Color Representation
Foley & Van Dam, Chapter 13

Visible Light Spectrum and Colors
Light is an electro-magnetic radiation

- **Hue**: distinguished among colors
- **Saturation**: how far is color from a gray of equal intensity
- **Lightness**: perceived intensity of a reflective surface
- **Brightness**: perceived intensity of emitting surface

Spectral Power Distribution
- The **Spectral Power Distribution** of a light is a function \( f(\lambda) \) defining the energy at each wavelength

Trichromatic Color Theory
- **Trichromatic**: “tri”=three “chroma”=color also tristimulus
color vision is based on three primaries (three dimensional)

- **Thomas Young**
  - A few different retinal receptors operating with different
  wavelength sensitivities allow humans to perceive colors
  - Suggested 3 receptors

- **Helmholtz & Maxwell**
  - Color matching with 3 primaries
The Human Eye

- Cones: Sensitive to high illumination levels (Photopic vision)
  - Less sensitive than rods
  - 5 million cones in each eye
  - Only cones in fovea (approx. 50,000)
  - Density decreases with distance from fovea
  - 3 types differing in their spectral sensitivity: L, M, and S

Retinal Photoreceptors

- Cones: Sensitive to high illumination levels (Photopic vision)
  - Less sensitive than rods
  - 5 million cones in each eye
  - Only cones in fovea (approx. 50,000)
  - Density decreases with distance from fovea
  - 3 types differing in their spectral sensitivity: L, M, and S

Linear Color Spaces

- Colors in 3D color space can be described as linear combinations of 3 basis colors called *primaries*

\[
\mathbf{I} = \mathbf{A} \cdot \mathbf{E} + \mathbf{B} \cdot \mathbf{E} + \mathbf{C} \cdot \mathbf{E}
\]

The representation of the color having spectrum:

Choosing The Primaries

- Stiles & Burch (1959) used 3 monochromatic primaries of wavelengths 444.4, 525.3 and 645.2

CIE Color Standard

- CIE: Commission Internationale d'Eclairage (1931) defined a standard system (CIE-XYZ) for color representation

- Weights are non-negative over the visible wavelengths
- The 3 primaries associated with x y z color matching functions cannot be easily realized in hardware
- y was chosen to equal *luminance* of monochromatic lights
If X, Y and Z are the weights used to define a color C, then the chromaticity values x, y, z (independent from the luminosity) are given by:

\[ x = \frac{X}{X+Y+Z} \]
\[ y = \frac{Y}{X+Y+Z} \]
\[ z = \frac{Z}{X+Y+Z} \]

(x, y, z) is a point on the plane \( X+Y+Z=1 \)

**CIE Chromaticity Diagram**

- **Color Gamut**: A convex sum of several colors

**RGB Color Representation**

- In a CRT each color can be defined by the required power of each electron gun:
  \[ C = rR + gG + bB \]
- The intensity is defined as:
  \[ I = r + g + b \]
- The chroma(ticy) is defined as:
  \[ C = \frac{rR + gG + bB}{r + g + b} \]

**RGB to CIE-XYZ Conversion**

- RGB to CIE-XYZ is a linear transformation:
  \[
  \begin{bmatrix}
  R \\
  G \\
  B 
  \end{bmatrix} = \begin{bmatrix}
  2.365 & -0.515 & 0.005 \\
  -0.897 & 1.426 & -0.014 \\
  -0.468 & 0.089 & 1.009 
  \end{bmatrix} \begin{bmatrix}
  X \\
  Y \\
  Z 
  \end{bmatrix}
  \]

- R = monochromatic primary 700nm
- G = monochromatic primary 546.1nm
- B = monochromatic primary 435.8nm

**RGB vs. CMY(K) Color Scheme**

- RGB and CMYK (Cyan, Magenta, Yellow and black) are **hardware-oriented** representations
- CMY is used in color photography and (with K) in most color printers

\[
\begin{bmatrix}
  C \\
  M \\
  Y \\
  B 
  \end{bmatrix} = \begin{bmatrix}
  1 & -1 & 0 & 0 \\
  0 & 1 & -1 & 0 \\
  0 & 0 & 1 & -1 \\
  0 & 0 & 0 & 1 
  \end{bmatrix} \begin{bmatrix}
  R \\
  G \\
  B 
  \end{bmatrix}
  \]

RGB is Additive, CMY is Subtractive
The HLS Color Model

- HLS: Hue Lightness, Saturation similar to HSV: Hue Saturation Value

![Munsell Book of Colors](image)

Hue (red, green, yellow, blue ...)
Saturation (pink, bright red, ....)
Lightness (black, grey, white ....)

The YIQ Color Model

- Based on the concept of opponent colors
- Used in NTSC Television (National Television Systems Committee)
- Similar method (YC_bC_r) used in JPEG and MPEG
- Y = Luminance
- I = Red-Green
- Q = Blue-Yellow

\[
\begin{bmatrix}
0.299 & 0.587 & 0.114 \\
0.596 & -0.275 & -0.321 \\
0.212 & -0.523 & 0.311
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
= 
\begin{bmatrix}
Y \\
I \\
Q
\end{bmatrix}
\]

The YIQ Color Model

- The human eye is more sensitive to luminosity than to colors, so it is possible to save space by encoding colors more coarsely
- Preferred by the NTSC because of backward compatibility with B/W TV

Original Y - Blur
I - Blur Q - Blur

Summary

- CIE-XYZ
  - Tristimulus Coordinates
  - Device Independent
  - Universal standard
- CIE-Lab
  - Perceptual Space, used to assess image quality
- RGB and CMY
  - Hardware oriented
  - Additive spaces used for CRT, printers, photography
- YIQ and YC_bC_r
  - Opponent Space
  - Used for color television broadcast and image compression
- HLS
  - Perceptual Digitized Space
  - Used for Human Interactive Painting