Johns Hopkins
Engineering for Professionals

605.767 Applied Computer Graphics

Brian Russin

JOHNS HOPKINS
WHITING SCHOOL
of ENGINEERING

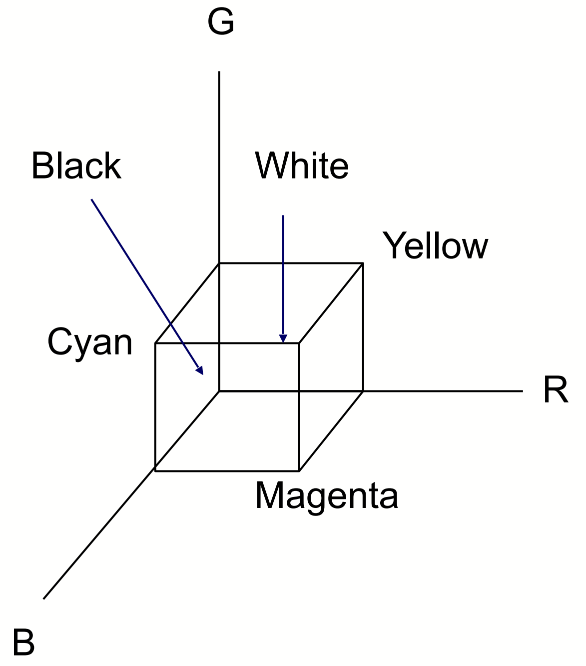
Module 4D
Color Spaces

Color Spaces in Computer Graphics

- RGB
- Cyan, Magenta, Yellow
- YIQ
- Hue, Saturation, Value
- Hue, Lightness, Saturation
- CIELUV and TekHVC

RGB Model

- A triple in this space produces a specific color on a specific monitor
  - Red+green= orange (yellow)
  - Red+blue=magenta (purple)
  - Green+blue=cyan(blue-green)
- Monitors (not to mention other display devices) can differ from each other
  - RGB triple may produce a different color on one monitor than another
- Describes a 3 sample version of spectral space

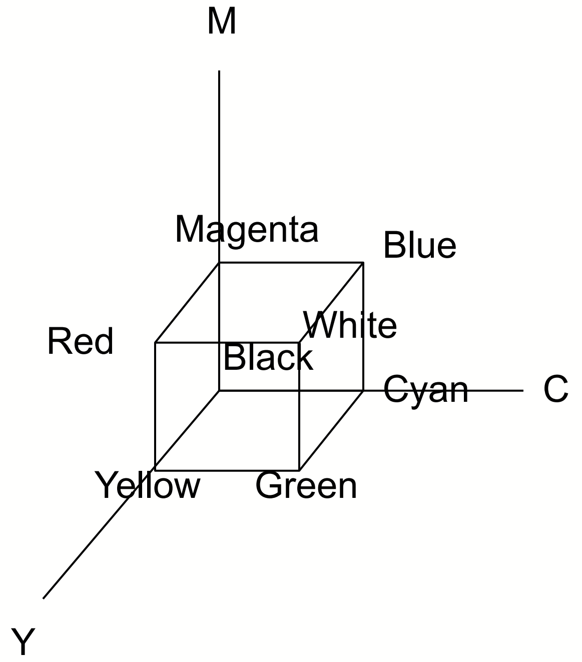


Problems with RGB Color Space

- Perceptually non-linear
  - Equal distances in RGB space are not perceptually equal
  - Low RGB values produce small changes in response on most monitors
    - Gamma response curve
- RGB is a subset of perceptual color space
- Not a good color description system
  - Other spaces provide better color selection mechanisms
- Different RGB values produce different colors on different output devices

Cyan, Yellow, Magenta (CMY)

