Volumetric Scene Reconstruction from Multiple Views

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Image-Based Scene Reconstruction

Goal

- *Automatic construction of photo-realistic 3D models of a scene from multiple images taken from a set of arbitrary viewpoints*
- *Image-based modeling; 3D photography*

Applications

- *Interactive visualization of remote environments or objects by a virtual video camera for flybys, mission rehearsal and planning, site analysis, treaty monitoring*
- *Virtual modification of a real scene for augmented reality tasks*

Two General Approaches

World Representation

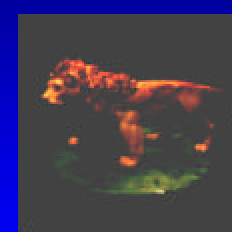
- **World centered: Recover a complete 3D geometric (and possibly photometric) model of scene**
- **Operations: feature correspondence, tracking, calibration, structure from motion, model fitting, ...**

Plenoptic Function Representation

- **Camera centered: Integration of images which sample scene geometry**
- **E.g., panoramas, light fields, LDIs**
- **Operations: image segmentation, registration, warping, compositing, interpolation, ...**

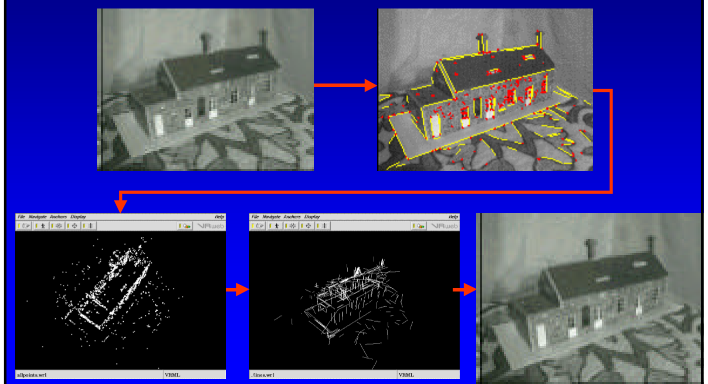
Light Fields

A range of viewpoints represented by a set of images [Levoy and Hanrahan, 1996]



Standard Approach: Multiple View Stereo

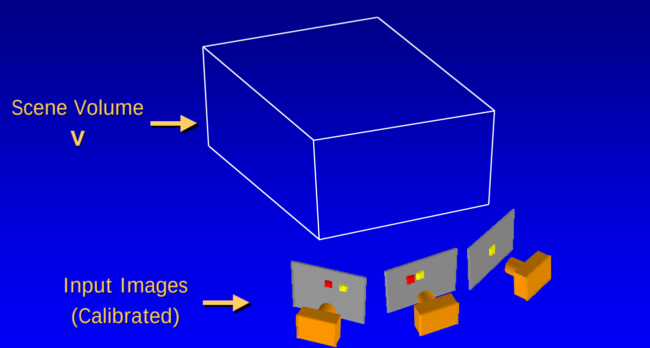
[Fitzgibbon and Zisserman, 1998]



Weaknesses of the Standard Approach

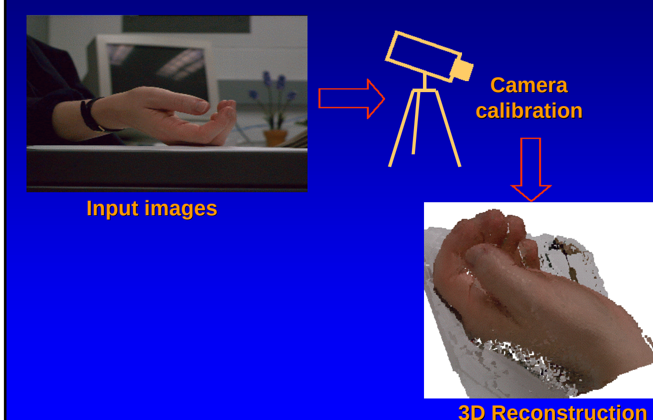
- ***Views must be close together in order to obtain point correspondences***
- ***Point correspondences must be tracked over many consecutive frames***
- ***Many partial models must be fused***
- ***Must fit a parameterized surface model to point features***
- ***No explicit handling of occlusion differences between views***

