# Image-based modeling (IBM) and image-based rendering (IBR)

CS 248 - Introduction to Computer Graphics

Autumn quarter, 2005

Slides for December 8 lecture

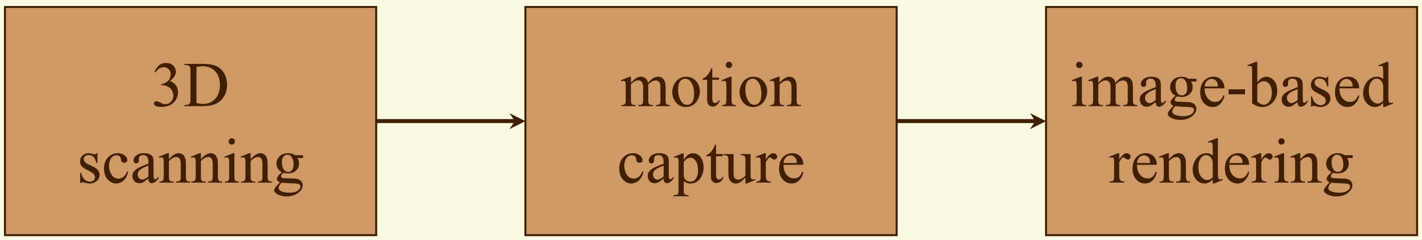
Marc Levoy

# The graphics pipeline

# The graphics pipeline

the traditional pipeline


the new pipeline?



# IBM / IBR

*"The study of image-based modeling and rendering is the study of sampled representations of geometry."*

# Image-based representations: the classics

more geometry

less geometry

3D

- model + texture/reflectance map [Blinn78]
- model + displacement map [Cook84]
- volume rendering [Levoy87, Drebin88]

2D + Z

- range images [Binford73]
- disparity maps [vision literature]

2.5D

- sprites [vis-sim, games]

n 2D

- epipolar plane images [Bolles87]
- movie maps [Lippman78]

2D

- environment maps, a.k.a. panoramas [19th century]

# Recent additions

more geometry

↕

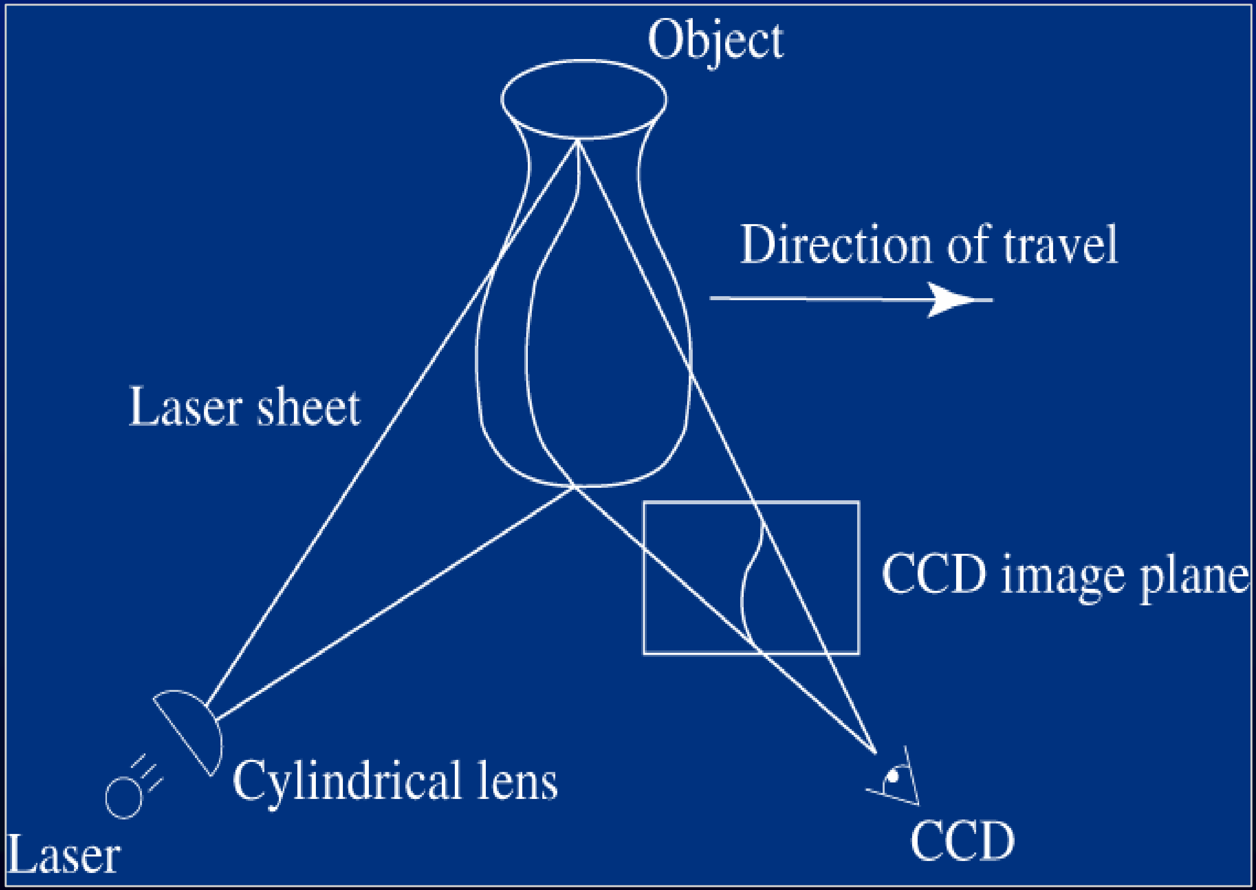
less geometry

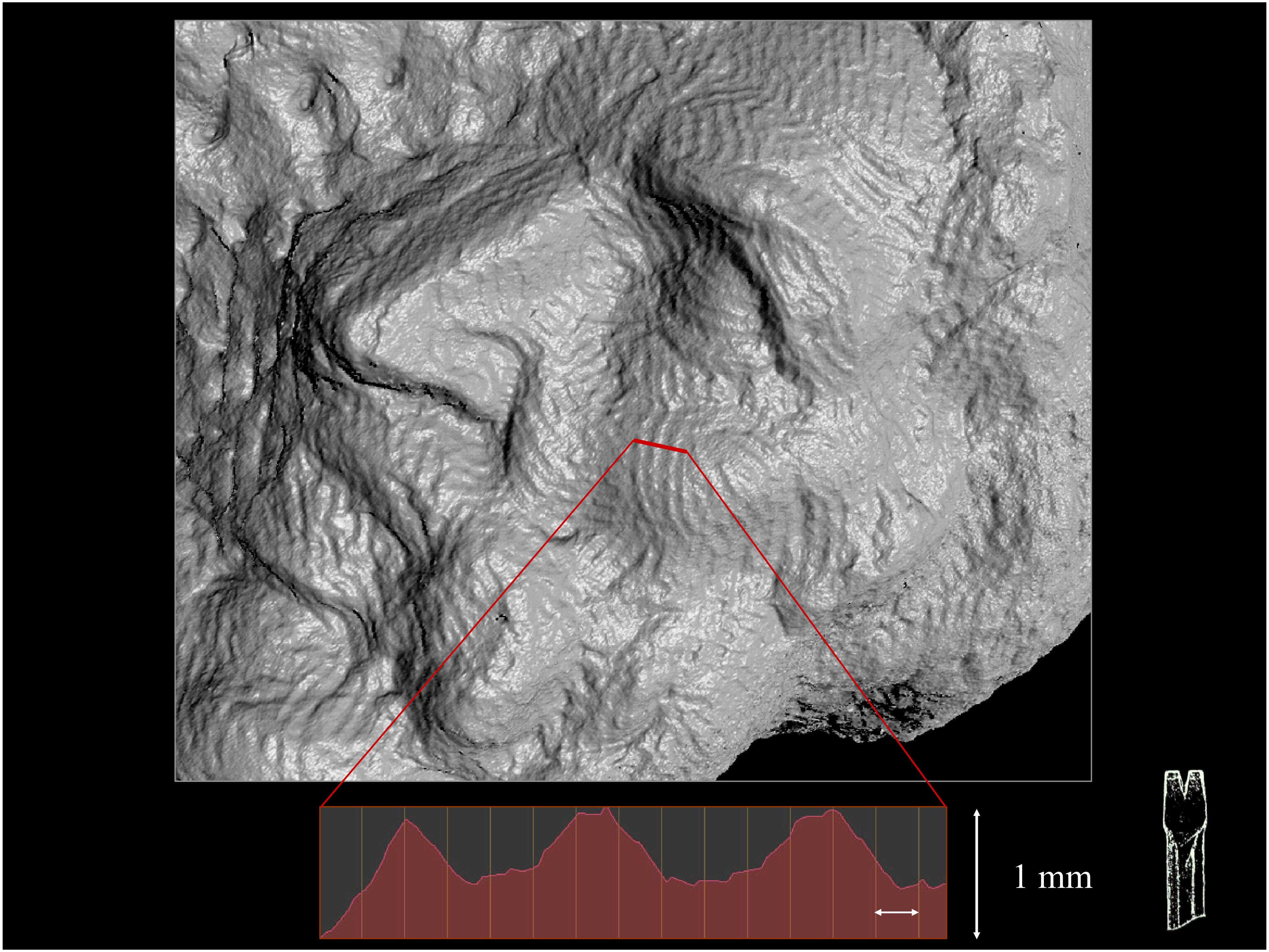
- full model
  - view-dependent textures [Debevec96]
  - surface light fields [Wood00]
  - Lumigraphs [Gortler96]
- sets of range images
  - view interpolation [Chen93, McMillan95, Mark97]
  - layered depth images [Shade98]
  - relief textures [Oliveira00]
- feature correspondences
  - plenoptic editing [Seitz98, Dorsey01]
- camera pose
  - image caching [Schaufler96, Shade96]
  - sprites + warps [Lengyel97]
  - light fields [Levoy96]
- no model
  - outward-looking QTVR [Chen95]

