Visual Computing Exercise 7: Light & Colors

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Exercise 7 - Light and Colors

- Theoretical – no programming
- Good for the exam
- Should be solved individually
- Goals
  - Definitions
  - Color Spaces
  - CIE chromaticity diagram

DEFINITIONS

Measuring Light

- Luminous Flux *F* [lumen]

Perceived power of light

$$F = const \cdot \int_{380nm}^{780nm} P(\lambda)V(\lambda)d\lambda$$

$P(\lambda)$: Relative Spectral Power Density

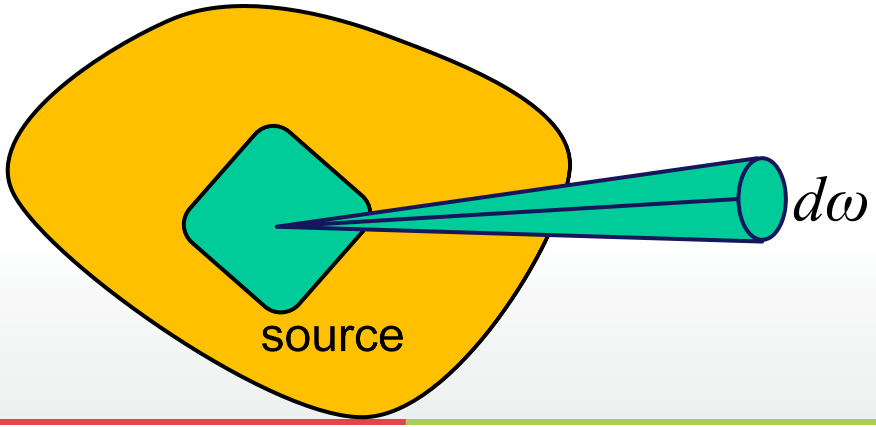
$V(\lambda)$: Relative Spectral Sensitivity

$const : 683 \frac{\text{lm}}{\text{W}}$

Measuring Light

- Luminous Intensity *I* [candela]

$$I = \frac{dF}{d\omega} \quad F = \int I d\omega$$



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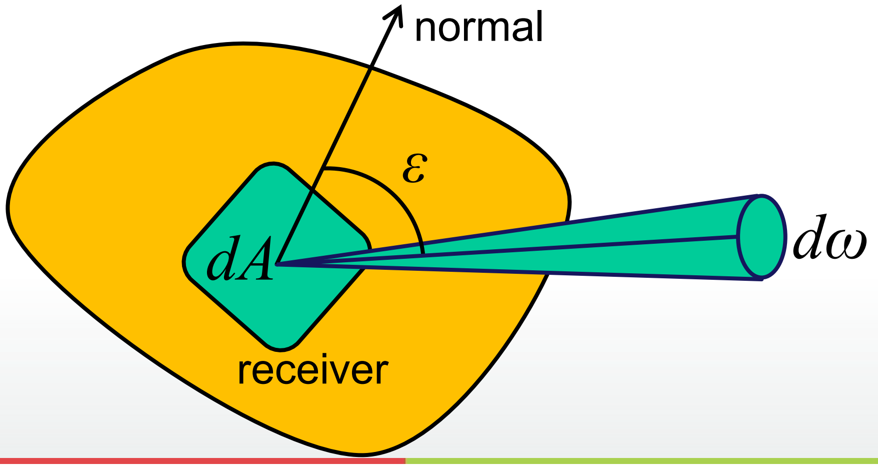
Measuring Light

- Luminance Y [candela/m^2]

$$Y = \frac{d^2 F}{dA \cos \varepsilon \, d\omega} \qquad I = \int Y dA \quad F = \iint Y dA d\omega$$



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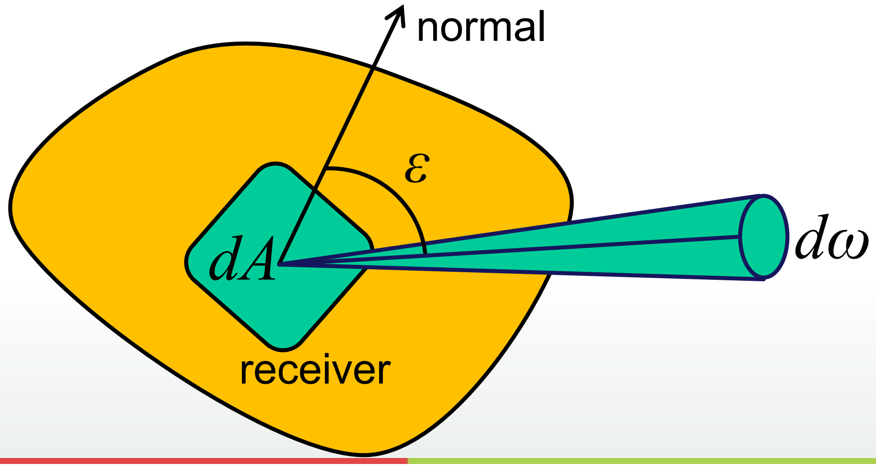
Measuring Light

- Illumination *B* [lux]

$$B = \frac{dF}{dA}$$



Luminous Flux *F* [lumen]

$$F = c \cdot \int_{380nm}^{780nm} P(\lambda) V(\lambda) d\lambda$$

Luminous Intensity *I* [candela]

