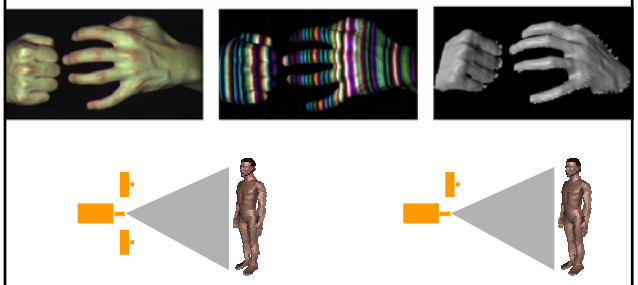
## Announcements

- Project 3 extension: **Wednesday at noon**
- Final project proposal extension: **Friday at noon**
  - > **consult with Steve, Rick, and/or Ian now!**
- Project 2 artifact winners...

Readings

- S. M. Seitz and C. R. Dyer, Photorealistic Scene Reconstruction by Voxel Coloring, *International Journal of Computer Vision*, 35(2), 1999, pp. 151-173.
  - > http://www.cs.washington.edu/homes/seitz/papers/ijcv99.pdf

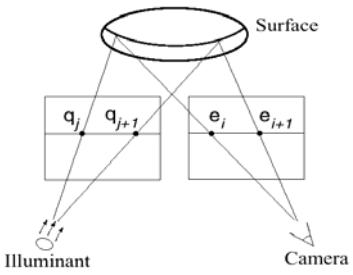
## Active stereo with structured light



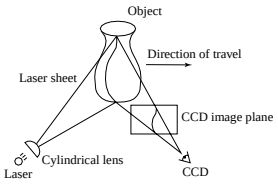
Project "structured" light patterns onto the object

- simplifies the correspondence problem

## Active stereo with structured light




## Laser scanning



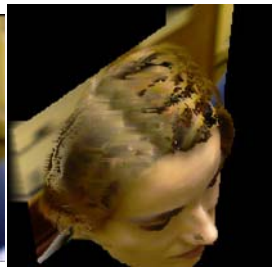

http://graphics.stanford.edu/projects/mich/

Optical triangulation

- Project a single stripe of laser light
- Scan it across the surface of the object
- This is a very precise version of structured light scanning

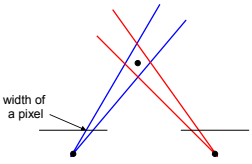
## 3D cameras

Portable 3D laser scanner (this one by Minolta)

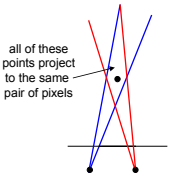


## Multiview stereo


## Choosing the stereo baseline




**Large Baseline**



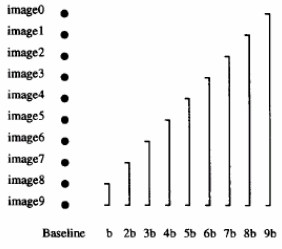

**Small Baseline**

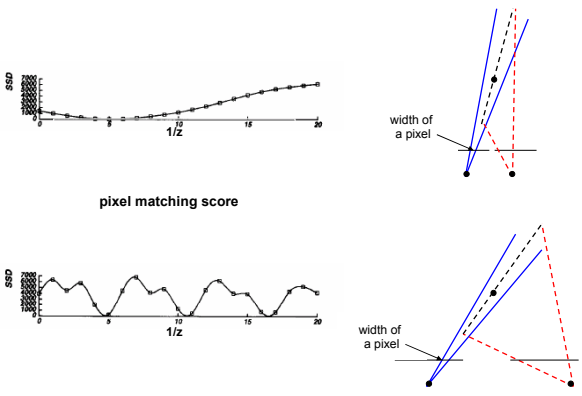
What's the optimal baseline?

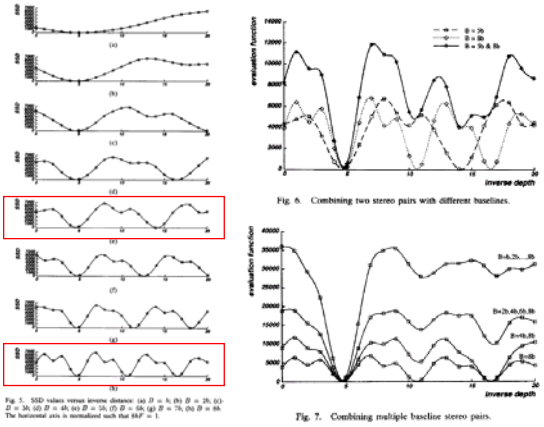
- Too small: large depth error
- Too large: difficult search problem

## The Effect of Baseline on Depth Estimation

Figure 2: An example scene. The grid pattern in the background has ambiguity of matching.