# Rangefinding technologies

- passive
  - shape from stereo
  - shape from focus
  - shape from motion, etc.
- active
  - texture-assisted shape-from-X
  - triangulation using structured-light
  - time-of-flight

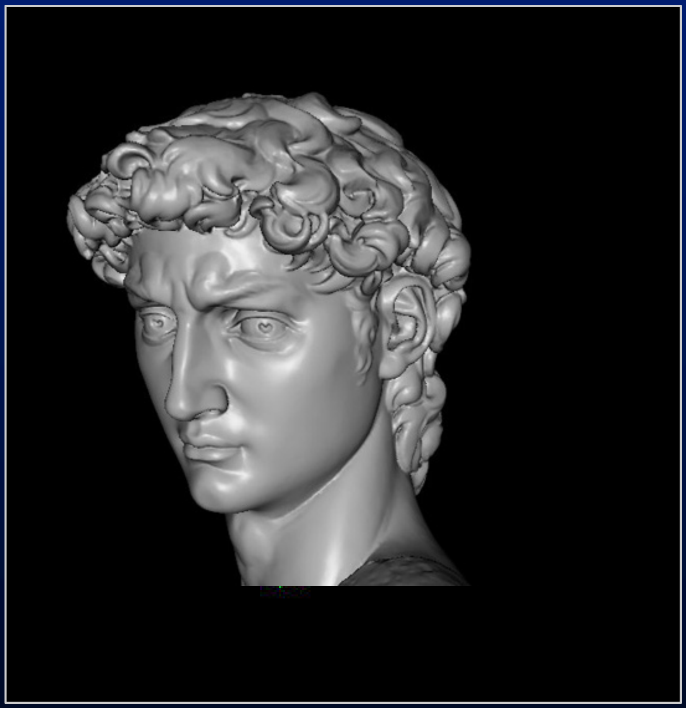
# Laser triangulation rangefinding

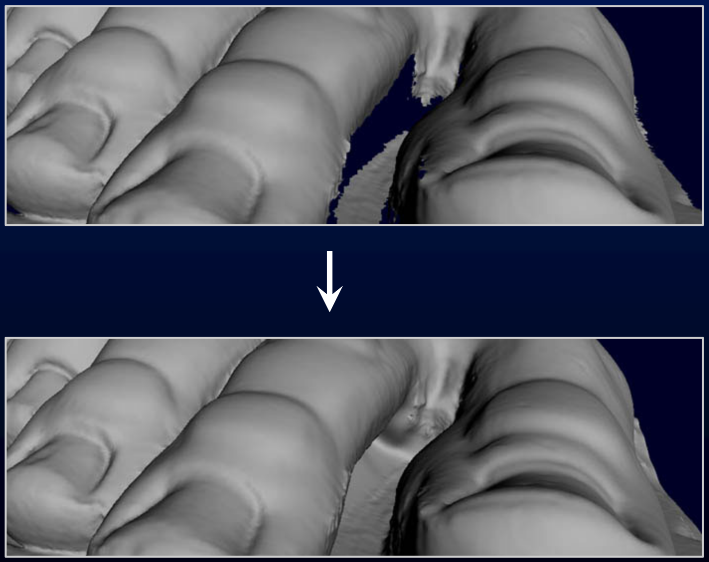



1 mm

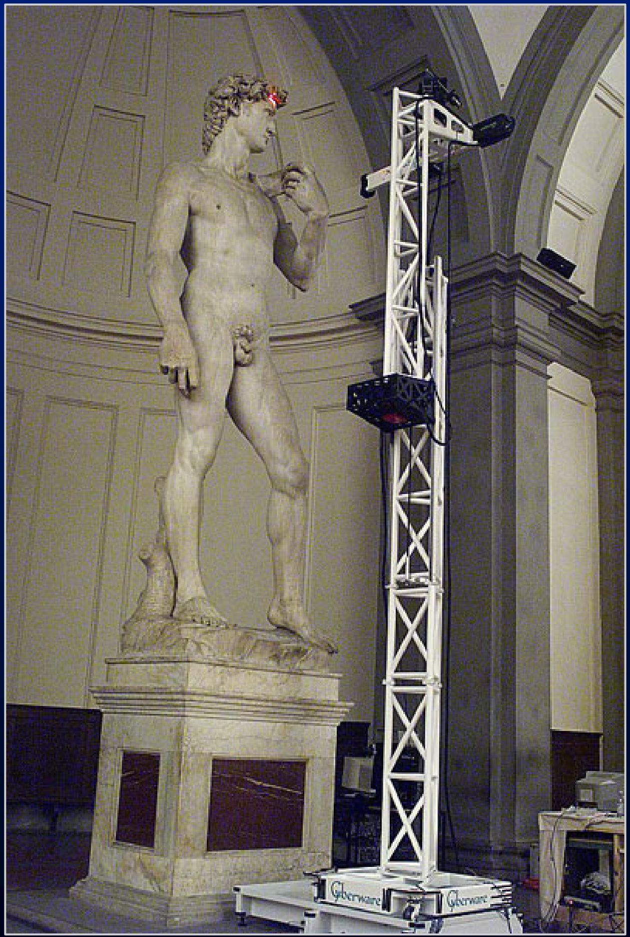
# Post-processing pipeline

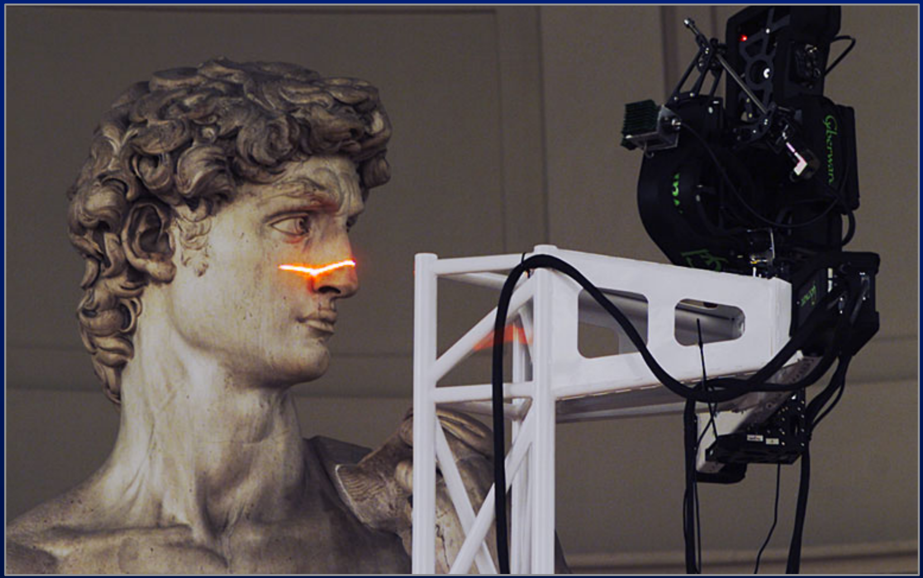
- steps
  1. aligning the scans
  2. combining aligned scans
  3. filling holes





# Digitizing the statues of Michelangelo using laser scanners





- 480 individually aimed scans
- 2 billion polygons
- 7,000 color images
- 30 nights of scanning
- 22 people

