Raster Graphics and Color

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CS445: Intro Graphics

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Overview

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

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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)

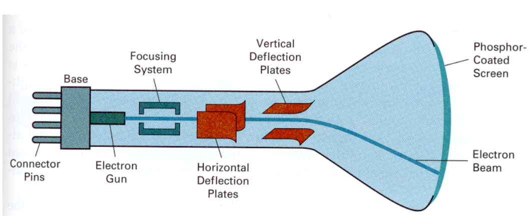

Figure 2.4 from H&B

Liquid Crystal Display (LCD)

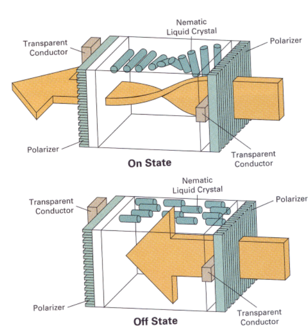

Figure 2.16 from H&B

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Raster Graphics Systems

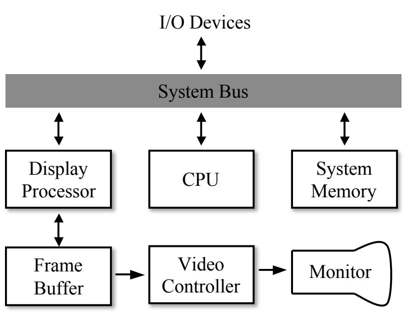


Figure 2.29 from H&B

Frame Buffer

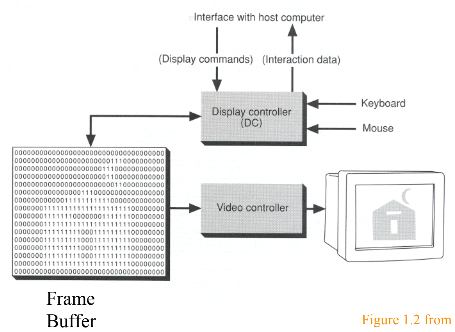
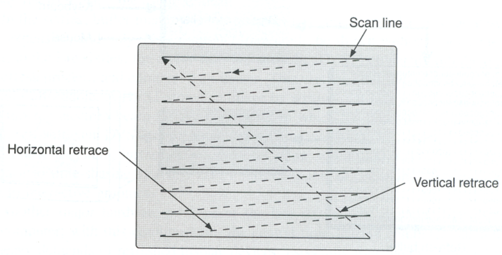


Figure 1.2 from FvDFH

Frame Buffer Refresh

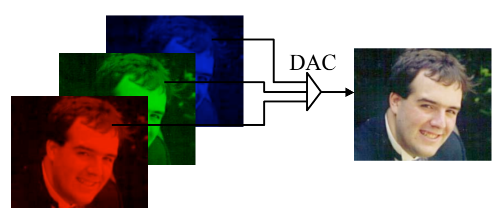


Refresh rate is usually 60-120 Hz

Figure 1.3 from FvDFH

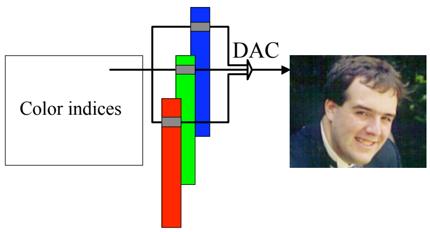
Direct Color Framebuffer

- 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



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 CRT

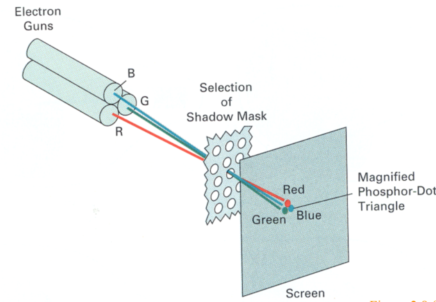


Figure 2.8 from H&B

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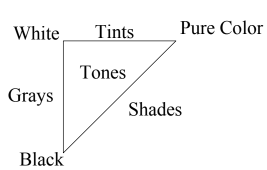
Specifying Color

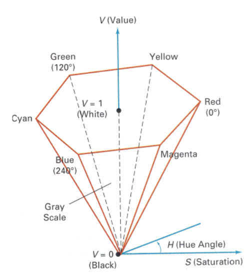
- Color perception usually involves three quantities:
  - *Hue*: Distinguishes between colors like red, green, blue, etc
  - *Saturation*: How far the color is from a gray of equal intensity
  - *Lightness*: The perceived intensity of a reflecting object
- Sometimes lightness is called *brightness* if 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



HSV Color Model



H	S	V	Color
0	1.0	1.0	Red
120	1.0	1.0	Green
240	1.0	1.0	Blue
*	0.0	1.0	White
*	0.0	0.5	Gray
*	*	0.0	Black
60	1.0	1.0	
270	0.5	1.0	
270	0.0	0.7	

Figure 15.16&15.17 from H&B

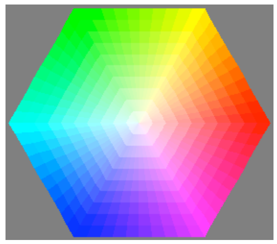
Intuitive Color Spaces

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"

