Color

Daniel Leventhal
Adapted from Andy van Dam (Brown)
CSE 457
Autumn 2011

Spectrum and Color
• Physical - Mixture of wavelengths
• Perception - Color

380nm/violet – 740nm/red

High Level Points
• Color is perceptual; spectral distributions are physical
• Elementary school was a simplification
• The eye is logarithmic

Dynamic Range
• Ratio of maximum to minimum light intensities
• Eye overall $10^3:1$
  – Adaptation by changing pupil size
  – 10,000:1 at any moment

<table>
<thead>
<tr>
<th>Source Media</th>
<th>Dynamic Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple 30&quot; HD Display</td>
<td>700:1</td>
</tr>
<tr>
<td>CRT</td>
<td>50-300:1</td>
</tr>
<tr>
<td>Photographic prints</td>
<td>1000:1</td>
</tr>
<tr>
<td>Photographic slides</td>
<td>10000:1</td>
</tr>
<tr>
<td>Coated paper printed in B/W</td>
<td>100:1</td>
</tr>
<tr>
<td>Coated paper printed in color</td>
<td>10:1</td>
</tr>
<tr>
<td>Newsprint printed in B/W</td>
<td>10:1</td>
</tr>
</tbody>
</table>

[Dyn. range not the same as gamut]
Perceived Brightness

- Relationship between perceived brightness $S$ and intensity $I$ is non-linear
- $S = C \cdot \log(I)$
- Efficiently use 256 intensity values

\[
\frac{I_{j+1}}{I_j} = \frac{I_j}{I_{j-1}} = r
\]

\[
I_0 = I_0 \quad I_1 = rI_0 \quad I_{255} = r^{255} I_0
\]

\[
r = \left( \frac{1}{I_0} \right)^{1/255}
\]

Power Law

- Log function based on subjective human judgments
- Stevens’ power law approximates the log well $S = c \cdot I^{0.4}$

Screen Non-linearity: Gamma

- $I = k \cdot V^\gamma$
- Mac gamma: 1.8, PC: 2.5

Luminous Efficiency

Perceived brightness of monochromatic light relative to 550nm
**Metamers**

- Consider a creature with two receptors (R1, R2)
- Both $I_1$ and $I_2$ produce the same response in $R_1$ and $R_2$
- In principle an infinite number of frequency distributions can produce the same response.

**Three Layers of Perception**

- Receptors in retina
  - Rods, three types of cones (tristimulus theory)
  - Note: receptors each respond to wide range of frequencies, not just RGB
- Opponent channels
  - Blue-yellow, red-green, black-white
- Opponent cells
  - Spatial (context) effects, e.g., simultaneous contrast, lateral inhibition

**Rods**

- See grays
- Work in low light
- Around periphery of retina
Cones

Not really RGB
Long, Medium, Short

Many more long cones, fewer medium, fewest short

Hering’s Chromatic Opponent Channels

- Additional processing
  - Cones feed into higher up neurons that correspond to opponent processes: red-green and yellow-blue
  - A color is never reddish-greenish or bluish-yellowish

Hue: Blue + Red = Violet

Each channel is a weighted sum of receptor outputs – linear mapping

Y-B
R-G
B-K-W

Lateral Inhibition / Mach Banding

Nature provides for contrast enhancement at boundaries between regions: edge detection. This is caused by lateral inhibition.

Describing Color

- Talked about intensity
- Hue: Which color
- Saturation: How pure the color is
- Distinguish between around 7 million colors
  - Determined by Just Noticeable Differences (JND)
  - JND smaller near center of visible range of light

- Three terms implies 3 dimensional space
Naming Color

• How do you compare colors?
• PANTONE® Matching System in printing industry
• Munsell color-order system
  – hue, value/lightness, chroma (saturation)
  – equal perceived distances between neighbors

Color Matching

• Need a way to precisely describe colors
• Choose three primaries (RGB), try and match T

• Three primaries can’t match all colors
• Adding a light to the test side lets you match all colors
• Can be thought of as -R

CIE Color Space

• Negative primary is awkward
• X, Y, Z replace red, green blue
• Y chosen so that \( y_\lambda \) matches luminous efficiency function

The mathematical color matching functions \( x_\lambda \), \( y_\lambda \), and \( z_\lambda \) for the 1931 CIE X, Y, and Z primaries. They are defined tabularly at 1 nm intervals for color samples that subtend 2° field of view on retina.
RGB in CIE

- Easily convert RGB <-> XYZ
  \[
  \begin{bmatrix}
  X \\
  Y \\
  Z
  \end{bmatrix} =
  \begin{bmatrix}
  0.412453 & 0.357520 & 0.180423 \\
  0.212671 & 0.715160 & 0.072169 \\
  0.019334 & 0.119199 & 0.950227
  \end{bmatrix}
  \begin{bmatrix}
  R \\
  G \\
  B
  \end{bmatrix}
  \]

- Visible gamut has irregular shape in CIE based on response curves

- RGB cube (right) distorted from projection

Color Spaces

- Programming for monitors easier in space defined by monitor: RGB space (RGB pixels for both CRT's and flat panels)

- Printers use CMY (cyan, magenta, yellow) for color printing: CMY(K) space

- Six-primary-color projection system: 6-color IRODORI space

- User-friendliness: Hue, Saturation, Value is easier than RGB

- Need perceptual uniformity in the space? Munsell or CIELab

RGB Color Model

- RGB color gamut
  - differs from one monitor to another
  - differs by company too:
    - Adobe RGB - larger space
    - sRGB (HP/Microsoft) - fewer colors, but allocated bit depth better and more than enough for most on-screen and Web uses

CMYK

- Used in most printers
  - Color ink is expensive, mix of inks dries slower

- Cyan, magenta, and yellow are complements of red, green, and blue

- Subtractive primaries: Color subtracted from white

- Subset is unit cube
  - White is at origin, black at \((1, 1, 1, 1)\):

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

\[K = \min(C, M, Y)\]
HSV

• Hue, saturation, value (kind of brightness)
• Polar coordinates

HLS

• Hue, lightness, saturation
• Easier to think of white as a point
• Maximally saturated hues at S=1, L = 0.5

Perceptual Uniformity

• Equal changes in color values are not perceived as equal (RGB, CMYK, HSV, HLS)
• CIE Lab introduced in 1976
  – L: luminosity
  – a: red/green axis
  – b: yellow/blue axis
• Color space dependent on white value

Interpolating Colors

• RGB is easy
  red = (1, 0, 0), green = (0, 1, 0)
  midpoint = (0.5, 0.5, 0)
  RGB_to_HSV = (60º, 1, 0.5)
• HSV is less obvious
  red = (0º, 1, 1), green = (120º, 1, 1)
  midpoint = (60º, 1, 1)
Quick UI Implications

• 1 in 10 men are color blind
  – Mostly: Red / Green
  – Rare: Yellow / Blue
  – Very Rare: No color
• Test UIs for color blind (approximation)
  – http://colorfilter.wickline.org/