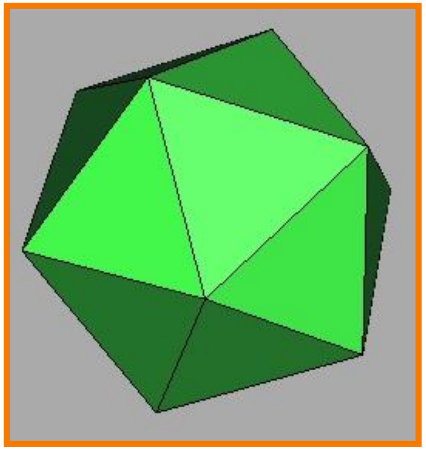
3D Object Representations

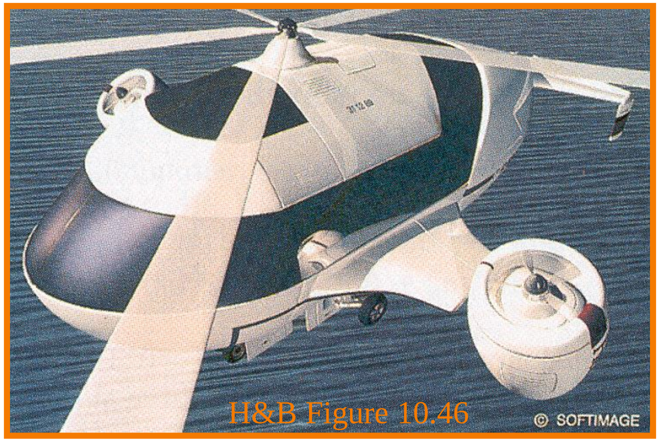
COS 526, Fall 2014

Princeton University

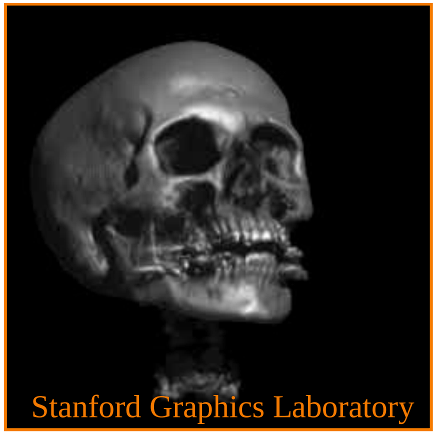
3D Object Representations

- How do we ...
  - Represent 3D objects in a computer?
  - Acquire computer representations of 3D objects?
  - Manipulate computer representations of 3D objects?





H&B Figure 10.46



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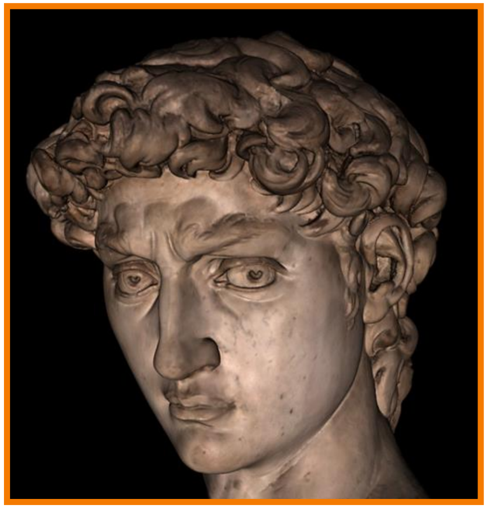
3D Object Representations

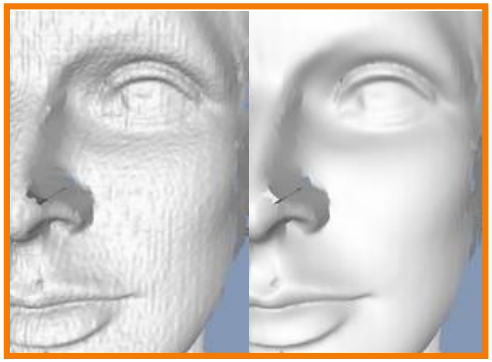
What can we do with a 3D object representation?

- Edit
- Transform
- Smooth
- Render
- Animate
- Morph
- Compress
- Transmit
- Analyze
- etc.

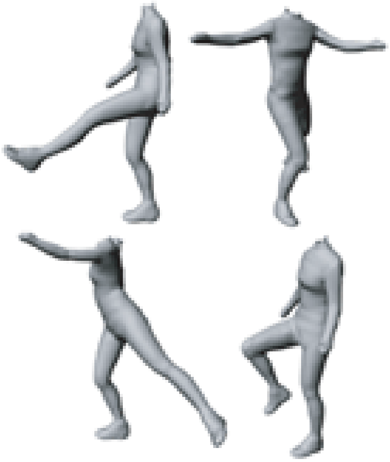


Digital Michelangelo

Pirates of the Caribbean



Thouis “Ray” Jones

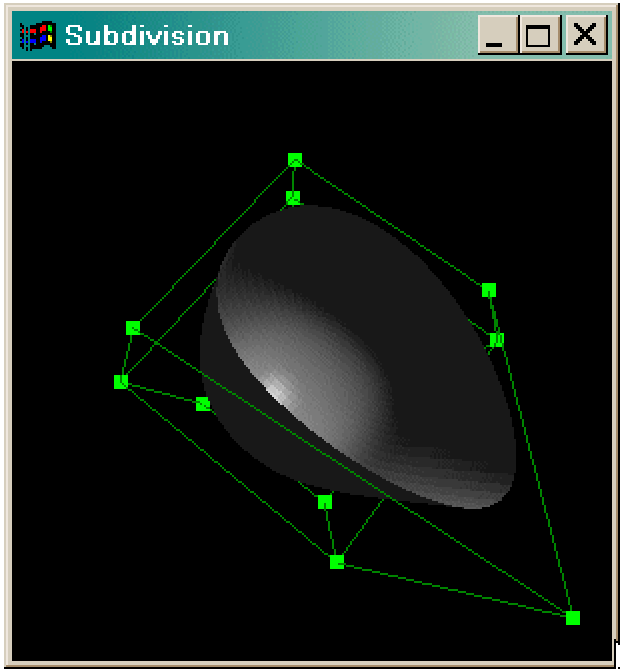


Sand et al.

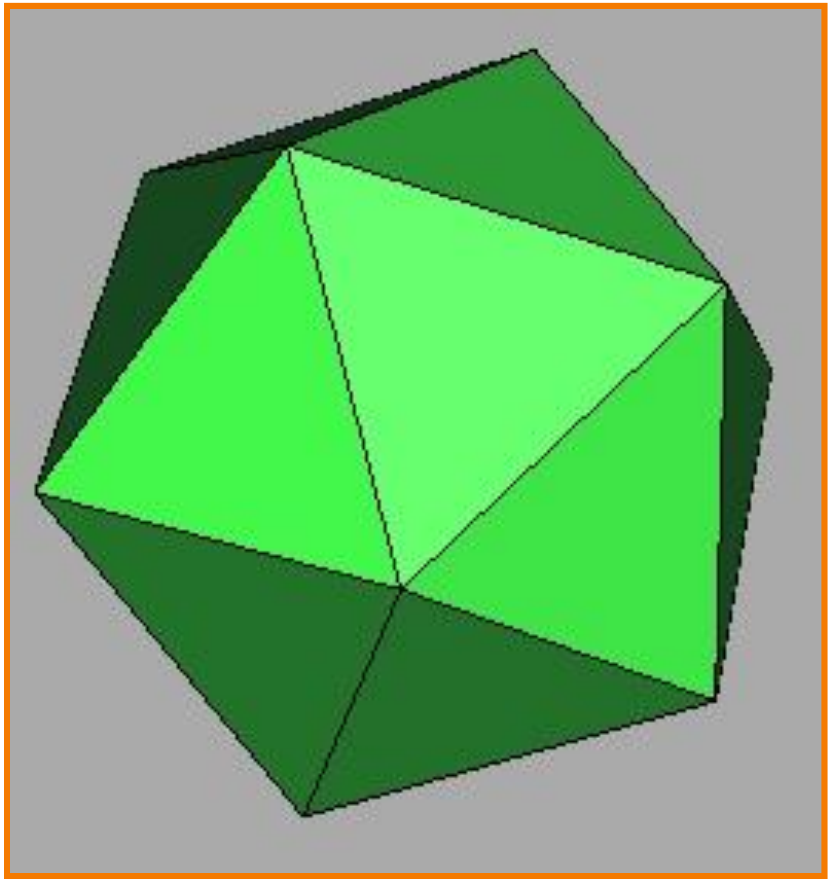
3D Object Representations

Desirable properties depend on intended use

- Easy to acquire
- Accurate
- Concise
- Intuitive editing
- Efficient editing
- Efficient display
- Efficient intersections
- Guaranteed validity
- Guaranteed smoothness
- etc.

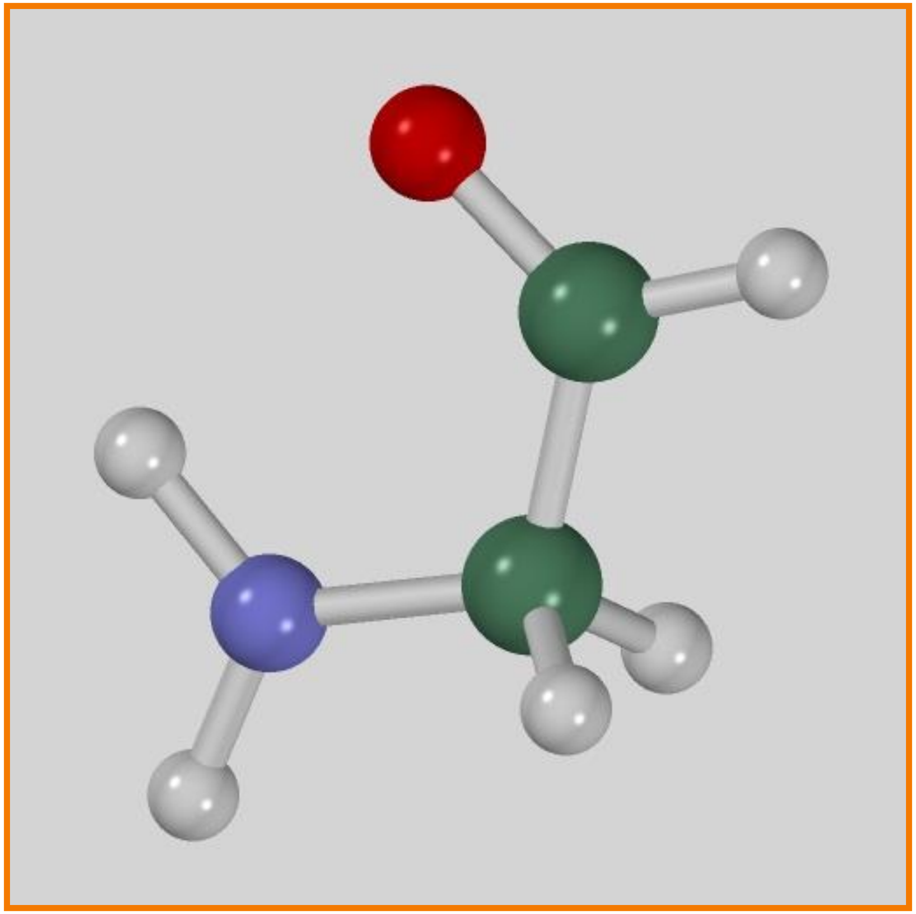


3D Object Representations



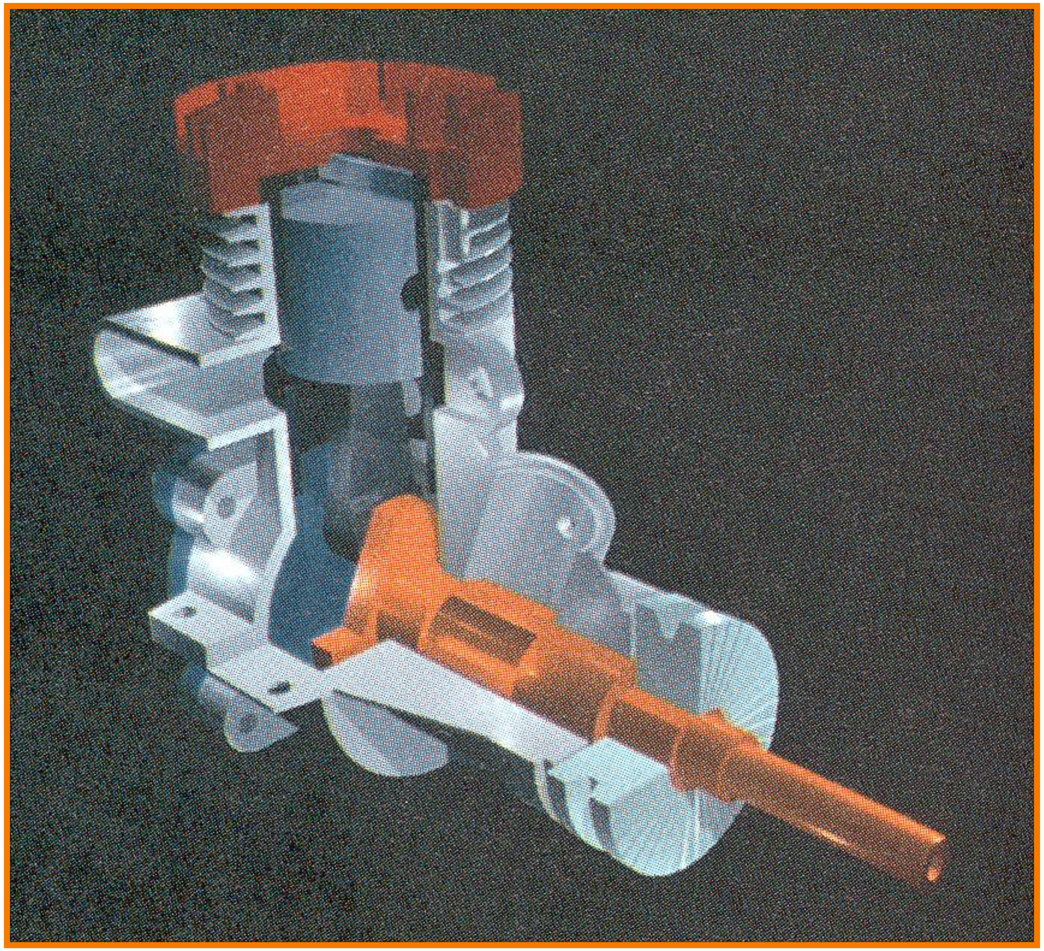
How can this object be represented in a computer?

