Color Reproduction

Visual Perception

What is color reproduction?

- Use a device to capture/display the original scene
- Success lies in how 'close' to the original
- Most of the time we do not have a reference

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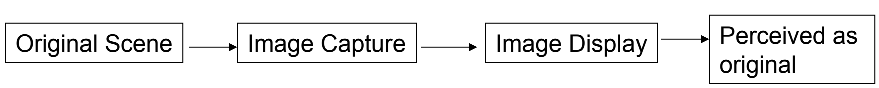
Two types of color reproduction

- Subtractive
  - Dyes and inks
  - Absorbs parts of the spectra
  - Cyan, Magenta and yellow are primaries
- Additive
  - Projectors, monitors (based on projection of light)
  - Red, Green and Blue

Color Reproduction has become difficult

- Traditionally linear model



- Currently star model

  - Require a device independent color space

Basic Principles

- Correct mapping of critical reference colors
- Correct mapping of the gray axis
  - Otherwise, color cast or color tint
- Control of tone reproduction
  - Maintain all details against tone compression
- Control of overall colorfulness
- Control of sharpness, texture and other artifacts

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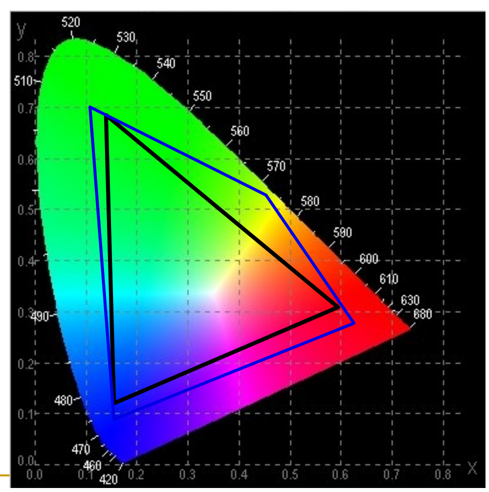
Characterizing additive displays

- Color gamut
  - Represented on chromaticity diagram
  - More saturated colors, bigger the gamut
  - Not possible to cover the entire range of colors seen by humans



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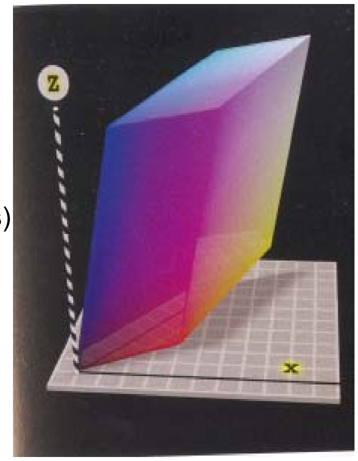
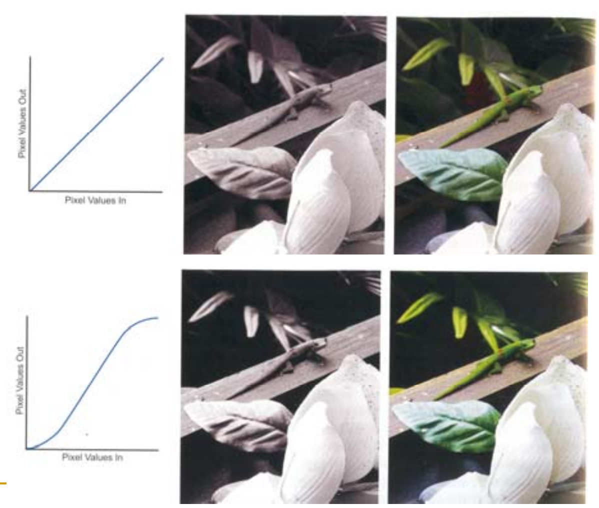
Characterizing additive displays

- Color gamut
  - Is this sufficient?
  - Information about the luminance
    - White point
    - Dynamic Range (contrast)
    - Maximum luminance (brightness)
  - Can reconstruct a 3D gamut in XYZ space from this information



