Large Format Displays

Aditi Majumder

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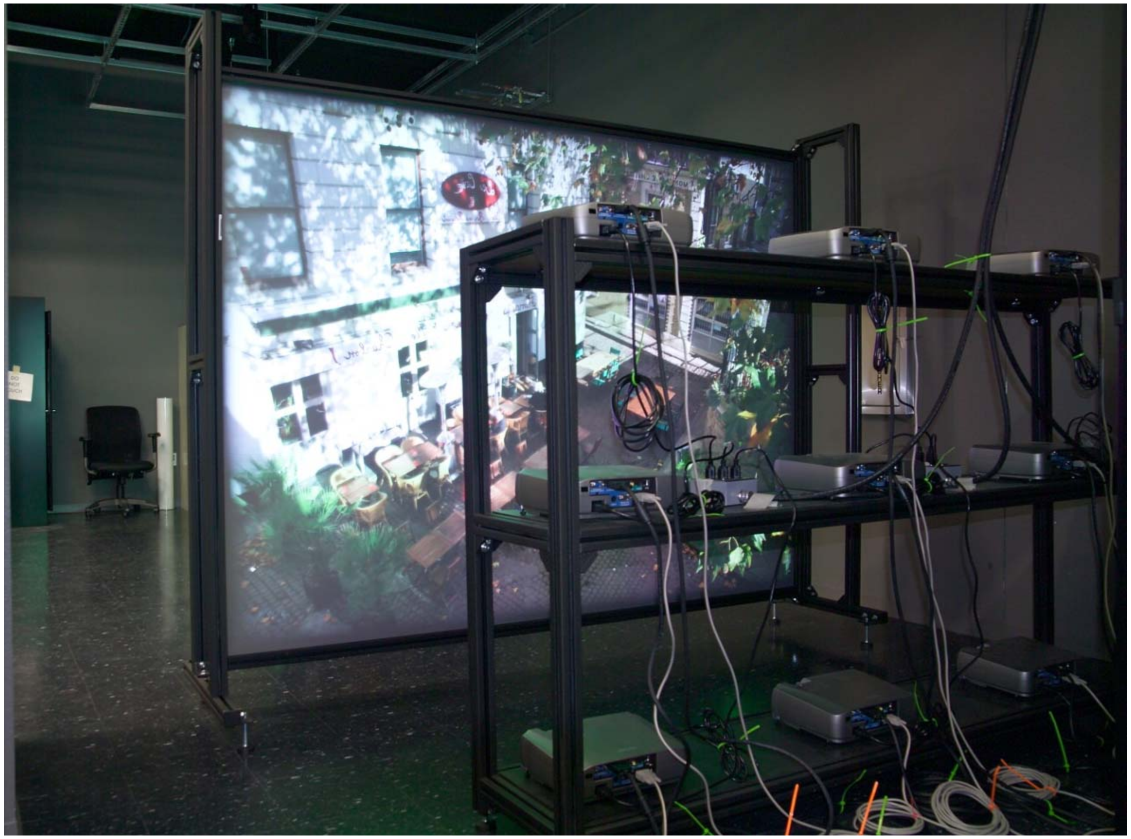
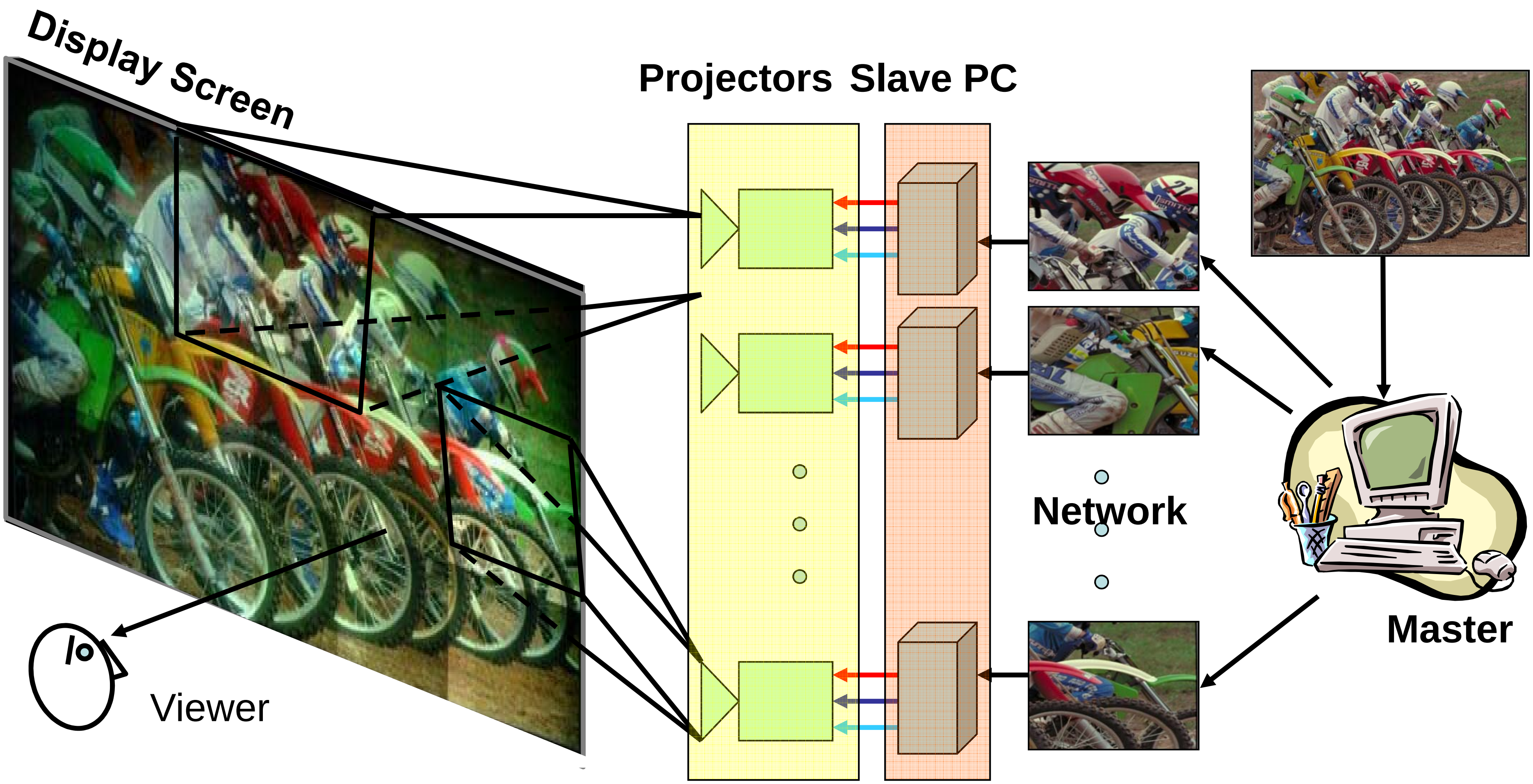
Multi-Projector Displays

- Tile projectors
- 9 projector display at UCI



Building Multi Projector Displays



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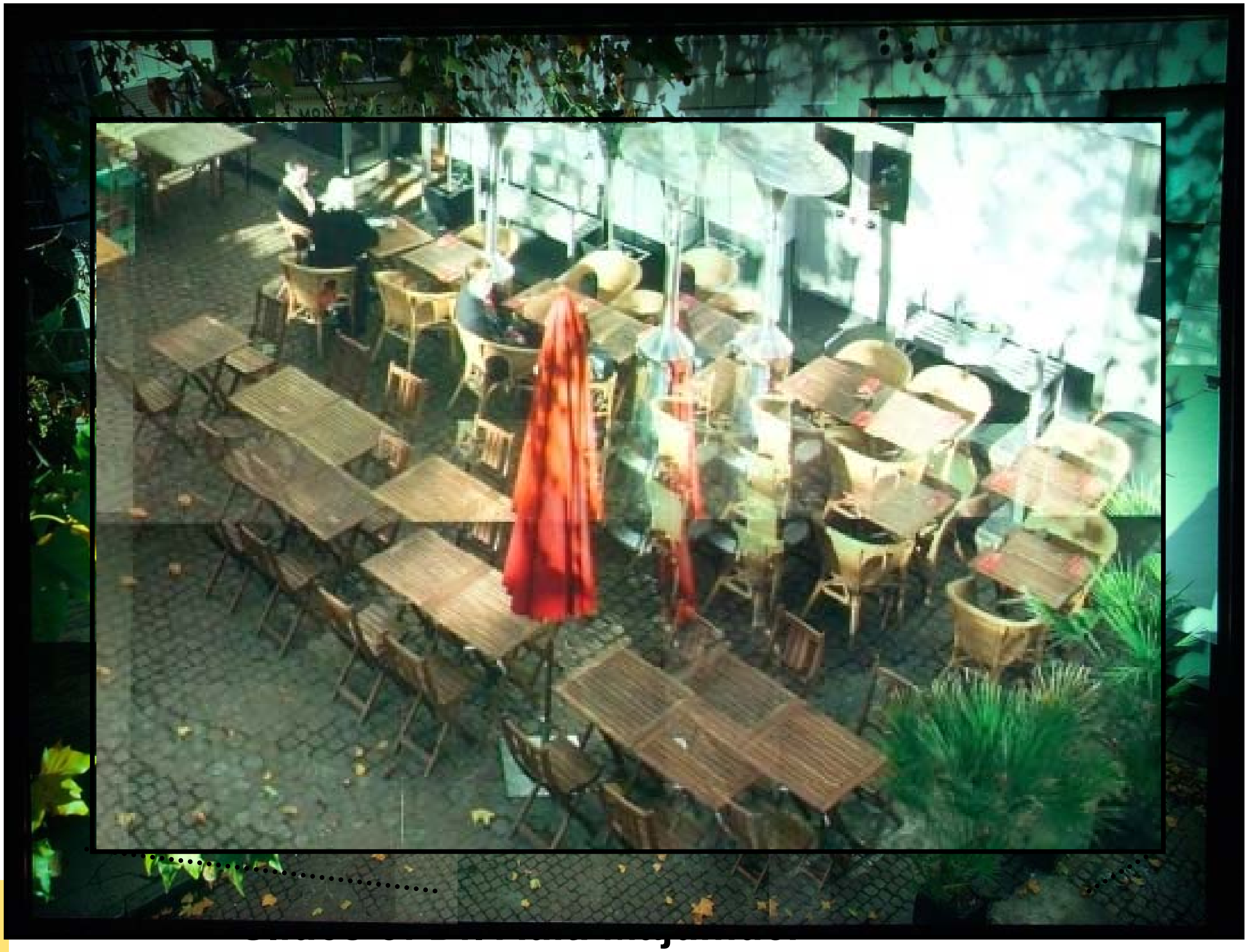
Geometric/Photometric Mismatch



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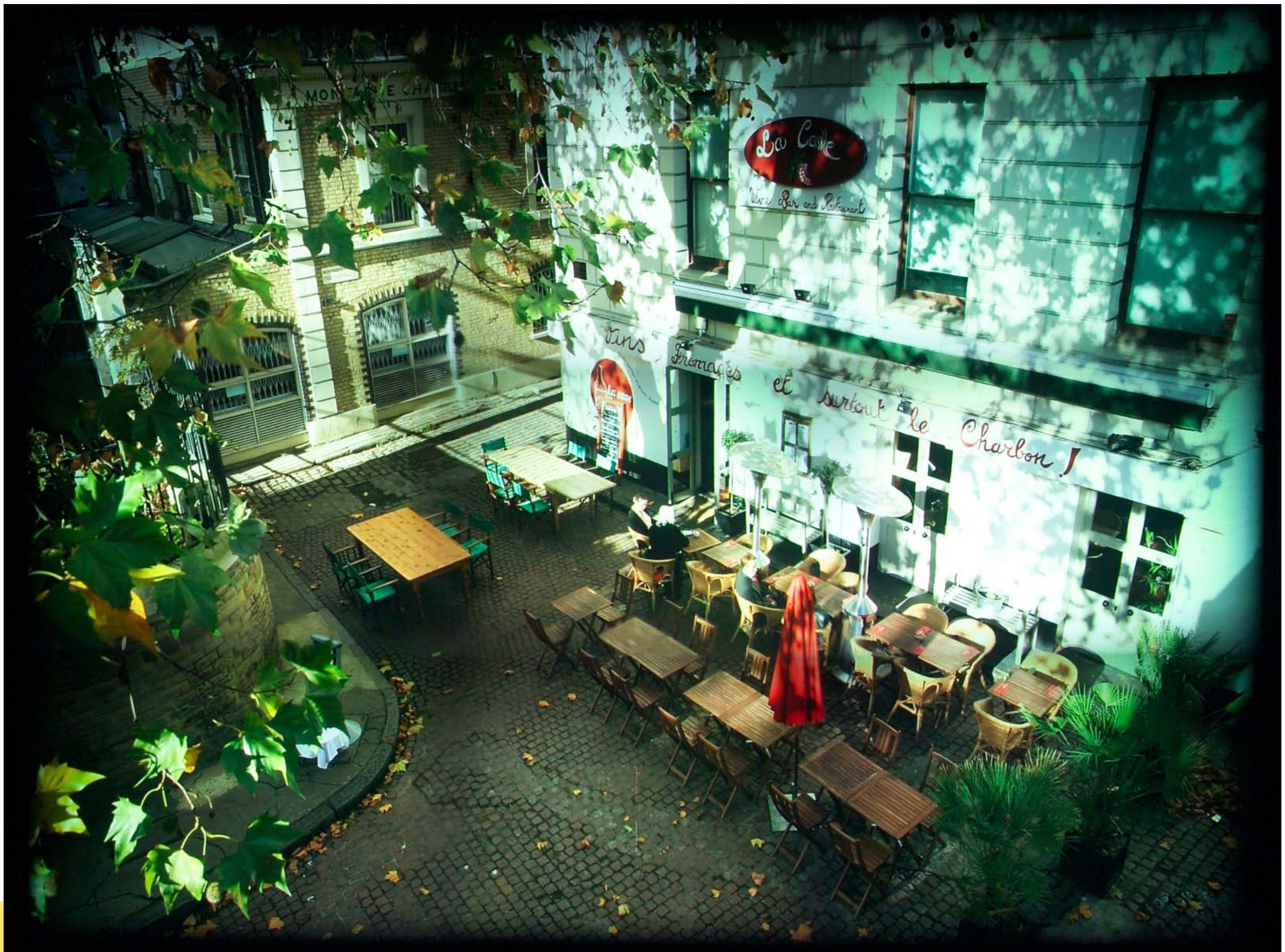
Registration for Seamless Display



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Camera Based Registration

- Camera feedback detects misregistration
- Encoded in a mathematical function
  - Both geometric and photometric
- Change the projected image digitally
  - Apply the inverse function
  - In real-time via GPU

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Overview

- Geometric Registration
- Photometric Registration
- PC Cluster Based Rendering
- Distributed Registration

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Overview

- Geometric Registration
- Photometric Registration
- PC Cluster Based Rendering
- Distributed Registration

Classification

- Based on nature of display surface
  - Parametric (Parameterized by two parameters)
    - Planar
    - Non-planar (e.g. cylinder, sphere)
  - Non-parametric
    - Non-planar complex

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Classification

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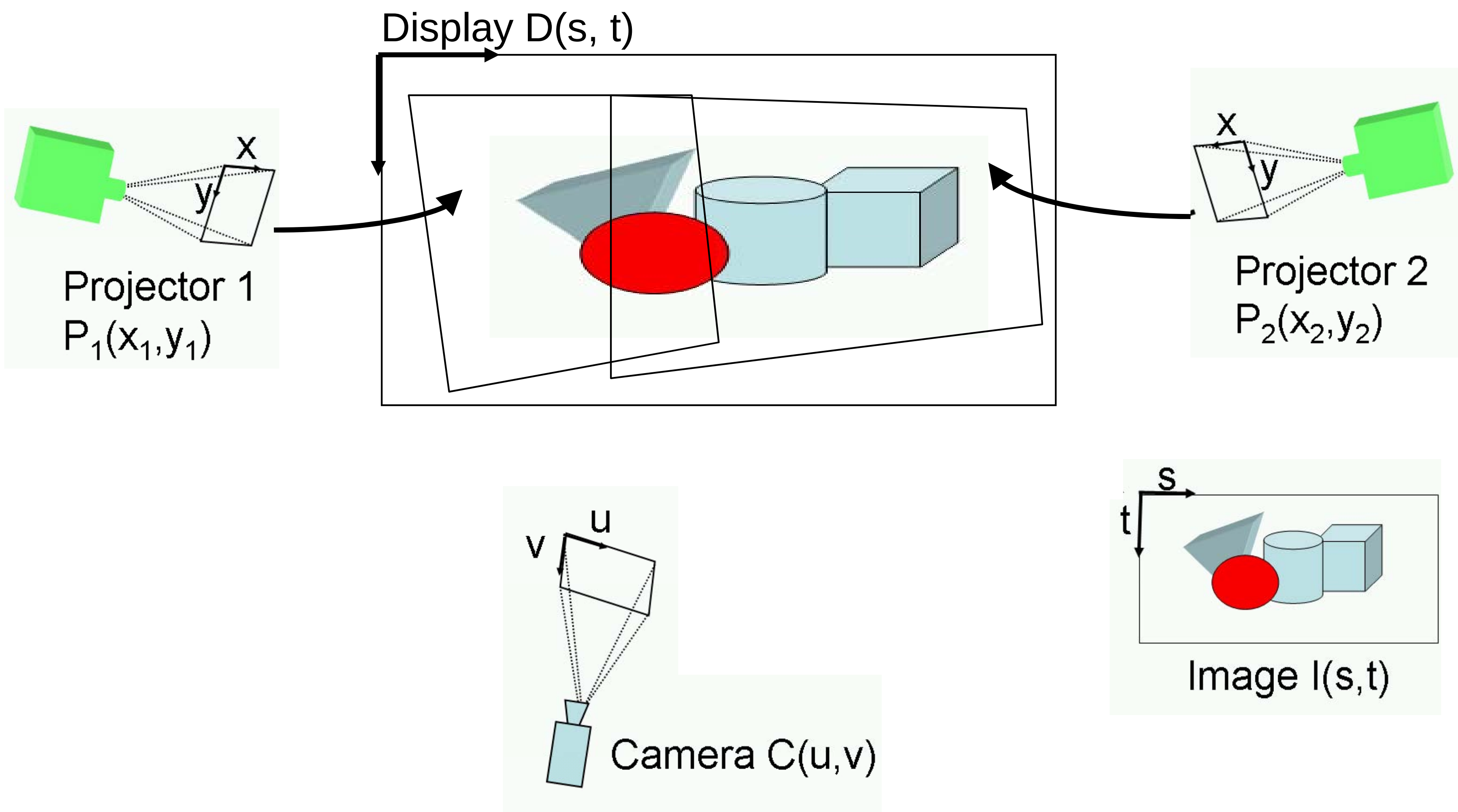
Different spaces



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Basic Idea

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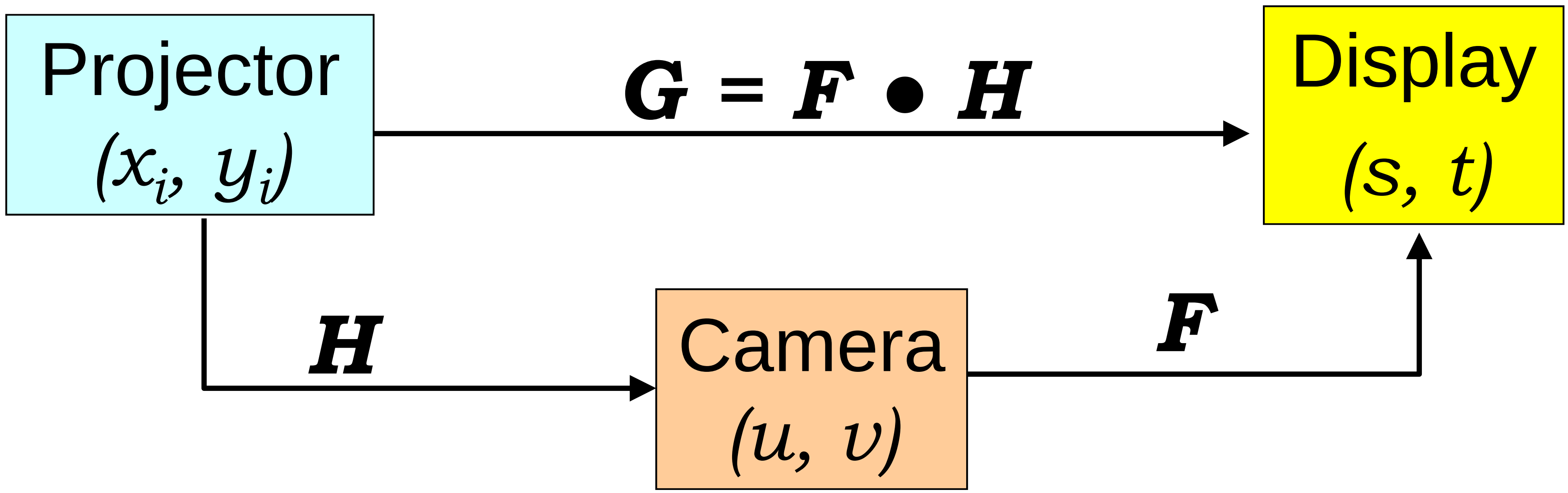
Basic Idea



Apply G^{-1} for registration

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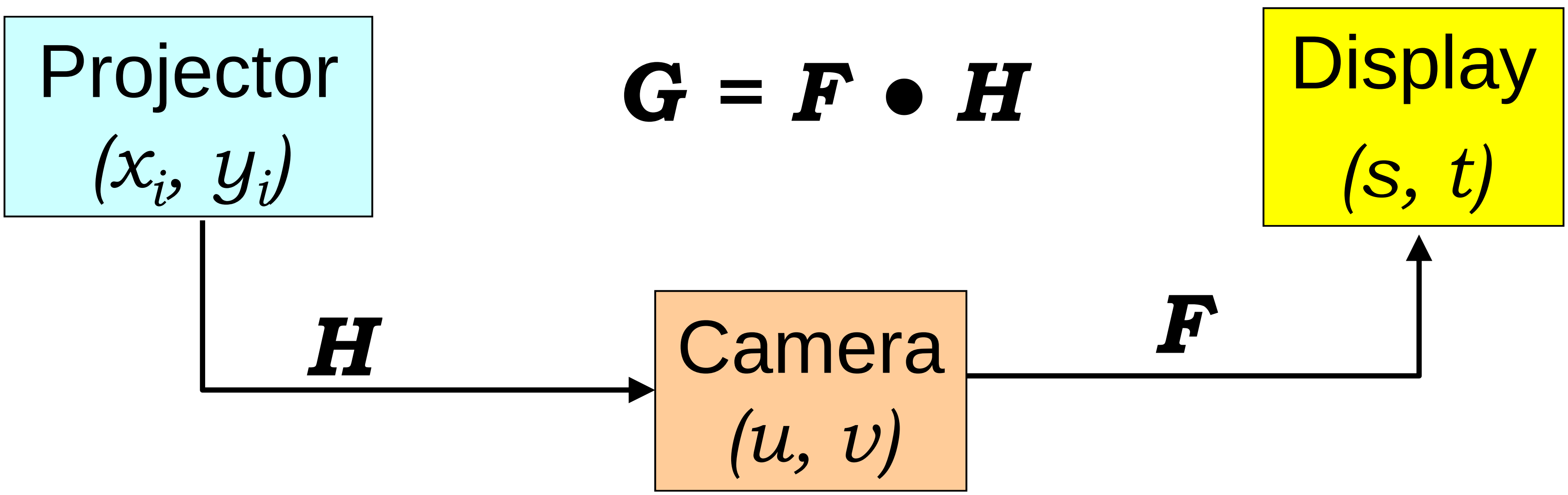
Planar Display

