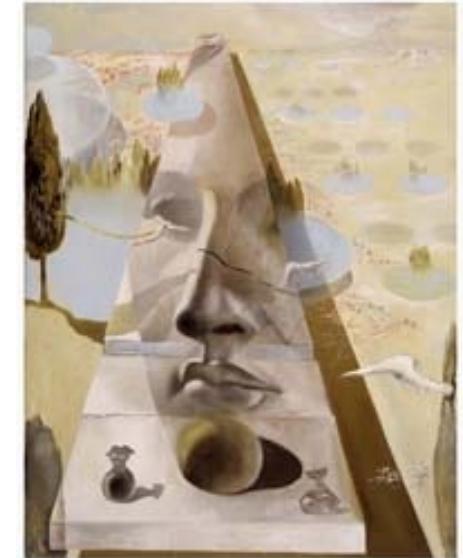


Lecture 8

Active stereo & Volumetric stereo



- Active stereo
 - Structured lighting
 - Depth sensing
- Volumetric stereo:
 - Space carving
 - Shadow carving
 - Voxel coloring

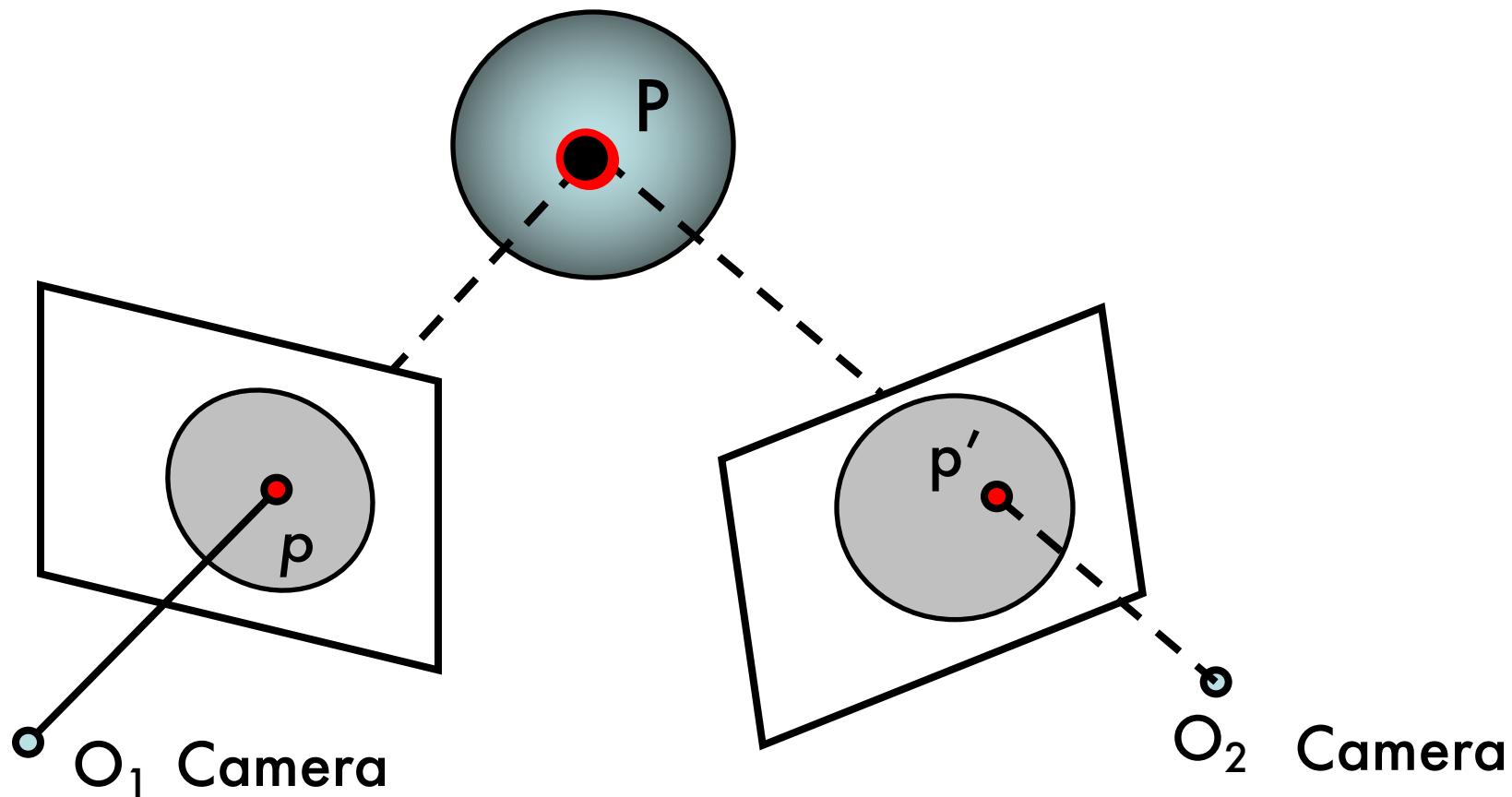
Reading:

[Szelisky] Chapter 11 “Multi-view stereo”

S. Savarese, M. Andreetto, H. Rushmeier, F. Bernardini and P. Perona, 3D Reconstruction by Shadow Carving: Theory and Practical Evaluation, International Journal of Computer Vision (IJCV) , 71(3), 305-336, 2006

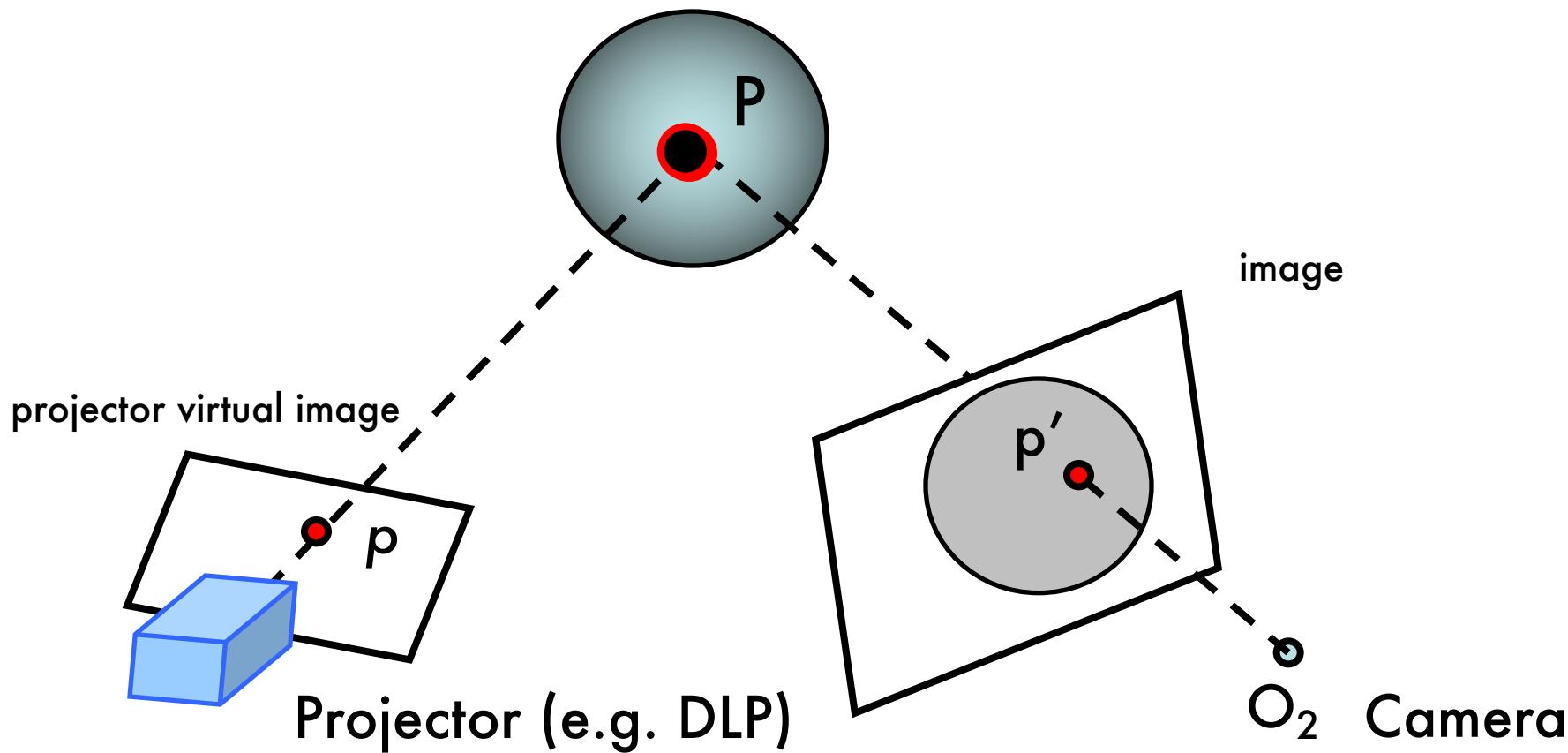
Seitz, S. M., & Dyer, C. R. (1999). Photorealistic scene reconstruction by voxel coloring. *International Journal of Computer Vision*, 35(2), 151-173.

Traditional stereo



What's the main problem in traditional stereo?
We need to find correspondences!

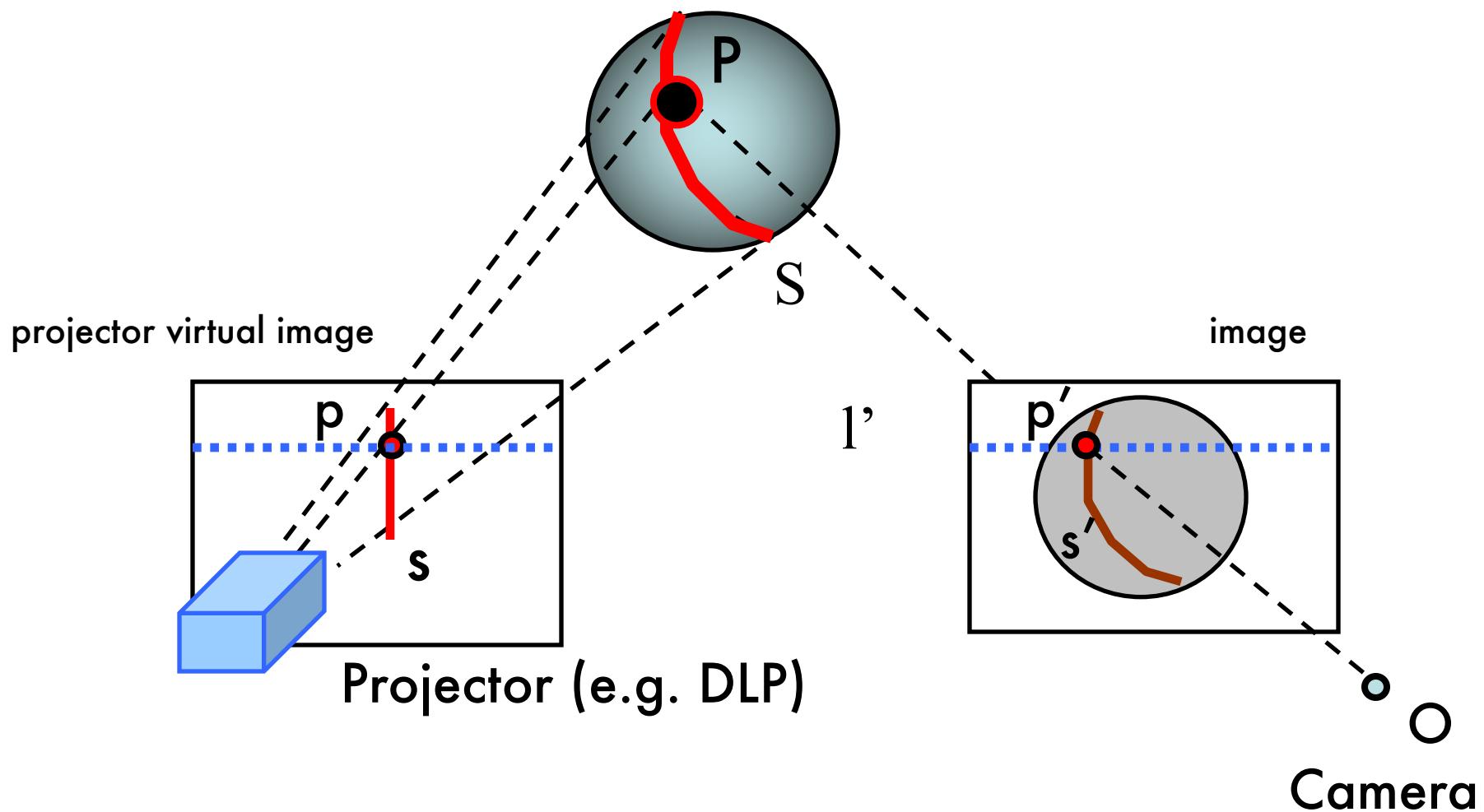
Active stereo (point)



Replace one of the two cameras by a projector

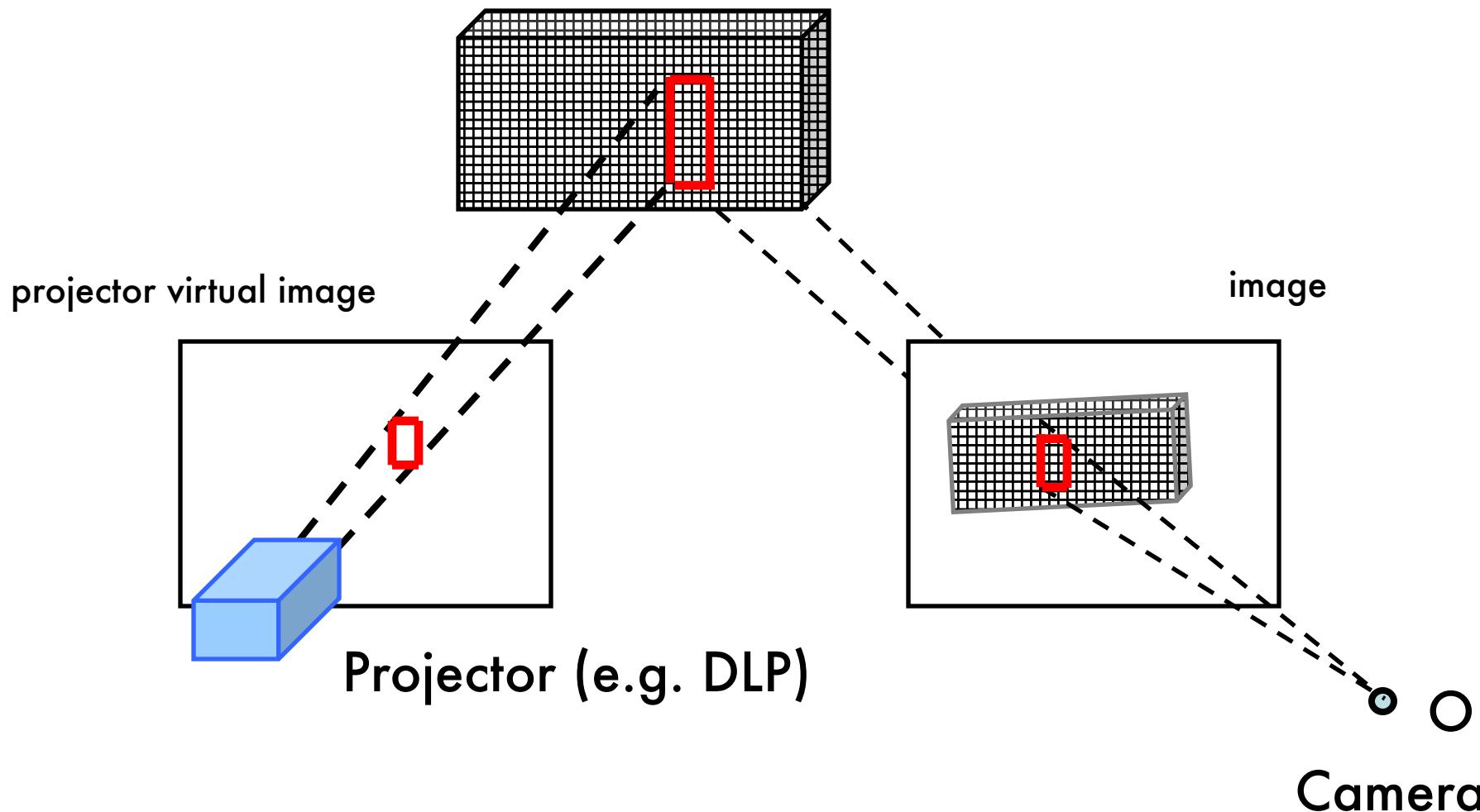
- Projector geometry calibrated
- What's the advantage of having the projector? Correspondence problem solved!
Any limitation??

Active stereo (stripe)



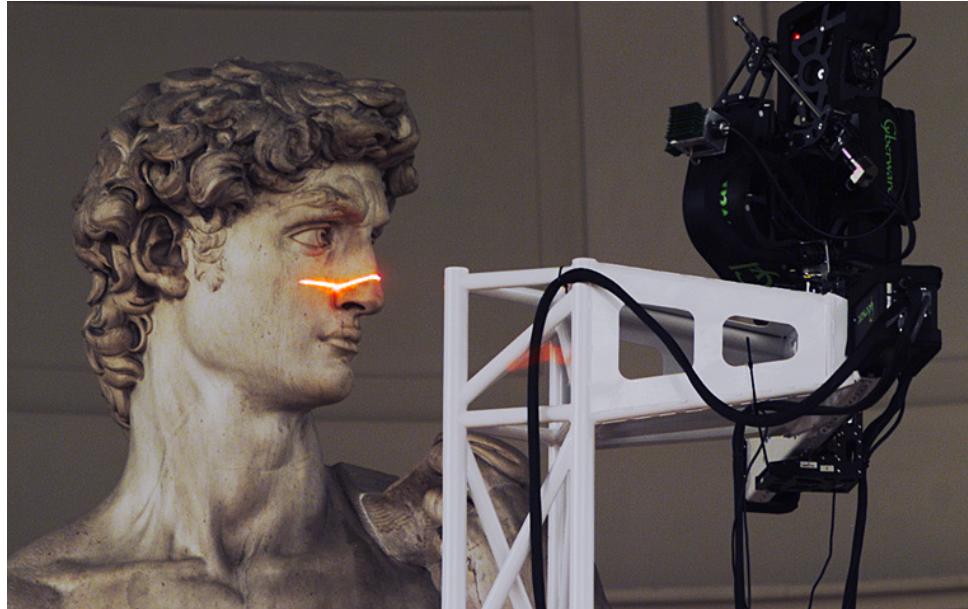
- Projector and camera are parallel
- Correspondence problem is solved!

Calibrating the system



- Use calibration rig to calibrate camera and localize rig in 3D
- Project patterns on rig and calibrate projector

Laser scanning



Digital Michelangelo Project (1990)
<http://graphics.stanford.edu/projects/mich/>

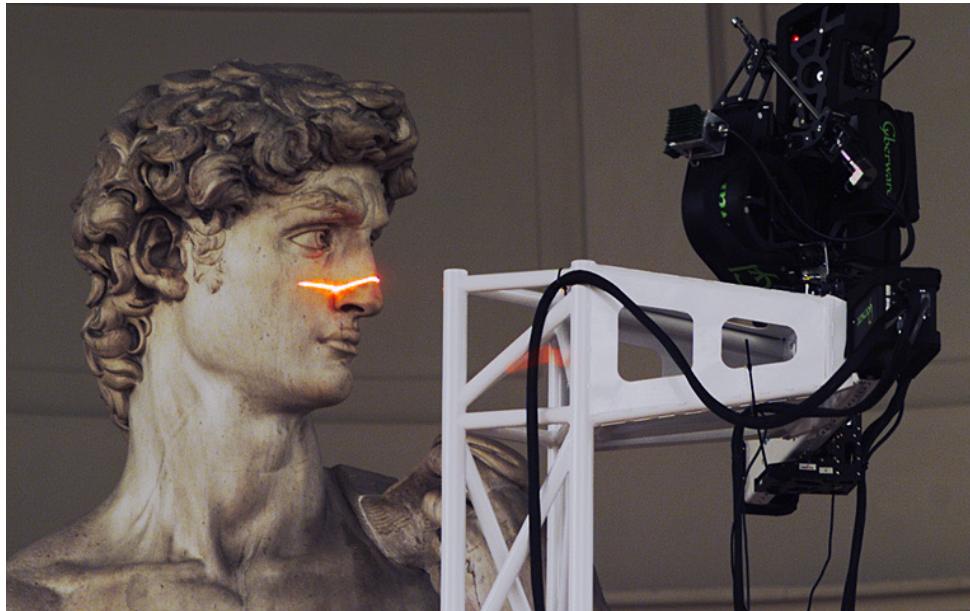
- **Optical triangulation**
 - Project a single stripe of laser light
 - Scan it across the surface of the object
 - This is a very precise version of structured light scanning

Laser scanning



The Digital Michelangelo Project, Levoy et al.

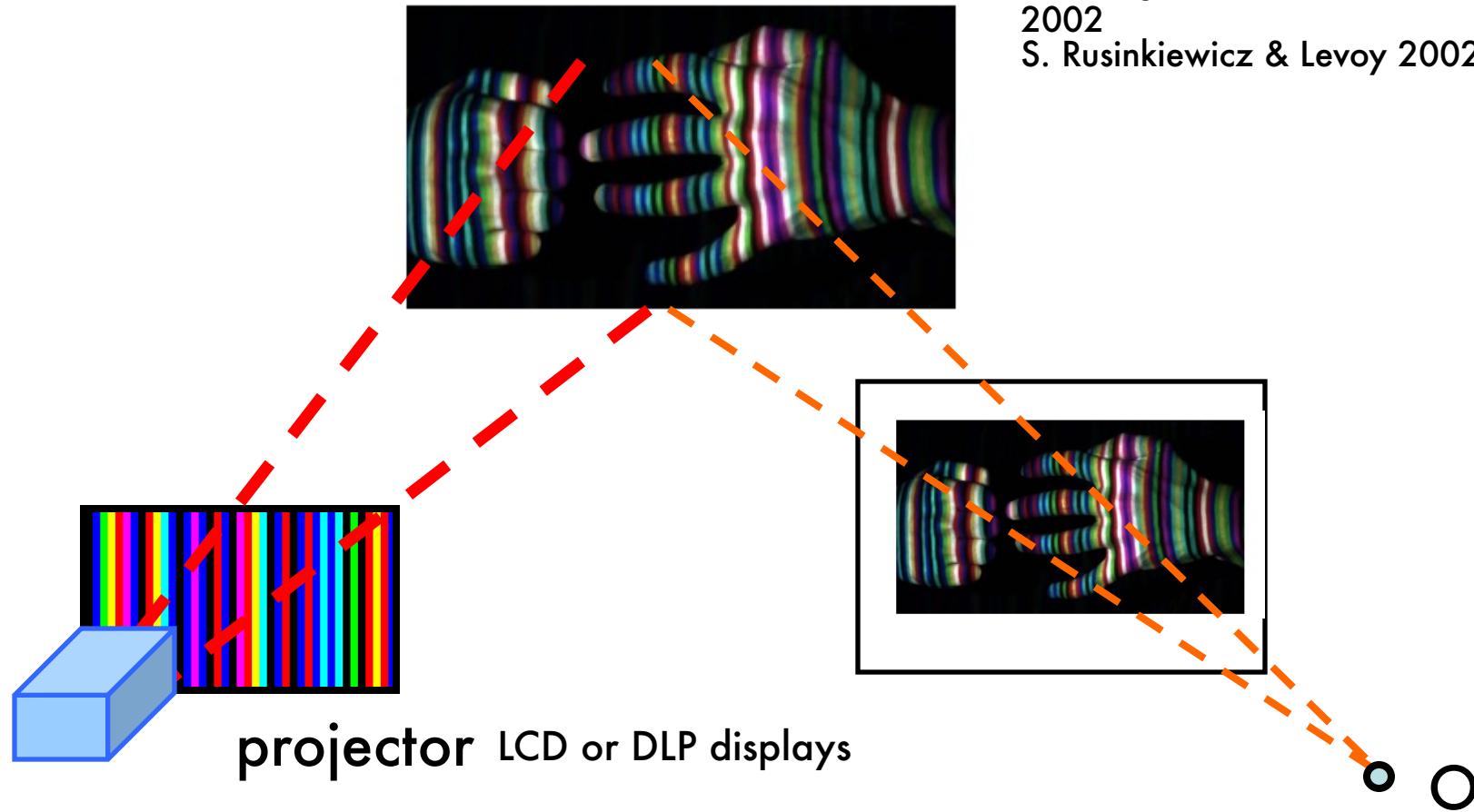
Limitations of Laser scanning



- Slow
- Cannot capture deformations in time

Active stereo (color-coded stripes)

L. Zhang, B. Curless, and S. M. Seitz
2002
S. Rusinkiewicz & Levoy 2002



- Dense reconstruction
- Correspondence problem again
- Get around it by using color codes

Active stereo (color-coded stripes)



Rapid shape acquisition: Projector + stereo cameras



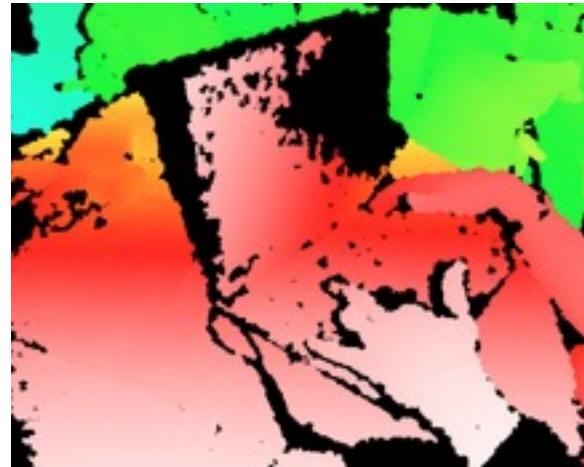
Active stereo - the kinect sensor



- Infrared laser projector combined with a CMOS sensor
- Captures video data in 3D under any ambient light conditions.



