Multiview Reconstruction

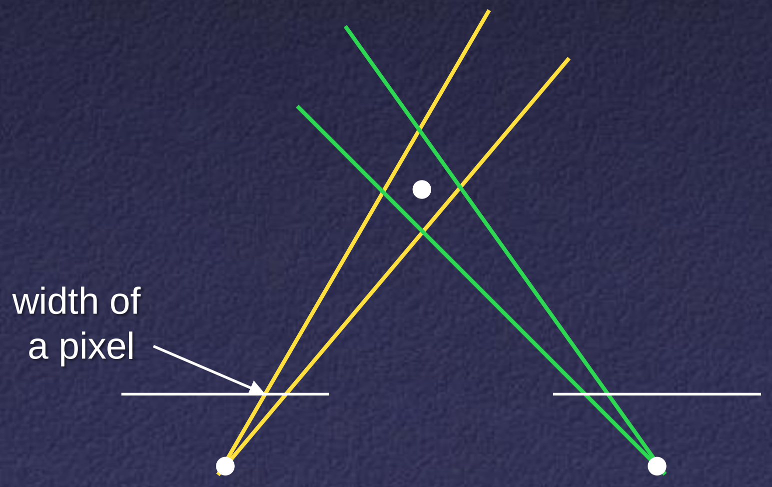
COS 429
Princeton University

Multiview Stereo

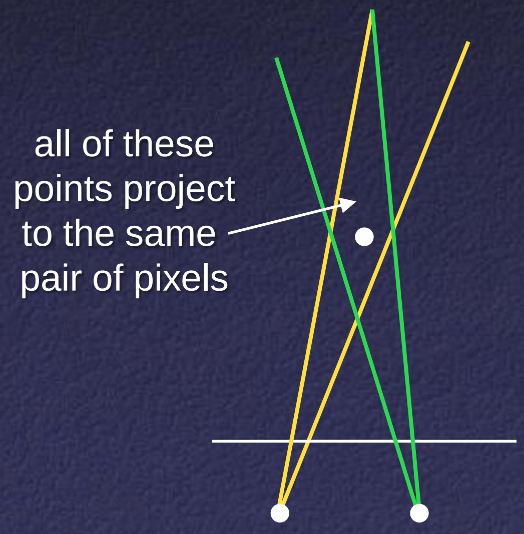
- Given multiple images of the same object or scene, compute a representation of its 3D shape

Why More Than 2 Views?

- Choosing a good baseline is hard
  - Too short – low accuracy
  - Too long – matching becomes hard



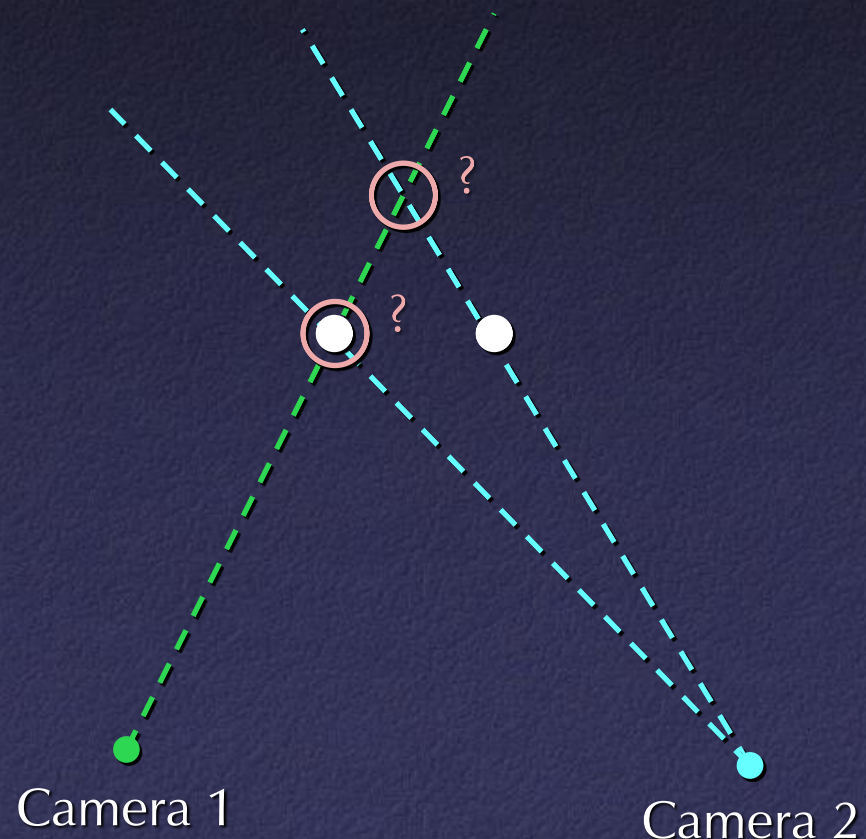
Large Baseline



Small Baseline

Why More Than 2 Views?

- Ambiguity with 2 views



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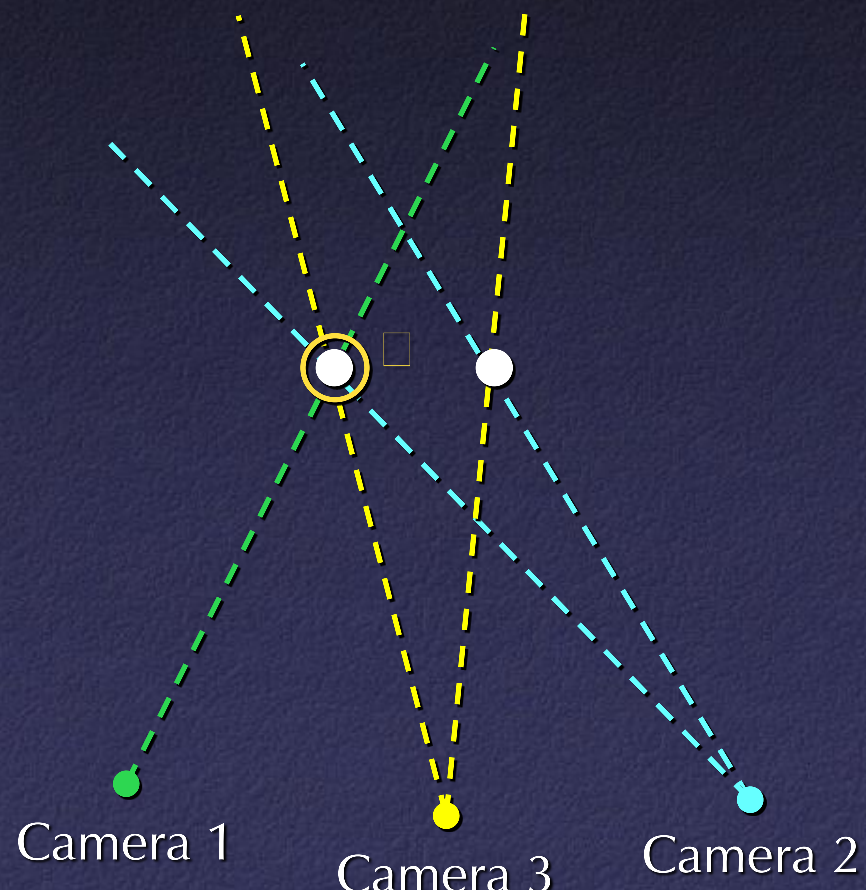

Outline

- Image-centric approaches
  - Multibaseline stereo
  - Plane-sweep stereo
- Volume-centric approaches
  - Silhouette carving
  - Voxel coloring
  - Space carving
- Surface-centric approaches
  - Feature detection + expansion/filtering
  - Mesh refinement

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Trinocular Stereo

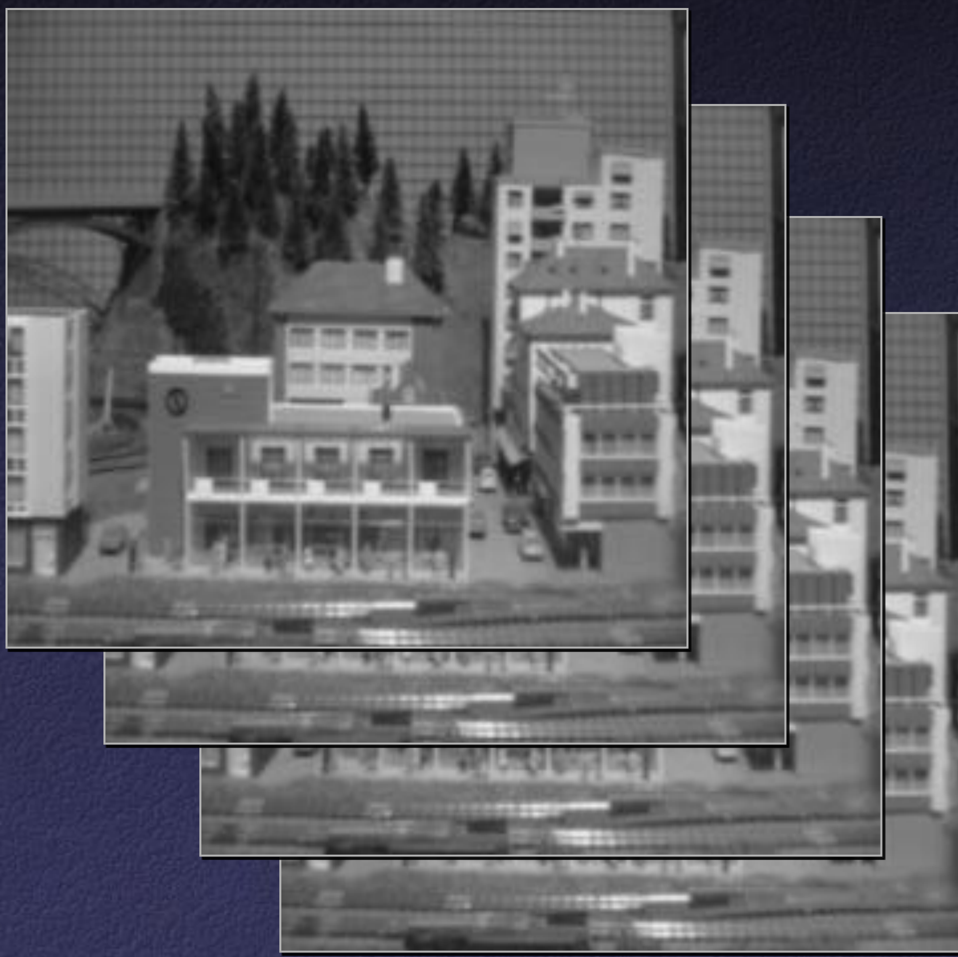
- Straightforward approach: use third view to eliminate bad correspondences
  - Pick 2 views, find correspondences
  - For each matching pair, reconstruct 3D point
  - Project point into 3^{rd} image
  - If can't find correspondence near predicted location, reject

Multibaseline Stereo

More generally, for N views …

- Pick one reference view
- For each candidate depth
  - Compute sum of squared differences to all other views, assuming correct disparity for view
- Resolves ambiguities: only correct depths will "constructively interfere"

Multibaseline Stereo



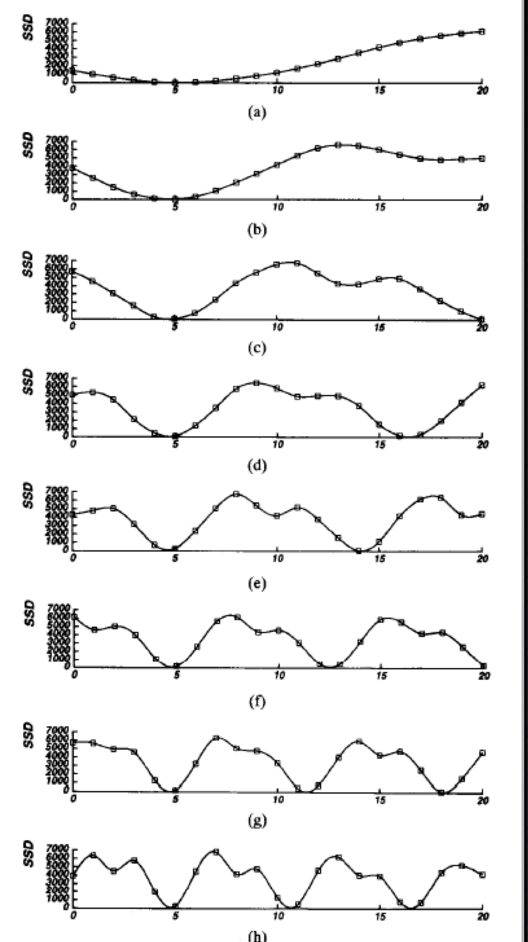
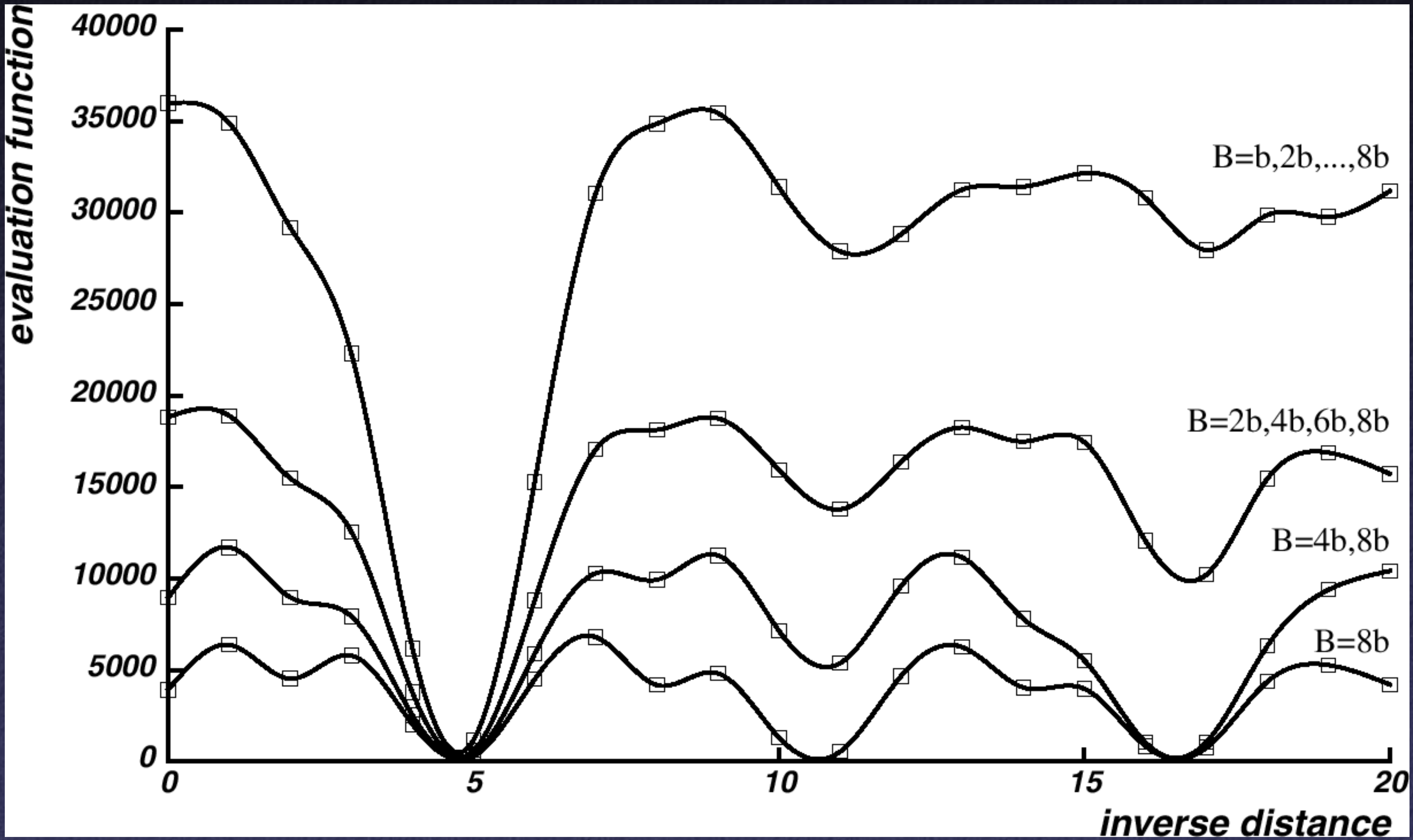


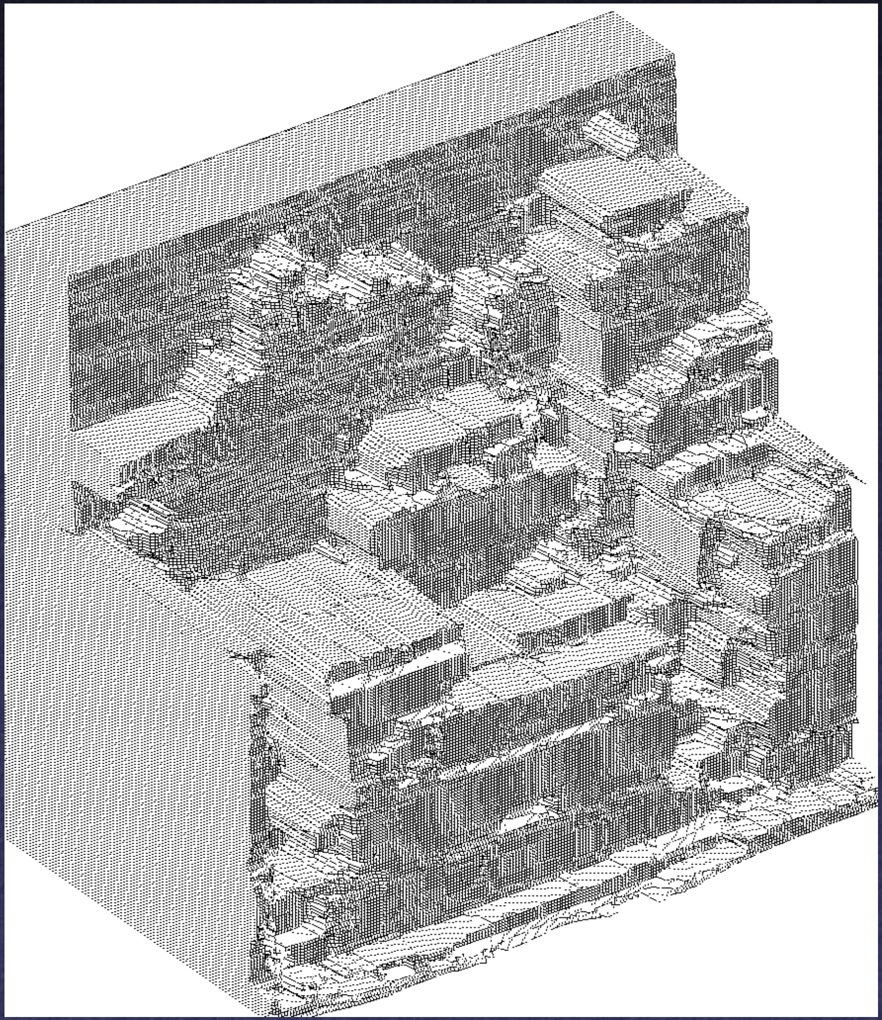
Fig. 5. SSD values versus inverse distance: (a) $B = b$; (b) $B = 2b$; (c) $B = 3b$; (d) $B = 4b$; (e) $B = 5b$; (f) $B = 6b$; (g) $B = 7b$; (h) $B = 8b$. The horizontal axis is normalized such that $8bF = 1$.

Multibaseline Stereo

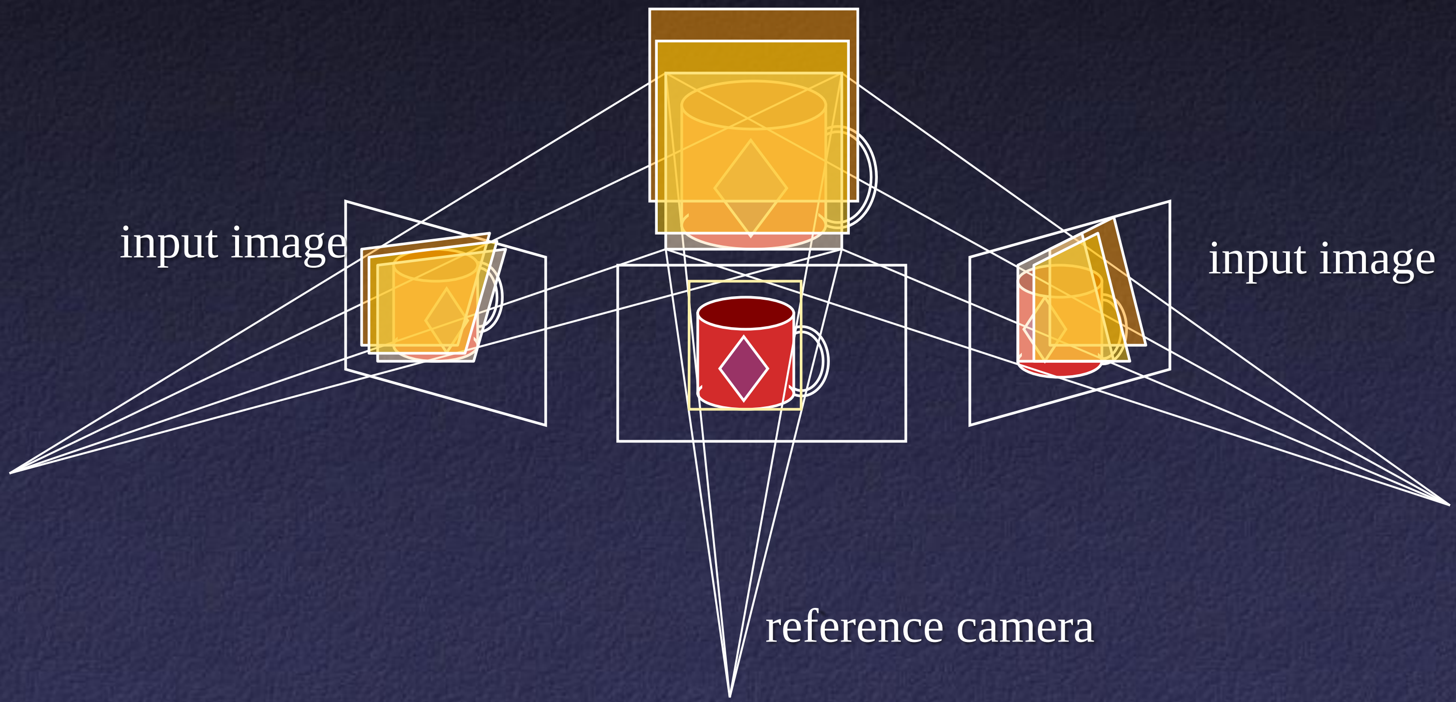


[Okutami & Kanade]

Multibaseline Stereo Results



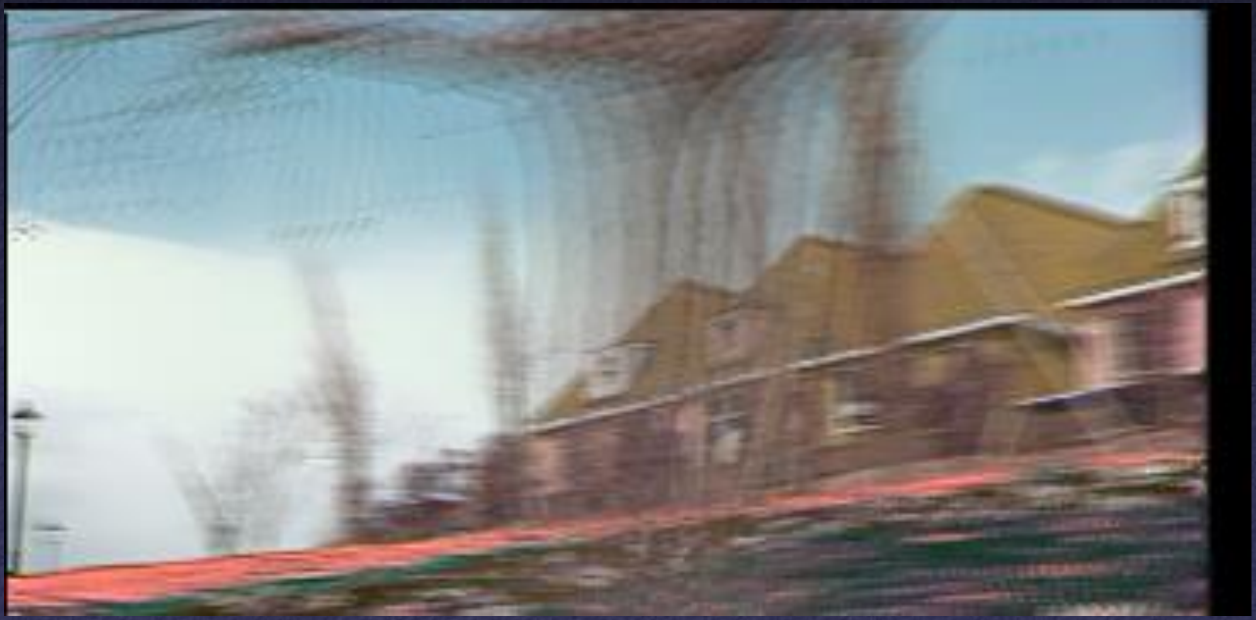
Plane Sweep Stereo



Each plane defines a homography warping each input image into the reference view

Plane Sweep Stereo

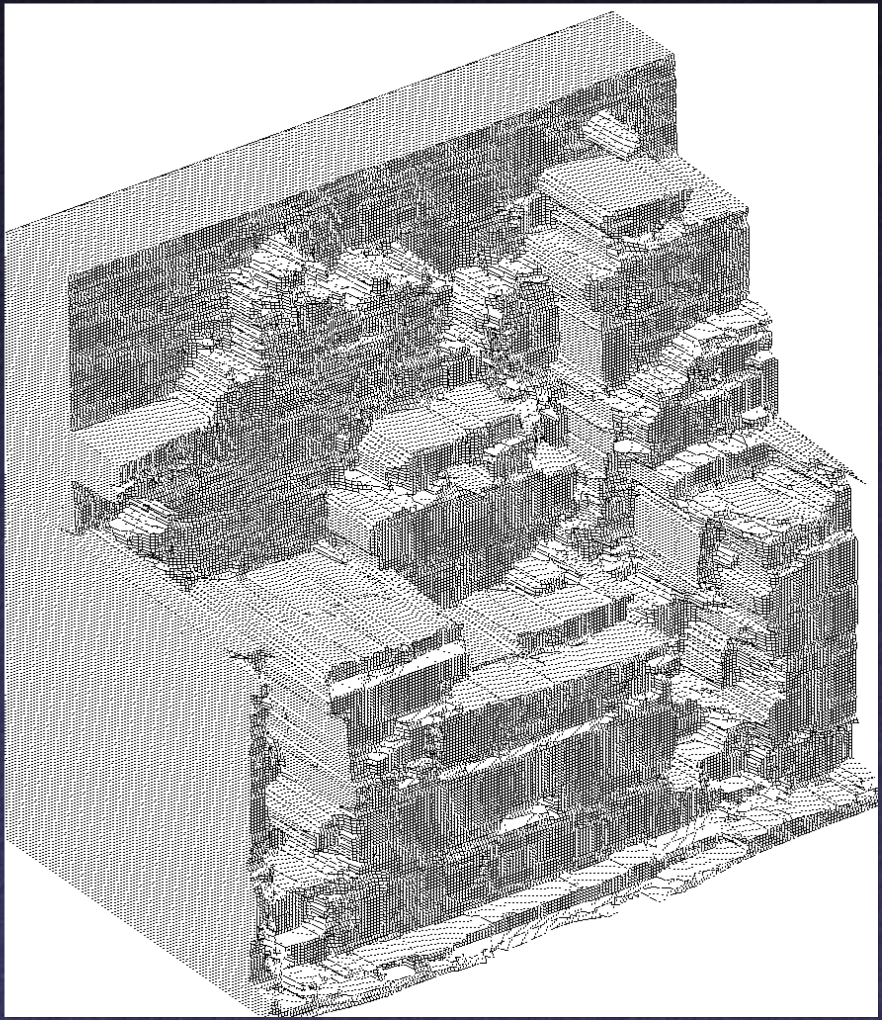
For each pixel, select the depth that gives the lowest variance



Problems with these approaches

- Limited types of 3D surfaces
  - Have to pick a reference view
- No consideration for visibility
  - With many cameras / large baseline, occlusion becomes likely
  - Contributes incorrect values to error function

