Implicit Surfaces & Solid Representations

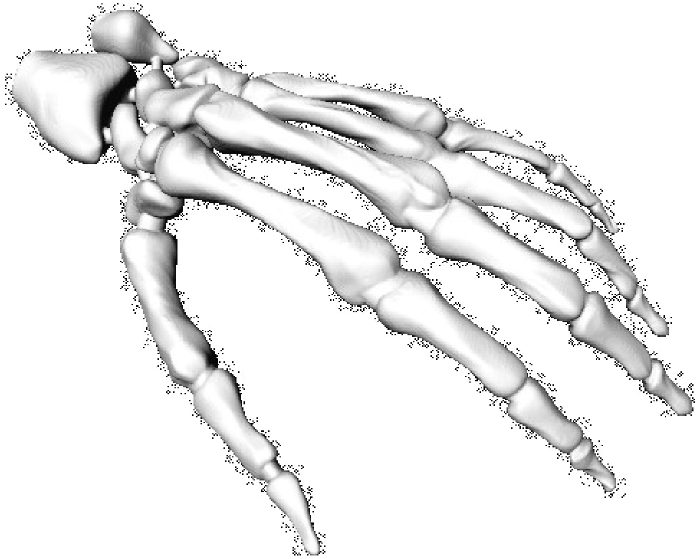
COS 426, Spring 2017
Princeton University

3D Object Representations

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

3D Object Representations

- Desirable properties of an object representation
  - Easy to acquire
  - Accurate
  - Concise
  - Intuitive editing
  - Efficient editing
  - Efficient display
  - Efficient intersections
  - Guaranteed validity
  - Guaranteed smoothness
  - etc.



Large Geometric Model Repository
Georgia Tech

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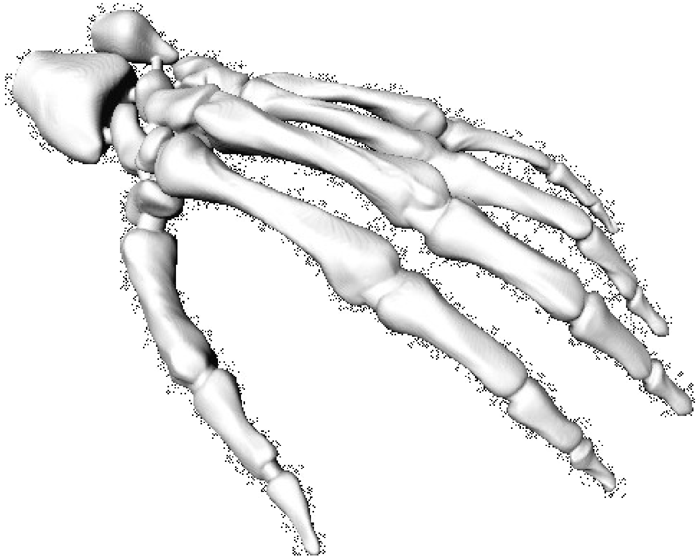

Large Geometric Model Repository
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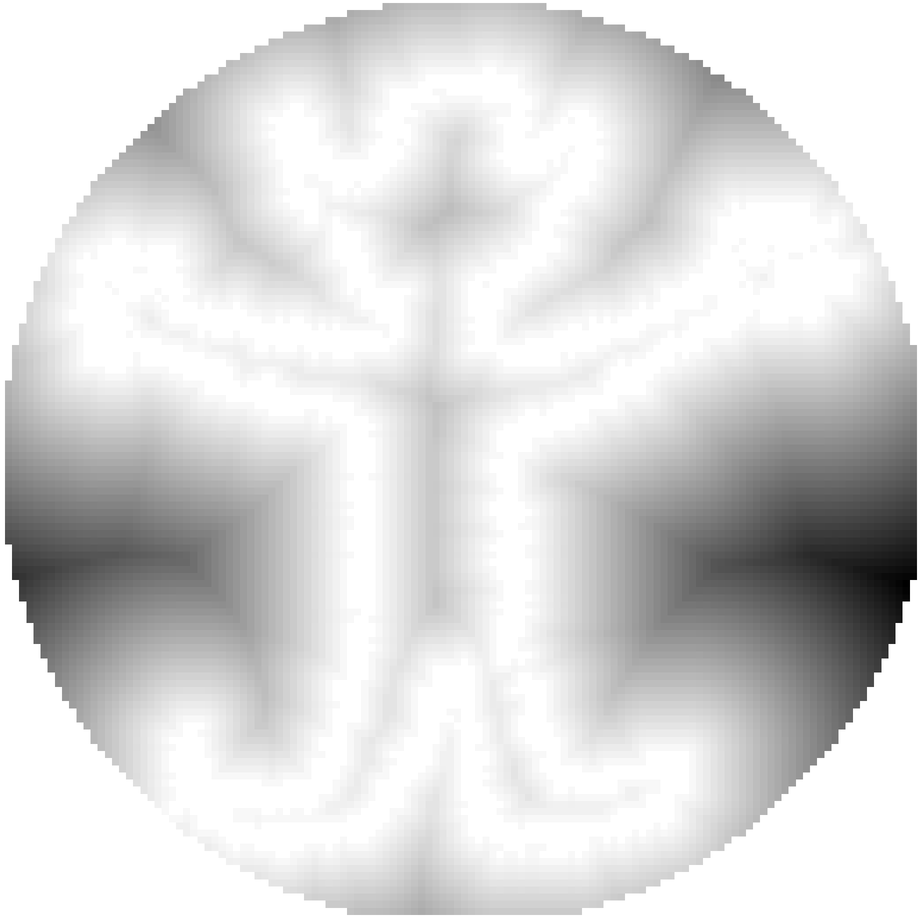
Implicit Surfaces

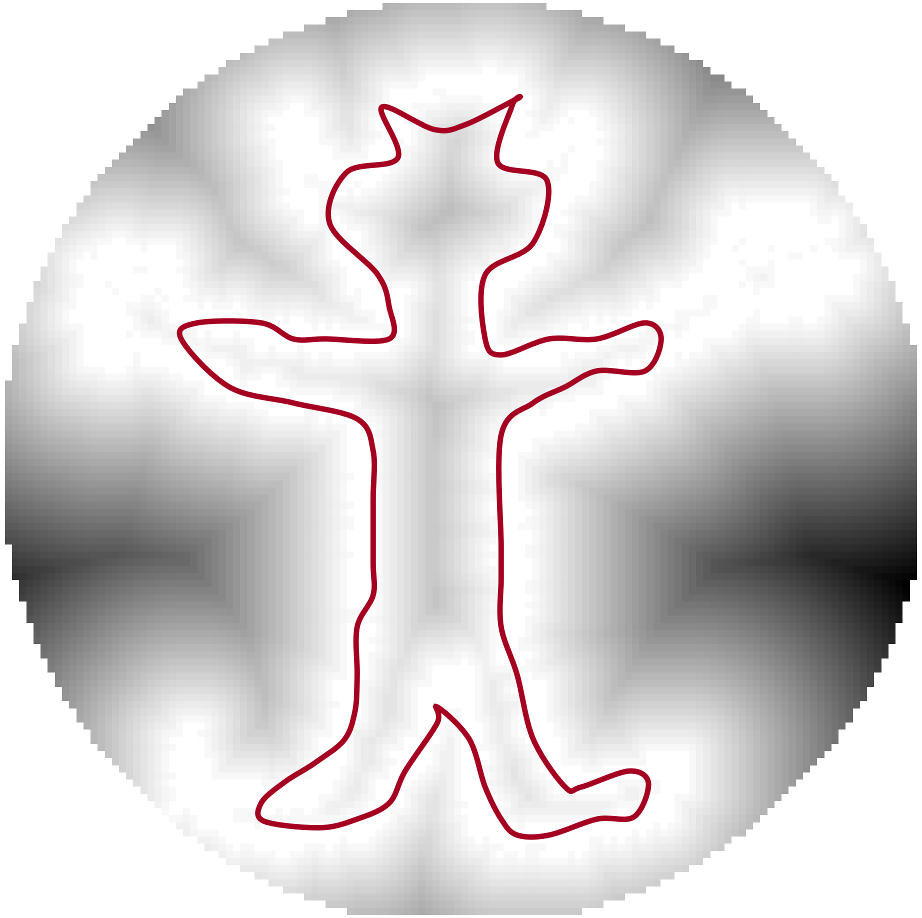
- Represent surface with function over all space



Kazhdan

Implicit Surfaces

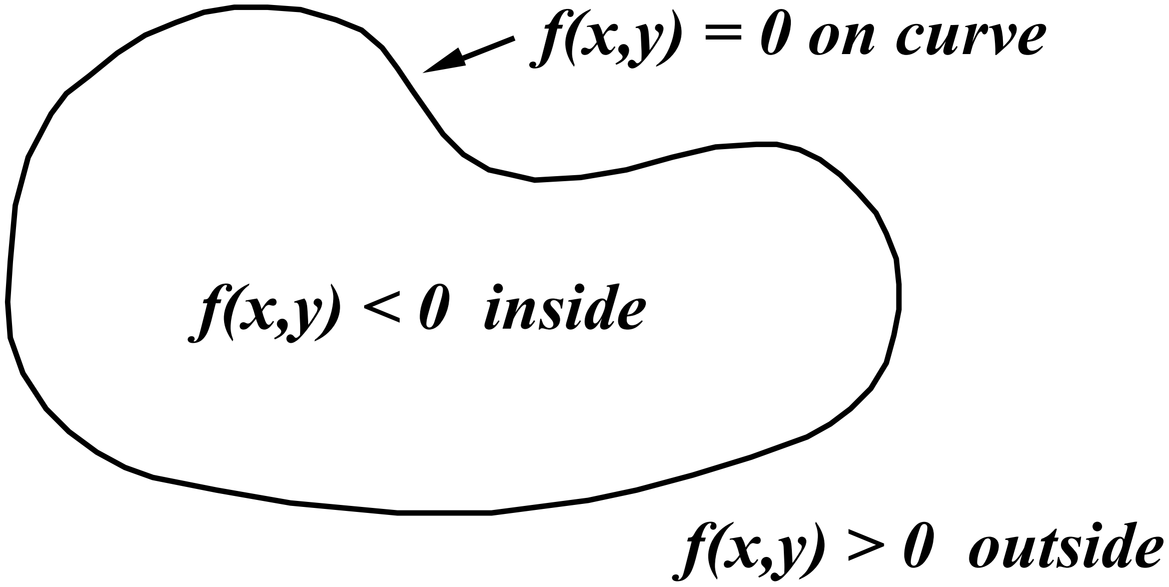
- Surface defined implicitly by function



Kazhdan

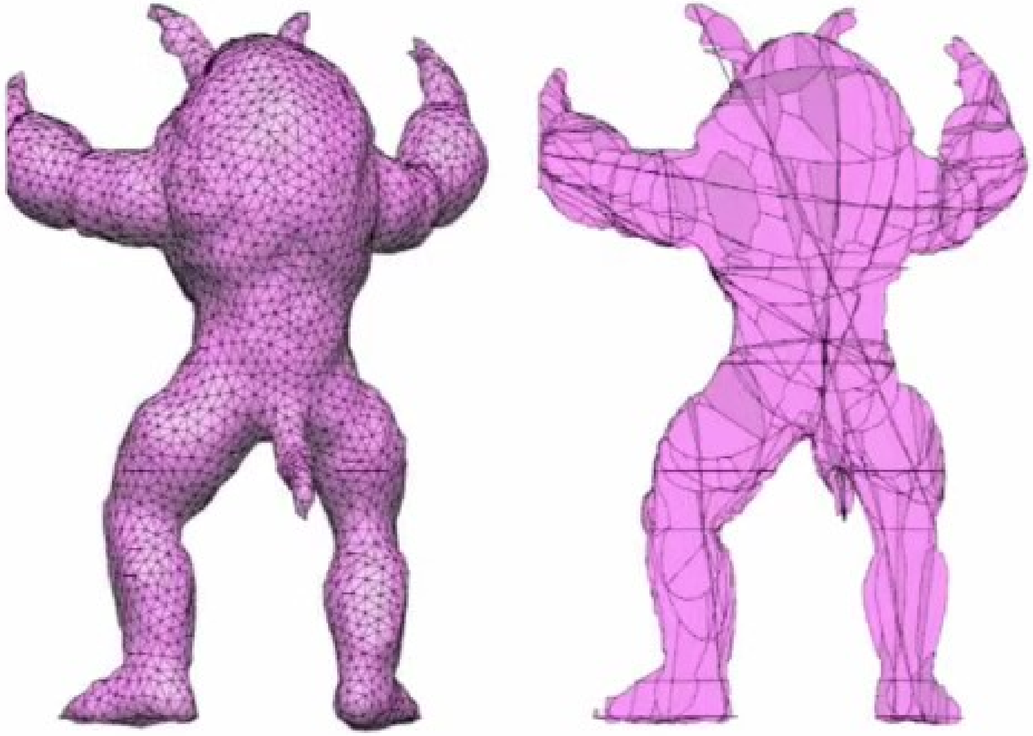
Implicit Surfaces

- Surface defined implicitly by function:
  - f (x, y, z) = 0 (on surface)
  - f (x, y, z) < 0 (inside)
  - f (x, y, z) > 0 (outside)