Pattern of projected infrared points to generate a dense 3D image



Depth map

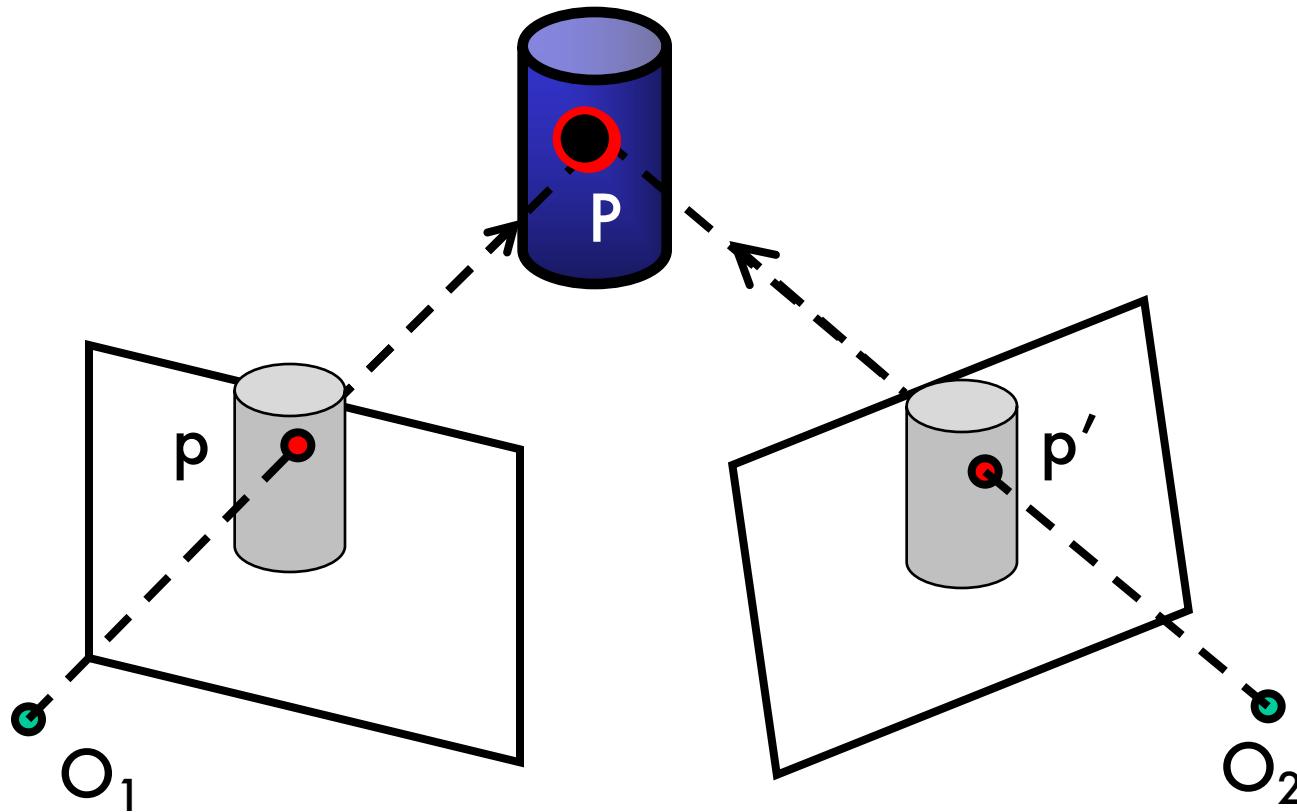
Lecture 8

Active stereo & Volumetric stereo



- Active stereo
 - Structured lighting
 - Depth sensing
- Volumetric stereo:
 - Space carving
 - Shadow carving
 - Voxel coloring

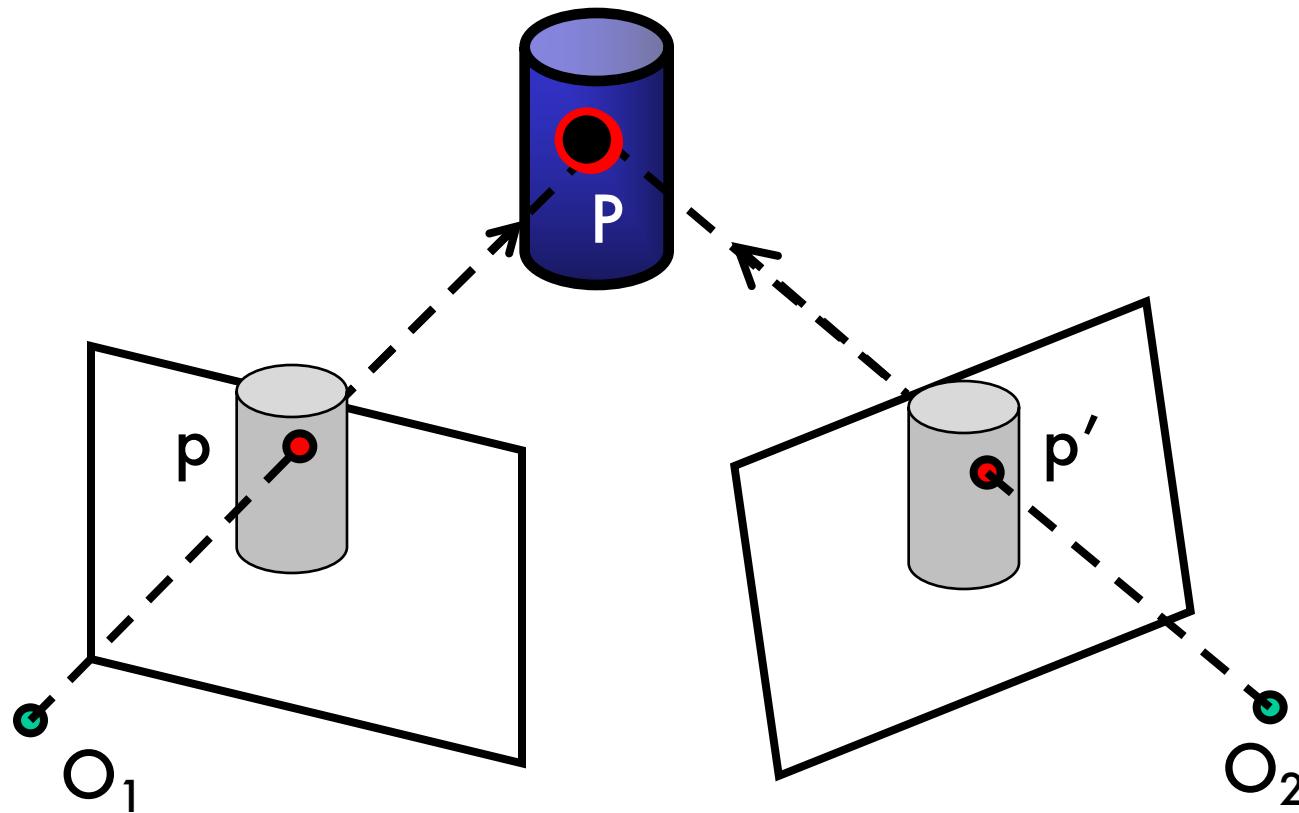
“Traditional” Stereo



Goal: estimate the position of P given the observation of P from two view points

Assumptions: known camera parameters and position (K, R, T)

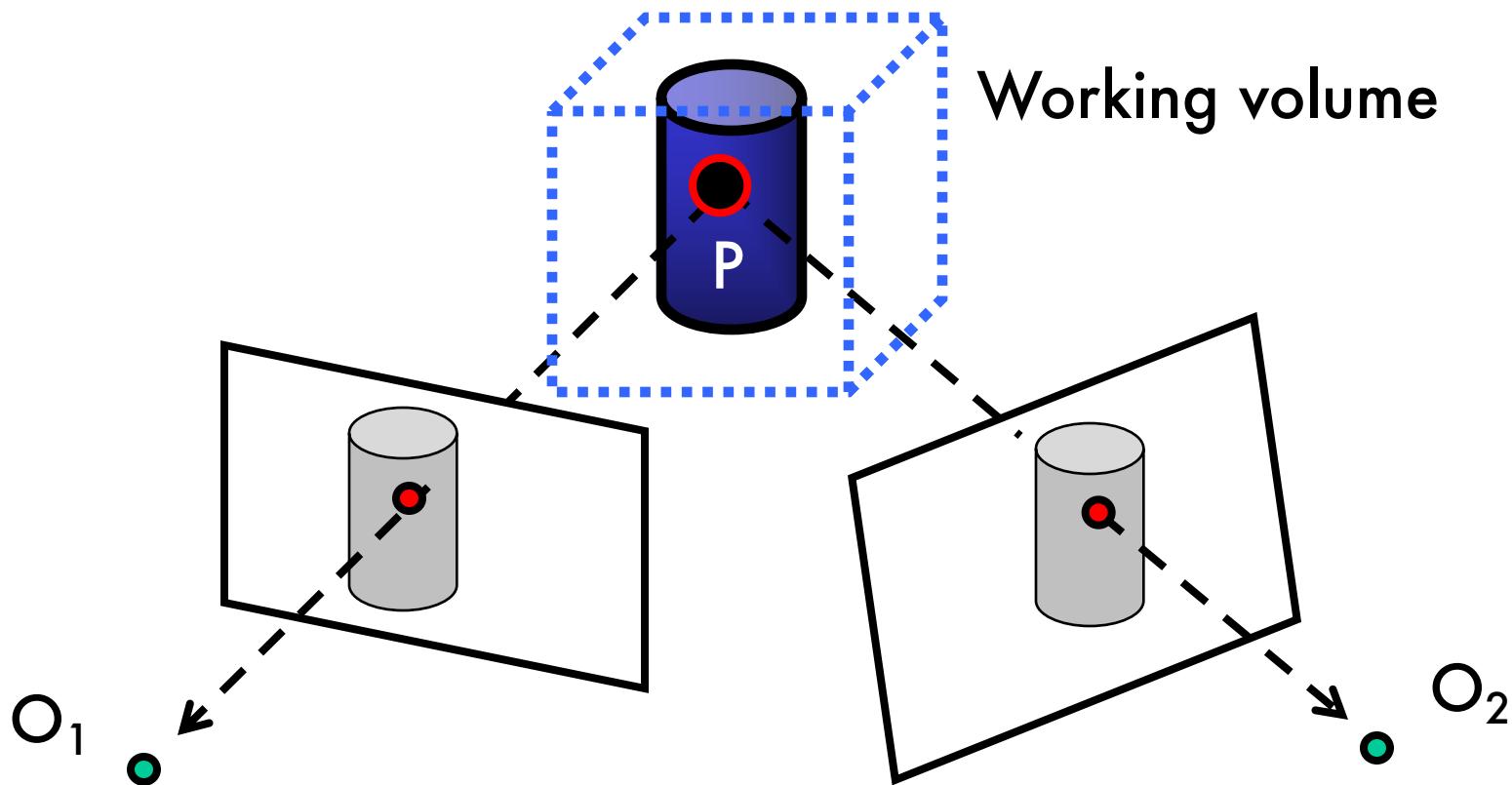
“Traditional” Stereo



Subgoals:

1. Solve the correspondence problem
2. Use corresponding observations to triangulate

Volumetric stereo



1. Hypothesis: pick up a point within the volume
2. Project this point into 2 (or more) images
3. Validation: are the observations **consistent?**

Assumptions: known camera parameters and position (K, R, T)

Consistency based on cues such as:

- Contours/silhouettes → Space carving
- Shadows → Shadow carving
- Colors → Voxel coloring

Lecture 8

Active stereo & Volumetric stereo



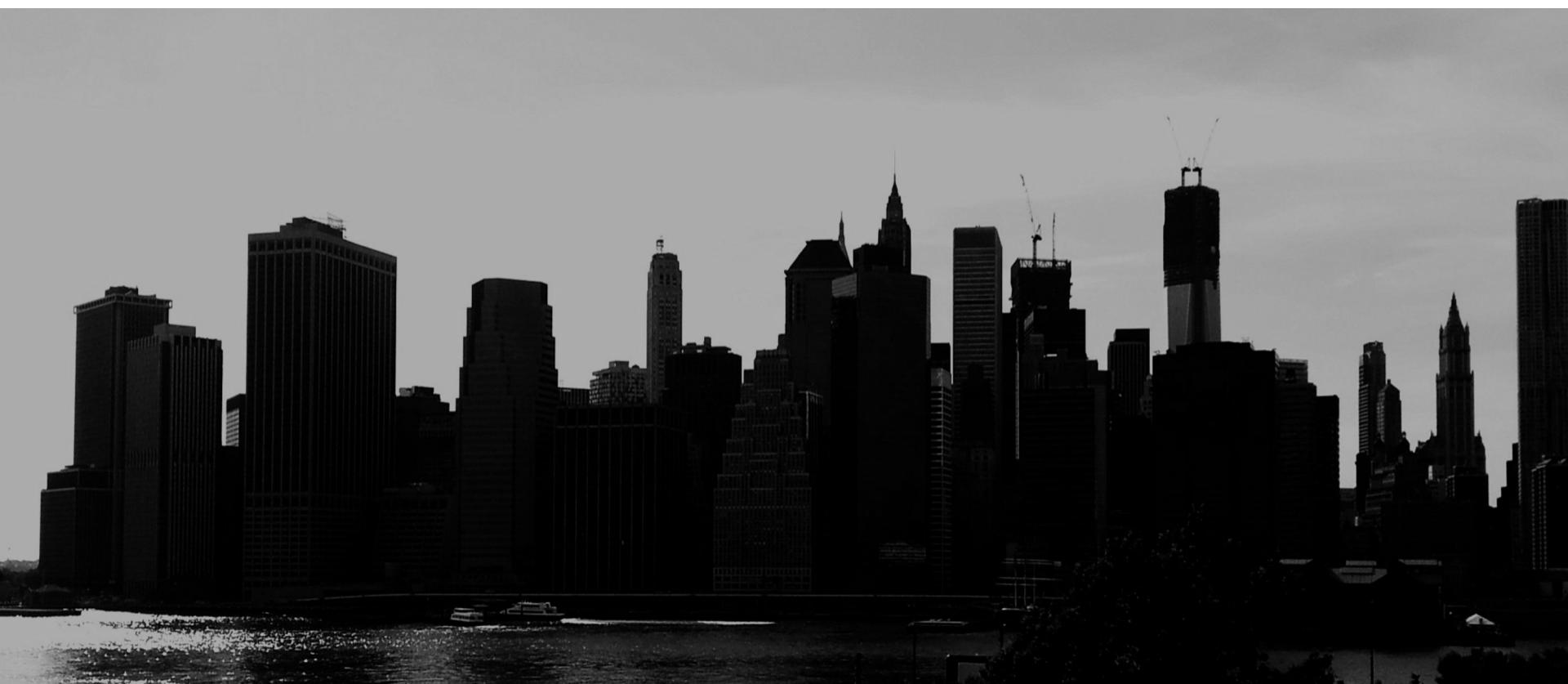
- Active stereo
 - Structured lighting
 - Depth sensing
- Volumetric stereo:
 - Space carving
 - Shadow carving
 - Voxel coloring

Reading:

[Szelisky] Chapter 11 “Multi-view stereo”

Contours/silhouettes

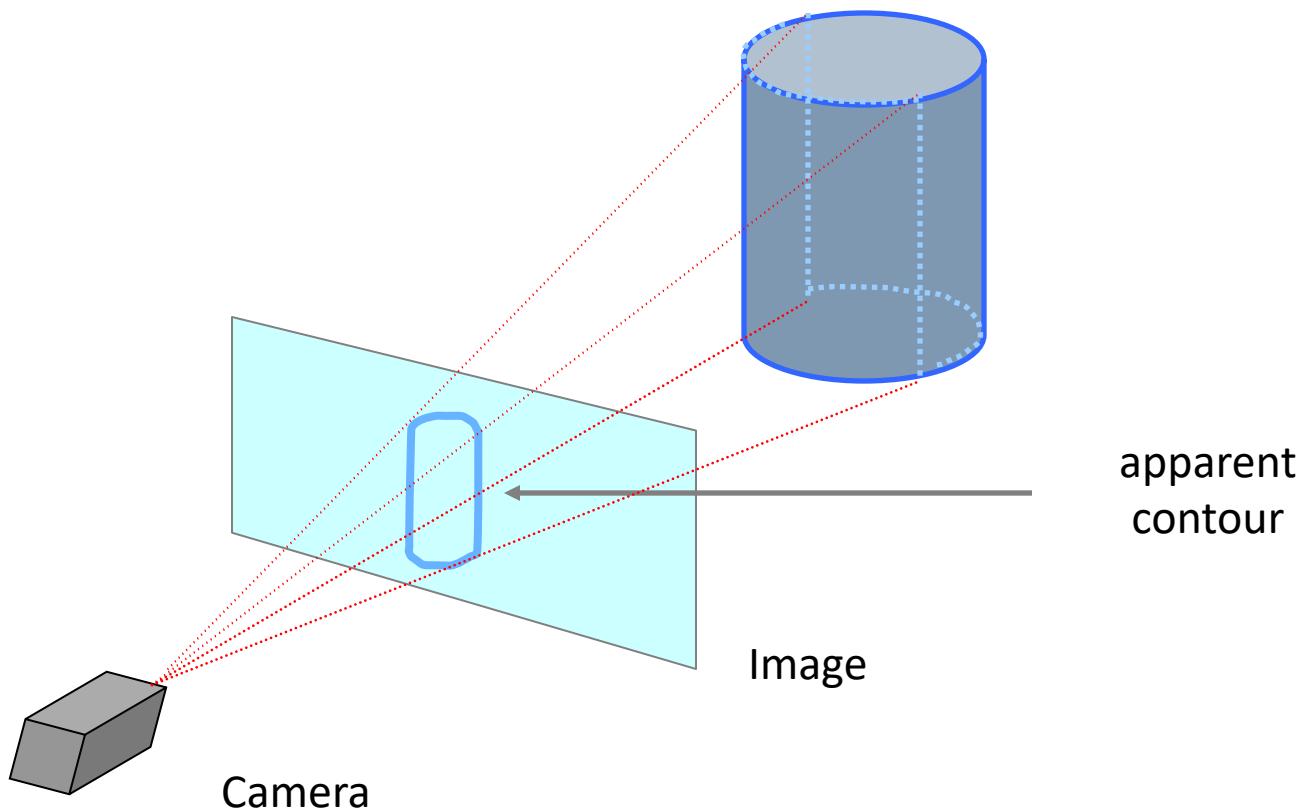
- Contours are a rich source of geometric information



Apparent Contours

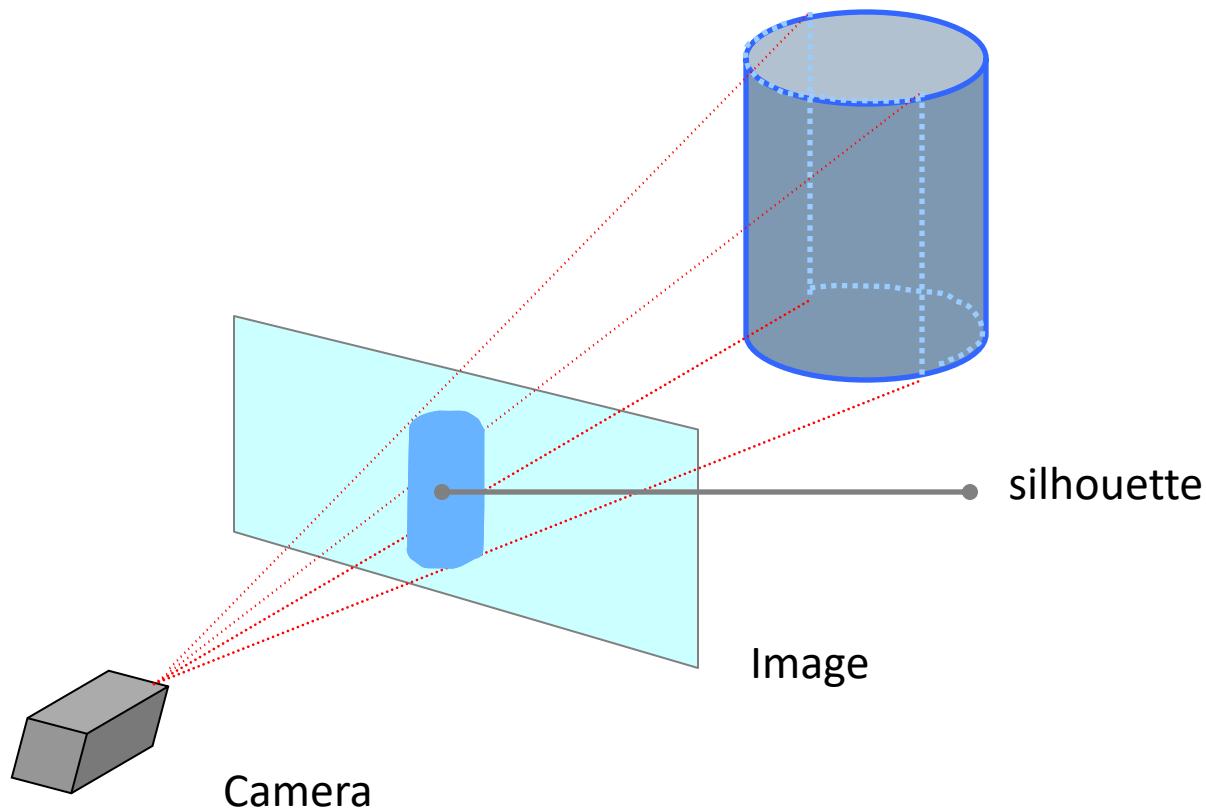
- Projection of the locus of points on the object surface which separate the visible and occluded parts on the surface

[sato & cipolla]

