Computer Graphics

– Image-based Rendering –

Hendrik Lensch

Overview

- **Today:**
  - Rendering with Images
- **Next:**
  - Input/Output devices

Motivation

Photography

- Easy acquisition
- Fast display
- Natural impression

Computer Graphics

- Time-consuming scene modeling
- Computation-intensive rendering
- Artificial appearance

Motivation II

- All we sometimes care about in rendering is generating images from new viewpoints

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- In geometry-based methods, we *compute* these new images
  - Projection
  - Lighting
  - Z-buffering

Motivation II

- All we sometimes care about in rendering is generating images from new viewpoints
- In geometry-based methods, we *compute* these new images
  - Projection
  - Lighting
  - Z-buffering
- Why not just *look-up* this information?

Overview

- Theoretical Basis
- “Pure” IBR Algorithms
- Geometry-assisted IBR Techniques

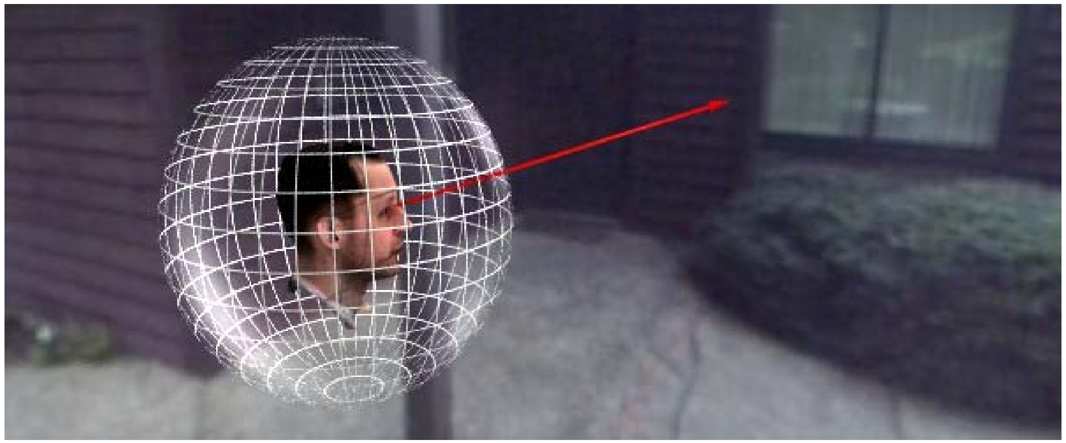
Overview

- **Plenoptic function**
- **Panoramas**
- **Concentric Mosaics**
- **Light Field Rendering**
- **The Lumigraph**
- **Layered Depth Images**
- **View-dependent Texture Mapping**
- **Surface Light Fields**
- **View Morphing**

The Plenoptic Function

- Observable light properties (wavelength, 1D) at every point in space (+3D) in all directions (+2D) at every time (+1D): 7D function

$$p = P(\lambda, V_x, V_y, V_z, \theta, \phi, t)$$



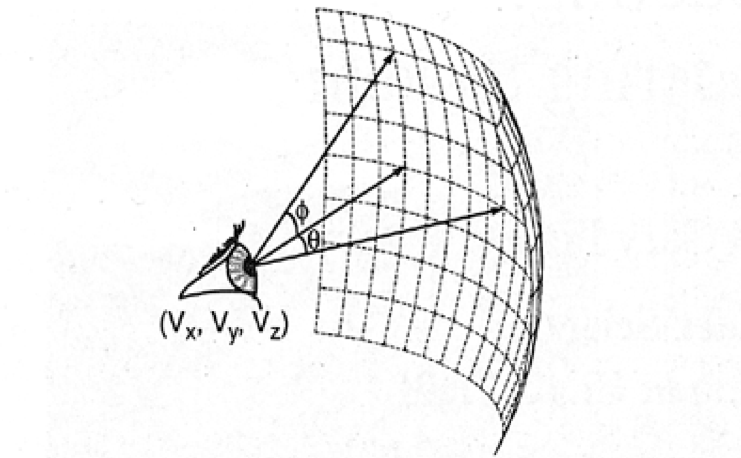


FIGURE 1. The plenoptic function describes all of the image information visible from a particular viewing position.

The Plenoptic Function II

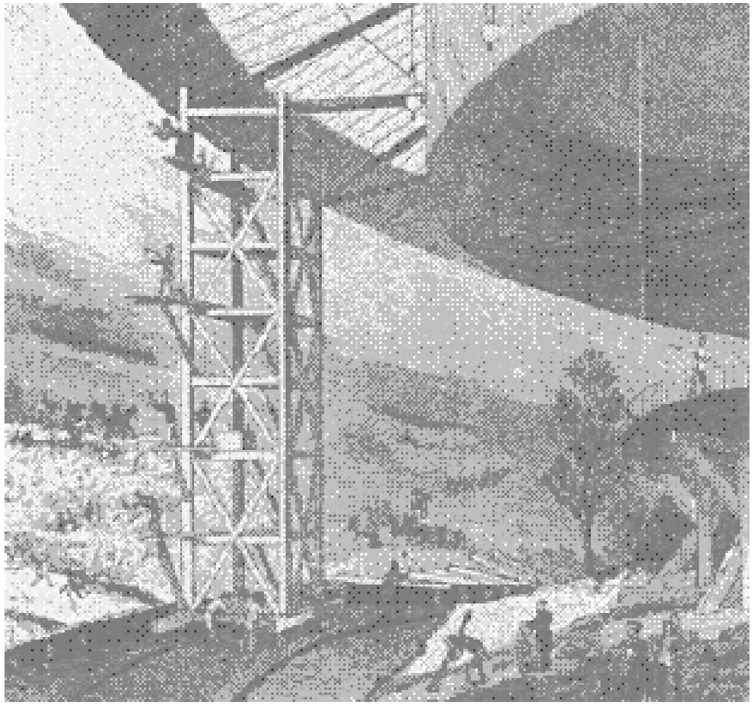
- Acquisition
  - Continuous function ⇒ appropriate discretization
  - High-dimensional ⇒ reduction in storage requirements
- Rendering
  - Continuous function ⇒ look up function value
  - Discretized data ⇒ re-sample and interpolate

Plenoptic Rendering Taxonomy

- Reduced Plenoptic Function
  - 5D: time and wavelength omitted
    $\Rightarrow$ static scene, RGB values
- Light Field Rendering
  - 4D: transparent space and opaque objects, viewpoint outside of the bounding box
- Concentric Mosaics
  - 3D: viewpoint constrained to lie within a circle
- Panoramas
  - 2D: fixed viewpoint

Panoramas - History

- Robert Barker's Panorama (1792)
  - Up to 17 meters high, 130 meters circumference
- Raoul Brimoin-Sansons Cineorama (1897)
  - 10 synchronized movie projectors, 100 meter circumference
- Disneys CircleVision
  - 9 35mm cameras
- Modern Cinemas
  - IMAX
  - OMNIMAX



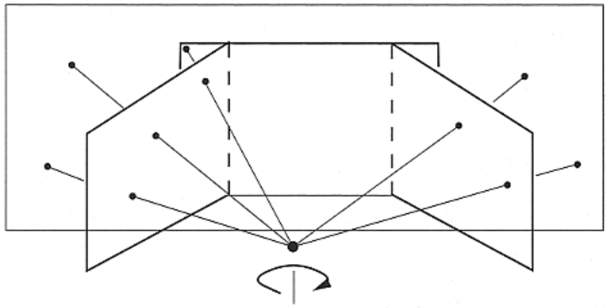
Panoramas

Fixed viewpoint, arbitrary viewing direction

- Acquisition
  - Multiple conventional images
  - Special panorama cameras
- Mosaicing
  - Image registration
  - Stitching
  - Warping
- Rendering
  - Resampling in real-time

Panoramic Mosaicing

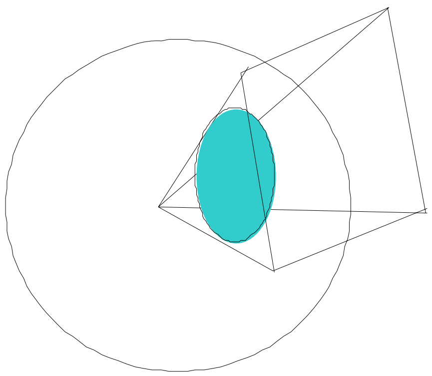
- Projection onto one common plane



⇒ Bow-tie shape

Panorama Parameterization

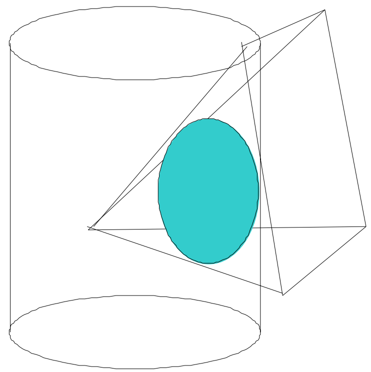
- Spherical projecting surface



  - Advantage
    - Area-constant representation
  - Disadvantage
    - Irregular resampling area

Panorama Parameterization II

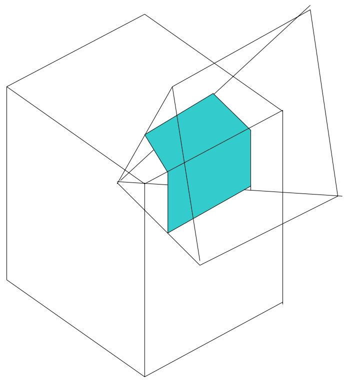
- Cylindrical projecting surface



  - Advantages
    - Simple querying
    - one data structure for all directions
  - Disadvantage
    - Vertical field of view is limited

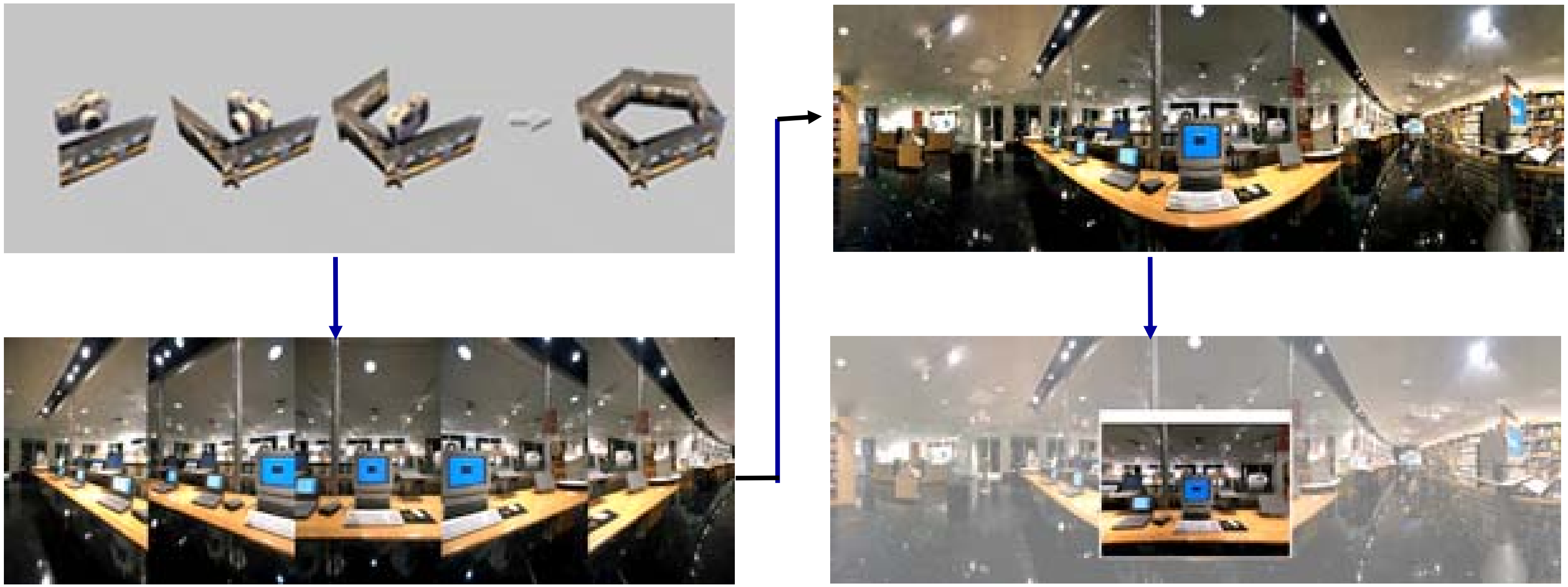
Panorama Parameterization

- Cubic projecting surface



  - Advantages
    - Simple data representation
    - All viewing directions
  - Disadvantages
    - 6 separate data slabs
    - Distortion towards edges

Cylindrical Panoramas



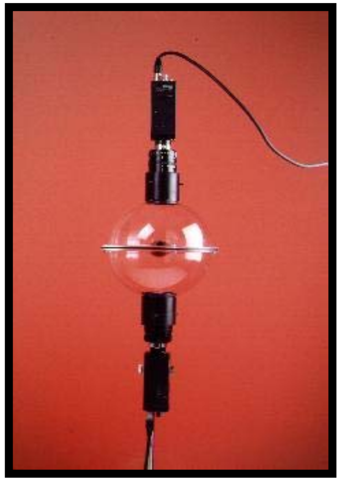
Panorama Mosaicing

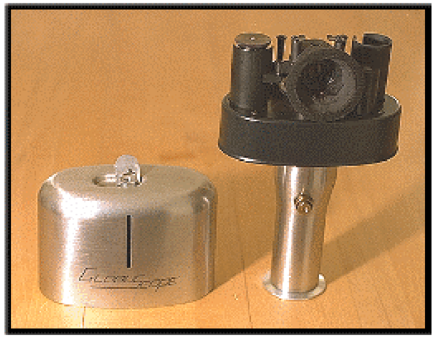
© James Davis

- Prewarping
  - Lens correction, radiometric correction, cylindrical projection
- Image Registration
  - Feature alignment
  - Minimizing pixel differences
- Compositing
  - Eliminate moving objects
- Resampling
  - Filling holes
  - Blending
  - Filtering

Panorama Cameras

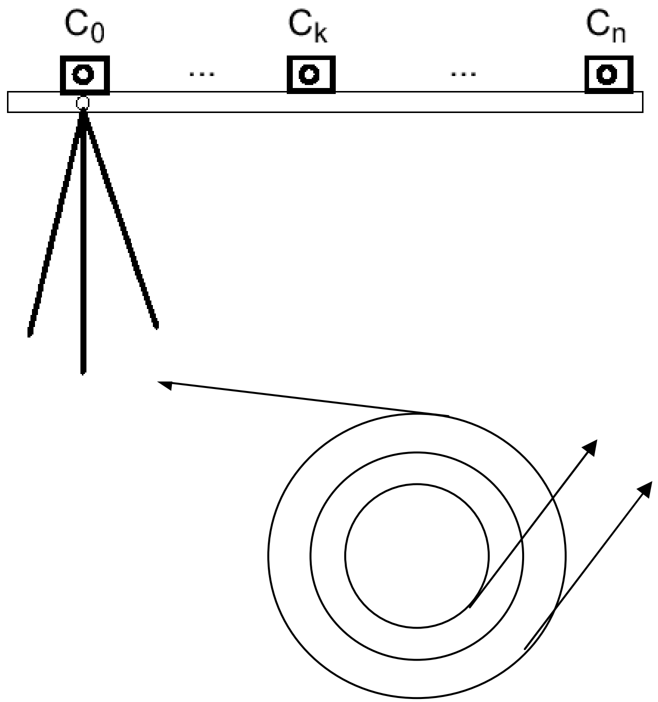
- Rotating Cameras
  - Kodak Cirkut
  - Globuscope
- Stationary Cameras
  - Be Here
  - OmniCam
  - ...