Reference View Problem

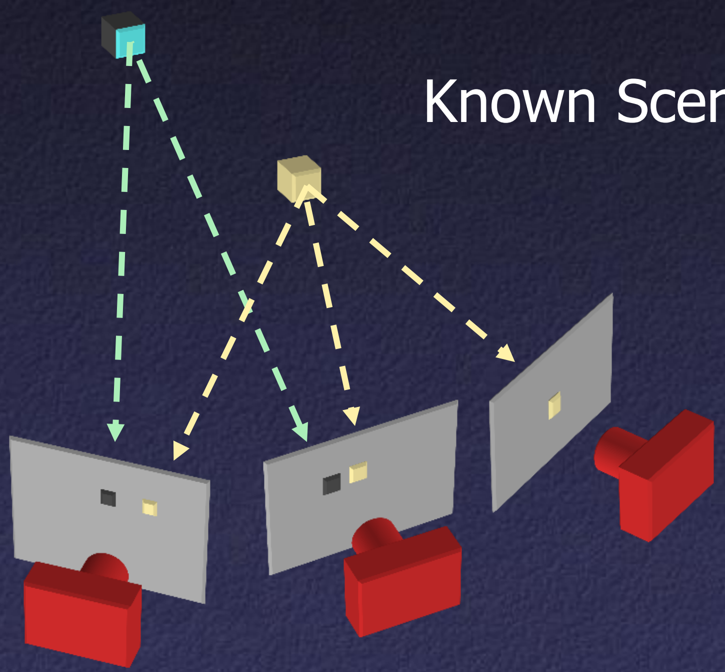


Visibility Problem

Which scene points are seen in which images

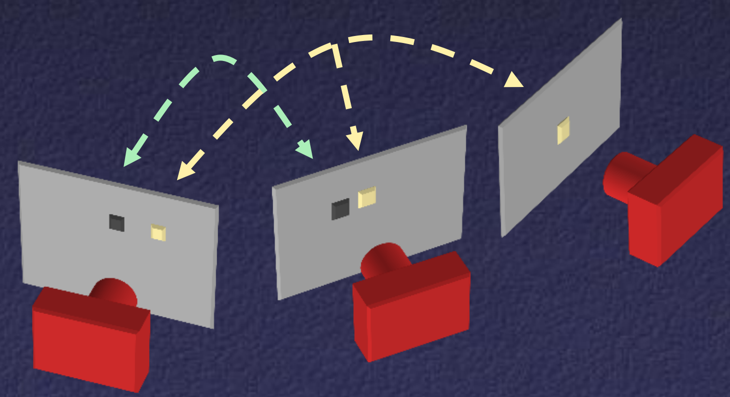
Known Scene

Unknown Scene



Forward Visibility

known scene



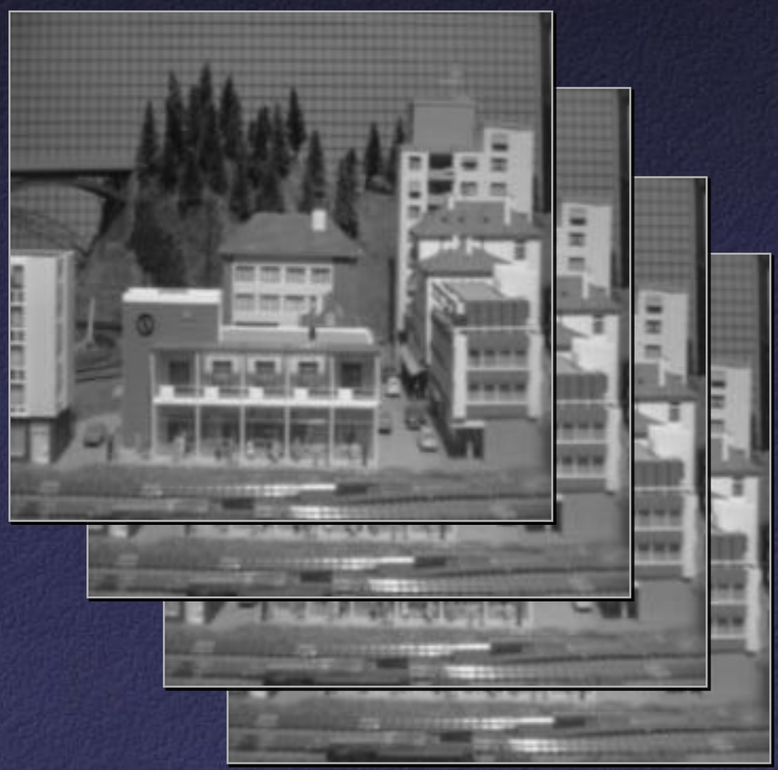
Inverse Visibility

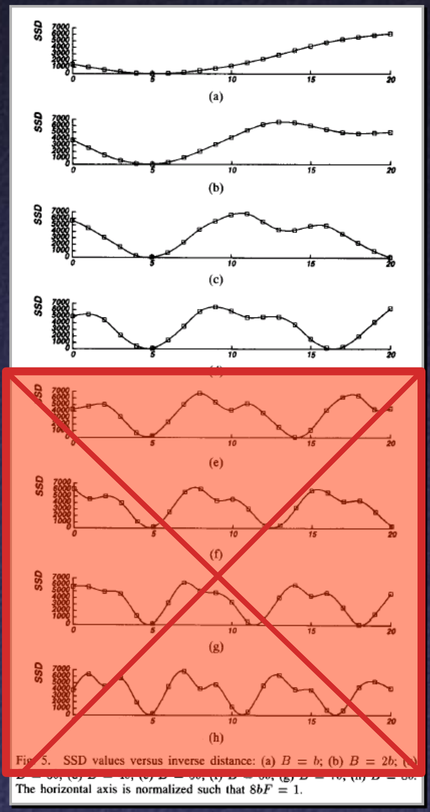
known images

Snavely

Visibility Problem

For larger baselines, occlusion is common





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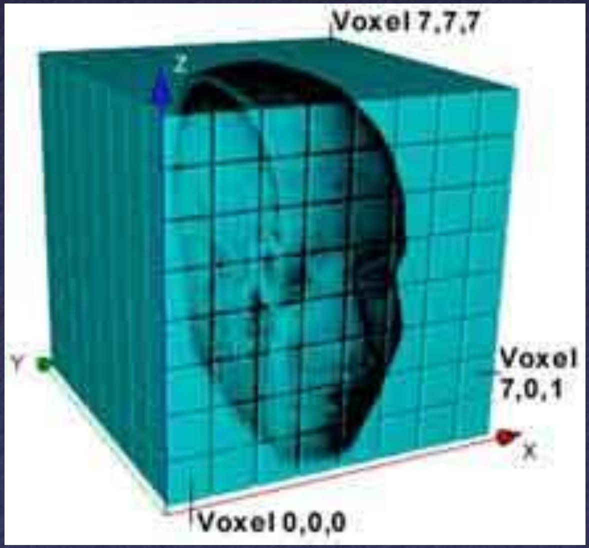
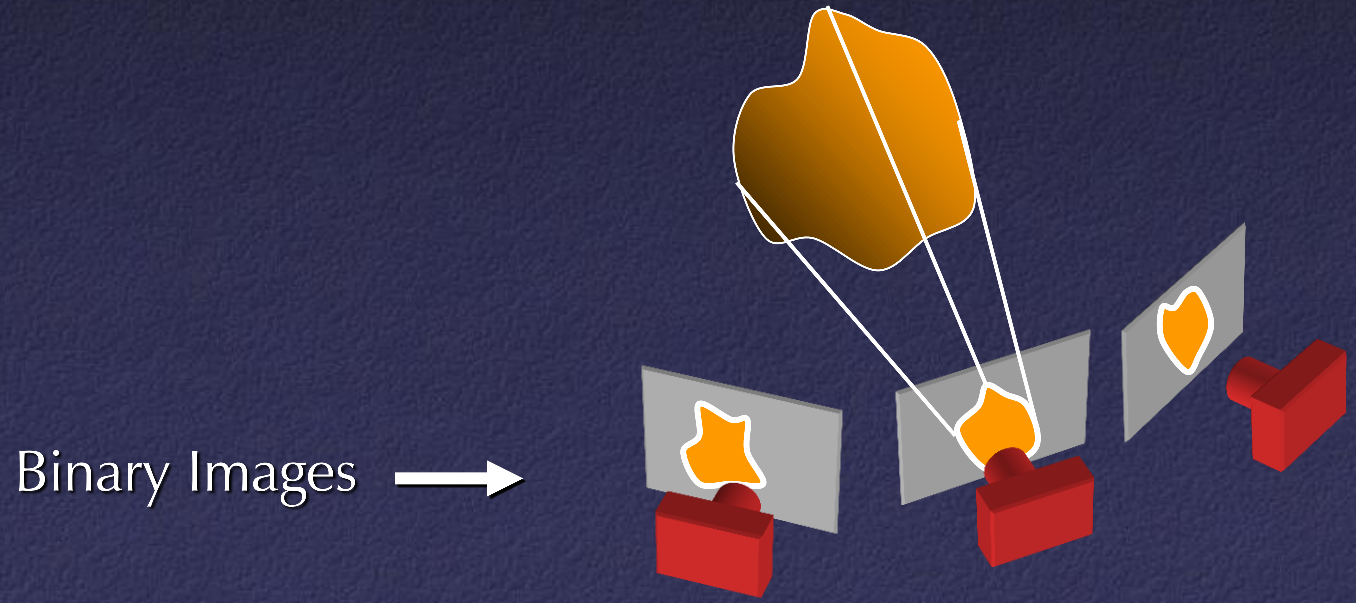
Volume-Centric Multiview Approaches

- Compute photoconsistency at 3D points
- Typically use discretized volume (voxel grid)
- For each voxel, predict whether 3D point is on surface, or inside/outside object



Silhouette Carving

- Find silhouettes in all images
- Exact version:
  - Back-project all silhouettes, find intersection



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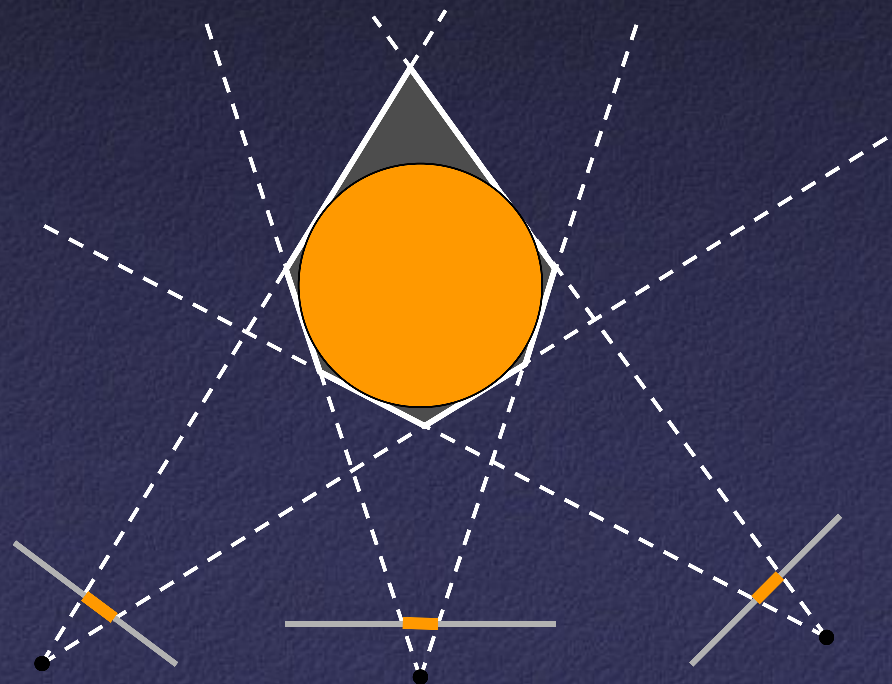
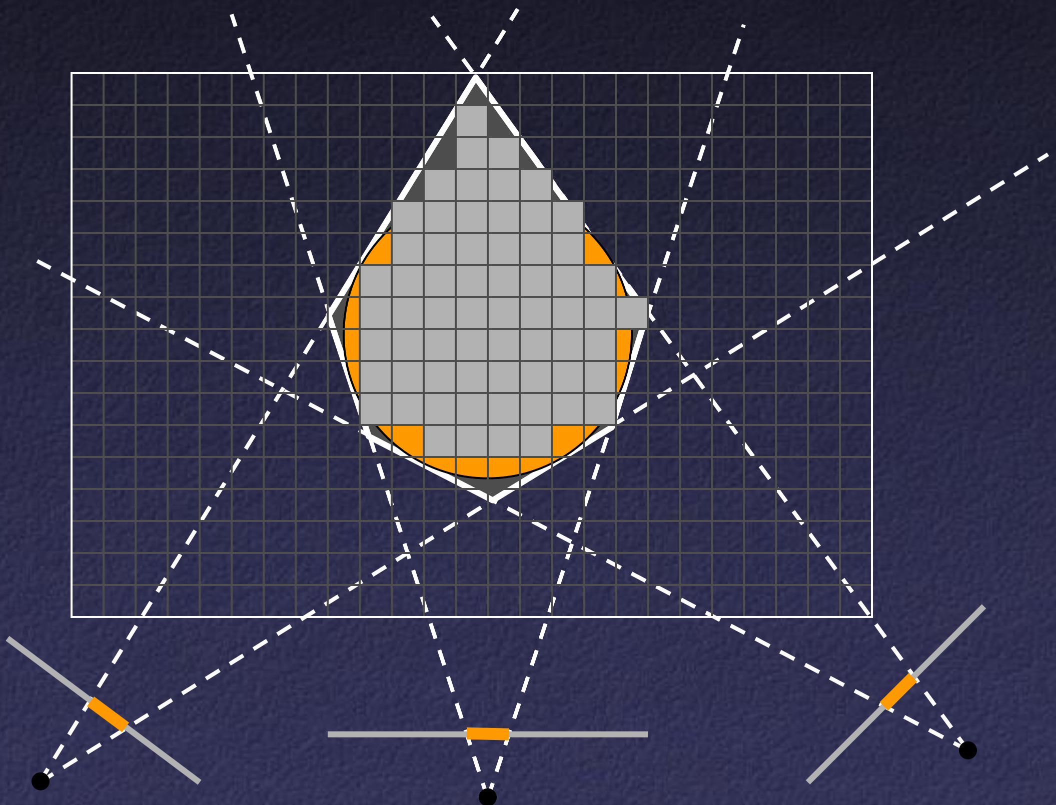


Silhouette Carving

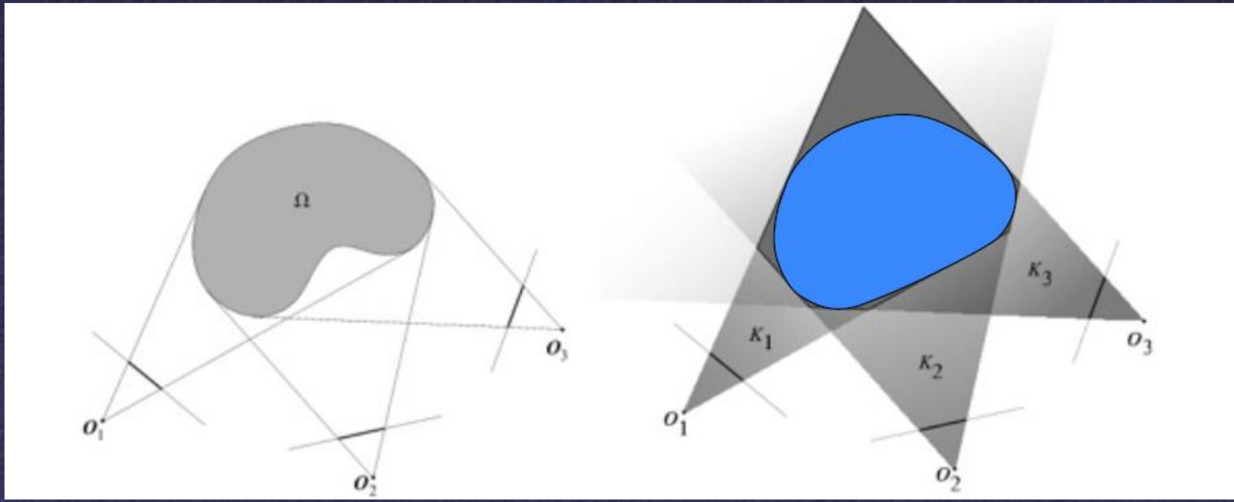
- Discrete version:
  - Loop over all voxels in some volume
  - If projection into images lies inside all silhouettes, mark as occupied
  - Else mark as free

Silhouette Carving



Silhouette Carving

- Limit of silhouette carving is *visual hull*
- In general not the same as object
  - Can't recover "pits" in object
- Not the same as convex hull



Silhouette Carving

- The visual hull is a good starting point for better algorithms (that consider photo-consistency)
  - Easy to compute
  - Tight outer boundary of the object
  - Parts of the visual hull (rims) already lie on the surface and are already photo-consistent

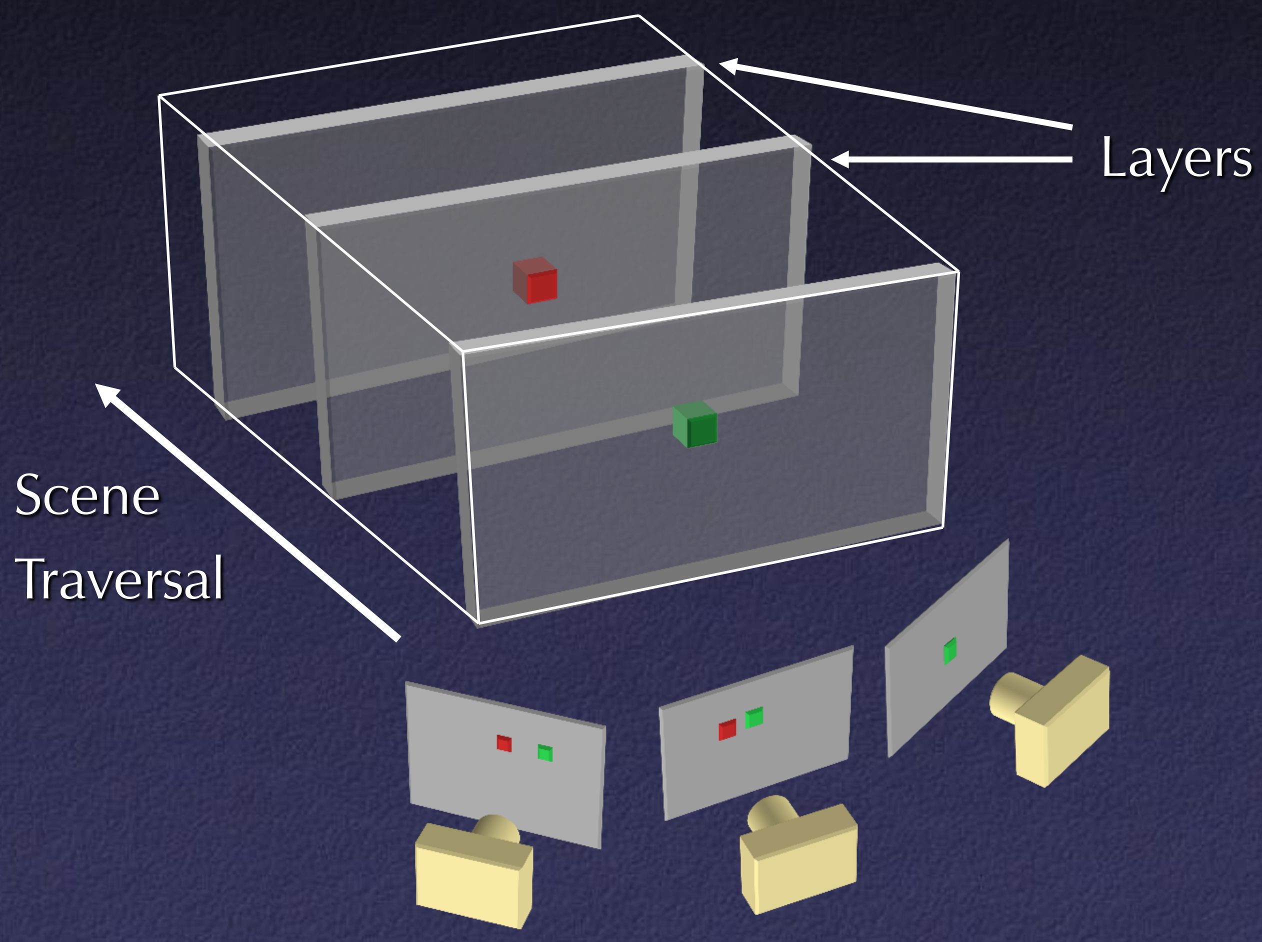
Voxel Coloring

- Basic idea:
  - Project each voxel into each image in which it is visible
  - If colors in images agree, mark voxel with color
  - Else, mark voxel as empty
- Agreement of colors based on comparing standard deviation of colors to threshold

Voxel Coloring and Occlusion

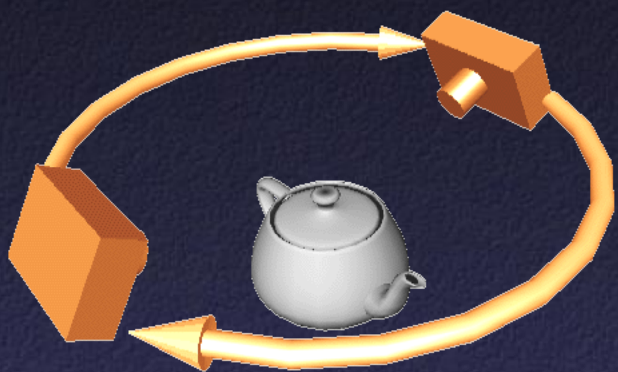
- Problem: which voxels are visible?
- Solution, part 1: constrain camera views
  - When a voxel is considered, necessary occlusion information must be available
  - Sweep occluders before occludees
  - Constrain camera positions to allow this sweep

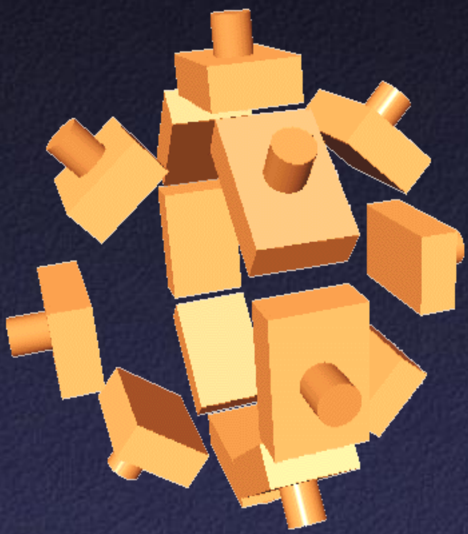
Voxel Coloring Sweep Order



Seitz

Voxel Coloring Camera Positions





Inward-looking
Cameras above scene

Outward-looking
Cameras inside scene

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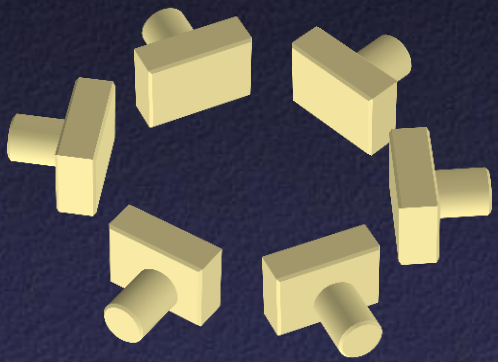
Panoramic Depth Ordering



- Cameras oriented in many different directions
- Planar depth ordering does not apply

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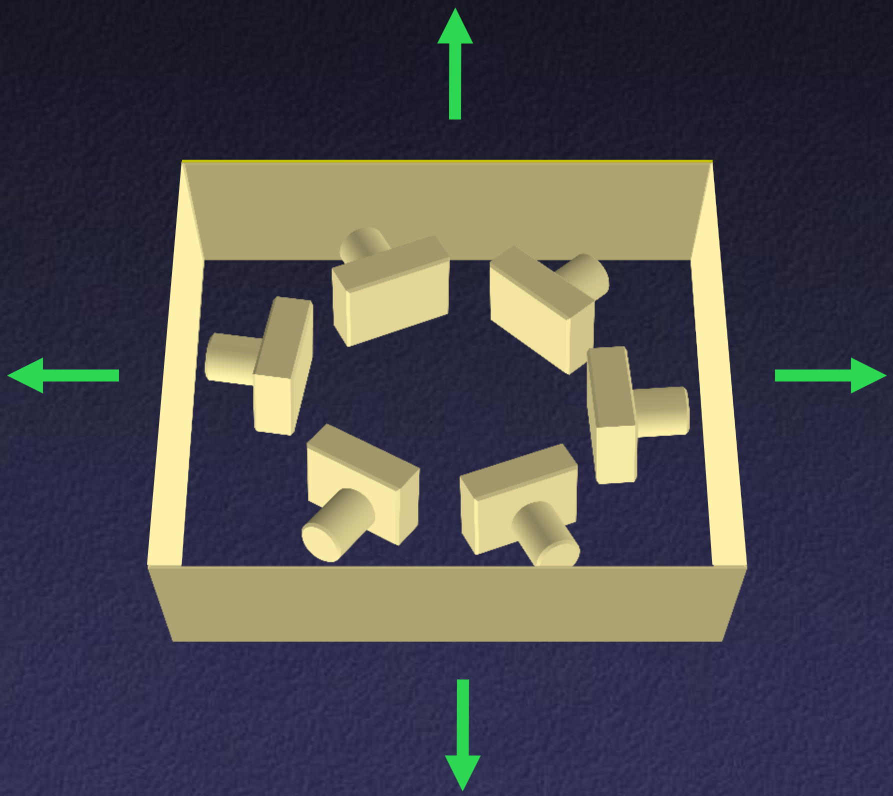
Panoramic Depth Ordering



Layers radiate outwards from cameras

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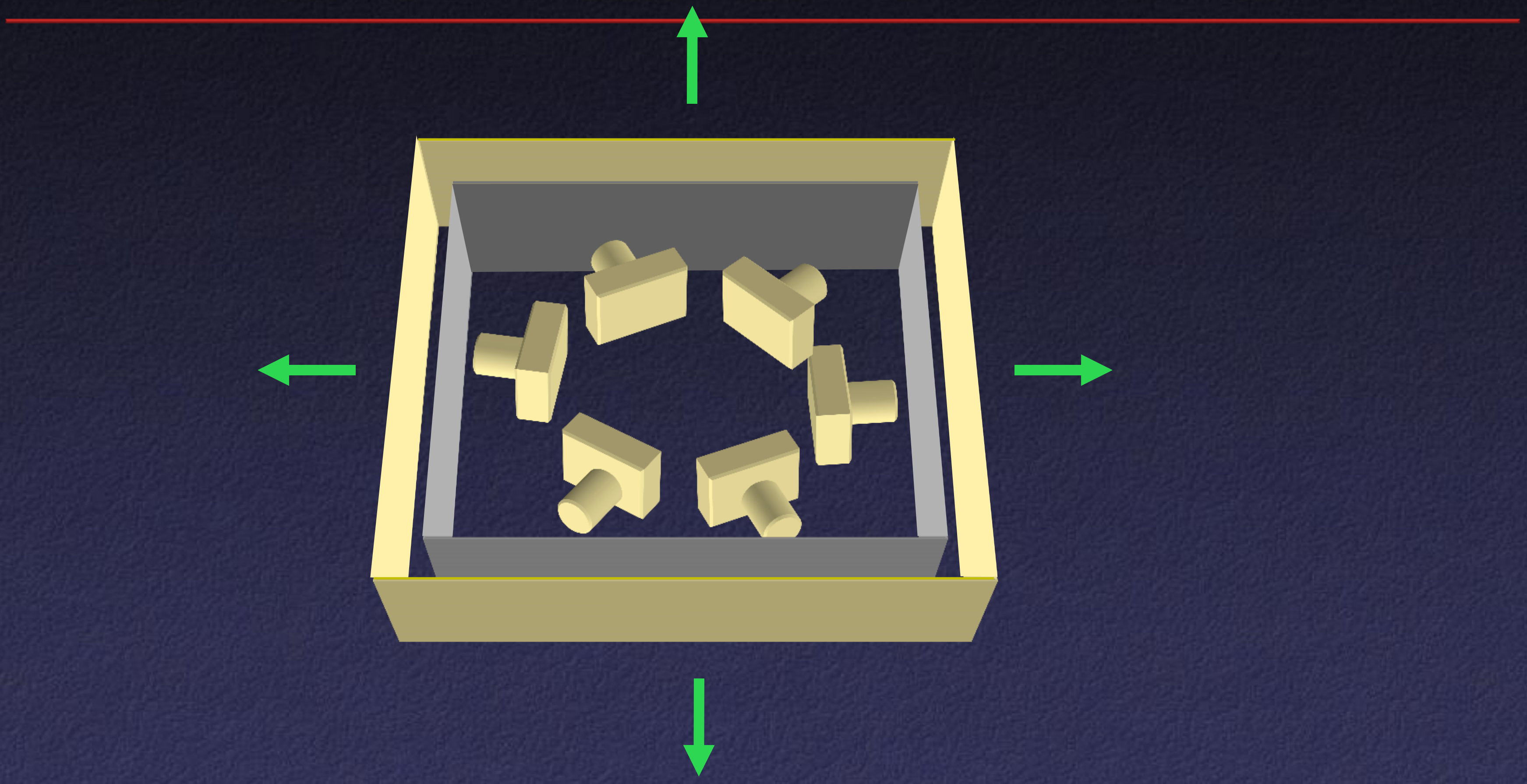

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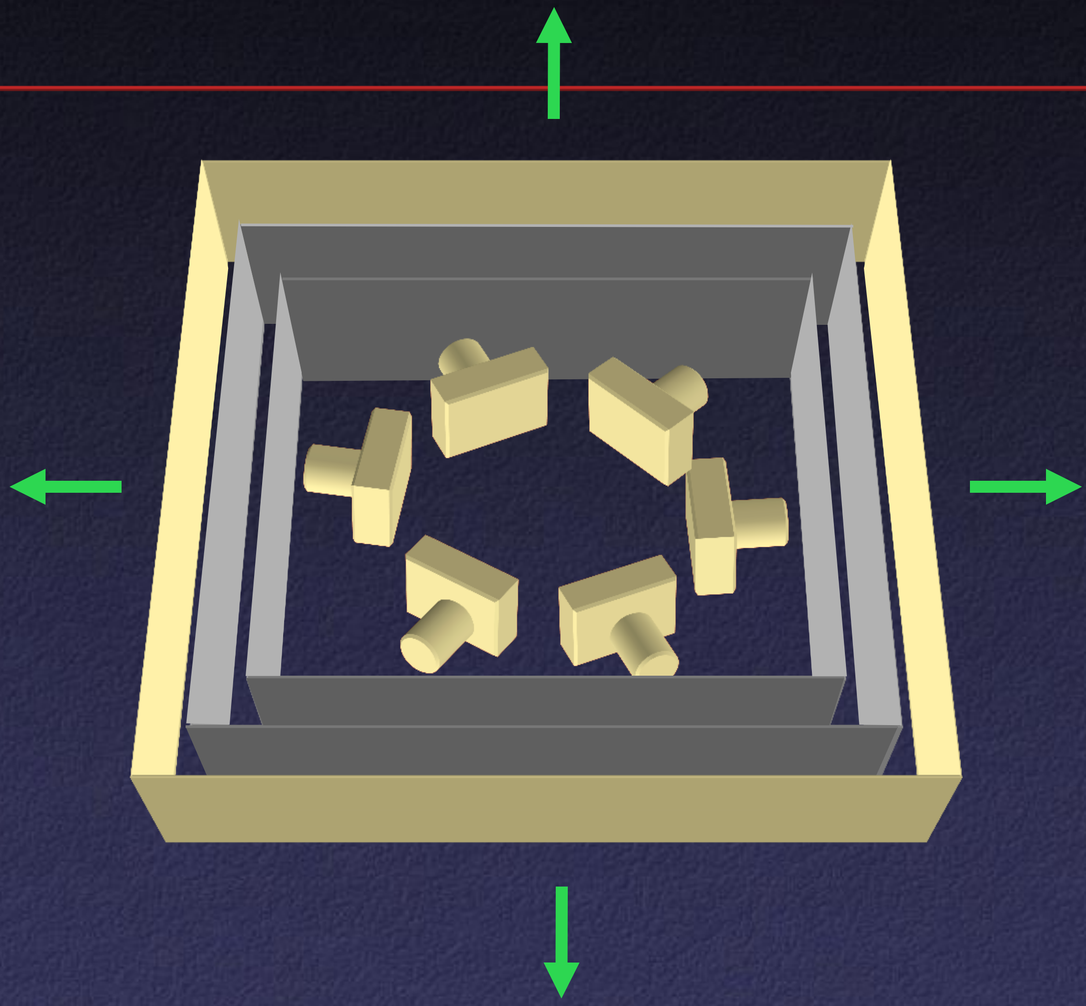

Layers radiate outwards from cameras

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Voxel Coloring and Occlusion

- Solution, part 2: per-image mask of which pixels have been used
  - Each pixel only used once
  - Mask filled in as sweep progresses

Voxel Coloring Results


Selected Dinosaur Images


Selected Flower Images

- Calibrated Turntable
- 360° rotation (21 images)

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Voxel Coloring Results

Dinosaur Reconstruction
72 K voxels colored
7.6 M voxels tested
7 min. to compute
on a 250MHz SGI

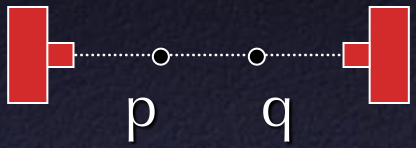
Flower Reconstruction
70 K voxels colored
7.6 M voxels tested
7 min. to compute
on a 250MHz SGI