- Defined with 'subtractive' primary colors
  - Subtractive process
    - White light reflected from cyan ink leaves no red component
    - Magenta subtracts green, yellow subtracts blue
- Used for hard copy devices like plotters
  - CMYK (cyan-magenta-yellow-black)
- Cyan, magenta inks produce blue
- Cyan, yellow inks produce green
- Yellow, magenta inks produce red



$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1.0 \\ 1.0 \\ 1.0 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix} \qquad \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.0 \\ 1.0 \\ 1.0 \end{bmatrix} - \begin{bmatrix} C \\ M \\ Y \end{bmatrix}$$

YIQ

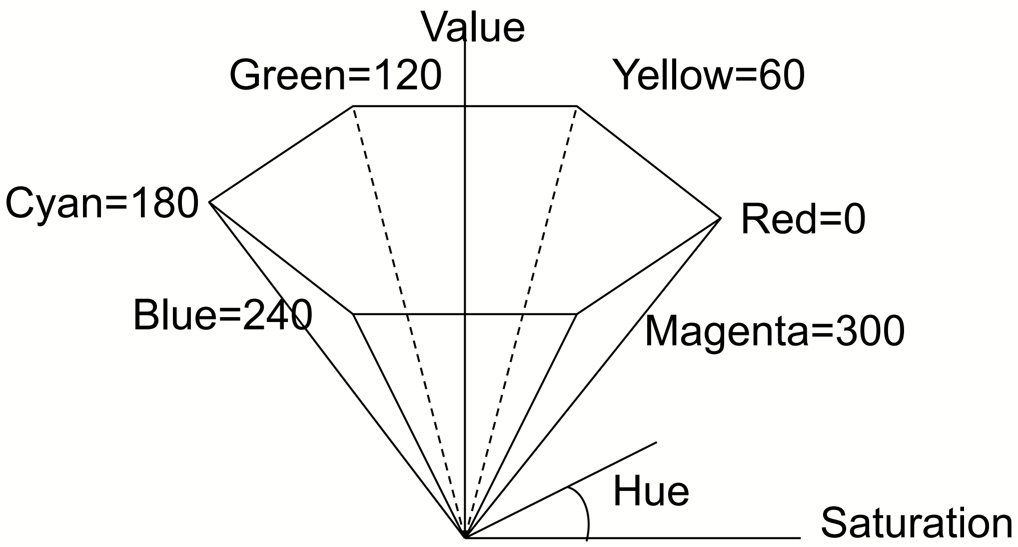
- Used in television broadcast
  - National Television System Committee (NTSC)
- Produces a single composite signal rather than separate RGB
- Y is the luminance term - same as CIE Y
  - Black and white TV only needs the Y information
- Chromaticity incorporated into the I and Q part of the signal
  - I contains the orange - cyan hue for flesh tone shading
  - Q contains green - magenta hue
- Transformation based on NTSC standard RGB chromaticities
  - Larger proportions of red and green assigned to Y
    - Red and green contribute more to luminance than blue

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

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.0 & 0.956 & 0.620 \\ 1.0 & -0.272 & -0.647 \\ 1.0 & -1.108 & 1.705 \end{bmatrix} \begin{bmatrix} Y \\ I \\ Q \end{bmatrix}$$

Hue, Saturation, Value

- Hexagonal cone
  - Value (similar to brightness) in the vertical axis
  - Pure hue along outside of the hexagon
  - Saturation from hexagon edge (fully saturated) to center axis (fully desaturated or white-gray)
- Based on polar coordinates
  - Hue is specified in the range 0 to 360
  - Complementary colors are 180 degrees apart



