Outline

- Light
- Physical Properties of Light and Color
- Eye Mechanism for Color
- Systems to Define Light and Color

Achromatic Light

- Light without color
- Basically Black-and-White
- Defined in terms of "energy" (physics)
  - Intensity and luminance
  - or Brightness (perceived intensity)

Selecting Intensities

- Suppose we want 256 “shades”
- Idea #1 (bad)
  - 128 levels from 0.0 – 0.9
  - 128 levels from 0.9 – 1.0
  - Problem: discontinuities at 0.9

Selecting Intensities

- Suppose we want 256 “shades”
- Idea #2 (also bad)
  - Distribute them evenly
  - Problem
    - This is not how the human eye works!
    - The eye is sensitive to relative intensity variations, not absolutes
      - 0.10 and 0.11 differ as much as 0.50 and 0.55

Optical Illusion

Checkerboard Illusion: The squares labeled 1 and 2 are the same shade of gray.

Edward H. Adelson
Optical Illusion Revealed

Selecting Intensities

- Idea #3
- Start with intensity $I_0$, goto $I_{255}=1$ by making $I_1 = r I_0$, $I_2 = r^2 I_0$, ..., $I_{255} = r^{255} I_0 = 1$
- Min intensity ~ $1/200^{th}$ to $1/40^{th}$ of max
- This is the *dynamic range* of a device
- *Gamma correction*: adjusting intensities to compensate for the medium

Chromatic Light!

- Let there be light!
- Major terms
  - Hue
    - Distinguish colors such as red, green, purple, etc.
  - Saturation
    - How far is the color from a gray of equal intensity (i.e. red=high saturation; pastels are low)
  - Lightness
    - Perceived intensity of the reflecting object
    - *Brightness* is used when the object is an emitter

Physics of Light and Color

- Light: a physical phenomenon:
  - Electromagnetic radiation in the [400 nm-700nm] wavelength range
- Color: psychological phenomenon:
  - Interaction of the light of different wavelength with our visual system.

Spectral Energy Distributions

<table>
<thead>
<tr>
<th>Color</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Violet</td>
<td>388-440nm</td>
</tr>
<tr>
<td>Blue</td>
<td>440-499nm</td>
</tr>
<tr>
<td>Green</td>
<td>490-565nm</td>
</tr>
<tr>
<td>Yellow</td>
<td>565-590nm</td>
</tr>
<tr>
<td>Orange</td>
<td>590-630nm</td>
</tr>
<tr>
<td>Red</td>
<td>630-780nm</td>
</tr>
</tbody>
</table>

Colorimetry (Physics)

- Define color in terms of the light spectrum and wavelengths
  - Dominant Wavelength: what we see
  - Excitation Purity: saturation
  - Luminance: intensity of light
- Ex:
  - Pure color, 100% saturated, no white light
  - White/gray lights are 0% saturated
Specifying Colors

• Can we specify colors using specter distributions?
  – We can but we do not want to.
  – It’s not how we perceive colors.
  – More then one specter corresponds to the same color. *Reason?*
  – Too much information

Seeing in Color

• The eye contains rods and cones
  – Rods work at low light levels and do not see color
  – Cones come in three types (experimentally and genetically proven), each responds in a different way to frequency distributions

Tristimulus Theory

• The human retina has 3 color sensors
  – the cones
• Cones are tuned to red, green and blue light wavelengths
  – Note: R&G are both “yellowish”
• Experimental data

Luminous-Efficiency Function

• The eye’s response to light of constant luminance as the dominant wavelength is varied
• Peak sensitivity is at ~550nm (yellow-green light)
• This is just the sum of the earlier curves

Specifying Colors

• Depends on the context
  – Compare against standard samples
    • I.e. the paint store, printing professions
    • PANTONE MATCHING SYSTEM
  – Artistic mixtures of *tint*, *shade*, and *tone*
    • Tint == white + pure color, decreasing saturation
    • Shade == black + pure color, decreasing lightness
    • Tone == both
• Both are subjective

Terms

• Perceptual Term
  – Hue
  – Saturation
  – Lightness
    • self reflecting objects
  – Brightness
    • self luminous objects
• Colorimetry
  – Dominant Wavelength
  – Excitation purity
  – Luminance
  – Luminance
Here's what we do…