Our Approach: Volumetric Scene Modeling

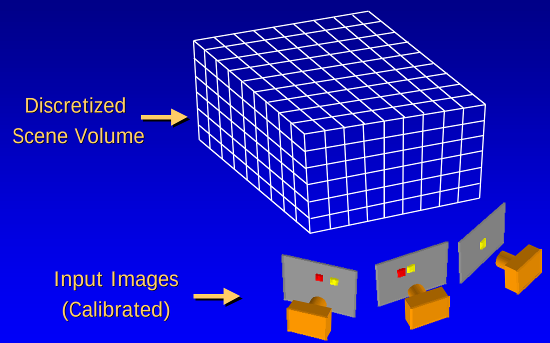


Goal: **Determine transparency and radiance of points in V**

3D Scene Reconstruction from Multiple Views

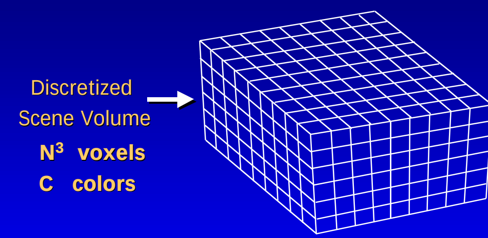


Discrete Formulation: Voxel Space



Goal: **Assign RGBA values to voxels in V that are *photo-consistent* with all input images**

Complexity and Computability



N^3 voxels
C colors

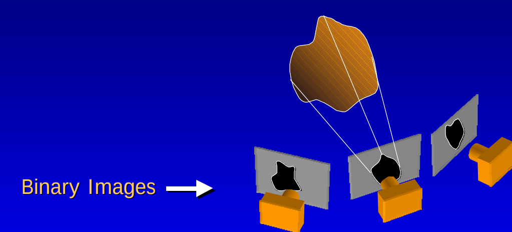
G = space of all colorings (C^{N^3})
P = space of all photo-consistent colorings (computable?)
S = true scene (not computable)

$$S \in P \subset G$$

Voxel-based Scene Reconstruction Methods

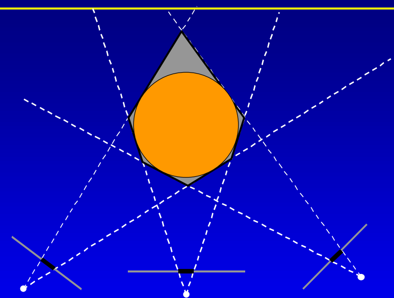
1. *Shape from Silhouettes*
   - **Volume intersection** [Martin & Aggarwal, 1983]
2. *Shape from Photo-Consistency*
   - **Voxel coloring** [Seitz & Dyer, 1997]
   - **Space carving** [Kutulakos & Seitz, 1999]

Reconstruction from Silhouettes



Approach:
- ***Backproject* each silhouette**
- **Intersect backprojected generalized-cone volumes**

Volume Intersection



Reconstruction contains the true scene

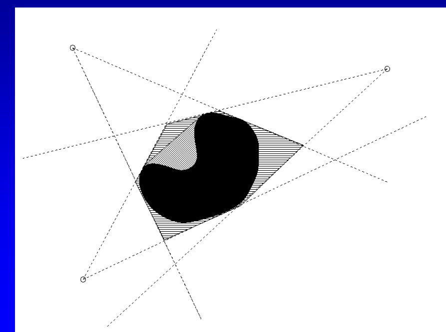
Best case (infinite # views): visual hull

(complement of all lines that don't intersect S)

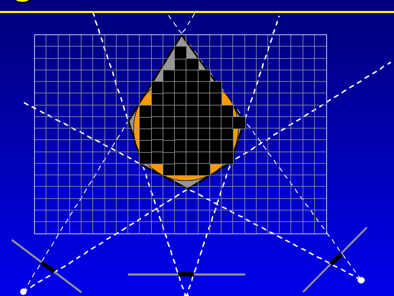
- 2D: convex hull
- 3D: convex hull – hyperbolic regions

Shape from Silhouettes

Reconstruction = object + concavities + points not visible



Voxel Algorithm for Volume Intersection



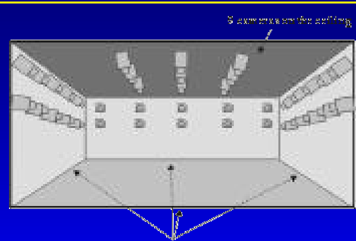
Color voxel black if in silhouette in every image

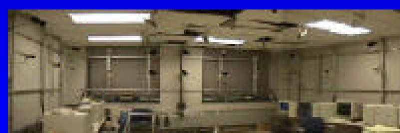
- **$O(MN^3)$ time for M images, N^3 voxels**
- **Don't have to search 2^{N^3} possible scenes**

Image-based Visual Hulls

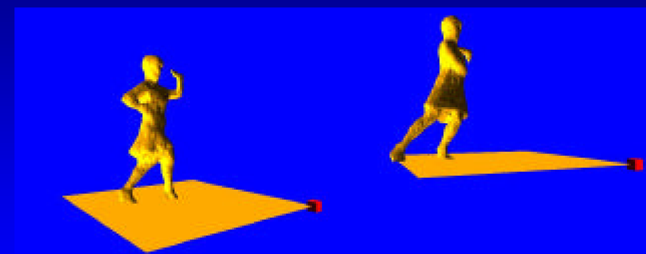
[Matusik *et al*., 2000]