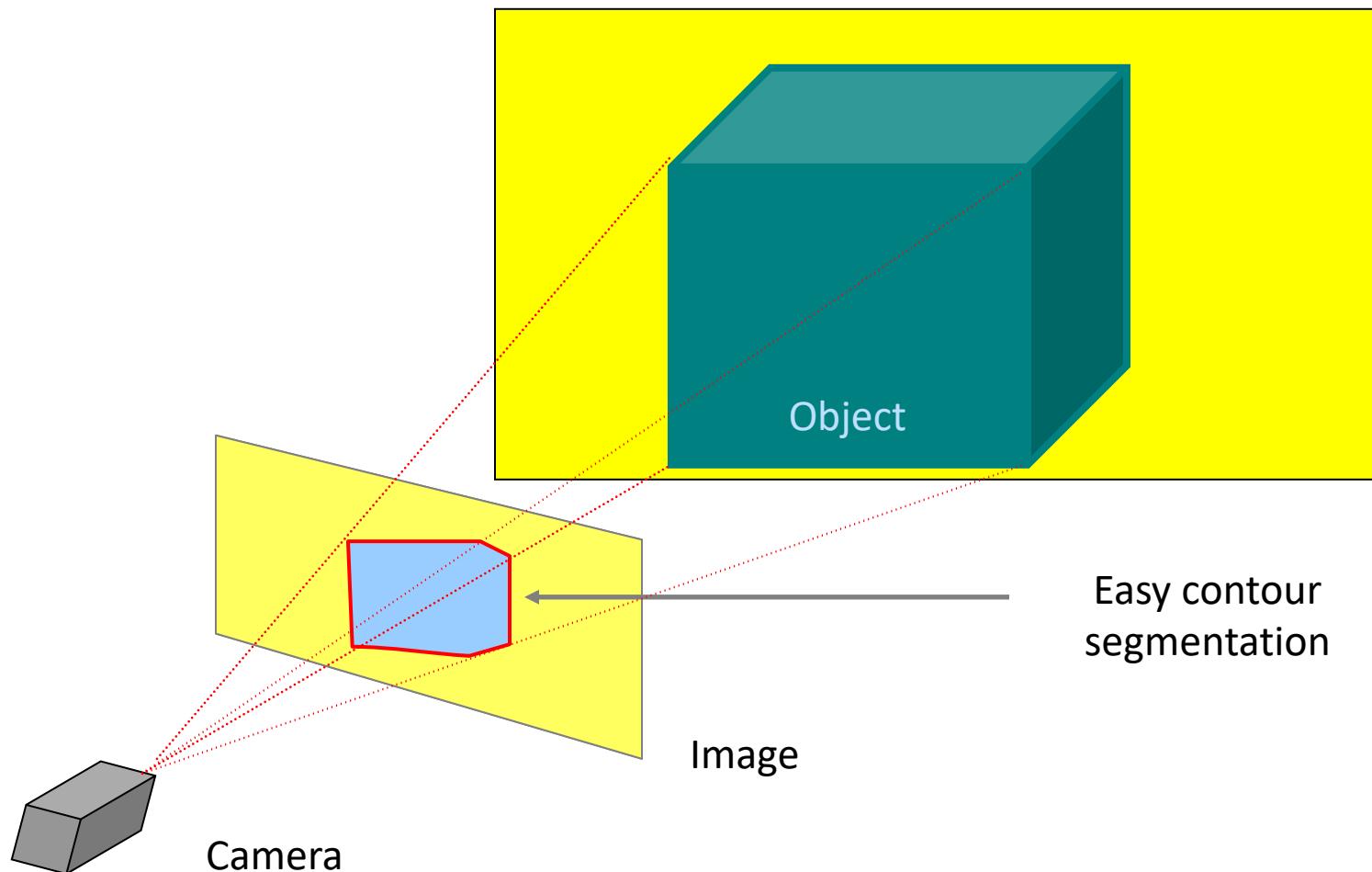


Silhouettes

A silhouette is defined as the area enclosed by the apparent contours



Detecting silhouettes

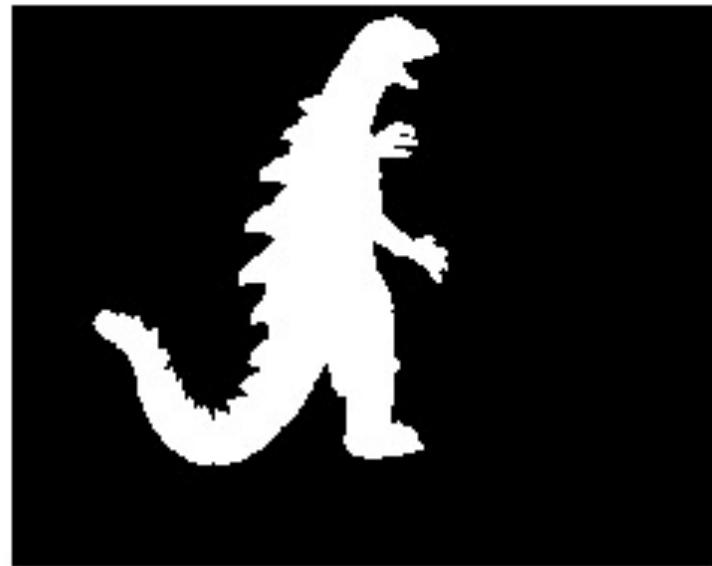


Detecting silhouettes

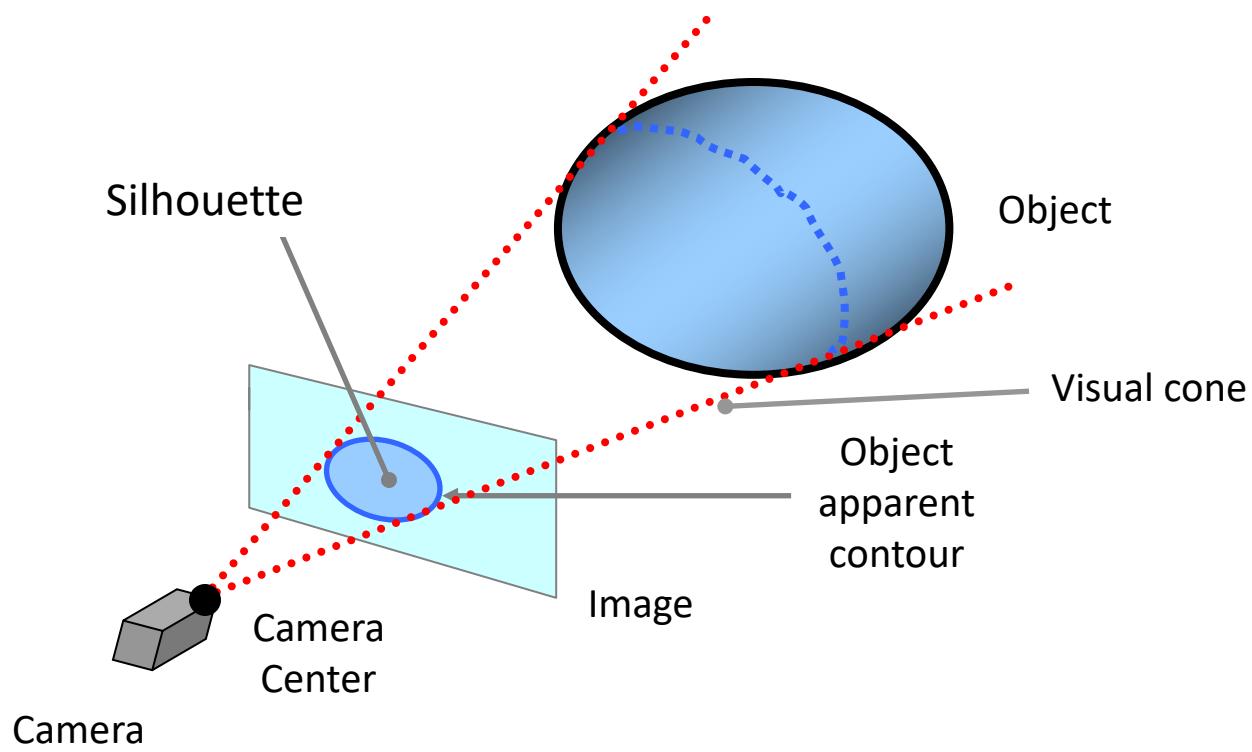
Original Image



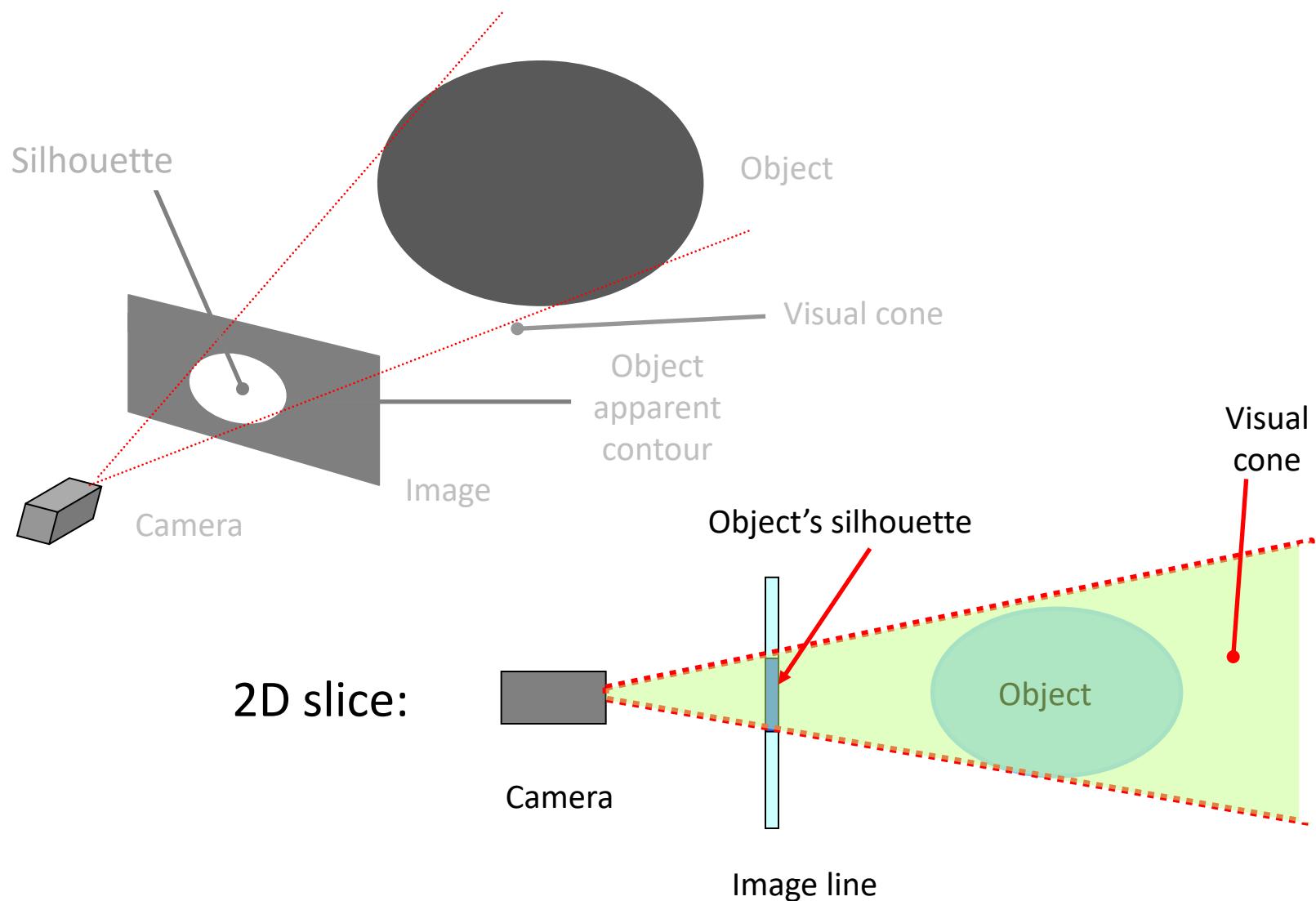
Silhouette



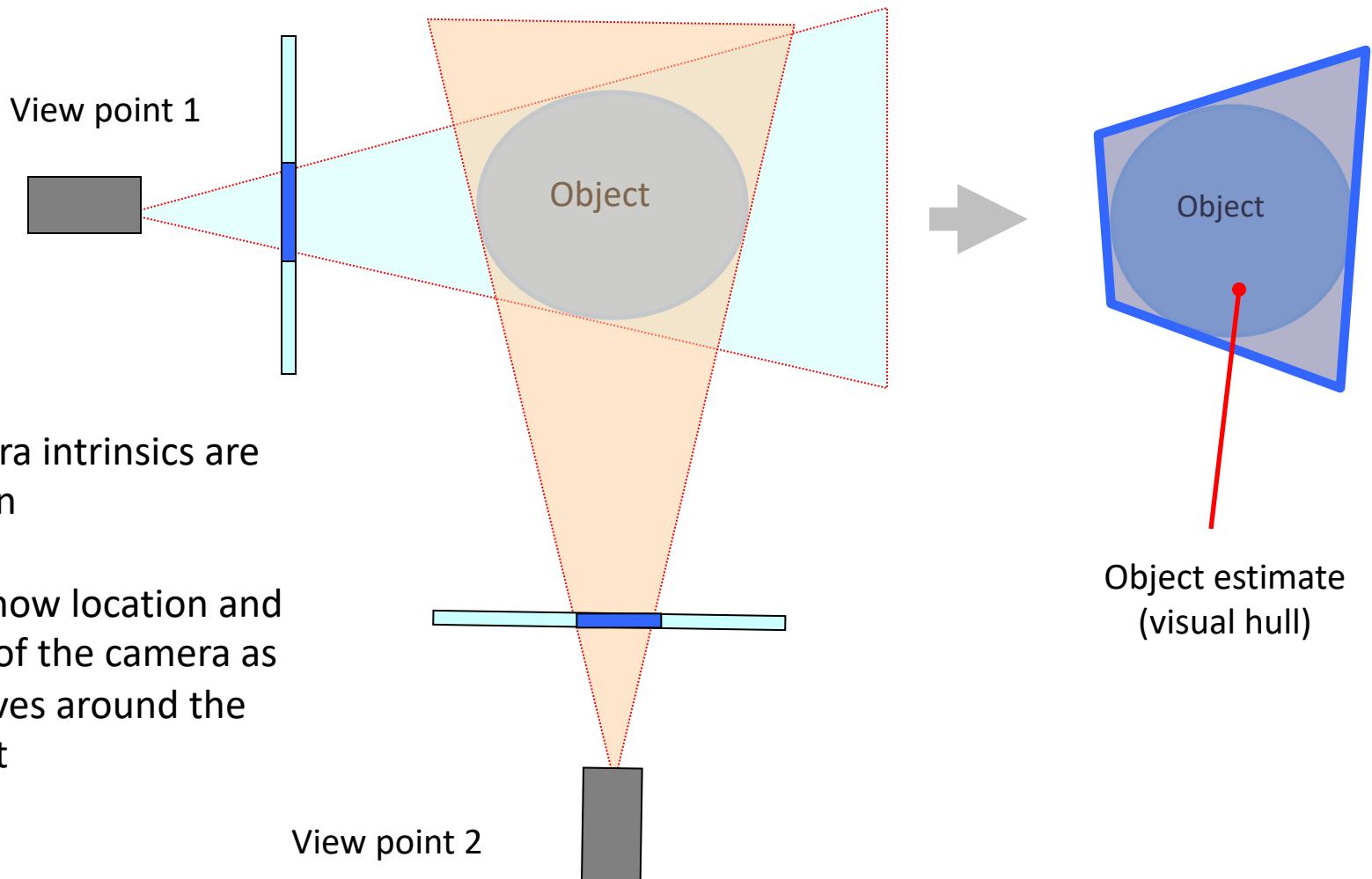
How can we use contours?



How can we use contours?

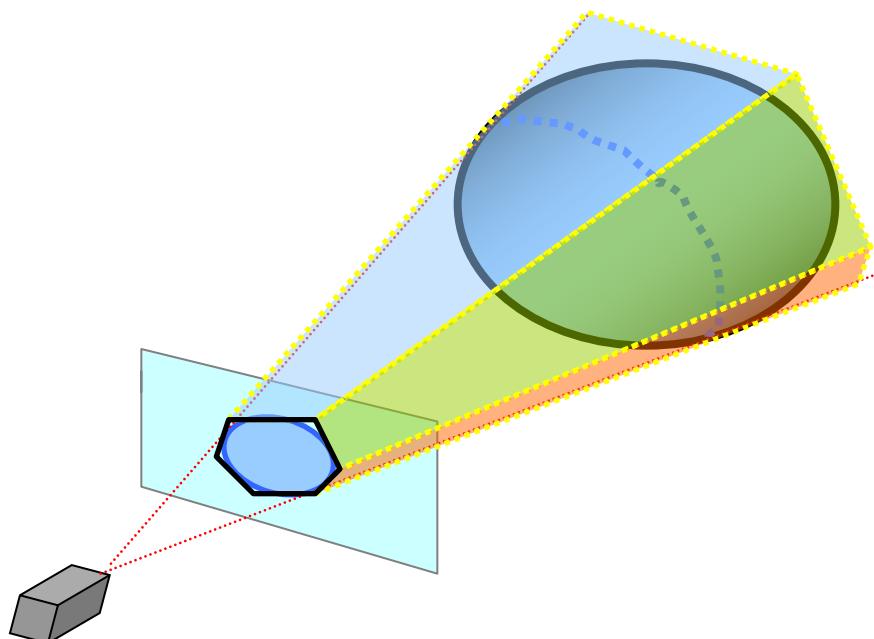


How can we use contours?



How to perform visual cones intersection?

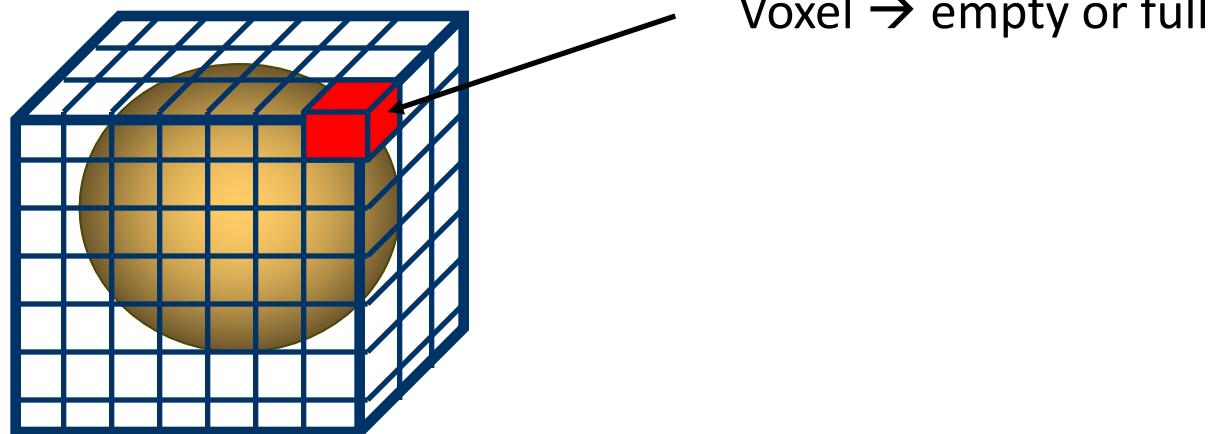
- Decompose visual cone in polygonal surfaces
(among others: Reed and Allen '99)



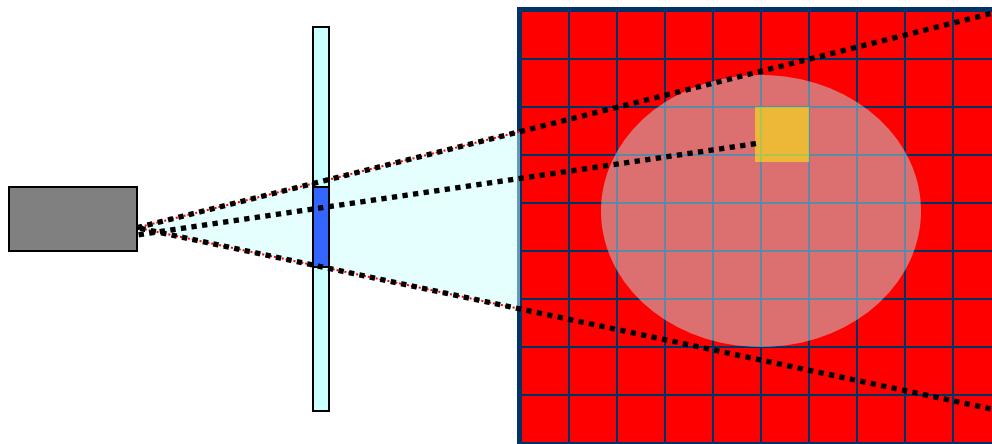
Space carving

[Martin and Aggarwal (1983)]

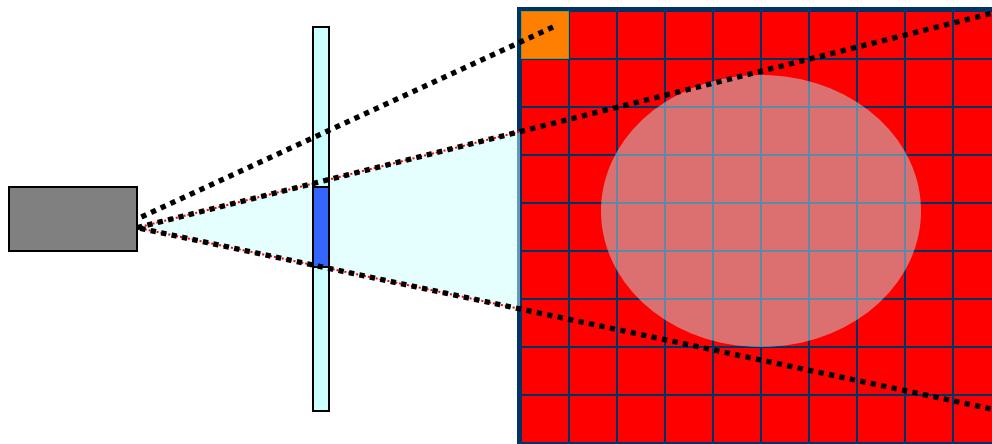
- Using contours/silhouettes in volumetric stereo, also called **space carving**



