Full Gamut Color Matching for Tiled Display Walls

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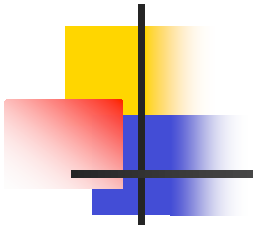
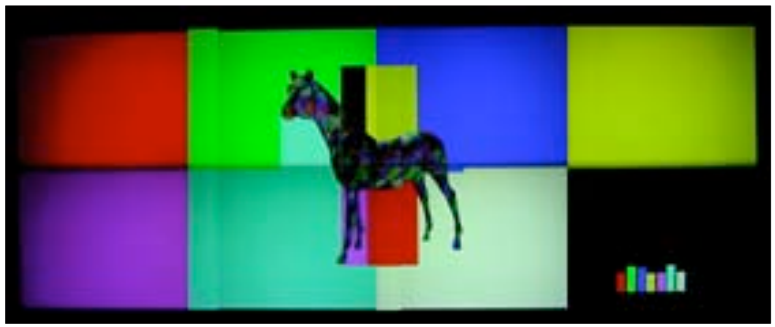


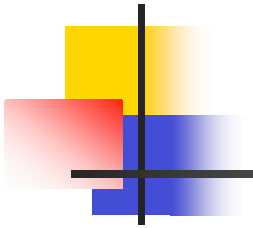
Talk Outline

- Introduction
- Previous Work
- Algorithm Description
- Algorithm Evaluation
- Questions and Comments

The Goal: Seamless Display Walls

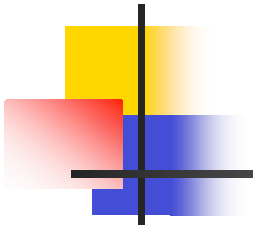
- Geometric Alignment
- Luminance Balancing
- Color Correction





Causes of Color Imbalance

- Differing color primaries
  - Projector bulbs
  - Color filters
- Differing RGB color proportions
  - Color temperature setting
  - RGB luminance mismatch
- Contributing to these
  - Manufacturing tolerances
  - Temporal decay
  - Differences in model/brand



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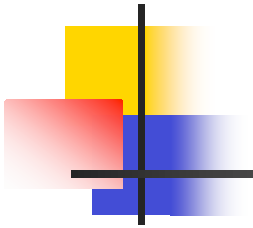


Previous Work

- Majumder et al
  - Generalized description of color balancing problem
  - Independent RGB channel balancing
- Stone et al
  - Algorithm to find common gamut of LCD projectors
  - Characterization of difficulties with DLP projectors
  - Independent channel balancing

New Challenges

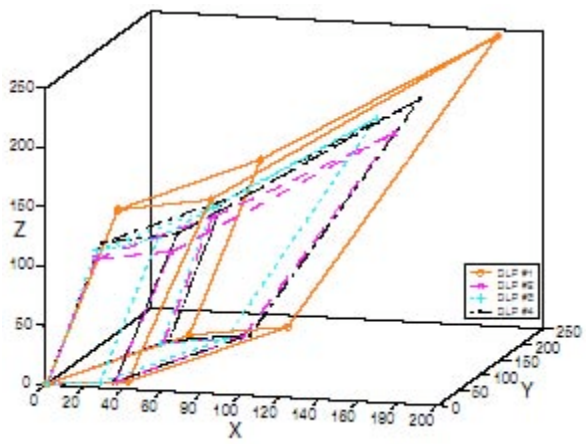
- DLP projectors have non-additive color response.
- Projectors of different model/brand may have different primary chromaticity values.

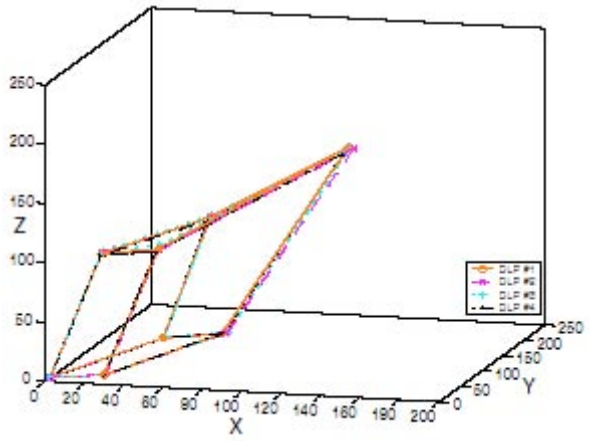
Color Gamuts

- A color gamut is the set of reproducible colors.

$$(X, Y, Z) = F(r, g, b) \quad r, g, b = 0...255$$

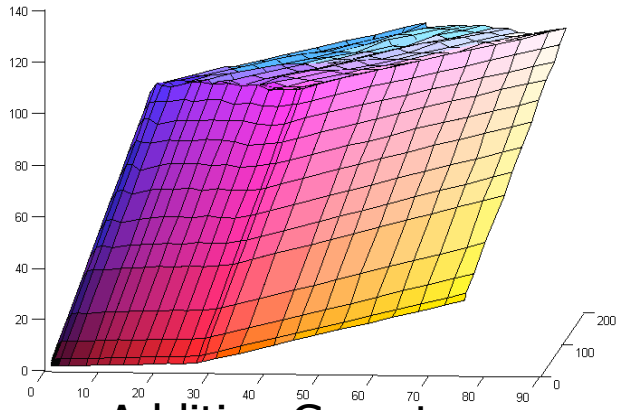
- Color gamuts are device dependent
- A collection of projectors are color balanced when
  - A standard gamut is defined within the intersecton of the individual gamuts
  - A standard color transfer function is used to map rgb triples into the standard gamut