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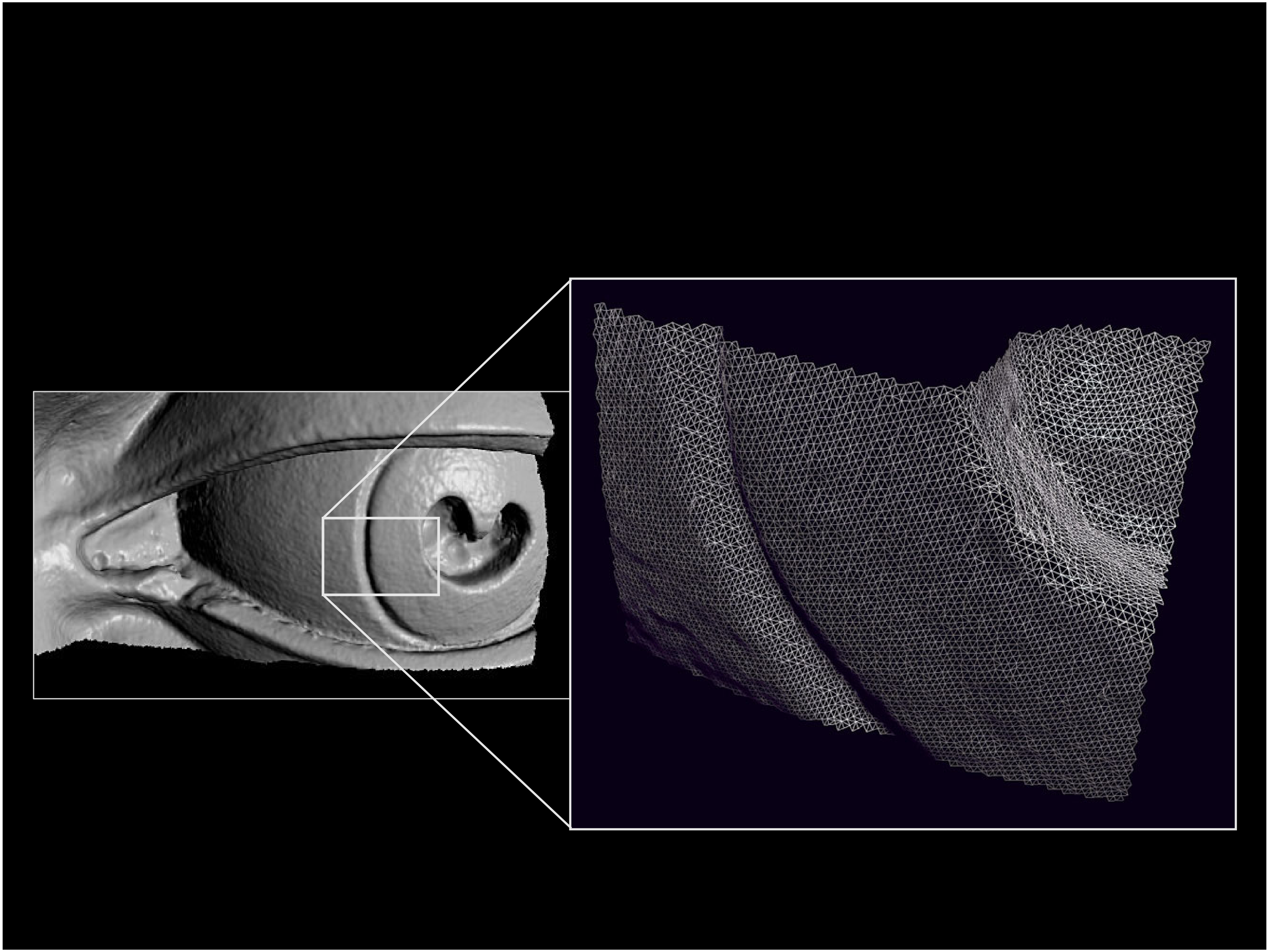
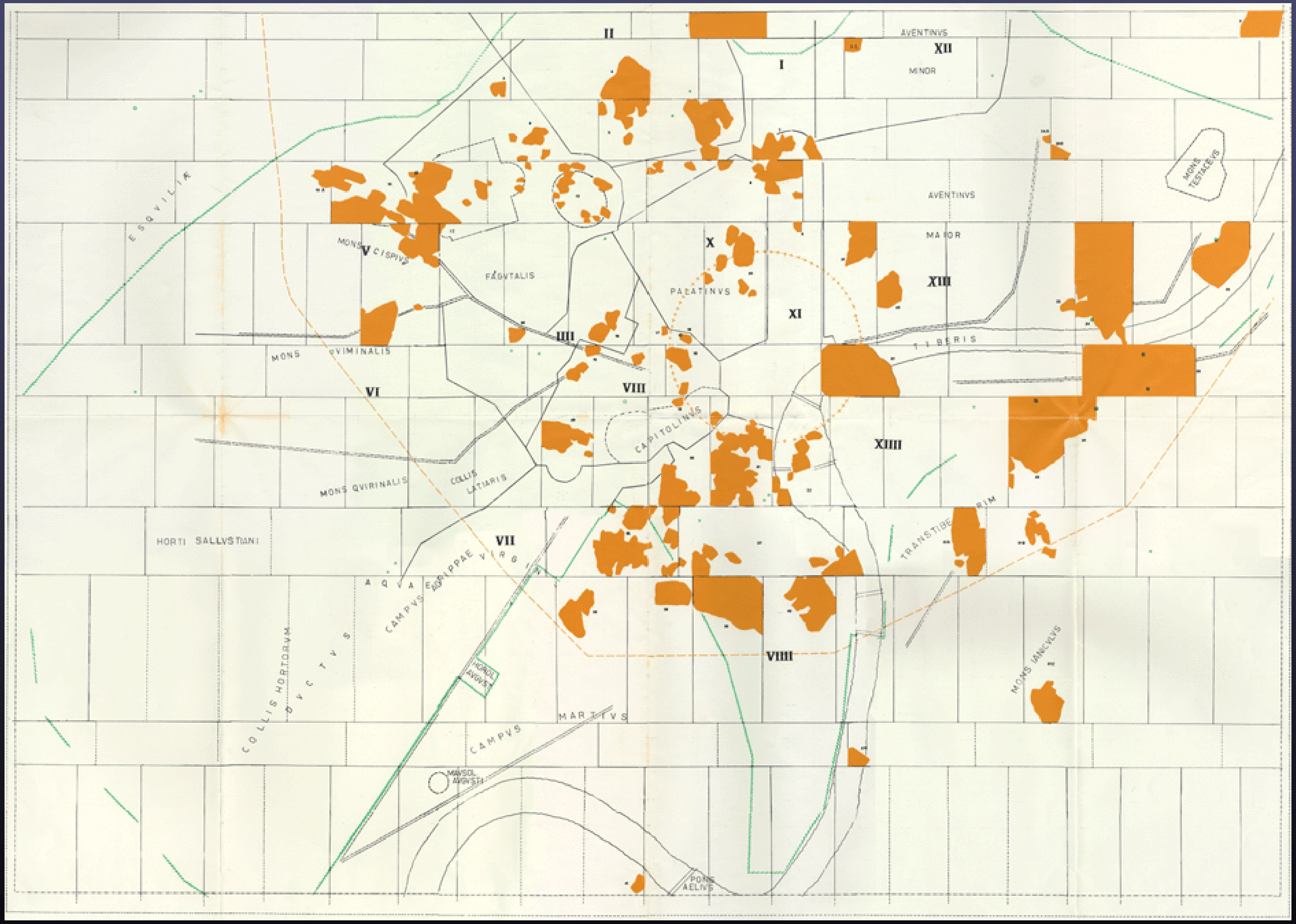


# Replica of Michelangelo's David
## (20 cm tall)

# Solving the jigsaw puzzle of the Forma Urbis Romae

# The puzzle as it now stands

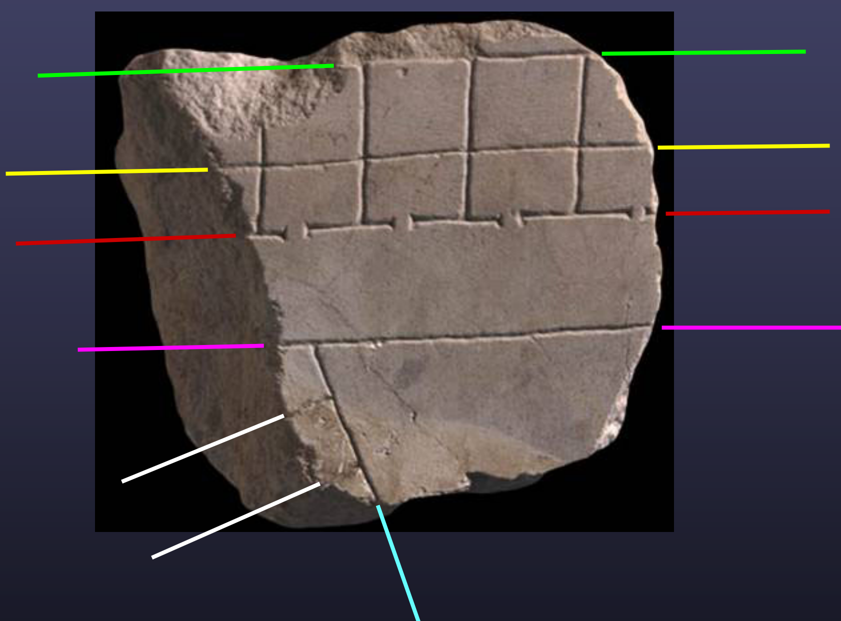


# Clues for solving the puzzle

- incised lines
- incision characteristics
- marble veining
- fragment thickness
- shapes of fractured surfaces
- rough / smooth bottom surface
- straight sides, indicating slab boundaries
- location and shapes of clamp holes
- the wall:  slab layout, clamp holes, stucco
- archaeological evidence