CMU's Virtualized Reality System



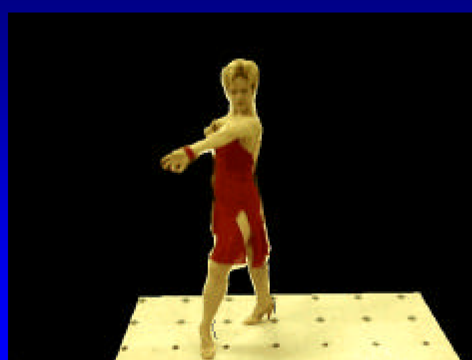


Shape from 49 Silhouettes



Surface model constructed using Marching Cubes algorithm

Virtual Camera Fly-By



Texture mapped and sound synthesized from 6 sources

Properties of Volume Intersection

Pros

- Easy to implement
- Accelerated via octrees

Cons

- Concavities are not reconstructed
- Reconstruction does not use photometric properties in each image
- Requires image segmentation to extract silhouettes

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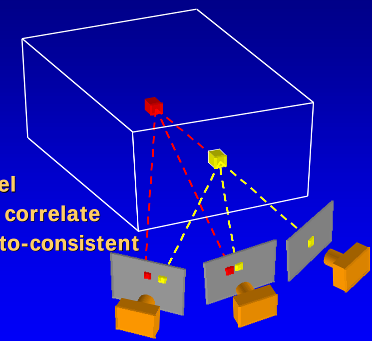
Voxel Coloring Approach

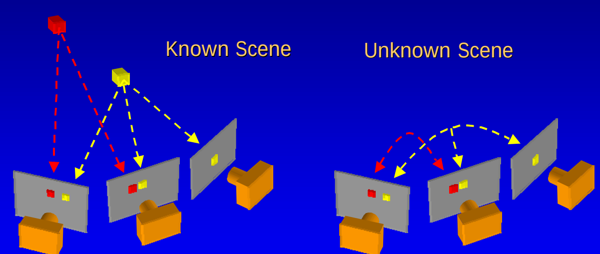


1. **Choose voxel**
2. **Project and correlate**
3. **Color if photo-consistent**

Visibility Problem: **In which images is each voxel visible?**

The Global Visibility Problem

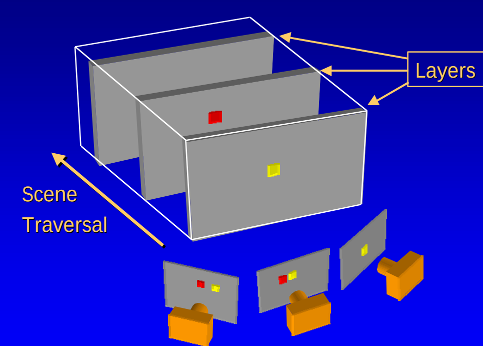
Which points are visible in which images?



Forward Visibility
known scene

Inverse Visibility
known images

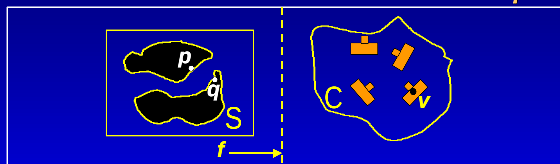
Depth Ordering: Visit Occluders First



Condition: **Depth order is *view-independent***

What is a *View-Independent* Depth Order?

A function f over a scene S and a camera space C



such that for all *p* and *q* in S, *v* in C

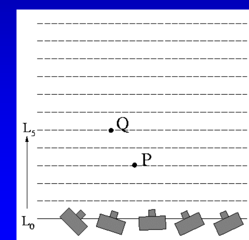
p occludes *q* from *v* *only if* `f(p) < f(q)`

For example: *f* = distance from separating plane

⇒ Plane Sweep order [Collins, 1996]

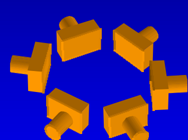
Example: 2D Scene and Line of Cameras

- *Arrange cameras to simplify occlusion relationships*
- *Depth-order traversal of voxels determines visibility*

