Color Representation

Foley & Van Dam, Chapter 13
Color Representation

- Visible Light Spectrum
- Color Matching
- Trichromatic Color Theory
- Psychophysics
- CIE standard
- RGB and CMYK Color Spaces
- HLS Color Model
- YIQ Color Model
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.
Color Matching Experiment

- Three primary lights are set to match a test light
- **Metamer**: two lights visually undistinguishable (they might have different spectral power distributions)

![Diagram showing color matching experiment](image.png)
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

- Lens
- Cornea
- Pupil
- Iris
- Ocular Muscle
- Fovea
- Vitreous Humor
- Optic Disc
- Retina
- Optic Nerve
- Cones
- Rods
- Bipolar
- Ganglion
- Horizontal
- Amacrine
- Light
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

![Graph showing relative sensitivity vs. wavelength for L, M, and S cones](chart.png)

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Relative Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>1</td>
</tr>
<tr>
<td>500</td>
<td>0.5</td>
</tr>
<tr>
<td>600</td>
<td>0.75</td>
</tr>
<tr>
<td>700</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Retinal Photoreceptors
Linear Color Spaces

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

\[ \text{The representation of the color having spectrum:} \]

\[ (A, B, C) \]
Choosing The Primaries

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

Problem: Subtractive components
CIE Color Standard

- **CIE**: Commision 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:

$$x = X/(X+Y+Z) \quad y = Y/(X+Y+Z) \quad z = Z/(X+Y+Z)$$

$(x,y,z)$ is a point on the plane $X+Y+Z=1$.
CIE Color Standard

- **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 Color Images
RGB to CIE-XYZ Conversion

• RGB to CIE-XYZ is a linear transformation:

\[
\begin{bmatrix}
2.365 & -0.515 & 0.005 \\
-0.897 & 1.426 & -0.014 \\
-0.468 & 0.089 & 1.009
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
=
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
\]

• 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.

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

RGB is Additive  
CMY is Subtractive
The HLS Color Model

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

**Munsell Book of Colors**

- **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

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

- \(Y\) = Luminance
- \(I\) = Red-Green
- \(Q\) = Blue-Yellow
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

![Original Image]

Y - Blur

![Y-Blur Image]

I - Blur

![I-Blur Image]

Q - Blur

![Q-Blur Image]
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 YCbCr
  - Opponent Space
  - Used for color television broadcast and image compression
- HLS
  - Perceptual Digitized Space
  - Used for Human Interactive Painting