Turk

Applications



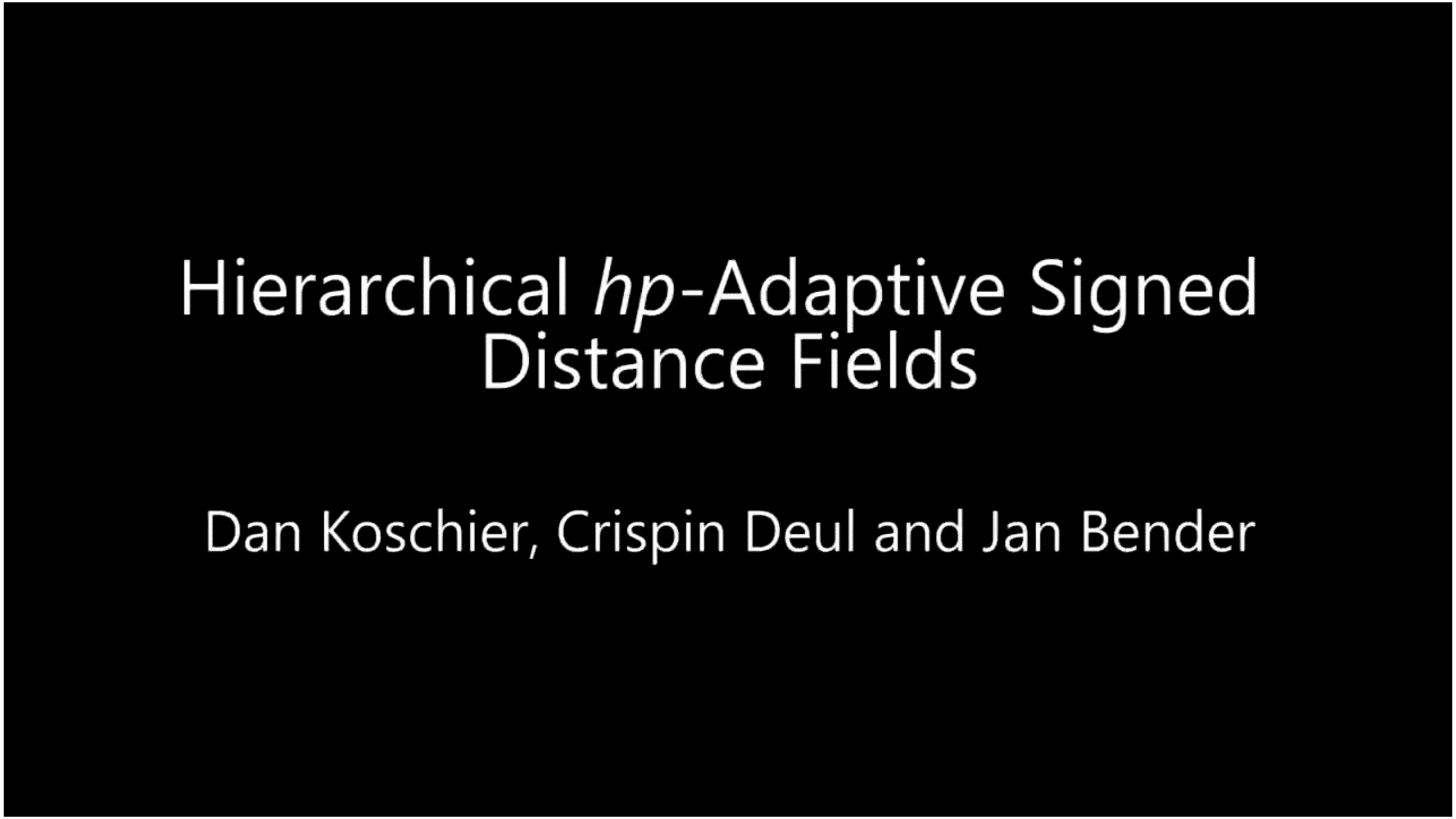
Online Reconstruction of 3D Objects from Arbitrary Cross-Sections
[Bermano et al. 2011]

Applications

Display Signed Distance Field Slices

Signed Distance Fields for Polygon Soup Meshes
[Xu et al. 2014]

Applications



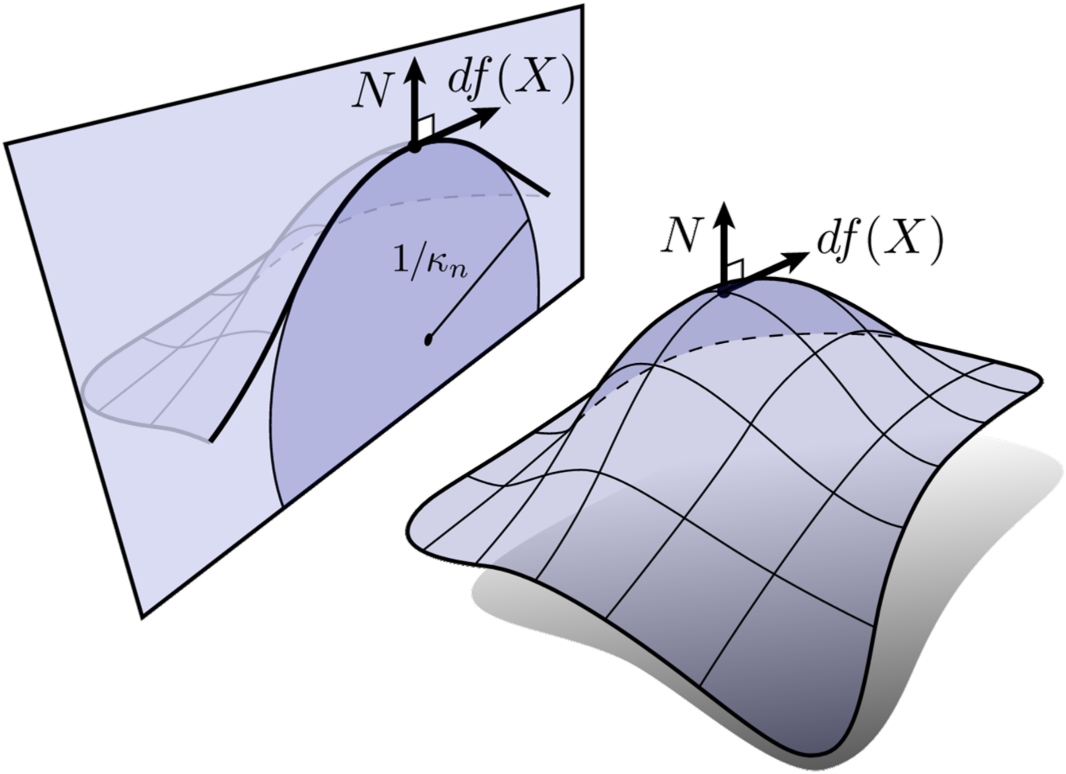
Hierarchical *hp*-Adaptive Signed Distance Fields

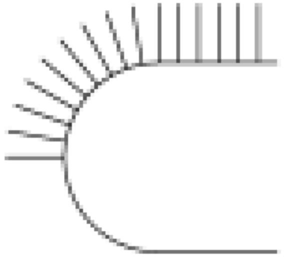
Dan Koschier, Crispin Deul and Jan Bender

Hierarchical hp-Adaptive Signed Distance Fields
[Koschier 2016]

Implicit Surfaces

- Normals defined by partial derivatives
  - Normal - $N(x, y, z) = normalize\left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}\right) = normalize(\vec{\nabla} f)$
    - Example: circle $x^2 + y^2 - 3^2 = 0$
    - Proof: straight forward with an arbitrary curve $\Gamma(t)$ and the chain rule
    - Intuition: Max change rate direction of f must perpendicular to isosurface direction



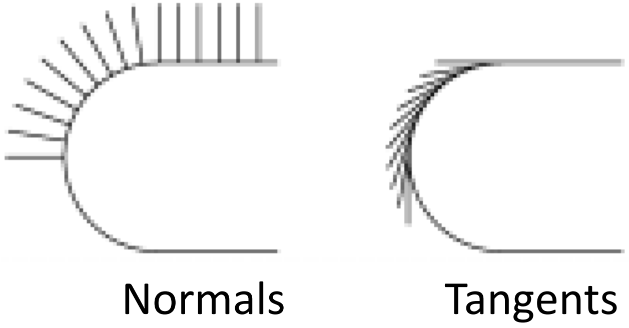


Normals

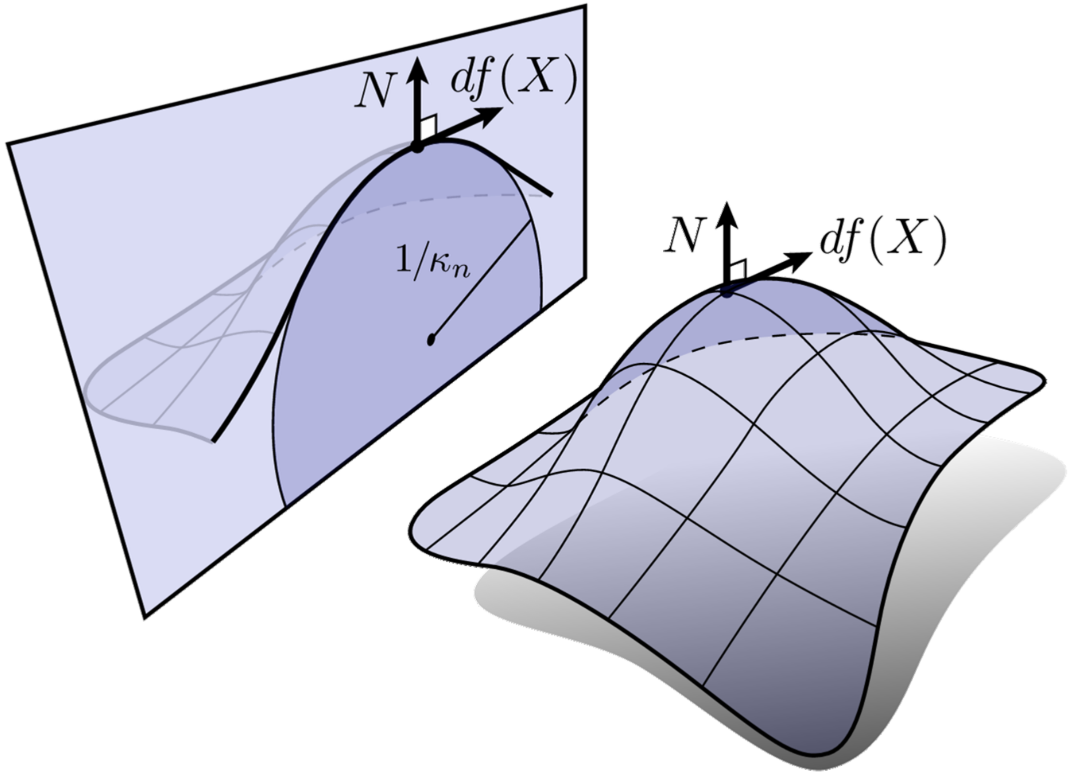
Bloomenthal

Implicit Surfaces

- Normals defined by partial derivatives
  - Normal - $N(x, y, z) = normalize\left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}\right) = normalize(\vec{\nabla} f)$
  - Tangent – $T = N_P \times N$
    - on specific plane P, with normal N_P
    - Otherwise infinite directions
    - Principal directions

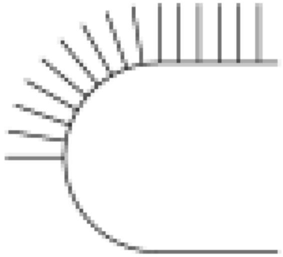


Bloomenthal

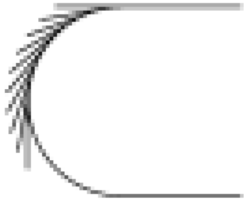


Implicit Surfaces

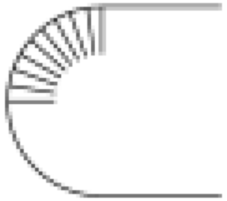
- Normals defined by partial derivatives
  - Normal - $N(x, y, z) = normalize\left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}\right) = normalize(\vec{\nabla} f)$
  - Tangent – $T = N_P \times N$
  - Curvature – change of rate N
    - Computation more involved
    - Through principal directions – A measure for convexity



Normals

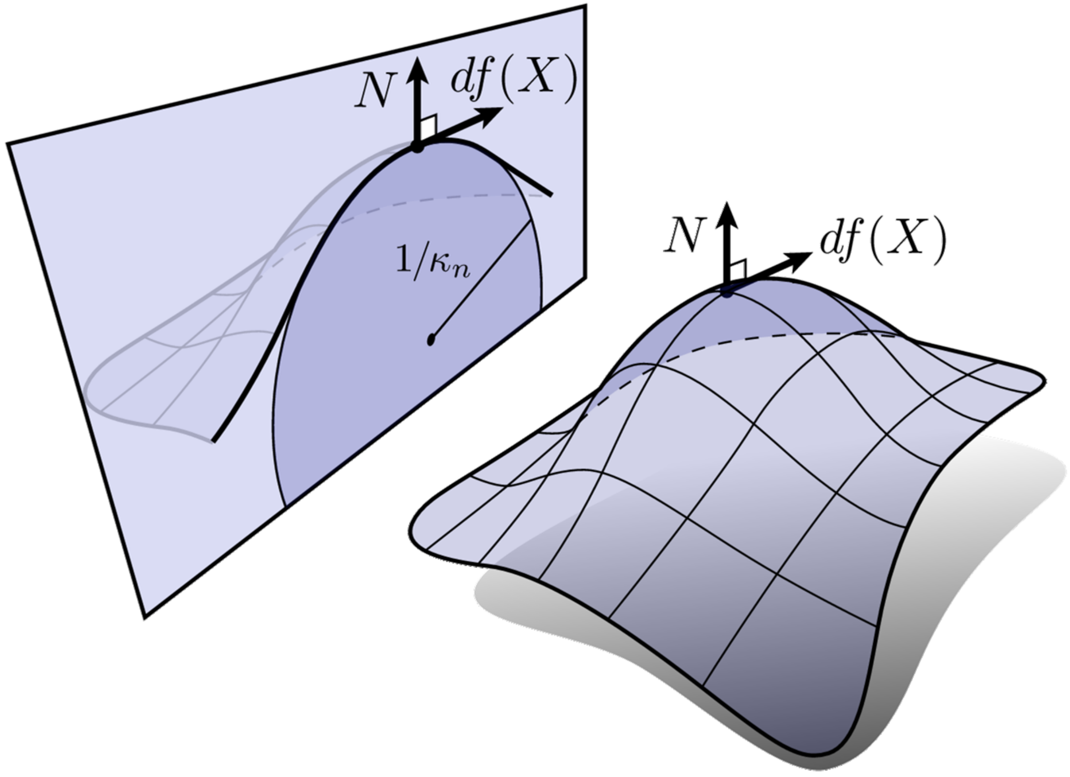


Tangents



Curvatures

Bloomenthal

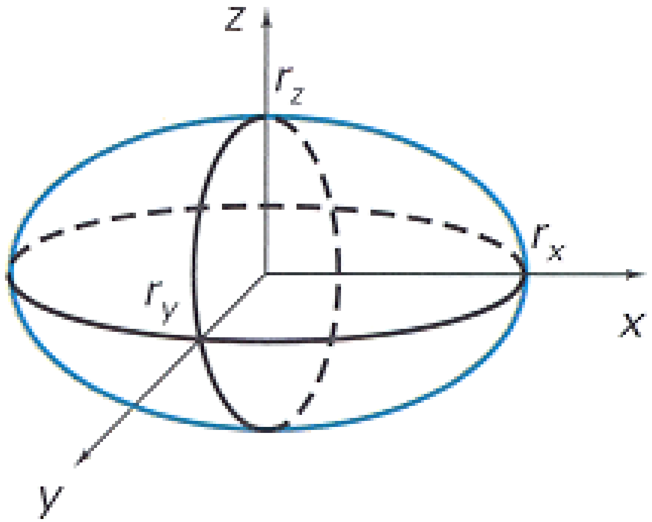


Implicit Surface Properties

(1) Efficient check for whether point is inside

- Evaluate f(x,y,z) to see if point is inside/outside/on
- Example: ellipsoid

$$f(x,y,z)=\left(\frac{x}{r_x}\right)^2+\left(\frac{y}{r_y}\right)^2+\left(\frac{z}{r_z}\right)^2-1$$