Characterizing additive displays

- Tone mapping
  - How the input value maps to output intensity
  - Affects brightness, contrast and saturation



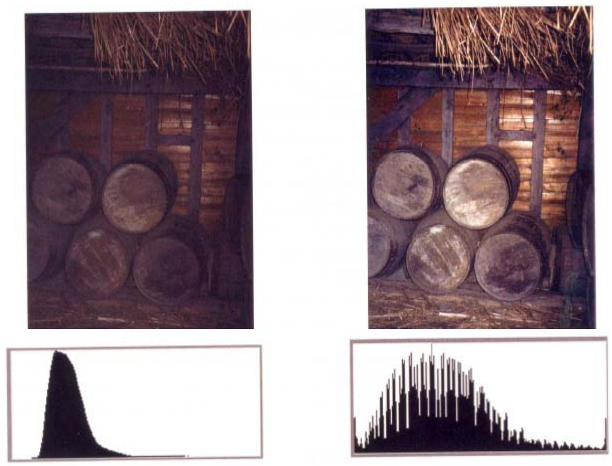
Characterizing additive displays

- Tone mapping
  - How the input value maps to output intensity
  - Affects brightness, contrast and saturation

Transfer Function

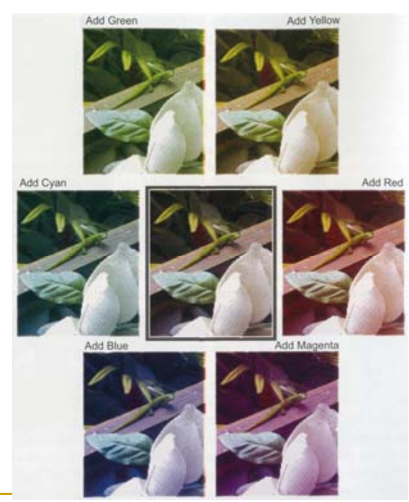
- Monotonic, smooth with no flat regions
- Brightness and contrast controls

Histogram Stretching



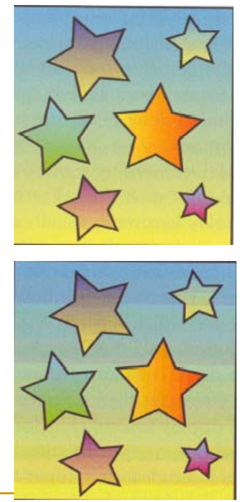
Characterizing additive displays

- Color Balance
  - Relative proportions of primaries while forming a color
  - Affects hue, saturation and brightness
  - Can be changed by changing the transfer function



Characterizing additive displays

- Intensity Resolution
  - Number of levels perceptually distinguishable
  - Number of digital levels
  - Contouring if insufficient resolution



CRT Displays

- sRGB gamut
  - Aging by decreasing brightness of primaries
  - Aging of blue is faster
  - Yellowish cast in the picture
  - Chromaticity of primaries remain same
  - But brightness changes leads to shift in white point
- Transfer function
  - $I = k (V_0+V)^{\gamma}$

LCD Displays

- Saturated primaries imply dim display
- Unsaturated primaries imply bright display
- High brightness backlight and saturated filters to assure bright and colorful display
  - Trade off with power consumption
- Black offset or Flare
- Primaries usually less saturated then CRTs
  - Smaller color gamut

