CS 536
Computer Graphics

Color!

Week 7, Lecture 12

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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)

http://www.thornlighting.com/
Quantizing Intensities

• Q: Given a limited number of colors/shades, which ones should we use?
• Suppose we want 256 “shades”
• Idea #1 (bad)
  – 128 levels from 0.0 – 0.9
  – 128 levels from 0.9 – 1.0
  – Problems
    • Discontinuities at 0.9
    • Uneven distribution of samples
Quantizing 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
    – The intensity change between 0.10 and 0.11 looks like the change between 0.50 and 0.55
Optical Illusion

Checker-shadow illusion:
The squares marked A and B are the same shade of gray.
Optical Illusion Revealed

Checker-shadow illusion:
The squares marked A and B are the same shade of gray.

Edward H. Adelson
Quantizing Intensities

- Idea #3
- Start with intensity $I_0$, go to $I_{255}=1$ by making $I_1 = r*I_0$, $I_2 = r*I_1$, etc.
- $I_0$, $I_1 = r*I_0$, $I_2 = r^2*I_0$, … $I_{255} = r^{255}*I_0 = 1$
- $r = (1/I_0)^{1/255} = I_0^{-1/255}$
- $r^j = I_0^{-j/255}$
- $I_j = r^j I_0 = I_0^{(1-j/255)} = I_0^{(255-j)/255}$
- $r = (1/I_0)^{1/n}$, $I_j = r^j I_0 = I_0^{(n-j)/n}$
Selecting Intensities

• \textit{Dynamic range} of a device
  – Max intensity/Min intensity
  – Min display intensity \sim 1/500^{th} \text{ to } 1/200^{th} \text{ of max}

• \textit{Gamma correction}: adjusting intensities to compensate for the device
  – \( I = v^\gamma \), \( \gamma : 2 \Rightarrow 2.5 \) Implement w/ look-up table

• \textit{How many intensities are enough?}
  – Can’t see changes below 1%
  – \( 1.01 = (1/I_0)^{1/n} \)
  – \( n = \log_{1.01}(1/I_0) \quad I_0 = 1/200, \ n = 532 \)
Chromatic Light!

• Let there be colored 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.

http://prometheus.cecs.csulb.edu/~jewett/colors/
# 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>440-490nm</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>

<table>
<thead>
<tr>
<th># Photons</th>
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</tr>
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<tbody>
<tr>
<td>^</td>
<td>400 500 600 700</td>
</tr>
</tbody>
</table>

- **Laser**
- **White**
- **Less White (Gray)**

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</tbody>
</table>

| Pure day light |
| 400 500 600 700 |
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 spectral distributions?
  – We can, but we do not want to.
  – More than one set of distributions 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

http://www.thornlighting.com/
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

Foley/VanDam, 1990/1994
Eye Sensitivity

- Can distinguish 100,000s 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
- Less sensitive to changes in hue when light is less saturated
- More sensitive at spectrum extremes to changes in saturation a
  - about 23 distinguishable saturation grades/steps
- Static luminance dynamic range: 10,000:1
Device Sensitivity

• Static eye luminance dynamic range
  – 10,000:1
• With iris adjustment
  – 1,000,000:1
• CRT luminance range, 200:1
• LCD luminance range, 5,000:1(?), 500:1
• How to recreate on a monitor/scanner what the eye perceives?
• The focus of high dynamic range (HDR) imaging research
HDR Image
Terms

- Perceptual Term
  - Hue
  - Saturation
  - Lightness
    - self reflecting objects
  - Brightness
    - self luminous objects

- Colorimetry
  - Dominant Wavelength
  - Excitation purity
  - Luminance
  - Luminance
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

Foley/VanDam, 1990/1994
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 + blue (#FFFFFF)
  - black = no light (#000000).

http://prometheus.cecs.csulb.edu/~jewett/colors/
RGB Color Cube

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

http://prometheus.cecs.csulb.edu/~jewett/colors/
Color Models CMY

- Describes hardcopy color output
- We see colors of reflected light
- Cyan ink absorbs red light and reflects green and blue
- To make blue, use cyan ink (to absorb red), and magenta ink (to absorb green)

http://prometheus.cecs.csulb.edu/~jewett/colors/
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).

http://prometheus.cecs.csulb.edu/~jewett/colors/
Color Models XYZ

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

\[
X = k \int P(\lambda) \bar{x}_\lambda d\lambda \quad Y = k \int P(\lambda) \bar{y}_\lambda d\lambda \quad Z = k \int P(\lambda) \bar{z}_\lambda d\lambda
\]
Color Models XYZ

- Cone of visible colors in CIE space
- $X+Y+Z=1$ plane is shown
- Constant luminance
- Only depends on dominant wavelength and saturation
CIE Chromaticity Diagram

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

\[
x = \frac{X}{X + Y + Z}
\]
\[
y = \frac{Y}{X + Y + Z}
\]
\[
z = \frac{Z}{X + Y + Z}
\]

• Gives us 2D Chromaticity Diagram

http://www.cs.rit.edu/~ncs/color/a_chroma.html
Working with Chromaticity Diagram

• C is “white” and close to \( x=y=z=1/3 \)
• E and F can be mixed to produce any color along the line EF
• Dominant wavelength of a color B is where the line from C through B meets the spectrum (D).
• BC/DC gives saturation

http://www.cs.rit.edu/~ncs/color/a_chroma.html
Working with Chromaticity Diagram

• A & B are "complementary" colors. They can be combined to produce white light
• Colors inside ijk are linear combinations of i, j & k

http://www.cs.rit.edu/~ncs/color/a_chroma.html
Gamut

- *Gamut*: all colors produced by adding colors - a polygon
- Green contour – RGB Monitor
- White – scanner
- Black – printer
- Problem: How to capture the color of an original image with a scanner, display it on the monitor and print out on the printer?

- A triangle can’t cover the space → Can’t produce all colors by adding 3 different colors together

http://www.cs.rit.edu/~ncs/color/a_chroma.html
Color Models YIQ

- National Television System Committee (NTSC)
  \[
  \begin{bmatrix}
  Y \\
  I \\
  Q
  \end{bmatrix} =
  \begin{bmatrix}
  0.299 & 0.587 & 0.114 \\
  0.596 & -0.275 & -0.321 \\
  0.212 & -0.528 & 0.311
  \end{bmatrix}
  \begin{bmatrix}
  R \\
  G \\
  B
  \end{bmatrix}
  \]

- 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.

Foley/VanDam, 1990/1994
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.

http://www.mathworks.nl/
HSL 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