H&B Figure 10.10

Implicit Surface Properties

(2) Efficient surface intersections

- Substitute to find intersections

Ray: $P = P_0 + tV$

Sphere: $|P - O|^2 - r^2 = 0$

Substituting for P, we get:

$$|P_0 + tV - O|^2 - r^2 = 0$$

Solve quadratic equation:

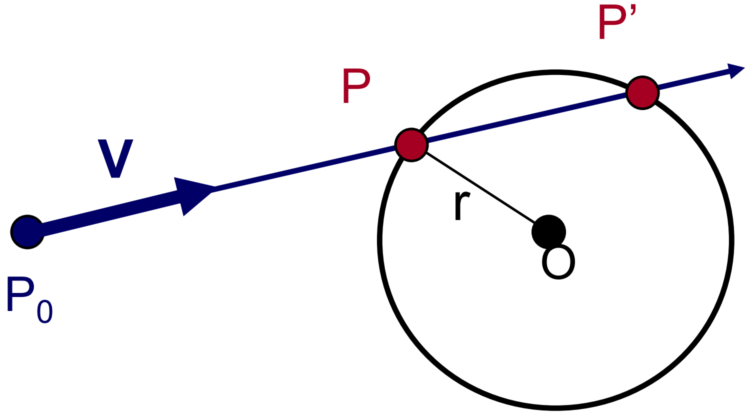
$$at^2 + bt + c = 0$$

where:

$$a = 1$$

$$b = 2\, V \bullet (P_0 - O)$$

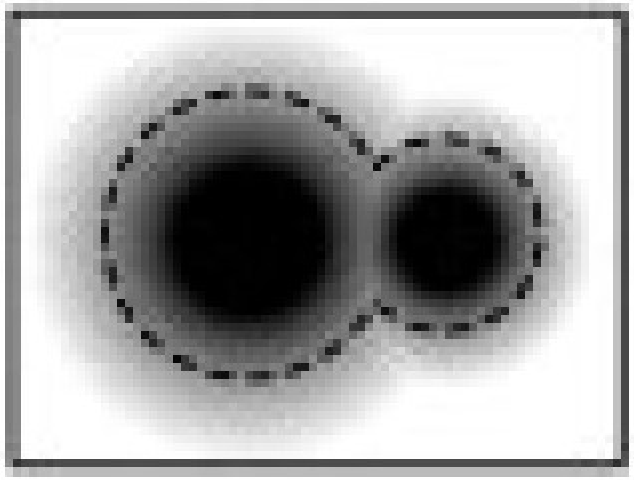
$$c = |P_0 - C|^2 - r^2 = 0$$



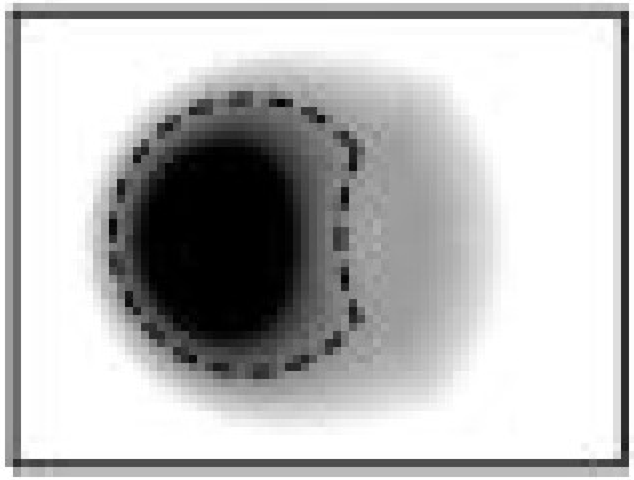
Implicit Surface Properties

(3) Efficient boolean operations (CSG)

- How would you implement:
  Union? Intersection? Difference?



Union



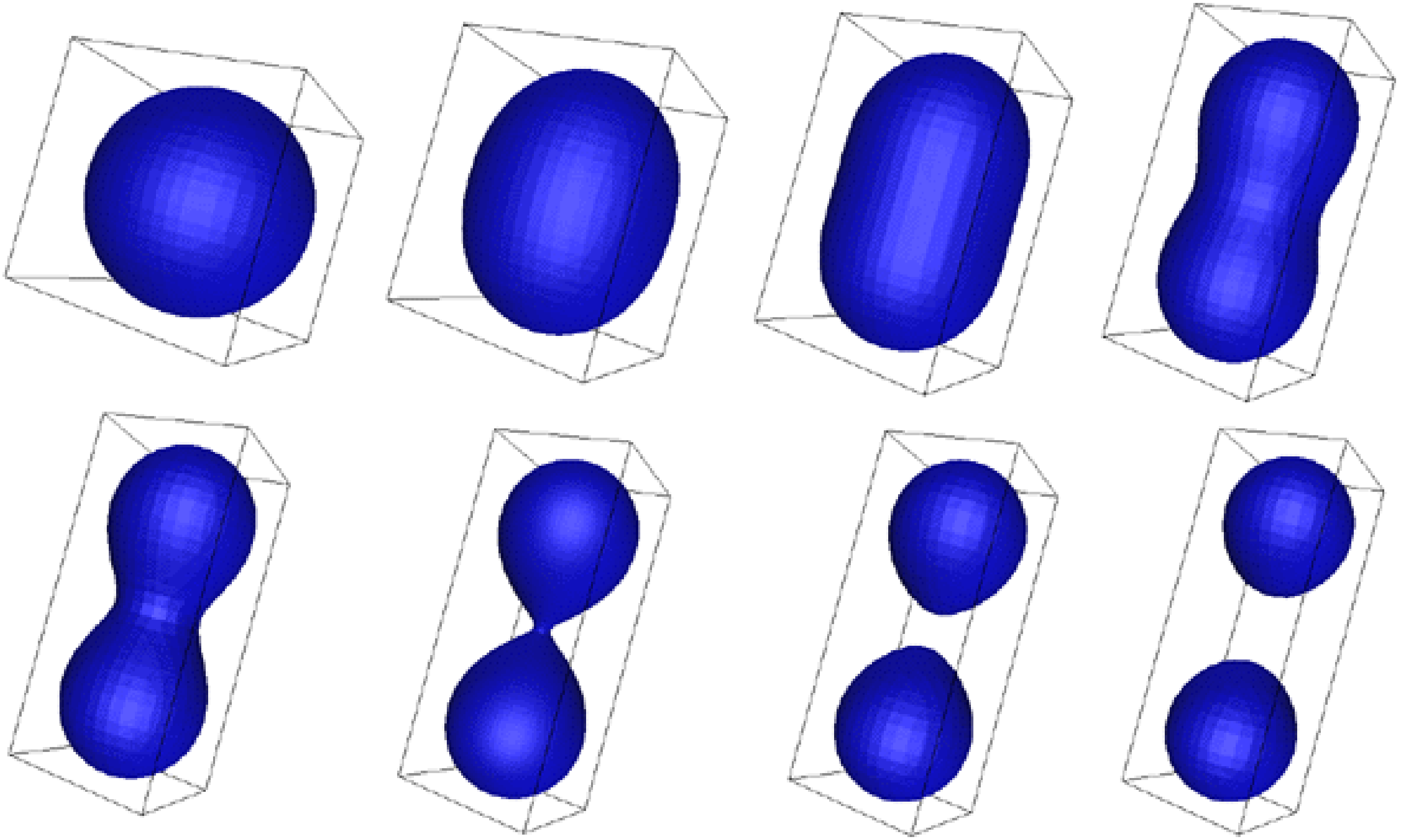
Difference

Bloomenthal

Implicit Surface Properties

(4) Efficient topology changes

- Surface is not represented explicitly!

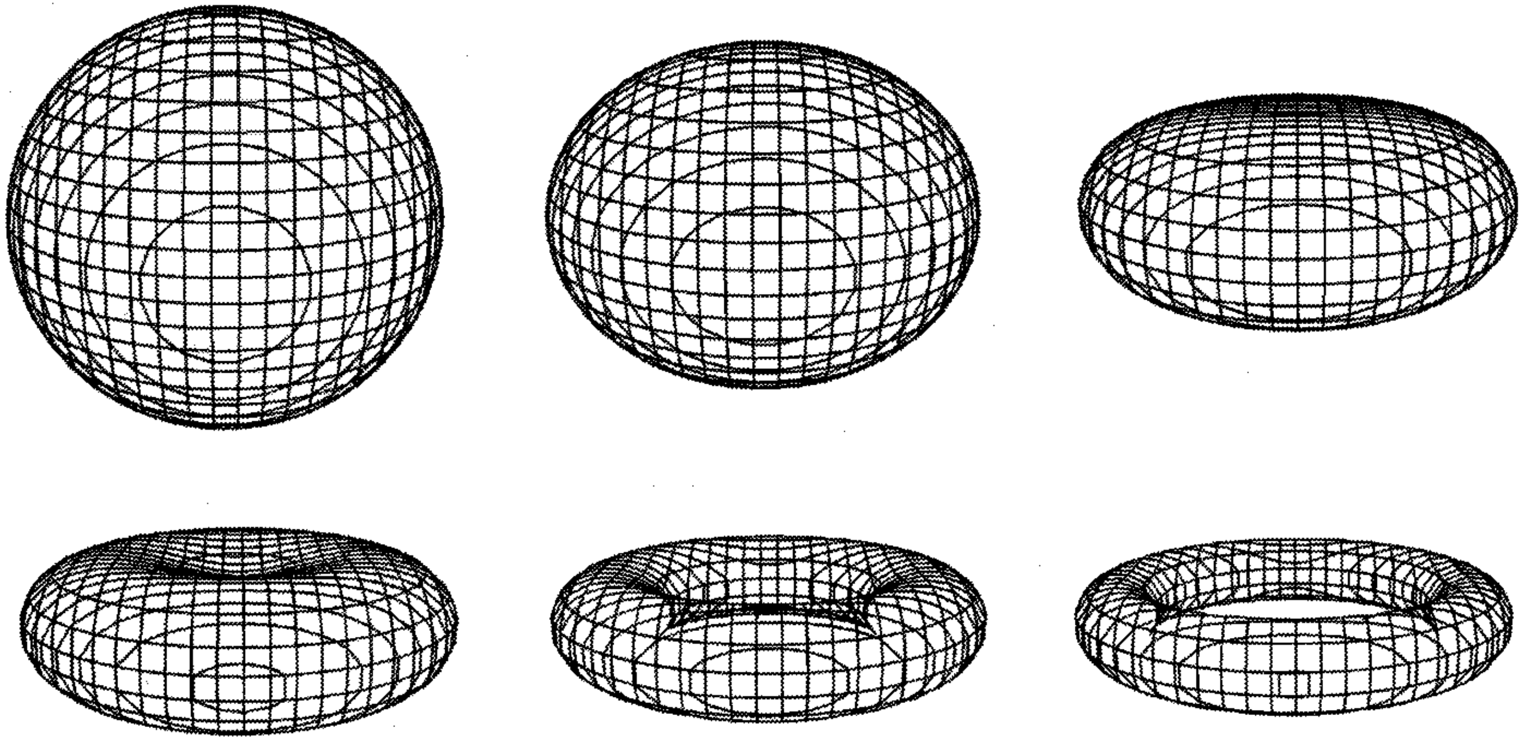


Bourke

Implicit Surface Properties

(4) Efficient topology changes

- Surface is not represented explicitly!