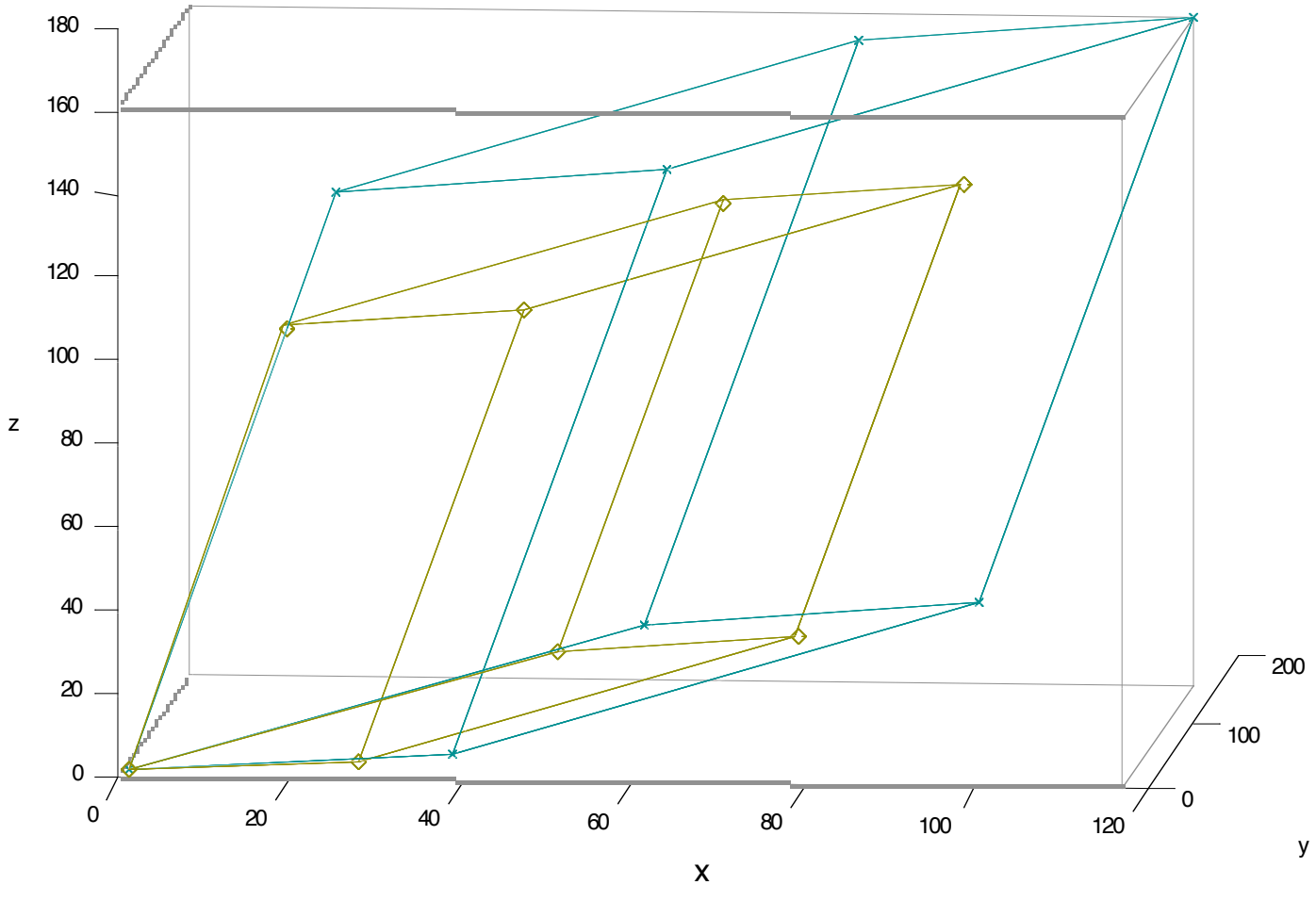
Additive Gamuts

- A gamut is additive if its color transfer function is distributive under addition.
  - Let F(r,g,b) be a device's color response to a rgb input
  - If F(r,g,b) = F(r,0,0) + F(0,g,0) + F(0,0,b)
    then F is defines an additive gamut.
- Nice properties of additive gamuts
  - The color transfer function F can be represented by a 3x3 matrix
  - Independent RGB channel balancing is effective at color balancing