## Multibaseline Stereo

### Basic Approach

- Choose a reference view
- Use your favorite stereo algorithm BUT
  - > replace two-view SSD with SSD over all baselines

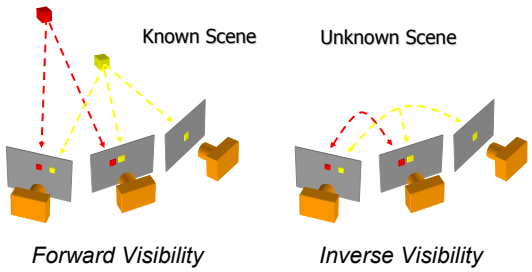
### Limitations

- Must choose a reference view (bad)
- Visibility!

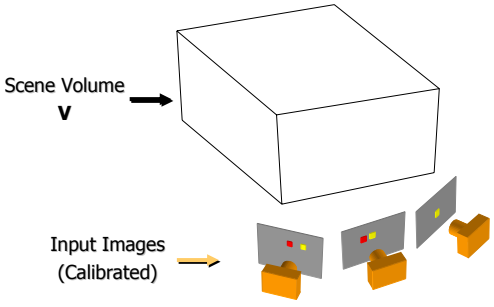
### CMU's 3D Room Video

## The visibility problem

Which points are visible in which images?

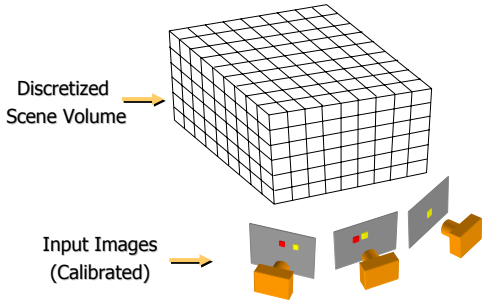


## Volumetric stereo



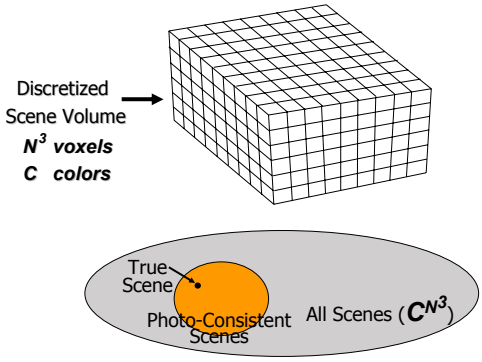

**Goal:** **Determine occupancy, "color" of points in V**

## Discrete formulation: Voxel Coloring




**Goal:** **Assign RGBA values to voxels in V**
***photo-consistent*** **with images**

## Complexity and computability




## Issues

Theoretical Questions

- Identify class of *all* photo-consistent scenes

Practical Questions

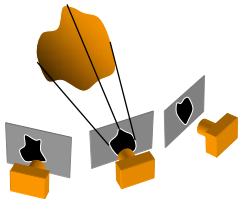
- How do we compute photo-consistent models?

## Voxel coloring solutions

1. C=2 (shape from silhouettes)
   - Volume intersection [Baumgart 1974]
     > For more info: *Rapid octree construction from image sequences.* R. Szeliski, CVGIP: Image Understanding, 58(1):23-32, July 1993. (this paper is apparently not available online) or
     > W. Matusik, C. Buehler, R. Raskar, L. McMillan, and S. J. Gortler, *Image-Based Visual Hulls*, SIGGRAPH 2000 ( pdf 1.6 MB )
2. C unconstrained, viewpoint constraints
   - Voxel coloring algorithm [Seitz & Dyer 97]
3. General Case
   - Space carving [Kutulakos & Seitz 98]