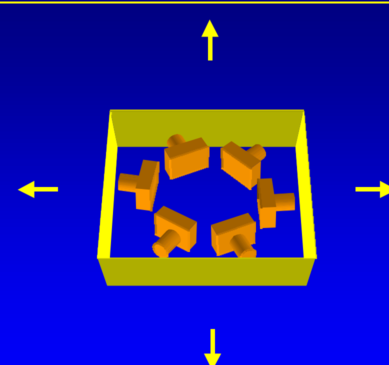


Panoramic Depth Ordering

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

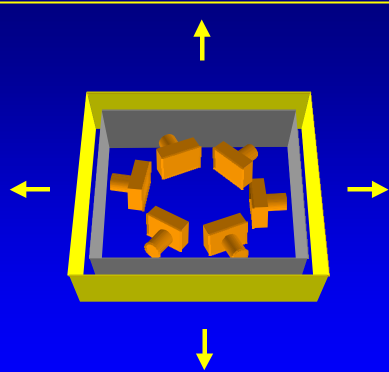


Panoramic Depth Ordering



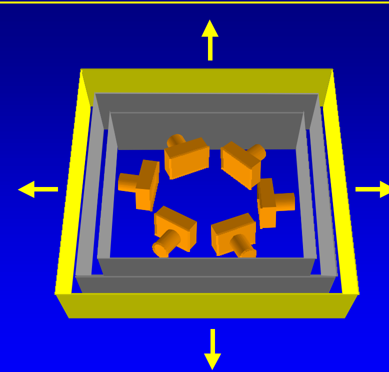
Layers radiate outwards from cameras

Panoramic Layering



Layers radiate outwards from cameras

Panoramic Layering

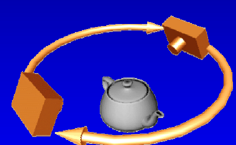


Layers radiate outwards from cameras

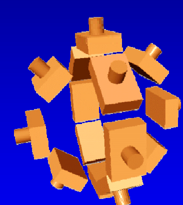
Compatible Camera Configurations

Depth-Order Constraint

- Scene outside convex hull of camera centers

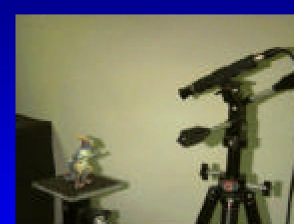


Inward-Looking
cameras above scene

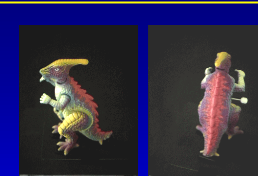


Outward-Looking
cameras inside scene

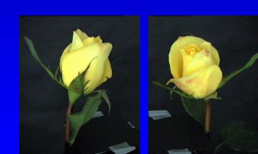
Calibrated Image Acquisition



Calibrated Turntable
360° rotation (21 images)

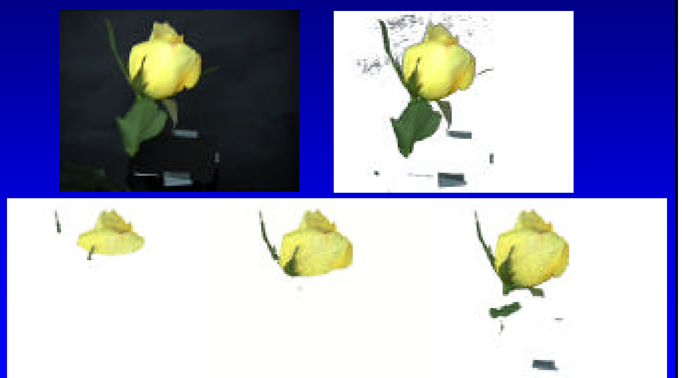


Selected Dinosaur Images



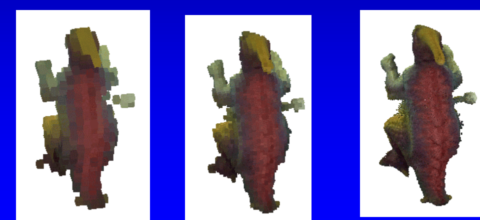
Selected Flower Images

Layered Scene Traversal



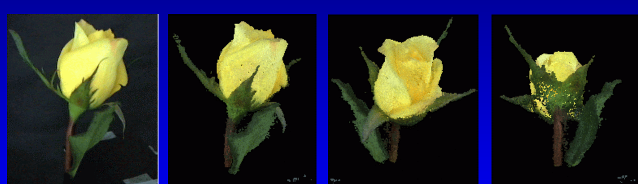
Results: Dinosaur

21 input images
spanning 360° rotation



1K voxels 5K voxels 72K voxels

Results: Rose



1 of 21 input images

3 synthesized views

Results

Dinosaur Reconstruction
21 input images
72 K voxels colored
7.6 M voxels tested

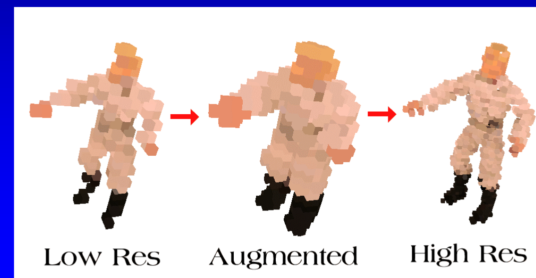
Flower Reconstruction
21 input images
70 K voxels colored
7.6 M voxels tested

Scaling Up Voxel Coloring

- *Time complexity µ #voxels ´ #images*
- *Too many voxels in large, high-resolution scenes*
- *Enhancements*
  - **Texture mapping – use hardware to project images to each layer of voxels**
  - **Variable voxel resolution – use octrees and coarse-to-fine processing**
  - **Volumetric warping – warp voxel space to extend to an infinite domain**

