COLOR

and the human response to light
Contents

- Introduction:
  - The nature of light
  - The physiology of human vision

- Color Spaces:
  - Linear
  - Artistic View

- Standard

- Distances between colors

- Color in the TV
How many dimension?

- RBG
- Lab
- CMY
- ...
Introduction
Electromagnetic Radiation - Spectrum

Wavelength in meters (m):
- Gamma: $10^{-12}$
- X rays: $10^{-8}$
- Ultraviolet: $10^{-4}$
- Infrared: 1
- Radar: $10^4$
- FM: $10^8$
- TV: $10^8$
- Short-wave: $10^8$
- AM: $10^8$
- AC electricity: $10^8$

Wavelength in nanometers (nm):
- 400 nm
- 500 nm
- 600 nm
- 700 nm

Visible light

WAVELENGTH

AMPLITUDE

CREST

TROUGH
The **Spectral Power Distribution** (SPD) of a light is a function $P(\lambda)$ which defines the power in the light at each wavelength.
Examples

2854 K
CIE Source A

6500 K
CIE Illuminant D_65

Average Daylight

Normal Florescent

RELATIVE POWER

WAVELENGTH in nanometers

RELATIVE POWER

WAVELENGTH in nanometers

RELATIVE POWER

WAVELENGTH in nanometers

RELATIVE POWER

WAVELENGTH in nanometers
The Interaction of Light and Matter

- Some or all of the light may be absorbed depending on the pigmentation of the object.
The Physiology of Human Vision
The Human Eye
The Human Retina

- rods
- cones
- bipolar
- horizontal
- amacrine
- ganglion
- light
The Human Retina
Retinal Photoreceptors
Cones

- High illumination levels (Photopic vision)
- Less sensitive than rods.
- 5 million cones in each eye.
- Density decreases with distance from fovea.
3 Types of Cones

- **L-cones**, most sensitive to red light (610 nm)
- **M-cones**, most sensitive to green light (560 nm)
- **S-cones**, most sensitive to blue light (430 nm)
Cones Spectral Sensitivity

\[(L, M, S) \iff L = \int P(\lambda) L(\lambda) d\lambda\]
Metamers

- Two lights that appear the same visually. They might have different SPDs (spectral power distributions)
History

- Tomas Young (1773-1829)
  “A few different retinal receptors operating with different wavelength sensitivities will allow humans to perceive the number of colors that they do. “

- James Clerk Maxwell (1872)
  “We are capable of feeling three different color sensations. Light of different kinds excites three sensations in different proportions, and it is by the different combinations of these three primary sensations that all the varieties of visible color are produced. “

- Trichromatic: “Tri”=three “chroma”=color
3D Color Spaces

- Three types of cones suggest color is a 3D quantity. How to define 3D color space?

Cubic Color Spaces  

Polar Color Spaces  

Opponent Color Spaces
Colors in 3D color space can be described as linear combinations of 3 basis colors, called primaries:

\[ \text{Color} = a \cdot \text{Primary}_a + b \cdot \text{Primary}_b + c \cdot \text{Primary}_c \]

The representation of:

is then given by: \((a, b, c)\)
RGB Color Model

- RGB = Red, Green, Blue
- Choose 3 primaries as the basis SPDs (Spectral Power Distribution.)
Color Matching Experiment

- Three primary lights are set to match a test light

![Diagram of color matching experiment]

**Test light**

![Graph of test light]

**Match light**

![Graph of match light]
CIE-RGB

- Primaries are: 444.4 525.3 645.2
- Given the 3 primaries, we can describe any light with 3 values (CIE-RGB):

  - (85, 38, 10)
  - (21, 45, 72)
  - (65, 54, 73)
## RGB Image

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### RGB Color Code
- **Red (R):** 36, 12, 126
- **Green (G):** 36, 12, 126
- **Blue (B):** 36, 12, 126

**Image Dimensions:** 240x240 pixels

**Resolution:** 72 dpi

**File Format:** RGB Image
CMYK Color Model

CMYK = Cyan, Magenta, Yellow, black

Cyan – removes Red

Magenta – removes Green

Yellow – removes Blue

Black – removes all
Combining Colors

Additive (RGB)  Subtractive (CMYK)
Example: red = magenta + yellow

magenta + yellow = red
CMY + Black

C + M + Y = K (black)

- Using three inks for black is expensive
- C+M+Y = dark brown not black
- Black instead of C+M+Y is crisper with more contrast
Example
Example
Example
Example
Example
From RGB to CMY

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

\[
\begin{pmatrix}
R \\
G \\
B
\end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \end{pmatrix} - \begin{pmatrix}
C \\
M \\
Y
\end{pmatrix}
\]
The Artist Point of View

- **Hue** - The color we see (red, green, purple)
- **Saturation** - How far is the color from gray (pink is less saturated than red, sky blue is less saturated than royal blue)
- **Brightness/Lightness (Luminance)** - How bright is the color
Munsell Color System

Equal perceptual steps in Hue Saturation Value.