- Calibrated camera (no radial distortion)
- ***F*** is linear (3x3 matrix called *homography*)



R. Raskar, *Immersive Planar Display using Roughly Aligned Projectors*, IEEE VR, 2000.

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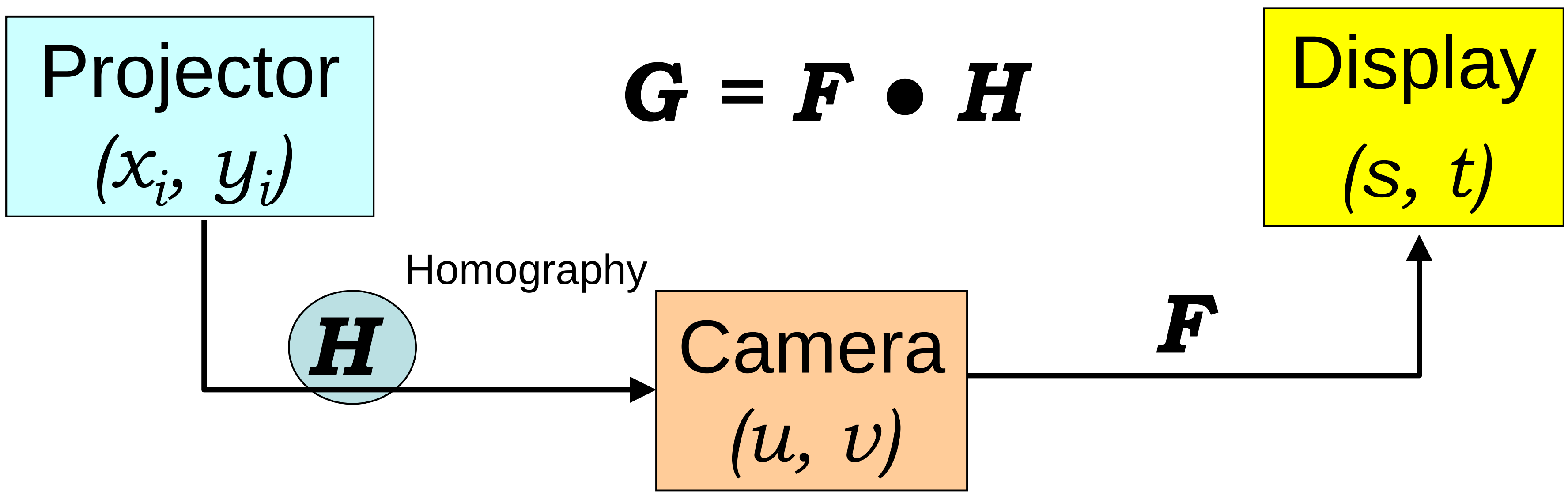
Perfect Projectors

- $\boldsymbol{G} = \boldsymbol{F} \times \boldsymbol{H}$
- $\boldsymbol{G}^{-1}$ is just a matrix inversion



R. Raskar, *Immersive Planar Display using Roughly Aligned Projectors*, IEEE VR, 2000.

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Linear ***G***

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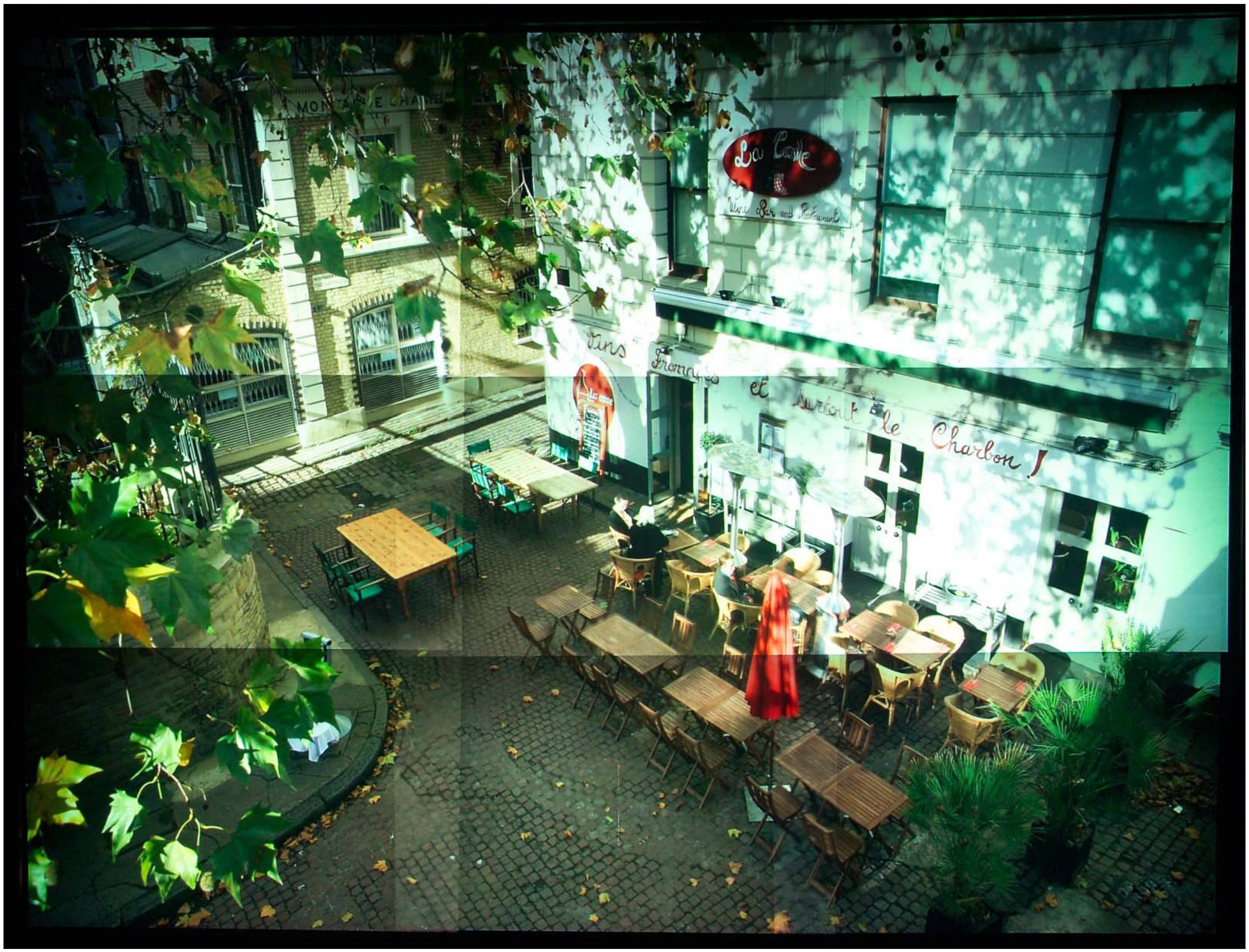
Corrected using G^{-1}



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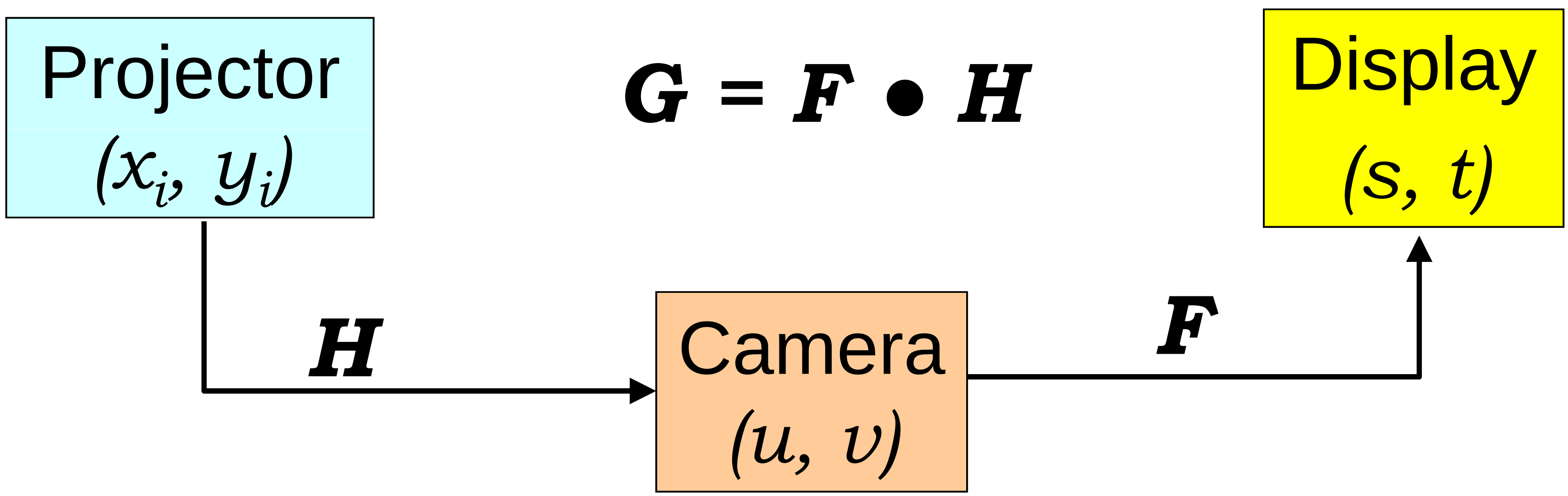
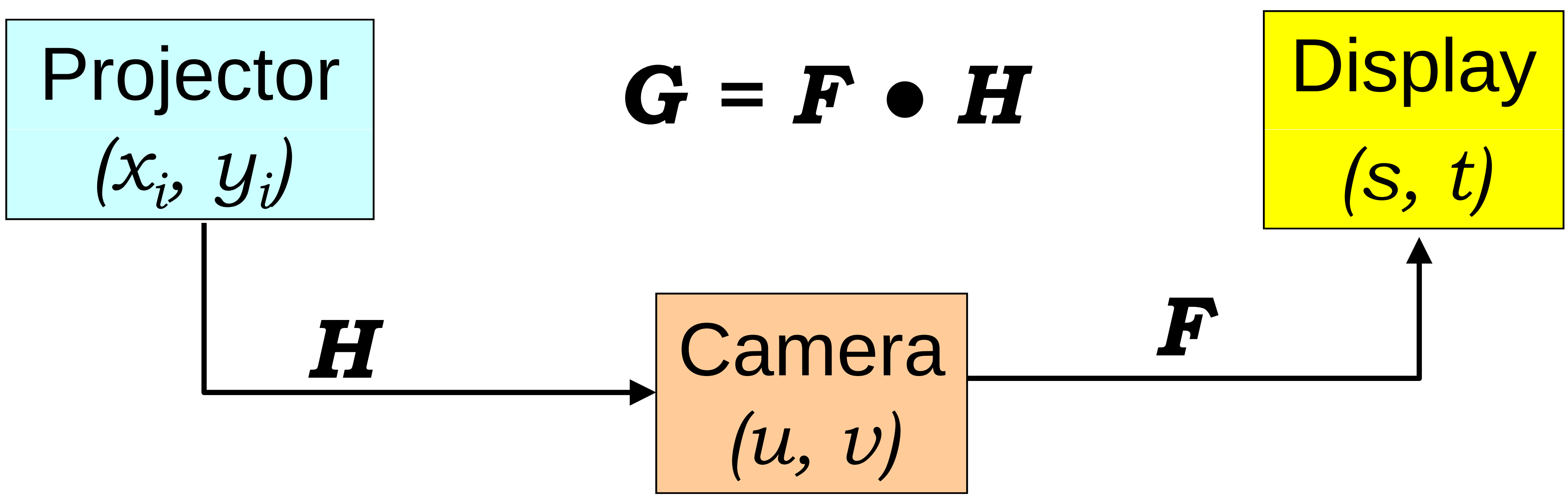
Imperfect Projectors

- $\boldsymbol{F}$ is still linear, $\boldsymbol{H}$ is not linear
- How to model $\boldsymbol{H}$?



Piecewise linear *H*

- ***H*** is a triangulation
- Dense sampling for accurate approximation



R. Yang, D. Gotz, J. Henseley, H. Towles, M. S. Brown, PixelFlex: A Reconfigurable Multi-Projector Display System, IEEE Visualization, 2001.

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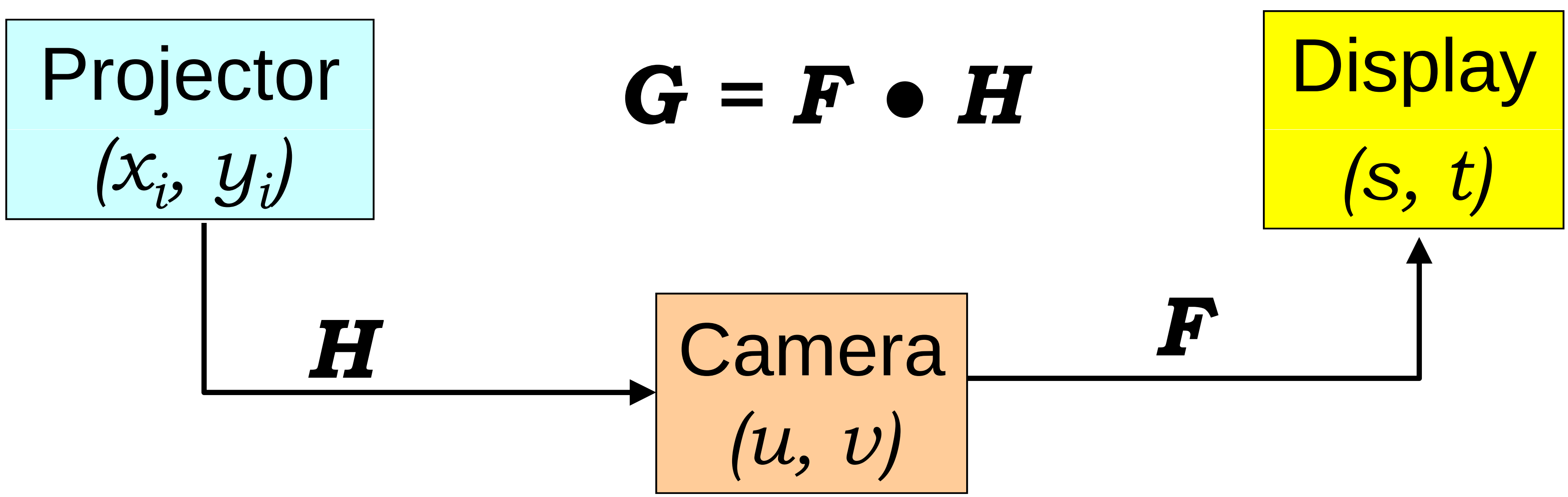
Cubic Polynomial ***H***

- Can we reduce sampling denisty?
  - Scale to more projectors

$$\boldsymbol{G} = \boldsymbol{F} \bullet \boldsymbol{H}$$



M. Hereld, I. Judson, R. Stevens, DottyToto: A Measurement Engine for Aligning Multi-Projector Display Systems, Argonne National Laboratory preprint ANL/MCS-P958-0502, 2002.

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Limitations

- ***H*** involves both radial distortion and perspective projection (keystoning)
- Cubic polynomial is not perspective projection invariant
  – Assumes near rectangular array (no keystoning)
- Dense sampling to allow small deviations from rectangular set-up

M. Hereld, I. Judson, R. Stevens, DottyToto: A Measurement Engine for Aligning Multi-Projector Display Systems, Argonne National Laboratory preprint ANL/MCS-P958-0502, 2002.

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Rational Bezier *H*

- Perspective projection invariant
  - Removes the restriction of rectangular
- Can tolerate large non-linearities
  - Radial distortion and more
- Sparse sampling
  - An order of magnitude smaller
  - Allows use of a low-resolution camera
- Compact Representation

E. Bhasker, R. Juang, A. Majumder, Registration Techniques for Using Imperfect and Partially Calibrated Devices in Planar Multi-Projector Displays, IEEE Visualization, 2007.

Results

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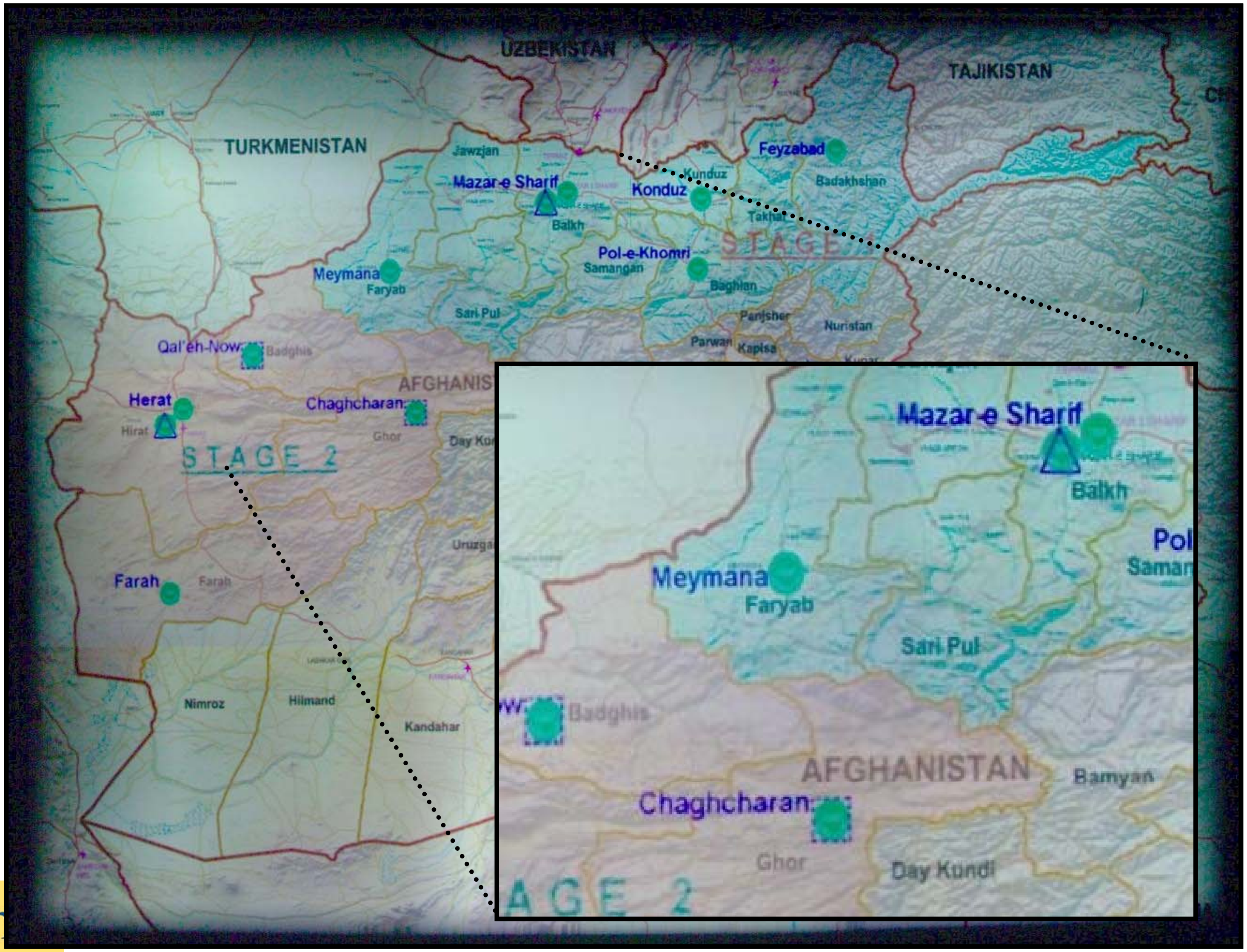
Results



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Using Multiple Cameras

- Scalability not limited by camera resolution
- Linear method can be scaled
  - Homographies can be concatenated
  - Homography tree
- Cheaper cameras with smaller FOV
  - Adjacent cameras FOV overlap

H. Chen, R. Sukthankar, G. Wallace, Scalable Alignment of Large-Format Multi-Projector Displays Using Camera Homography Trees, IEEE Visualization, 2002.

Classification

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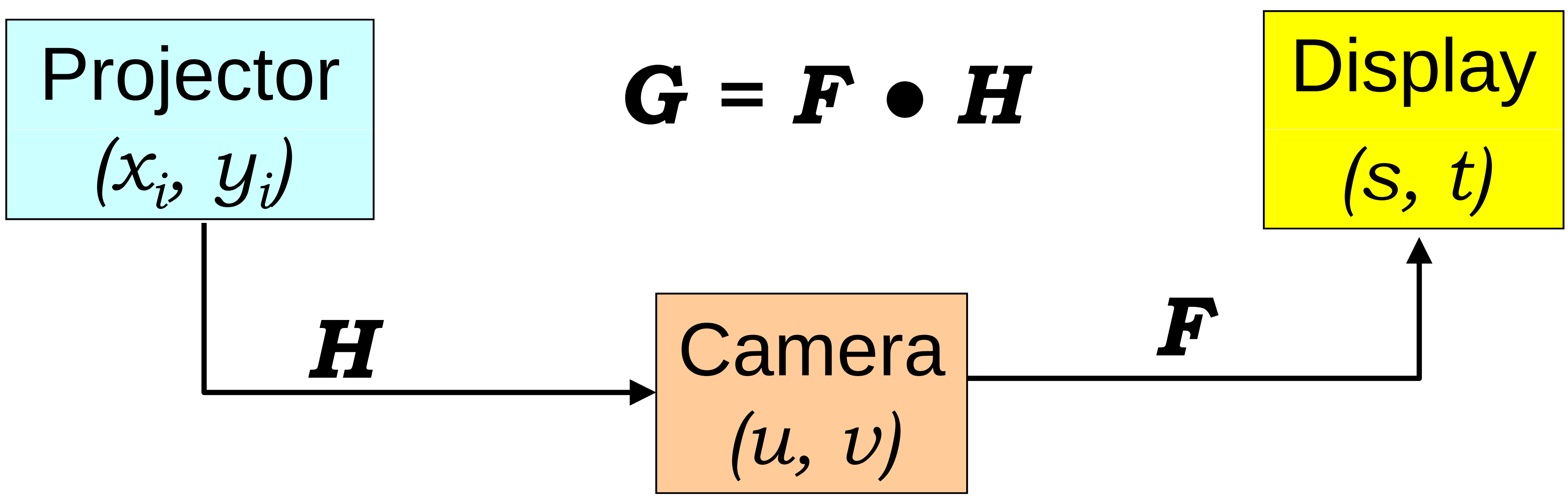
Parametric Cylindrical Display

- ***F*** and ***H*** are both piecewise linear
- Find ***F*** -- Use markers



M. Harville, B. Culbertson, I. Sobel, D. Gelb, A. Futzhugh, D. Tanguay, Practical Methods for Geometric and Photometric Correction of Tiled Projector Displays on Curved Screens, IEEE PROCAMS, 2006.