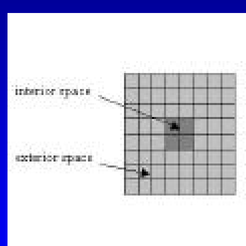
Coarse-to-Fine Voxel Coloring: Octrees

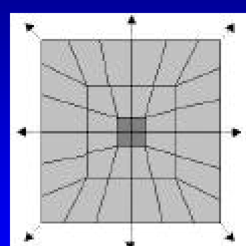
Determine colored voxels at current level
Spatial coherence Þ add neighboring voxels
Decompose colored voxels into octants; repeat



Volumetric Warping

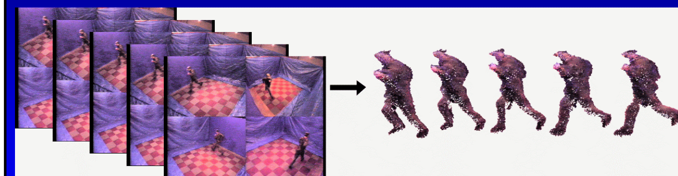
- *G. Slabaugh, T. Malzbender, B. Culbertson, 2000*





Results

Voxel Coloring for Dynamic Scenes



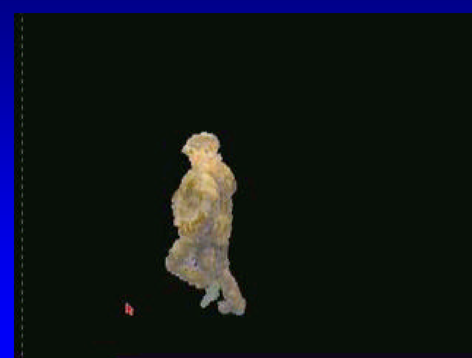
Given: Video sequences from multiple cameras

Goal: Interactive, real-time fly-by of dynamic scene

Dynamic Voxel Coloring: Input Views

Reconstruction for One Time Instant

Sequence of Reconstructions

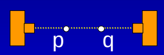


Voxel Coloring for Dynamic Scenes

- *Coarse-to-fine recursive decomposition focuses on regions of interest*
- *Exploit temporal coherence*
  - **Use coloring at time t_k to initialize lowest resolution voxels at time t_{k+1}**
  - **Trace rays from changed pixels only**

Limitations of Depth Ordering

A view-independent depth order may not exist:



Need more general algorithm
- **Unconstrained camera positions**
- **Unconstrained scene geometry and topology**

Voxel-based Scene Reconstruction Methods

1. *Shape from Silhouettes*
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2. *Shape from Photo-Consistency*
   - **Voxel coloring** [Seitz & Dyer, 1997]
   - **Space carving** [Kutulakos & Seitz, 1999]

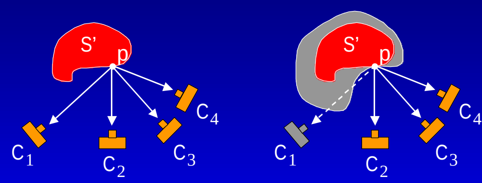
Space Carving Algorithm

Step 1: Initialize V to volume containing true scene with all voxels marked opaque

Step 2: For every voxel on surface of V
- Test *photo-consistency* of voxel with those cameras that are "in front of" it
- If voxel is inconsistent, carve it (i.e., mark it *transparent*)

Step 3: Repeat Step 2 until all voxels consistent

Visibility Property



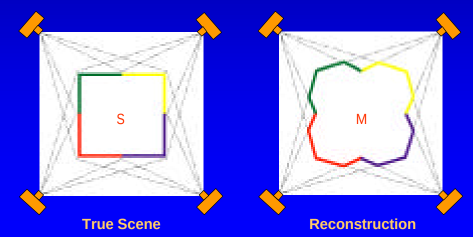
p Î S´ consistent Þ p Î consistent

p Î inconsistent Þ p Î S´ inconsistent

This property ensures that carving converges

Space Carving Convergence

- **Guaranteed convergence to the *photo hull*, i.e., union of all photo-consistent scenes**
- ***Worst case* # consistency checks:**
  (# cameras)^2(# voxels)



Space Carving Algorithm

Optimal algorithm is unwieldy

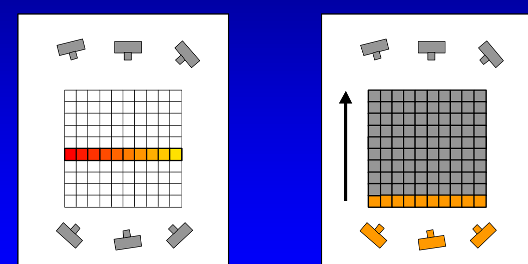
- **Complex visibility update procedure**