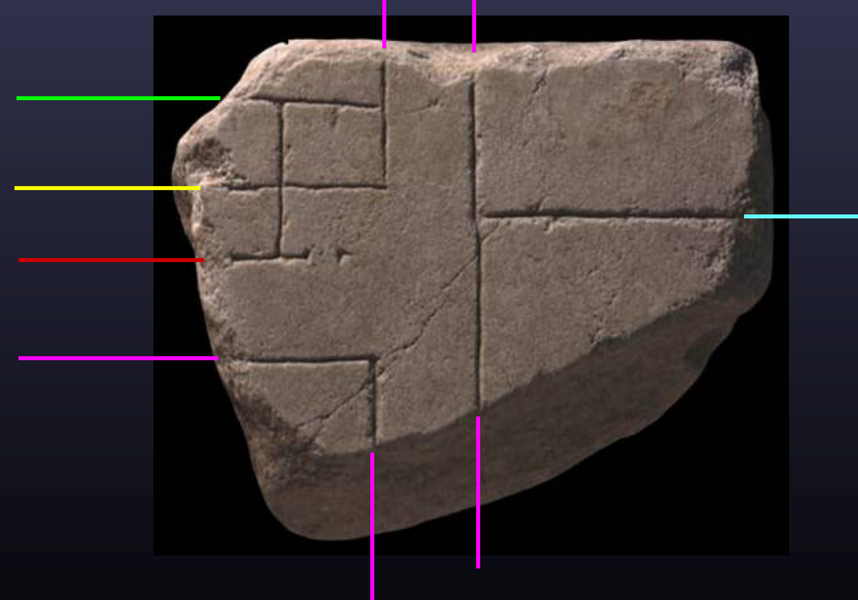
# Matching incised lines

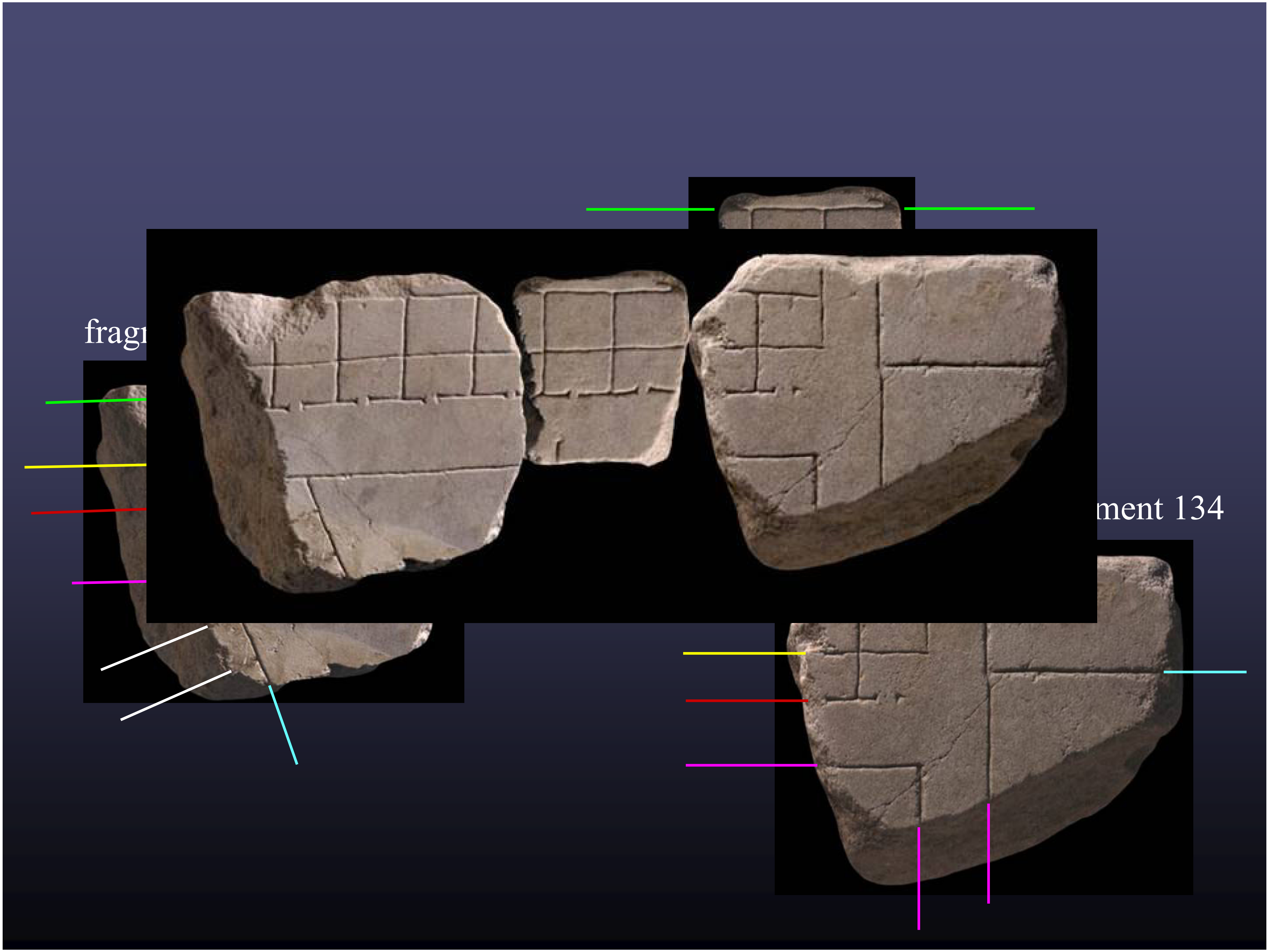
fragment 156



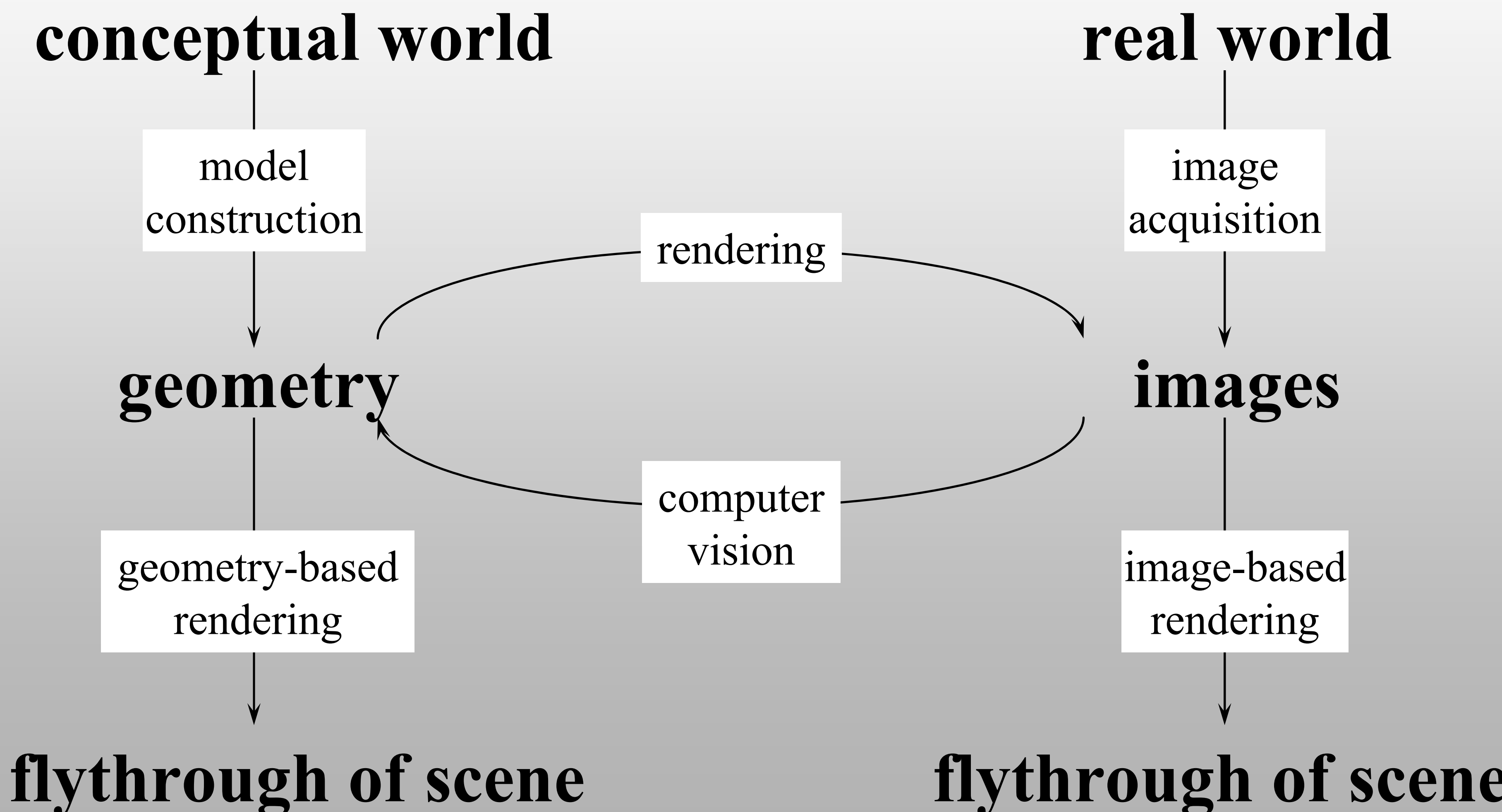
fragment 167

fragment 134




frag
ment 134

# Geometry-based versus image-based rendering

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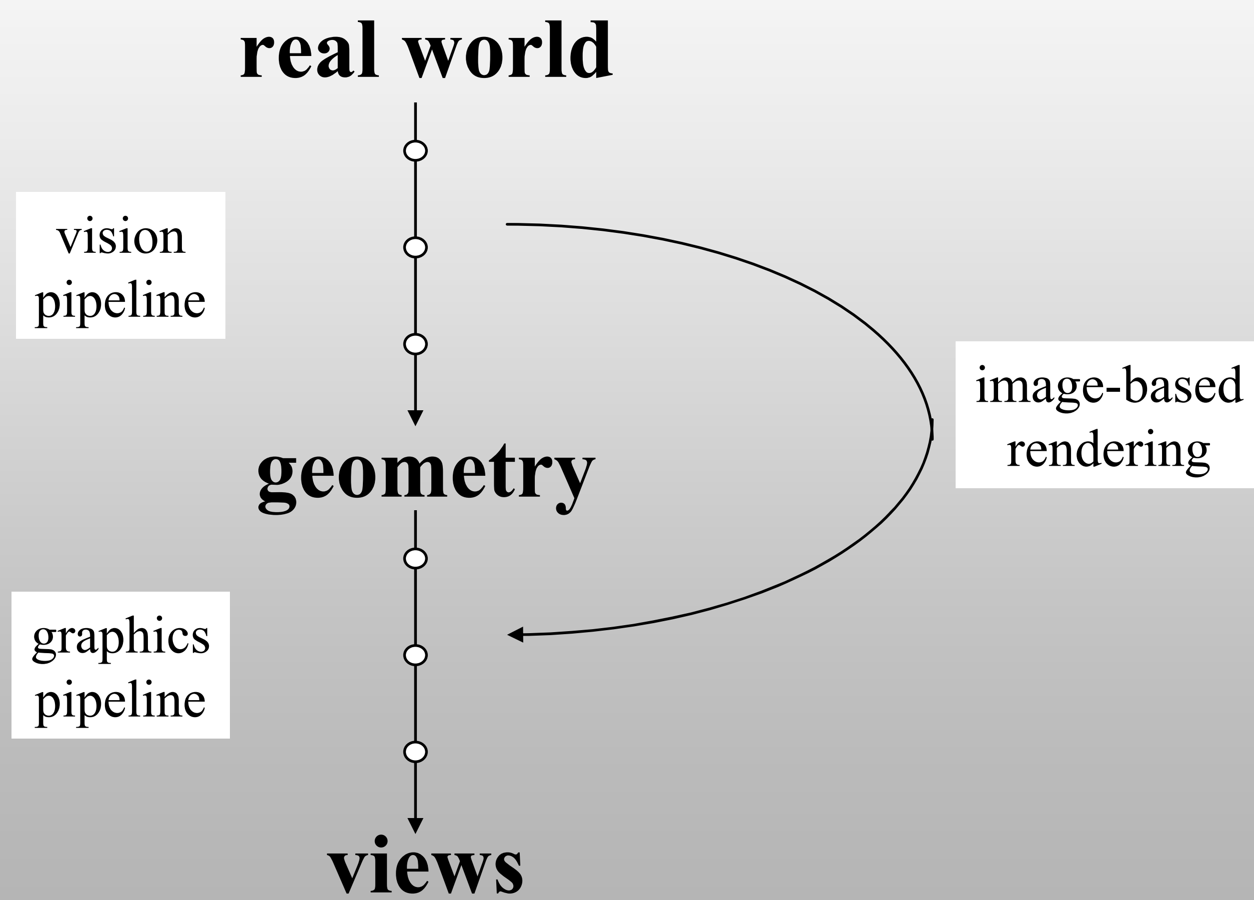
# Shortcutting the vision/graphics pipeline