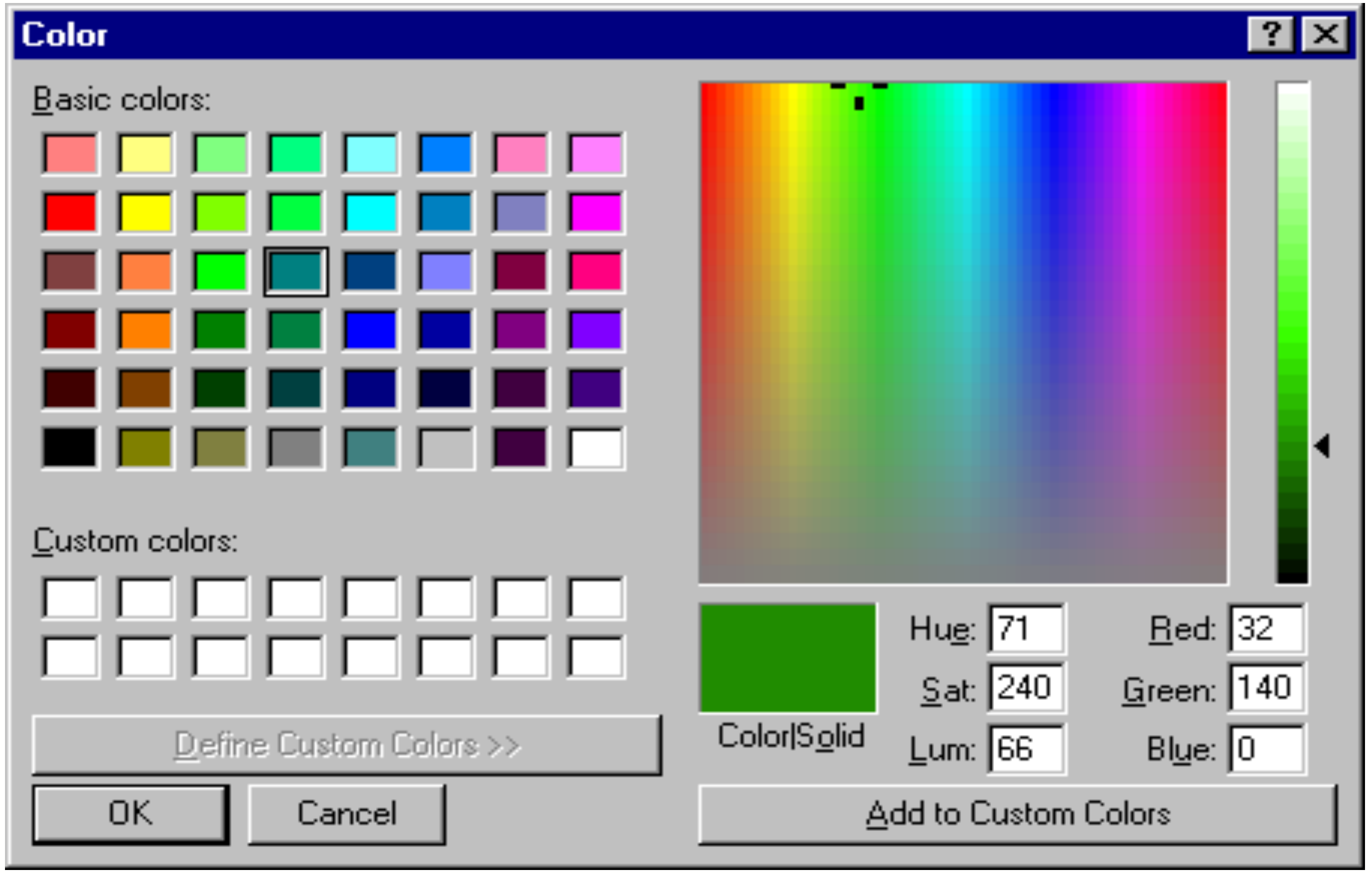
Hue, Saturation, Value (cont.)