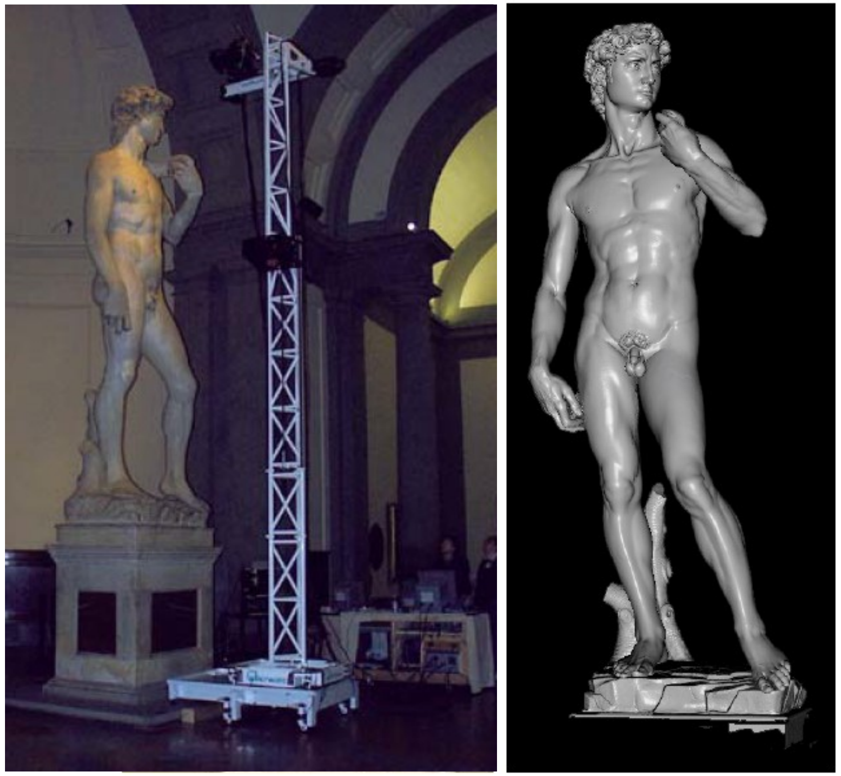


Bloomenthal

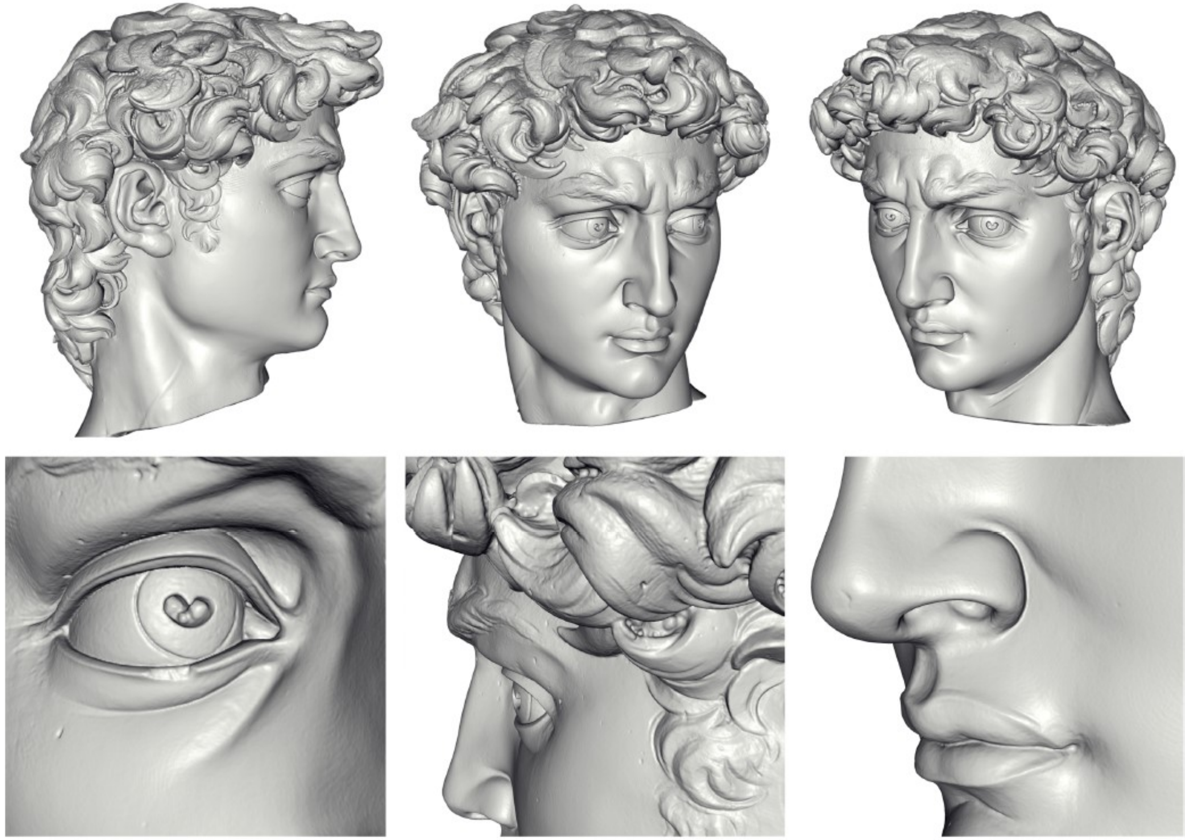
Implicit Surface Properties

(5) Computations in the volume

- Allows for continuity and smoothness
- Suitable for tasks such as reconstruction



1G sample points → 8M triangles



Poisson Surface Reconstruction [Kazhdan 06]

Comparison to Parametric Surfaces

- Implicit
  - Efficient intersections & topology changes
- Parametric
  - Efficient “marching” along surface & rendering

Implicit Surface Representations

- How do we define implicit function?
  - f(x,y,z) = ?

Implicit Surface Representations

- How do we define implicit function?
  - Algebraics
  - Voxels
  - Basis functions
  - Others

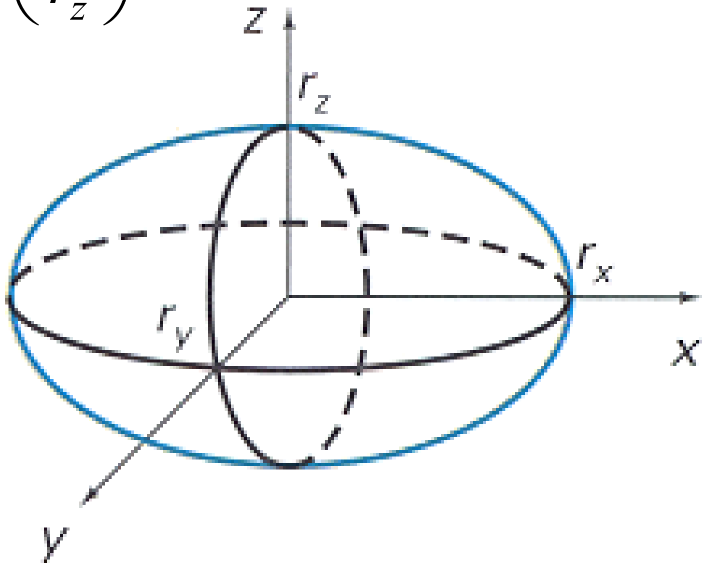
Implicit Surface Representations

- How do we define implicit function?
  - ➢Algebraics
  - Voxels
  - Basis functions
  - Others

Algebraic Surfaces

- Implicit function is polynomial
  - $f(x,y,z)=ax^d+by^d+cz^d+dx^{d-1}y+dx^{d-1}z +dy^{d-1}x+\ldots$

$$f(x,y,z)=\left(\frac{x}{r_x}\right)^2+\left(\frac{y}{r_y}\right)^2+\left(\frac{z}{r_z}\right)^2-1$$



H&B Figure 10.10

Algebraic Surfaces

- Most common form: quadrics
  - $f(x,y,z)=ax^2+by^2+cz^2+2dxy+2eyz+2fxz+2gx+2hy+2jz+k$

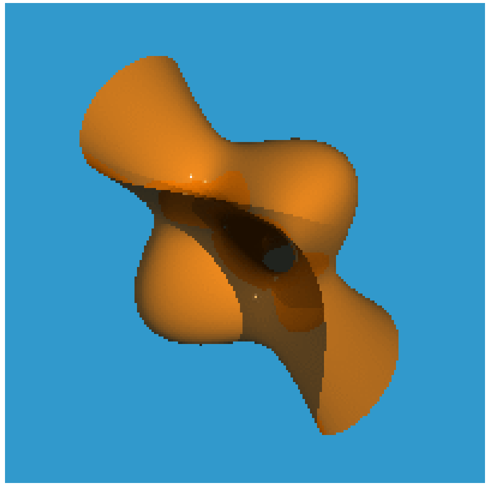
- Examples
  - Sphere
  - Ellipsoid
  - Paraboloid
  - Hyperboloid

http://tutorial.math.lamar.edu/Classes/CalcIII/QuadricSurfaces.aspx

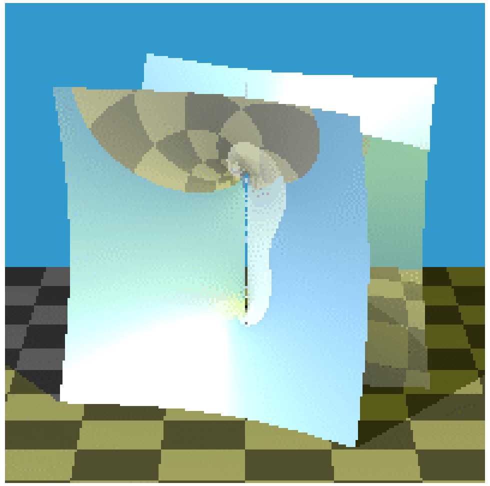
Menon

Algebraic Surfaces

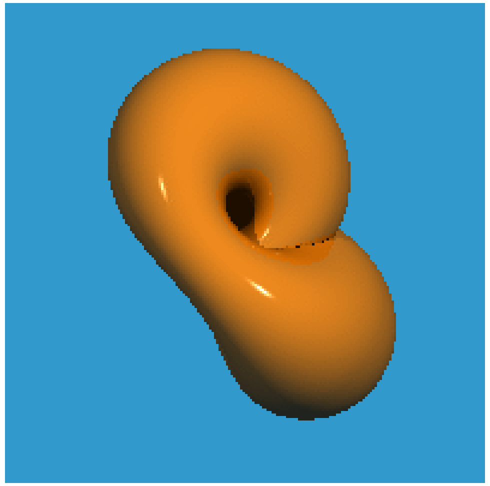
- Higher degree algebraics



Cubic



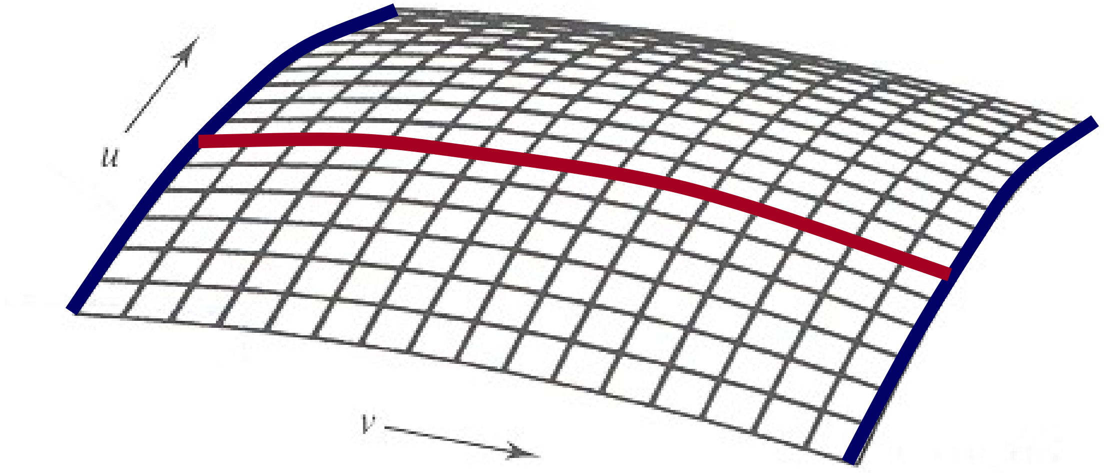
Quartic



Degree six

Algebraic Surfaces

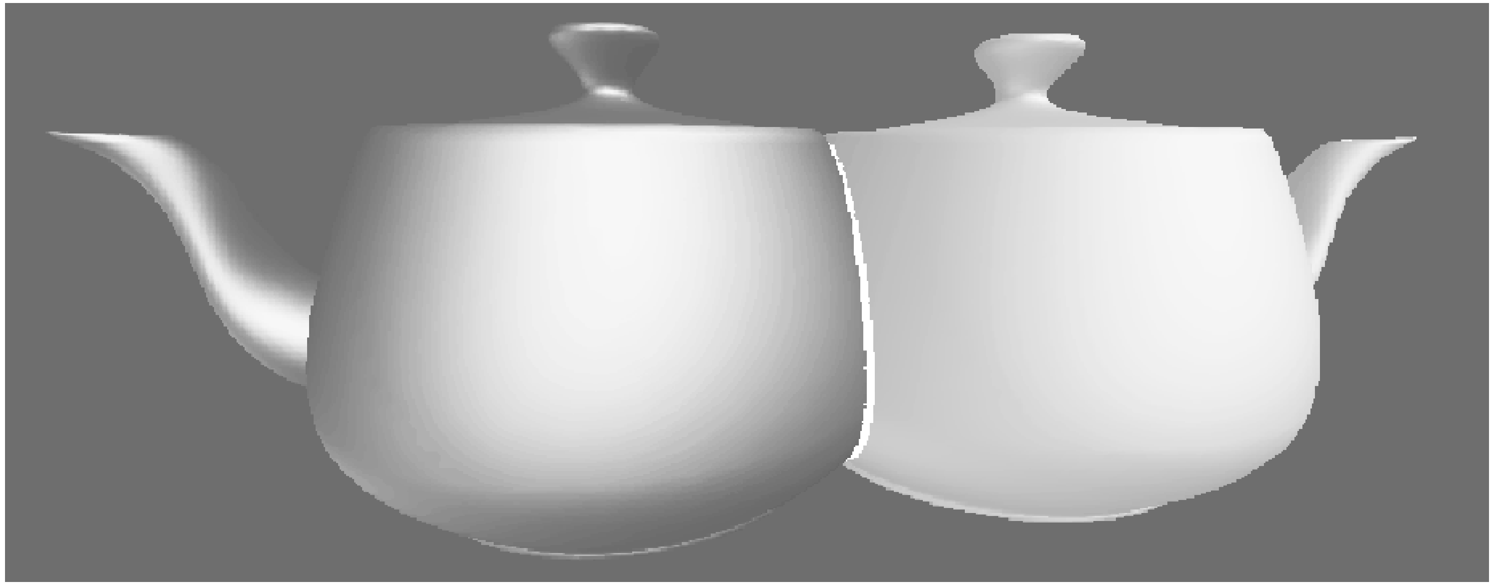
- Equivalent parametric surface
    - Tensor product patch of degree m and n curves yields algebraic function with degree 2mn



Bicubic patch has degree 18!

