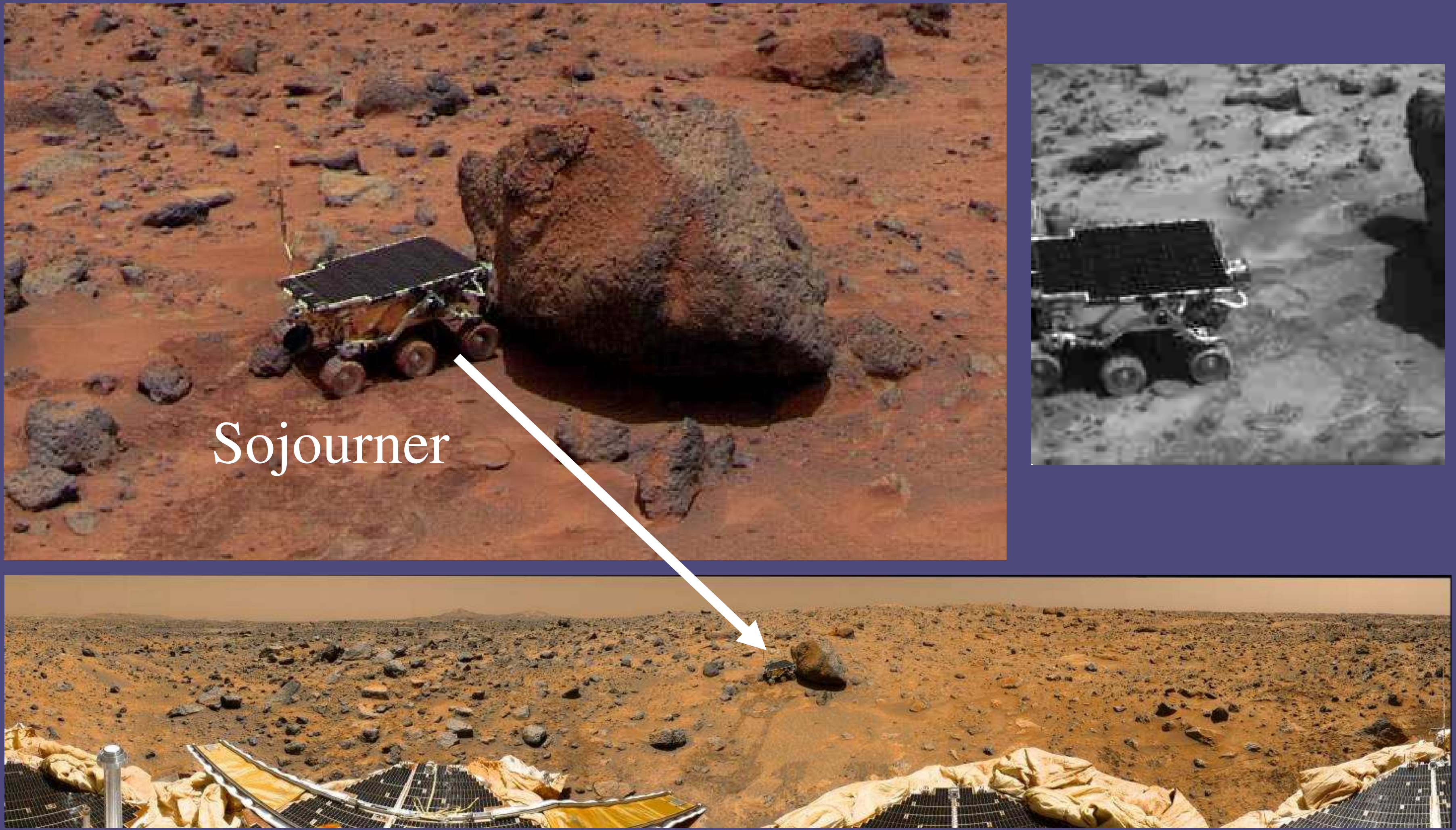
From 2D Images to 3D Tangible Models: Reconstruction and Visualization of Martian Rocks

Cagatay Basdogan, Ph.D.
College of Engineering
Koc University

The Old Story ... (July 04, 1997)



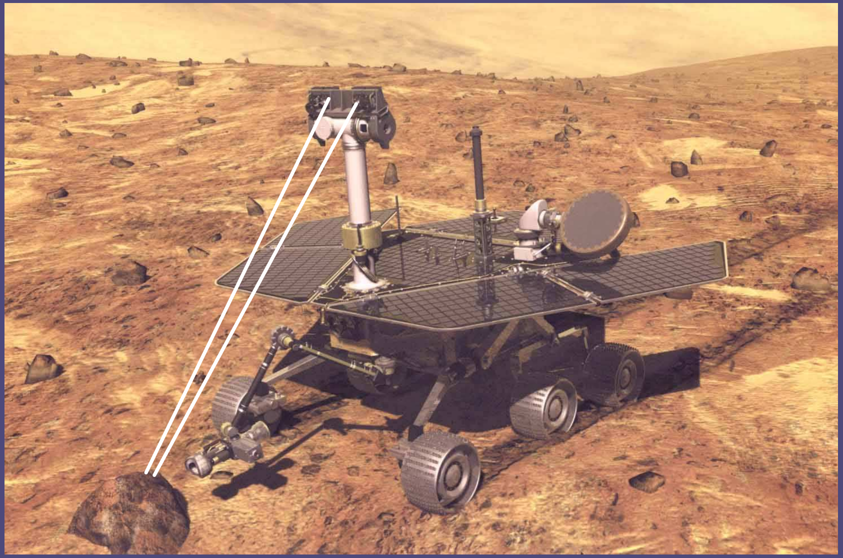
The New Story ... January 04, 2004

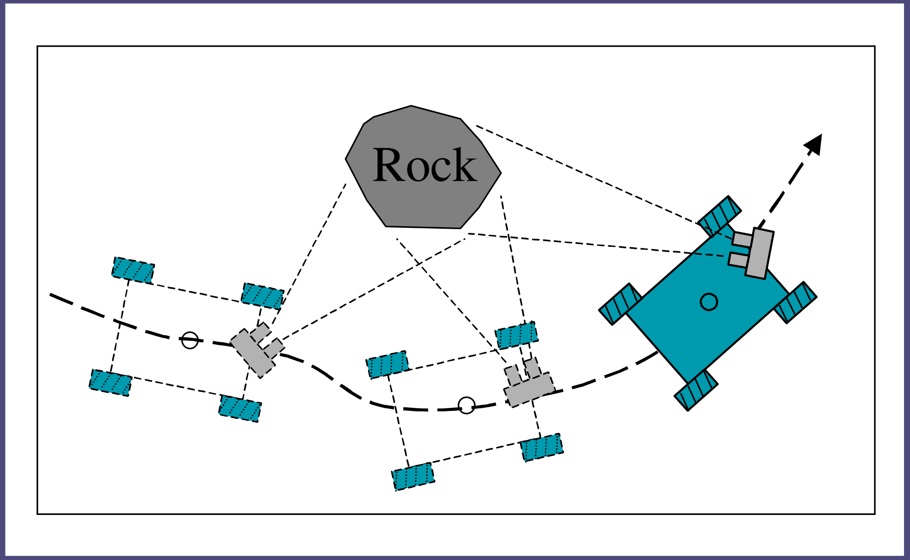
2003 Mars Rover

Press Release Animation

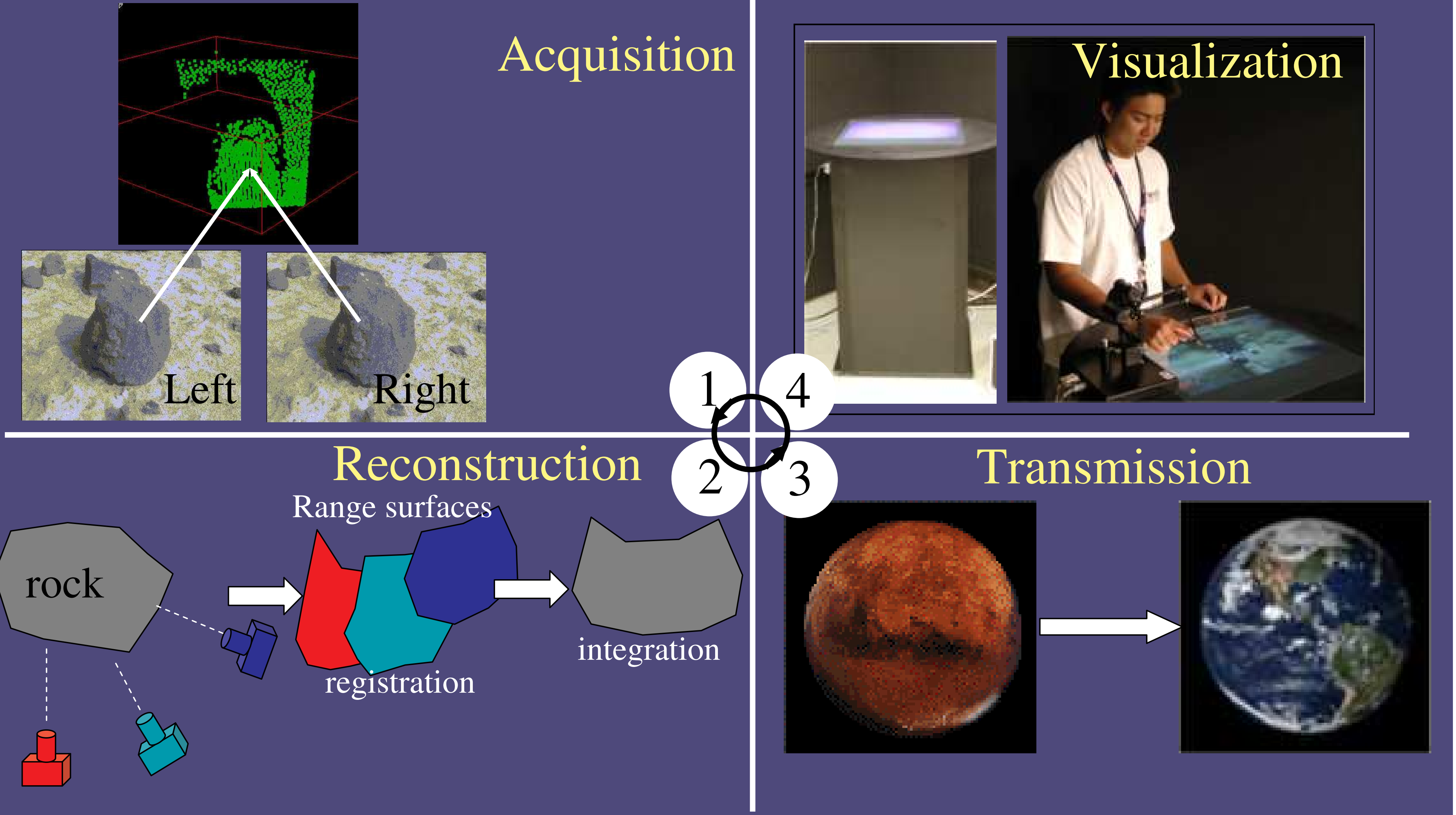
Dan Maas
dmaas@dcine.com

Our goal ...





From 2D Images to 3D Models



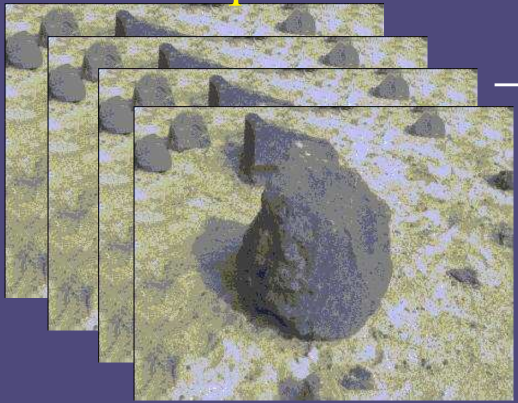
Limitations ...

Sojourner

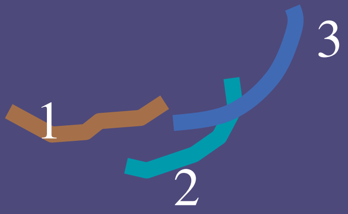
Laptop

	Sojourner	Laptop
• CPU:	2MHz	2 GHz
• Memory:	768Kb	256 Mb + 40 Gb
• Transmission Rate:	<5 bytes/sec	100 Mb/sec
• Transmission Delay	~ 20 min.	< 200 msec
• Transmission Interval	~ 2 hours	anytime
• Transmission Reliability	poor	good

Data Acquisition

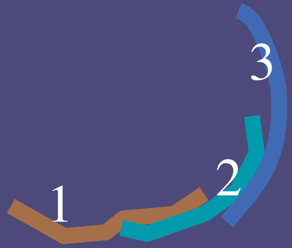


Range surfaces



Registration

Transformed
Range surfaces



Octree-Based
Data Representation
and Integration

Merged Range Data

Progressive
Transmission

Multi-Resolution
Transmitted Range Data

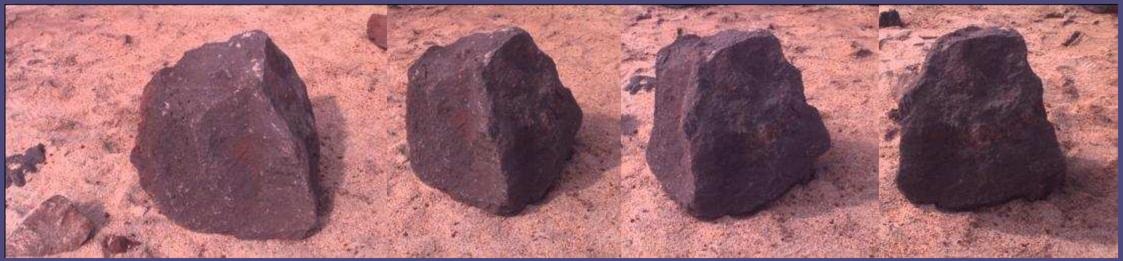
Iso-surface
Extraction

3D Model

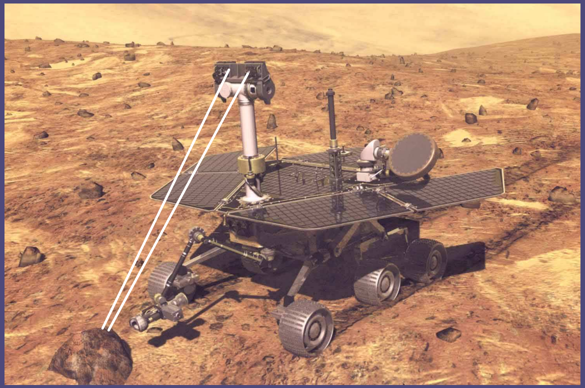
Image-Based Rendering

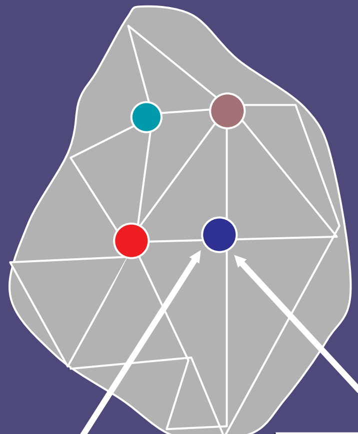
Data Acquisition

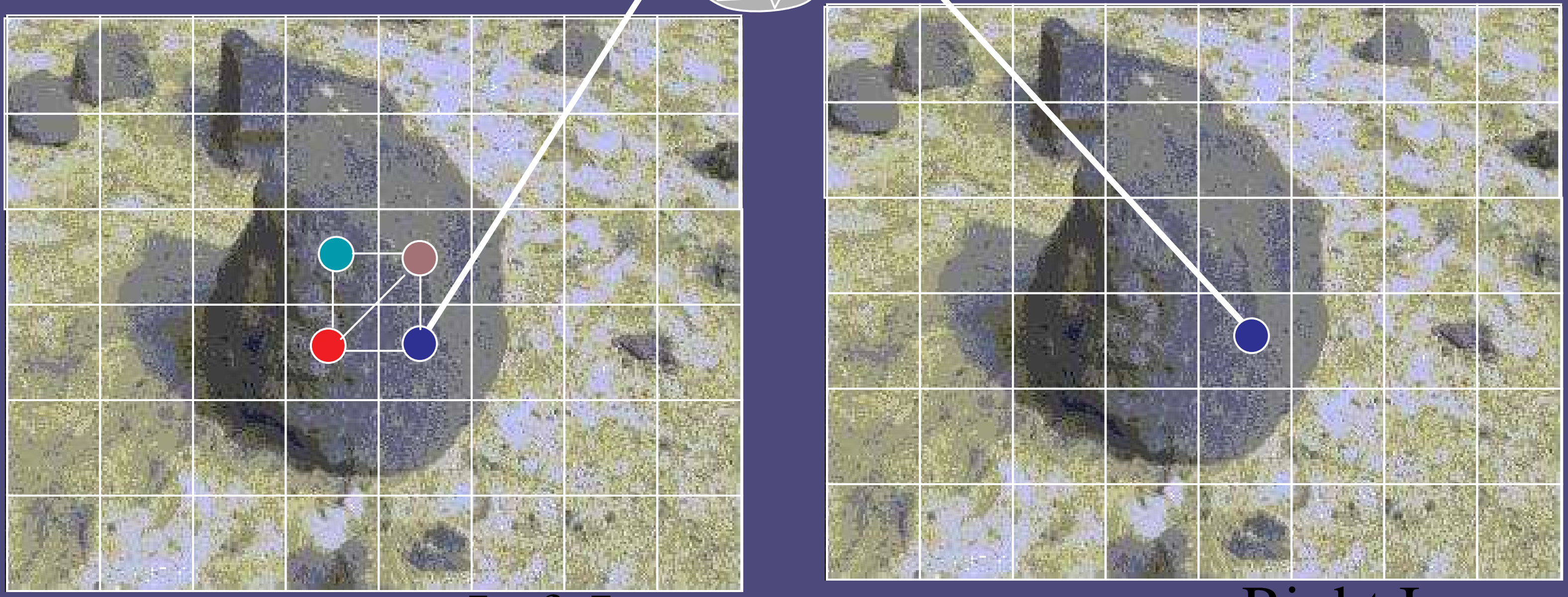
JPL – Marsyard (http://marsyard.jpl.nasa.gov)