- Can assign hue names to numbers
  - Provide a color naming system
  - Similar to Munsell terms
    - Munsell developed a color classification system
    - Hue, chroma, value in a standard set of color plates
- Non-linear transformation of the RGB space
  - Another way of defining colors in the display device gamut
- Uses terms relating more to perceptual elements
  - Still many perceptual non-linearities
    - Perceptual changes in hue are non-linear in hue angle
- Easier to conceptualize than RGB
  - Better method than RGB for novice users to specify color
- Transformation from HSV to RGB (and the inverse) is provided in Hearn and Baker and Foley and van Dam
  - Not a single equation but a straightforward algorithm

Hue, Saturation, Lightness

- Modification of the HSV hexcone
  - Value now called lightness
    - Still corresponds to 'brightness'
  - L extends upwards to form a double hexcone
- White and black are single points
  - L = 0.0 is black
  - L = 1.0 is white
- Pure (fully saturated) hues lie at L = 0.5
  - Disadvantage when using the model as a software interface for color selection
- Conversion to RGB (and inverse) is provided online
  - https://www.rapidtables.com/convert/color/hsl-to-rgb.html

Sample Interactive Color Selection

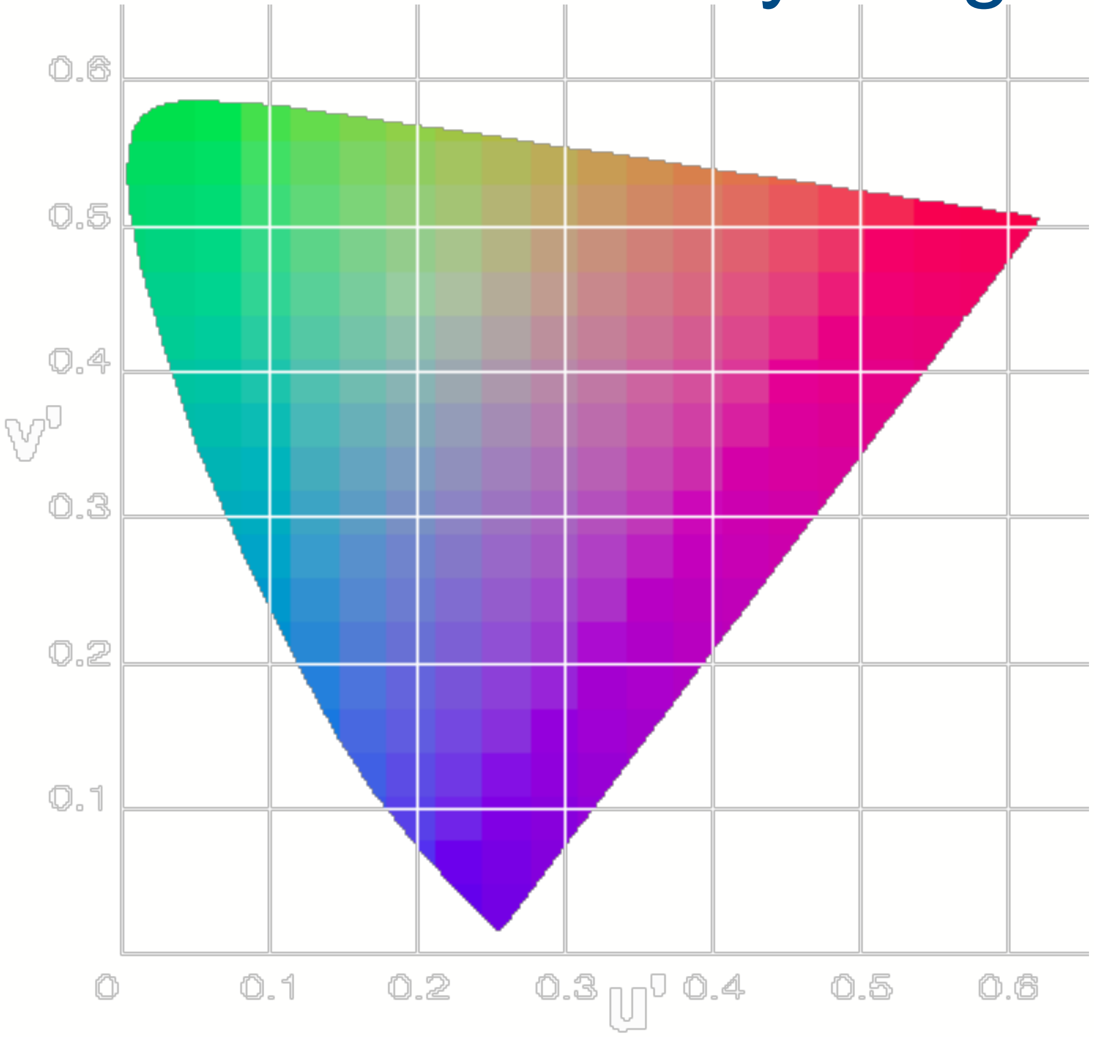


Microsoft Windows 98 control panel

CIELUV

- 1976 CIE modified the xyY color space to produce a more perceptually uniform color space
  - Based on color matching experiments
  - Can be described in a cylindrical coordinate system
- Defines chromaticity (u',v') as a transformation of x,y
  - $u' = 2x / (6y - x + 1.5)$
  - $v' = 4.5 y / (6y - x + 1.5)$
  - Y remains unchanged (still corresponds to luminance)
- 1976 **CIELUV (L*u*v*)** system transforms this space so that black-white axis lies at 0,0 to 0,100
  - $L^* = 116 (Y/Y_w)1/3 -16$
  - $u^* = 13L^* \ (u' - v'_w)$
  - $v^* = 13L^* \ (v' - v'_w)$
  - Where u_w, v_w, and Y_w are coordinates of a reference white