## Reconstruction from Silhouettes (C = 2)

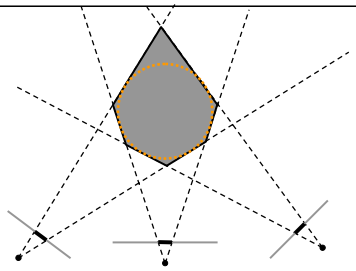
Binary Images →



Approach:

- *Backproject* each silhouette
- Intersect backprojected volumes

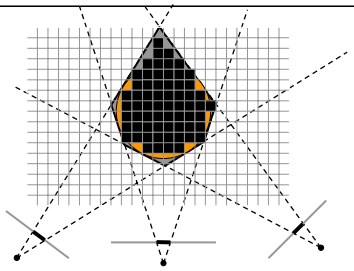
## Volume intersection



Reconstruction Contains the True Scene

- But is generally not the same
- In the limit (all views) get *visual hull*
  > Complement of all lines that don't intersect S

## Voxel algorithm for volume intersection



Color voxel black if on silhouette in every image

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

## Properties of Volume Intersection

Pros

- Easy to implement, fast
- Accelerated via octrees [Szeliski 1993] or interval techniques [Matusik 2000]

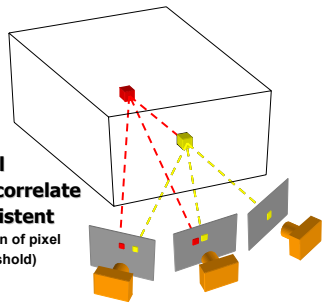
Cons

- No concavities
- Reconstruction is not photo-consistent
- Requires identification of silhouettes

## Voxel Coloring Solutions

1. C=2 (silhouettes)
   - Volume intersection [Baumgart 1974]
2. C unconstrained, viewpoint constraints
   - Voxel coloring algorithm [Seitz & Dyer 97]
     > For more info: http://www.cs.washington.edu/homes/seitz/papers/ijcv99.pdf
3. General Case
   - Space carving [Kutulakos & Seitz 98]

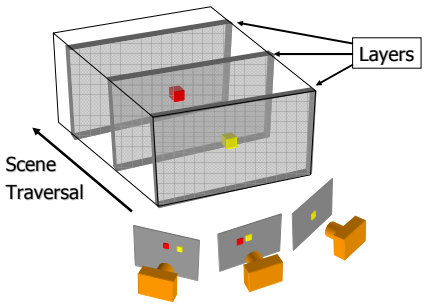
## Voxel Coloring Approach



1. **Choose voxel**
2. **Project and correlate**
3. **Color if consistent**
   **(standard deviation of pixel colors below threshold)**

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

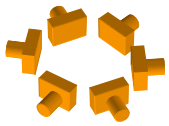
## Depth Ordering: visit occluders first!



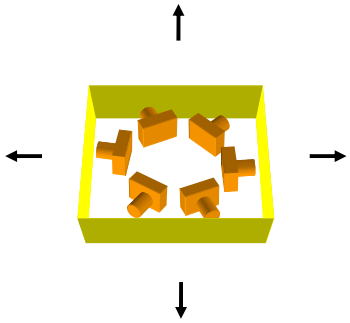

**Condition:** **depth order is the *same for all input views***

## Panoramic Depth Ordering

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

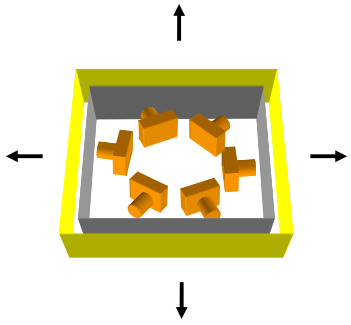


## Panoramic Depth Ordering



**Layers radiate outwards from cameras**

## Panoramic Layering



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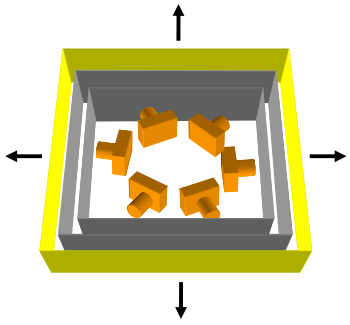
## Panoramic Layering