Input: Range Scans

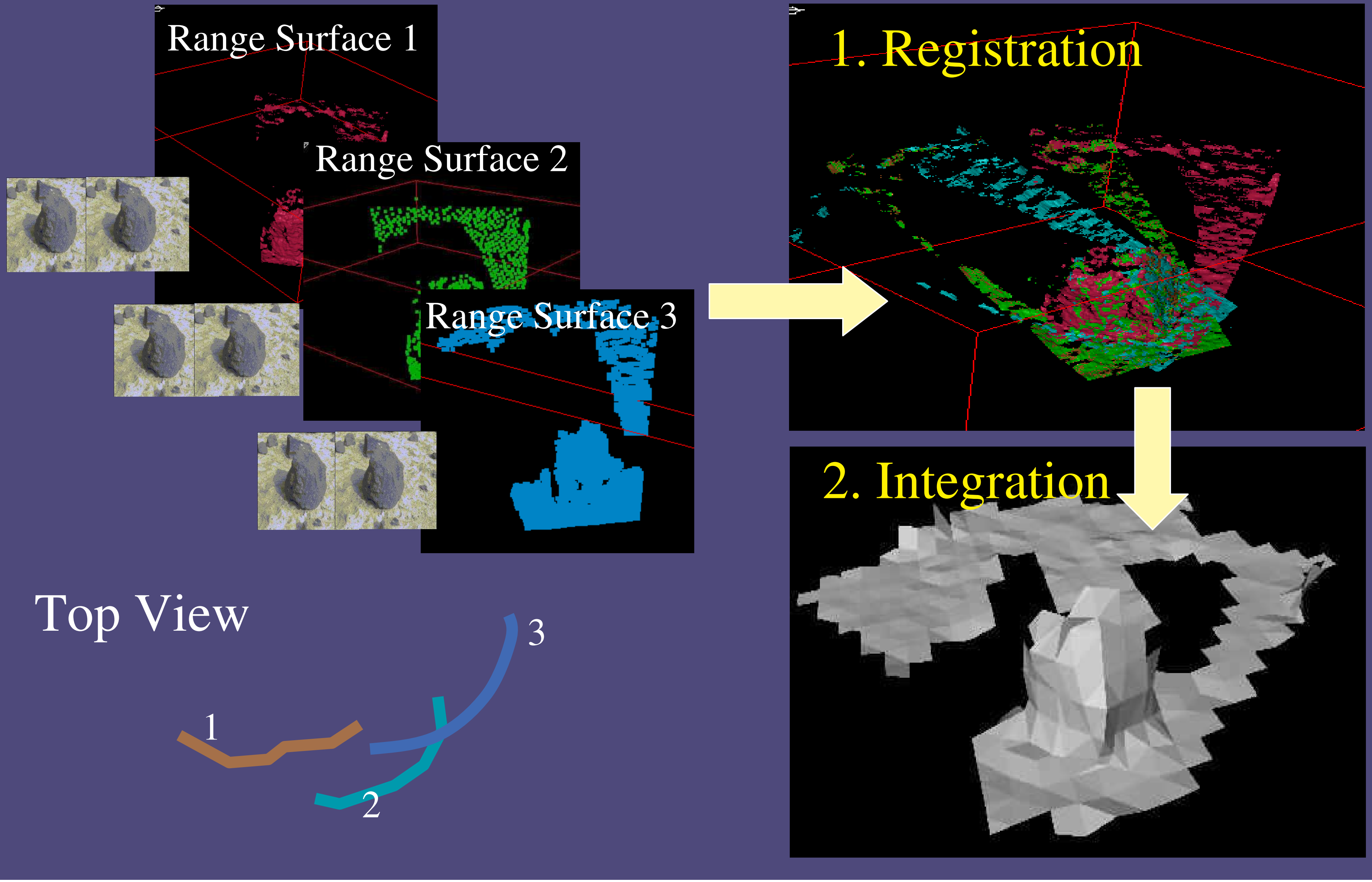






3D range surface:
coordinates
connectivity

3D Reconstruction

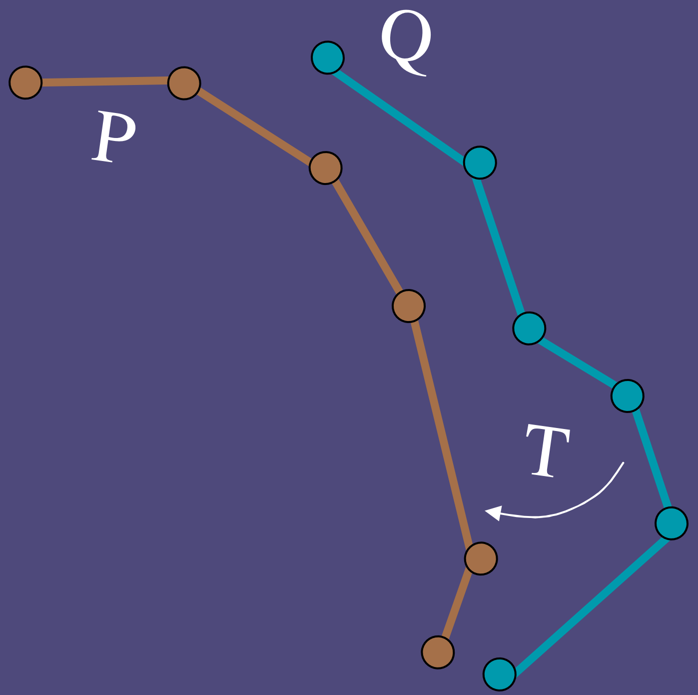


3D Registration

Pair-wise registration problem:

Given 2 overlapping range scans what is the rigid transformation, T, that minimizes the distance between them ?

$$E = \sum_{i}^{N} \| p_i - T q_i \|^2$$



Solution: ICP algorithm (Besl and Kay, 1992)

```
do
    Identify corresponding points
    Compute the optimal T
while (E < threshold)
```

3D Registration : Computation of T

$$E = \sum_{i}^{N} \| p_i - (R q_i + t) \|^2$$

R: Rotation Matrix
t: translation vector

Solution by Horn, 1990:

$$R = M (M^T M)^{-1/2}$$
$$t = \overline{p} - R\overline{q}$$

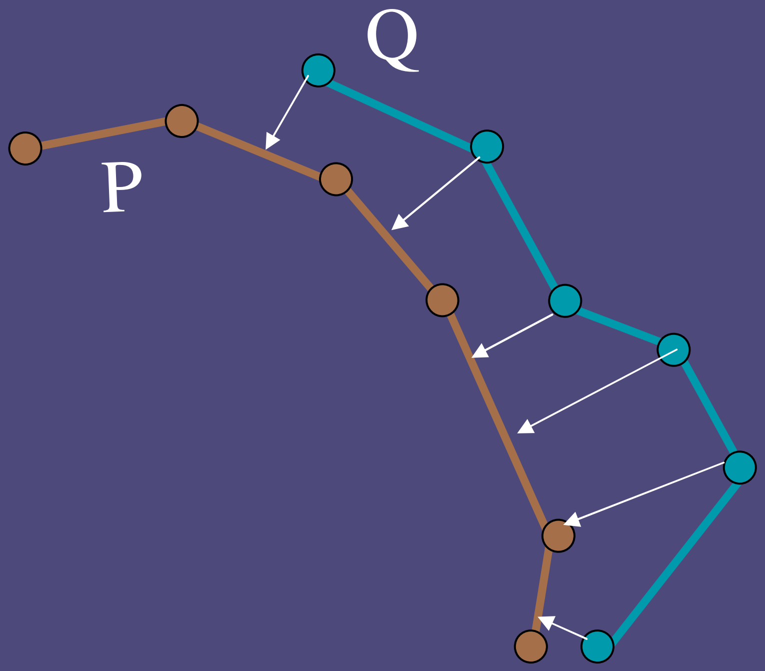
where,

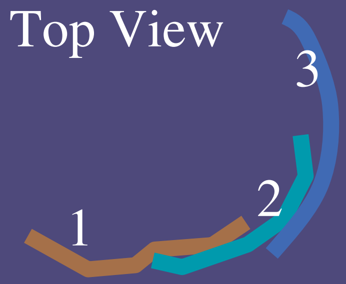
$$M = \sum_{i}^{N} (p_i - \overline{p})(q_i - \overline{q})^T$$

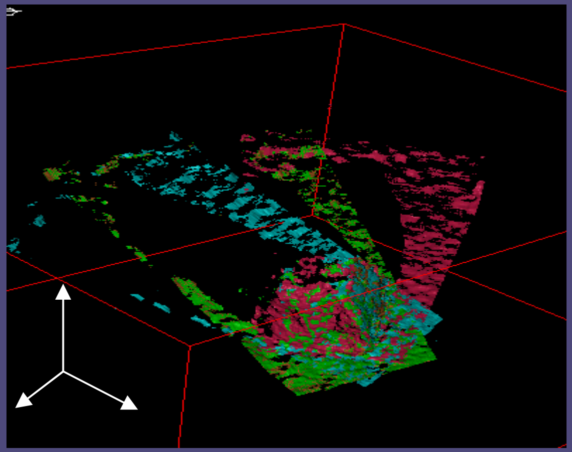
3D Registration: Corresponding Points

We now have a closed form solution, how do we get the corresponding points in two scans?

Nearest points along the direction of the normal at q_i







3D Integration

Problem: Given a set of registered range scans, reconstruct a 3D surface that closely approximates the original shape.

Methods:

- Delaunay-Based (Amenta et al., Siggraph'98)
- Surface-Based (Turk and Levoy, Siggraph'94)
- Volumetric (Curless and Levoy, Siggraph'96)

Which one is better ?

Computationally Complexity
Robustness
Memory Usage
...

3D Integration: Volumetric Approach

Input:
registered
range surfaces

→ Volumetric Integration →

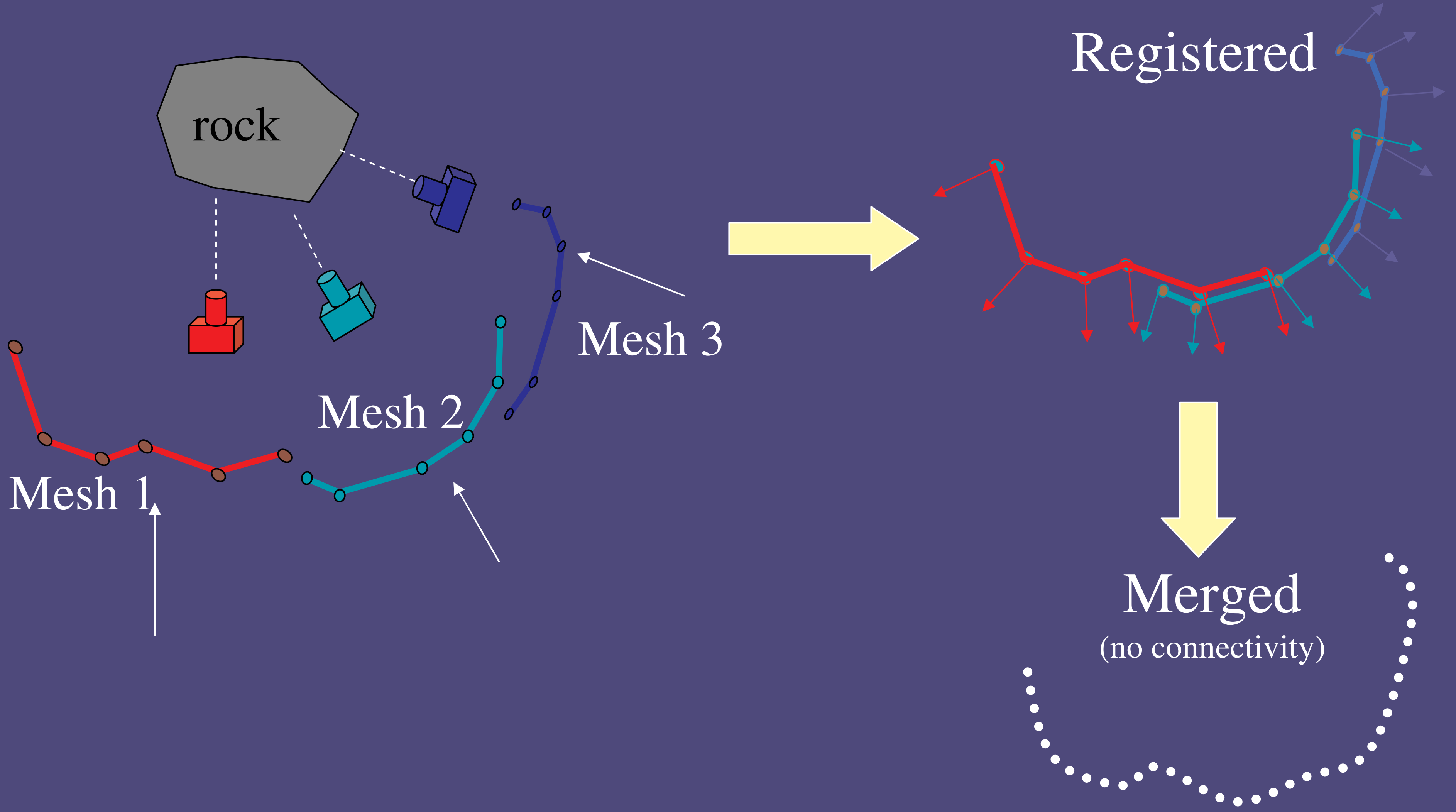
Output:
3D Mesh

Our implementation:

Step 1:
Merge the registered range surfaces using an *octree*

Step 2:
Extract an *isosurface* using the *Marching Cubes* algorithm

3D Integration (Step 1): Merge Range Images



rock

Mesh 1

Mesh 2

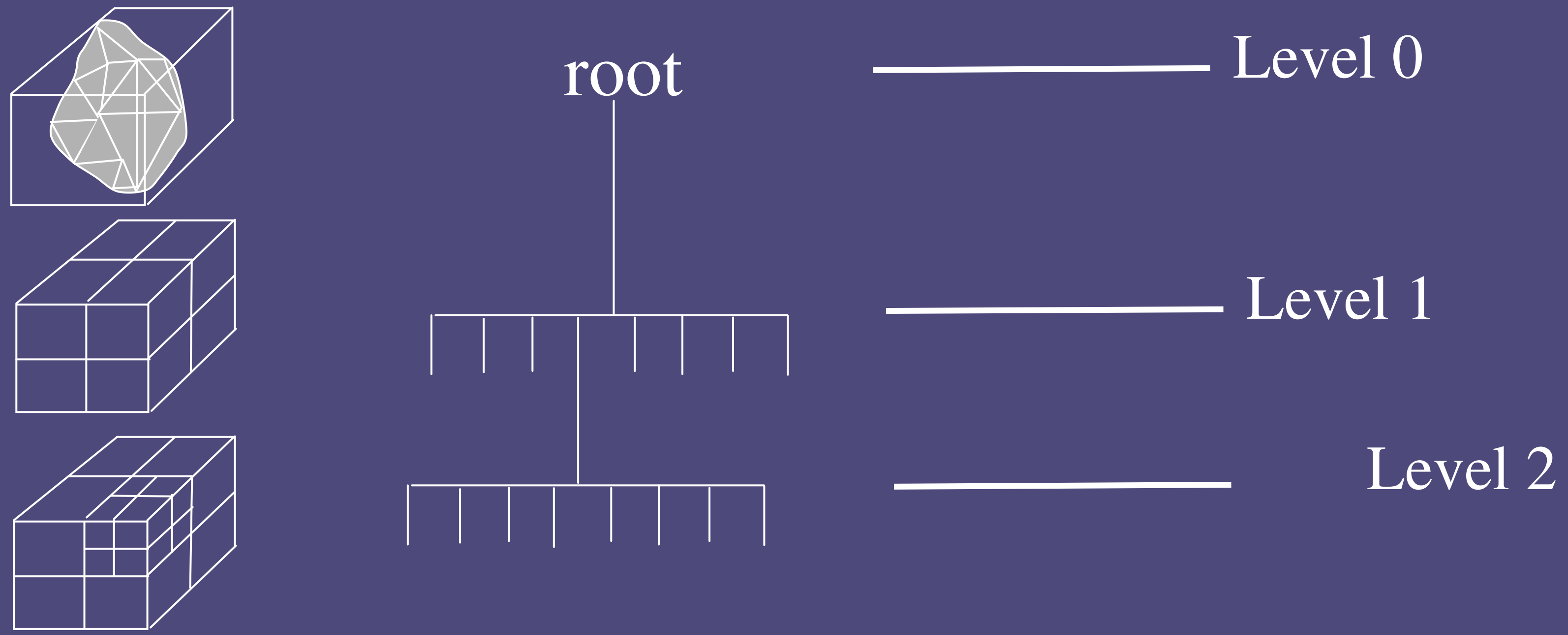
Mesh 3

Registered

Merged

(no connectivity)