Seitz

Voxel Coloring Results

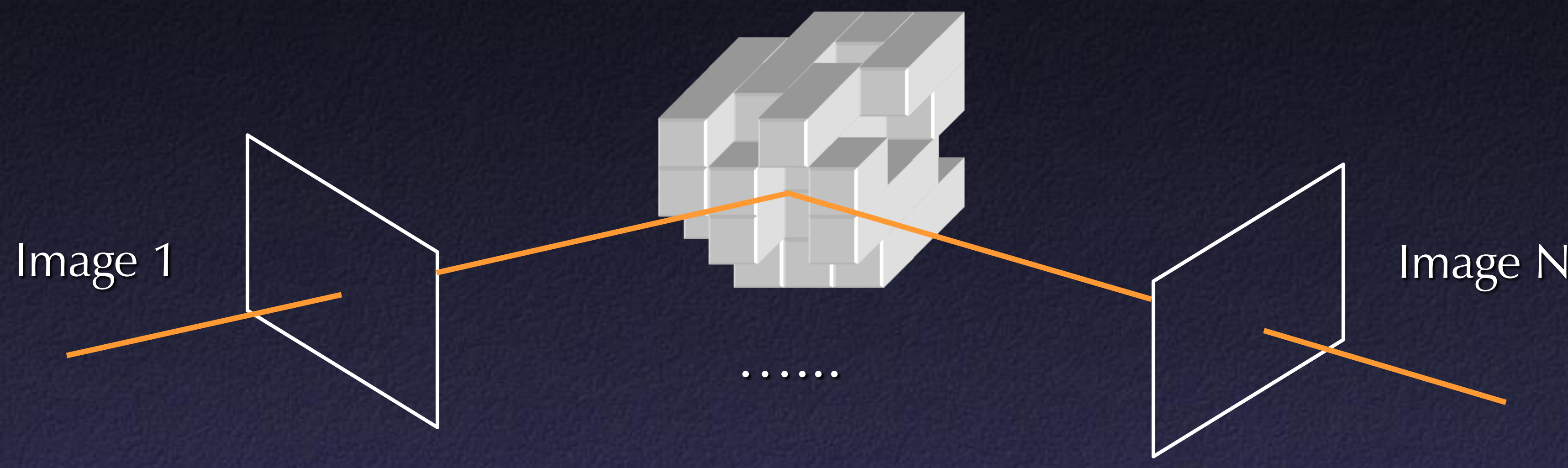
- With texture: good results
- Without texture: regions tend to “bulge out”
  - Voxels colored at earliest time at which projection into images is consistent
  - Model good for re-rendering: image will look correct for viewpoints near the original ones

Limitations of Voxel Coloring



- A view-independent depth order may not exist
- Need more powerful general-case algorithms
  - Unconstrained camera positions
  - Unconstrained scene geometry/topology

Space Carving



Initialize to a volume V containing the true scene
Choose a voxel on the current surface
Project to visible input images
Carve if not photo-consistent
Repeat until convergence

Kutulakos & Seitz

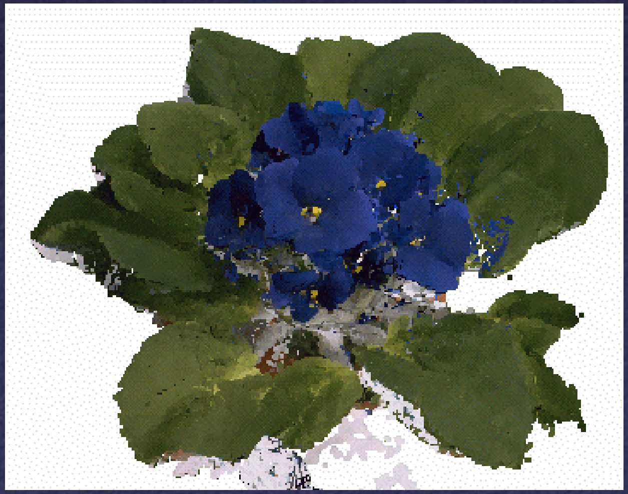
Multi-Pass Plane Sweep

- Faster alternative:
  - Sweep plane in each of 6 principal directions
  - Consider cameras on only one side of plane
  - Repeat until convergence

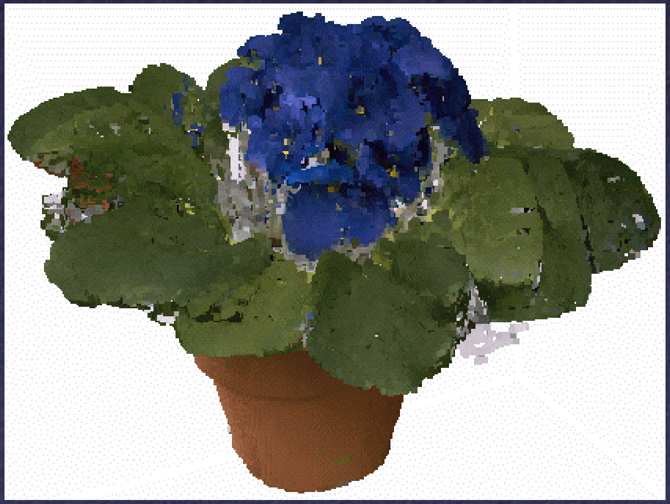
Space Carving Results: African Violet

Input Image (1 of 45)

Reconstruction



Reconstruction



Reconstruction

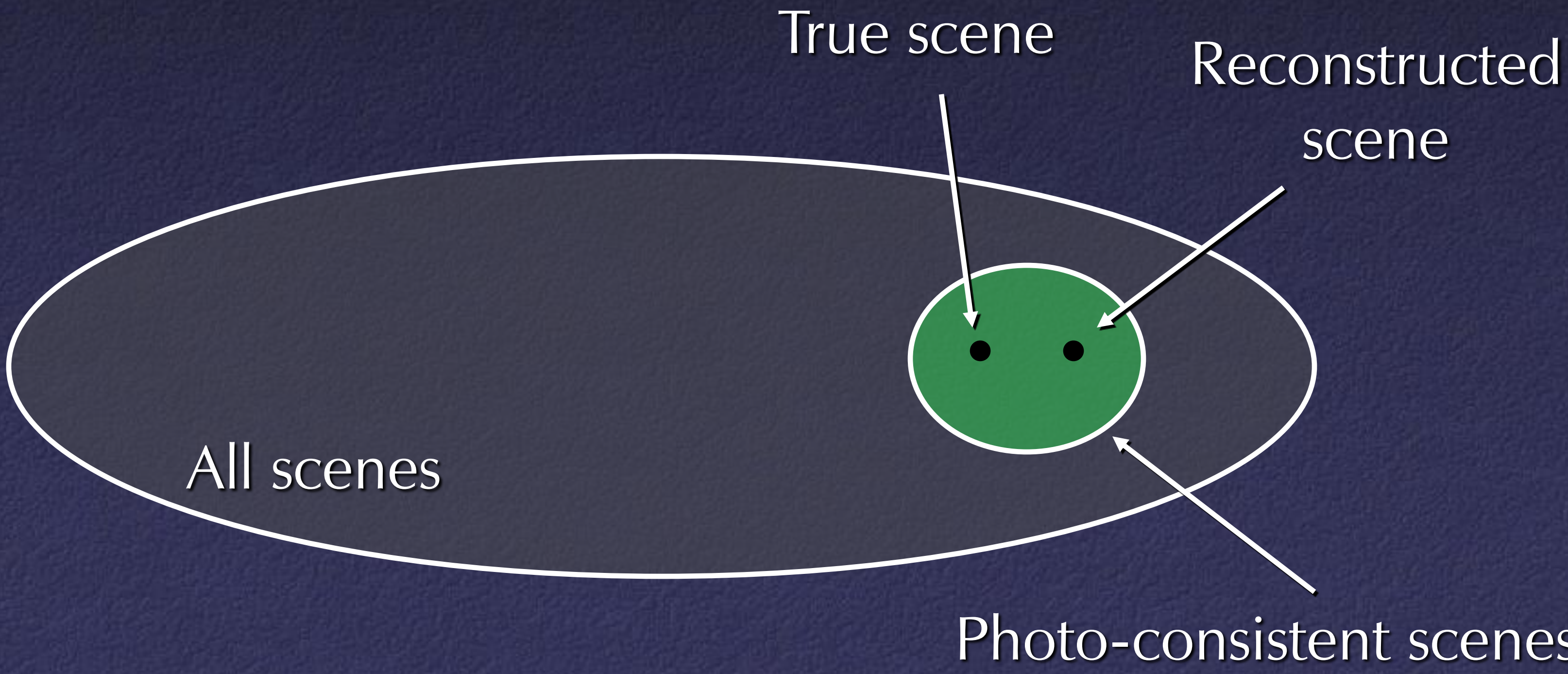
Space Carving Results: Hand

Input Image
(1 of 100)

Views of Reconstruction

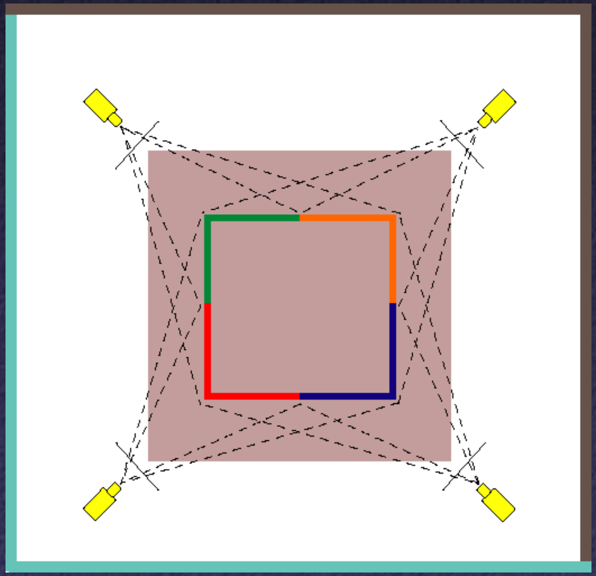
Caveat

- Result: not necessarily correct scene
- Many scenes may be photoconsistent with the input images



Caveat

Photo-consistency vs. silhouette-consistency



True Scene

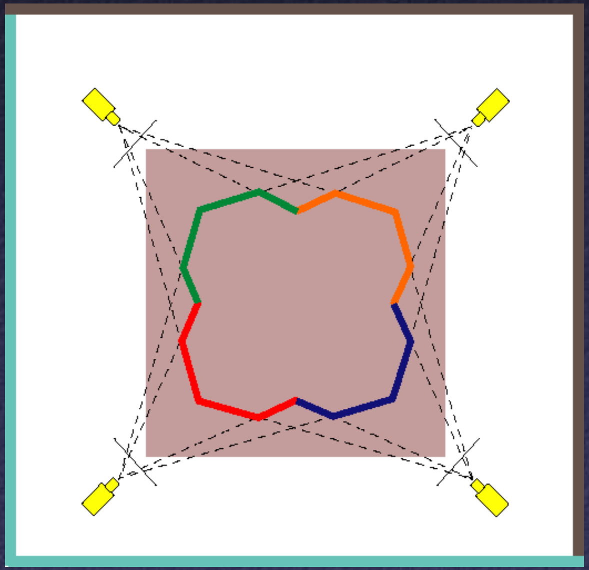
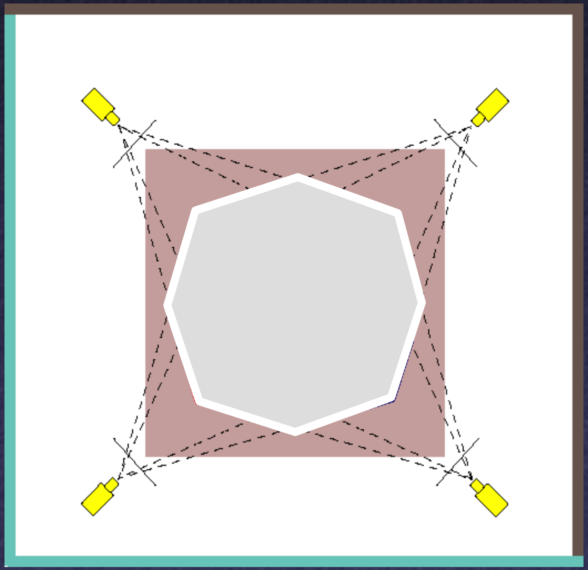


Photo Hull



Visual Hull

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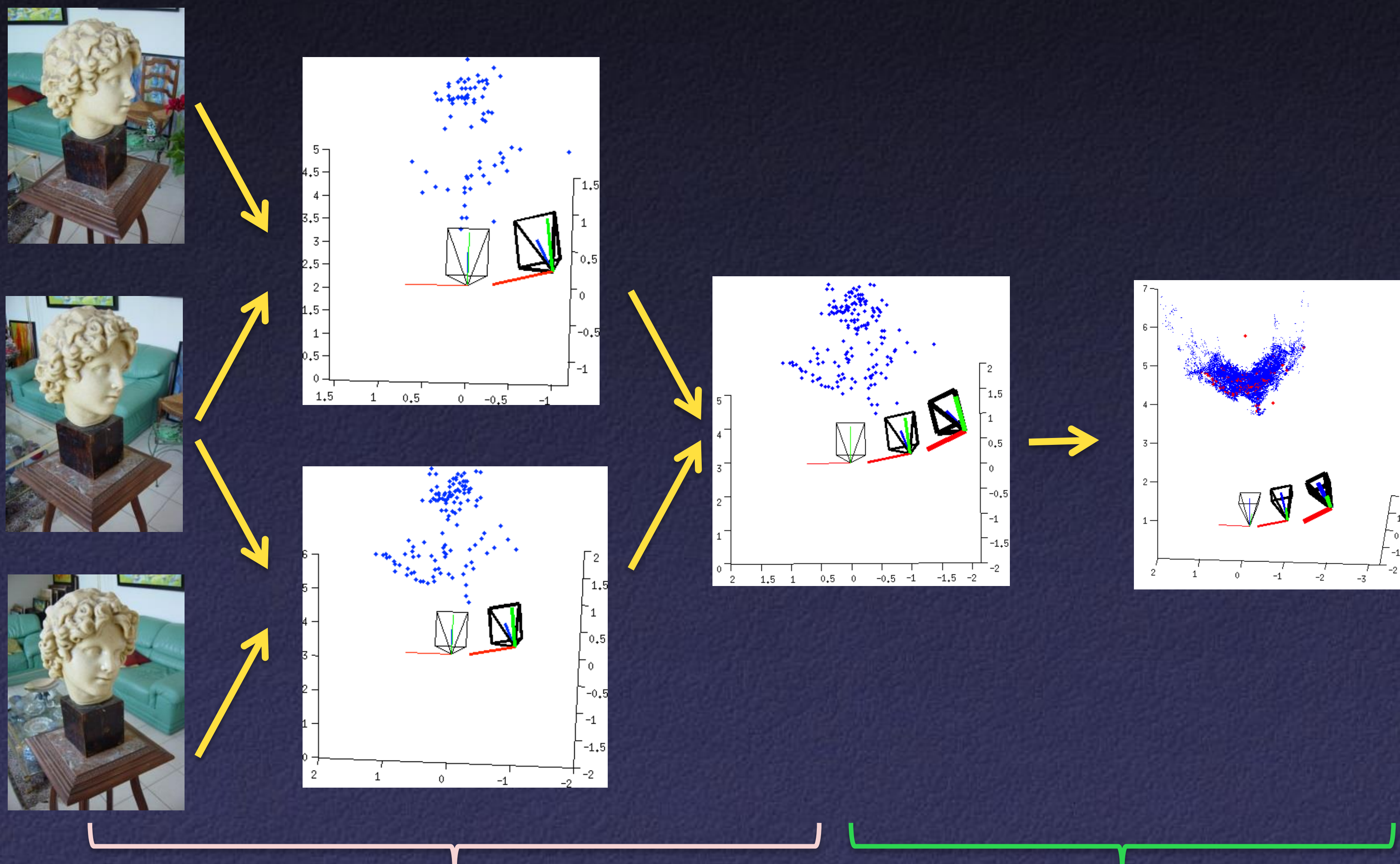
Patch-Based Approaches



Structure from Motion (SFM) Multi-view Stereo (MVS)

Patch-Based Approaches

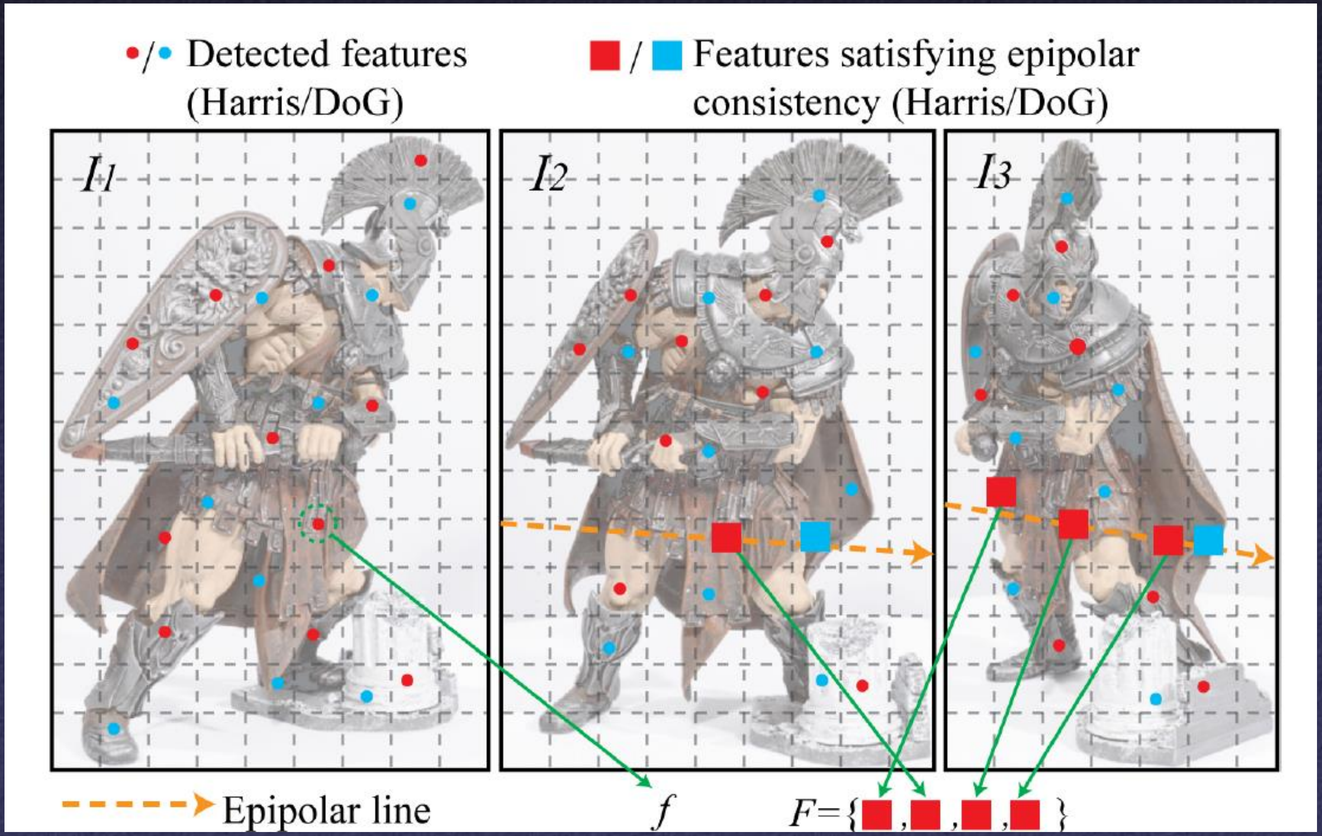
Detect feature correspondences, and then expand/filter based on consistency in other views

One Input Features Correspondences Expansion Final Surface

Furukawa

Patch-Based Approaches

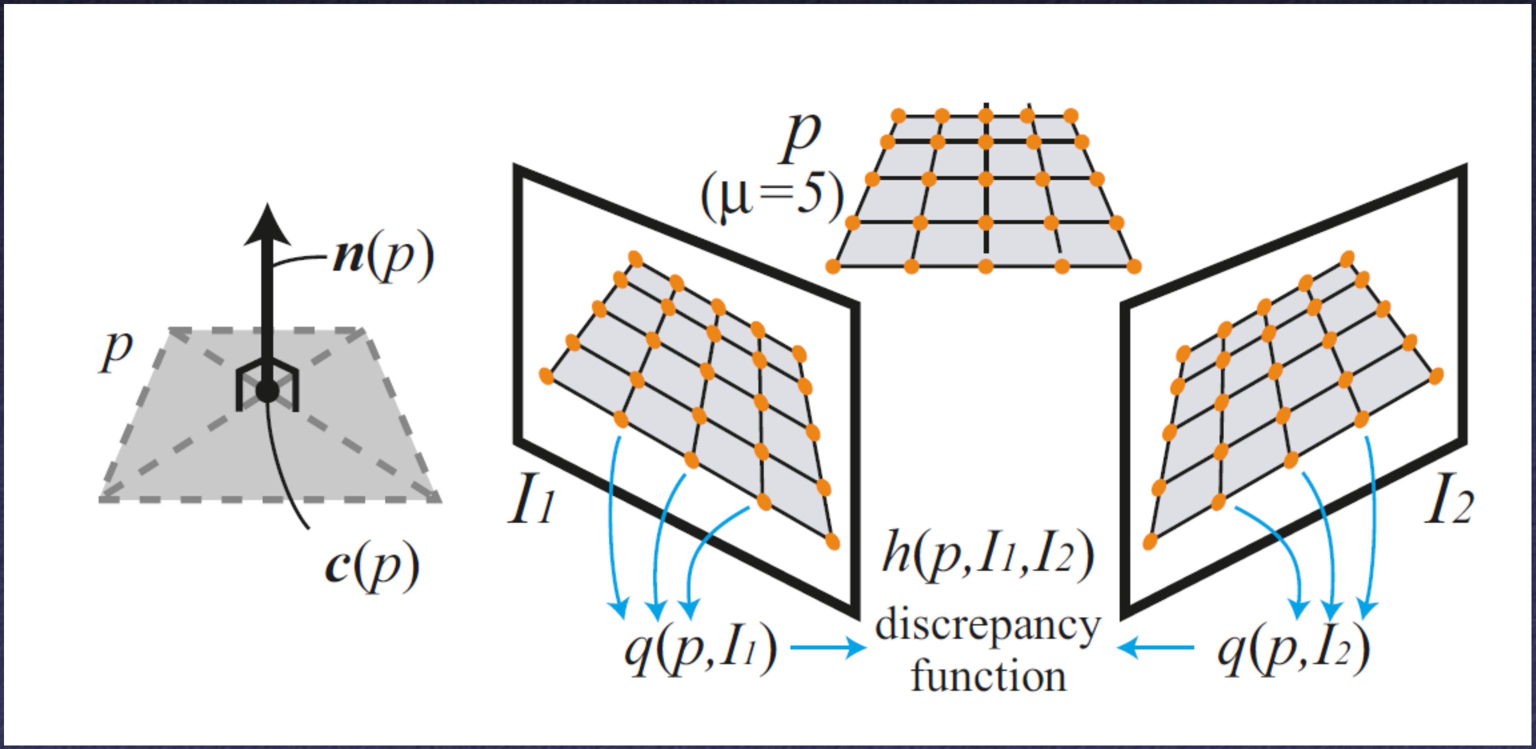
1) Detect feature correspondences



Furukawa

Patch-Based Approaches

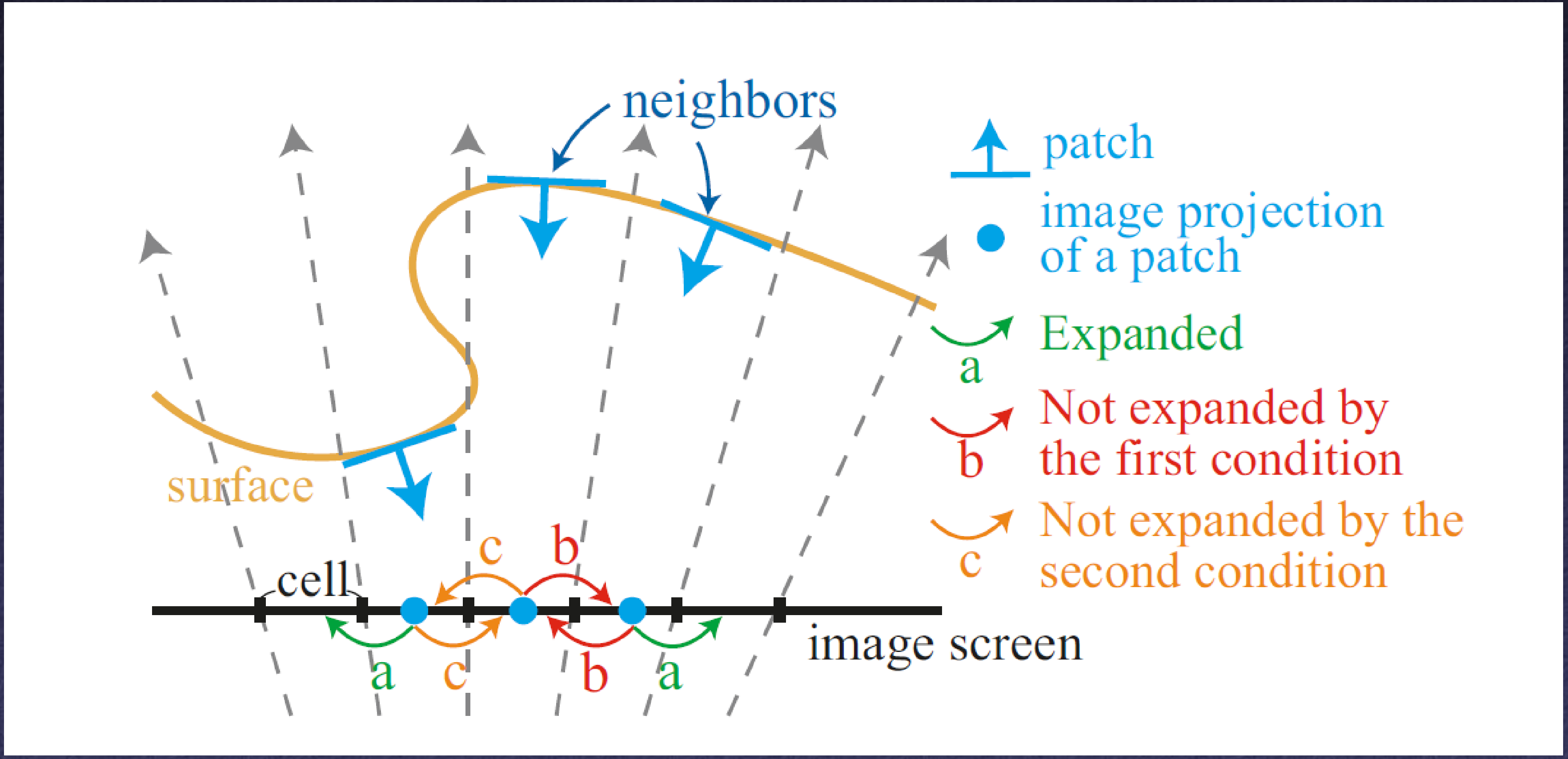
2) Construct seed patches



Furukawa

Patch-Based Approaches

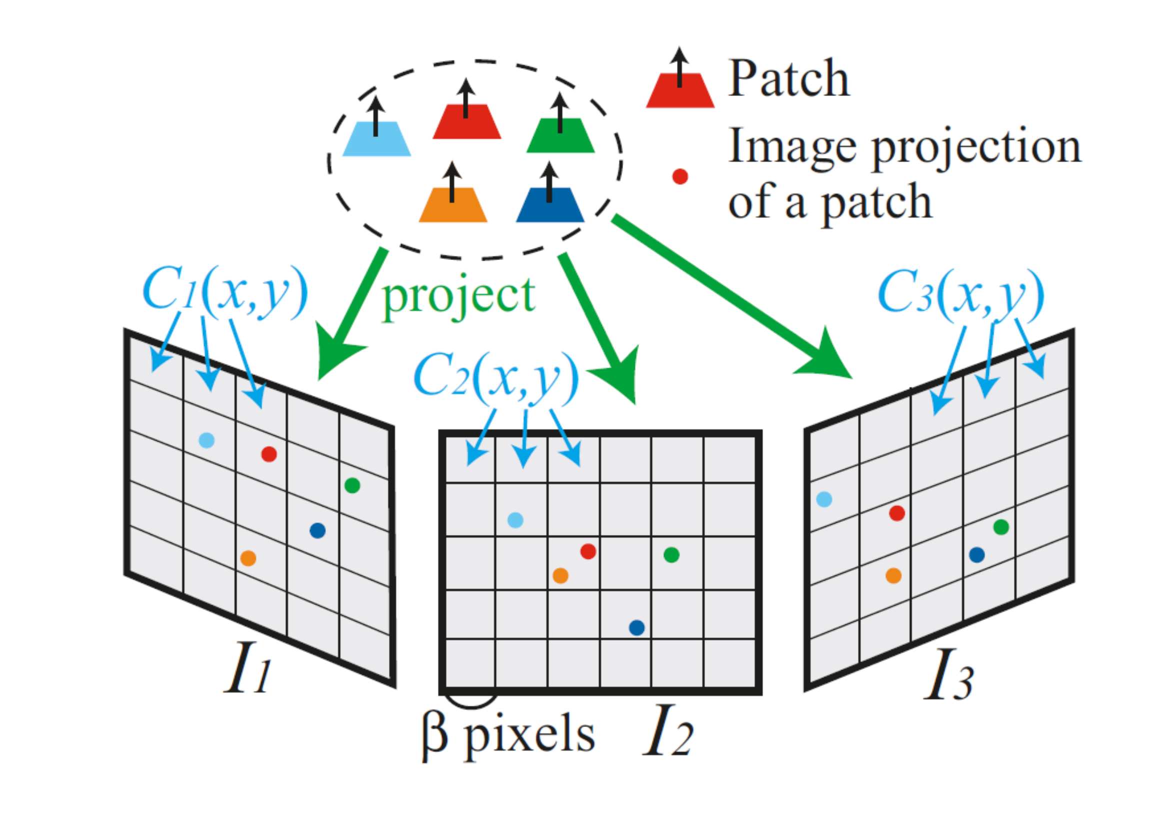
3b) Expand patches to neighbors



Furukawa

Patch-Based Approaches

3a) Filter inconsistent patches



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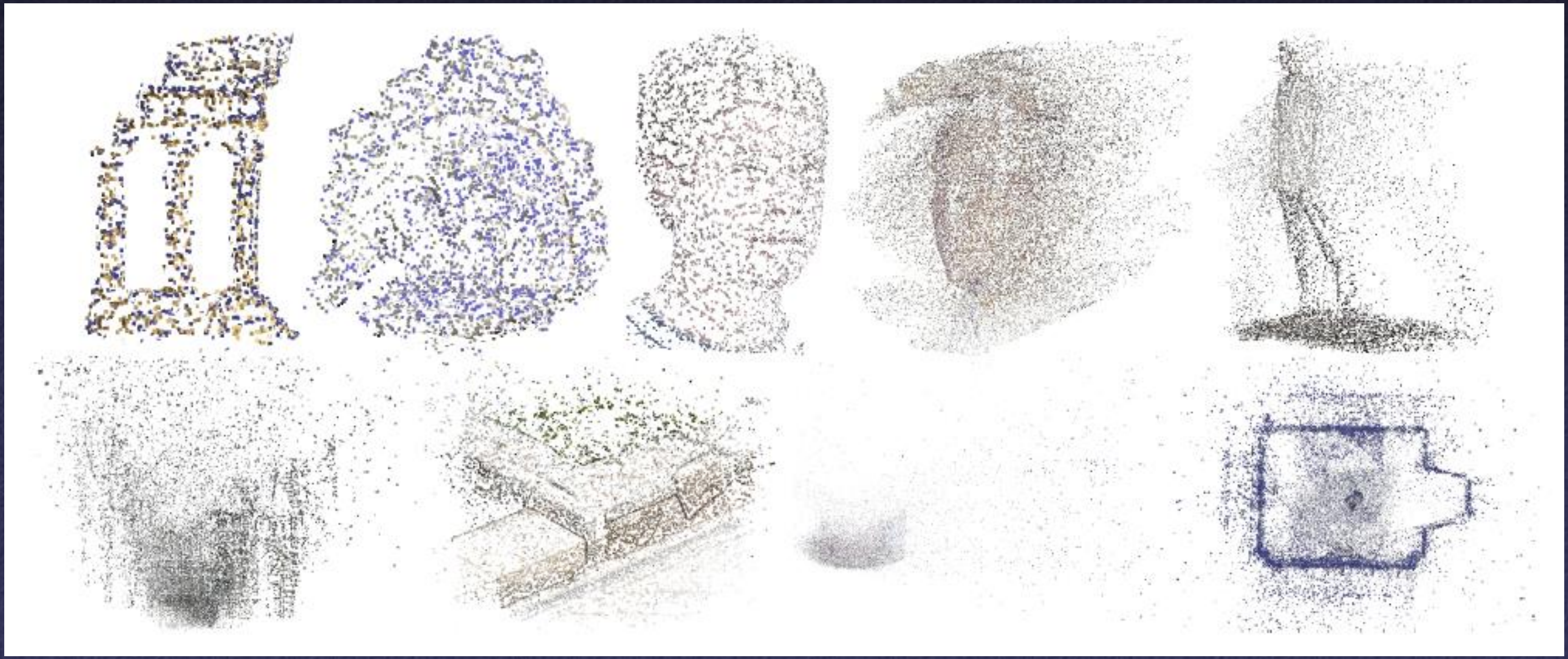
Patch-Based Results

