Outlines

- Color Perception
- RGB color space
- HSV and HLS
- Color Models for TV and Video
- Color Models for Printing
- Colorimetric Color Spaces

Sources:
- Burger and Burge “Digital Image Processing” Chapter 12
Color Perception

- Color perception is a fascinating and complicated phenomenon that has occupied the interest of scientists, psychologists, philosophers, and artists for hundreds of years.
- Color plays an important role in object recognition.
- What is the best way to represent colors in the digital domain?

Complications of color

- Spectral composition of light
  - Newton’s original prism experiment
  - Light decomposed into its spectral components
Complications of color

- Why does the prism separate the light into its spectral components?
  - prism bends different wavelengths of light by different amounts
    - refractive index is a function of wavelength
    - shorter wavelengths are refracted more strongly than longer wavelengths

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Color (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>Red</td>
</tr>
<tr>
<td>610</td>
<td>Orange</td>
</tr>
<tr>
<td>580</td>
<td>Yellow</td>
</tr>
<tr>
<td>540</td>
<td>Green</td>
</tr>
<tr>
<td>480</td>
<td>Blue</td>
</tr>
<tr>
<td>400</td>
<td>Violet</td>
</tr>
</tbody>
</table>

* - viewed in isolation

Complications of color

4.4 THE SPECTRAL POWER DISTRIBUTION of two important light sources are shown: (left) blue skylight and (right) a tungsten bulb.
Cones and color - recall

- Three different types of cones
  - they differ in their sensitivity to different wavelengths of light (blue-violet, green, yellow-red)

RGB color images

- Three primary colors: Red, Green, blue
- Widely used in transmission, representation, storage of color images.
- RGB is additive color system: add primary colored-light to form different colors
It is hard to determine the color of a pixel from knowing its R,G,B components.

RGB is not a perceptually uniform representation: measured distance in the RGB color space doesn’t correspond to our perception of color.
RGB representation

- True color images: represent each pixel with its R,G,B values.
  - Component ordering
  - Packed ordering

RGB representation

- Alternative representation: Indexed images:
  - make a color table
  - each pixel’s color is represented by its color’s index in the table
- Advantages?
- Limitations?
RGB Limitations:
- It is hard to determine the color of a pixel from knowing its R,G,B components.
- RGB is not a perceptually uniform representation: measured distance in the RGB color space doesn’t correspond to our perception of color.
- Brightness changes in the RGB color space are not perceived linearly.

Other Color Spaces
- HSV/HSB and HLS
- TV Color Spaces:
  - YUV, YIQ, YCbCr
- Color spaces for printing:
  - CMY, CMYK
- Colorimetric Color Spaces:
  - CIE XYZ
  - CIE L*a*b*
Three important concepts:
- Hue
- Saturation
- Luminance

From RGB to Grayscale
- How to compute luminance value $Y$ from RGB
  \[ Y = \frac{R + G + B}{3} \]
- We perceive red and green as being brighter than blue
  \[ Y = \text{Lum}(R, G, B) = w_R R + w_G G + w_B B \]
- For analog color TV signal
  \[ w_R = 0.299 \quad w_G = 0.587 \quad w_B = 0.114 \]
- For digital color encoding ITY-BT.709
  \[ w_R = 0.2125 \quad w_G = 0.7154 \quad w_B = 0.072 \]
Desaturating Color Images

\[
\begin{pmatrix} R_d \\ G_d \\ B_d \end{pmatrix} = \begin{pmatrix} Y \\ Y \\ Y \end{pmatrix} + s_{\text{col}} \begin{pmatrix} R - Y \\ G - Y \\ B - Y \end{pmatrix}
\]

HSV color space

- Represent three components:
  - Hue
  - Saturation
  - Value (brightness)
- Also called HSB or HIS
- Upside-down six-sided pyramid
HLS color space

- Similar to HSV:
  - Hue
  - Luminance
  - Saturation
- Also called HSL
- Double pyramid representation (like a diamond)
**RGB to HSV**

- Easier represented as a cylinder.