Concentric Mosaics

H.-Y. Shum and L.-W. He, “Rendering with Concentric Mosaics”, Siggraph’99

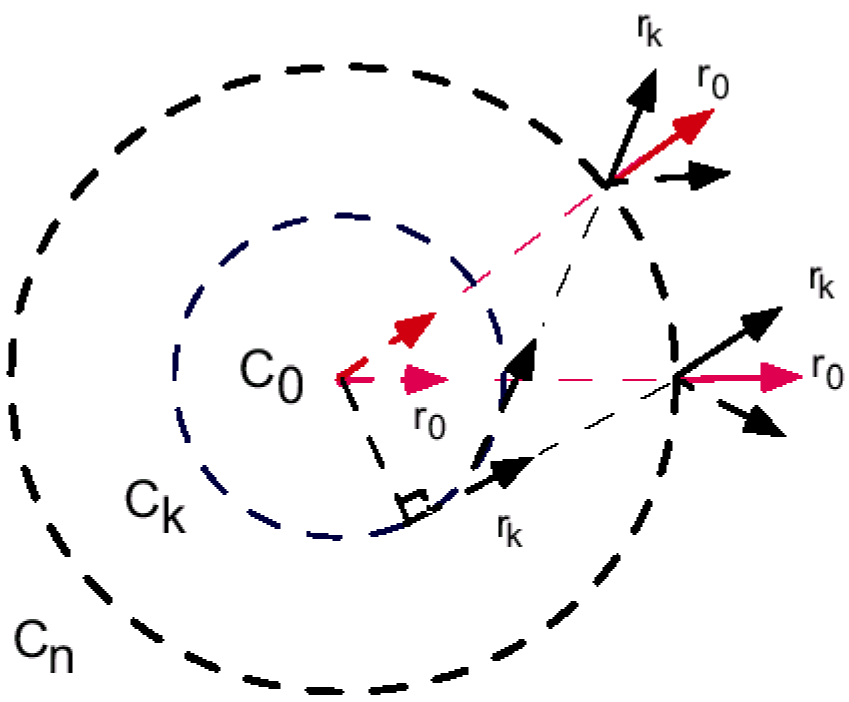


Viewpoint on confined plane

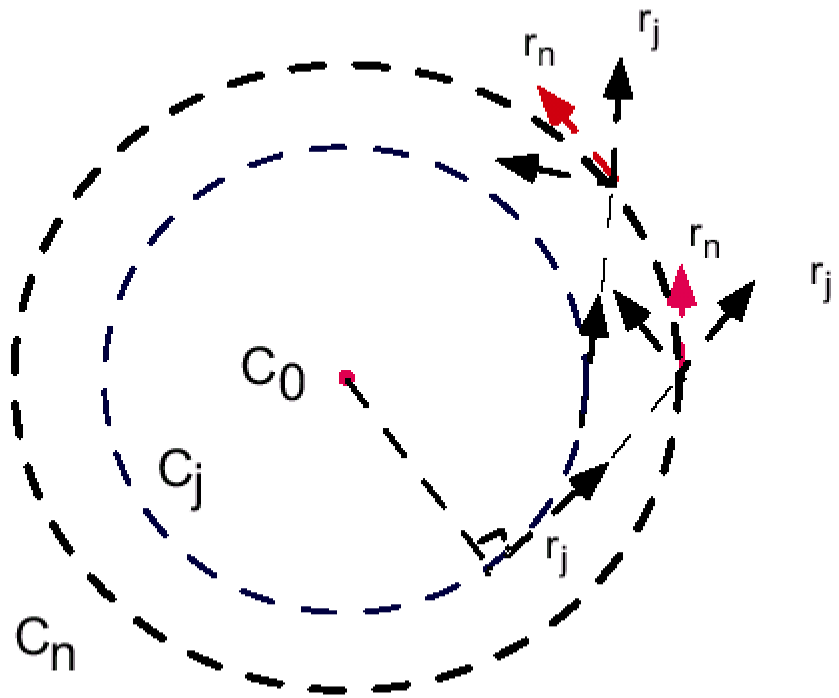
- Acquisition
  - Off-axis rotating camera
  - Different radii
- Optical axis alignment
  - Tangential or radial
- Stored as tangent slit images (vertical lines)

⇒ Conveys horizontal parallax

Concentric Mosaics – Optical Axis Orientation



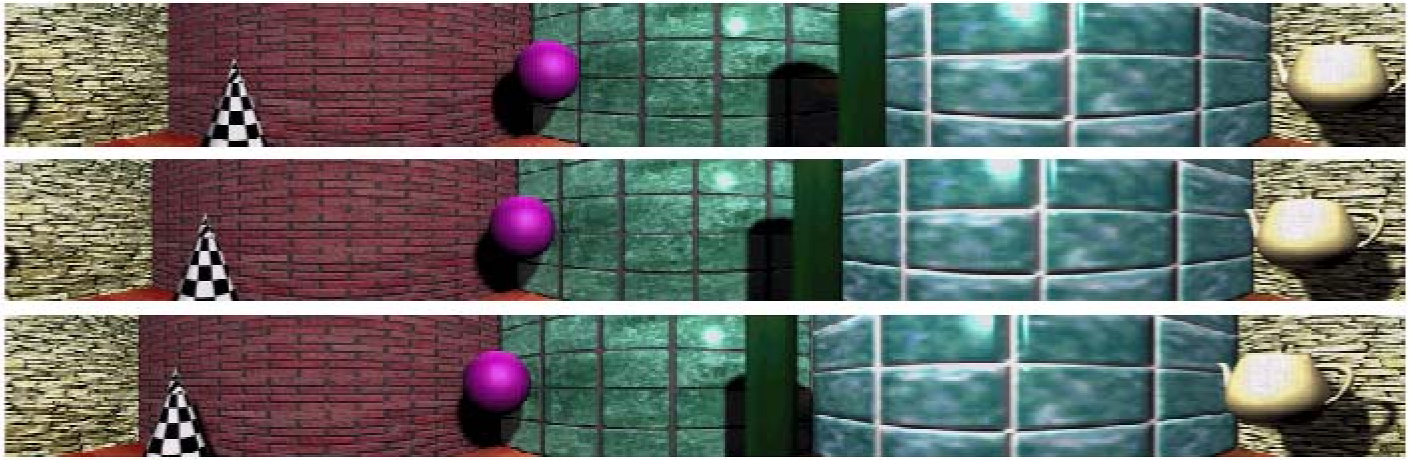
Radial axis alignment

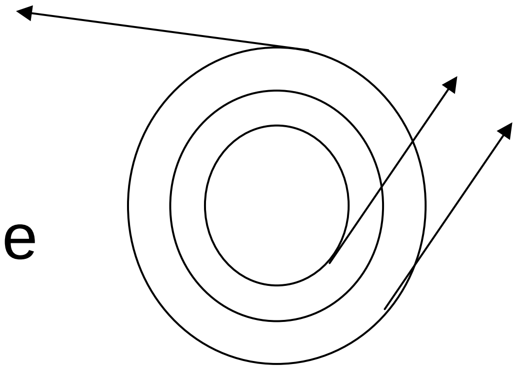


Tangential axis alignment

- Parameterize each vertical line as tangent to circle

Concentric Mosaics – Data Representation





- Along one circle

  Tangential parameterization

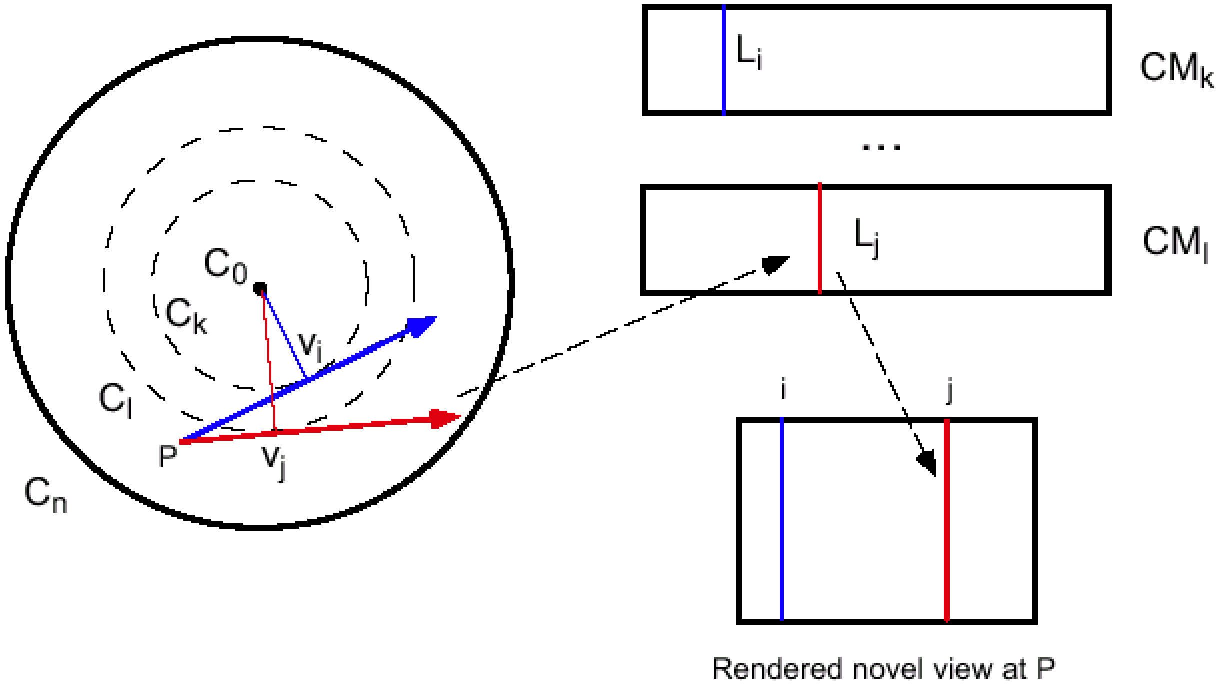
  – Multiple centers-of-projection image

  – Pushbroom camera

- Between circles of different radii

  – Horizontal parallax for different scene depths

Concentric Mosaics - Rendering



For each vertical line:

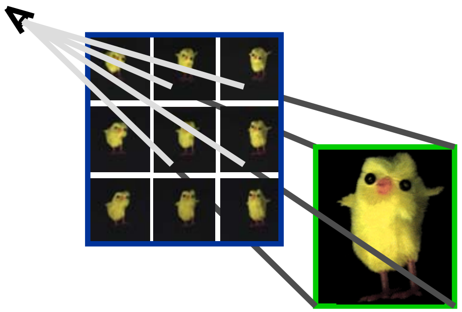
- Find tangent line to circle
- Select nearest circle
- Select closest recording position

Concentric Mosaic – Example

- Horizontal parallax
- Reflection effects
- Dense sampling to avoid aliasing

IBR Taxonomy

image-based ⟷ geometry-based

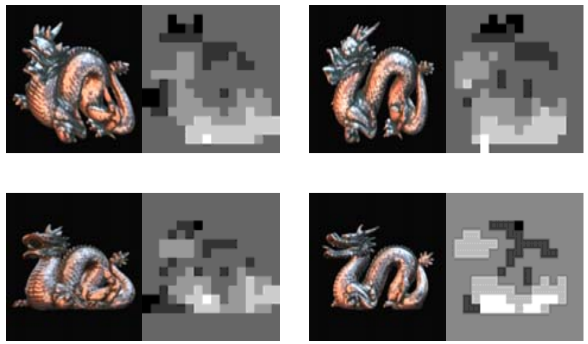


Light Field Rendering

- images only

+ no scene restrictions

– lots of images

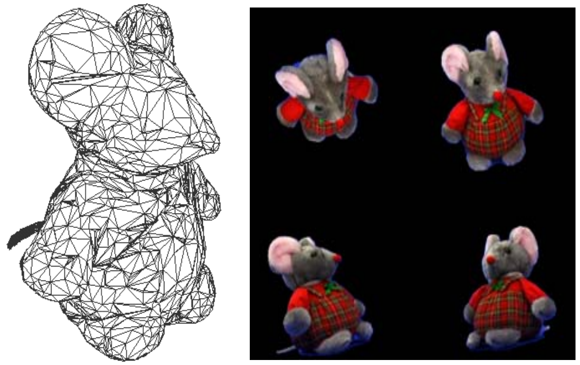


Lumigraph, Layered Depth Images

- images & per-pixel depth

+ improved rendering quality

– increased rendering complexity



View-dep. Text. Map., Surface Light Fields

- images & 3-D model

+ fast rendering (hardware)

– geometry acquisition/ reconstruction

Light Field Rendering

Levoy and Hanrahan, “Light Field Rendering”, Siggraph’96

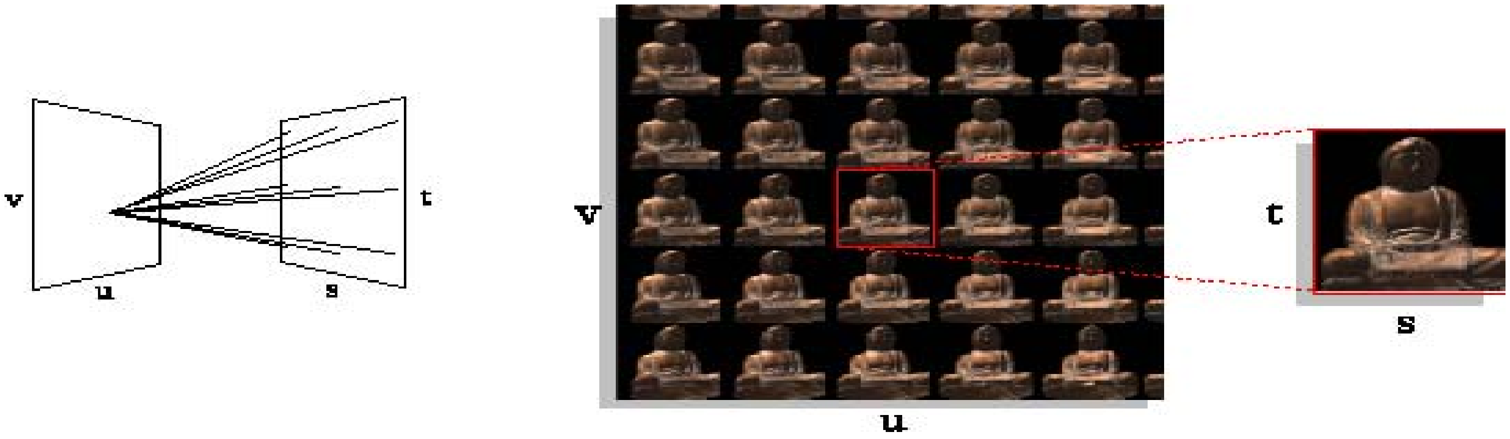
graphics.stanford.edu/projects/lightfield/

- Viewpoint outside bounding visual hull
- Assumption: light properties don’t change along ray
- 2D matrix of 2D images: 4D structure