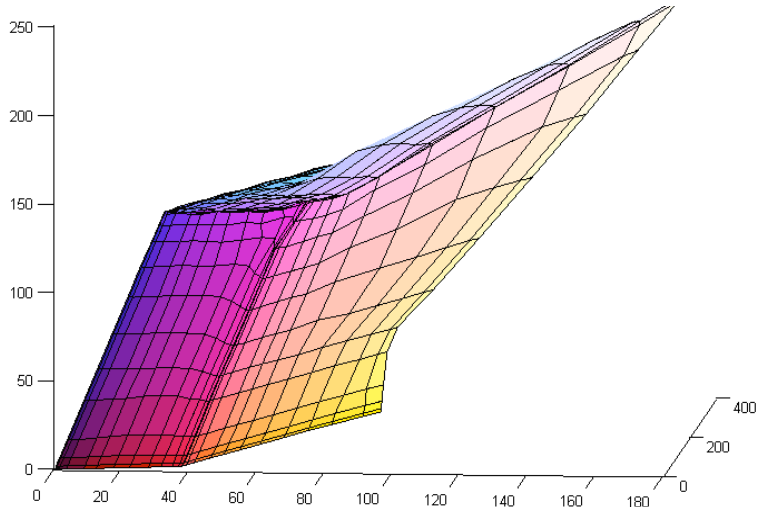
Additive Gamut

Channel balancing is effective on additive gamuts



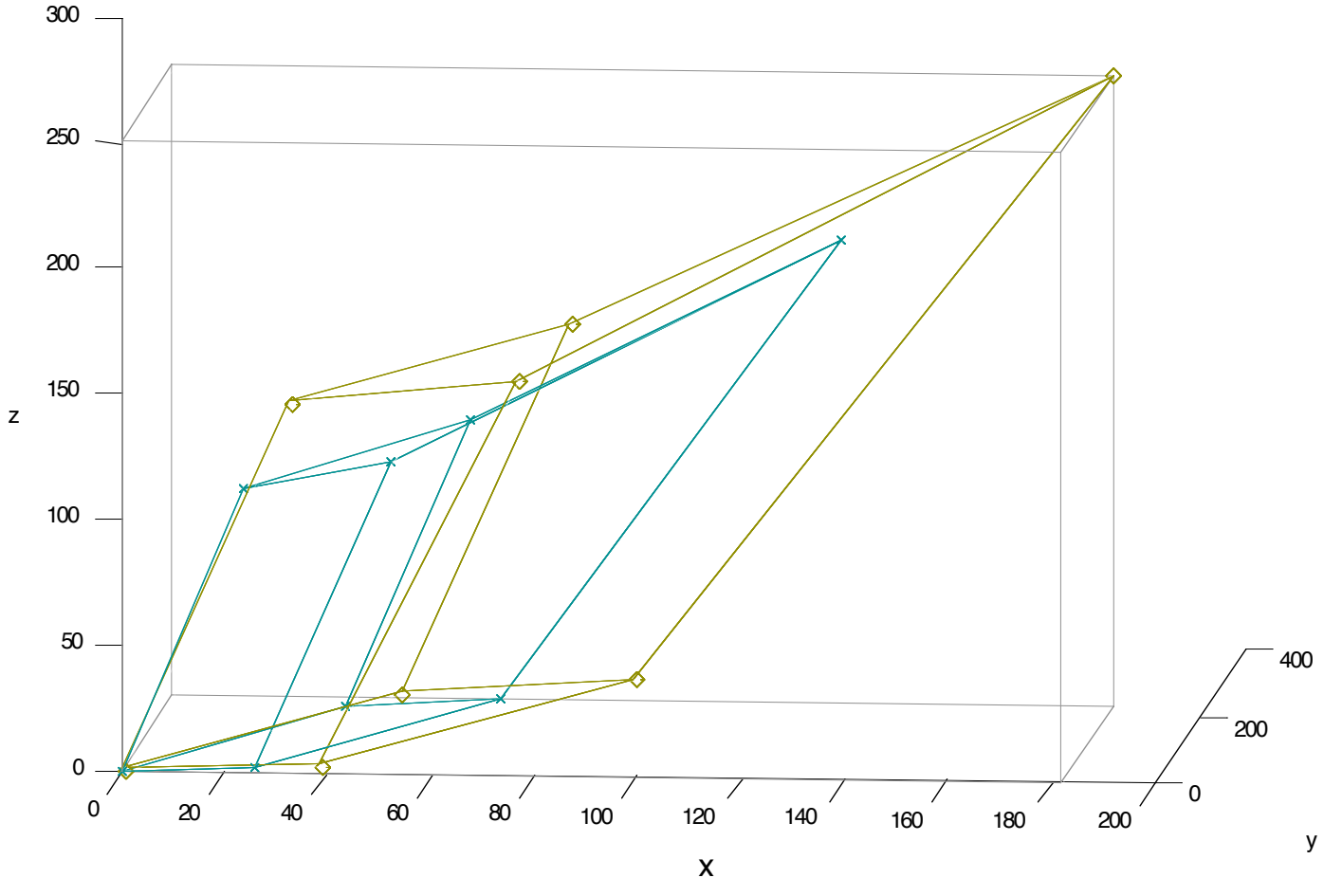
DLP Projectors

- DLP projectors commonly use "white enhancement" to increase the contrast ratio
  - Four color filters are used – red, green, blue and clear (white)
  - White is added based on a function of the RGB input values
  - Similar to CMYK color printing
- White enhancement creates a non-additive gamut