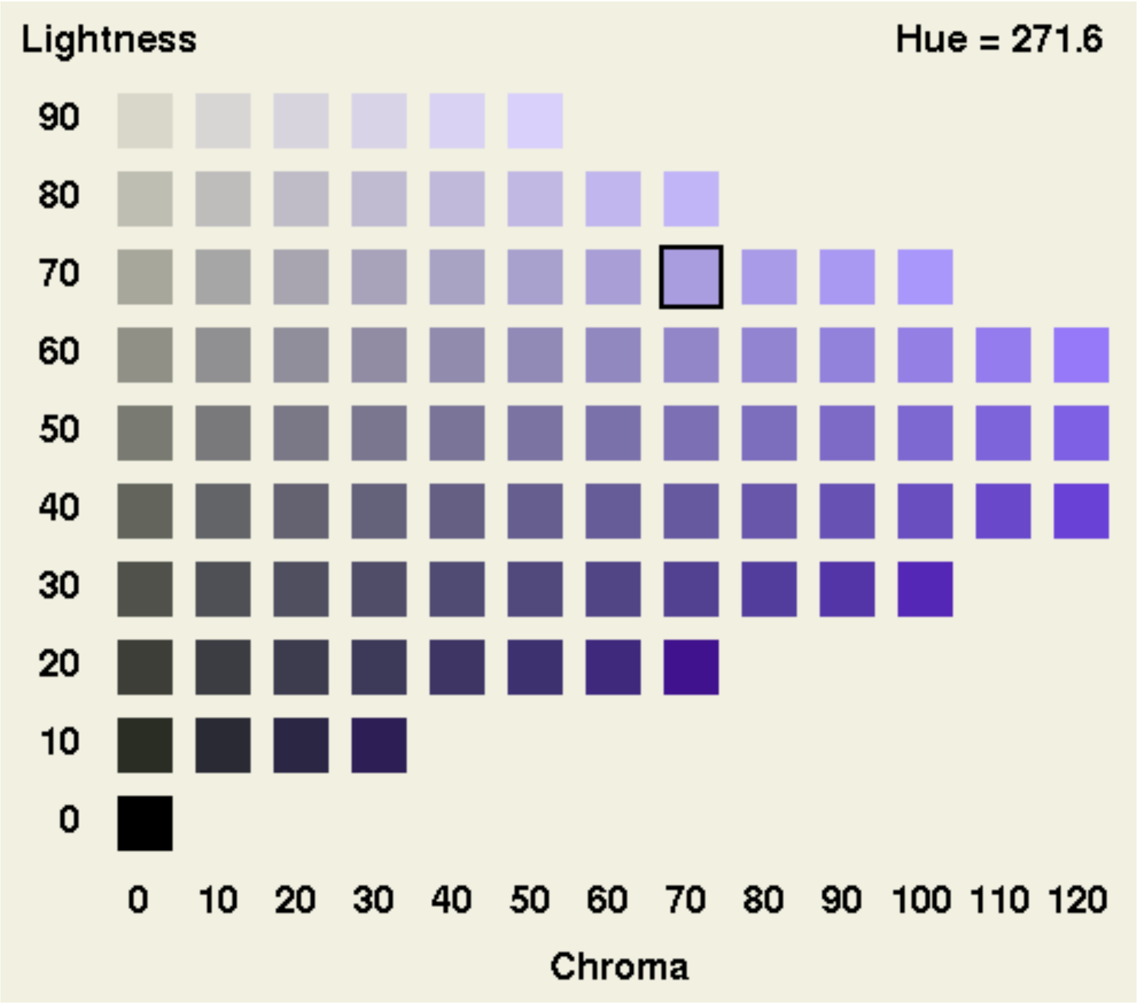
1976 CIE Chromaticity Diagram