Initial set of seed patches



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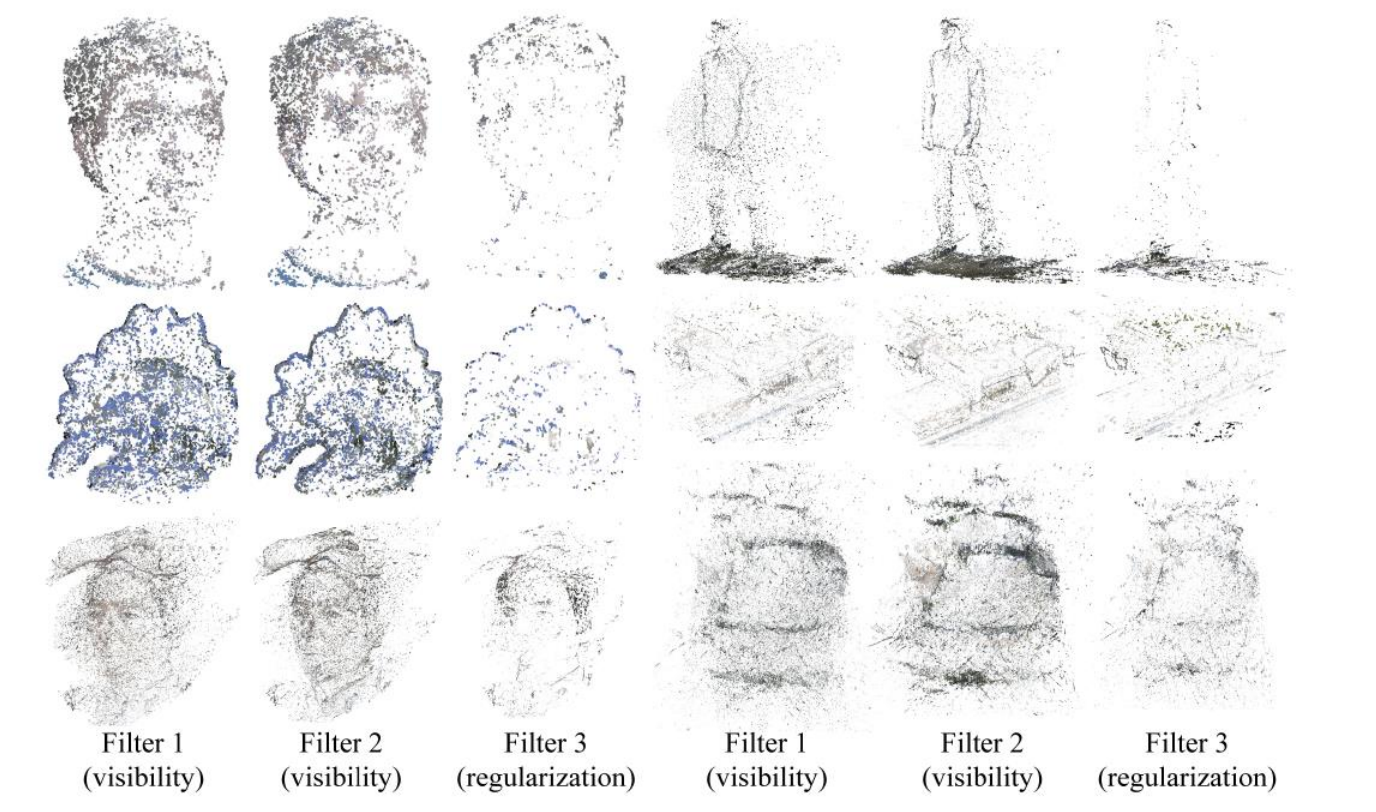
Patch-Based Results

After filtering inconsistent patches



Furukawa

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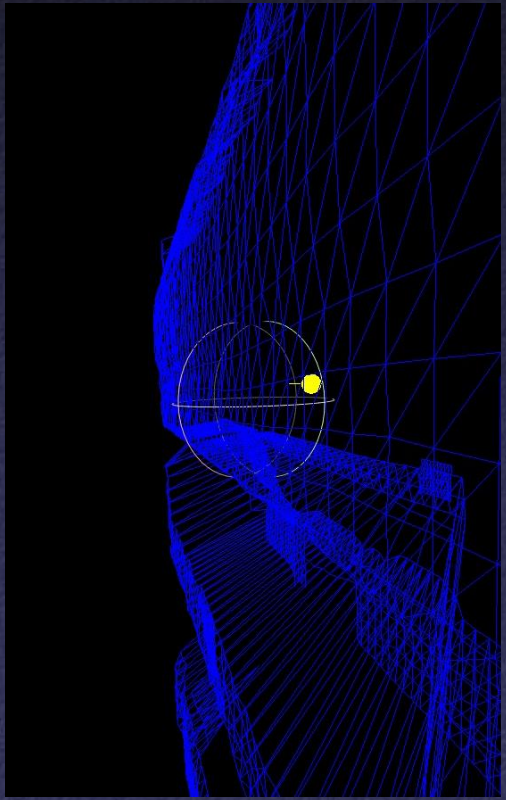
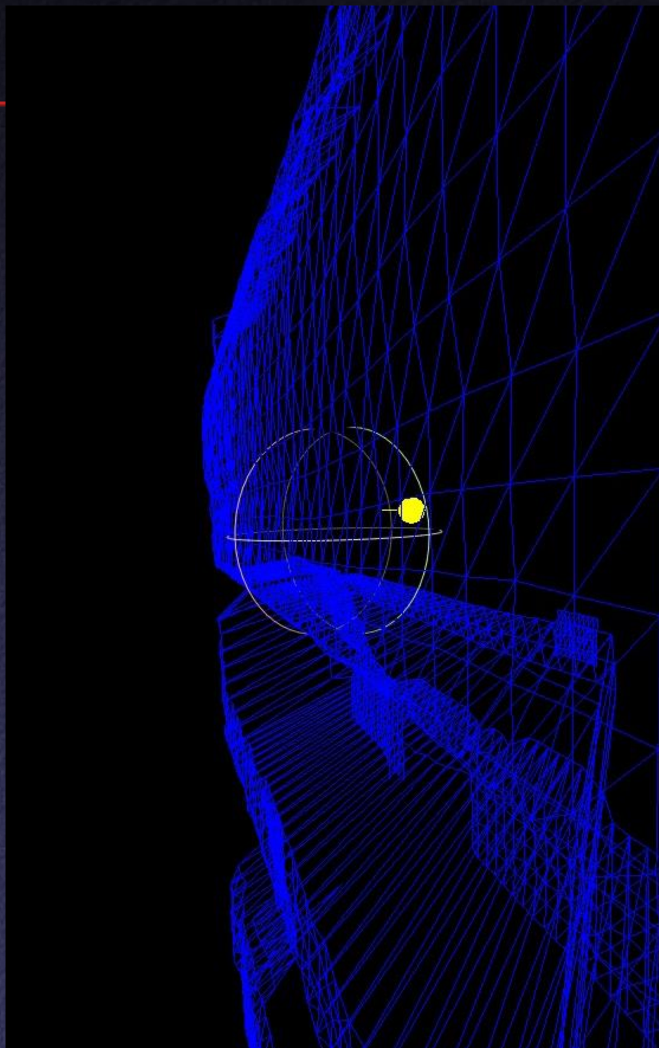
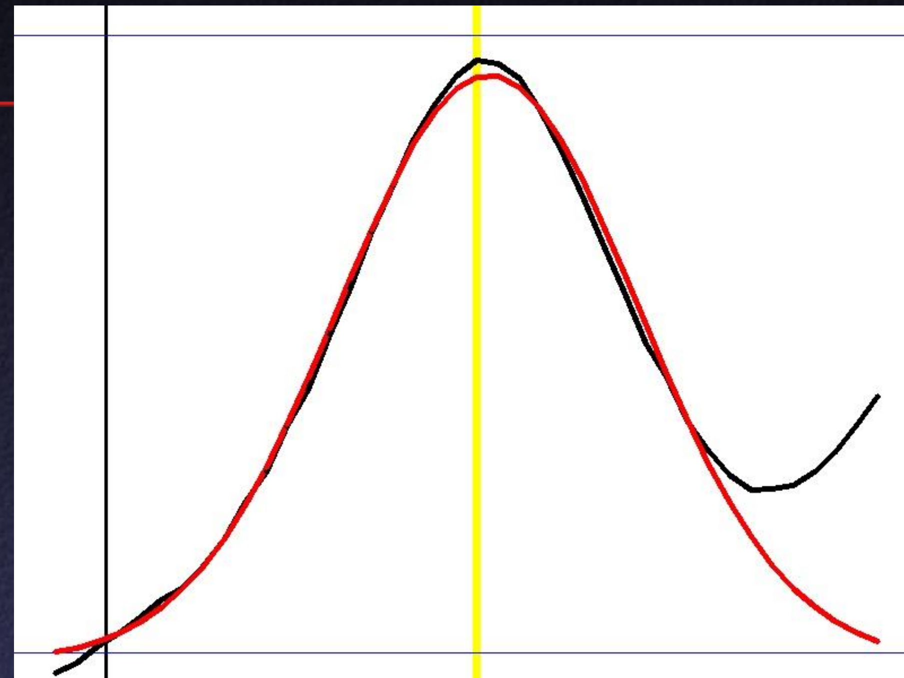
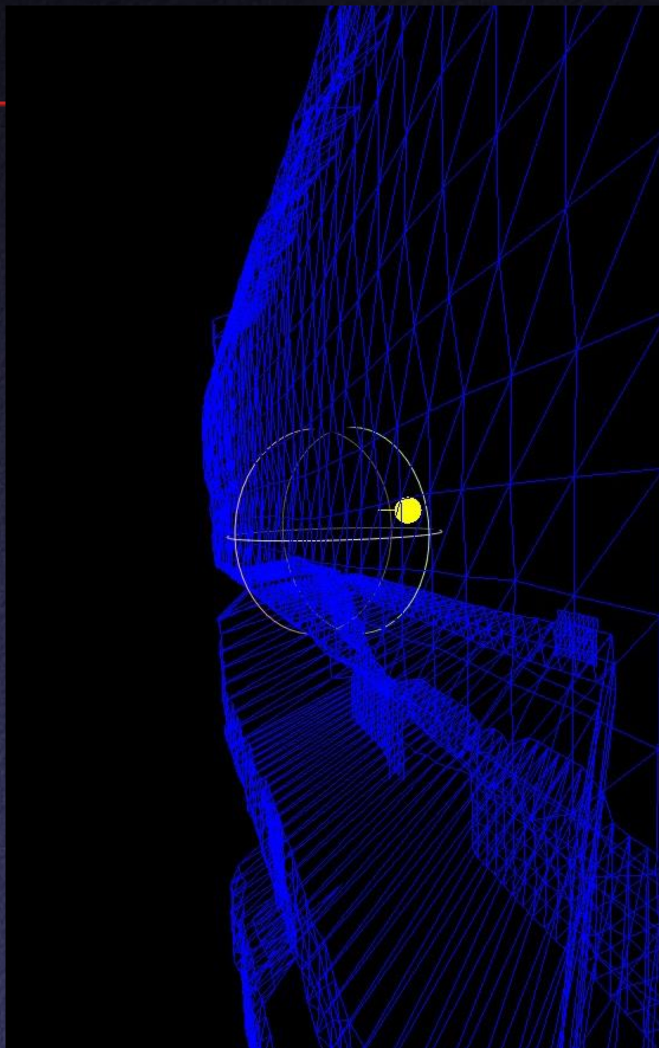
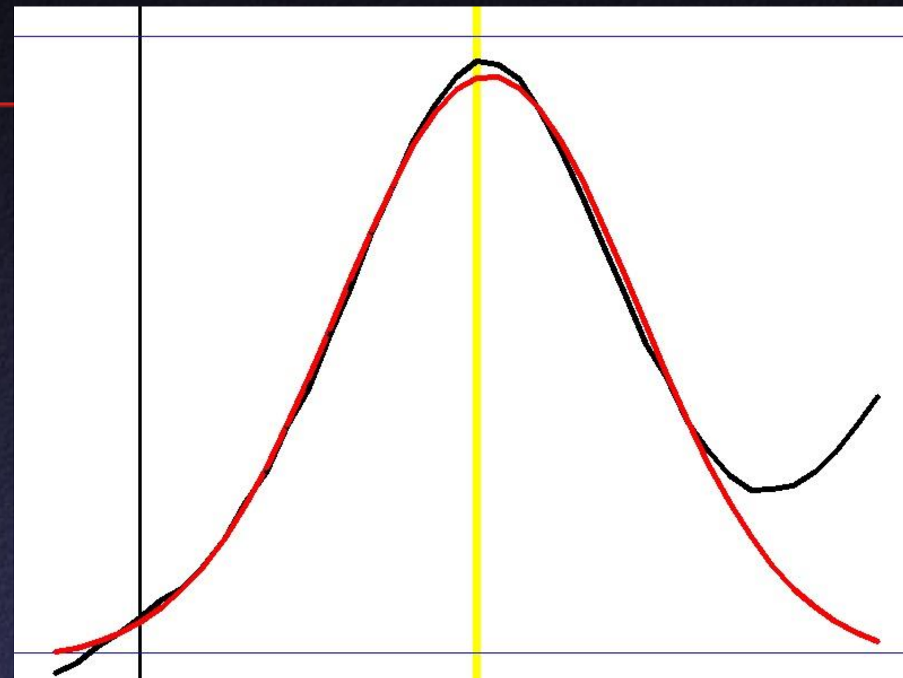
Mesh-Based Methods

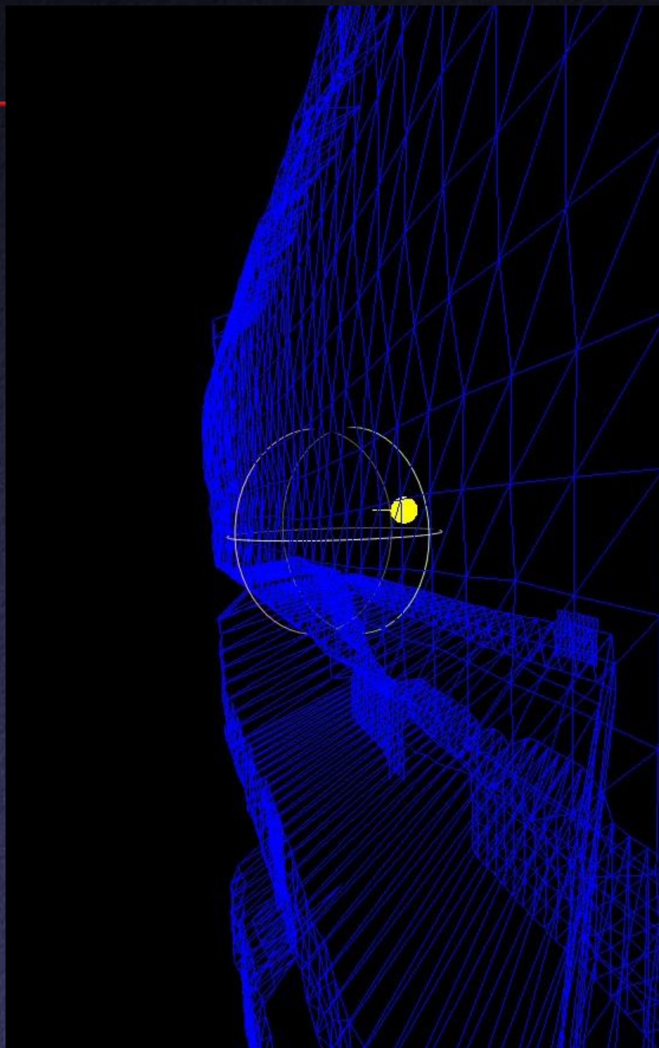
- Optimize vertices of a 3D triangle mesh surface to maximize photoconsistency
  - Generate initial mesh (e.g., connecting patches)
  - Move vertices along normal direction to improve photoconsistency (e.g., NCC)

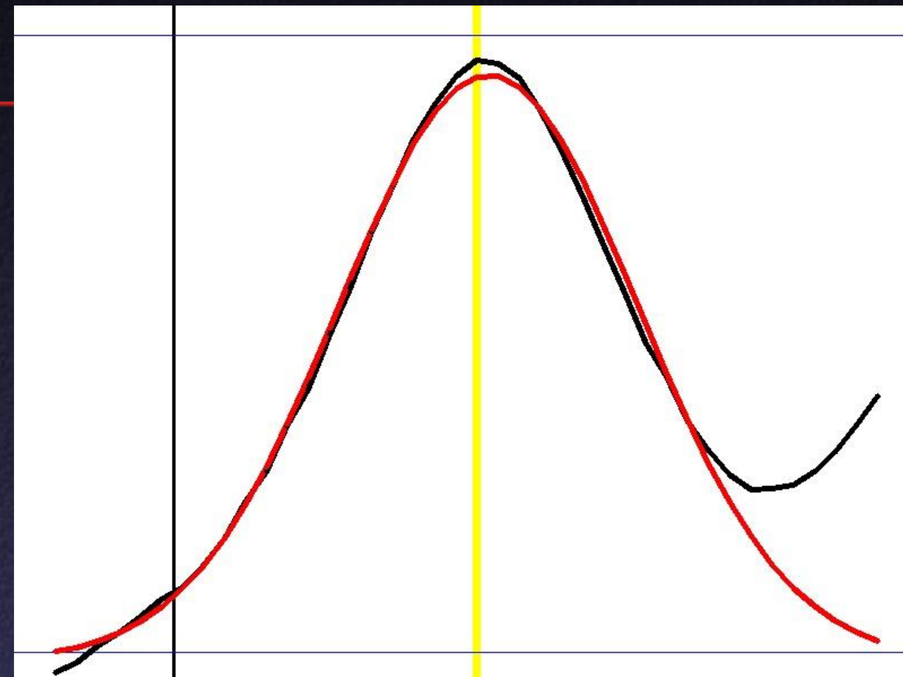


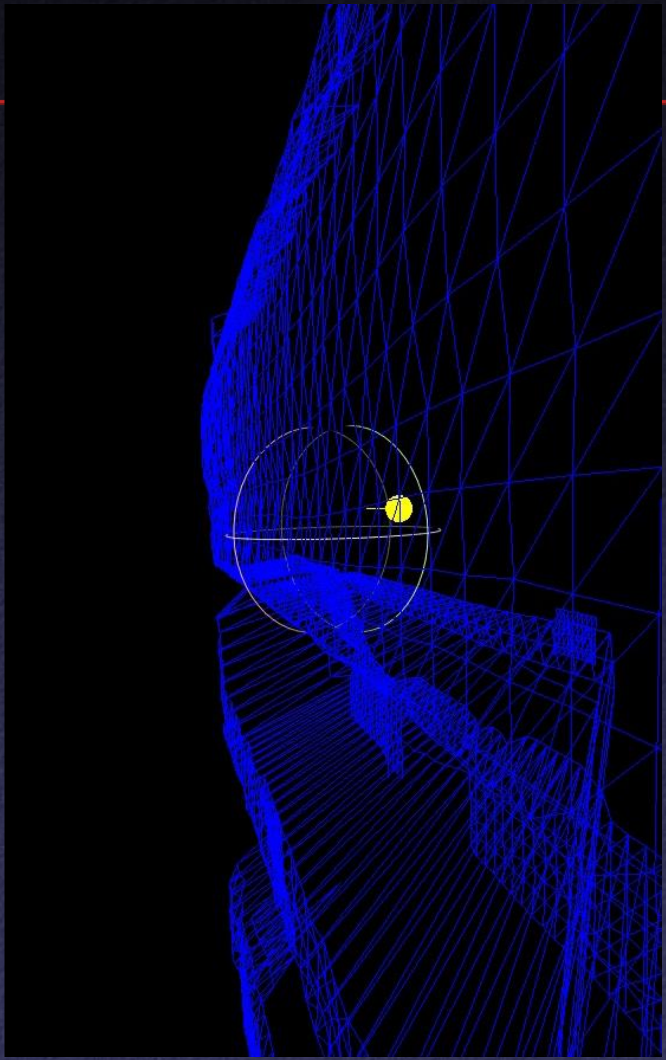
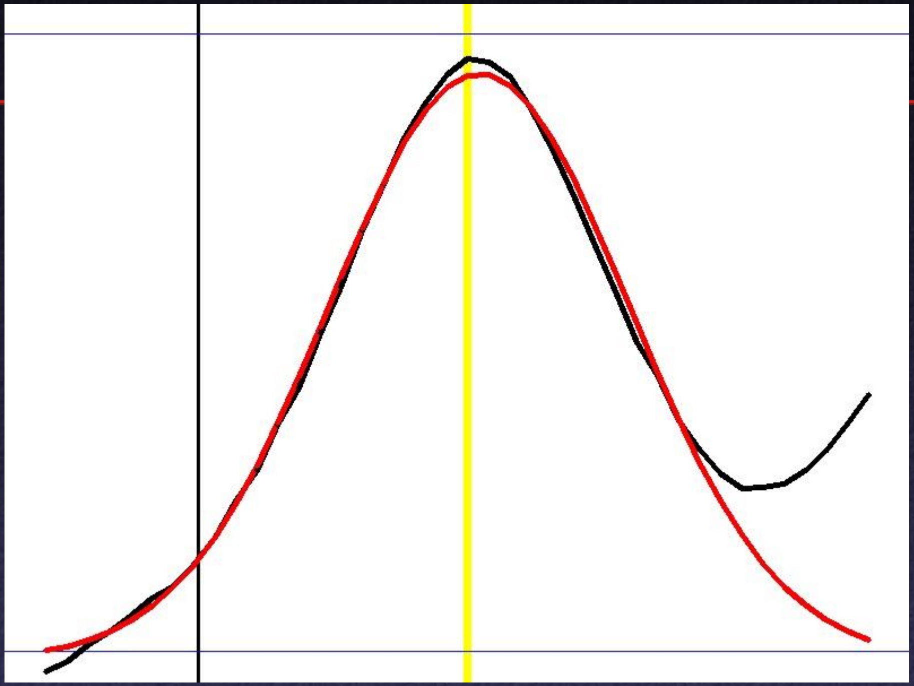