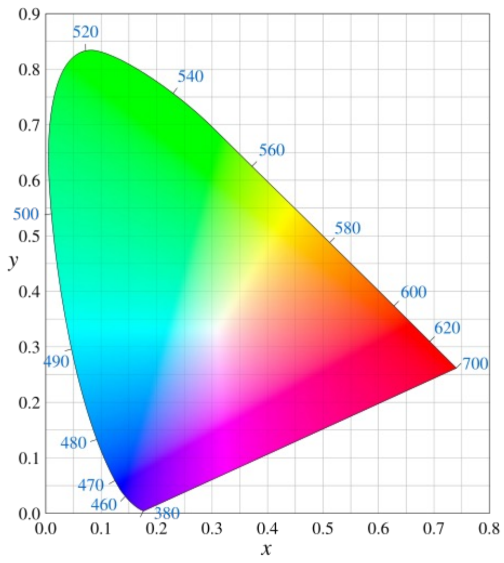
$$I = \frac{dF}{d\omega}$$

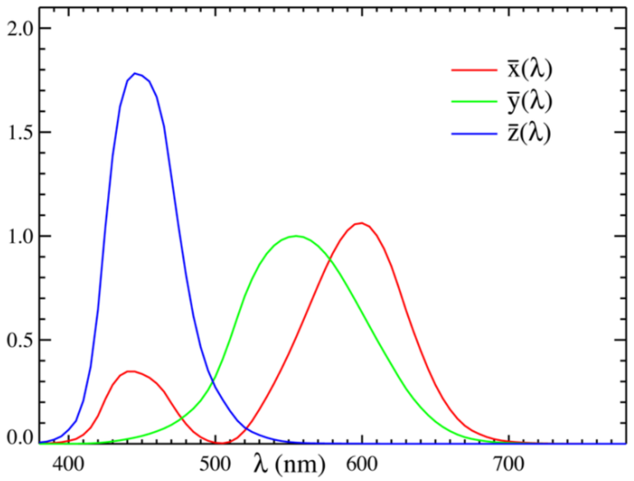
Luminance *Y* [candela / m^2]

$$Y = \frac{d^2 F}{dA \cos \varepsilon \, d\omega}$$

Illumination *B* [lux]

$$B = \frac{dF}{dA}$$





THE CIE CHART

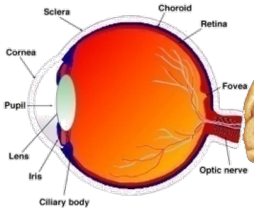
Overview

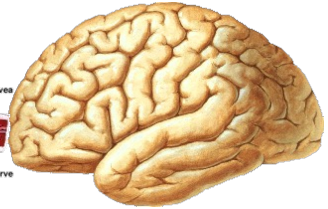
- What is color?

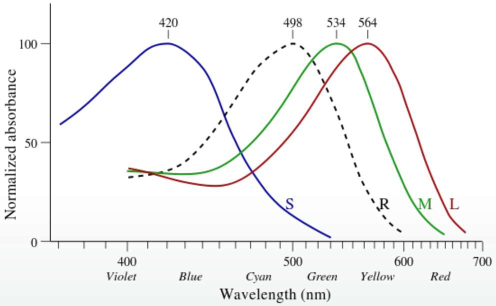
Perception

Real World

vs.



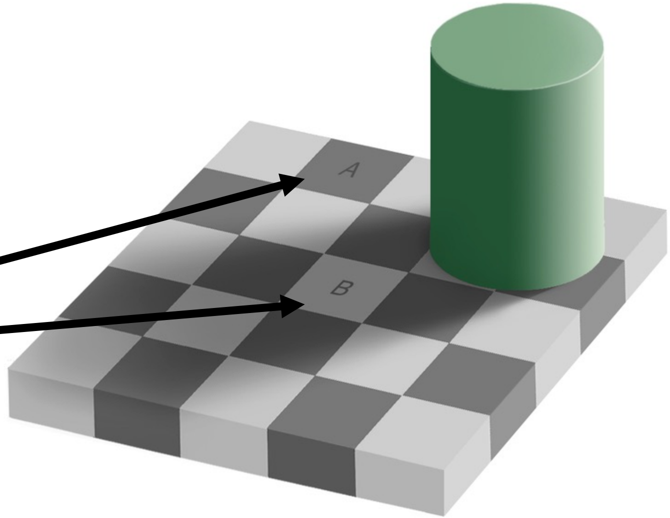




Overview

- What is color?

Have the
same color



Overview

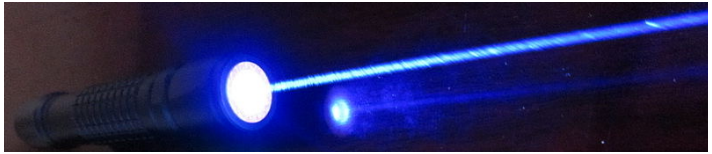
- Light can be described by frequencies

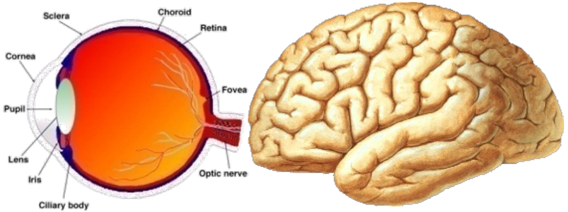
$$P(\lambda)$$

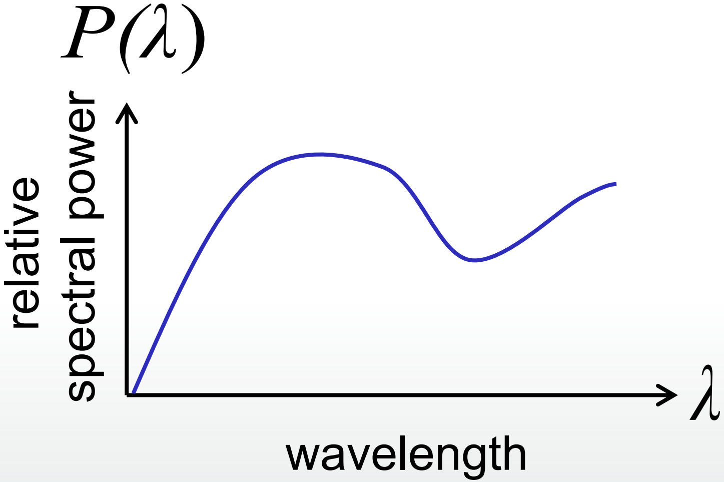
- Light containing certain frequencies is perceived as colors

Overview

- What is the mapping from frequencies to colors?