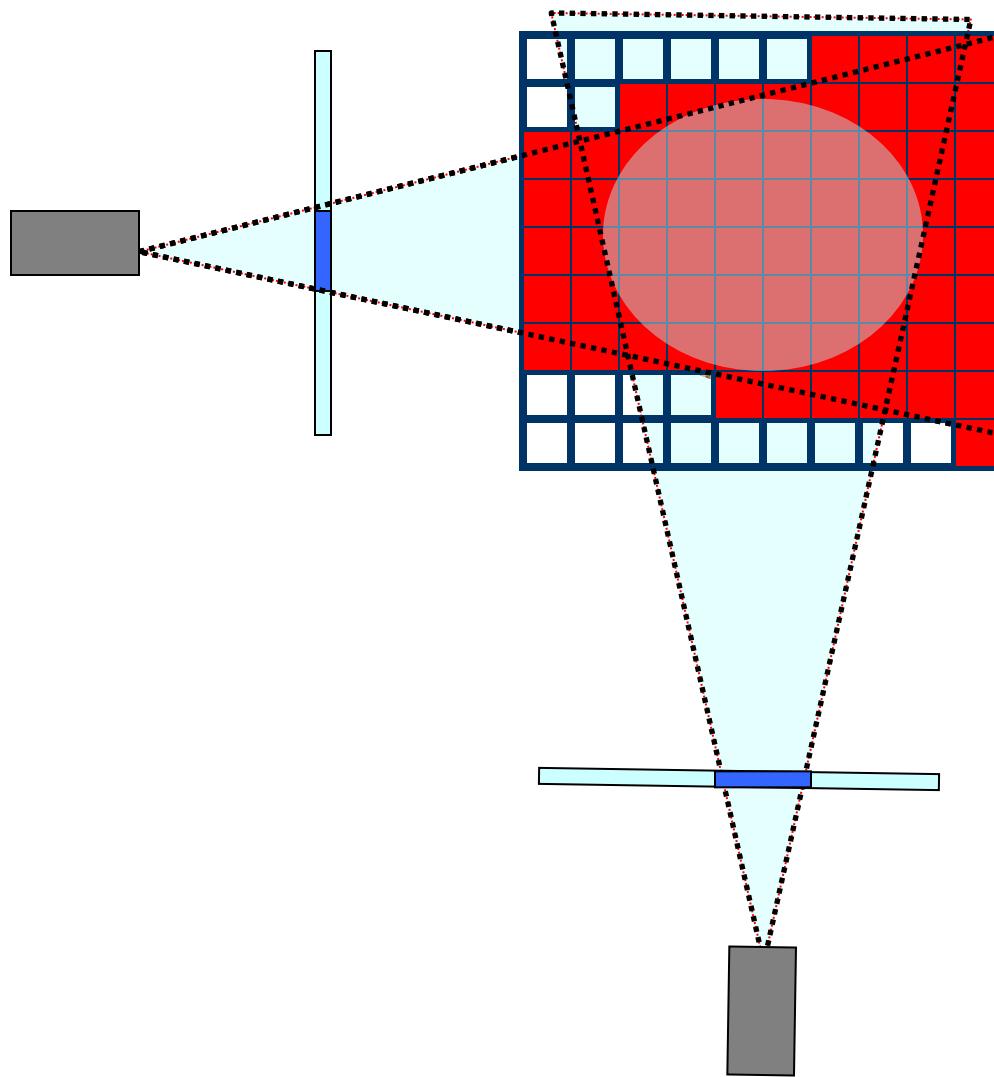
Computing Visual Hull in 2D



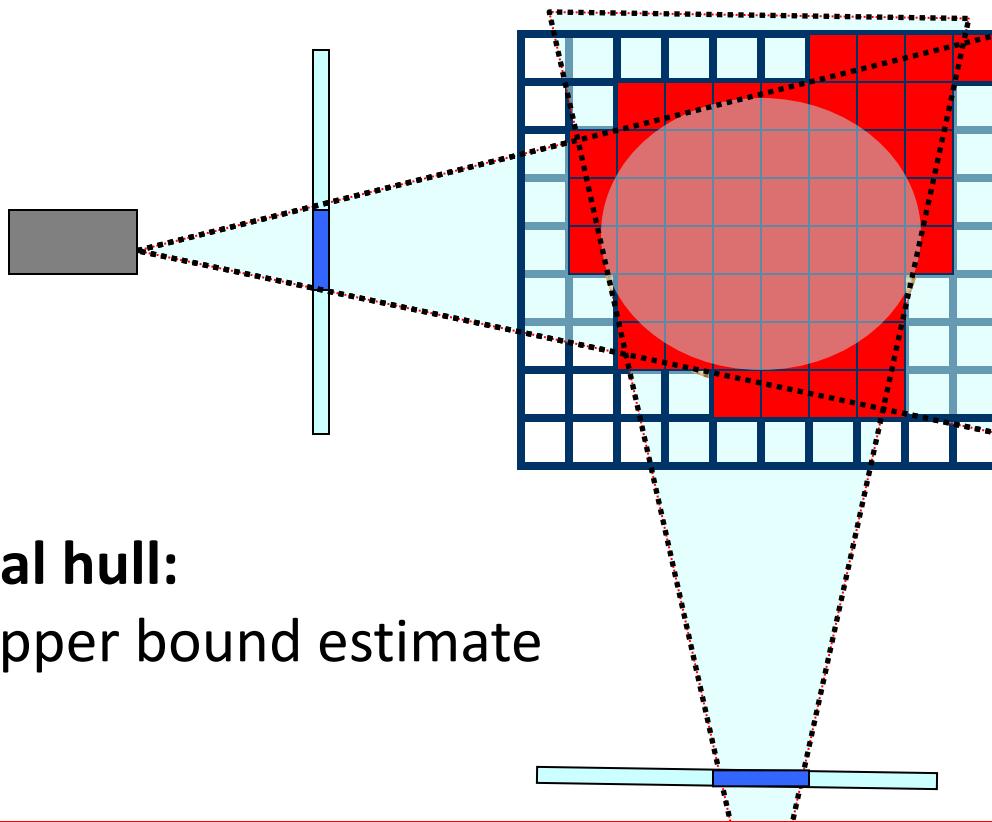
Computing Visual Hull in 2D



Computing Visual Hull in 2D



Computing Visual Hull in 2D



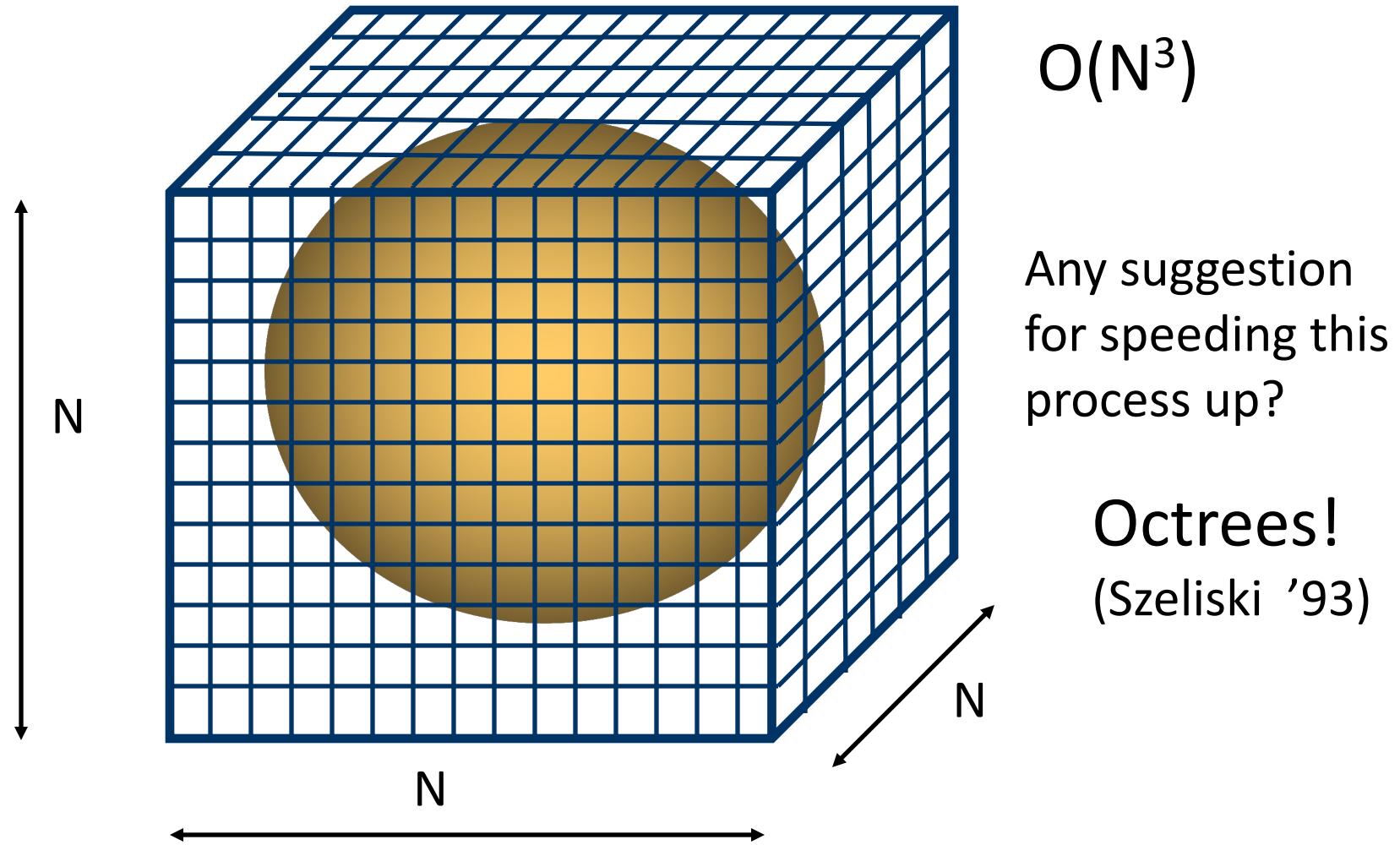
Visual hull:

an upper bound estimate

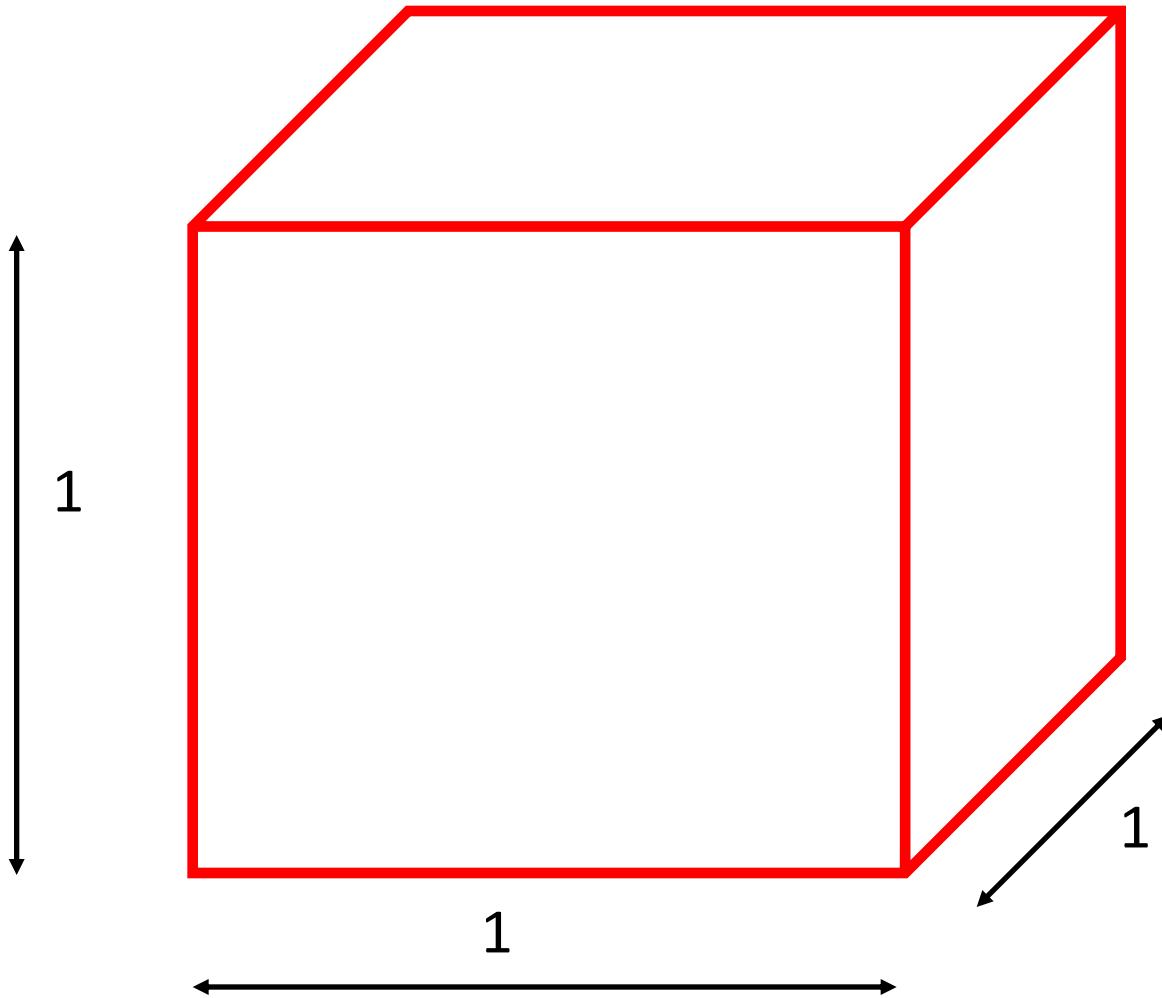
Consistency:

A voxel must be projected into a silhouette in each image

Space carving has complexity ...

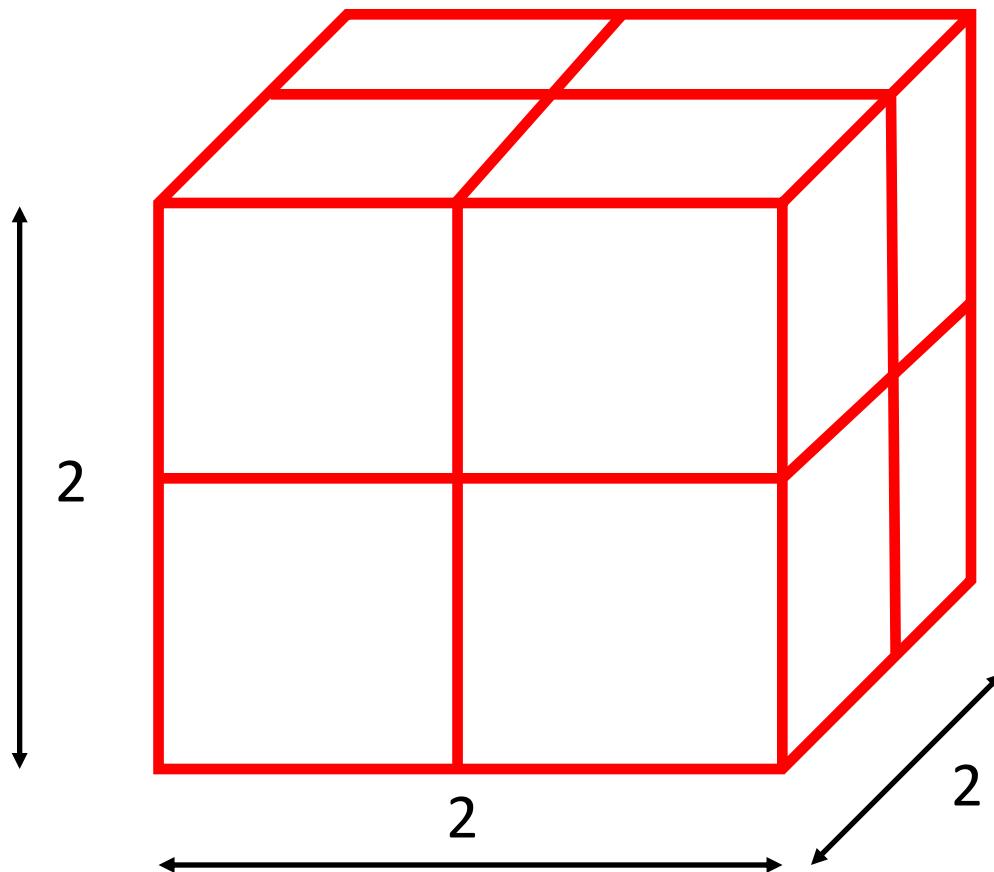


Complexity Reduction: Octrees

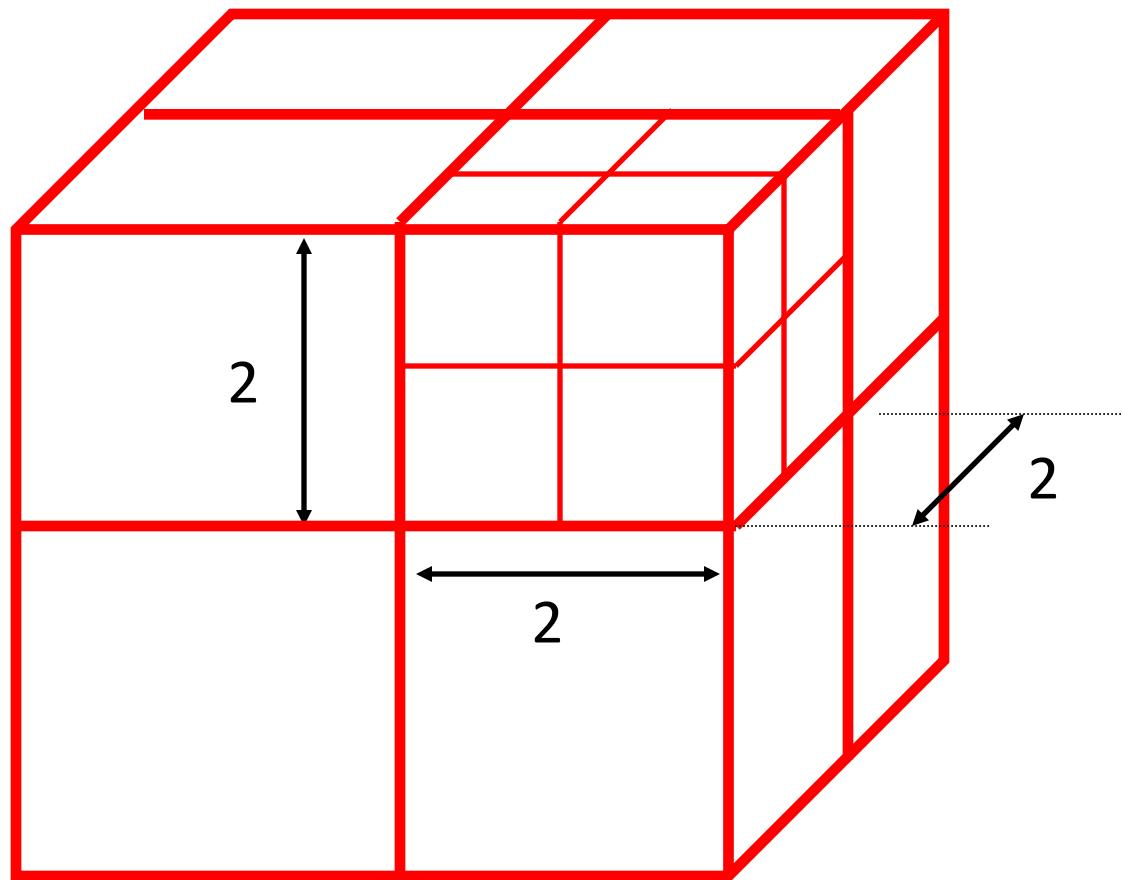


Complexity Reduction: Octrees

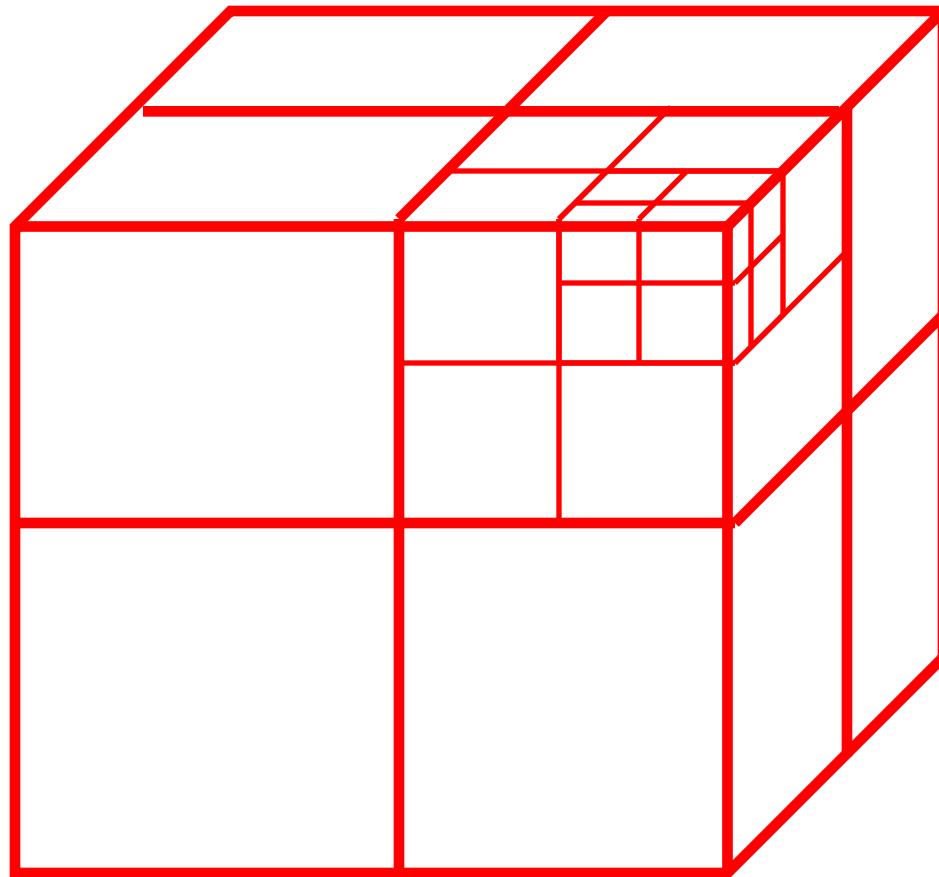
- Subdividing volume in sub-volumes of progressive smaller size