\[
S_{HSV} = \begin{cases} 
\frac{C_{\text{max}}}{C_{\text{high}}} & \text{for } C_{\text{high}} > 0 \\
0 & \text{otherwise}
\end{cases}
\]

\[
V_{HSV} = \frac{C_{\text{high}}}{C_{\text{max}}}
\]

\[
H' = \begin{cases} 
\frac{B' - G'}{R' - G' + 2} & \text{if } R = C_{\text{high}} \\
\frac{R' - B'}{R' - B' + 2} & \text{if } G = C_{\text{high}} \\
\frac{G' - R'}{G' - R' + 4} & \text{if } B = C_{\text{high}}
\end{cases}
\]

\[
H_{HSV} = \frac{1}{6} \left( H' + 6 \right) \text{ for } H' < 0 \\
H' \text{ otherwise}
\]
RGB to HLS

\[ H_{\text{HLS}} = H_{\text{HSV}} \]
\[ L_{\text{HLS}} = \frac{C_{\text{high}} + C_{\text{low}}}{2} \]
\[ S_{\text{HLS}} = \begin{cases} 
0 & \text{for } L_{\text{HLS}} = 0 \\
0.5 \cdot \frac{C_{\text{high}}}{L_{\text{HLS}}} & \text{for } 0 < L_{\text{HLS}} \leq 0.5 \\
0.5 \cdot \frac{C_{\text{low}}}{1 - L_{\text{HLS}}} & \text{for } 0.5 < L_{\text{HLS}} < 1 \\
0 & \text{for } L_{\text{HLS}} = 1
\end{cases} \]

**RGB/HLs Values**

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<thead>
<tr>
<th>Pt.</th>
<th>Color</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>H</th>
<th>S</th>
<th>L</th>
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<tbody>
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<td>0.00</td>
<td>0.00</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
<td>0.50</td>
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<tr>
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<td>Yellow</td>
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<td>1.00</td>
<td>0.00</td>
<td>1/6</td>
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<tr>
<td>G</td>
<td>Green</td>
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<td>1.00</td>
<td>0.00</td>
<td>2/6</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>C</td>
<td>Cyan</td>
<td>0.00</td>
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<td>1.00</td>
<td>3/6</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>B</td>
<td>Blue</td>
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<td>0.00</td>
<td>1.00</td>
<td>4/6</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
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<td>Magenta</td>
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<td>0.00</td>
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<td>5/6</td>
<td>1.00</td>
<td>0.50</td>
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<td>6/6</td>
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<td>R_75%</td>
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<td>R</td>
<td>G</td>
<td>B</td>
<td>H</td>
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<td>Green</td>
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<td>2/6</td>
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<tr>
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<tr>
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<tr>
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<td>0</td>
<td>0.5</td>
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<tr>
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<td>5/6</td>
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<tr>
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<td>0.00</td>
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<td>0/6</td>
<td>1.00</td>
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</tbody>
</table>

**Color Maps:**
- **HSV**
- **HLS**
- **Difference**

**View Maps:**
- **HSV**
- **HLS**
- **View - HLS**
Color Models in TV and Video

- Part of the standards for recording, storage, transmission, and display of TV signals
- YIQ: used in analog NTSC systems. Also in VHS videotape coding. (N. America and Japan)
- YUV: used in European TV standard (SECAM)
- YCbCr: a variation of YUV that is used in digital video and digital TV. Also in JPEG
- Common ideas:
  - A separate luminance component Y
  - Two chroma components
  - Encode color difference instead of absolute colors
  - More bandwidth for luminance than chroma components.
  - Linear transformation from RGB (a matrix multiplication for conversion.)
**YUV**

- **Luminance component:**
  
  \[ Y = 0.299 \cdot R + 0.587 \cdot G + 0.114 \cdot B \]

- **Chroma components: based on differences between the luminance and the blue and red components:**

  \[
  \begin{pmatrix}
  Y \\
  U \\
  V
  \end{pmatrix} = \begin{pmatrix}
  0.299 & 0.587 & 0.114 \\
  -0.167 & -0.289 & 0.436 \\
  0.615 & -0.515 & -0.100
  \end{pmatrix}
  \begin{pmatrix}
  R \\
  G \\
  B
  \end{pmatrix}
  \]

  \[
  \begin{pmatrix}
  R \\
  G \\
  B
  \end{pmatrix} = \begin{pmatrix}
  1.000 & 0.000 & 1.140 \\
  1.000 & -0.395 & -0.581 \\
  1.000 & 2.032 & 0.000
  \end{pmatrix}
  \begin{pmatrix}
  Y \\
  U \\
  V
  \end{pmatrix}
  \]
YIQ and YCbCr