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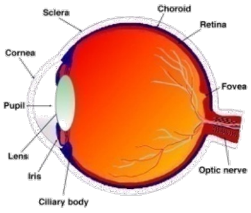
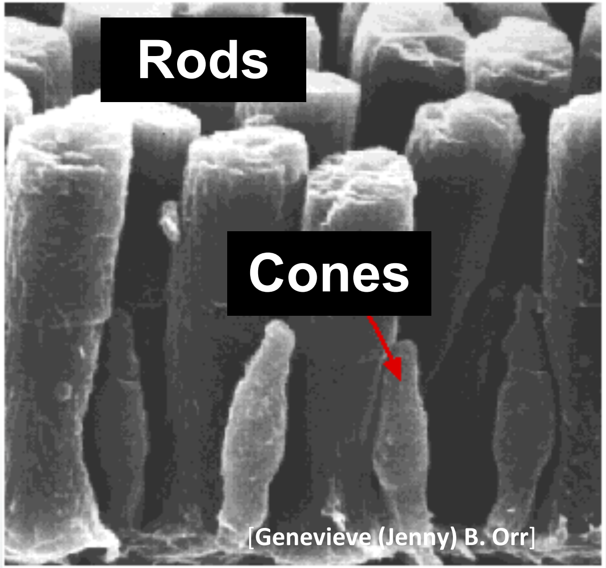
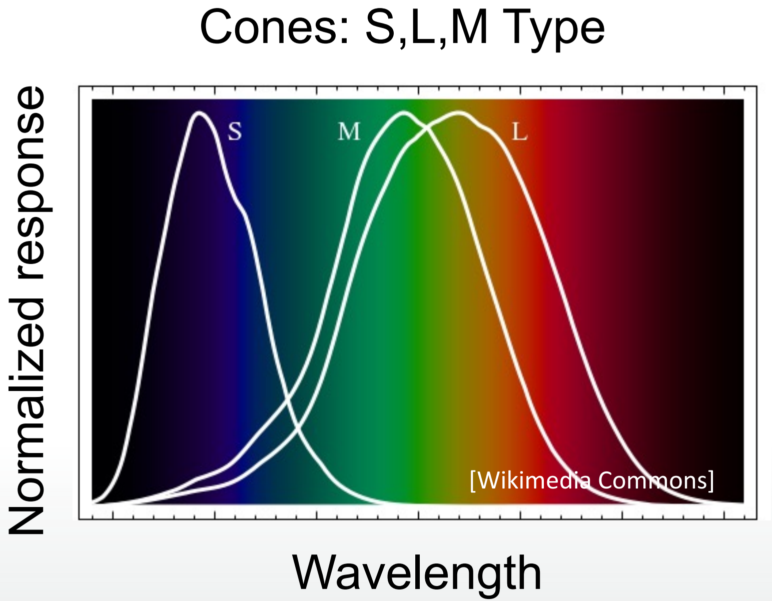
Overview

- The human eye has photosensitive cells

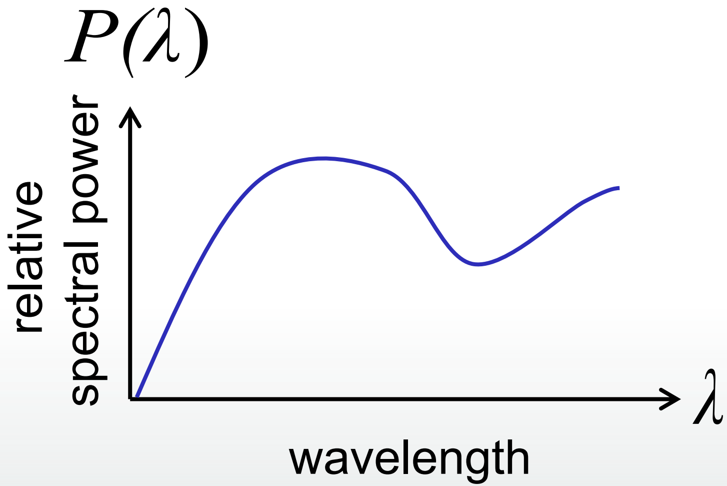






Overview

- Only three cone cell types
- Humans project the light signal into R^3



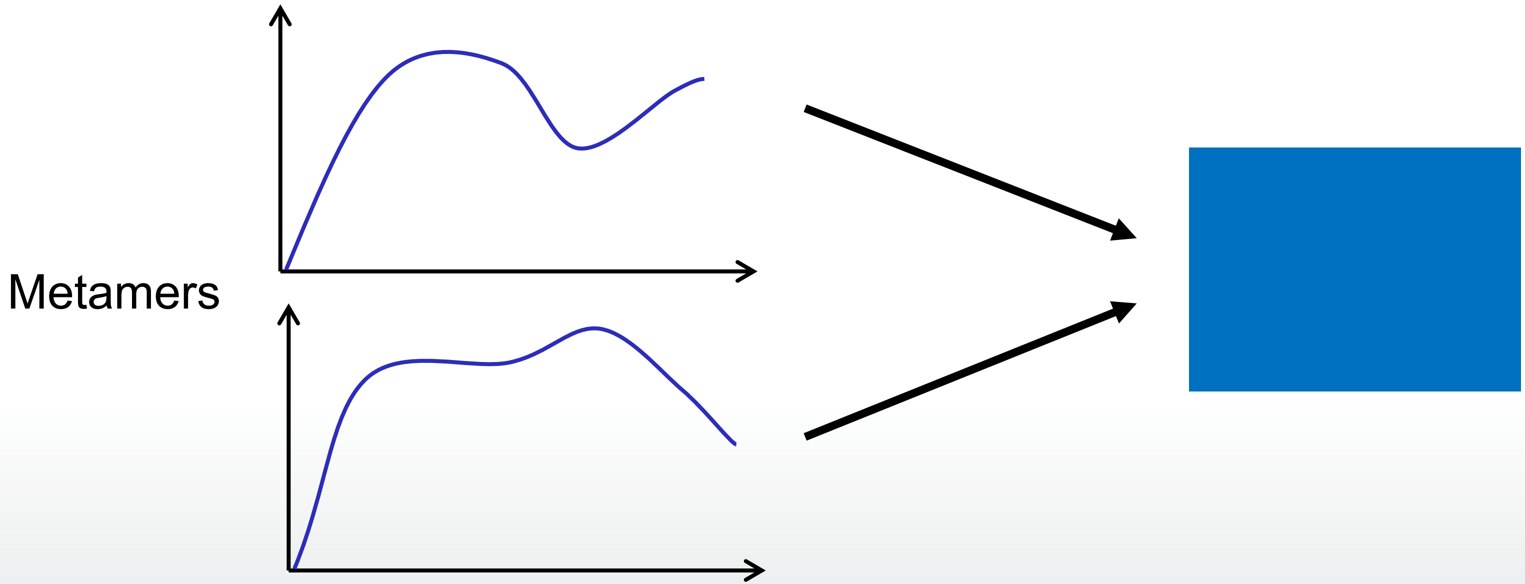
$$\int_{380nm}^{780nm} P(\lambda)\, S(\lambda)\, d\lambda$$