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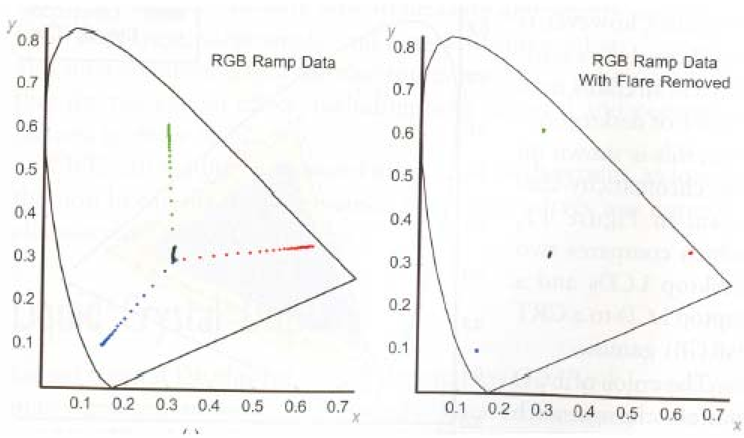
LCD Displays



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Projection Displays

- LCD arrays
  - Three LCD micropanels
    - Light division and later combination via lens
  - One LCD micropanel
    - Color wheel, shared temporally between primaries
- DLP
  - Array of Digital Micromirror Devices (DMD)
    - Intensity controlled by the time they are on
  - Three panels or color wheel with a single panel

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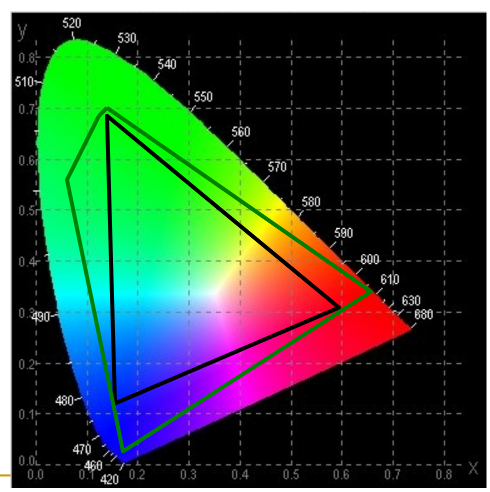
Projection Displays

- LCD or DMD
- Can have an extra filter
- Consequence of 4 primaries



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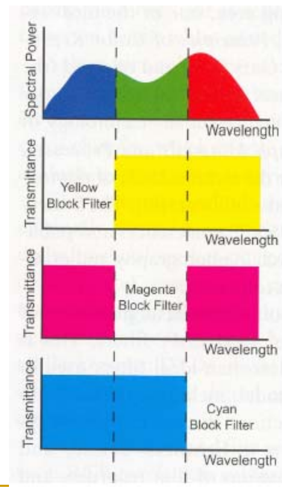
Subtractive Color System

- Layers of cyan, yellow and magenta dyes
  - Absorb red, blue and green light
- Depends on the illuminant
- Act as absorption filter
  - Ideally block filters
- Overlaying all the three dyes absorbs all wavelengths creating black



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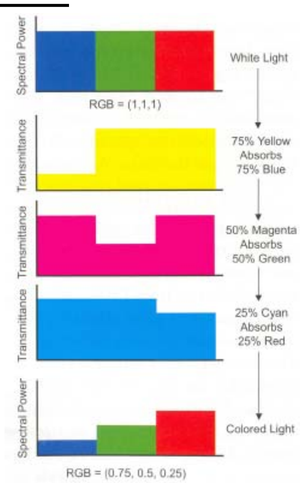
Creation of a color

- CMY = (1, 1, 1) – RGB
- (0.25, 0.5, 0.75) = (1, 1, 1) – (0.75, 0.5, 0.25)
- This works only for block filters



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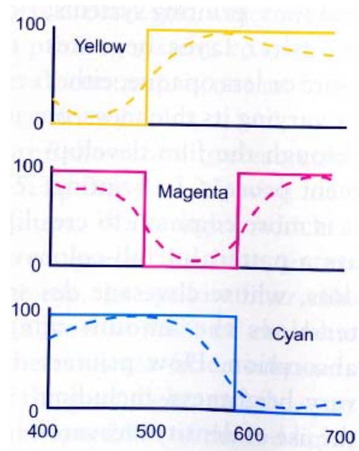
Real Fiilters

- Are not block filters
- Cross talk across different filters
- Due to ink impurities
- Grays should be formed by equal amount of three primaries
  - Seldom happens



Why use black?