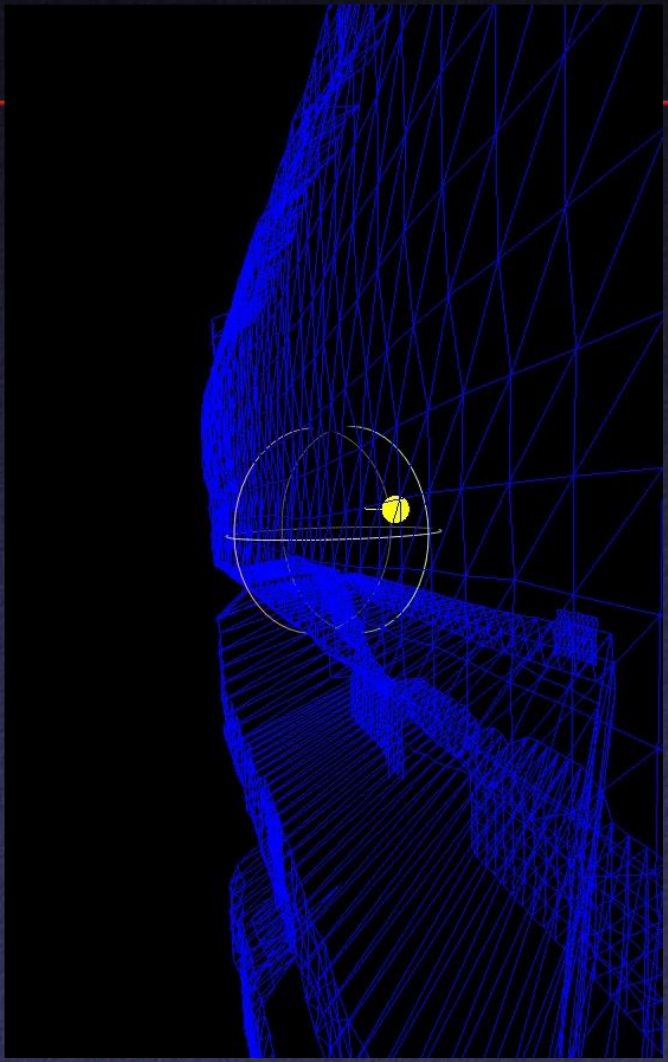


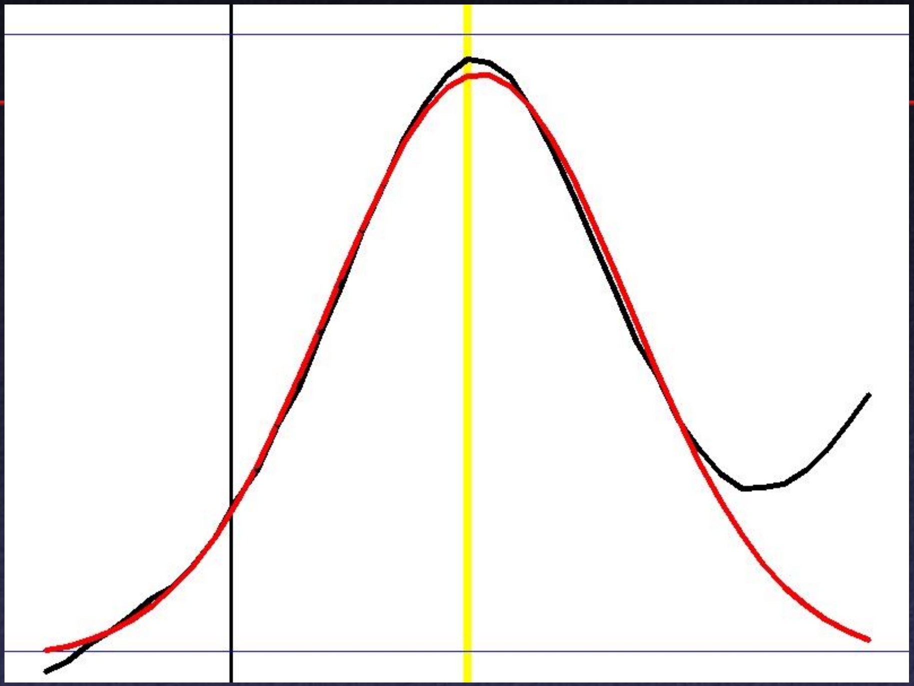



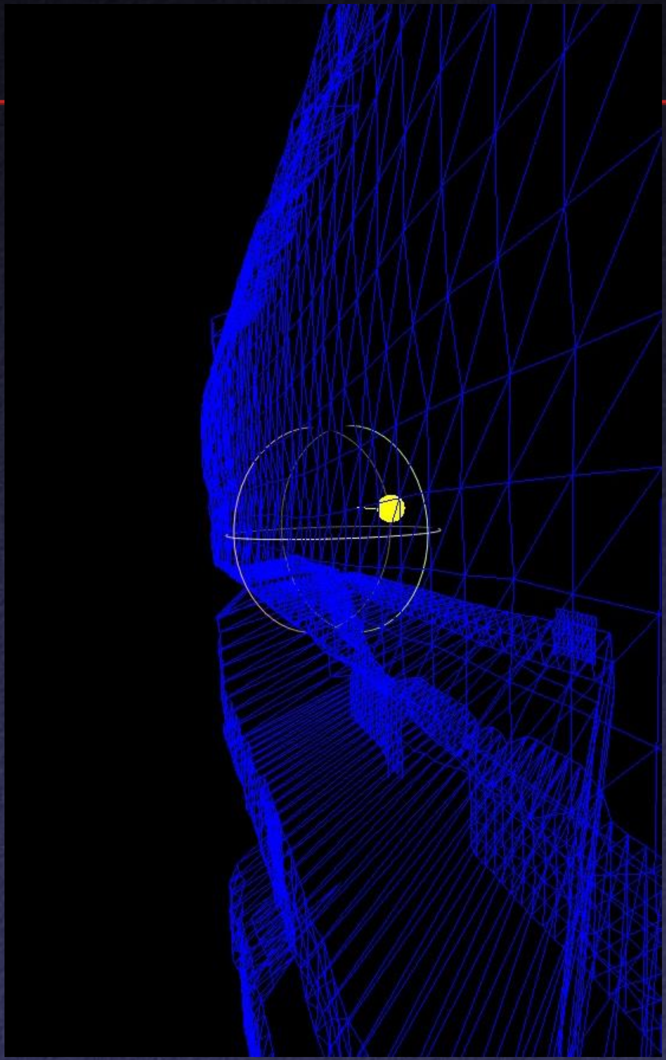



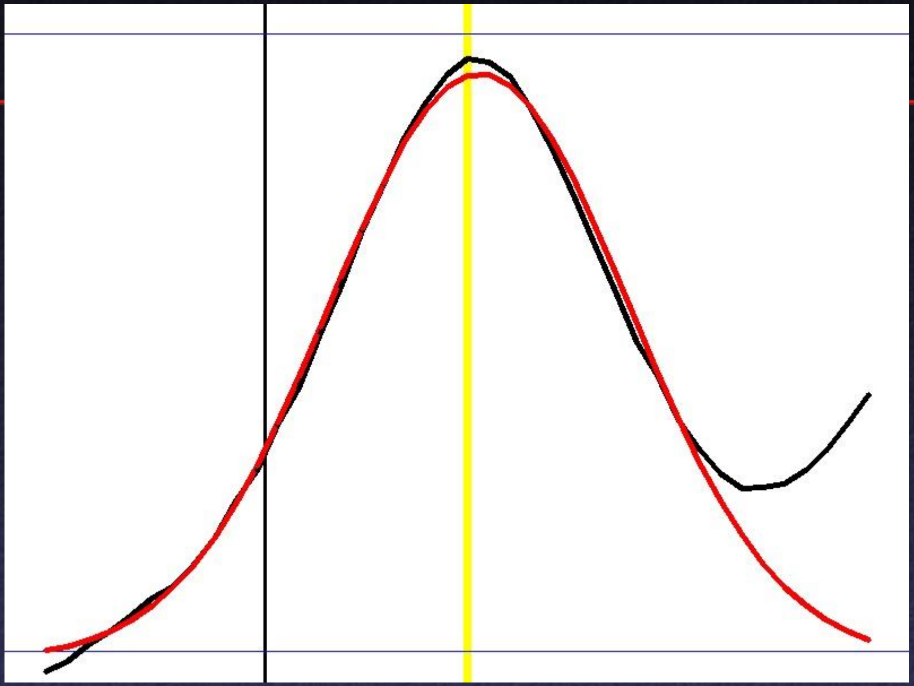


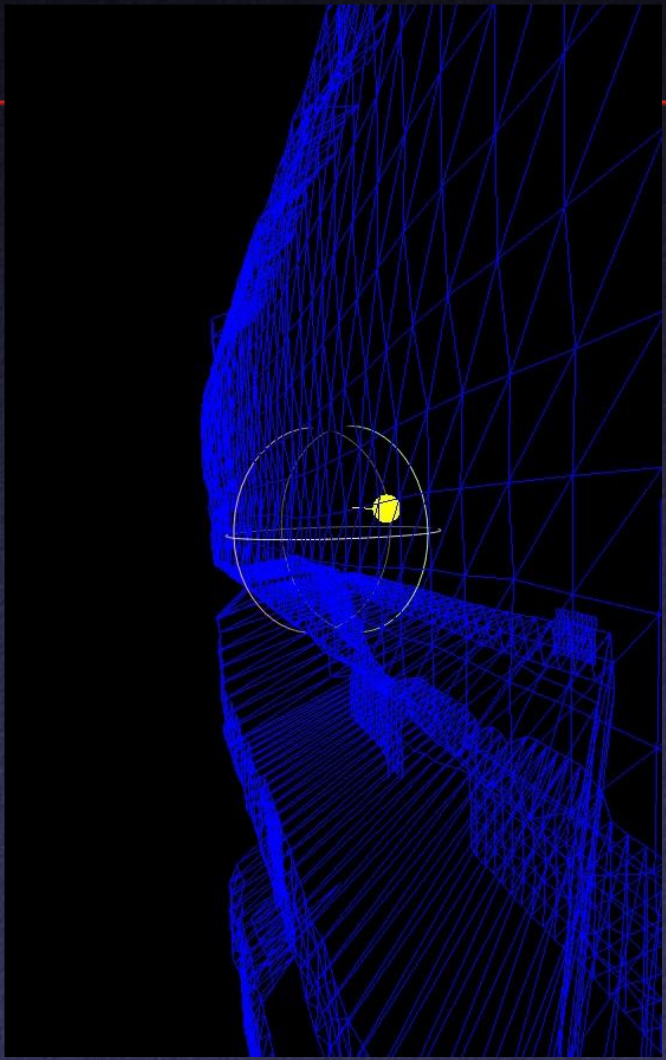



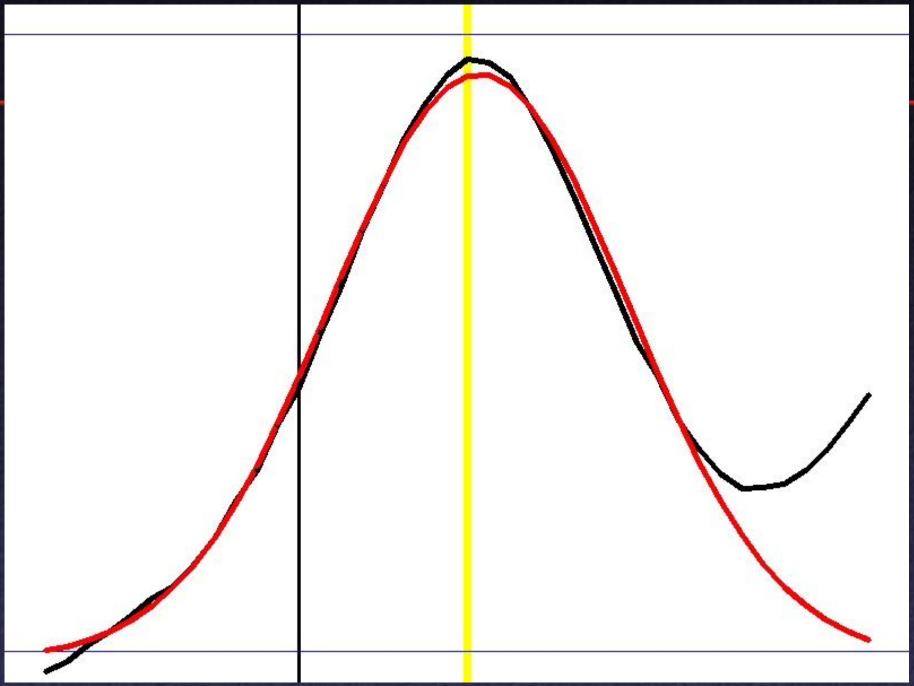



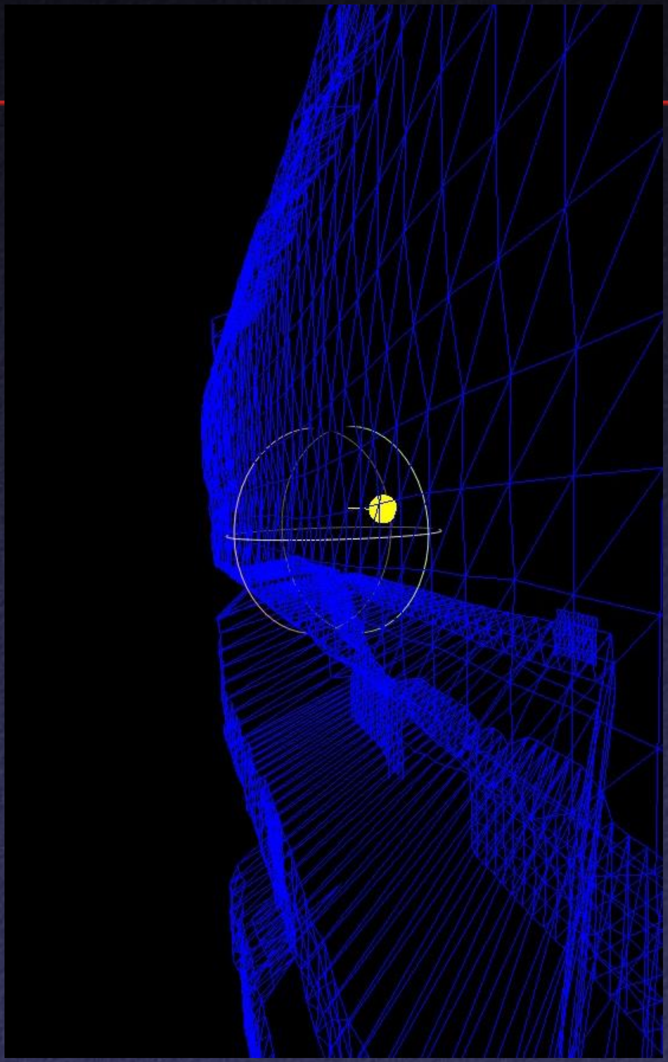


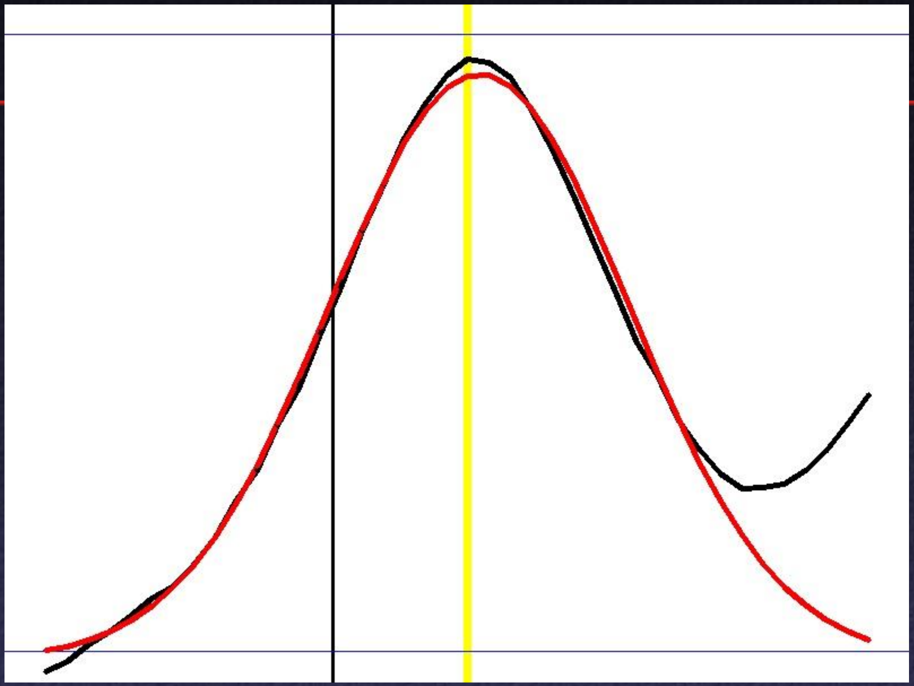


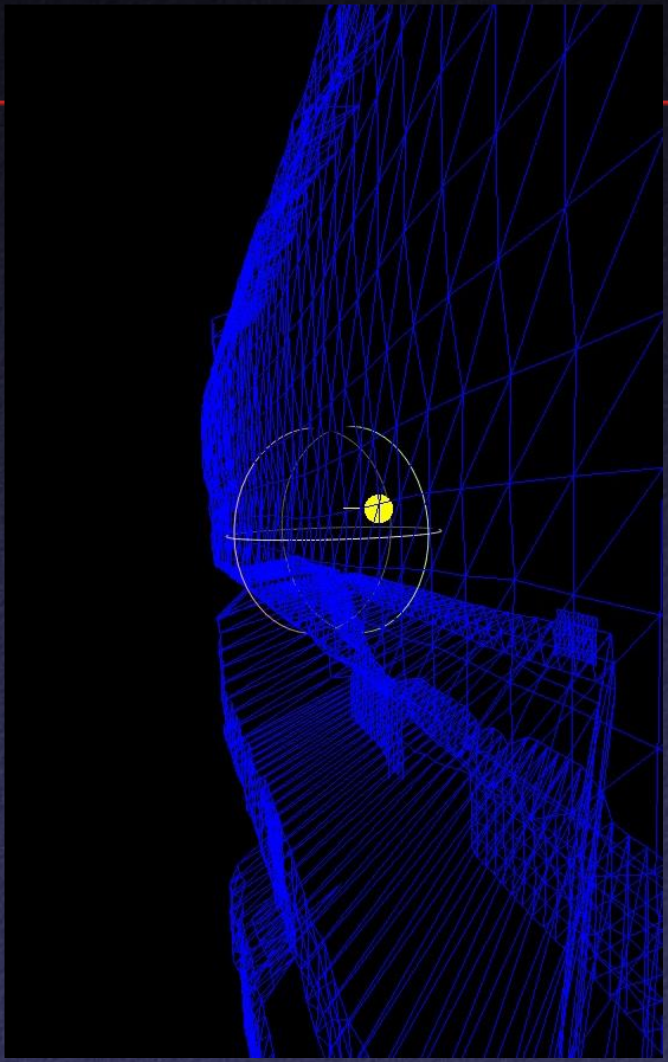


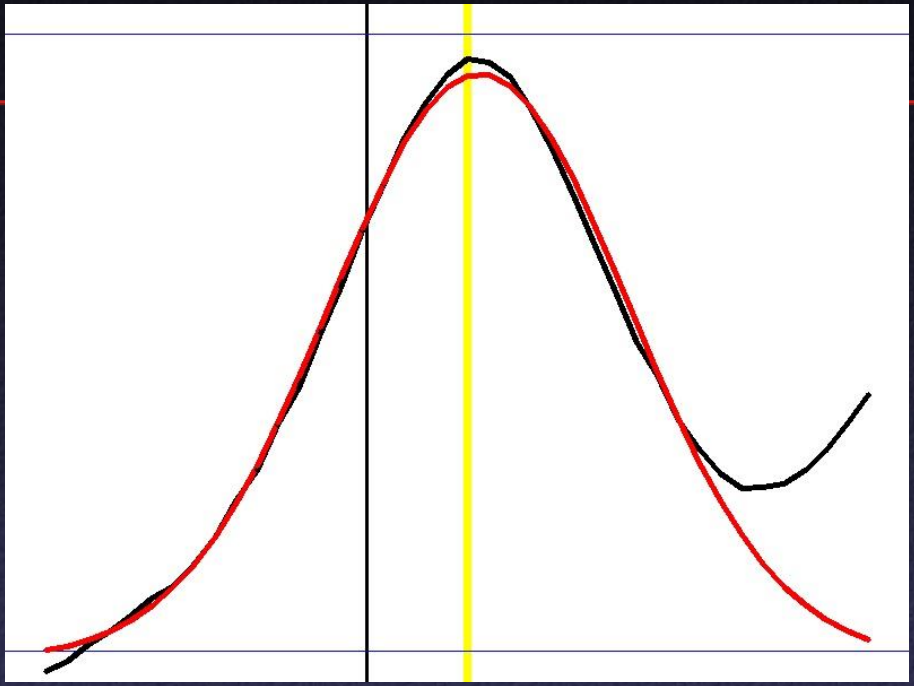


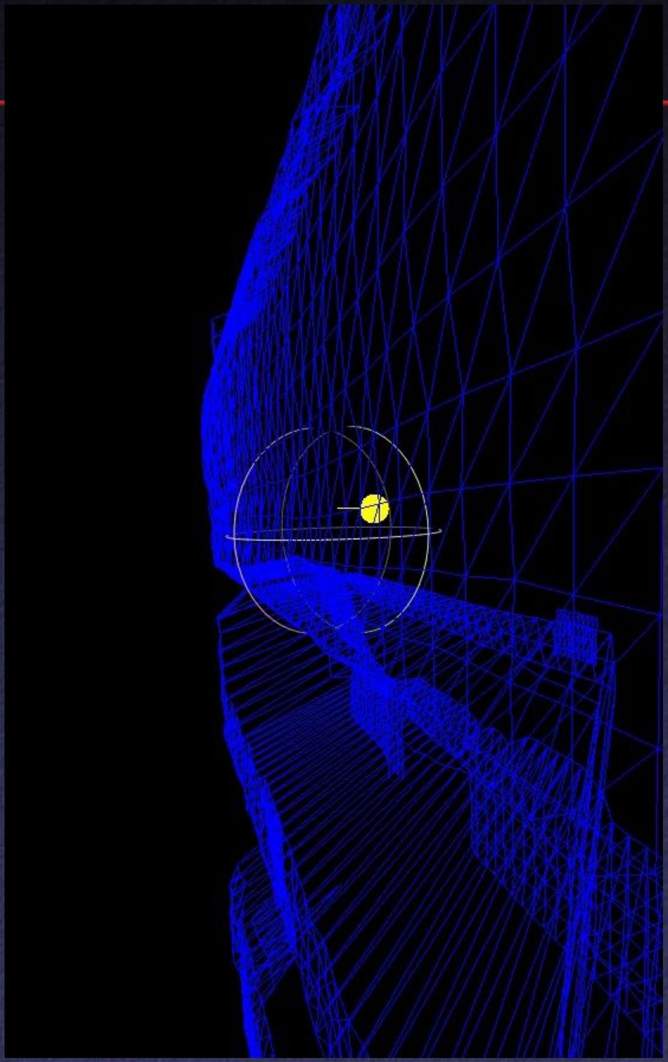


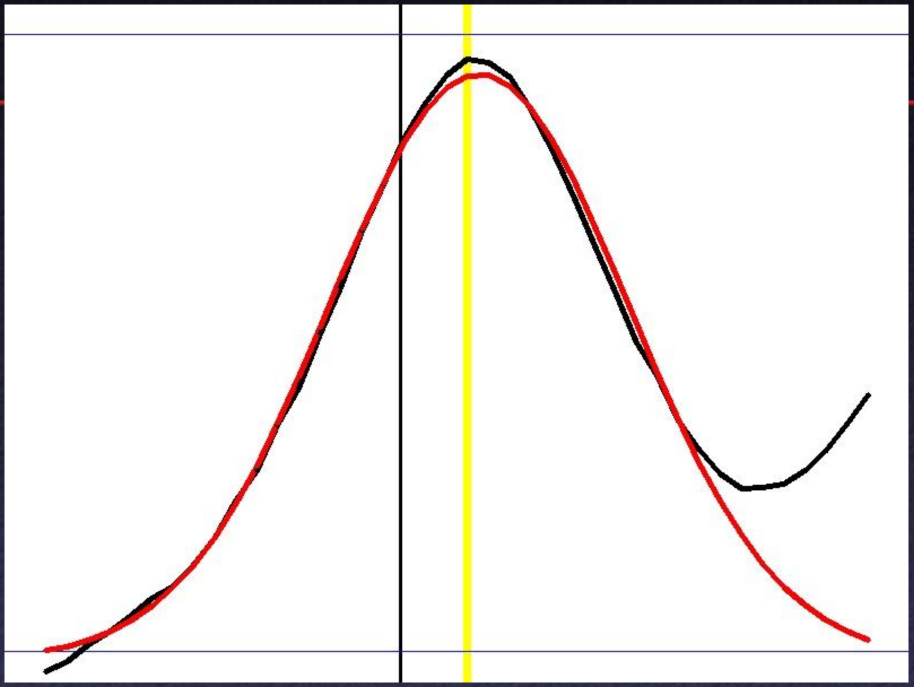


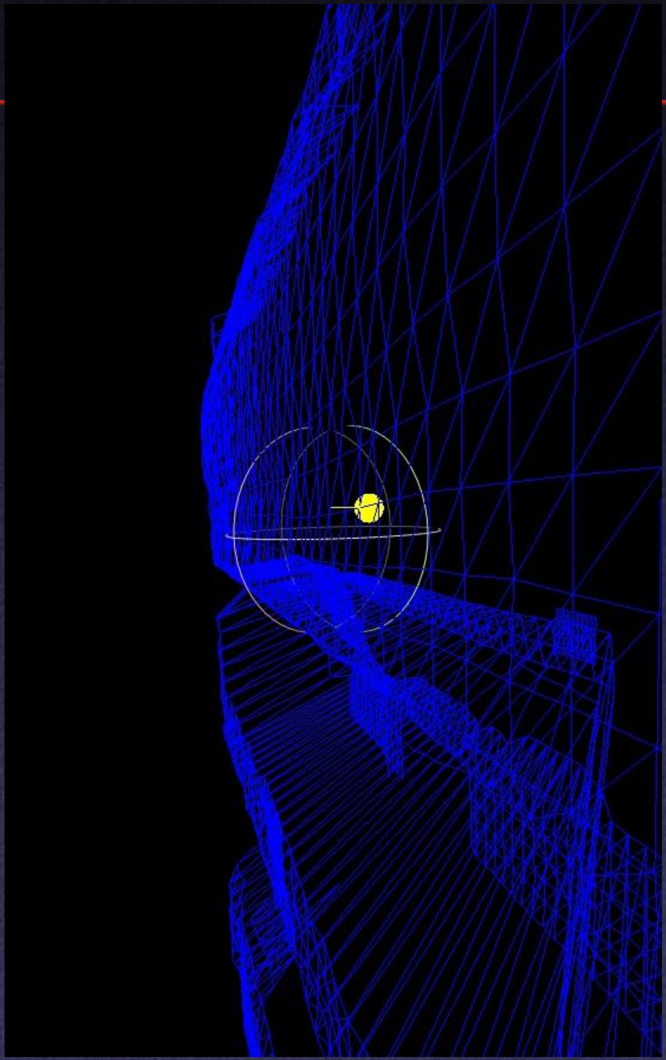


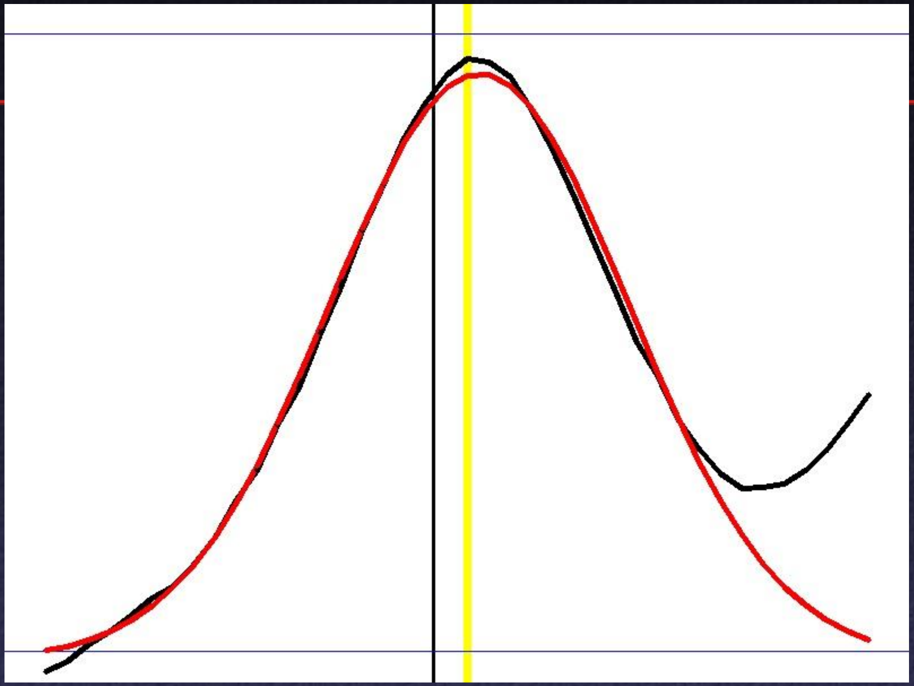


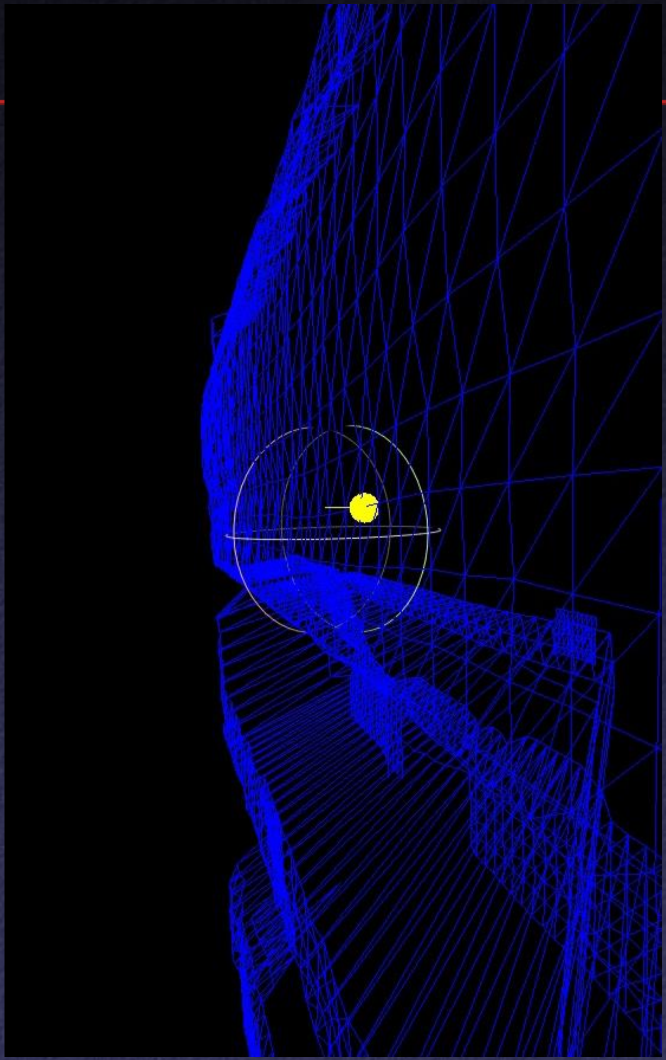


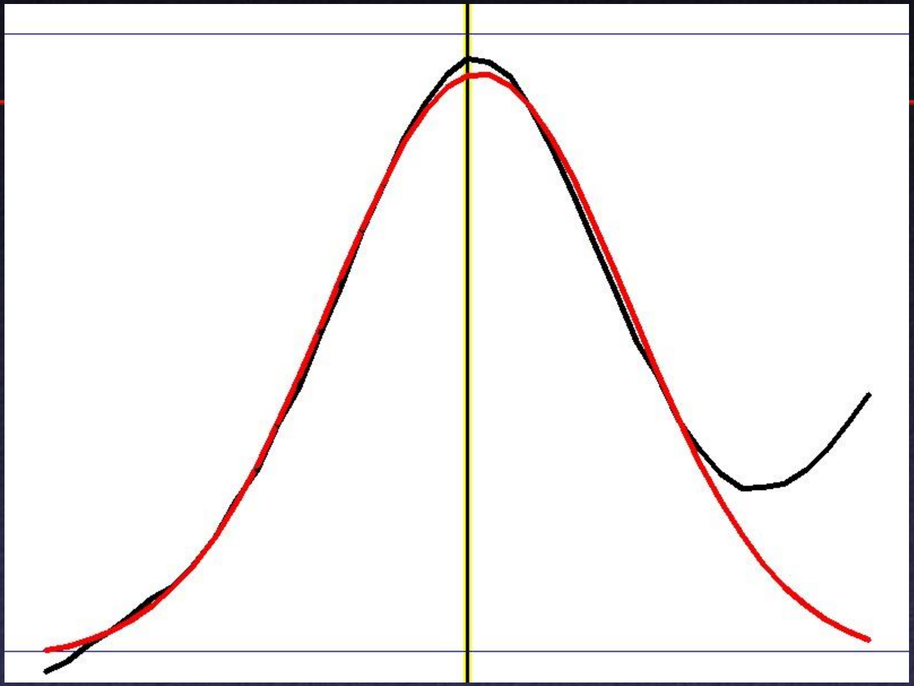


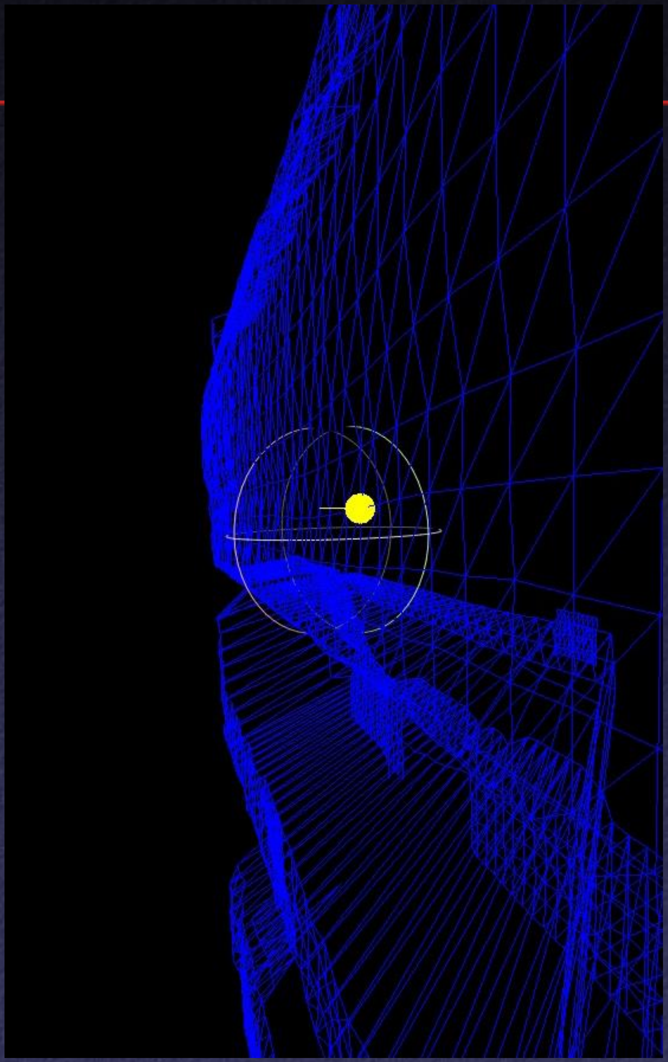


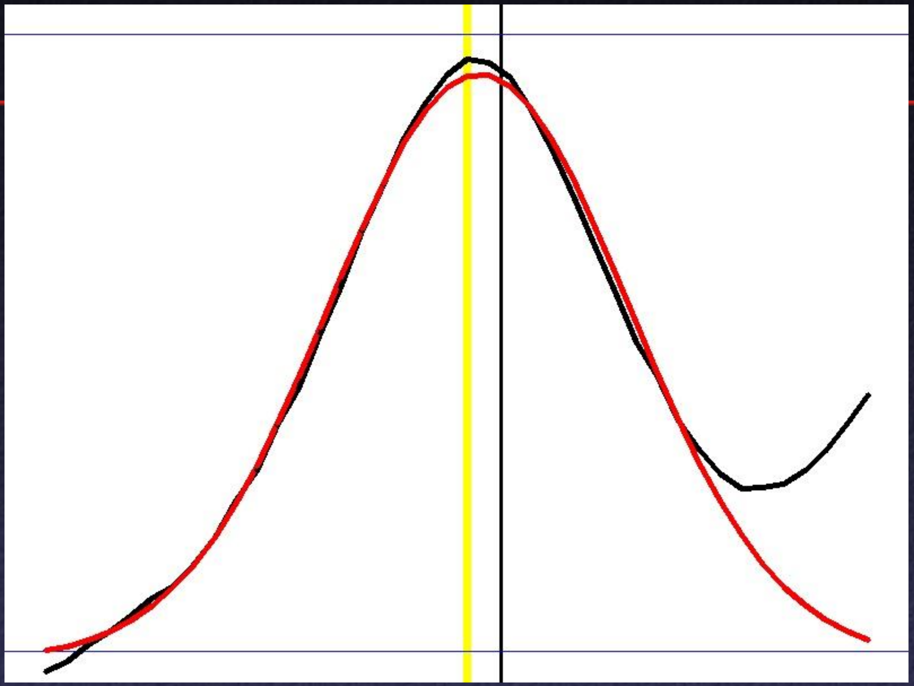


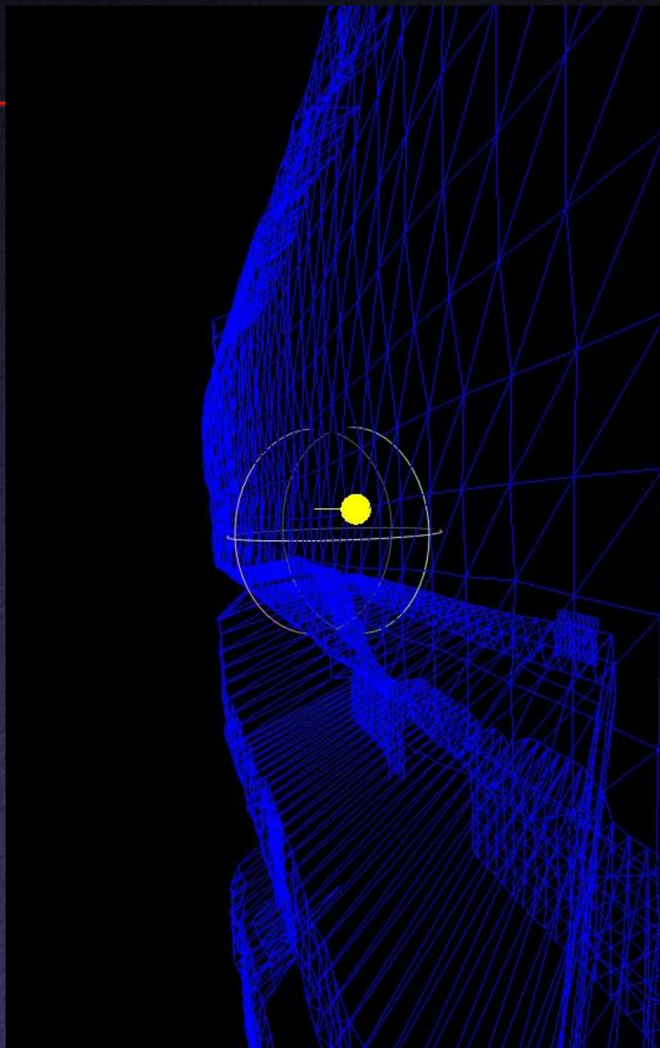
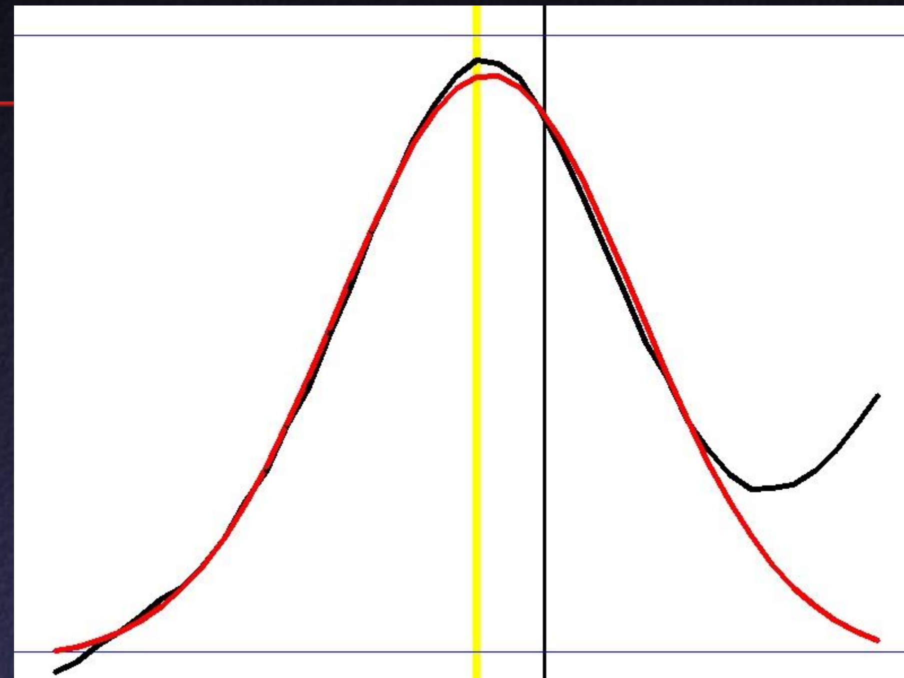