3D Object Representations



How about this one?

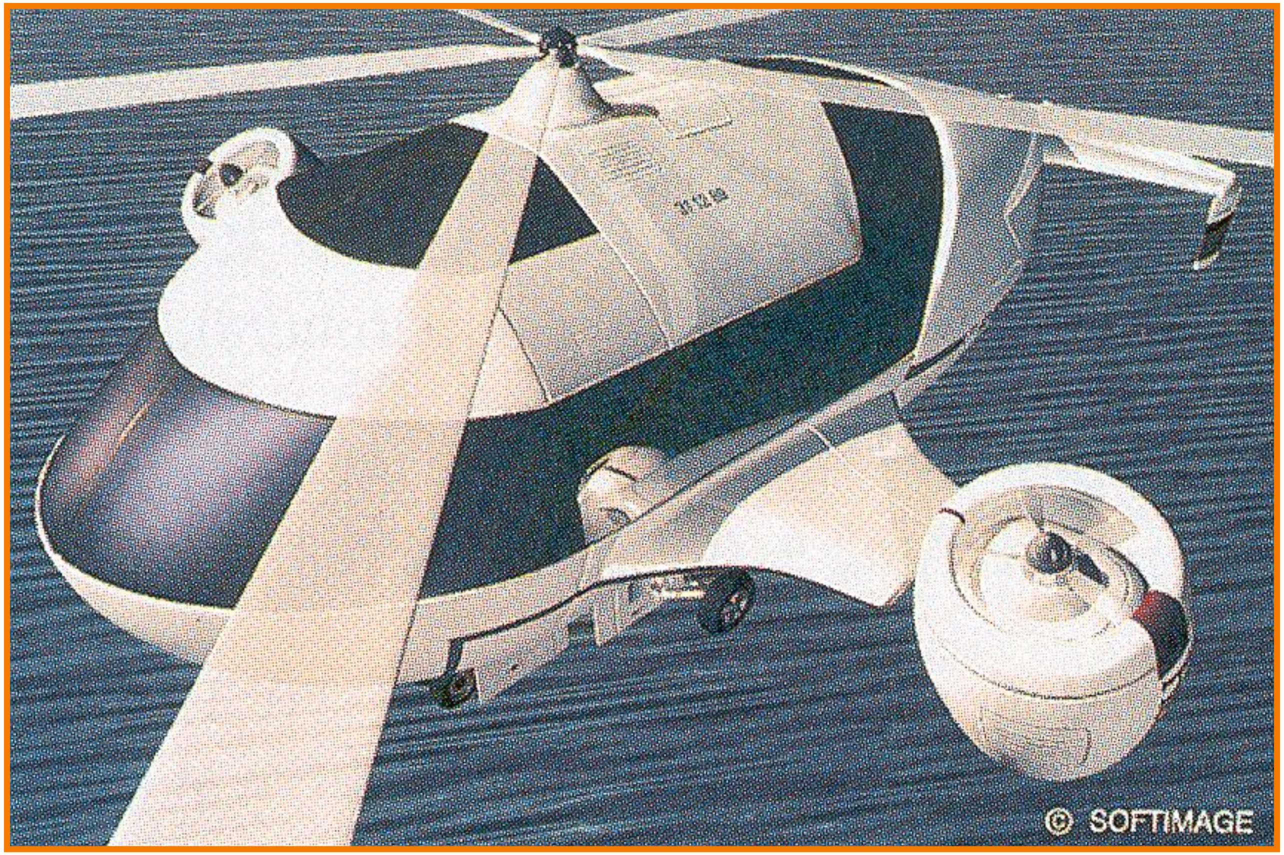
3D Object Representations



H&B Figure 9.9

This one?

3D Object Representations



H&B Figure 10.46

This one?

3D Object Representations

This one?

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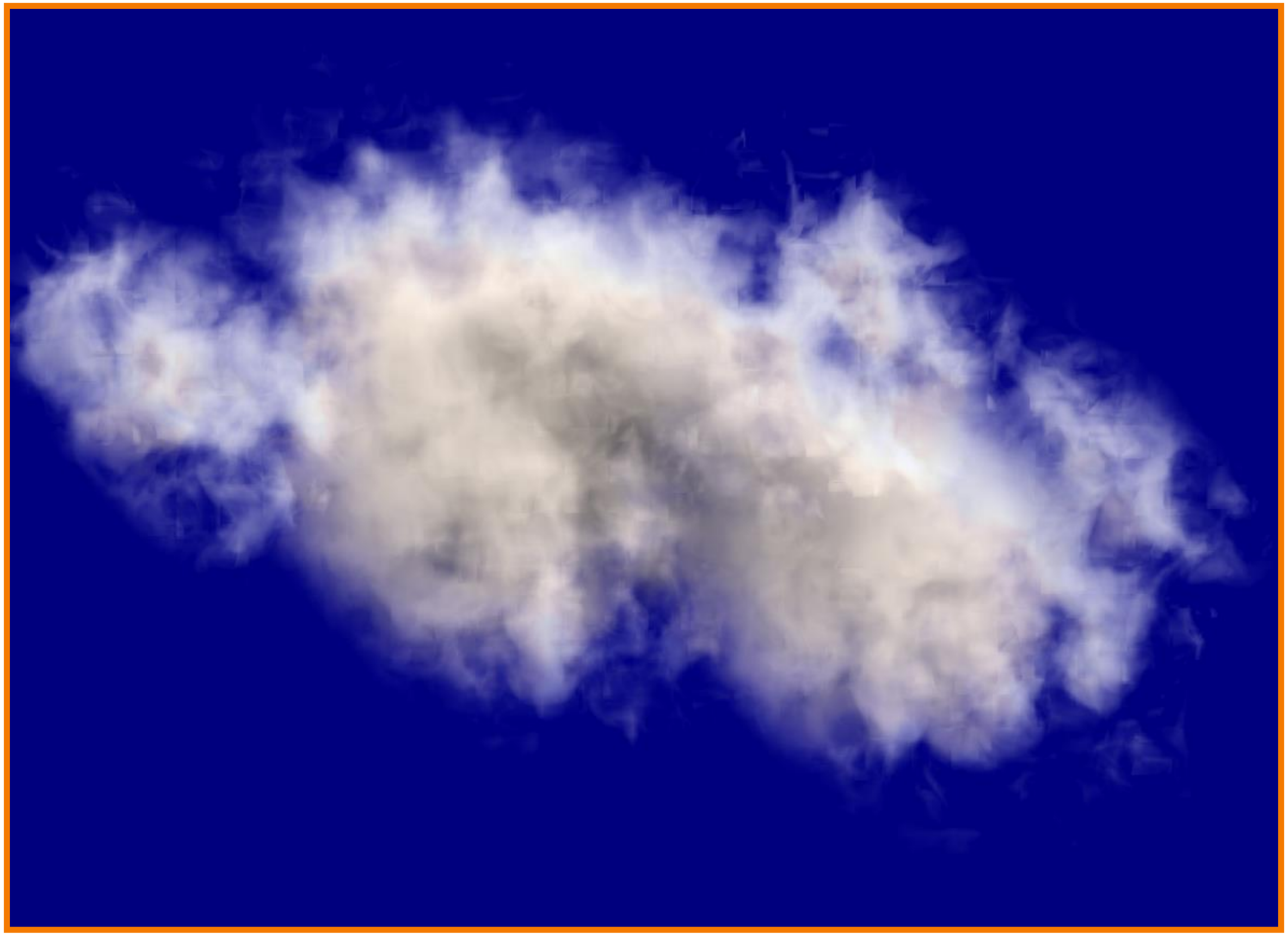
3D Object Representations



This one?

3D Object Representations

- Points
  - Range image
  - Point cloud
- Surfaces
  - Polygonal mesh
  - Subdivision
  - Parametric
  - Implicit
- Solids
  - Voxels
  - BSP tree
  - CSG
  - Sweep
- High-level structures
  - Scene graph
  - Application specific

Equivalence of Representations

- Thesis:
  - Each representation has enough expressive power to model the shape of any geometric object
  - It is possible to perform all geometric operations with any fundamental representation
- Analogous to Turing-equivalence
  - Computers and programming languages are Turing-equivalent, but each has its benefits…

Why Different Representations?

Efficiency for different tasks

- Acquisition
- Rendering
- Manipulation
- Animation
- Analysis

Data structures determine algorithms

Why Different Representations?

- Efficiency
  - Representational complexity (e.g. volume vs. surface)
  - Computational complexity (e.g. $O(n^2)$ vs $O(n^3)$)
  - Space/time trade-offs (e.g. z-buffer)
  - Numerical accuracy/stability (e.g. degree of polynomial)
- Simplicity
  - Ease of acquisition
  - Hardware acceleration
  - Software creation and maintenance
- Usability
  - Designer interface vs. computational engine

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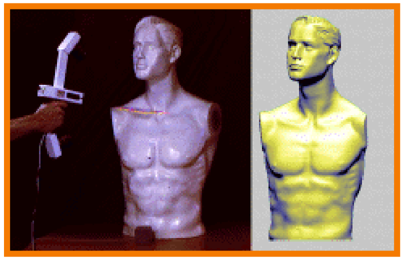
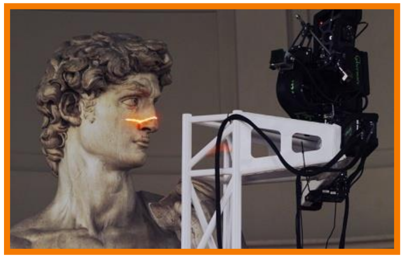
Range Image

Set of 3D points mapping to pixels of depth image

- Can be acquired from range scanner



Cyberware



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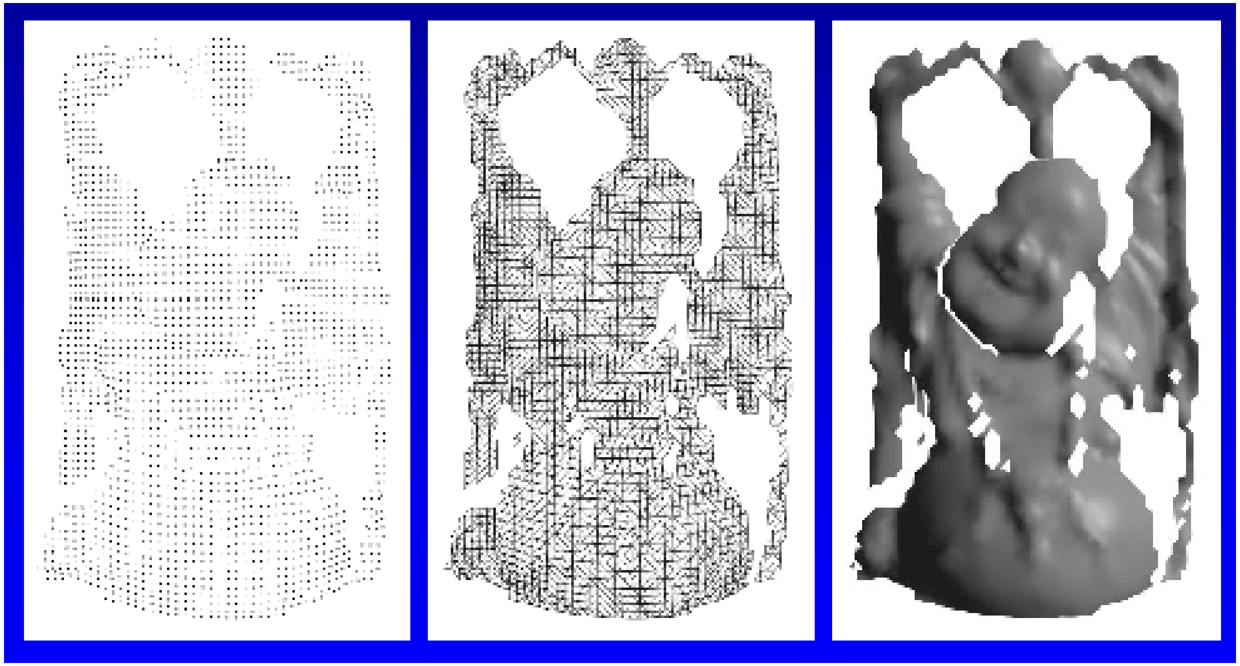

Range Image   Tesselation   Range Surface

Brian Curless
SIGGRAPH 99
Course #4 Notes

Point Cloud

Unstructured set of 3D point samples

- Acquired from range finder, computer vision, etc

Polhemus

Microscribe-3D

Hoppe

Hoppe

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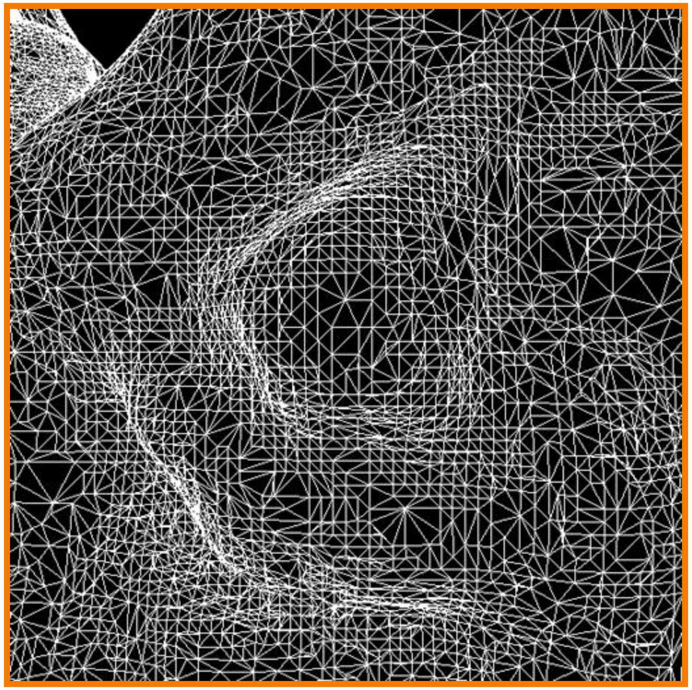
Polygonal Mesh