- Better contrast
- Use of inexpensive black in place of expensive colored dyes
- Superimposing multiple dyes cause tearing of wet paper
- K for key
- Not an independent primary
  - Hence makes dark colors darker

How to use black?

- Initially only for neutral colors
  - Called *undercolor removal (UCR)*
- Colors with three components
  - Minimum of the three is the gray component
- Full gray component replacement
  - Only in inkjets where registration is a problem
- Partial gray component replacement
  - To achieve the best contrast

Gray Balancing

- The first step in printing is to decide how much of GCR to be used for the neutral grays
- However, every gray needs to be decided separately
- Called gray balancing
- Usually done by iteration
- No simple tristimulus model to decide components

Display/Sensor Model

$$
\begin{aligned}
E(i,u,v) = & \oplus h_r(i_r) \otimes (Q_r(u,v), x_r, y_r) \\
& \oplus h_g(i_g) \otimes (Q_g(u,v), x_g, y_g) \\
& \oplus h_b(i_b) \otimes (Q_b(u,v), x_b, y_b) \\
& \oplus (B(u,v), x_B, y_B)
\end{aligned}
$$

Display/Sensor Model

$$
\begin{aligned}
E(i,u,v) = & \oplus h_r(i_r) \otimes (Q_r(u,v), x_r, y_r) \\
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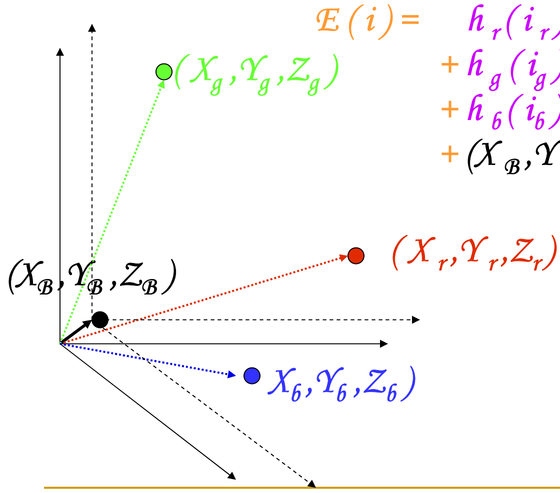
& \oplus h_b(i_b) \otimes (Q_b(u,v), x_b, y_b) \\
& \oplus (B(u,v), x_B, y_B)
\end{aligned}
$$

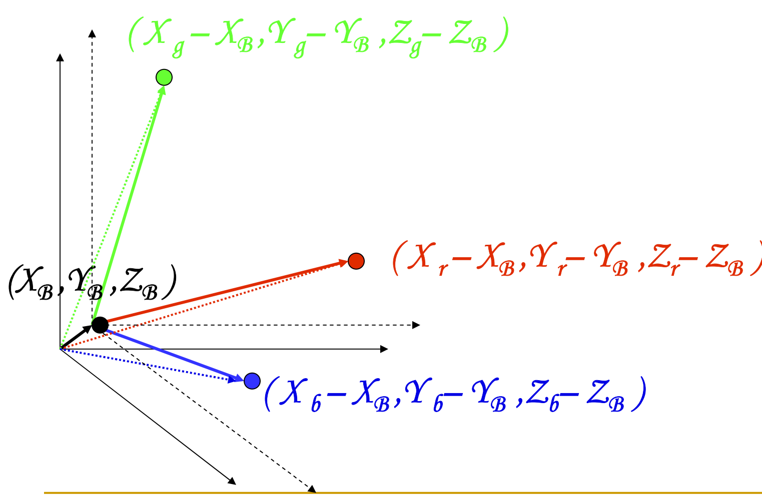
$$
\begin{aligned}
E(i) = & \; h_r(i_r)\,(X_r - X_B, Y_r - Y_B, Z_r - Z_B) \\
& + h_g(i_g)\,(X_g - X_B, Y_g - Y_B, Z_g - Z_B) \\
& + h_b(i_b)\,(X_b - X_B, Y_b - Y_B, Z_b - Z_B) \\
& + (X_B, Y_B, Z_B)
\end{aligned}
$$