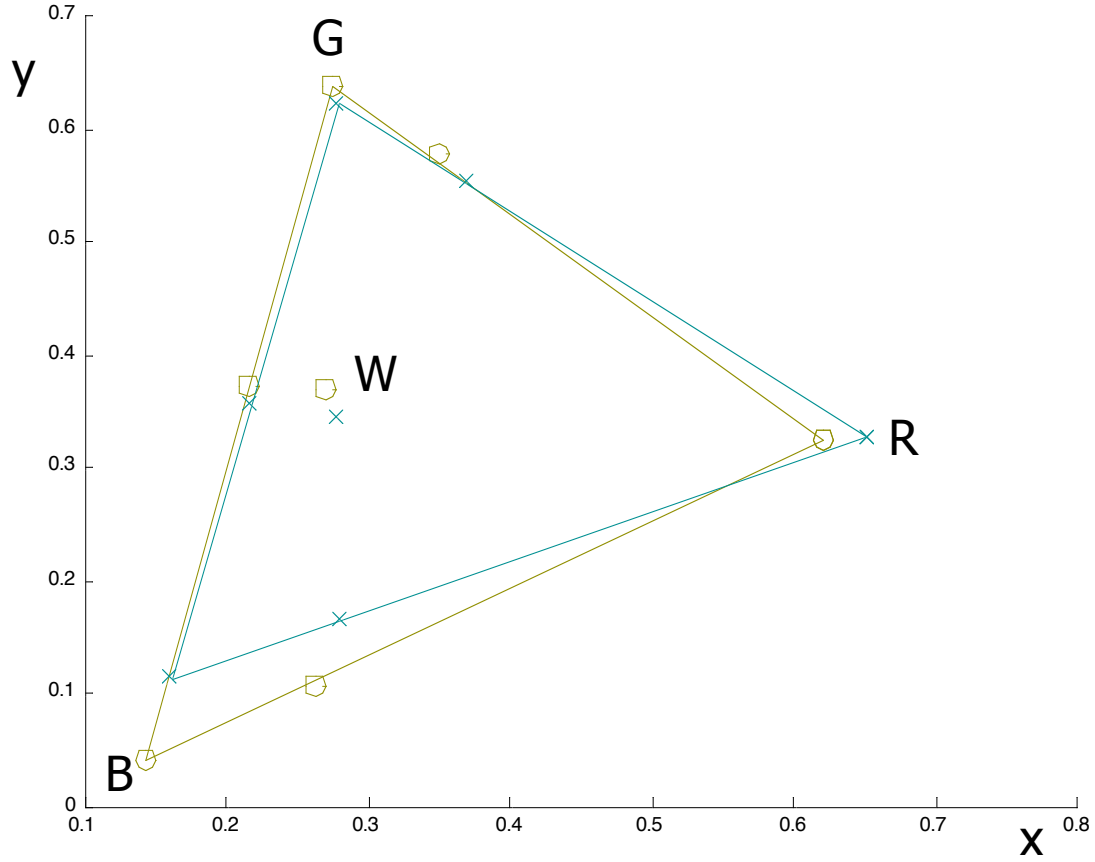
Typical Gamut of a DLP Projector

Channel balancing cannot completely match non-additive gamuts



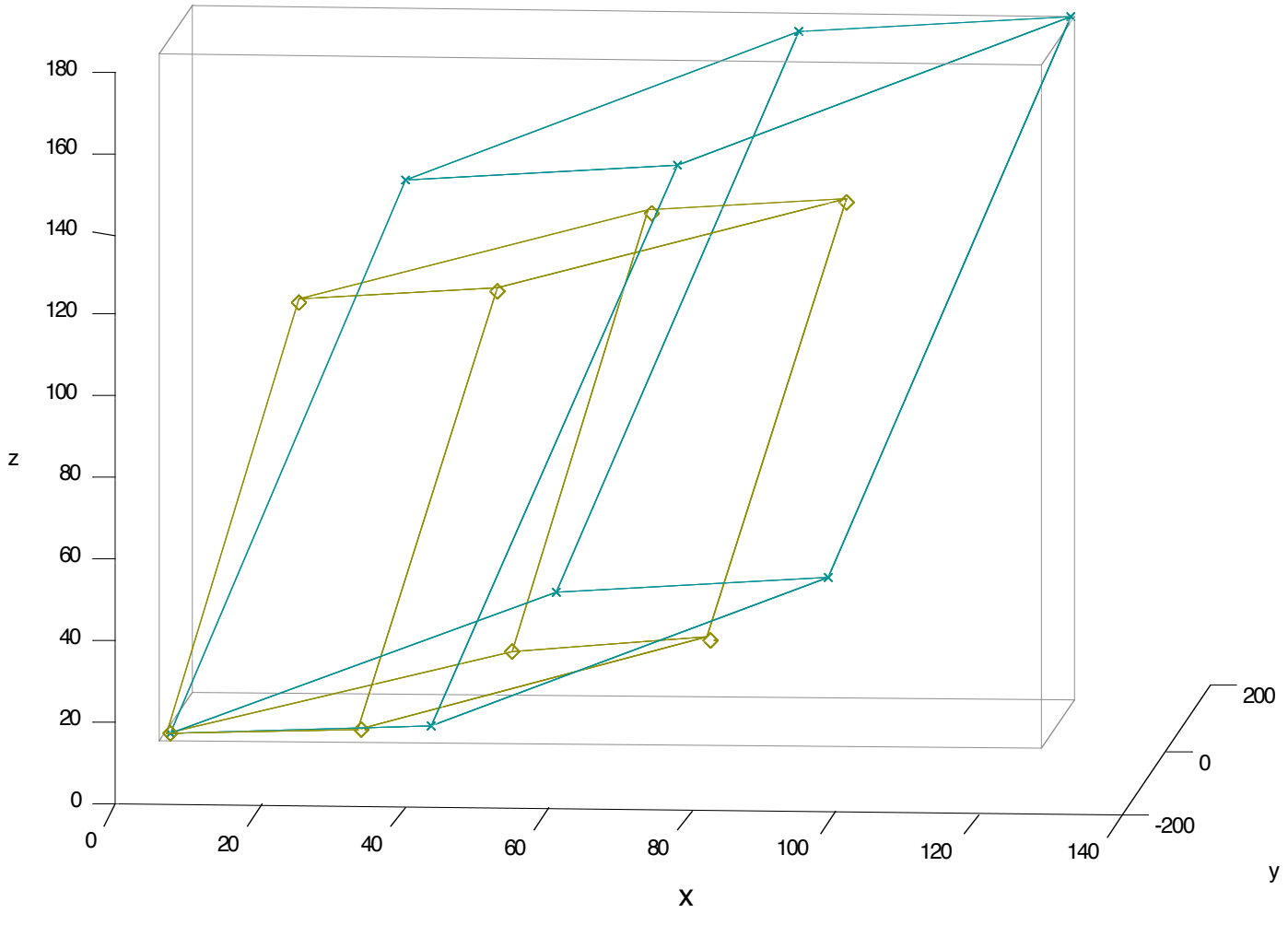
Mixed Vendor Projector Arrays

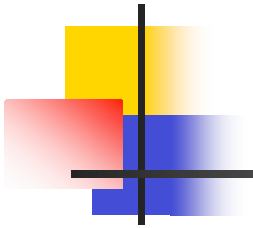
- Projectors from different vendors typically have different primary chromaticity values



Comparing CIE x-y Plot for a LCD and DLP Projector

Channel balancing not effective for differing primary chromaticity values





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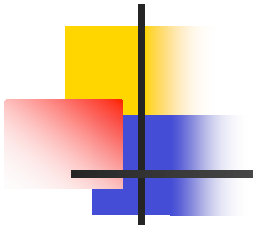
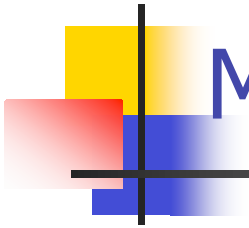


Full Gamut Color Matching

- Generalized approach
  - Treat projectors as black box
    - Color transfer function and parameters unknown
    - Type and characteristics of projector unknown
  - Handle all cases
    - Non-additive gamuts
    - Differing primary chromaticity values
- Method
  - Sub-sample the color response of each projector
  - Define a common gamut in the intersection of the projector gamuts
  - Remap color transfer function into common gamut