Connected set of polygons (usually triangles)



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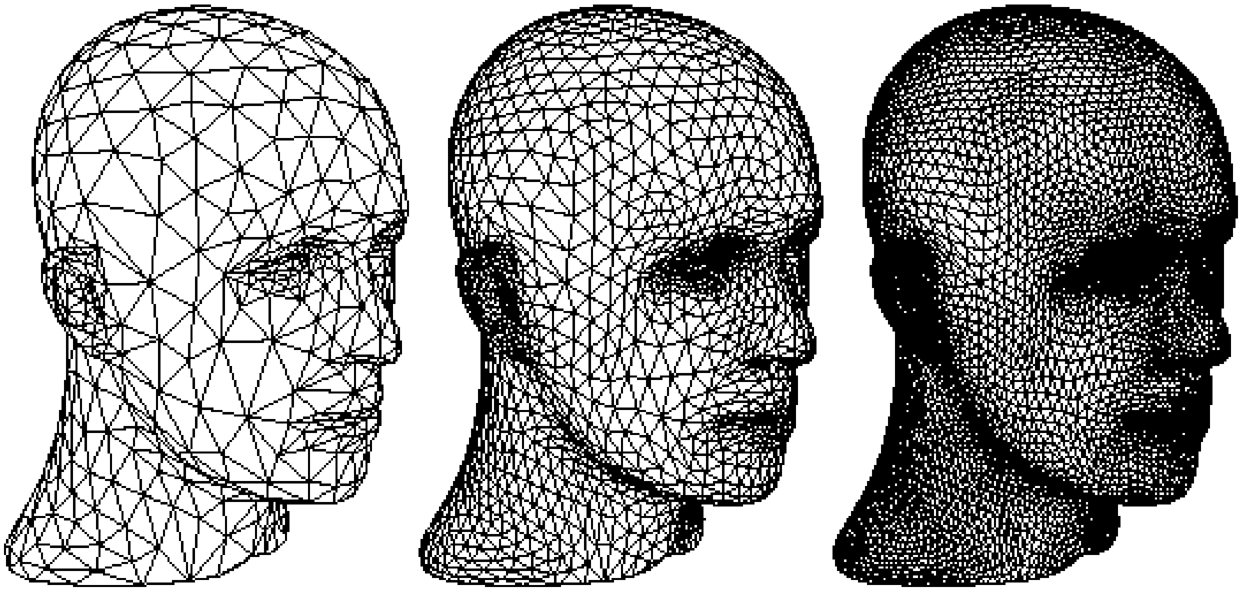
Subdivision Surface

Coarse mesh & subdivision rule

- Smooth surface is limit of sequence of refinements

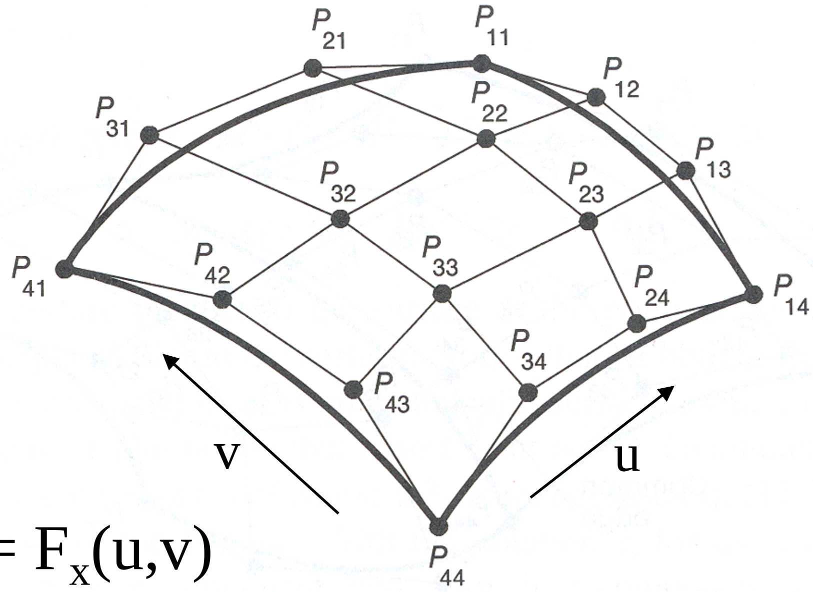


Zorin & Schroeder
SIGGRAPH 99
Course Notes

Parametric Surface

Tensor-product spline patches

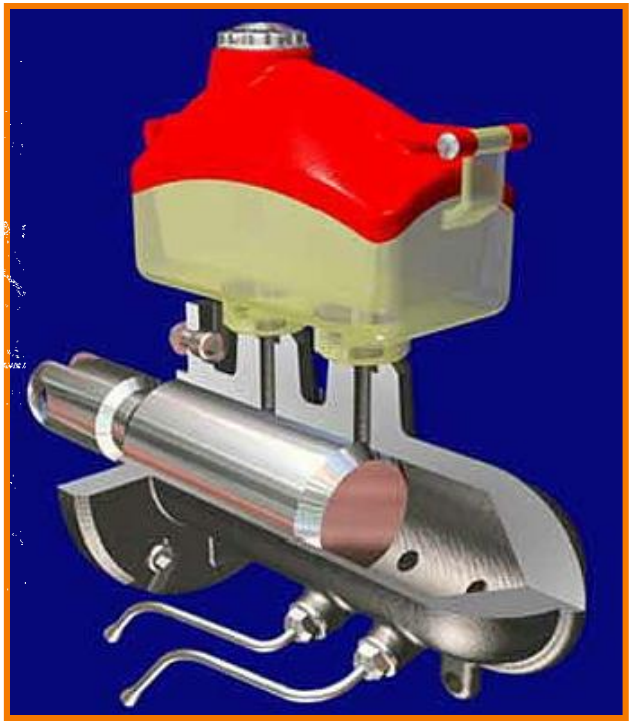
- Each patch is parametric function
- Careful constraints to maintain continuity



$x = F_x(u,v)$

$y = F_y(u,v)$

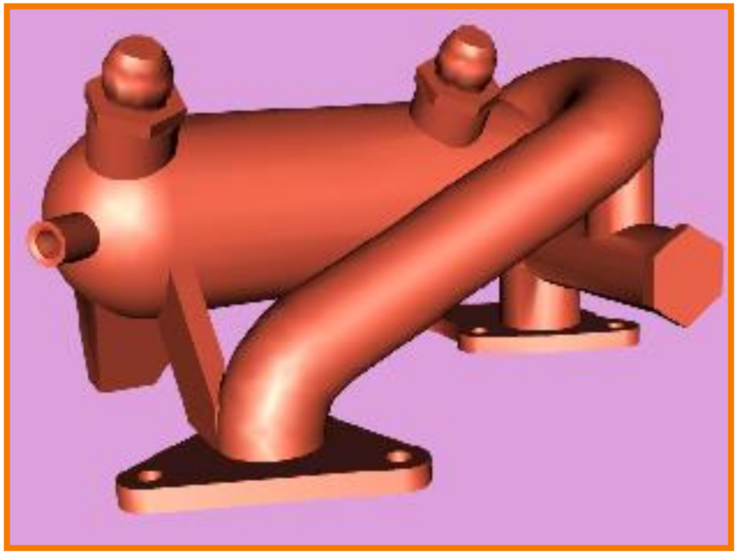
$z = F_z(u,v)$



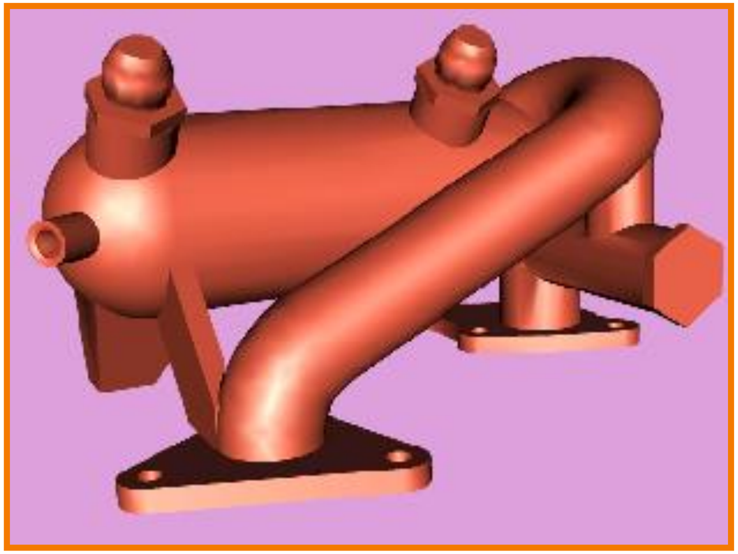
FvDFH Figure 11.44

Implicit Surface

Set of all points satisfying: $F(x,y,z) = 0$



Polygonal Model



Implicit Model

Bill Lorensen
SIGGRAPH 99
Course #4 Notes

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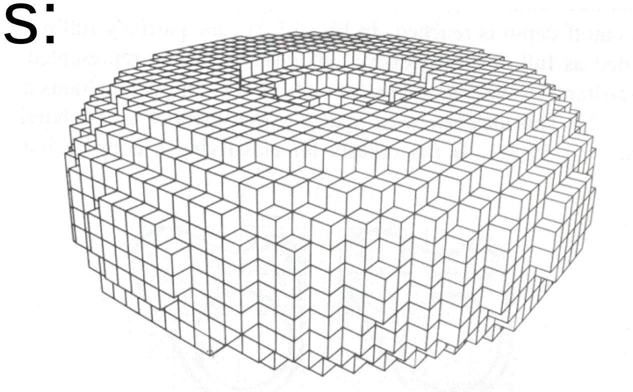
Voxel grid

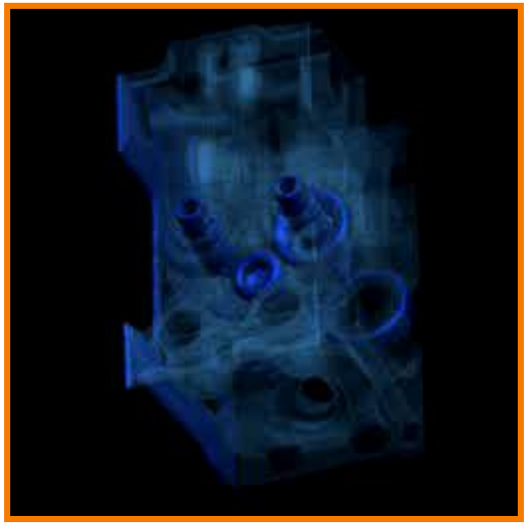
Uniform volumetric grid of samples:

- Occupancy
  (object vs. empty space)
- Density
- Color
- Other function
  (speed, temperature, etc.)

- Often acquired via simulation or from CAT, MRI, etc.



FvDFH Figure 12.20



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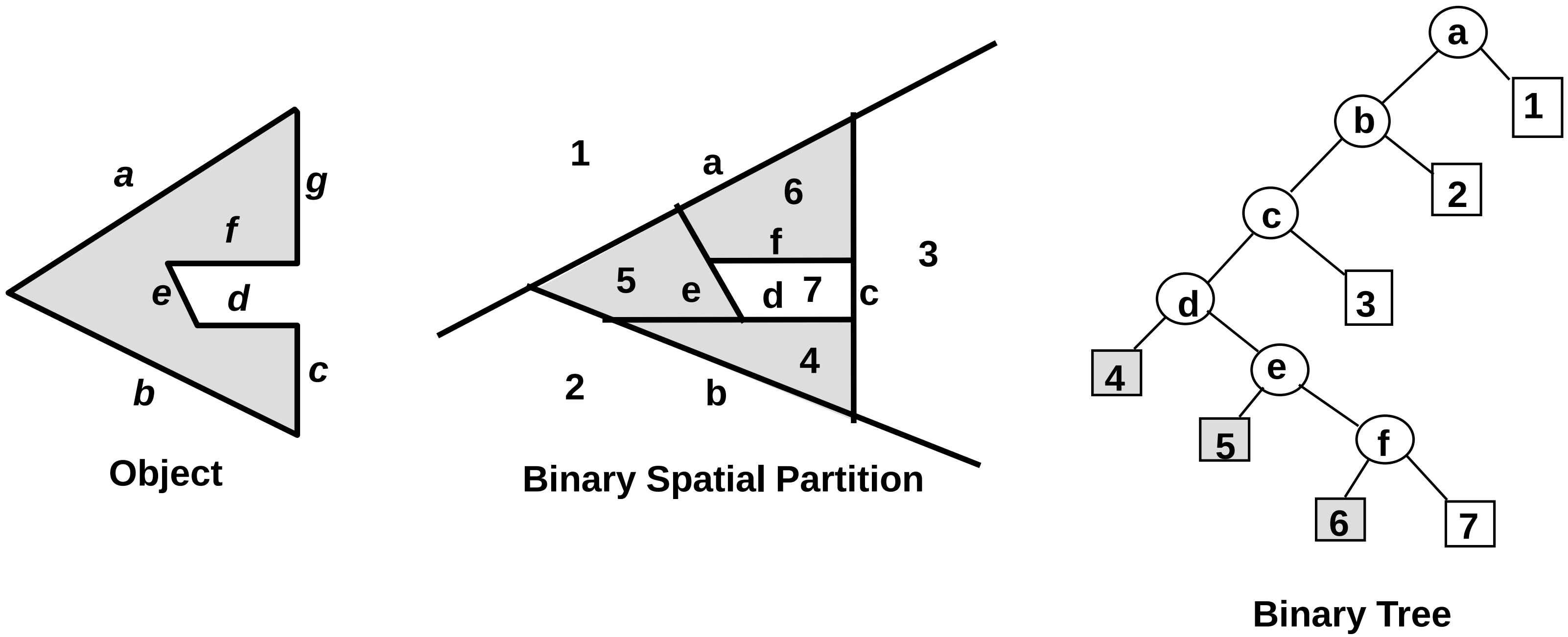
BSP Tree