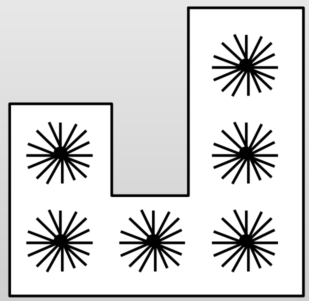



(from M. Cohen)

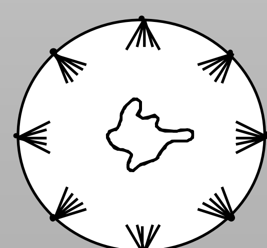
# Apple QuickTime VR

[Chen, Siggraph ’95]

- outward-looking
  - panoramic views taken at regularly spaced points

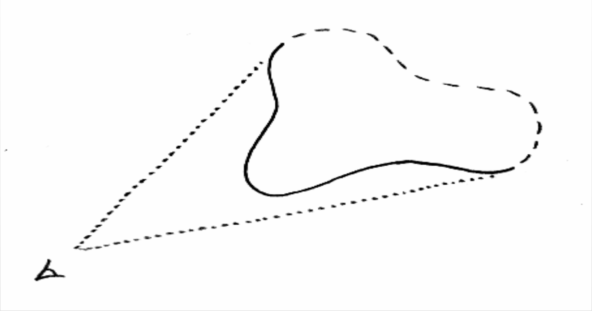


- inward-looking
  - views taken at points on the surface of a sphere

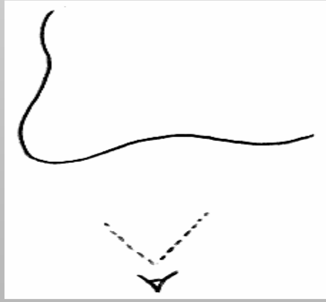


# View interpolation from a single view

1. Render object
2. Convert Z-buffer to range image
3. Tesselate to create polygon mesh



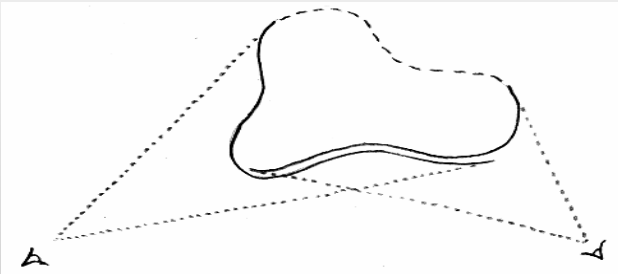
4. Re-render from new viewpoint
5. Use depths to resolve overlaps



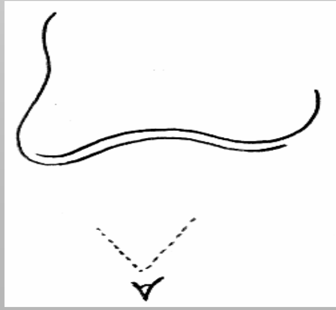
Q. How to fill in holes?

# View interpolation from multiple views

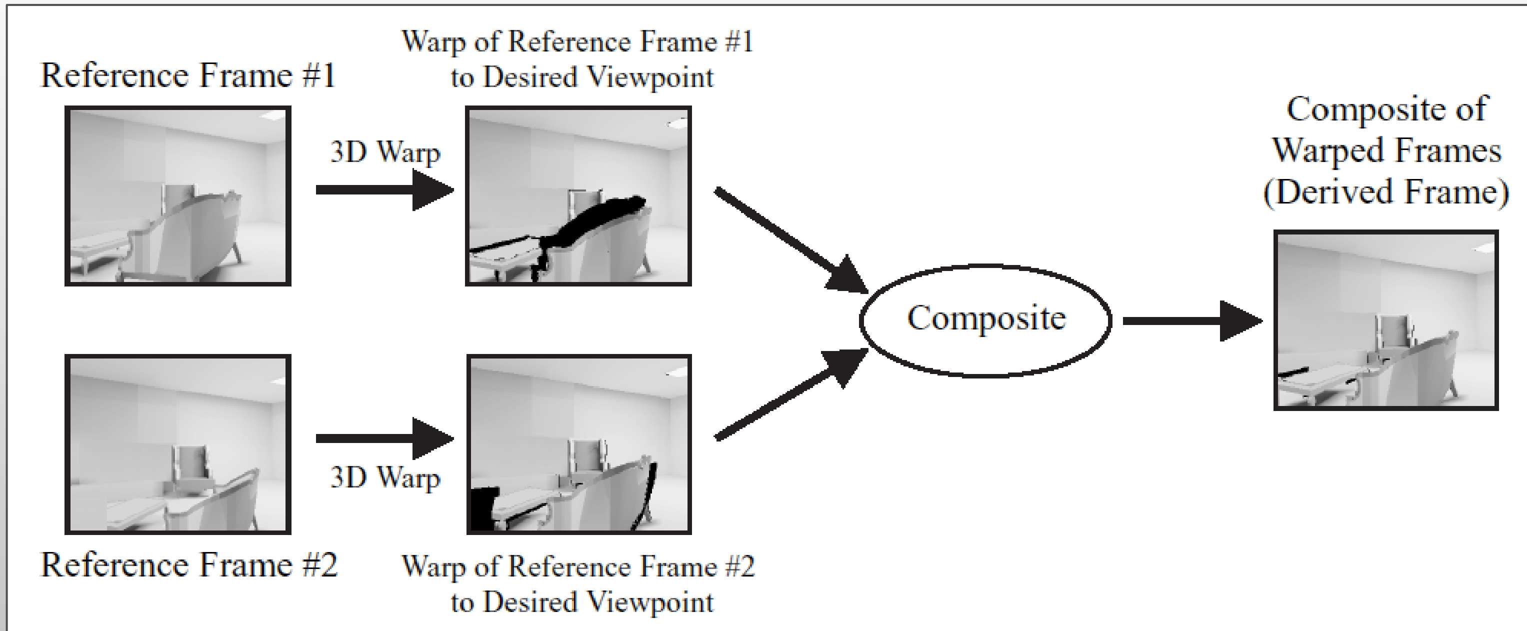
1. Render object from multiple viewpoints
2. Convert Z-buffers to range images
3. Tesselate to create multiple meshes



4. Re-render from new viewpoint
5. Use depths to resolve overlaps
6. Use multiple views to fill in holes



# Post-rendering 3D warping
[Mark et al., I3D97]



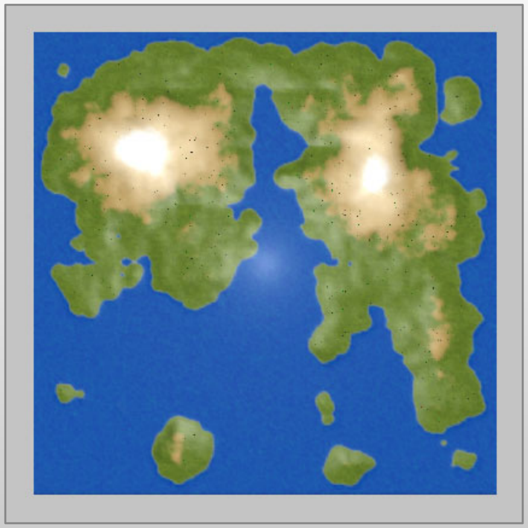

- render at low frame rate
- interpolate to real-time frame rate
  - interpolate observer viewpoint using B-Spline
  - convert reference images to polygon meshes
  - warp meshes to interpolated viewpoint
  - composite by Z-buffer comparison and conditional write

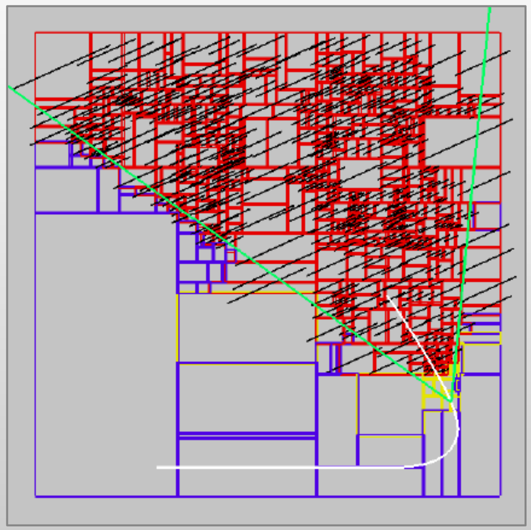
# Results

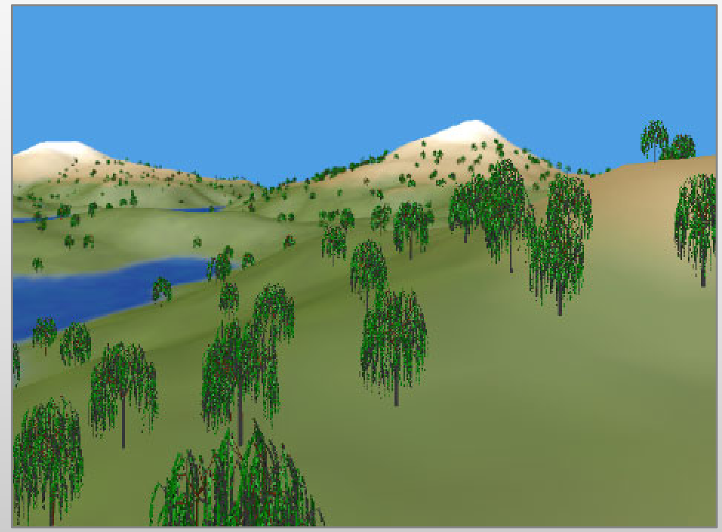
- rendered at 5 fps, interpolated to 30 fps
- live system requires reliable motion prediction
  - tradeoff between accuracy and latency
- fails on specular objects