3D Integration (Step 1): Data Representation Using an Octree

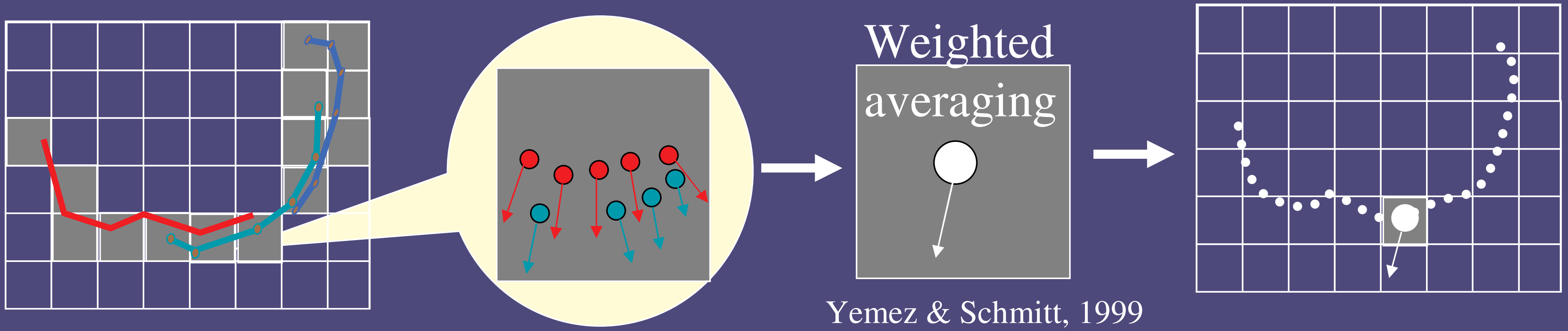


root

Level 0

Level 1

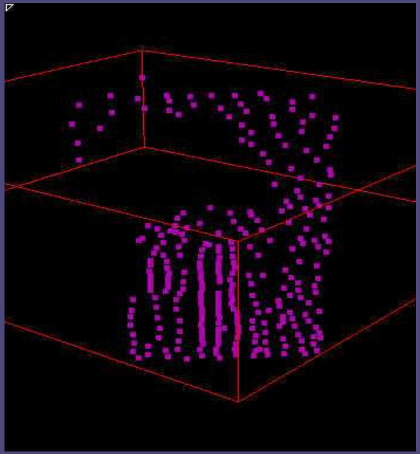
Level 2



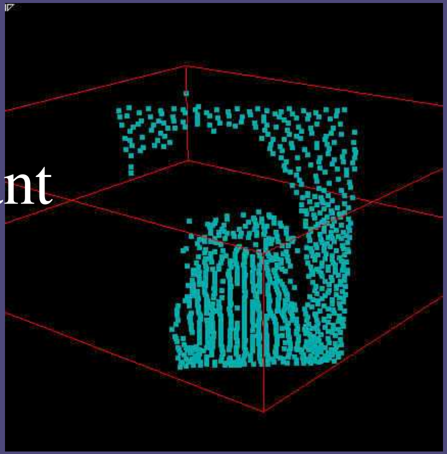
Weighted averaging

Yemez & Schmitt, 1999

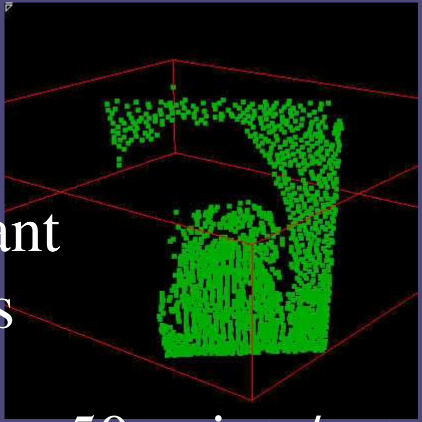
Data Reduction Using an Octree



Max 500 points/octant
Total: 273 points

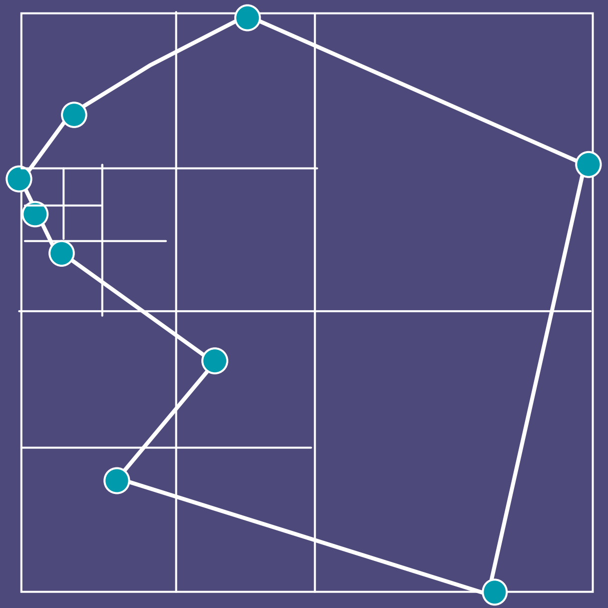


Max 100 points/octant
Total: 1052 points



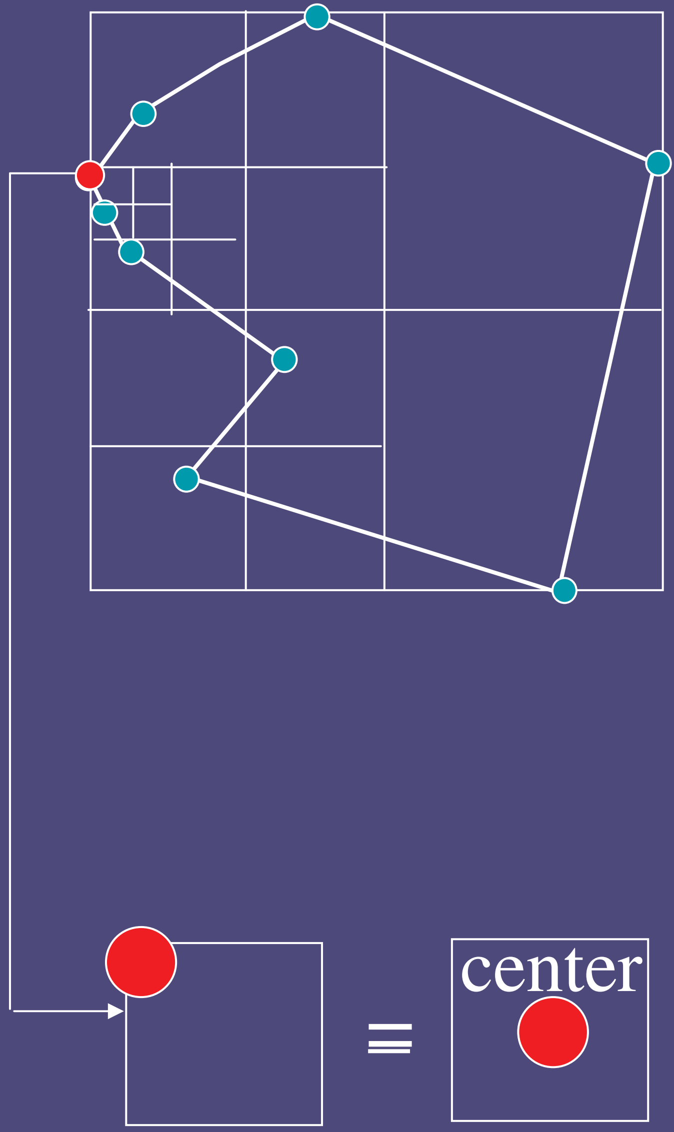
Max 50 points/octant
Total: 1870 points

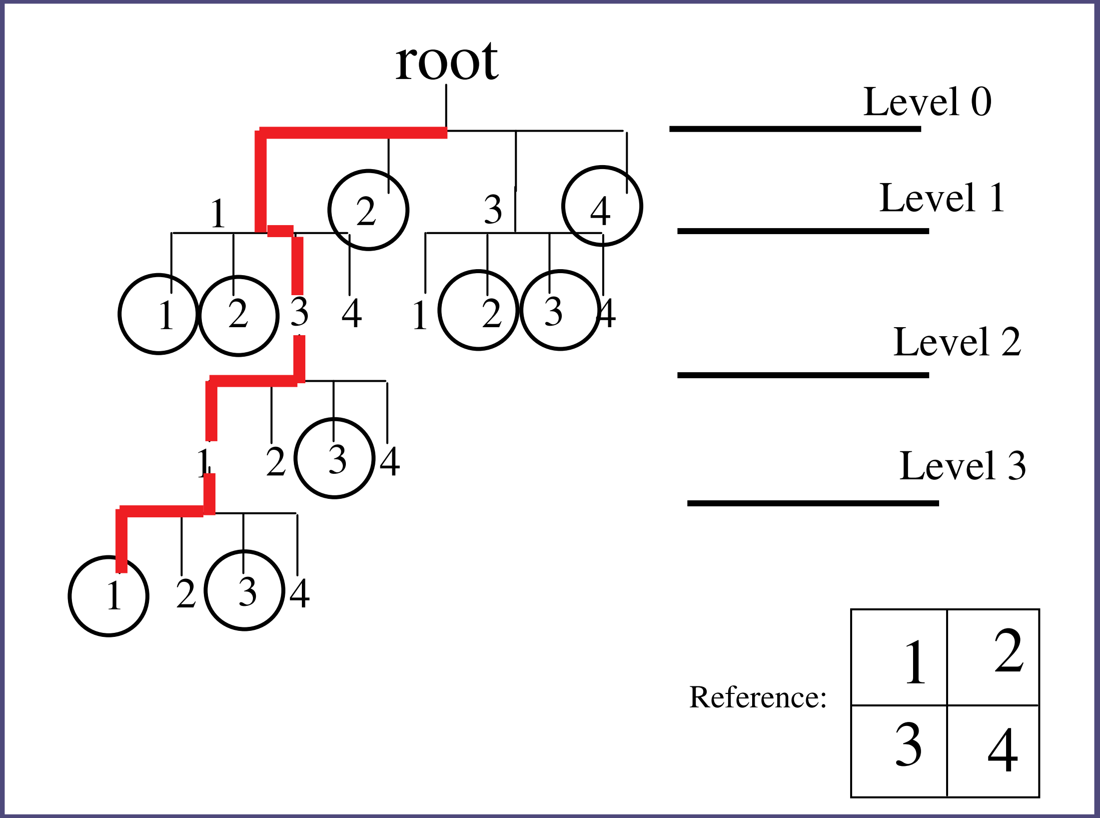
Original Model: 47724 points



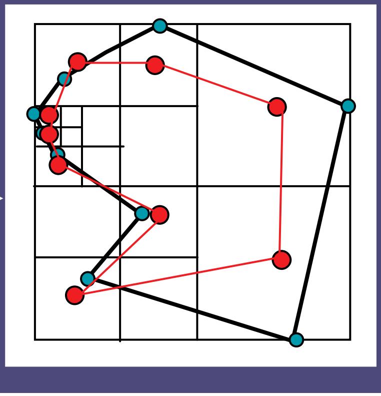
2D Example: Quadtree
Max 1 point/rectangle

Octree Representation: Our Implementation





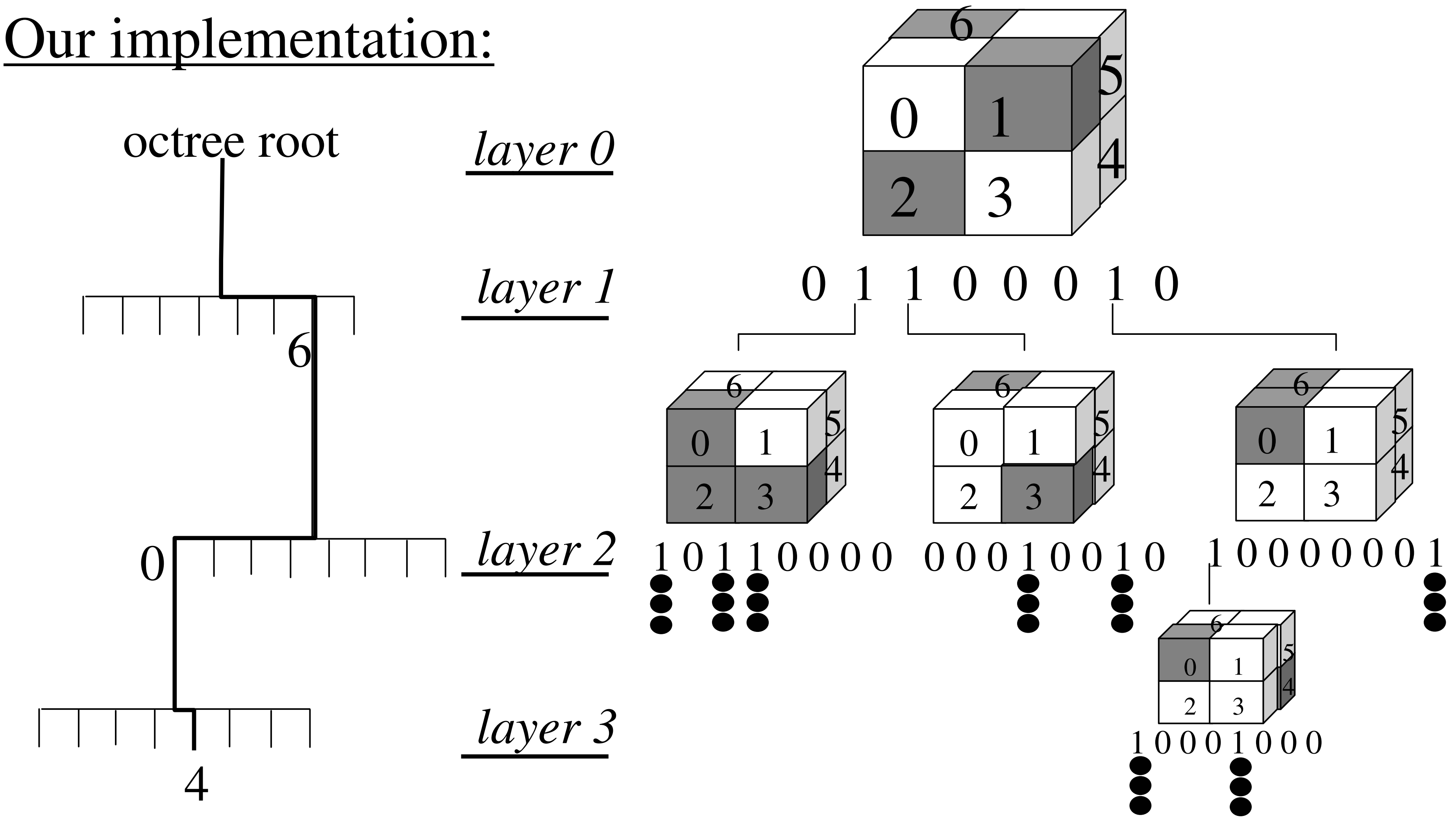
Path : 1 3 1 1 → estimated coordinate and shape →



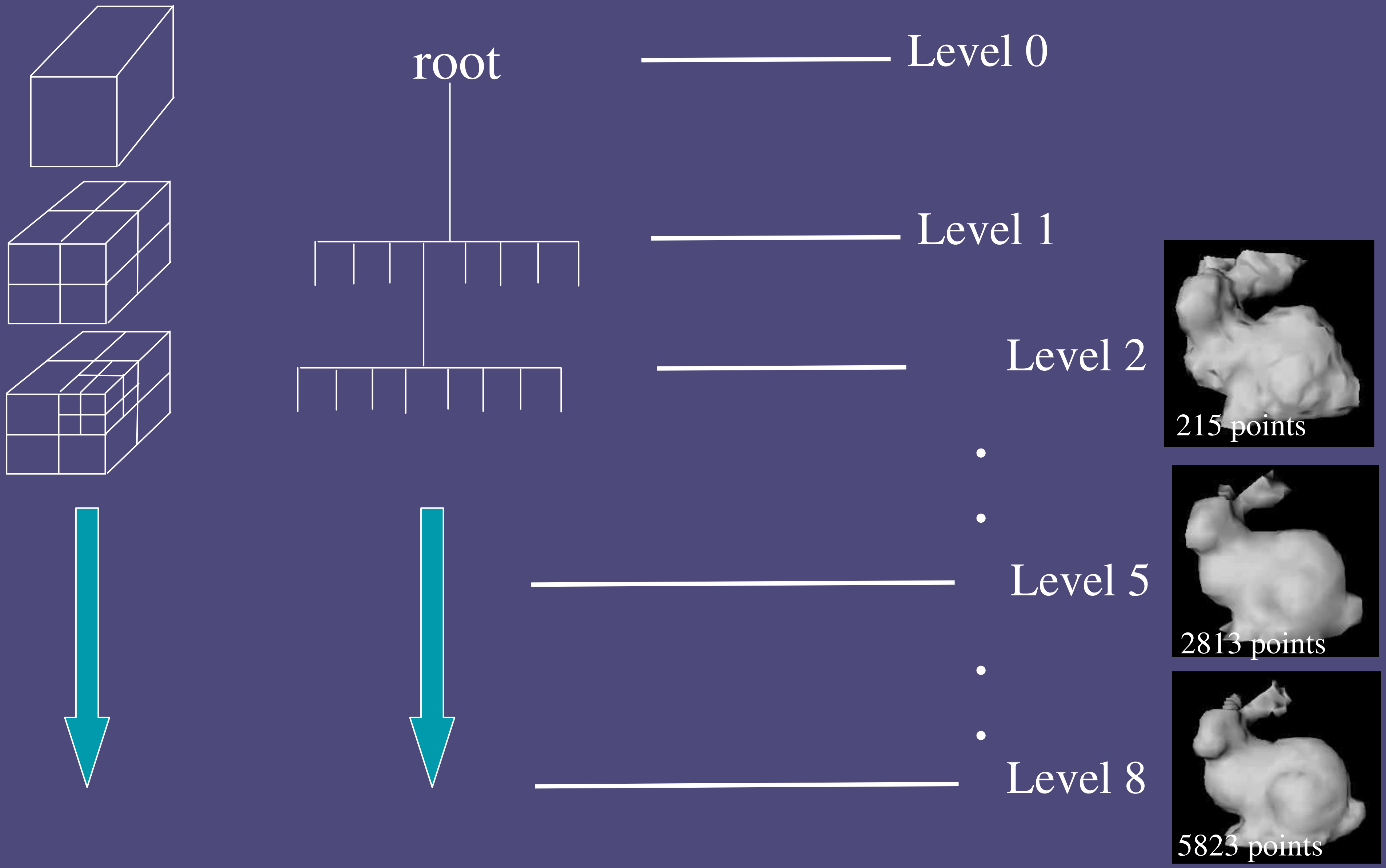
Octree Encoding

Yemez & Schmitt, 1999

Our implementation:



