Lecture 8
Active stereo & Volumetric stereo

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

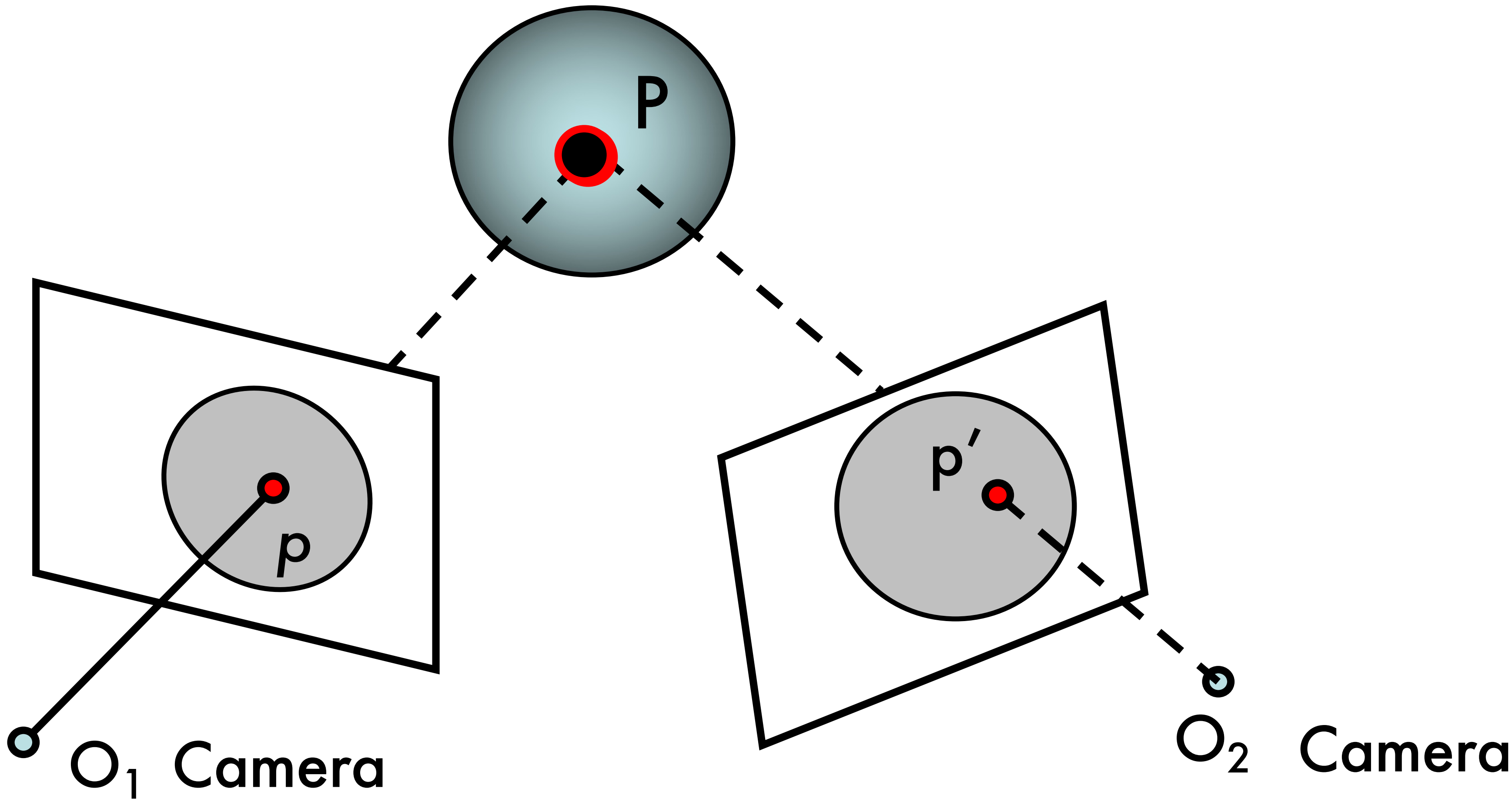
Reading:

[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

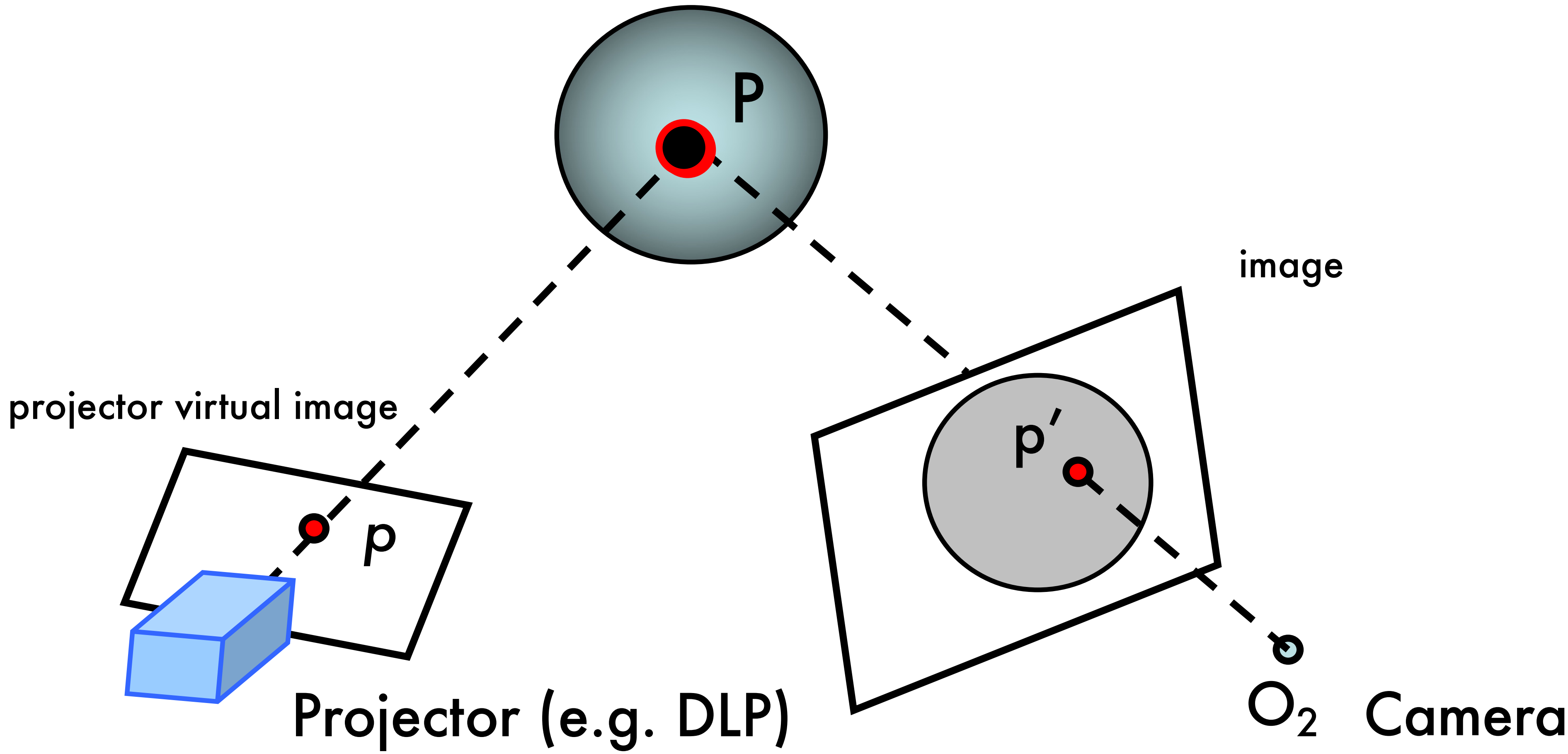
Seitz, S. M., & Dyer, C. R. (1999). Photorealistic scene reconstruction by voxel coloring.*International Journal of Computer Vision*, *35*(2), 151-173.

Traditional stereo



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

Active stereo (point)

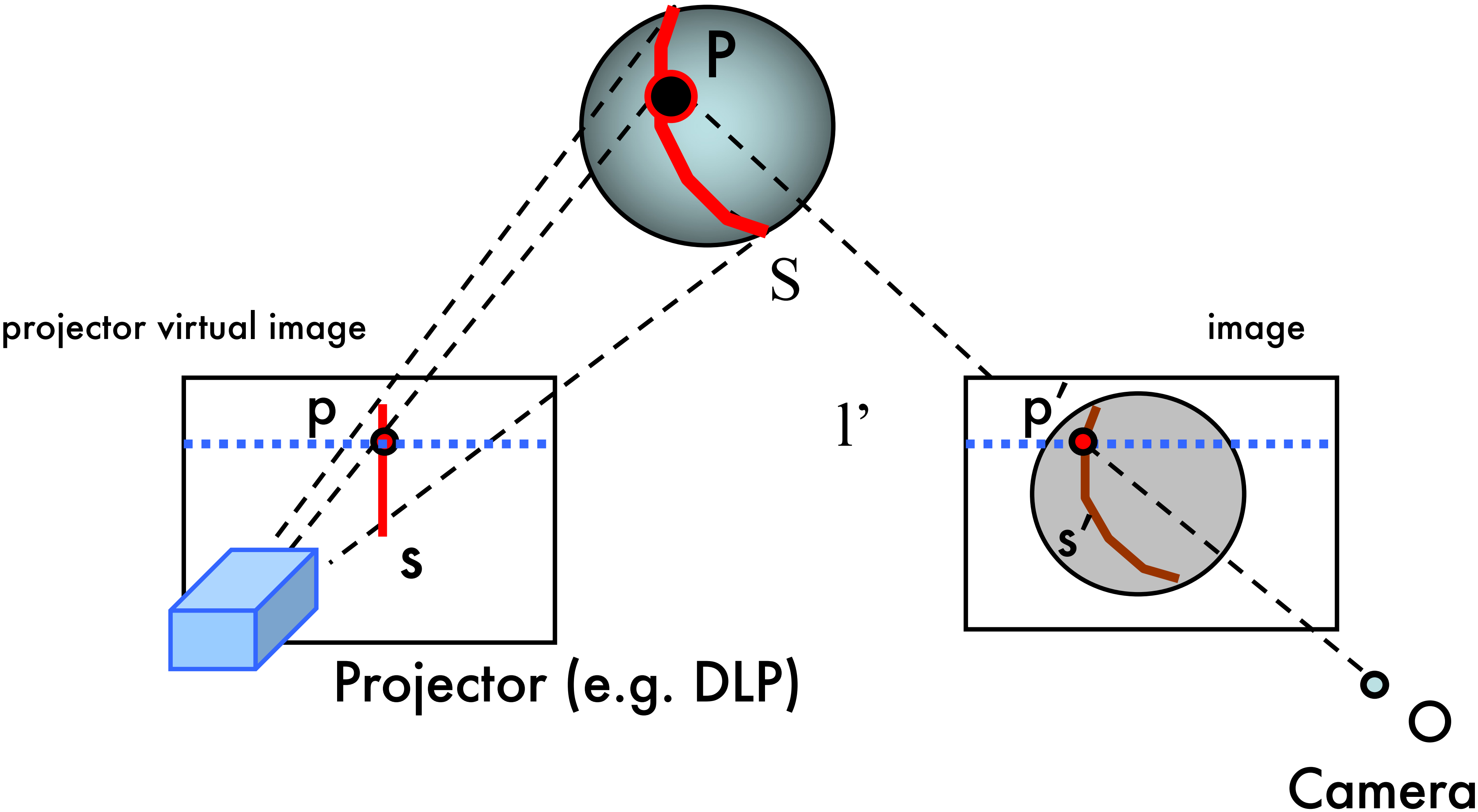


Replace one of the two cameras by a projector

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

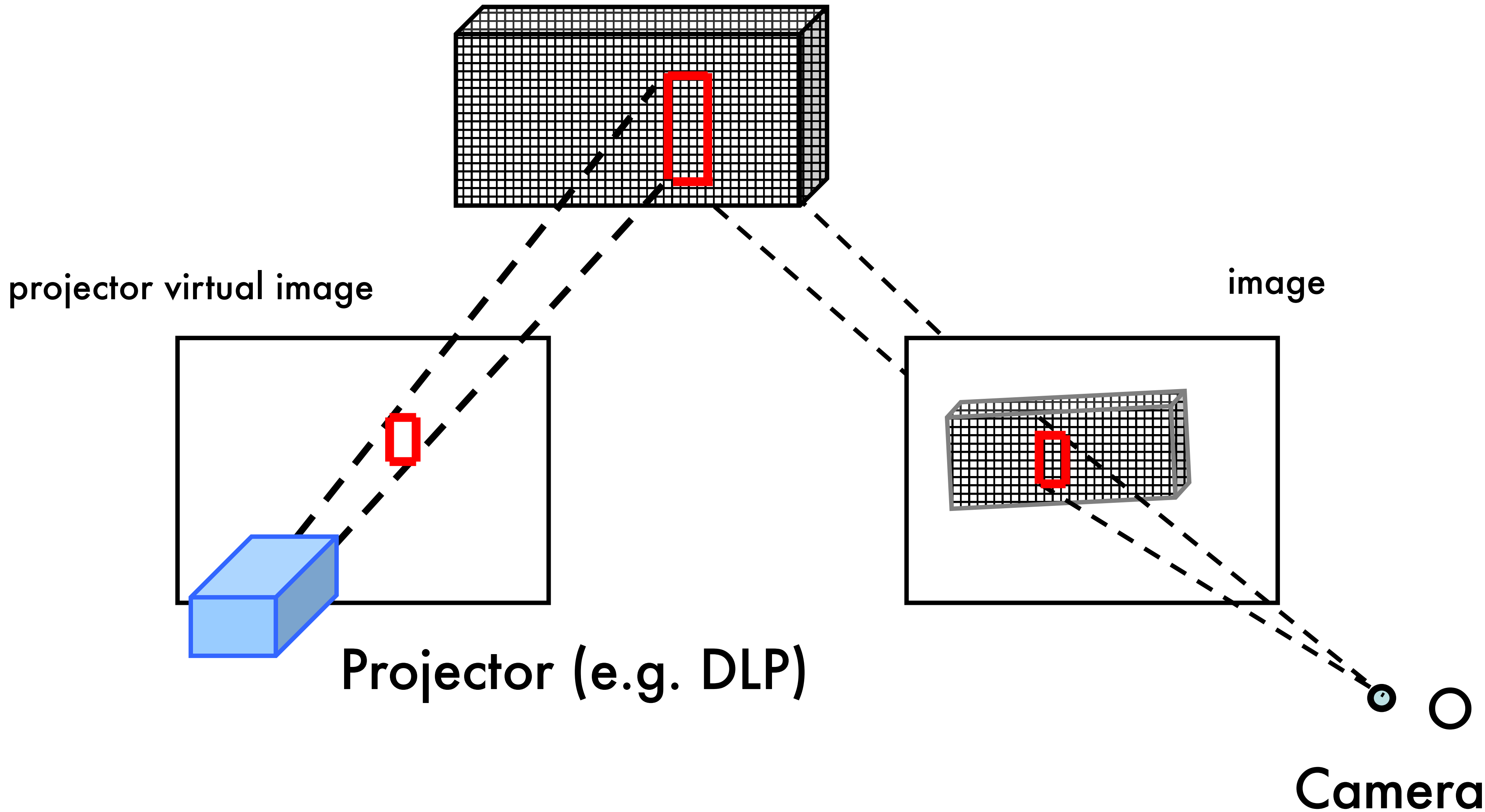
Any limitation??

Active stereo (stripe)



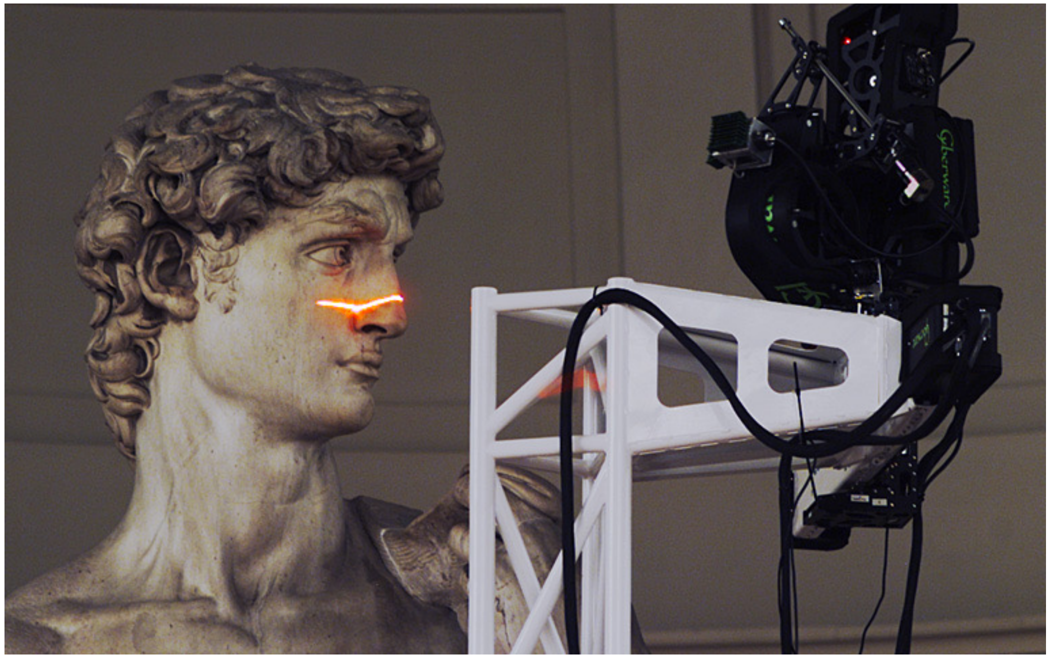
- Projector and camera are parallel
- Correspondence problem is solved!

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

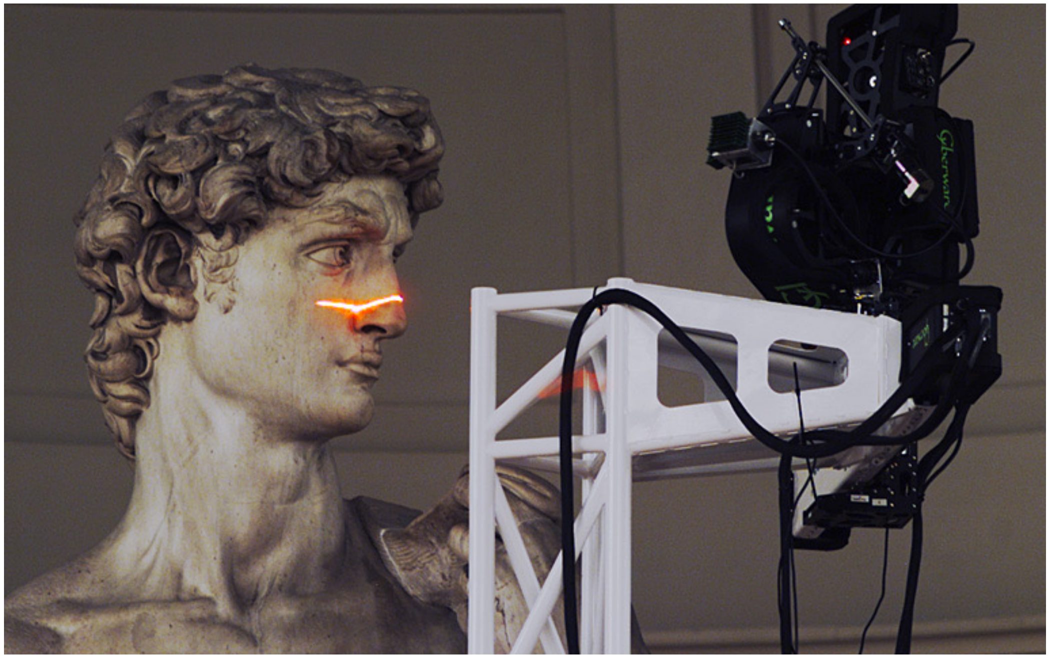
Source: S. Seitz

Laser scanning

The Digital Michelangelo Project, Levoy et al.

Source: S. Seitz

Limitations of Laser scanning

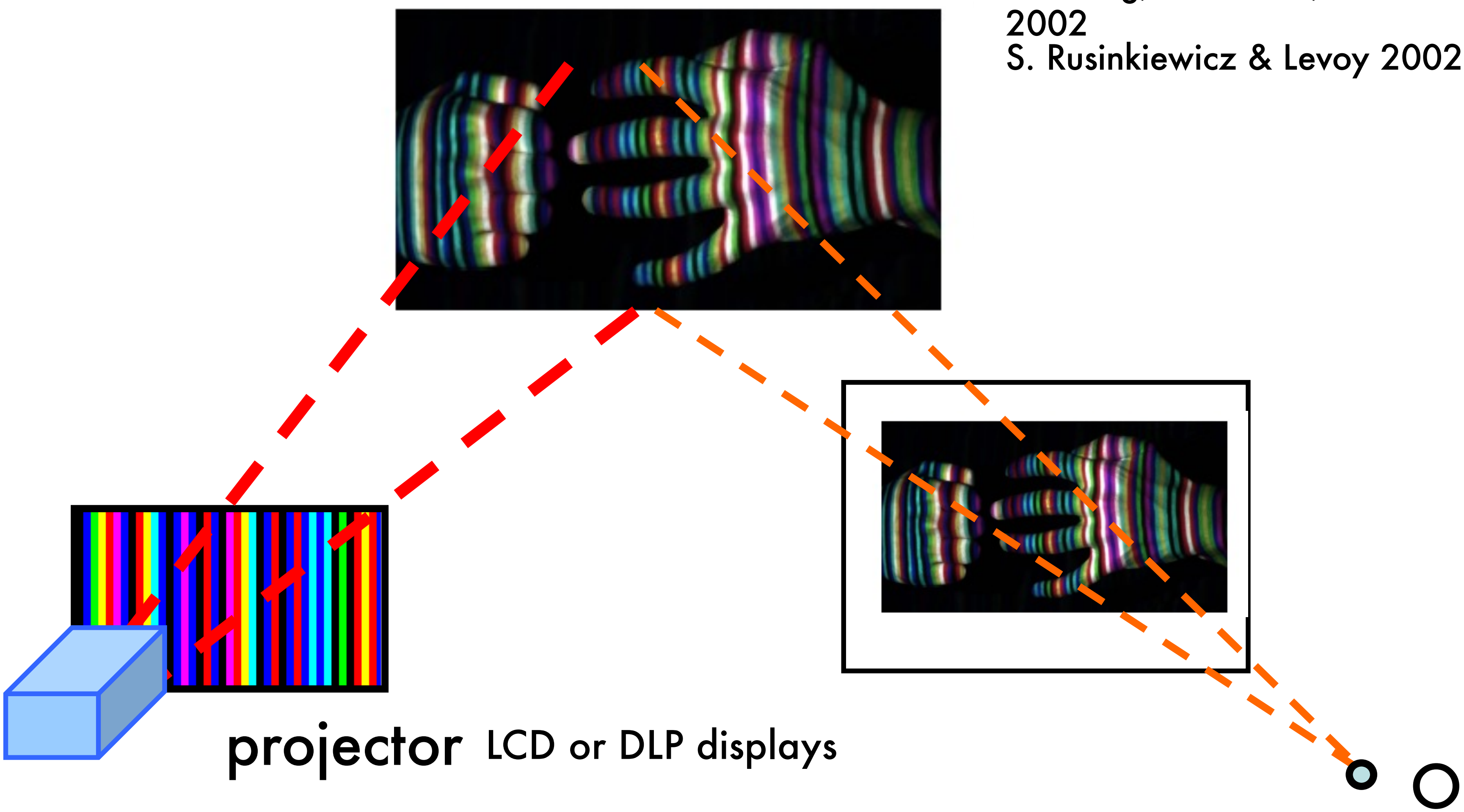


- Slow
- Cannot capture deformations in time

Source: S. Seitz

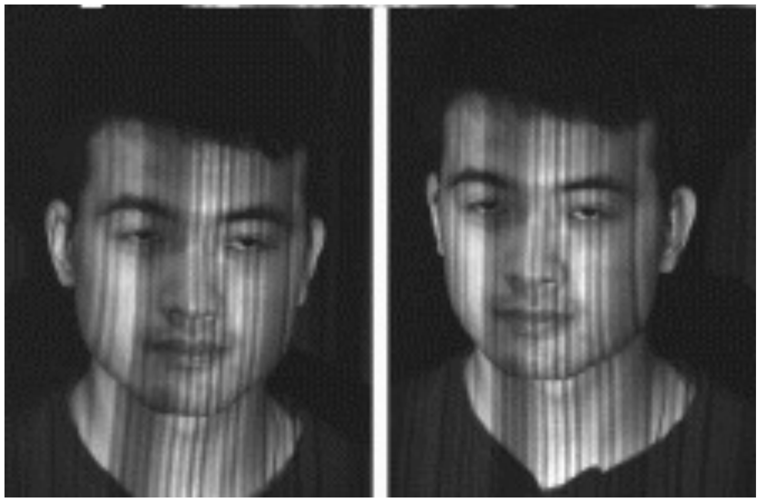
Active stereo (color-coded stripes)

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

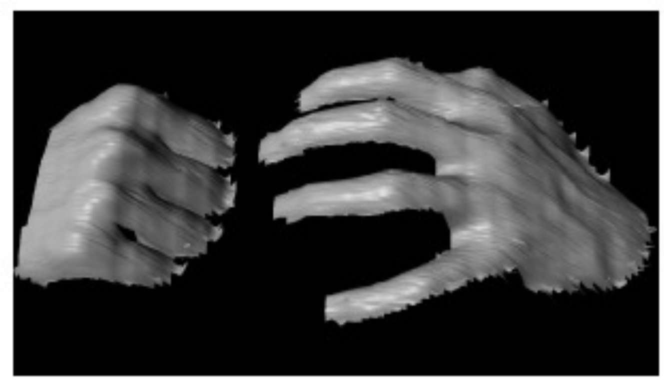


- Dense reconstruction
- Correspondence problem again
- Get around it by using color codes

Active stereo (color-coded stripes)



Rapid shape acquisition: Projector + stereo cameras

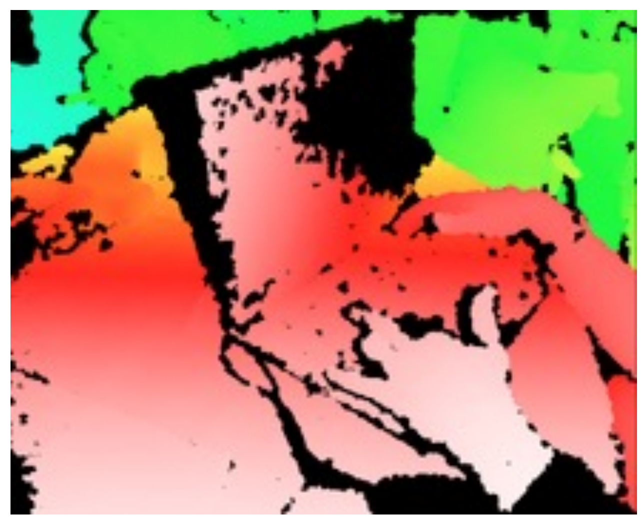


L. Zhang, B. Curless, and S. M. Seitz. Rapid Shape Acquisition Using Color Structured Light and Multi-pass Dynamic Programming. *3DPVT* 2002

Active stereo – depth sensors

- Infrared projector combined with an IR camera
- Captures video data in 3D under any ambient light conditions.