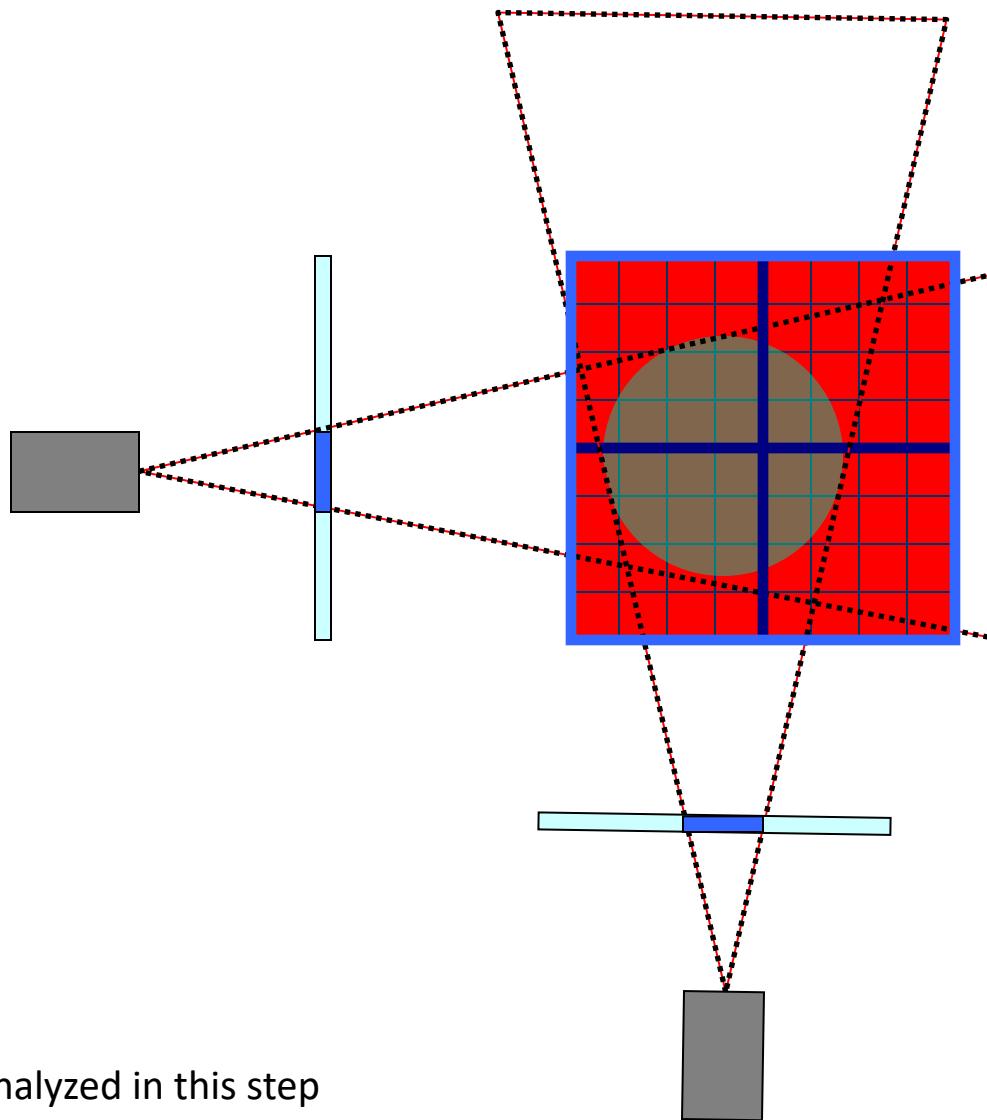
Complexity Reduction: Octrees



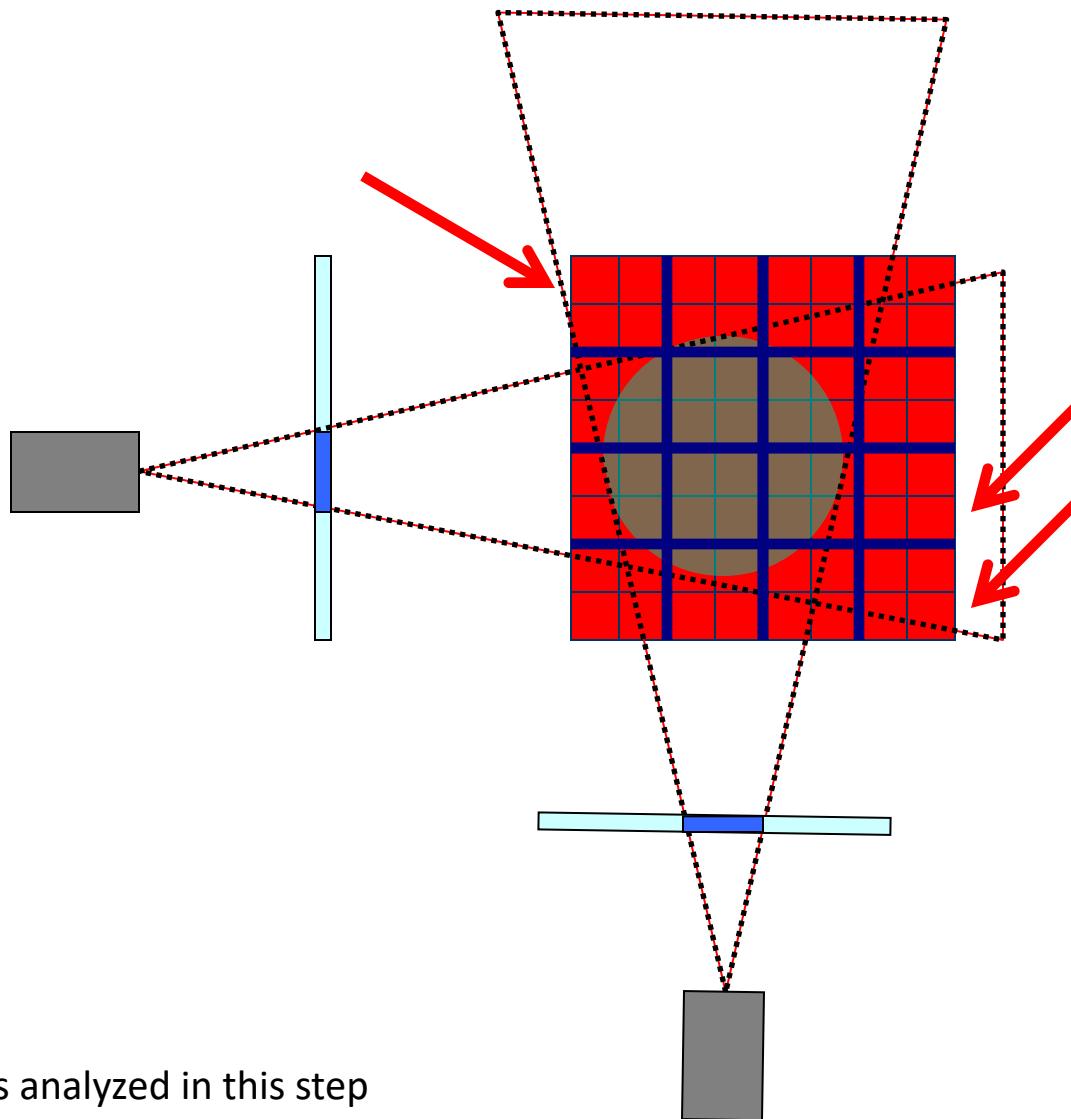
Complexity Reduction: Octrees



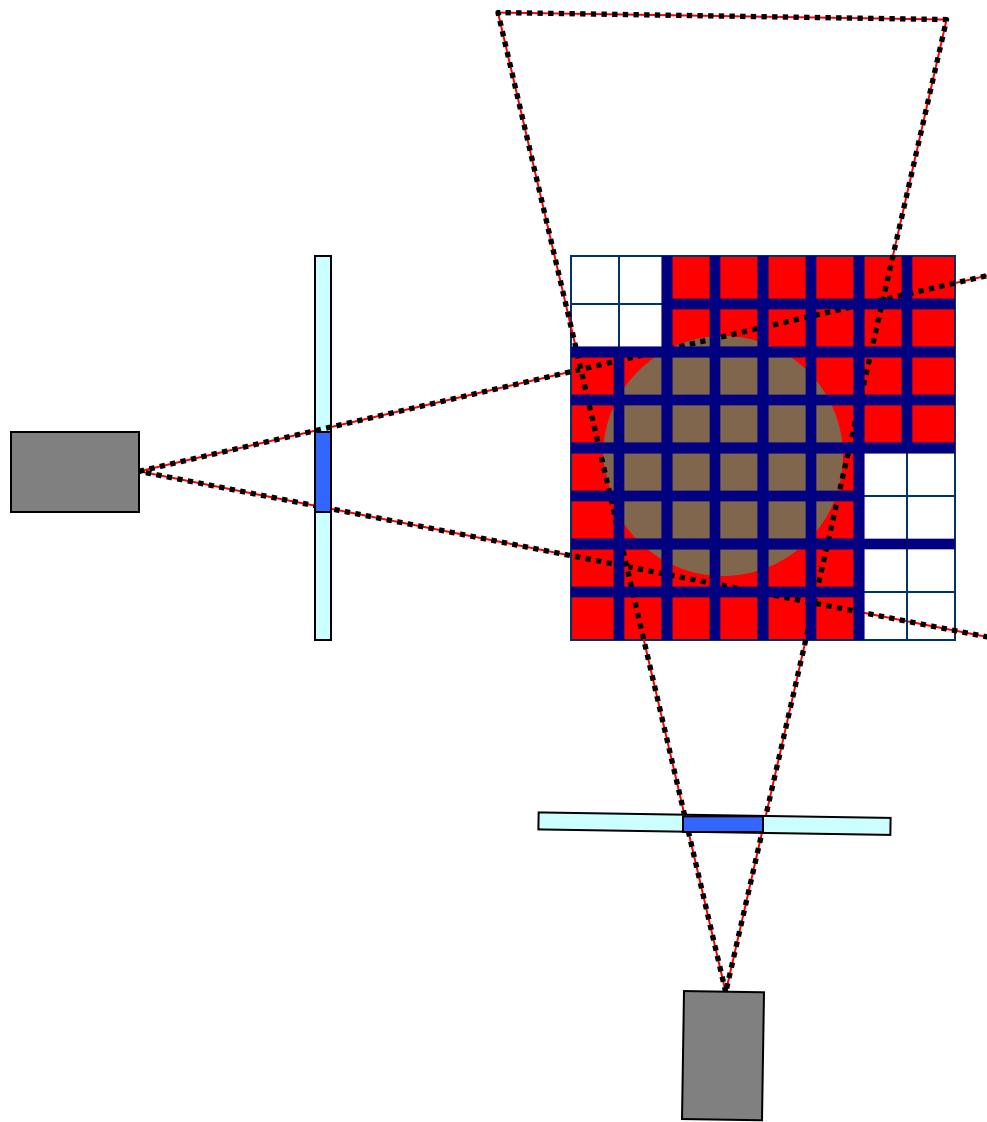
Complexity reduction: 2D example



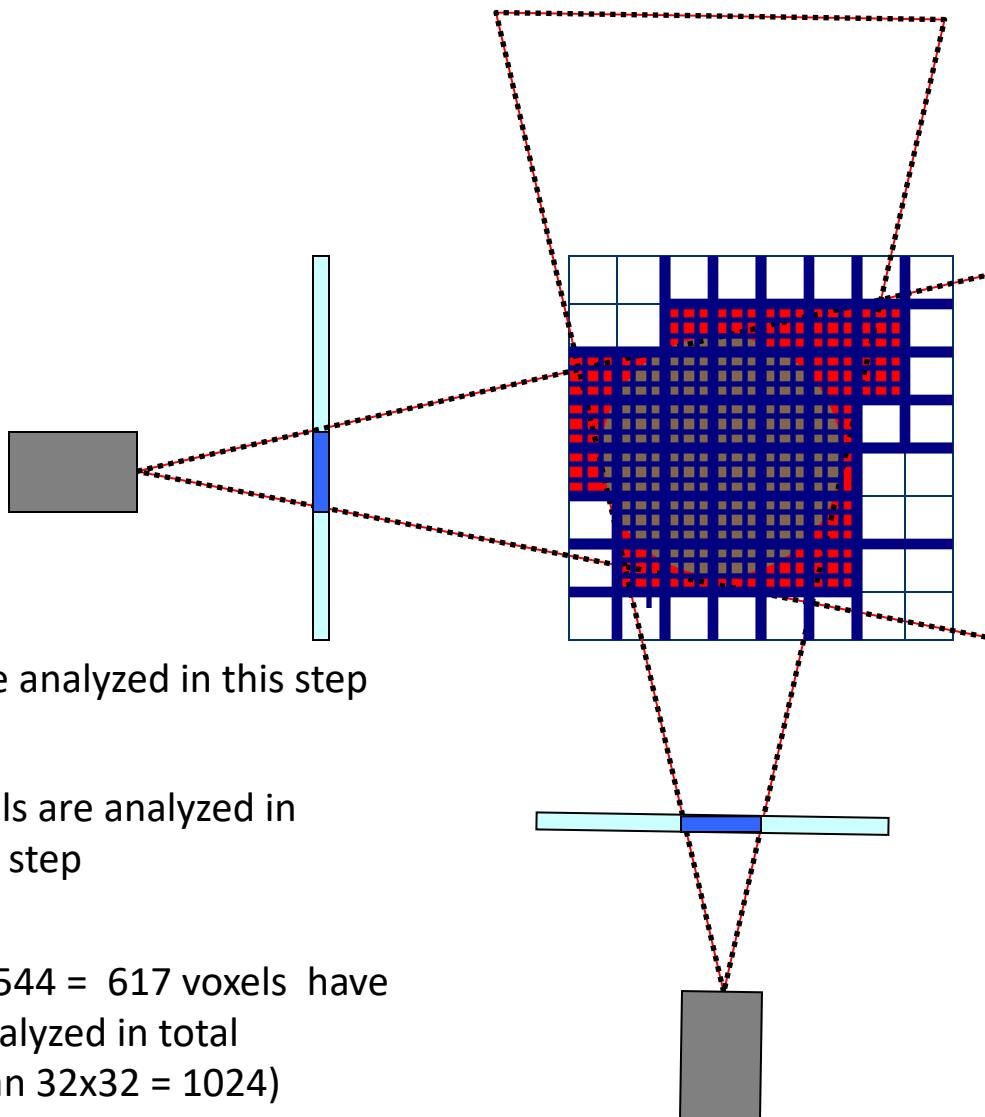
Complexity reduction: 2D example



Complexity reduction: 2D example



Complexity reduction: 2D example



52 elements are analyzed in this step

$16 \times 34 = 544$ voxels are analyzed in
this step

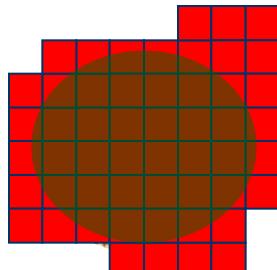
$1 + 4 + 16 + 52 + 544 = 617$ voxels have
been analyzed in total
(rather than $32 \times 32 = 1024$)

Advantages of Space carving

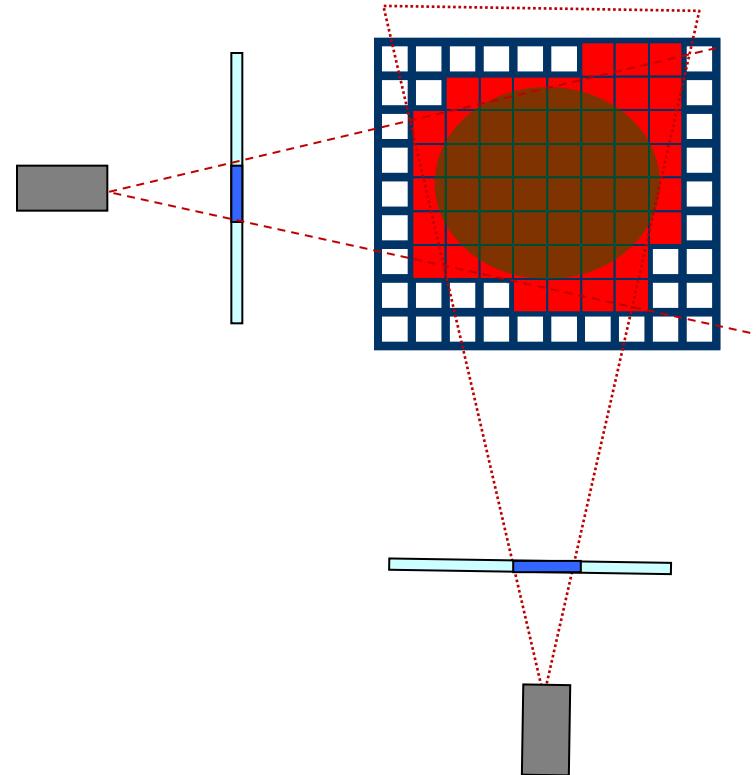
- Robust and simple
- No need to solve for correspondences

Limitations of Space carving

- Accuracy function of number of views



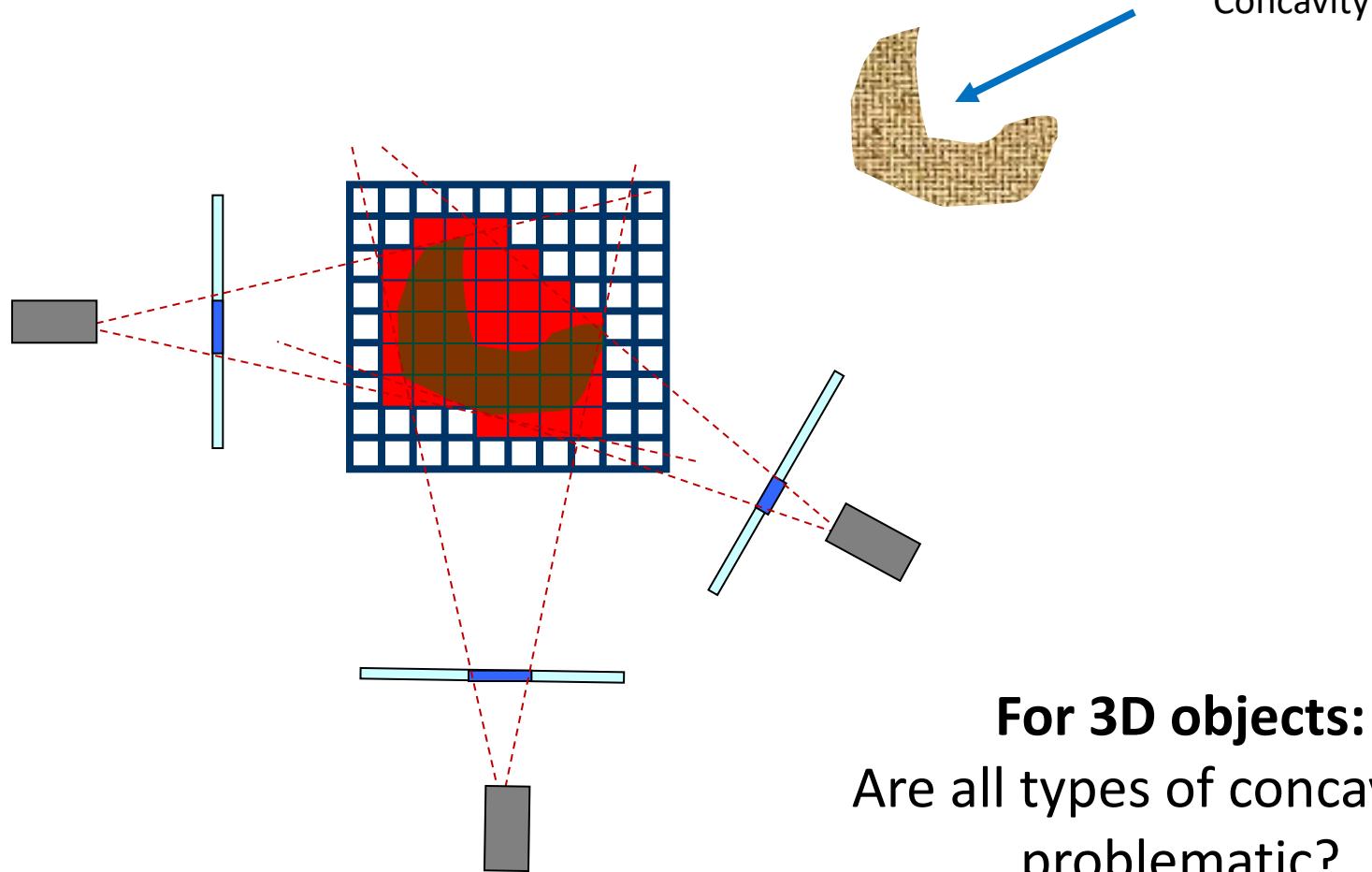
Not a good estimate



What else?

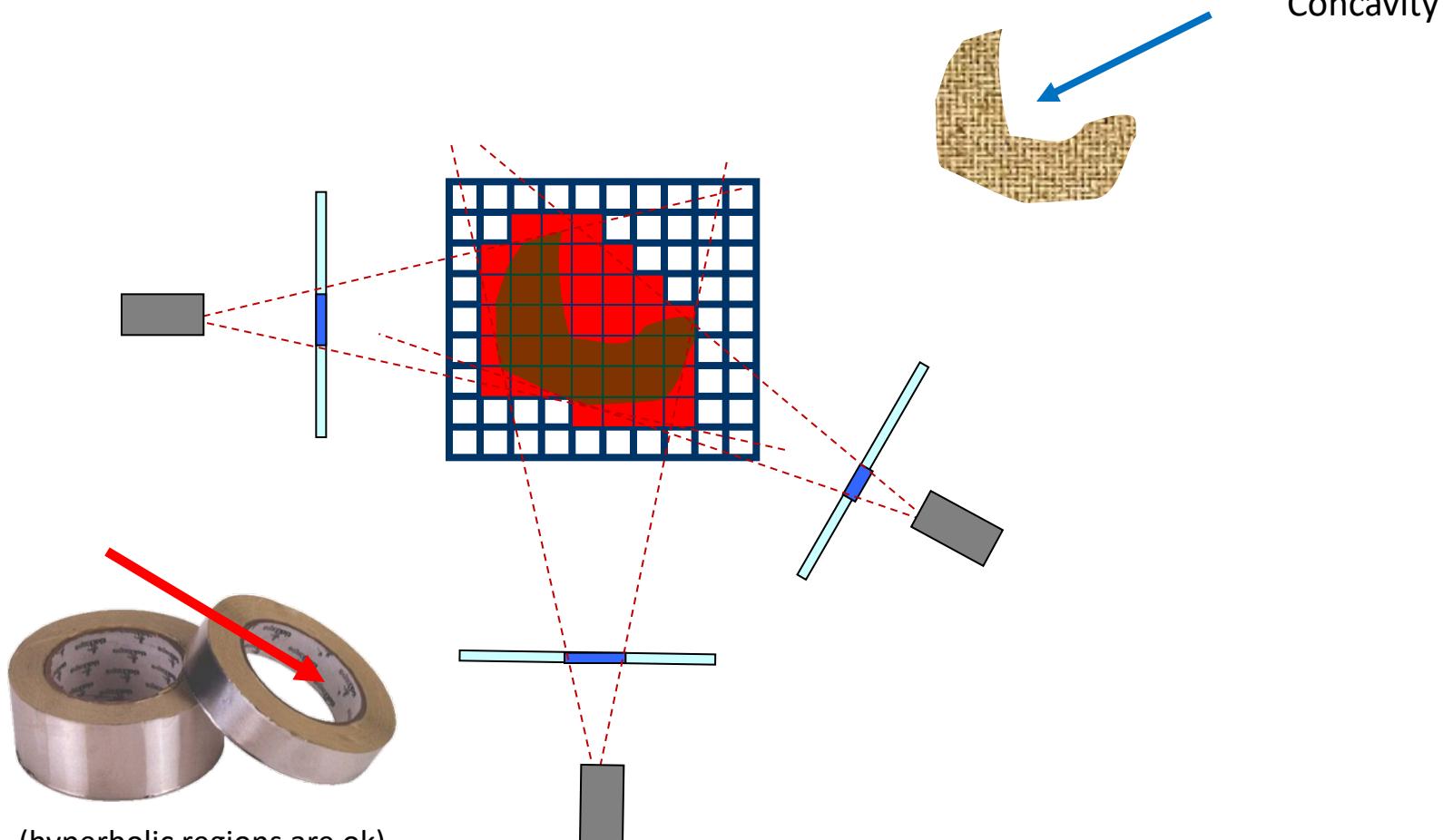
Limitations of Space carving

- Concavities are not modeled



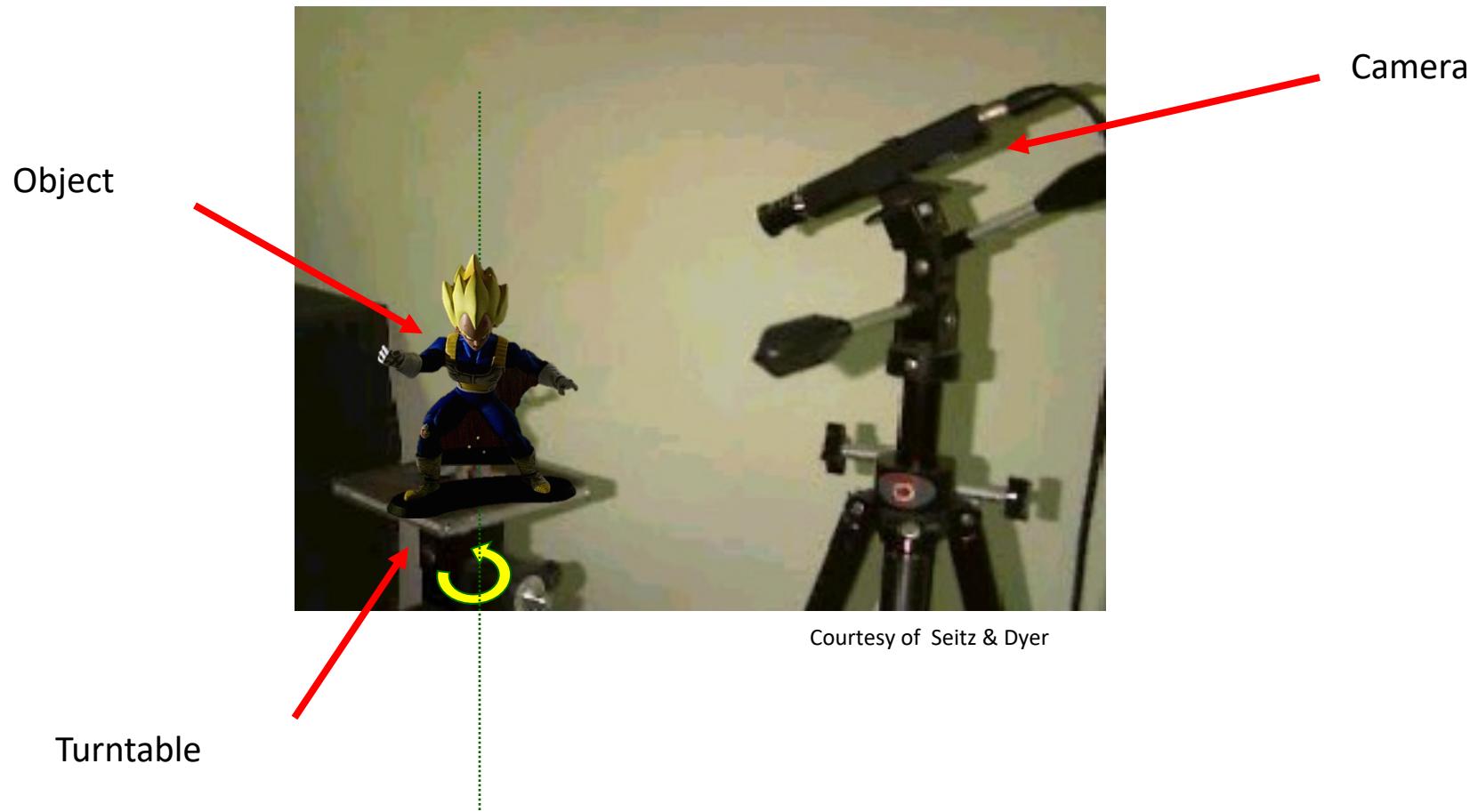
Limitations of Space carving

- Concavities are not modeled



-- see Laurentini (1995)

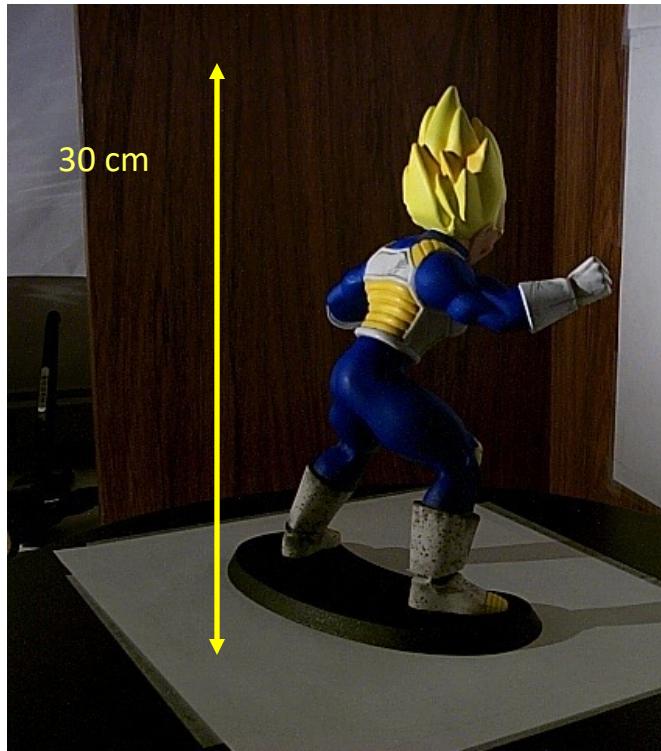
Space carving: A Classic Setup



Space carving: A Classic Setup

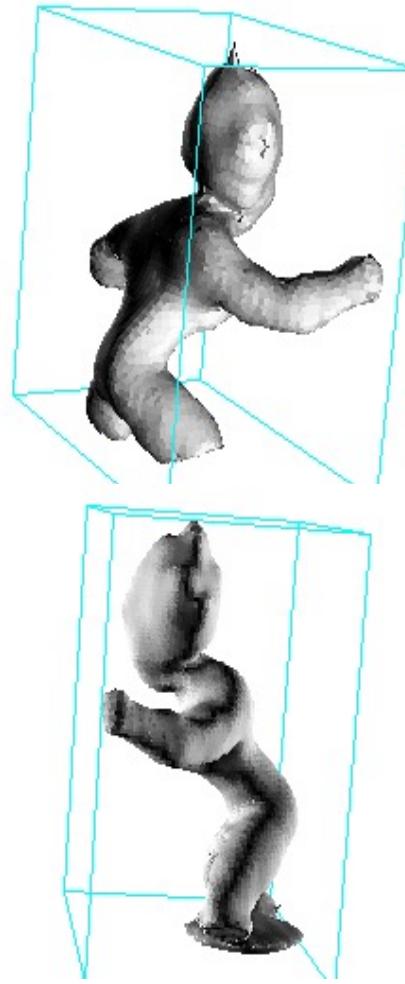


Space carving: Experiments

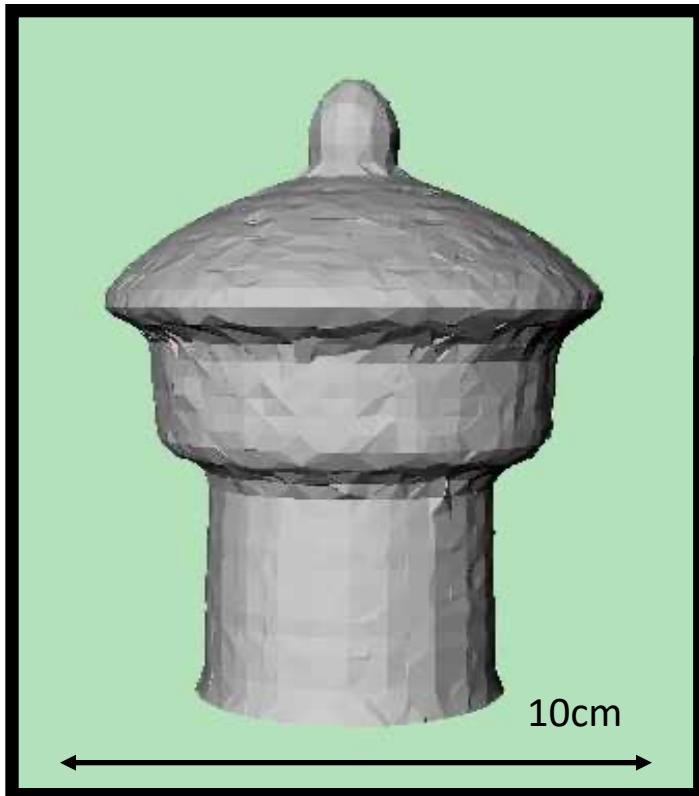


24 poses (15°)

voxel size = 1mm

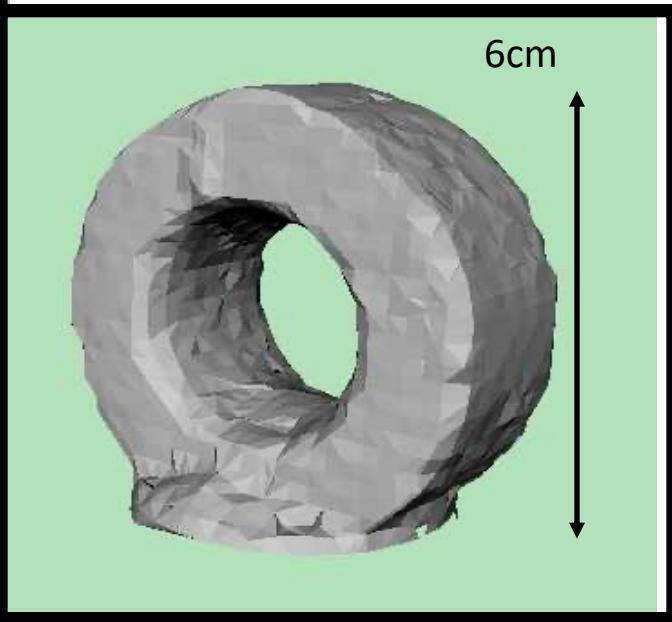


Space carving: Experiments



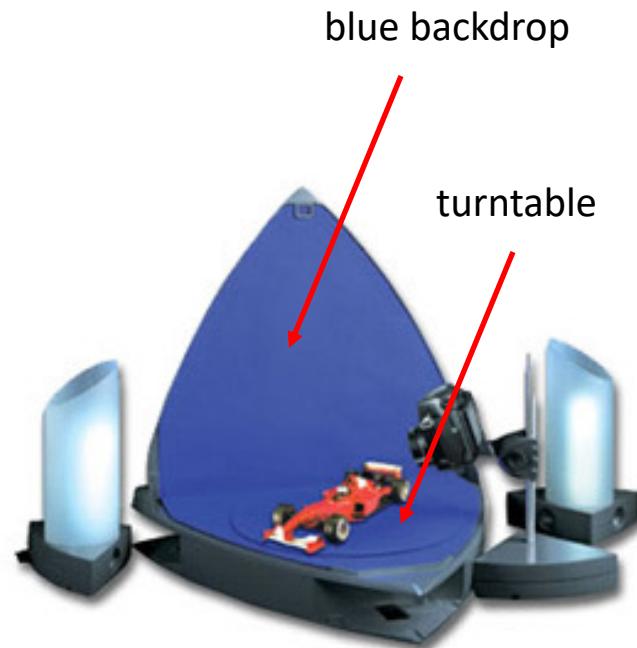
24 poses (15°)

voxel size = 2mm



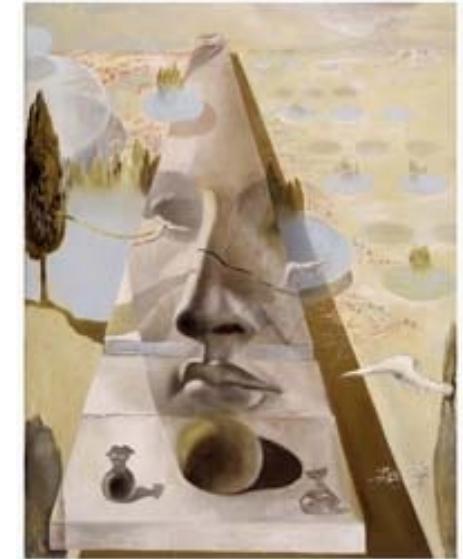
Space carving: Conclusions

- Robust
- Produce conservative estimates
- Concavities can be a problem
- Low-end commercial 3D scanners