Octrees for 3D Progressive Data Transmission



root

Level 0

Level 1

Level 2

215 points

Level 5

2813 points

Level 8

5823 points

3D Integration (Step 2): Iso-surface Extraction

Merged Data

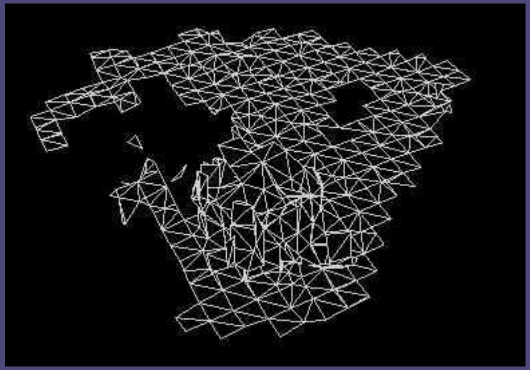
Progressive Transmission

Transmitted Data

Iso-surface Extraction: ***Marching Cubes***

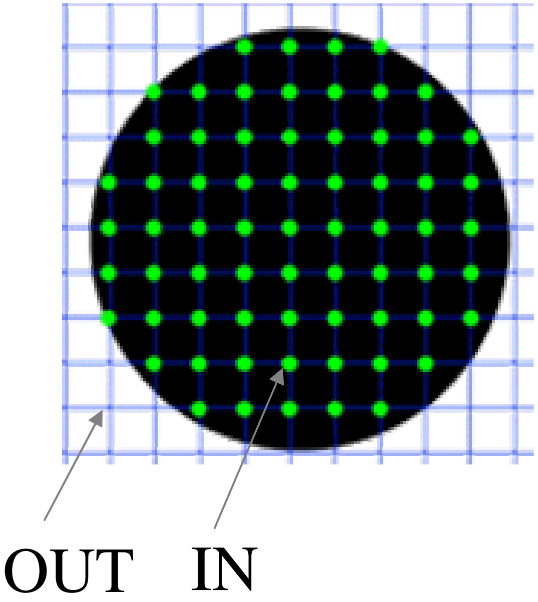
3D Mesh

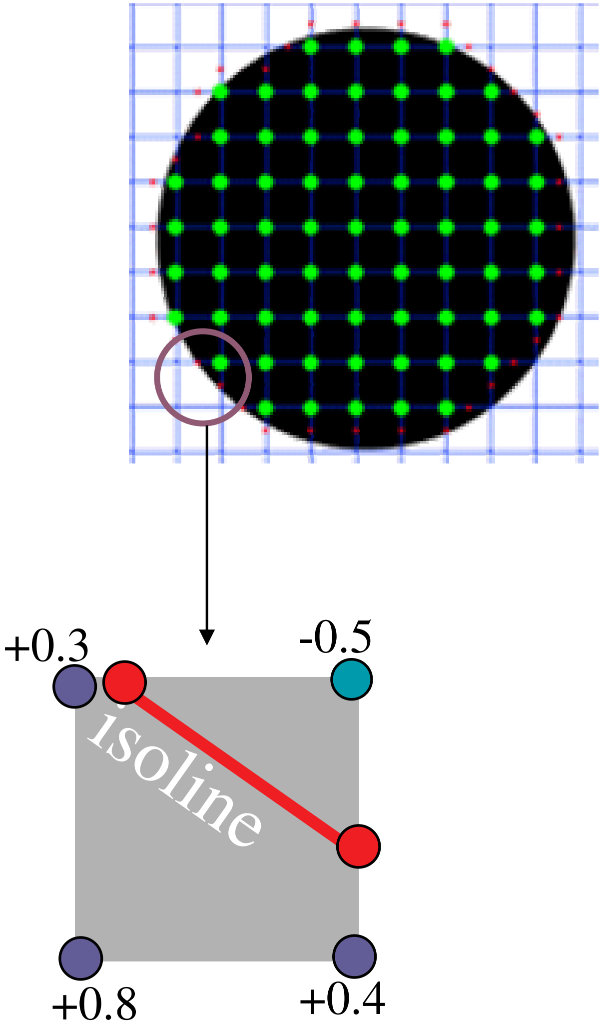
v1x v1y v1z v2x v2y v2z …	Coordinates	High Priority
rgb1 rgb2 ...	Colors	
n1x n1y n1z n2x n2y n2z ...	Normals	Low Priority

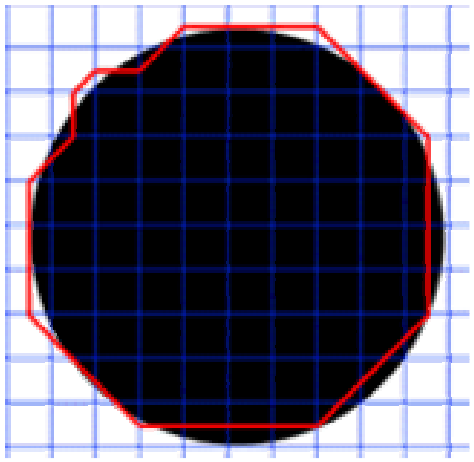


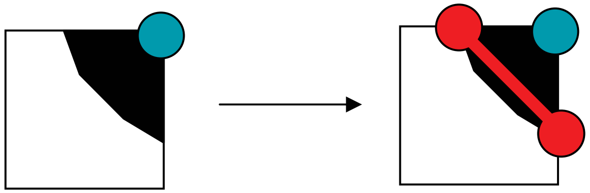
3D Integration (Step 2): Marching Cubes

2-D Example





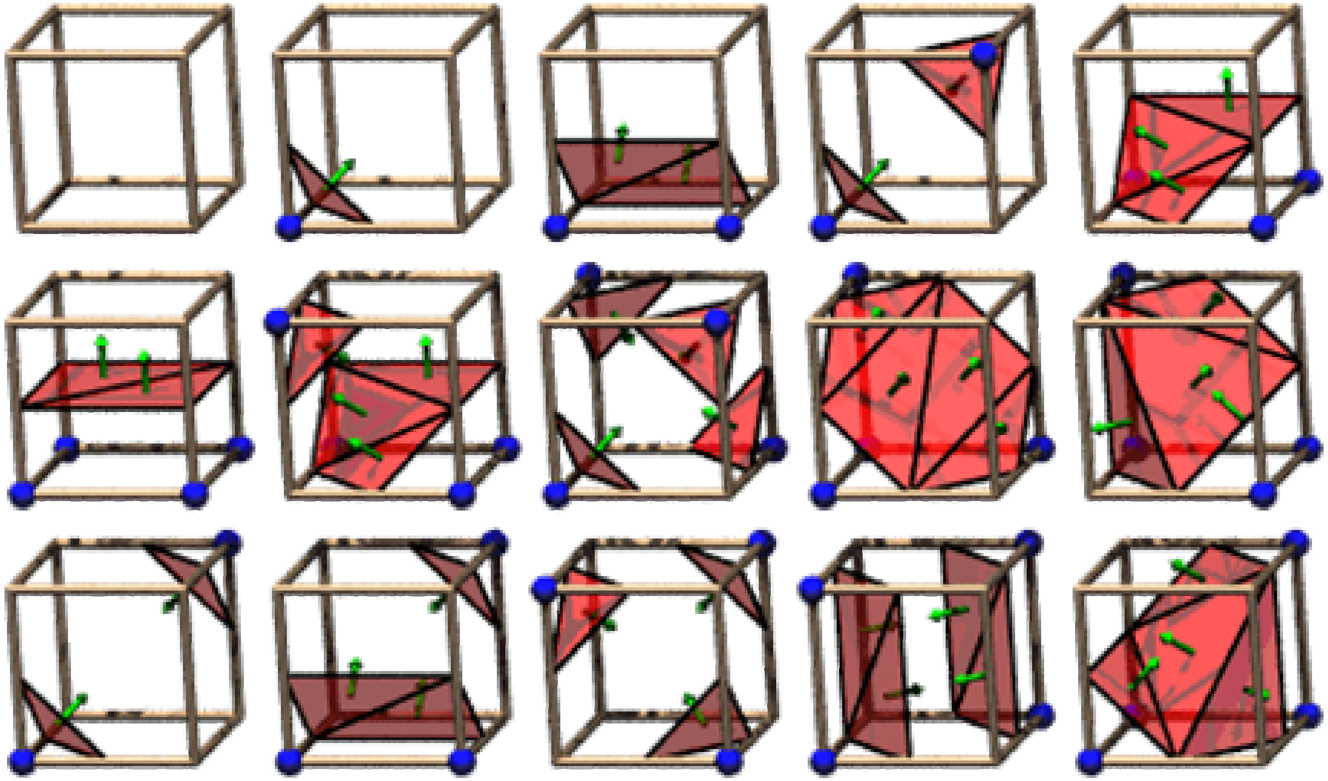




$2^4 = 16$ possible cases

Marching Cubes Algorithm : 3D Case

(Lorensen et al., Siggraph'87)

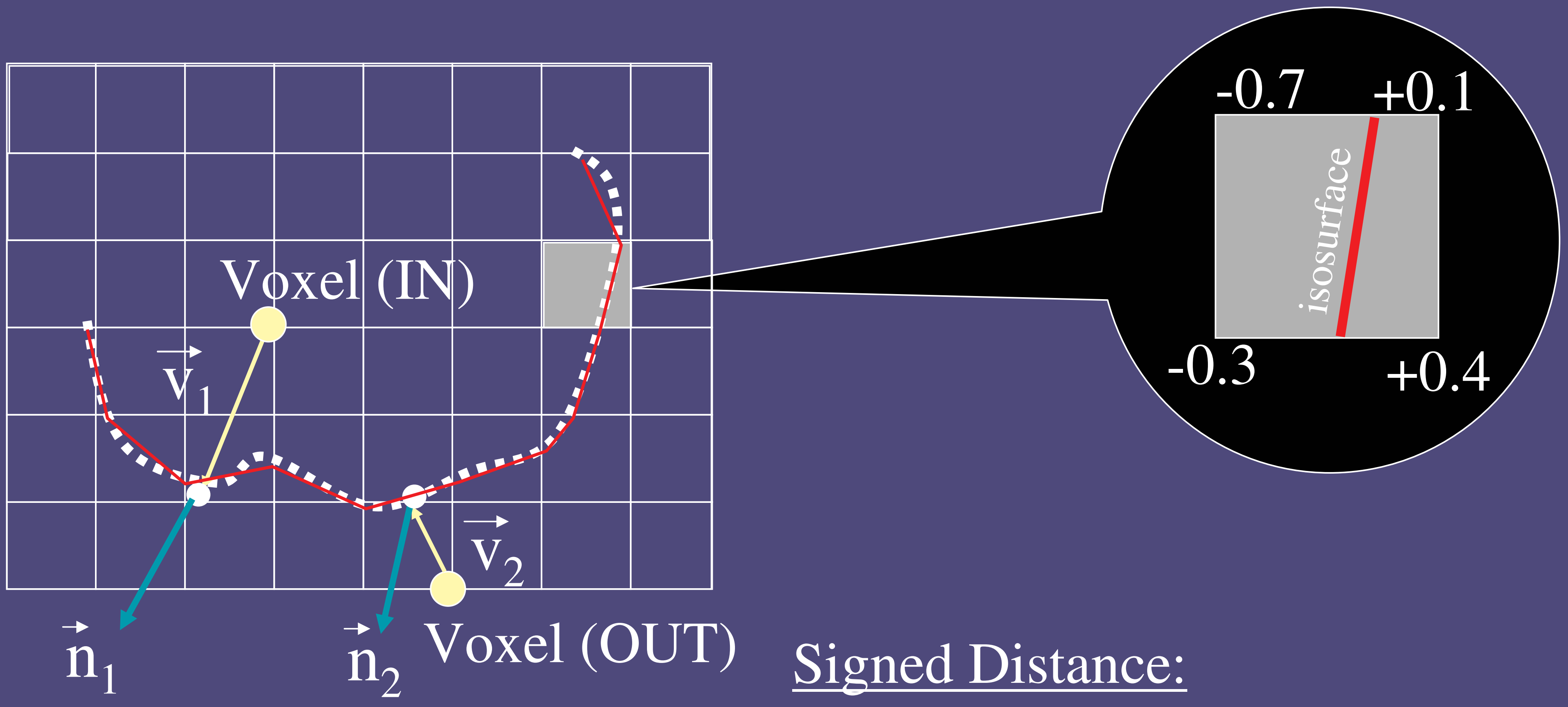


The 15 Cube Combinations

2^8 = 256 possible cases

(a look-up table reduces to 15 cases)

3D Integration: Step 2: Signed Distance Computation



Signed Distance:

dot(v1,n1) > 0 → IN, distance = -|v1|

dot(v2,n2) < 0 → OUT, distance = +|v2|

Can I estimate Normals?

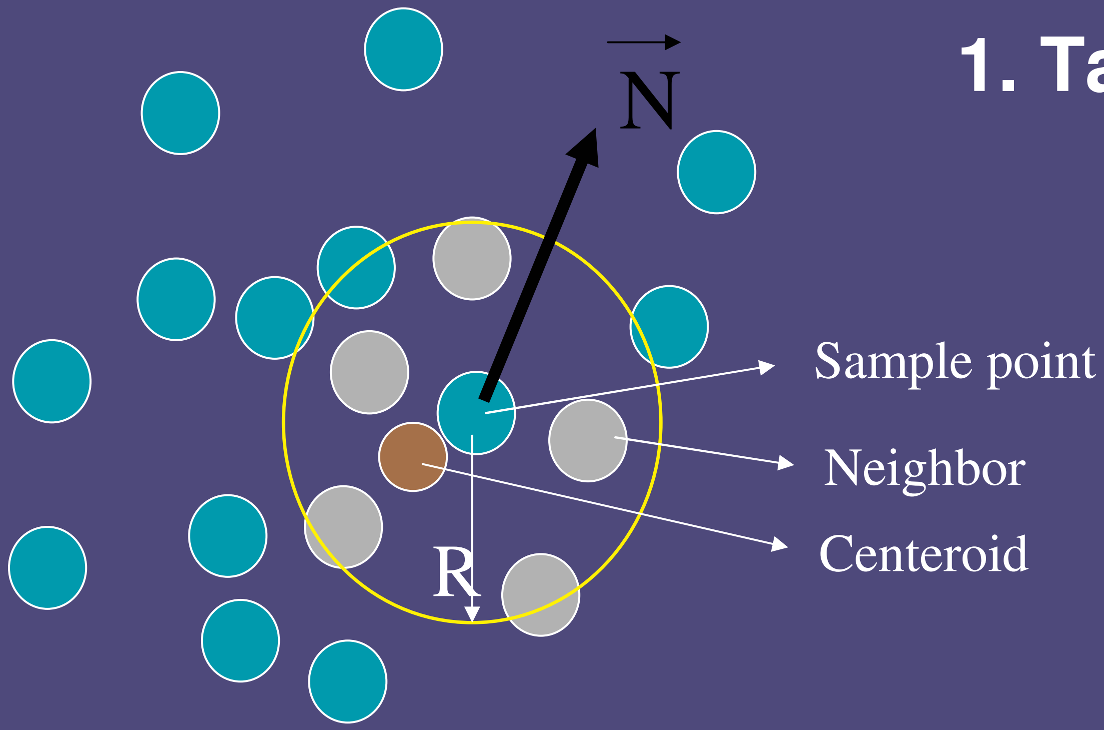
Problem: Given a set of P *unorganized* sample points, estimate the point normals.