Algebraic Surfaces

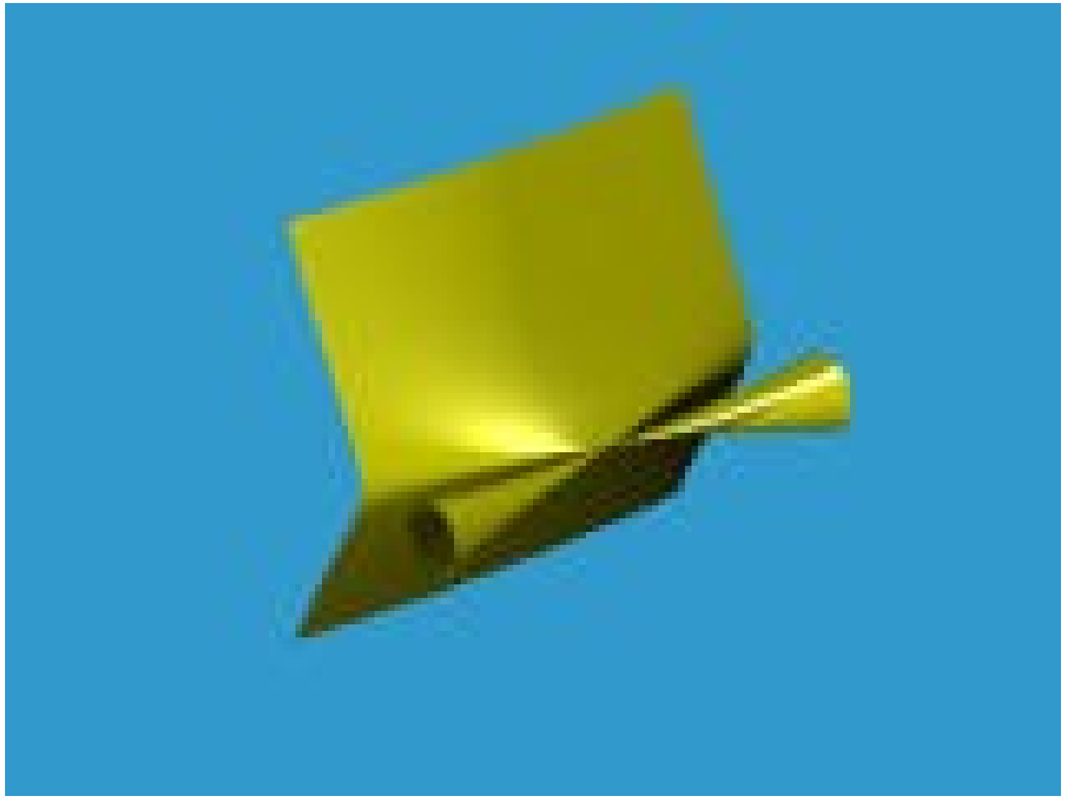
- Intersection
  - Intersection of degree m and n algebraic surfaces yields curve with degree mn



Intersection of bicubic patches has degree 324!

Algebraic Surfaces

- Function extends to infinity
  - Must trim to get desired patch (this is difficult!)

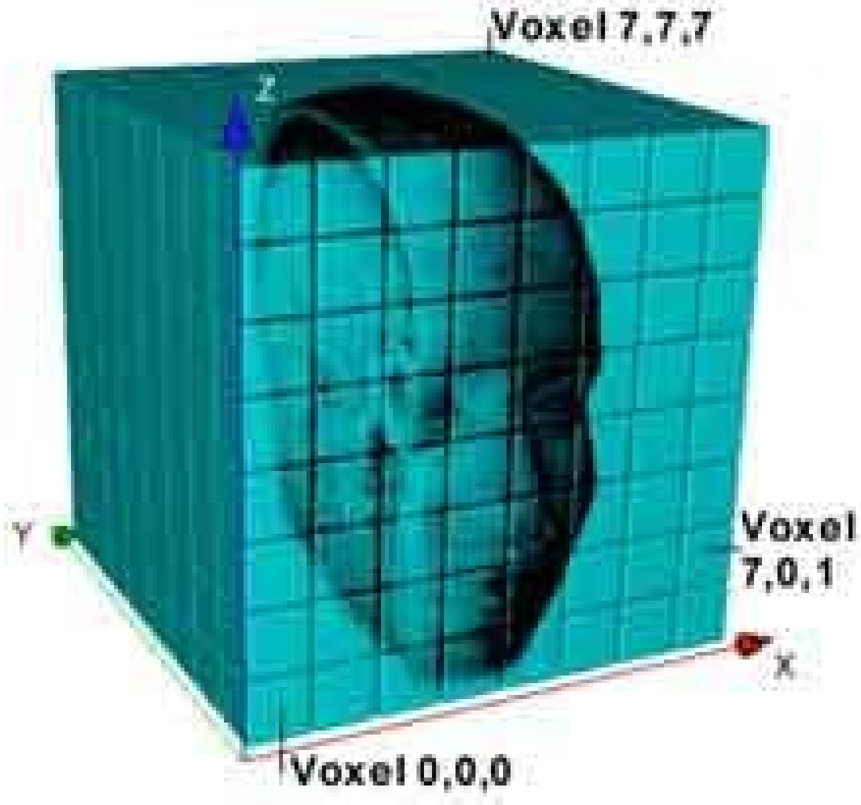


Implicit Surface Representations

- How do we define implicit function?
  - Algebraics
  - ➢Voxels
  - Basis functions

Voxels

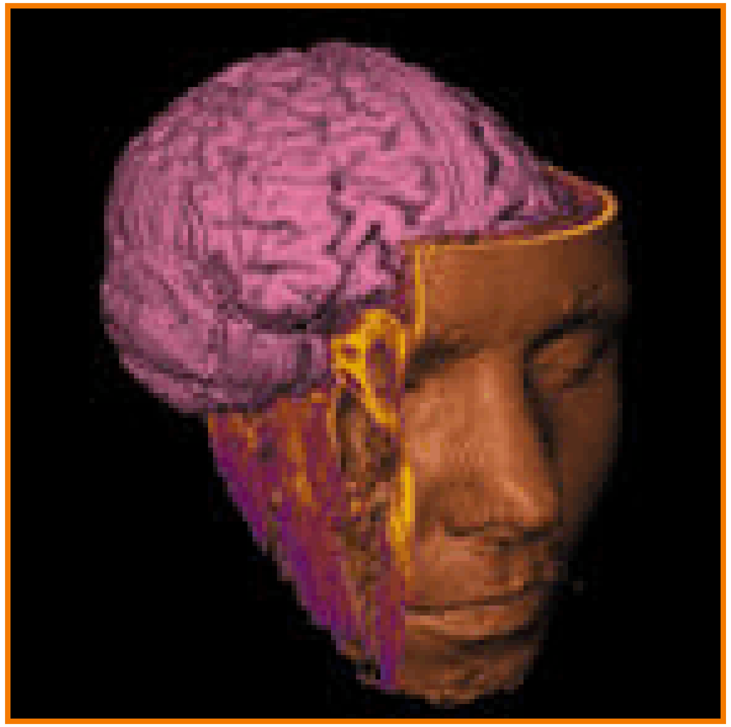
- Regular array of 3D samples (like image)
    - Samples are called *voxels* ("**vo**lume pi**xels**")



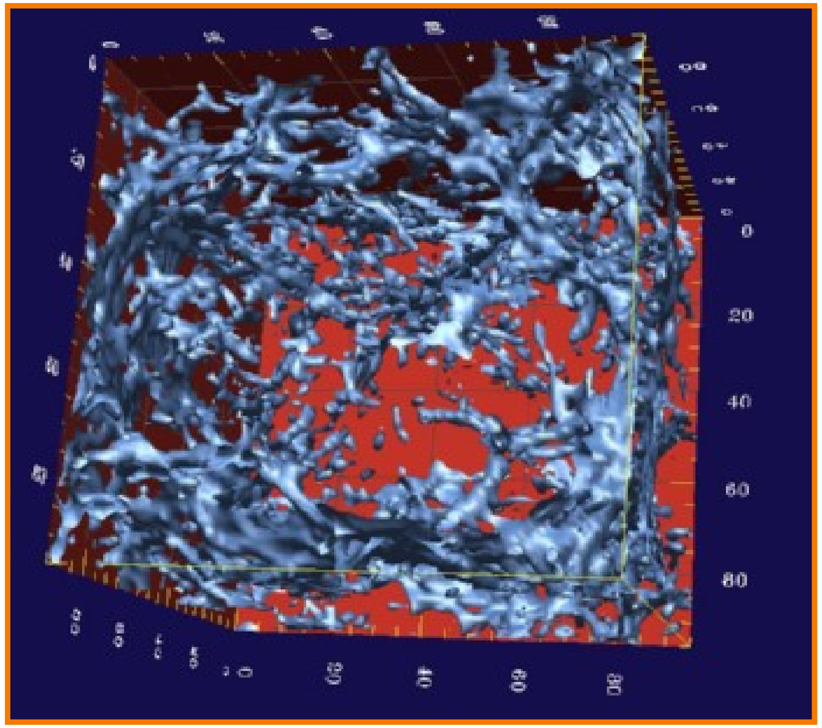
www.volumegraphics.com

Voxels

- Example isosurfaces



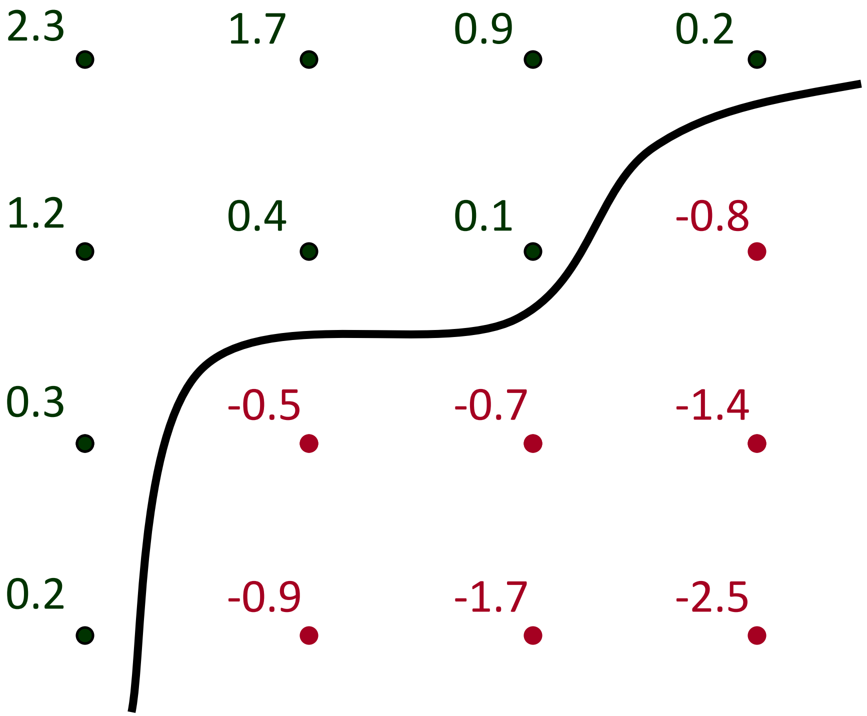
SUNY Stoney Brook



Princeton University

Voxels

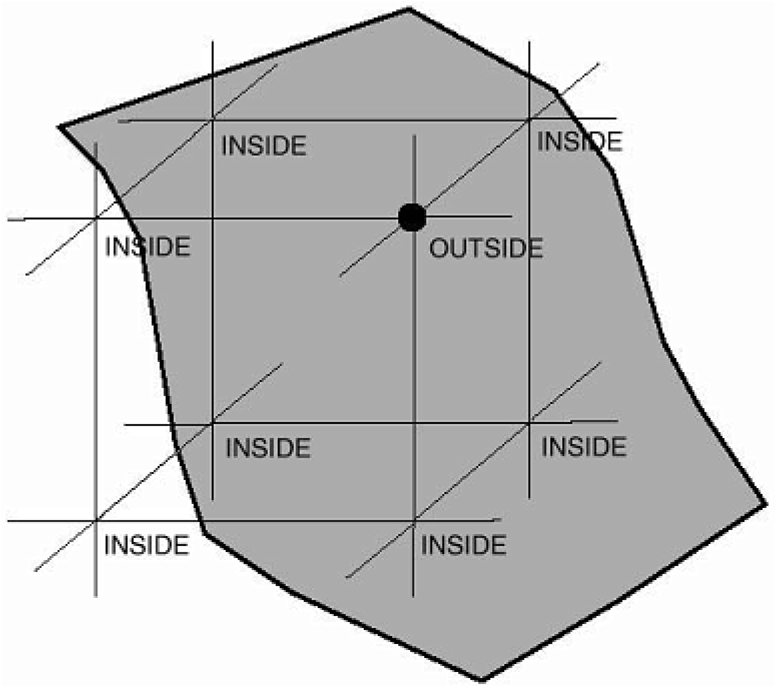
- Regular array of 3D samples (like image)
  - Applying reconstruction filter (e.g. trilinear) yields f(x,y,z)
  - Isosurface at f(x,y,z) = 0 defines surface