Alternative: Multi-Pass Plane Sweep Algorithm

- **Efficient, can use texture-mapping hardware**
- **Converges quickly in practice**
- **Easy to implement**

Multi-Pass Plane Sweep

- **Sweep plane in each of 6 principle directions**
- **Consider cameras on only one side of plane**
- **Repeat until convergence**



True Scene　　　Reconstruction

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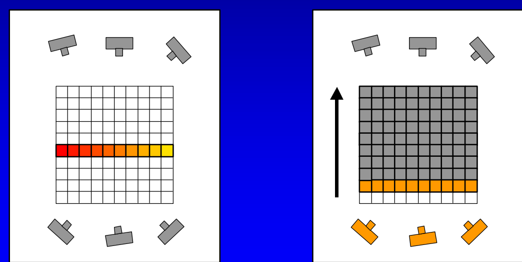

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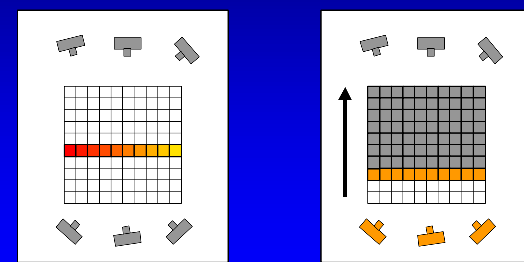

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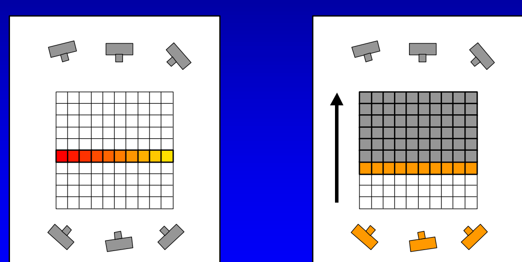

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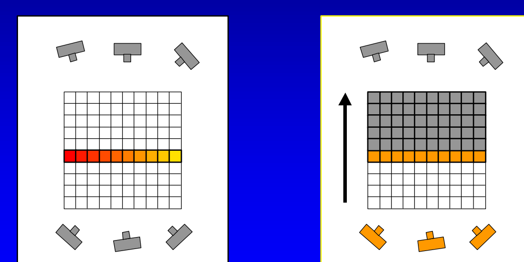

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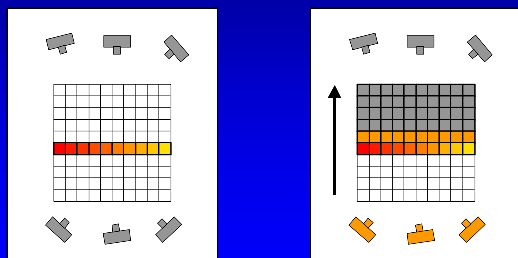

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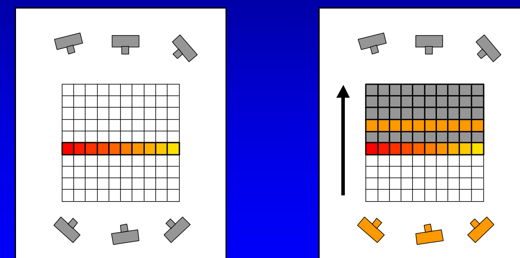

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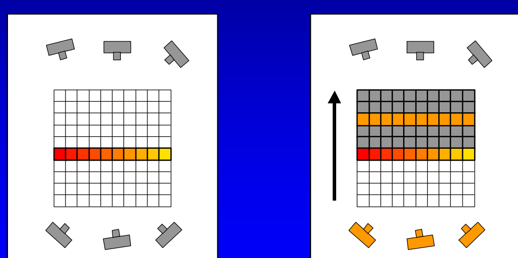

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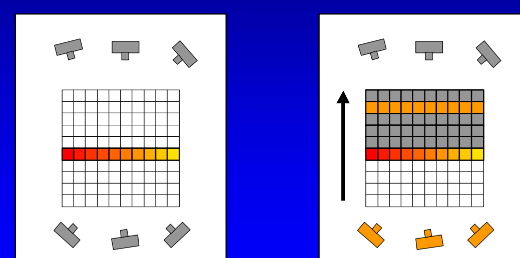

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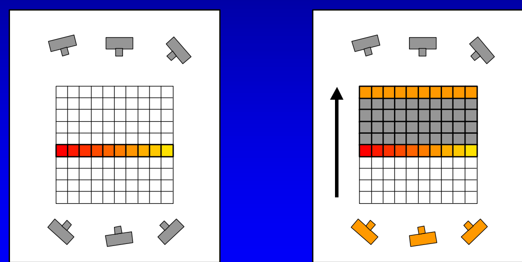