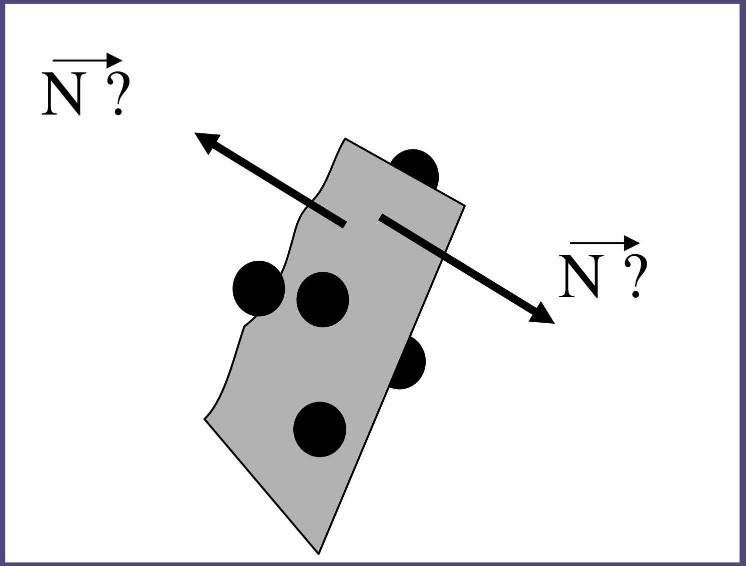
Algorithm by Hoppe (Siggraph'92):

Step 1: Tangent Plane Estimation

Step 2: Consistent Tangent Plane Orientation

1. Tangent Plane Estimation





$$R \sim (\underset{\substack{\downarrow \\ \text{Noise}}}{\sigma} + \underset{\substack{\downarrow \\ \text{Density}}}{\rho})$$

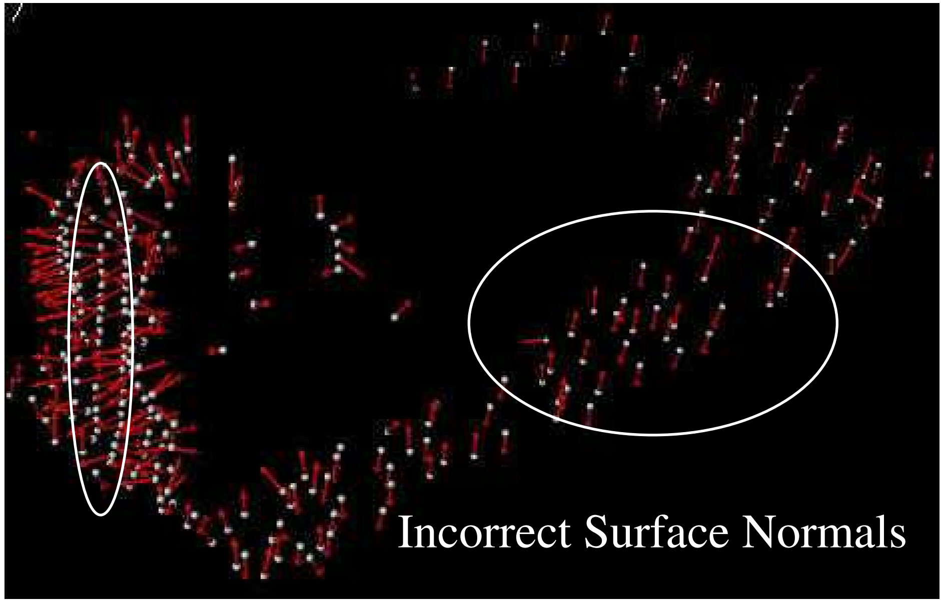
Use covariance matrix to compute $\vec{N}$

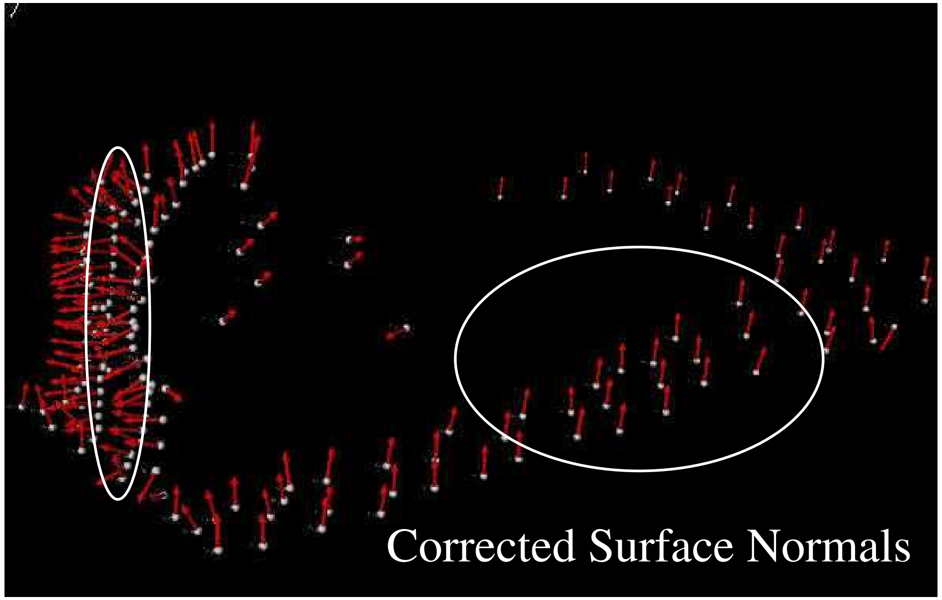
SVD : eigenvalues : $\lambda_1 > \lambda_2 > \lambda_3$

eigenvectors : v_1, v_2, v_3

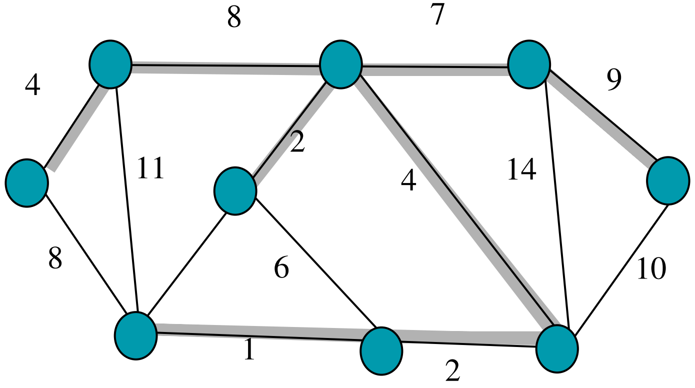
$$\vec{N} \begin{cases} \rightarrow v_3 \\ \rightarrow -v_3 \end{cases}$$

2. Consistent Tangent Plane Orientation: Graph Optimization Problem


Incorrect Surface Normals

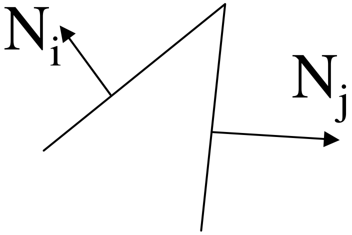

Corrected Surface Normals

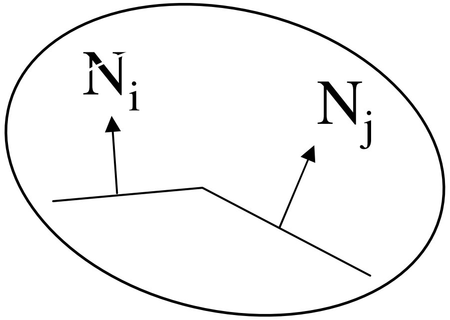
MST: A minimal spanning tree for
a connected graph

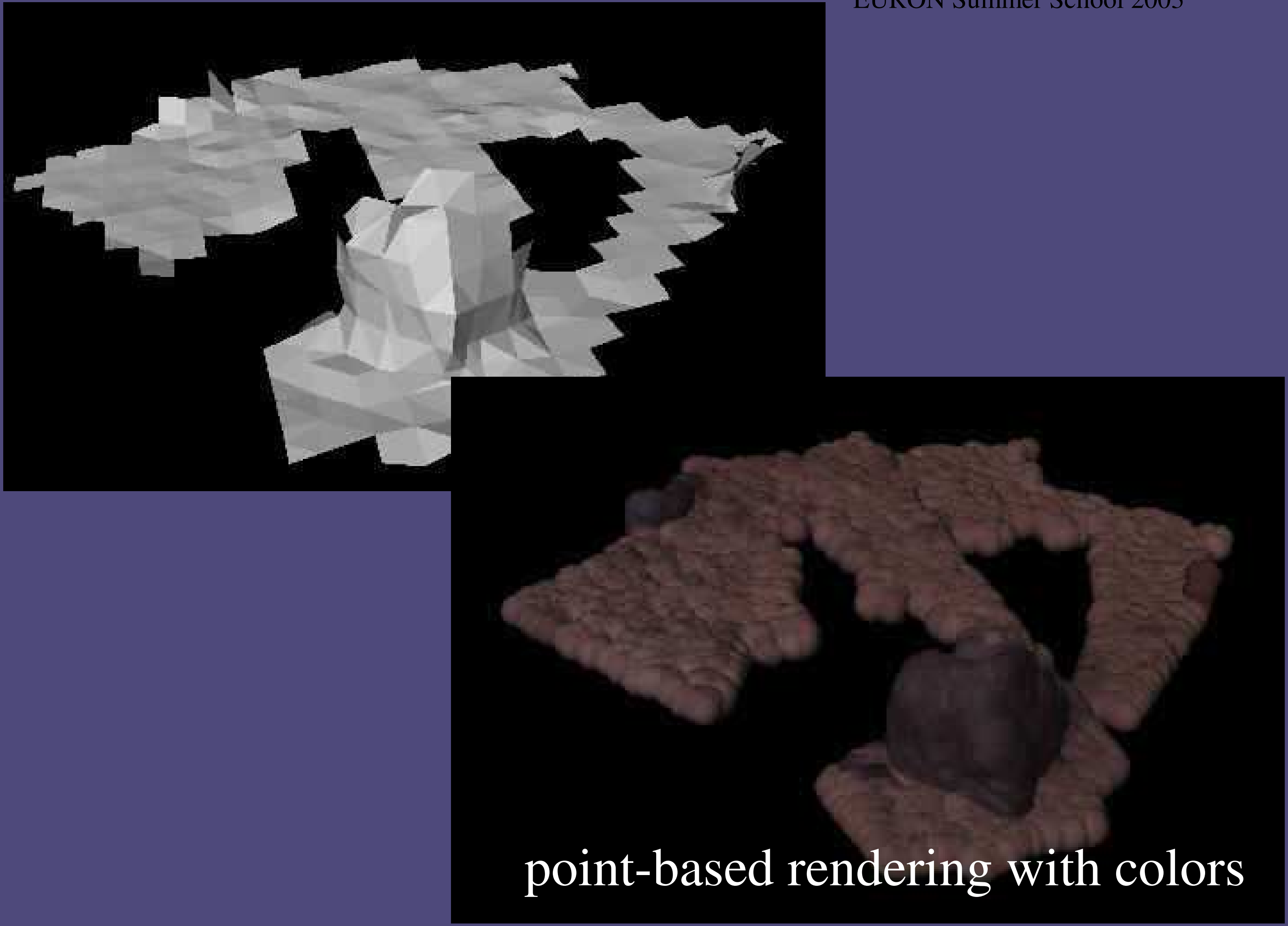


Cost on edge: $1 - N_i . N_j$

Propagate along directions of low curvature!





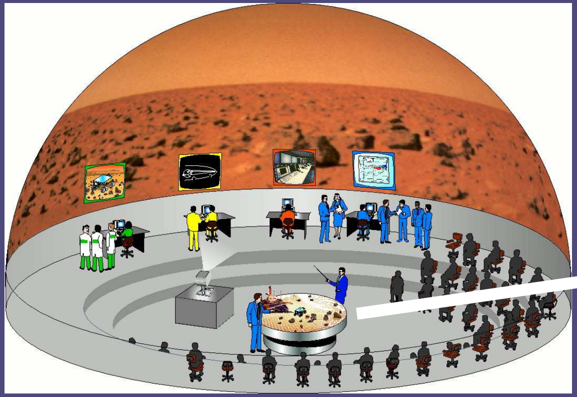


point-based rendering with colors

3D Visualization

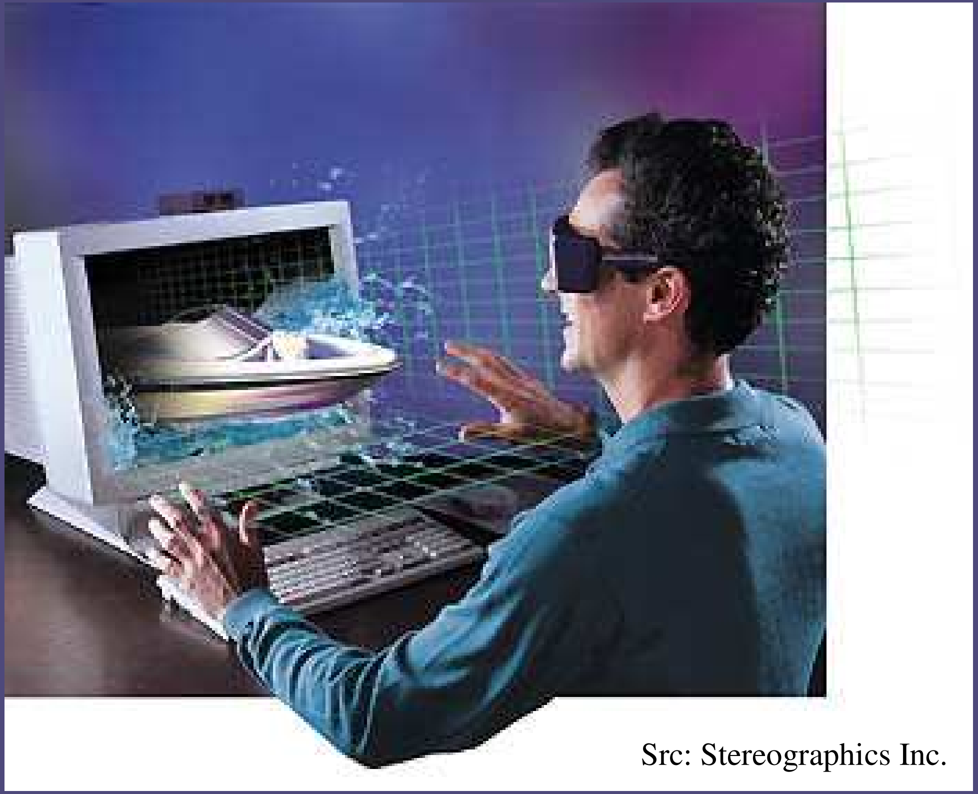
Iso-surface Extraction

3D Mesh
3D Texture



Autostereoscopic Visualization

3D Visualization without any eye wear !

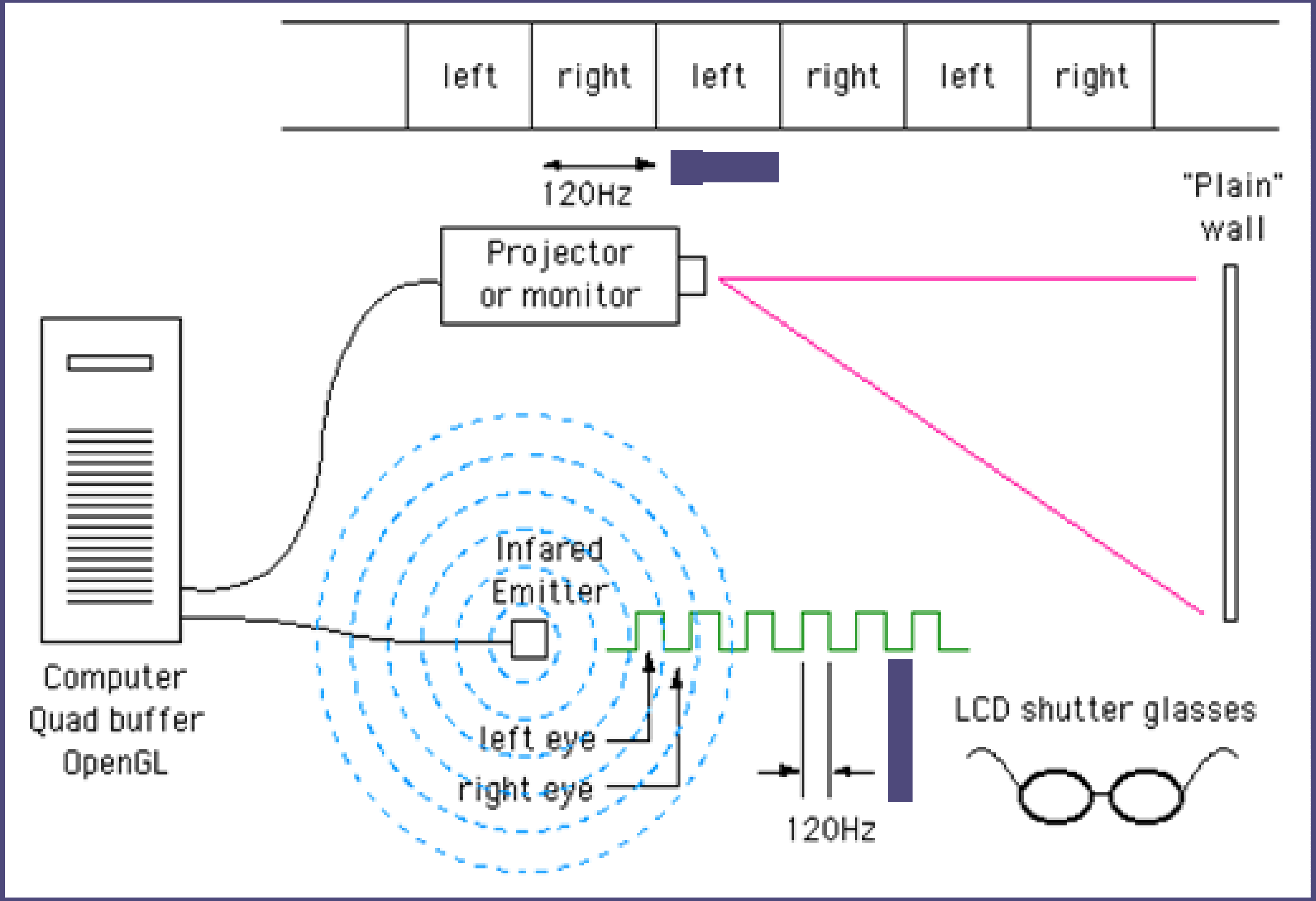


Src: Stereographics Inc.