$$\int_{380nm}^{780nm} P(\lambda)\, L(\lambda)\, d\lambda$$

$$\int_{380nm}^{780nm} P(\lambda)\, M(\lambda)\, d\lambda$$

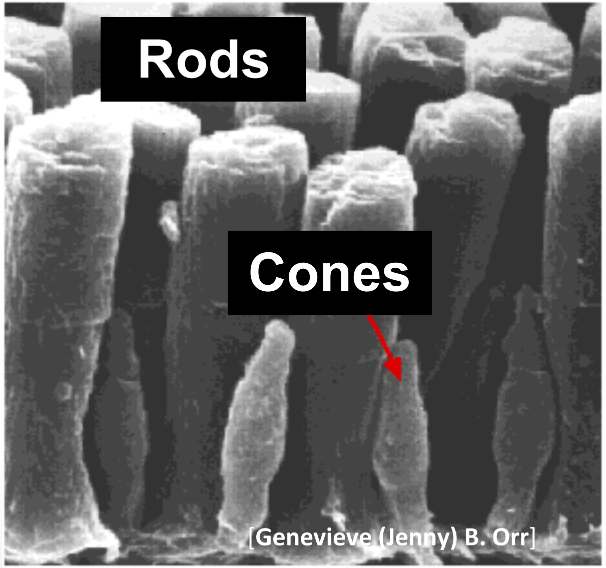
Overview

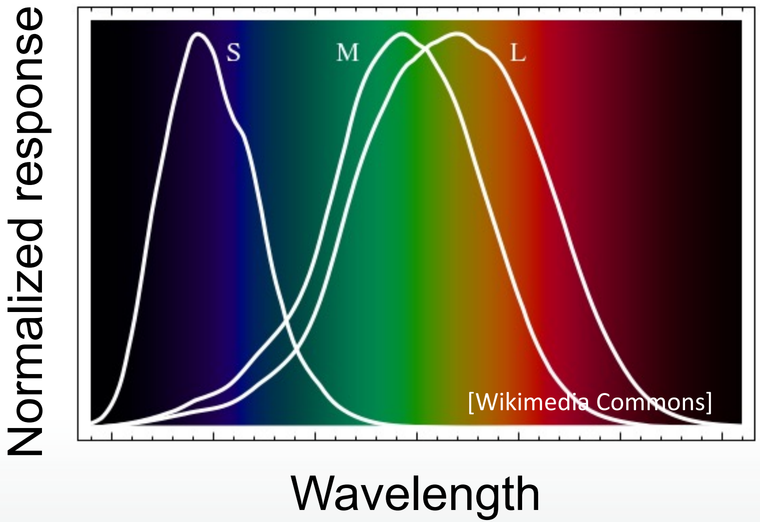
- Light with different spectrum can map to the same color: metamers



Overview

- How to determine these responses?





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Experiment (CIE, 1931)

Primaries (single frequency light)

$r(\lambda)=\delta(\lambda-700)$

λ

700nm

$g(\lambda)=\delta(\lambda-546)$

λ

546nm

$b(\lambda)=\delta(\lambda-435)$

λ

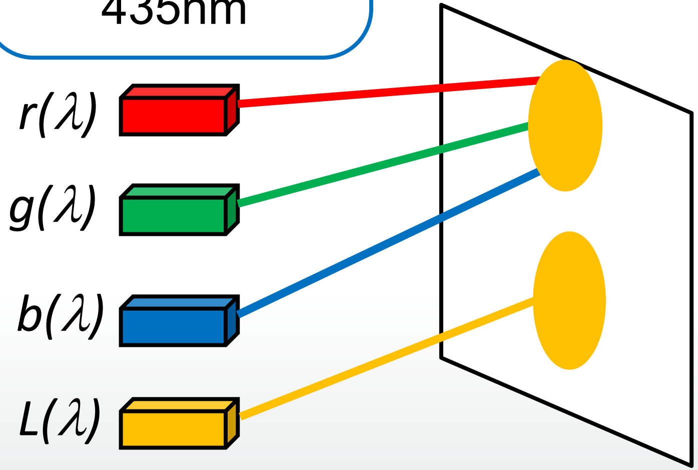
435nm

Reference

$L(\lambda)=\delta(\lambda-v)$

λ

v



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Experiment (CIE, 1931)

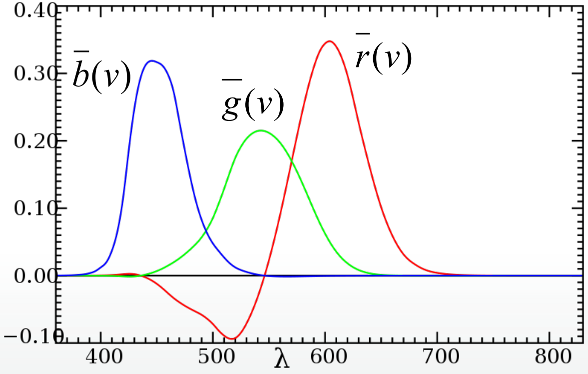
Perceptual equivalence

Primaries

Reference

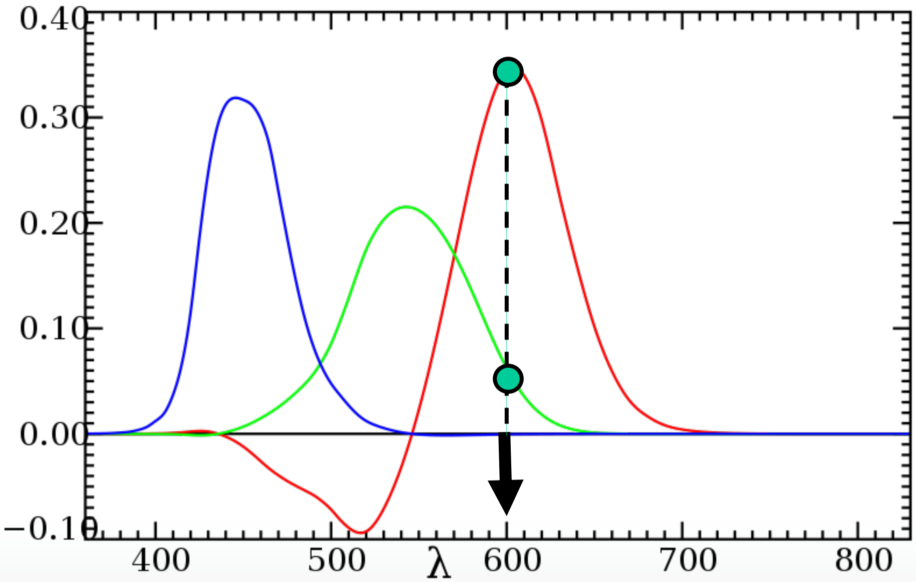
$$\delta(\lambda - v) \triangleq \bar{r}(v)r(\lambda) + \bar{g}(v)g(\lambda) + \bar{b}(v)b(\lambda)$$