Hierarchical **B**inary **S**pace **P**artition with solid/empty cells labeled

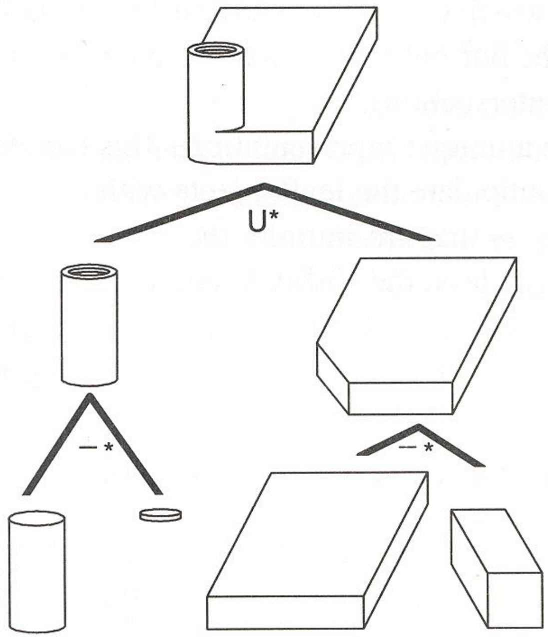
- Constructed from polygonal representations



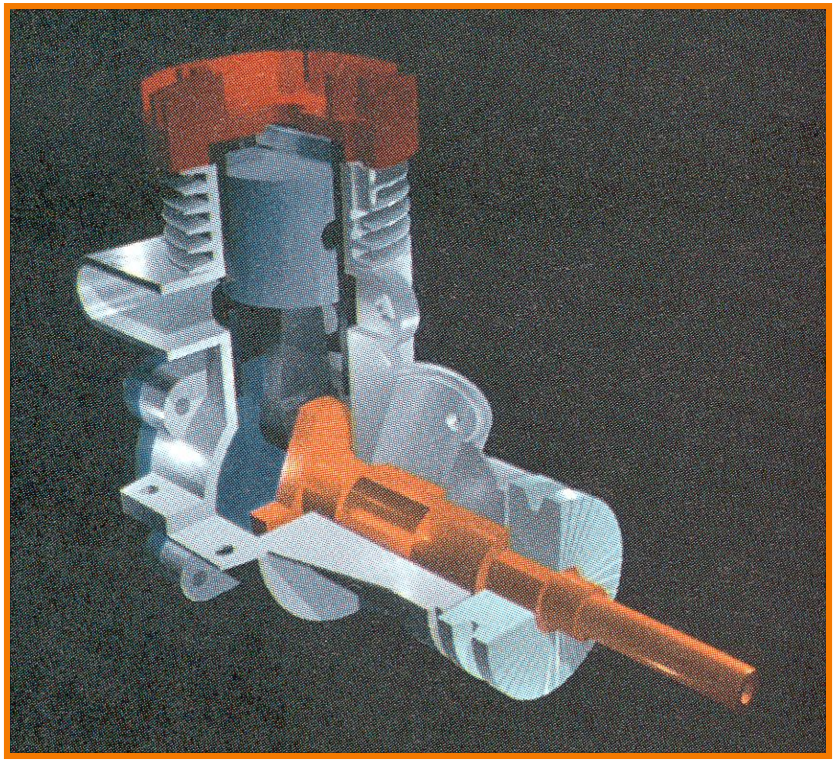
Naylor

CSG

Constructive **S**olid **G**eometry: set operations (union, difference, intersection) applied to simple shapes



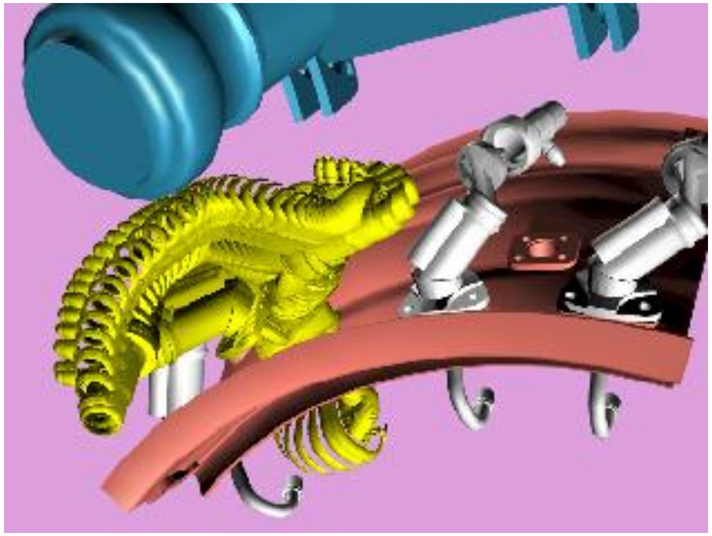
FvDFH Figure 12.27



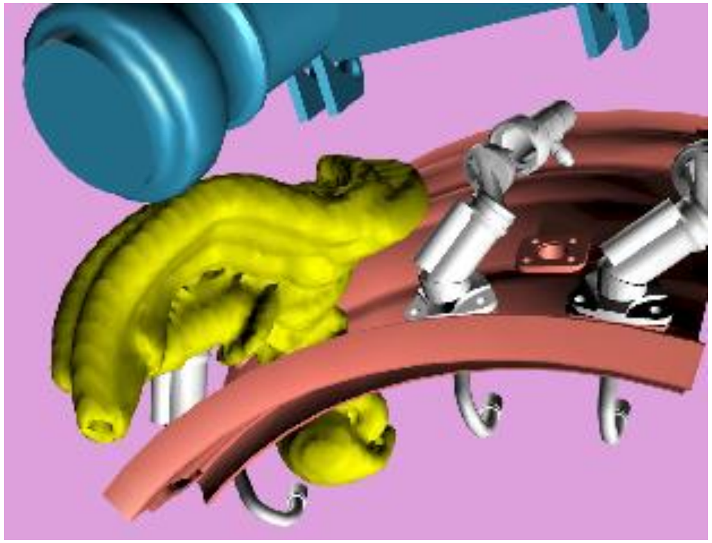
H&B Figure 9.9

Sweep

Solid swept by curve along trajectory



Removal Path



Sweep Model

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SIGGRAPH 99
Course #4 Notes

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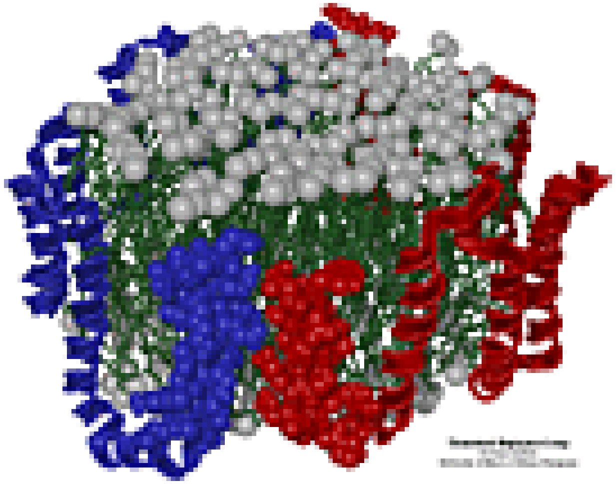
Scene Graph

Union of objects at leaf nodes

Bell Laboratories

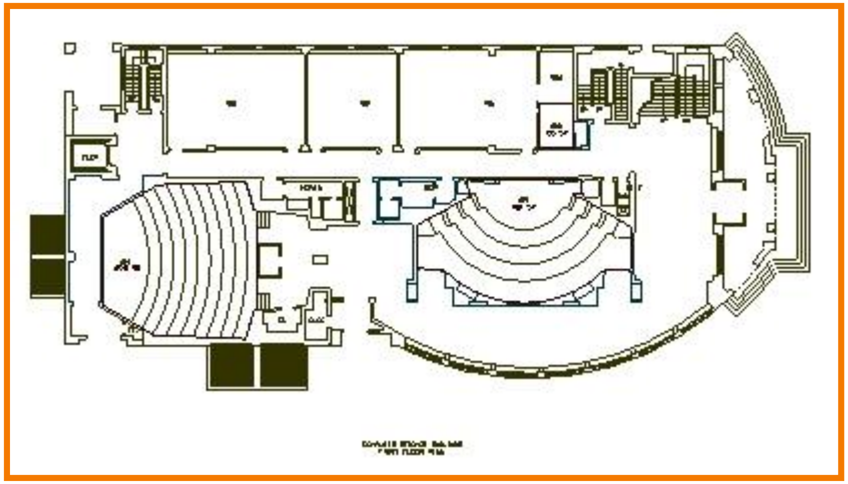
avalon.viewpoint.com

Application Specific



Apo A-1

(Theoretical Biophysics Group, University of Illinois at Urbana-Champaign)



Architectural Floorplan

(CS Building, Princeton University)

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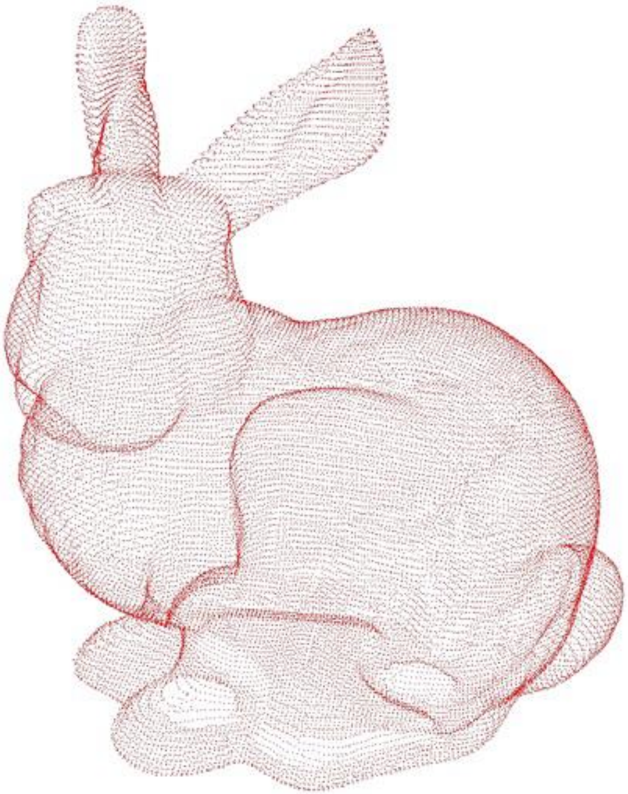
Point Clouds

Represent surface by a set of points

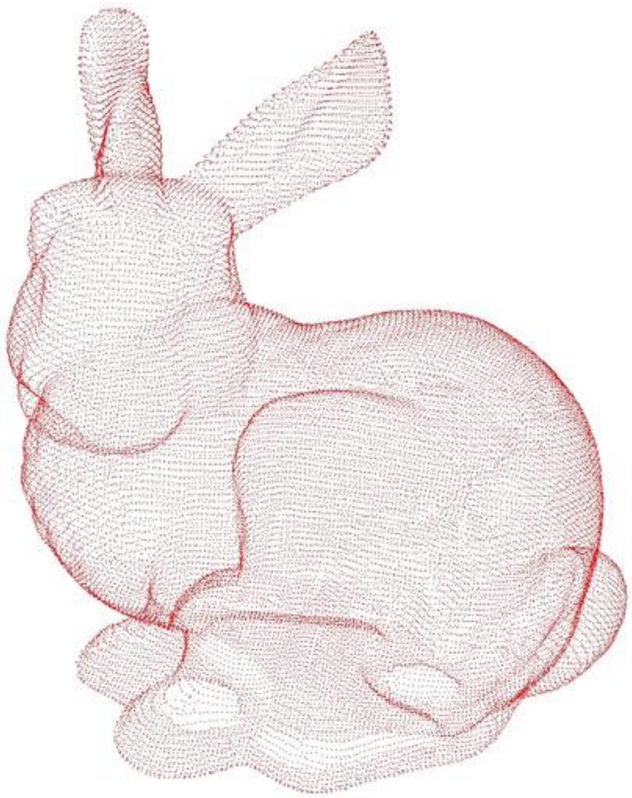
- Each point is represented by (x, y, z)
- No connectivity between points



Point Clouds

Properties?

- Easy to acquire
- Accurate
- Concise
- Intuitive editing
- Efficient editing
- Efficient display
- Efficient intersections
- Guaranteed validity
- Guaranteed smoothness
- etc.



