Overview

• Display hardware
  - How are images displayed?

• Raster graphics systems
  - How are imaging systems organized?

• Color models
  - How can we describe and represent colors?

Display Hardware

• Video display devices
  - Cathode Ray Tube (CRT)
  - Liquid Crystal Display (LCD)
  - Plasma panels
  - Thin-film electroluminescent displays
  - Light-emitting diodes (LED)

• Hard-copy devices
  - Ink-jet printer
  - Laser printer
  - Film recorder
  - Electrostatic printer
  - Pen plotter

Cathode Ray Tube (CRT)

Liquid Crystal Display (LCD)
Display Hardware

- Video display devices
  - Cathode Ray Tube (CRT)
  - Liquid Crystal Display (LCD)
  - Plasma panels
  - Thin-film electroluminescent displays
  - Light-emitting diodes (LED)

- Hard-copy devices
  - Ink-jet printer
  - Laser printer
  - Film recorder
  - Electrostatic printer
  - Pen plotter

Overview

- Display hardware
  - How are images displayed?
- Raster graphics systems
  - How are imaging systems organized?
- Color models
  - How can we describe and represent colors?

Raster Graphics Systems

Frame Buffer

Frame Buffer Refresh

Direct Color Framebuffer

- Store the actual intensities of R, G, and B individually in the framebuffer
- 24 bits per pixel = 8 bits red, 8 bits green, 8 bits blue
- 16 bits per pixel = ? bits red, ? bits green, ? bits blue

Refresh rate is usually 60-120 Hz
Color Lookup Framebuffer

- Store indices (usually 8 bits) in framebuffer
- Display controller looks up the R,G,B values before triggering the electron guns

![Color Lookup Framebuffer Diagram]

Color CRT

![Color CRT Diagram]

Overview

- Display hardware
  - How are images displayed?
- Raster graphics systems
  - How are imaging systems organized?
  - Color models
    - How can we describe and represent colors?

Specifying Color

- Color perception usually involves three quantities:
  - **Hue**: Distinguishes between colors like red, green, blue, etc
  - **Saturation**: How far the color is from a gray of equal intensity
  - **Lightness**: The perceived intensity of a reflecting object
- Sometimes lightness is called **brightness** if the object is emitting light instead of reflecting it.
- In order to use color precisely in computer graphics, we need to be able to specify and measure colors.

How Do Artists Do It?

- Artists often specify color as tints, shades, and tones of saturated (pure) pigments
- **Tint**: Adding white to a pure pigment, decreasing saturation
- **Shade**: Adding black to a pure pigment, decreasing lightness
- **Tone**: Adding white and black to a pure pigment

![Color Models Diagram]

HSV Color Model

<table>
<thead>
<tr>
<th>H</th>
<th>S</th>
<th>V</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
<td>Red</td>
</tr>
<tr>
<td>120</td>
<td>1.0</td>
<td>1.0</td>
<td>Green</td>
</tr>
<tr>
<td>240</td>
<td>1.0</td>
<td>1.0</td>
<td>Blue</td>
</tr>
<tr>
<td>*</td>
<td>0.0</td>
<td>1.0</td>
<td>White</td>
</tr>
<tr>
<td>*</td>
<td>0.0</td>
<td>0.5</td>
<td>Gray</td>
</tr>
<tr>
<td>*</td>
<td>*</td>
<td>0.0</td>
<td>Black</td>
</tr>
<tr>
<td>60</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>270</td>
<td>0.5</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>270</td>
<td>0.0</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

![HSV Color Model Diagram]
Intuitive Color Spaces

HSV is an intuitive color space, corresponding to our perceptual notions of tint, shade, and tone.

- **Hue (H)** is the angle around the vertical axis.
- **Saturation (S)** is a value from 0 to 1 indicating how far from the vertical axis the color lies.
- **Value (V)** is the height of the “hexcone”.

Precise Color Specifications

- Pigment-mixing is subjective — depends on human observer, surrounding colors, lighting of the environment, etc.
- We need an objective color specification.
- Light is electromagnetic energy in the 400 to 700 nm wavelength range.
- **Dominant wavelength** is the wavelength of the color we “see.”
- **Excitation purity** is the proportion of pure colored light to white light.
- **Luminance** is the amount (or intensity) of the light.

Electromagnetic Spectrum

- Visible light frequencies range between ...
  - Red = $4.3 \times 10^{14}$ hertz (700nm)
  - Violet = $7.5 \times 10^{14}$ hertz (400nm)

Visible Light

- **Hue** = dominant frequency (highest peak)
- **Saturation** = excitation purity (ratio of highest to rest).
- **Lightness** = luminance (area under curve).