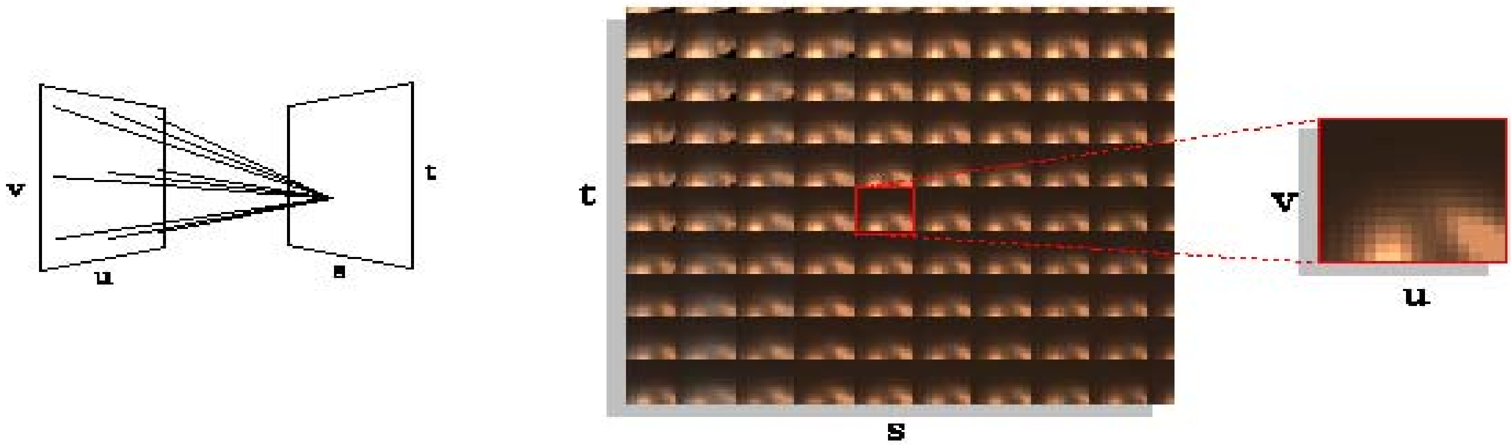
⇒ Conveys full parallax

⇒ captures complex BRDFs

Two-Plane Parameterization



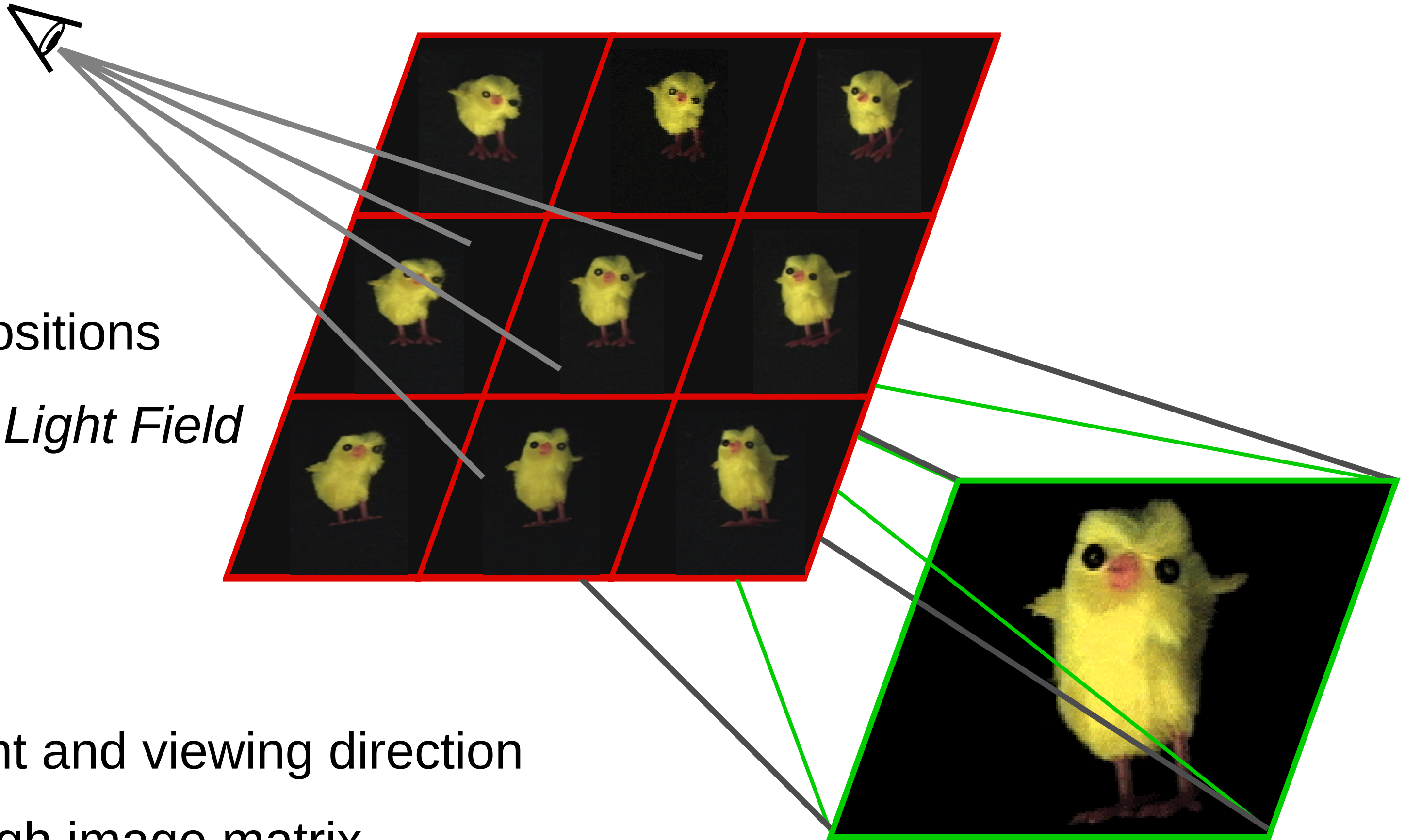
uv array of st images



st array of uv images

The Buddha Light Field

Light Field Rendering



Acquisition

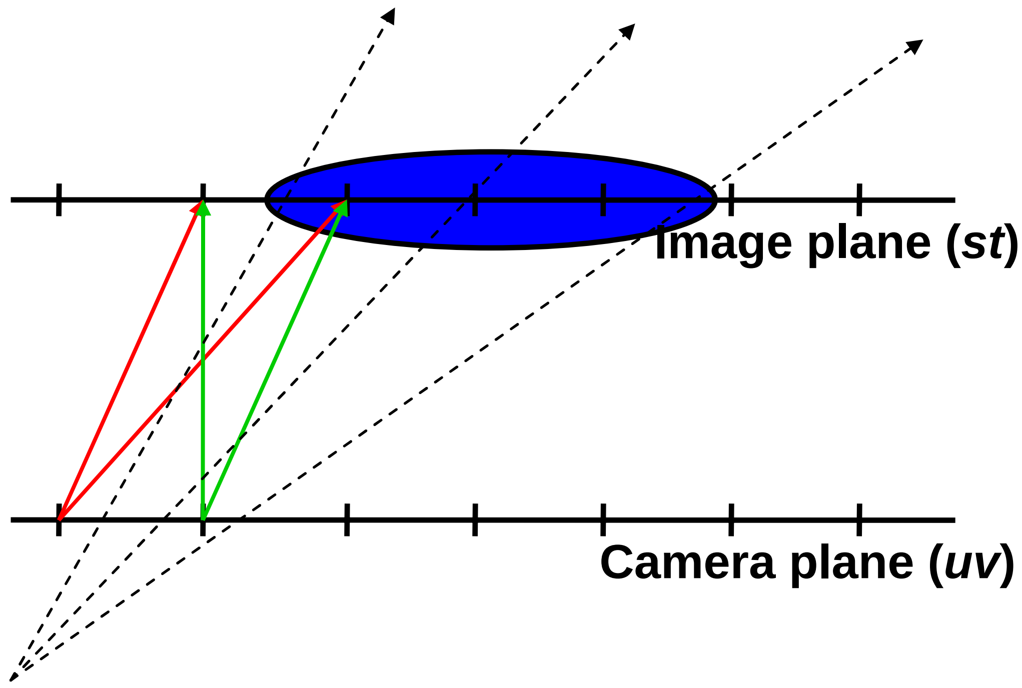
- Static 3D scene
- Known camera positions
- 2D image matrix: *Light Field*

Rendering

- Arbitrary viewpoint and viewing direction
- Ray-tracing through image matrix
- Pixel color determined by intersection with camera plane/image plane

Light Fields – Quadralinear Interpolation

- For each desired ray:
  - Compute intersection with *uv* and *st* planes
  - Take closest ray
- Variants: interpolation
  - Bilinear in (u,v) only
  - Bilinear in (s,t) only
  - Quadrilinear in (u,v,s,t)



Light Field Rendering - Example

2-plane parameterization closest image quadralinear interpolation

Aliasing-free rendering: number of images $\propto$ image resolution

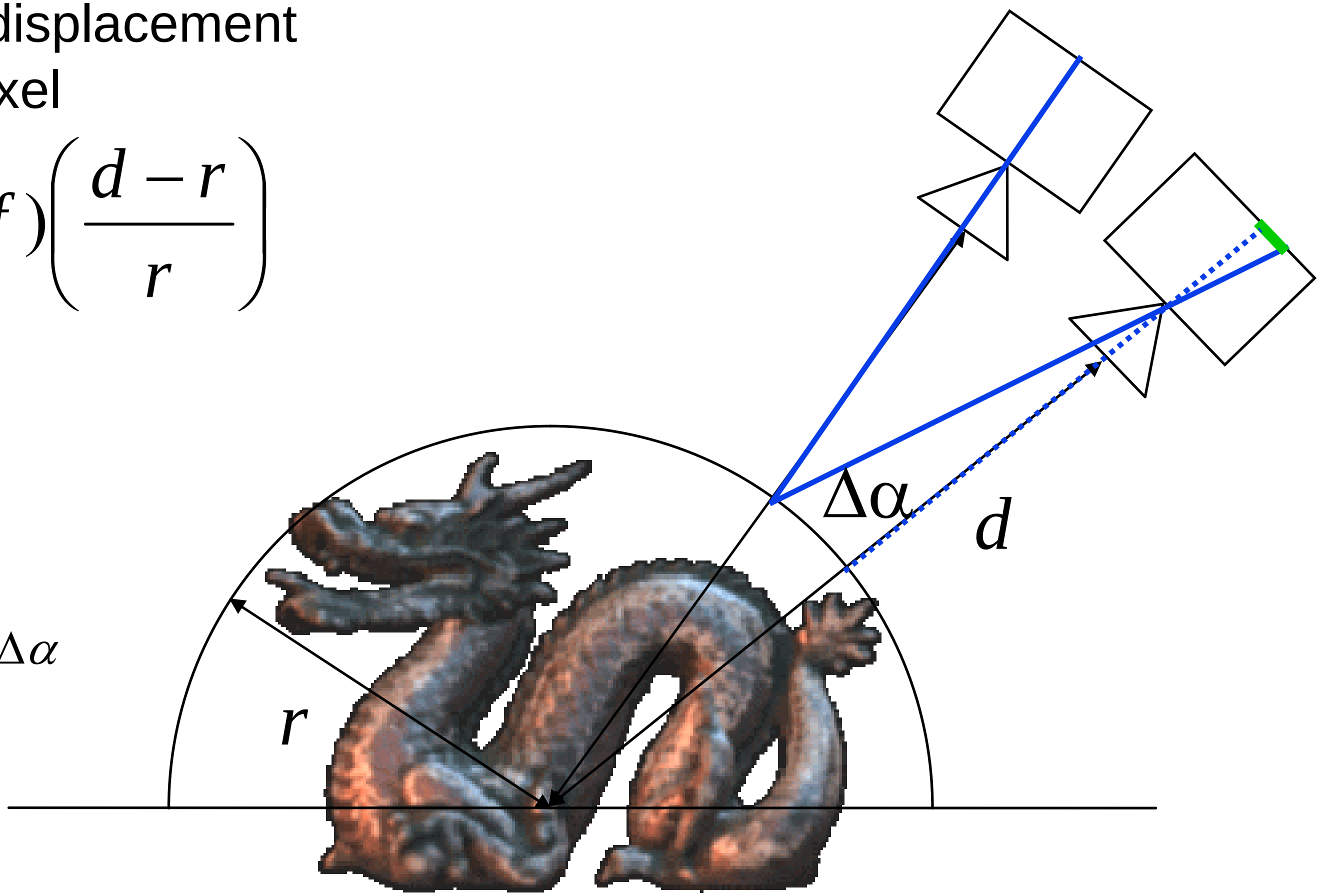
Photorealistic rendering results: lots of images necessary !

Light Field Sampling

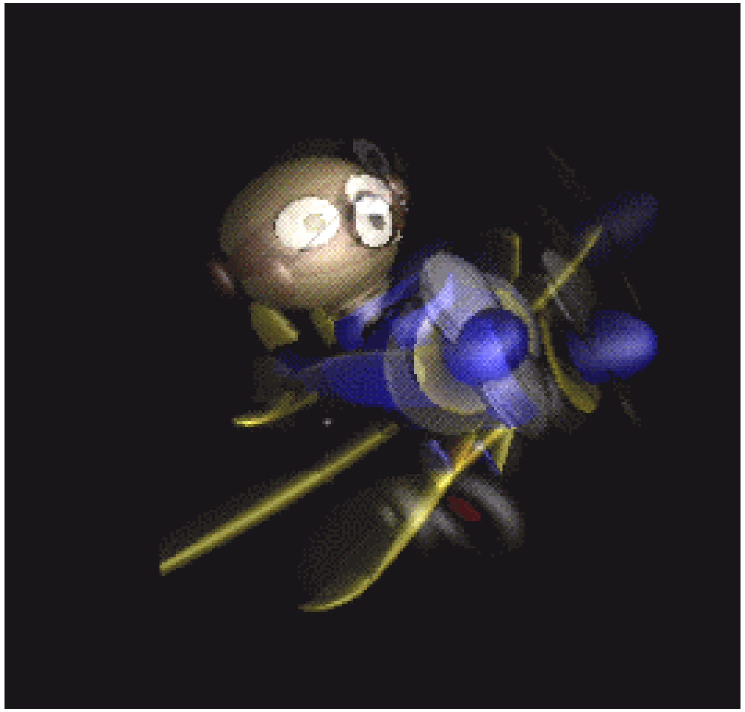
- Maximum camera movement
  - Disparity must be smaller than one pixel under camera displacement
  - Disparity < 1 pixel

$$\Delta\alpha = \frac{\Delta s}{df}(d - f)\left(\frac{d - r}{r}\right)$$

- pixel size: Δs
- object radius: r
- focal length: f
- recording distance: d
- displacement angle: $\Delta\alpha$



Light Field Rendering – Aliasing Artifacts



rendered from heavily subsampled representation

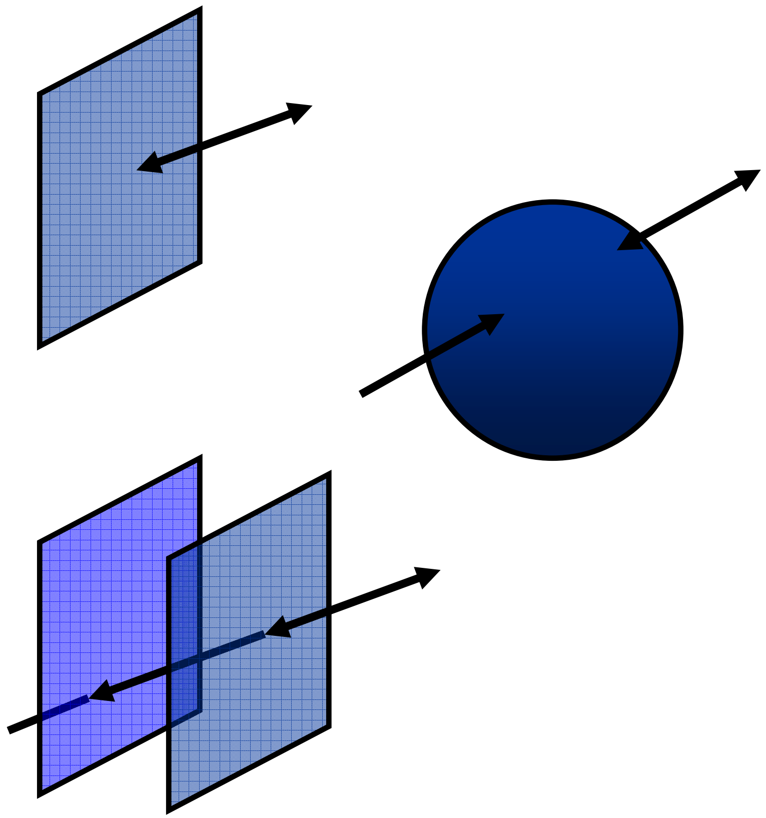
rendered from moderately subsampled representation

Aliasing / blurring artifacts

⇒ Apply scene geometry to estimate missing light-field information

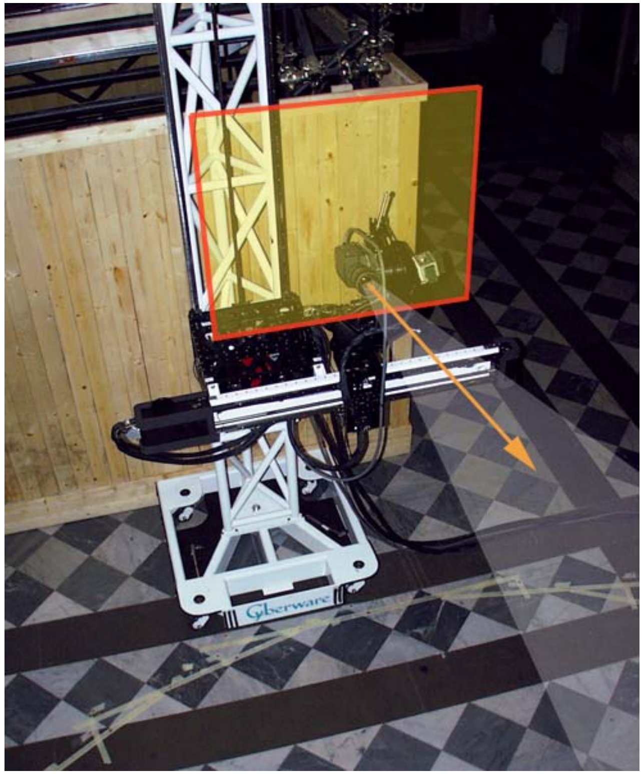
Light Field Parameterization

- Point / angle
- Two points on a sphere
- Points on two planes
- Original images and camera positions



Light Field Acquisition

- Calibrated light field capture
  - Computer-controlled camera rig
  - Moves camera to grid of locations on a plane



Light Field Acquisition II

- Spherical motion of camera around object
- Samples space of directions uniformly
- Single Camera
  - Static scene – Sequential recording
  - Calibrated motion – Mechanical gantry
  - Photometric calibration easy

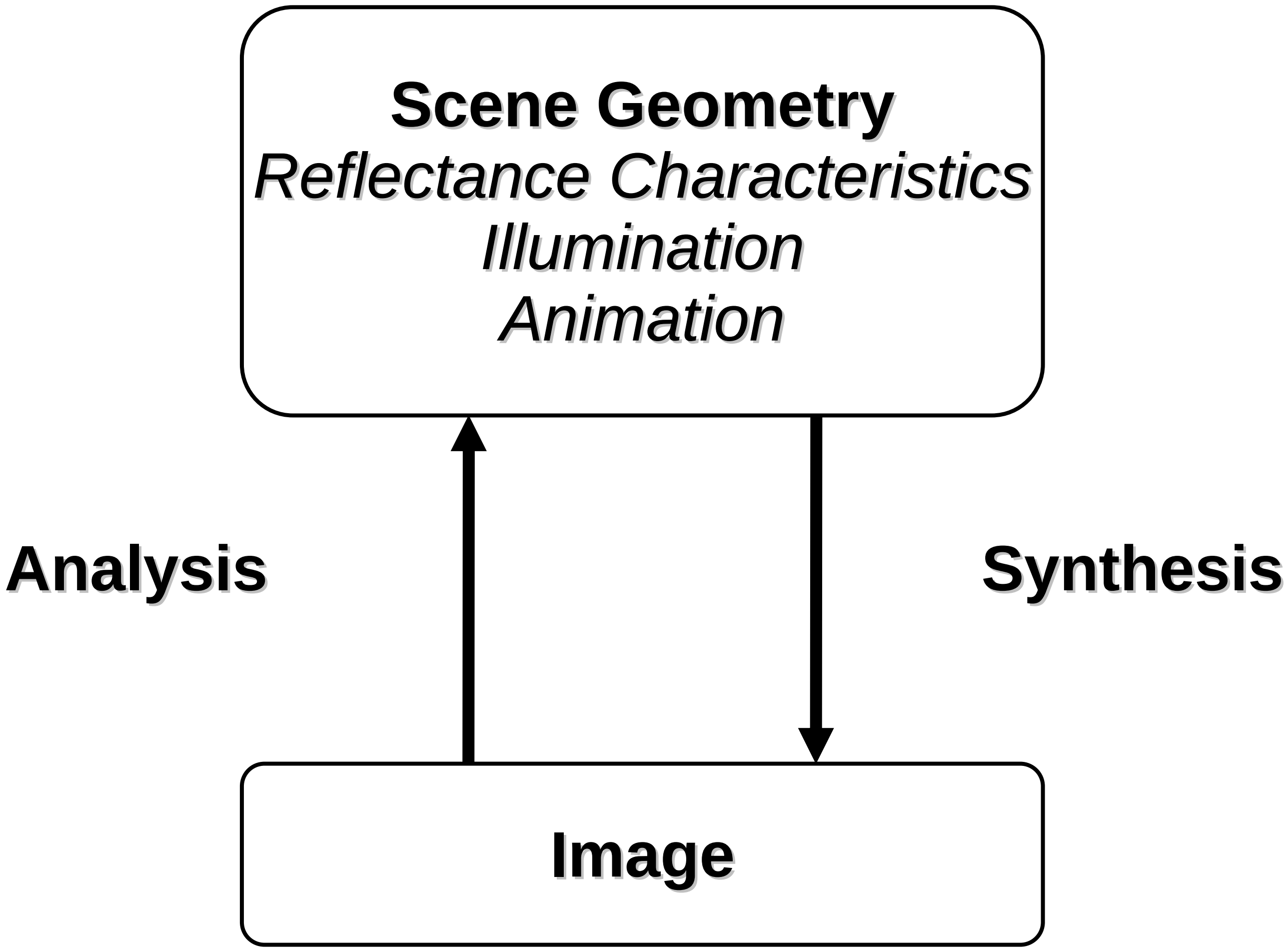
Light Fields - Summary

- Advantages
  - Simpler computation vs. traditional CG
  - Cost independent of scene complexity
  - Cost independent of material properties and other optical effects
- Disadvantages
  - Static geometry
  - Fixed lighting
  - High storage cost / aliasing