# Image caching

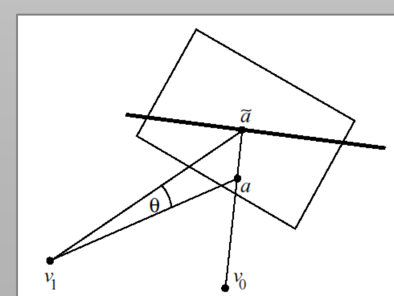
[Shade et al., SIGGRAPH 1996]



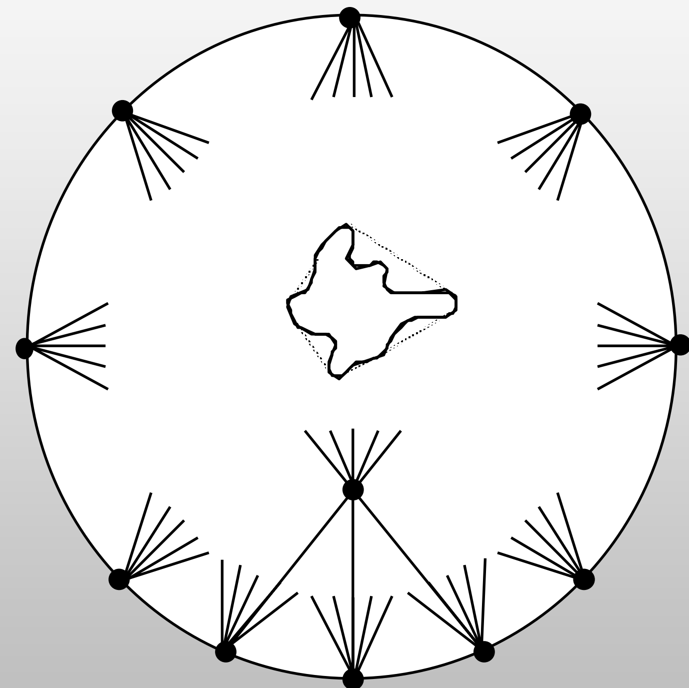




- precompute BSP tree of scene (2D in this case)
- for first observer position
  - draw nearby nodes (yellow) as geometry
  - render distant nodes (red) to RGB images (black)
  - composite images together
- as observer moves
  - if disparity exceeds a threshold, rerender image



# Light field rendering
[Levoy & Hanrahan, SIGGRAPH 1996]



- must stay outside convex hull of the object
- like rebinning in computed tomography

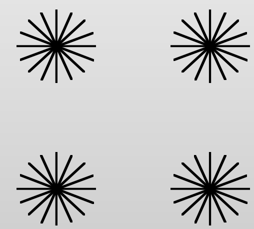
# The plenoptic function

*Radiance as a function of position and direction in a static scene with fixed illumination*

- for general scenes

  5D function

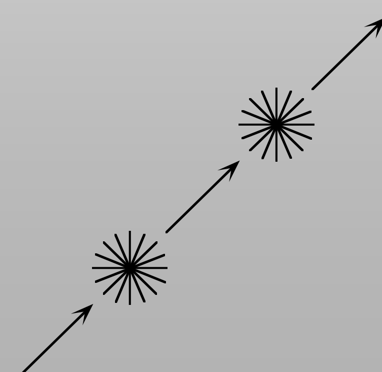
  L ( x, y, z, )



- in free space

  4D function

  “ the (scalar) light field”

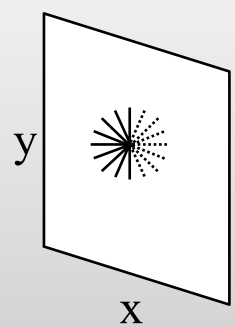


# The free-space assumption

- applications for free-space light fields
  - flying around a compact object
  - flying through an uncluttered environment

# Some candidate parameterizations

Point-on-plane + direction

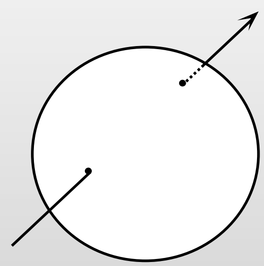



L ( x, y, )

- convenient for measuring luminaires

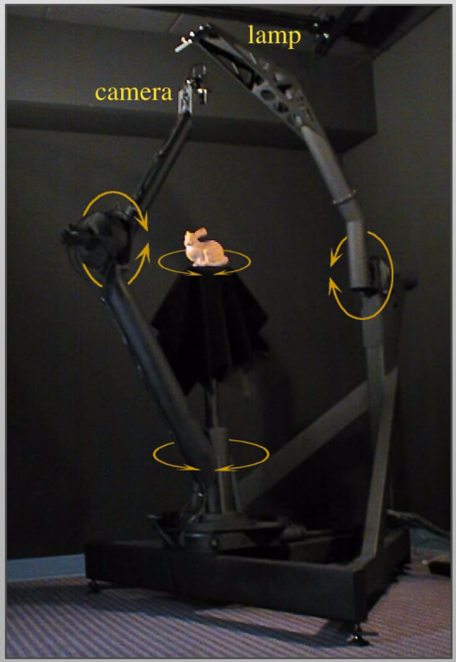
# More parameterizations

Chords of a sphere

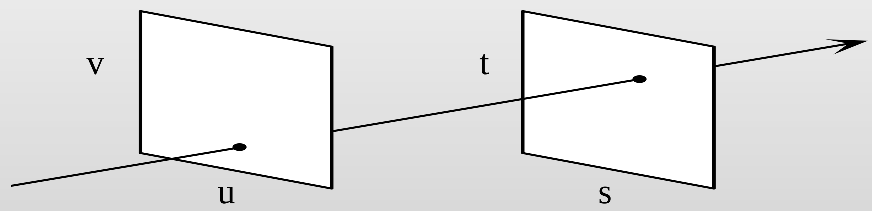


L (        ,        )

- convenient for spherical gantry
- facilitates uniform sampling



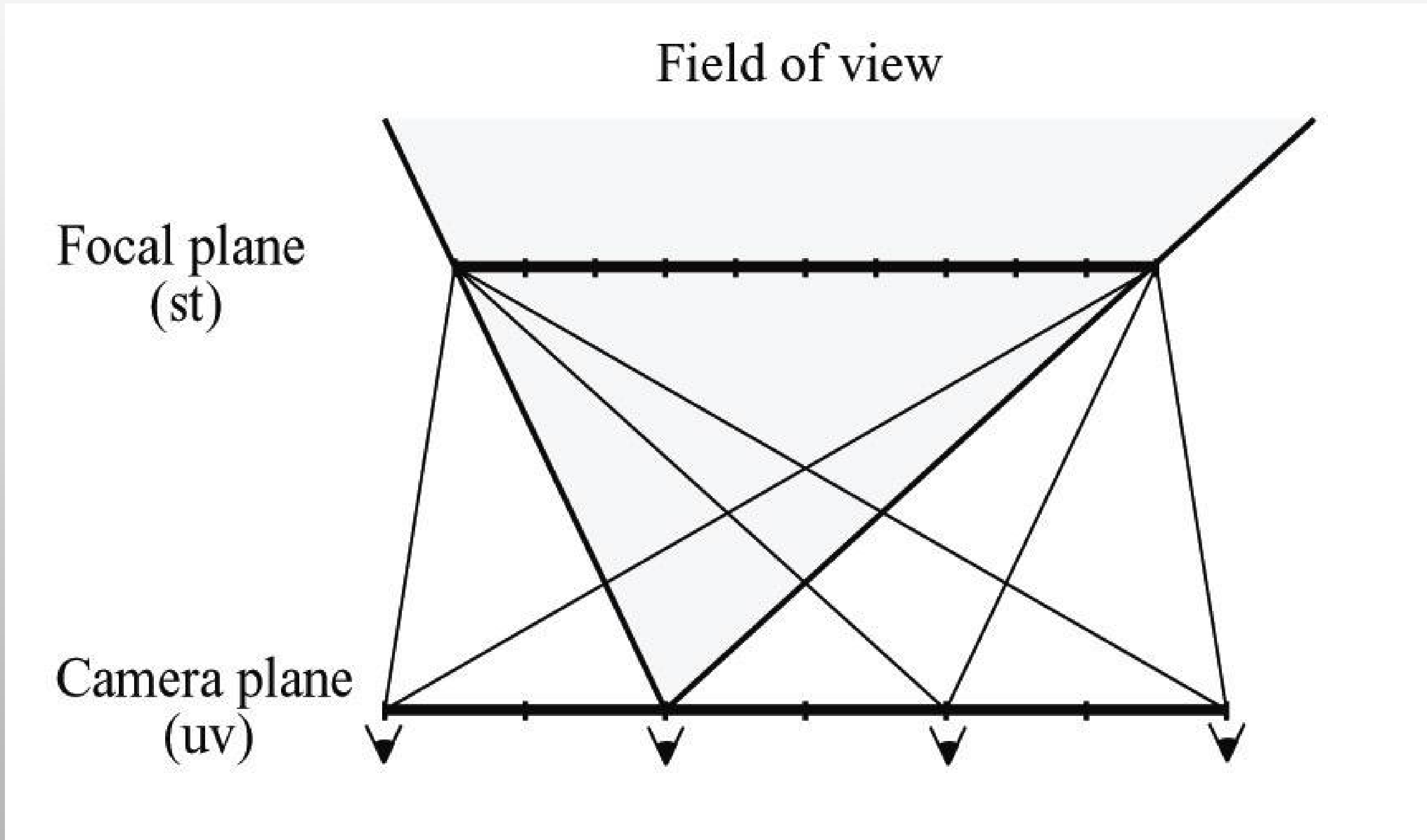
## Two planes ("light slab")