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Results

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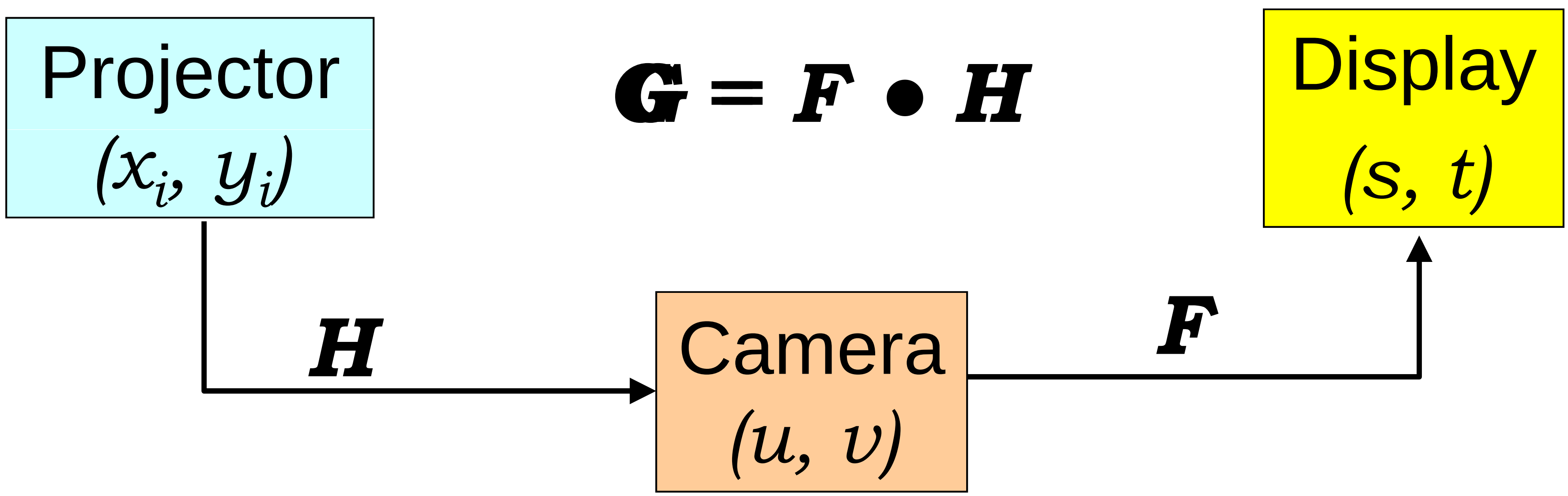
Question: What is correct?

- Single view point
  - Camera (u, v) = Display (s, t)



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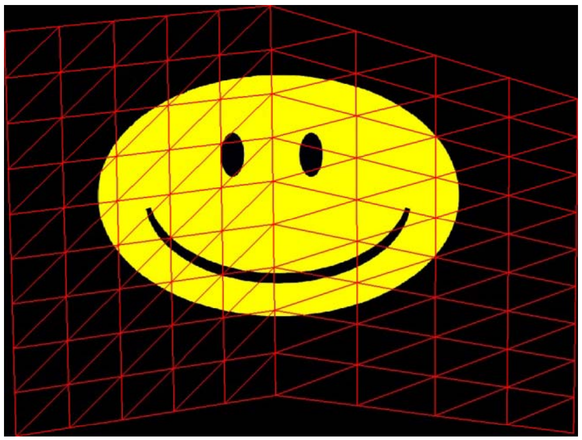
Question: What is correct?

- Single view point
  - Camera *(u, v)* = Display *(s, t)*
  - May not be correct from other viewpoints
  - Users can tolerate a large deviation from viewpoint

1) *M. S. Brown, W. B. Seales, A Practical and Flexible Tiled Display System, IEEE Pacific Graphics, 2002*
2) *R. Raskar, M.S. Brown, R. Yang, W. Chen, H. Towles, B. Seales, H. Fuchs, Multi Projector Displays Using Camera Based Registration, IEEE Visualization, 1999.*

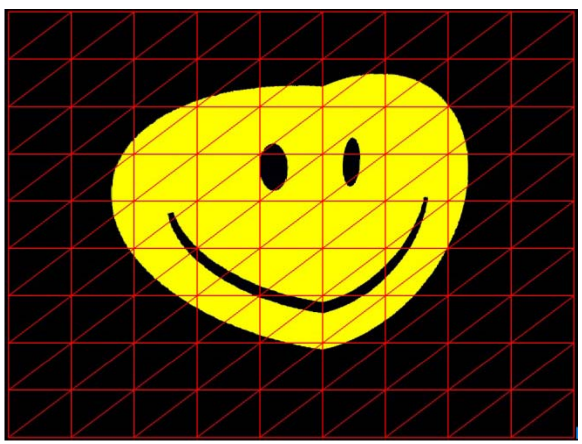
Corner : Single View

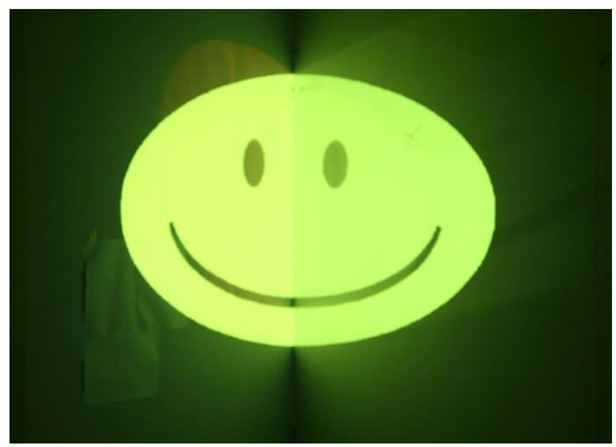
Original projector input



Projected image is distorted

Warped projector input





Projected image is undistorted from camera’s viewpoint

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Question: What is correct?

- Wall paper with local correctness
  - Globally incorrect from any one view point
  - Locally correct from normal at that point
  - Conformal mapping

1) *R. Raskar, J. van Baar, P. Beardsley, T. Willwacher, S. Rao, C. Forlines, iLamps: Geometrically Aware and Self-Configuring Projectors, SIGGRAPH 2003*
2) *R. Raskar, J. van Baar, T. Willwacher, S. Rao, Quadric Image Transfer for Immersive Curved Screen Displays, Eurographics 2004.*

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Corner : Conformal Mapping

Before

After

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Overview

- Geometric Registration
- Photometric Registration
- PC Cluster Based Rendering
- Distributed Rendering

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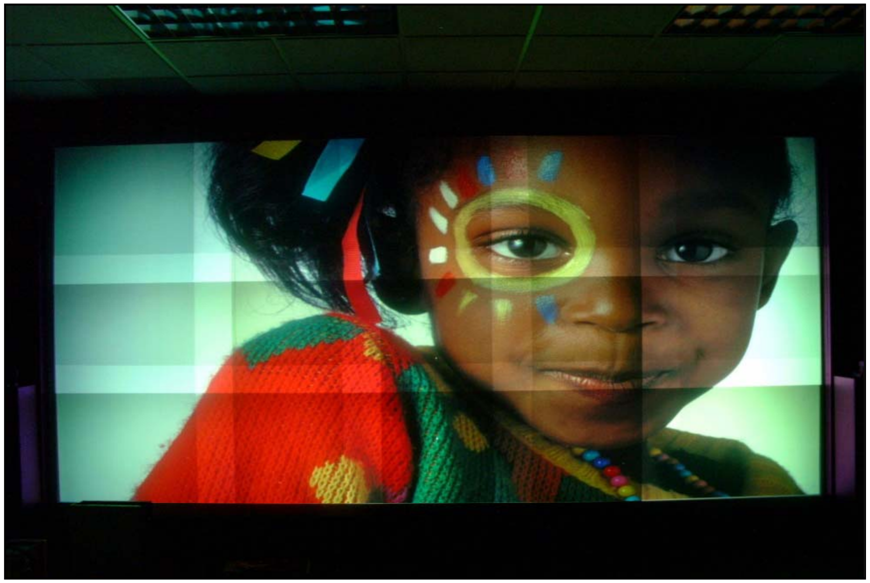
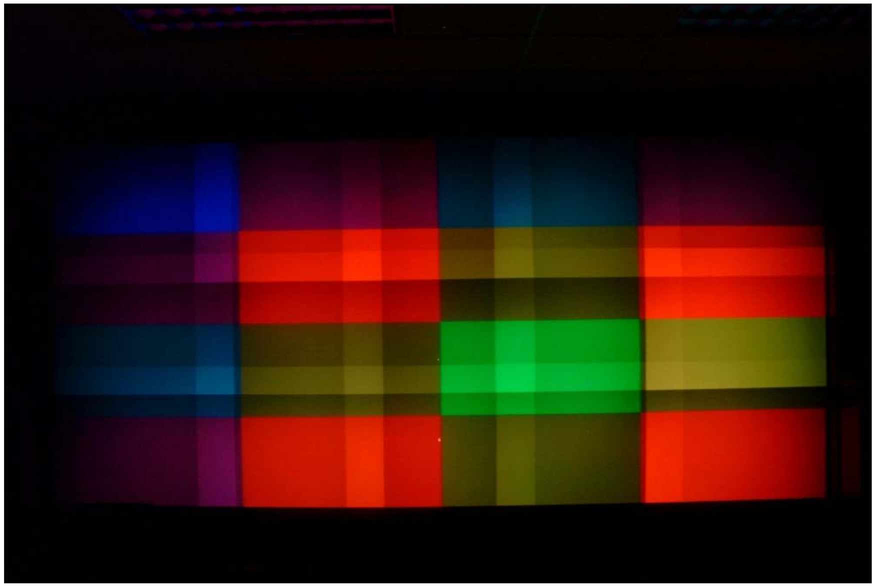
The Problem

- Perfect geometric alignment
- Color variation problem not addressed
- Breaks the illusion of a single display





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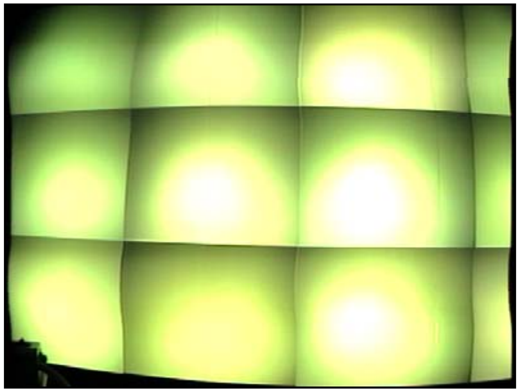
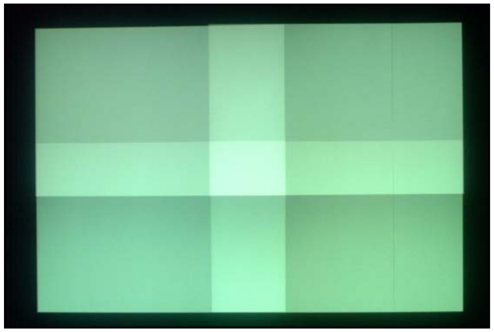
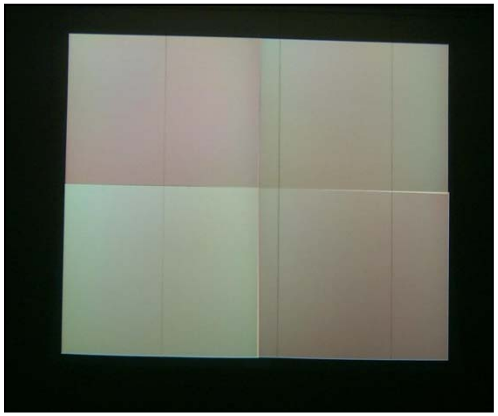
Properties of Color Variation

- Intra-projector
  - Within a single projector
- Inter-projector
  - Across different projectors
- Overlaps







1) A. Majumder, *Properties of Color Variation in Multi Projector Displays*, SID Eurodisplay, 2002.
2) A. Majumder and R. Stevens, *Color Non-Uniformity in Multi Projector Displays: Analysis and Solutions*, IEEE Transactions on Visualization and Computer Graphics, Vol. 10, No. 2, 2003.

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Existing Methods

- Edge Blending (Overlaps)
- Gamut Matching (Inter)
- PRISM (Inter + Intra + Overlap)
- Color Calibration in LED projectors

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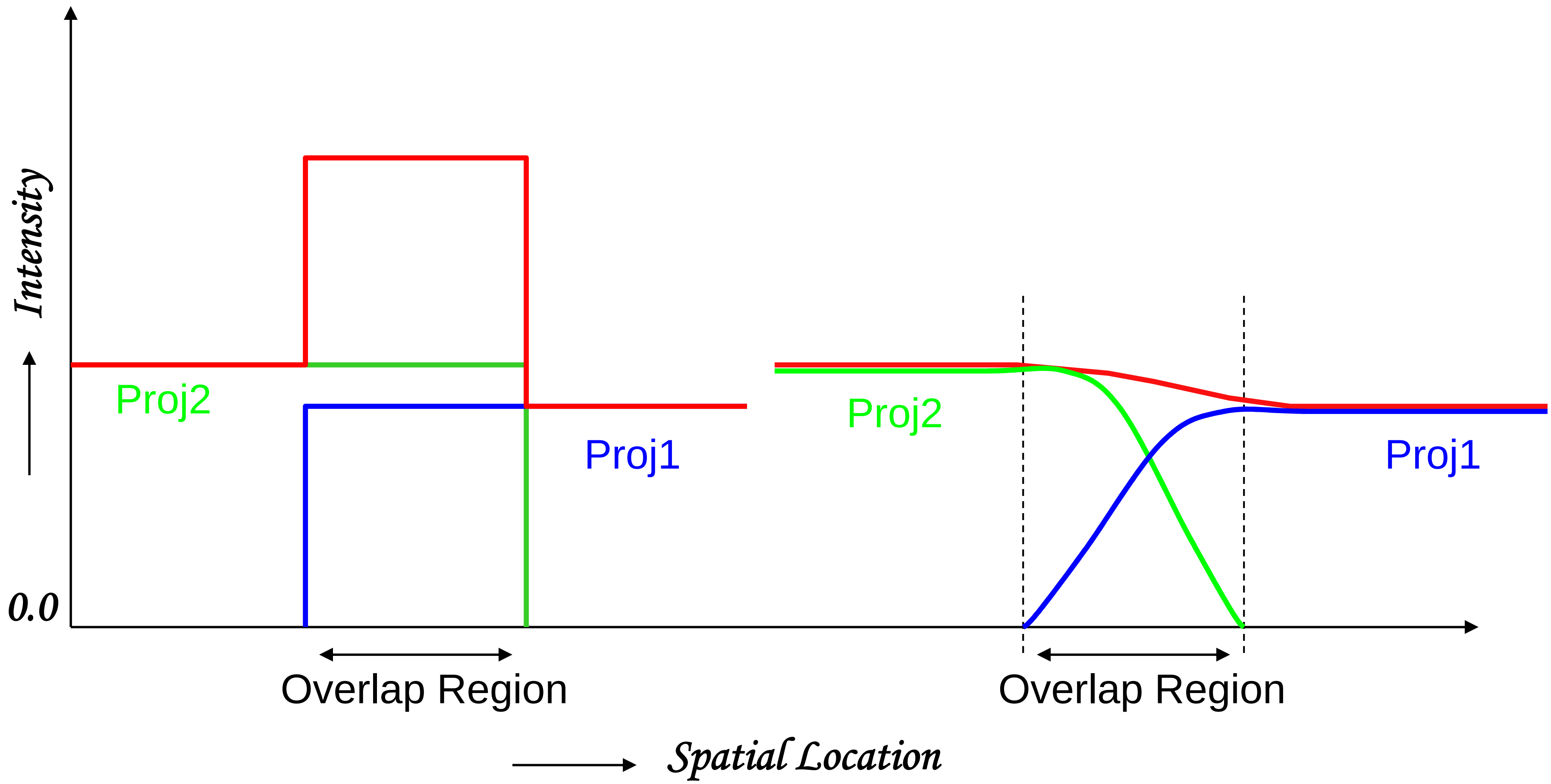
Edge Blending



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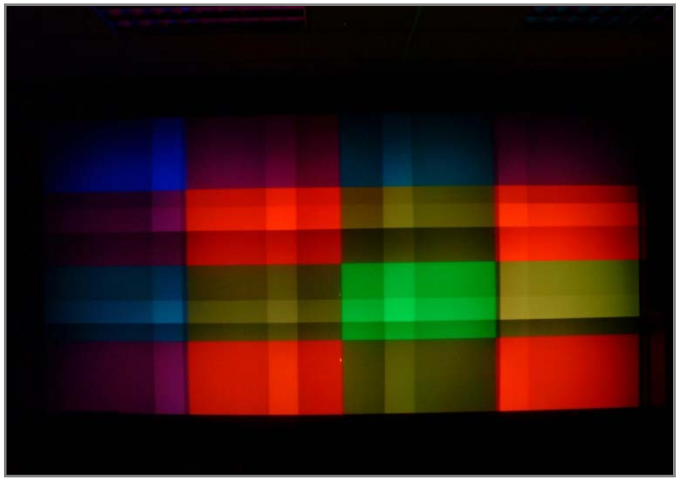
Edge Blending

Before



Software Blending

1) Lyon Paul, *Edge-blending Multiple Projection Displays On A Dome Surface To Form Continuous Wide Angle Fields-of-View*, Proceedings of 7th I/ITEC, 203-209, 1985.
2) R. Raskar et al, *Seamless Camera-Registered Multi-Projector Displays Over Irregular Surfaces*, Proceedings of IEEE Visualization, 161-168, 1999.
3) K. Li et.al, *Early experiences and challenges in building and using a scalable display wall system*, IEEE Computer Graphics and Applications 20(4), 671-680, 2000.

Screen door effect

- Works for linear projectors
- Works if projectors are adjusted to be very similar

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Existing Methods

- Edge Blending (Overlaps)
- Gamut Matching (Inter)
- PRISM (Inter + Intra + Overlap)
- Color Calibration in LED projectors

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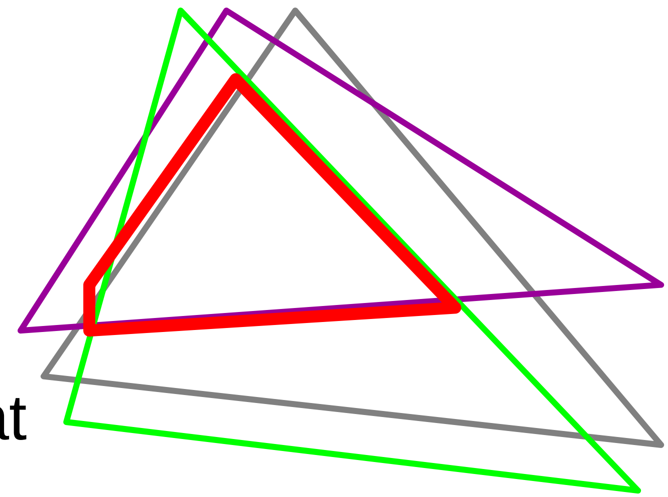
Gamut Matching

- Assumes no intra-projector variation
- Use a photometer to capture the color gamut
  - One measurement per projector
- Find the common color gamut that all the projectors can reproduce
- Use linear transformations to achieve the matching



1) G. Wallace, H. Chen, and K. Li, Color gamut matching for tiled display walls, Immersive Projection Technology Workshop, 2003.
2) M. Bern and D. Eppstein, Optimized color gamuts for tiled displays, 19th ACM Symposium on Computational Geometry, 2003.

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Gamut Matching

- Finding common gamut is not scalable
- Simple method of matching transfer functions across projector
  - Will take care of inter-projector luminance variations only

1) *M.C. Stone, Color balancing experimental projection displays, 9th IS&T/SID Color Imaging Conference, 2001.*
2) *M. C. Stone, Color and brightness appearance issues in tiled displays, IEEE Computer Graphics and Applications, 2001.*
3) *A. Majumder, Z. He, H. Towles and G. Welch, Achieving Color Uniformity in Multi-Projector Displays, IEEE Visualization, 2000.*

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What we want?