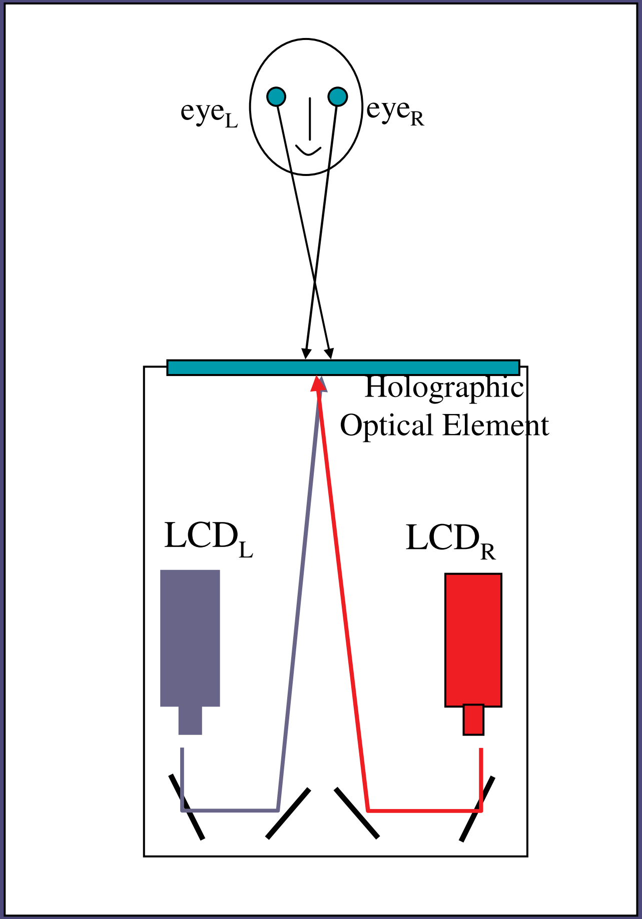
Stereoscopic viewing

Autostereoscopic viewing

Stereoscopic Visualization



Stereoscopic viewing

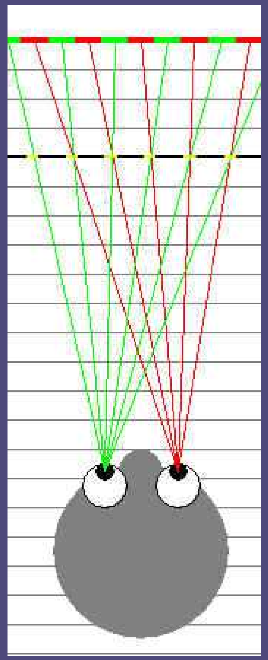


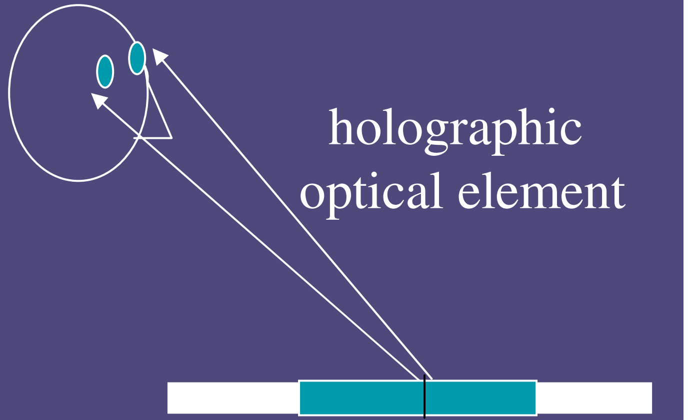
Autostereoscopic viewing

Autostereoscopic Displays

Relatively new area !

Hale et al., 1997, Siggraph
Perlin et al., 2000, Siggraph

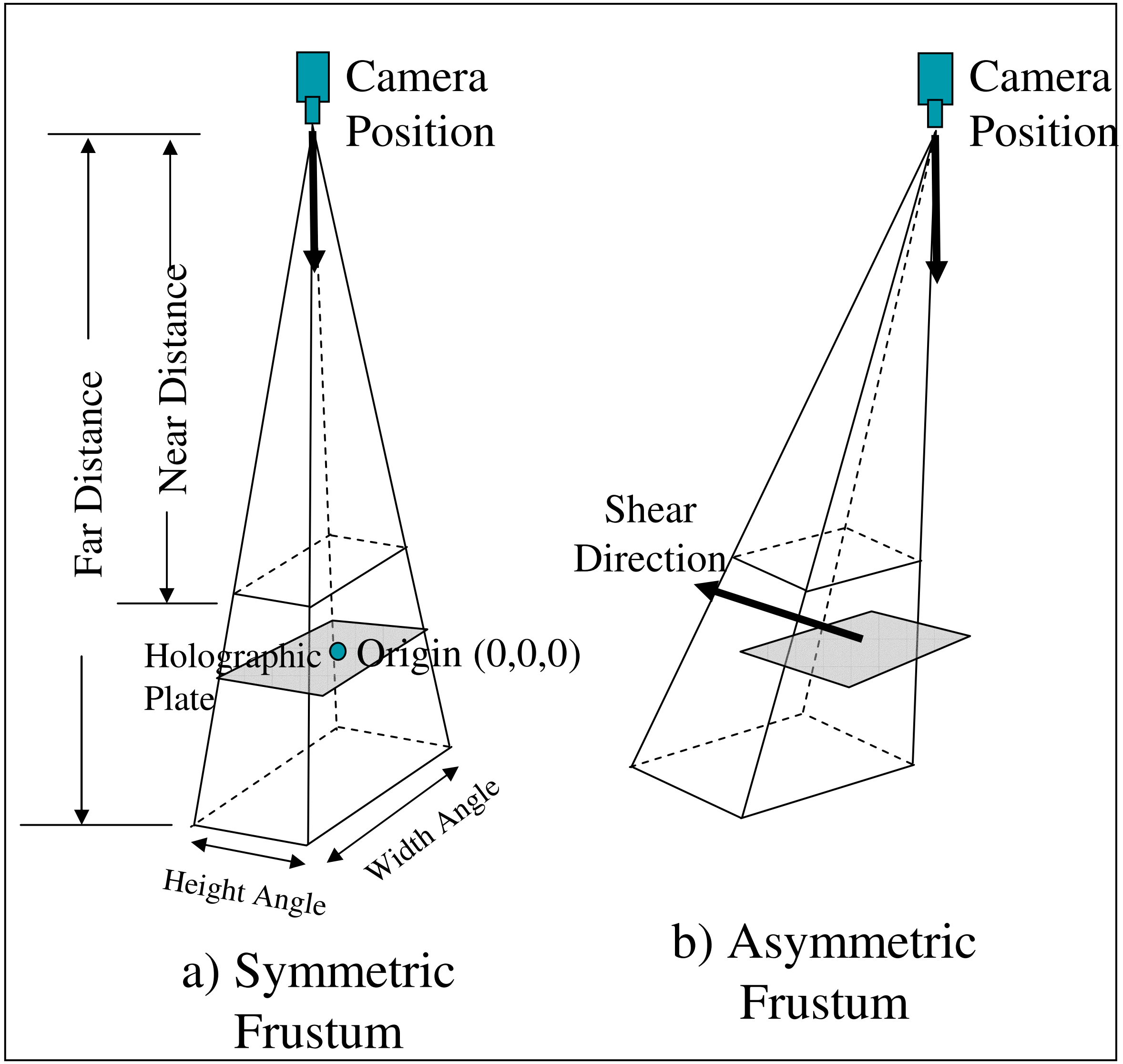




Classification by Hale et al.:

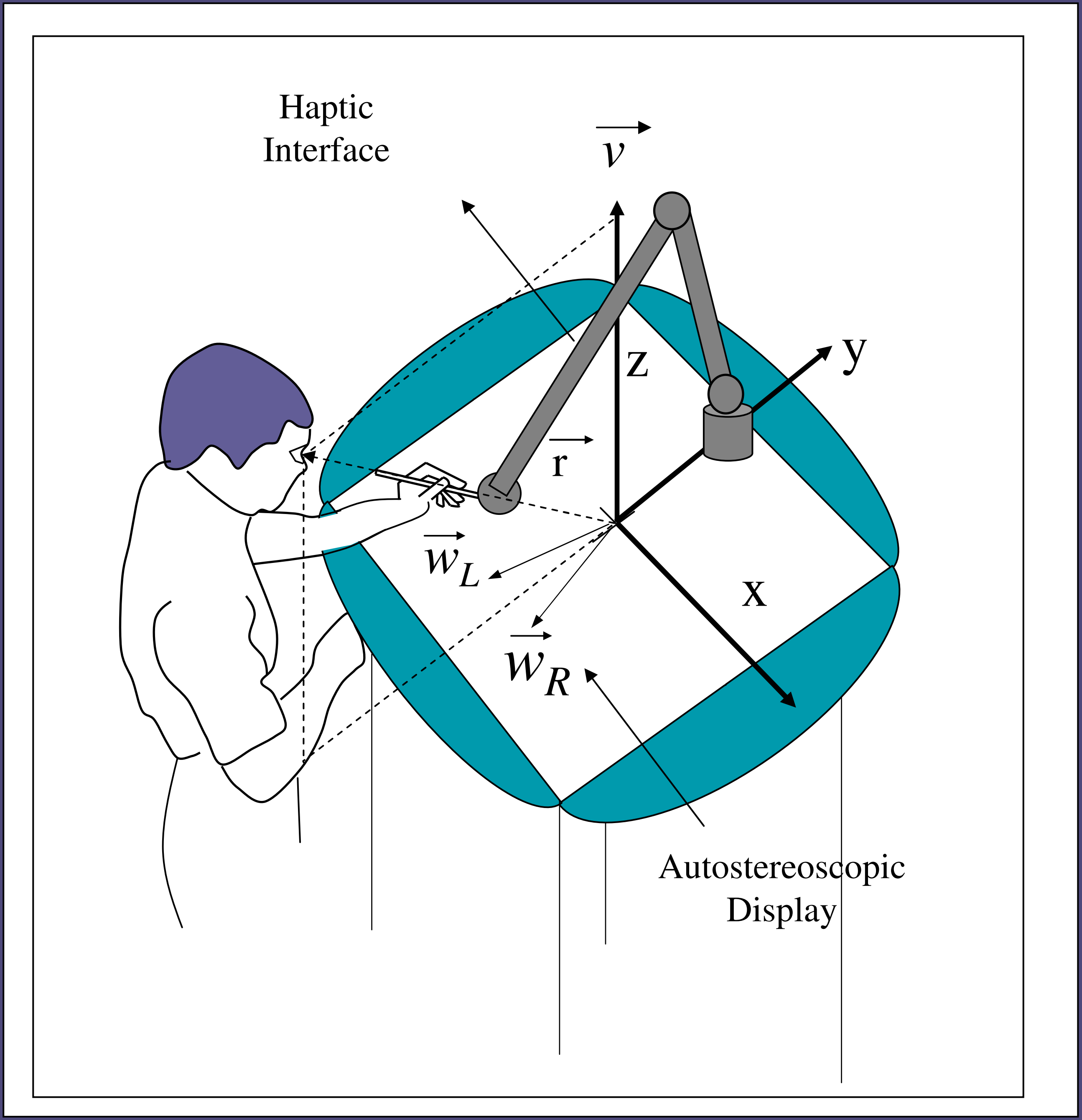
- Re-imaging displays
- Volumetric displays
- Parallax displays
  - Holograms
  - Parallax Barrier Displays
  - Lenticular Sheet Displays
  - Holographic Stereograms
  - Electro-Holography

Stereo Rendering : Shear Transform



a) Symmetric Frustum

b) Asymmetric Frustum



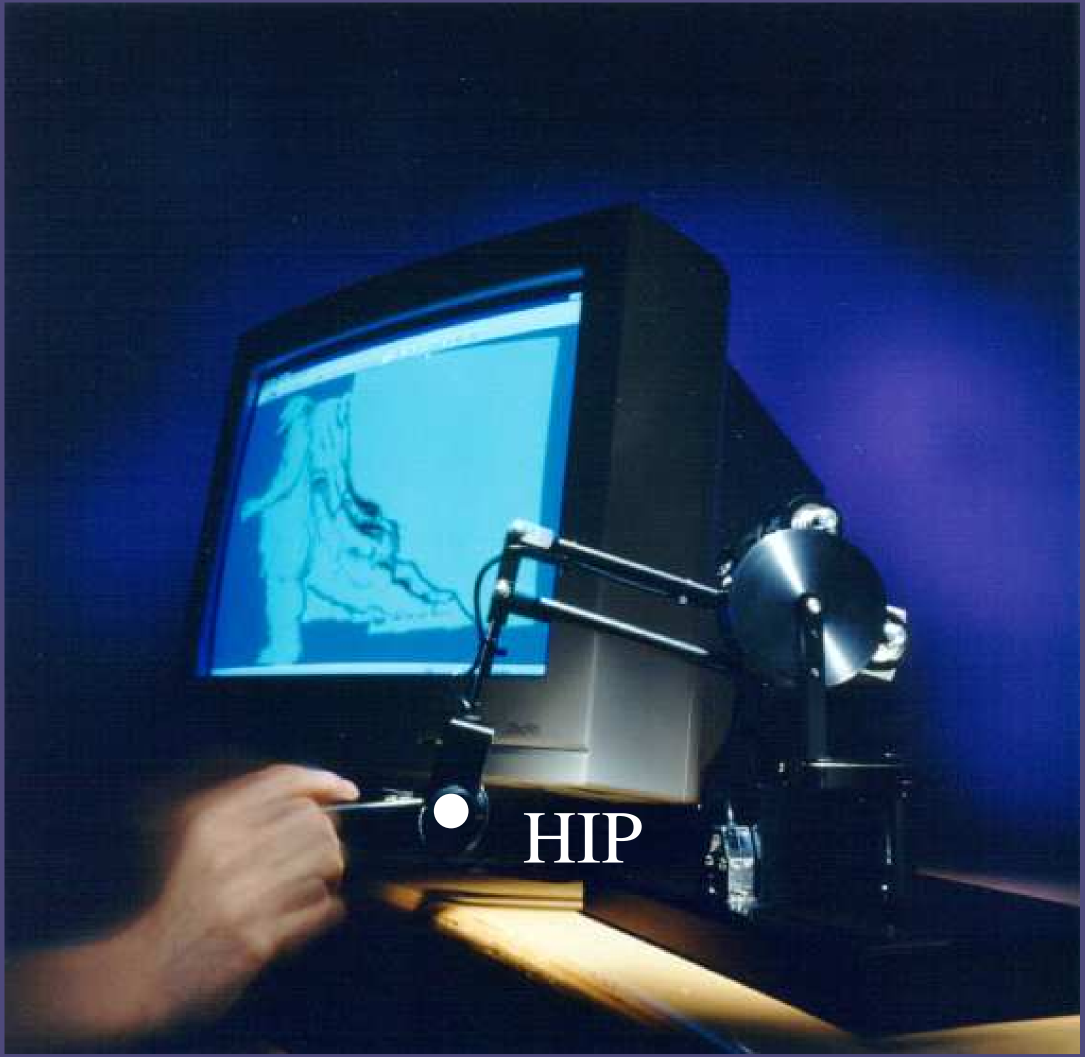
Shear Transform:

$$\mathbf{S} = \begin{bmatrix} I + \tan(\varphi)(\vec{v}^T \vec{w}) & 0 \\ -(\vec{Q} \cdot \vec{v})\vec{w} & 1 \end{bmatrix}$$

$$\mathbf{S}_{camera} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ \frac{r_x}{r_z} & -\frac{r_y}{r_z} & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

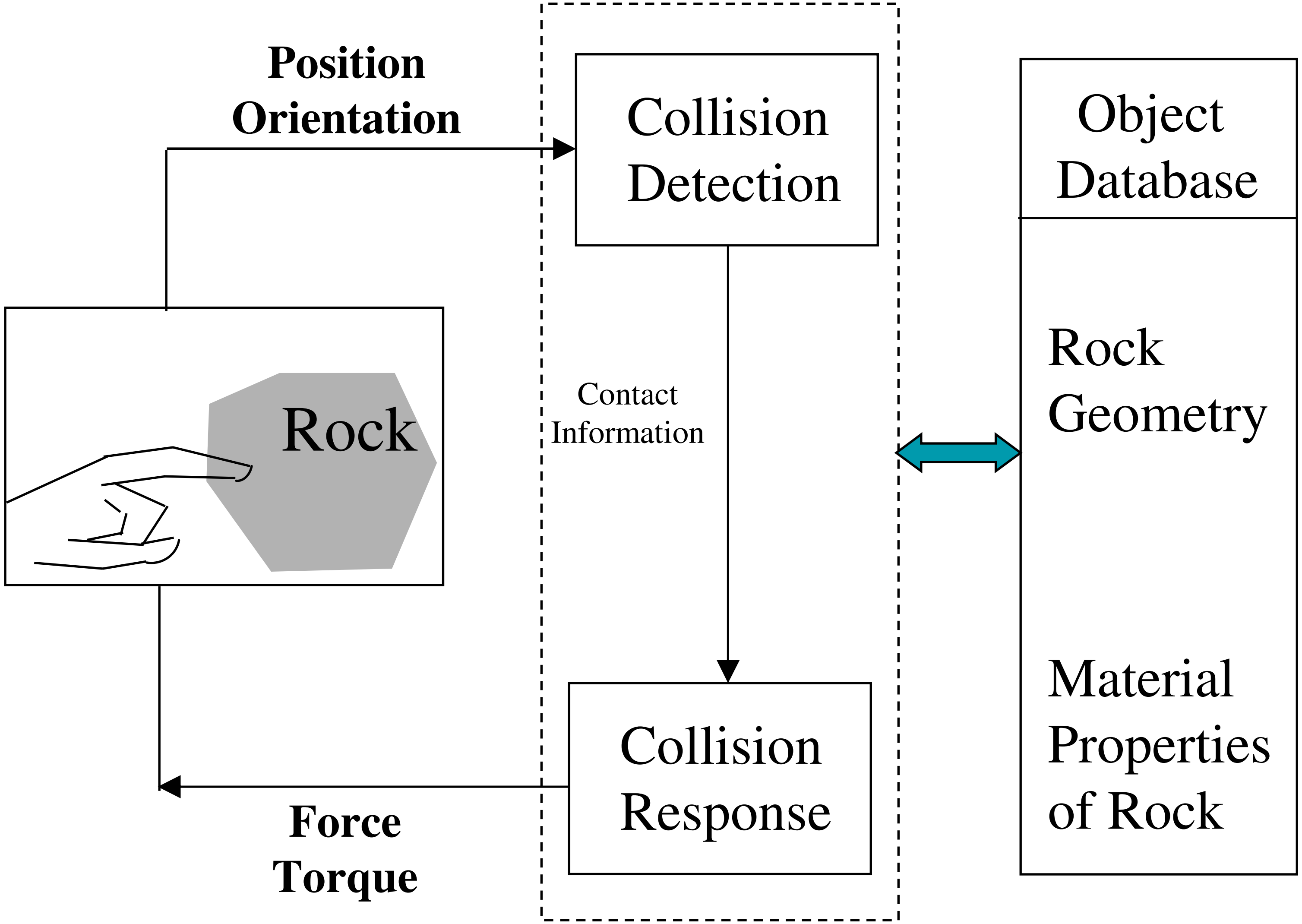
Eye pos: $\begin{bmatrix} r_x & r_y & r_z \end{bmatrix}$