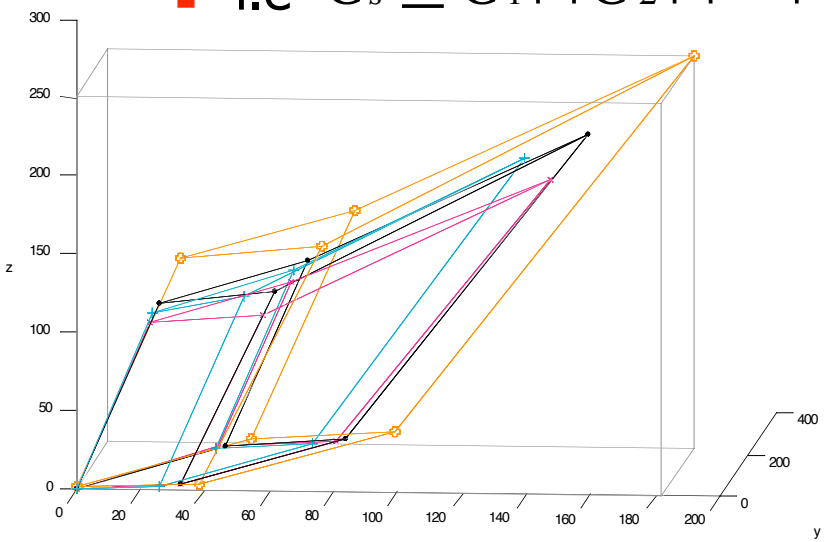


Measuring the Color Transfer Function

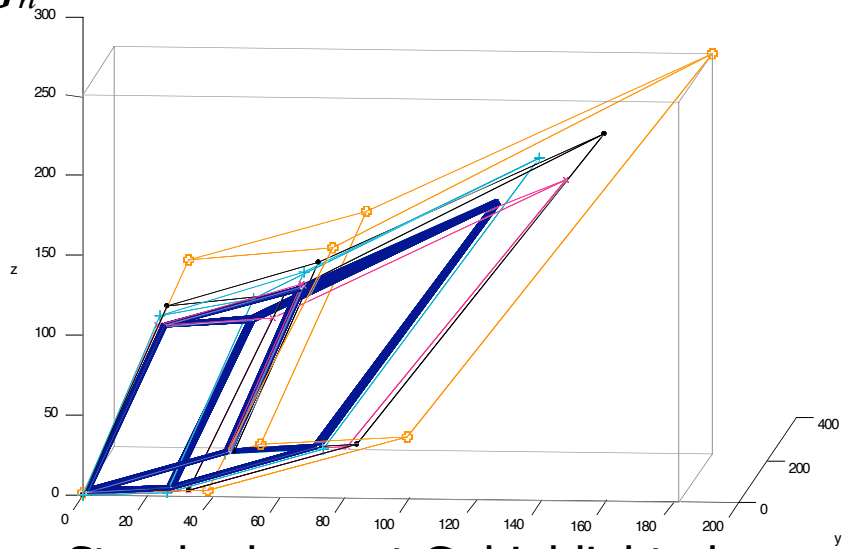
- 24 bit color = 16 Million colors (too many to measure)
- Subsample at a lower spatial frequency
  - Non-uniform sampling grid
  - Use 32 increment for RGB < 128
  - Use 16 increment for RGB > 128
  - This gives 13 grid points per channel
    0, 32, 64, 96, 128, 144, 160, 176, 192, 208, 224, 240, 255
  - 13^3 (2197) sample points total

Finding a Standard Color Gamut

- Choose an initial standard color gamut G_s
  - We can choose to have a shape similar to the average gamut
  - Or we can choose any reference gamut (useful for mixed arrays)
- Maximize the volume of G_s
  - Constraint: G_s must be contained in the intersection of the projector gamuts
  - i.e $G_s \subseteq G_1 \cap G_2 \cap \cdots \cap G_n$



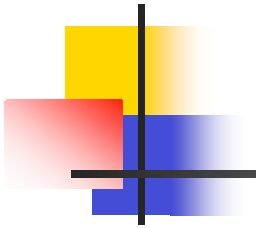
Projector Gamuts



Standard gamut G_s highlighted

Color Maps

- A color map M_i is needed for each projector to emulate the standard gamut G_s
- This map can be generated once G_s is defined
  - Let F_i be a projector's native color transfer function
  - Let F_s be the color transfer function that generates Gs
  - We want $F_i \circ M_i = F_s$
  - Therefore $M_i = F_i^{-1} \circ Fs \quad \text{where } M_i : RGB \rightarrow RGB$
- M_i must be pre-applied to all imagery

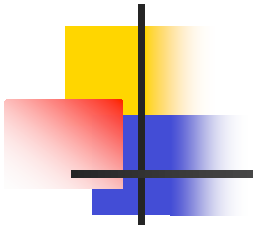


Applying Color Map

- Applying in CPU too costly
- Latest graphics cards and libraries can support color mapping
  - Nvidia GeForce4 and ATI Radeon 9700
  - DirectX Pixel Shader and OpenGL Texture Shader
- Process
  - Load color map M as a volume texture
  - RGB pixel value used as texture coordinate into M, returns the mapped color

Sample Cope

```
// Sample code ps 1.2
// t0 is the rendered texture
tex t0
// t1 is the color map
texreg2rgb t1, t0
// t2 is the luminance map
tex t2
mov r1, t1
mul r0, t2, r1
```



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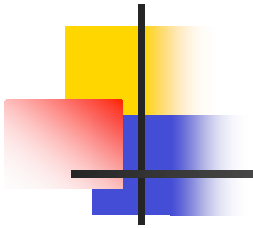