Color matching functions



Experiment (CIE, 1931)

Experient gives: how much of each primary is required for the given reference



Reference wavelength

Experiment (CIE, 1931)

For arbitrary spectral power density function P(λ)

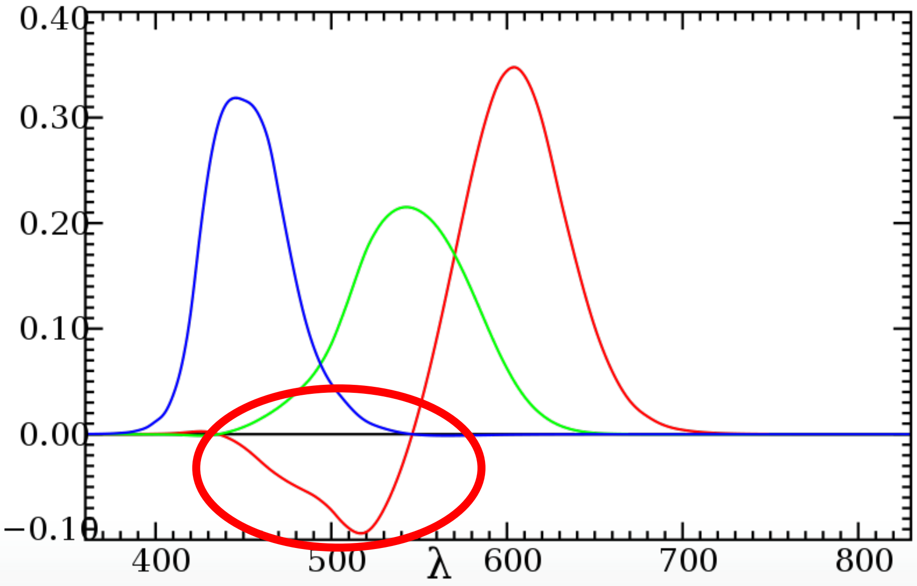
$$P(\lambda)=\int P(v)\delta(\lambda-v)dv \hat{=} \int P(v)(\bar{r}(v)r(\lambda)+\bar{g}(v)g(\lambda)+\bar{b}(v)b(\lambda))dv$$

$$=\underbrace{(\int P(v)\bar{r}(v)dv)}_{R}\cdot r(\lambda)+\underbrace{(\int P(v)\bar{g}(v)dv)}_{G}\cdot g(\lambda)+\underbrace{(\int P(v)\bar{b}(v)dv)}_{B}\cdot b(\lambda)$$

Hence, any color can be generated

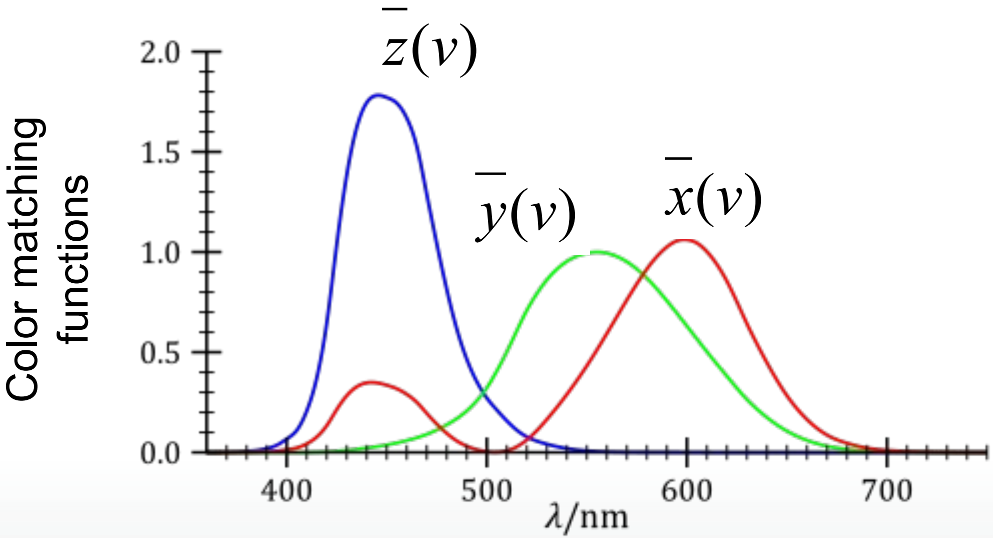
Experiment (CIE, 1931)

Problem: negative color matching function. Cannot emit negative light!



Experiment (CIE, 1931)

Solution: new primaries and color matching functions
But imaginary primaries



Experiment (CIE, 1931)