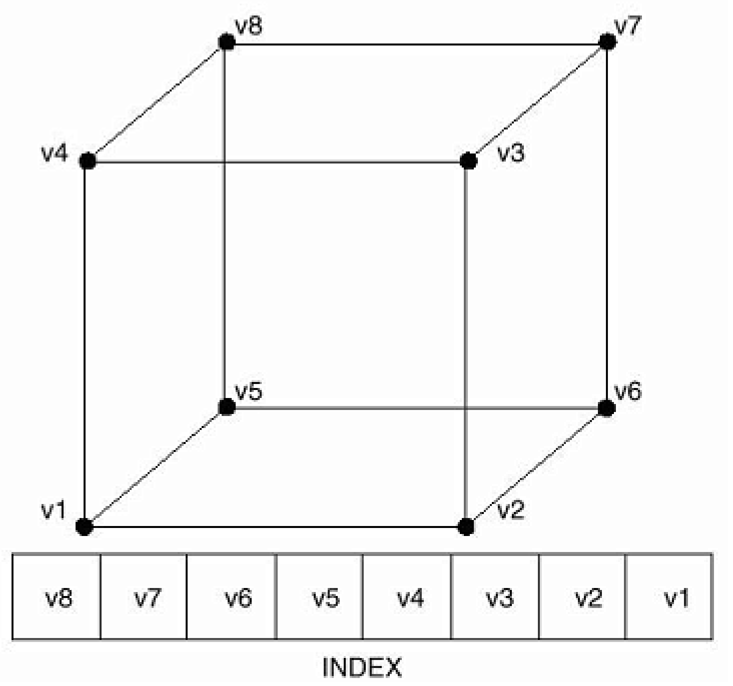


2.3	1.7	0.9	0.2
1.2	0.4	0.1	-0.8
0.3	-0.5	-0.7	-1.4
0.2	-0.9	-1.7	-2.5

Voxels

- Iso-surface extraction algorithm
    - e.g., Marching cubes



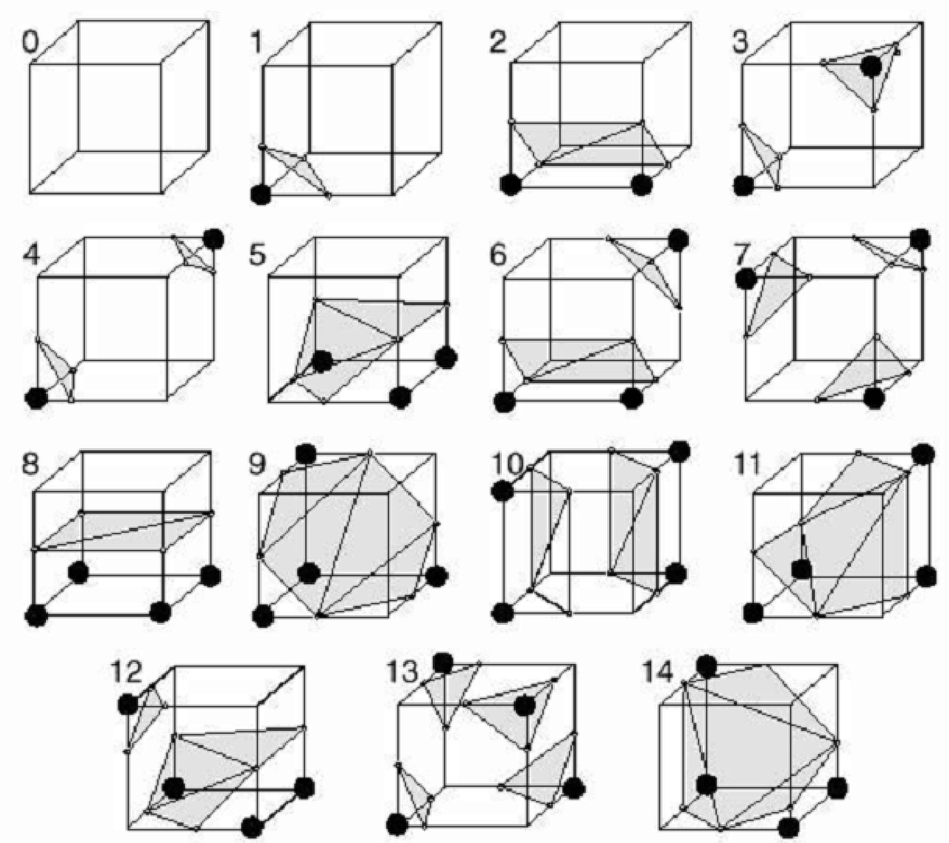


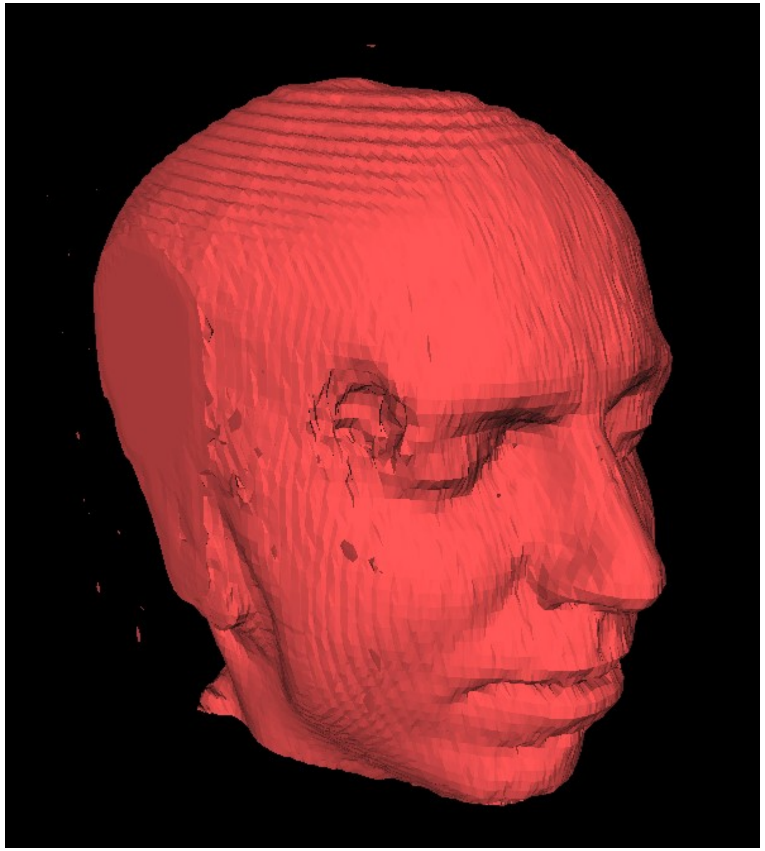
v8	v7	v6	v5	v4	v3	v2	v1

INDEX

Voxels

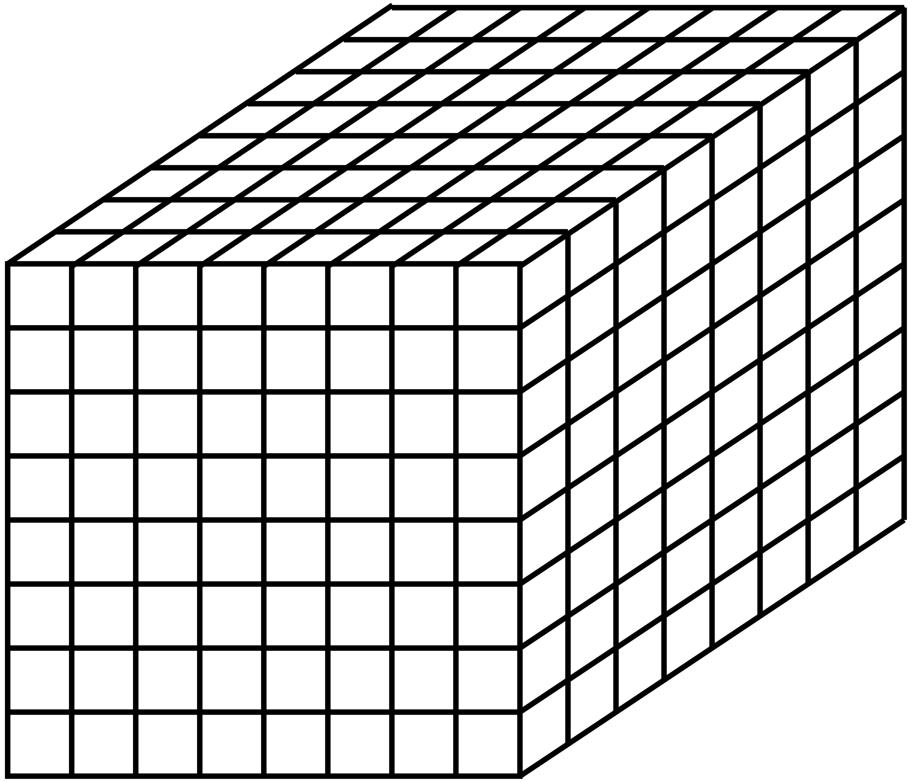
- Iso-surface extraction algorithm
  - e.g., Marching cubes (15 cases)





Voxel Storage

- $O(n^3)$ storage for n x n x n grid
    - 1 billion voxels for 1000 x 1000 x 1000



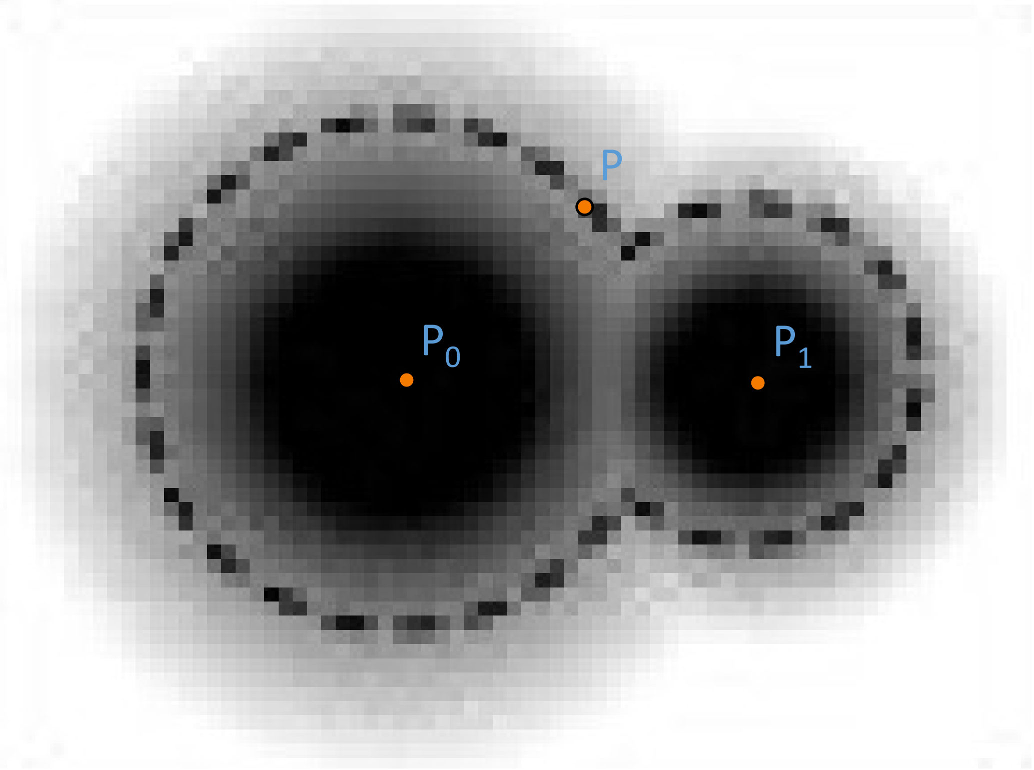
Implicit Surface Representations

- How do we define implicit function?
  - Algebraics
  - Voxels
  - ➢Basis functions

Basis functions

- Implicit function is sum of basis functions
  - Example:

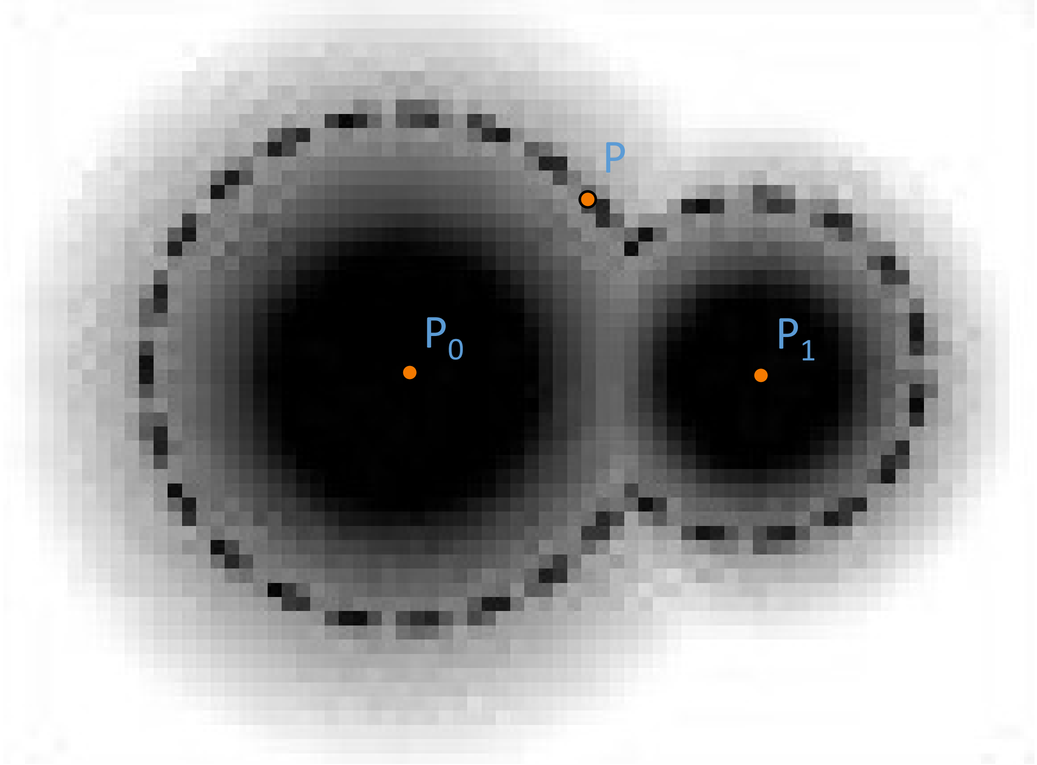
$$f(P) = a_0 e^{-b_0 d(P,P_0)^2} + a_1 e^{-b_1 d(P,P_1)^2} + \cdots - \tau$$