Hue:  R, YR, Y, GY, G, BG, B, PB, P, RP
      (each subdivided into 10)

Value:  0 ... 10  (dark ... pure white)

Chroma:  0 ... 20  (neutral ... saturated)

Example:  5YR 8/4
Munsell Book of Colors
Munsell Book of Colors
HSV/HSB Color Space

HSV = Hue Saturation Value
HSB = Hue Saturation Brightness

Saturation Scale

Brightness Scale
HSV

Hue

Saturation

Value
HLS Color Space

HLS = Hue Lightness Saturation
Back to RGB

Problem 1: RGB differ from one device to another
Color Matching Experiment

- Three primary lights are set to match a test light

![Diagram illustrating color matching experiment](image)
Back to RGB

Problem 2: RGB cannot represent all colors
CIE Color Standard - 1931

- CIE - Commision Internationale d’Eclairage
- 1931 - defined a standard system for color representation.
- XYZ tristimulus coordinate system.
XYZ Spectral Power Distribution

- Non negative over the visible wavelengths.
- The 3 primaries associated with x y z spectral power distribution are unrealizable (negative power in some of the wavelengths).
- The color matching of Y is equal to the spectral luminous efficiency curve.
RGB to XYZ

- RGB to XYZ is a linear transformation

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} =
\begin{bmatrix}
0.490 & 0.310 & 0.200 \\
0.177 & 0.813 & 0.011 \\
0.000 & 0.010 & 0.990
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]
A linear transformation
CIE Chromaticity Diagram

\[
\begin{align*}
X & \rightarrow \frac{X}{X+Y+Z} = x \\
Y & \rightarrow \frac{Y}{X+Y+Z} = y \\
Z & \rightarrow \frac{Z}{X+Y+Z} = z \\
\end{align*}
\]

\[x+y+z = 1\]
Color Naming
Blackbody Radiators and CIE Standard Illuminants

CIE Standard Illuminants:

2500 - tungsten light (A)
4800 - Sunset
10K - blue sky
6500 - Average daylight (D65)
Chromaticity Defined in Polar Coordinates

Given a reference white.

**Dominant Wavelength** – wavelength of the spectral color which added to the reference white, produces the given color.
Chromaticity Defined in Polar Coordinates

Given a reference white.

**Dominant Wavelength**

**Complementary Wavelength** - wavelength of the spectral color which added to the given color, produces the reference white.
Chromaticity Defined in Polar Coordinates

Given a reference white.

Dominant Wavelength

Complementary Wavelength

Excitation Purity – the ratio of the lengths between the given color and reference white and between the dominant wavelength light and reference white. Ranges between 0 .. 1.
Device Color Gamut

- We can use the CIE chromaticity diagram to compare the gamut of various devices:

- Note, for example, that a color printer cannot reproduce all shades available on a color monitor.
Luminance v.s. Brightness

Luminance (intensity) vs Brightness (Lightness)
Y in XYZ V in HSV

Equal intensity steps:

Equal brightness steps:

\[ I_1 < I_2, \quad \Delta I_1 = \Delta I_2 \]
Weber’s Law

In general, $\Delta I$ needed for just noticeable difference (JND) over background $I$ was found to satisfy:

$$\frac{\Delta I}{I} = \text{constant}$$

($I$ is intensity, $\Delta I$ is change in intensity)

Weber’s Law:

Perceived Brightness $= \log (I)$
Munsell lines of constant Hue and Chroma
MacAdam Ellipses of JND

(Just Noticeable Difference)

(Ellipses scaled by 10)
Perceptual Color Spaces

- An improvement over CIE-XYZ that represents better uniform color spaces.
- The transformation from XYZ space to perceptual space is **Non Linear**.
- Two standards adopted by CIE are $L^*u'v'$ and $L^*a^*b^*$.
- The $L^*$ line in both spaces is a replacement of the Y lightness scale in the XYZ model, but it is more indicative of the actual visual differences.
Munsell Lines and MacAdam Ellipses plotted in CIE-L*u’v’ coordinates
Distances between colors

- Distances are not linear in any color space.
- In perceptual color space distances are more suitable for our conception.
- Measuring color differences between pixels is more useful in perceptual color spaces.
Opponent Color Spaces

- black
- white
- red
- green
- blue
- yellow
YIQ Color Model

- **YIQ** is the color model used for color TV in America (NTSC= National Television Systems Committee)
- **Y** is luminance, **I** & **Q** are color (I=red/green, Q=blue/yellow)
  - Note: **Y** is the same as CIE’s **Y**
  - Result: backwards compatibility with B/W TV!
- Convert from RGB to YIQ:
  \[
  \begin{align*}
  Y &= \begin{bmatrix} 0.30 & 0.59 & 0.11 \end{bmatrix} R \\
  I &= \begin{bmatrix} 0.60 & -0.28 & -0.32 \end{bmatrix} G \\
  Q &= \begin{bmatrix} 0.21 & -0.52 & 0.31 \end{bmatrix} B
  \end{align*}
  \]
- The YIQ model exploits properties of our visual system, which allows to assign different bandwidth for each of the primaries (4 MHz to **Y**, 1.5 to **I** and 0.6 to **Q**)
YUV Color Model

- **YUV** is the color model used for color TV in Israel (PAL), and in video. Also called YCbCr.
- **Y** is luminance as in YIQ.
- U and V are blue and red (Cb and Cr).
- The YUV uses the same benefits as YIQ, (5.5 MHz for Y, 1.3 for U and V).
- Converting from RGB to YUV:
  - \( Y = 0.299R + 0.587G + 0.114B \)
  - \( U = 0.492(B - Y) \)
  - \( V = 0.877(R - Y) \)
YUV - Example

\[ Y \quad U \quad V \]
Summary

- Light → Eye (Cones, Rods) → [l, m, s] → Color
- Color standards (Munsell, CIE)
- Many 3D color models:
  - RGB, CMY, Munsell(HSV/HLS), XYZ, Perceptual(Luv, Lab), Opponent(YIQ, YUV).
- Reproducing **Metamers** to Colors
- Different reproduction **Gamut**
- Non-linear distances between colors