- Take advantage of our perceptual inefficiencies…
  - The eye can distinguish 1000s of colors, side by side
  - When color only differs in hue, wavelength between noticeably different colors is between 2nm and 10nm (most within 4nm)
  - Hence, 128 fully saturated hues can be distinguished
  - Eye is
    - less sensitive to changes in hue when light is less saturated
    - more sensitive at spectrum extremes to changes in saturation for fixed hue and lightness
  - About 23 distinguishable grades/steps exist

Color Models RGB

- Idea: specify color in terms of weighted sums of R-G-B
- Almost: may need some <0 values to match wavelengths
- Hence, some colors cannot be represented as sums of the primaries

RGB is an Additive Color Model

- Primary colors:
  - red, green, blue
- Secondary colors:
  - yellow = red + green,
  - cyan = green + blue,
  - magenta = blue + red.
- All colors:
  - white = red + green
  - black = no light

RGB Color Cube

- RGB used in Monitors and other light emitting devices
- TV uses YIQ encoding which is somewhat similar to RGB

Color Models CMY

- Describes hardcopy color output
- We see colors of reflected light

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

CMY(K) is a Subtractive Color Model

- Primary colors:
  - cyan, magenta, yellow
- Secondary colors:
  - blue = cyan + magenta,
  - red = magenta + yellow,
  - green = yellow + cyan.
- All colors:
  - black = cyan + magenta + yellow (in theory).
  - Black (K) ink is used in addition to C,M,Y to produce solid black.
  - white = no color of ink (on white paper, of course).
Color Models XYZ

- Standard defined by International Commission on Illumination (CIE) since 1931
- Defined to avoid negative weights
- These are not real colors

\[
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = \begin{bmatrix}
2.77 & 1.75 & 1.13 \\
1.00 & 4.59 & 0.06 \\
0.00 & 0.57 & 5.59
\end{bmatrix}\begin{bmatrix}
R \\
G \\
B
\end{bmatrix}
\]

CIE Chromaticity Diagram

- Plot colors on the $x + y + z = 1$ plane (normalize by brightness)

\[
\begin{align*}
x &= \frac{X}{X + Y + Z} \\
y &= \frac{Y}{X + Y + Z} \\
z &= \frac{Z}{X + Y + Z}
\end{align*}
\]
- Gives us 2D Chromaticity Diagram

Working with Chromaticity Diagram

- C is “white” and close to $x=y=z=1/3$
- Dominant wavelength of a colour $B$, is where the line from C through $B$ meets the spectrum.
- $A$ and $B$ can be mixed to produce any colour along the line $AB$
- True for $ijk$ (includes white)

Gamut

- The gamut of all colors perceivable is thus a three-dimensional shape in $X,Y,Z$
- Green contour – RGB Monitor
- White – scanner
- Black – printer
- Problem: How to capture the color of the original with the scanner, display it on the monitor and print out on the printer?

Color Models YIQ

- National Television System Committee (NTSC)
- $Y$ is same as XYZ model and represents brightness. Uses 4MHz of bandwidth.
- $I$ contains orange-cyan hue information (skin tones). Uses about 1.5 MHz
- $Q$ contains green-magenta hue information. Uses about 1.5 MHz
- B/W TVs use only $Y$ signal.

Tint-Shade-Tone

- Relationships of tints, shades and tones.
  - Tints - mixture of color with white.
  - Shades – mixture of color with black.
- Both ignore one dimension.
- Tones respect all three.
HSB: hue, saturation, and brightness

- Also called HSV (hue saturation value)
- Hue is the actual color. Measured in degrees around the cone (red = 0 or 360 yellow = 60, green = 120, etc.).
- Saturation is the purity of the color, measured in percent from the center of the cone (0) to the surface (100). At 0% saturation, hue is meaningless.
- Brightness is measured in percent from black (0) to white (100). At 0% brightness, both hue and saturation are meaningless.

HLS hue, lightness, saturation

- Developed by Tektronix
- Hue define like in HSB.
- Complimentary colors 180 apart
- Gray scale along vertical axis L from 0 black to 1 white
- Pure hues lie in the L=0.5 plane
- Saturation again is similar to HSB model

The END