Blobby Models

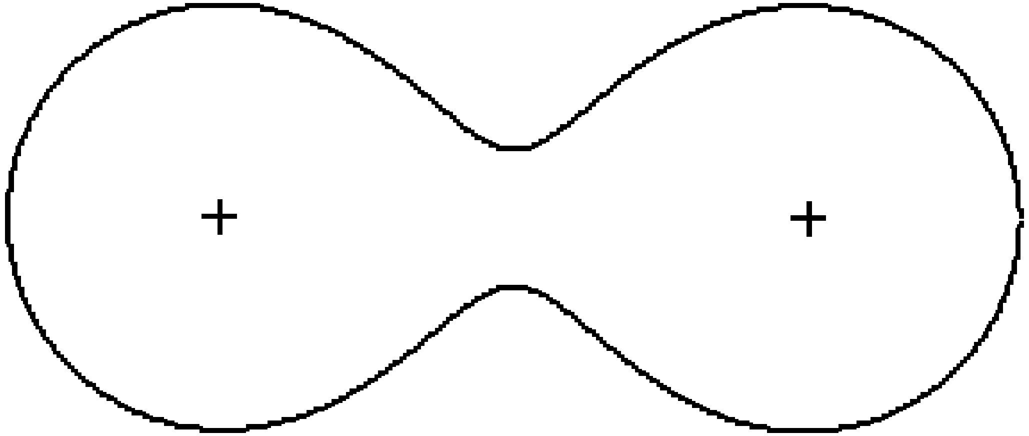
- Implicit function is sum of Gaussians

$$f(P) = a_0 e^{-b_0 d(P,P_0)^2} + a_1 e^{-b_1 d(P,P_1)^2} + \cdots - \tau$$



Blobby Models

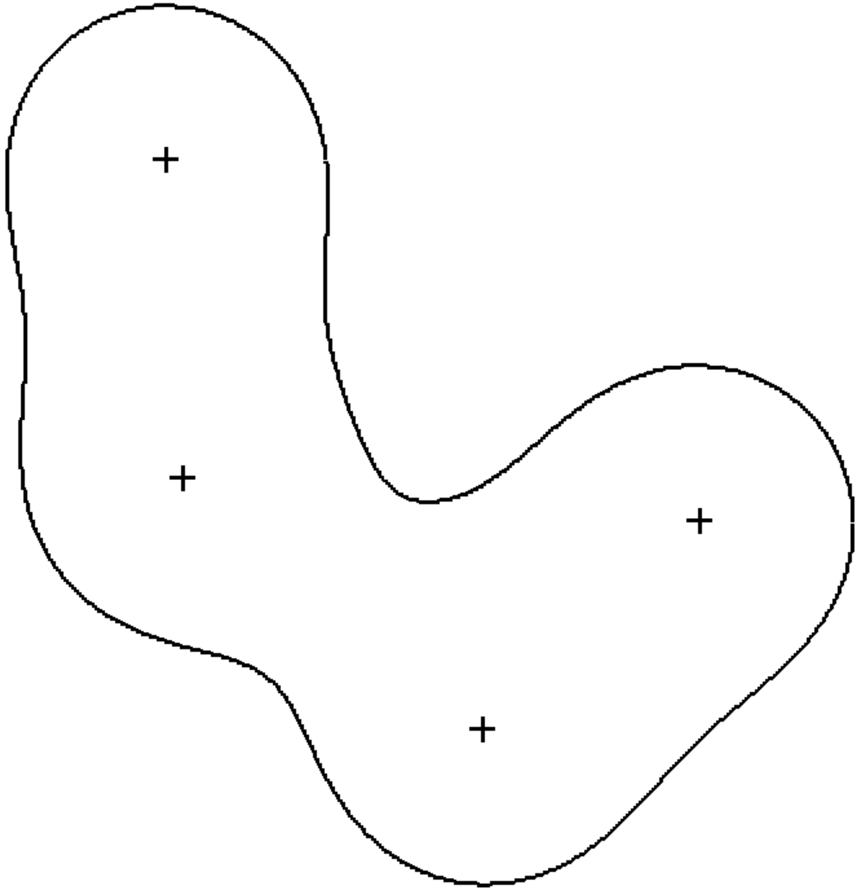
- Sum of two blobs



Turk

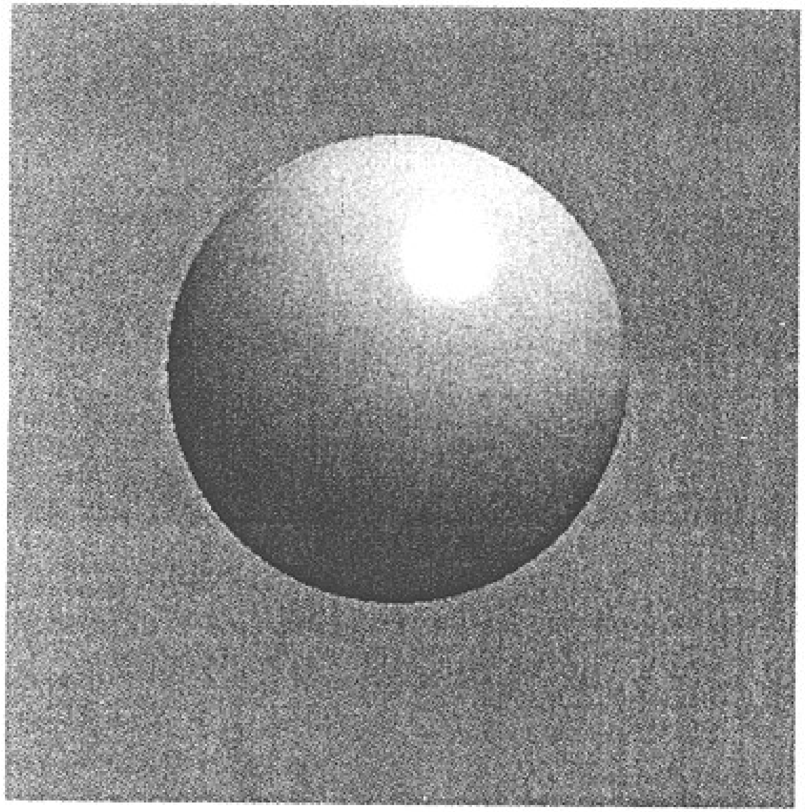
Blobby Models

- Sum of four blobs

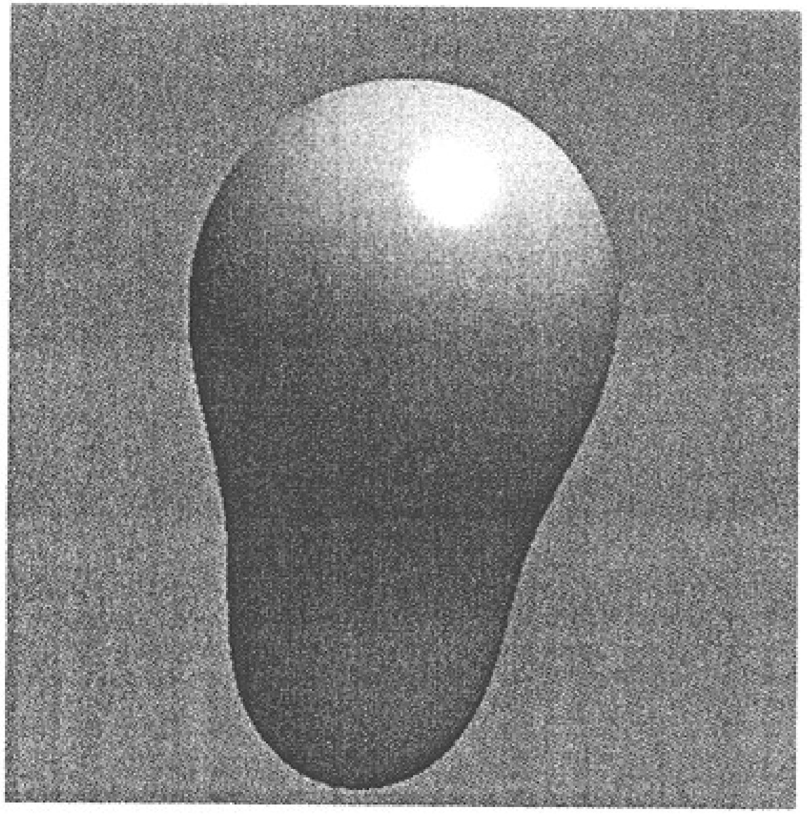


Turk

Blobby Model of Head

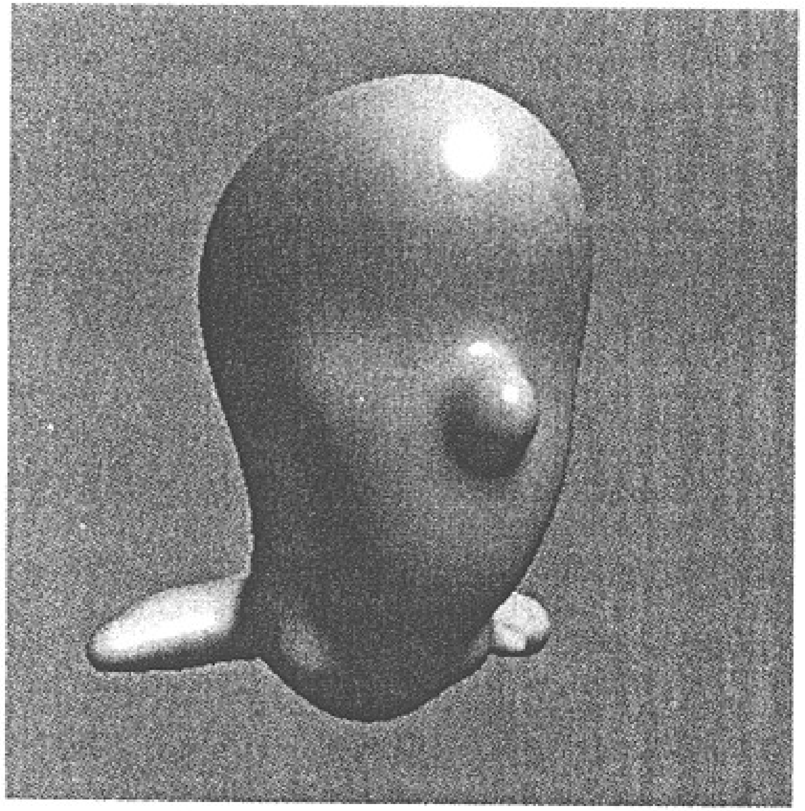


(a) $N = 1$

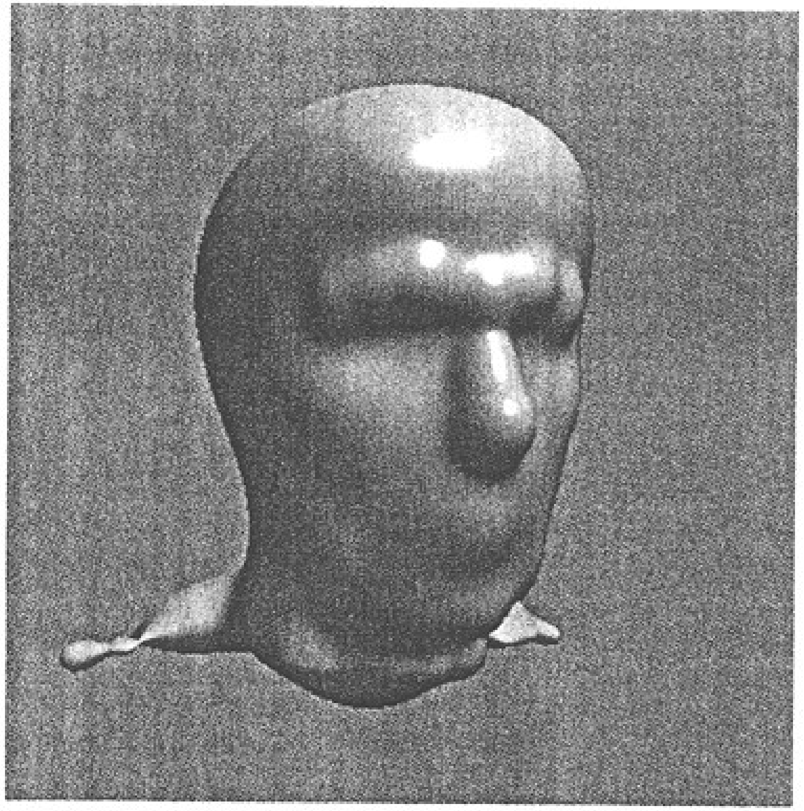


(b) $N = 2$

Blobby Model of Head