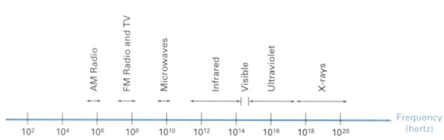


Precise Color Specifications

- 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

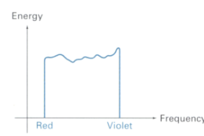
- Visible light frequencies range between ...
  - Red = 4.3 x 10^{14} hertz (700nm)
  - Violet = 7.5 x 10^{14} hertz (400nm)



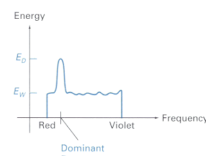
Figures 15.1 from H&B

Visible Light

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



White Light

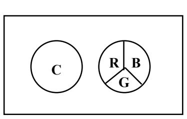


Orange Light

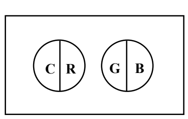
Figures 15.3-4 from H&B

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 = color to be matched
  - RGB = laser sources (R=700nm, G=546nm, B=435nm)



C = R + G + B



C + R = G + B

- 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

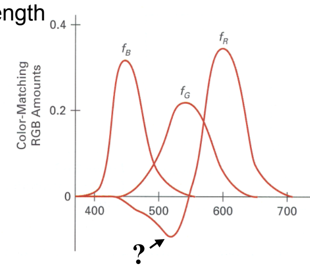


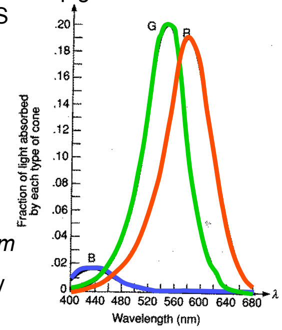
Figure 15.5 from H&B

Human Color Vision

- Humans have 3 light sensitive pigments in their cones, called L, M, and S
- Each has a different *spectral response curve*:

$$L = \int L(\lambda)E(\lambda)d\lambda$$
$$M = \int M(\lambda)E(\lambda)d\lambda$$
$$S = \int S(\lambda)E(\lambda)d\lambda$$

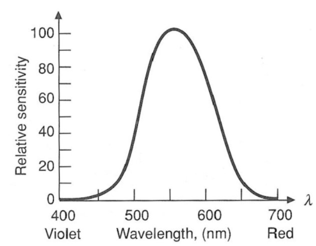
- This leads to *metamerism*
- "Tristimulus" color theory



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

Luminance

Y = .30R + .59G + .11B

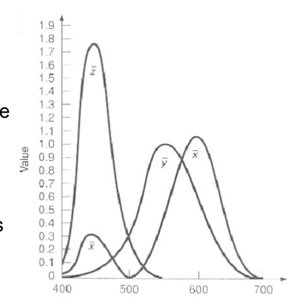
Color signal on a BW TV (Except for gamma)

Chromaticity and the CIE

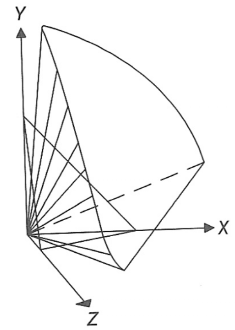
- Negative spectral matching functions?
- Some colors cannot be represented by RGB
- Enter the *CIE*
- Three new standard primaries called **X, Y,** and **Z**
- **Y** has a spectral matching function exactly equal to the human response to *luminance*

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

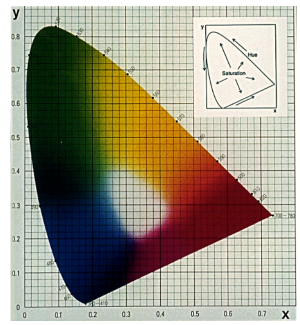


Spectral Locus



Human perceptual gamut

Chromaticity Diagram



Converting from RGB to XYZ is a snap:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 2.77 & 1.75 & 1.13 \\ 1.00 & 4.59 & 0.06 \\ 0.00 & 0.57 & 5.59 \end{bmatrix} \begin{bmatrix} R_\lambda \\ G_\lambda \\ B_\lambda \end{bmatrix}$$

$$x = \frac{X}{X+Y+Z}$$

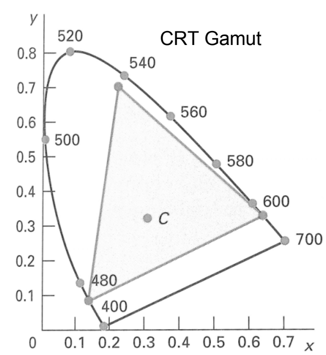
$$y = \frac{Y}{X+Y+Z}$$

Given x, y, and **Y**, we can recover the **X**,**Y**,**Z** coordinates

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

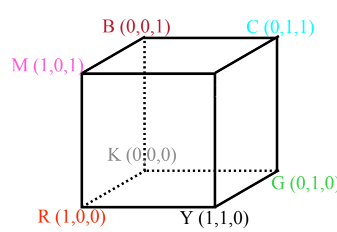


A Problem With XYZ Colors

- 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 chromaticites 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

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

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 chromaticity 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