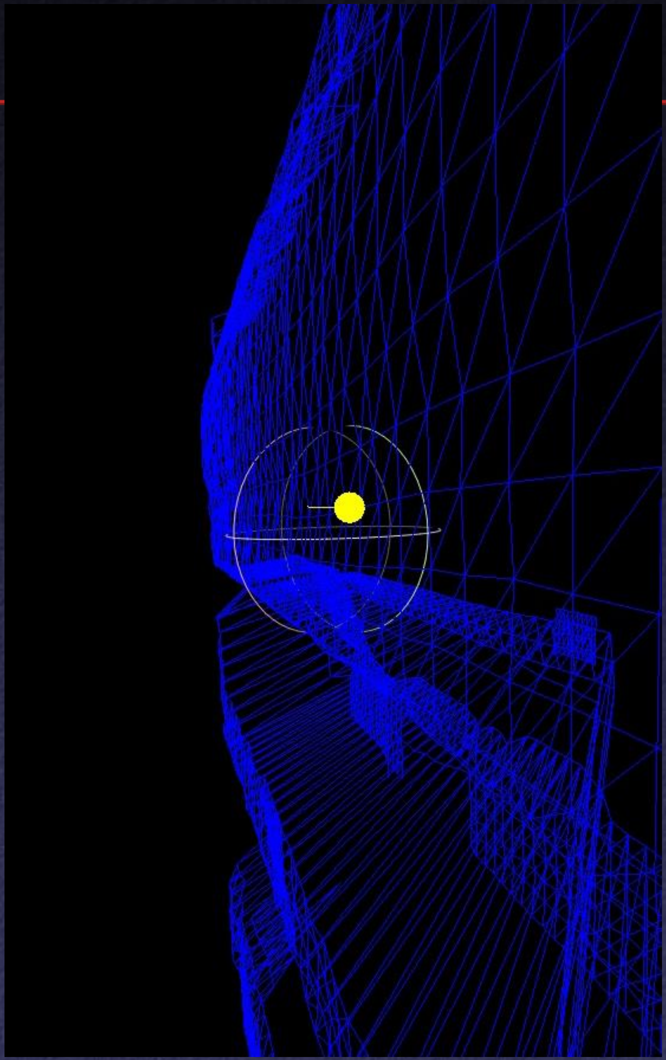


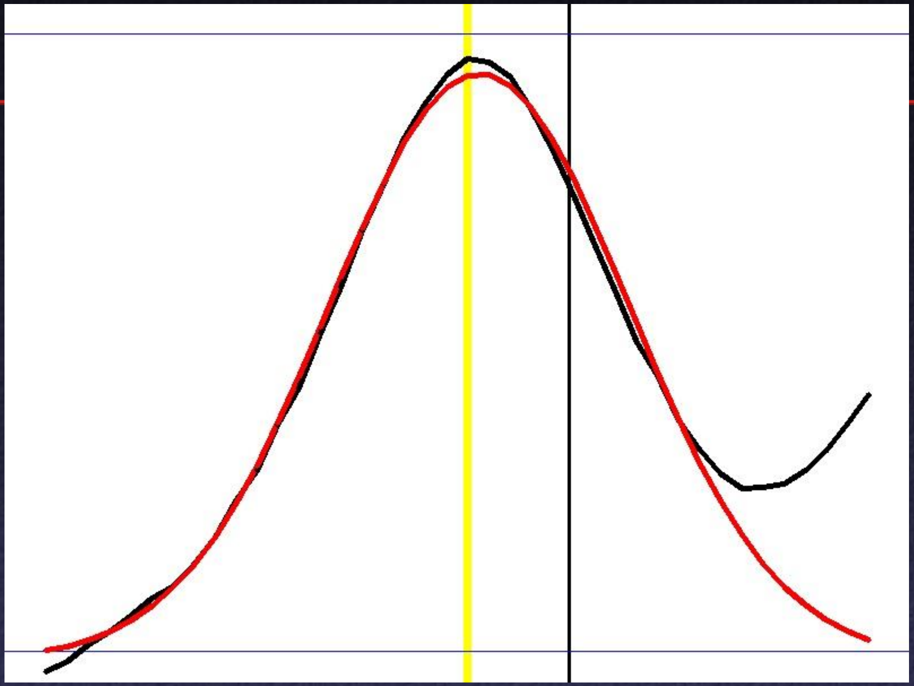


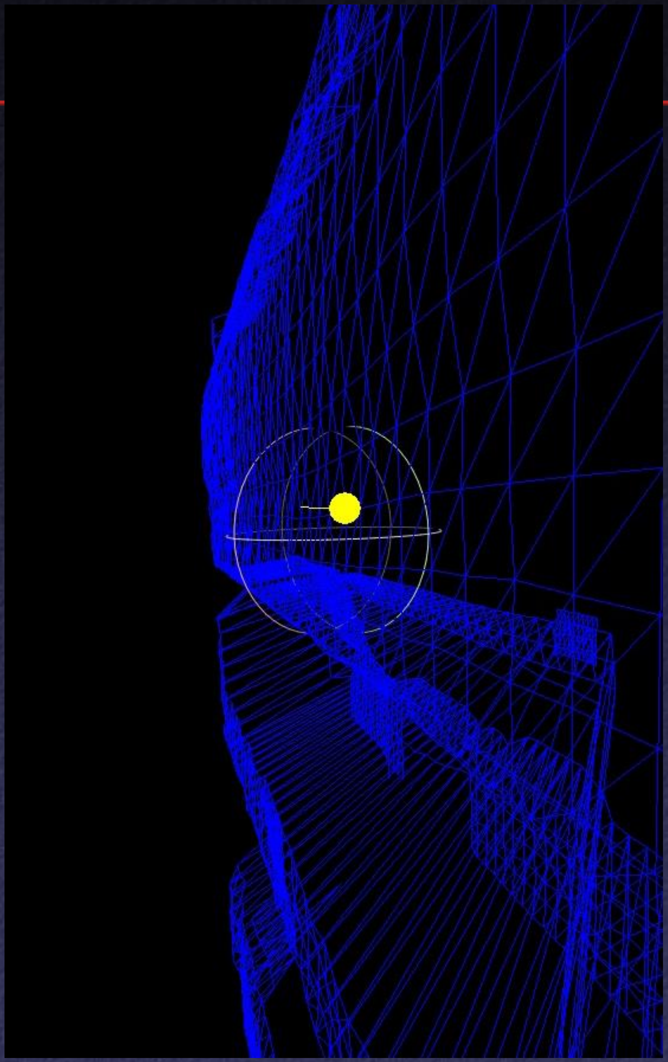


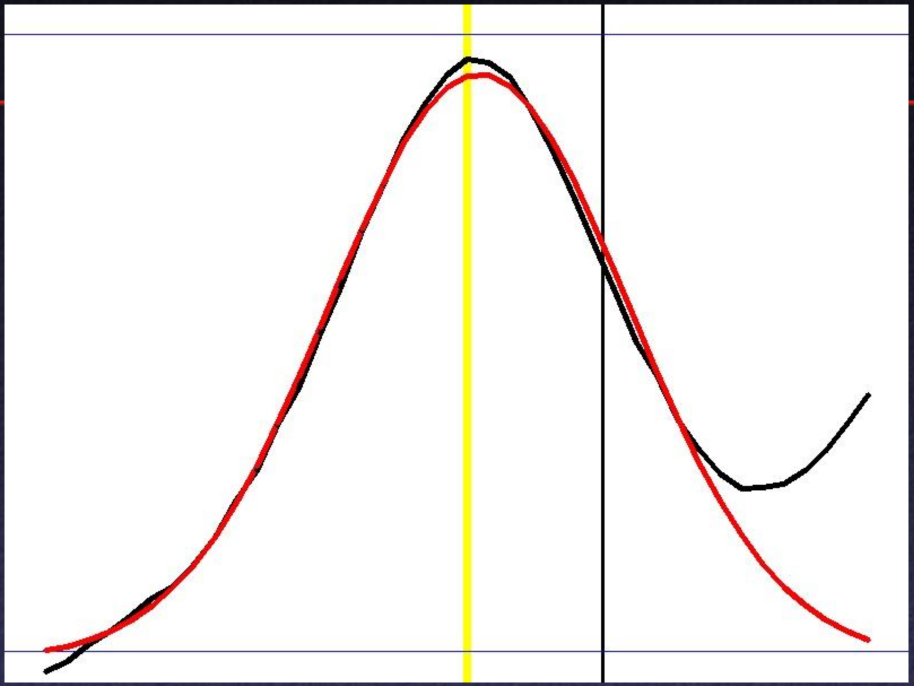


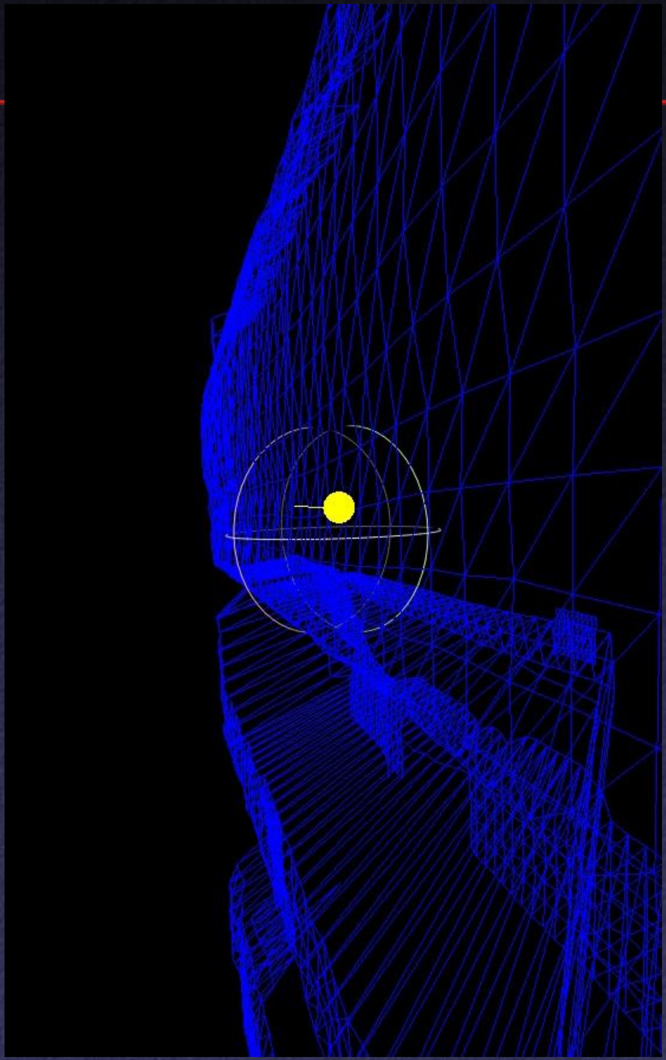



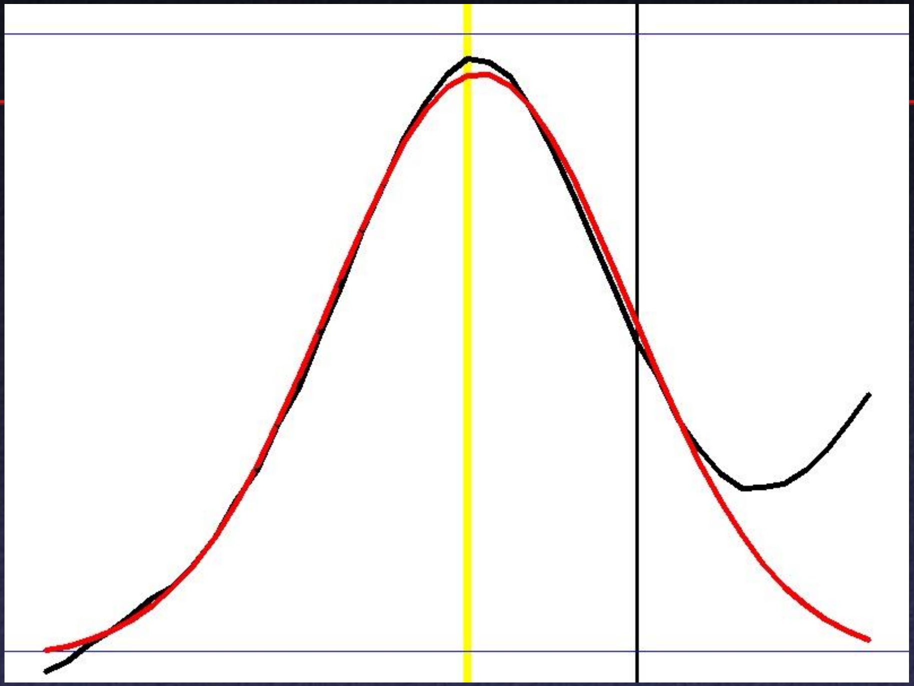



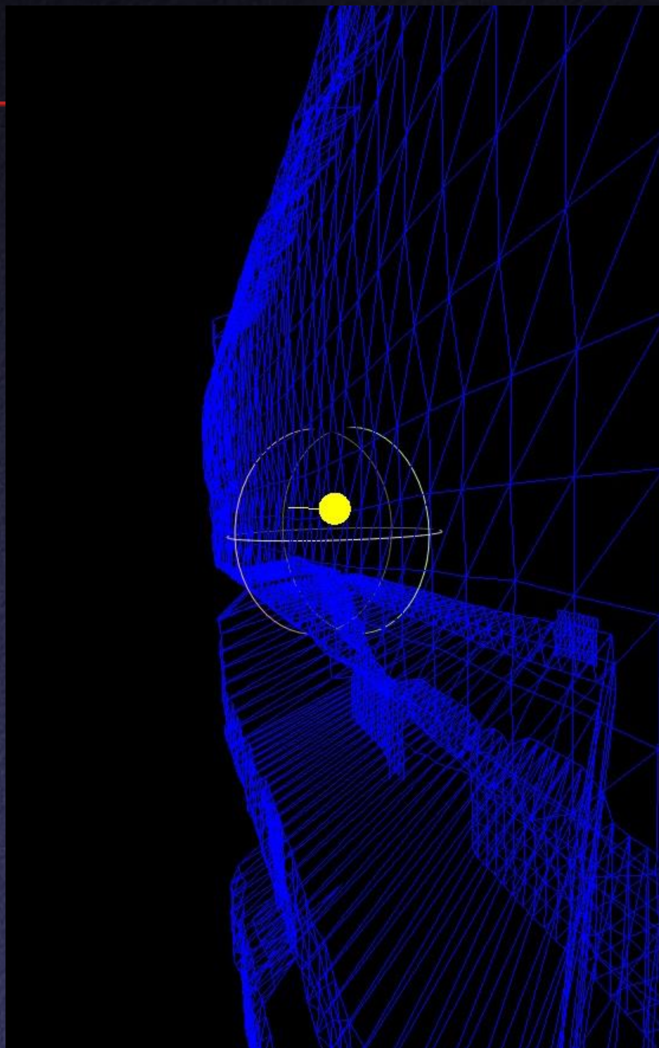


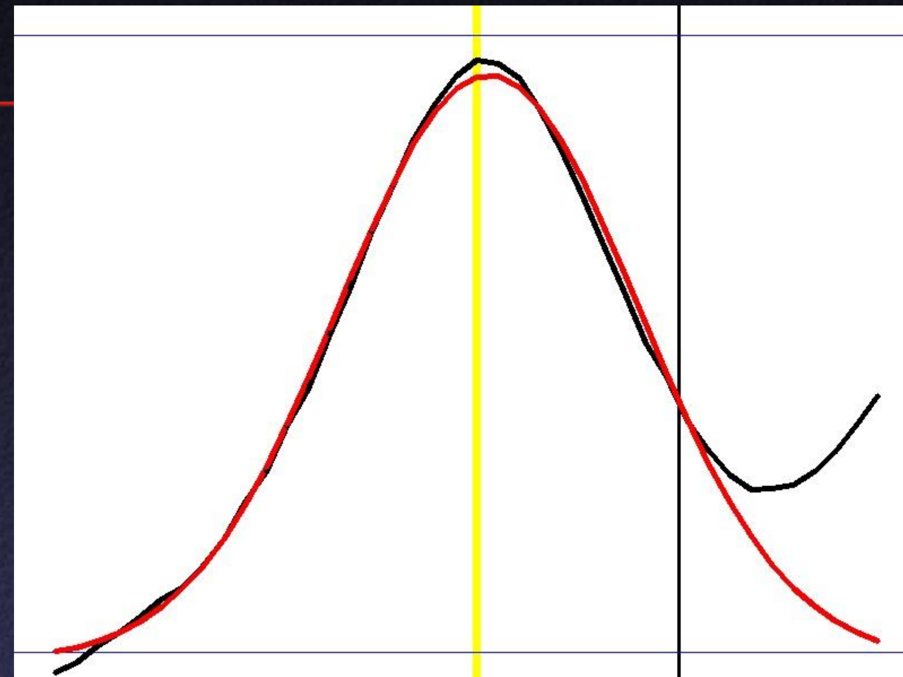


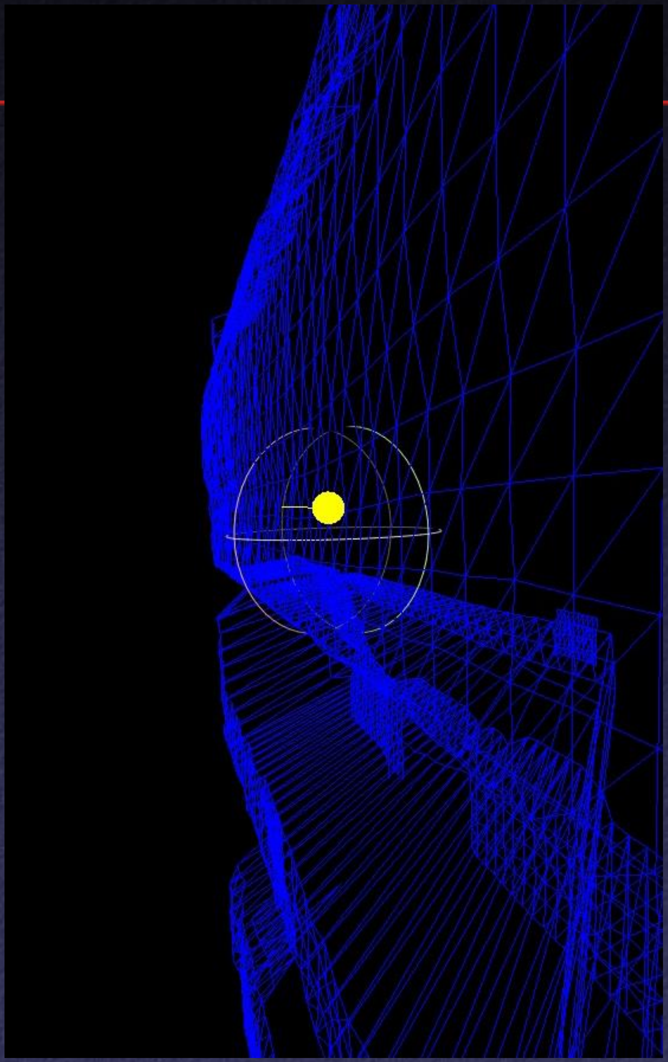


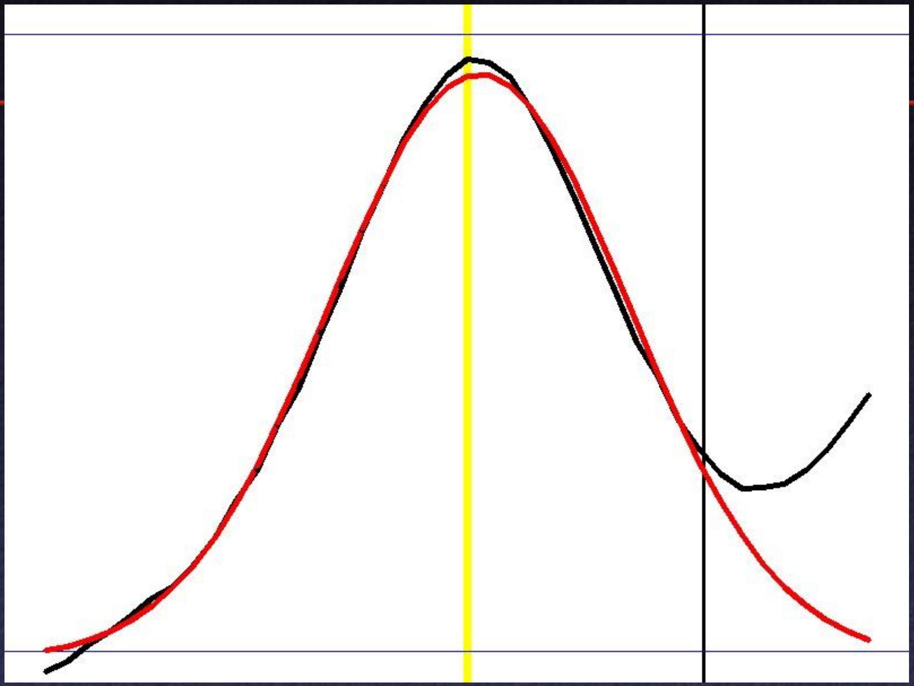


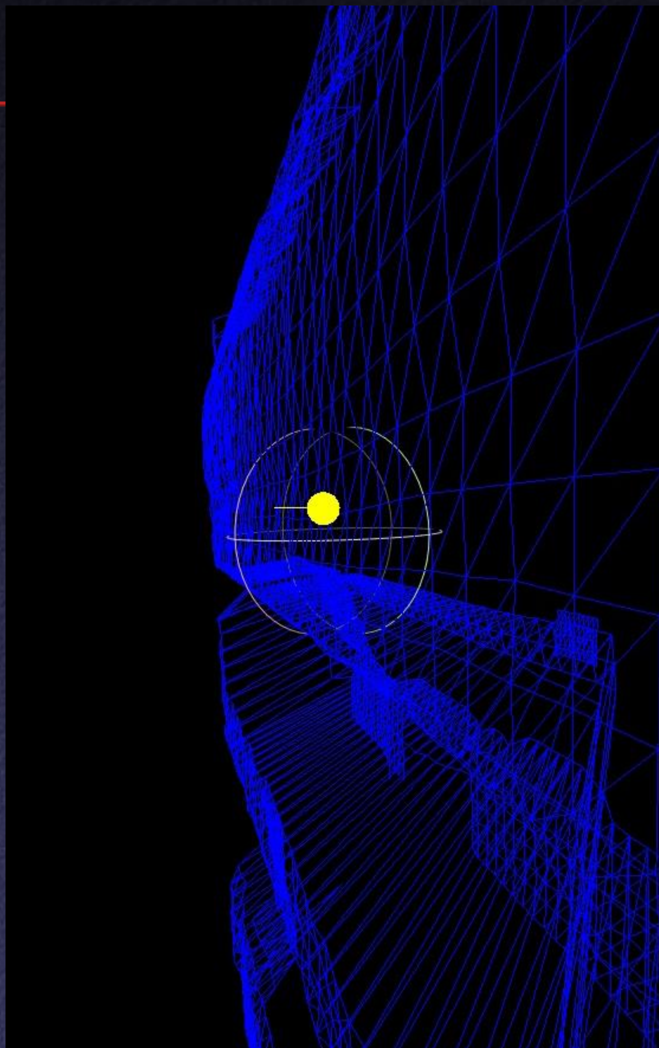


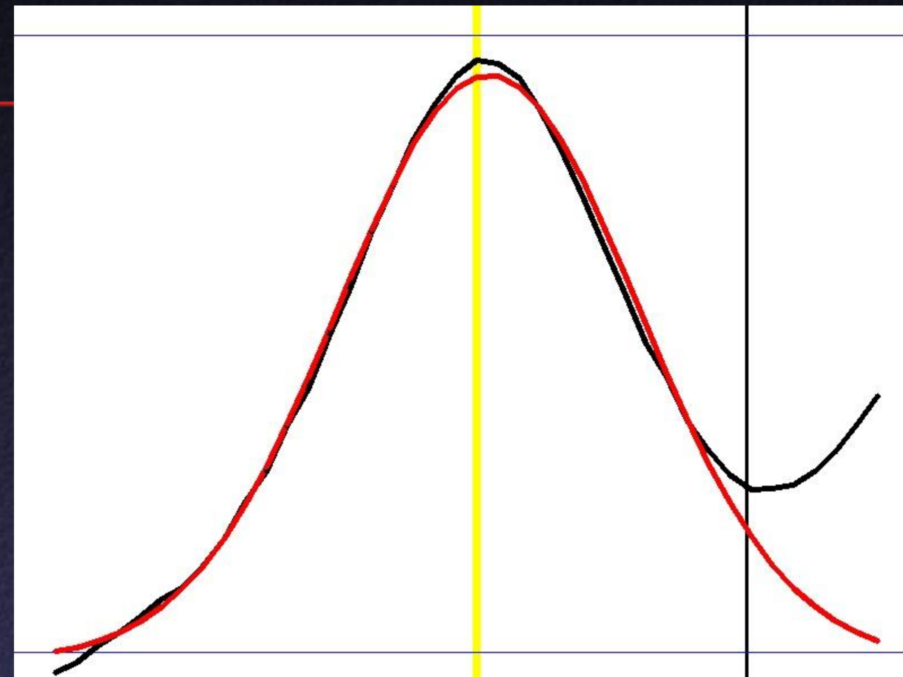


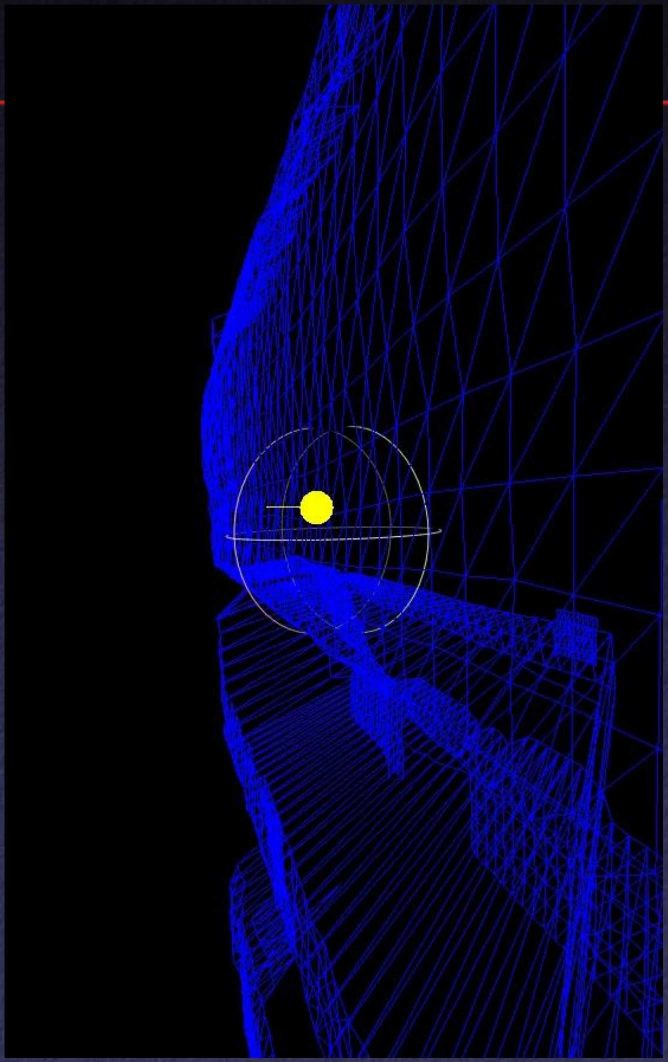


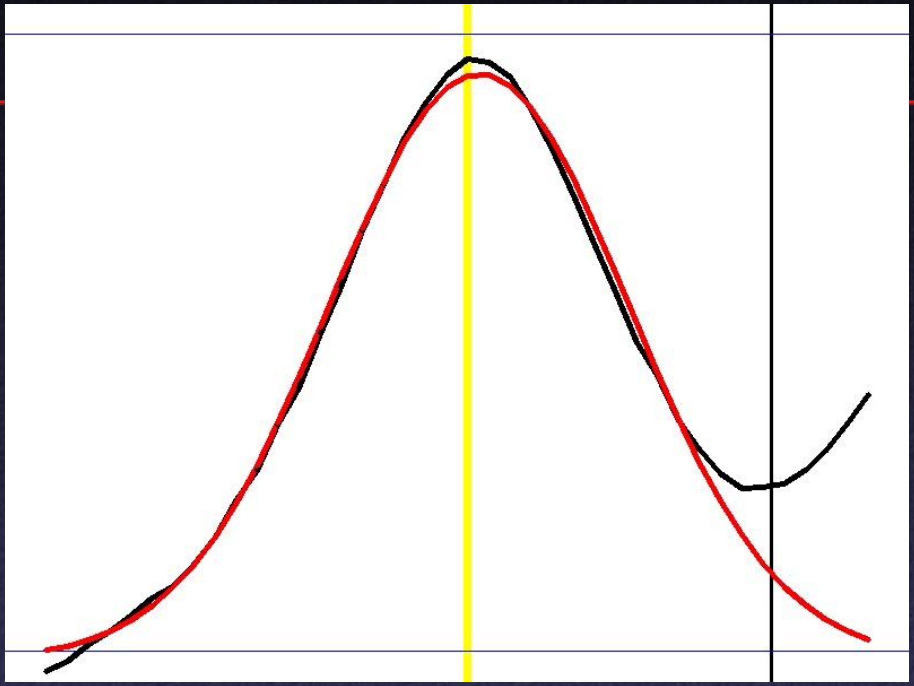