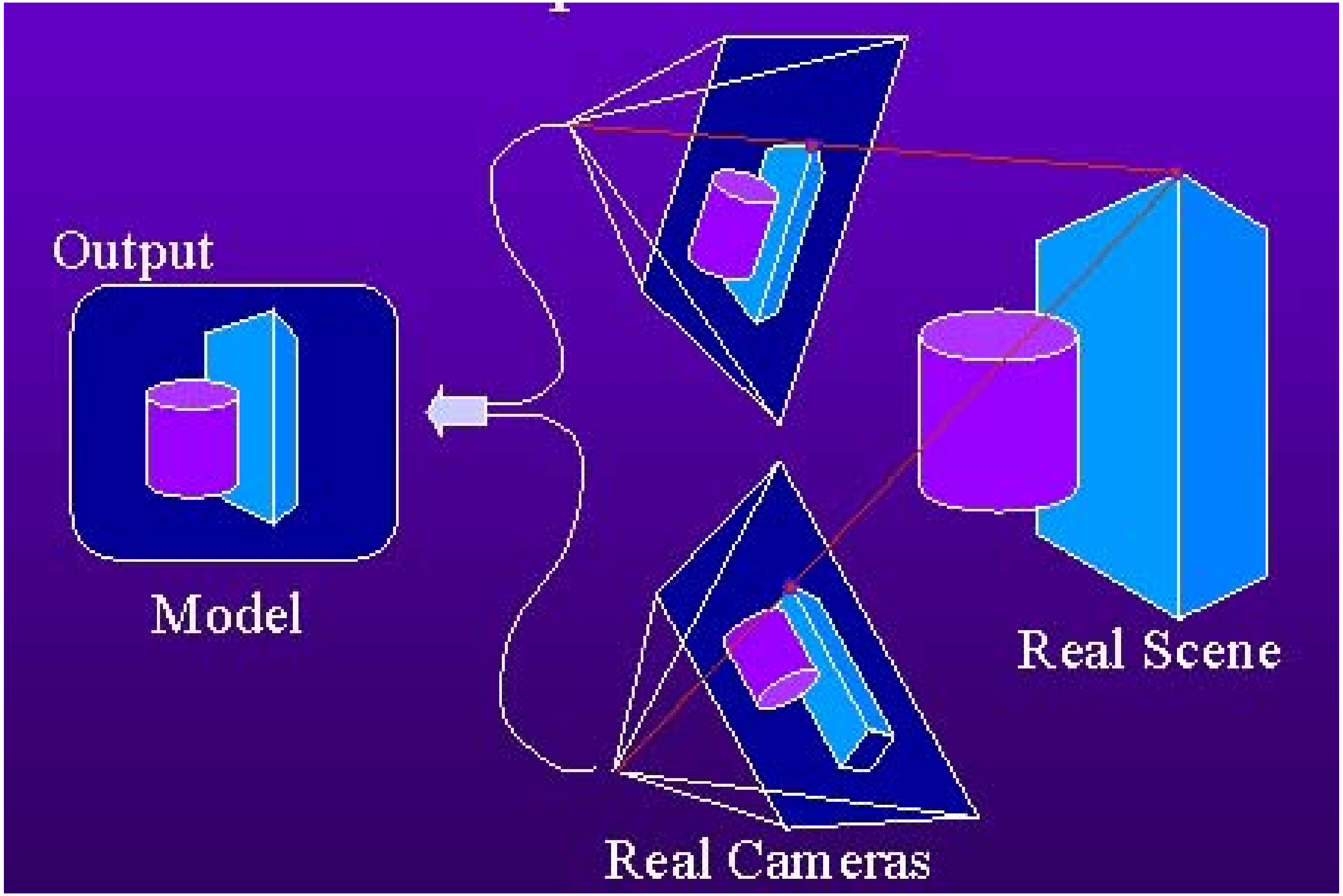
Geometry-assisted IBR Methods

- Fundamental idea of IBR:
  Generate new views of a scene directly from recorded views
- “Pure” IBR $\Rightarrow$ Light Field Rendering
- Enormous amount of images necessary
- Highly redundant data
- Other IBR techniques try to obtain higher quality with less storage by exploiting scene geometry information

Computer Graphics – Computer Vision

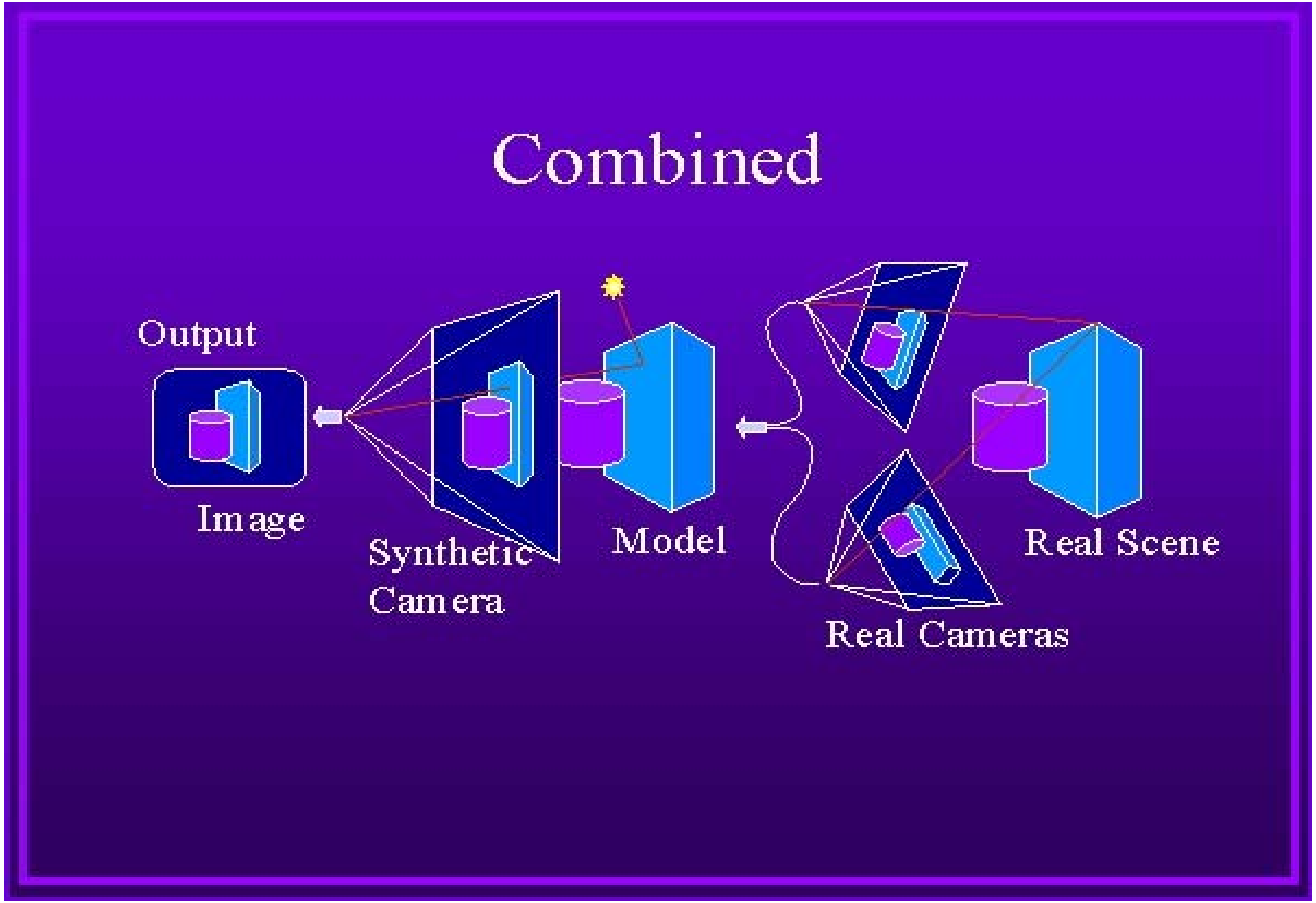


Geometry Reconstruction

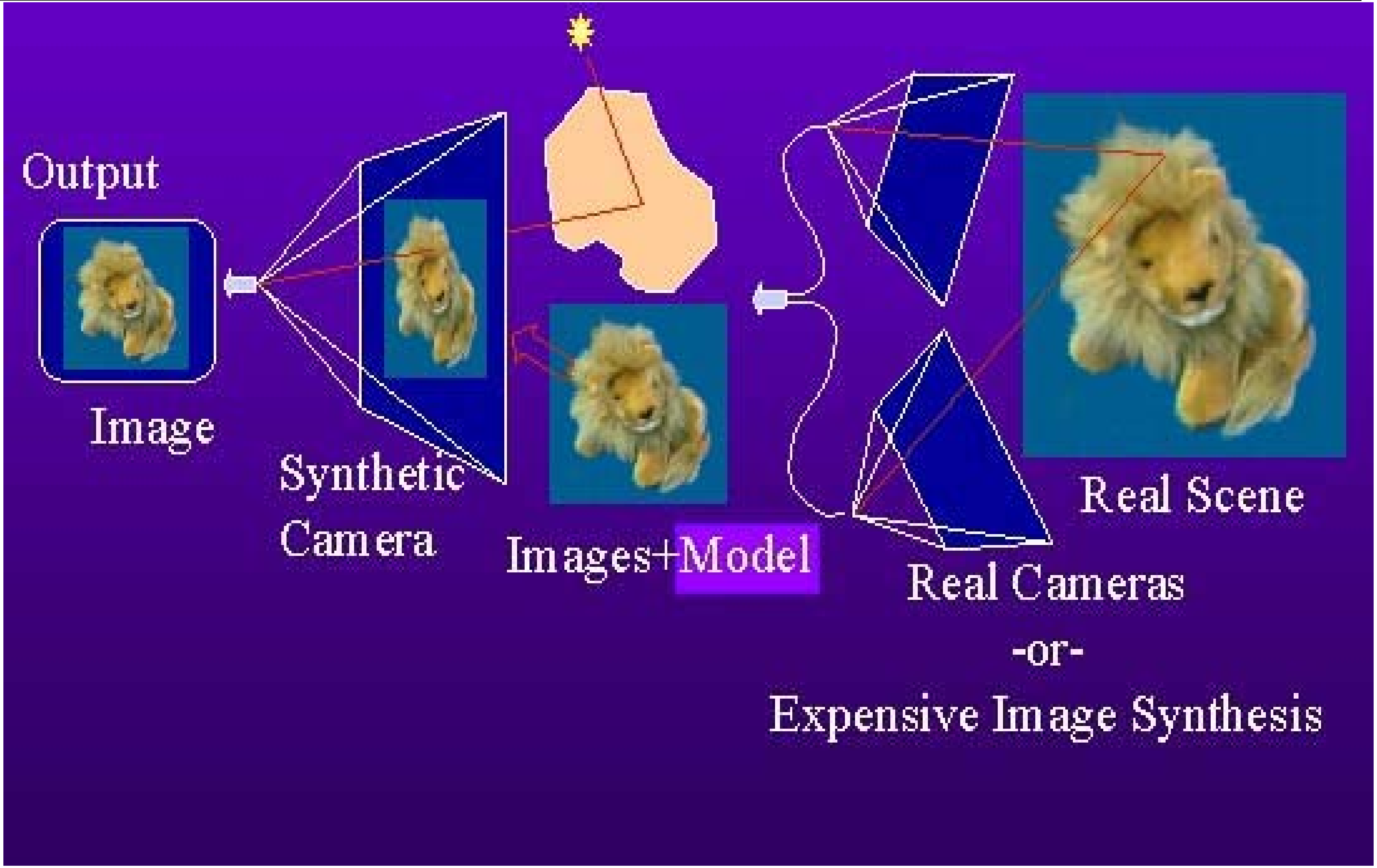


© Michael Cohen

Vision – Geometry Pipeline

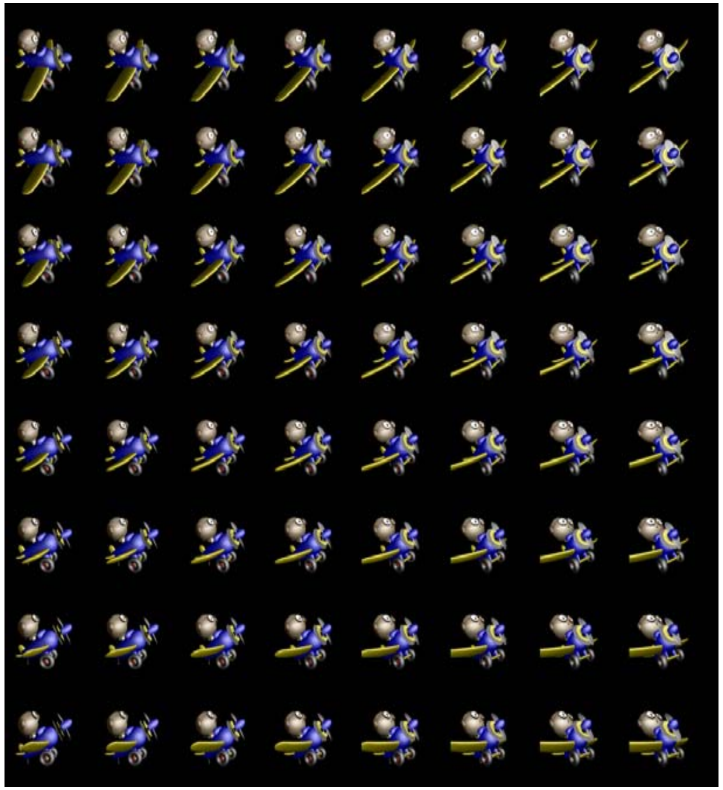


Geometry-assisted IBR



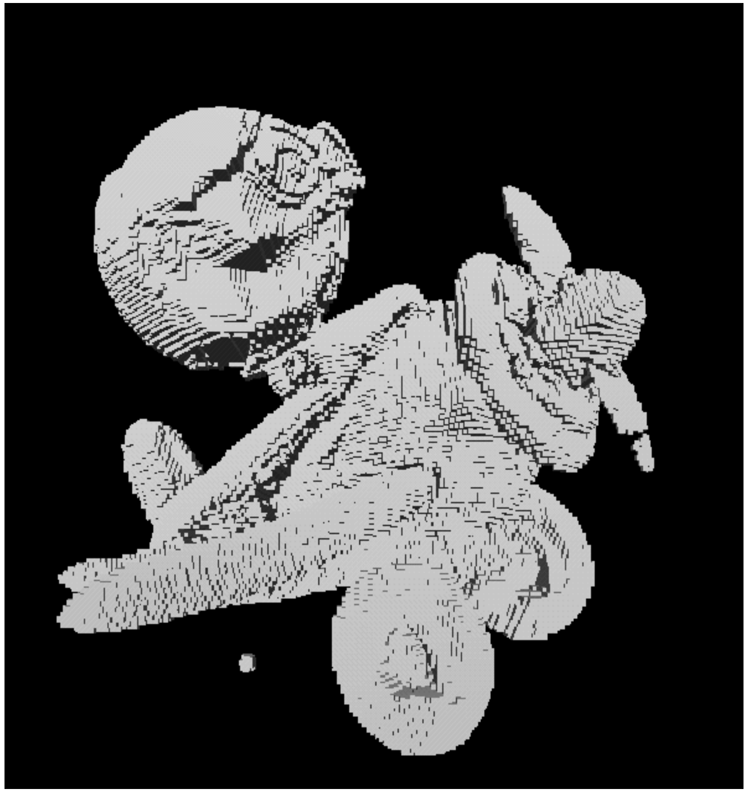
Geometry-assisted IBR: Example

Airplane Light Field



- 8×8 images, 256×256 pixels

Reconstructed voxel model



- $250 \times 260 \times 200$ voxels
- object surface: 450,000 voxels

The Lumigraph

Gortler et al., “The Lumigraph”, Siggraph’96, pp. 43-52

research.microsoft.com/siggraph96/96/lumigraph.htm

- Input: multiple images
- Resample into 2-plane parameterization

⇒ Equivalent to Light Field Rendering

- Reconstruct approximate per-pixel depth from images

⇒ Disparity-corrected rendering

Lumigraph – Depth-corrected Rendering

What color has ray (s,u) ?