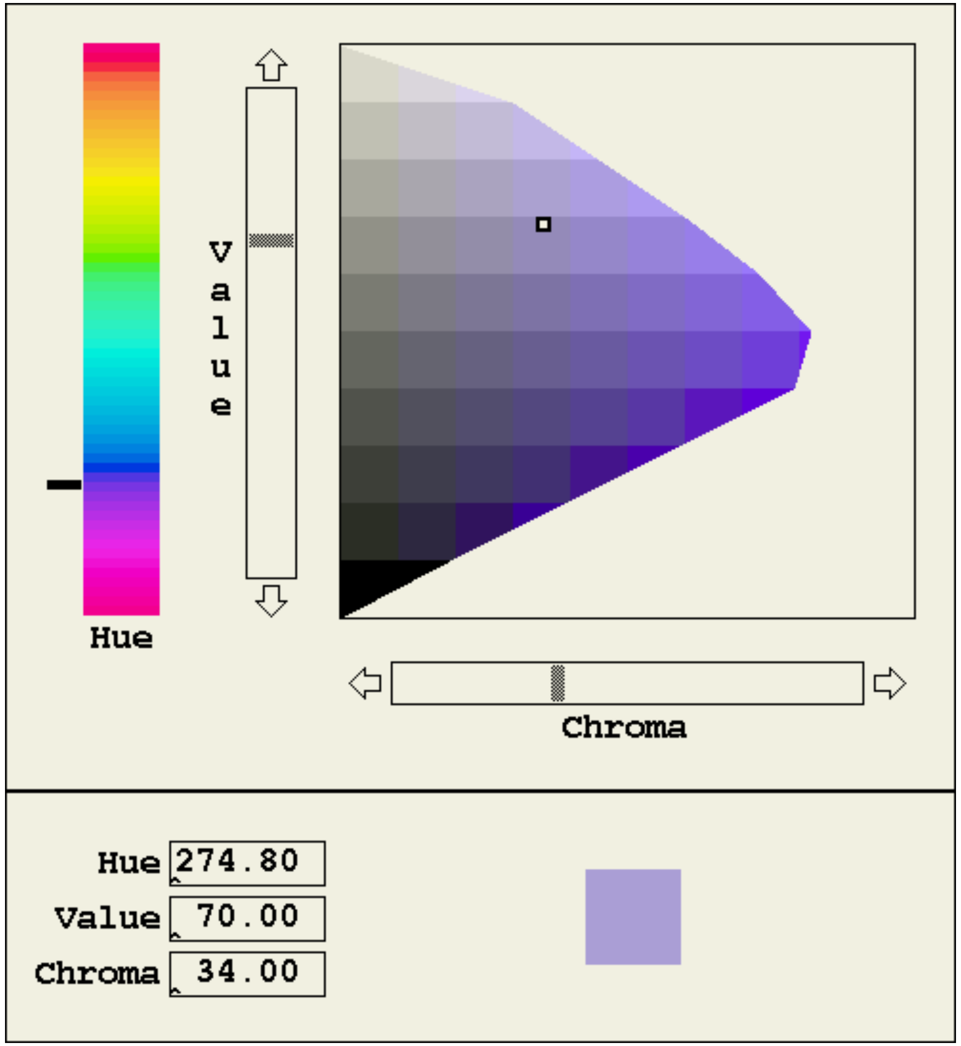
CIELUV (cont.)