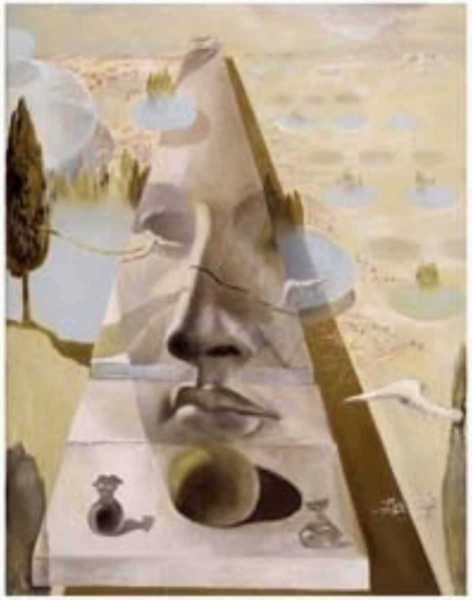
Pattern of projected infrared points to generate a dense 3D image



Depth map

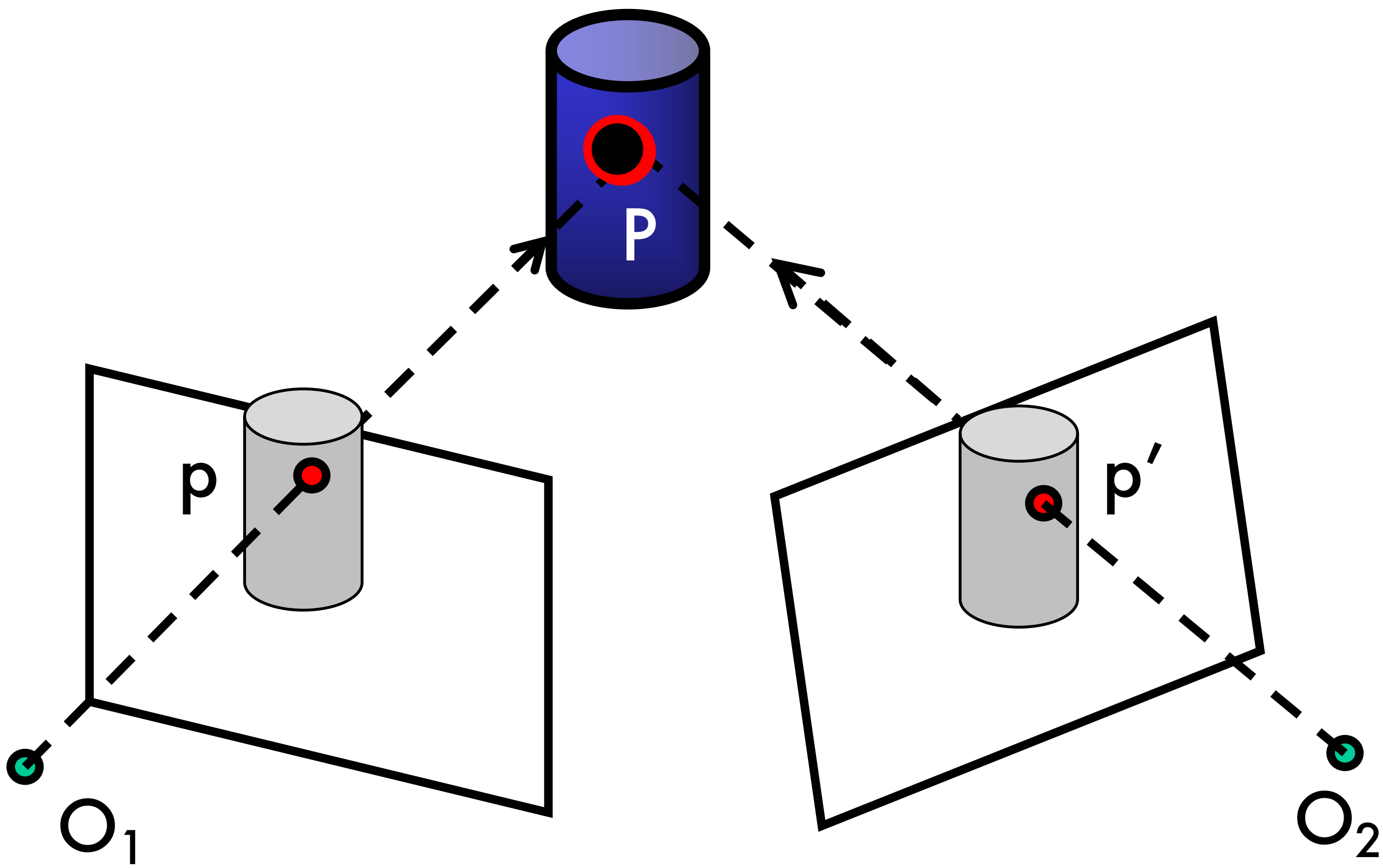
Source: wikipedia

Lecture 8
Active stereo & Volumetric stereo



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

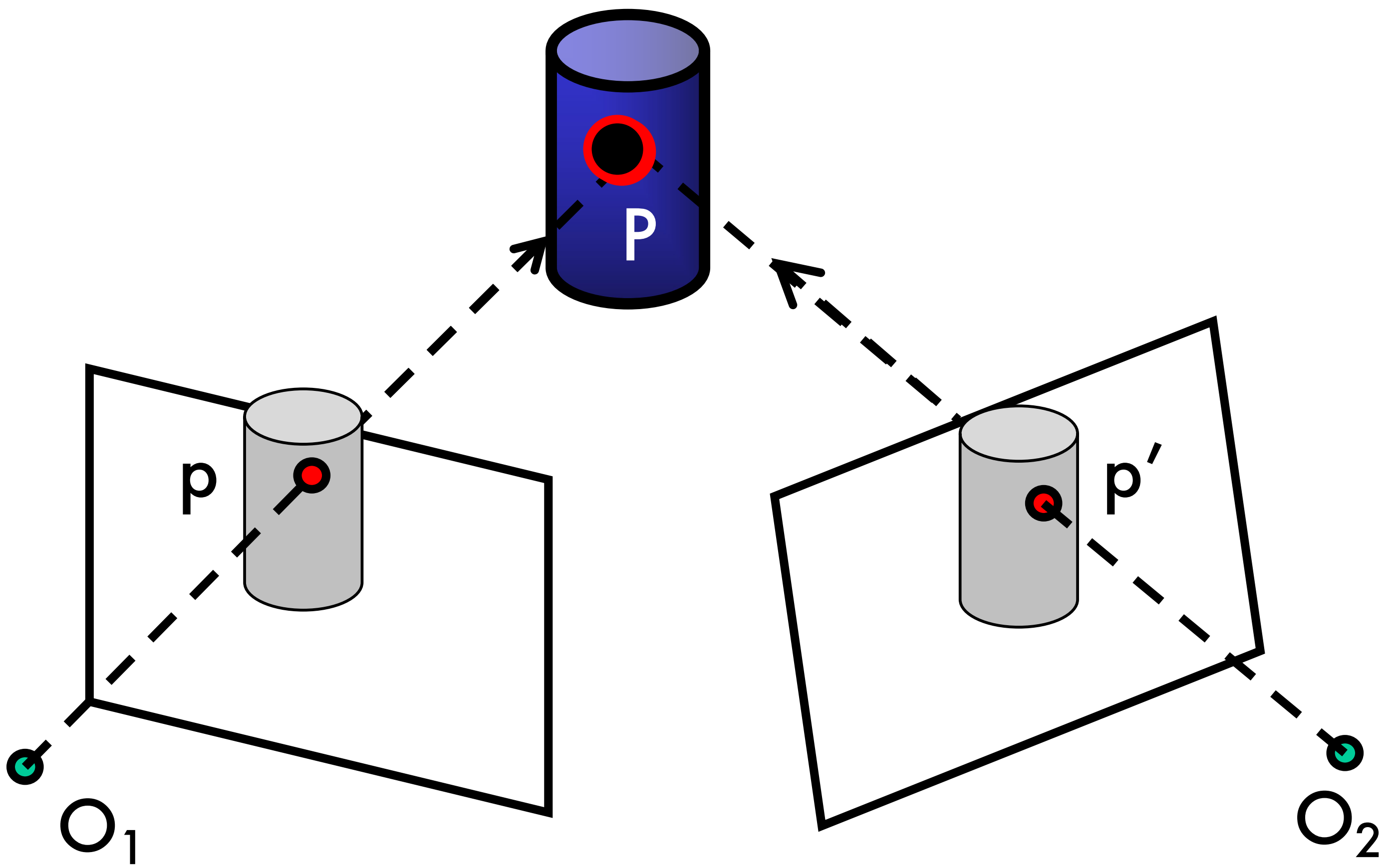
"Traditional" Stereo



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

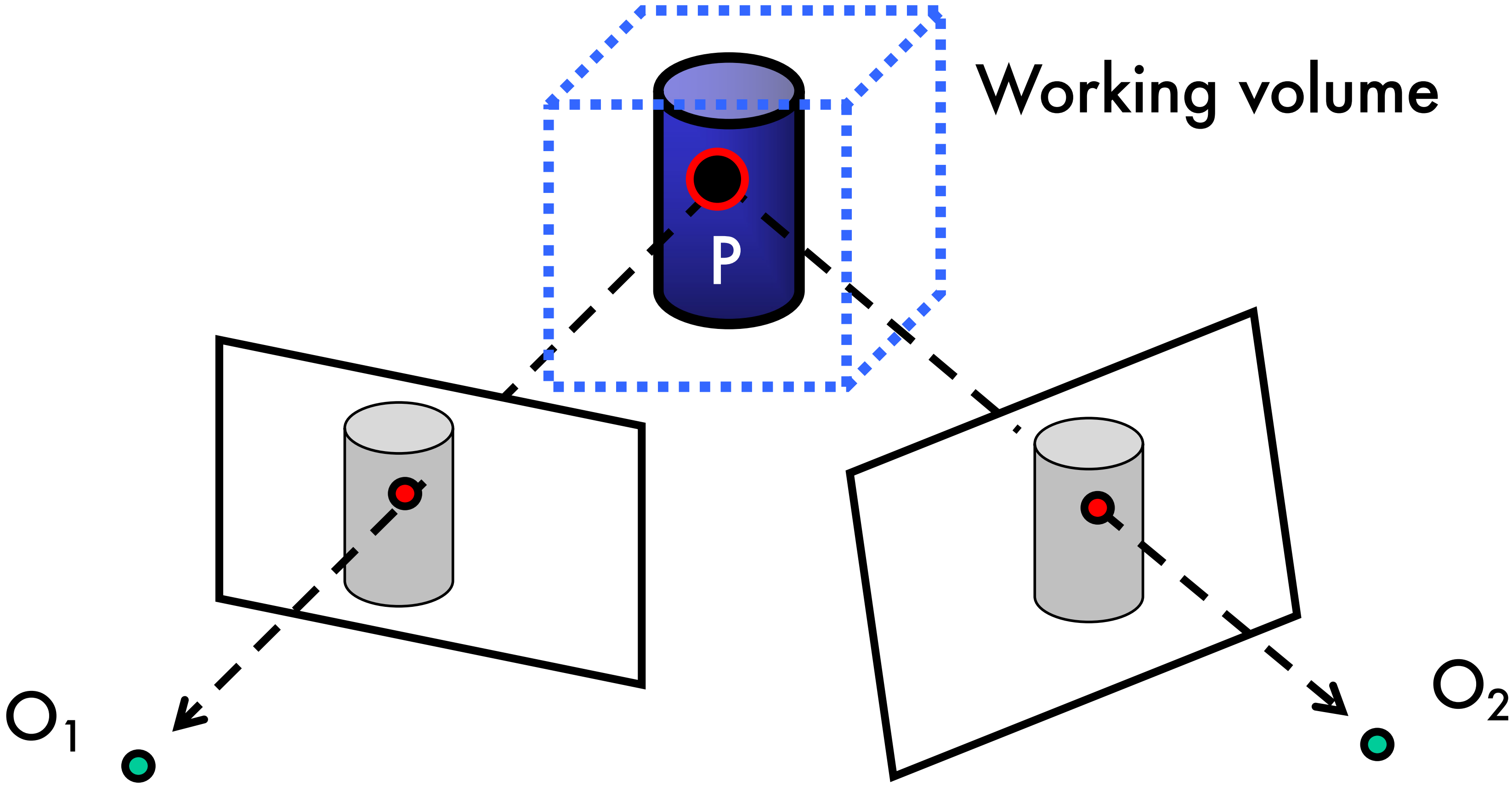
Assumptions: known camera parameters and position (K, R, T)

“Traditional” Stereo



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

Volumetric stereo



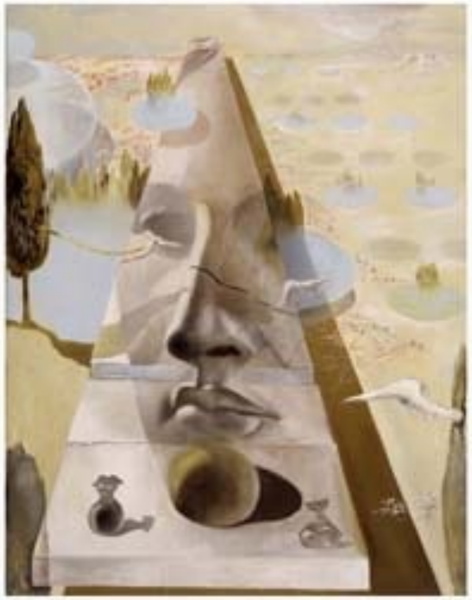
1. Hypothesis: pick up a point within the volume
2. Project this point into 2 (or more) images
3. Validation: are the observations consistent?

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
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- Volumetric stereo:
  - Space carving
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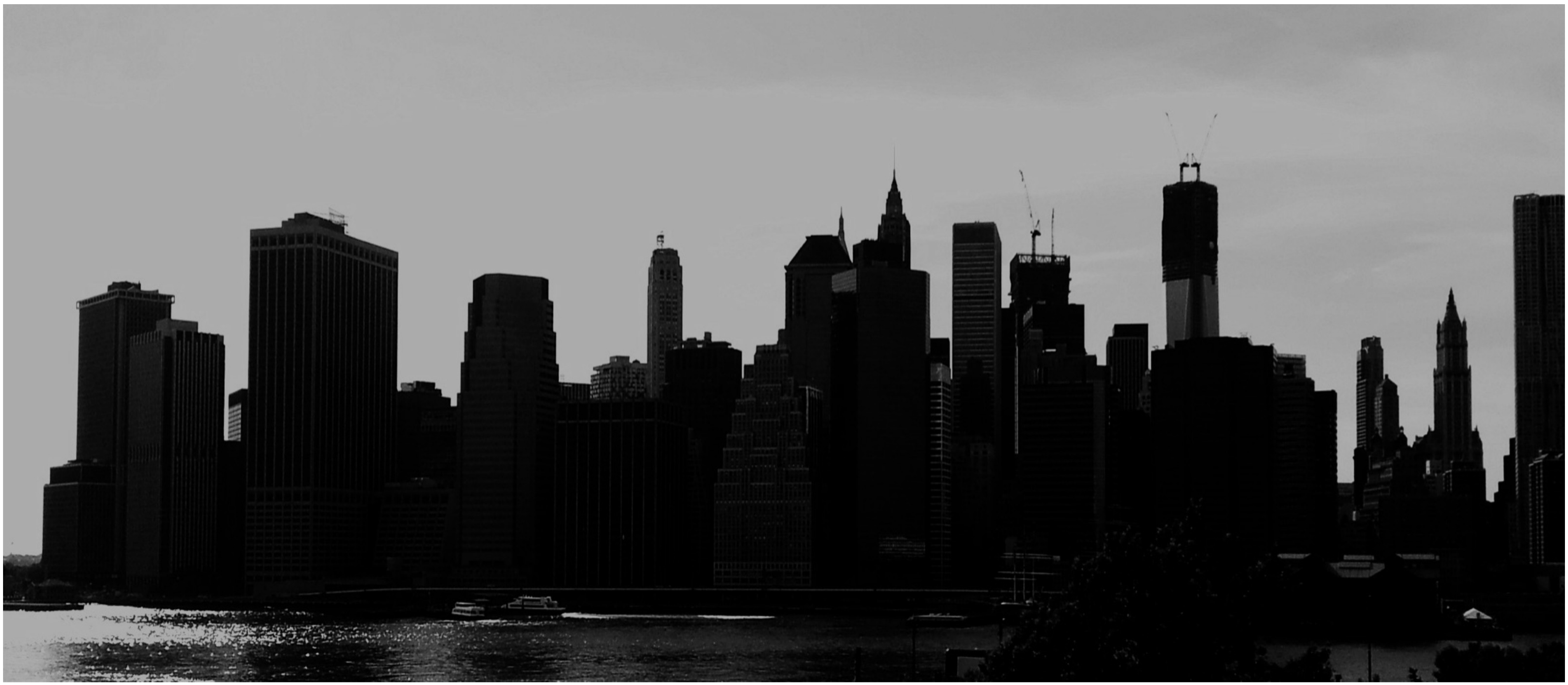
  - Voxel coloring

Reading:
[Szelisky] Chapter 11 “Multi-view stereo”

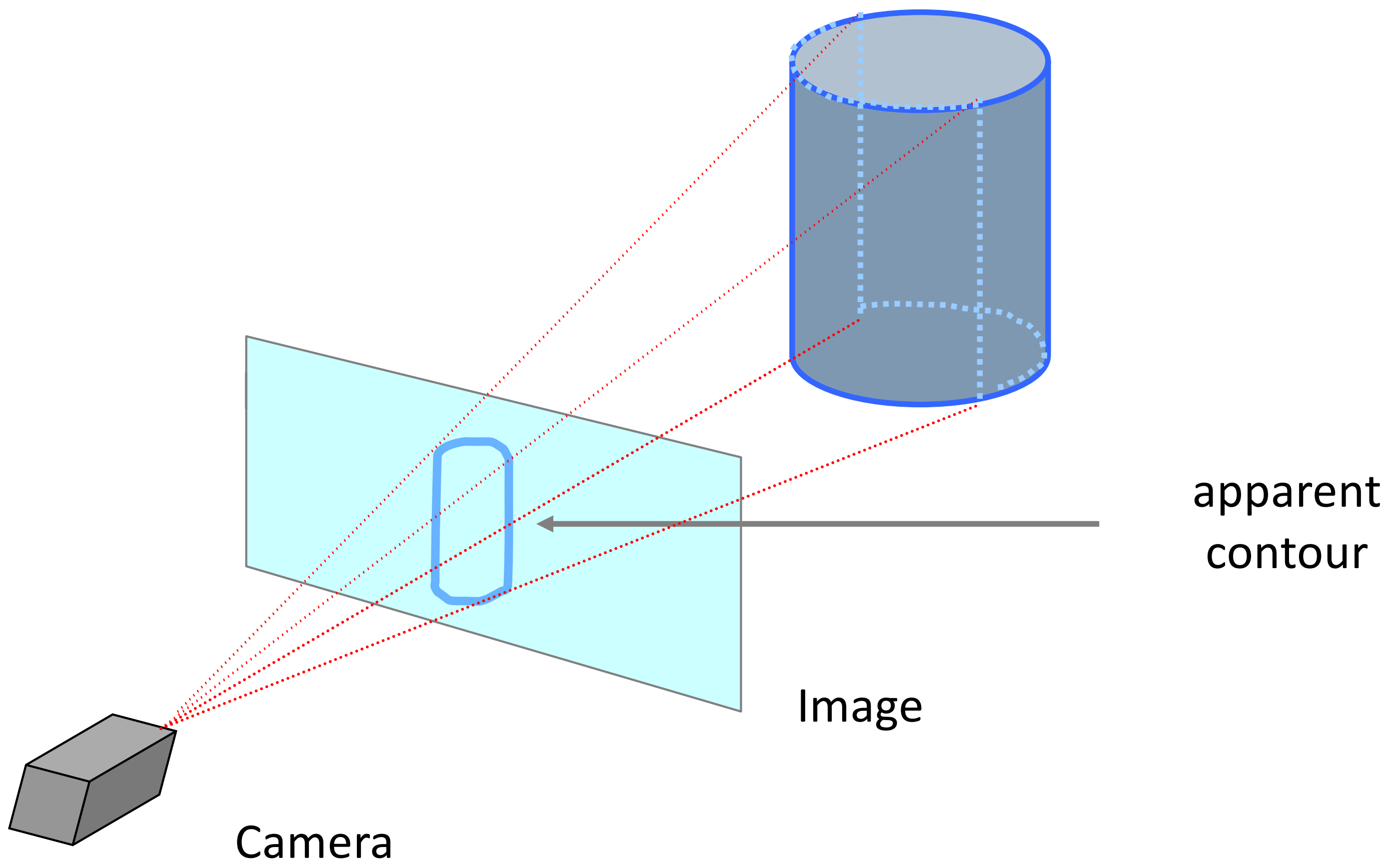
Contours/silhouettes

- Contours are a rich source of geometric information



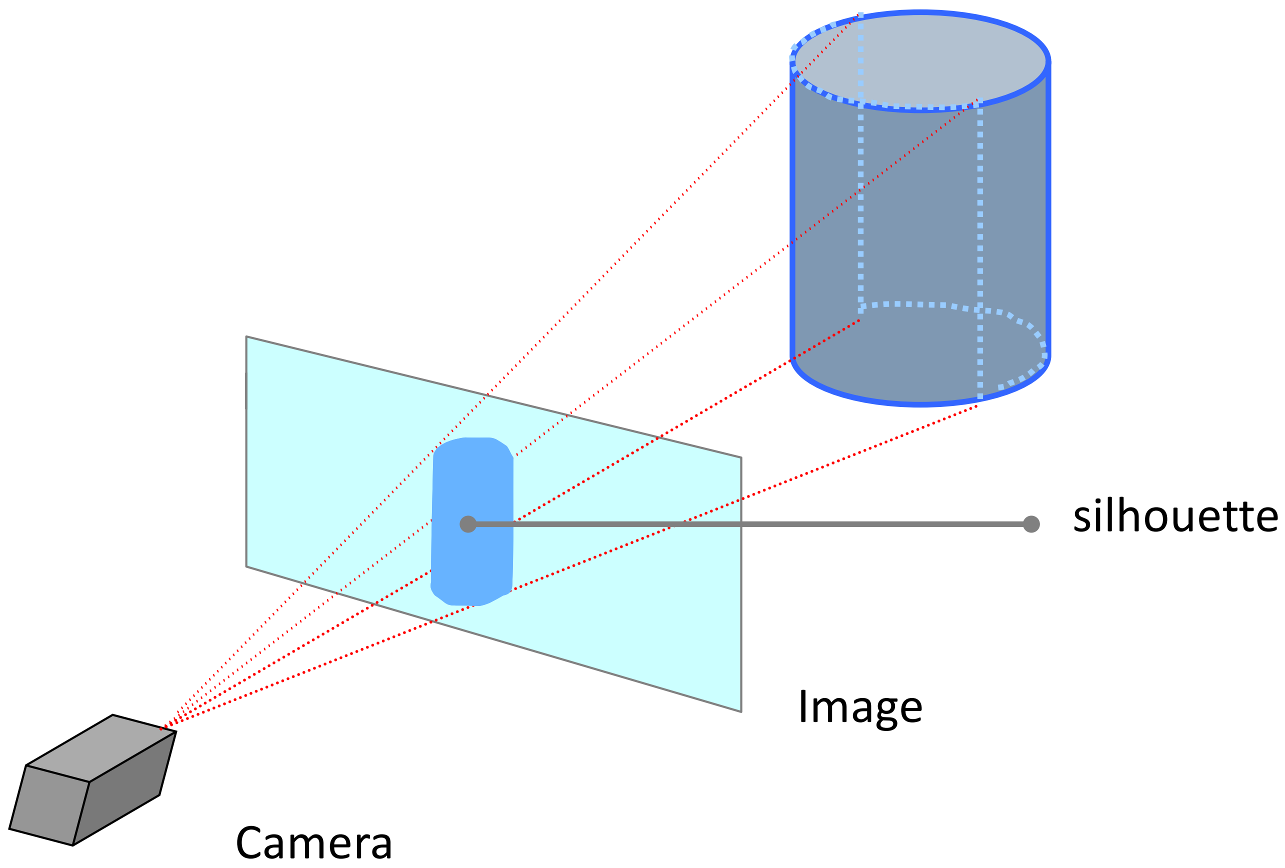
Apparent Contours

- Projection of the locus of points on the object surface which separate the visible and occluded parts on the surface [sato & cipolla]