Color Matching

- In order to *match* a color, we can adjust the brightness of 3 overlapping primaries until the two colors look the same.
  - $C = \text{color to be matched}$
  - RGB = laser sources (R=700nm, G=546nm, B=435nm)

Humans have trichromatic color vision.

Linear Color Matching

*Grassman’s Laws:*

1. Scaling the color and the primaries by the same factor preserves the match: $2C = 2R + 2G + 2B$
2. To match a color formed by adding two colors, add the primaries for each color: $C_1 + C_2 = (R_1 + R_2) + (G_1 + G_2) + (B_1 + B_2)$
RGB Spectral Colors

- Match each pure color in the visible spectrum (rainbow)
- Record the color coordinates as a function of wavelength

![Figure 15.5 from H&B](image)

Human Color Vision

- Humans have 3 light sensitive pigments in their cones, called L, M, and S
- Each has a different spectral response curve:
  \[ L = \int L(\lambda)E(\lambda)d\lambda \]
  \[ M = \int M(\lambda)E(\lambda)d\lambda \]
  \[ S = \int S(\lambda)E(\lambda)d\lambda \]
- This leads to metamerism
- "Tristimulus" color theory

Just Noticeable Differences

- The human eye can distinguish hundreds of thousands of different colors
- When two colors differ only in hue, the wavelength between just noticeably different colors varies with the wavelength:
  - More than 10 nm at the extremes of the spectrum
  - Less than 2 nm around blue and yellow
  - Most JND hues are within 4 nm.
- Altogether, the eye can distinguish about 128 fully saturated hues
- Human eyes are less sensitive to hue changes in less saturated light (not a surprise)

Luminance

- Compare color source to a gray source

\[ Y = .30R + .59G + .11B \]

Color signal on a BW TV (Except for gamma)

Chromaticity and the CIE

- Negative spectral matching functions?
- Some colors cannot be represented by RGB
- Enter the CIE
- Three new standard primaries called X, Y, and Z
- Y has a spectral matching function exactly equal to the human response to luminance

XYZ Matching Functions

- Match all visible colors with only positive weights
- Y matches luminance
- These functions are defined tabularly at 1-nm intervals
- Linear combinations of the R,G,B matching functions
Spectral Locus

Measuring Color

• Colorimeters measure the X, Y, and Z values for any color
• A line between the “white point” of the chromaticity diagram and the measured color intersects the horseshoe curve at exactly the dominant wavelength of the measured color
• A ratio of lengths will give the excitation purity of the color
• Complementary colors are two colors that mix to produce pure white
• Some colors are non-spectral — their dominant wavelength is defined as the same as their complimentary color, with a “c” on the end

Gamuts

A Problem With XYZ Colors

• If we have two colors C1 and C2, and we add ΔC to both of them, the differences between the original and new colors will not be perceived to be equal
• This is due to the variation of the just noticeable differences in saturated hues
• XYZ space is not perceptually uniform
• LUV space was created to address this problem

The RGB Color Model

• This is the model used in color CRT monitors
• RGB are additive primaries
• We can represent this space as a unit cube:
More on RGB
- The color gamut covered by the RGB model is determined by the chromaticities of the three phosphors.
- To convert a color from the gamut of one monitor to the gamut of another, we first measure the chromaticities of the phosphors.
- Then, convert the color to XYZ space, and finally to the gamut of the second monitor.
- We can do this all with a single matrix multiply.

The CMY Color Model
- Cyan, magenta, and yellow are the complements of red, green, and blue.
  - We can use them as filters to subtract from white.
  - The space is the same as RGB except the origin is white instead of black.
- This is useful for hardcopy devices like laser printers.
  - If you put cyan ink on the page, no red light is reflected.

\[
\begin{bmatrix}
C \\
M \\
Y
\end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 \\ 1 & 0 & -1 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}
\]

CMYK
- Most printers actually add a fourth color, black.
- Use black in place of equal amounts of C, M, and Y.

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

- Why?
  - Black ink is darker than mixing C, M, and Y.
  - Black ink is cheaper than colored ink.

The YIQ Color Model
- YIQ is used to encode television signals.
  - Y is the CIE Y primary, not yellow.
  - Y is luminance, so I and Q encode the chromaticities of the color.
- If we just throw I and Q away, we have black and white TV.

\[
\begin{bmatrix}
Y \\
I \\
Q
\end{bmatrix} = \begin{bmatrix} 0.299 & 0.587 & 0.114 \\ 0.596 & -0.275 & -0.321 \\ 0.212 & -0.528 & 0.311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}
\]

- This assumes known chromaticities for your monitor.

- Backwards compatibility with black and white TV.
- More bandwidth can be assigned to Y.