- Closest recorded ray

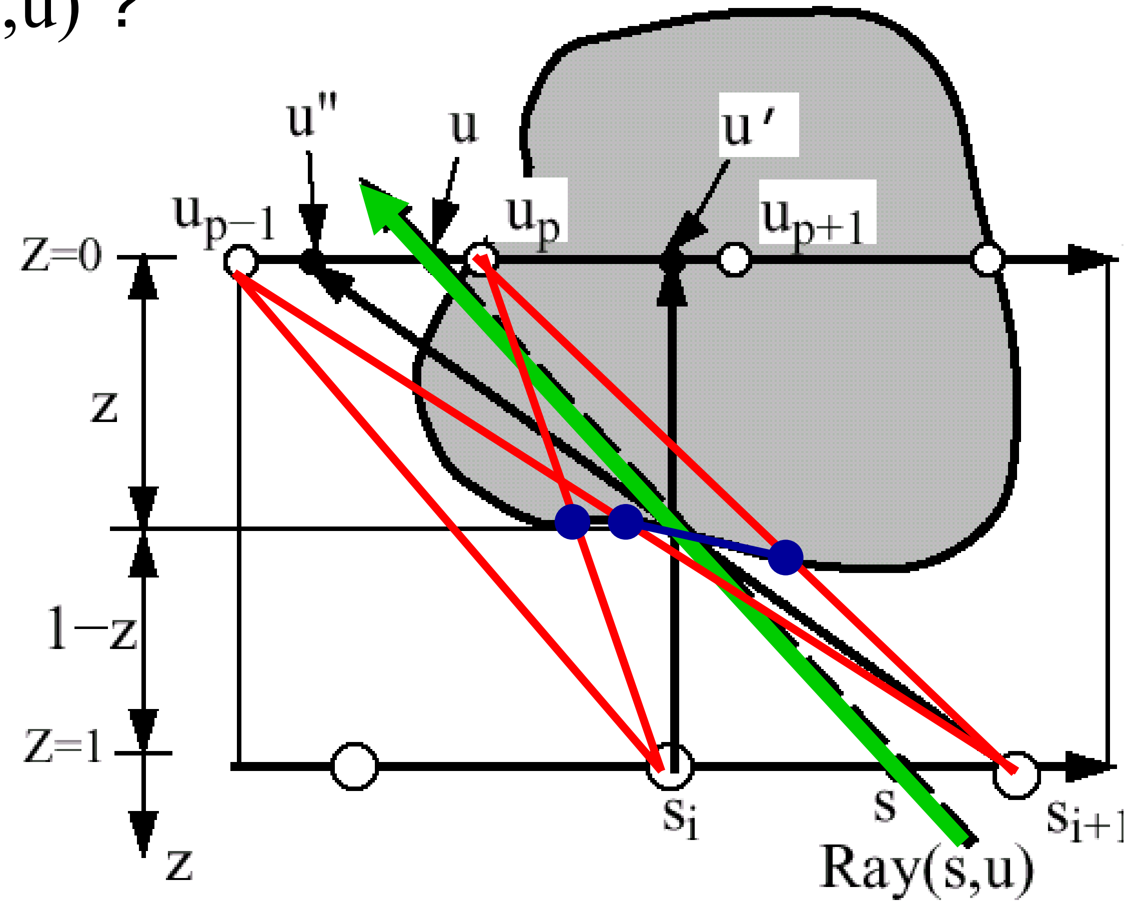
⇒ Wrong surface point

- Neighboring rays

⇒ find surface point closest to ray (s,u)

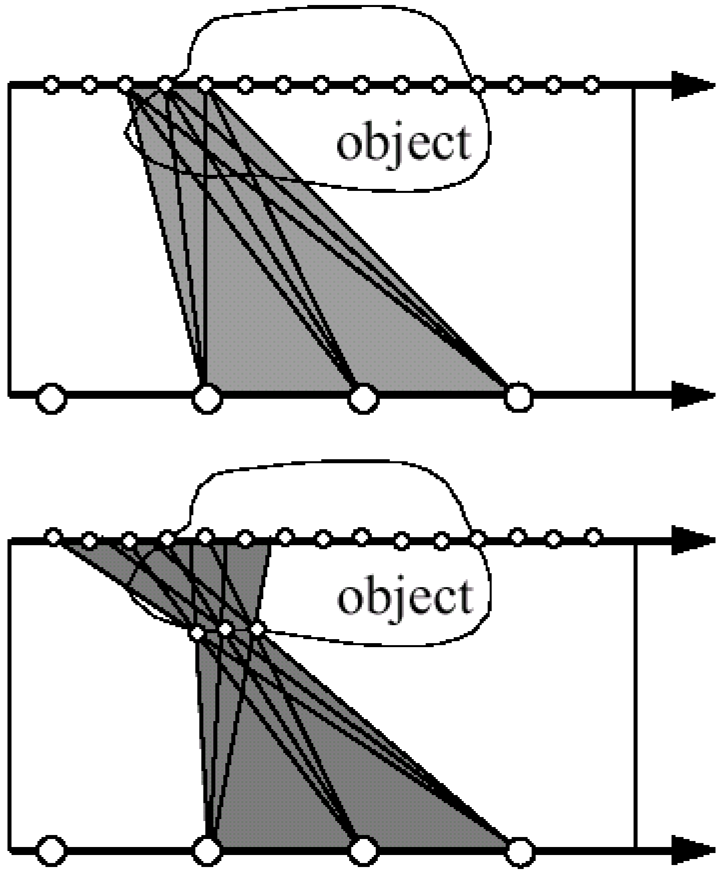
- Fit planar surface

⇒ interpolate between closest rays



Lumigraph Rendering

- **Approximate depth correction**
  – Backward problem
- **Parallax included**
- **Reduced aliasing**
- **Occluded regions still a problem**

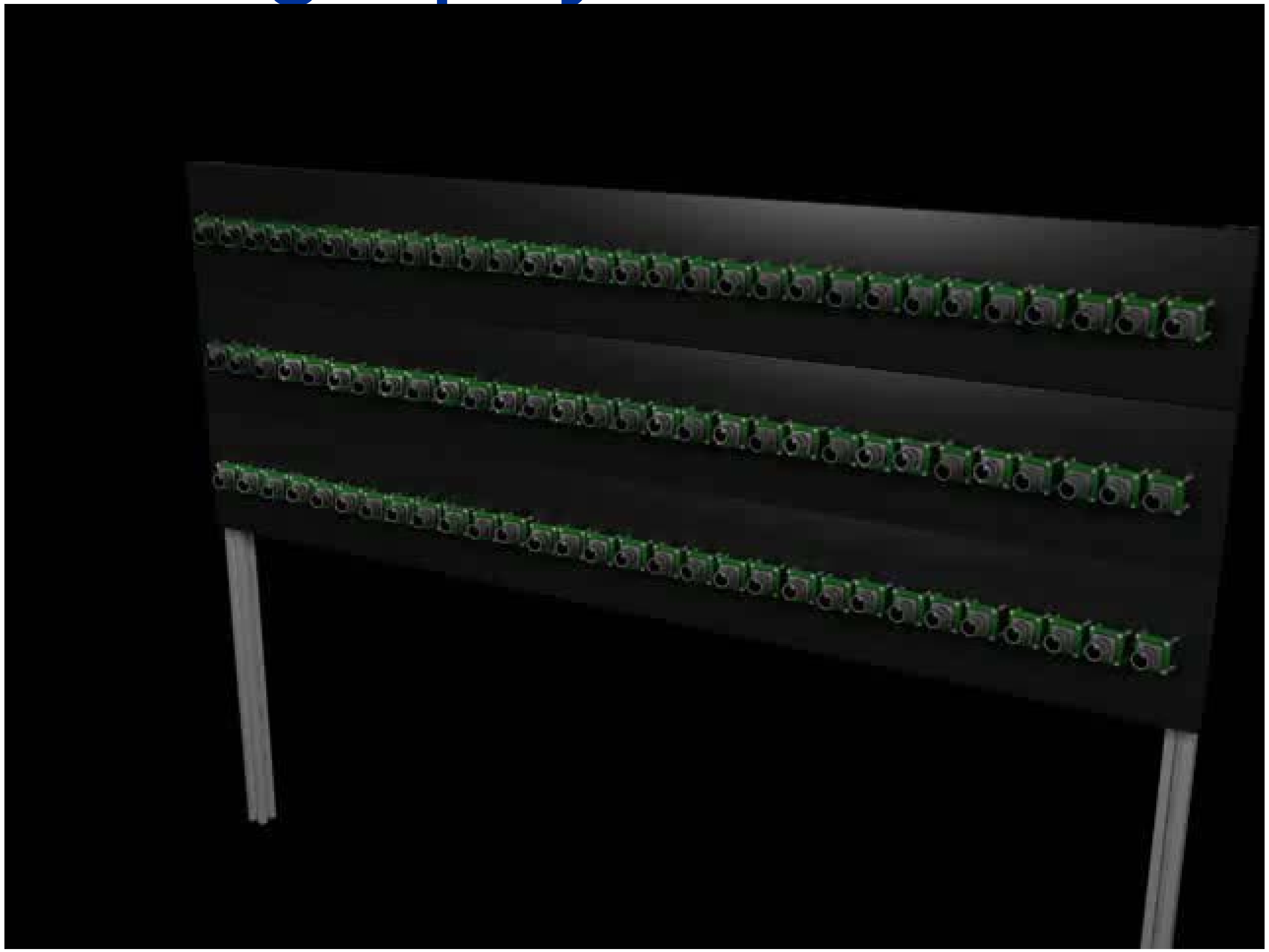


The Lumigraph – Rendering Results

Without using geometry
→ Light Field Rendering

Using approximate geometry

Synthetic Aperture Photography

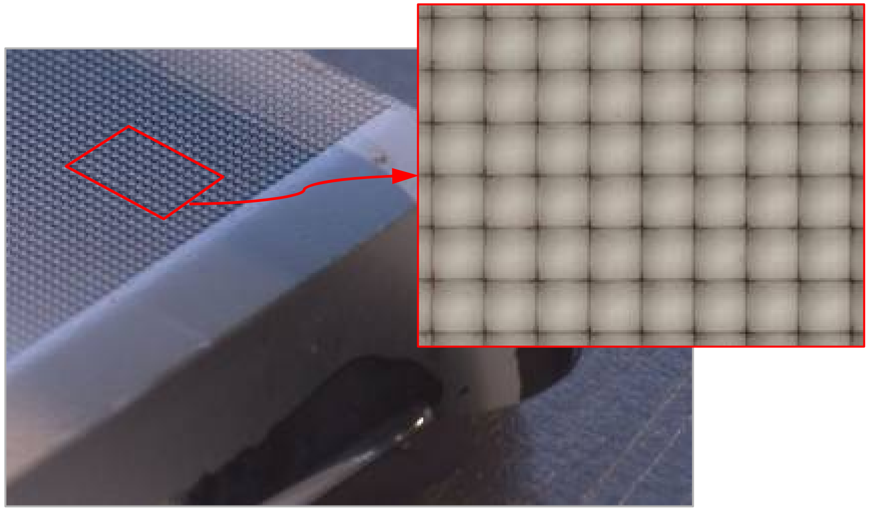


Synthetic Aperture Photography

Light Fields – Acquisition & Applications

- **Plenoptic Camera [Ng05]**
  - conventional lens + microlens array
  - 4000x4000 pixels
  - 129x129 microlenses
  - =14x14 pixels per microlens
- **Applications:**
  - viewpoint shifts
  - perspective changes
  - digital refocusing

Kodak 16-megapixel sensor

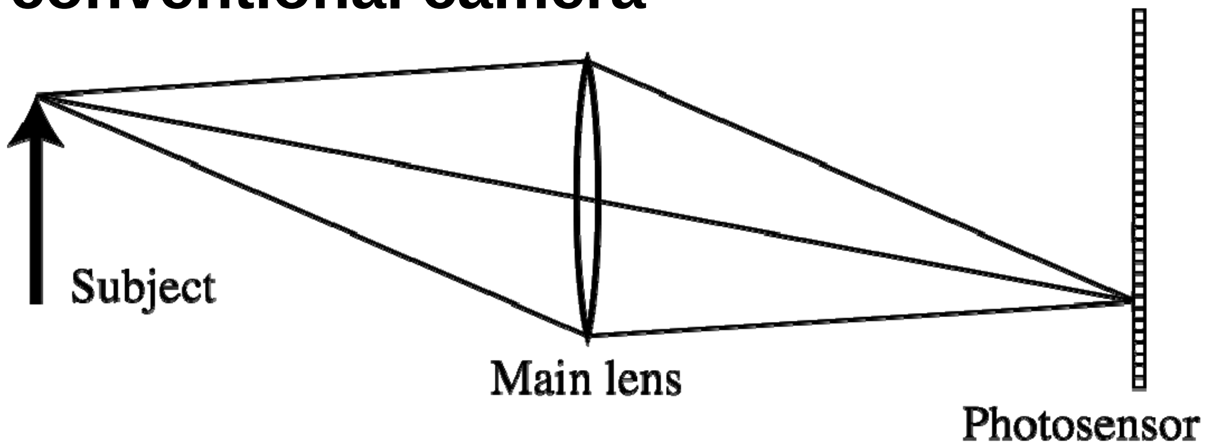


125µ square-sided microlenses

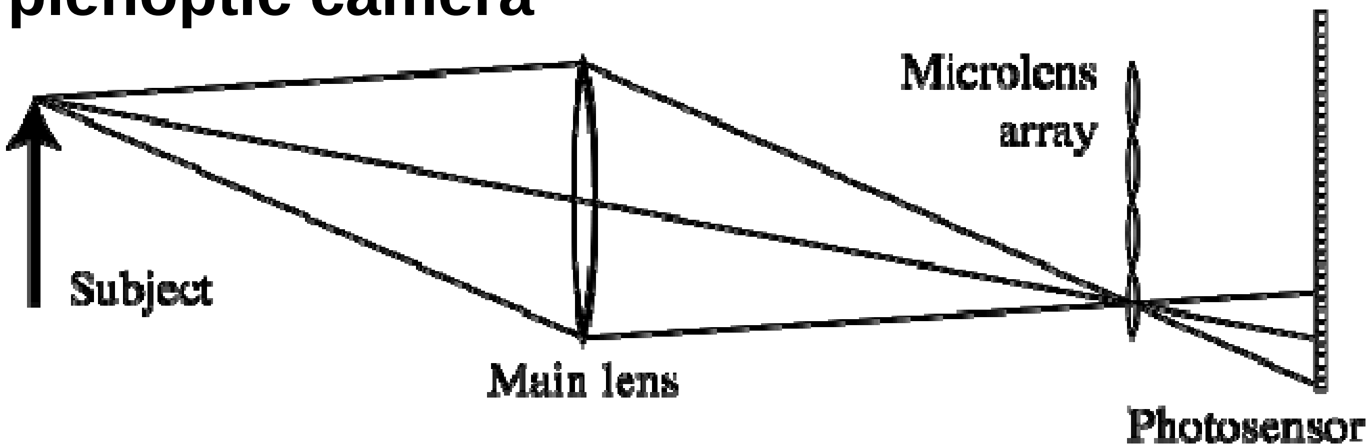
Light Fields – Acquisition & Applications