- YIQ: similar to YUV (rotate and mirror the UV)
  \[
  \begin{pmatrix}
  I \\
  Q
  \end{pmatrix} = \begin{pmatrix}
  0 & 1 \\
  1 & 0
  \end{pmatrix}
  \begin{pmatrix}
  \cos \beta & \sin \beta \\
  -\sin \beta & \cos \beta
  \end{pmatrix}
  \begin{pmatrix}
  U \\
  V
  \end{pmatrix}
  \]

- YCbCr:
  \[
  Y = w_B \cdot R + (1 - w_B - w_R) \cdot G + w_B \cdot B \\
  C_b = \frac{0.5}{1 - w_B} \cdot (B - Y) \\
  C_r = \frac{0.5}{1 - w_B} \cdot (R - Y)
  \]

- Setting the weights to \( w_B = 0.299 \) and \( w_R = 0.114 \)

\[
\begin{pmatrix}
  Y \\
  C_b \\
  C_r
\end{pmatrix} = \begin{pmatrix}
  0.299 & 0.587 & 0.114 \\
  -0.169 & -0.331 & 0.500 \\
  0.500 & -0.419 & -0.081
\end{pmatrix}
\begin{pmatrix}
  R \\
  G \\
  B
\end{pmatrix}
\]

Color Models for Printing

- Subtractive color models: CMY and CMYK
- Color printing requires a minimum of three primary colors: traditionally: Cyan, Magenta, and Yellow
- White: C=M=Y=0 (no ink)
- Black: C=M=Y=1 (complete subtraction of light)
- CMY from RGB (simplified):
  \[
  C = 1 - R \\
  M = 1 - G \\
  Y = 1 - B
  \]
CMYK

- In actual printing, CMY is not sufficient, we need a black ink as well. K component
- How to determine the amount of black ink?
  \[ K = \min(C, M, Y) \]
- The more the black the less the C, M, Y ink should be
- If C=M=Y, we only need black ink
- Different conversions are possible.
- Very complicated task in reality, which depends on the printer used

CMY to CMYK

- **Version 1**
  \[
  \begin{pmatrix}
  C' \\
  M' \\
  Y' \\
  K'
  \end{pmatrix} = \begin{pmatrix}
  C - K \\
  M - K \\
  Y - K \\
  K
  \end{pmatrix}
  \]

- **Version 2**
  \[
  \begin{pmatrix}
  C' \\
  M' \\
  Y' \\
  K'
  \end{pmatrix} = \begin{pmatrix}
  C - K \\
  M - K \\
  Y - K \\
  K
  \end{pmatrix}
  \]
  \[ f(K) = \begin{cases} 
  \frac{1}{R} & \text{for } K < 1 \\
  1 & \text{otherwise} 
  \end{cases} \]

- **Version 3**
  \[
  \begin{pmatrix}
  C' \\
  M' \\
  Y' \\
  K'
  \end{pmatrix} = \begin{pmatrix}
  C - f_{UCR}(K) \\
  M - f_{UCR}(K) \\
  Y - f_{UCR}(K) \\
  f_{BG}(K)
  \end{pmatrix}
  \]
  \[ f_{UCR}(K) = s_K \cdot K \]
  \[ f_{BG}(K) = \begin{cases} 
  0 & \text{for } K < K_0 \\
  \frac{K - K_0}{K - K_0} & \text{for } K \geq K_0 
  \end{cases} \]
Colorimetric Color Spaces

- Goal: measure colors independent of devices
- A calibrated device-independent color system
- CIE XYZ, CIE x,y, CIE L*a*b*
CIE XYZ

- Three imaginary primary colors X, Y, Z
- All the visible colors are summations of positive components.
- All visible colors lie inside a cone-shaped region, which doesn’t include the X,Y, Z
- Y corresponds to the luminosity of the color (lightness)
- RGB cube is a distorted cube in the XYZ space.
- Linear transformation between RGB and XYZ
- Similar to RGB, the space is nonlinear wrt human color perception
RGB to CIE XYZ - a linear transformation

<table>
<thead>
<tr>
<th>Pt.</th>
<th>Color</th>
<th>R</th>
<th>G</th>
<th>B</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>x</th>
<th>y</th>
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<td>0.3290</td>
</tr>
<tr>
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</tbody>
</table>

CIE x,y chromaticity

- How to separate the color hue from the luminance
- A central projection (through S) to the plane \( X + Y + Z = 1 \)
  \[
  x = \frac{X}{X + Y + Z}, \quad y = \frac{Y}{X + Y + Z}, \quad z = \frac{Z}{X + Y + Z}
  \]
- Then, project to the XY plane (use only the x,y - drop z )
CIE-xy chromaticity diagram