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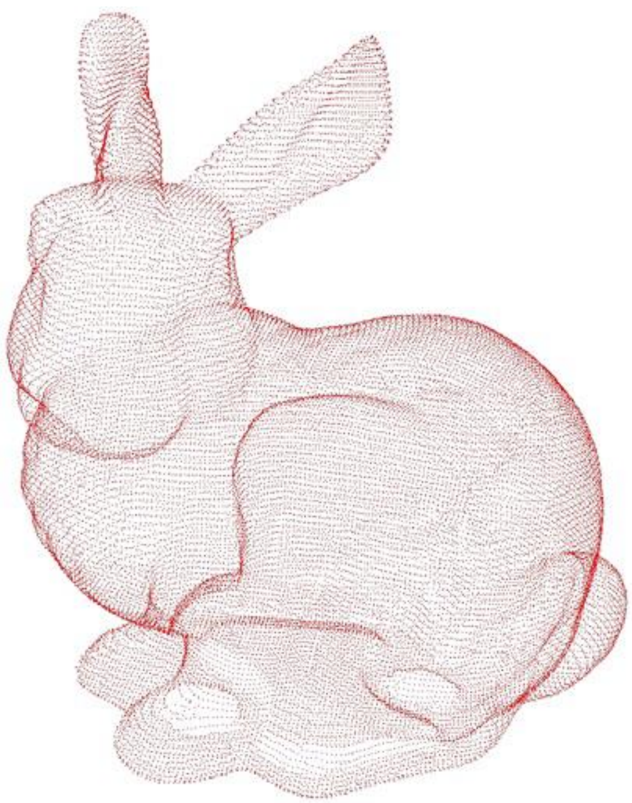


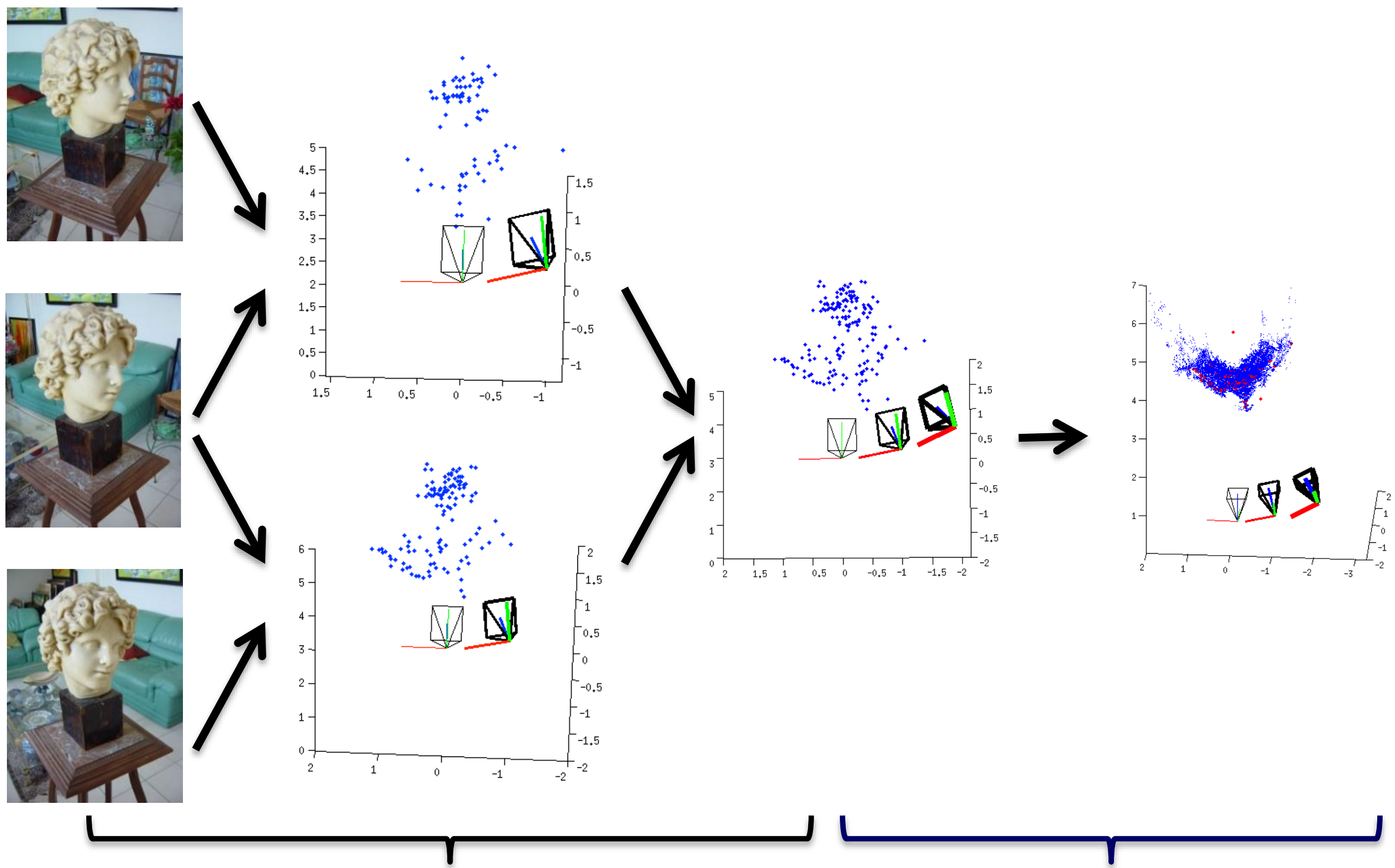
Point Cloud Acquisition

Passive
- Structure from motion

Active
- Touch probes
- Reflectance scanning
  - Time of flight
  - Triangulation
    - Laser
    - Structured light

Structure from Motion

Solve for 3D structure of pixel correspondences in multiple images



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

Structure from Motion

Advantages:

- Has been demonstrated for large photo collections
- Passive

Disadvantages:

- Only works for points where pixel correspondences can be found

Touch Probes

Capture points on object with tracked tip of probe

- Physical contact with the object
- Manual or computer-guided

Touch Probes

Advantages:

- Can be very precise
- Can scan **any** solid surface

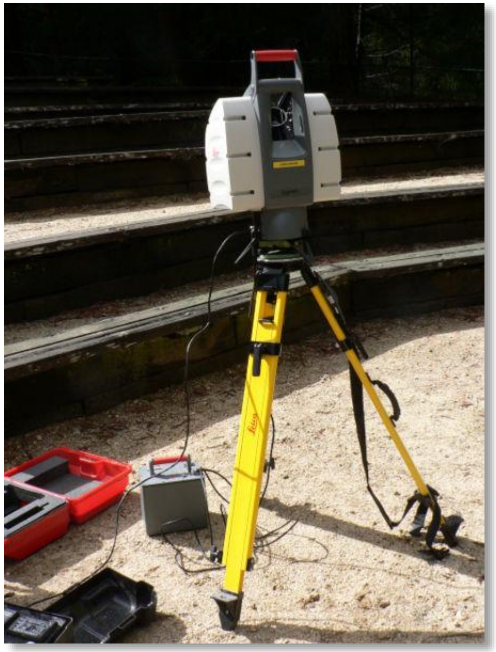
Disadvantages:

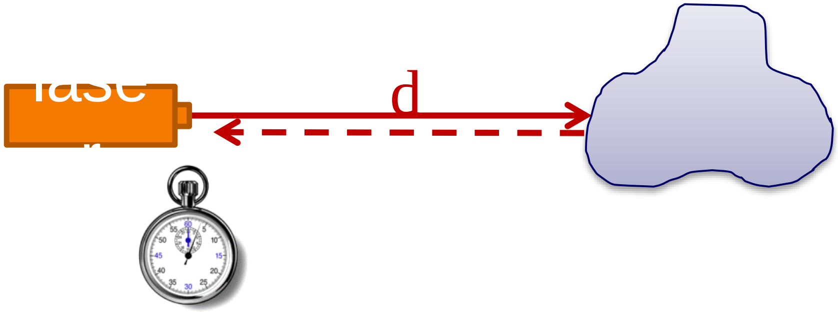
- Slow, small scale
- Can’t use on fragile objects

Time of Flight Laser Scanning

Measures the time it takes the laser beam to hit the object and come back

e.g., LIDAR





$d = 0.5\ t \cdot c$

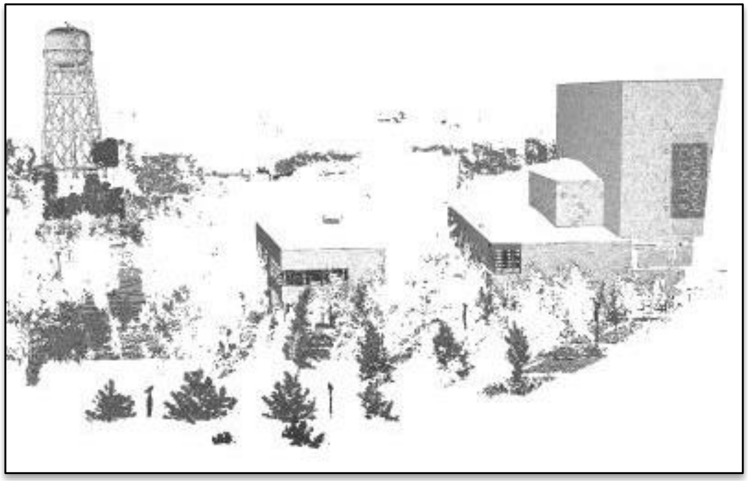
Time of Flight Laser Scanning

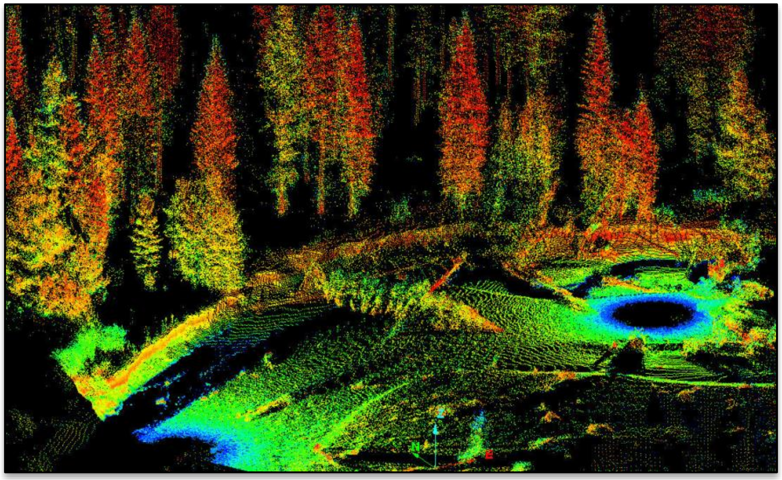
Advantages

- Accommodates large range – up to several miles (suitable for buildings, rocks)

Disadvantages

- Lower accuracy

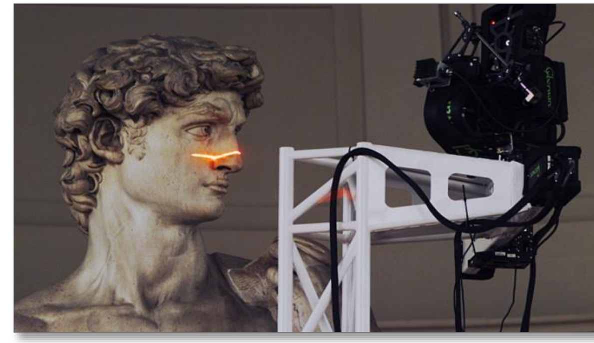




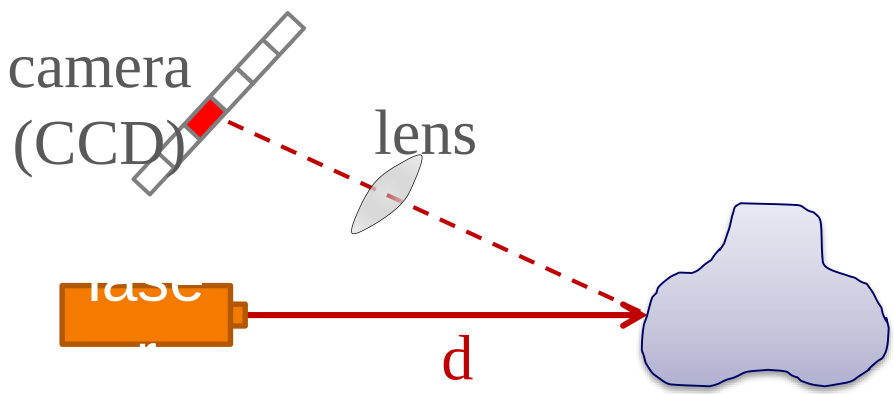
Triangulation Laser Scanning

System includes calibrated laser beam and camera

- Laser dot is photographed



The location of the dot in the image allows triangulation: tells distance to the object



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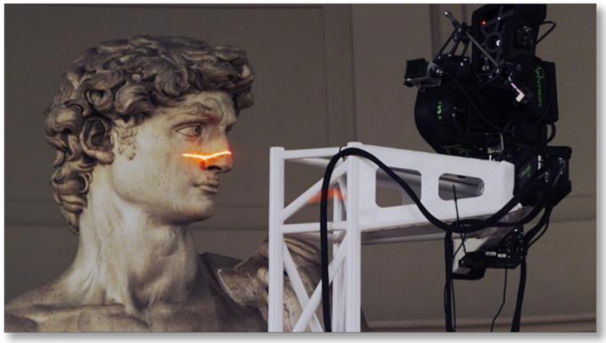

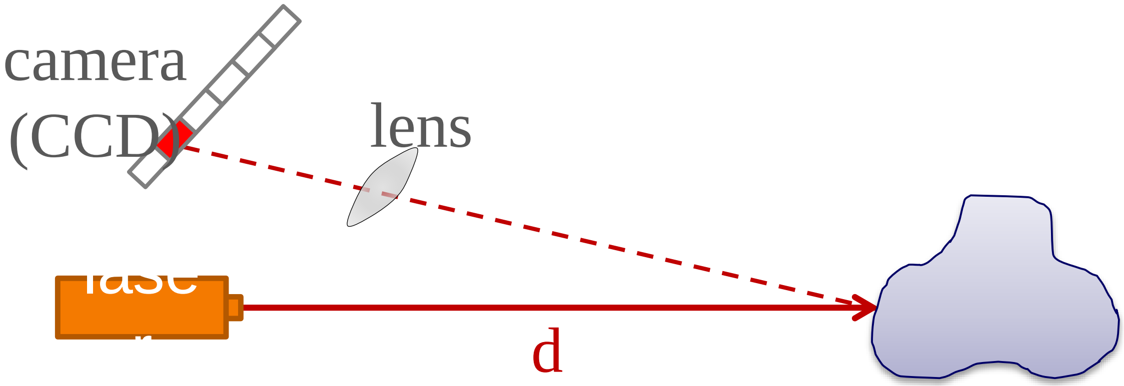

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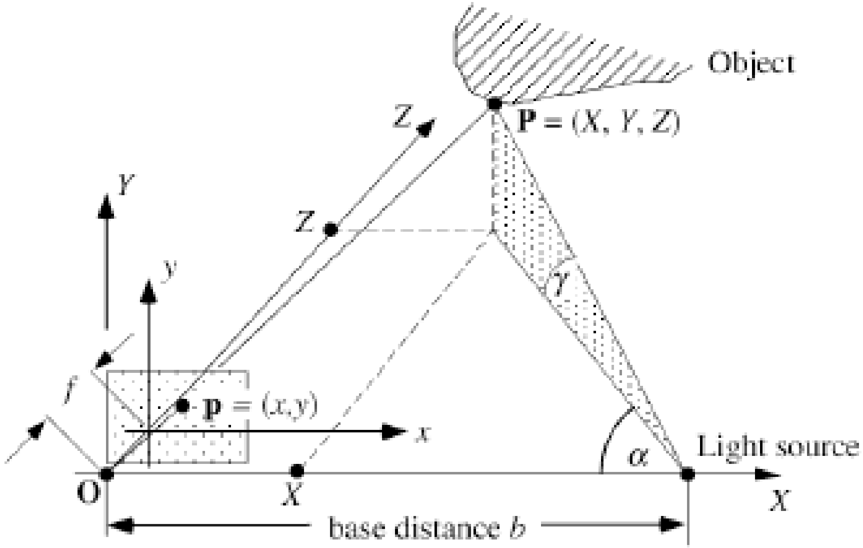