- CIELUV L* is known as the psychometric lightness
  - Closer relation to perceived brightness / lightness
- Can define HSL in terms of CIELUV
  - Hue (0-360 degrees) = atan (v*/u*)
  - Value = L* (ranges from 0-100)
  - Saturation = $(u^{*2} + v^{*2})^{1/2}$ (called the CIELUV 1976 **uv chroma**)
- Tektronix HVC system uses CIELUV as as the basis for a color selection interface
  - Combines advantages of HSL as an interface with the perceptual benefits of CIELUV as a color space
  - An “electronic” version of the Munsell color system
  - Patented
    - https://patents.google.com/patent/US1617024A/en

Hue, Value, Chroma



Tektronix HVC User Input



Mapping Colors from One Gamut to Another

- Two CRTs with different phosphors have different color gamuts
  - To map from one to another, map each into XYZ

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{bmatrix} \begin{bmatrix} R_m \\ G_m \\ B_m \end{bmatrix}$$

  - Terms of the matrix are the weights applied to monitor's RGB to find X, Y, Z
- With M_1 and M_2 as matrices that convert each monitor into XYZ:
  - $M_2^{-1}M_1$ converts from the RGB of monitor 1 into the RGB of monitor 2

Deriving the Color Mapping Matrices

- Derived based on display device
  - For accuracy requires precise measurement and calibration of the display device
  - Use device phosphor coordinates
  - Assumes equal RGB voltages (1,1,1) produce the desired white
    - Known as color temperature
    - Usually desirable to be near D_{65} (x=0.313, y = 0.329, z = 0.358)
  - See Watt: Section 15.5.2

Assuming calibration to D_{65} reference white and phosphor chromaticities of red (0.620, 0.330), green (0.210, 0.685), and blue (0.150, 0.063):

$$M = \begin{bmatrix} 0.584 & 0.188 & 0.179 \\ 0.311 & 0.614 & 0.075 \\ 0.047 & 0.103 & 0.939 \end{bmatrix} \qquad M^{-1} = \begin{bmatrix} 2.043 & -0.568 & -0.344 \\ -1.035 & 1.939 & 0.042 \\ 0.011 & -0.184 & 1.078 \end{bmatrix}$$

Note: Haines and Moller present different matrices on page 278 (p. 215 3rd Edition)
See http://www.brucelindbloom.com/index.html?Eqn_XYZ_to_RGB.html
for more examples based on RGB "Working Space"

Color Clipping

- Color clipping is necessary if color transformation produces colors outside the display device gamut
  - When converting a color from one device space to another
  - Common when converting from CRT to a printer/plotter
  - Chromaticity outside the gamut (negative RGB values)
  - Chromaticity inside the gamut but intensity unattainable (RGB > 1 or max)
- Simple clamping of values to range [0,1] works but:
  - Multiple input colors map to same color
  - Bad approach when color differences need to be presented
- Other approaches produce a shift in hue, saturation, or value (brightness)
  - Watt describes a couple approaches
  - Foley and van Dam reference a method by Hall