- Horseshoe-shaped
- The outer boundary represents monochromatic (spectrally pure), maximally saturated colors.
- Neutral point (E) where x=y=1/3, (X=Y=Z=1)
- Saturation falls off towards E
- Complementary colors?
- We cannot reconstruct the XYZ from xy only
- We can reconstruct the XYZ if we know x, y, and Y

\[ X = x \cdot \frac{Y}{y} \quad Z = z \cdot \frac{Y}{y} = (1 - x - y) \cdot \frac{Y}{y} \]

- Standard illuminants
  - D50: emulate direct sunlight illumination
  - D65: emulate overcast daylight illumination
- These are important reference points to transform between color spaces and devices
- Gamut: the set of all colors that can be handled by a certain media device or can be represented by a given color space.

<table>
<thead>
<tr>
<th>D50</th>
<th>CIE L′a′b′</th>
<th>Laser Display</th>
<th>Adobe RGB</th>
<th>sRGB</th>
<th>CMYK</th>
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<tbody>
<tr>
<td>5000 K</td>
<td>0.964209</td>
<td>0.168098</td>
<td>0.049255</td>
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<tr>
<td>6500 K</td>
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<tr>
<td>E</td>
<td>5400 K</td>
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<td>1</td>
<td>1/\sqrt{3}</td>
<td>1/\sqrt{3}</td>
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</table>
CIE L*a*b*

- XYZ is not perceptually uniform
- L*a*b* is a similar color space but more uniform
- Green-red, blue-yellow hue axis.

\[

t = 116 \cdot Y^* - 16 \\
\omega = 500 \cdot (X^* - Y^*) \\
B = 200 \cdot (Y^* - Z^*) \\
X' = f_1 \left( \frac{X}{X_0} \right) \\
Y' = f_1 \left( \frac{Y}{Y_0} \right) \\
Z' = f_1 \left( \frac{Z}{Z_0} \right) \\
f_1(c) = \begin{cases} \\
5 \frac{c}{c^*} & \text{for } c > 0.008856 \\
7.787 \cdot c + \frac{16}{116} & \text{for } c \leq 0.008856 \\
\end{cases}
\]

sRGB

- Standard RGB: precisely specifying where are the R,G,B colors and the white reference point in the XYZ space.
- Important standard (developed by HP and MS)
- Used in JPEG, PNG, HTML4,...
\[
\begin{align*}
M_{\text{Color}} &= \begin{pmatrix} 3.1910 & -1.5276 & 0.0804 \\ -0.0002 & 1.5799 & 0.0016 \\ 0.0018 & -0.0026 & 1.0000 \end{pmatrix}, \\
M_{\text{RGB}} &= \begin{pmatrix} 0.4346 & 0.3510 & 0.1295 \\ 0.2702 & 0.5706 & 0.0788 \\ 0.0000 & 0.1380 & 0.8627 \end{pmatrix}
\end{align*}
\]

\[
\begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = M_{\text{RGB}} \begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} R' \\ G' \\ B' \end{pmatrix} = M_{\text{Color}}^{-1} \begin{pmatrix} R \\ G \\ B \end{pmatrix}
\]

\[
R' = f_x(R) \quad G' = f_x(G) \quad B' = f_x(B)
\]

\[
f_x(e) = \begin{cases} 
 1.055 \cdot e^{\frac{1}{2.4}} - 0.055 & \text{for } e > 0.0031308 \\
 12.92 \cdot e & \text{for } e \leq 0.0031308
\end{cases}
\]

\[
\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \xrightarrow{\text{linear mapping}} \begin{pmatrix} R \\ G \\ B \end{pmatrix} \xrightarrow{\text{gamma correction}} \begin{pmatrix} R' \\ G' \\ B' \end{pmatrix}
\]

<table>
<thead>
<tr>
<th>Pt.</th>
<th>Color</th>
<th>(R' )</th>
<th>(G' )</th>
<th>(B' )</th>
<th>(X_{\text{CIE}} )</th>
<th>(Y_{\text{CIE}} )</th>
<th>(Z_{\text{CIE}} )</th>
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<td>0.2140</td>
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<td>0.5225</td>
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<tr>
<td>R50</td>
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</tbody>
</table>