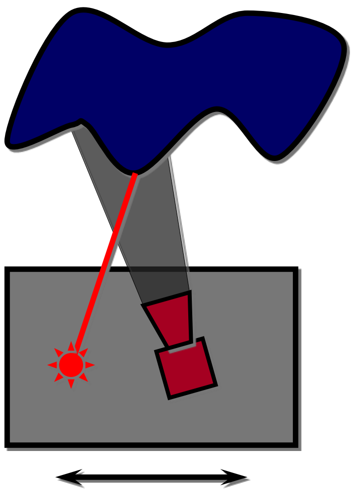
The ray theorem (of central projection) tells us that $\frac{X}{x} = \frac{Z}{f} = \frac{Y}{y}$, and from the trigonometry of right triangles we know that $\tan\alpha = \frac{Z}{b-X}$. It follows that

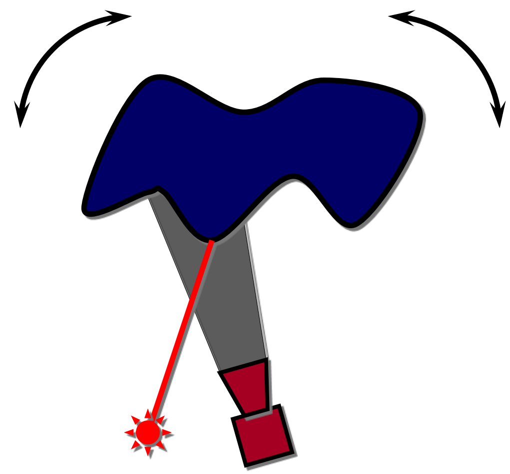
$$Z = \frac{X}{x} \cdot f = \tan\alpha \cdot (b - X) \quad \text{and} \quad X \cdot \left(\frac{f}{x} + \tan\alpha\right) = \tan\alpha \cdot b$$

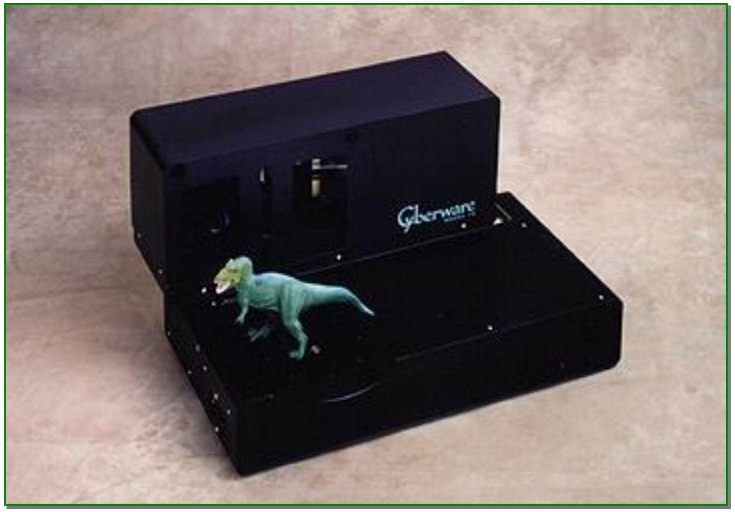
The solution is

$$X = \frac{\tan\alpha \cdot b \cdot x}{f + x \cdot \tan\alpha}, \; Y = \frac{\tan\alpha \cdot b \cdot y}{f + x \cdot \tan\alpha}, \; Z = \frac{\tan\alpha \cdot b \cdot f}{f + x \cdot \tan\alpha}$$

Triangulation Laser Scanning

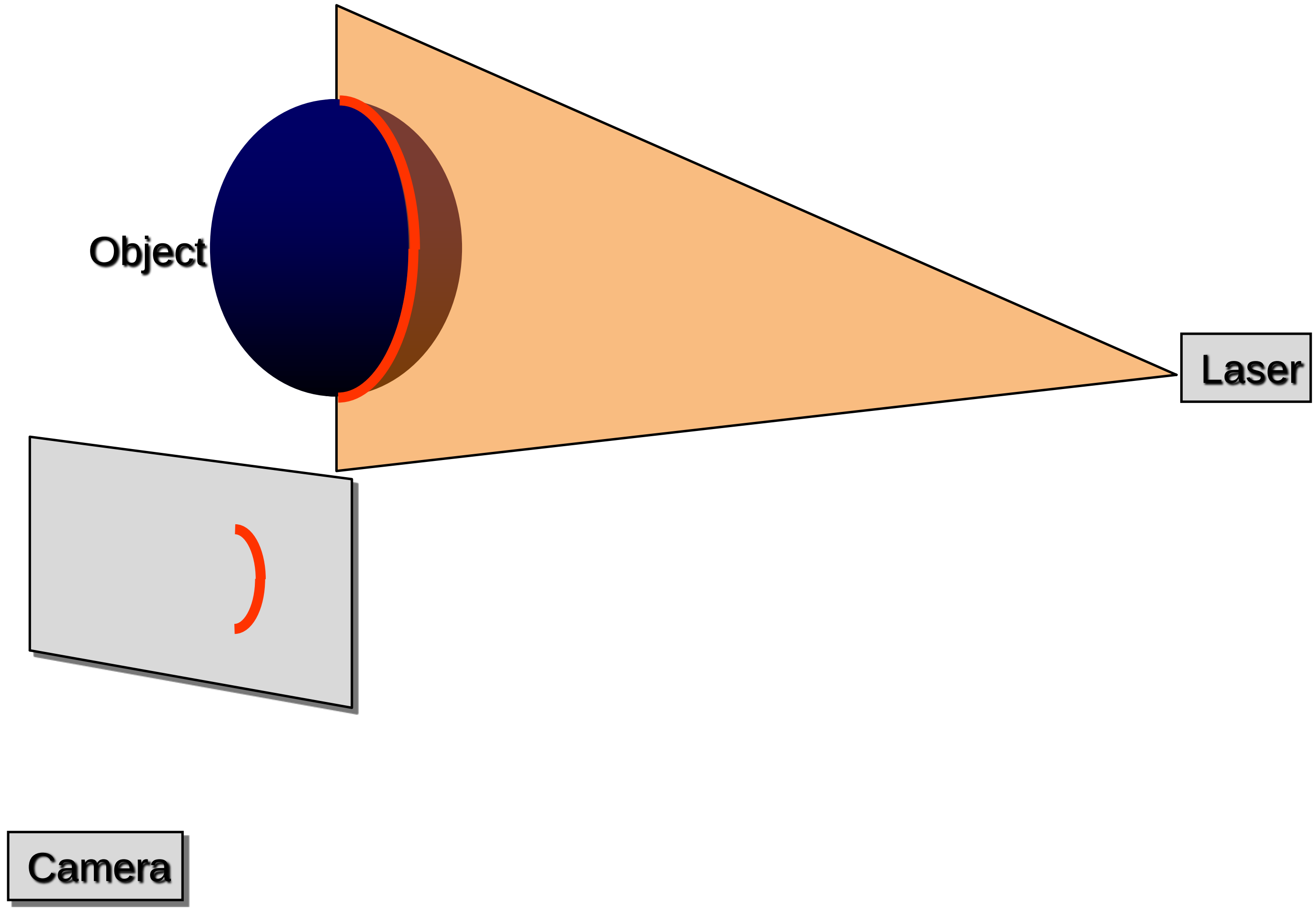






Triangulation Laser Scanning

Stripe triangulation



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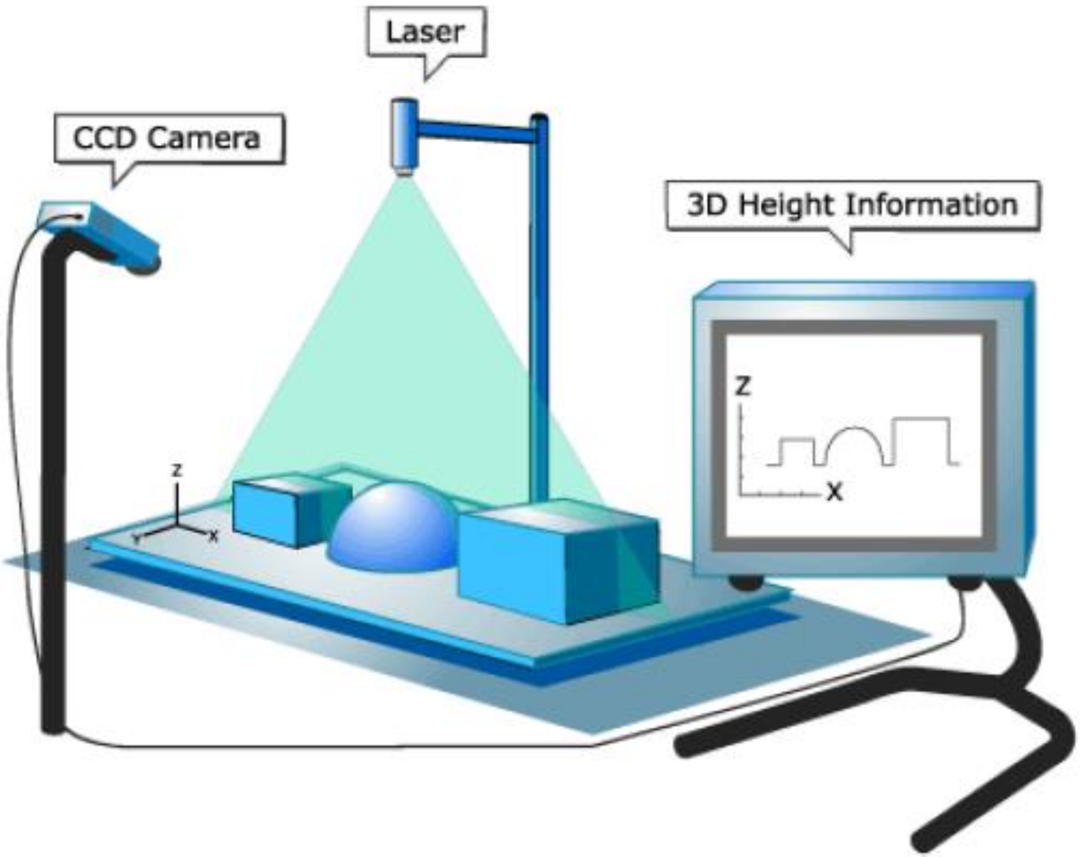

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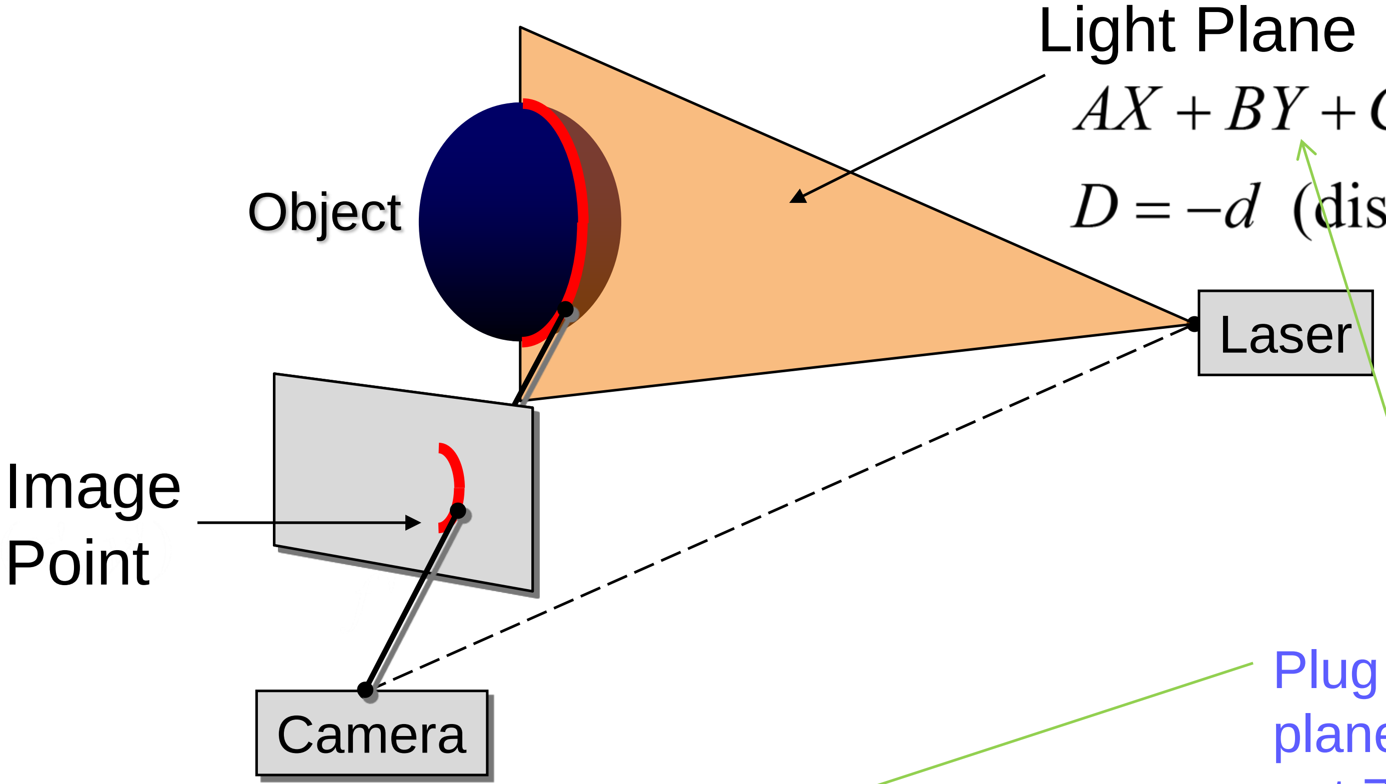