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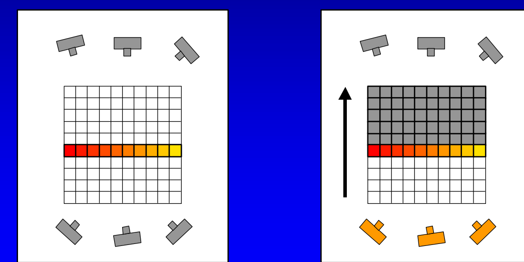

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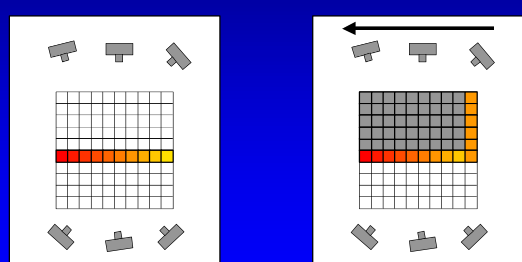

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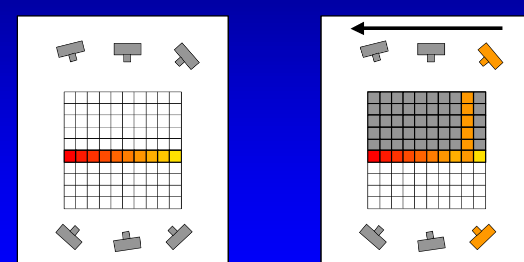
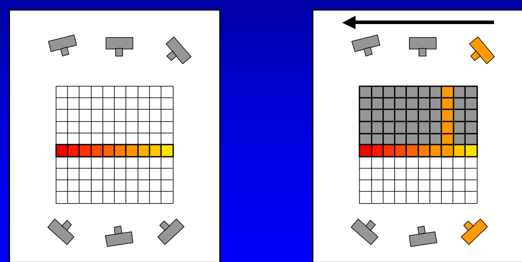


Multi-Pass Plane Sweep

- Sweep plane in each of 6 principle directions
- Consider cameras on only one side of plane
- Repeat until convergence



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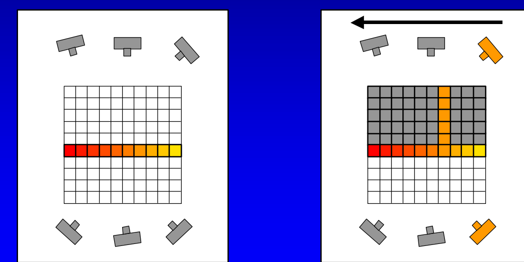

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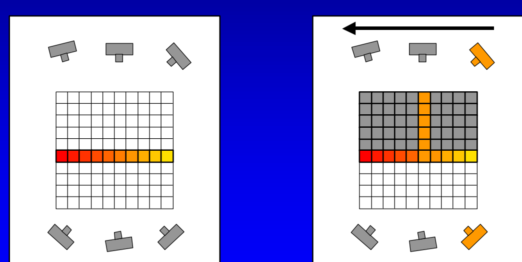

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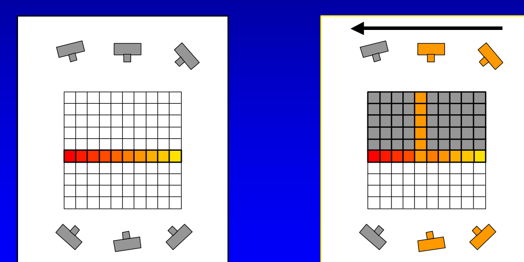

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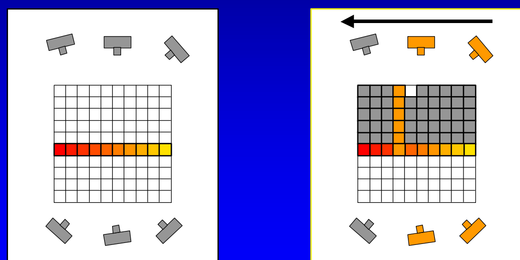

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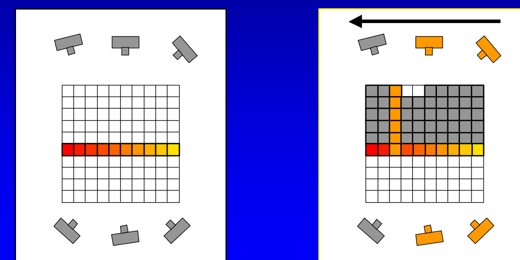

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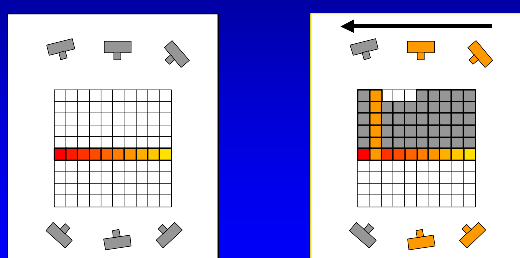