Lecture 8

Active stereo & Volumetric stereo



- Active stereo
 - Structured lighting
 - Depth sensing
- Volumetric stereo:
 - Space carving
 - Shadow carving
 - Voxel coloring

Shape from Shadows

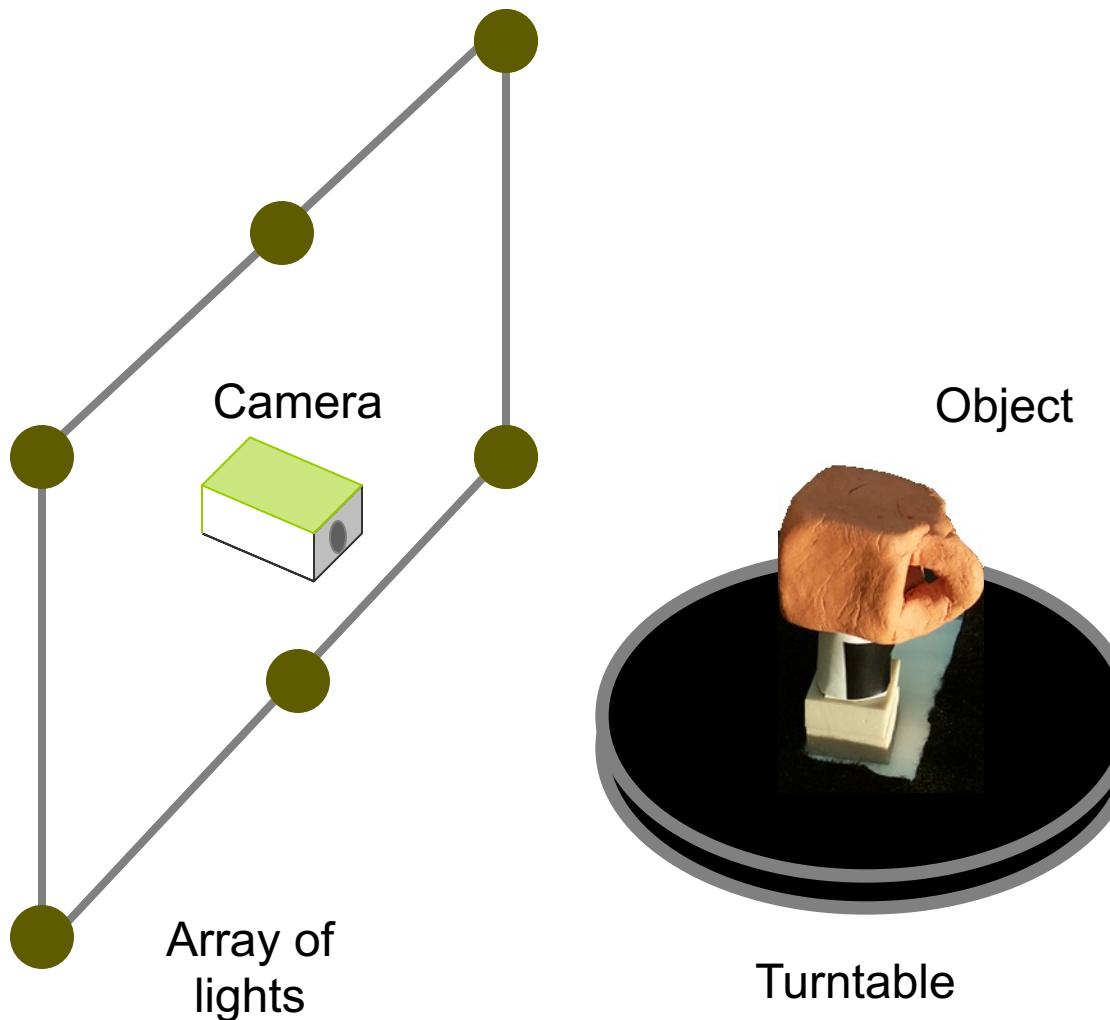
- Self-shadows are visual cues for shape recovery



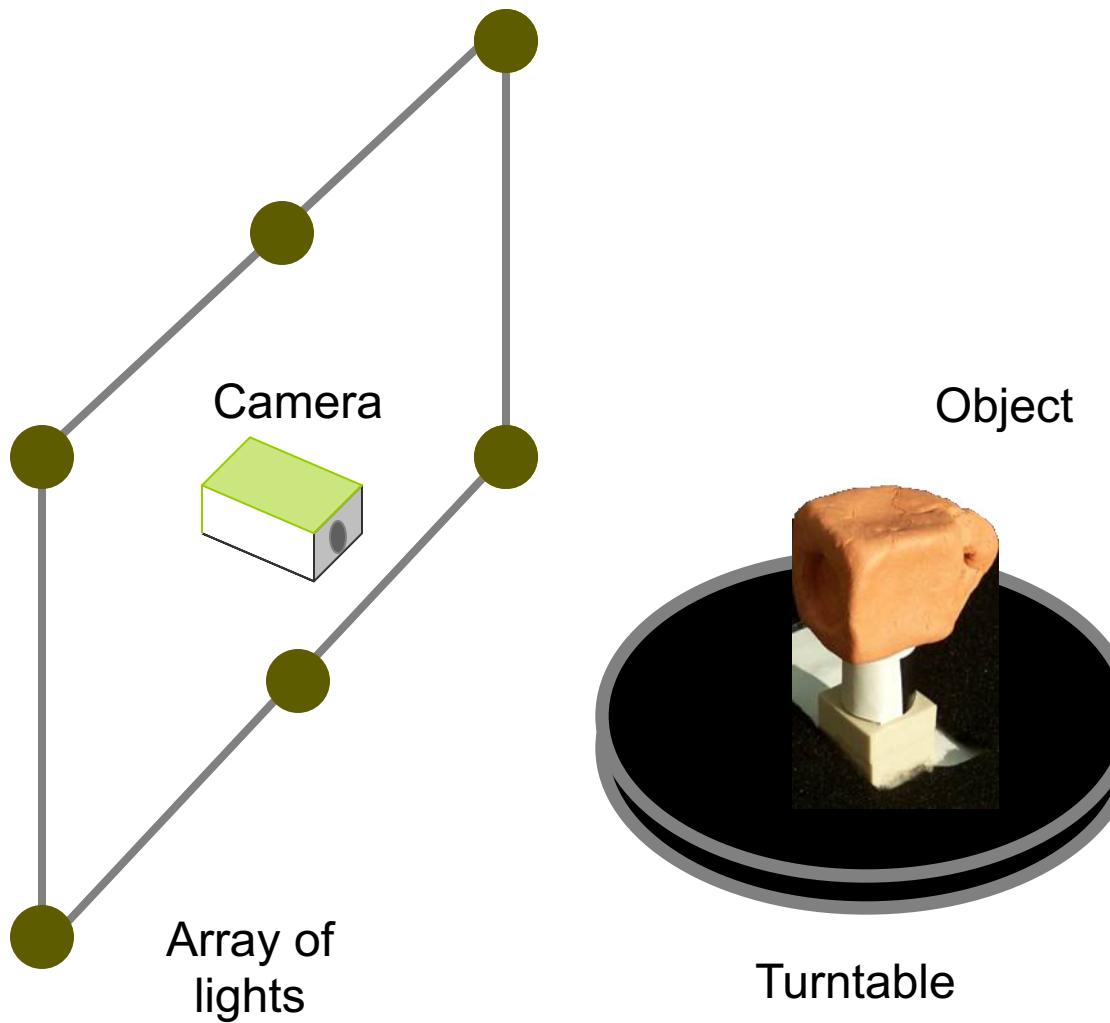
Self-shadows indicate concavities
(no modeled by contours)



Shadow carving: The Setup

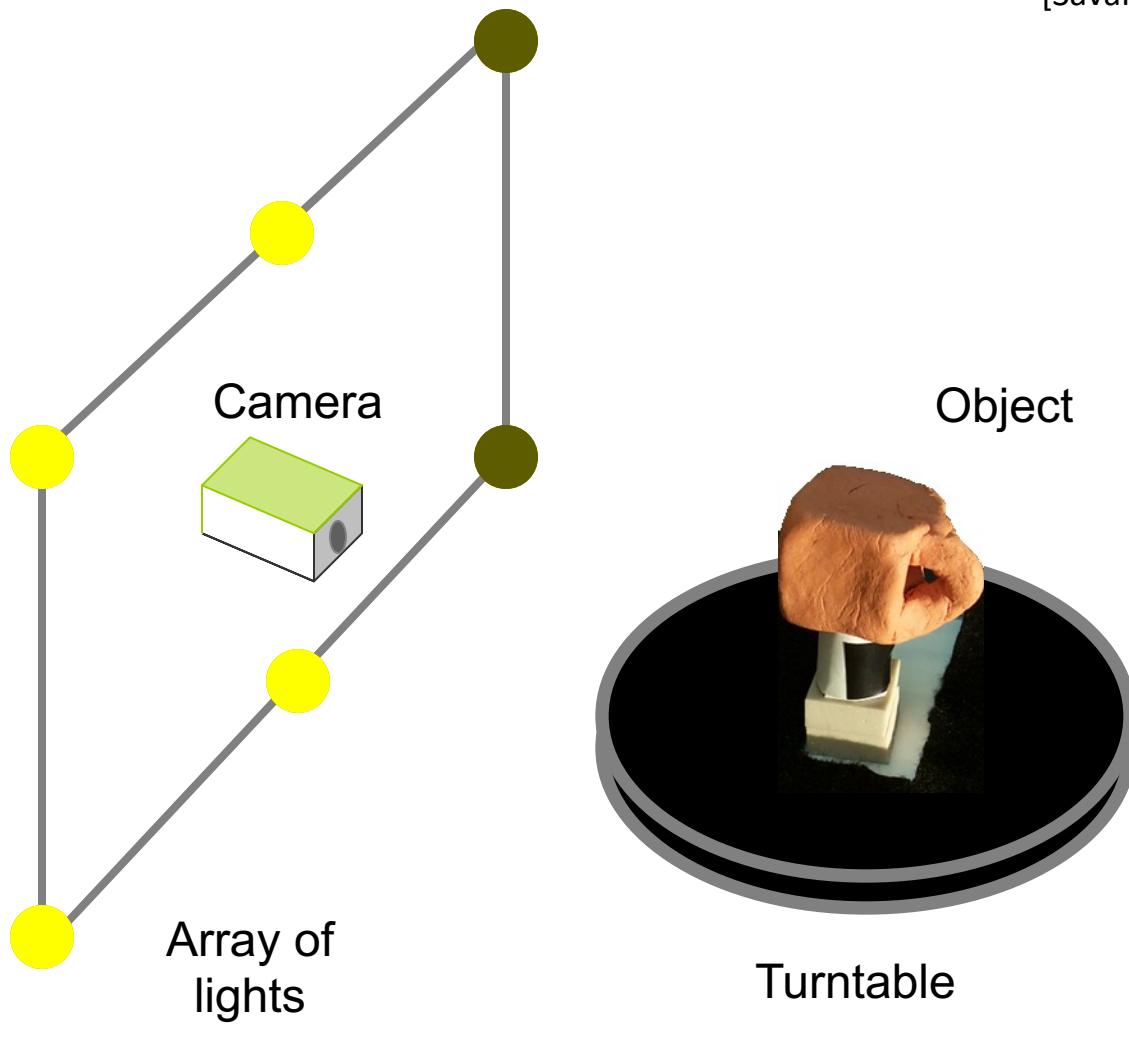
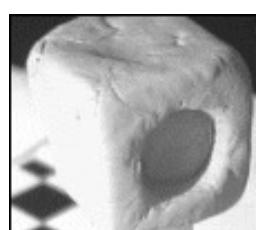
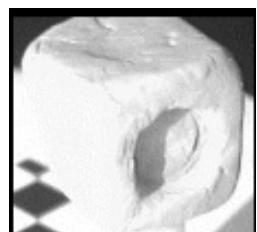
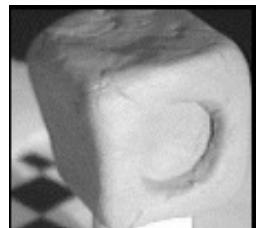


Shadow carving: The Setup



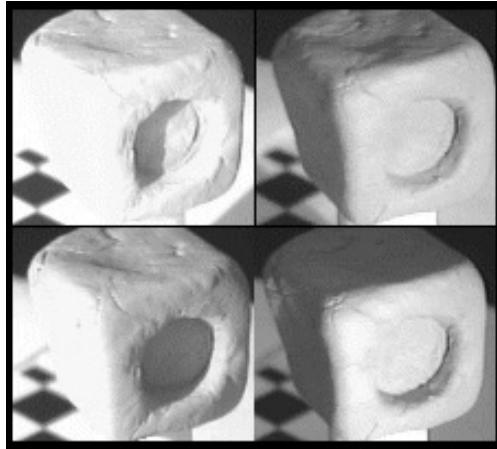
Shadow carving: The Setup

[Savarese et al '01]



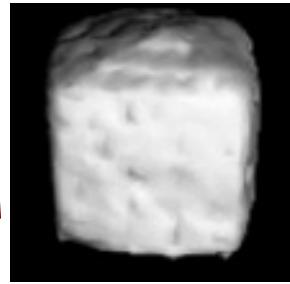
Shadow carving

[Savarese et al '01]

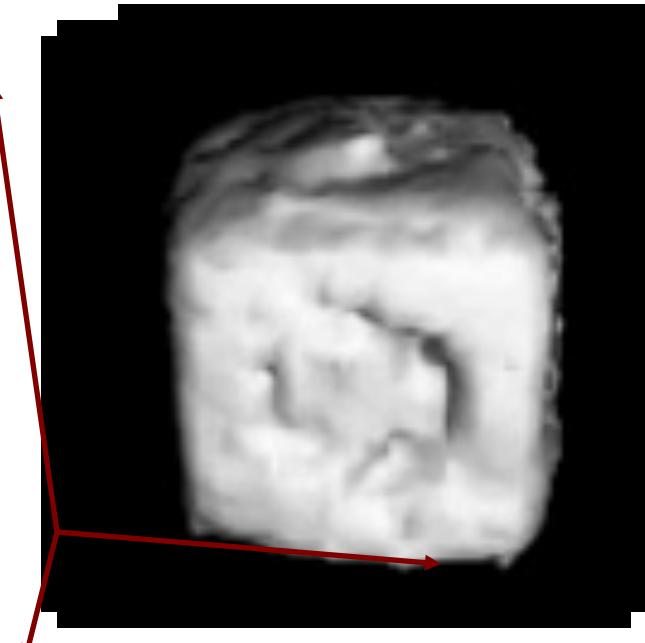
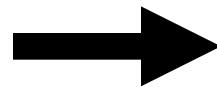


Self-shadows

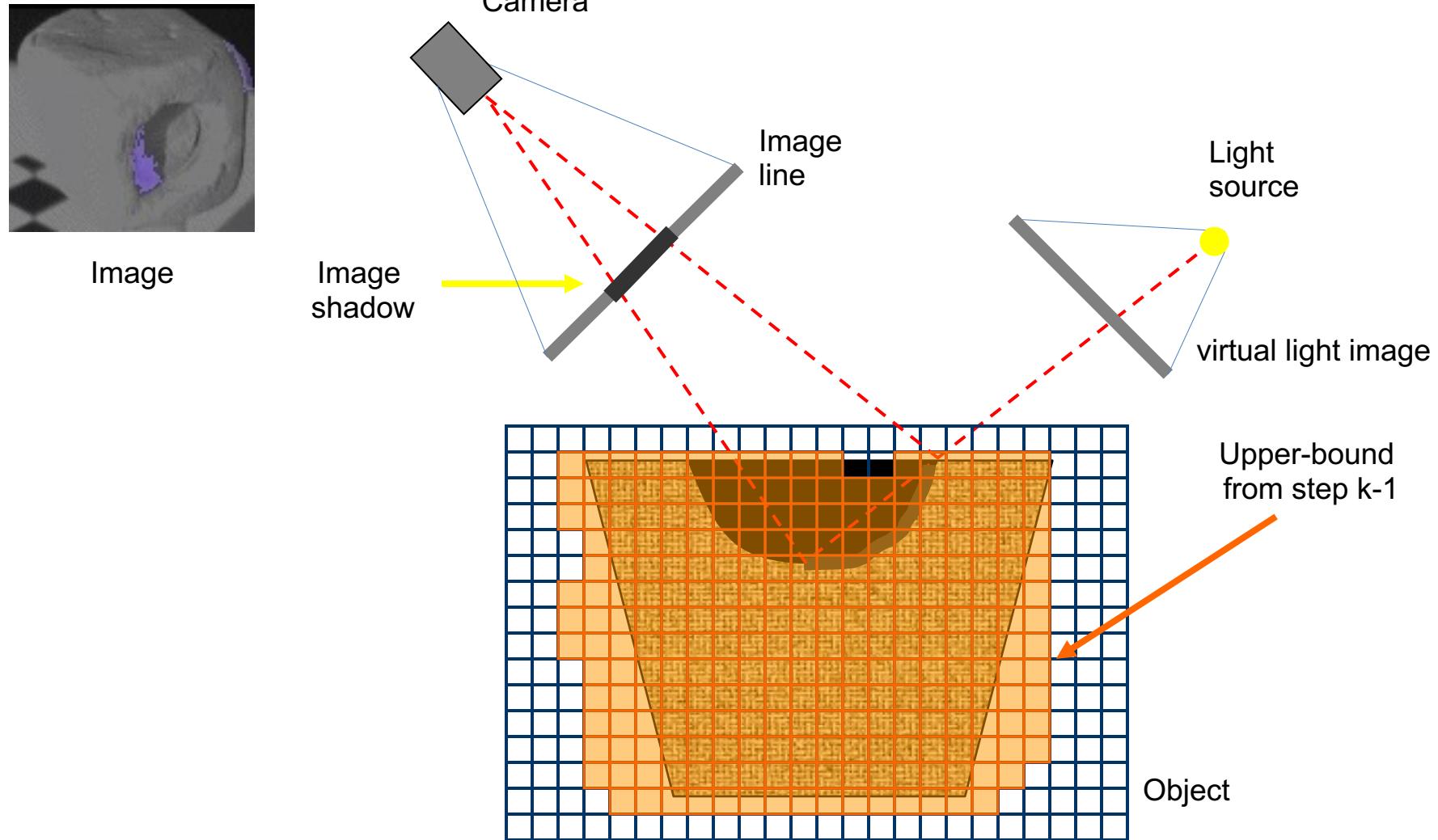
+



Object's upper bound



Algorithm: Step k

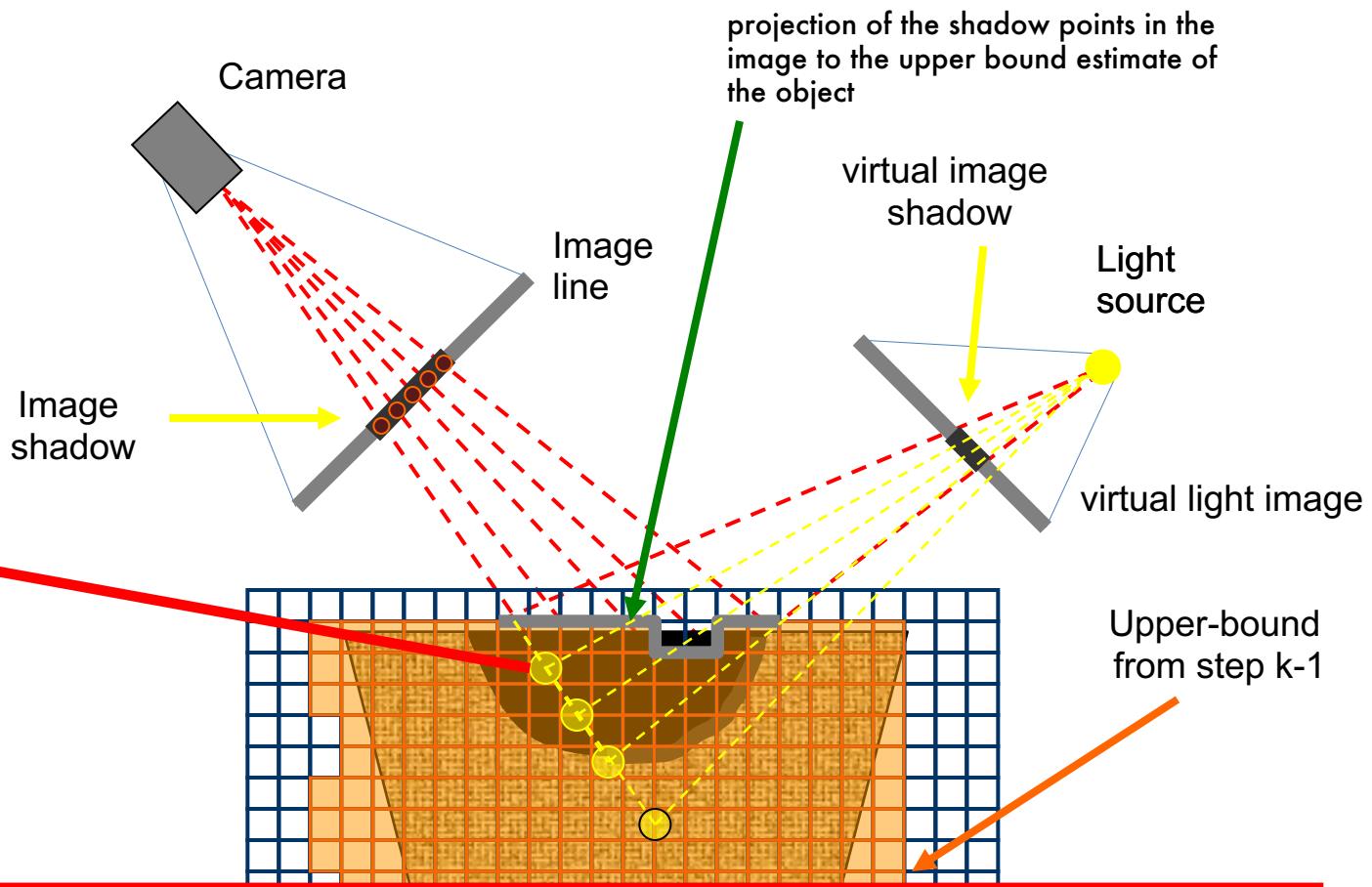


Algorithm: Step k



Image

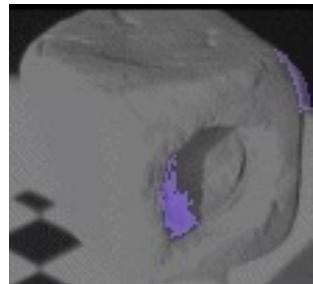
?