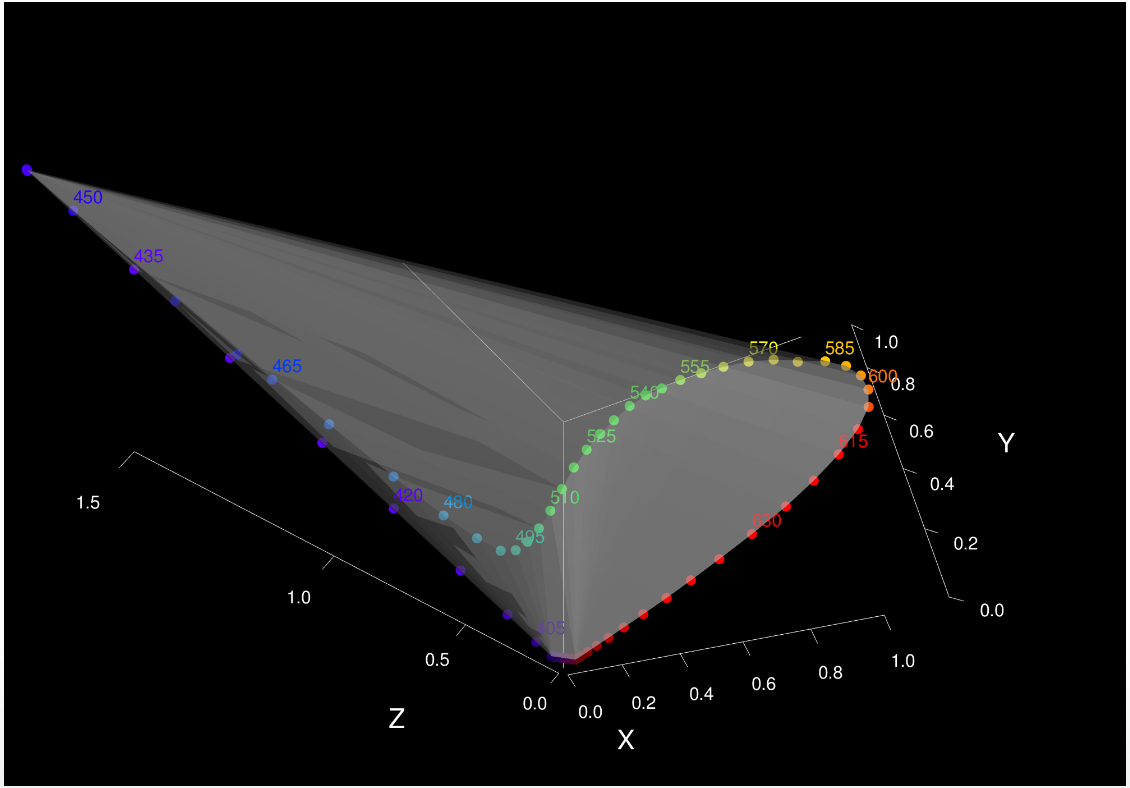
Solution: new primaries and color matching functions
They define the CIE XYZ space

$$X = \int_{380nm}^{780nm} P(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int_{380nm}^{780nm} P(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = \int_{380nm}^{780nm} P(\lambda)\bar{z}(\lambda)d\lambda$$

CIE XYZ in 3D



source: wiki commons

The CIE Chromacity Diagram

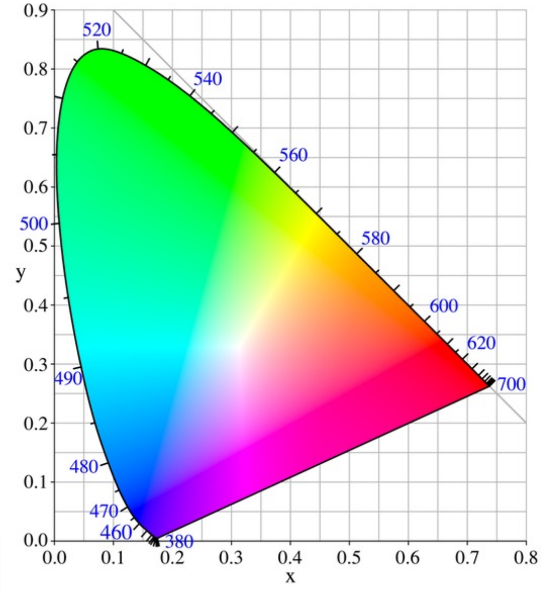
- X, Y, Z contain luminance
- Normalize to get chromacity: x, y, Y

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

- Plot in 2D: The CIE Chromacity Diagram

The CIE Chromacity Diagram

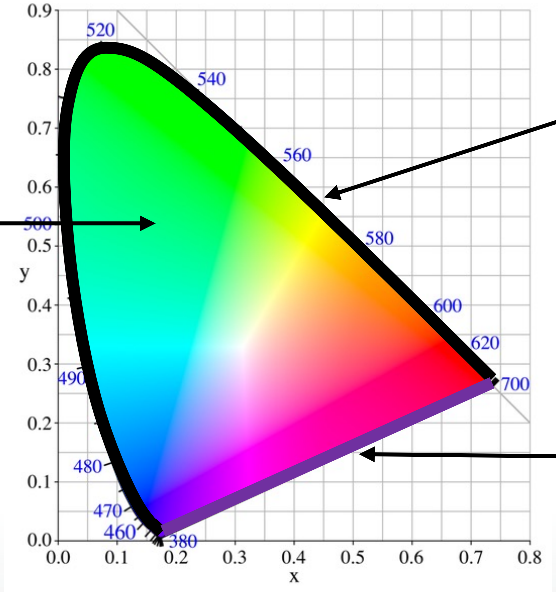
- Plot in 2D: the CIE Chromacity Diagram