L ( u, v, s, t )

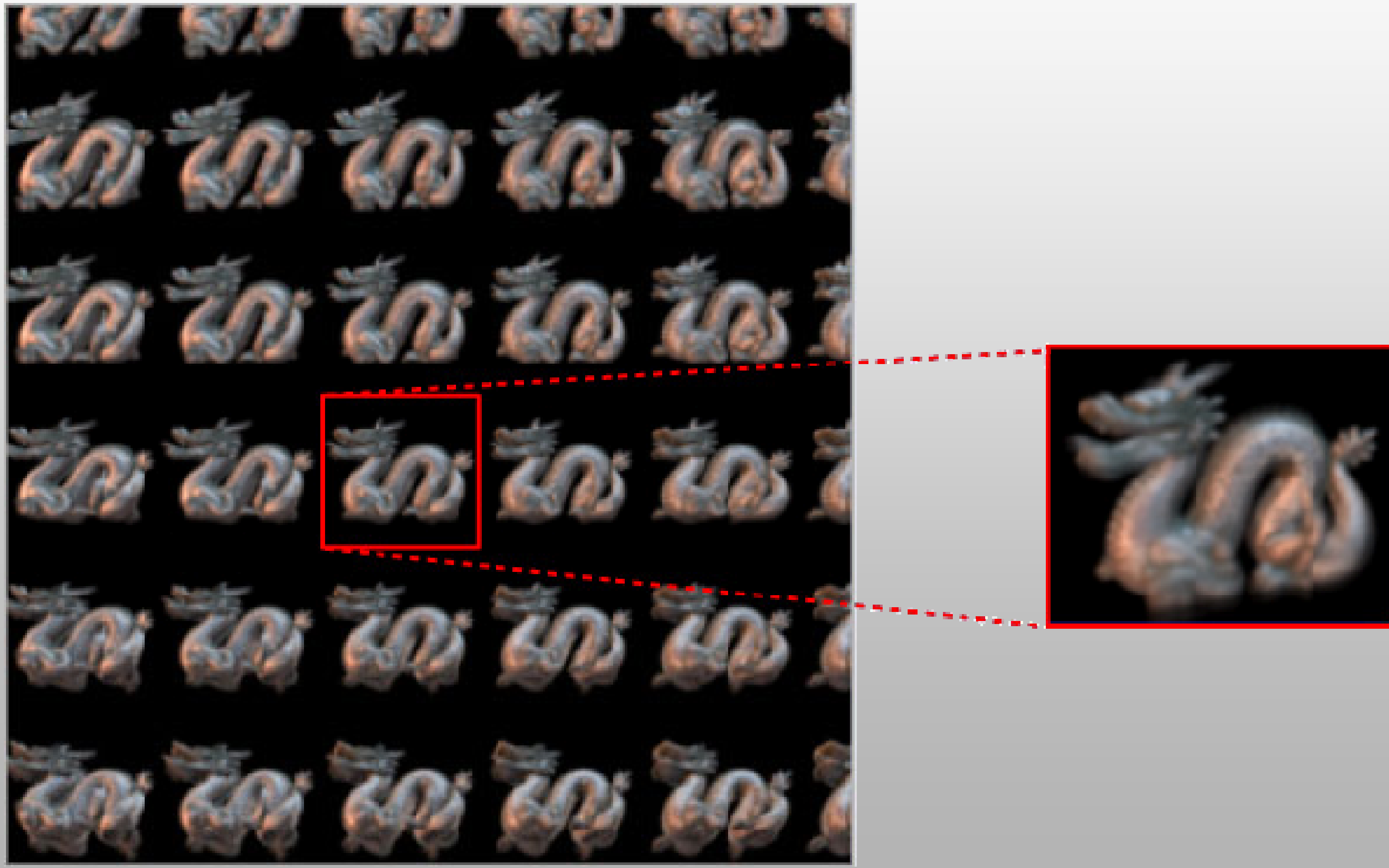
- uses projective geometry
  - fast incremental display algorithms

# Creating a light field




- off-axis (sheared) perspective views

# A light field is an array of images



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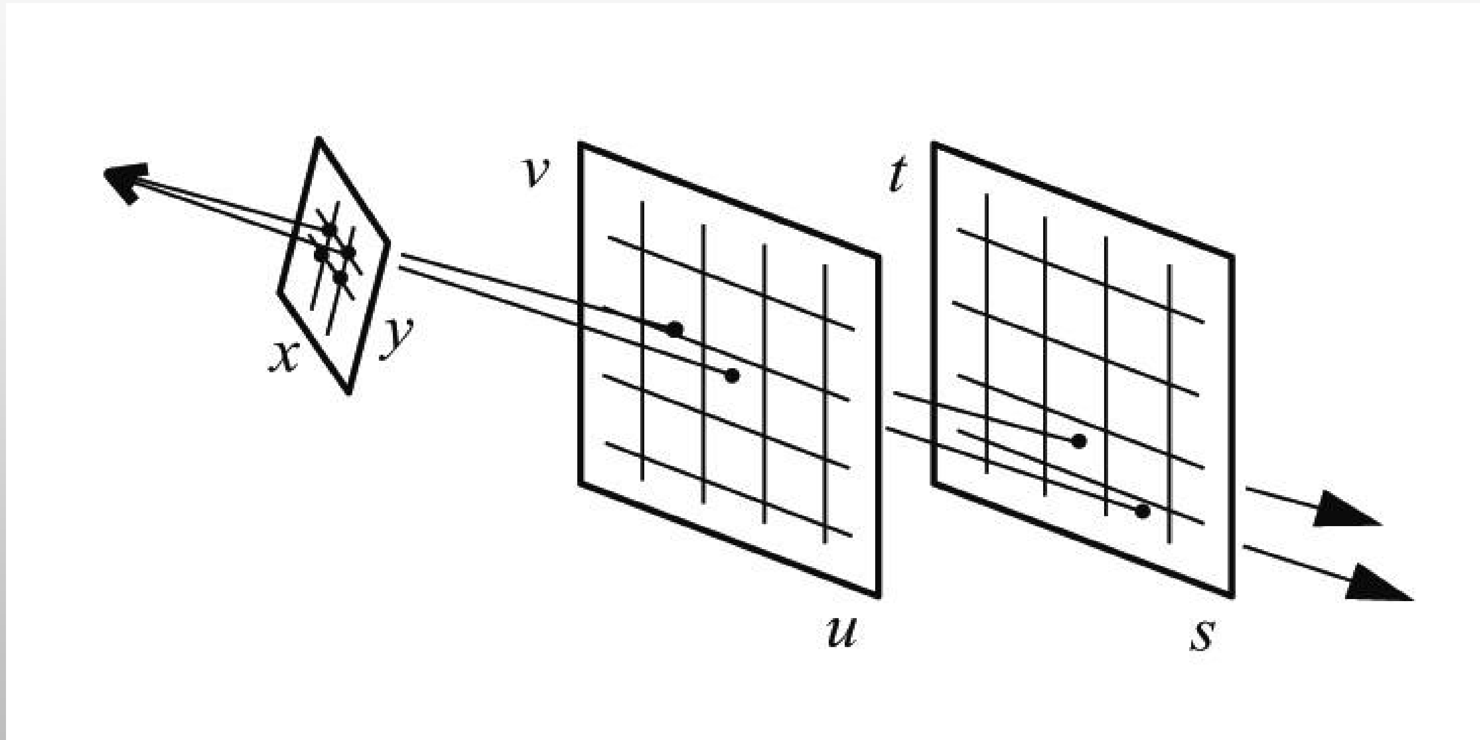
# Displaying a light field




```
foreach x,y
     compute u,v,s,t
     I(x,y) = L(u,v,s,t)
```