- **principle of plenoptic camera**

conventional camera



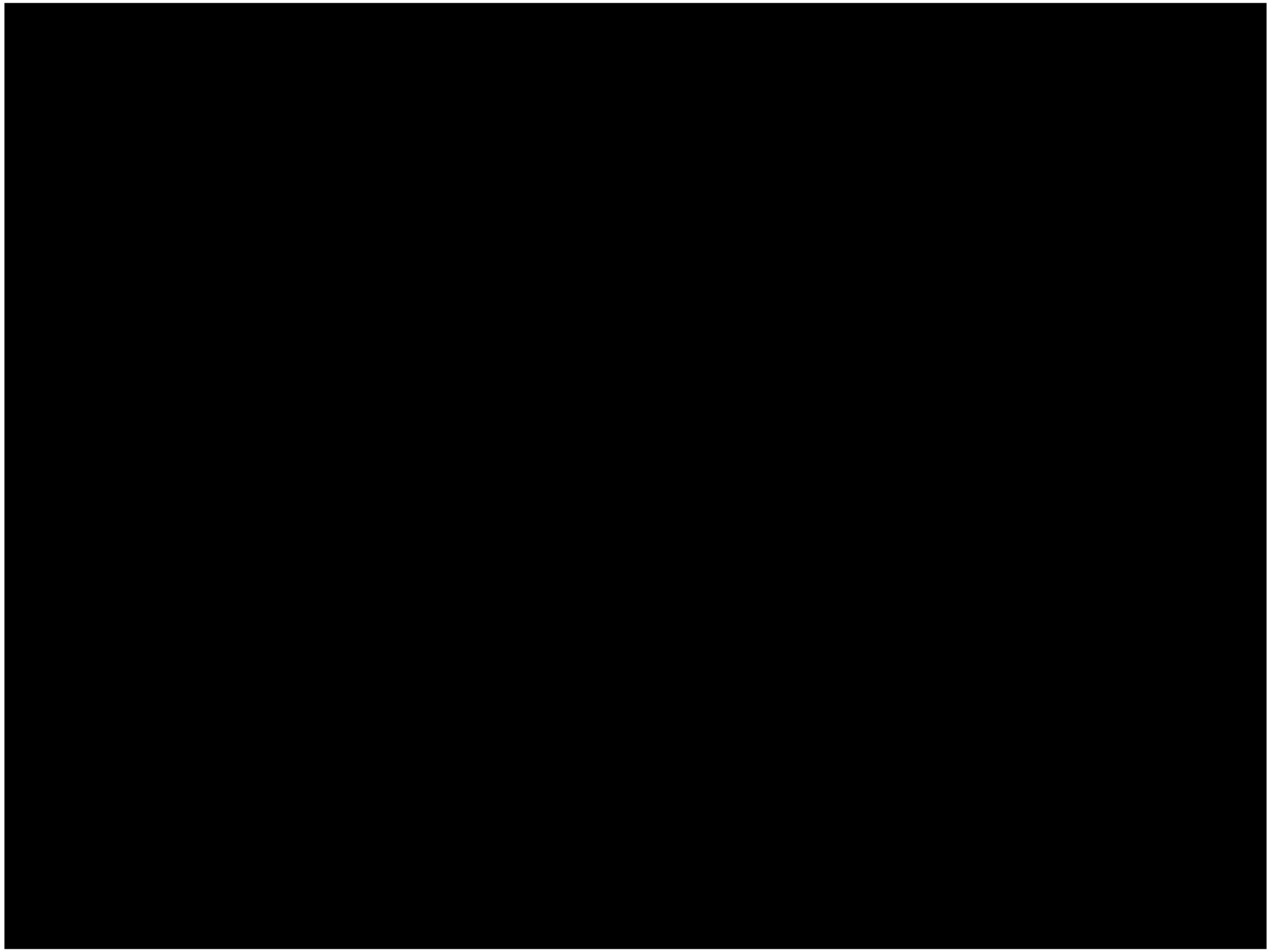
plenoptic camera



Light Fields – Acquisition & Applications

- **refocusing example**
- **only one photograph taken**
- **refocus is performed computationally by**
- **light field manipulation**

Light Field Camera

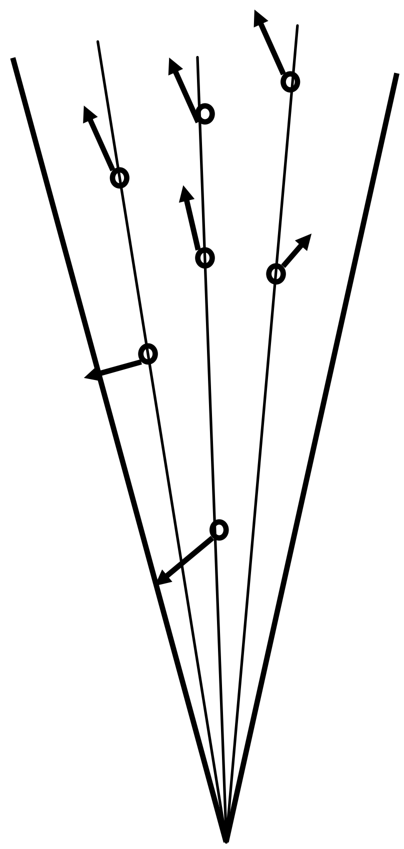


Layered Depth Images

J. Shade et al., “Layered Depth Images”, Siggraph’98

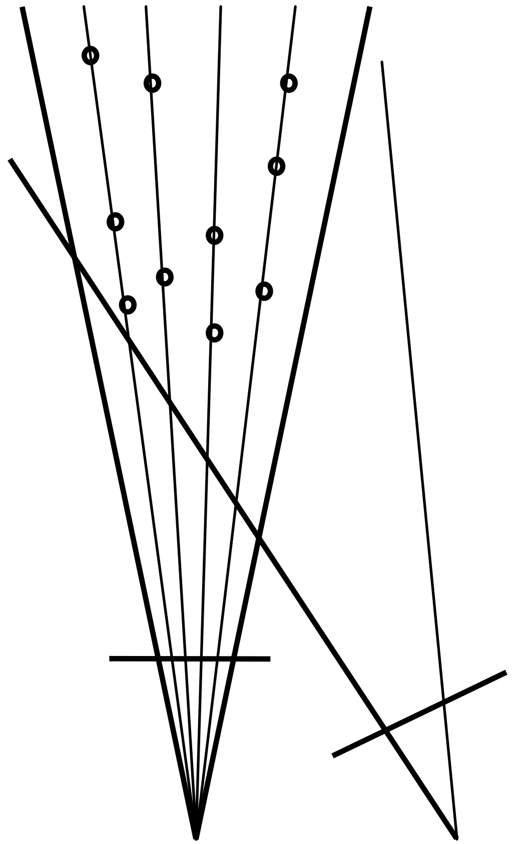
grail.cs.washington.edu/projects/ldi/

- **Idea:**
  - Handle disocclusion
  - Store invisible geometry in depth images
- **Data structure:**
  - Per pixel list of depth samples
  - Per depth sample:
    - RGBA
    - Z
    - Normal direction (compressed)



Layered Depth Images II

- **Computation:**
  - Incremental warping computation
    - Implicit ordering information
  - Splat size computation
    - Table lookup
    - Fixed splat templates
  - Clipping of LDIs



View Morphing

S. Seitz and C. Dyer, “View Morphing”, Siggraph’96

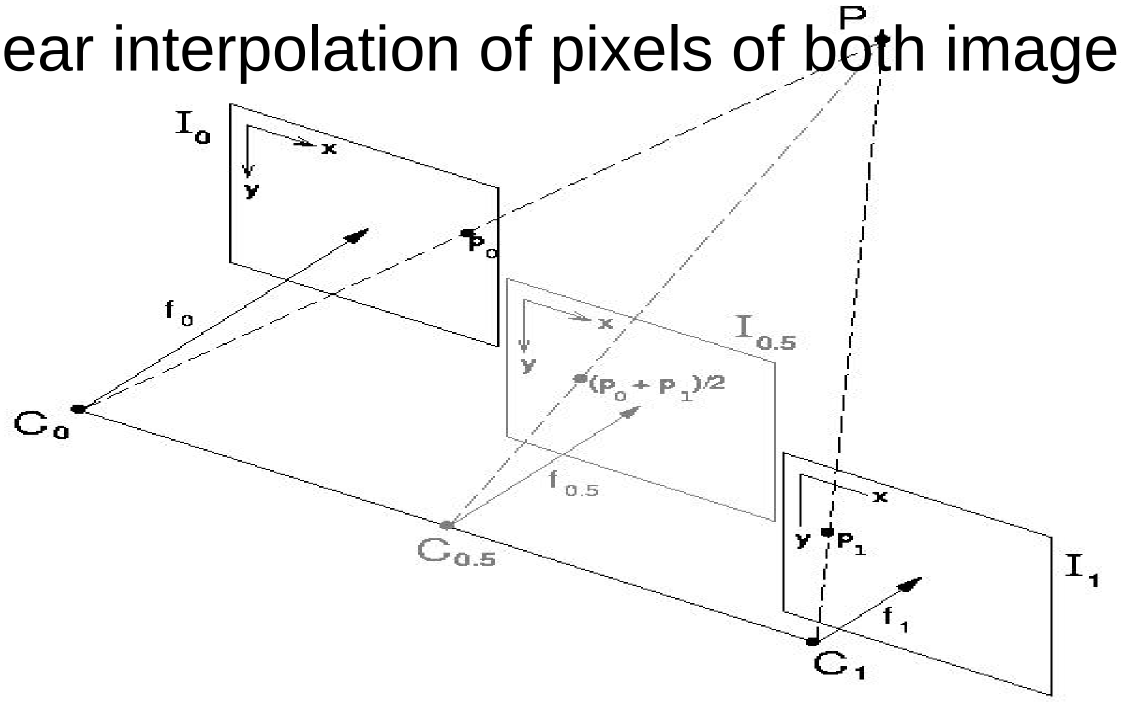
www.cs.washington.edu/homes/seitz/vmorph/vmorph.htm

- Warping between 2 (or more) images
- Cameras’ **F** matrices known
- Image correspondences known for all pixels

$\Rightarrow$ Continuously warp one image into the other giving a physically plausible impression

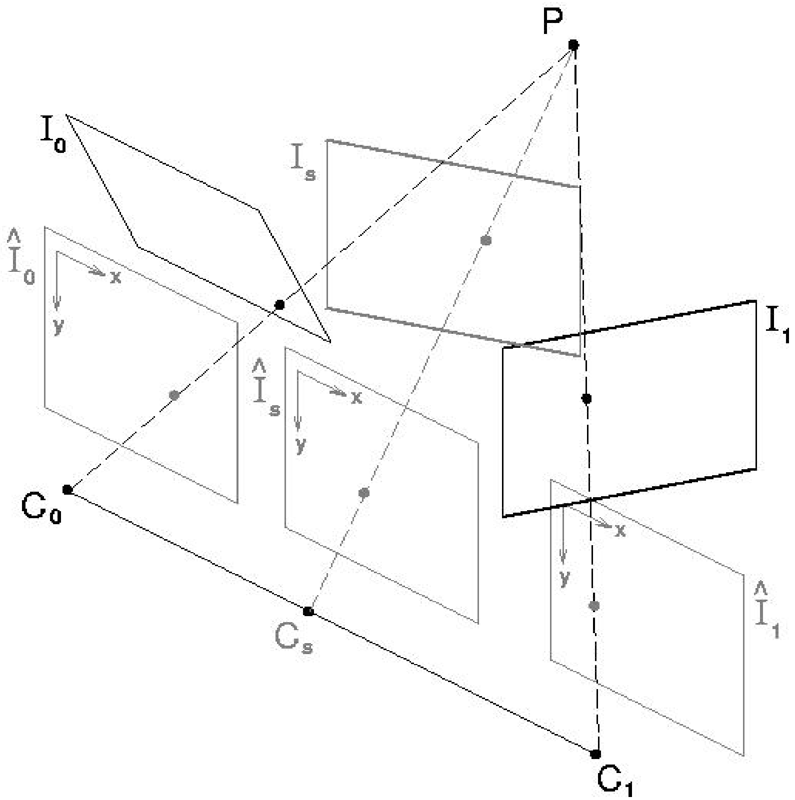
View Morphing II

- Morphing between parallel views
  - Epipolar lines are parallel
    - Lines
  - Simple depth - disparity correspondence
  - Linear interpolation of pixels of both images

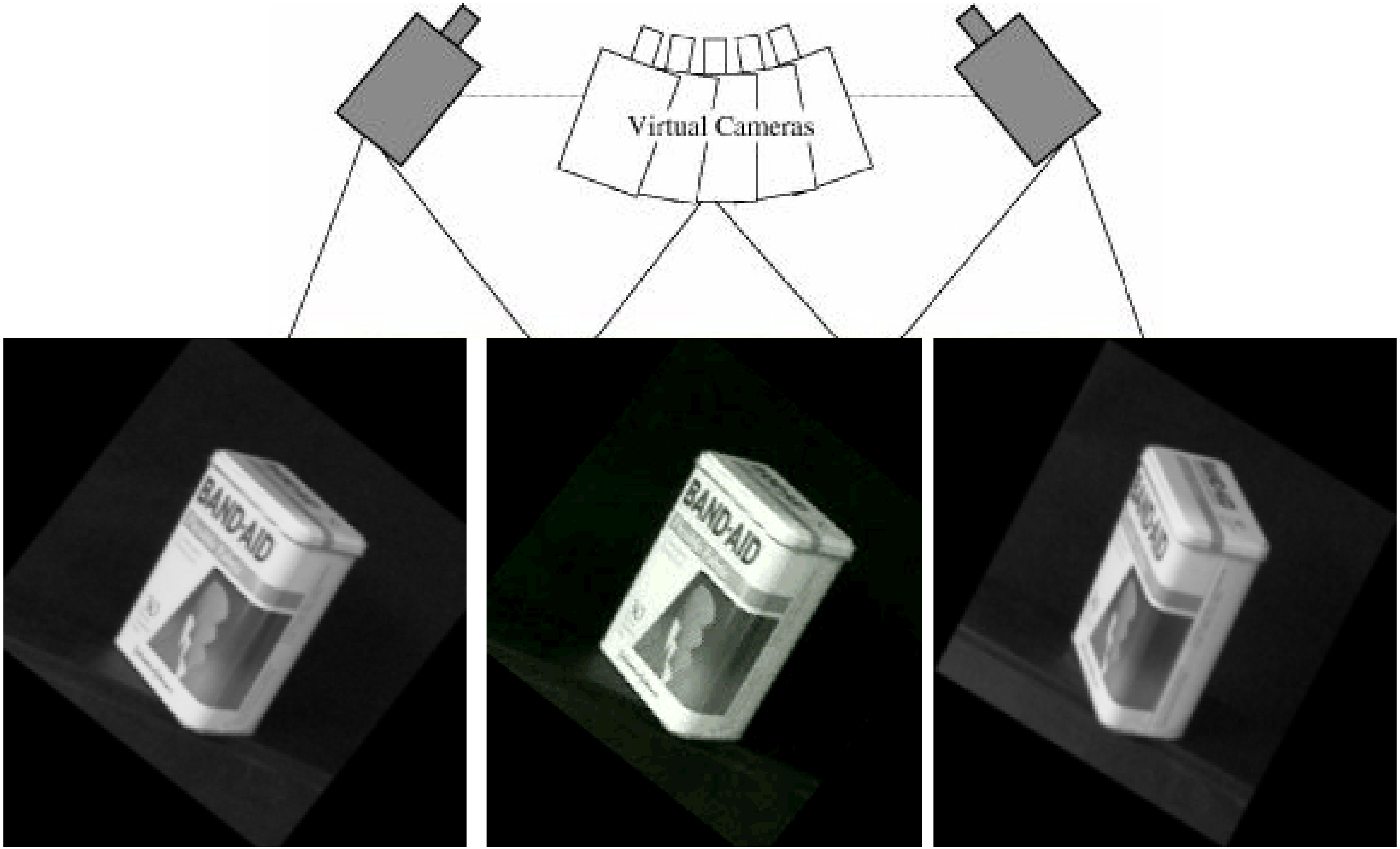


View Morphing III

- Morphing between Non-parallel views
  - Prewarp to common plane (homography)
  - Morph
  - Postwarp



View Morphing - Results



View-dependent Texture Mapping

P. Debevec et al.,

"Efficient View-Dependent Image-based Rendering with Projective Texture-Mapping",

Eurographics Rendering Workshop'98

www.debevec.org

Paul E. Debevec, Camillo J. Taylor, and Jitendra Malik.
Modeling and Rendering Architecture from Photographs:
A Hybrid Geometry- and Image-Based Approach.

In SIGGRAPH 96, August 1996.