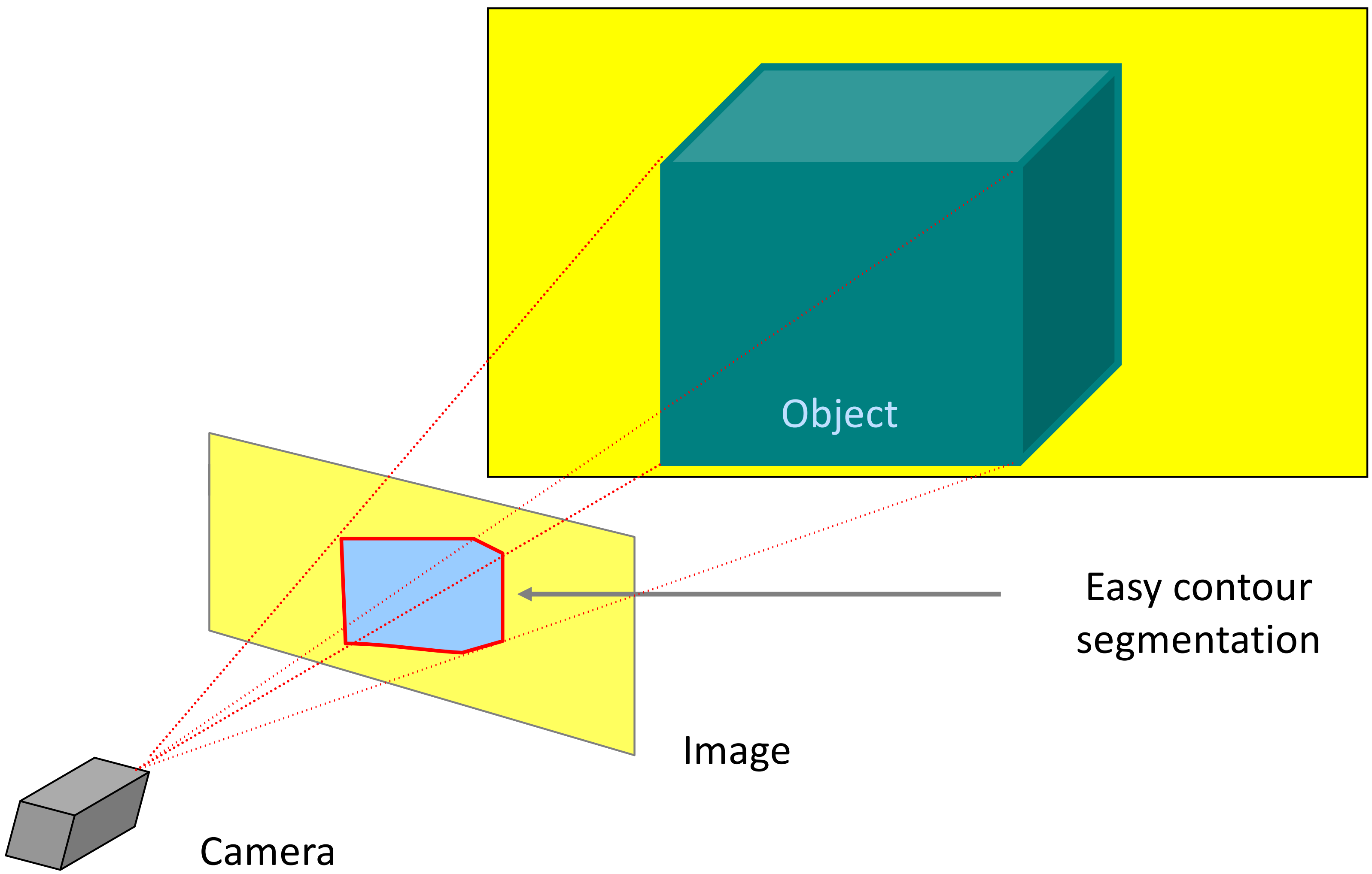


Silhouettes

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

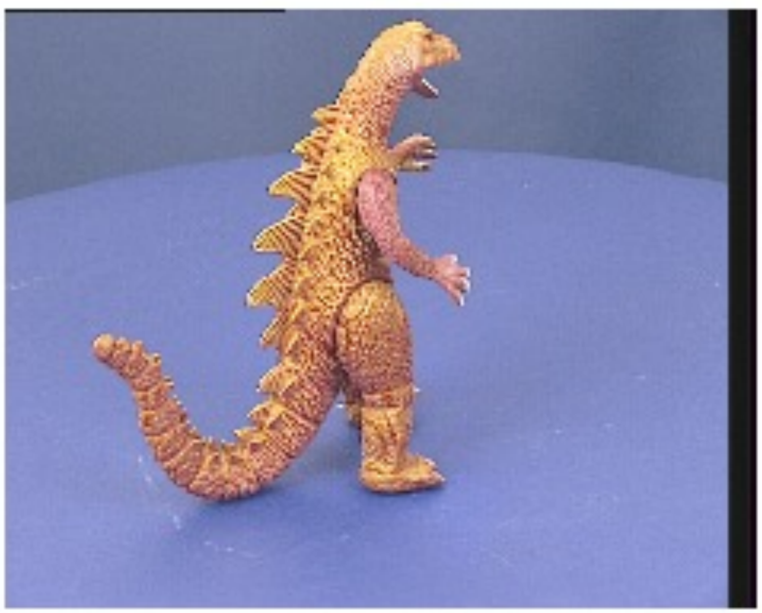


Detecting silhouettes



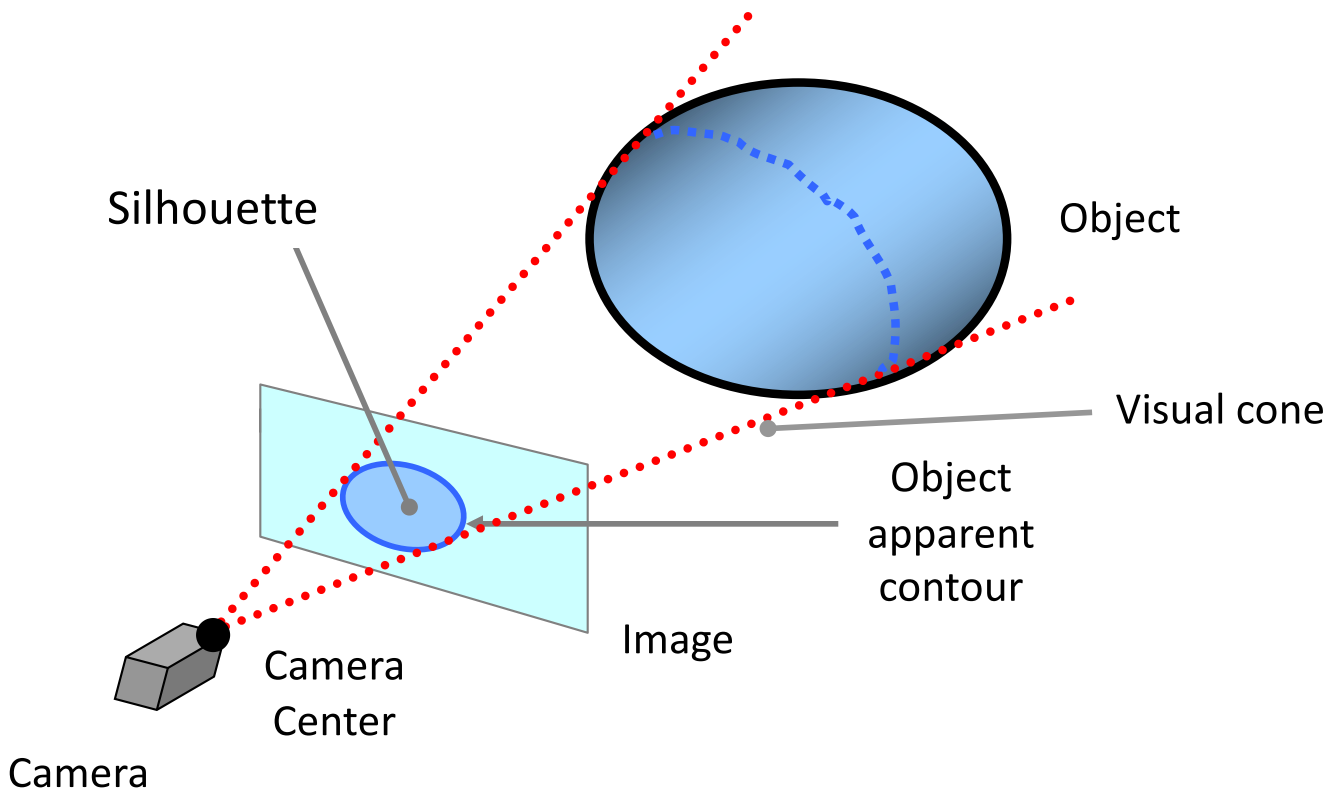
Detecting silhouettes

Original Image

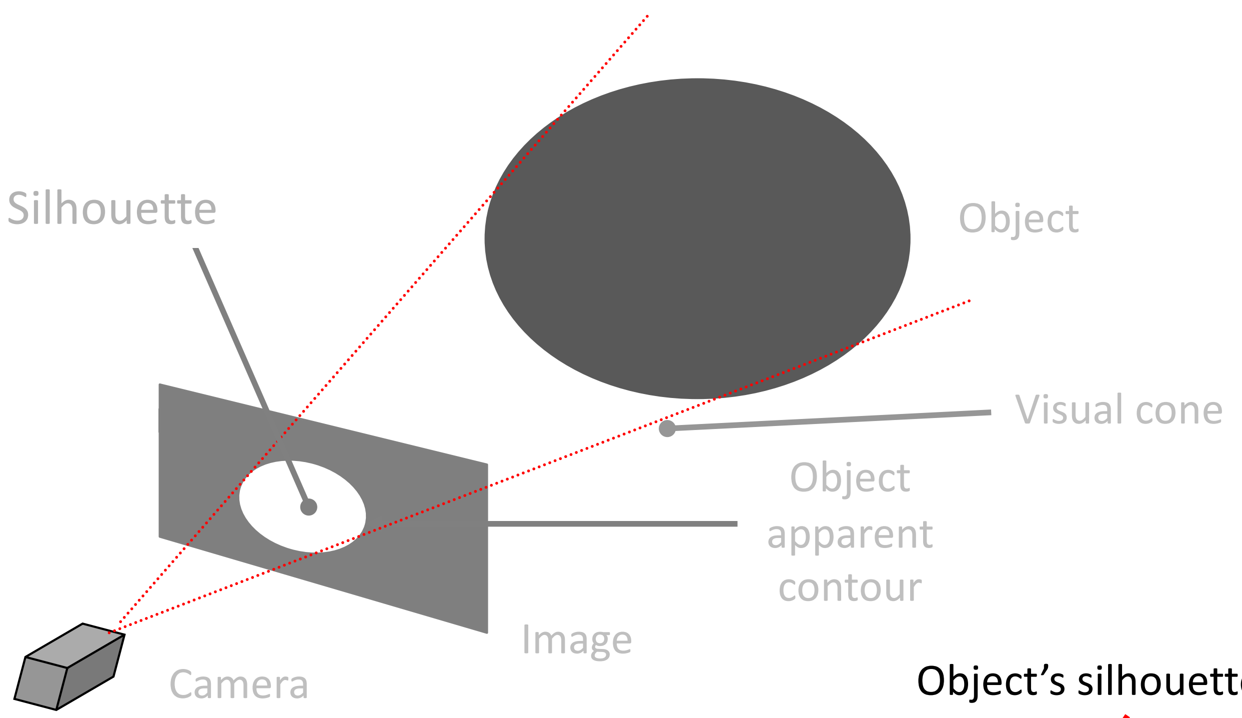


Silhouette

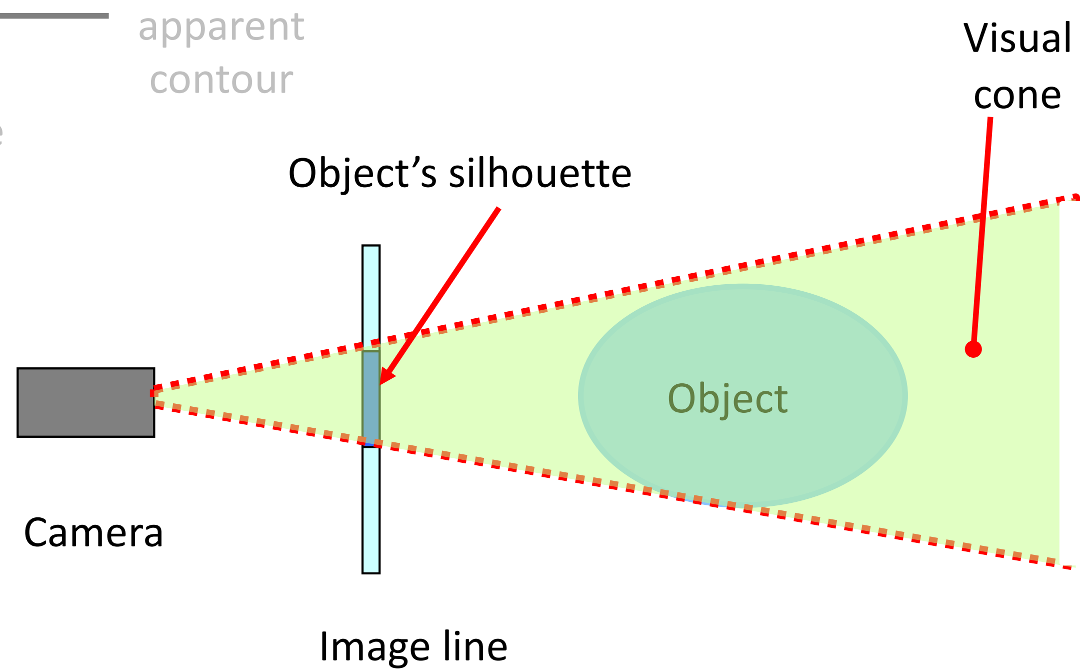
How can we use contours?



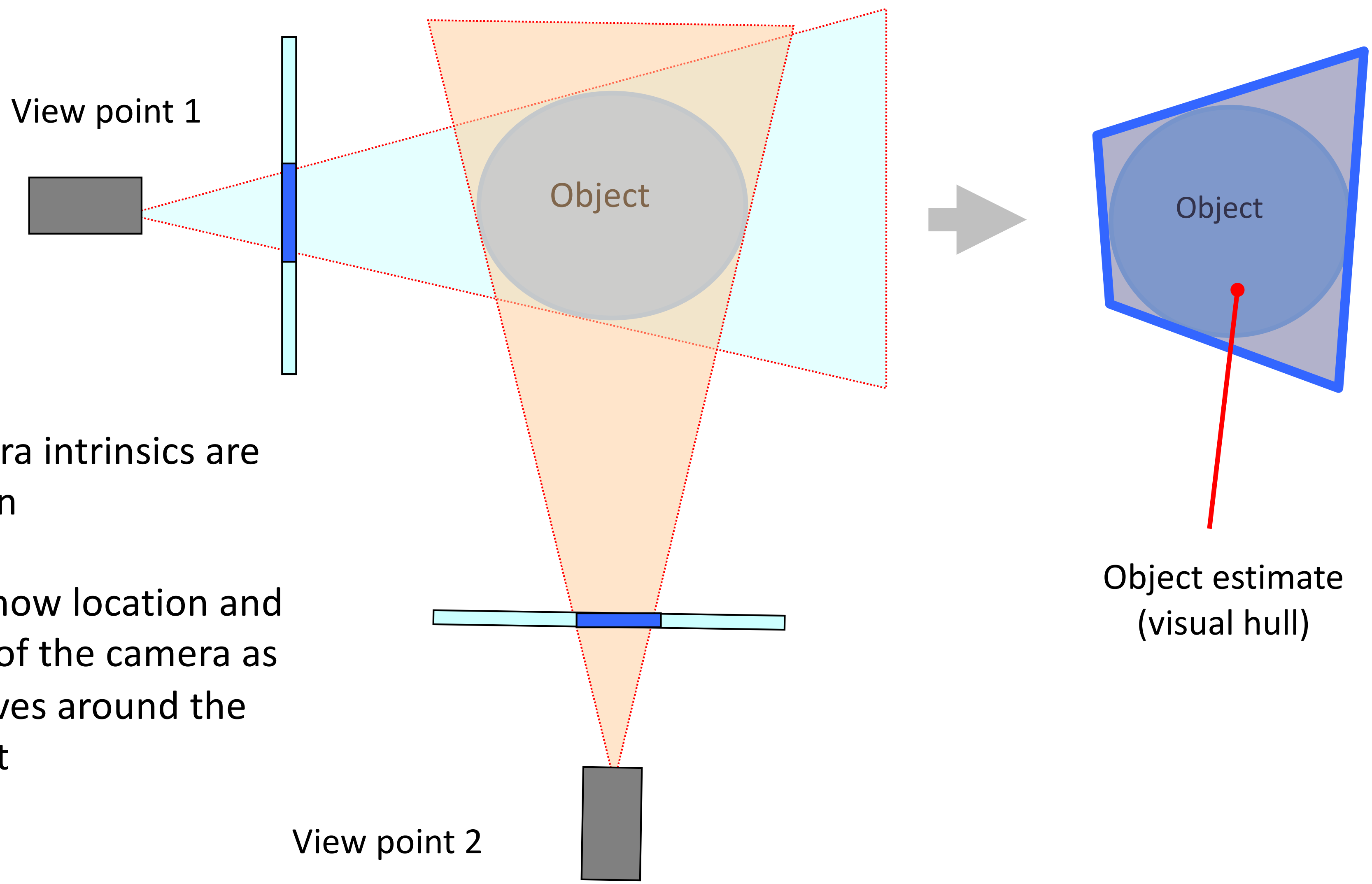
How can we use contours?



2D slice:



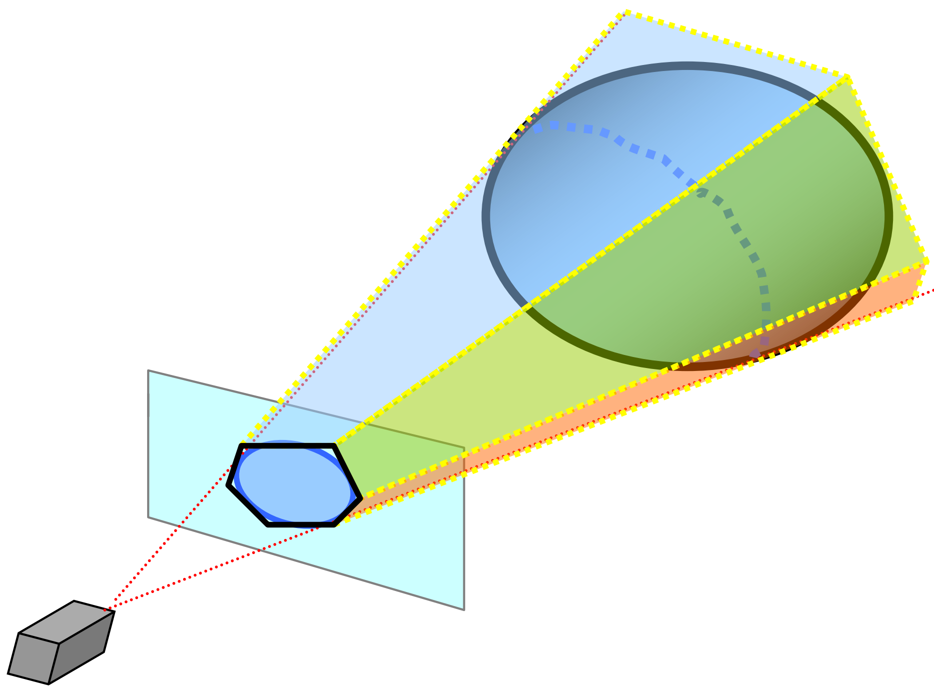
How can we use contours?



- Camera intrinsics are known
- We know location and pose of the camera as it moves around the object

How to perform visual cones intersection?

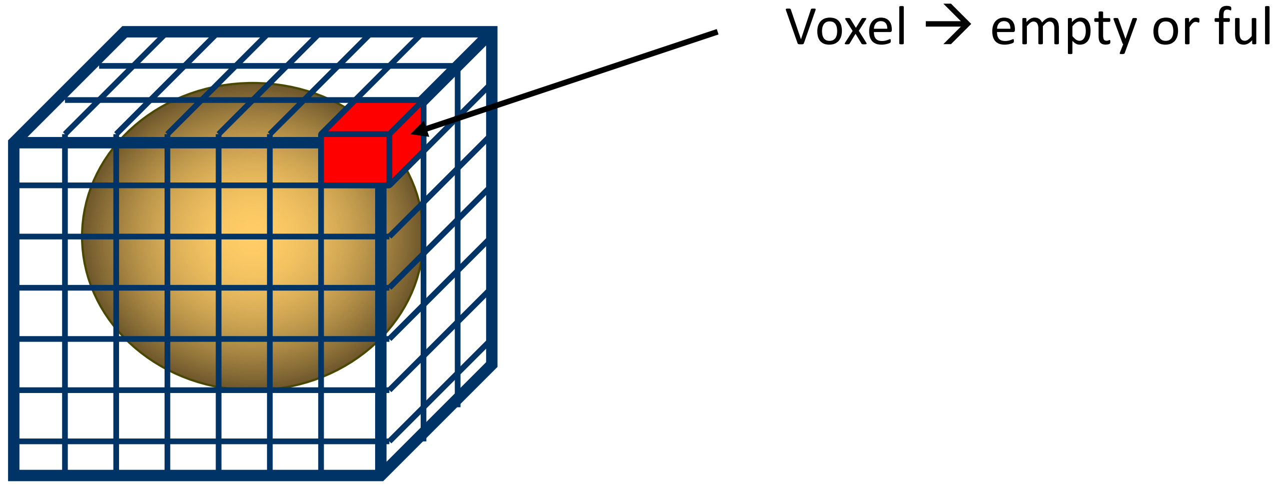
- Decompose visual cone in polygonal surfaces (among others: Reed and Allen '99)



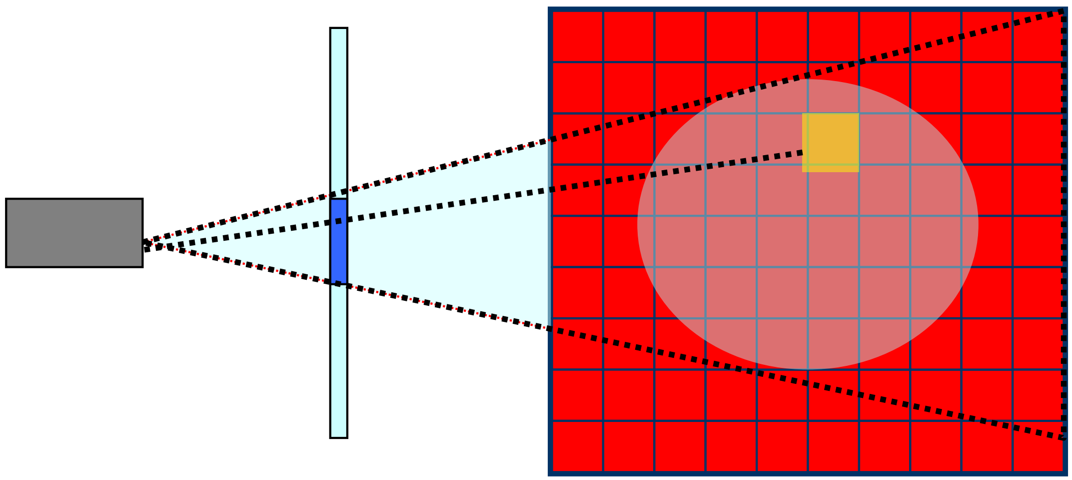
Space carving

[Martin and Aggarwal (1983)]

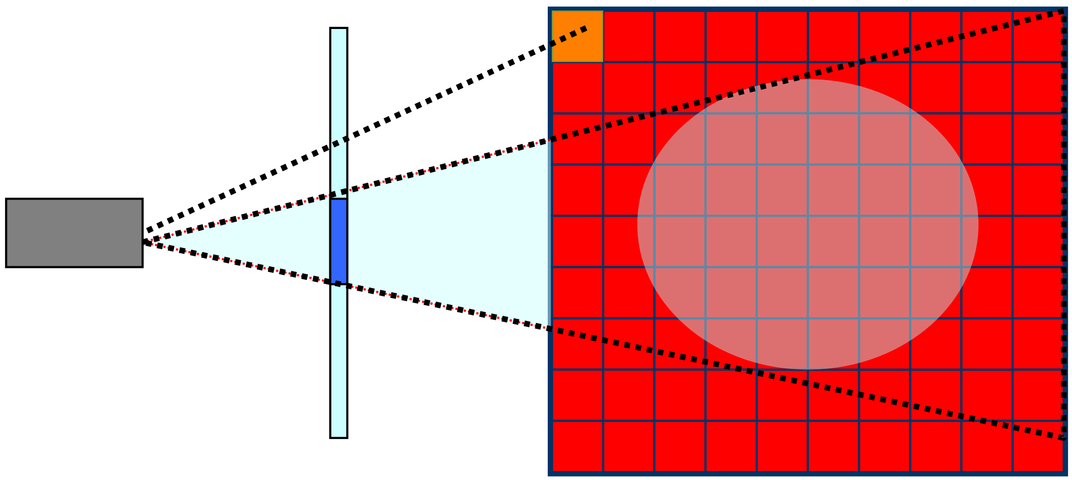
- Using contours/silhouettes in volumetric stereo, also called **space carving**



