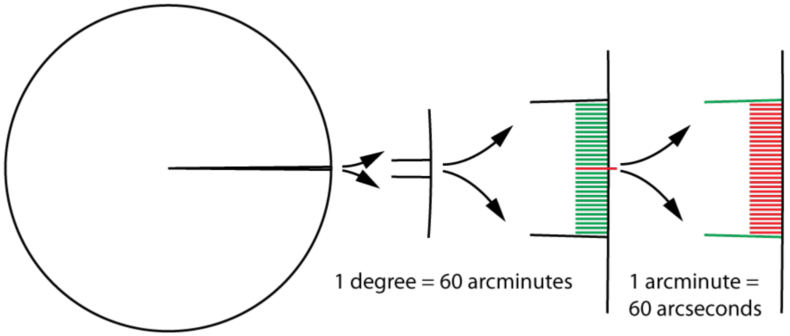
Ruch & Fulton, 1960

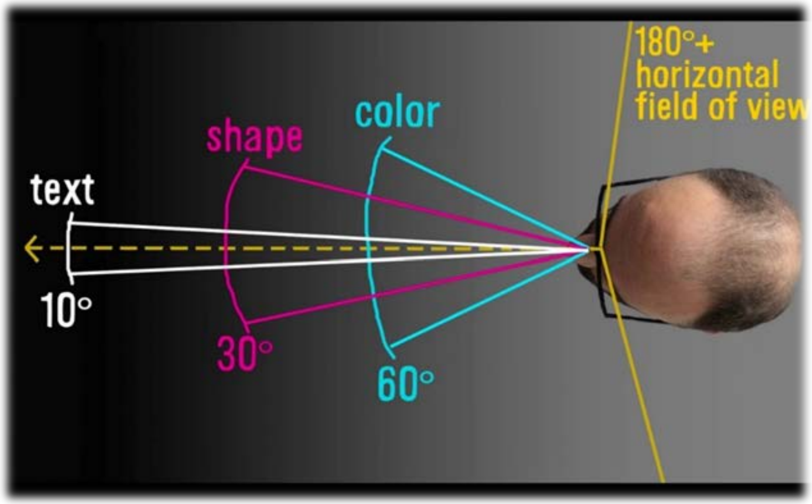
Horizontal field of view: ~145° per eye
Vertical field of view: ~135°