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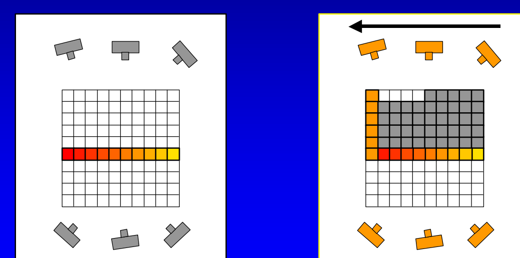

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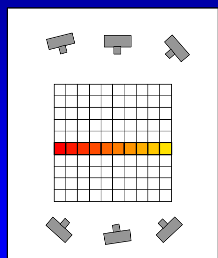
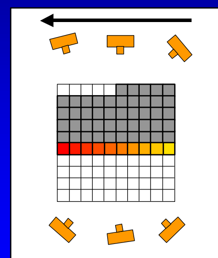
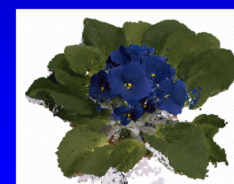




Results: African Violet

Input Image (1 of 45)

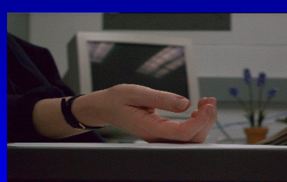
Reconstruction



Reconstruction

Reconstruction

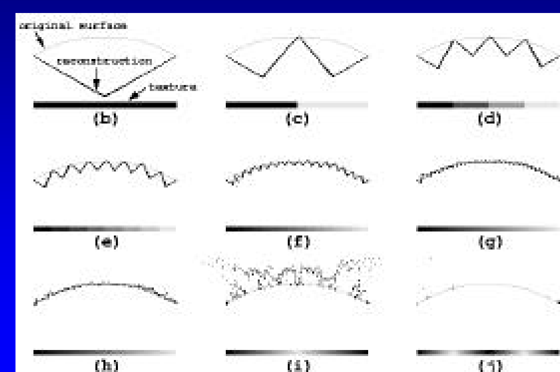
Results: Hand



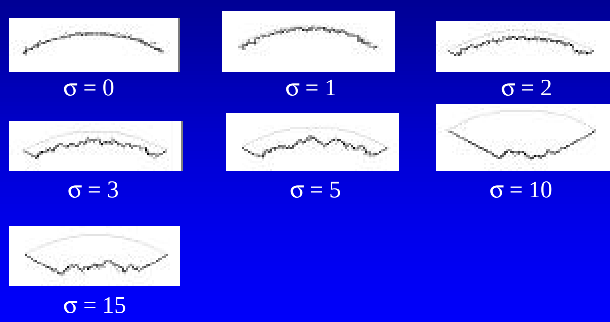
Input Image
(1 of 100)

Views of Reconstruction

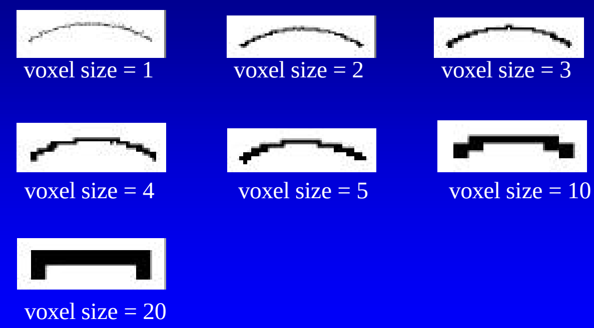
Texture Effects on Voxel Coloring



Effects of Noise



Effects of Voxel Resolution



Other Extensions

- ***Dealing with calibration errors***
  - **Kutulakos, 2000**
  - **Construct approximate photo hull defined by weakening the definition of photo-consistency so that it requires only that there exists a photo-consistent pixel within distance *r* of the ideal position**
- ***Partly transparent scenes***
  - **De Bonet and Viola, 1999**
  - **Compute at each voxel the probability that it is visible (or the degree of opacity)**
  - **Optimization algorithm finds best linear combination of colors and opacities at the voxels along each visual ray to minimize the error with the input image colors**

Voxel Coloring / Space Carving Summary

"The more the marble wastes, the more the statue grows."
– Michelangelo

Pros
- **Non-parametric**
  - Can model arbitrary geometry and topology
- **Camera positions unconstrained**
- **Guaranteed convergence**

Cons
- **Expensive to process high resolution voxel grids**
- **Carving stops at *first* consistent voxel, not *best***
- **Assumes simple, known surface reflectance model, usually Lambertian**

Collaborators
- **Steve Seitz, Andrew Prock, Kyros Kutulakos**

Current Work

- ***BRDF estimation from multiple views***
  - ***Modeling is more than geometry – need to simultaneously recover surface reflectance models***
- **Wide-baseline feature point correspondence**
- **Calibration from multiple moving objects**
- **Metric self-calibration from static scenes**