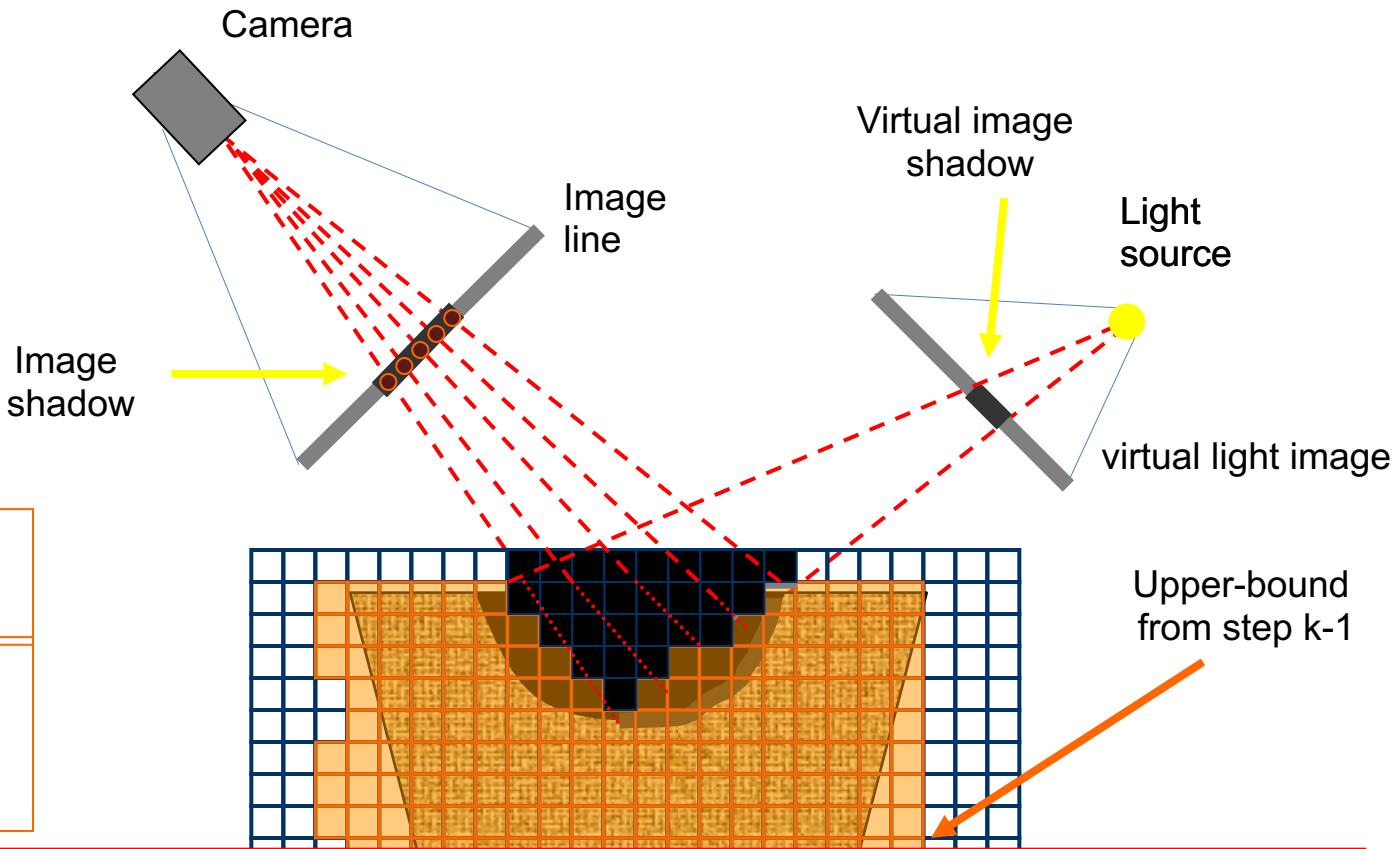
Theorem:

A voxel that projects into an image shadow AND an virtual image shadow cannot belong to the object.

Algorithm: Step k



Image



Properties:

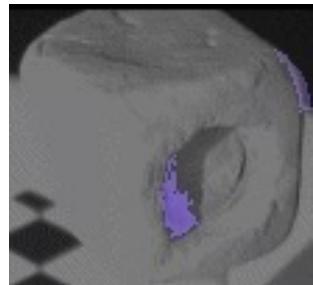
No further volume can be removed

Carving process
always
conservative

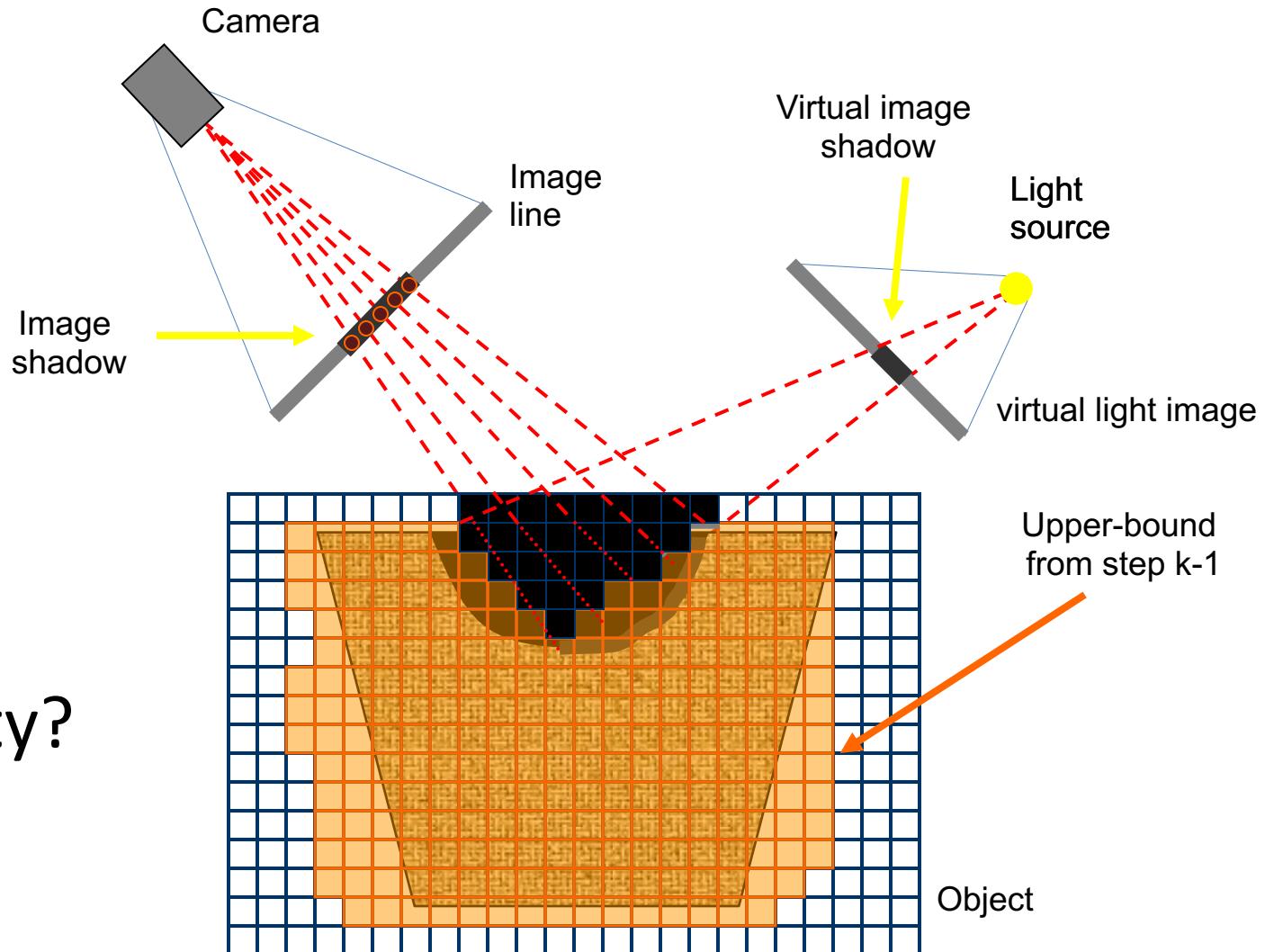
Consistency:

In order for a voxel to be removed it must project into both
image shadow and virtual image shadow

Algorithm: Step k



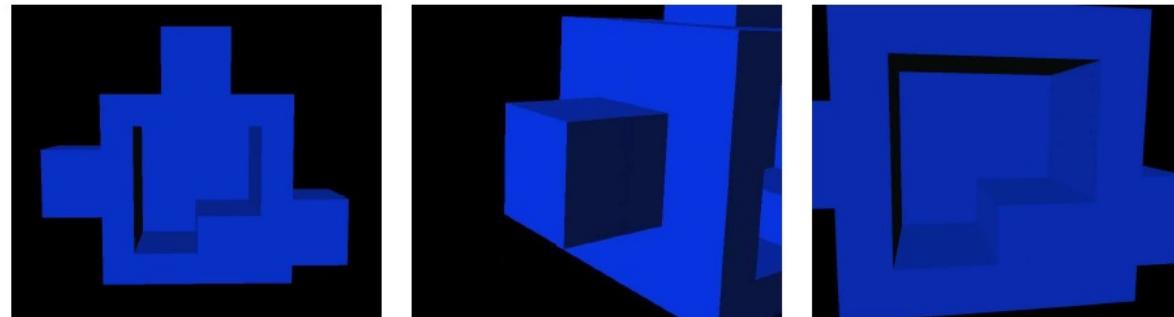
Image



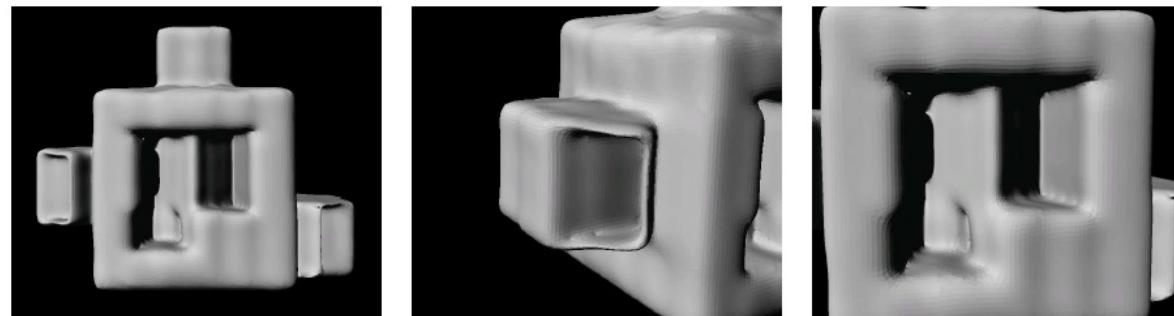
Complexity?

$$O(2N^3)$$

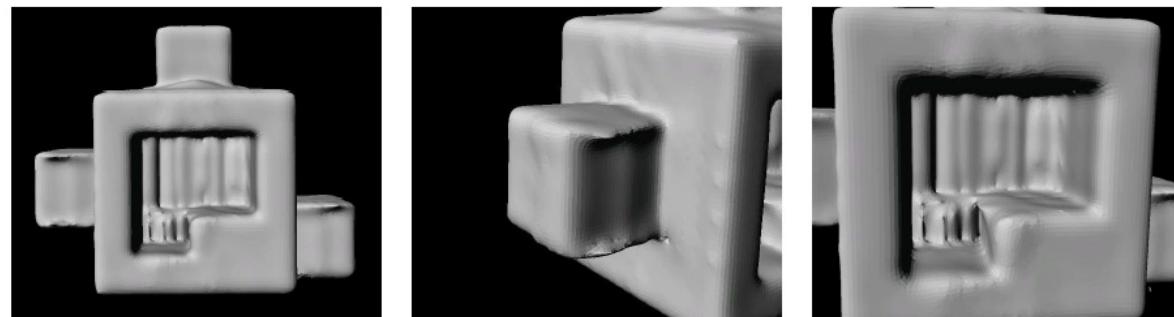
Simulating the System



- 24 positions
- 4 lights



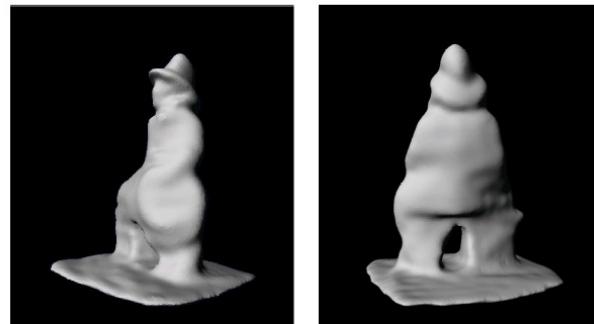
- 72 positions
- 8 lights



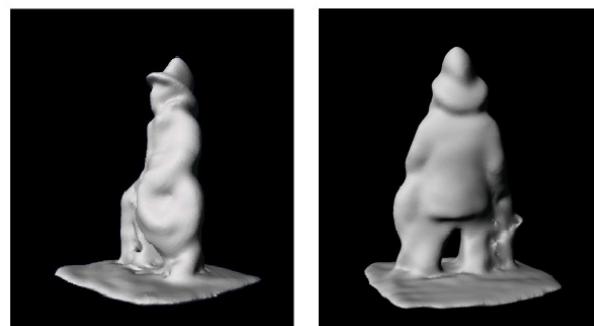
Results



- 16 positions
- 4 lights

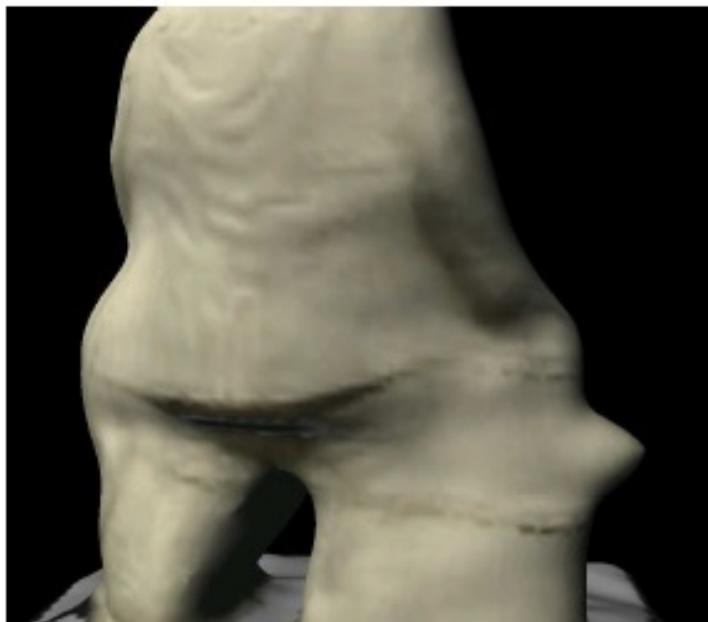


Space carving



Shadow carving

Results



Space carving



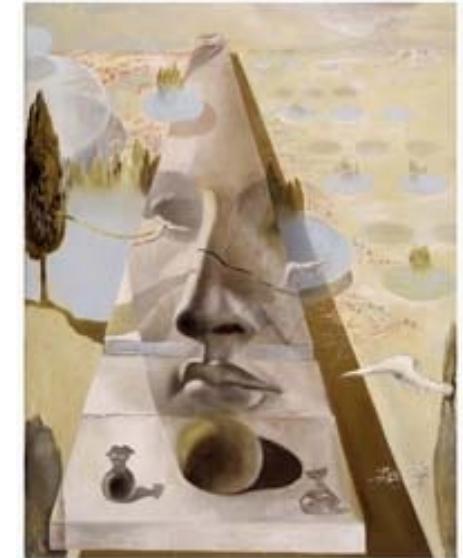
Shadow carving

Shadow carving: Summary

- Produces a conservative volume estimate
- Accuracy depending on view point and light source number
- Limitations with reflective & low albedo regions

Lecture 8

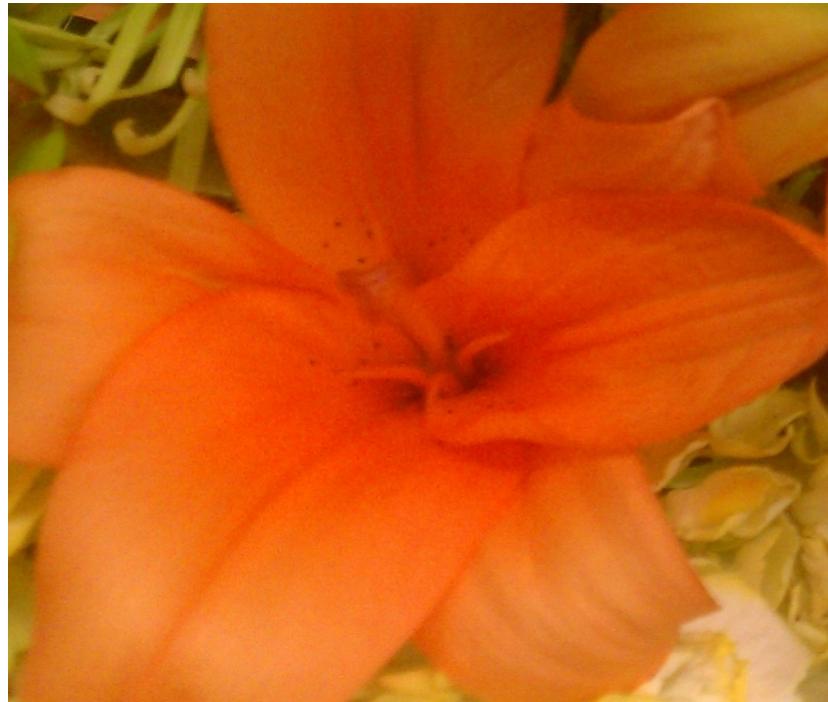
Active stereo & Volumetric stereo



- Active stereo
 - Structured lighting
 - Depth sensing
- Volumetric stereo:
 - Space carving
 - Shadow carving
 - Voxel coloring

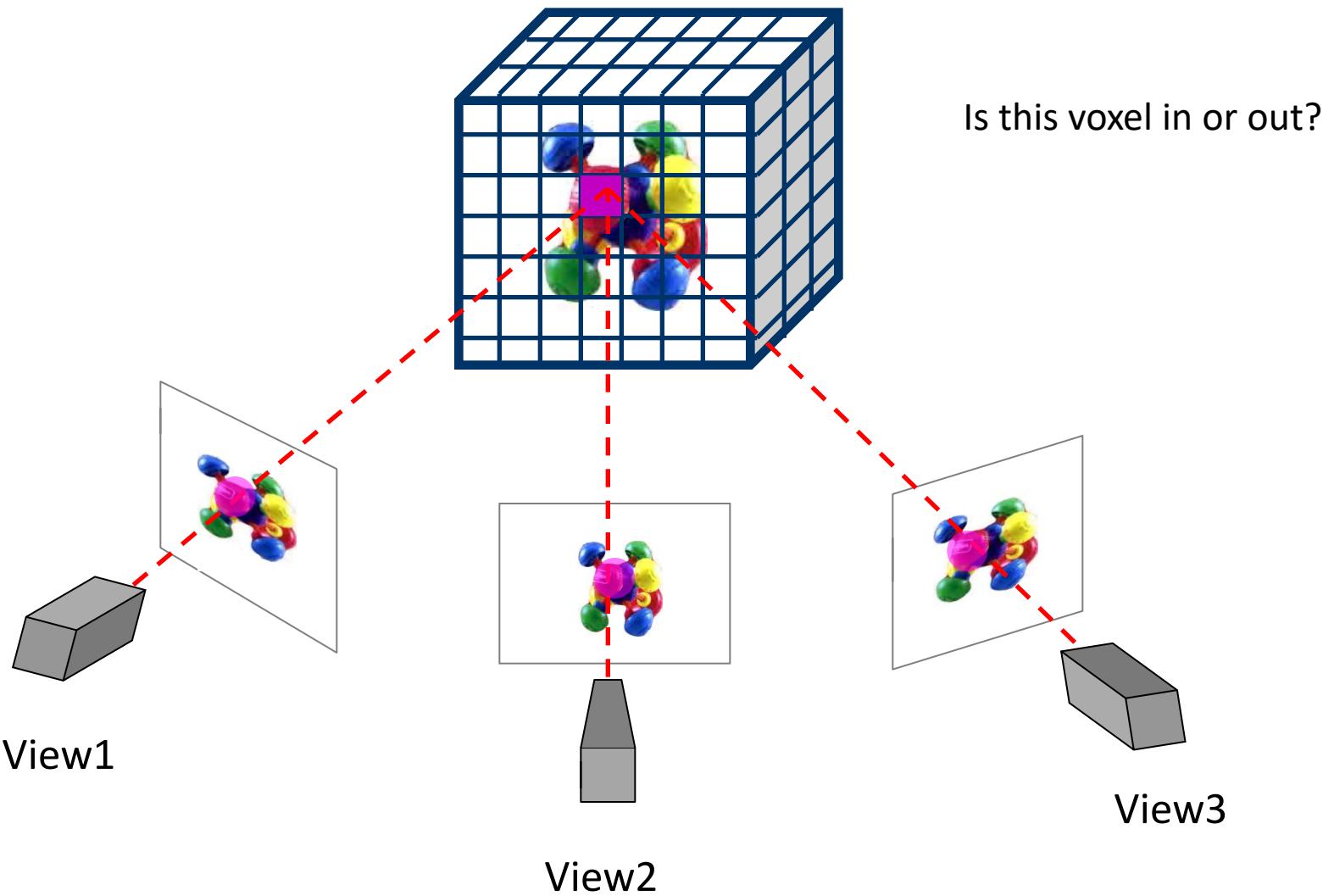
Voxel Coloring

[Seitz & Dyer ('97)]
[R. Collins (Space Sweep, '96)]