- Addresses parts of the problem only
  - Overlaps and Inter Projector Variations
- Intra-projector variation needs to be addressed
- Spatial variation
  - Measured at high resolution
- Desire an unified method
  - Takes care of inter, intra and overlap together

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Existing Methods

- Edge Blending (Overlaps)
- Gamut Matching (Inter projector variation)
- PRISM (Inter + Intra + Overlap)
  - PeRceptual Seamlessness in Multi-Projector Displays
- Color Calibration in LED projectors

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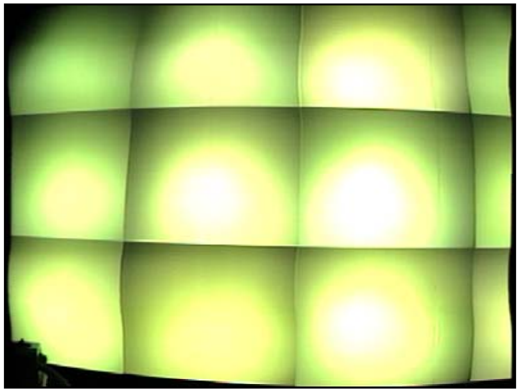
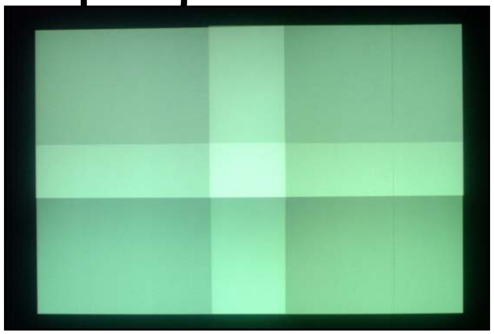
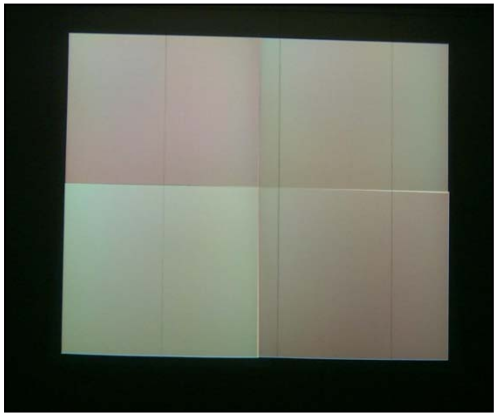
Addresses Luminance Variation



- Intra-projector
  - Within a single projector
- Inter-projector
  - Across different projectors
- Overlaps

Luminance variation is more significant





1) A. Majumder, *Properties of Color Variation in Multi Projector Displays*, *SID Eurodisplay, 2002.*
2) A. Majumder and R. Stevens, *Color Non-Uniformity in Multi Projector Displays: Analysis and Solutions*, *IEEE Transactions on Visualization and Computer Graphics, Vol. 10, No. 2, 2003.*

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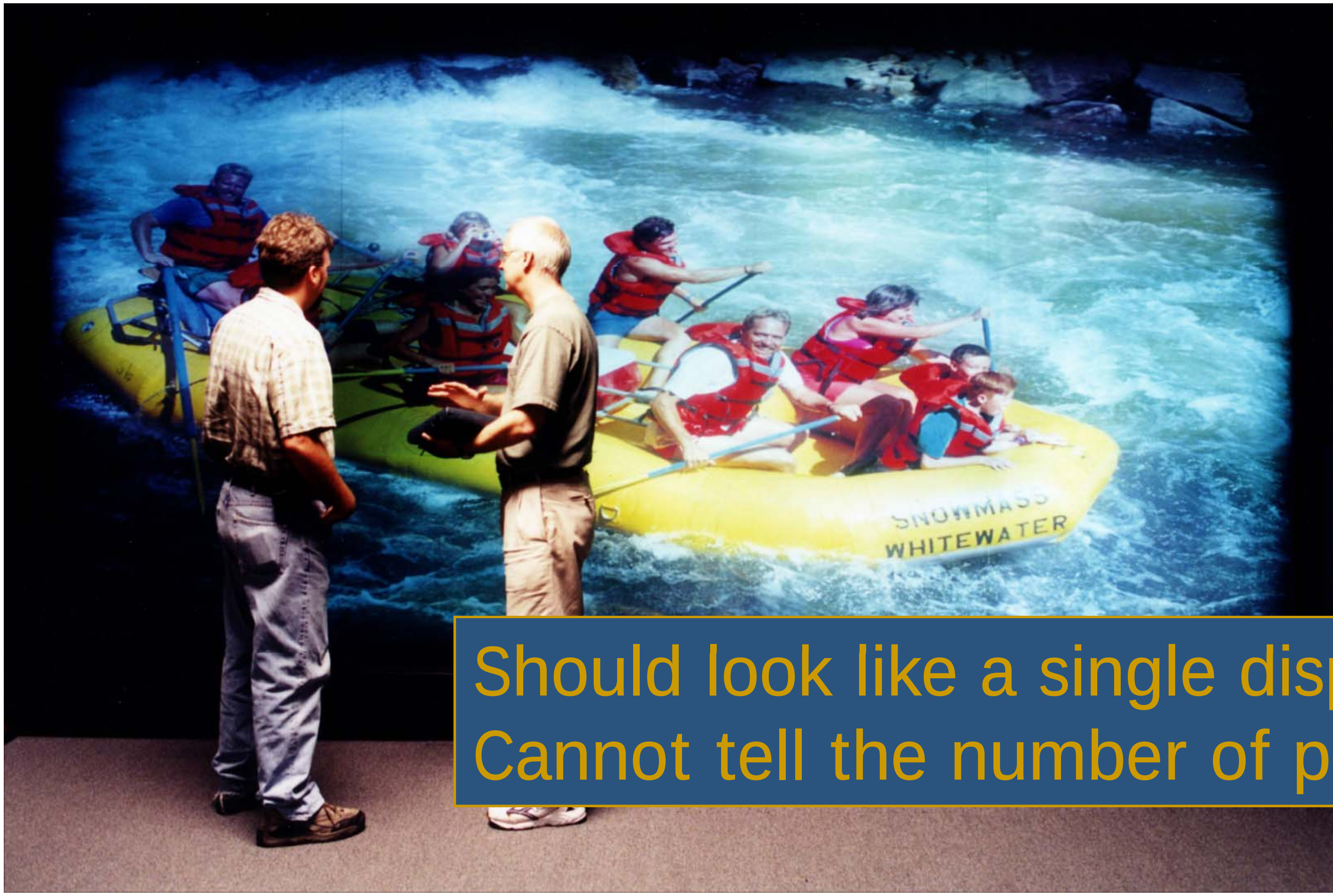
The Goal

The Goal



Should look like a single display
Cannot tell the number of projectors

PRISM

- Reconstruction
- Modification
- Reprojection

PRISM

- Reconstruction
- Modification
- Reprojection

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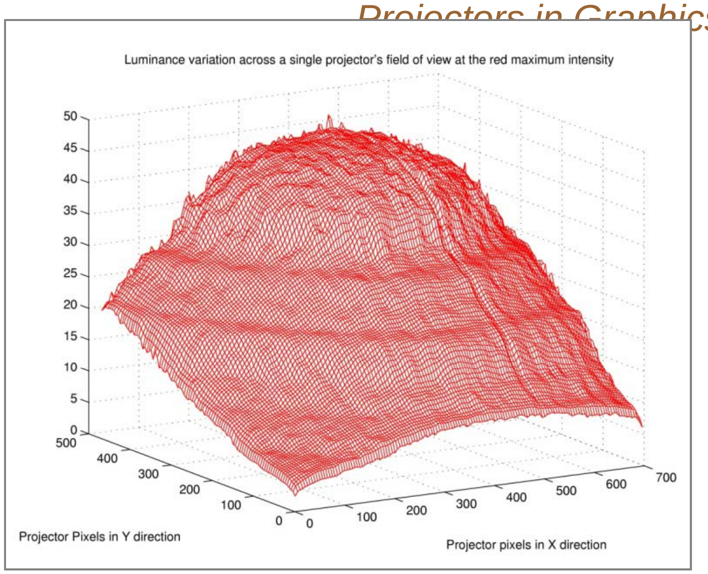
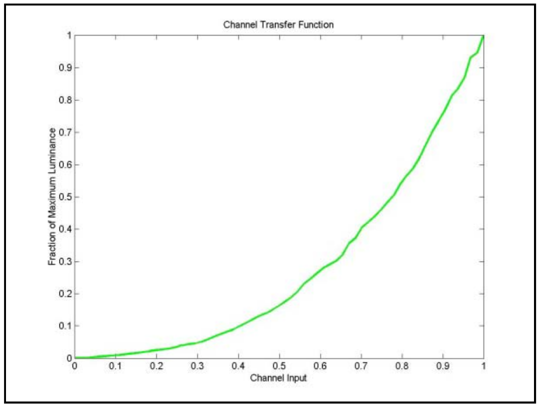
Each projector

- Using a camera find
  - Luminance function
  - Transfer function
- Calibrated camera
  - HDR imaging





1) *A. Majumder, R. Stevens, LAM: Luminance Attenuation Map for Photometric Uniformity Across Projection Based Displays, ACM Virtual Reality Software and Technology, 2002.*
2) *A. Raij, G. Gill, A. Majumder, H. Towles, H. Fuchs, PixelFlex2: A Comprehensive, Automatic, Casually-Aligned Multi-Projector Display, IEEE PROCAMS, 2003*

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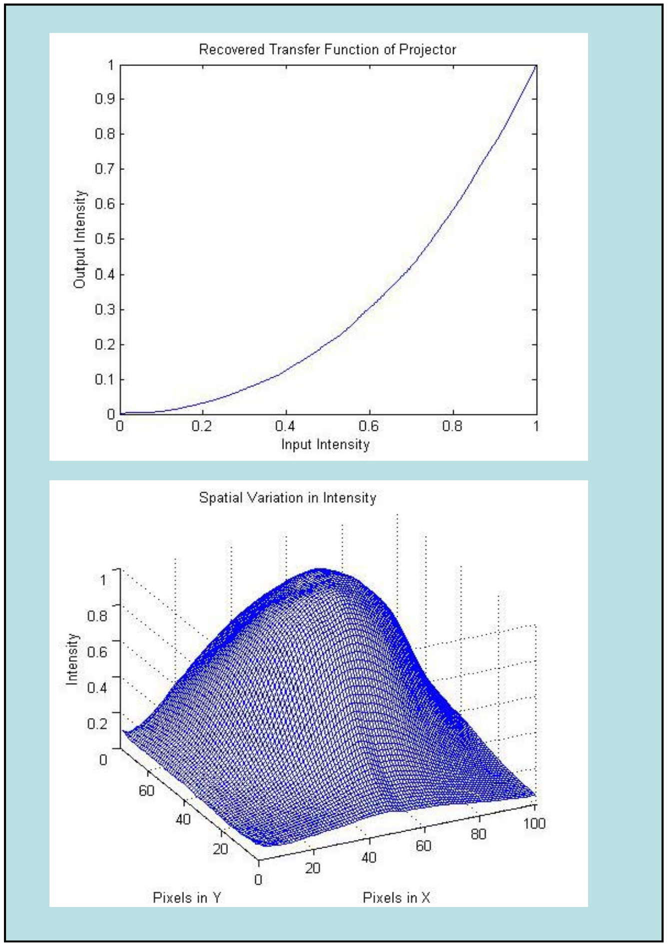
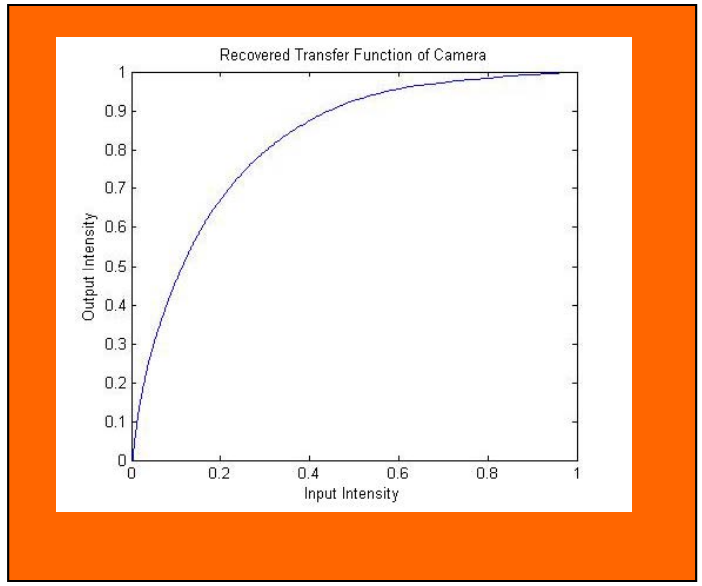
Projector-camera self-calibration





Camera

1) R. Juang, E. Bhasker, A. Majumder, *Registration Techniques for Using Imperfect and Partially Calibrated Devices in Planar Multi-Projector Displays*, IEEE Visualization, 2007.
2) R. Juang, A. Majumder, *Photometric Self-Calibration of Projector-Camera Systems*, IEEE PROCAMS 2007.

Projector

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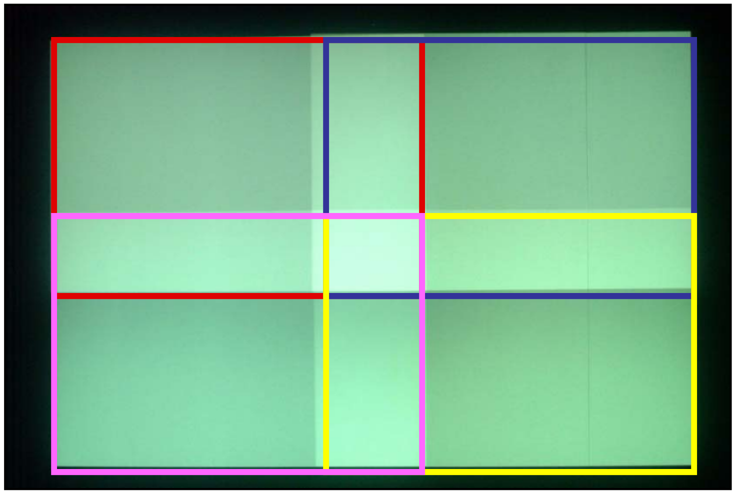
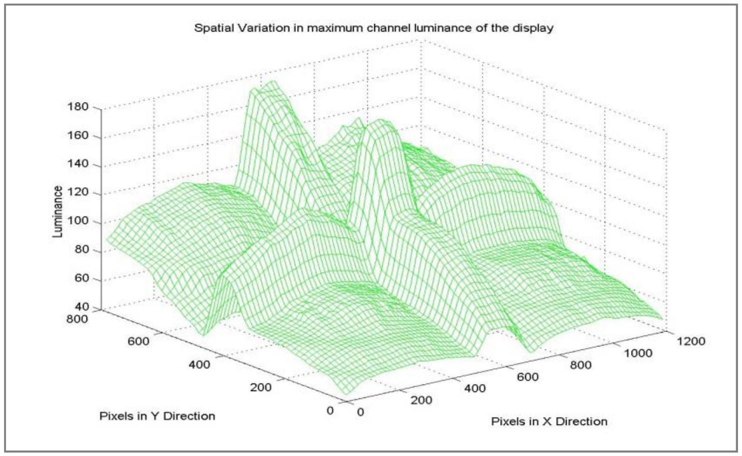
Display Luminance Variation

- Add luminance function of each projector





PRISM

- Reconstruction
- Modification
- Reprojection

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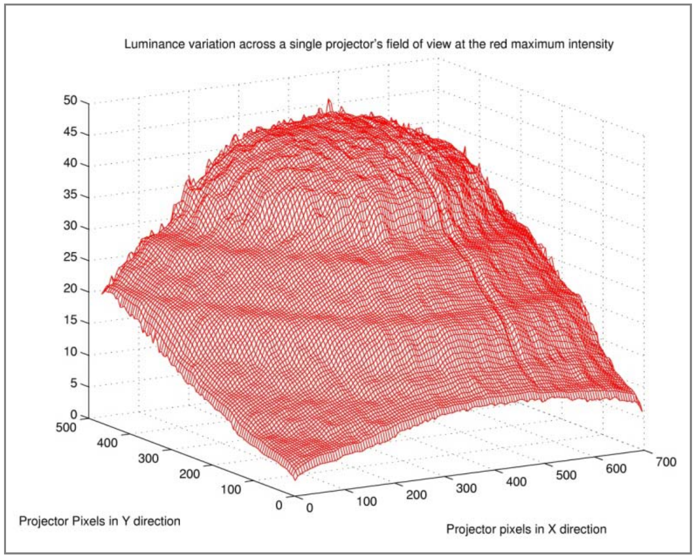
Goal: Make it look like one projector

- Single projector
  - Spatially constant transfer function
  - Spatially smooth luminance function



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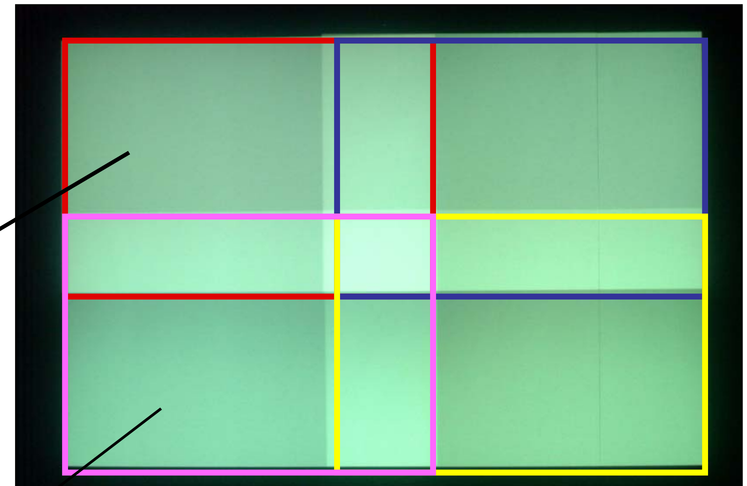
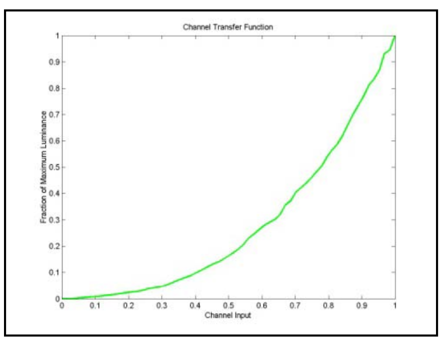
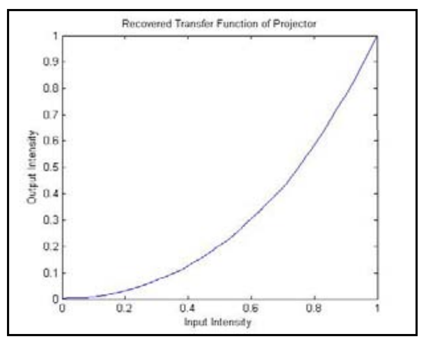
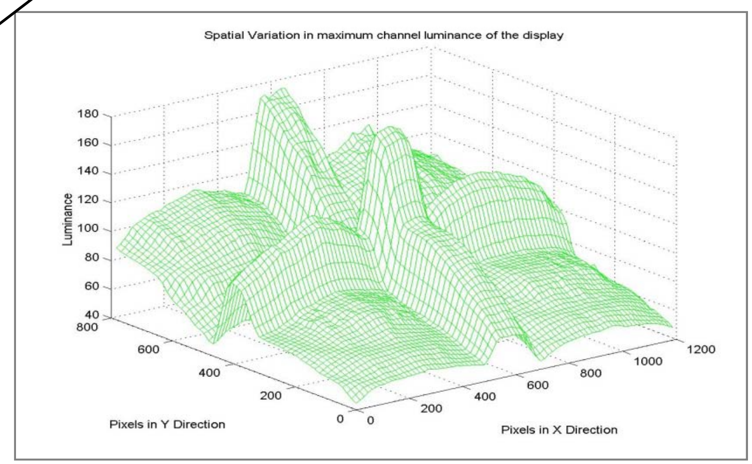
Multi-Projector Variation

- Luminance function shows sharp changes
- Spatially varying transfer function









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Modification

- Design a new luminance function that does not have sharp discontinuities
- Design a common transfer function for all projectors
  - Usually a quadratic function is good

Modification

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- Design a common transfer function for all projectors
  - Usually a quadratic function is good

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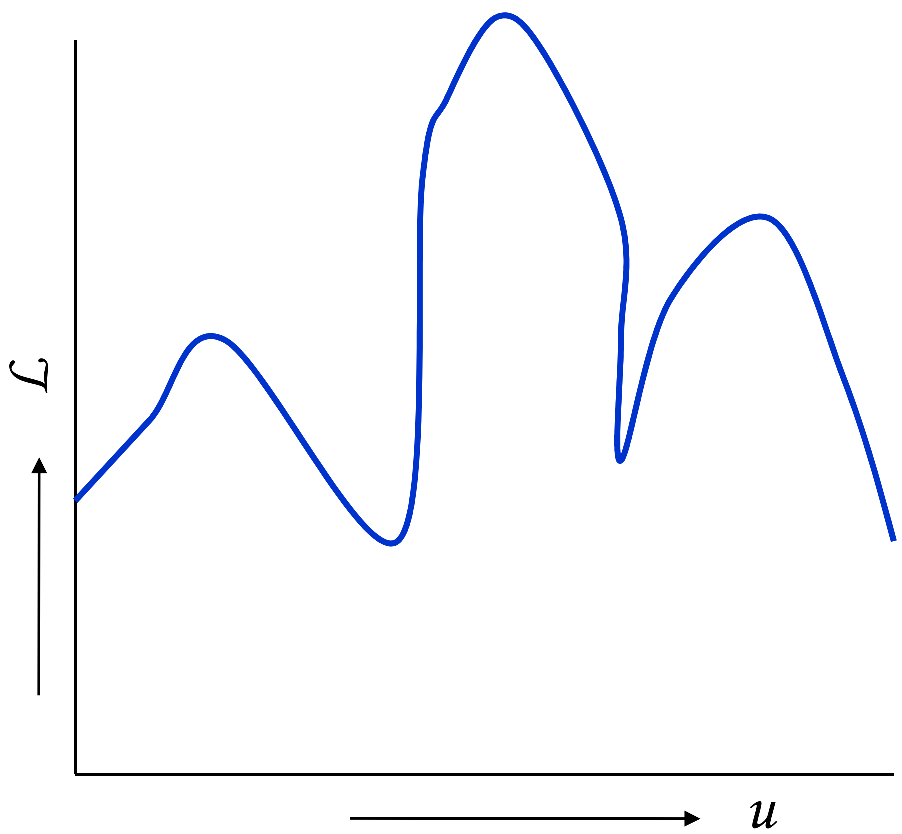
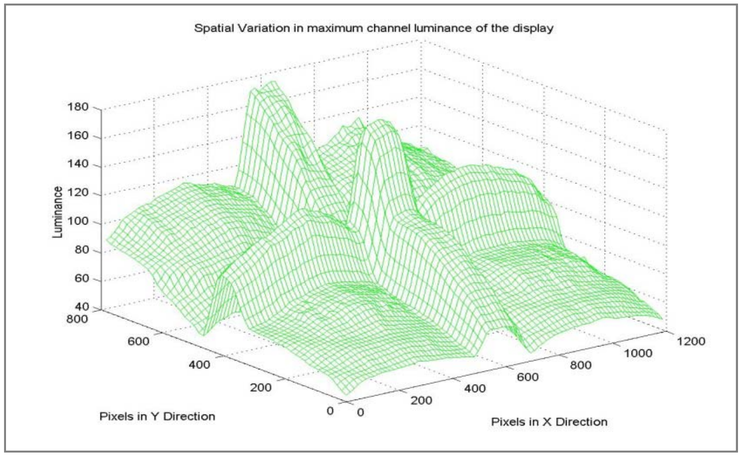
Strict Luminance Uniformity





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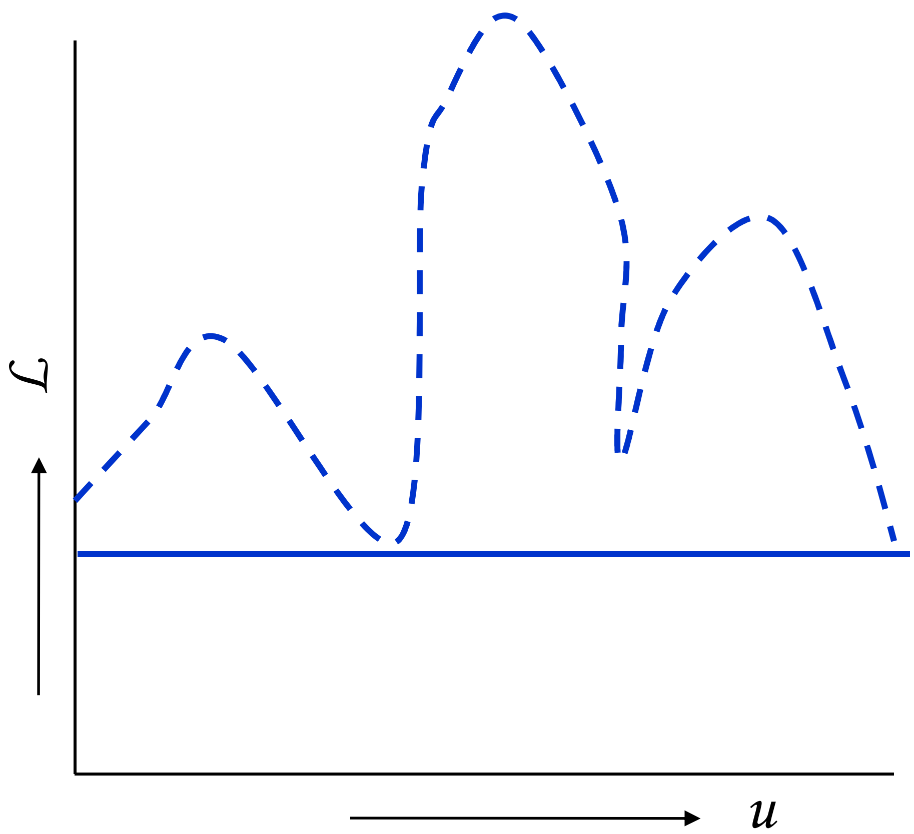
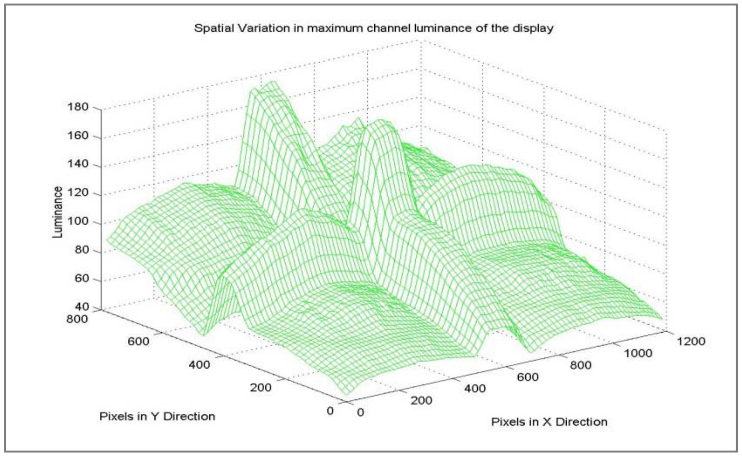
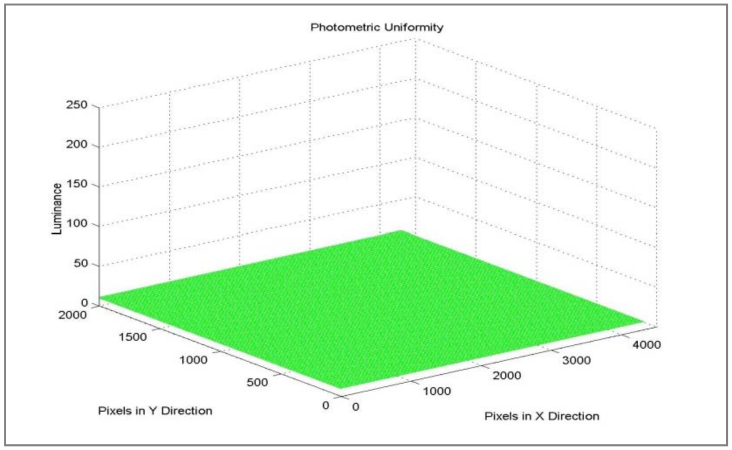
Strict Luminance Uniformity