Experimental Setup

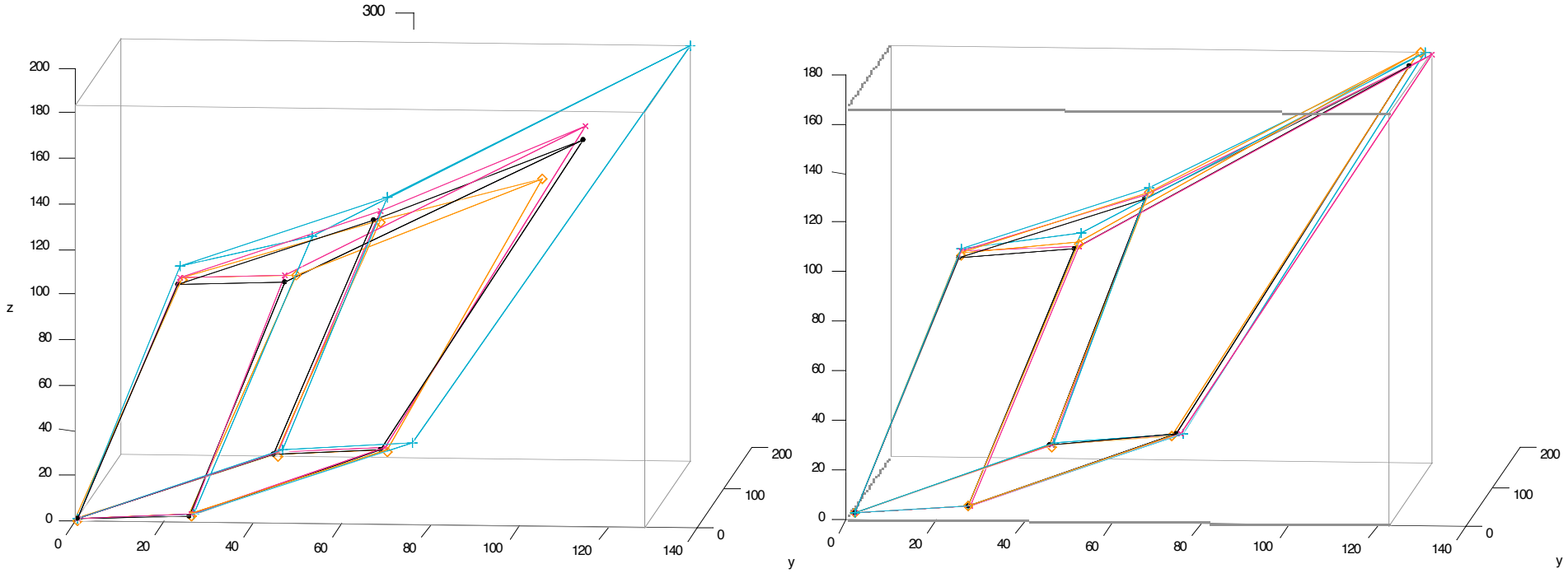
- Two test cases
  - Case 1: 4 DLP projectors
  - Case 2: 1 DLP and 1 LCD projector
- Measurement - Sequel Chroma IV colorimeter
  - Inexpensive CIE XYZ measuring device ~ 200 USD
  - Average measurement consistency of 0.4% on DLP projectors
- Channel balancing algorithm implemented for comparison
- Color corrected projectors remeasured
  - Using same colorimeter
  - Lower spatial frequency 9^3 (729) samples
- Error Metric
  - Average deviation of a test color from the mean
  - Gives an indication of color consistency among projectors

Results Case 1: DLP Projector Array

- Display Wall of 4 Compaq MP1800 DLP projectors
- Compare color consistency from three sets of measurements: No correction, Channel balancing, and Full gamut matching

Color	None	ICB	FGCM
Red (R)	10.22%	1.78%	0.75%
Green (G)	7.36%	1.71%	0.77%
Blue (B)	10.75%	2.38%	1.20%
Cyan (C)	9.54%	2.41%	0.86%
Magenta (M)	11.02%	5.95%	1.61%
Yellow (Y)	8.64%	3.26%	1.14%
Black (K)	15.59%	19.48%	3.26%
White (W)	10.40%	8.95%	1.11%
Total	11.12%	3.40%	1.47%