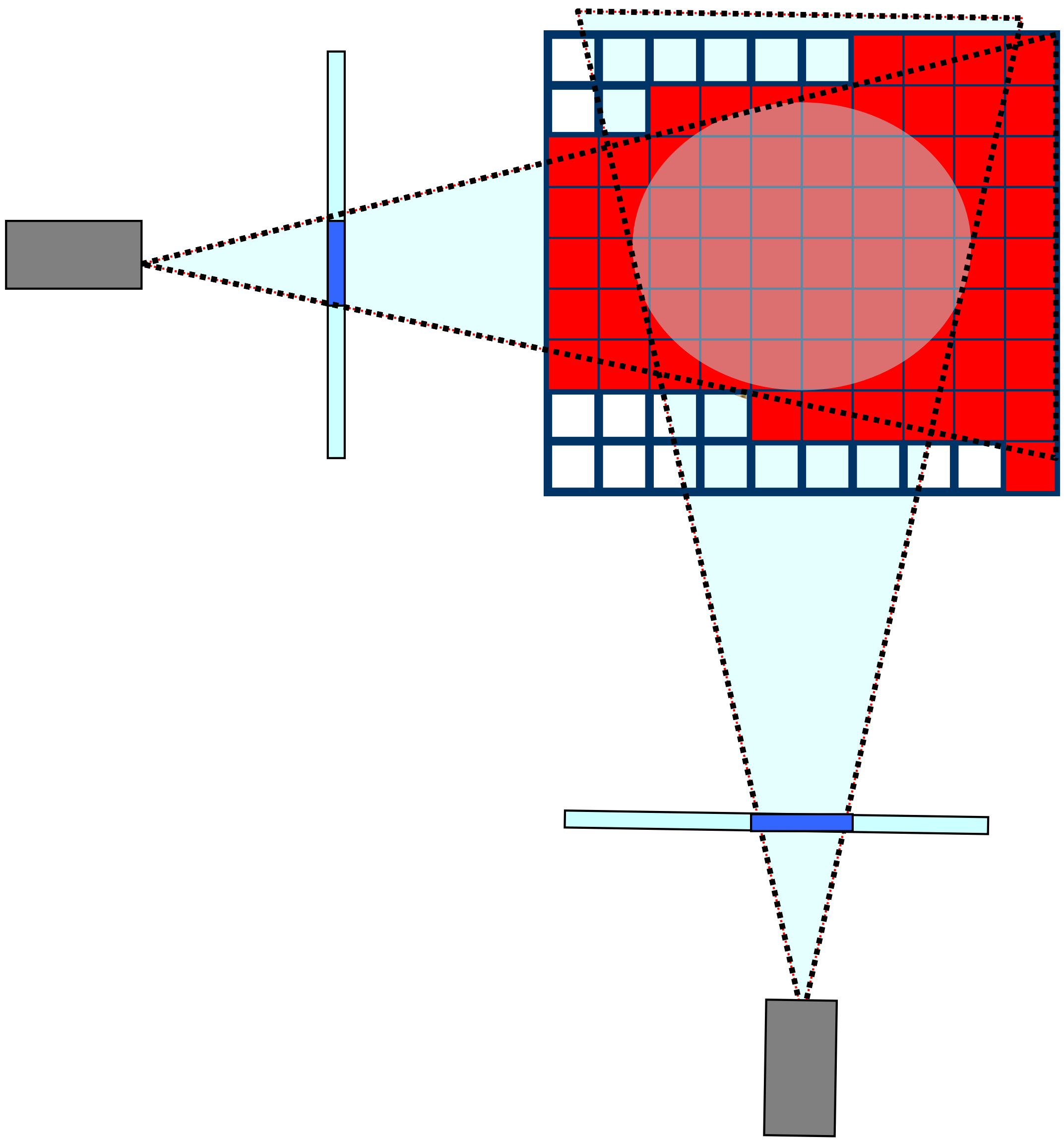
Computing Visual Hull in 2D



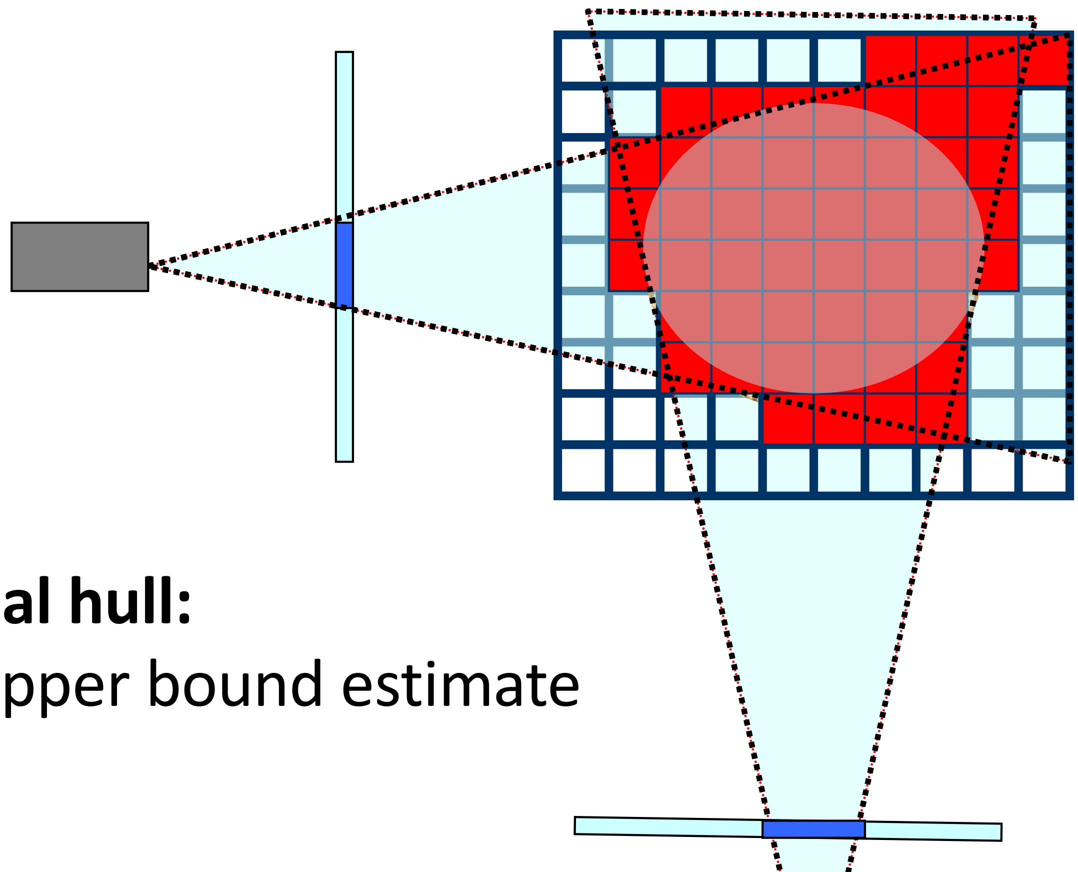
Computing Visual Hull in 2D



Computing Visual Hull in 2D



Computing Visual Hull in 2D

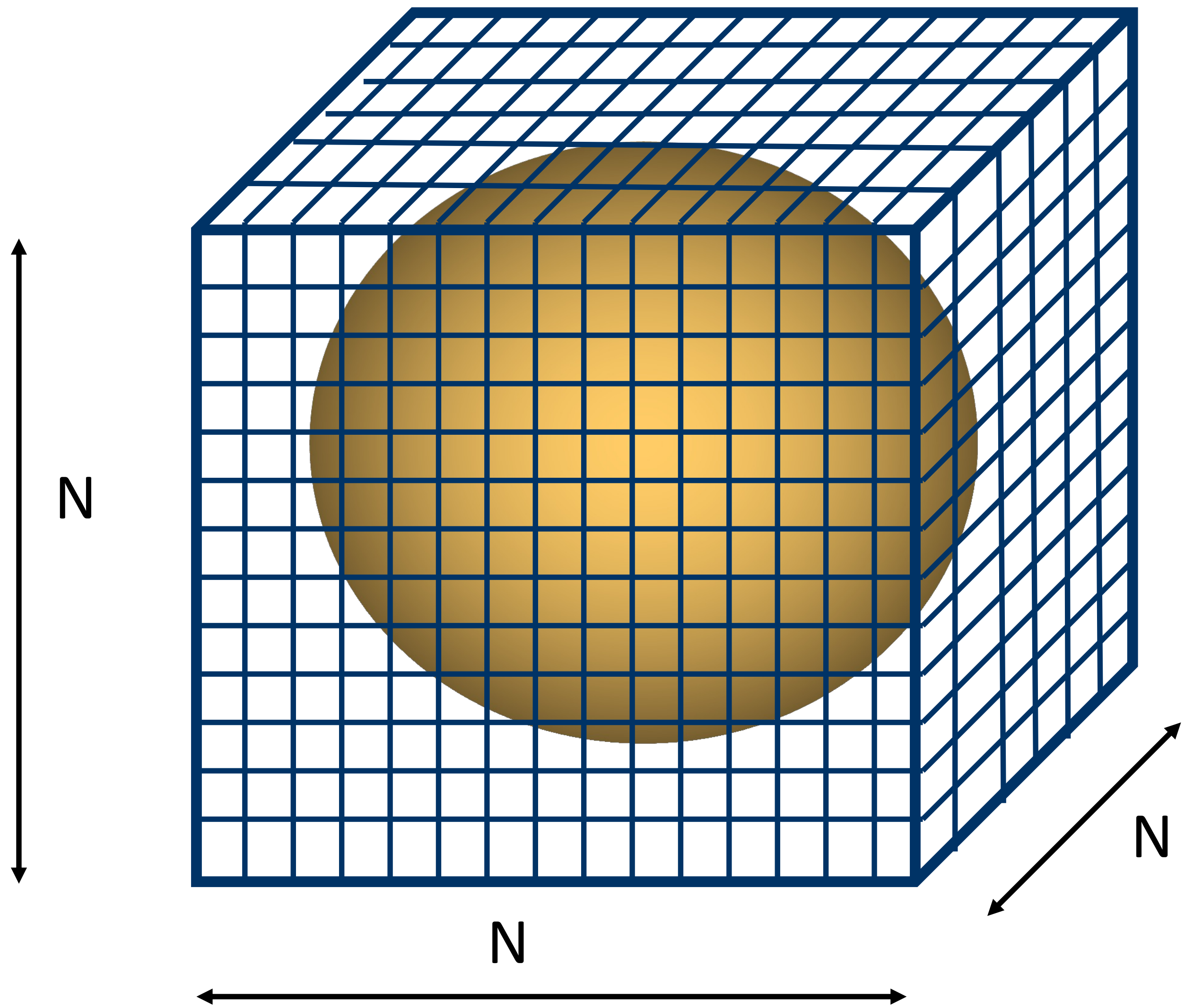


Visual hull:
an upper bound estimate

Consistency:

A voxel must be projected into a silhouette in each image

Space carving has complexity …



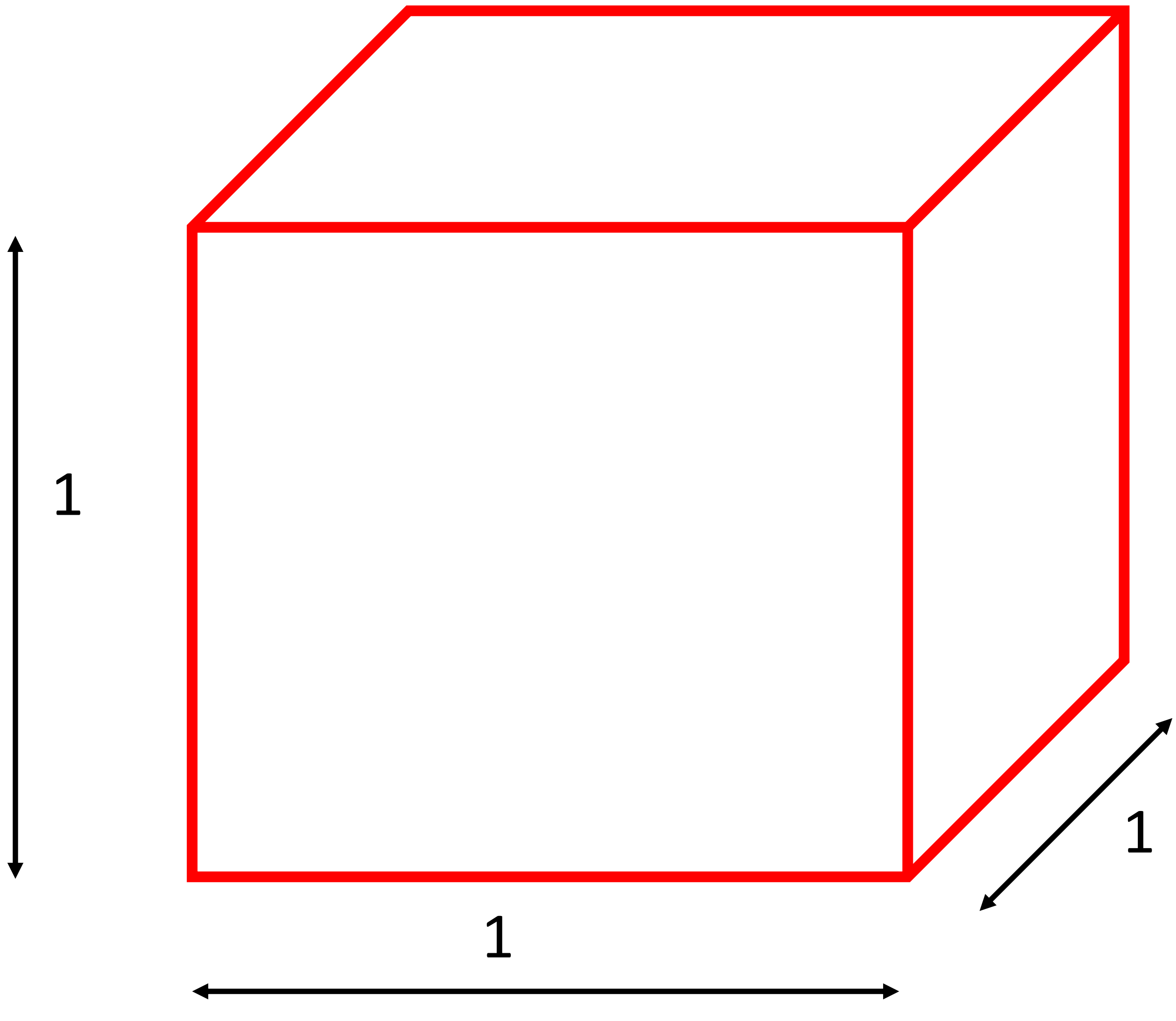
$O(N^3)$

Any suggestion for speeding this process up?

Octrees!

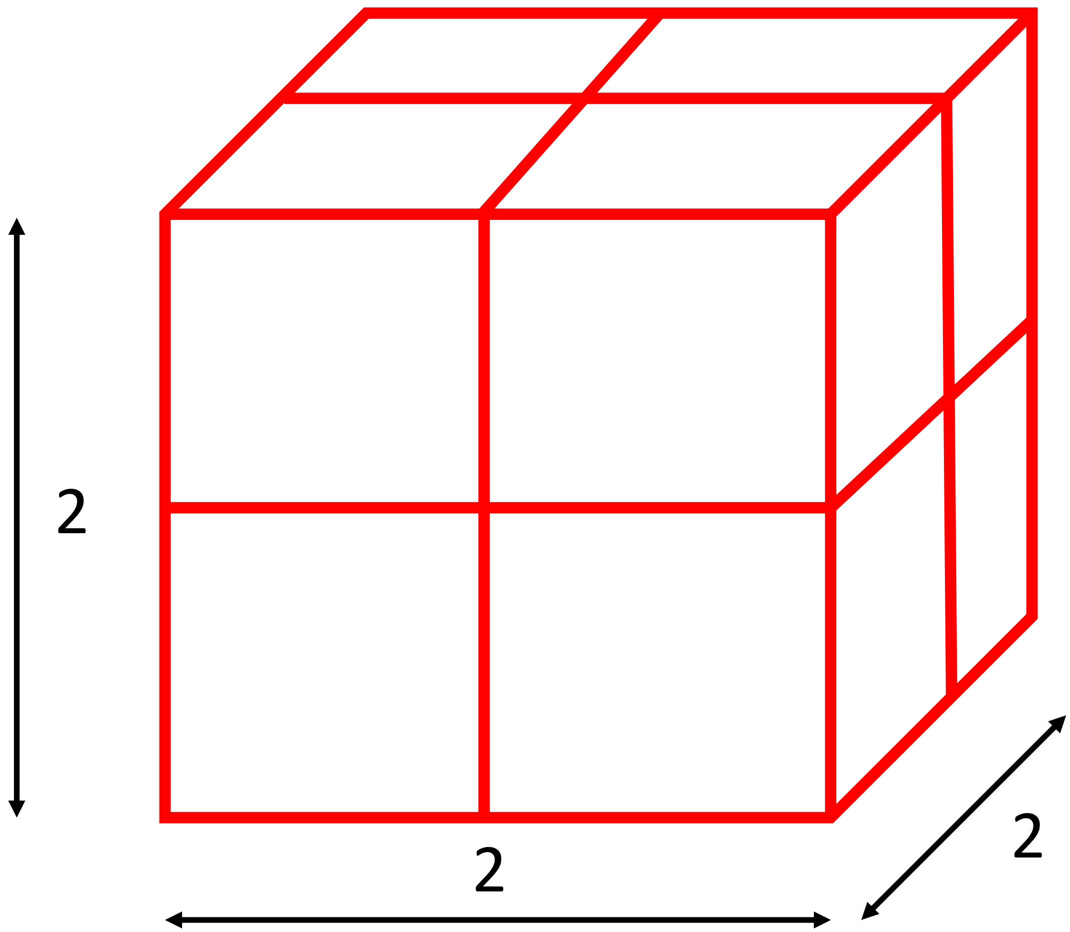
(Szeliski ’93)

Complexity Reduction: Octrees

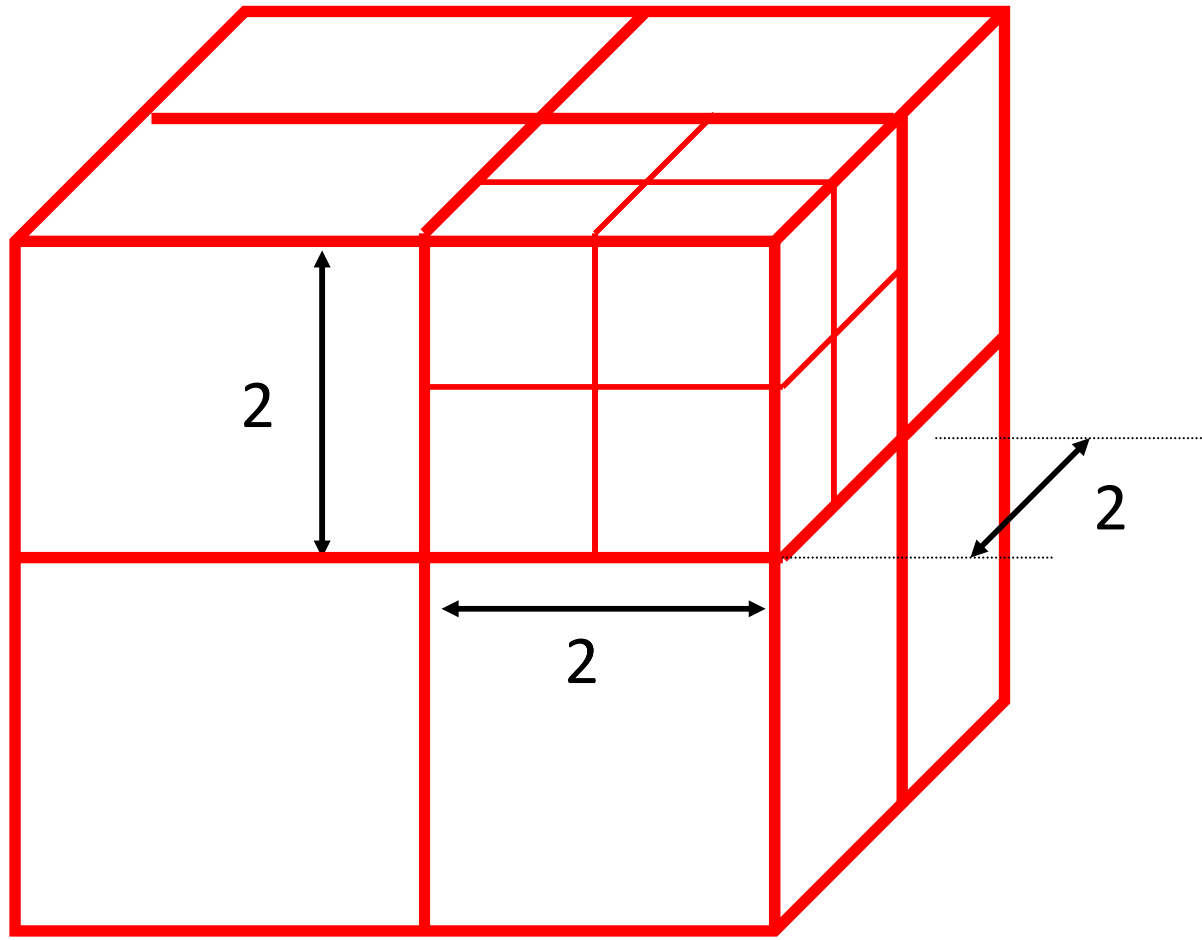


Complexity Reduction: Octrees

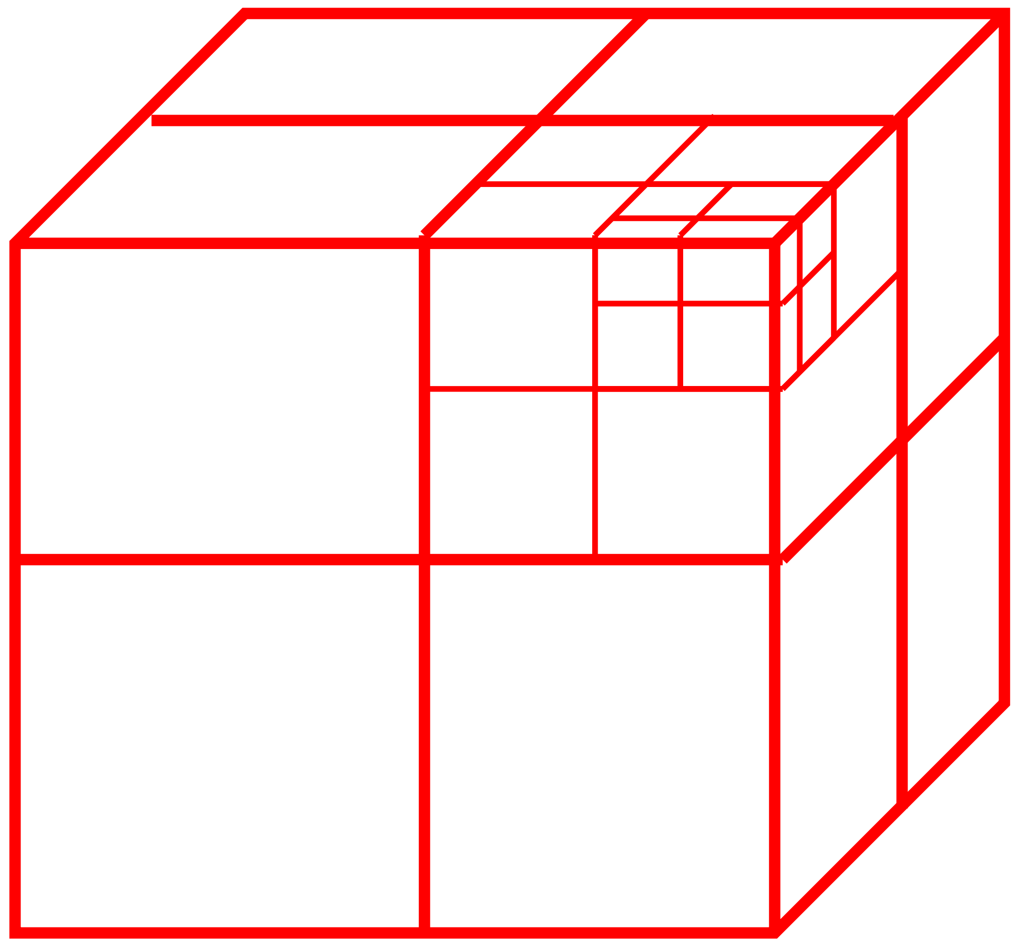
- Subdiving volume in sub-volumes of progressive smaller size