Display/Sensor Model

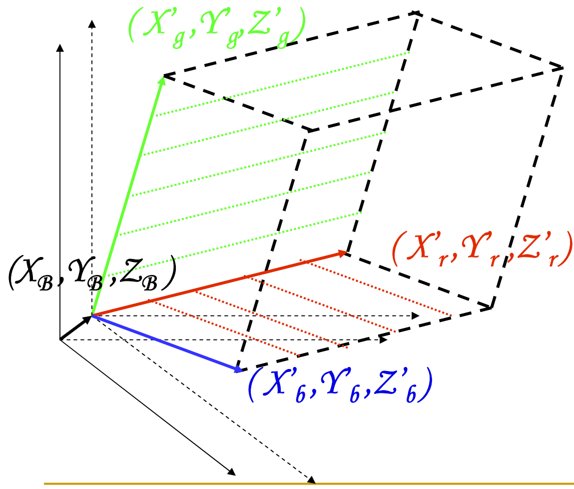
$$E(i) = h_r(i_r)\,(X_r - X_B, Y_r - Y_B, Z_r - Z_B) + h_g(i_g)\,(X_g - X_B, Y_g - Y_B, Z_g - Z_B) + h_b(i_b)\,(X_b - X_B, Y_b - Y_B, Z_b - Z_B) + (X_B, Y_B, Z_B)$$



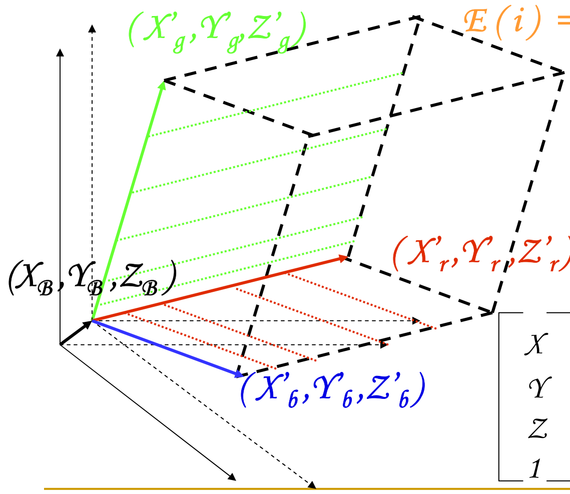
Display/Sensor Model



Display/Sensor Model



Display/Sensor Model



$$E(i) = h_r(i_r)\,(X'_r, Y'_r, Z'_r) + h_g(i_g)\,(X'_g, Y'_g, Z'_g) + h_b(i_b)\,(X'_b, Y'_b, Z'_b) + (X_B, Y_B, Z_B)$$

$$\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \begin{bmatrix} X'_r & X'_g & X'_b & X_B \\ Y'_r & Y'_g & Y'_b & Y_B \\ Z'_r & Z'_g & Z'_b & Z_B \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} h_r(i_r) \\ h_g(i_g) \\ h_b(i_b) \\ 1 \end{bmatrix}$$

Linear Devices

- $[X\ Y\ Z\ 1]^T = M\ [R\ G\ B\ 1]^T$
- Two devices
  - $[X\ Y\ Z\ 1]^T = M_1\ [R_1\ G_1\ B_1\ 1]^T$
  - $[X\ Y\ Z\ 1]^T = M_2\ [R_2\ G_2\ B_2\ 1]^T$
- $[R_2\ G_2\ B_2\ 1]^T = M_2^{-1}[X\ Y\ Z\ 1]$
  $= M_2^{-1}M_1[R_1\ G_1\ B_1\ 1]^T$