The CIE Chromacity Diagram

- Plot in 2D: the CIE Chromacity Diagram

Color

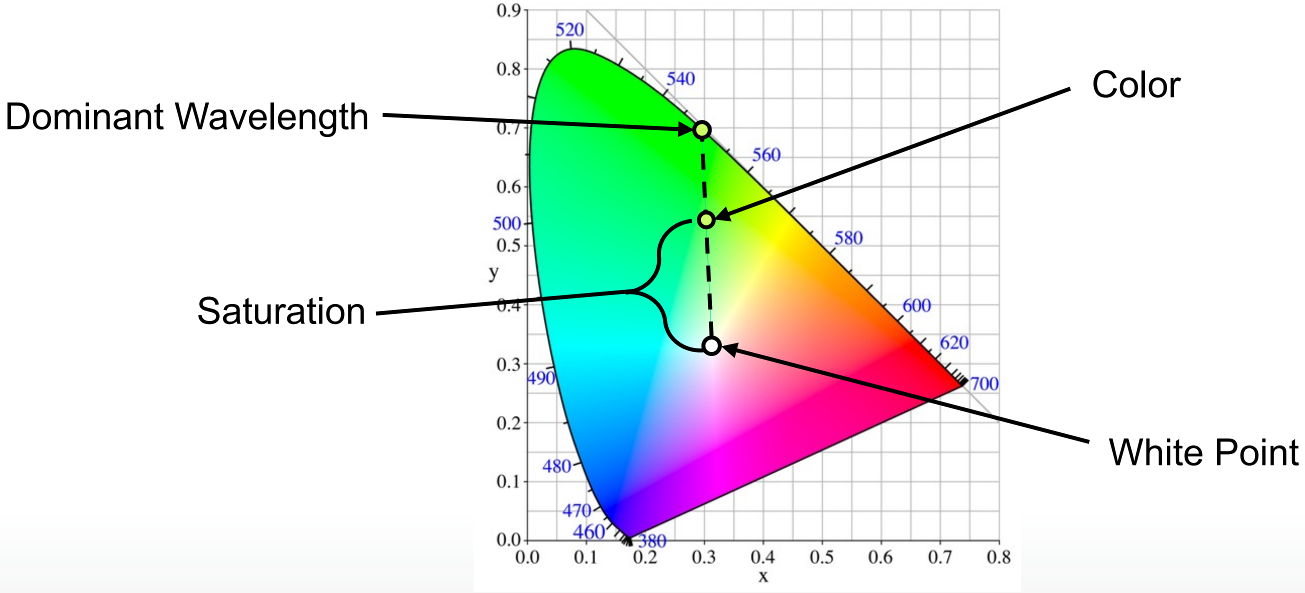


Boundary: colors of single wavelength light

Boundary: purple line

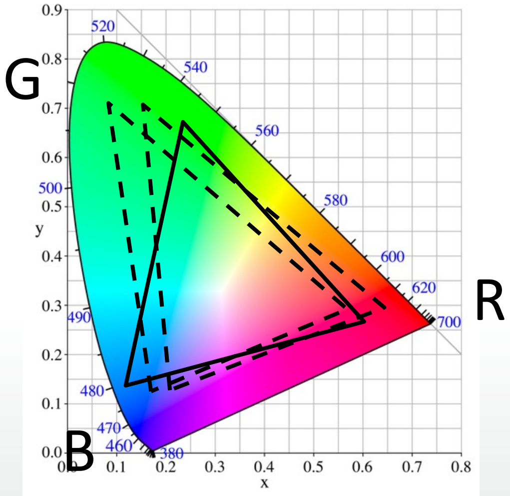
The CIE Chromacity Diagram

- Plot in 2D: the CIE Chromacity Diagram



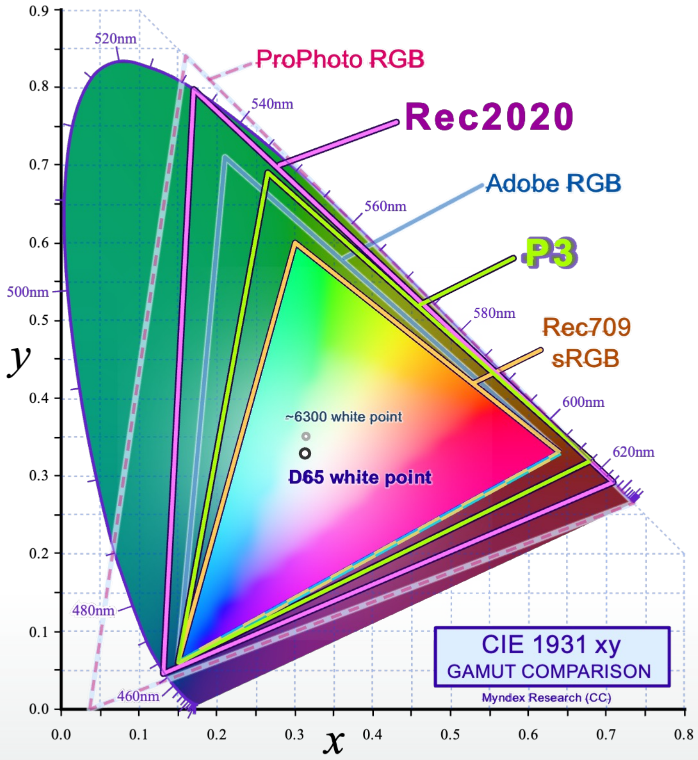
CIE XYZ and RGB

- While CIE XYZ is a canonical color space, images/devices rarely work directly with XYZ.
- RGB primaries dominate the industry, this is because we can produce RGB light sources (LEDs, phosphorus for CRT monitors, filters, etc)



Standard RGB (sRGB) – Rec. 709

- In 1996, Microsoft and HP defined a set of “standard” RGB primaries.
- This was considered an RGB space achievable by most devices at the time.



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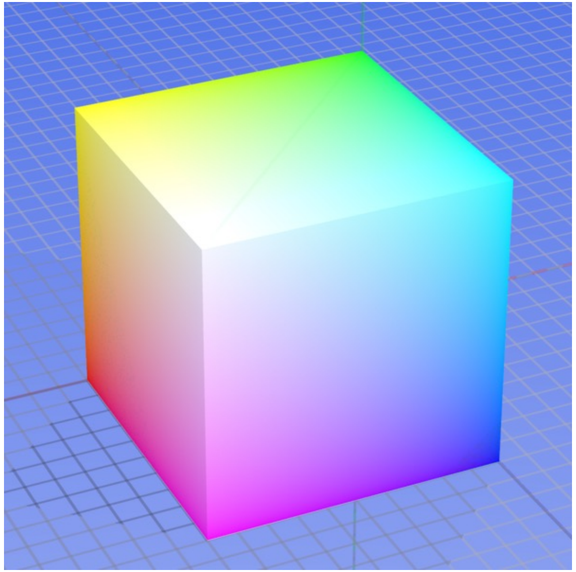
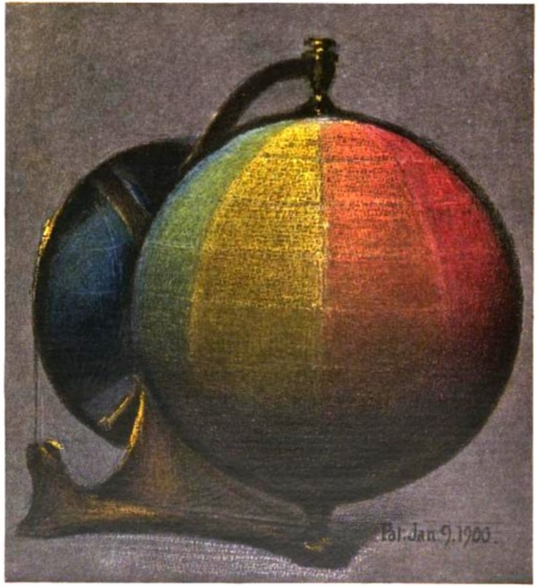
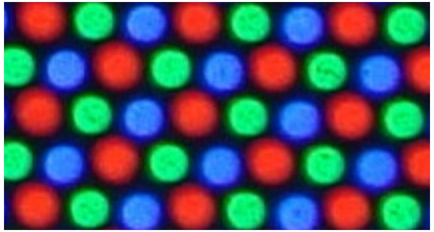