Haptic Visualization



- Rendering rock textures
- Displaying 3D rock shapes
- Tele-science experiments
- Guiding user's movements
- Positioning rover instruments

Haptic Display of Shape



Position
Orientation

Rock

Collision Detection

Contact Information

Collision Response

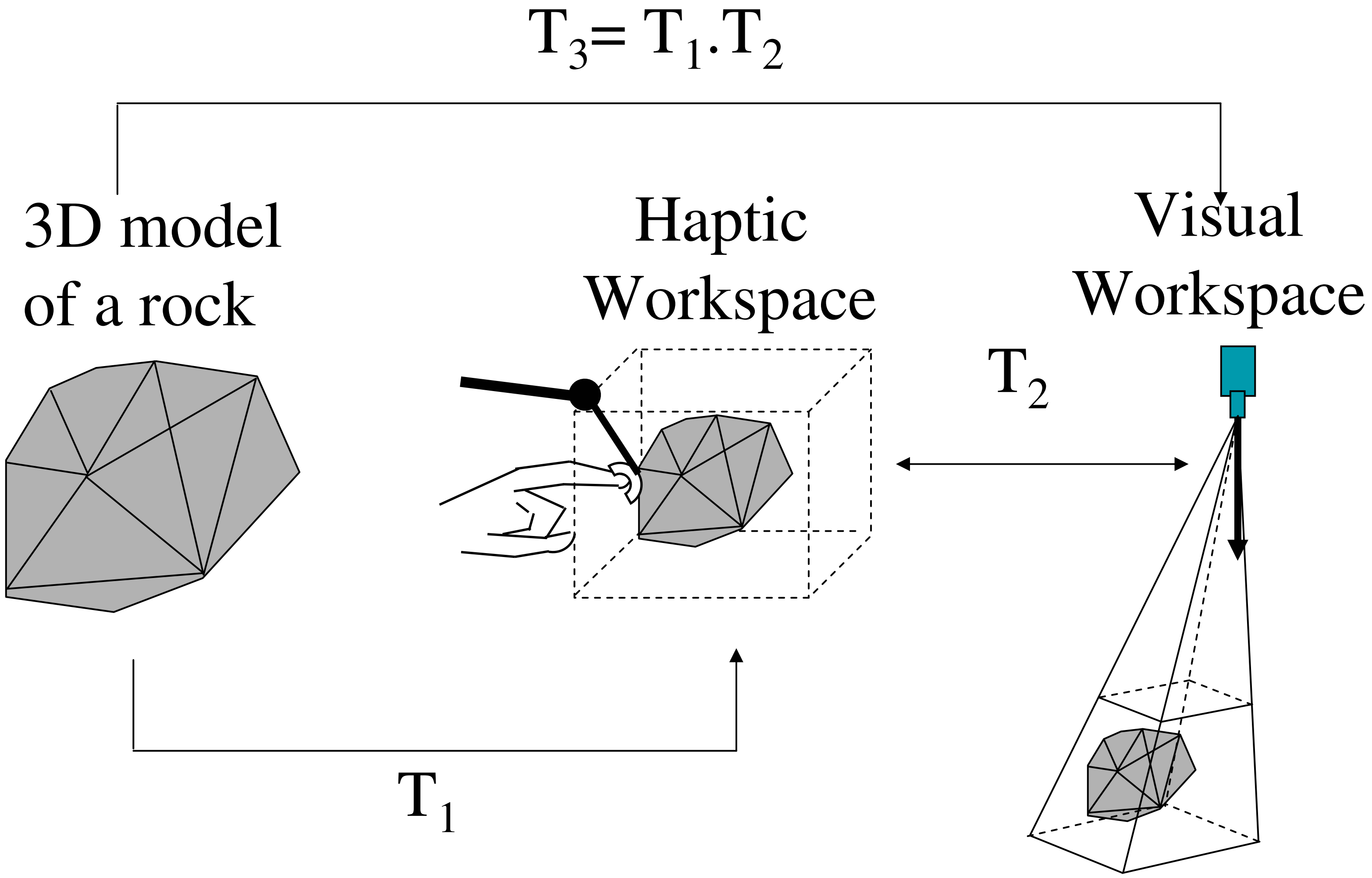
Force
Torque

Object Database

Rock Geometry

Material Properties of Rock

Mapping Between Visual and Haptic Workspaces



$T_3 = T_1 . T_2$

3D model
of a rock

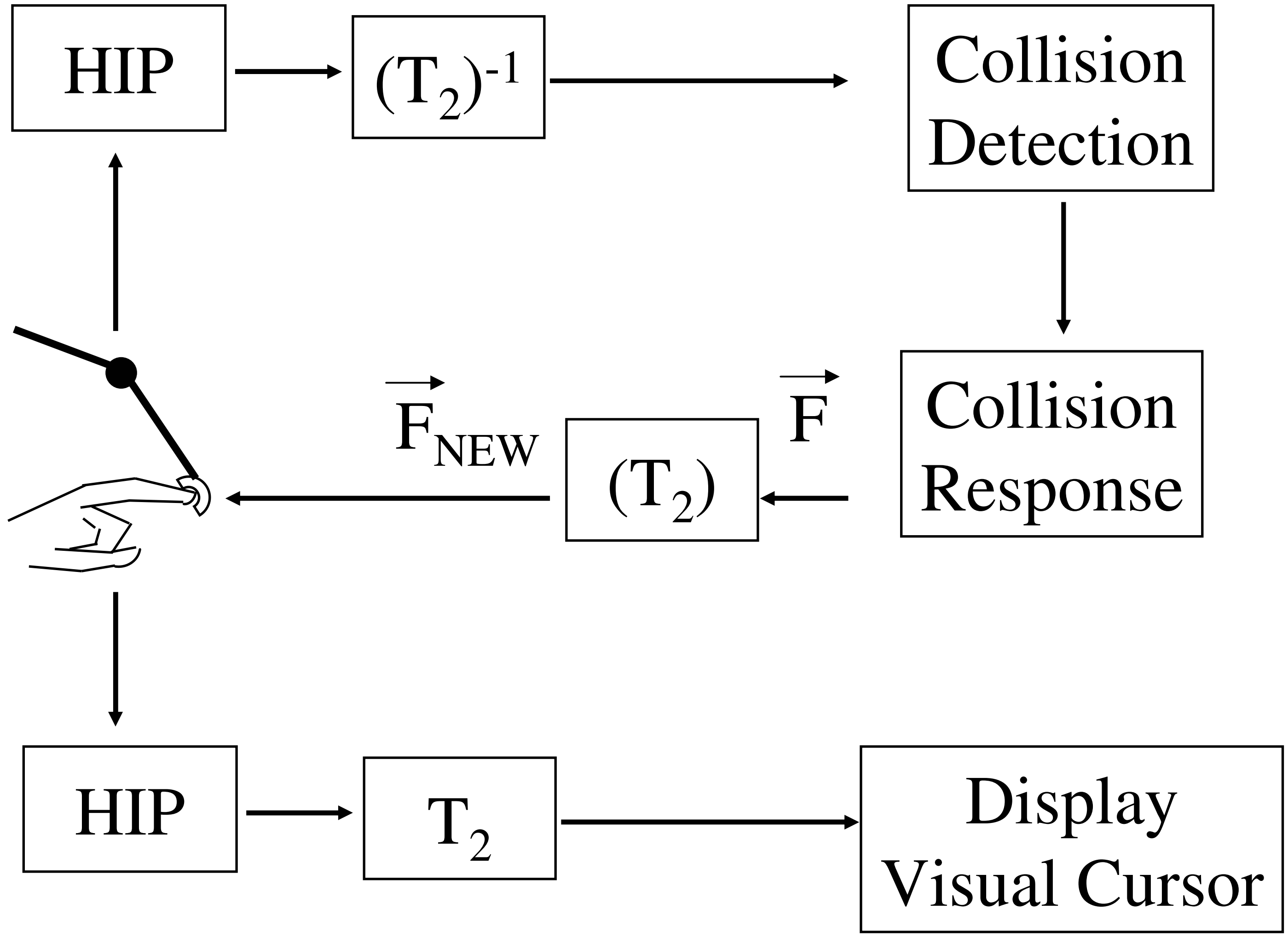
Haptic
Workspace

Visual
Workspace

T_2

T_1

Synchronization of Cursor Movements



HIP → $(T_2)^{-1}$ → Collision Detection

Collision Detection → Collision Response

Collision Response → $\vec{F}$ → (T_2) → $\vec{F}_{NEW}$

HIP → T_2 → Display Visual Cursor


JPL
Jet Propulsion Laboratory

Unsolved/Untouched Problems

- 3D Registration: problems with ICP, global registration
- 3D Integration: robustness, storage requirements
- 3D Transmission: 3D geometry comp. vs 3D data comp.
- More effective transmission of normals and colors
- 3D Visual and Haptic Texturing
- Image-Based rendering
- Optimized computation (e.g. efficient data structures such as ADFs)
- Missing link between image analysis and 3d modeling
- More efficient graphical rendering (e.g. point-based rendering)
- Missing link between real-time 3D modeling and rover navigation
- Unified data structures for transmission of multi-modal data

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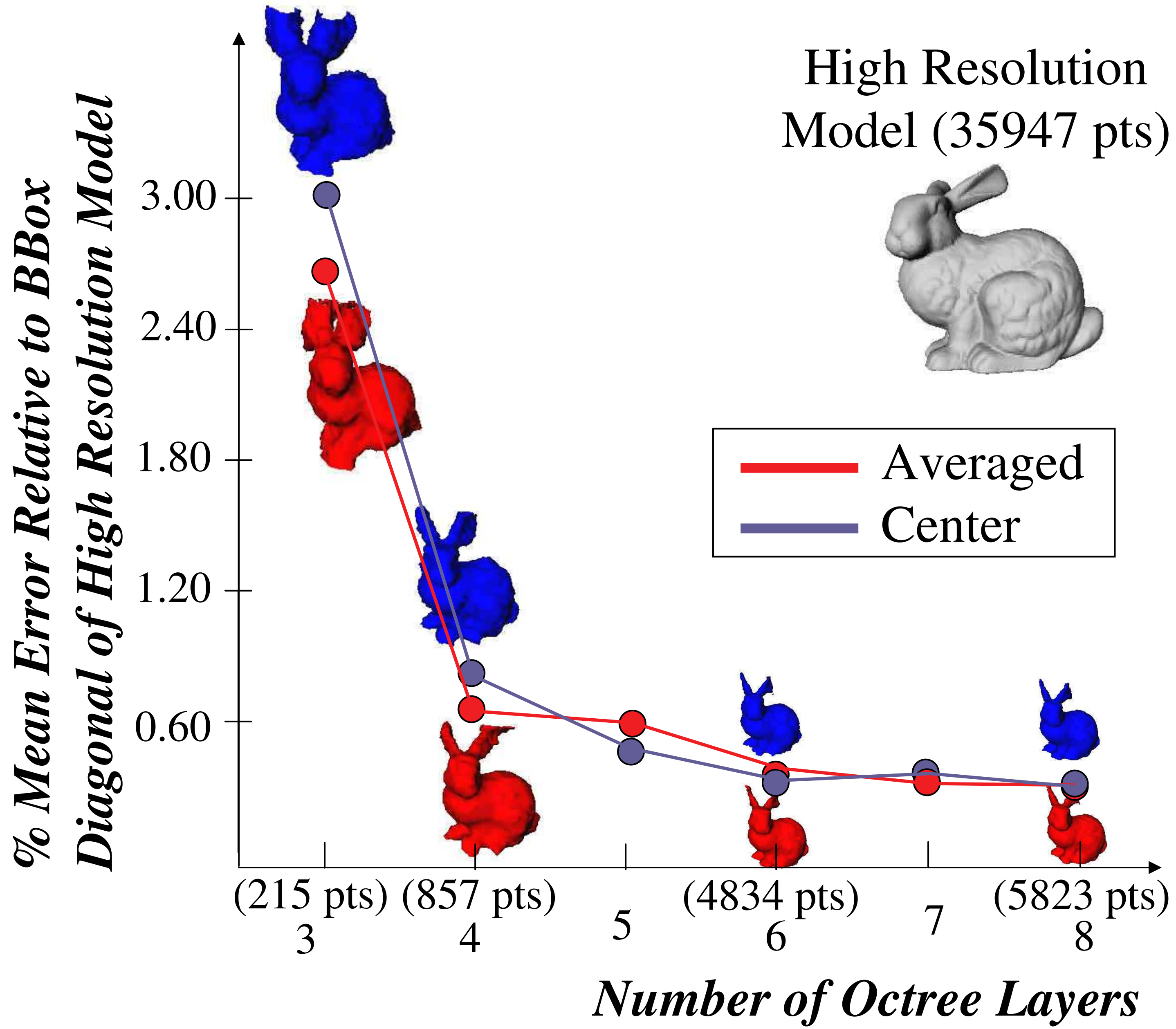
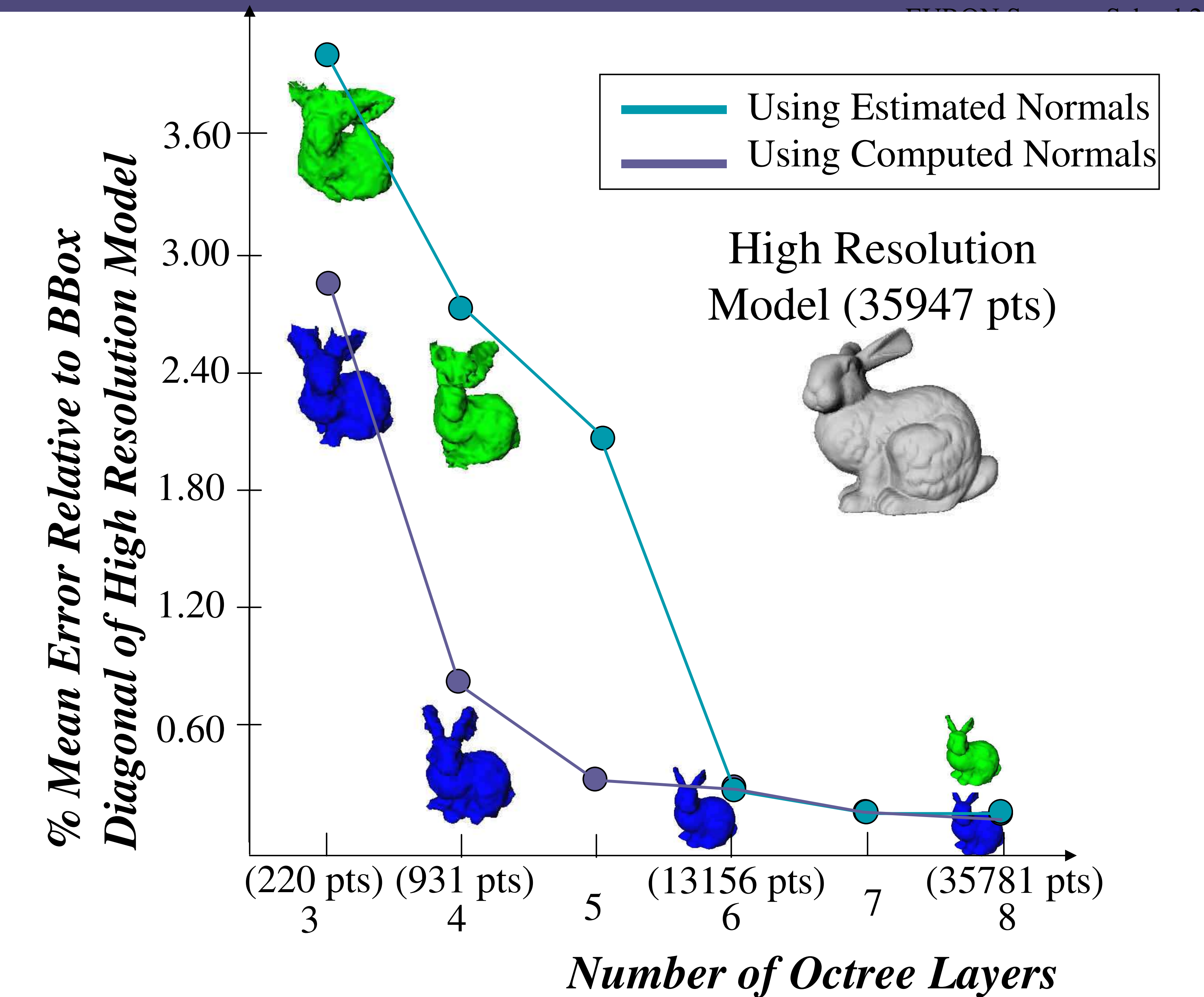
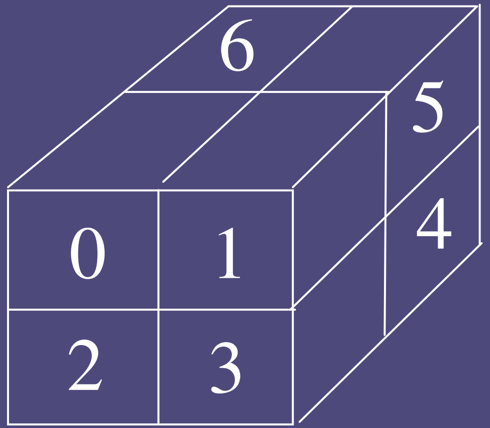
Prof. Brian Curless, UW (3D photography notes; public domain)
Dr. Huges Hoppe, Microsoft (Ph.D. Thesis and 3D reconstruction code; public domain)