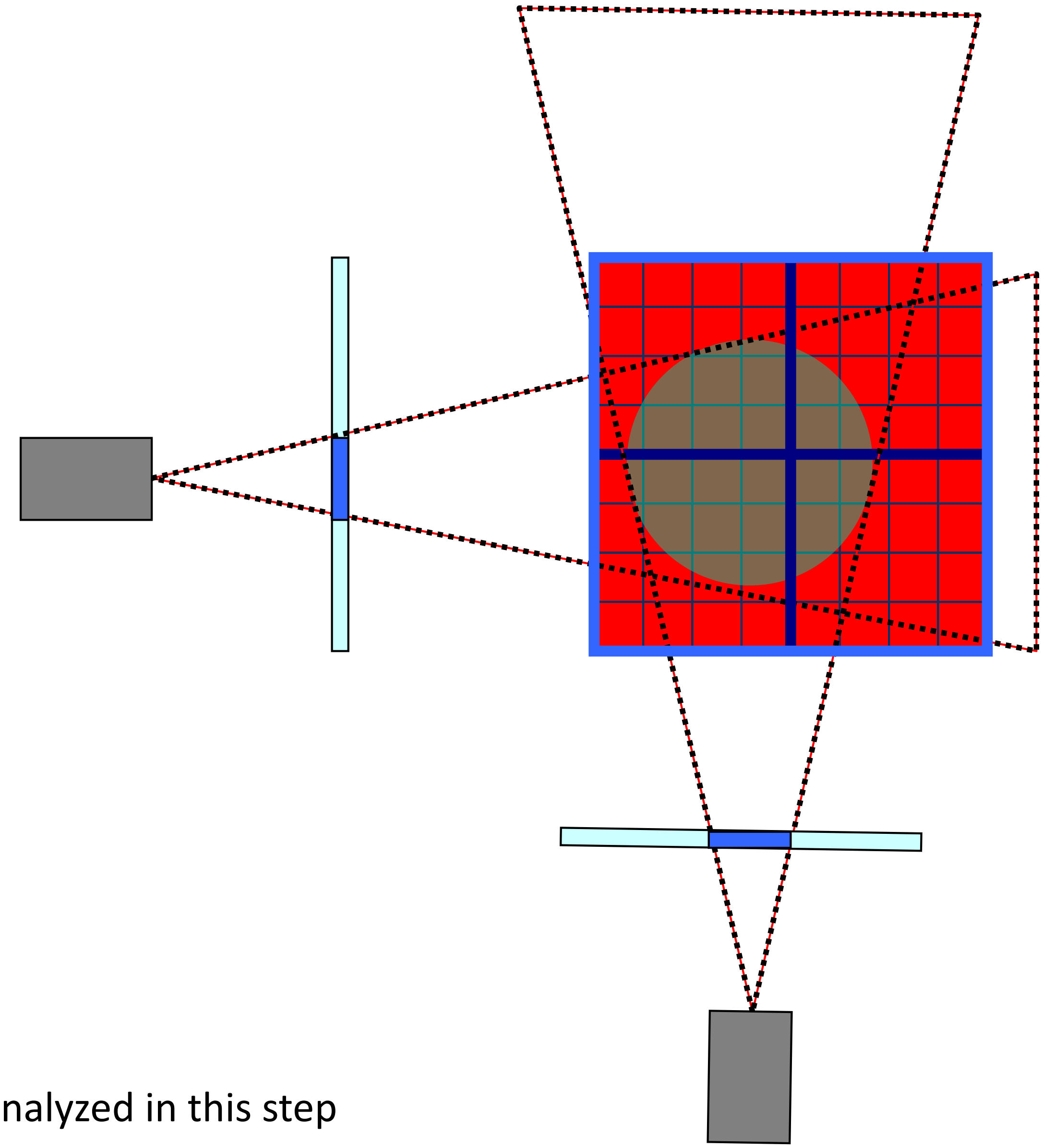
Complexity Reduction: Octrees



Complexity Reduction: Octrees

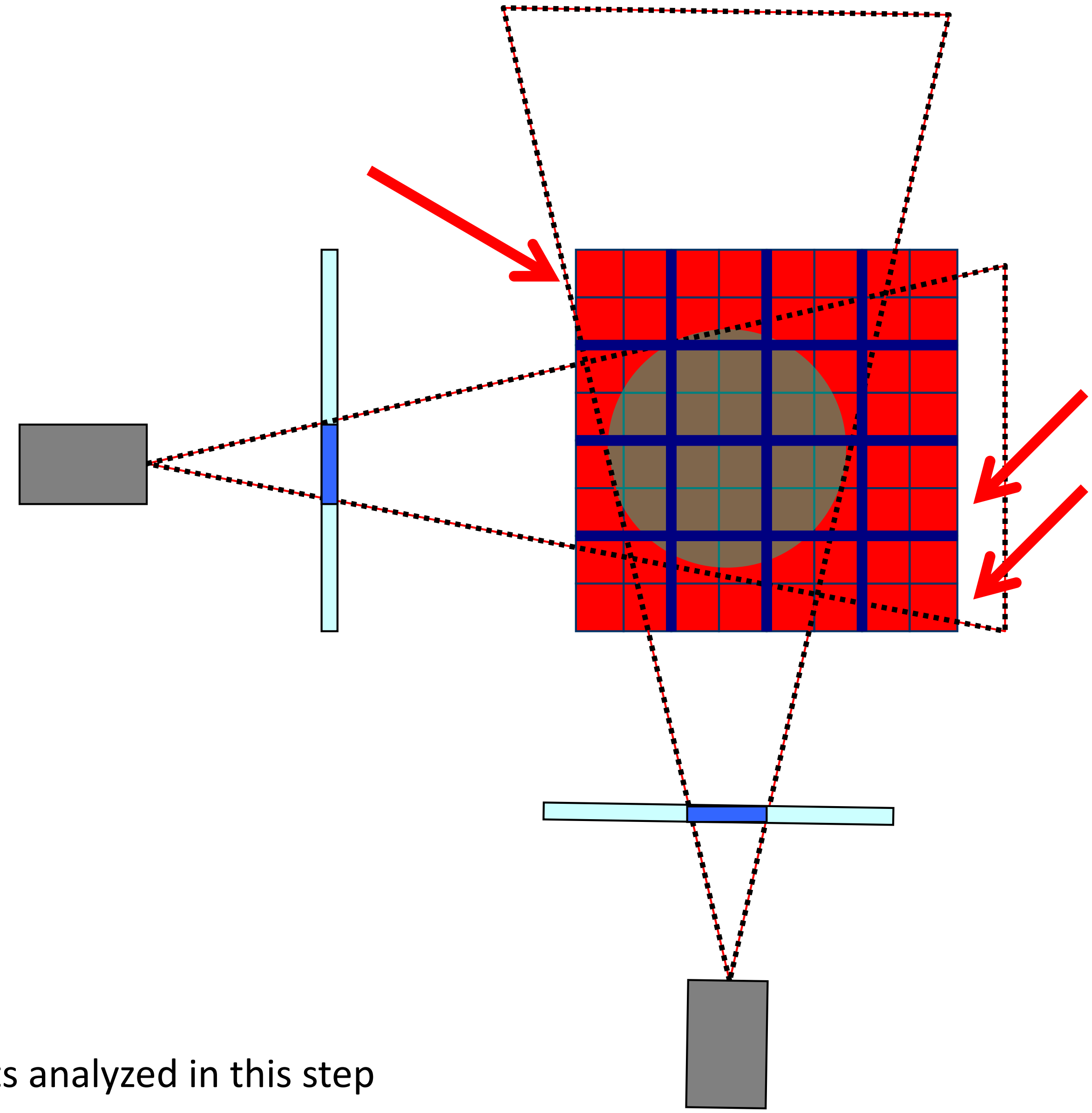


Complexity reduction: 2D example



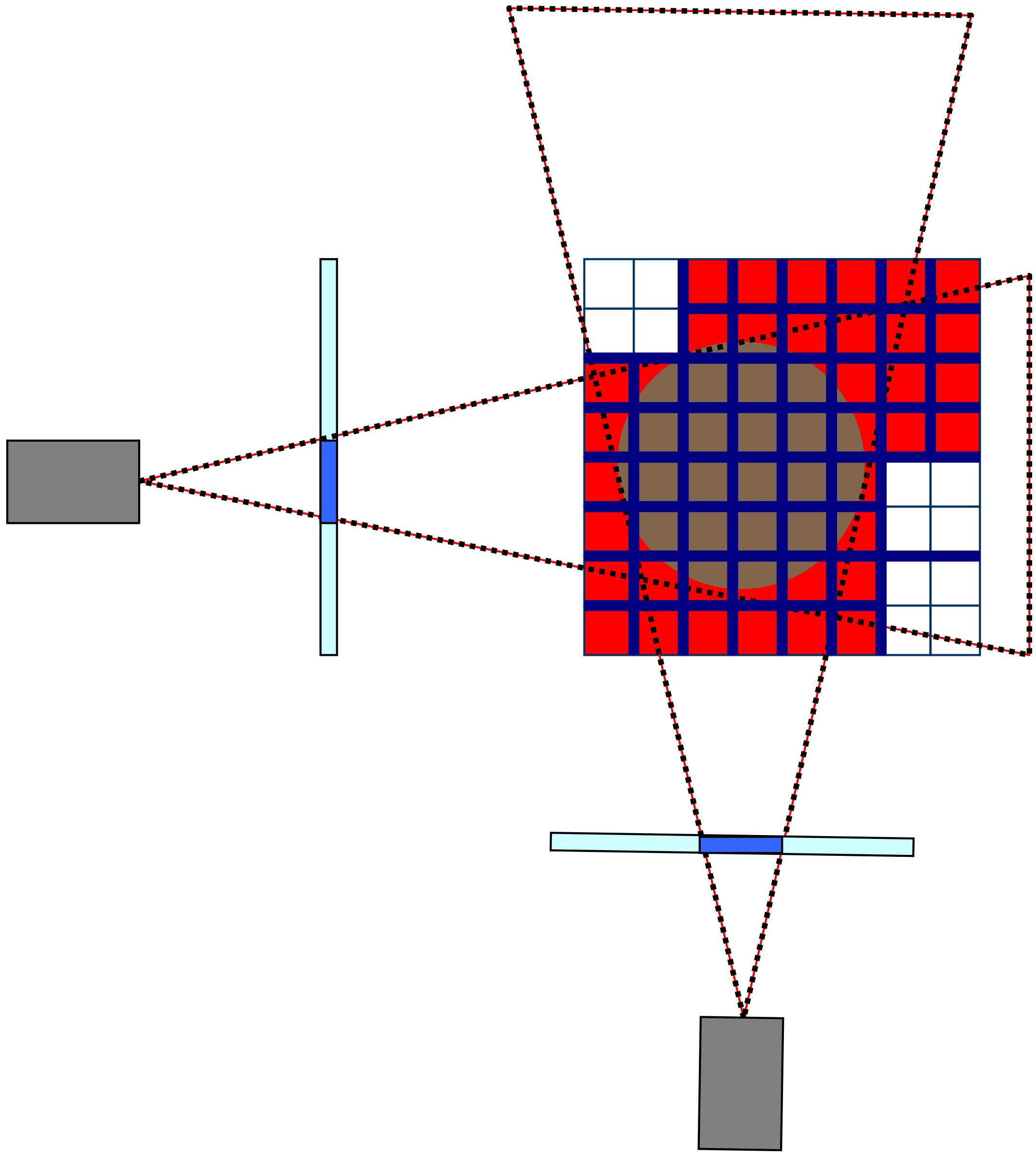
4 elements analyzed in this step

Complexity reduction: 2D example

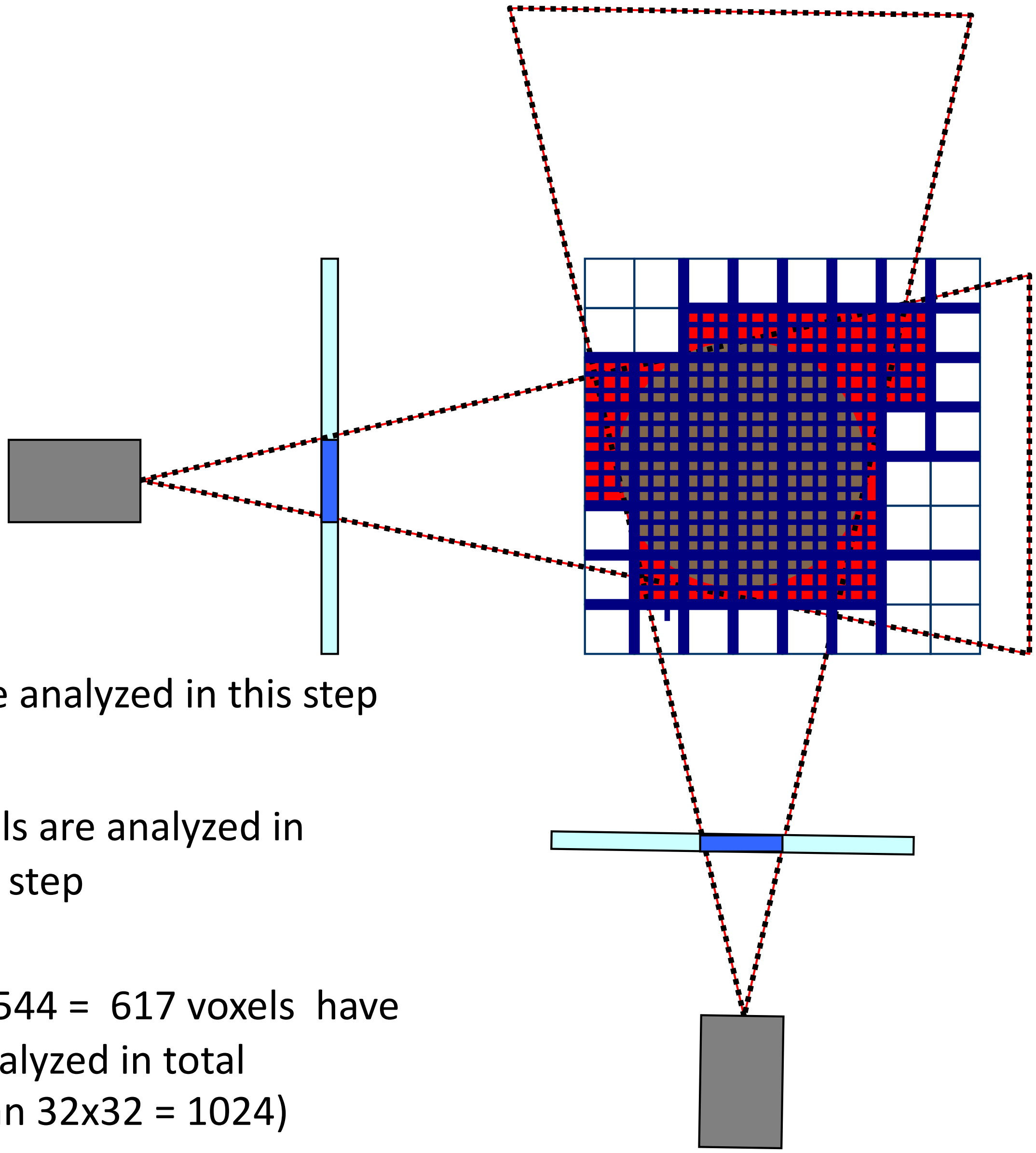


16 elements analyzed in this step

Complexity reduction: 2D example



Complexity reduction: 2D example



52 elements are analyzed in this step

16x34=544 voxels are analyzed in this step

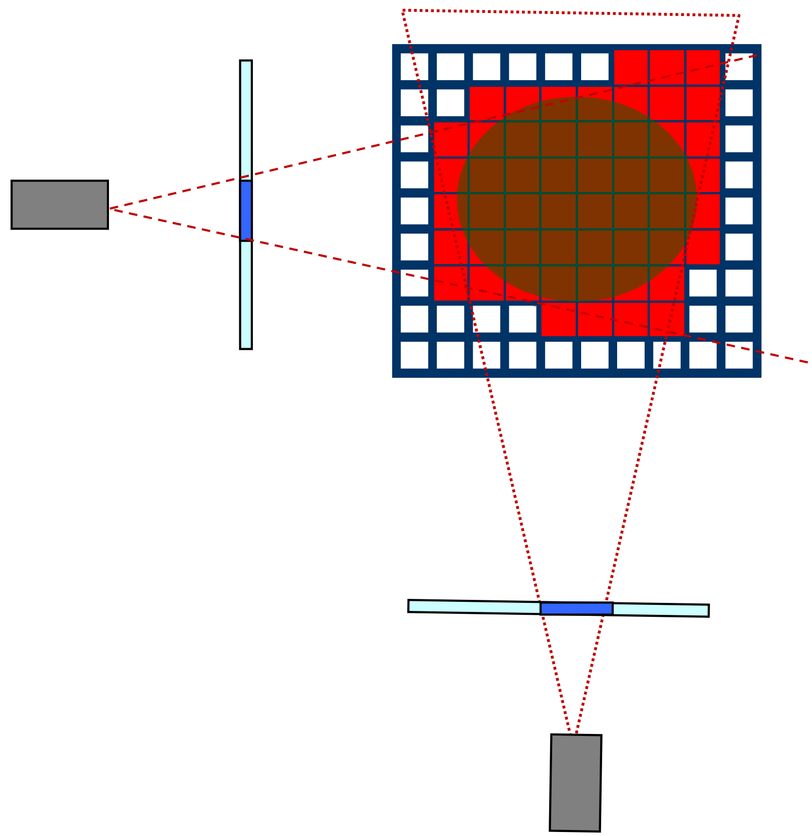
1+ 4 + 16 + 52 + 544 = 617 voxels have been analyzed in total (rather than 32x32 = 1024)

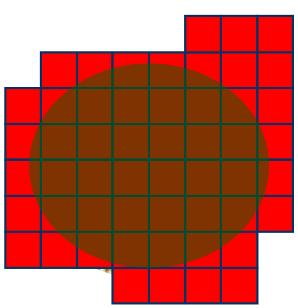
Advantages of Space carving

- Robust and simple
- No need to solve for correspondences

Limitations of Space carving

- Accuracy function of number of views



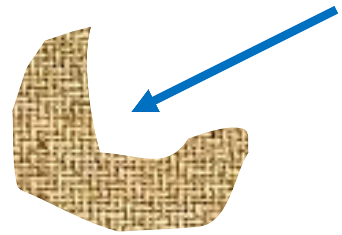


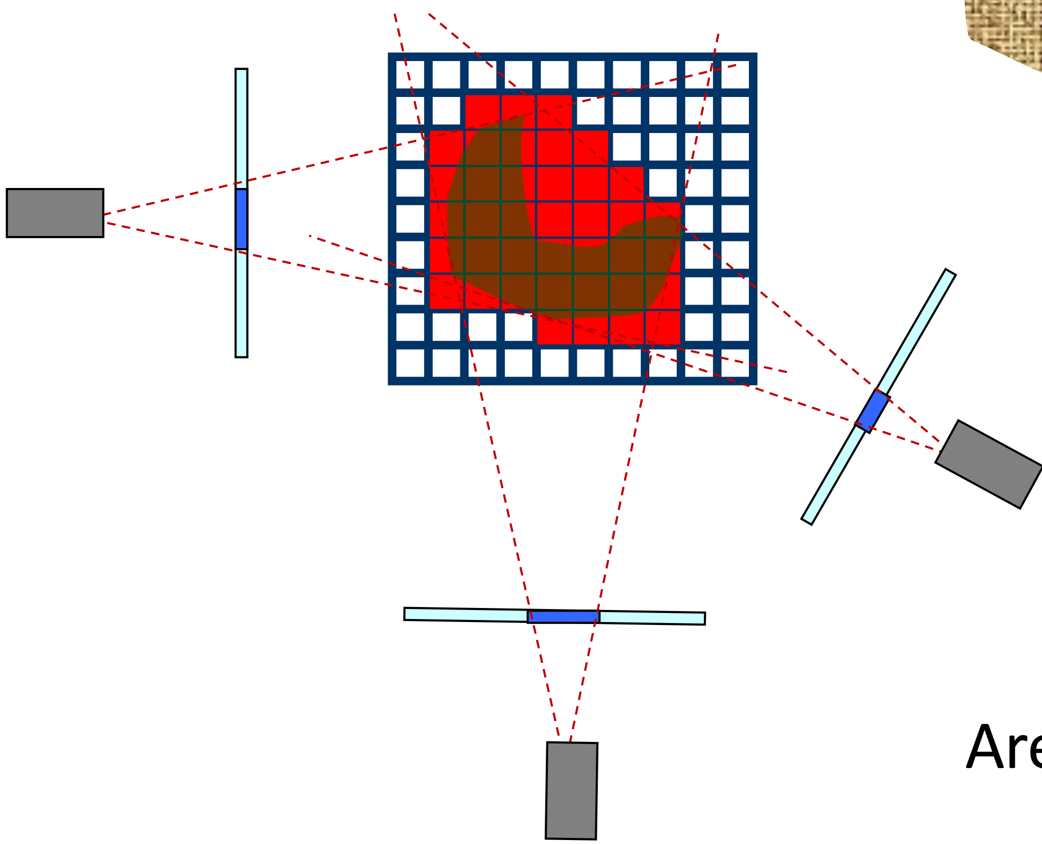
Not a good estimate

What else?

Limitations of Space carving

- Concavities are not modeled





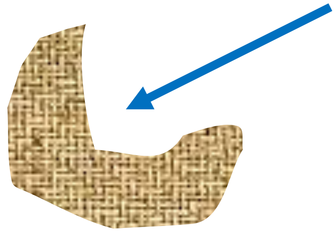
For 3D objects:

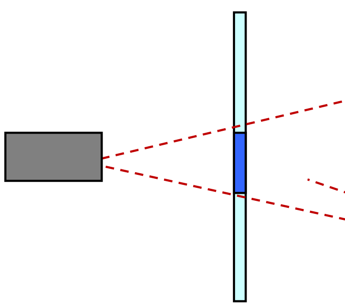
Are all types of concavities problematic?

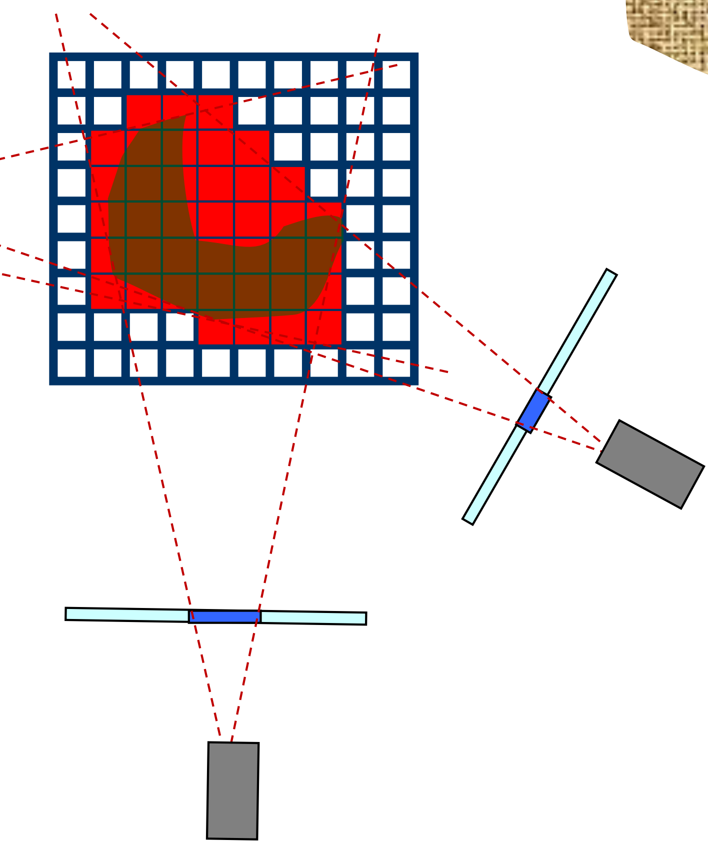
Limitations of Space carving

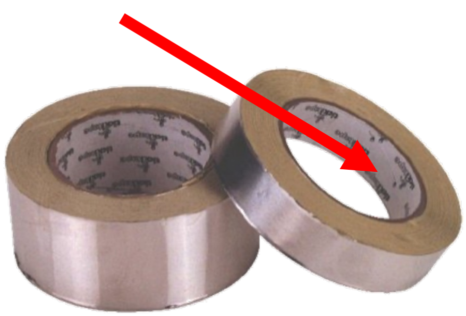
- Concavities are not modeled

Concavity





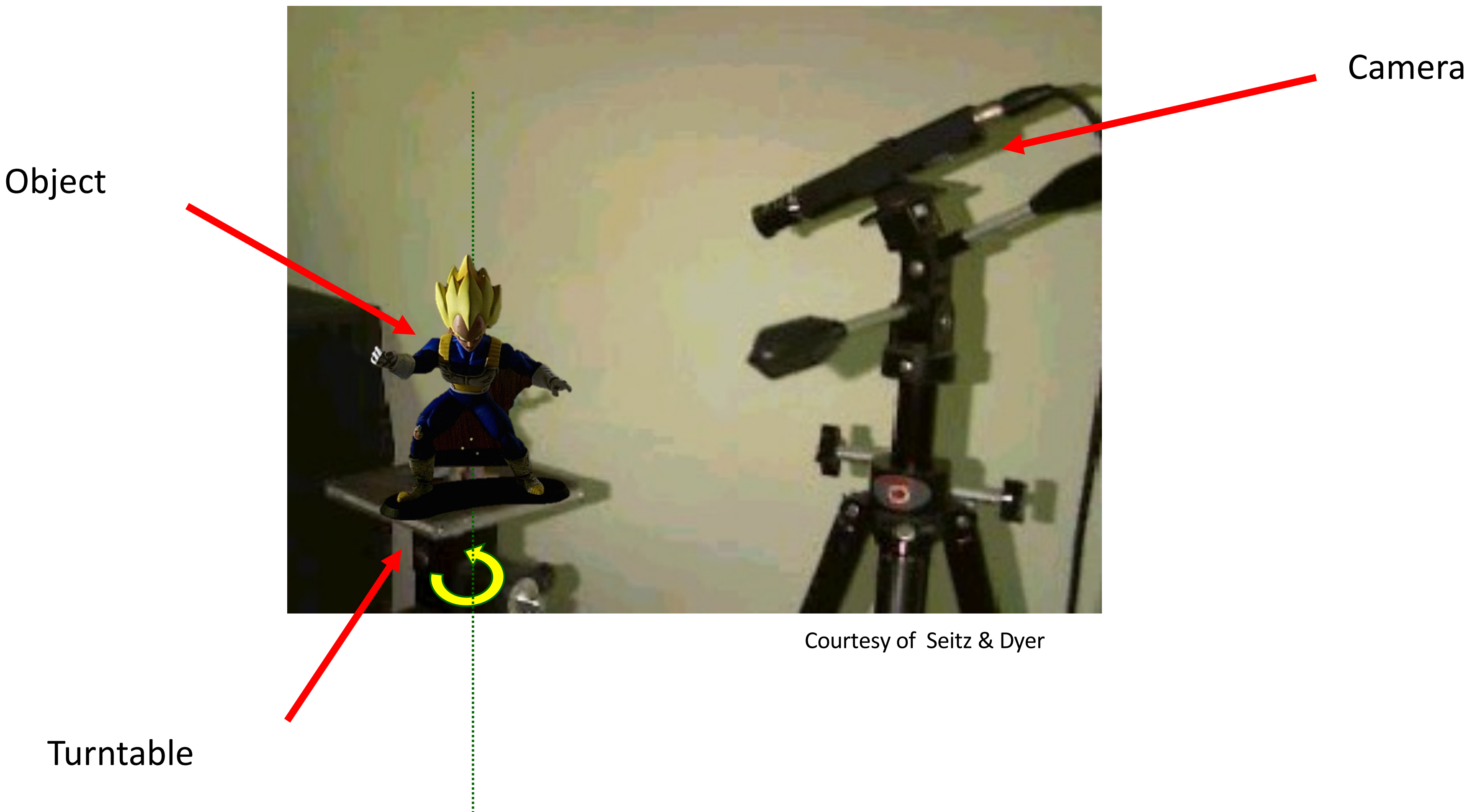




(hyperbolic regions are ok)