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Results

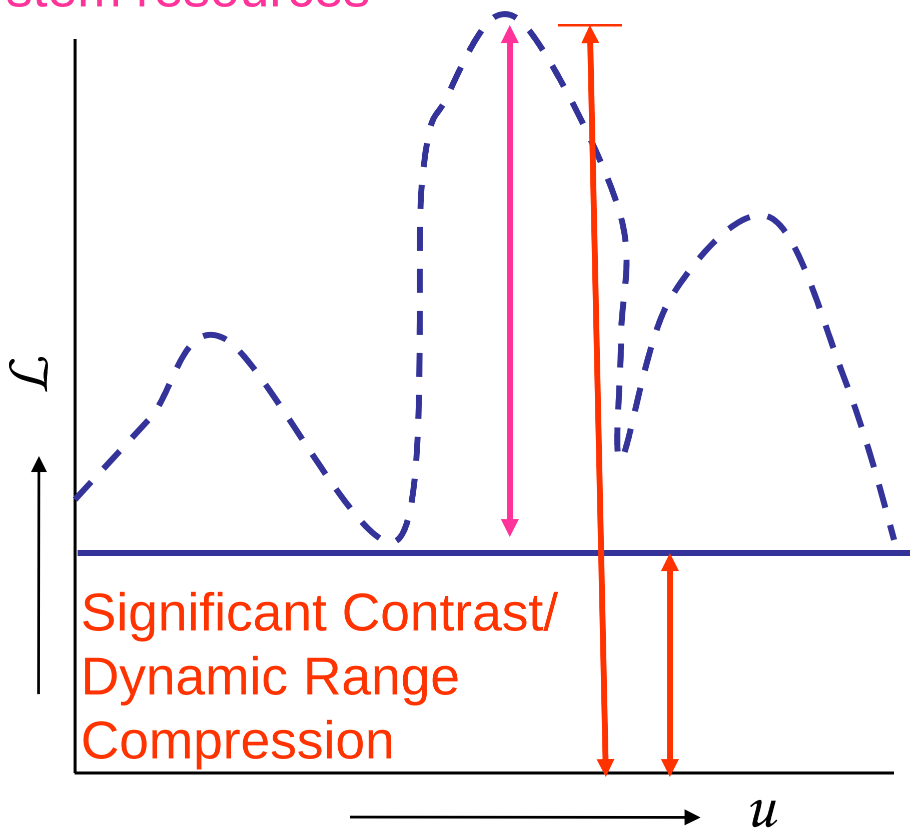
Before

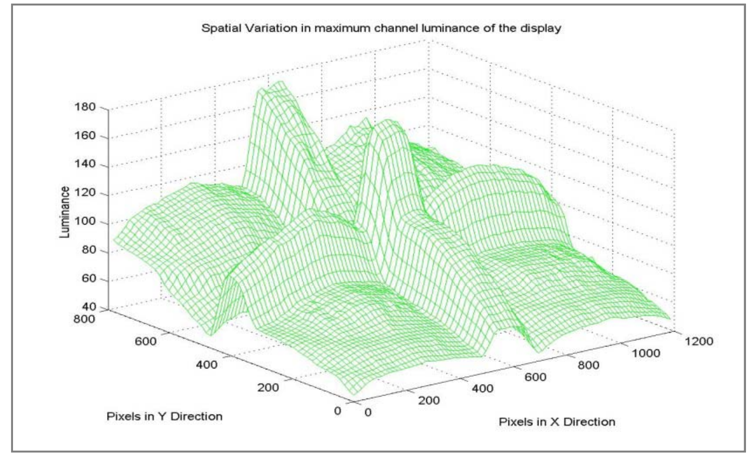
After Strict Luminance Uniformity

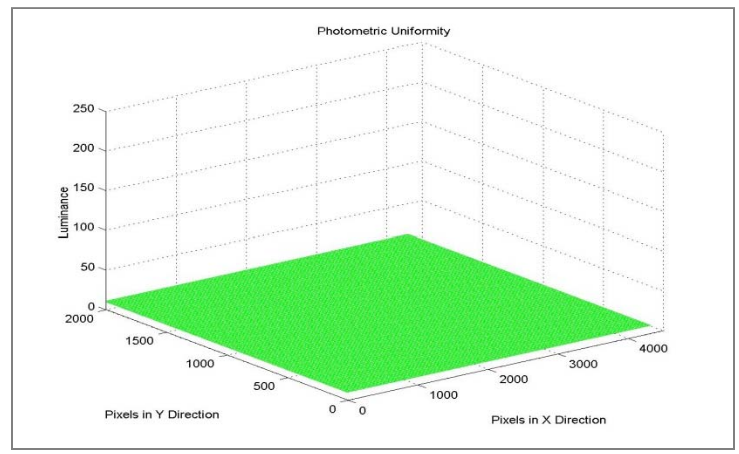
A. Majumder and R. Stevens, Color Non-Uniformity in Multi Projector Displays: Analysis and Solutions, IEEE Transactions on Visualization and Computer Graphics, Vol. 10, No. 2, 2003.

Strict Luminance Uniformity

Suboptimal use of system resources







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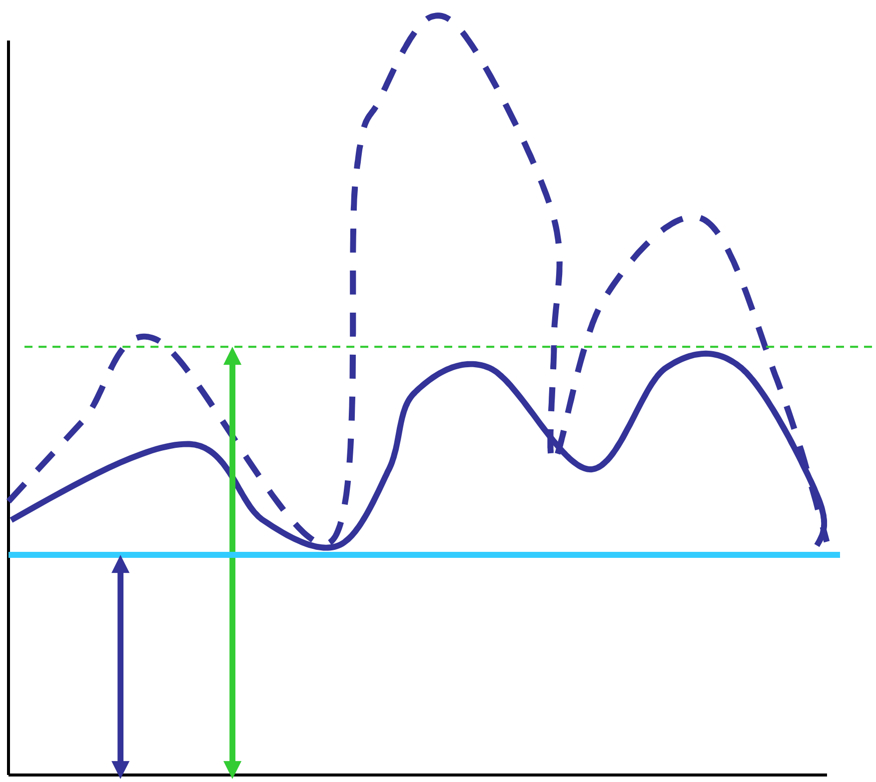
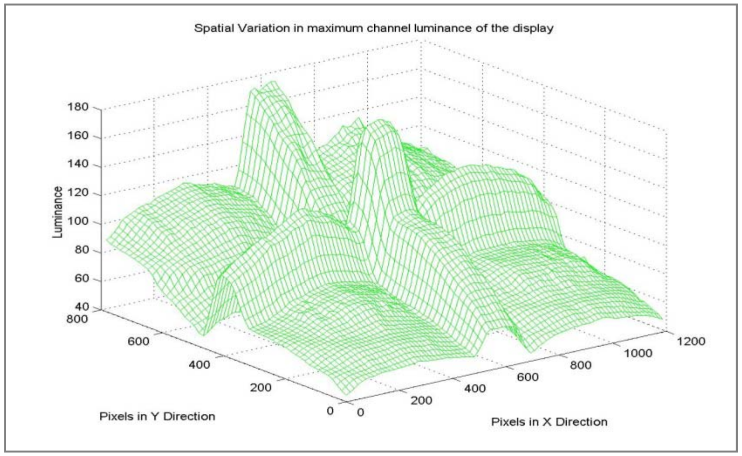
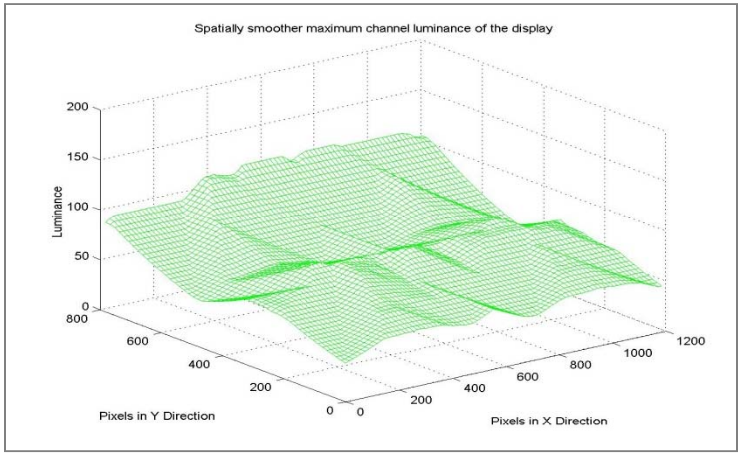
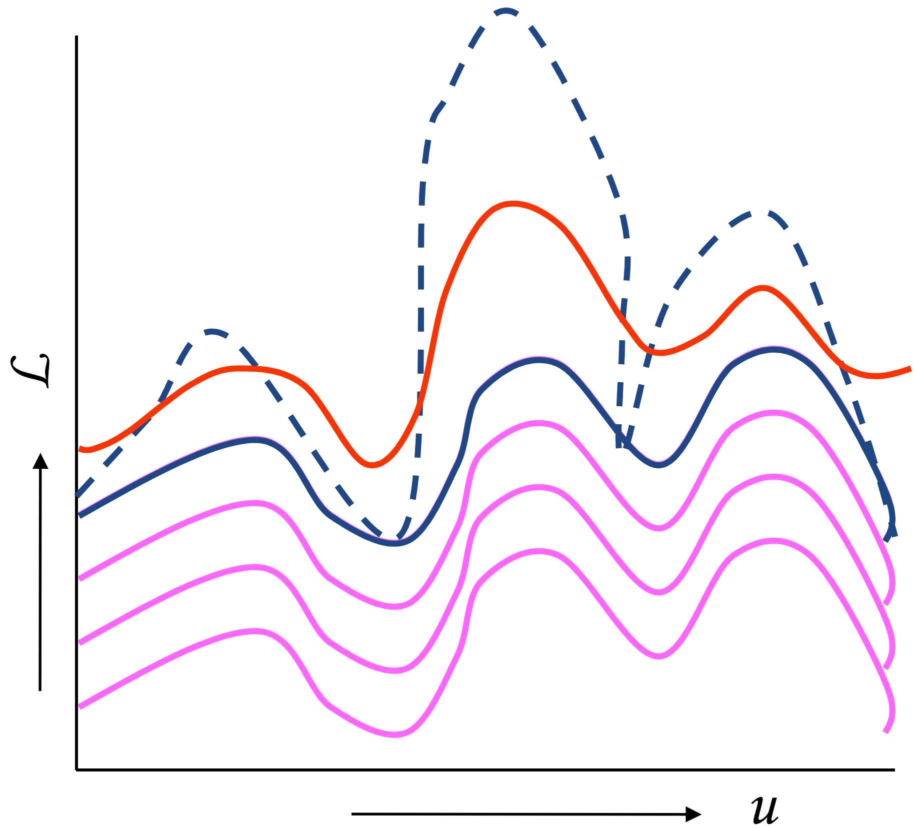
Smooth the Luminance function

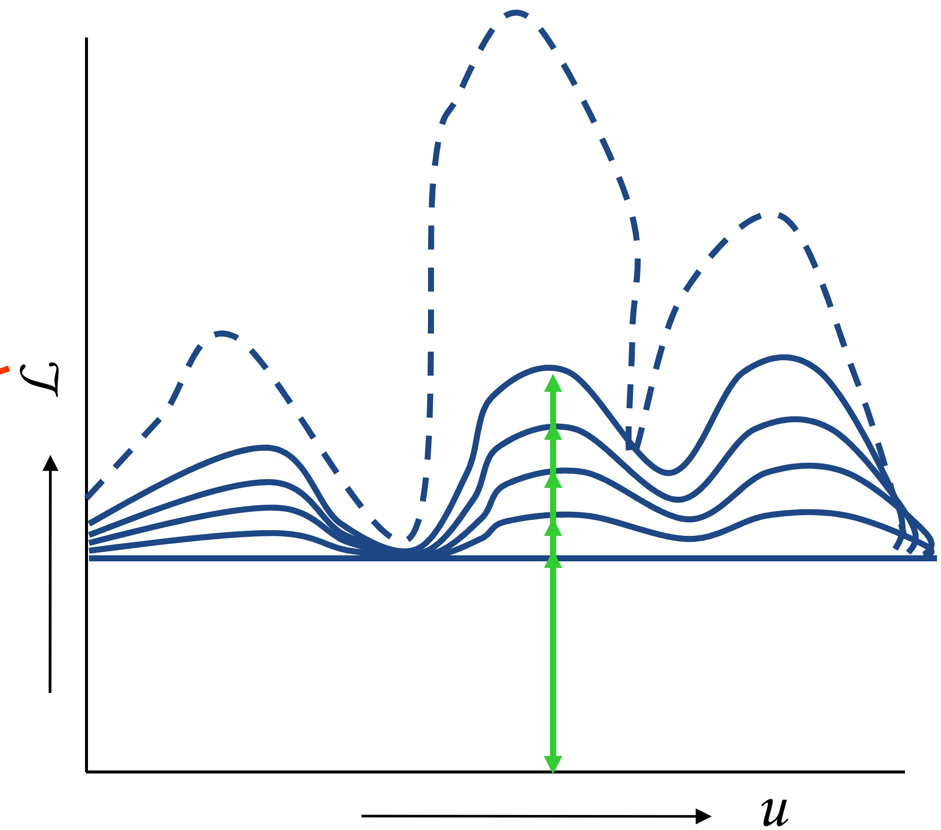






Optimization Problem





Strict luminance uniformity is a special case.

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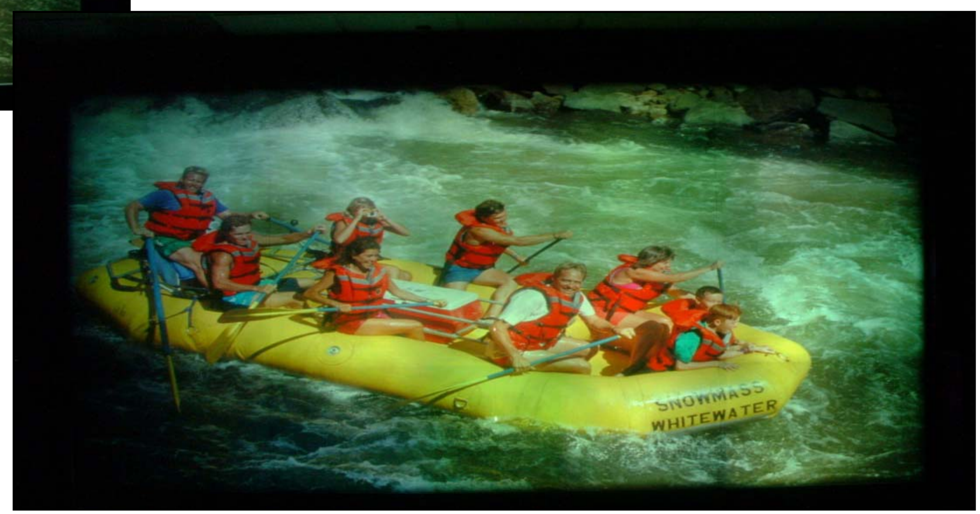
Results

Before

After Strict Luminance Uniformity

Results

After Luminance Smoothing



Before

1) A. Majumder, R. Stevens, *Perceptual Photometric Seamlessness in Tiled Projection Based Displays*, ACM Transactions on Graphics, Vol. 24, No. 1, 2005.
2) A. Majumder, *Improving Contrast of Multi-Displays Using Human Contrast Sensitivity*, IEEE CVPR 2005.

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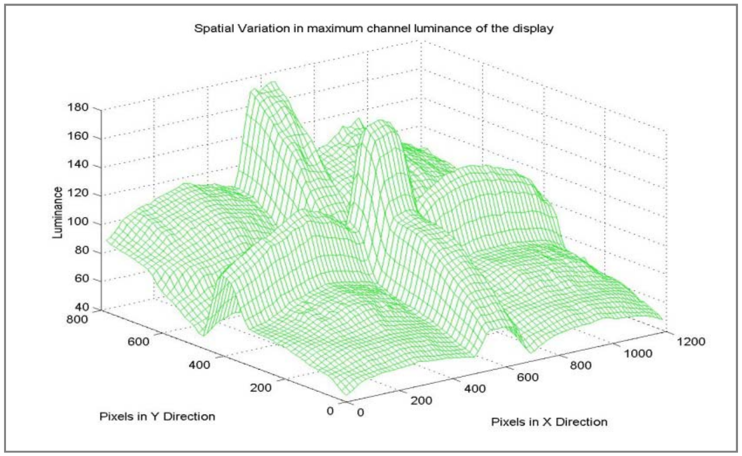
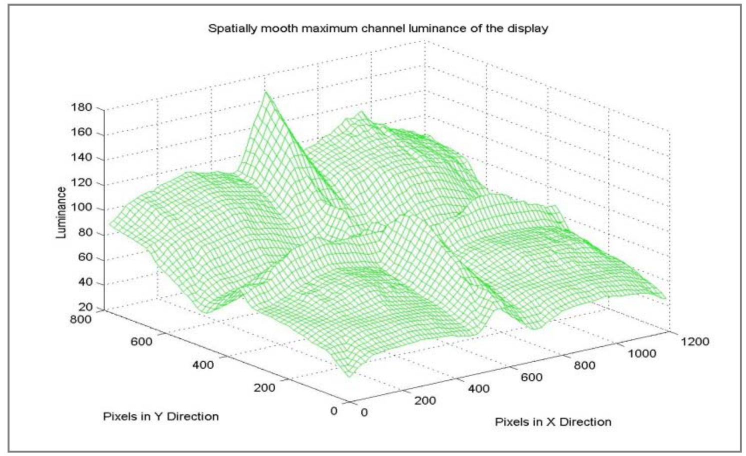
Different smoothing parameters (2x2 array of four projectors)

Smooth

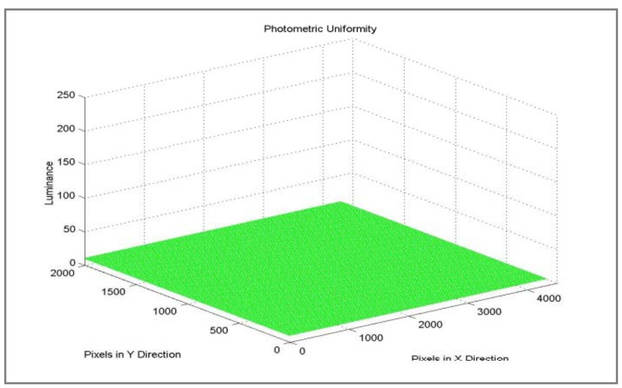


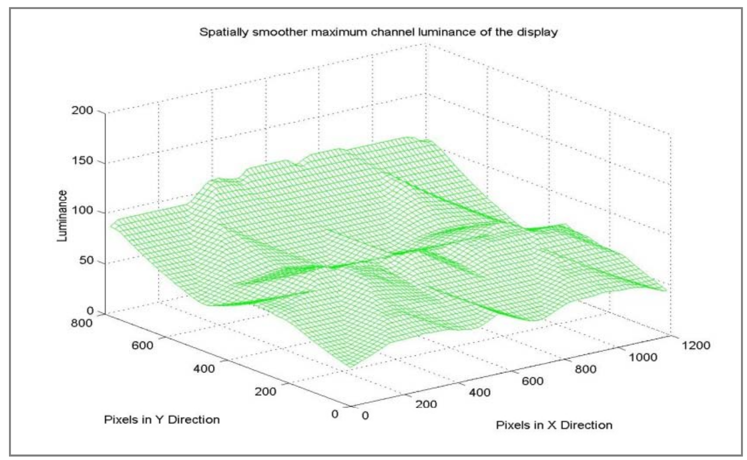


Original

Smoother

Flat





Different smoothing parameters (3x5 array of fifteen projectors)

Smooth

Original

Smoother

Flat

PRISM

- Reconstruction
- Modification
- Reprojection

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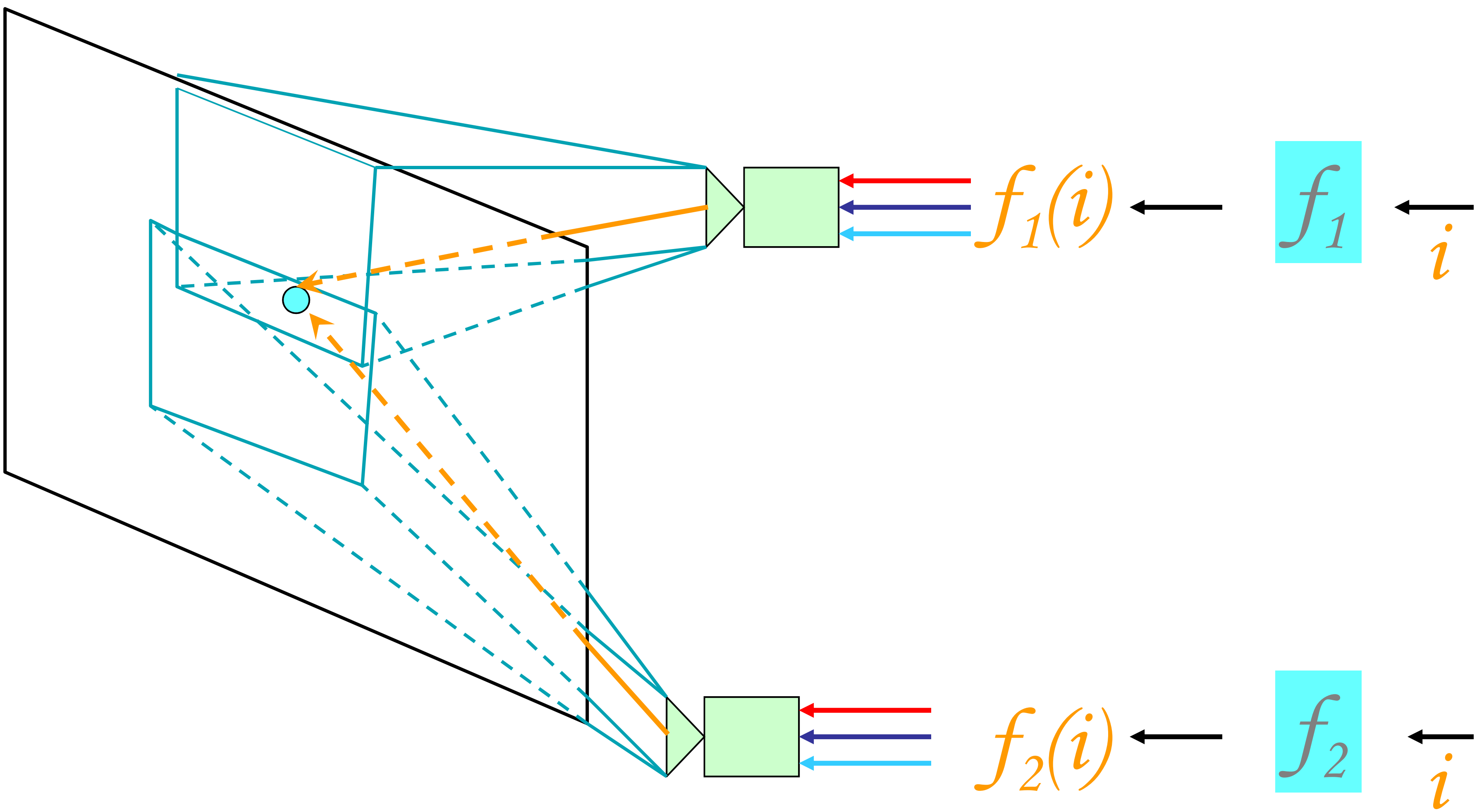
How to modify input?