Results Case 1: DLP Projector Array



Channel Balance Correction

Uncorrected Projector Gamuts

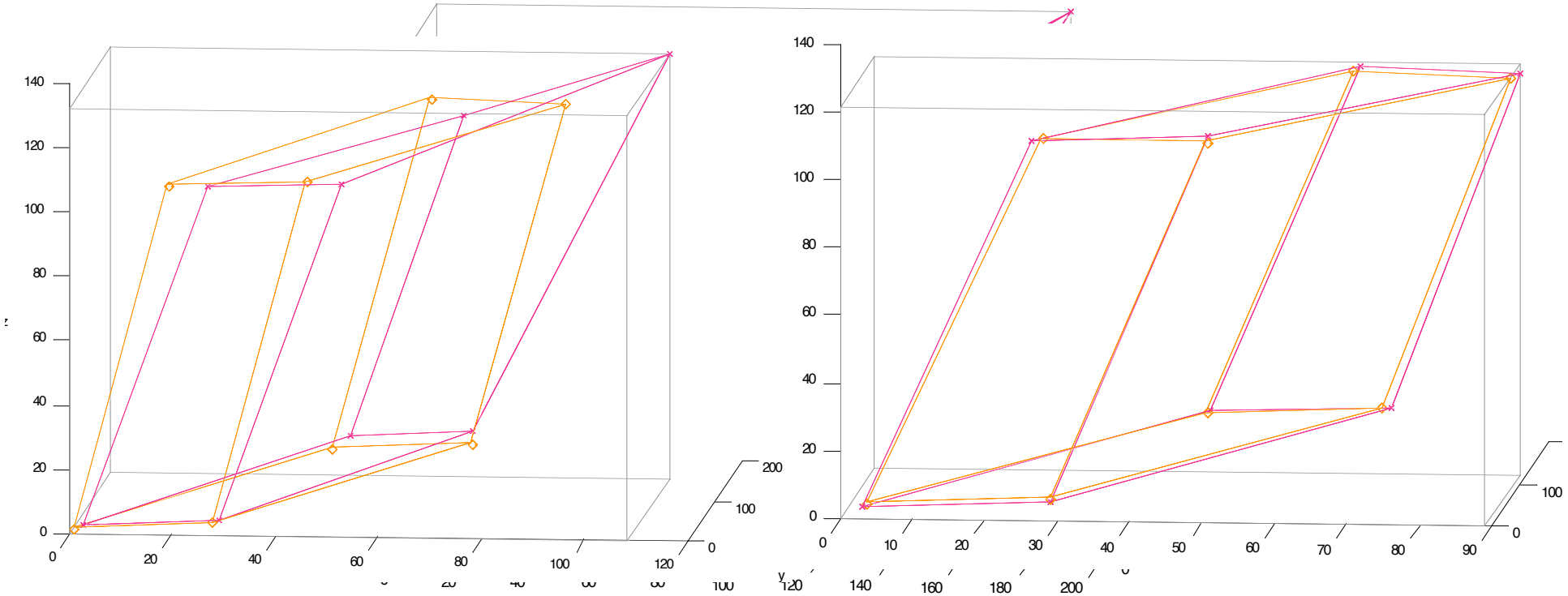
Full Gamut Correction

Results Case 2: Mixed DLP-LCD Array

- Display Wall contains a Compaq MP1800 DLP projector and a Toshiba TLP511U LCD projector
- Compare color consistency from three sets of measurements: No correction, Channel balancing, and Full gamut matching

Color	None	ICB	FGCM
Red (R)	17.03%	5.28%	1.33%
Green (G)	2.37%	3.90%	0.64%
Blue (B)	15.42%	8.25%	1.28%
Cyan (C)	11.20%	5.49%	0.82%
Magenta (M)	19.38%	7.46%	0.67%
Yellow (Y)	10.09%	2.66%	1.19%
Black (K)	50.22%	40.02%	11.93%
White (W)	32.54%	8.28%	0.74%
Total	12.95%	6.21%	1.27%

Results Case 2: Mixed DLP-LCD Array



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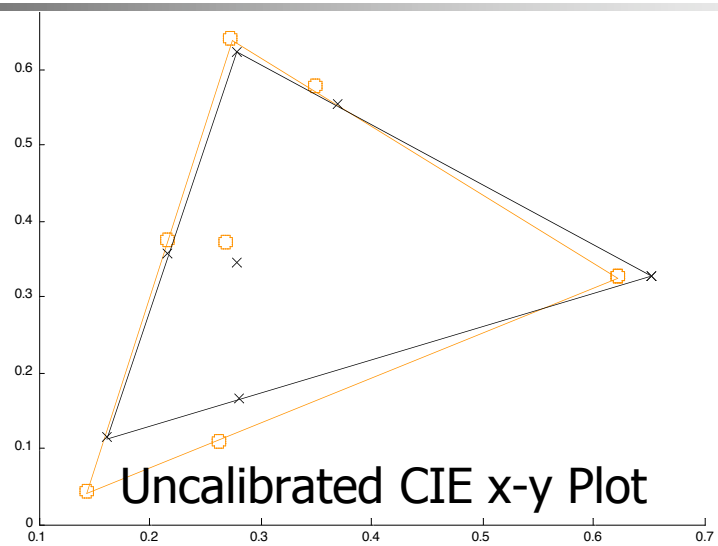
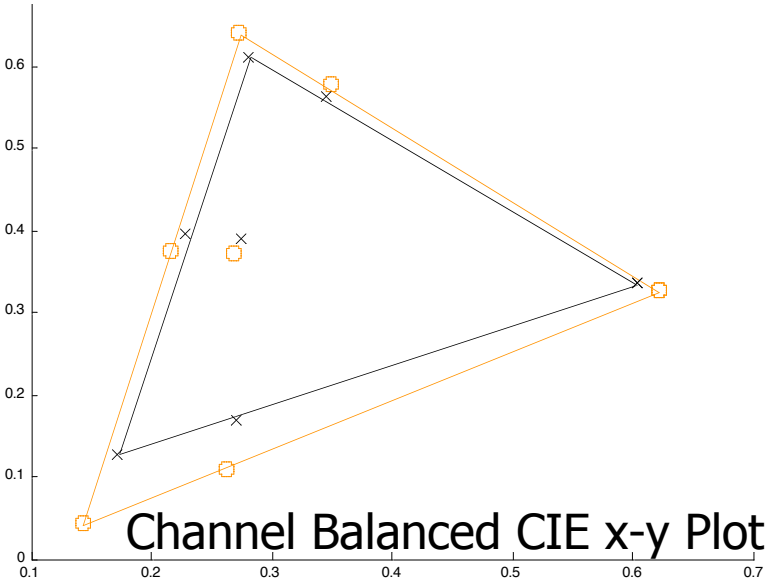
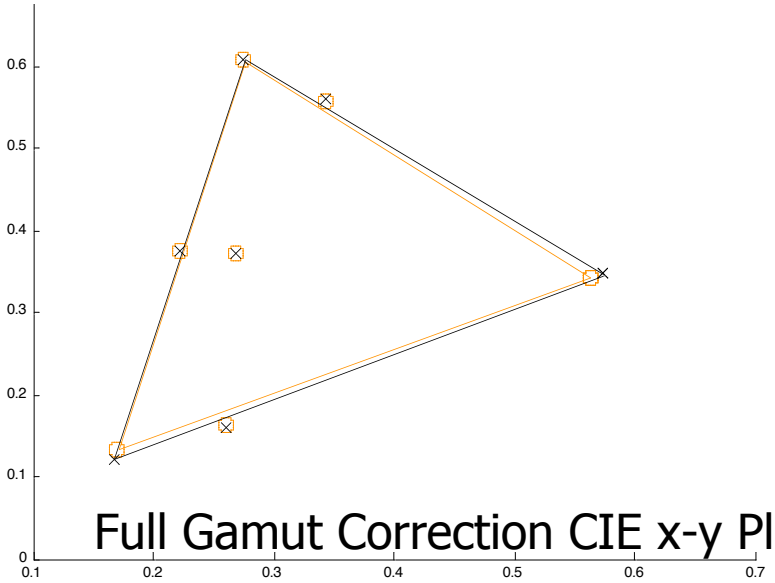