-- see Laurentini (1995)

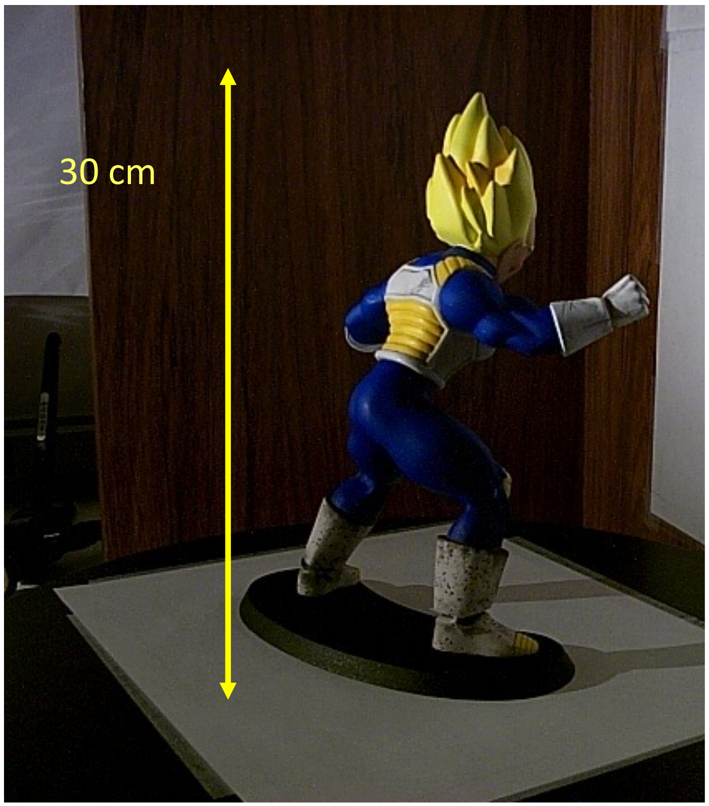
Space carving: A Classic Setup



Courtesy of Seitz & Dyer

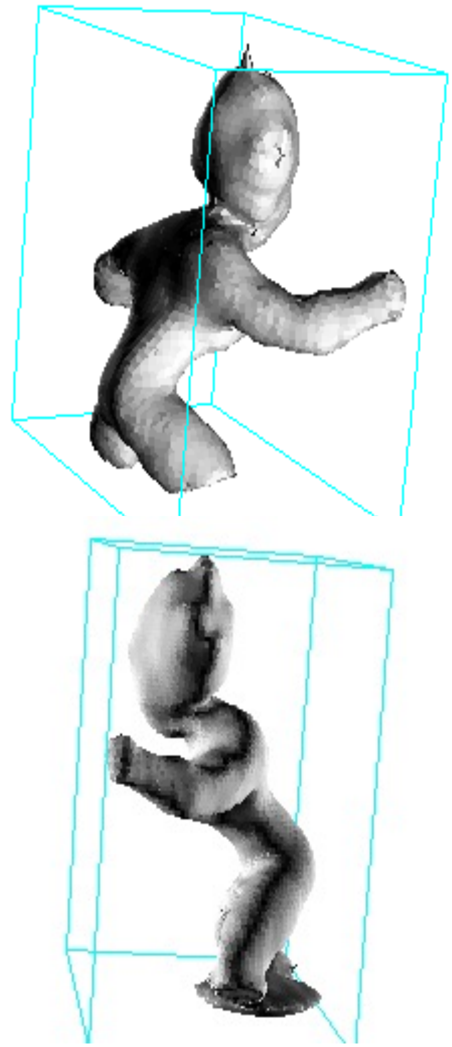
Space carving: A Classic Setup

Space carving: Experiments



24 poses (15^{o})

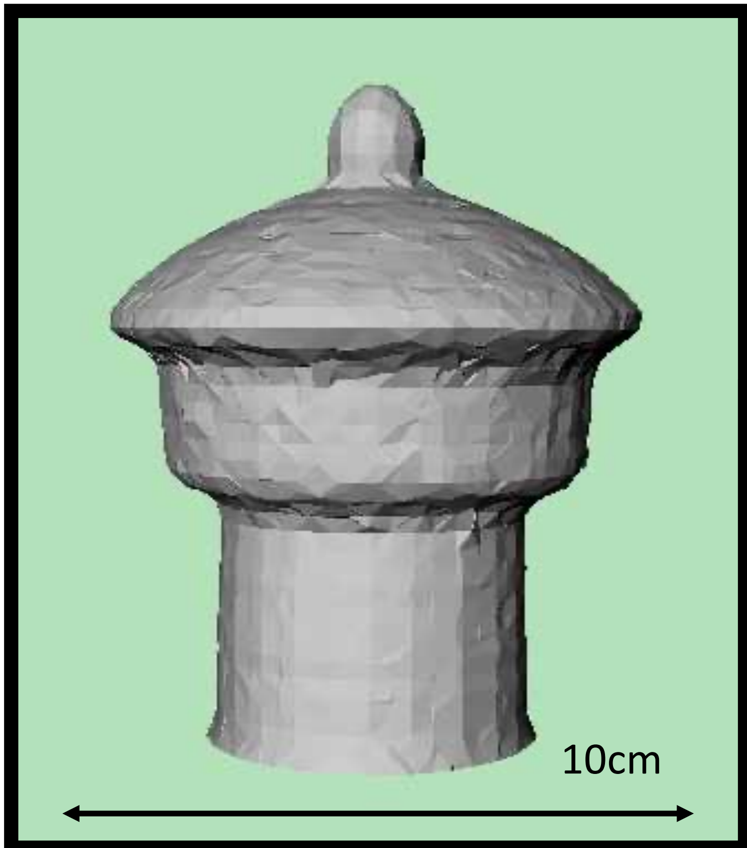
voxel size = 1mm

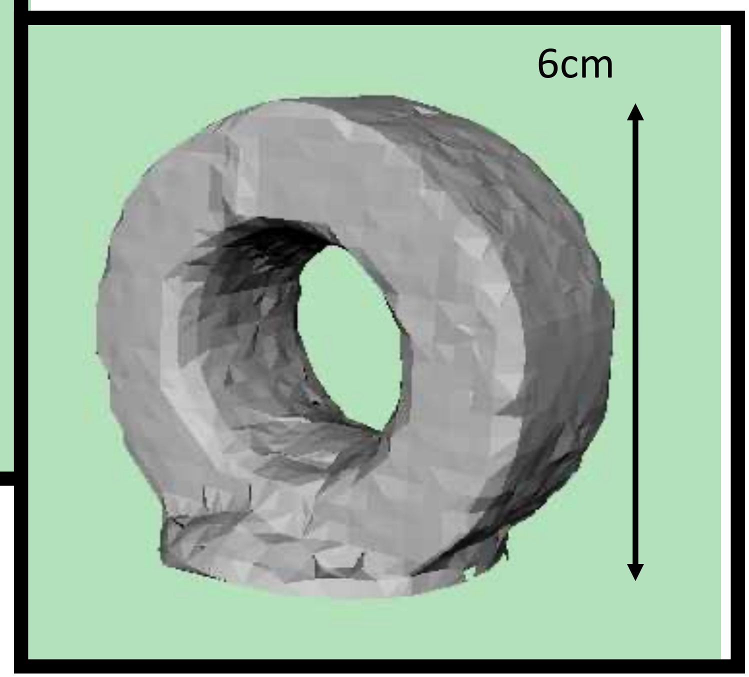


Space carving: Experiments

24 poses (15^{O})

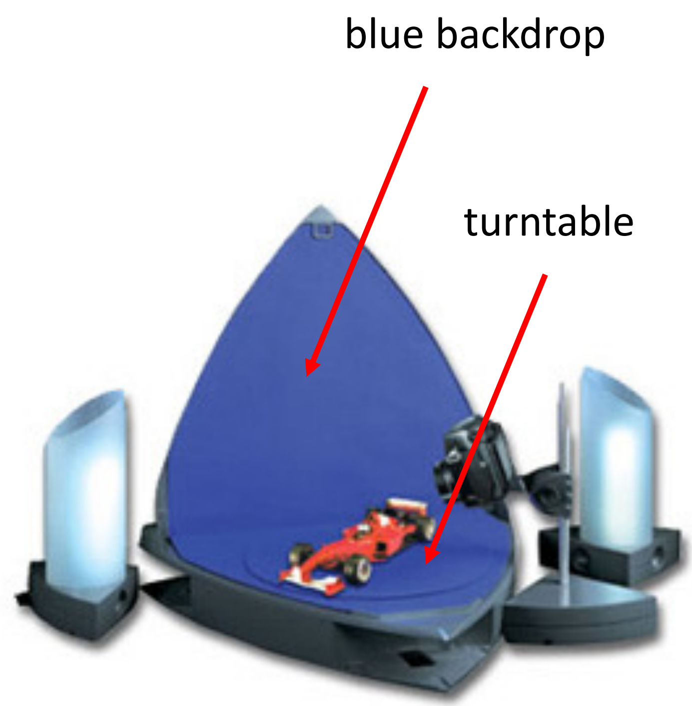
voxel size = 2mm



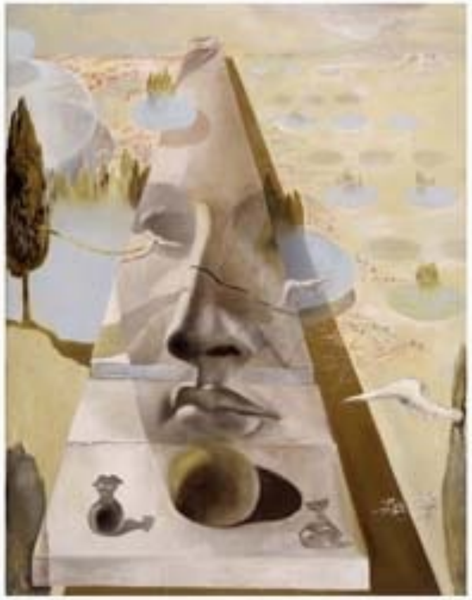


Space carving: Conclusions

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



Lecture 8
Active stereo & Volumetric stereo



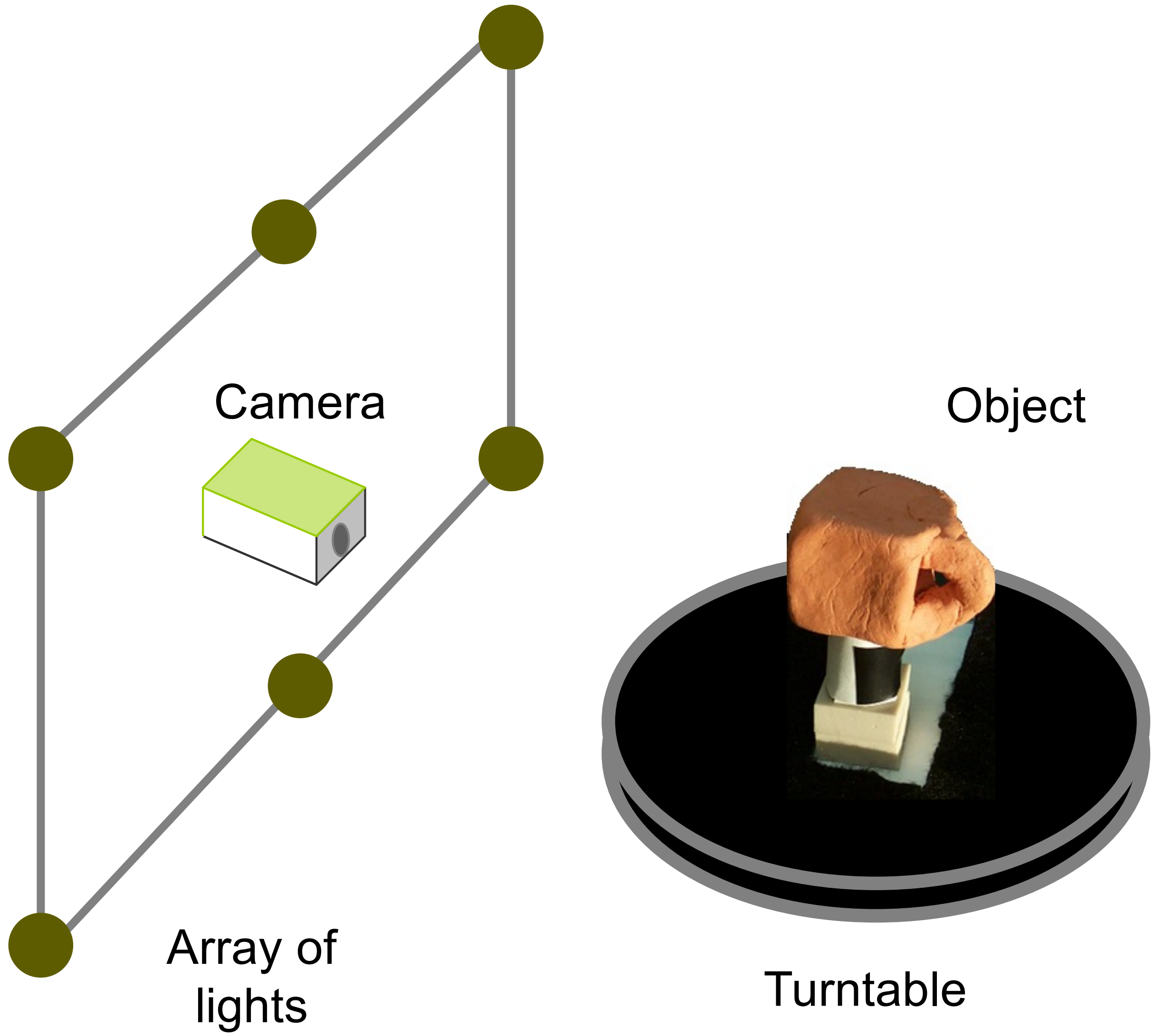
- Active stereo
  - Structured lighting
  - Depth sensing
- Volumetric stereo:
  - Space carving
  - Shadow carving
  - Voxel coloring

Shape from Shadows

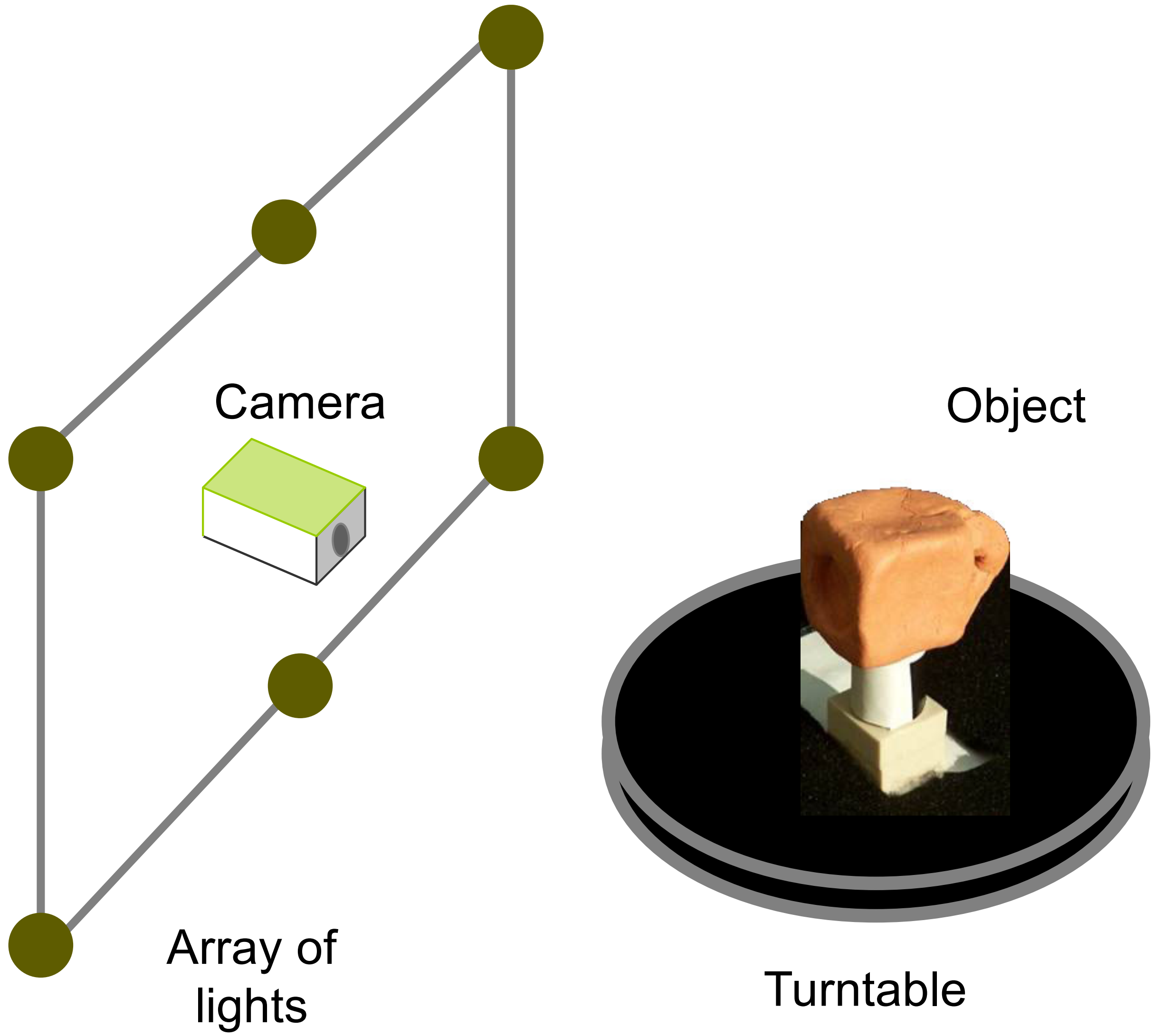
- Self-shadows are visual cues for shape recovery

Self-shadows indicate concavities
(no modeled by contours)

Shadow carving: The Setup

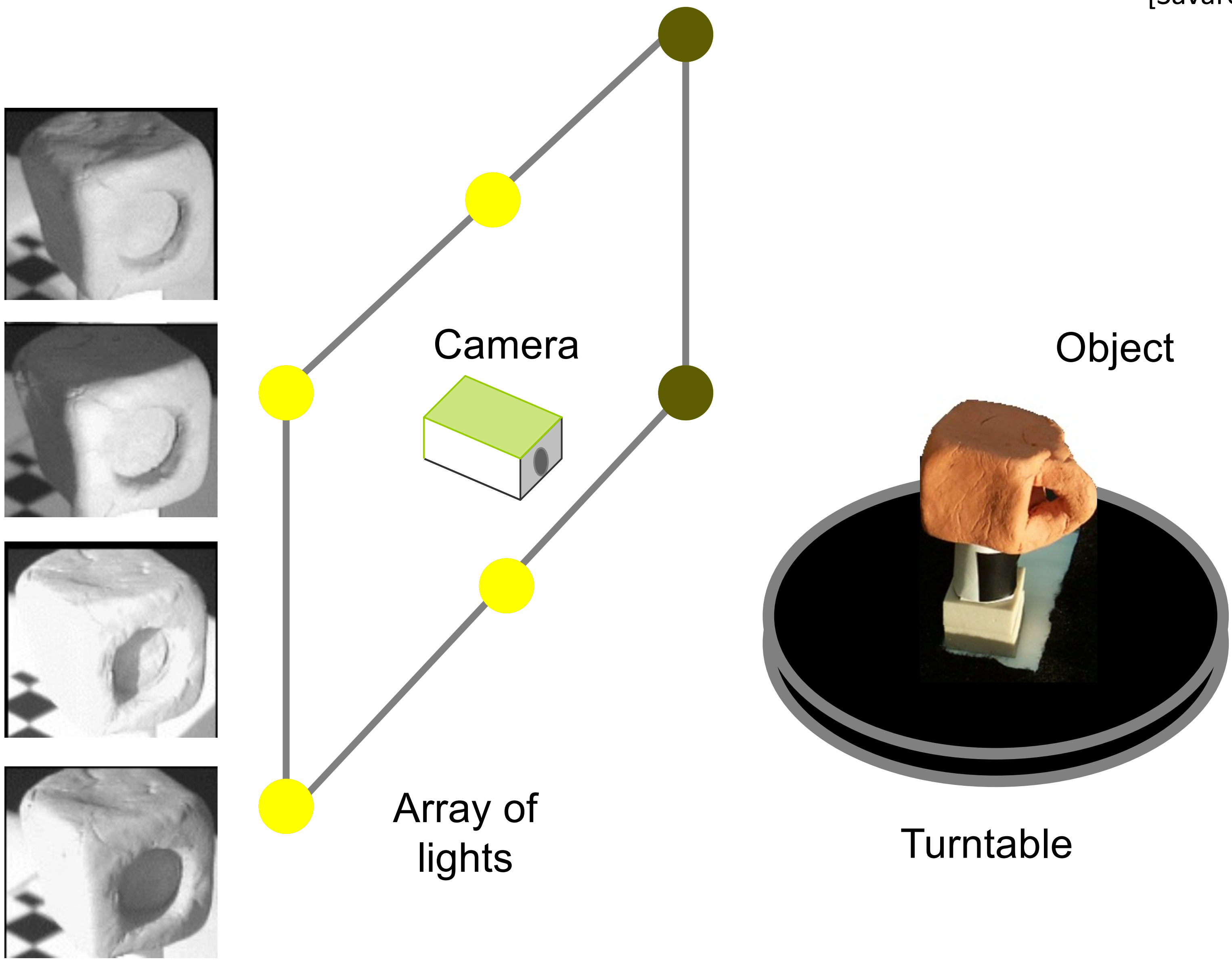


Shadow carving: The Setup



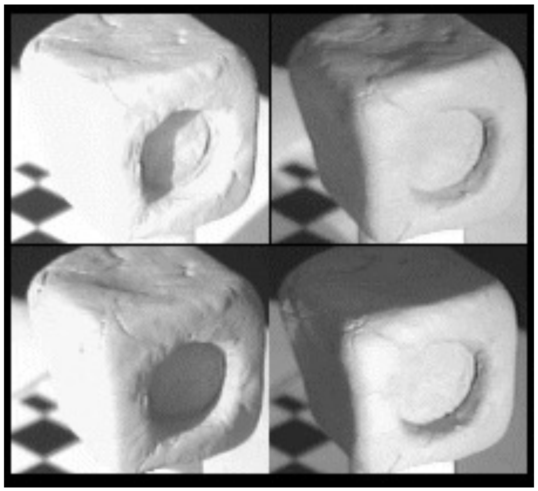
Shadow carving: The Setup

[Savarese et al '01]



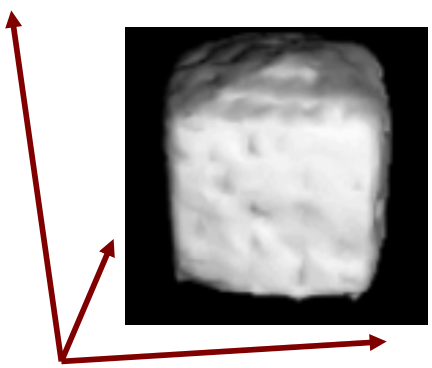
Shadow carving

[Savarese et al. 2001]