$$AX + BY + CZ + D = 0$$

$$D = -d \quad \text{(distance)}$$

Plug X, Y into plane equation to get Z

$$X = x' Z / f' \qquad Y = y' Z / f' \qquad Z = \frac{-Df'}{Ax' + By' + Cf'}$$

Courtesy S. Narasimhan, CMU

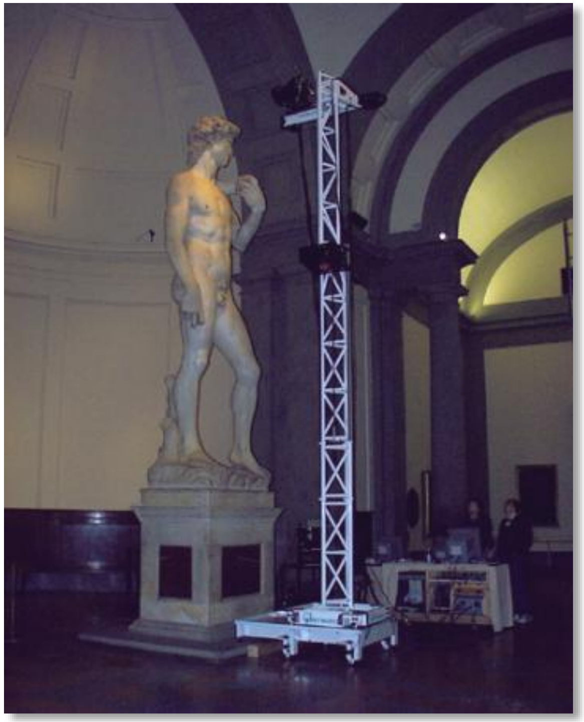
Triangulation Laser Scanning

Advantages

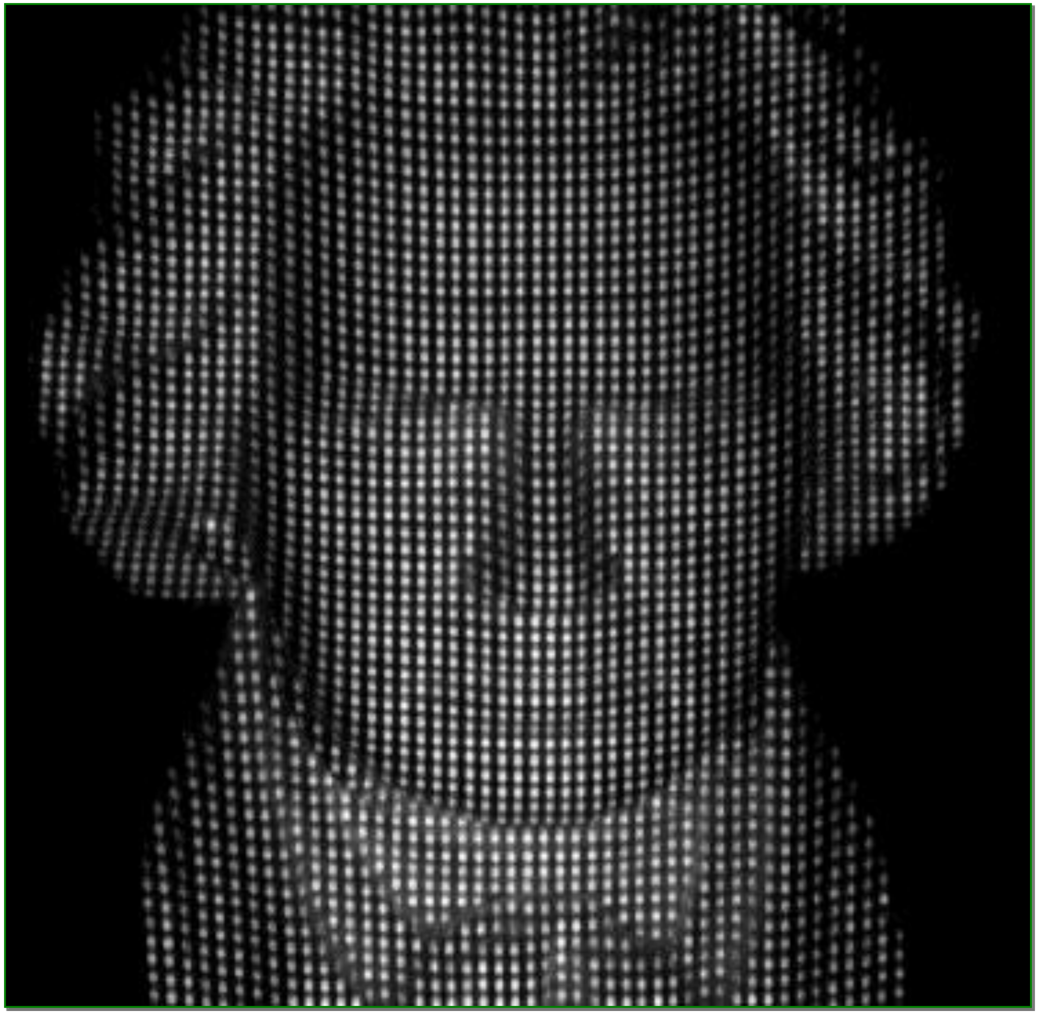
- Very precise (tens of microns)

Disadvantages

- Small distances (meters)
- Inaccessible regions

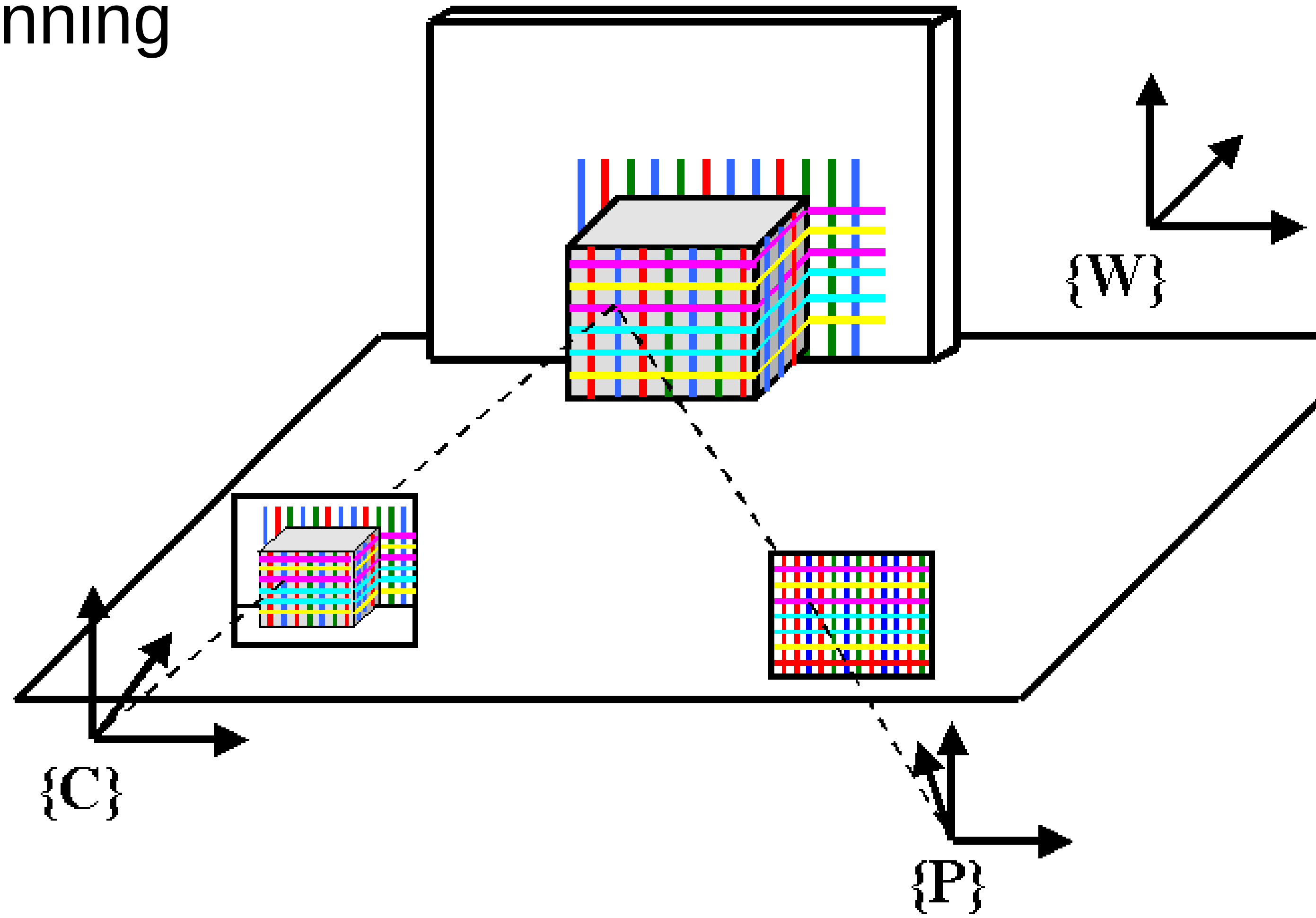


Multi-Stripe Triangulation



Color-Coded Stripe Triangulation

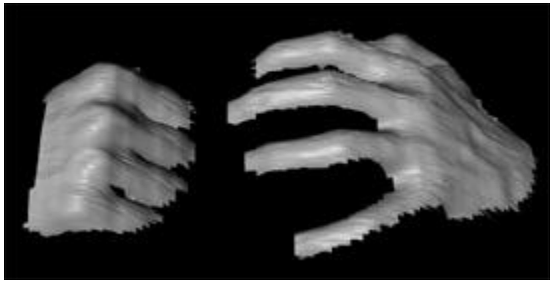
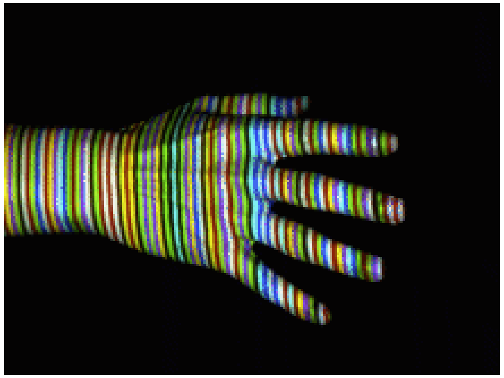
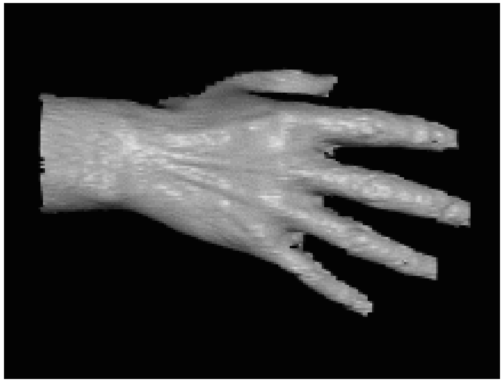
Active
Scanning