A BALANCED COLOR SPHERE

OTHER COLOR SPACES

RGB and XYZ



	R	**G**	**B**
x	x_R=0.64	x_G=0.30	x_B=0.15
y	y_R=0.33	y_G=0.60	y_B=0.06

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} x_R C_R & x_G C_G & x_B C_B \\ y_R C_R & y_G C_G & y_B C_B \\ (1 - x_R - y_R)\, C_R & (1 - x_G - y_G)\, C_G & (1 - x_B - y_B)\, C_B \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

White point calibration

- Find the parameters C_R, C_G, C_B

White point specification

RGB White point = $(1, 1, 1)^T$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} x_R C_R & x_G C_G & x_B C_B \\ y_R C_R & y_G C_G & y_B C_B \\ (1 - x_R - y_R)\, C_R & (1 - x_G - y_G)\, C_G & (1 - x_B - y_B)\, C_B \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}$$

CMY(K) – Substractive for printers

- Cyan, Magenta and Yellow as basis vectors
- Key as additional color

$$\begin{pmatrix} C \\ M \\ Y \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} - \begin{pmatrix} R \\ G \\ B \end{pmatrix} \quad \text{resp.} \quad \begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} - \begin{pmatrix} C \\ M \\ Y \end{pmatrix}$$

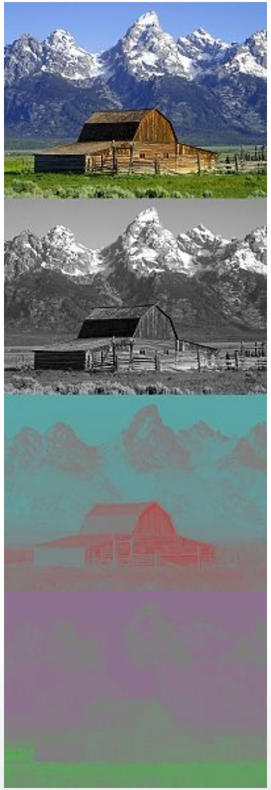
YIQ – Perceptual

- NTSC US-color TV standard
- Y as luma information

  (used by b/w televisions)
- I for in-phase (orange-blue)

  (natural skin color)
- Q for quadrature (purple-green)
- Bandwidth partitioning

  (2.4MHz, 1.5MHz, 0.6MHz)
- Check lecture slides for the linear transformation from RGB



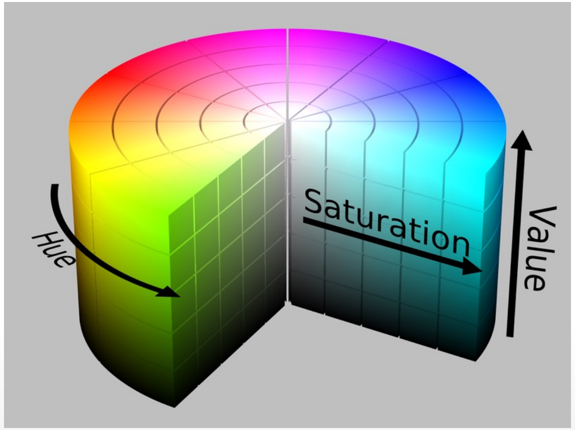
Y

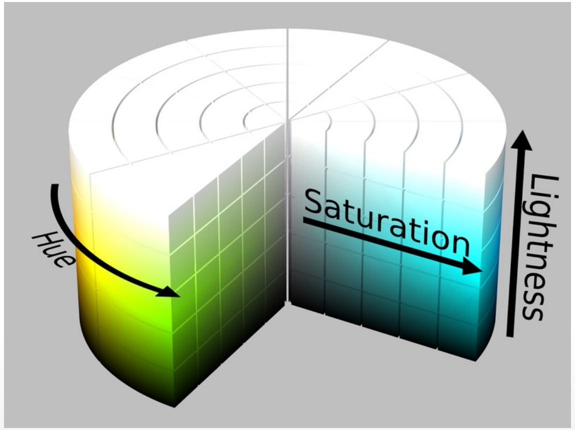
I

Q

HSL/HSV – Intuitive picking

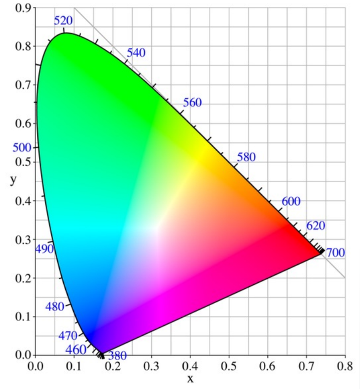
- Perceptually motivated
- Hue, Saturation, Lightness (Value)
- Simple conversion from RGB (check slides)

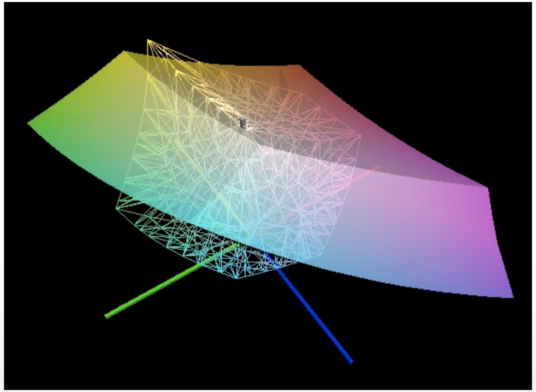




L*a*b / Luv – Perceptual distance

- CIE does not provide perceptually correct distances
- Determine ellipses of approximately the same color
- Map them to circles
- L*a*b and Luv are nonlinear warps of the CIE chart





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