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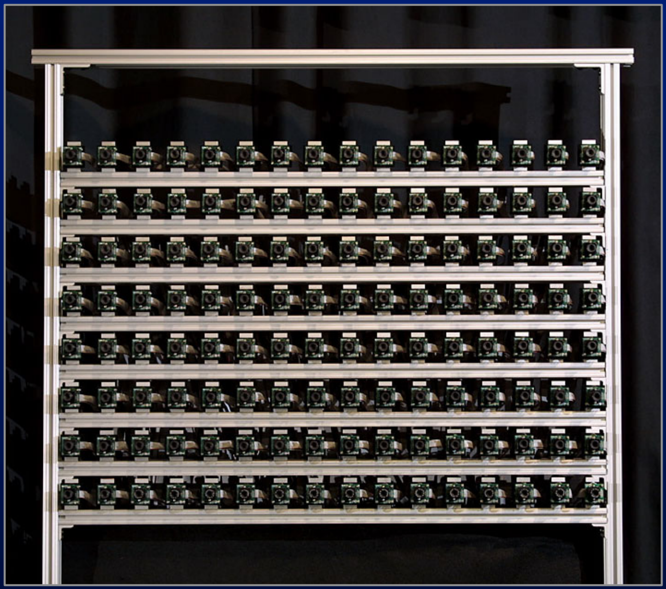
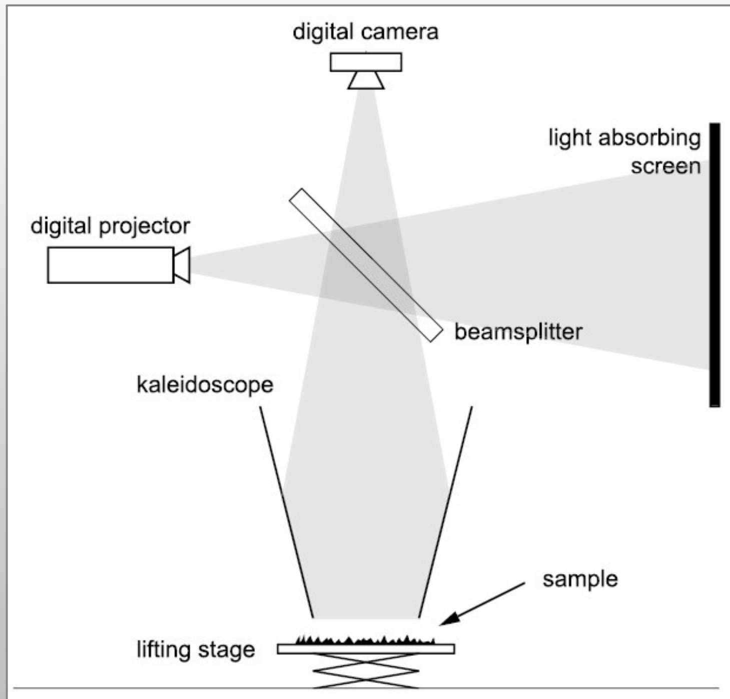
# Devices for capturing light fields: Stanford Multi-Camera Array

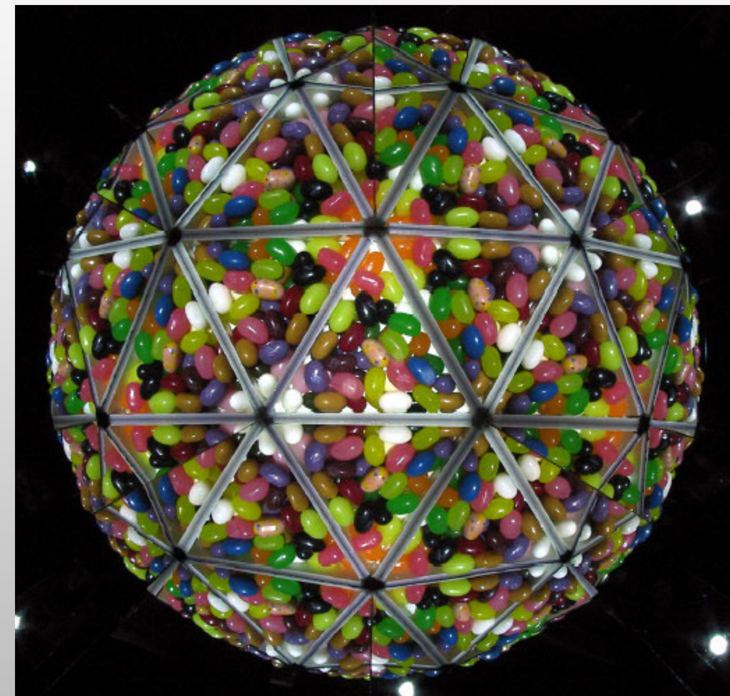


- cameras closely packed
  - high-X imaging
  - synthetic aperture photography
- cameras widely spaced
  - video light fields
  - new computer vision algorithms

# The BRDF kaleidoscope

[Han et al., SIGGRAPH 2003]

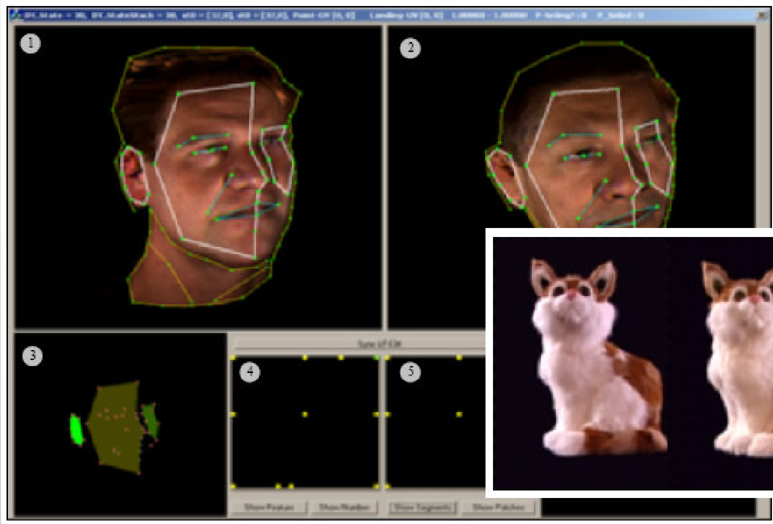


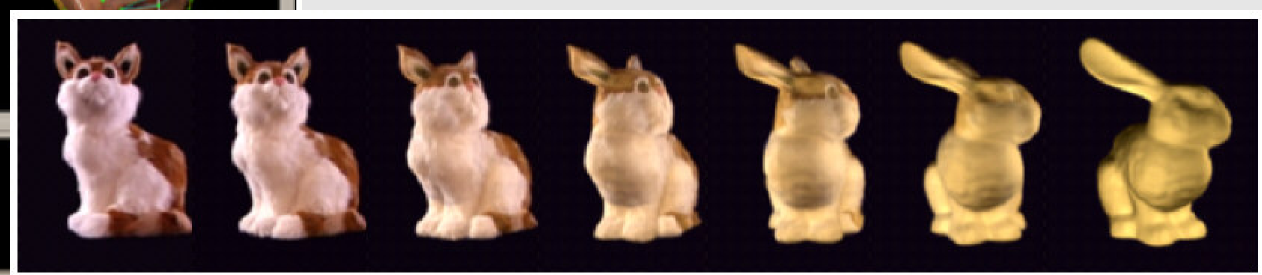



- discrete number of views
- hard to capture grazing angles
- uniformity?

# Light field morphing

[Zhang et al., SIGGRAPH 2002]





sample morph

UI for specifying feature polygons
and their correspondences

- feature correspondences = 3D model

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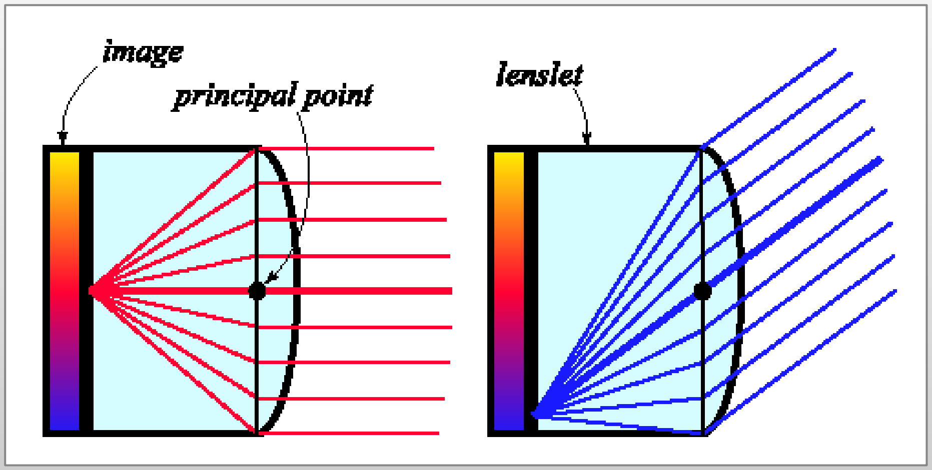
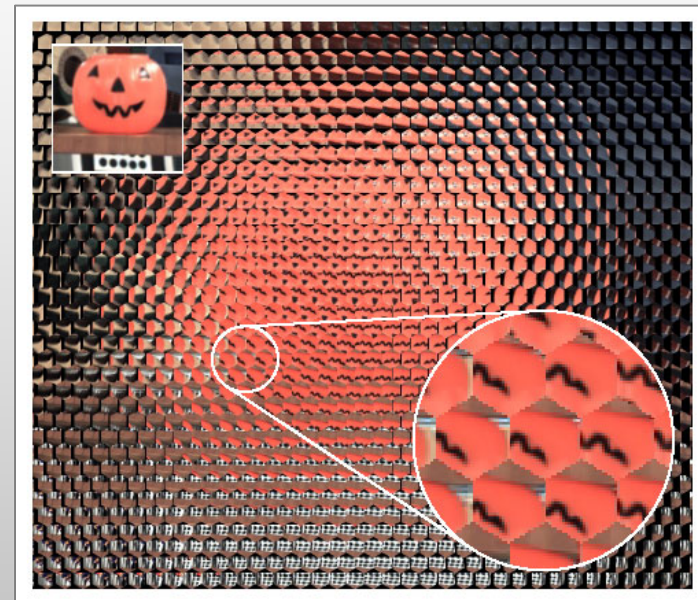
# Autostereoscopic display of light fields

[Isaksen et al., SIGGRAPH 2000]



- image is at focal distance of lenslet     collimated rays
- spatial resolution ~ # of lenslets in the array
- angular resolution ~ # of pixels behind each lenslet
- each eye sees a different sets of pixels     stereo

# End-to-end 3D television

[Matusik et al., SIGGRAPH 2005]

- 16 cameras, 16 video projectors, lenticular lens array
- spatial resolution ~ # of pixels in a camera and projector
- angular resolution ~ # of cameras and projectors
- horizontal parallax only

# Why didn’t IBR take over the world?

- warping and rendering range images is slow
  - pixel-sized triangles are inefficient
  - just as many pixels need to be touched as in normal rendering
- arms race against improvements in 3D rendering
  - level of detail (LOD)
  - culling techniques
  - hierarchical Z-buffer
  - etc.
- visual artifacts are objectionable
  - not small and homogeneous like 3D rendering artifacts