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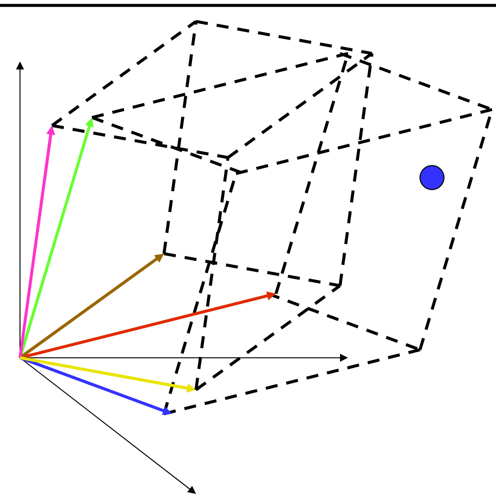
Display/Sensor Model



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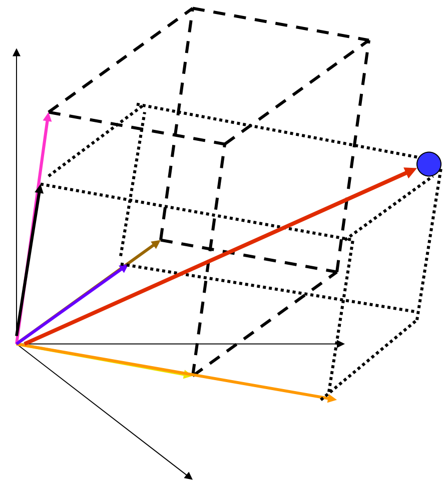
Out-of-Gamut Colors



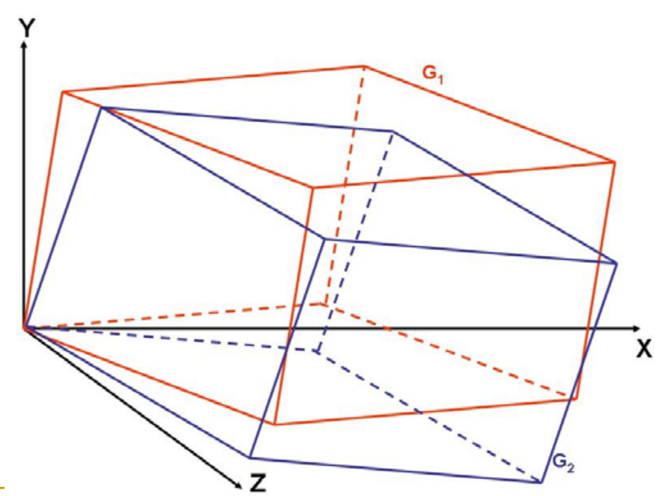
Gamut Mapping

- How to handle out of gamut colors?
  - Mapping them to an in-gamut colors
  - Many methods
- Used when going from devices to devices
  - Monitors to Printers