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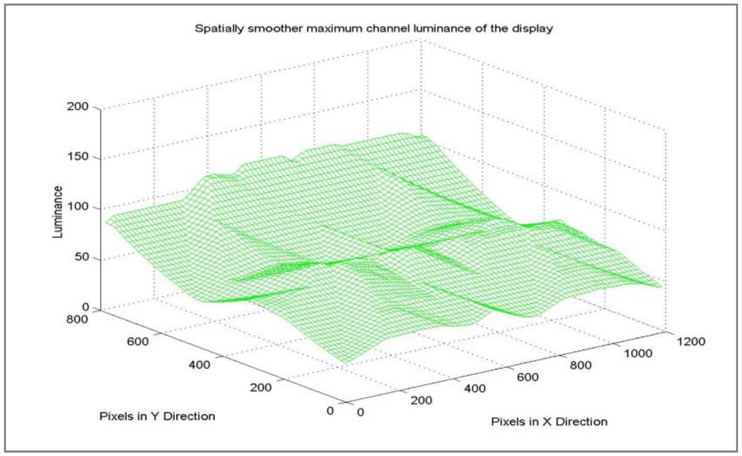
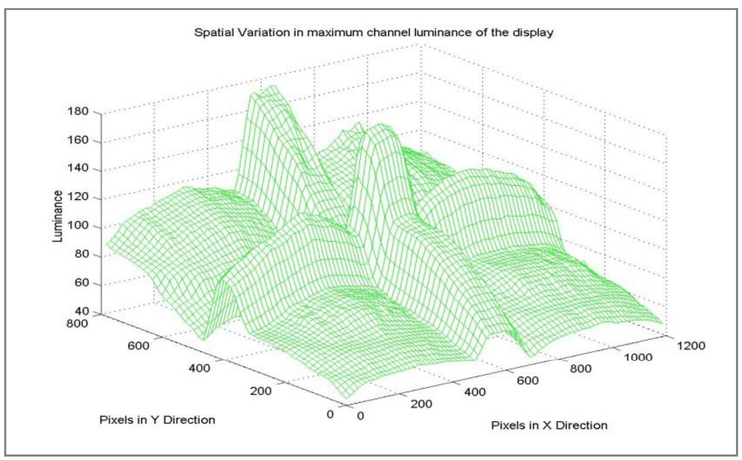
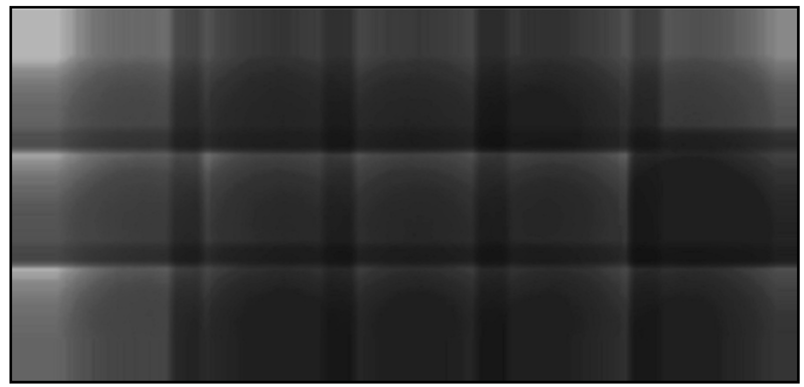
Luminance Attenuation Map (LAM)





=

Per pixel luminance attenuation factors



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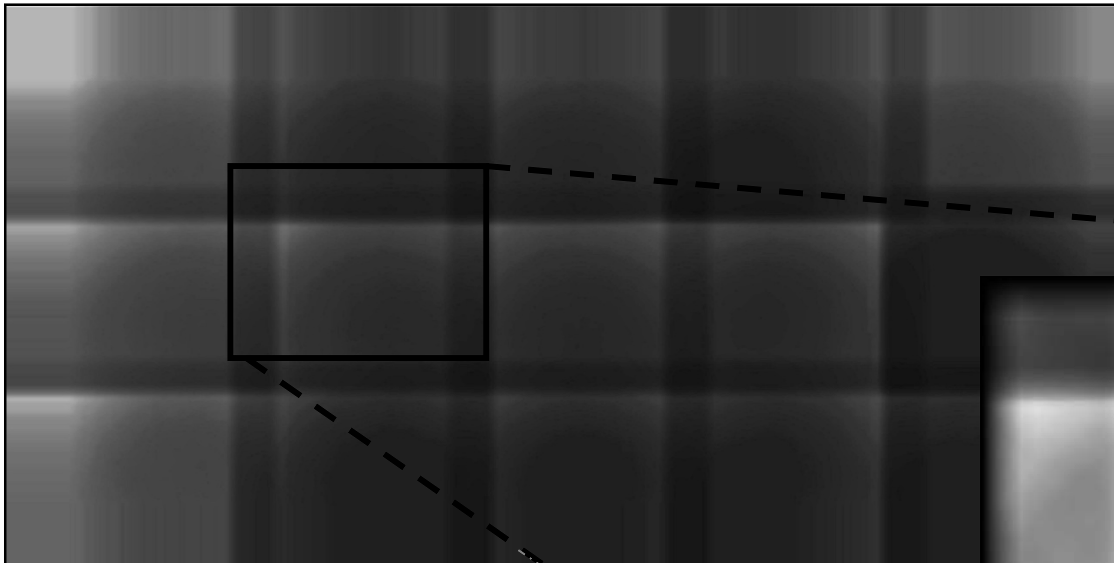
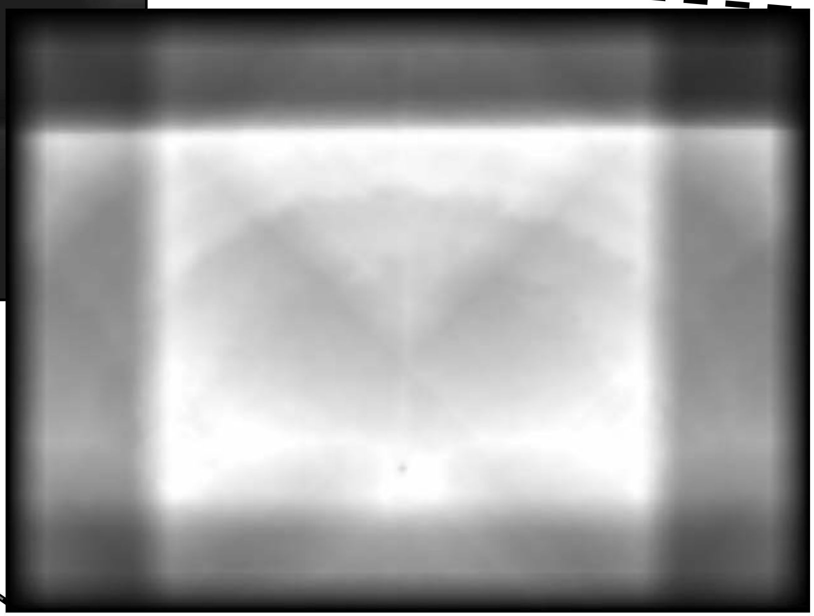
Projector LAM



Display Attenuation Map

(15 projector display)



Projector Attenuation Map

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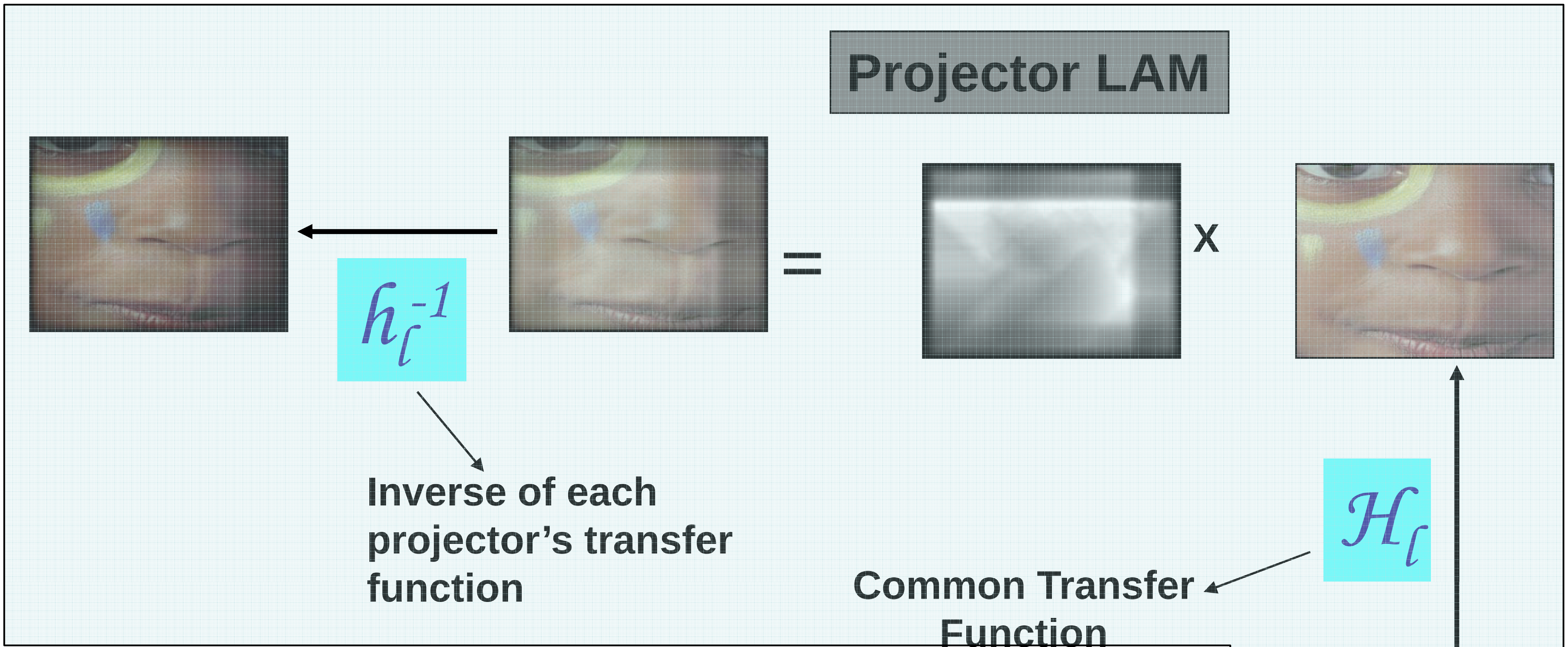
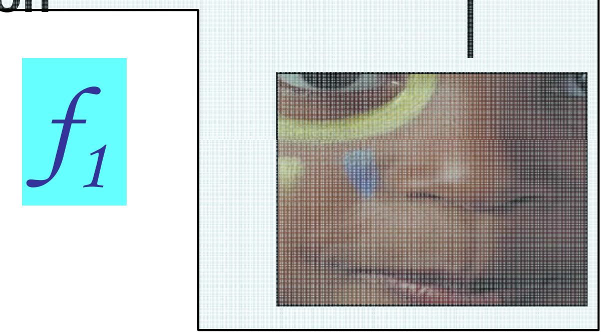
Per Projector Image Correction





A. Majumder, R. Stevens, Perceptual Photometric Seamlessness in Tiled Projection Based Displays, ACM Transactions on Graphics, Vol. 24, No. 1, 2005.

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Results (Before)

6 Projector Display

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Results (After)

Results (Before)

15 Projector Display

Results (After)

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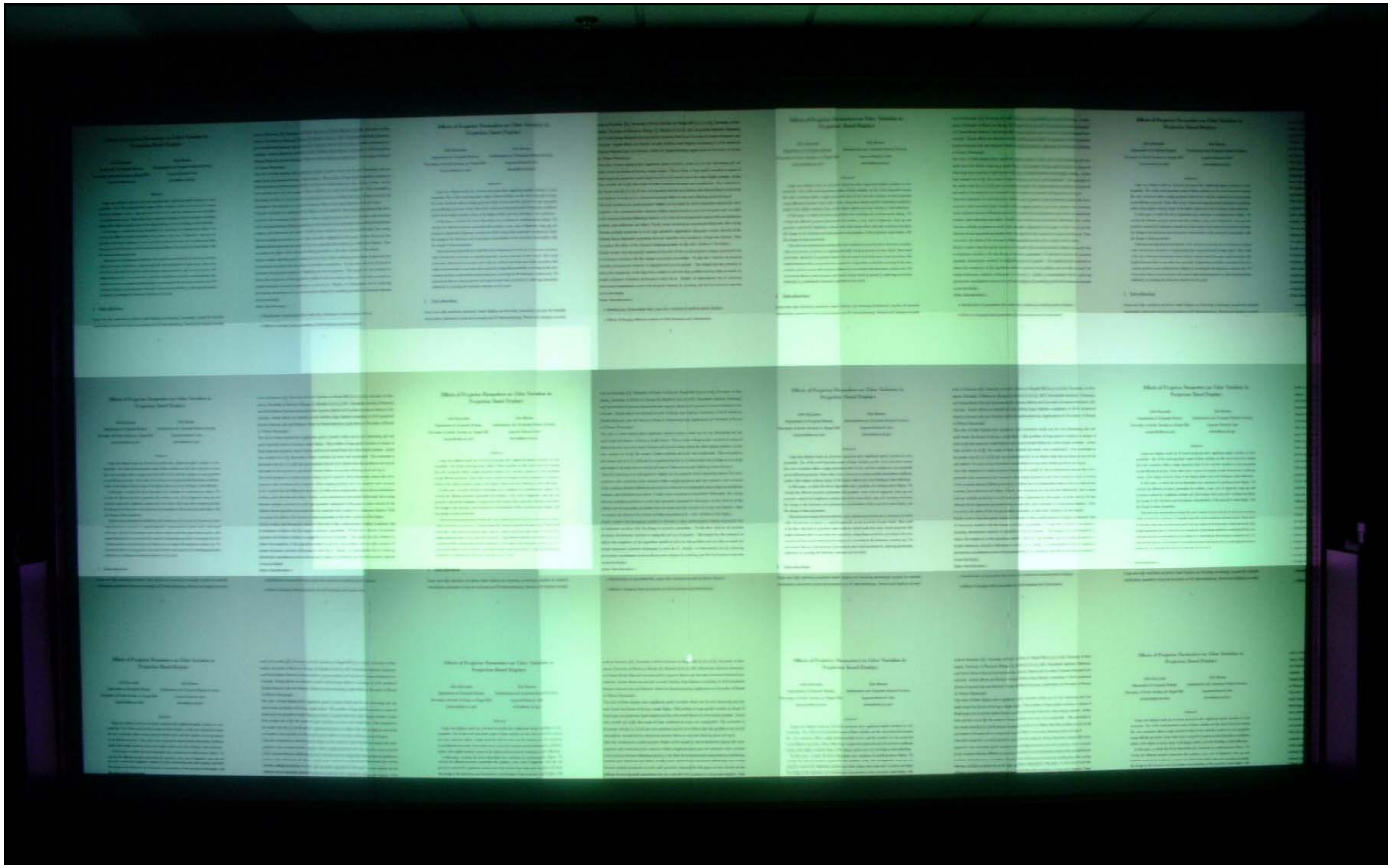
Handling Chrominance

Before



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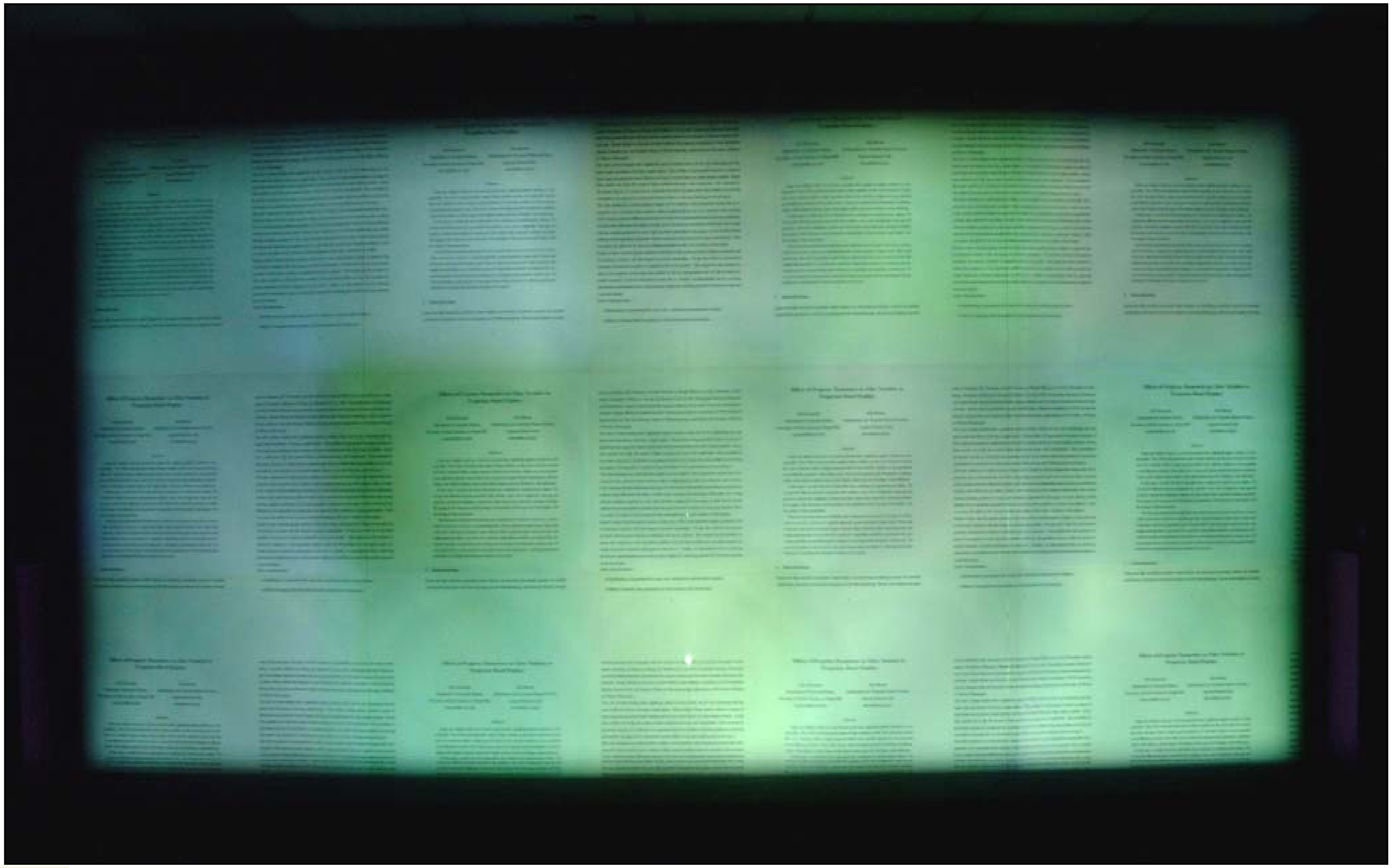
Handling Chrominance

