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
Amazing
Electromagnetic Radiation - Spectrum

Wavelength in meters (m):

- Gamma: $10^{-12}$
- X rays: $10^{-8}$
- Ultraviolet
- Infrared
- Radar
- FM
- TV
- Short-wave
- AM
- AC electricity: $10^8$

Wavelength in nanometers (nm):

- 400 nm
- 500 nm
- 600 nm
- 700 nm

Visible light:

- 400 nm
- 500 nm
- 600 nm
- 700 nm
The **Spectral Power Distribution (SPD)** of a light is a function $P(\lambda)$ which defines the power in the light at each wavelength.
Spectral Power Distribution

White Light

Orange Light

Figures 15.3-4 from H&B
Examples
The Interaction of Light and Matter

- Some or all of the light may be absorbed depending on the pigmentation of the object.
Interlude: Color is Complicated

What colors make up the spirals?
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 suggests color is a 3D quantity. How to define 3D color space?

- **Cubic Color Spaces**
  - G
  - B
  - R

- **Polar Color Spaces**
  - Brightness
  - Hue

- **Opponent Color Spaces**
  - black-white
  - blue-yellow
  - red-green
Linear Color Spaces

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

\[ = a \bullet + b \bullet + c \bullet \]

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

Test light vs. Match light graphs are shown, illustrating the spectral characteristics of the lights.
CI E-RGB

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

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

Colors are additive.

<table>
<thead>
<tr>
<th>R</th>
<th>G</th>
<th>B</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>Black</td>
</tr>
<tr>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
<td>Red</td>
</tr>
<tr>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td>Green</td>
</tr>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>Blue</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>0.0</td>
<td>Yellow</td>
</tr>
<tr>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
<td>Magenta</td>
</tr>
<tr>
<td>0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>Cyan</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>White</td>
</tr>
<tr>
<td>0.5</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>0.5</td>
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<td></td>
</tr>
<tr>
<td>0.5</td>
<td>0.3</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

Plate II.3 from FvDFH
Figures 15.11&15.12 from H&B
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
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
HLS Color Space

HLS = Hue Lightness Saturation
Back to RGB

Problem 1: RGB differ from one device to another
Experiments produced three functions: \( r(\lambda), g(\lambda), b(\lambda) \)

Functions were normalized to have a constant area beneath them

Therefore, RGB tristimulus values for a color \( I(\lambda) \) would be:

\[
R = \int_0^\infty I(\lambda) \bar{r}(\lambda) \, d\lambda \\
G = \int_0^\infty I(\lambda) \bar{g}(\lambda) \, d\lambda \\
B = \int_0^\infty I(\lambda) \bar{b}(\lambda) \, d\lambda
\]
CIE 1931 Color space

- We can parameterize chromaticity by defining:

\[ r = \frac{R}{R + G + B}, g = \frac{G}{R + G + B} \]
Cl E-XYZ

- Transforming the triangle to (0,0),(0,1),(1,0) is a linear transformation
XYZ Color Model (CIE)

Amounts of CIE primaries needed to display spectral colors

CIE primaries are imaginary

Figure 15.6 from H&B
Back to RGB

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

- ClE - Commission Internationale d’Eclairage
- 1931 - defined a standard system for color representation.
- XYZ tristimulus coordinate system.
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

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix}
= \begin{bmatrix}
0.490 & 0.310 & 0.200 \\
0.177 & 0.813 & 0.011 \\
0.000 & 0.010 & 0.990
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]
\[ \begin{align*}
\text{l} &= z + y + x \\
z &= \frac{Z + y + x}{Z} \\
y &= \frac{Z + y + x}{y} \\
x &= \frac{Z + y + x}{x}
\end{align*} \]
Color Naming

![Color Diagram]

- Color spectrum ranging from blue to red with specific wavelengths and color names.
- X and Y axes representing different wavelengths and color intensities.
Blackbody Radiators and CIE Standard Illuminants

CIE Standard Illuminants:

2500 - tungsten light (A)
4800 - Sunset
10K - blue sky
6500 - Average daylight (D65)
RGB Color Gamut for typical monitor

Figure 15.13 from H&B
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
But wait there’s more

- We still haven’t talked about
- Color appearance model
- Dynamic range (low and high)
Luminance v.s. Brightness

Luminance (intensity) vs Brightness (Lightness)

Y in XYZ vs V in HSV

Equal intensity steps:

Equal brightness steps:

$I_1 < I_2$, $\Delta I_1 = \Delta I_2$
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 standard 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 CI E-L\(^*\)u’v’ coordinates

Value =5/

![Graph showing Munsell Lines and MacAdam Ellipses in CIE-L\(^*\)u’v’ coordinates.](image)
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:

\[
\begin{bmatrix}
Y \\
I \\
Q
\end{bmatrix} =
\begin{bmatrix}
0.30 & 0.59 & 0.11 \\
0.60 & -0.28 & -0.32 \\
0.21 & -0.52 & 0.31
\end{bmatrix}
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]

- 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
Summary

- Light $\rightarrow$ Eye (Cones, Rods) $\rightarrow$ [l,m,s] $\rightarrow$ 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