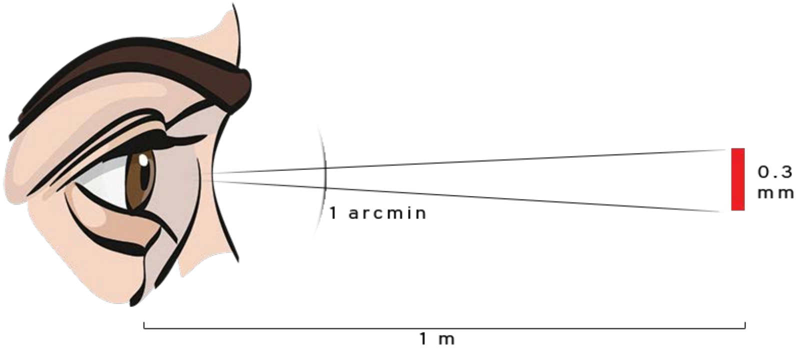
Spatial Resolution

~150 pixels/degree in center of field of view

Less towards edge







Retina VR Display

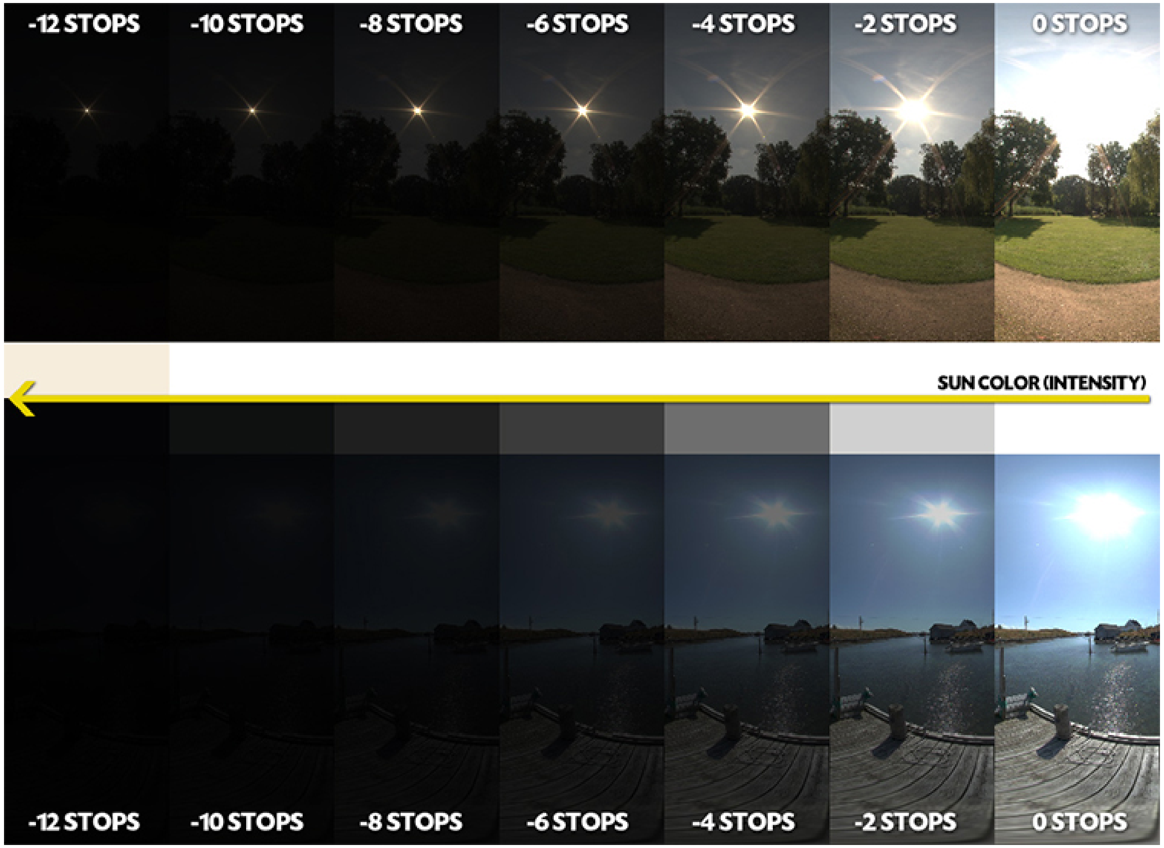
- Resolution per eye:
  - 145° x 135° field of view at 150 pixels/degree resolution

    → 21,750 x 20,250 pixels = 440 Mpixels
- For two eyes (stereoscopic vision):
  - 2 x 440 Mpixels = 880 Mpixels

Temporal Resolution

~60-150 Hz (varies with brightness)

Dynamic Range



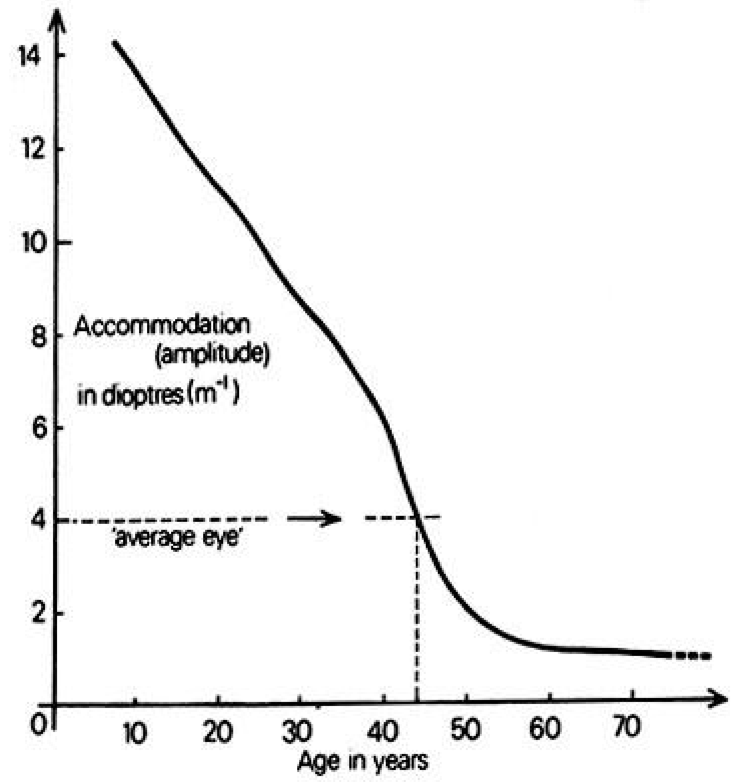
100:1 (retina), 1 billion:1 (with iris)

Accommodation Range

Age dependent

An 'average eye' likes to have things 25 cm away, or farther, for comfortable vision.

Young children can accommodate down to about 7 cm.



Summary

- Colors: 32 bits per pixel
- Horizontal field of view: ~145° per eye
- Vertical field of view: ~135°
- Pixel resolution: 150 pixels/degree
- Stereoscopic vision
- Temporal resolution: ~60-150 Hz (varies with brightness)
- Dynamic range: 100:1 (retina), 1 billion:1 (with iris)
- Accommodation range: ~7cm to infinity