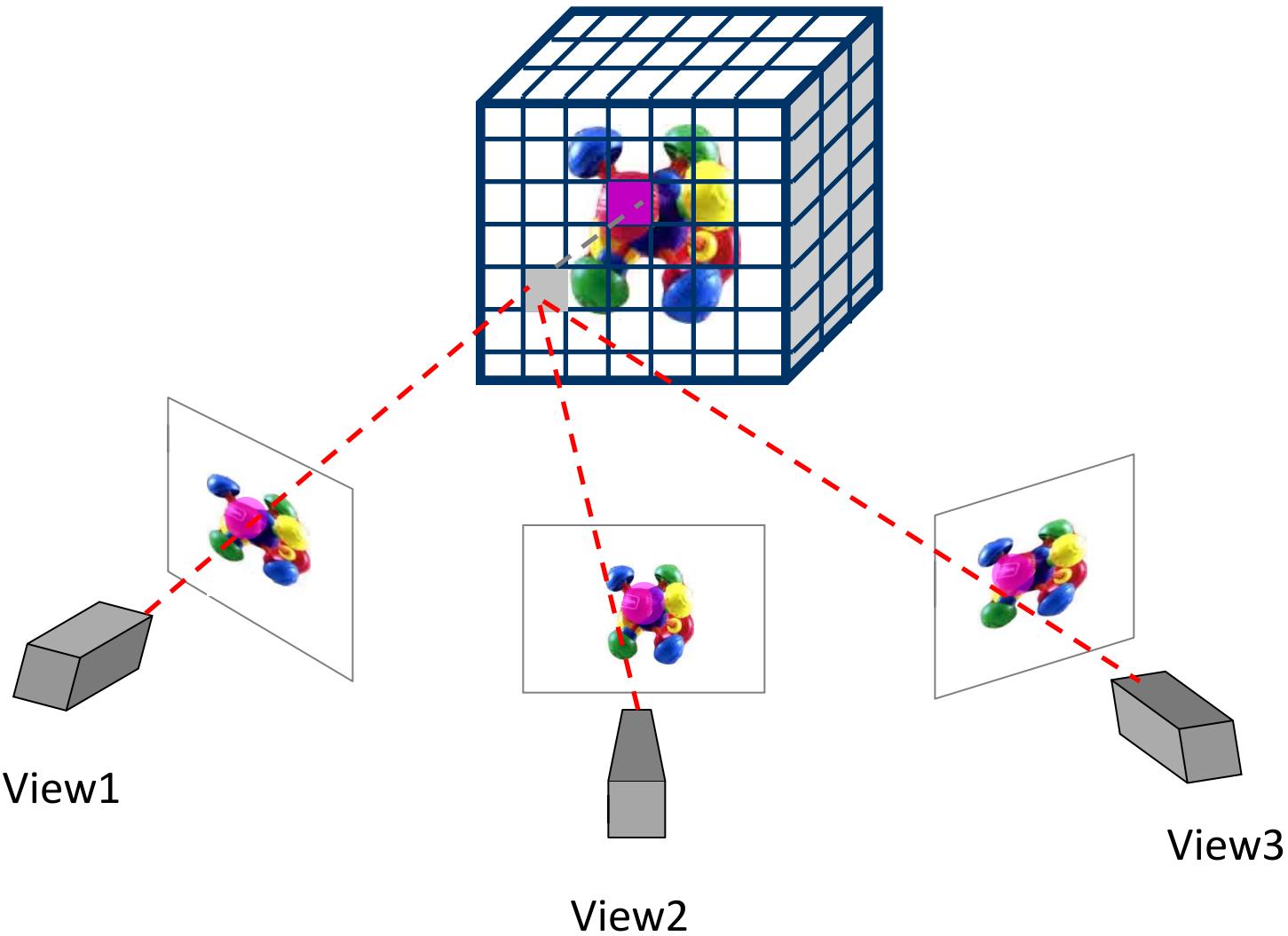


- Color/photo-consistency
- Jointly model structure and appearance

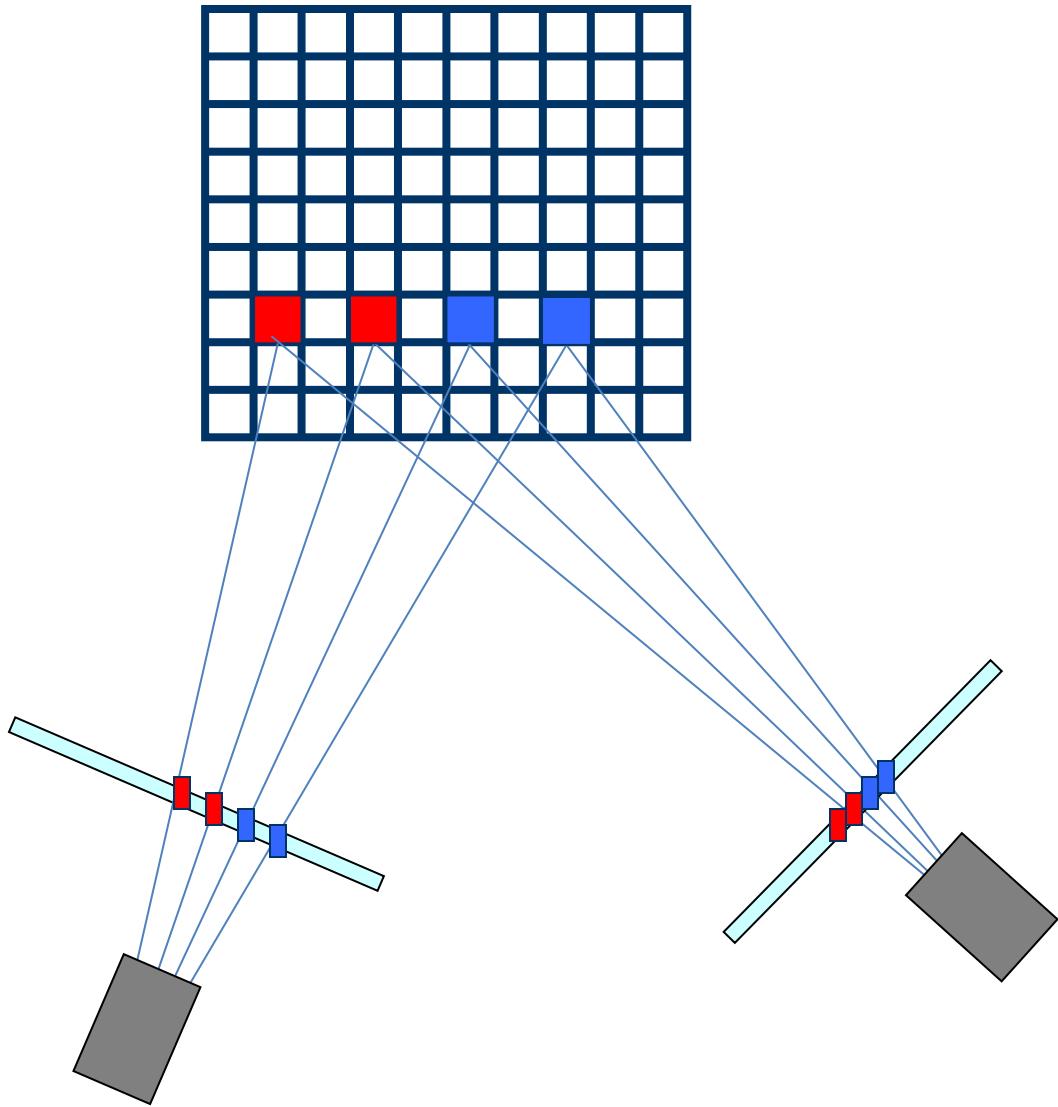
Basic Idea



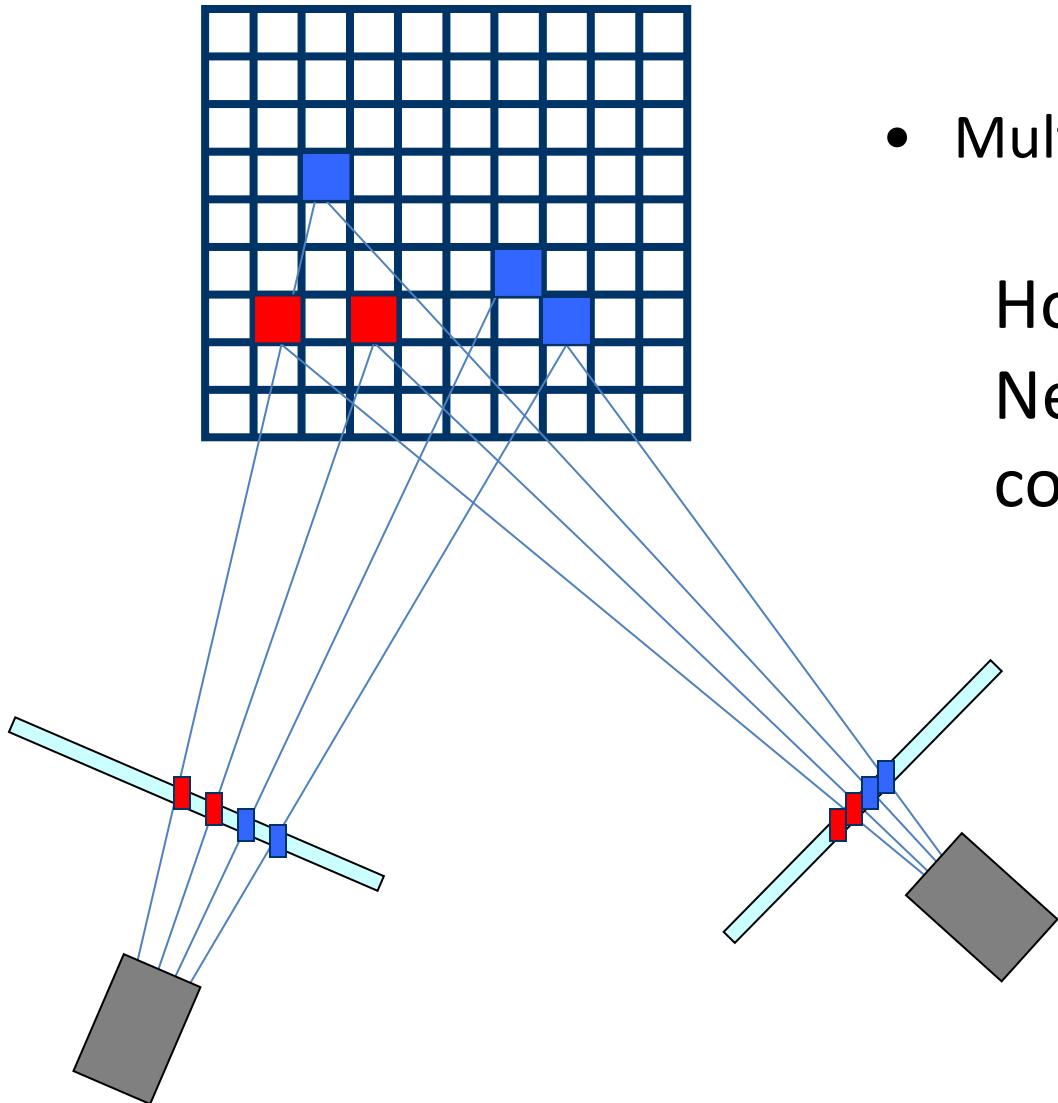
Basic Idea



Uniqueness



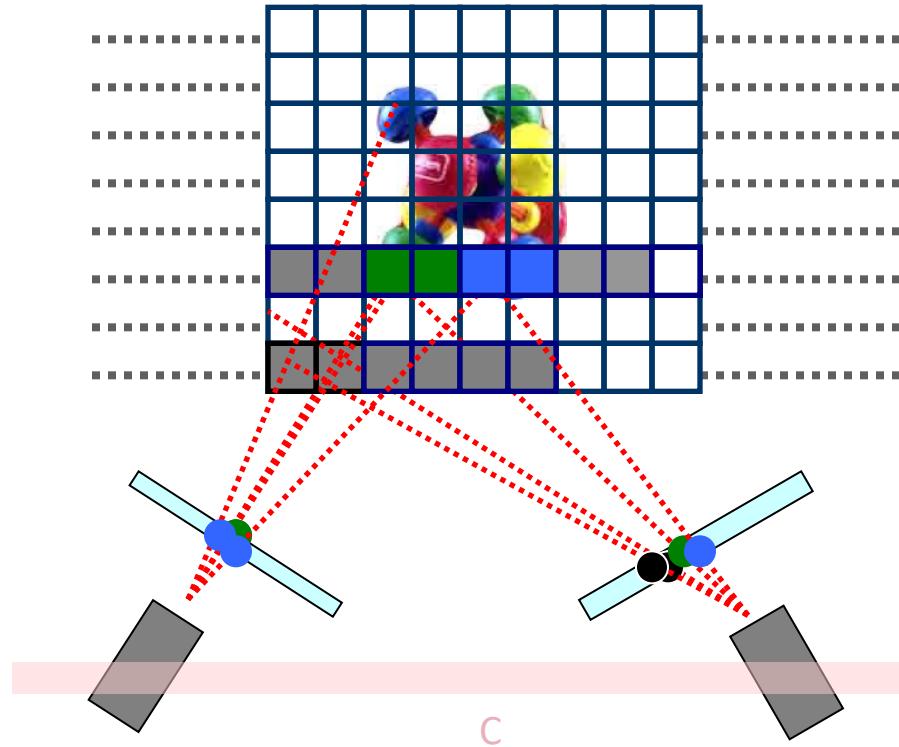
Uniqueness



- Multiple consistent scenes

How to fix this?
Need to use a visibility constraint

Algorithm for enforcing visibility constraints



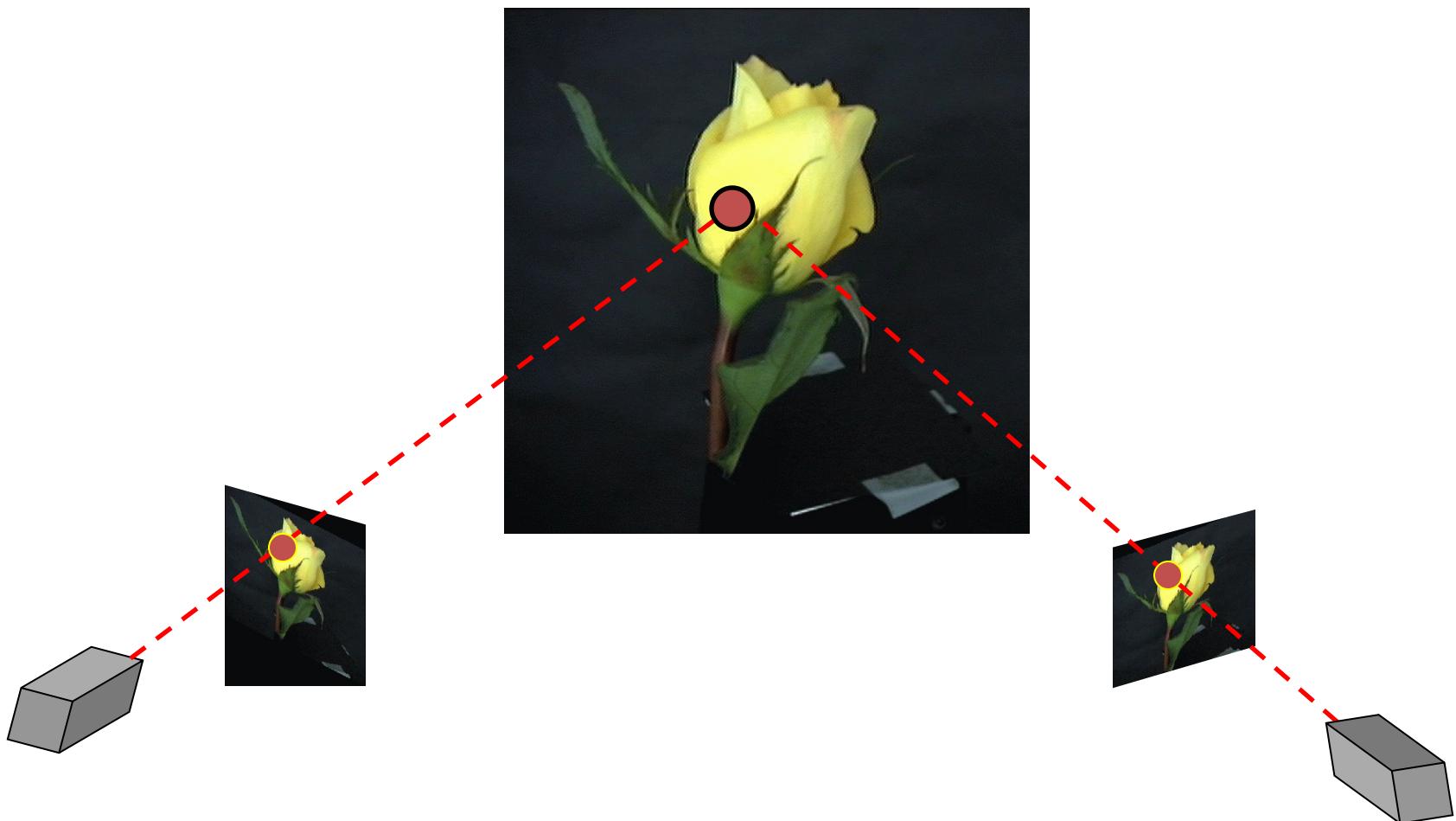
Algorithm Complexity

- Voxel coloring visits each N^3 voxels only once
- Project each voxel into L images

$$\rightarrow O(L N^3)$$

NOTE: not function of the number of colors

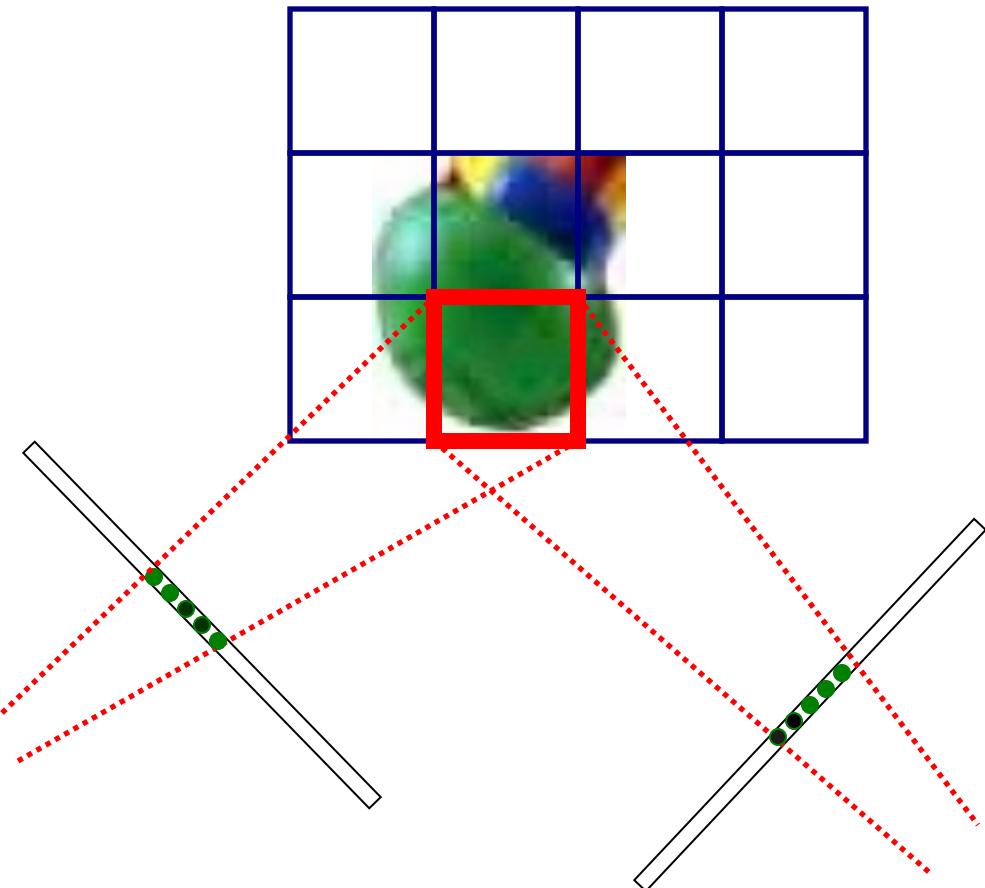
A Critical Assumption: Lambertian Surfaces



Non Lambertian Surfaces



Photoconsistency Test



$$C = \text{corr} (\begin{array}{c} \bullet \\ \bullet \\ \bullet \\ \bullet \end{array}, \begin{array}{c} \bullet \\ \bullet \\ \bullet \\ \bullet \end{array}) \\ w \quad w'$$

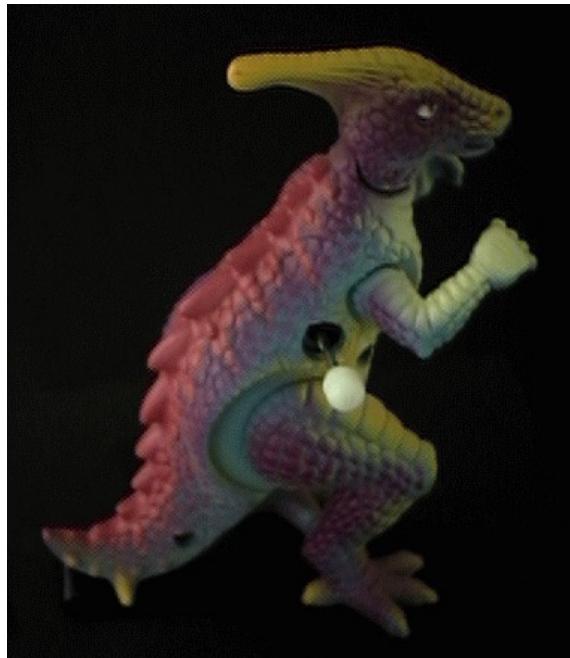
$$C = \frac{(w - \bar{w})(w' - \bar{w}')}{\|(w - \bar{w})\| \|(w' - \bar{w}')\|}$$

$$\bar{w} = \text{mean}(w)$$

$$\bar{w}' = \text{mean}(w')$$

If $C > \lambda = \text{threshold} \rightarrow \text{voxel consistent}$

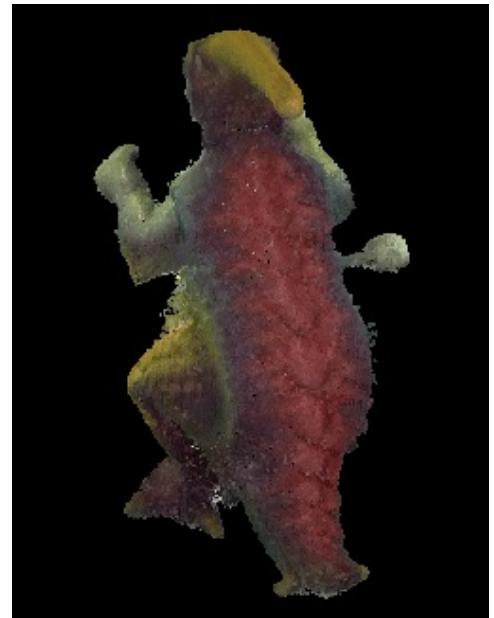
Experimental Results



Dinosaur



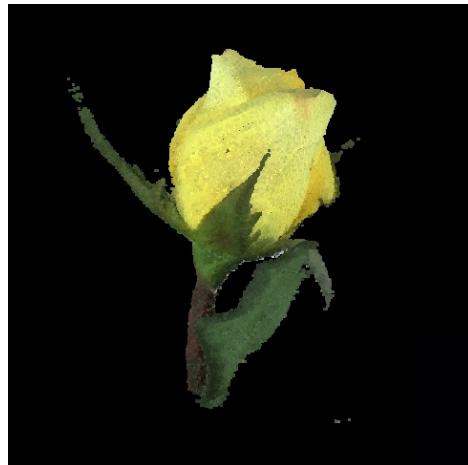
72 k voxels colored
7.6 M voxels tested
7 min to compute on a 250MHz



Experimental Results



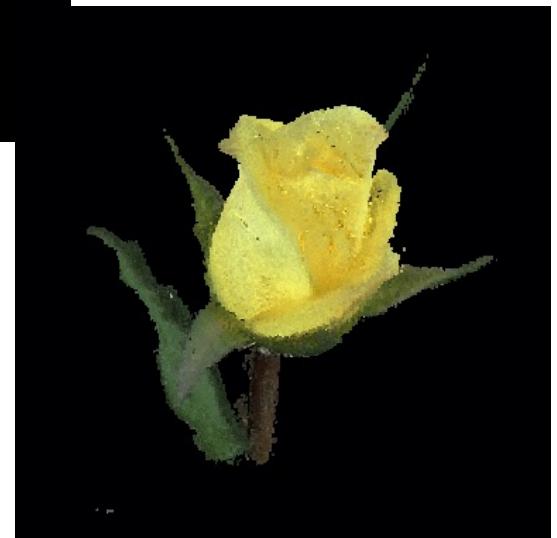
Flower



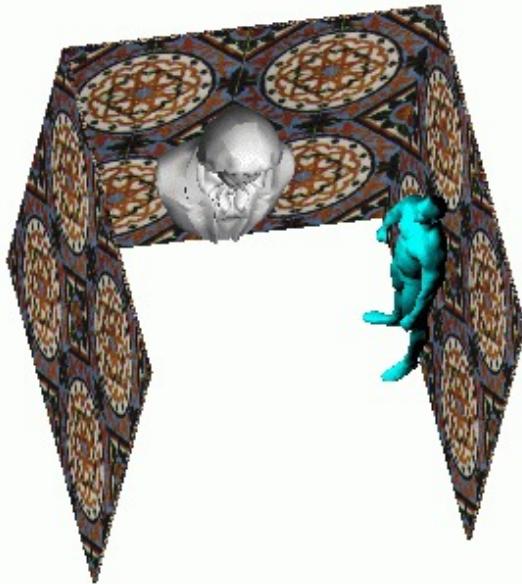
70 k voxels colored

7.6 M voxels tested

7 min to compute on a 250MHz



Experimental Results



Room + weird people

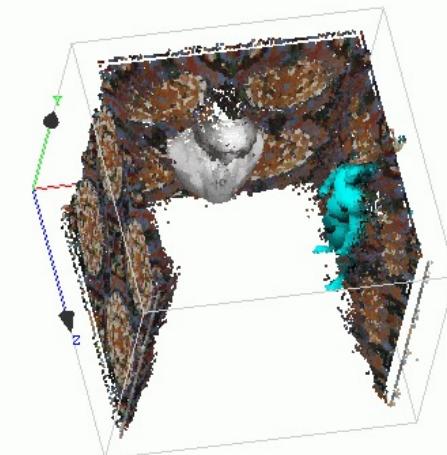
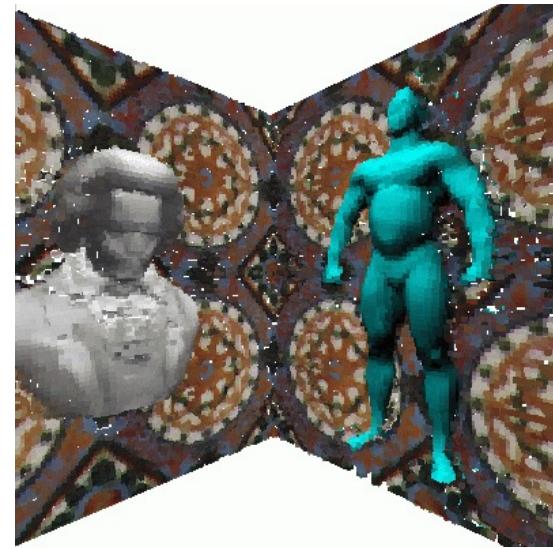


Image source: <http://www.cs.cmu.edu/~seitz/vcolor.html>

Voxel Coloring: Conclusions

- Good things
 - Model intrinsic scene colors and texture
 - No assumptions on scene topology
- Limitations:
 - Constrained camera positions
 - Lambertian assumption

Further Contributions

- A Theory of Space carving [Kutulakos & Seitz '99]
 - Voxel coloring in more general framework
 - No restrictions on camera position
- Probabilistic Space carving
 - [Broadhurst & Cipolla, ICCV 2001]
 - [Bhotika, Kutulakos et. al, ECCV 2002]
- CNN & voxel coloring
 - Incorporate reprojection error in the loss function for estimating object shape

Next lecture...

Fitting and Matching