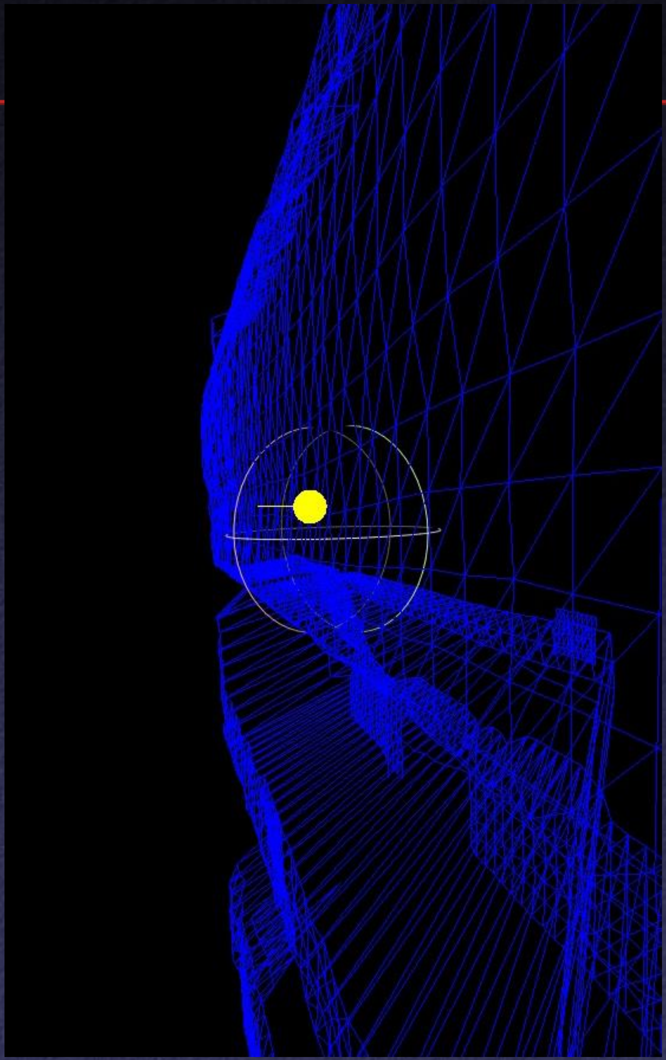
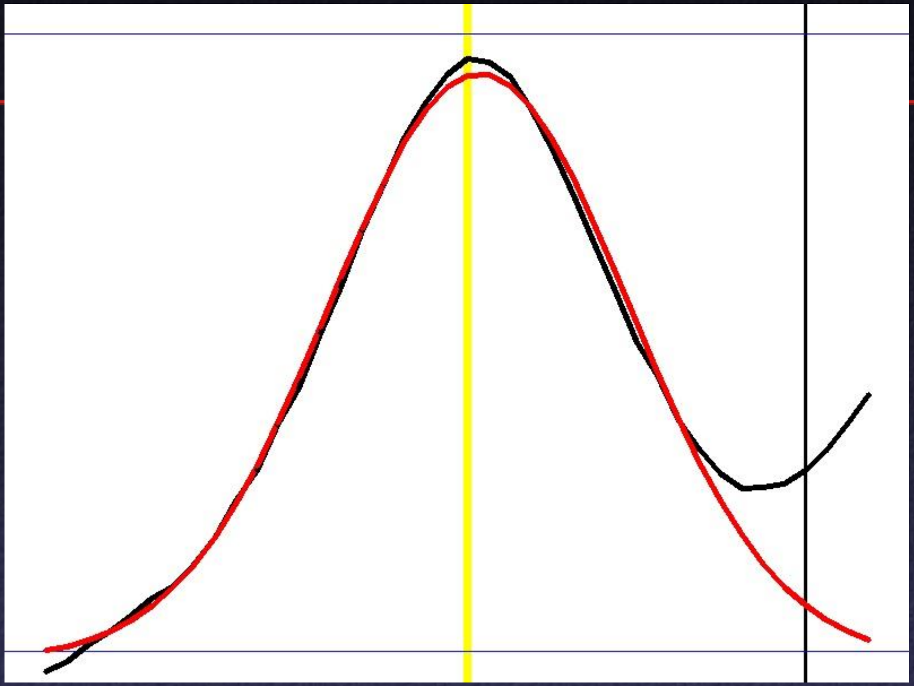


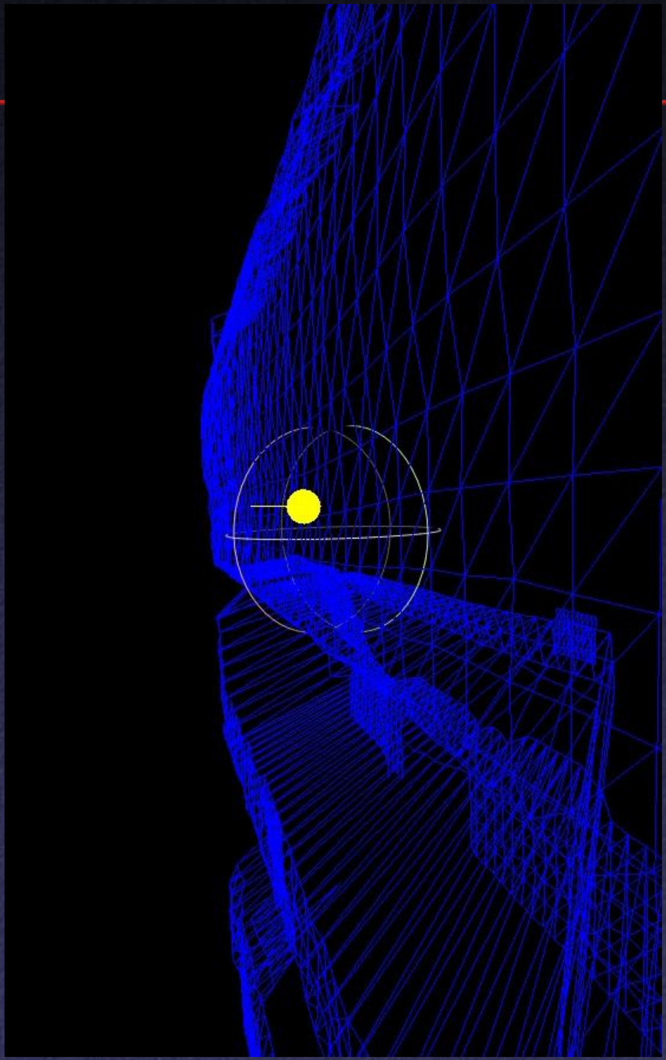
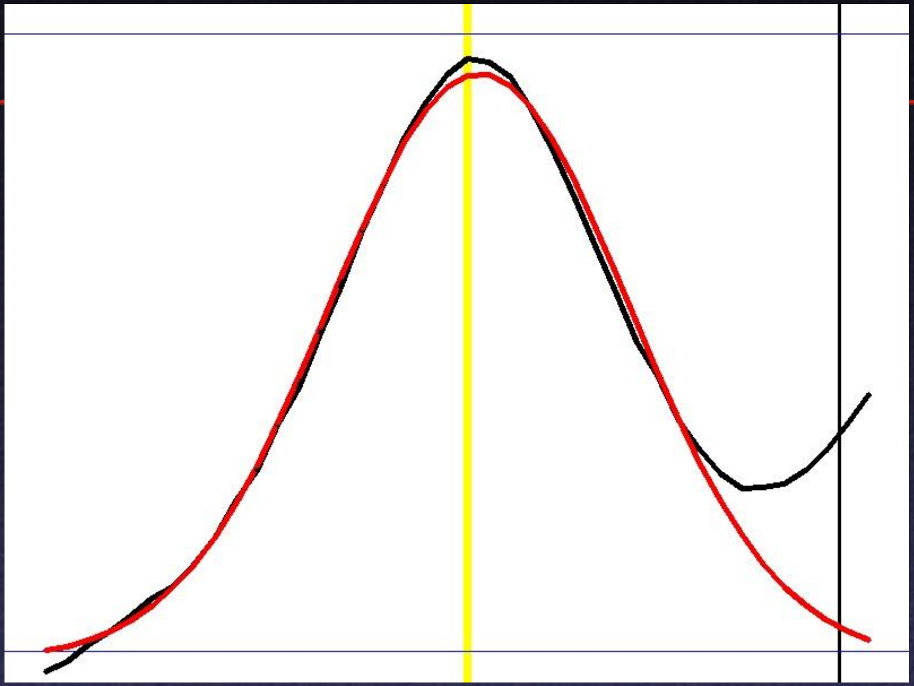


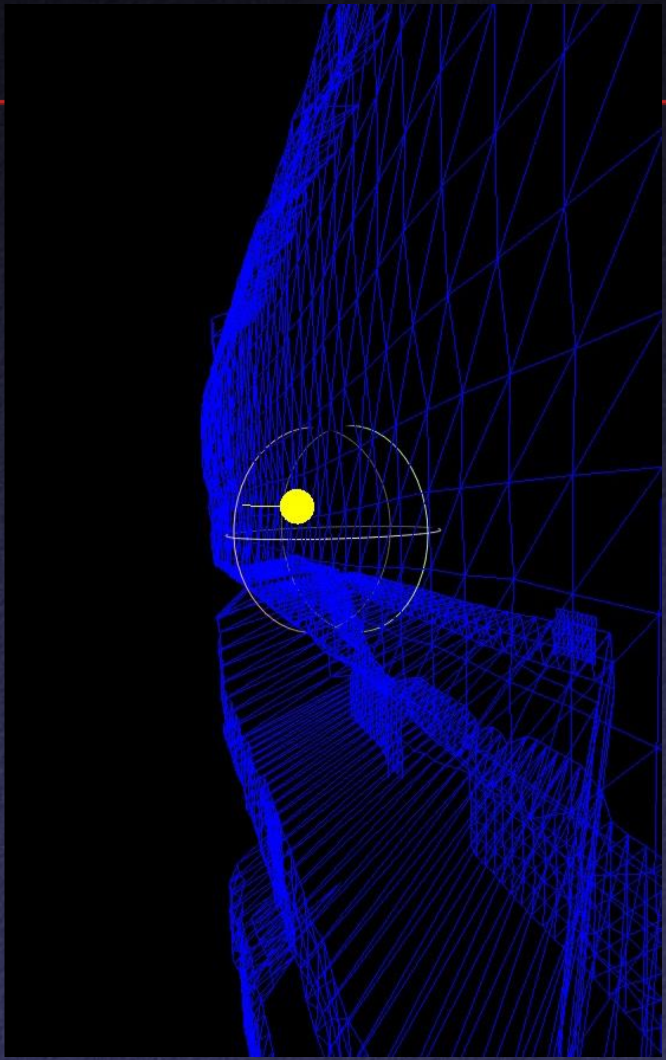
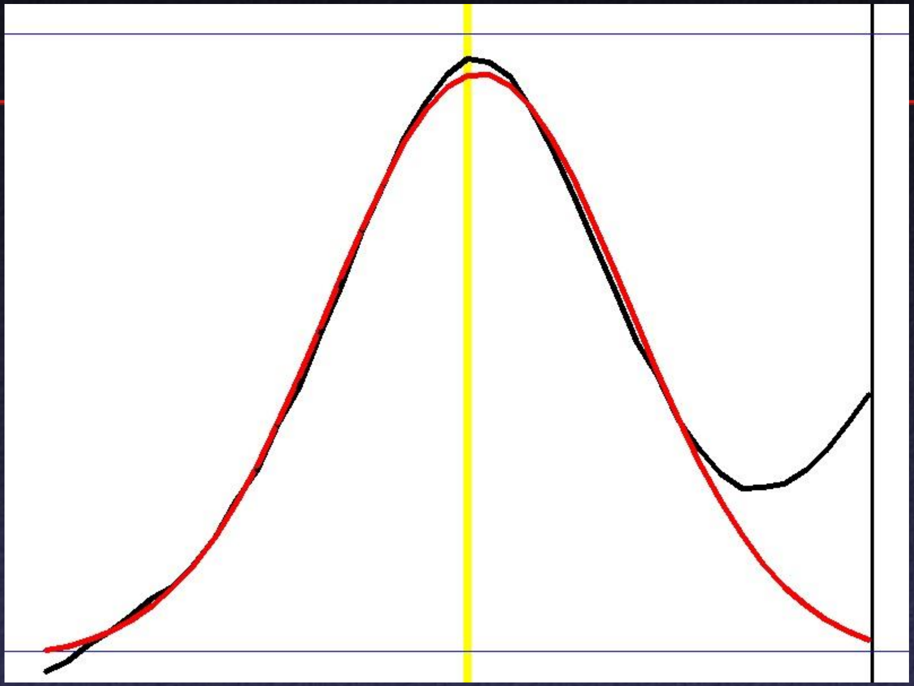




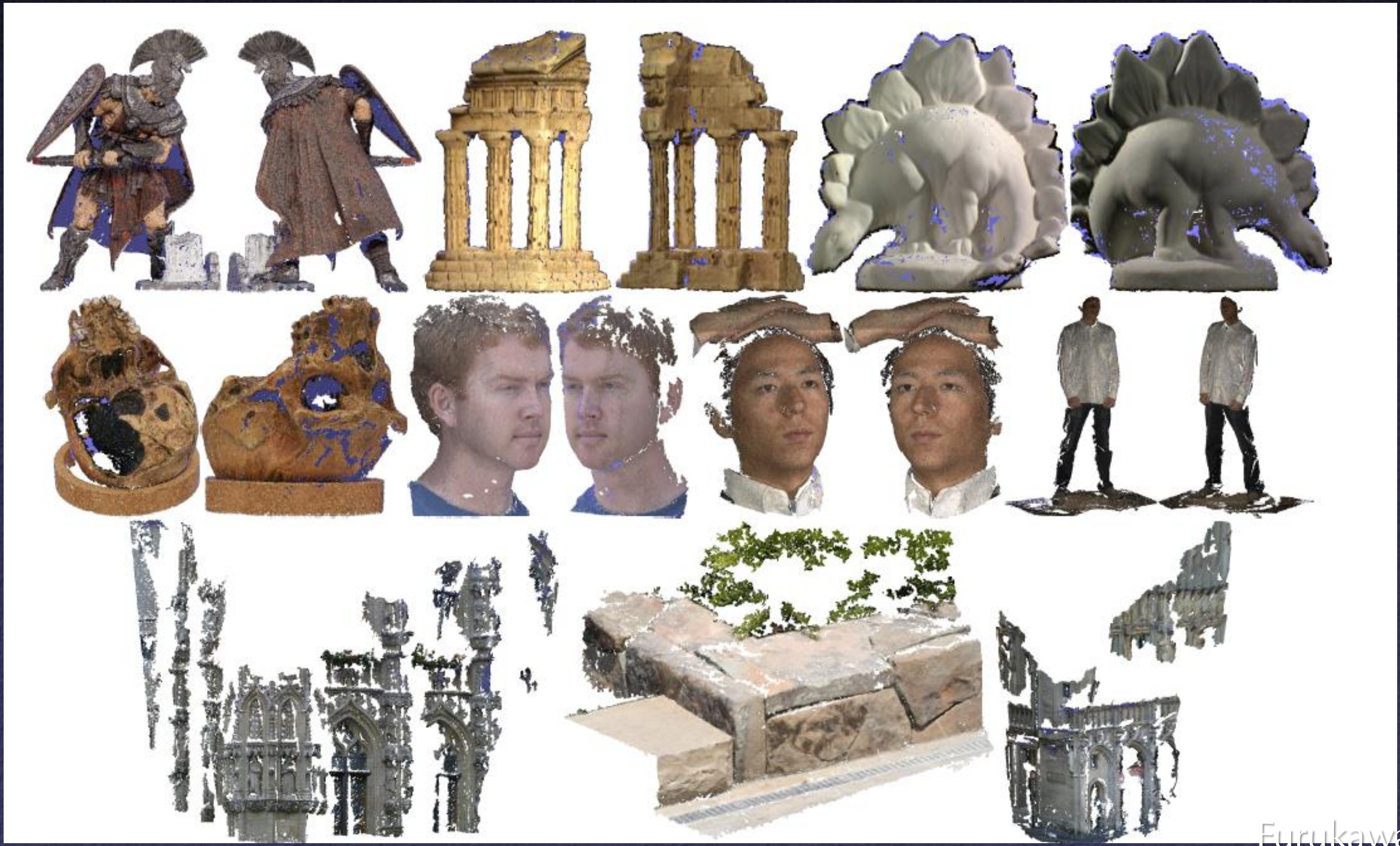



Patch + Mesh Results



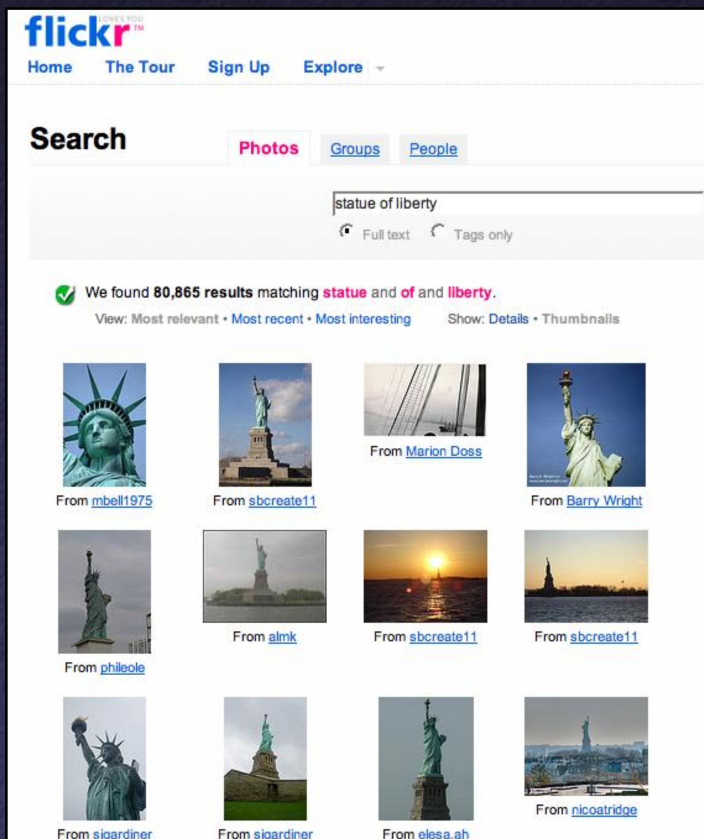
Furukawa

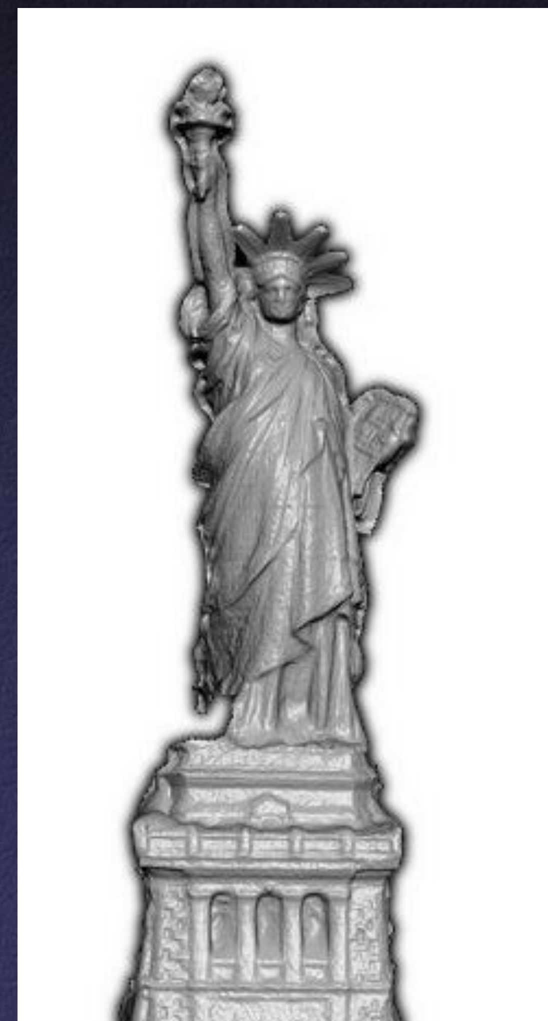
Patch + Mesh Results

Furukawa

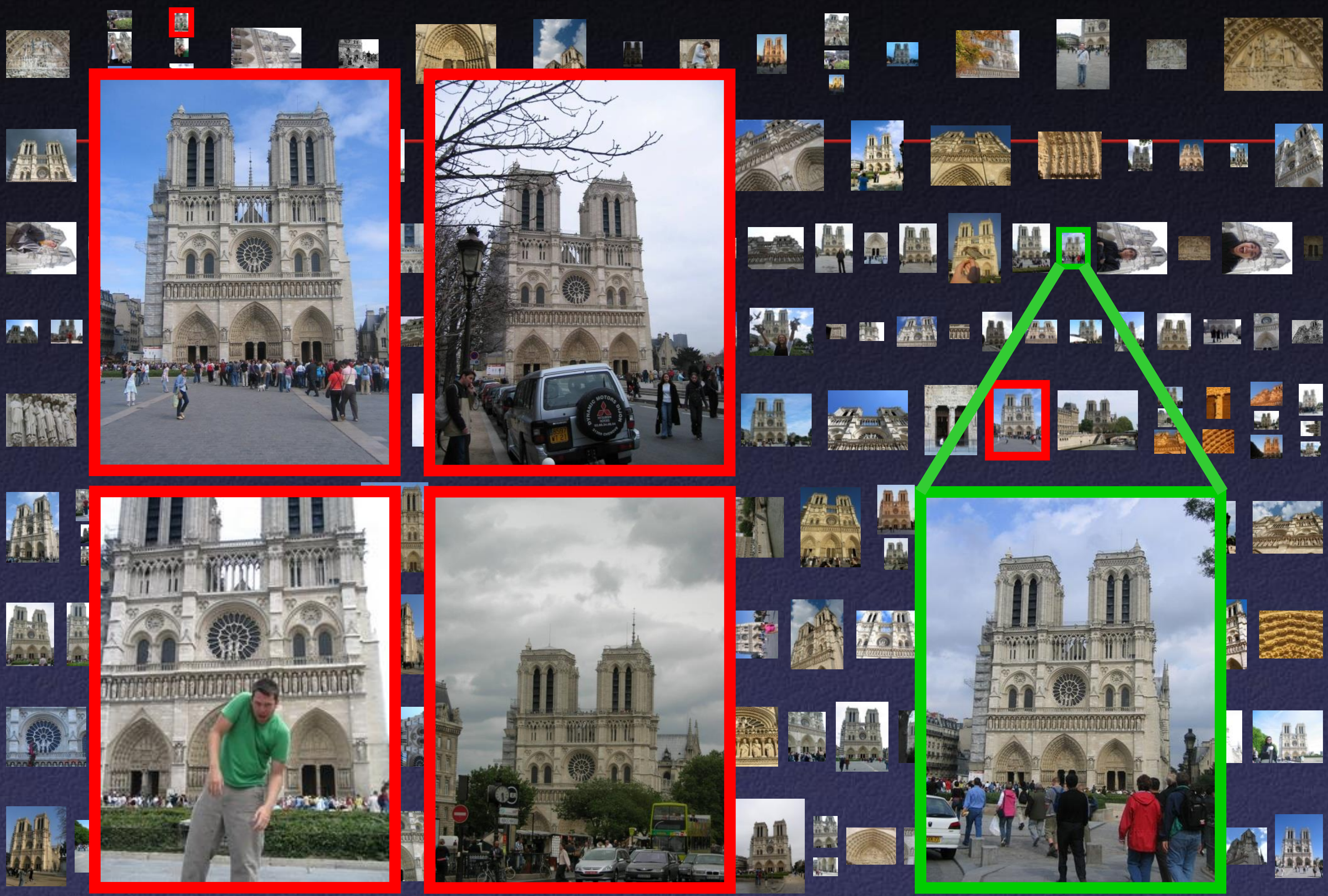
Multi-view stereo from Internet Collections

[Goesele, Snavely, Curless, Hoppe, Seitz, ICCV 2007]