- Multiple fully calibrated photographs
- Rough 3D model

⇒ Map photos as texture onto geometry

⇒ Use image closest to viewing direction for texturing

View-dependent Texture Mapping

Original photograph with marked edges

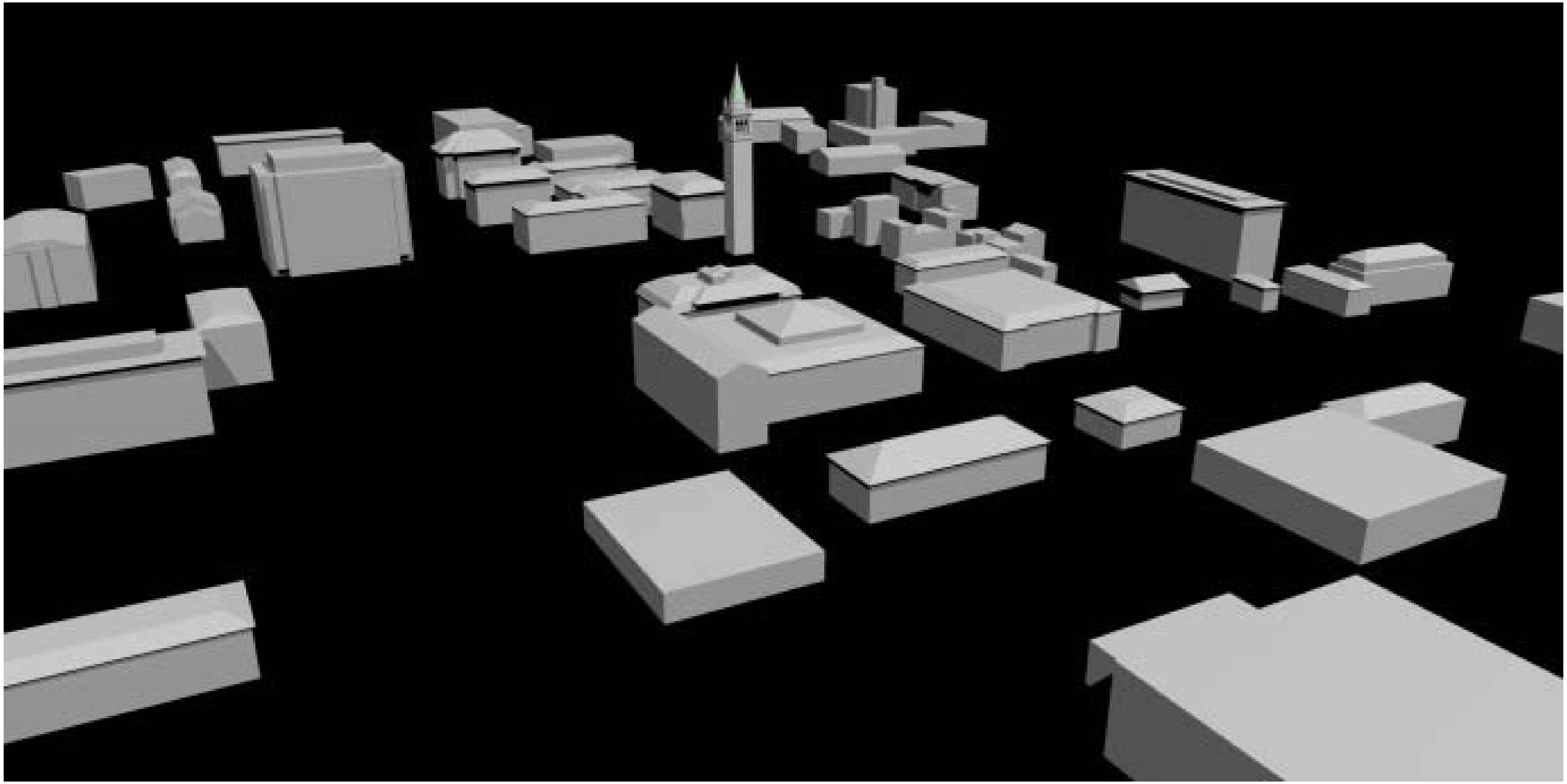
Recovered model

Model edges projected onto photograph

Synthetic rendering

Movie

View-dependent Texture Mapping



View-dependent Texture Mapping

View-dependent Texture Mapping

Movie

The Facade System
www.debevec.org

Surface Light Fields

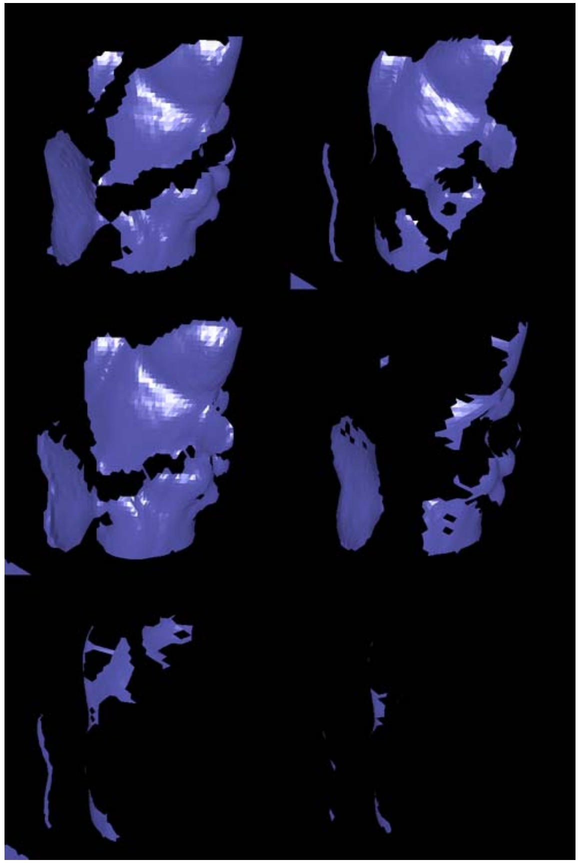
D. Wood et al., “Surface Light Fields for 3D Photography”, Siggraph’00

http://grail.cs.washington.edu/projects/slf/

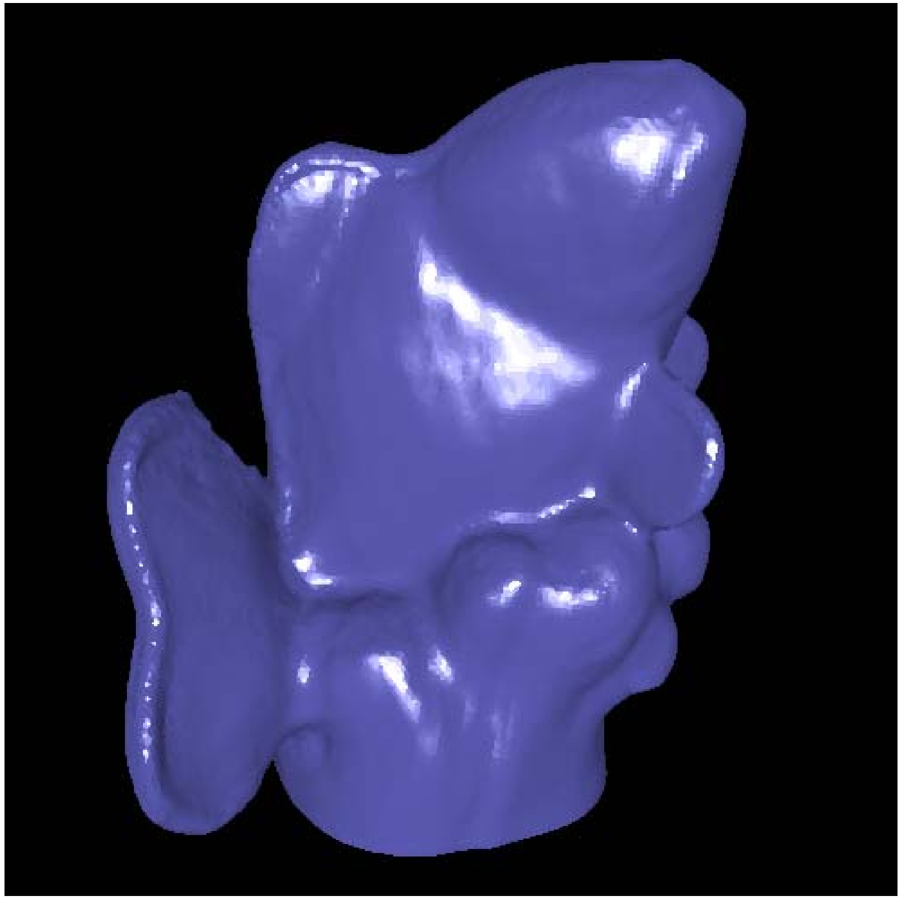
- Complete 3D scene geometry model
- Multiple photographs
- Fully calibrated camera

$\Rightarrow$ Parameterize Light Field over object surface

SLF: Geometry Model Acquisition

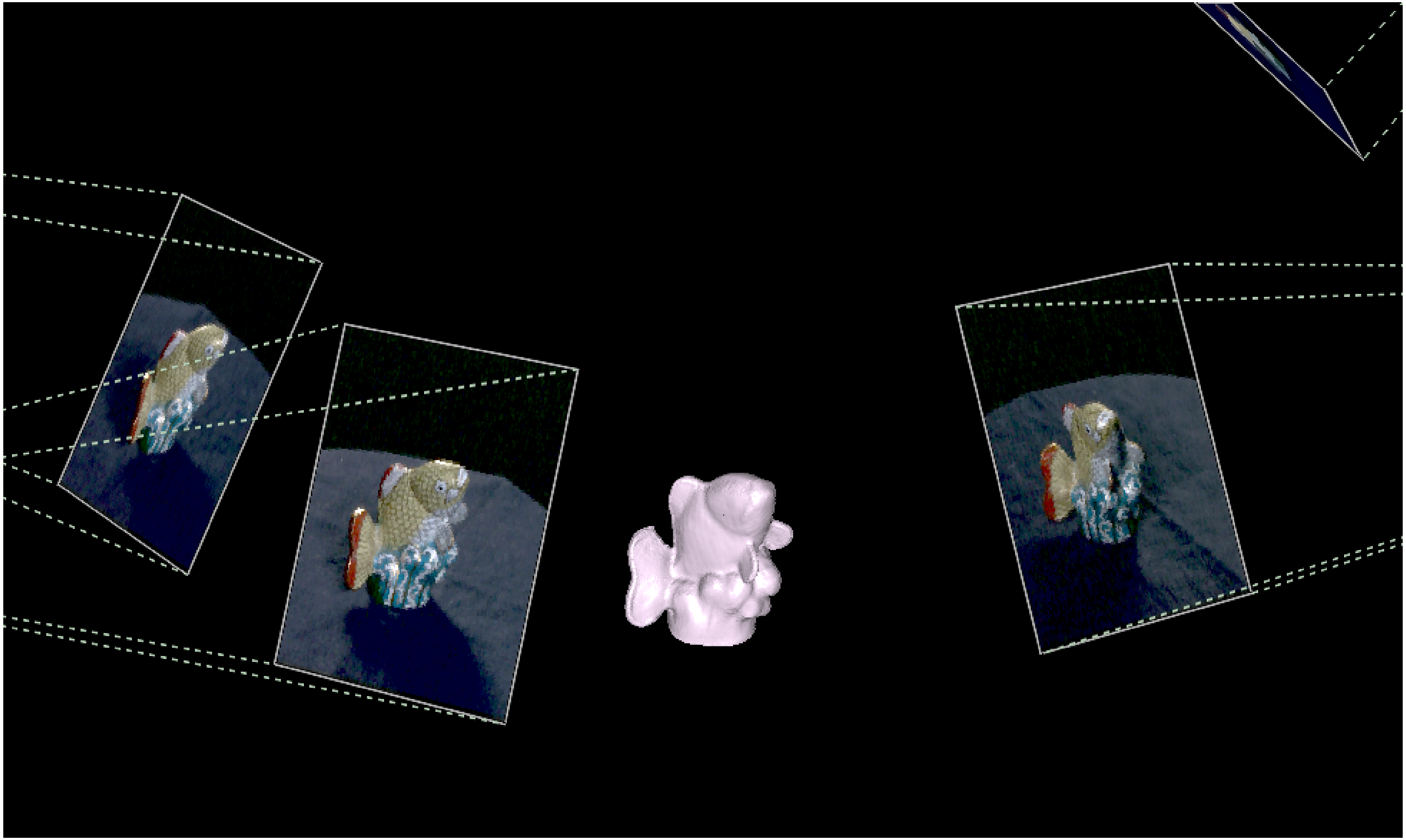


Range scans
(only a few shown . . .)