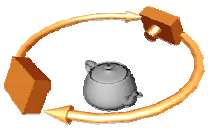


**Layers radiate outwards from cameras**

## Compatible Camera Configurations

Depth-Order Constraint

- Scene outside convex hull of camera centers



*Inward-Looking*

*Outward-Looking*

## Calibrated Image Acquisition

*Calibrated Turntable*

**Selected Dinosaur Images**

**Selected Flower Images**

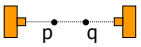
## Voxel Coloring Results (Video)

**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**

## Limitations of Depth Ordering

A view-independent depth order may not exist



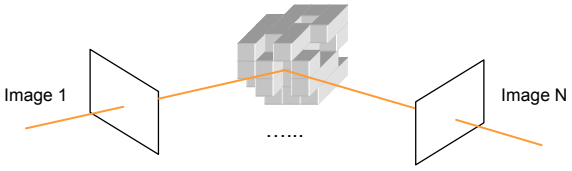

Need more powerful general-case algorithms

- Unconstrained camera positions
- Unconstrained scene geometry/topology

## Voxel Coloring Solutions

1. C=2 (silhouettes)
   - Volume intersection [Baumgart 1974]
2. C unconstrained, viewpoint constraints
   - Voxel coloring algorithm [Seitz & Dyer 97]
3. General Case
   - Space carving [Kutulakos & Seitz 98]
     > For more info: http://www.cs.washington.edu/homes/seitz/papers/kutu-ijcv00.pdf

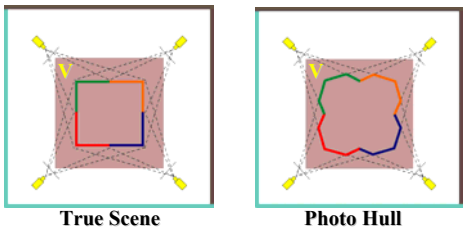
## Space Carving Algorithm




### Space Carving Algorithm

- 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

## Which shape do you get?




True Scene  Photo Hull

The Photo Hull *is the UNION of all photo-consistent scenes in V*

- It is a photo-consistent scene reconstruction
- Tightest possible bound on the true scene

## Space Carving Algorithm

### The Basic Algorithm is Unwieldy

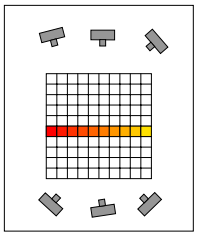
- Complex update procedure

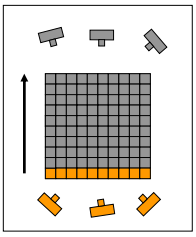
### Alternative: Multi-Pass Plane Sweep

- 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





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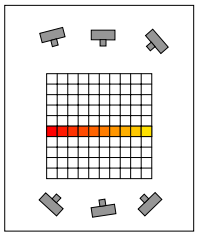

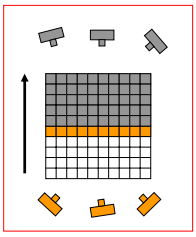

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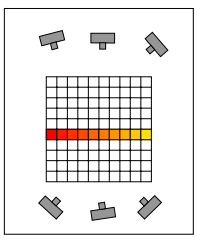

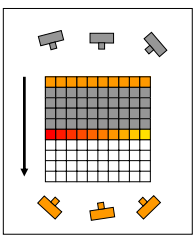

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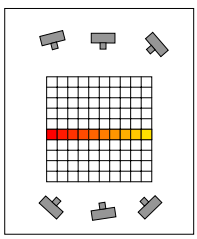

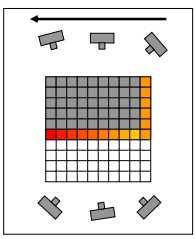

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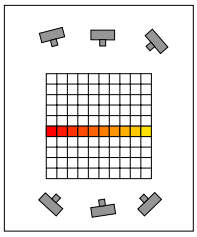

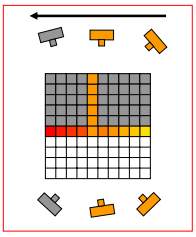

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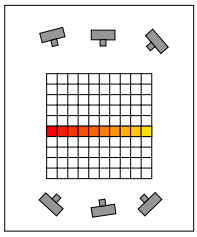
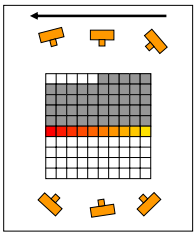




## Space Carving Results: African Violet

**Input Image (1 of 45)**

**Reconstruction**

**Reconstruction**

**Reconstruction**

## Space Carving Results: Hand

**Input Image (1 of 100)**

**Views of Reconstruction**

## Properties of Space Carving

Pros

- Voxel coloring version is easy to implement, fast
- Photo-consistent results
- No smoothness prior

Cons

- Bulging
- No smoothness prior

## Alternatives to space carving

Optimizing space carving

- recent surveys
  - >Slabaugh et al., 2001
  - >Dyer et al., 2001
- many others...