After



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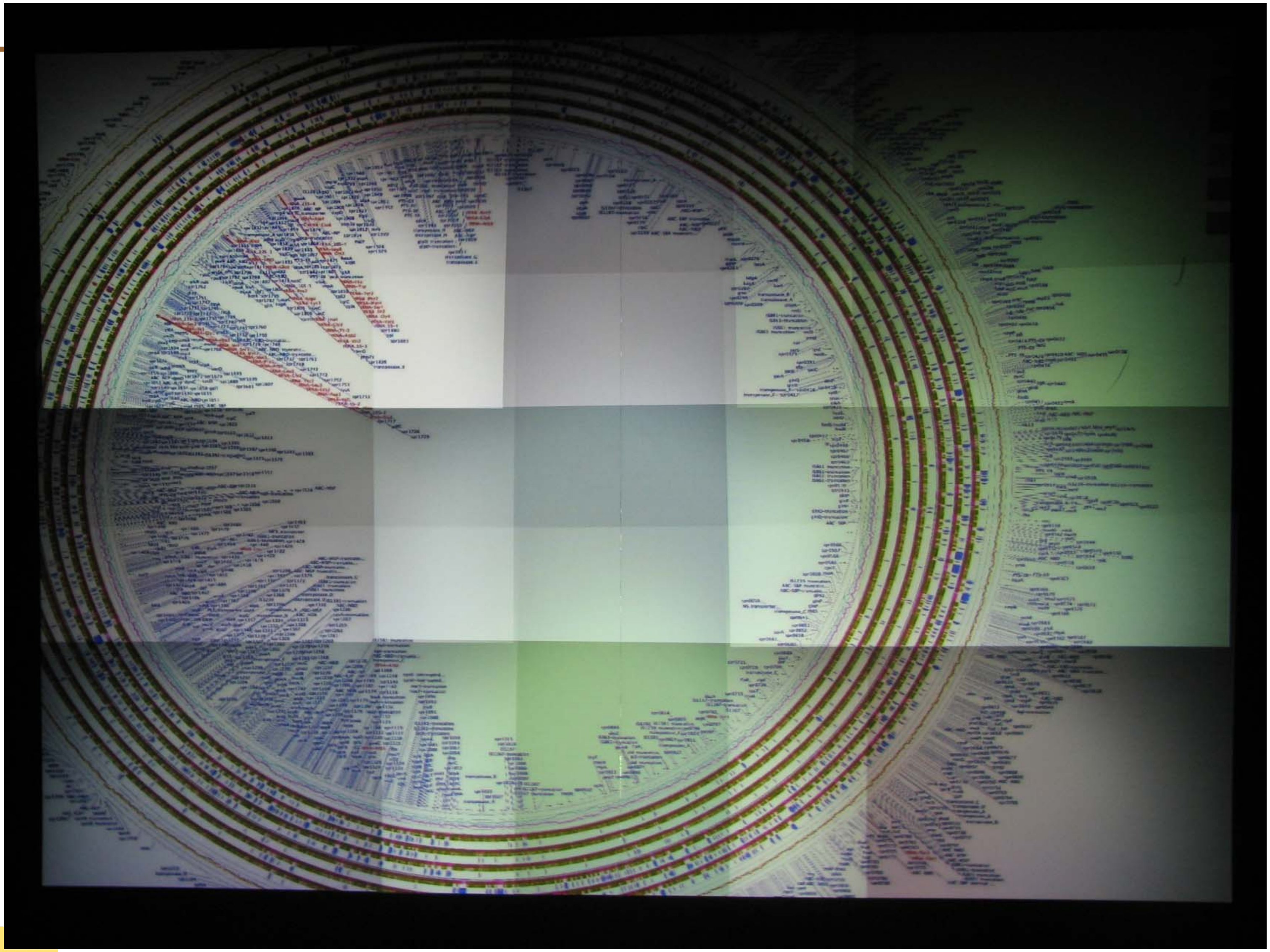
Getting worse



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Existing Methods

- Edge Blending (Overlaps)
- Gamut Matching (Inter projector variation)
- PRISM (Inter + Intra + Overlap)
- Color Calibration in LED projectors

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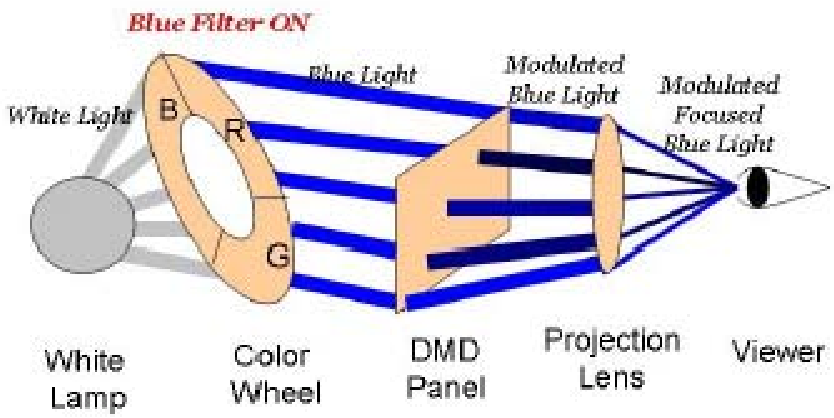
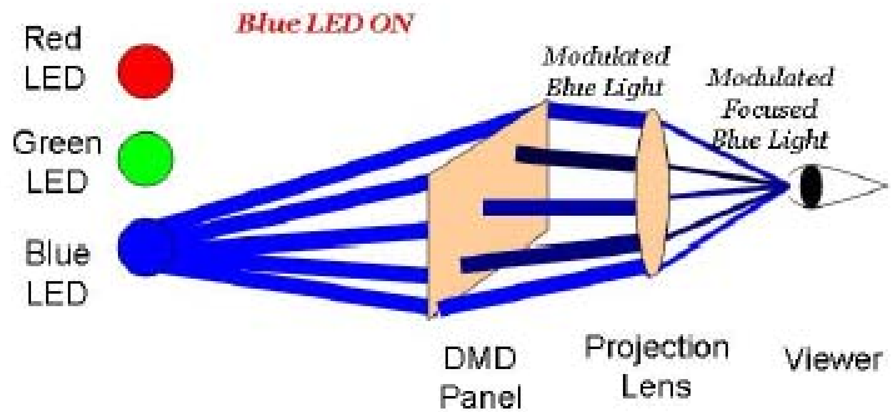
LED Based Projectors

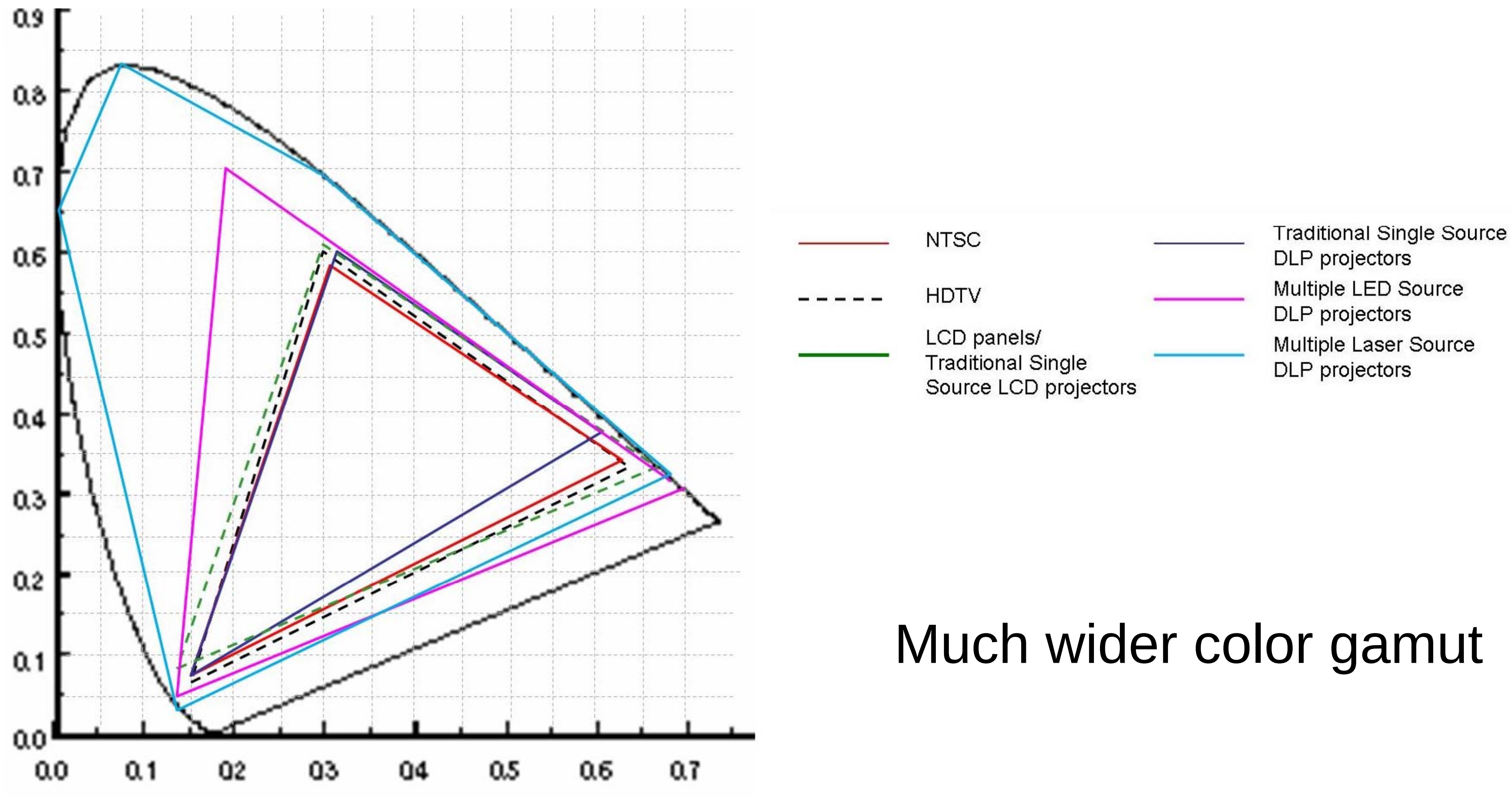


Traditional DLP Projectors



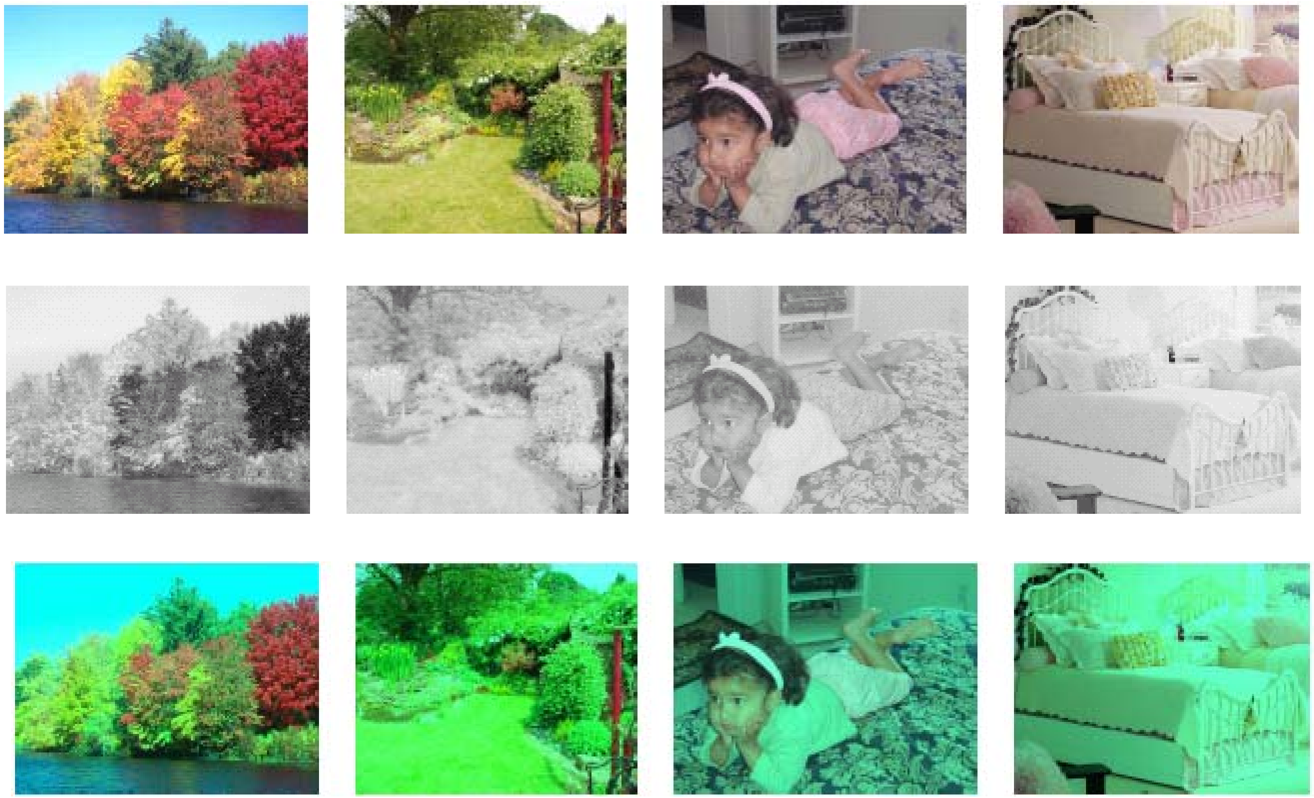
LED Projectors

Wider color gamut



Much wider color gamut

Results of Gamut Expansion



Original

JND (in grayscale) between original and the one displayed by LED (a difference of 3JND is visible)

The displayed image captured by a camera in a projector-camera application.

Gamut Extrapolation

- Moves colors to use the wider gamut
- The content needs to be transformed
  - Differently for different standards
- Different colors in different projectors
  - Mismatch, especially in overlap region

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Advantages

- Simultaneous ON-time for LEDs
- Hence, color of the primaries can be changed easily
  - Manipulating DLP timings
- Reshape the gamut
  - Accurate emulation of 2D gamut
    - Maximizes the dynamic range
  - Achieves color balancing for multiple projectors
- The content needs no transformation

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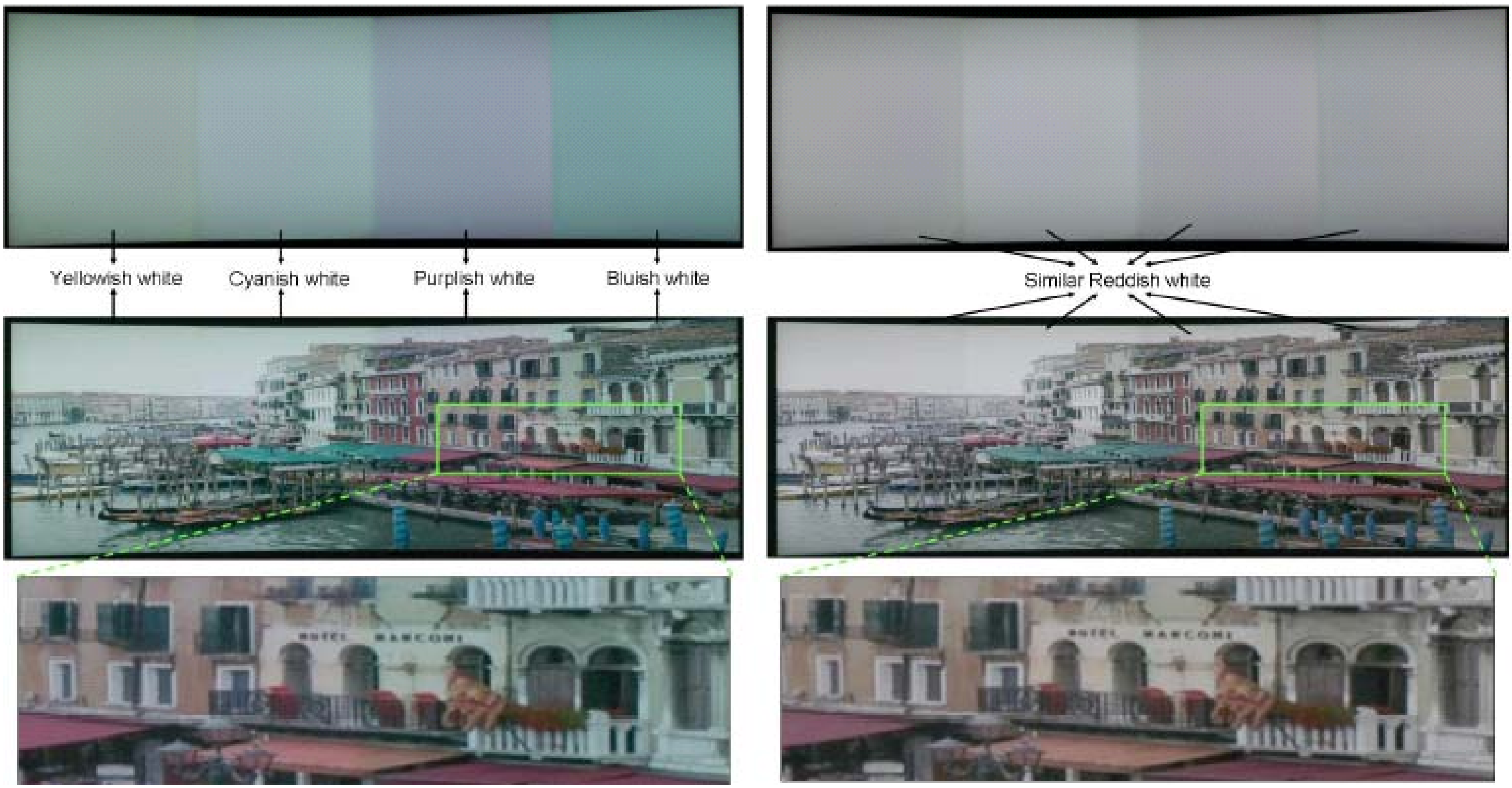
Results (4 projector curved screen)



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Results (16 projector planar)

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First multi-projector curved desktop

- Ostendo Technologies, Carlsbad
  - Demo in PROCAMS

R. Yang, A. Majumder, M. S. Brown, Camera-Based Calibration Techniques for Seamless Multi-Projector Displays, IEEE Transactions on Visualization and Computer Graphics 11(2), 2005

Model	*CRVD-42DWX+
Diagonal	42.4”
Native Resolution	2880 x 900 – Double WXGA+
Curved Seamless Image	Yes
Response Time	<0.02milliseconds
Dynamic Range	12-bit - 4,096 levels
Color Gamut sRGB Adobe RGB	Coverage / Size 100% / 160% 99.3% / 119%
Number of Colors	68.7 billion
Contrast	>10,000:1
Brightness	>300 nits
Field of View	H90°@ 24” x V30° @ 24”
Screen Dimensions (flat)	W: 40.4” x H: 12.6”
Pixel Pitch	0.36mm, 71 DPI
Aspect Ratio	3.2 : 1
Monitor Weight (no stand)	25 lbs
General Availability	Q4 2008

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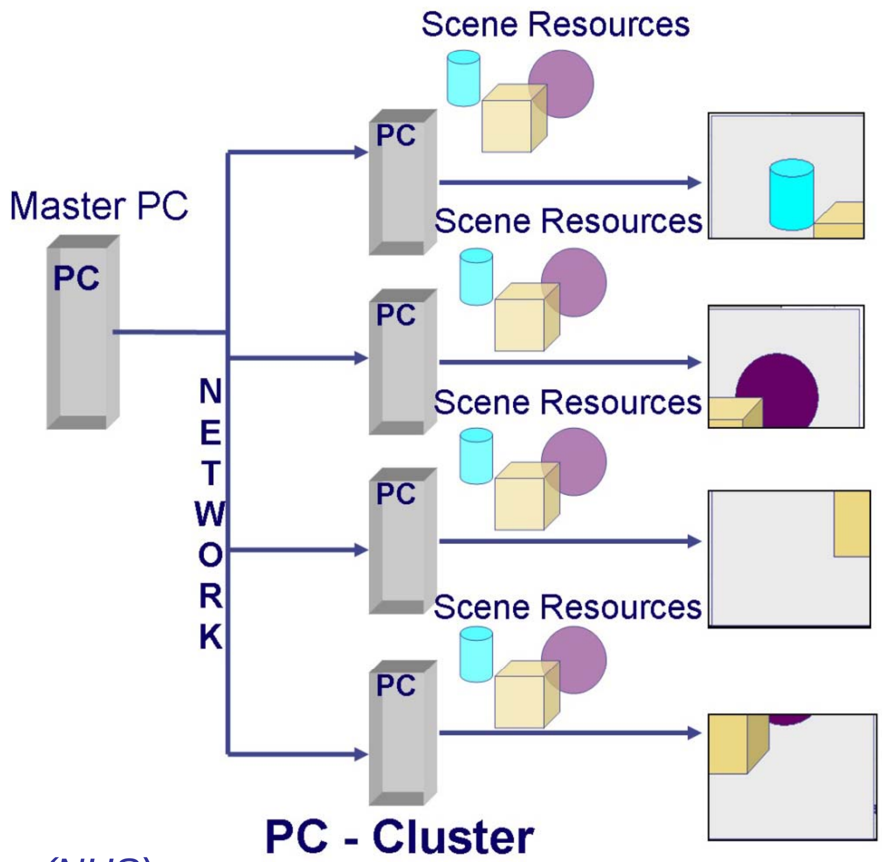
Overview

- Geometric Registration
- Photometric Registration
- PC Cluster Based Rendering
- Distributed Rendering

PC Cluster Rendering Framework



Courtesy: Michael S. Brown (NUS)

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PC Cluster Rendering Solutions

- WireGL
- Chromium
- VR Jugglers
- All use PC cluster + network to render a large “logical” framebuffer
  - Rendering is synchronized via the network

Courtesy: Michael S. Brown (NUS)

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Chromium

- Designed to support OpenGL API
  - No change to existing OpenGL applications
- Each PC renders a logical *tile*
- Tiles can overlap completely, partially or none
- Well suited for our application
  - Each PC drives a projector
  - Has partial overlap
- Use this to incorporate geometric/photometric corrections

Courtesy: Michael S. Brown (NUS)

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PC Based Rendering

References:

- *G. Humphreys, P. Hanrahan, A Distributed Graphics System for Large Tiled Displays, IEEE Visualization, 1999.*

- *G. Humphreys, M. Eldridge, I. Buck, G. Stoll, M. Everett, P. Hanrahan, WireGL: A Scalable Graphics Systems for Clusters, SIGGRAPH 2001.*

- *G. Humphreys, M. Houston, R. Ng, R. Frank, S. Ahem, P. Kirchner, J. Klosowski, Chromium: A Stream Processing Framework for Interactive Rendering on Clusters, ACM Transactions on Graphics, 2002.*

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Overview

- Geometric Registration
- Photometric Registration
- PC Cluster Based Rendering
- Distributed Registration

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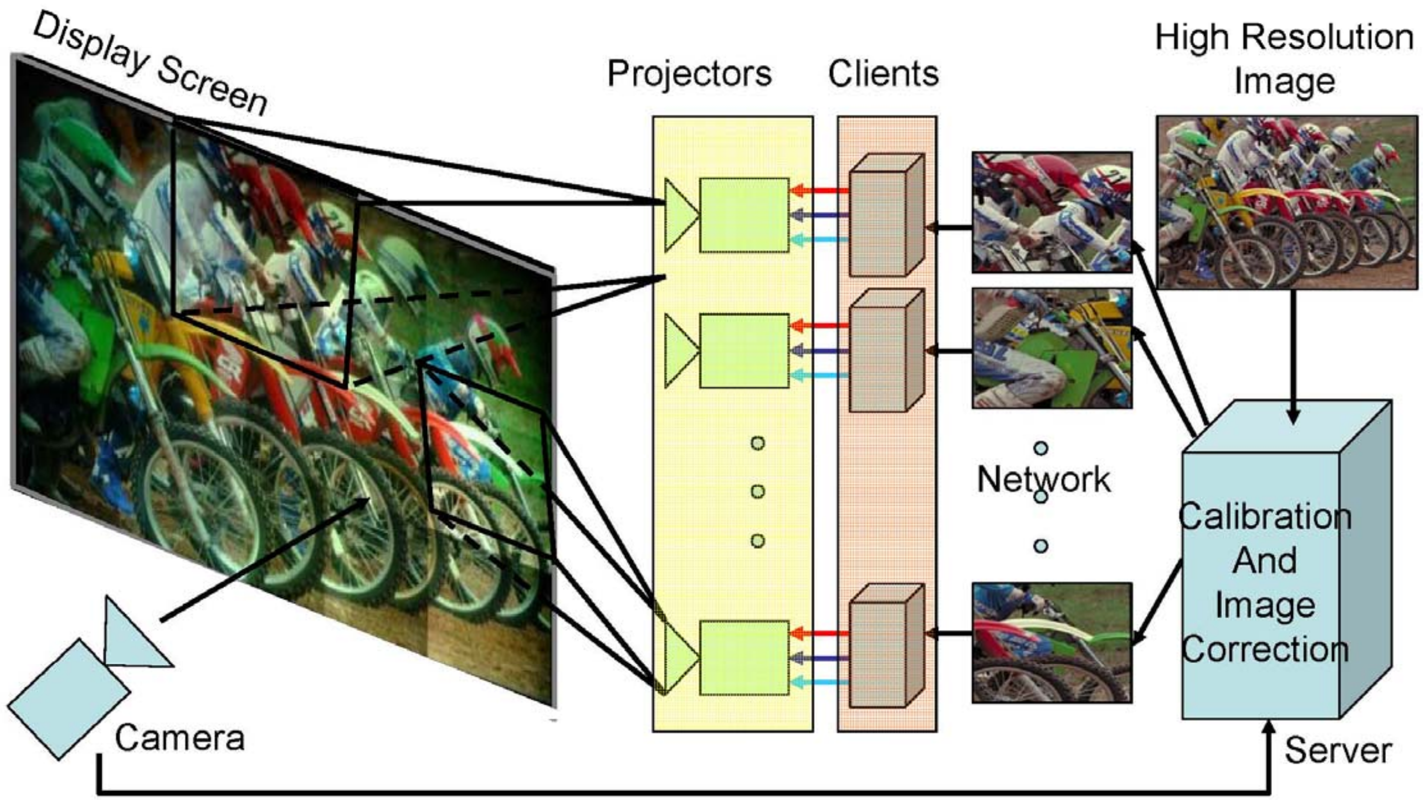
Centralized Architecture



Centralized Server must use synchronized push

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Limitations

- Educated User
  - Difficult to deploy
- Not easy to add/remove projectors
  - Not scalable (Limited by camera resolution)
- Not easy to rearrange projectors
  - Not reconfigurable
- Not easy to tolerate faults

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Imagine…

- A display that can calibrate itself with no user intervention
- Can detect addition/removal and recalibrate itself
- Can detect faults and function at a limited capability

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Distributed Approach

- Plug-and-Play Projector (PPP)
- Distributed Architecture
- Asynchronous Distributed Calibration

E. Bhasker, P. Sinha, A. Majumder, Asynchronous Distributed Calibration for Scalable and Reconfigurable Multi-Projector Displays, IEEE Visualization, 2006.