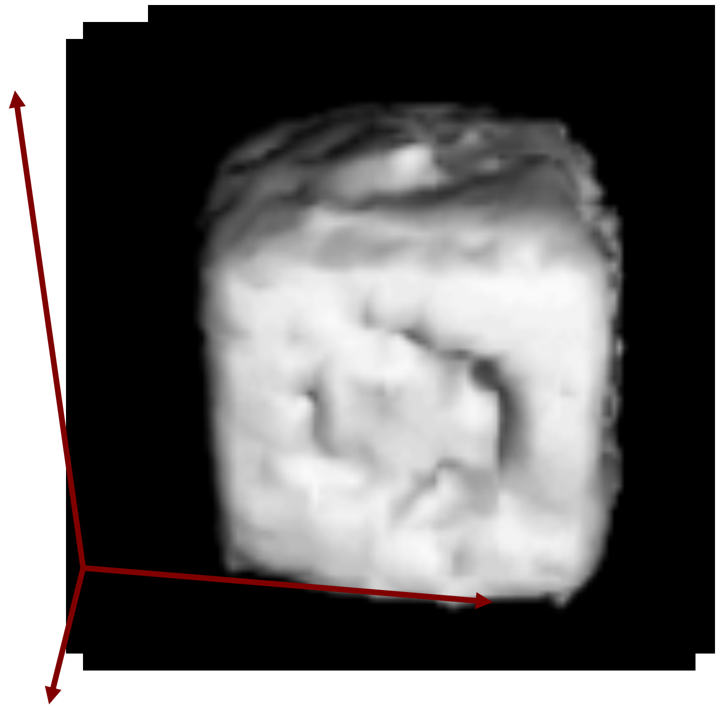


Self-shadows

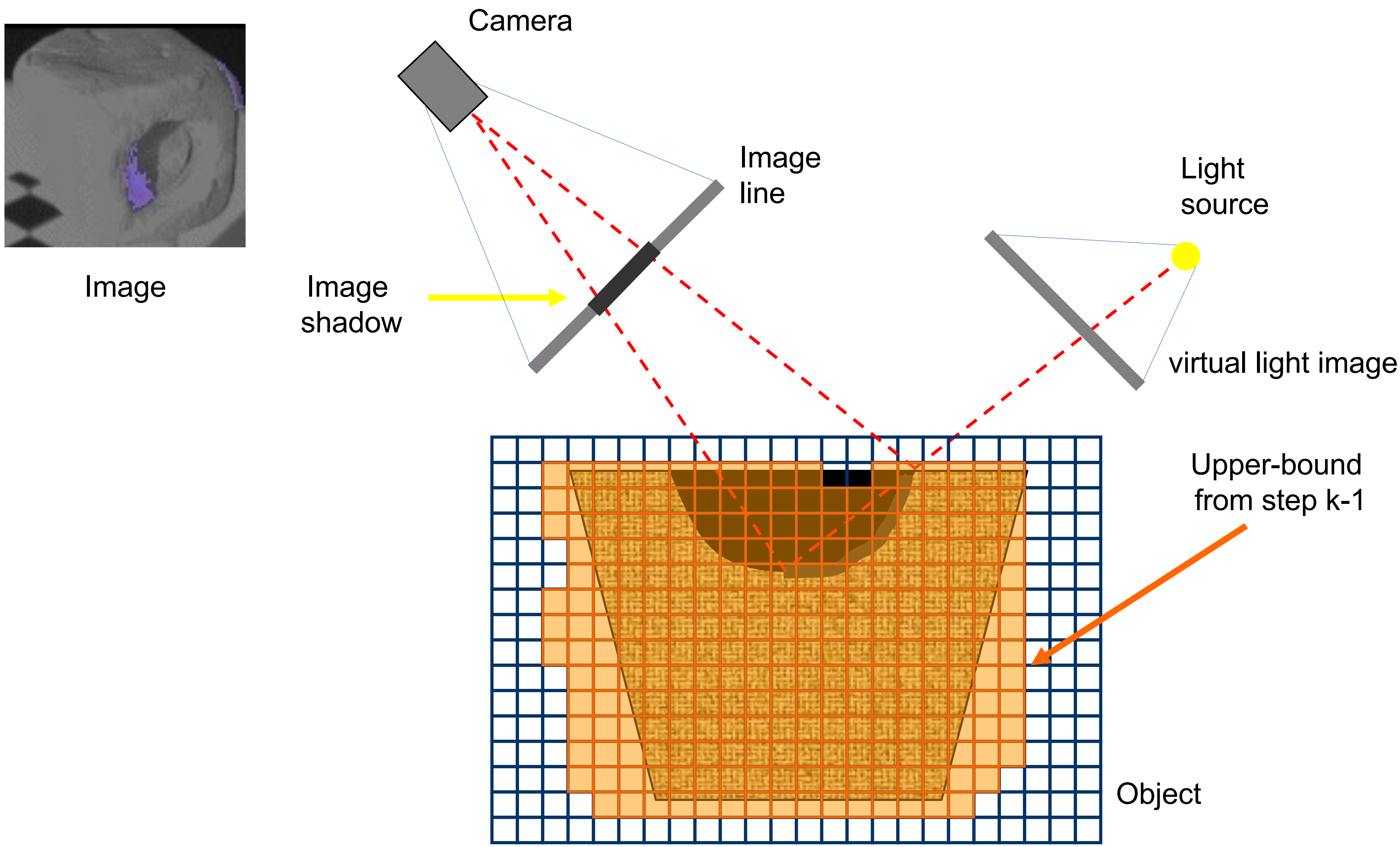
+



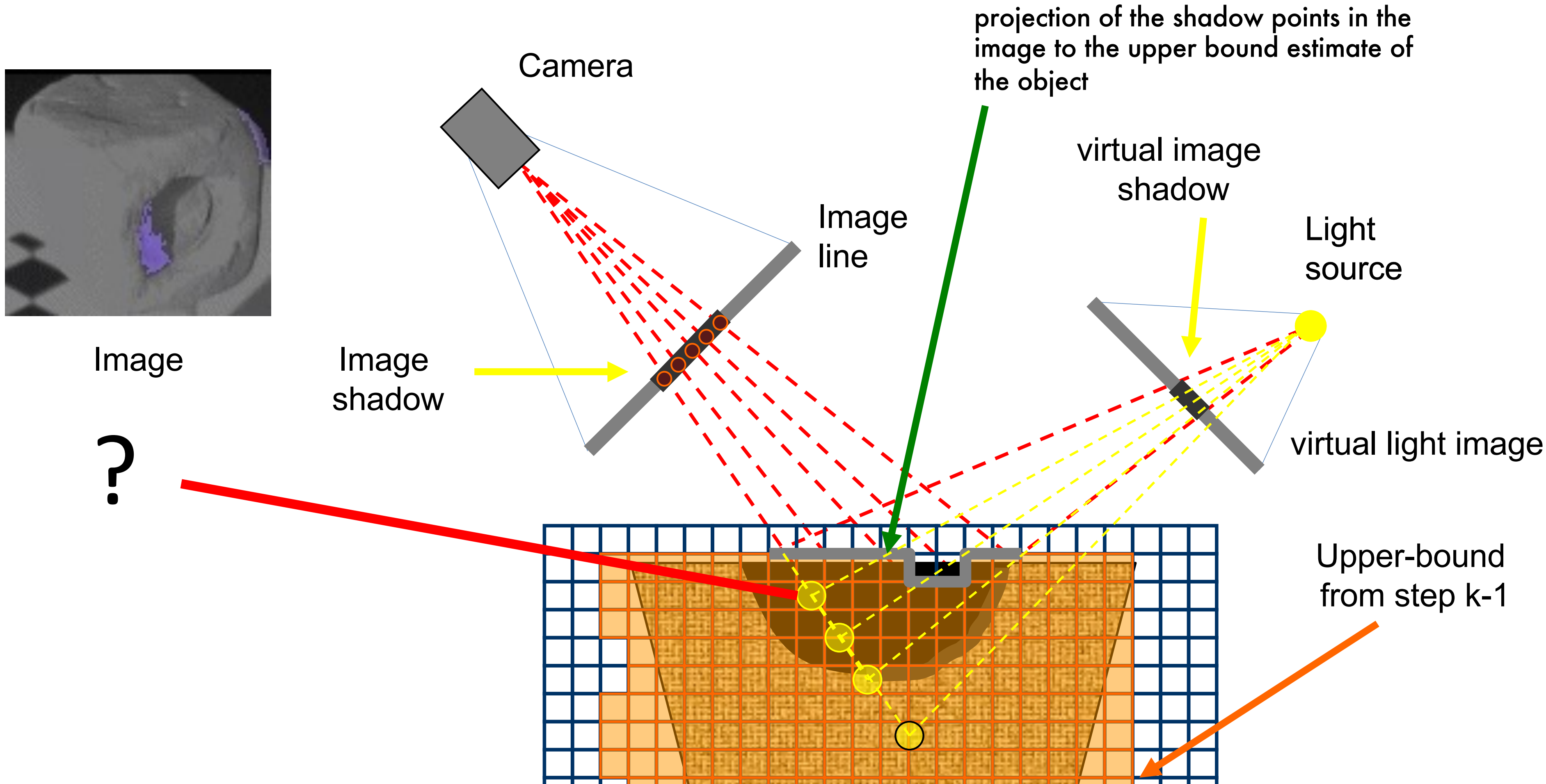
Object's upper bound



Algorithm: Step k



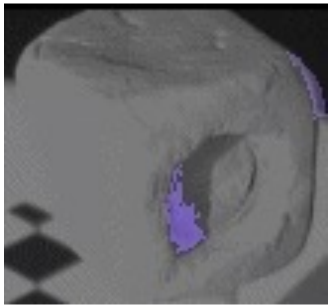
Algorithm: Step k



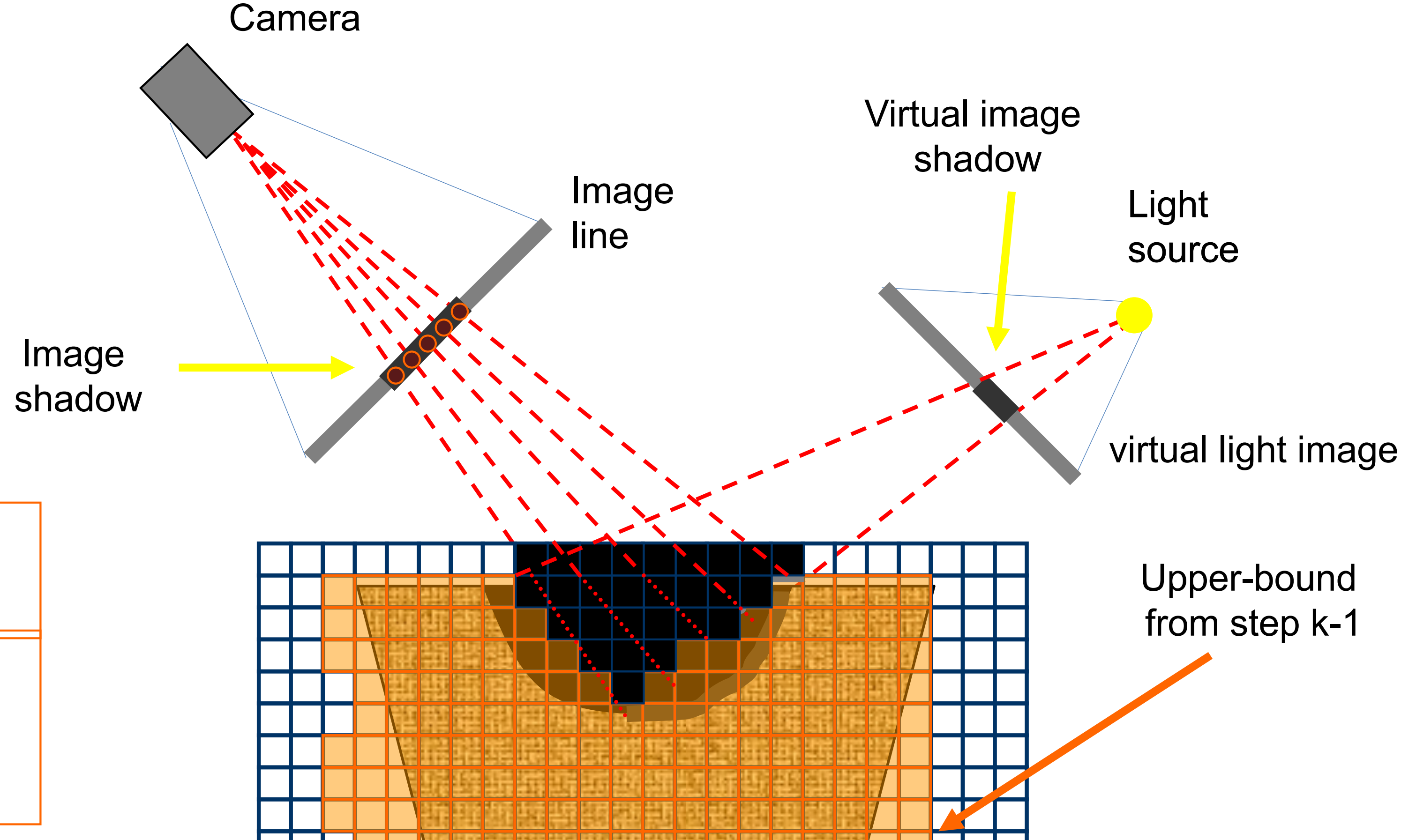
Theorem:

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

Algorithm: Step k



Image



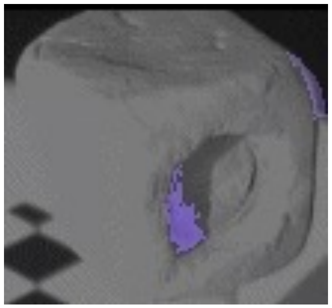
Properties:

No further volume can be removed
Carving process always conservative

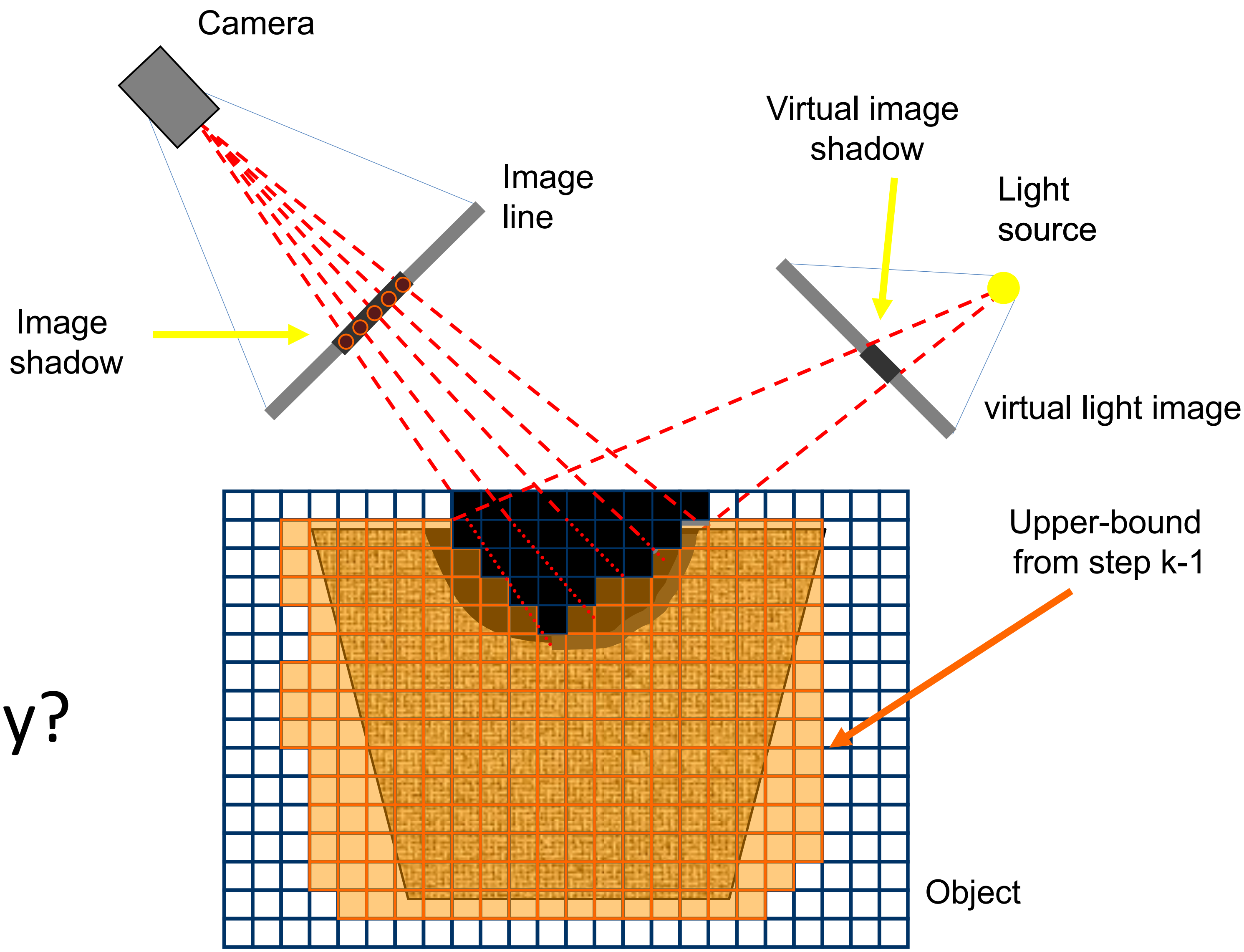
Consistency:

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

Algorithm: Step k



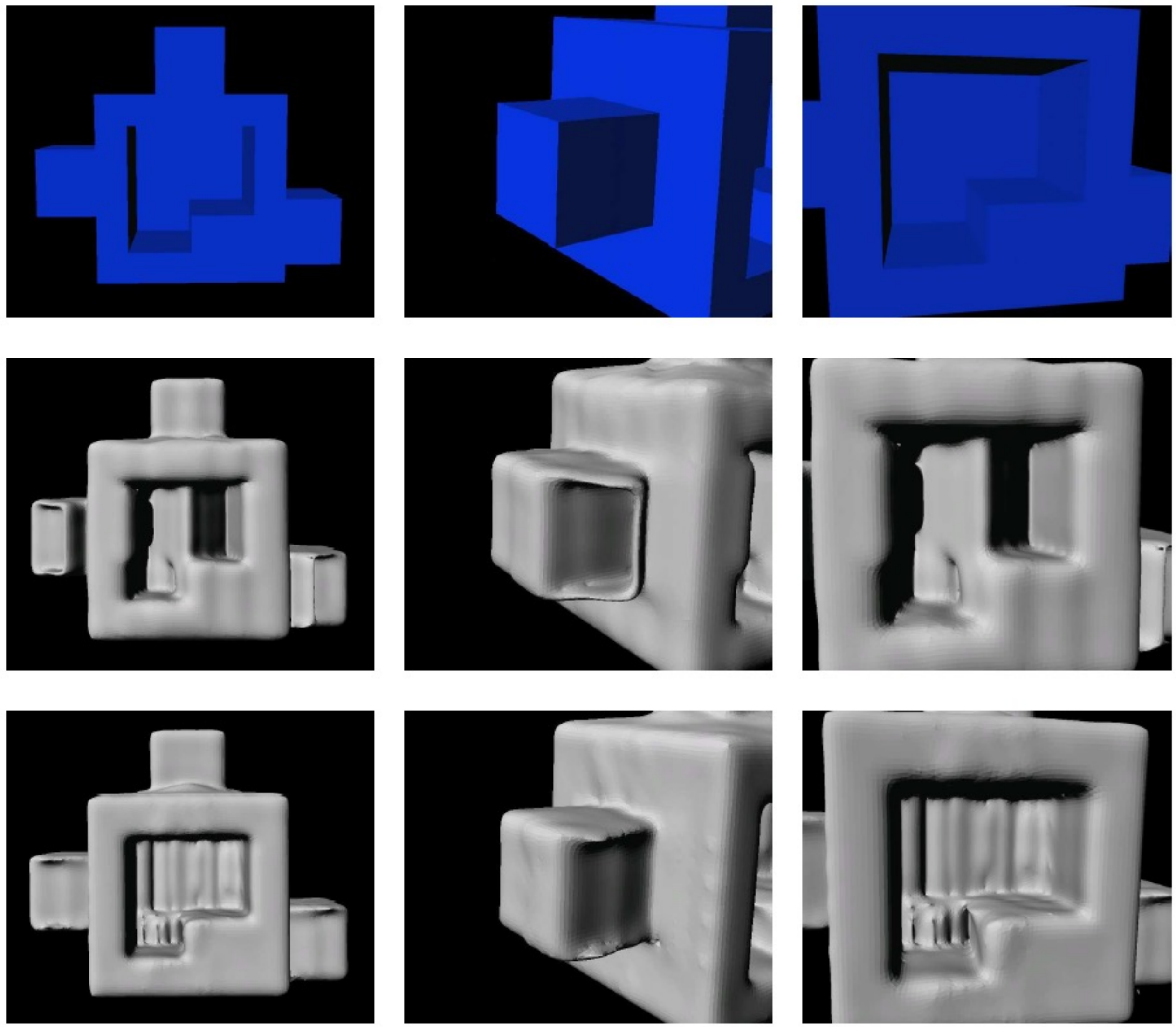
Image



Complexity?