High Resolution
Model (35947 pts)
Averaged
Center
3.00
2.40
1.80
1.20
0.60
% Mean Error Relative to BBox
Diagonal of High Resolution Model
(215 pts)
3
(857 pts)
4
5
(4834 pts)
6
7
(5823 pts)
8
Number of Octree Layers


% Mean Error Relative to BBox
Diagonal of High Resolution Model
3.60
3.00
2.40
1.80
1.20
0.60
Using Estimated Normals
Using Computed Normals
High Resolution
Model (35947 pts)
(220 pts)
3
(931 pts)
4
5
(13156 pts)
6
7
(35781 pts)
8
Number of Octree Layers

Octrees for 3D Data Transmission: Encoding

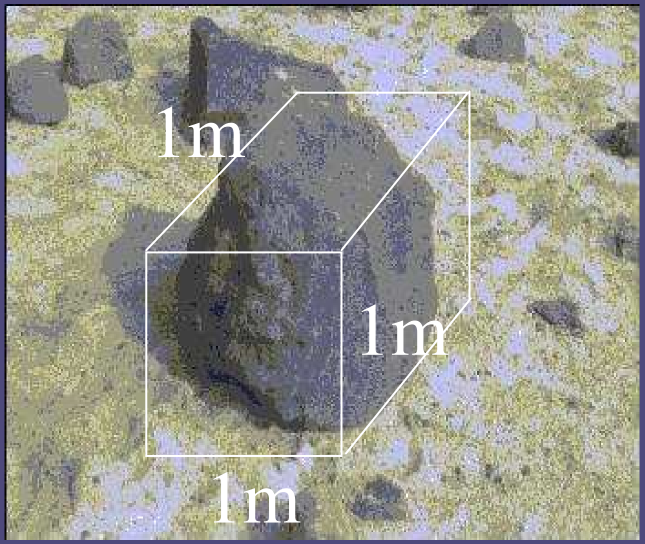


3 bites/octant

abc	
000	0
001	1
010	2
..	
111	7

$a*2^2 + b*2 + c$

Ref: Yemez and Schmitt, 1999



Path to a leaf node: 3 4 1 7 0 3 3 2

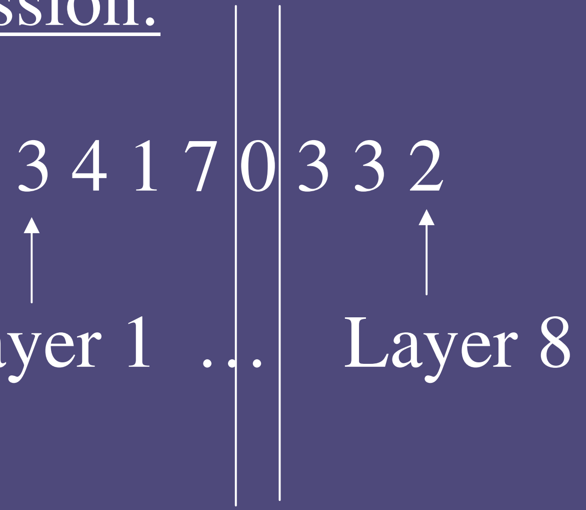
8 layers = 2^8 X 2^8 X 2^8 cubes
Resolution = 1000 mm / 2^8 = ~ 4 mm !!!

Octrees for Progressive Transmission

All data is transmitted at once (Maximum 8 layers):

2^8 X 2^8 X 2^8 cubes * 3 bites/cube * 1 byte/8 bits = ~ 6.3 MB !!

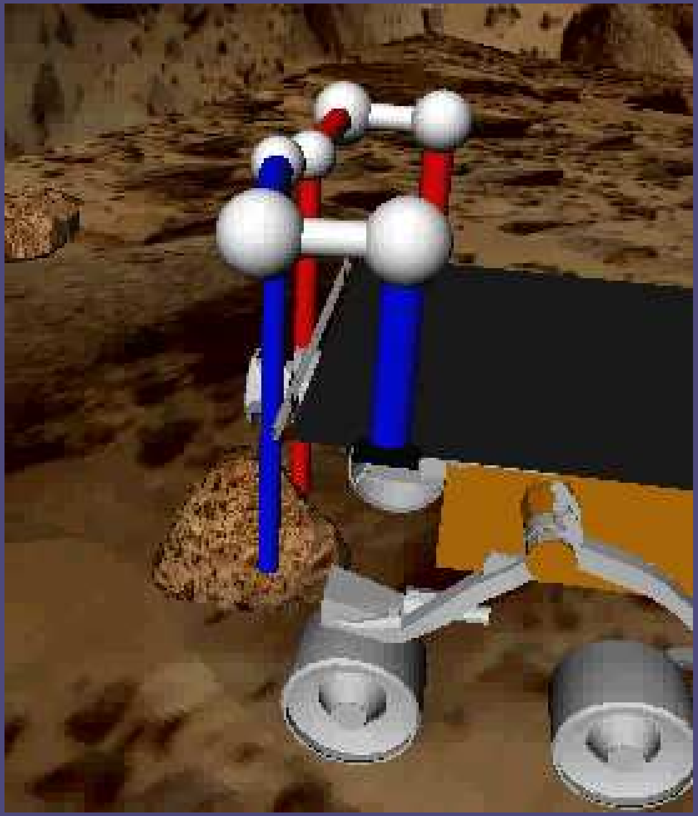
Progressive Transmission:



Path to a leaf node: 3 4 1 7 0 3 3 2

Layer 1 . . . Layer 8

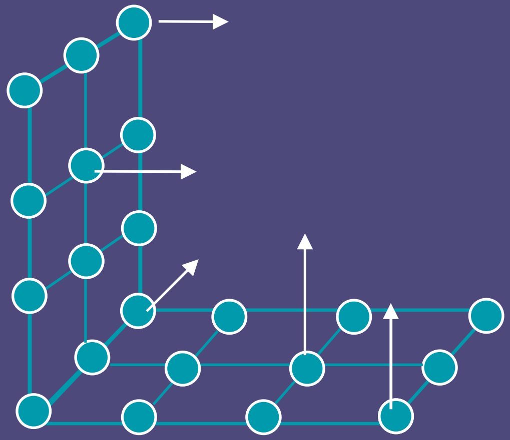
If we transmit the difference
between layer 4 to 5 : ~ 10 KB ! (not even compressed)

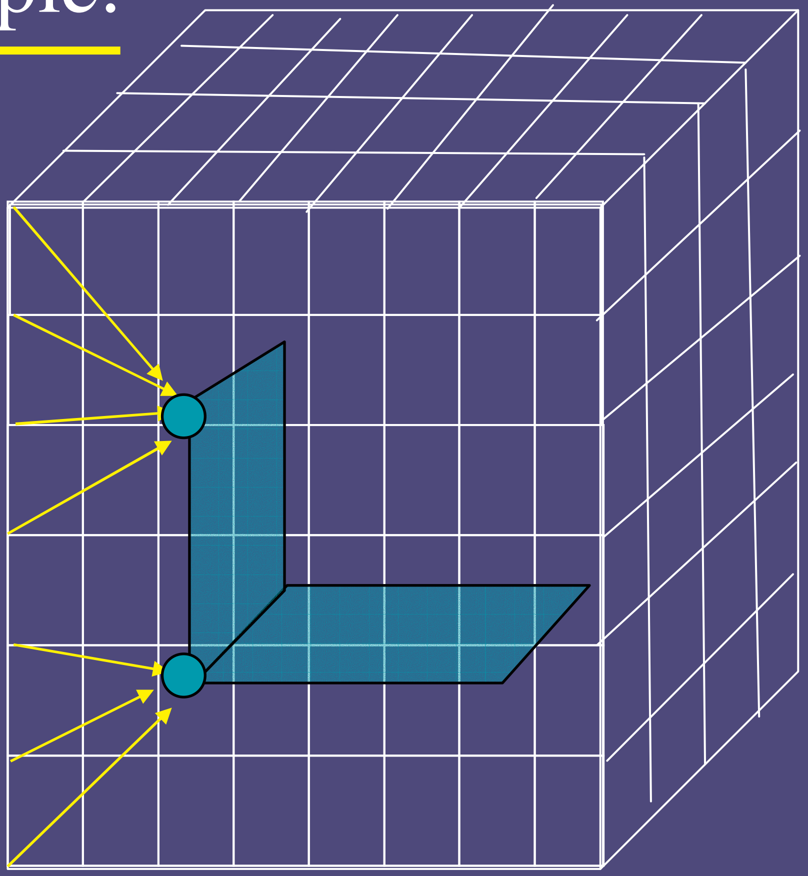


A Simple 3D Example:

Input Data:

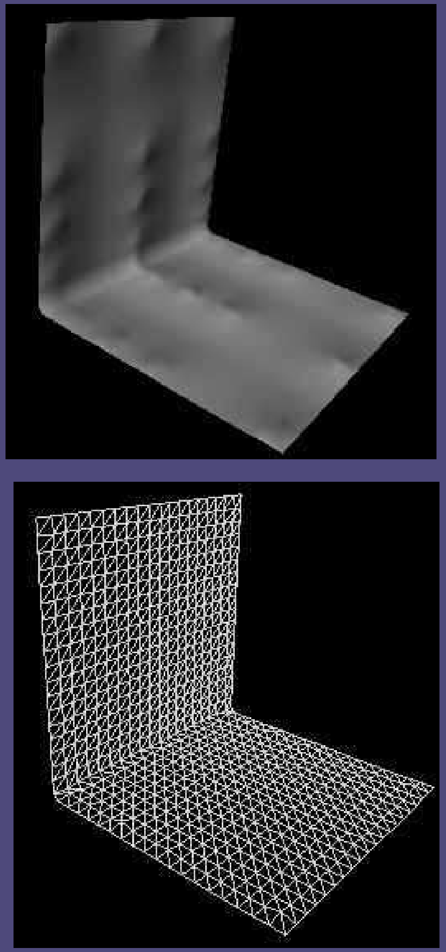
v1x v1y v1z
v2x v2y v2z
…
v10x v10y v10z
n1x n1y n1z
n2x n2y n2z
…
n10x n10y n10z





Voxelization

Output



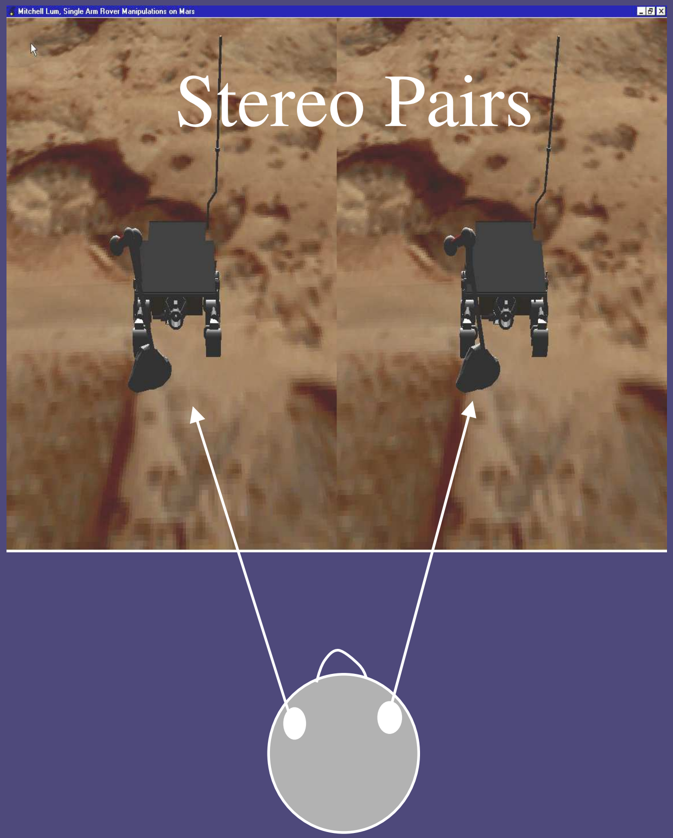
Stereoscopic Visualization: Depth Perception

2D:

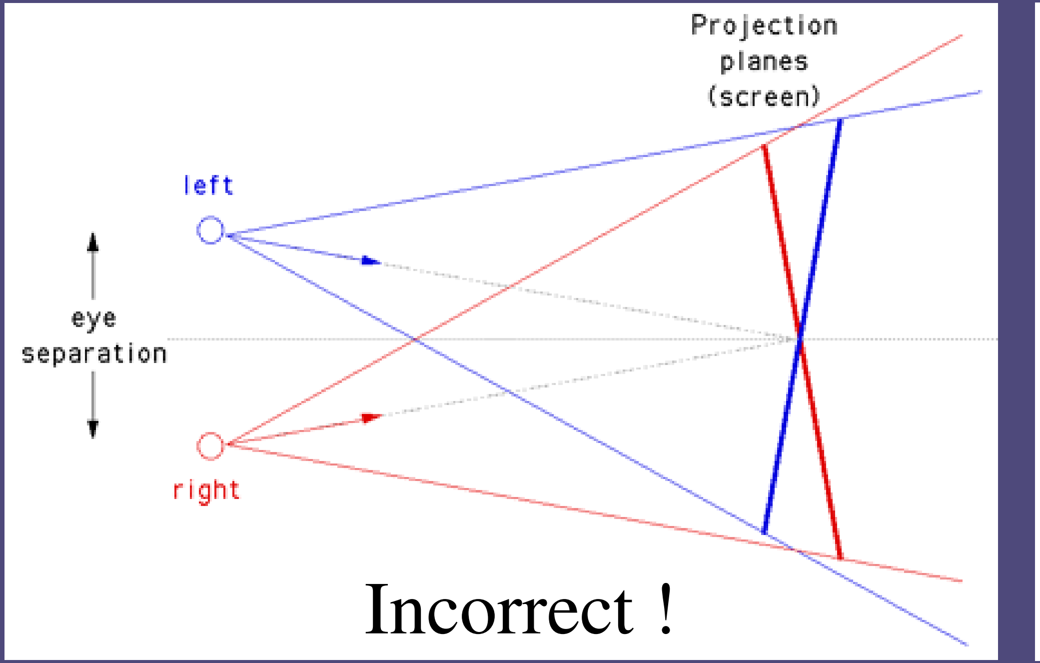
- Perspective
- Occlusion
- Lighting, shadows
- Relative motion
- Texture

3D:

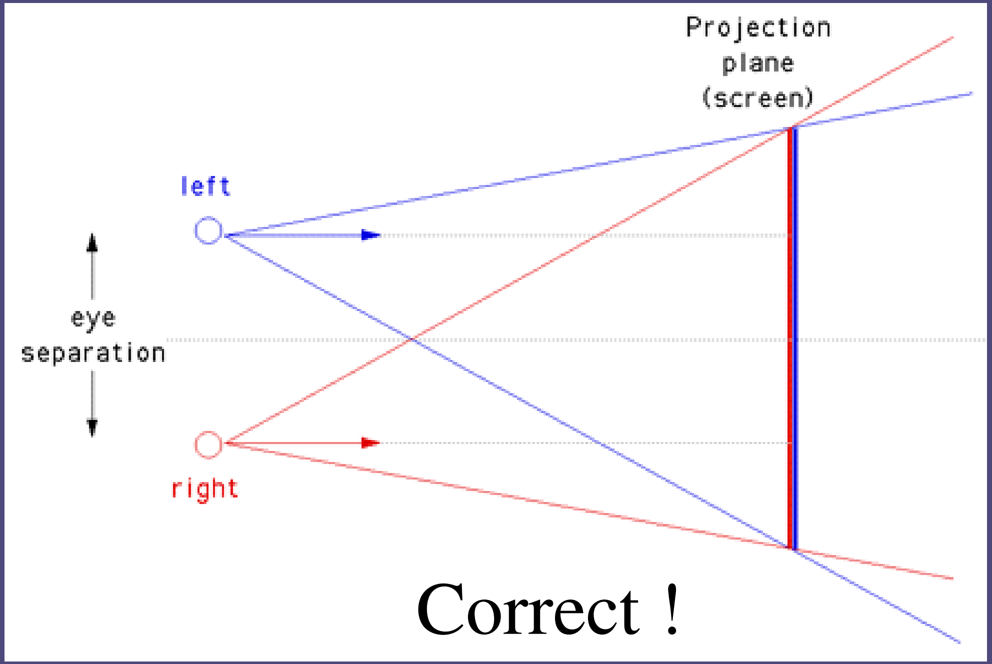
- Binocular disparity
- Accommodation
- Convergence



Stereo Rendering



Incorrect !



Correct !