Zhang et al, 3DPVT 2002

Color-Coded Stripe Triangulation

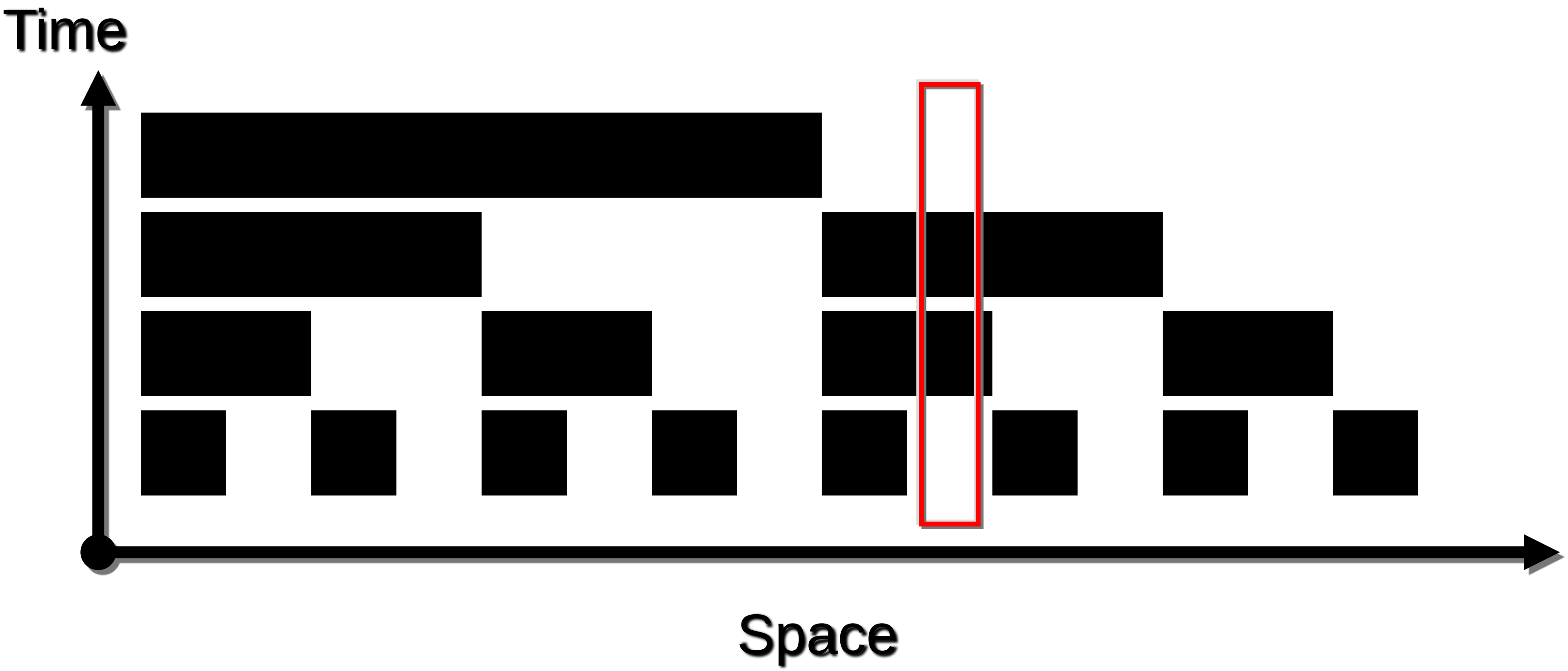


Zhang et al, 3DPVT 2002

Time-Coded Stripe Triangulation

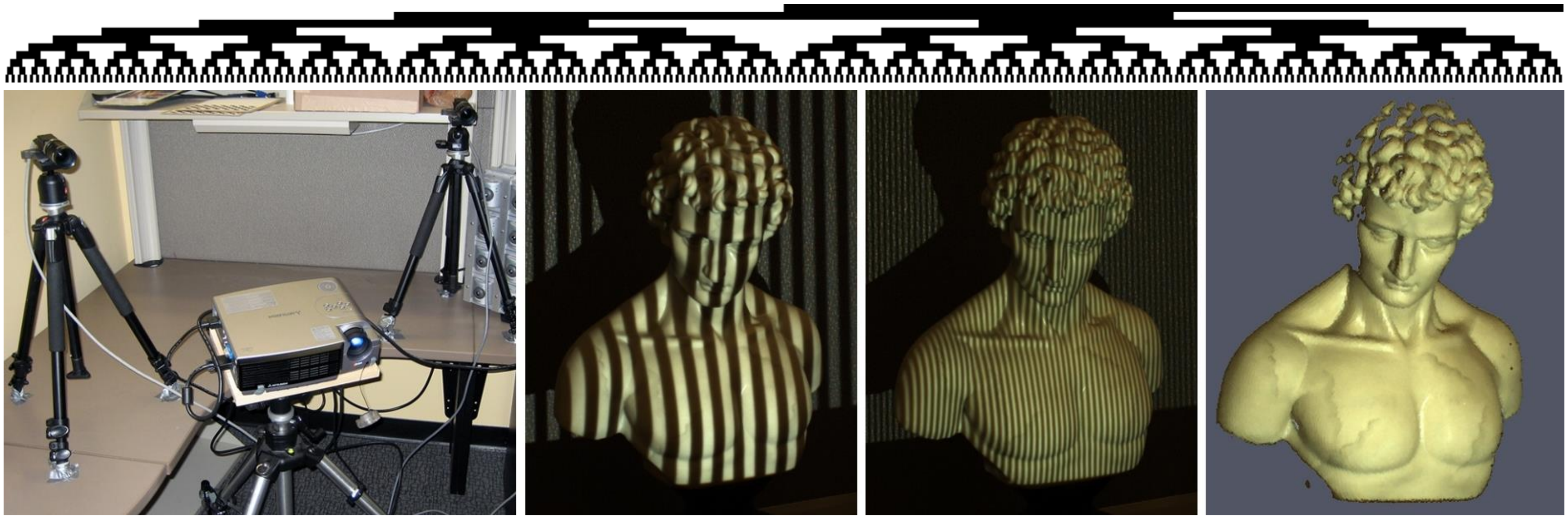
Assign each stripe a unique illumination code over time



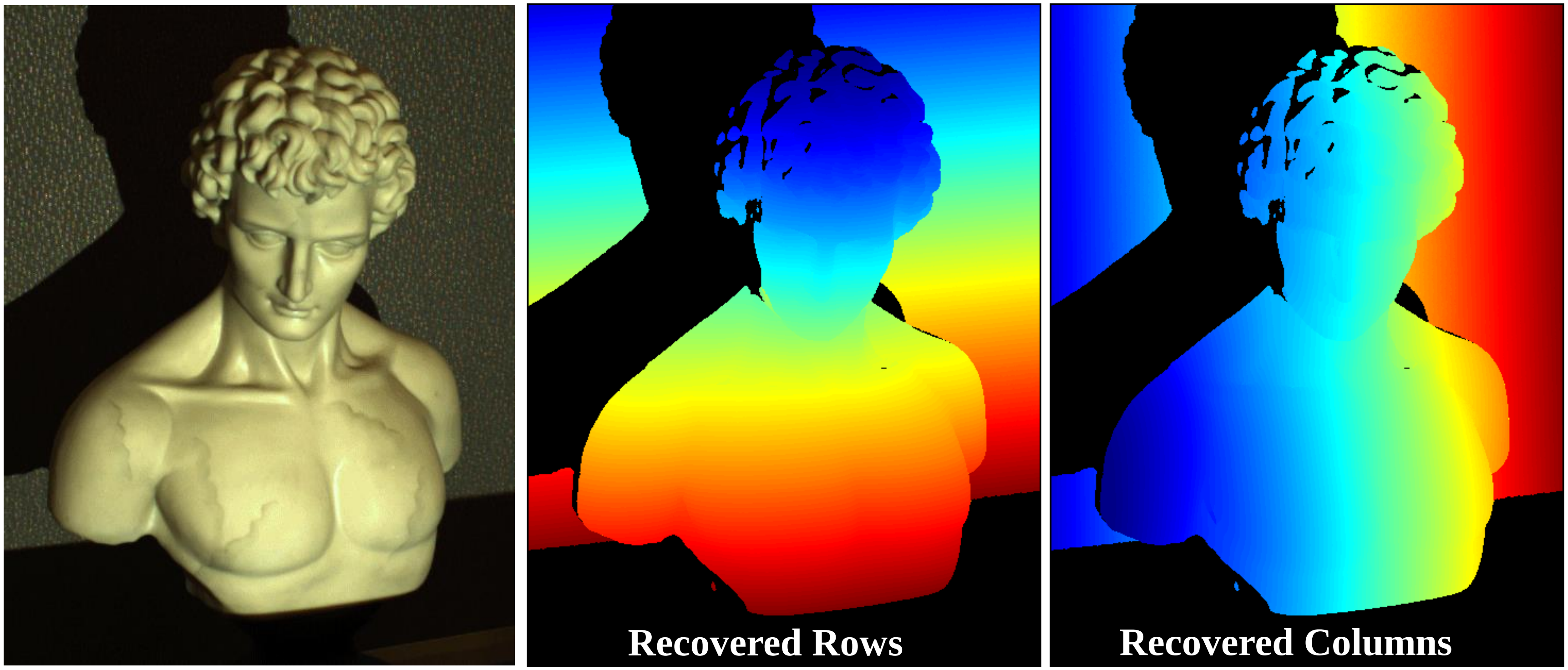
[Posdamer 82]

Time-Coded Stripe Triangulation

Time-Coded Stripe Triangulation

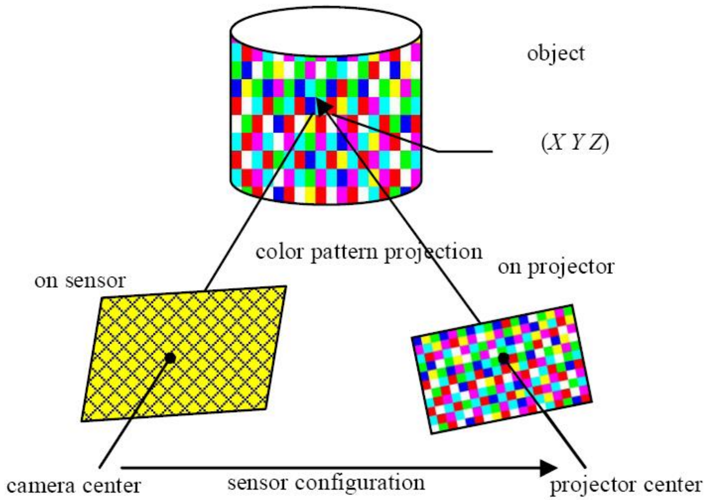


Time-Coded Stripe Triangulation

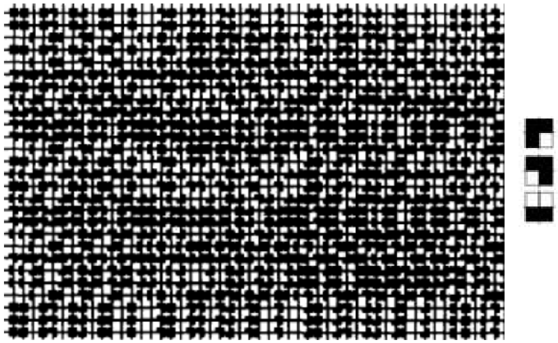


3D Reconstruction using Structured Light [Inokuchi 1984]

Structured Light Patterns



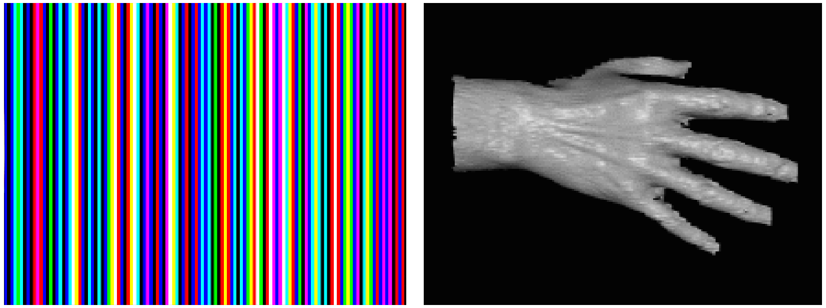
Spatial encoding strategies [Chen et al. 2007]



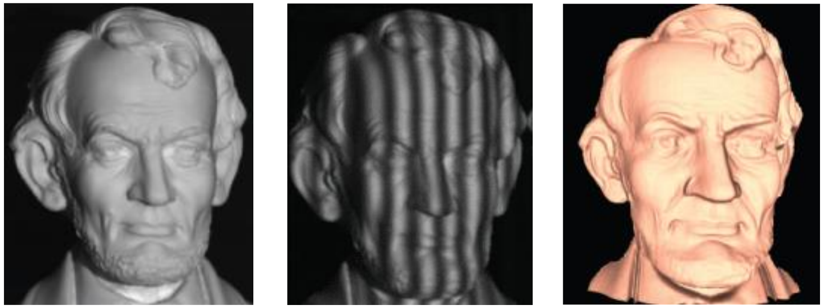
Pseudorandom and M-arrays [Griffin 1992]

J. Salvi, J. Pagès, and J. Batlle. Pattern Codification Strategies in Structured Light Systems

"Single-shot" patterns (N-arrays, **grids**, random, etc.)

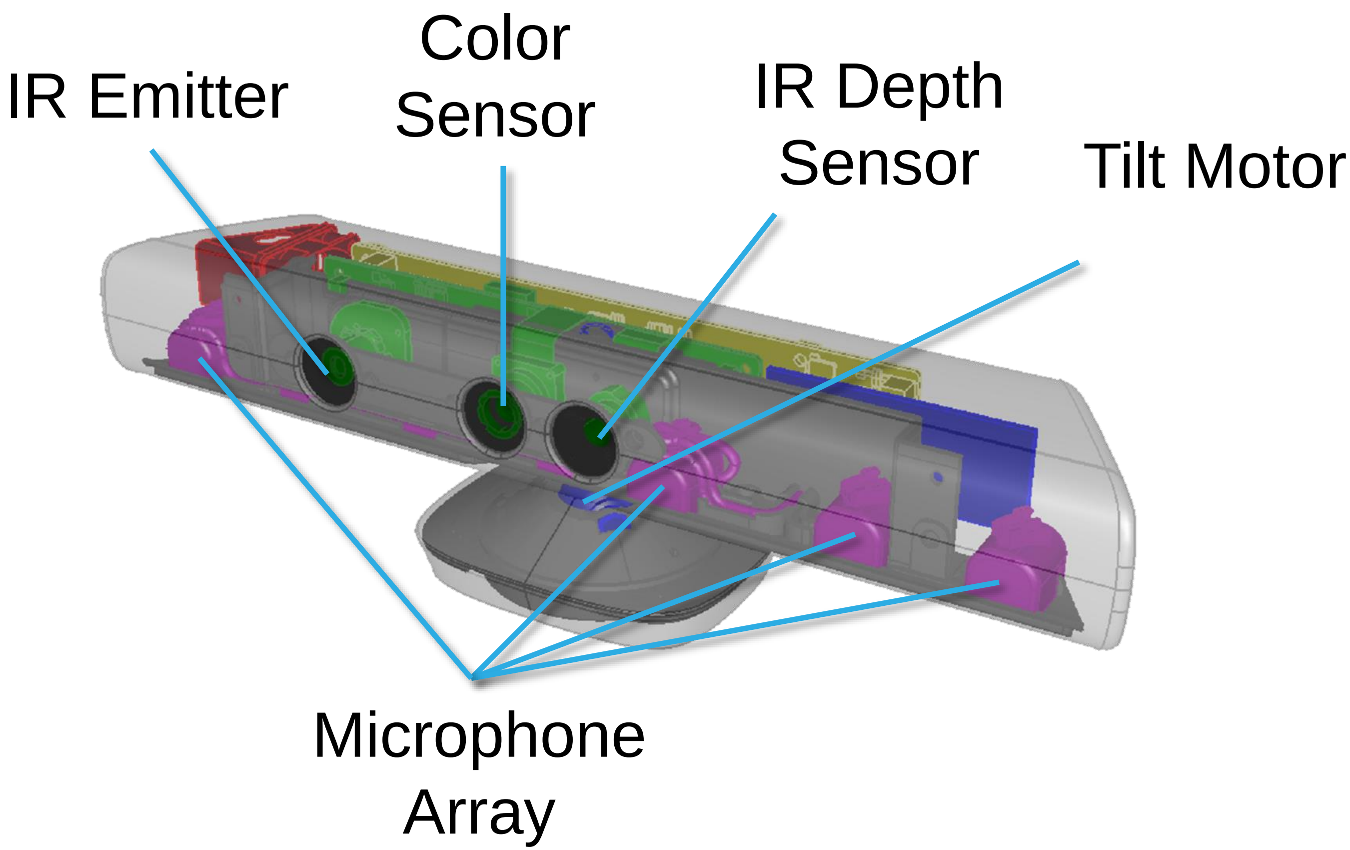


De Bruijn sequences [Zhang et al. 2002]



Phase-shifting [Zhang et al. 2004]

Structured Light Scanning: Kinect



Structured Light Scanning: Kinect

Projected IR Pattern

Structured Light Scanning: Kinect

Depth Map

RGB Image

Structured Light Scanning: Kinect

http://www.youtube.com/watch?v=uq9SEJxZiUg

Structured Light Scanning: Kinect

http://users.dickinson.edu/~jmac/selected-talks/kinect.pdf

Structured Light Scanning

Advantages:

- Very fast – 2D pattern at once

Disadvantages:

- Prone to noise

Next Time

Point cloud processing and surface reconstruction

Zhou and Koltun, SIGGRAPH 2014