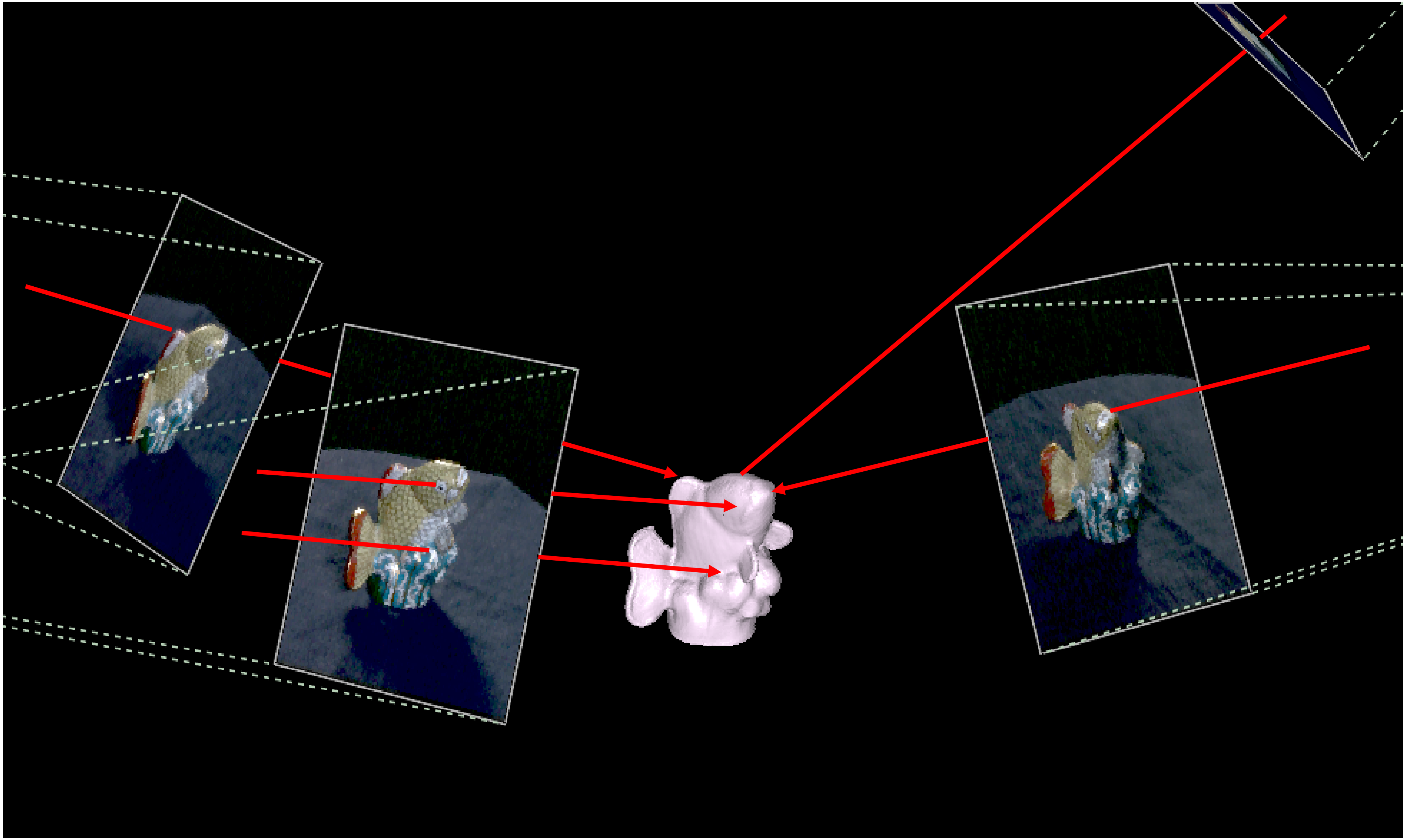


Merged geometry model

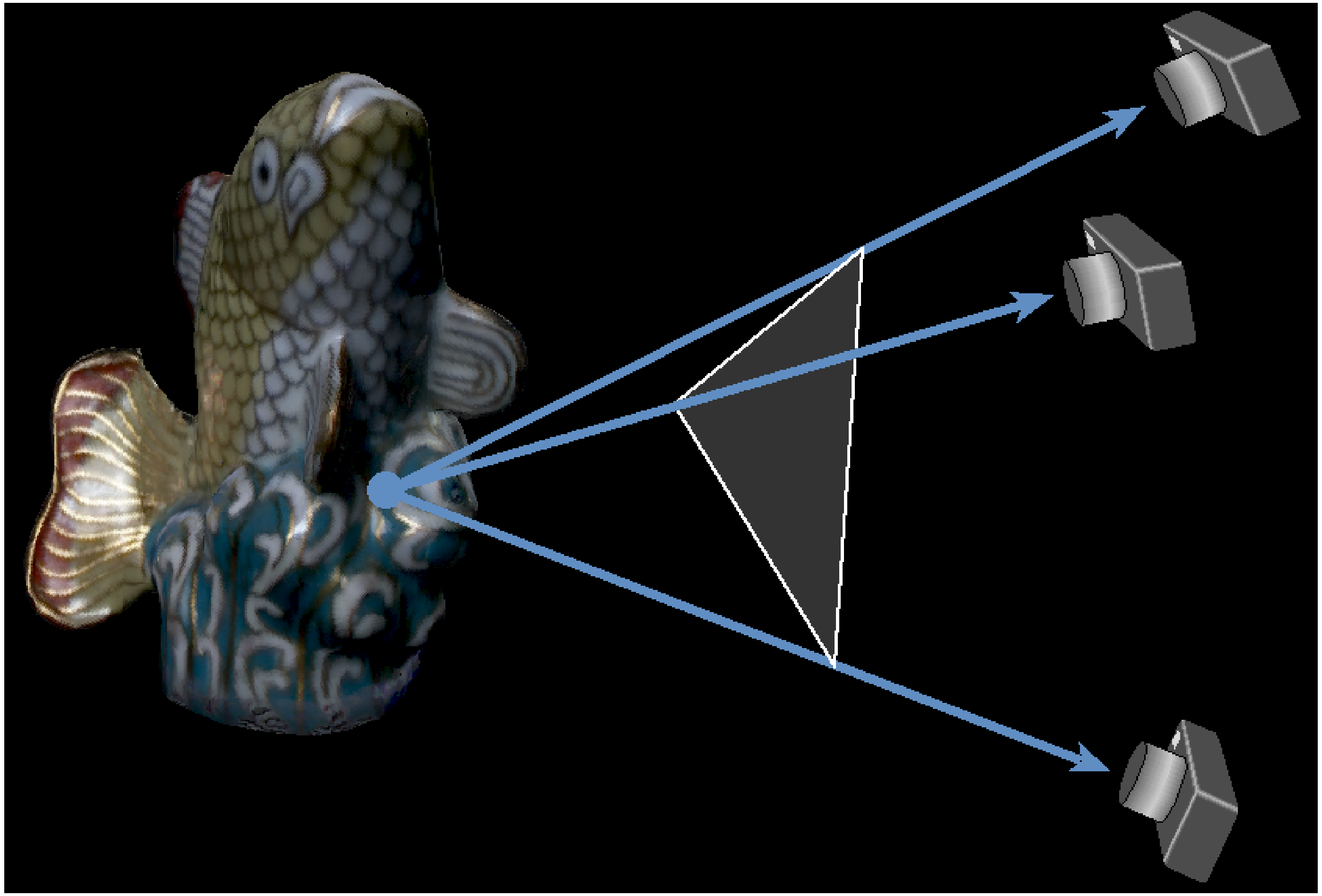
SLF: Register Images to Geometry



SLF: Register Images to Geometry

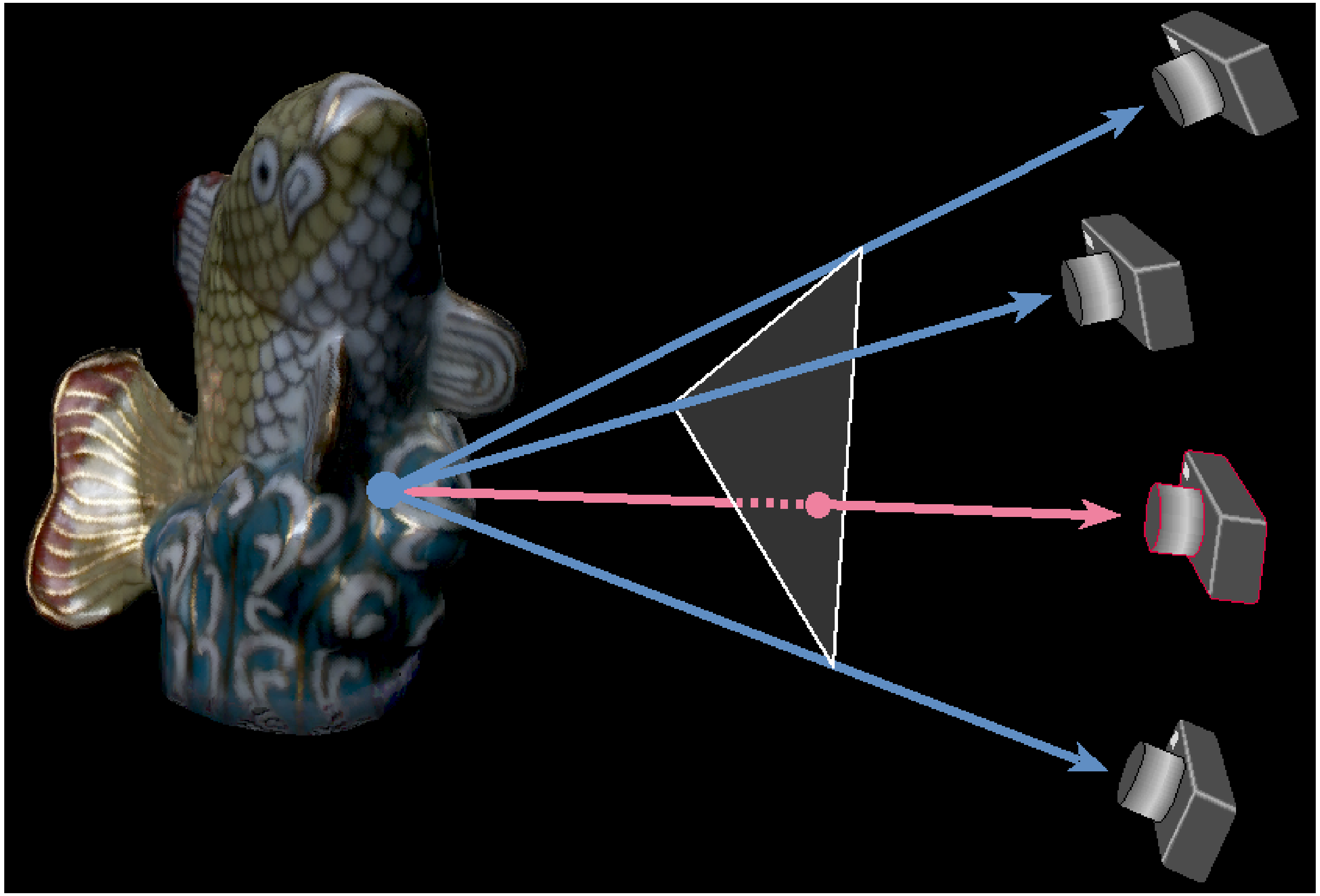


SLF vs. View-dependent Texture Mapping



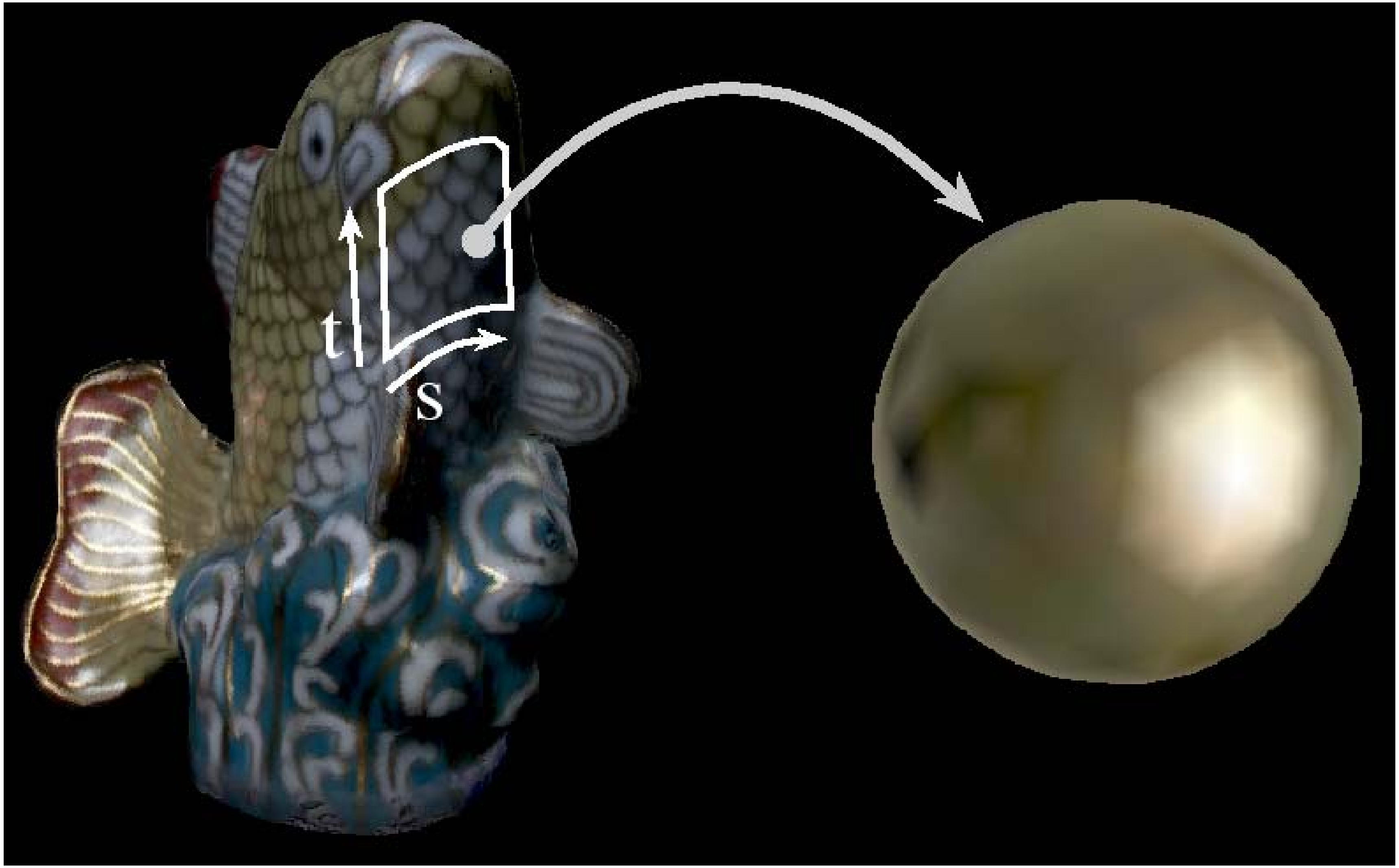
Debevec *et al.* 1996, 1998
Pulli *et al.* 1997

SLF vs. View-dependent Texture Mapping

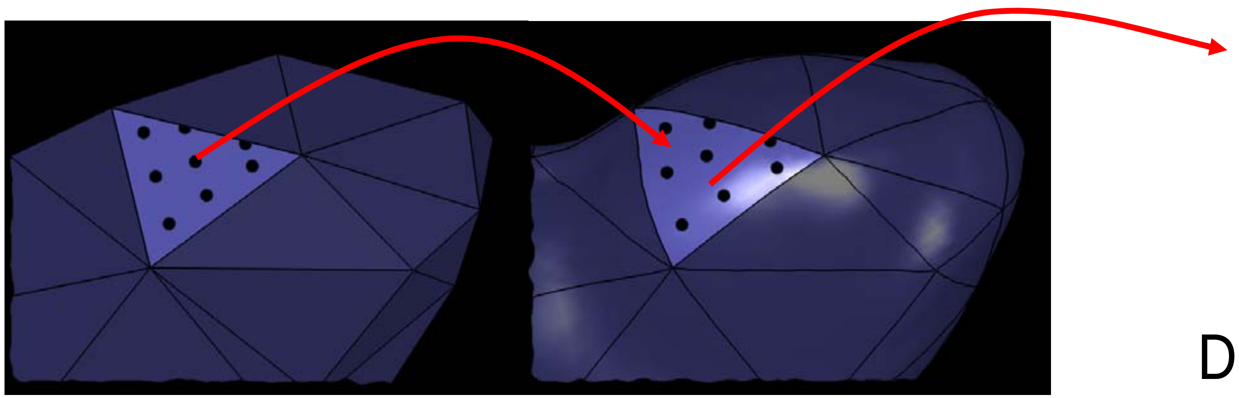


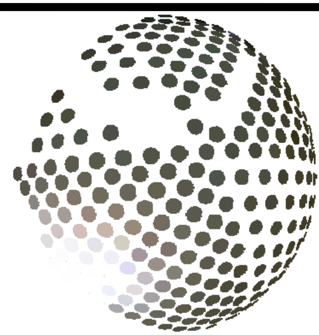
Debevec *et al.* 1996, 1998
Pulli *et al.* 1997

SLF: Lumispheres

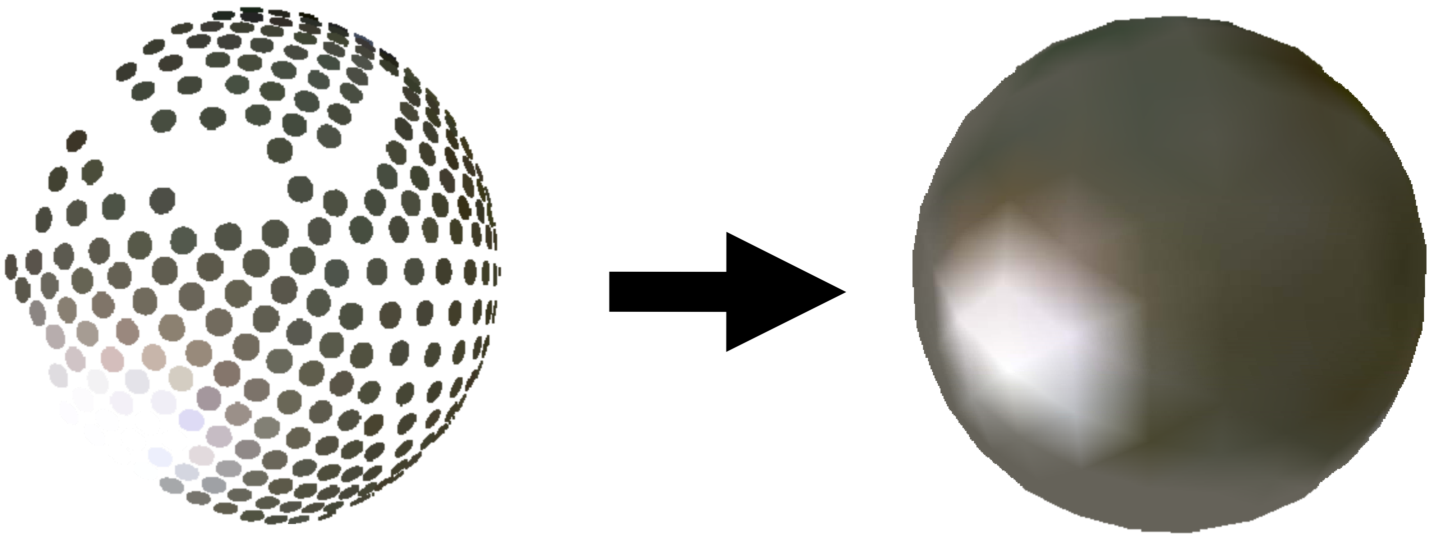


SLF: Lumisphere Fairing



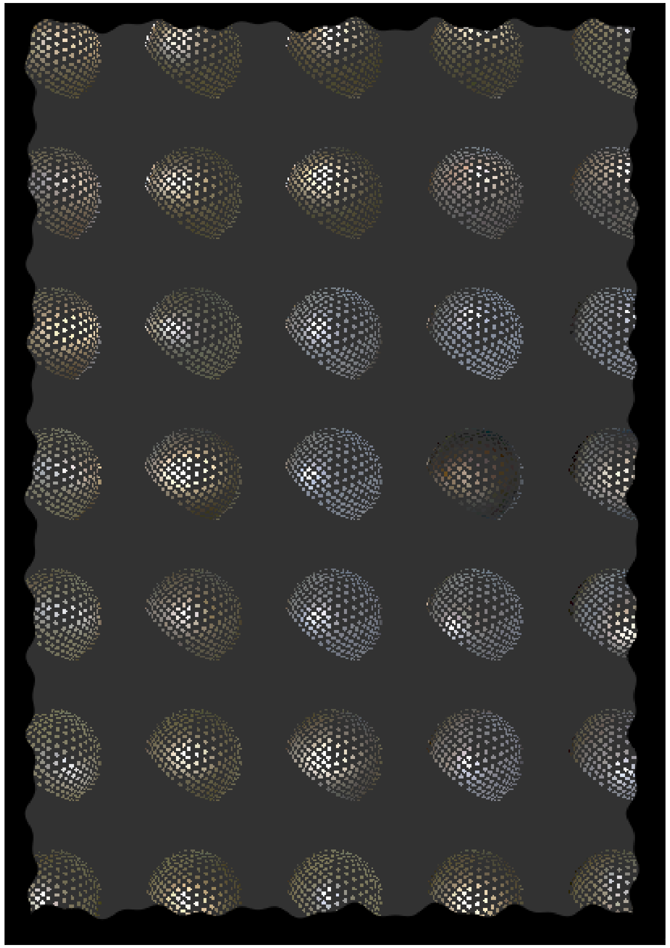


Data lumisphere

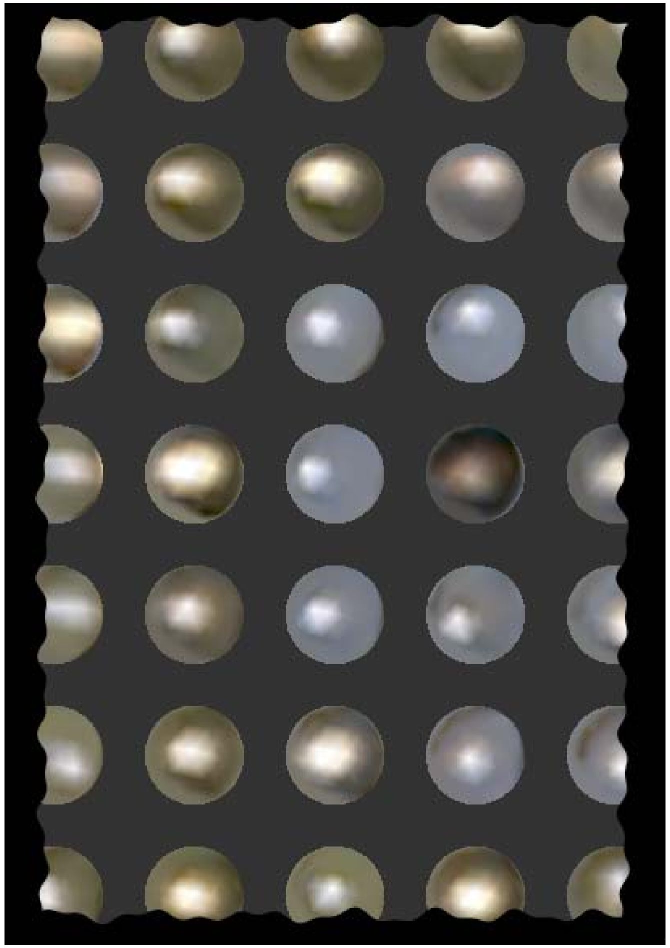


Data lumisphere Faired lumisphere

SLF: Lumisphere Matrix



Many input data lumispheres



Many faired lumispheres

Wrap-Up

Theoretical Background

- Plenoptic Function

“Pure” IBR

- Panoramas
- Concentric Mosaics
- Light Field Rendering

Geometry-assisted IBR

- The Lumigraph
- Layered Depth Images
- View Morphing
- View-dependent Texture Mapping
- Surface Light Fields