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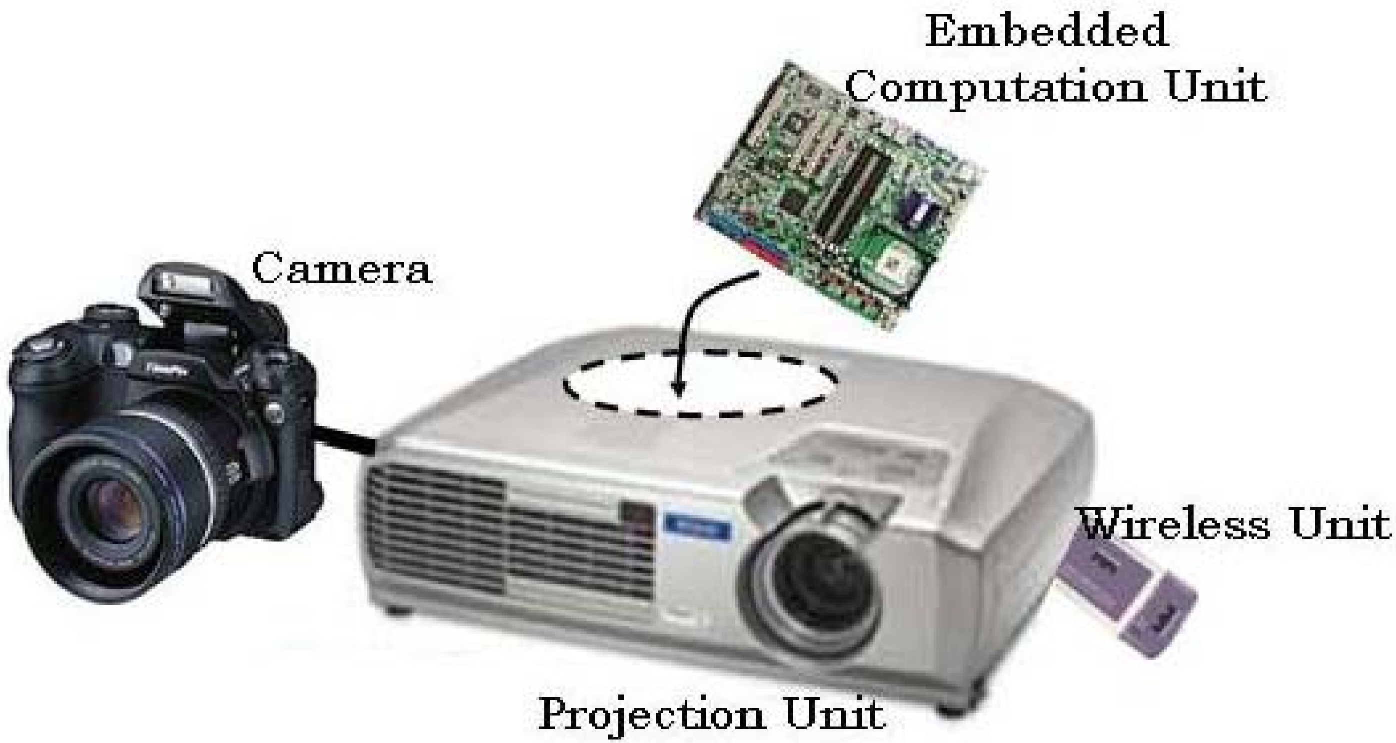
Plug-and-Play Projectors (PPP)



Projector, Camera, Wireless Unit, Embedded Computation Unit
(Inspired by Rasker '03)

Plug-and-Play Projectors (PPP)

Our Prototype

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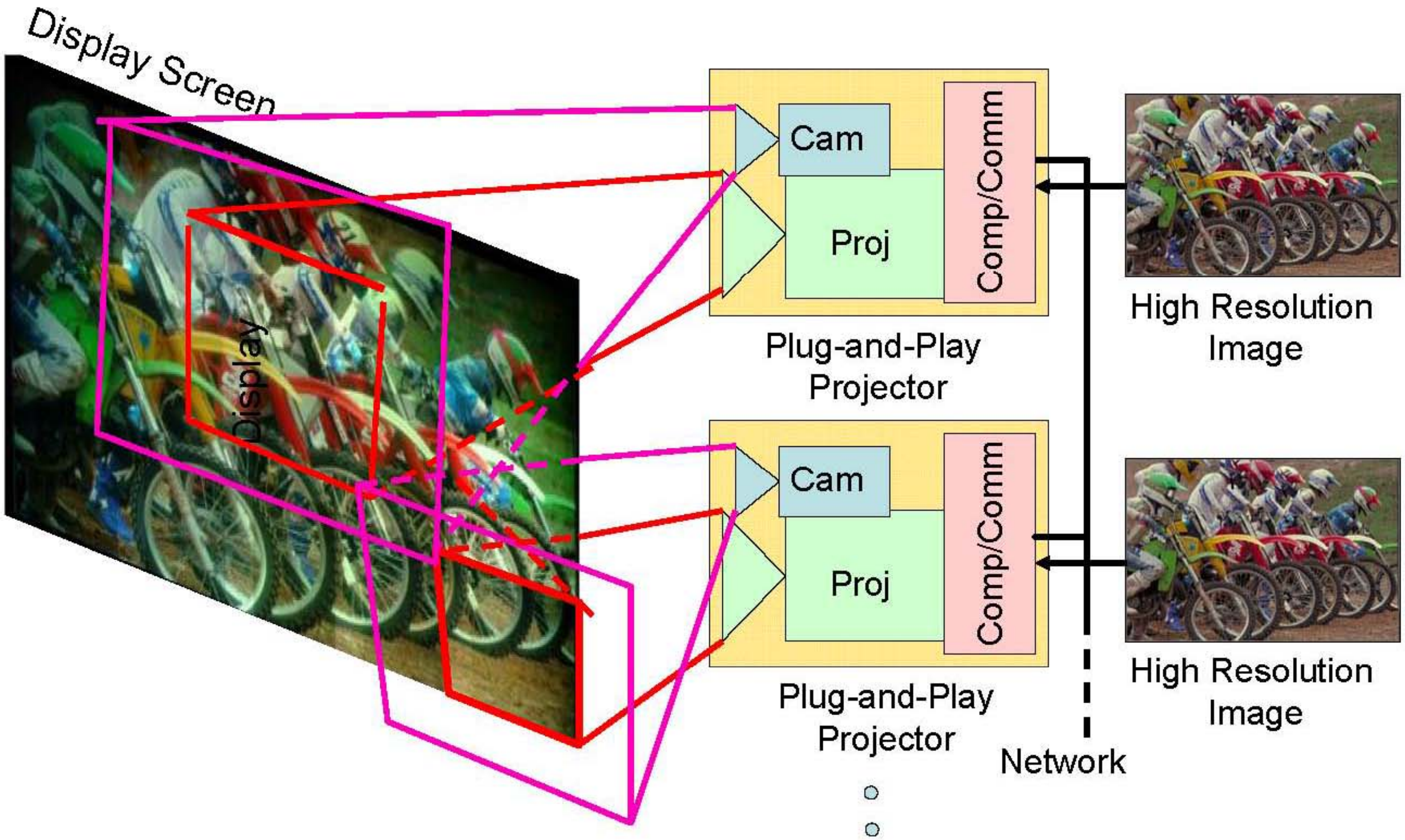
Distributed Architecture



Camera has a larger FOV than projector – Communication

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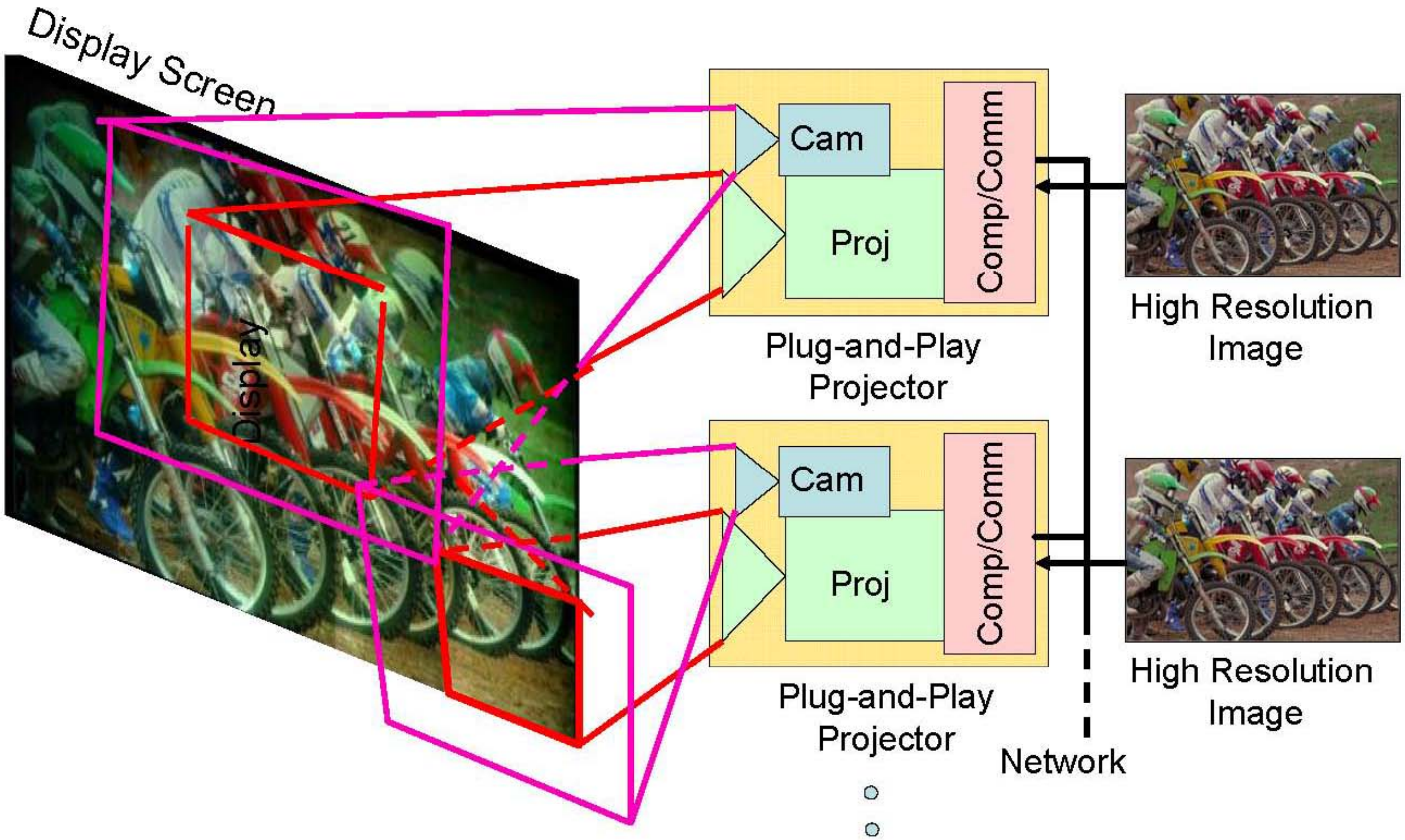
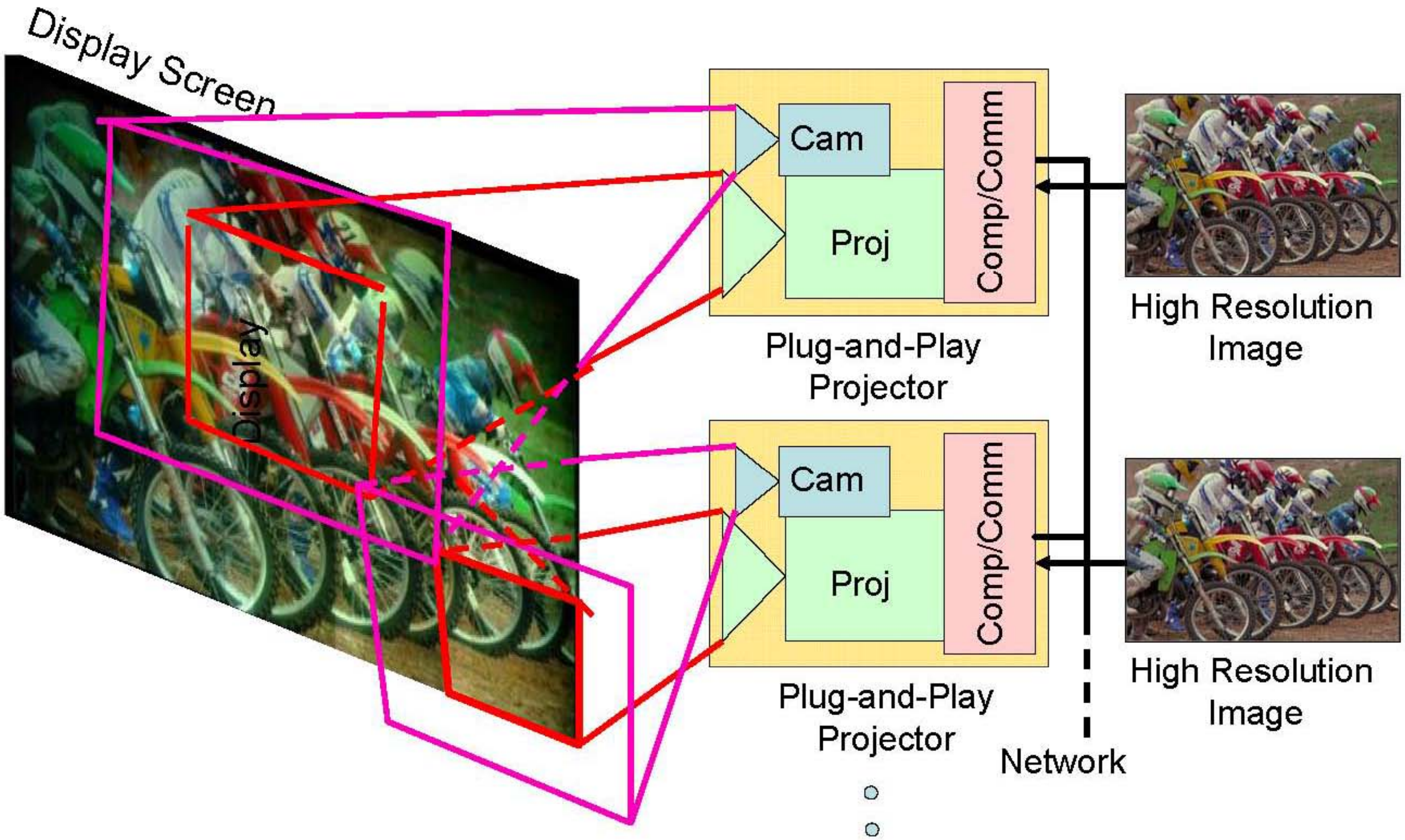
Distributed Architecture



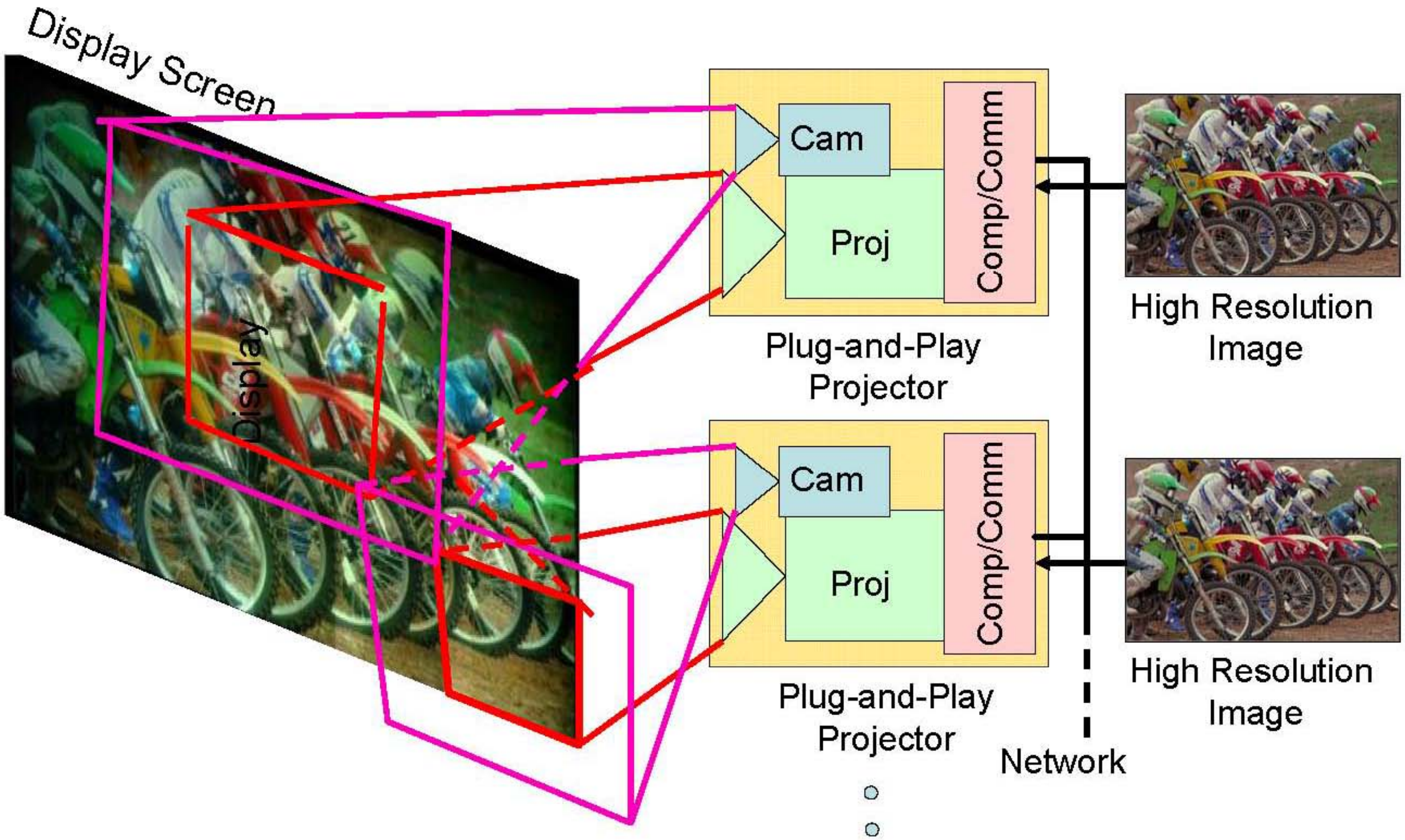
Use this to find neighbors, configurations, faults and so on

Distributed Architecture



Each PPP pulls his own data from the data server

Distributed Architecture



Each PPP does own pixel management

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Initially…

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Distributed Calibration

- Each PPP runs asynchronous distributed SPMD algorithm
  - Discovers neighbors
  - Discovers configuration
  - Registers with others

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Geometric Alignment and Blending

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Distributed Calibration

- Each PPP runs asynchronous distributed SPMD algorithm
  - Discovers neighbors
  - Discovers configuration
  - Registers with others
- Self-calibrates
  - With change in configuration
  - With fault

Video

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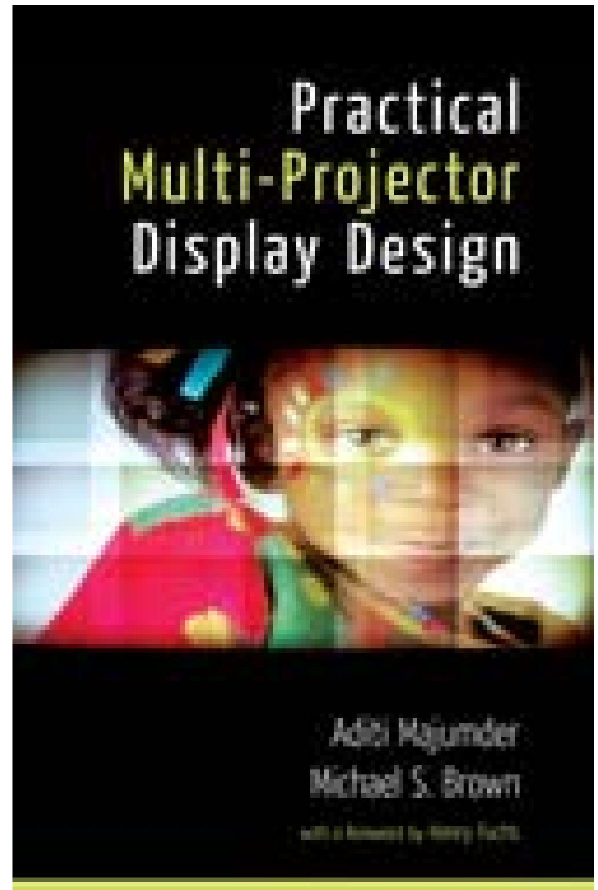
Primary Reference

- Most common issues
- Many Examples
- Sample code for PC cluster rendering
- Booth #821 in exhibition



THE END