Uncalibrated CIE x-y Plot



Channel Balanced CIE x-y Plot



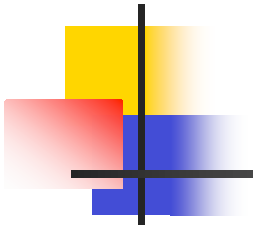
Full Gamut Correction CIE x-y Plot

Performance Results

- We tested the performance of Full Gamut Color Mapping on two platforms
  - 550 MHz Pentium III w/ GeForce4 card
  - 3.06 GHz Pentium 4 w/ ATI Radeon card
- We compare with the following transformations
  - A – applies only geometric alignment
  - B – applies geometric alignment and alpha mask
  - C – applies geometric alignment with color map
  - D – applies geometric alignment, alpha mask and color map

Platform	A	B	C	D
550 MHz P3/GeForce4	22.9	22.6	22.3	22.1
3.06 GHz P4/Radeon	86.4	86.5	86.4	86.4

Performance of image viewer in Frames Per Second



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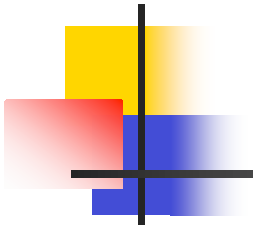
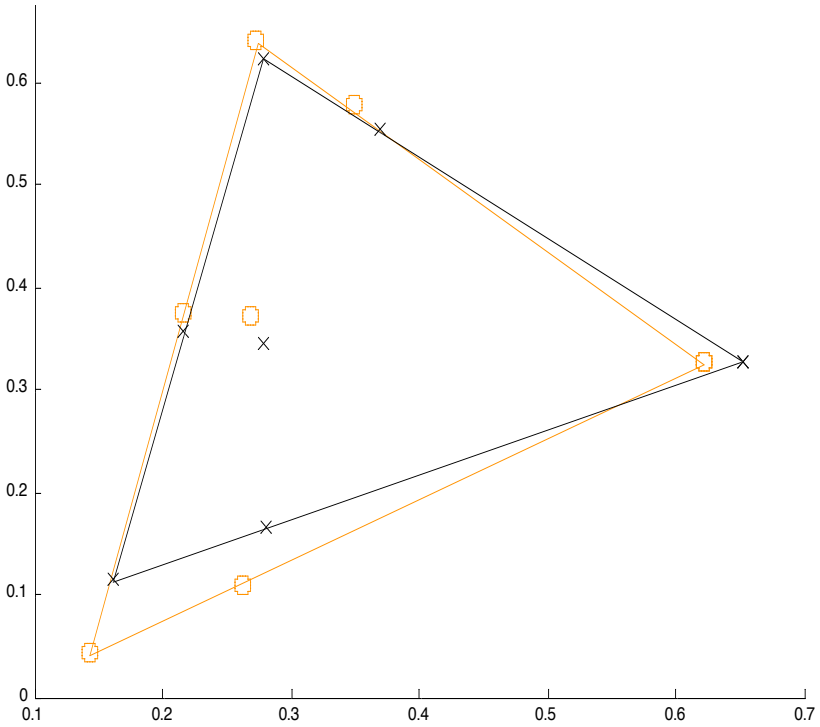


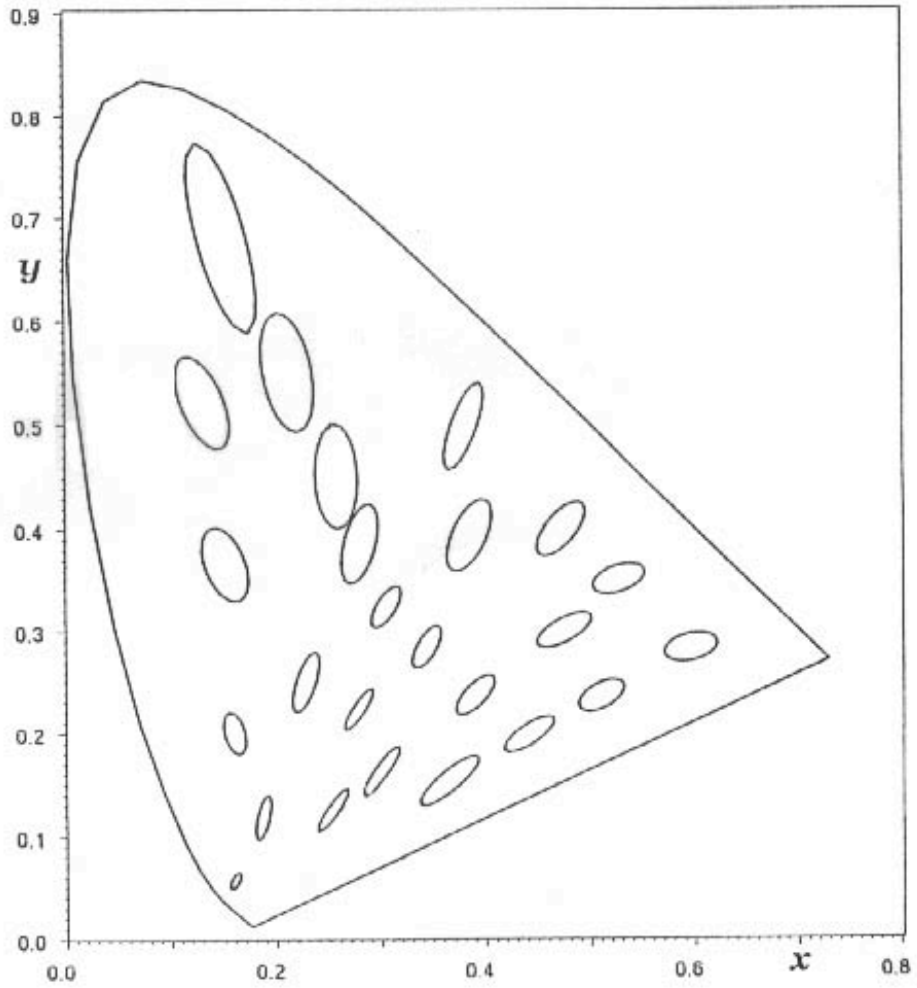
The End

- Questions and Comments?
- Further Information
  - www.cs.princeton.edu/omnimedia

Perceptible Color Differences



DLP-LCD
Chromaticity Variance



MacAdam ellipses
magnified 10 times