$O(2N^3)$

Simulating the System



- 24 positions
- 4 lights

- 72 positions
- 8 lights

Results

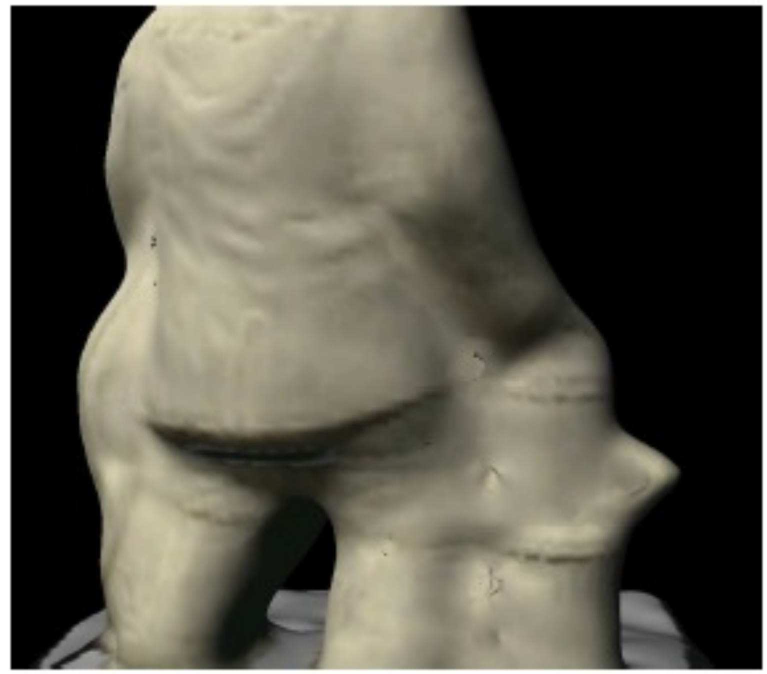
- 16 positions
- 4 lights

Space carving

Shadow carving

Results

Space carving



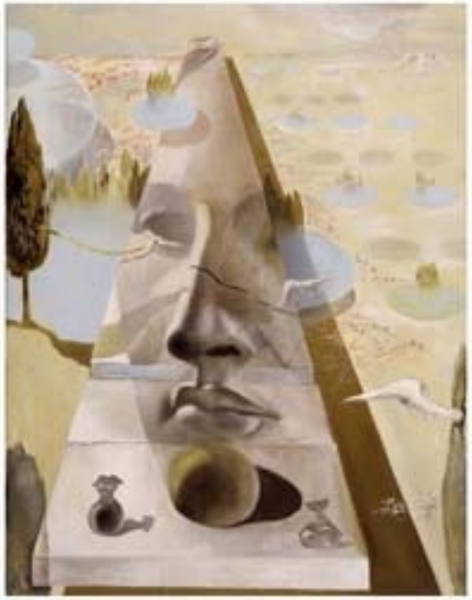
Shadow carving

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

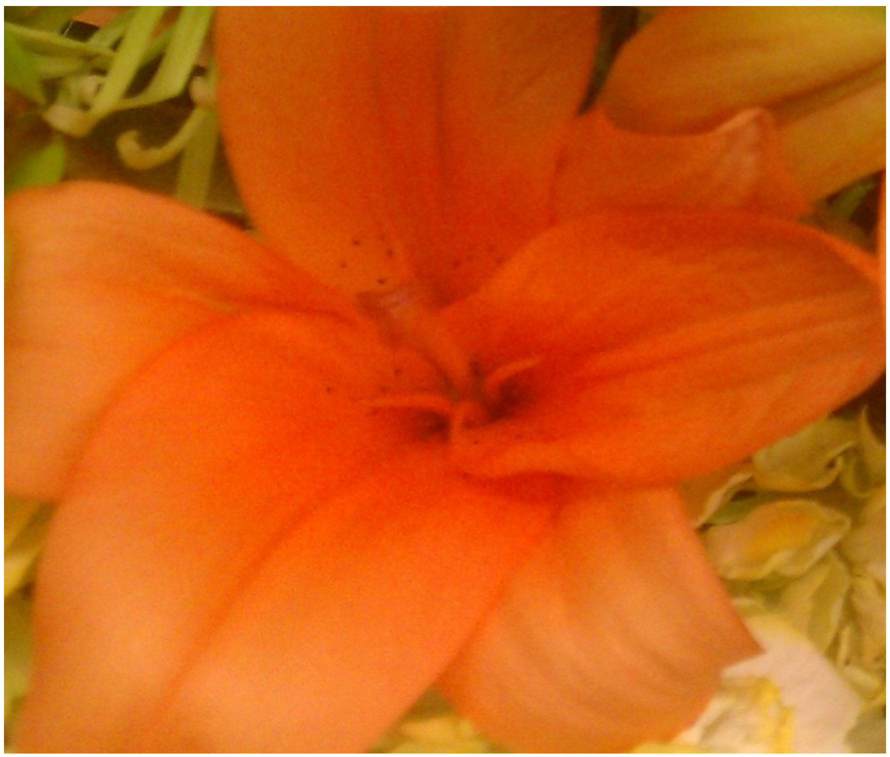
Active stereo & Volumetric stereo



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

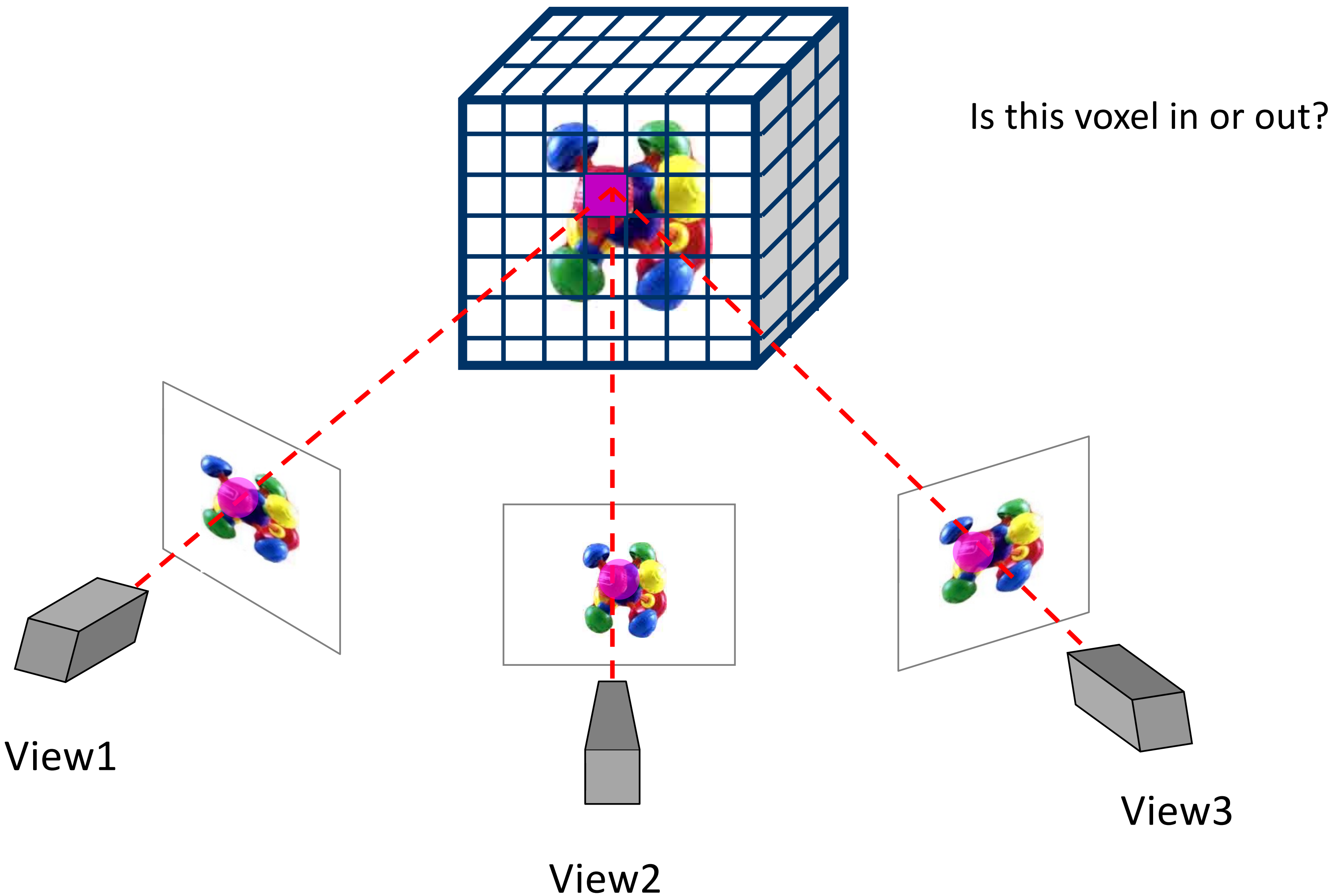
Voxel Coloring

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

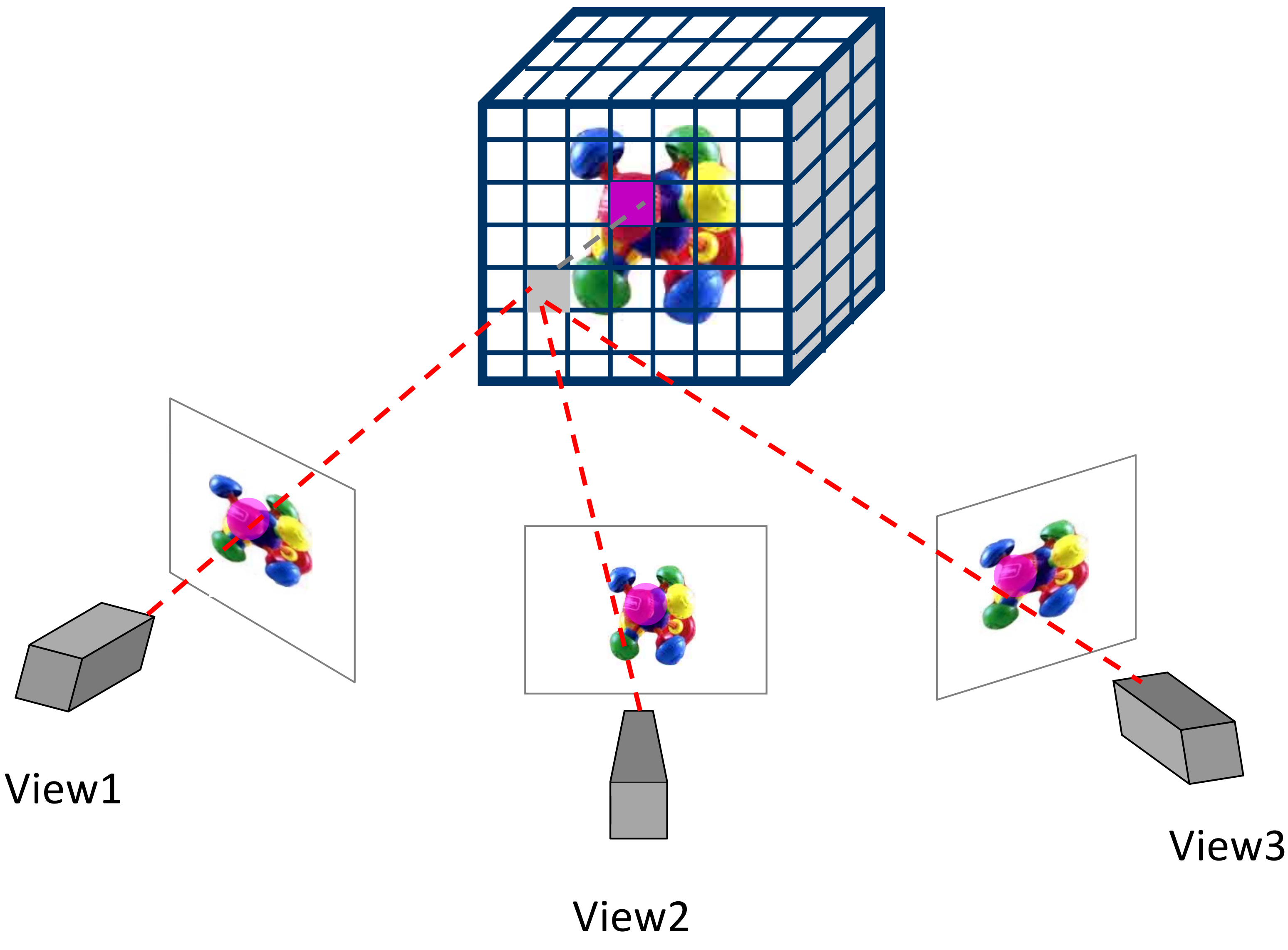


- Color/photo-consistency
- Jointly model structure and appearance

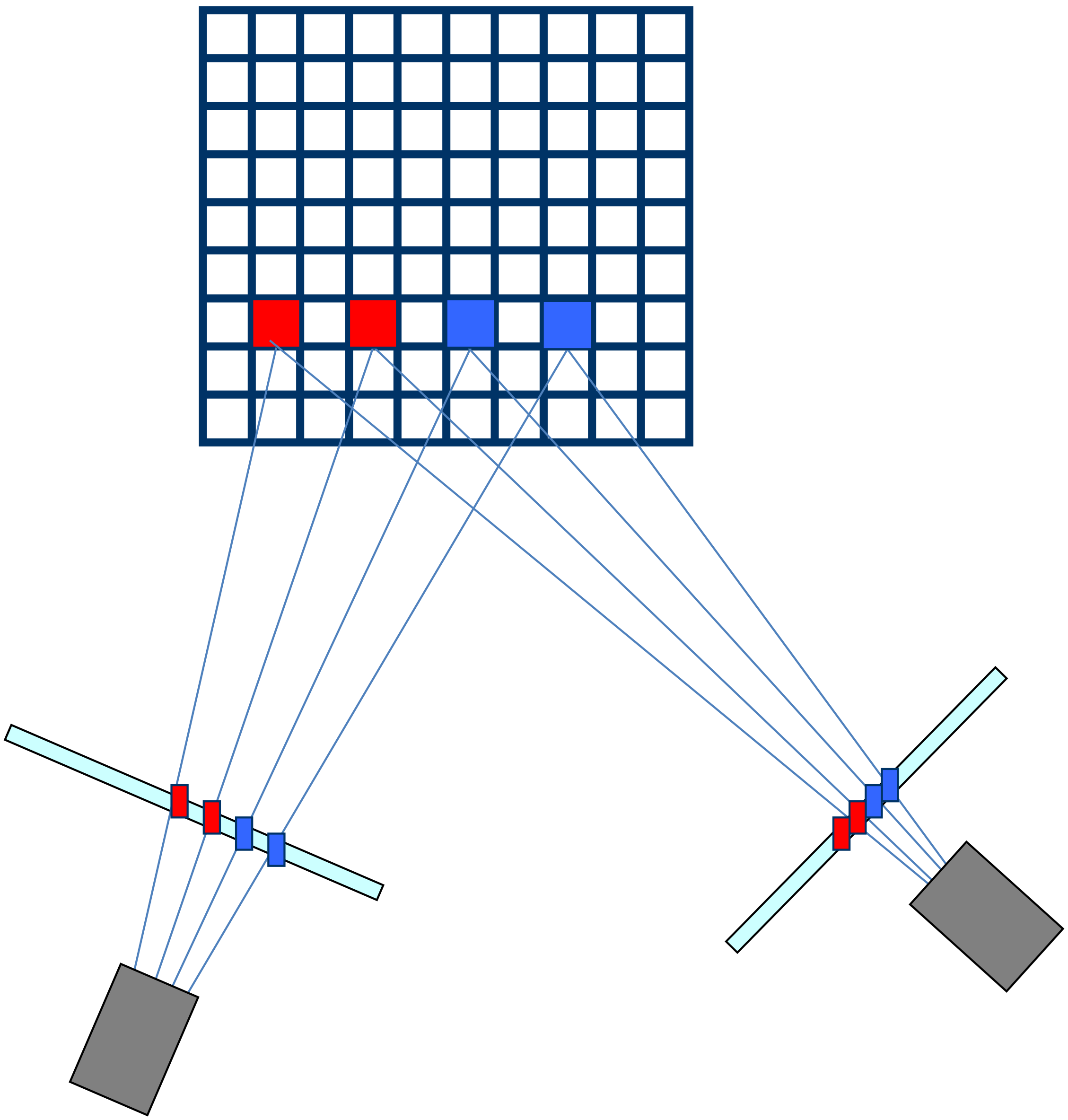
Basic Idea



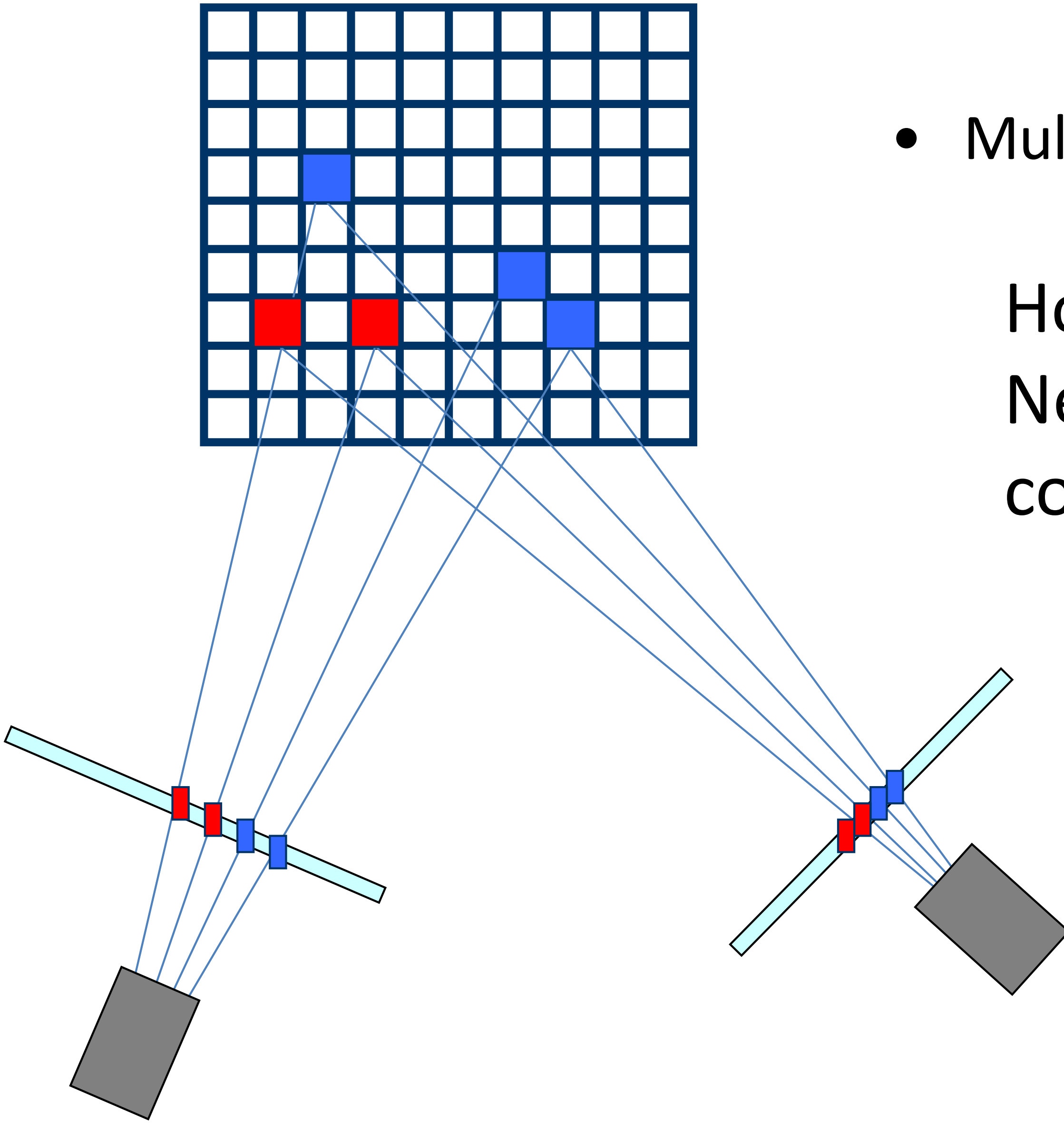
Basic Idea



Uniqueness



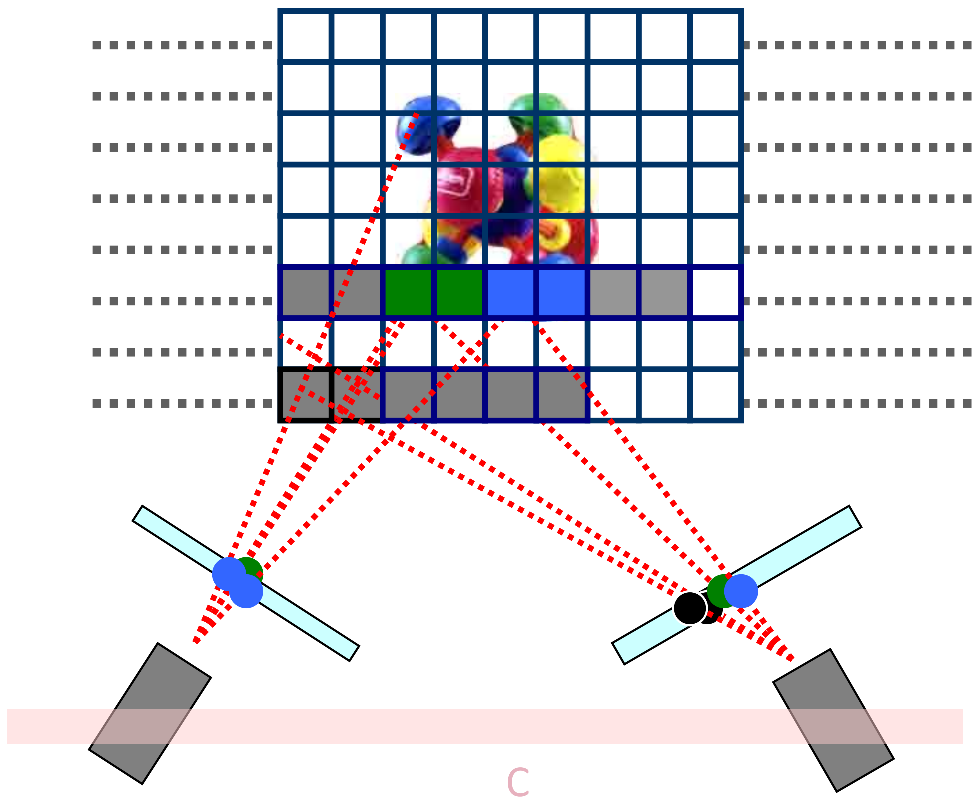
Uniqueness



- Multiple consistent scenes

How to fix this?
Need to use a visibility constraint

Algorithm for enforcing visibility constraints



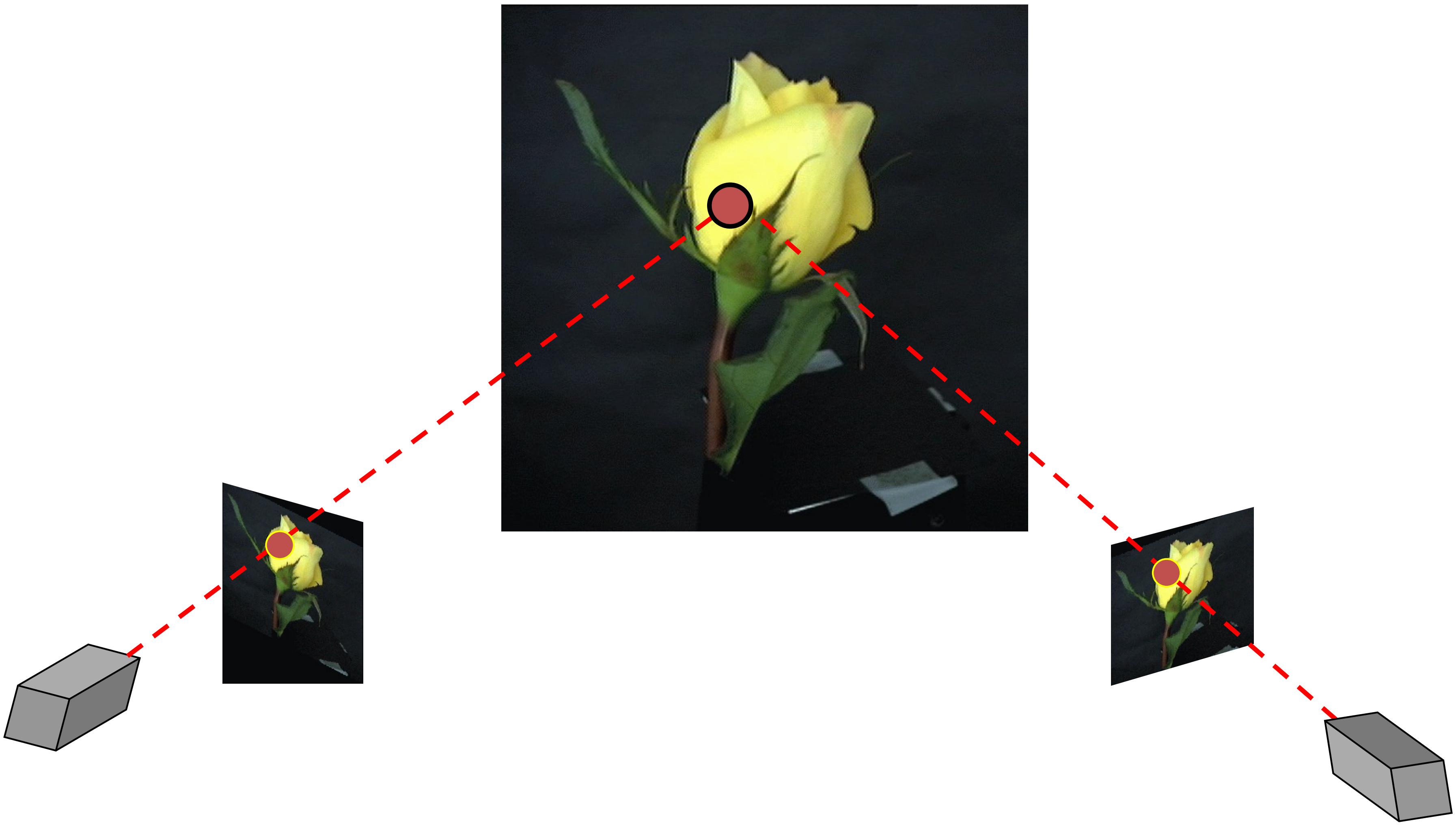
Algorithm Complexity

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

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

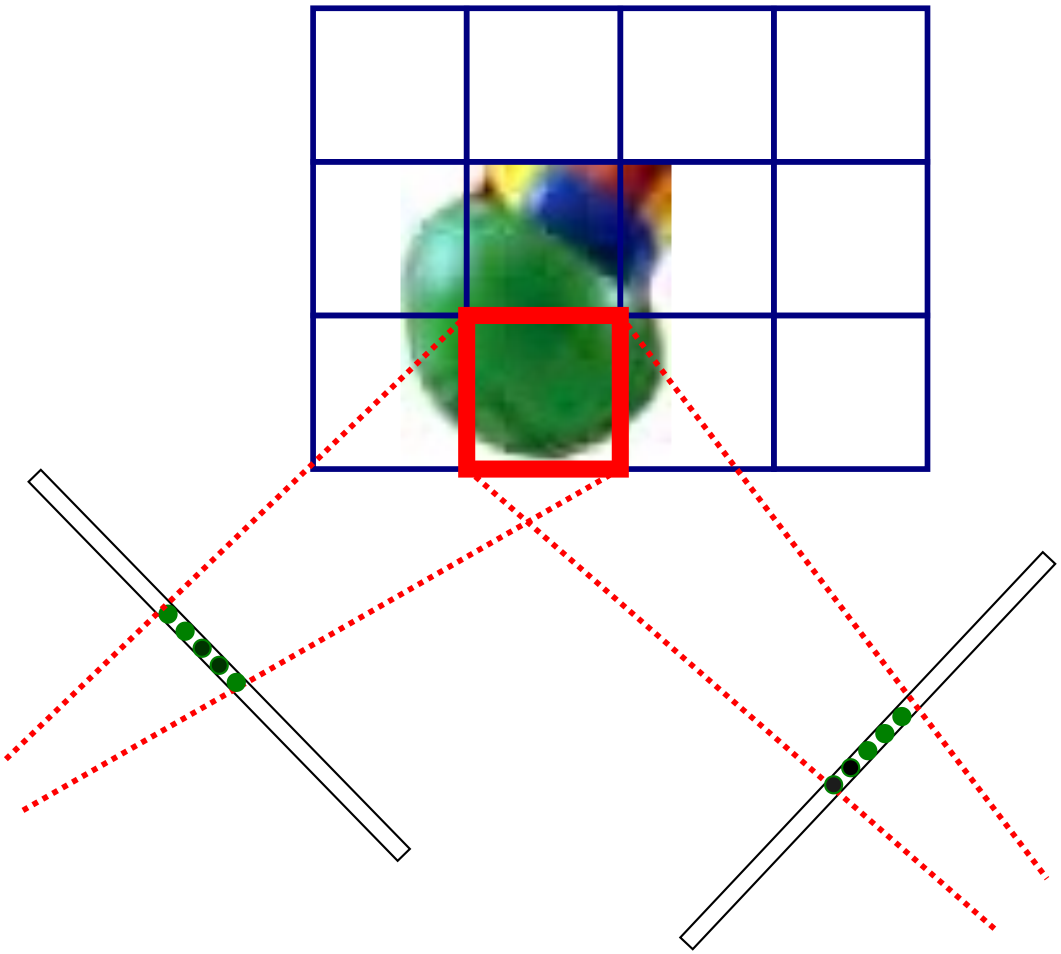
NOTE: not function of the number of colors

A Critical Assumption: Lambertian Surfaces

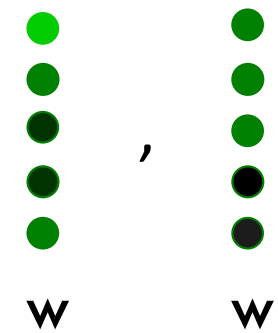


Non Lambertian Surfaces

Photoconsistency Test



C = corr (



)

$$C = \frac{(w-\overline{w})(w'-\overline{w}')}{\left\|(w-\overline{w})\right\|\left\|(w'-\overline{w}')\right\|}$$

$$\overline{w} = mean(w)$$

$$\overline{w}' = mean(w')$$

If $C > \lambda$ = threshold ➔ voxel consistent

Experimental Results

Dinosaur

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

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

Experimental Results

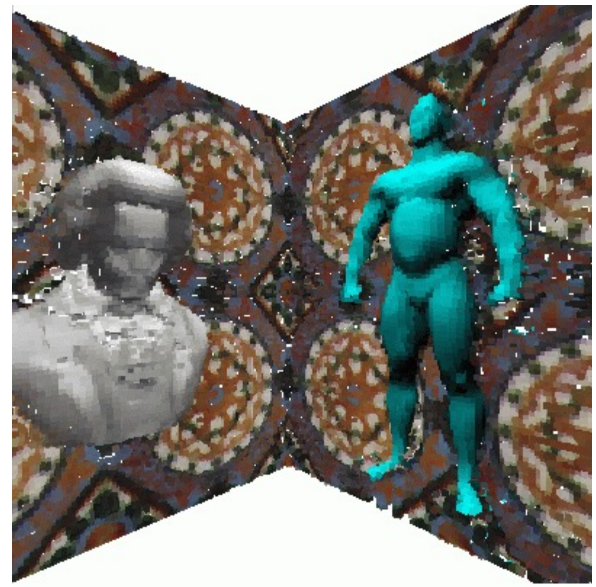
Flower

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

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

Experimental Results

Room + weird people



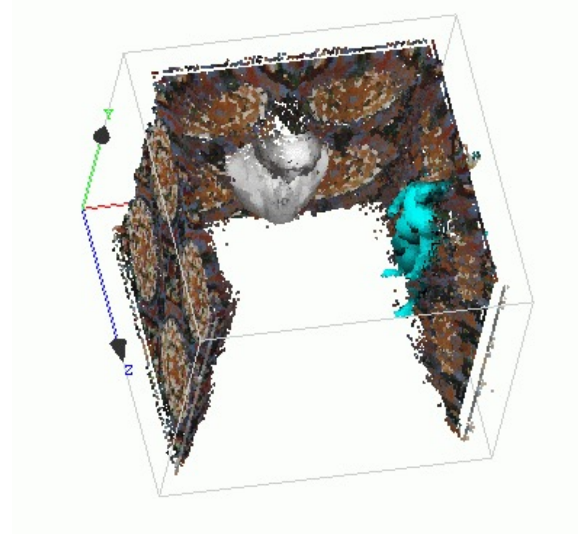


Image source: http://www.cs.cmu.edu/~seitz/vcolor.html

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