Topics

Physics
- Spectrum
- Sources, filters, sensors
Perception
- Trichromatic theory
- Opponent theory
- Luminance and lightness
Art
- Color terms
Light

Newton's experiment for splitting white light into a spectrum

Image from Clive Maxfield
Electromagnetic Spectrum

Image from Clive Maxfield

Sources

Visible spectra power distribution
Sources

Visible spectra power distribution

Adding Light
Reflecting Light

Light Operations

Add spectra

\[ L(\lambda) = S_1(\lambda) + S_2(\lambda) \]

Multiply spectra (reflection and transmission)

\[ L(\lambda) = T(\lambda)S(\lambda) \]
Photon Detector

Measuring light

\[ R = \int R(\lambda) L(\lambda) \, d\lambda \]

Perception
Color Matching

Adjust brightness of 3 primaries to “match” color

C - color to be matched

Lasers: R=700 nm, G=546 nm, B=435 nm

Therefore: humans have trichromatic color vision

Three Cones/Pigments

 Typical humans are trichromats
(three color cone/pigment types – blue, blue-green, and yellow-green)
Cone Response

- Three cones
  - L (long) \( L = \int L(\lambda) E(\lambda) \, d\lambda \)
  - M (medium) \( M = \int M(\lambda) E(\lambda) \, d\lambda \)
  - S (short) \( S = \int S(\lambda) E(\lambda) \, d\lambda \)
- Metamerism - Different spectra; same response

Color Blindness

Dichromacy - missing pigment (genetic)
- Proctanopia - missing L
- Deuteranopia - missing M (red-green)
- Tritanopia - missing S

www.vischeck.com
Ishihara Test


Grassman’s Laws

Color matching is linear!

1. Scaling the color and the primaries by the same factor preserves the match

\[ 2(C) = 2(R) + 2(G) + 2(B) \]

2. To match a color formed by adding two colors, add the primaries for each color

\[ (C_1) + (C_2) = (R_1) + (R_2) + (G_1) + (G_2) + (B_1) + (B_2) \]
Spectral Matching Functions

Spectral matching curves

Match each pure color in the visible spectrum (rainbow), and record the color coordinates as a function of wavelength

Absolute Color Space

- Spectral locus
- Region inside locus
  - All possible colors
  - Human gamut
- CIEXYZ color space

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} =
\begin{bmatrix}
2.77 & 1.75 & 1.13 \\
1.00 & 4.59 & 0.06 \\
0.00 & 0.57 & 5.59
\end{bmatrix}
\begin{bmatrix}
R_x \\
G_x \\
B_x
\end{bmatrix}
\]
CIE Chromaticity Coordinates

\[ x = X/(X+Y+Z) \]
\[ y = Y/(X+Y+Z) \]
\[ z = Z/(X+Y+Z) \]

Rod

Humans also have rod cells (black, white, shades of gray)
Luminance and Lightness

Luminance (Lumens)

\[ Y = 0.30R + 0.59G + 0.11B \]

Color signal on a BW TV (Except for gamma)

Lightness

\[ L^* = Y^{1/3} \]

Light Measurement

Radiometry
- Units: Watts = Joules/Second

Photometry
- Units: Lumens

Colorimetry
- CIEXYZ
- CIELAB
- ...

Units: Watts = Joules/Second
Perceptual Organization

- Lightness
- Colorfulness
- Hue

Opponent Color

History
- Herring (1878)
- Jameson & Hurvich (1955)

Experiments
- No Rish-G or Bish-Y
- Color afterimages
Early Visual Processing

\[ A = R + G + B \]
\[ (Y - B) = R + G - B \]
\[ (R - G) = R - G \]

Munsell Color Space

- Book of painted chips
- Perceptually uniform

Hue

Chroma vs. Value
CIELAB

\[ L^* = 116 \left( \frac{Y}{Y_n} \right)^{1/3} - \frac{16}{116} \]

\[ a^* = 500 \left[ \left( \frac{X}{X_n} \right)^{1/3} - \left( \frac{Y}{Y_n} \right)^{1/3} \right] \]

\[ b^* = 200 \left[ \left( \frac{Y}{Y_n} \right)^{1/3} - \left( \frac{Z}{Z_n} \right)^{1/3} \right] \]

\( X_n, Y_n, Z_n \) are the tristimulus values of the reference white.

Color “distance”: \( \Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \)
Art
Color Cube

Intuitive Color Spaces
HSV and HSL

\[
\begin{align*}
M &= \max(R, G, B), \\
m &= \min(R, G, B) \\
r &= \frac{M-R}{M-m} \\
g &= \frac{M-G}{M-m} \\
b &= \frac{M-B}{M-m} \\
if(M==R) & \quad H = \frac{6+b-g}{6} \\
\end{align*}
\]

\[
\begin{align*}
L &= \frac{M+m}{2} \\
S &= \frac{M-m}{M+m} \\
V &= M \\
S &= \frac{M-m}{M} \\
\end{align*}
\]