Graph cuts

- Kolmogorov & Zabih

Level sets

- introduce smoothness term
- surface represented as an implicit function in 3D volume
- optimize by solving PDE's


## Alternatives to space carving

Optimizing space carving

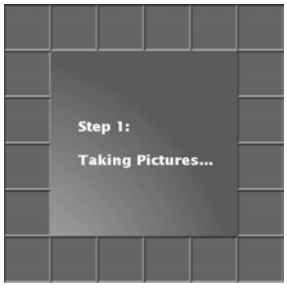
- recent surveys
  - >Slabaugh et al., 2001
  - >Dyer et al., 2001
- many others...

Graph cuts

- Ramin Zabih's lecture

Level sets

- introduce smoothness term
- surface represented as an implicit function in 3D volume
- optimize by solving PDE's




## Level sets vs. space carving

Advantages of level sets

- optimizes consistency with images + smoothness term
- excellent results for smooth things
- does not require as many images

Advantages of space carving

- much simpler to implement
- runs faster (orders of magnitude)
- works better for thin structures, discontinuities

For more info on level set stereo:

- Renaud Keriven's page:
  - > http://cermics.enpc.fr/~keriven/stereo.html

## Current/Future Trends

Optimizing with visibility

- Kolmogorov & Zabih

## Current/Future Trends

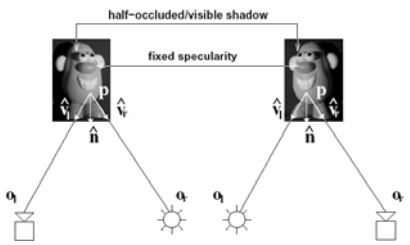
Real-time algorithms

- e.g., Buehler et al., *image-based visual hulls, SIGGRAPH 2000*

## Current/Future Trends

Modeling shiny things (BRDF's and materials)

- e.g., Zickler et al., *Helmholtz Stereopsis*




## References

### Volume Intersection


- Martin & Aggarwal, "Volumetric description of objects from multiple views", Trans. Pattern Analysis and Machine Intelligence, 5(2), 1991, pp. 150-158.
- Szeliski, "Rapid Octree Construction from Image Sequences", Computer Vision, Graphics, and Image Processing: Image Understanding, 58(1), 1993, pp. 23-32.
- Matusik, Buehler, Raskar, McMillan, and Gortler , "Image-Based Visual Hulls", Proc. SIGGRAPH 2000, pp. 369-374.


### Voxel Coloring and Space Carving


- Seitz & Dyer, "Photorealistic Scene Reconstruction by Voxel Coloring", Intl. Journal of Computer Vision (IJCV), 1999, 35(2), pp. 151-173.
- Kutulakos & Seitz, "A Theory of Shape by Space Carving", International Journal of Computer Vision, 2000, 38(3), pp. 199-218.
- **Recent surveys**
  - > Slabaugh, Culbertson, Malzbender, & Schafer, "A Survey of Volumetric Scene Reconstruction Methods from Photographs", Proc. workshop on Volume Graphics 2001, pp. 81-100. http://users.ece.gatech.edu/~slabaugh/personal/publications/vg01.pdf
  - > Dyer, "Volumetric Scene Reconstruction from Multiple Views", Foundations of Image Understanding, L. S. Davis, ed., Kluwer, Boston, 2001, 469-489. ftp://ftp.cs.wisc.edu/computer-vision/repository/PDF/dyer.2001.fia.pdf

# References

## Other references from this talk


- **Multibaseline Stereo**: Masatoshi Okutomi and Takeo Kanade. A multiple-baseline stereo. IEEE Trans. on Pattern Analysis and Machine Intelligence (PAMI), 15(4), 1993, pp. 353–363.
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