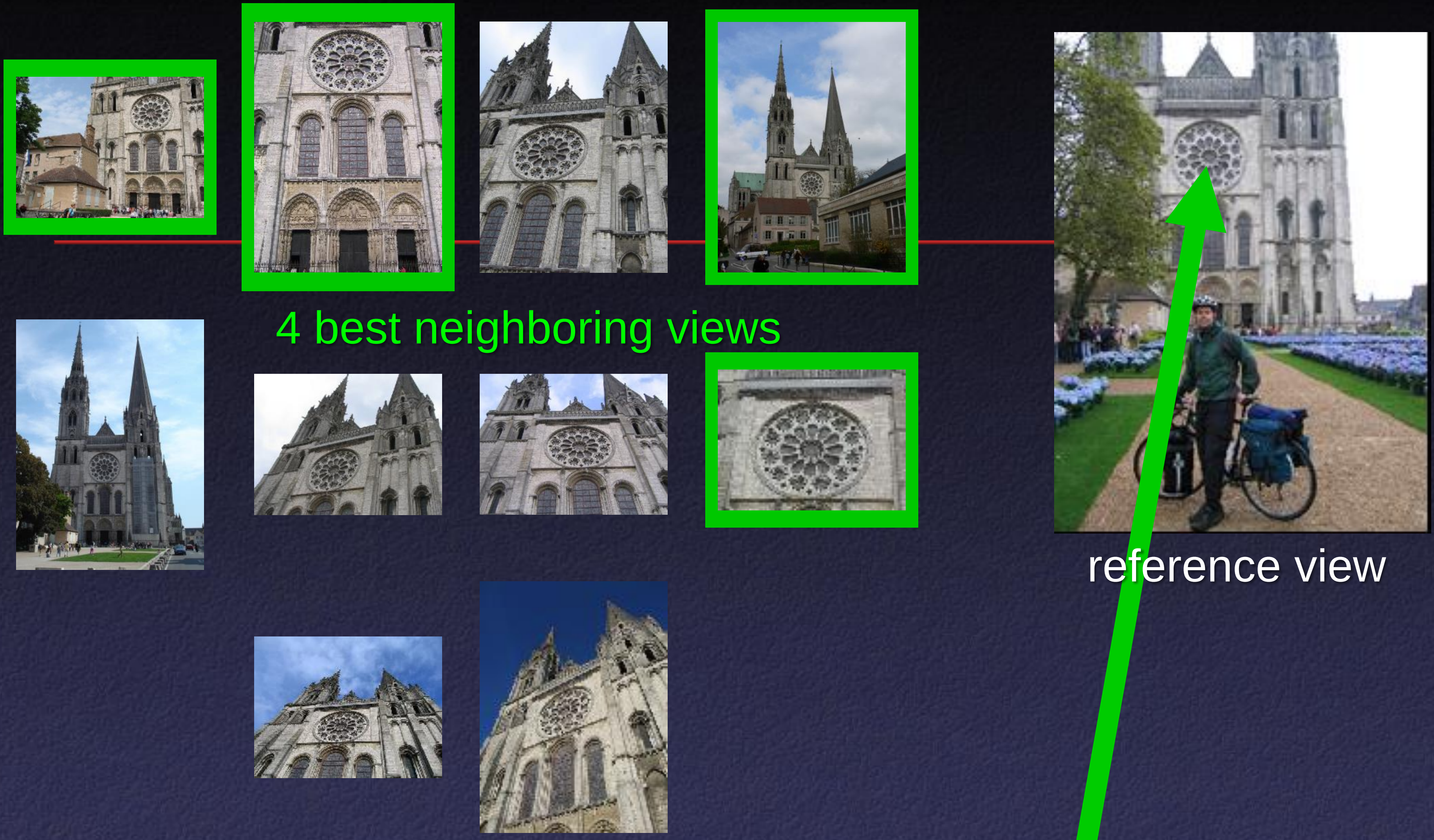




Law of Large Image Collections

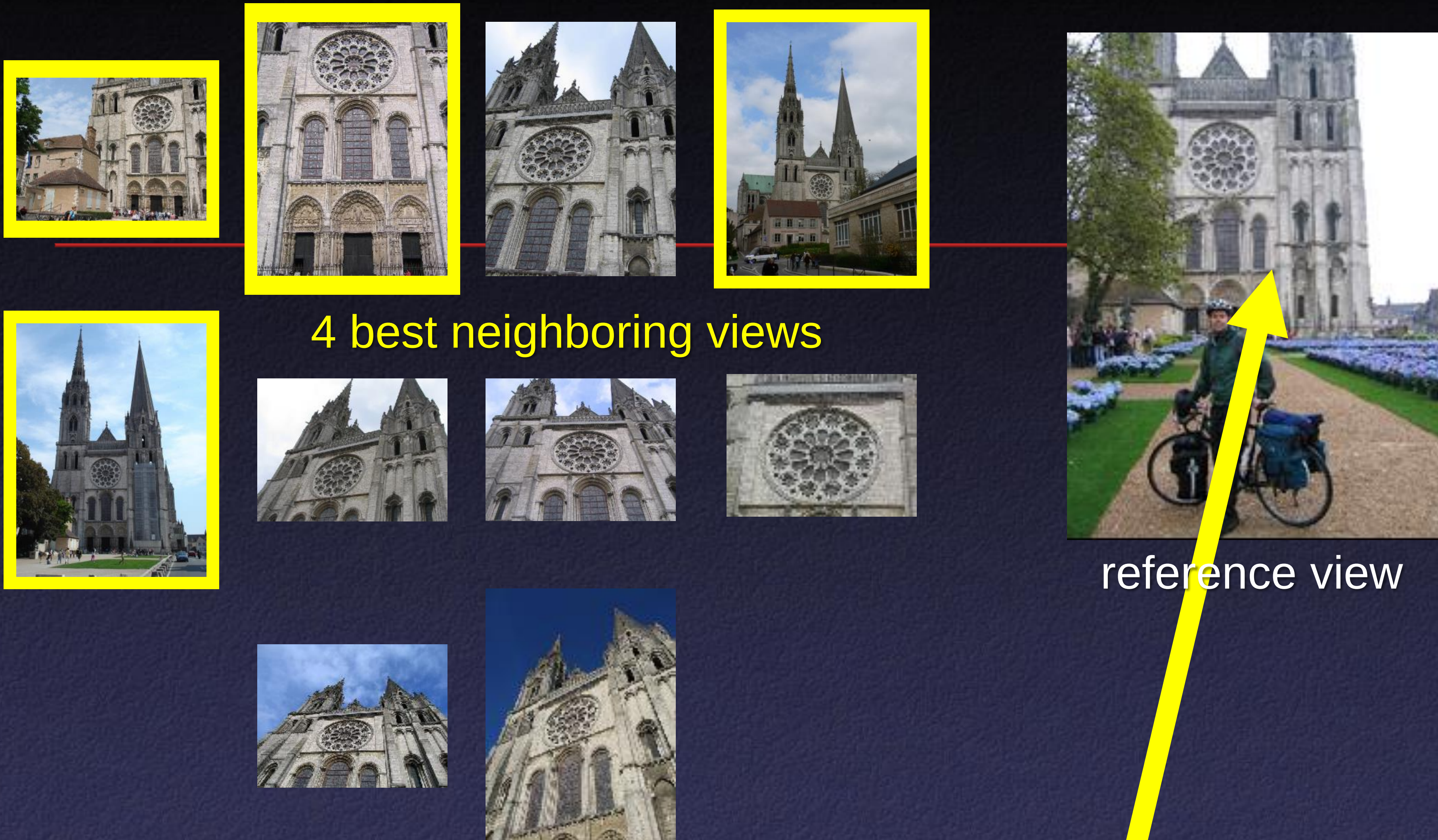


206 *Flickr* images taken by 92 photographers



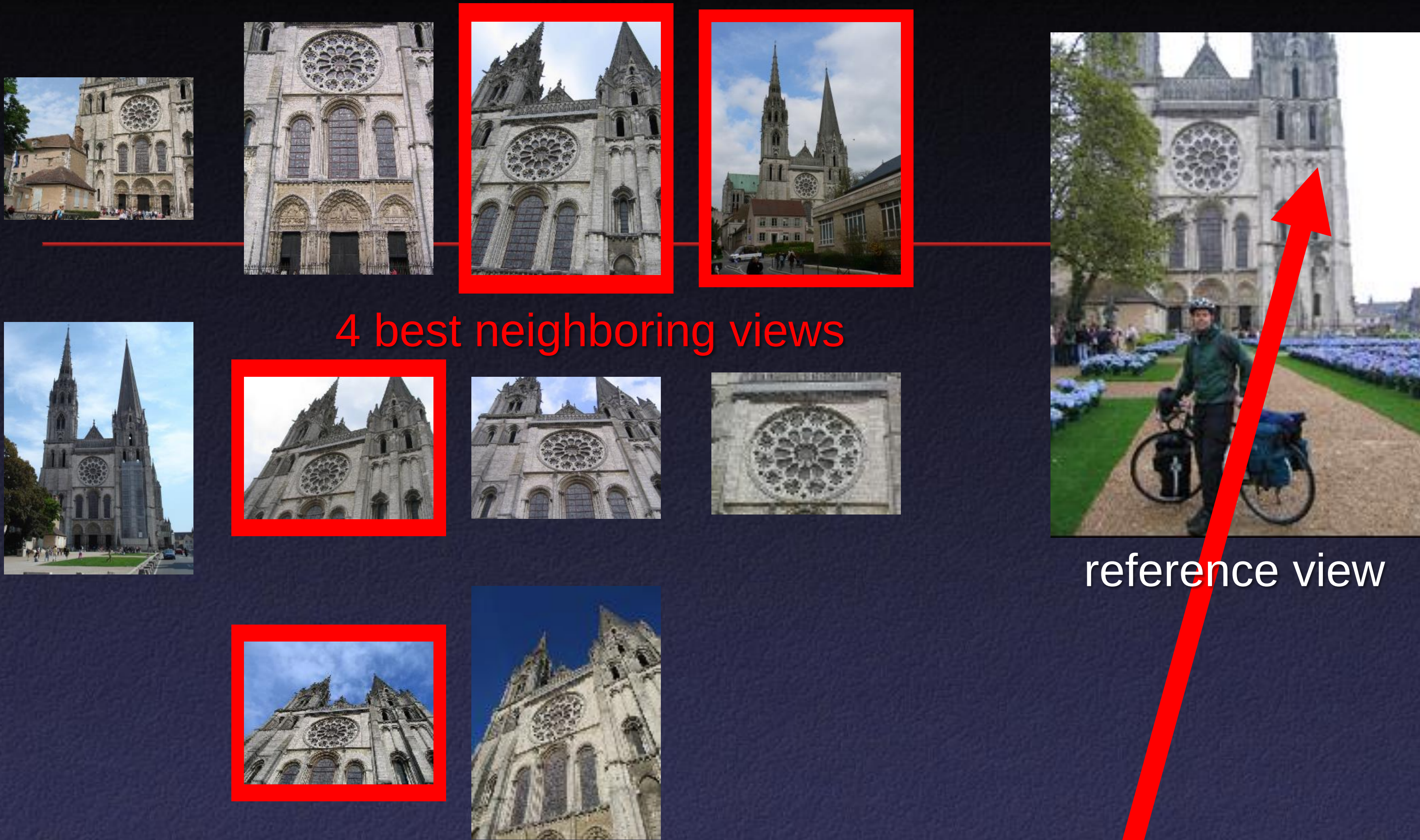
Local view selection

- Automatically select neighboring views for each point in the image
  - Desiderata: good matches AND good baselines



Local view selection

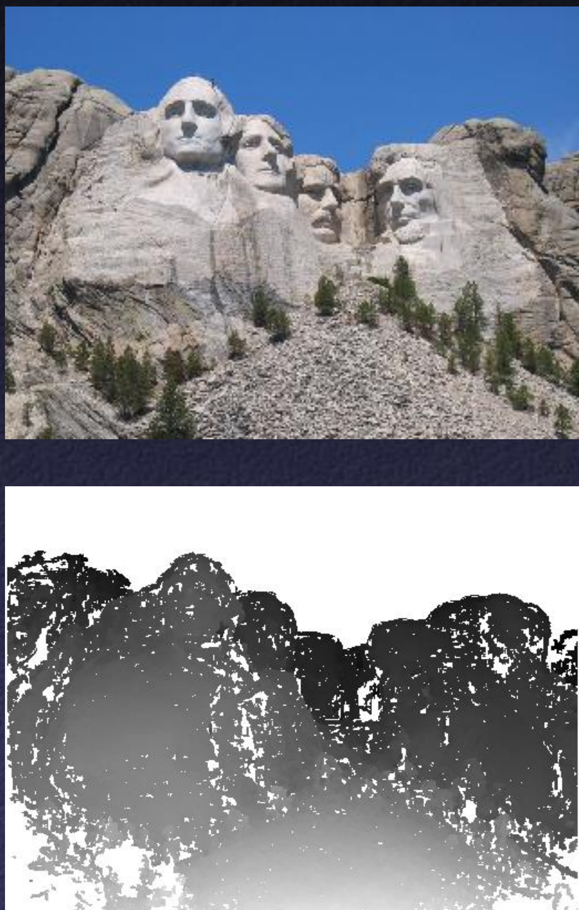
- Automatically select neighboring views for each point in the image
  - Desiderata: good matches AND good baselines



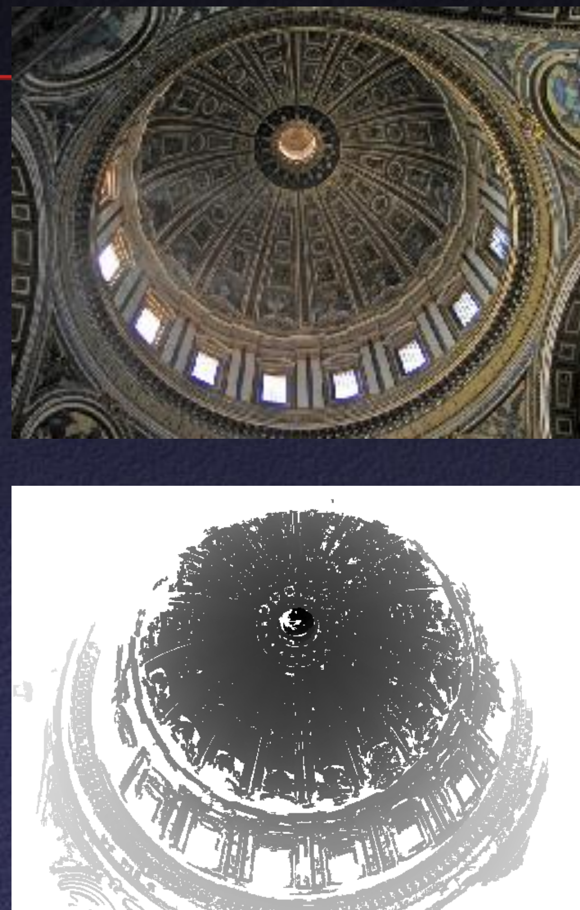
Local view selection

- Automatically select neighboring views for each point in the image
  - Desiderata: good matches AND good baselines

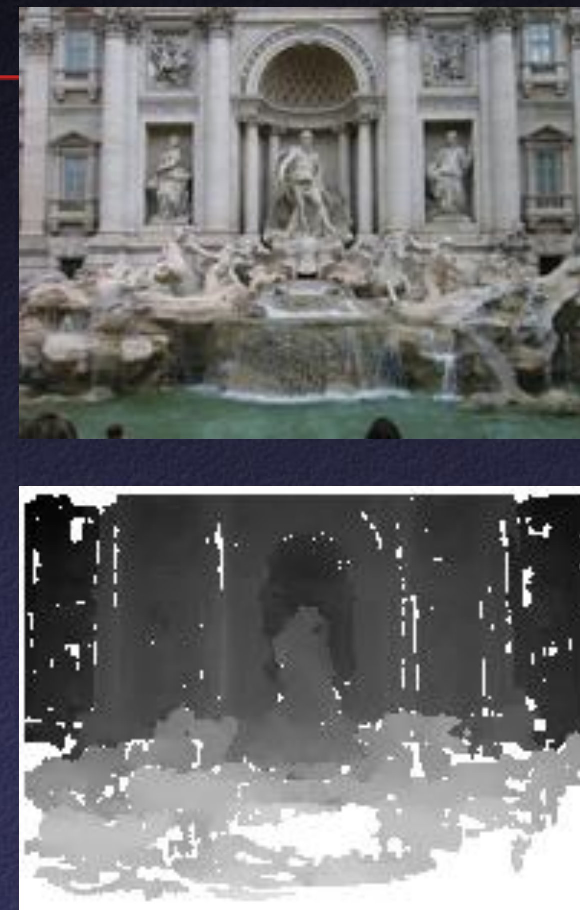
Results



Mt. Rushmore
160 images
60 photographers



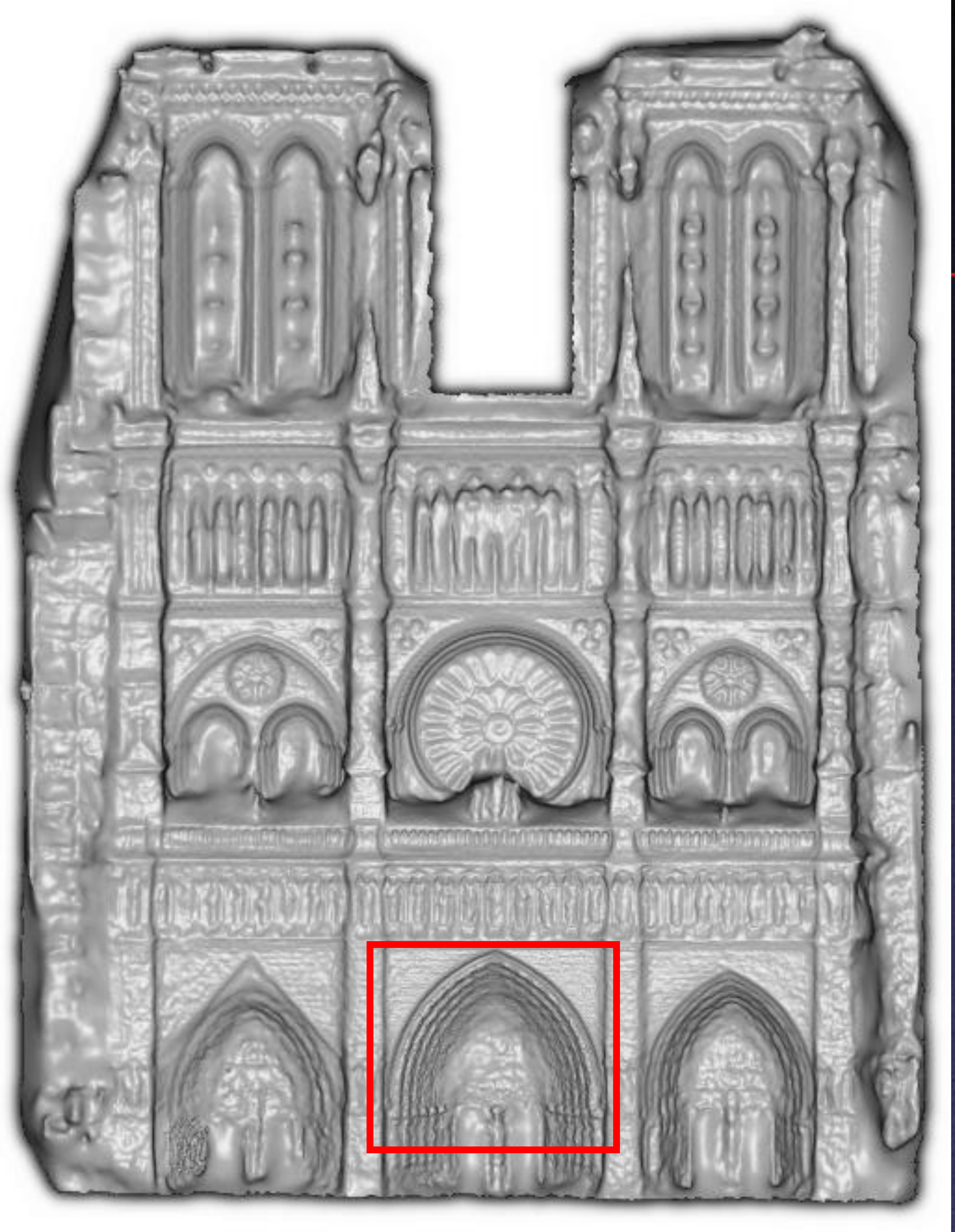
St. Peter
151 images
50 photographers

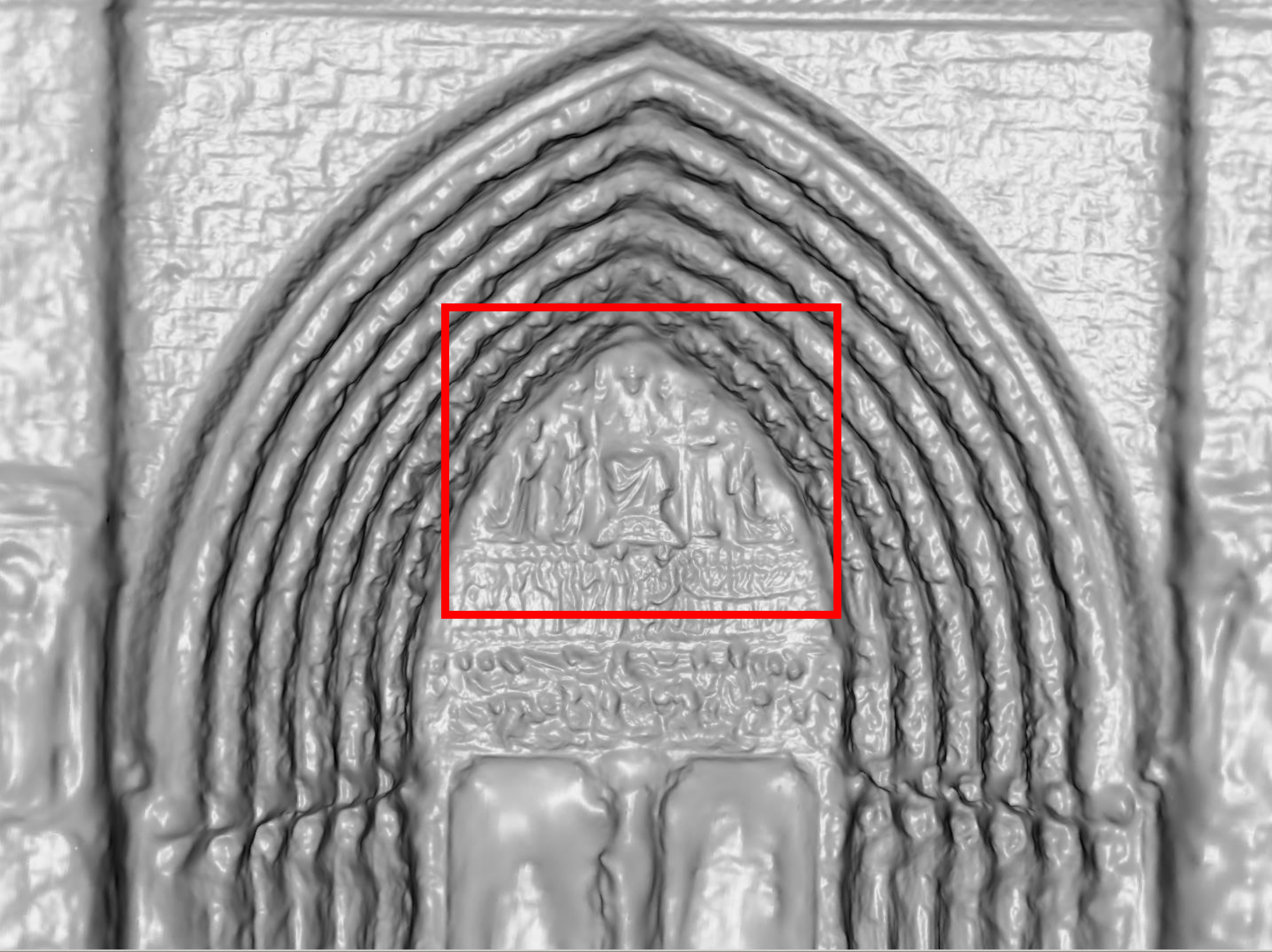


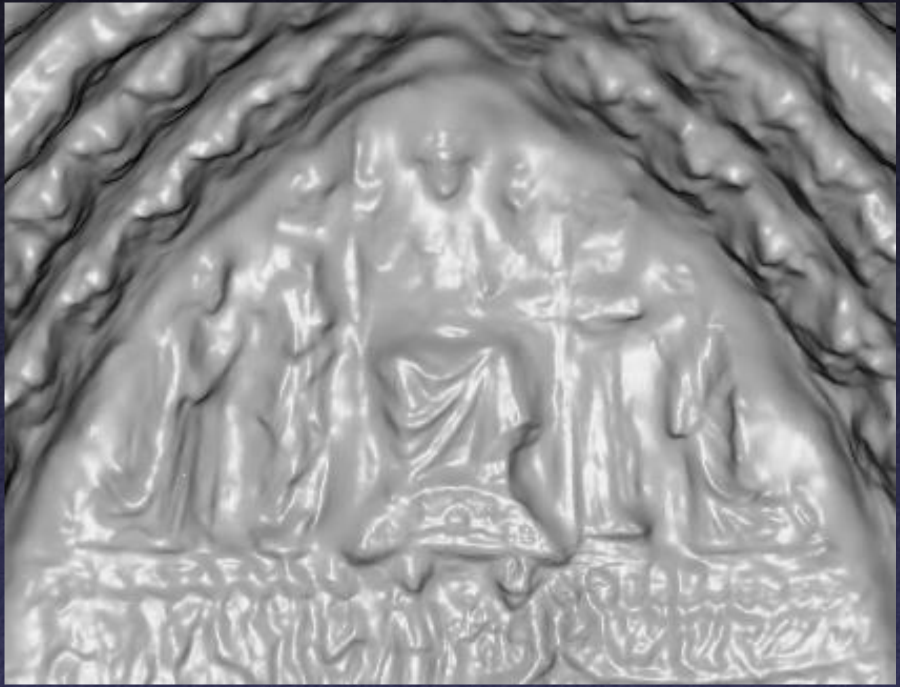
Trevi Fountain
106 images
51 photographers

Notre Dame de Paris

653 images
313 photographers



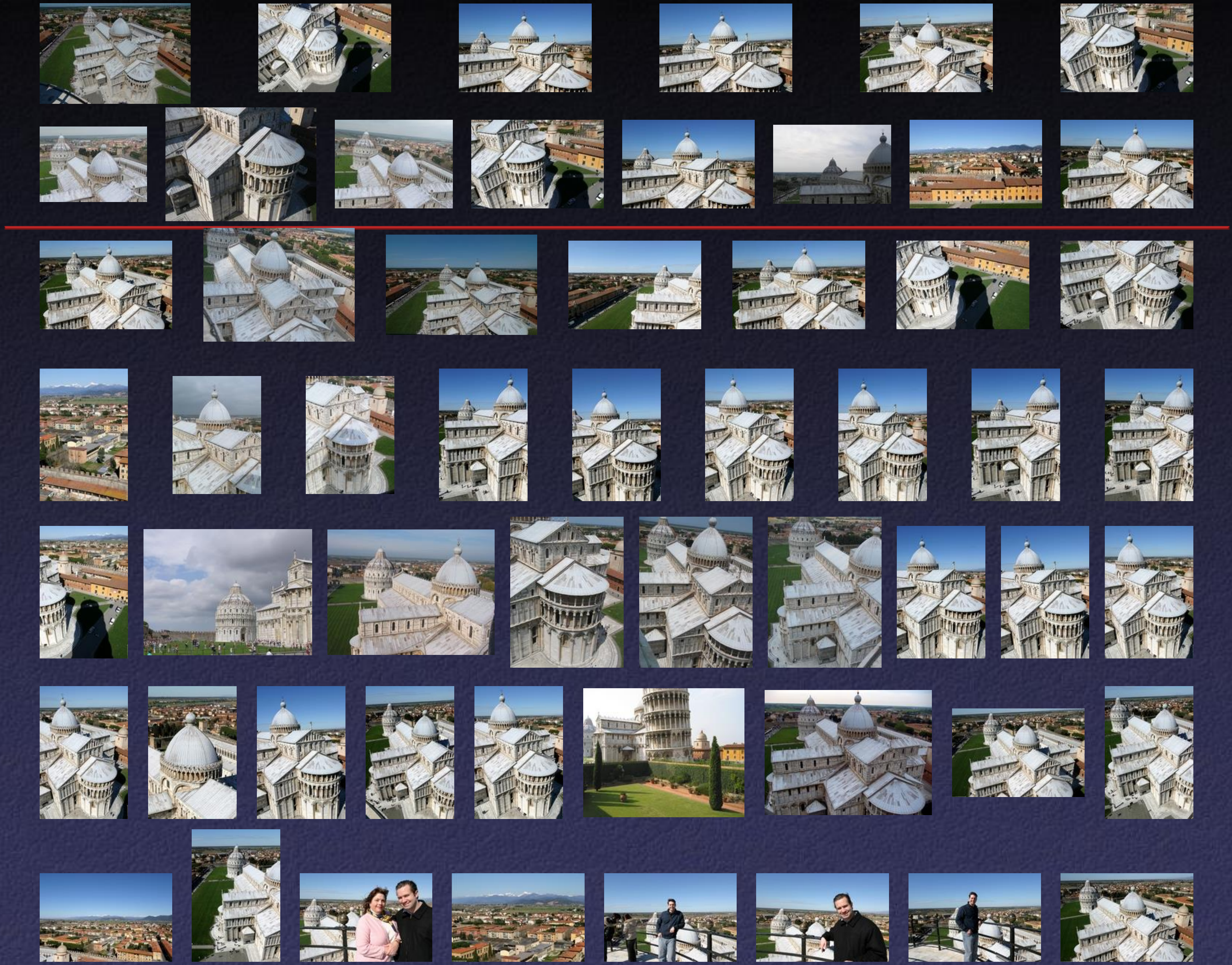




129 *Flickr* images taken by 98 photographers

Results

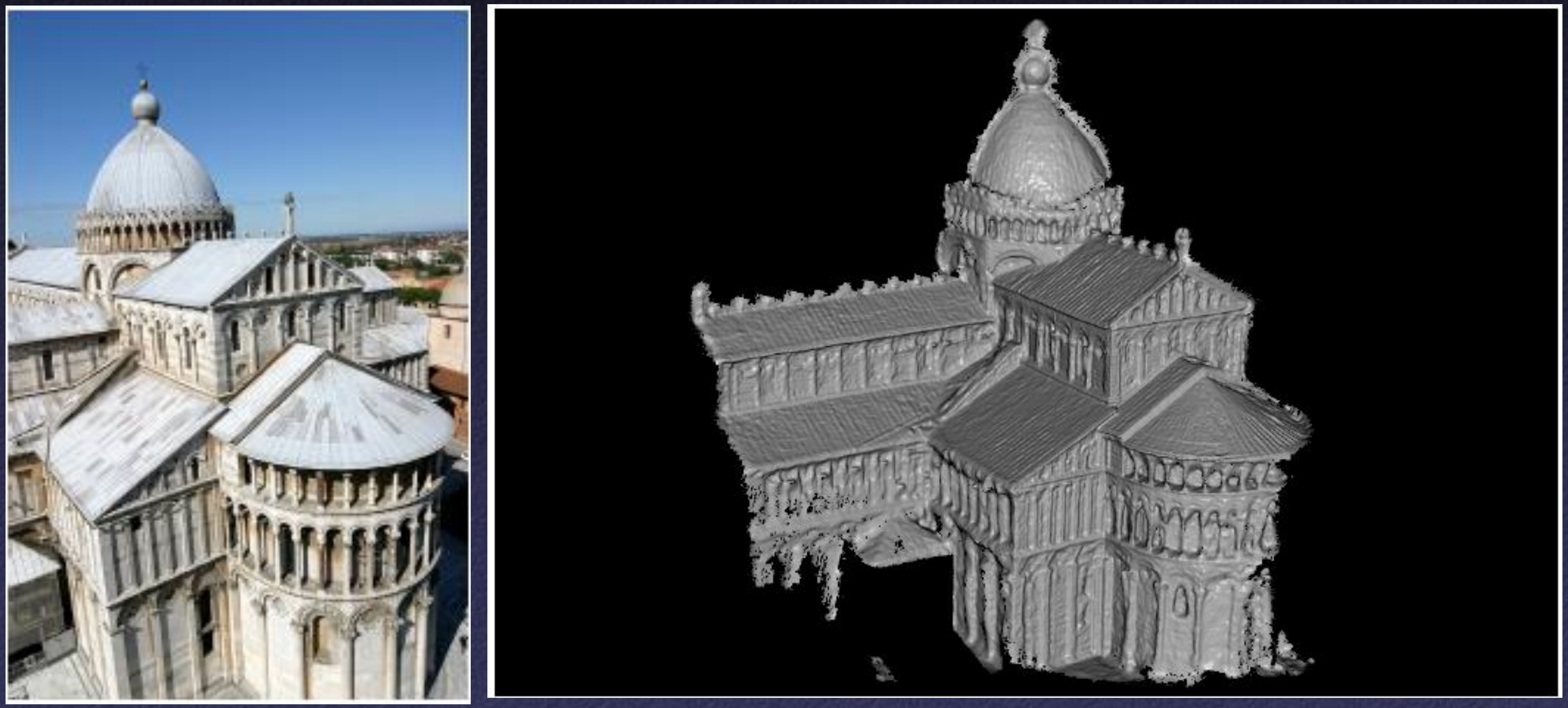
merged model of Venus de Milo



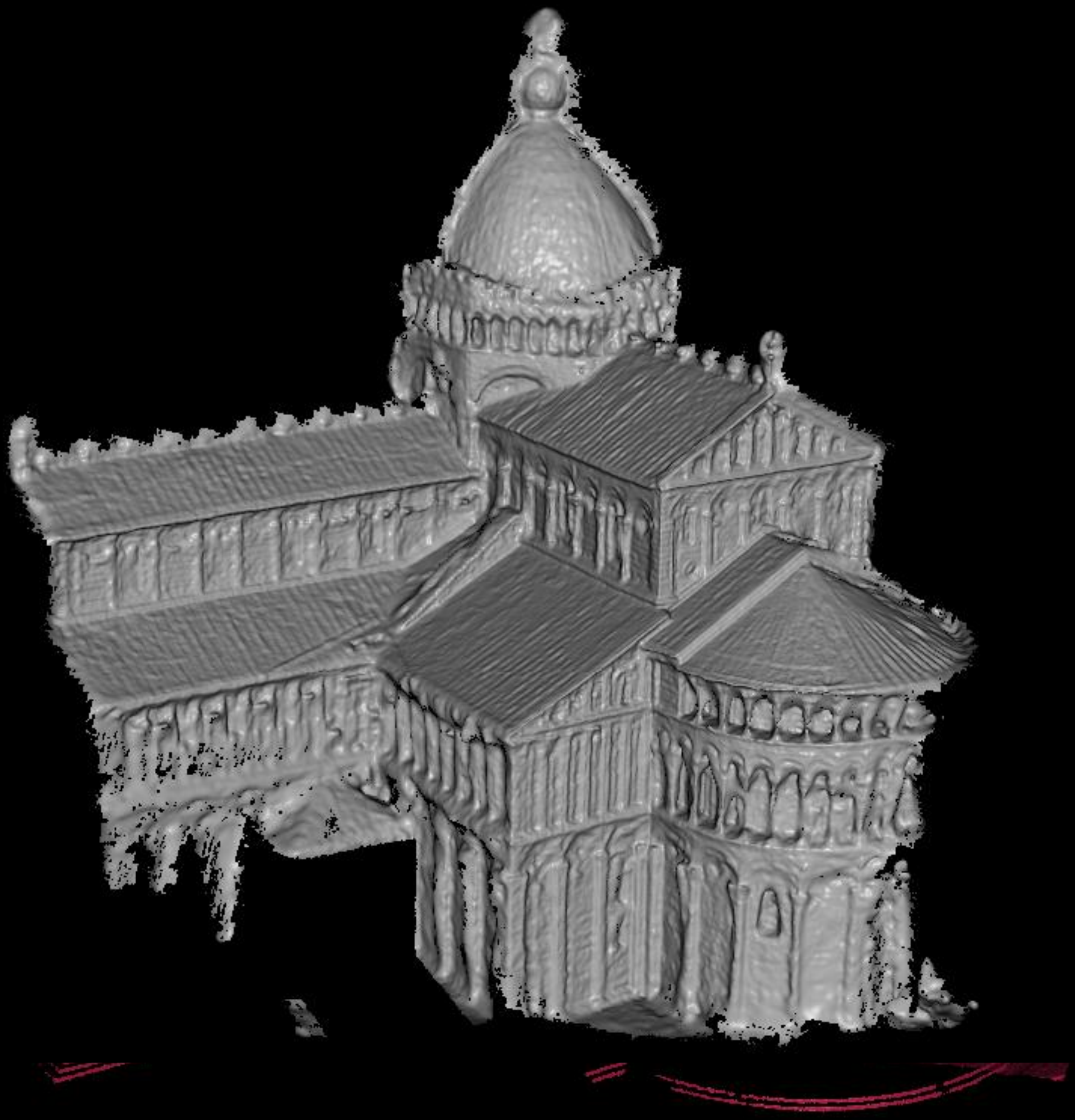
56 *Flickr* images taken by 8 photographers

[redacted]

Results



merged model of Pisa Cathedral



Accuracy compared to laser scanned model:
90% of points within *0.25%* of ground truth

Summary

- Image-centric approaches
  - Multibaseline stereo
  - Plane-sweep stereo
- Voxel-centric approaches
  - Silhouette carving
  - Voxel coloring
  - Space carving
- Surface-centric approaches
  - Feature detection + expansion/filtering
  - Mesh refinement