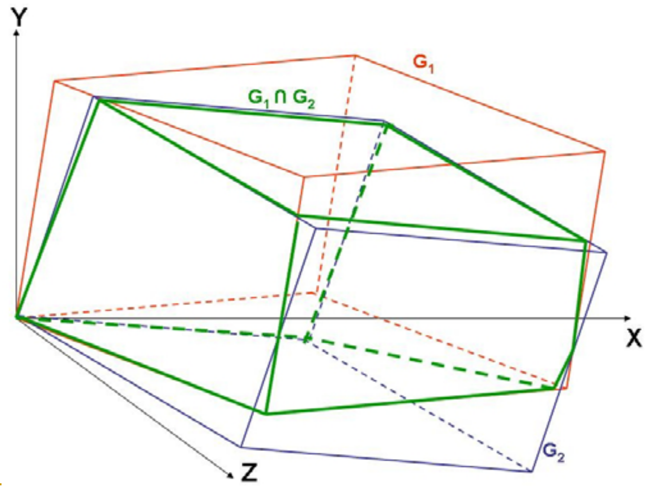
Gamut Matching

- Find a common color gamut defined by R_c, G_c, B_c
- Find the common function M_c
  - $[X\ Y\ Z\ 1]^T = M_c\ [R_c\ G_c\ B_c\ 1]^T$
- For any device i
  - $[R_i\ G_i\ B_i\ 1]^T = M_i^{-1}M_c\ [R_c\ G_c\ B_c\ 1]^T$

Two gamut

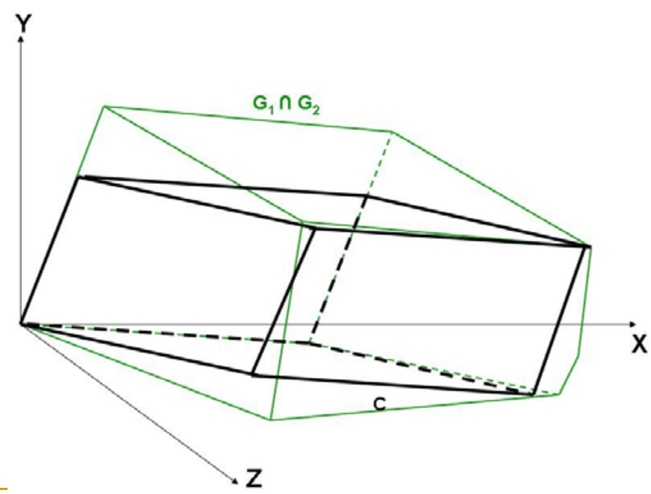


Find their intersection

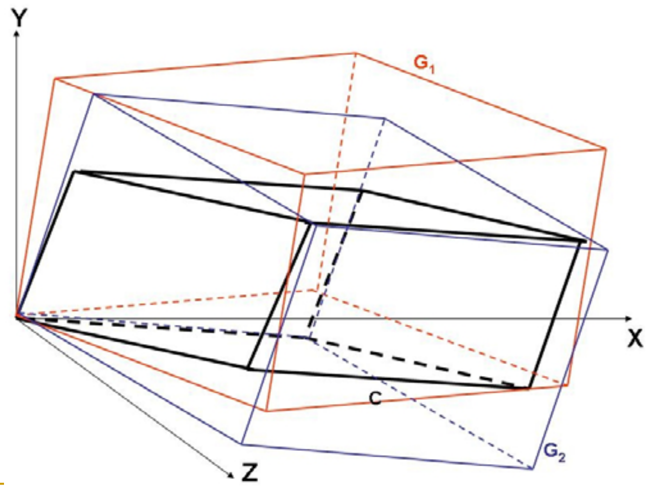


Need not be a parallelopipped

Find the common gamut



Find the mapping function



Gamut Matching

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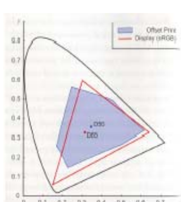
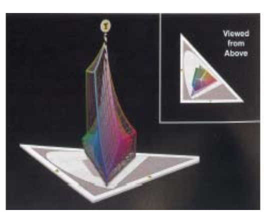
- For any device i
  - $[R_i\ G_i\ B_i\ 1]^T = M_i^{-1} M_c\ [R_c\ G_c\ B_c\ 1]^T$

Three/Four Primary Systems

- We dealt with only three primary systems
- Any n non-parallel vector form a basis in n-dimensional space
  - Vectors will be linearly independent
  - All other vectors can be expressed as a linear combination of the basis vectors
  - Gamut will always be convex polytope
- The primaries form basis in 3D color space

Additive subtractive mapping

Gamut Mapping

- Perceptual
- Saturated
- Relative colorimetric