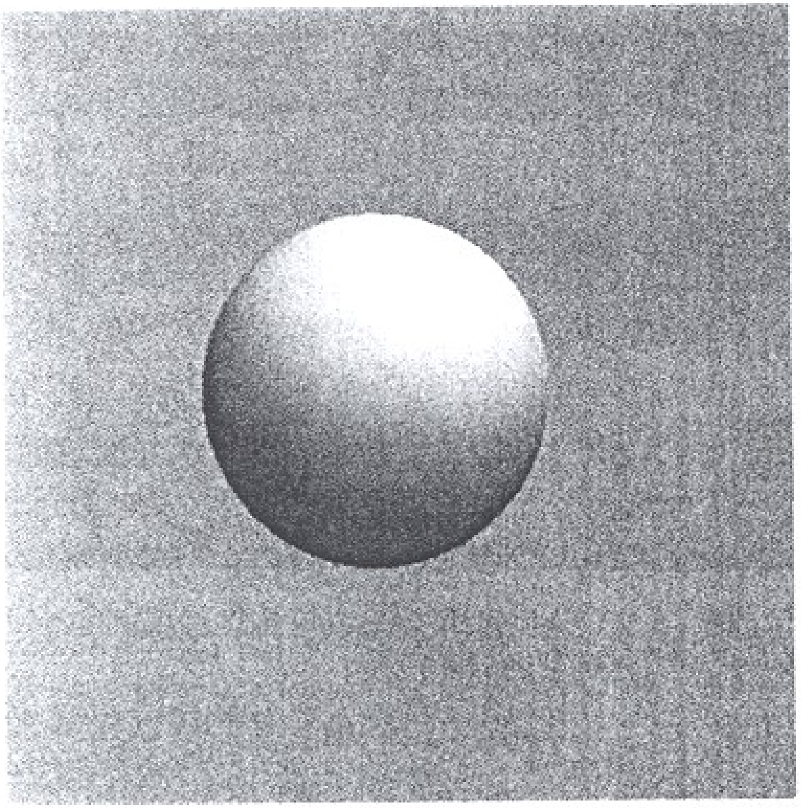


(c) $N = 20$

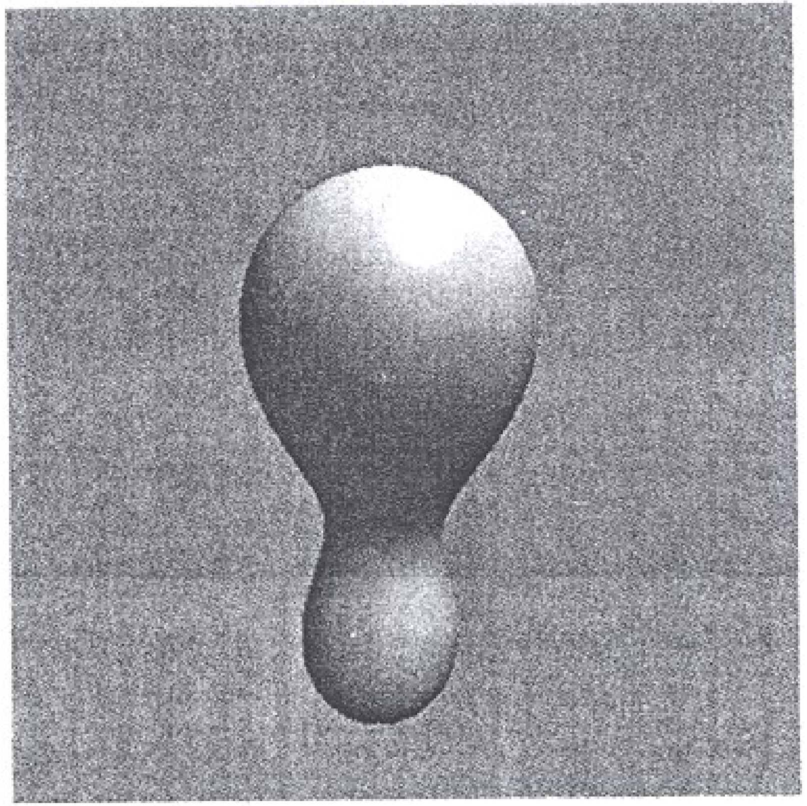


(d) $N = 60$

Blobby Model of Face

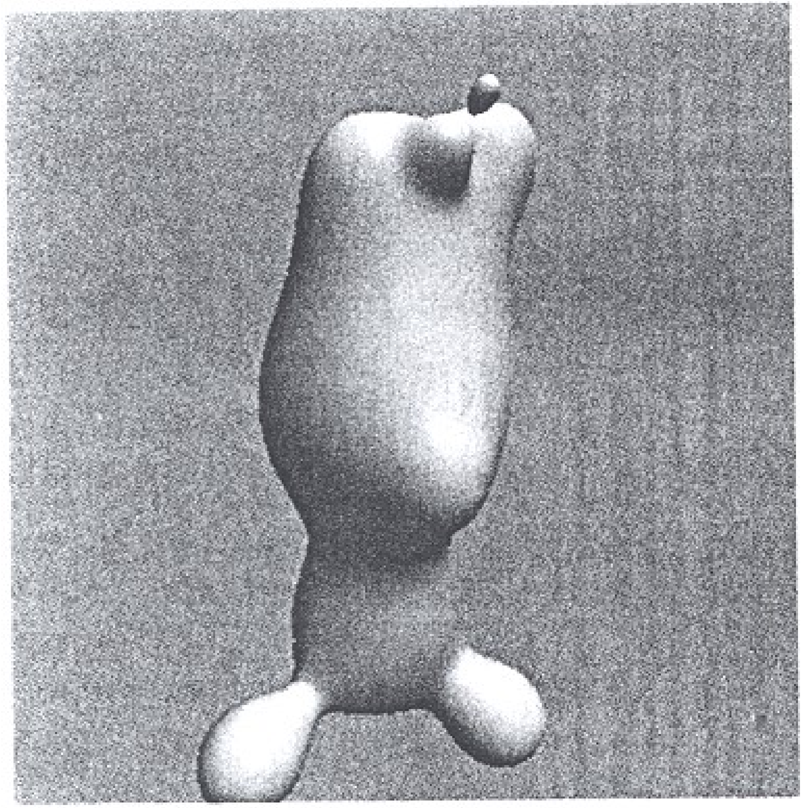


(a) $N = 1$

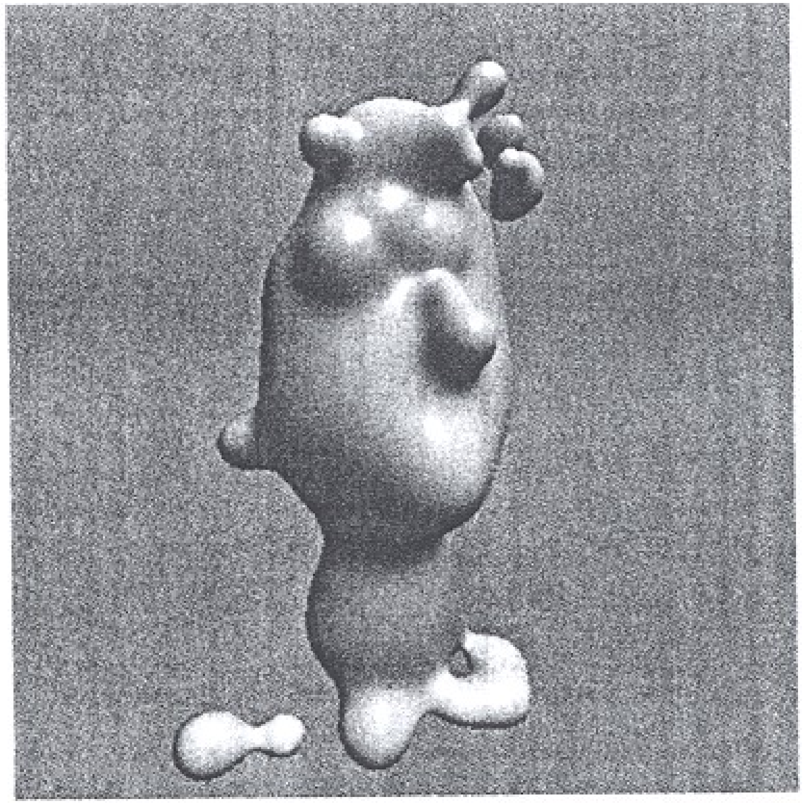


(b) $N = 2$

Blobby Model of Face

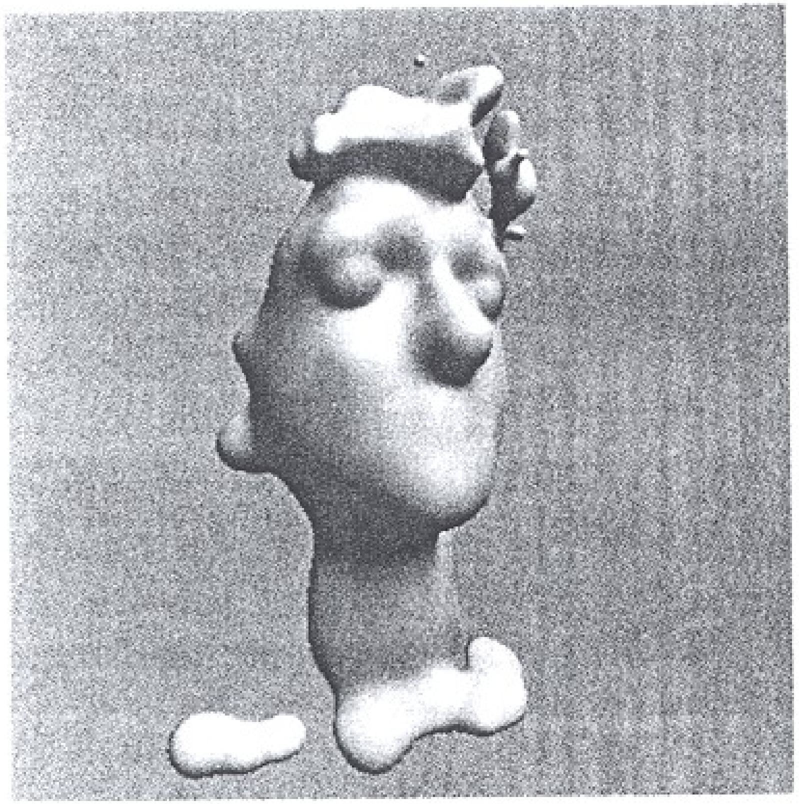


(c) $N = 10$

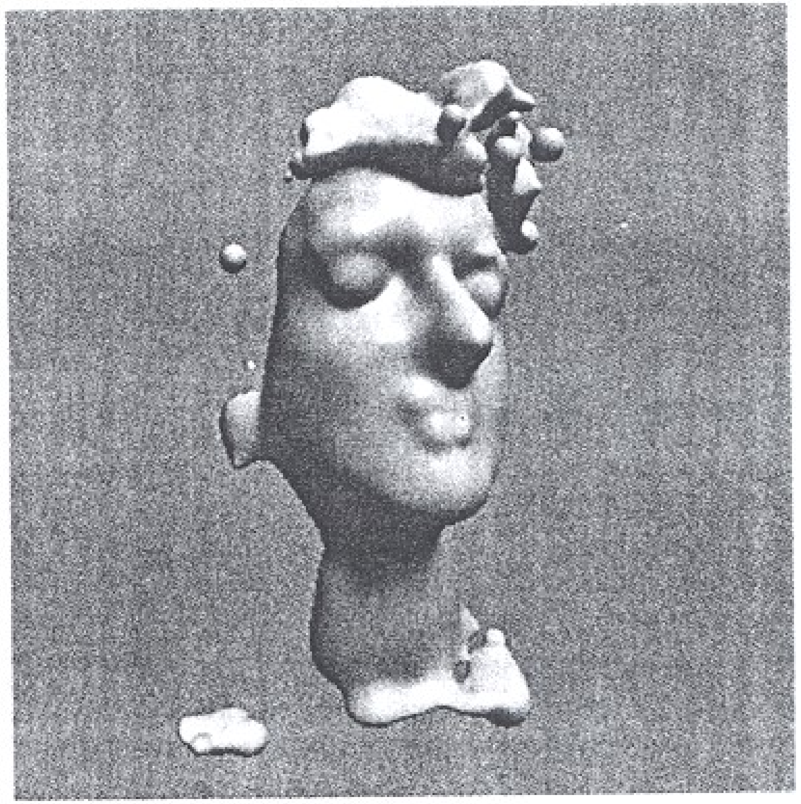


(d) $N = 35$

Blobby Model of Face

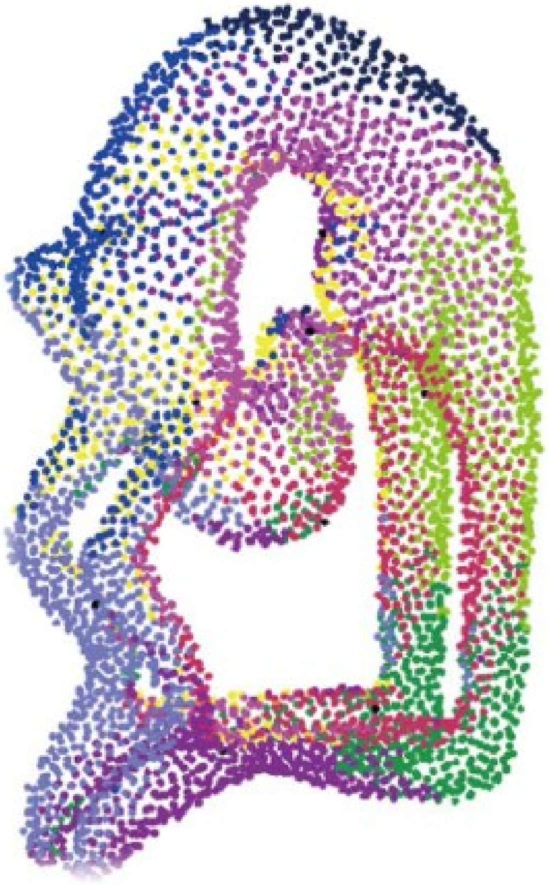


(e) $N = 70$

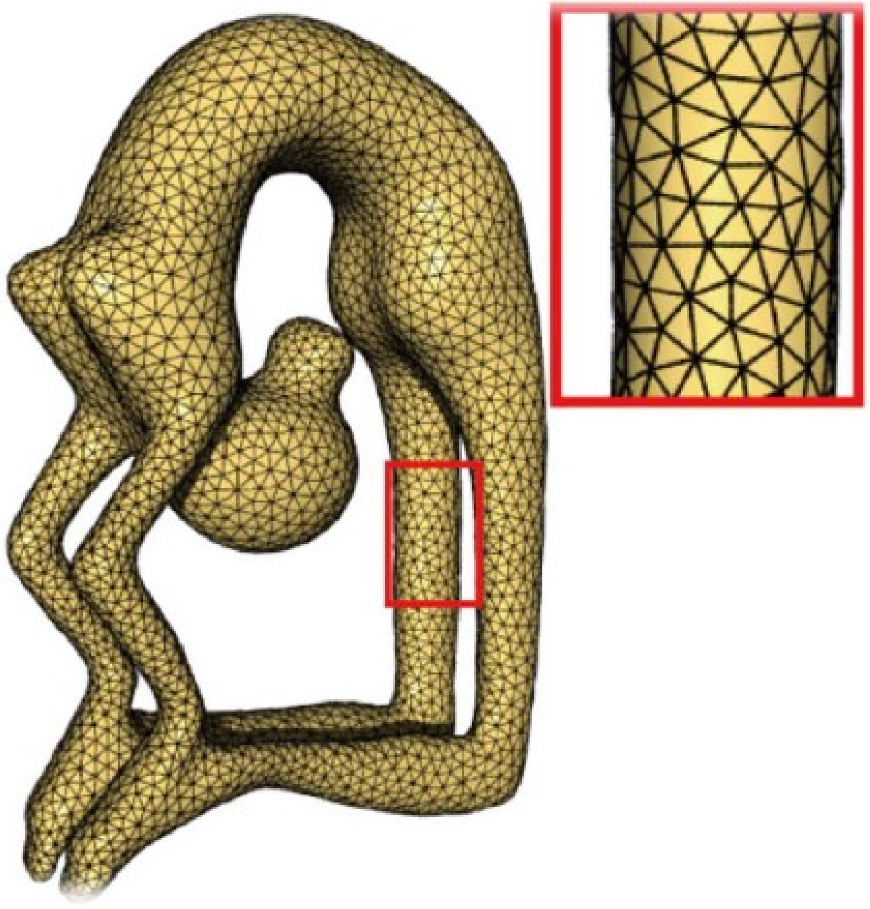


(f) $N = 243$

Reconstruction from Pointsets



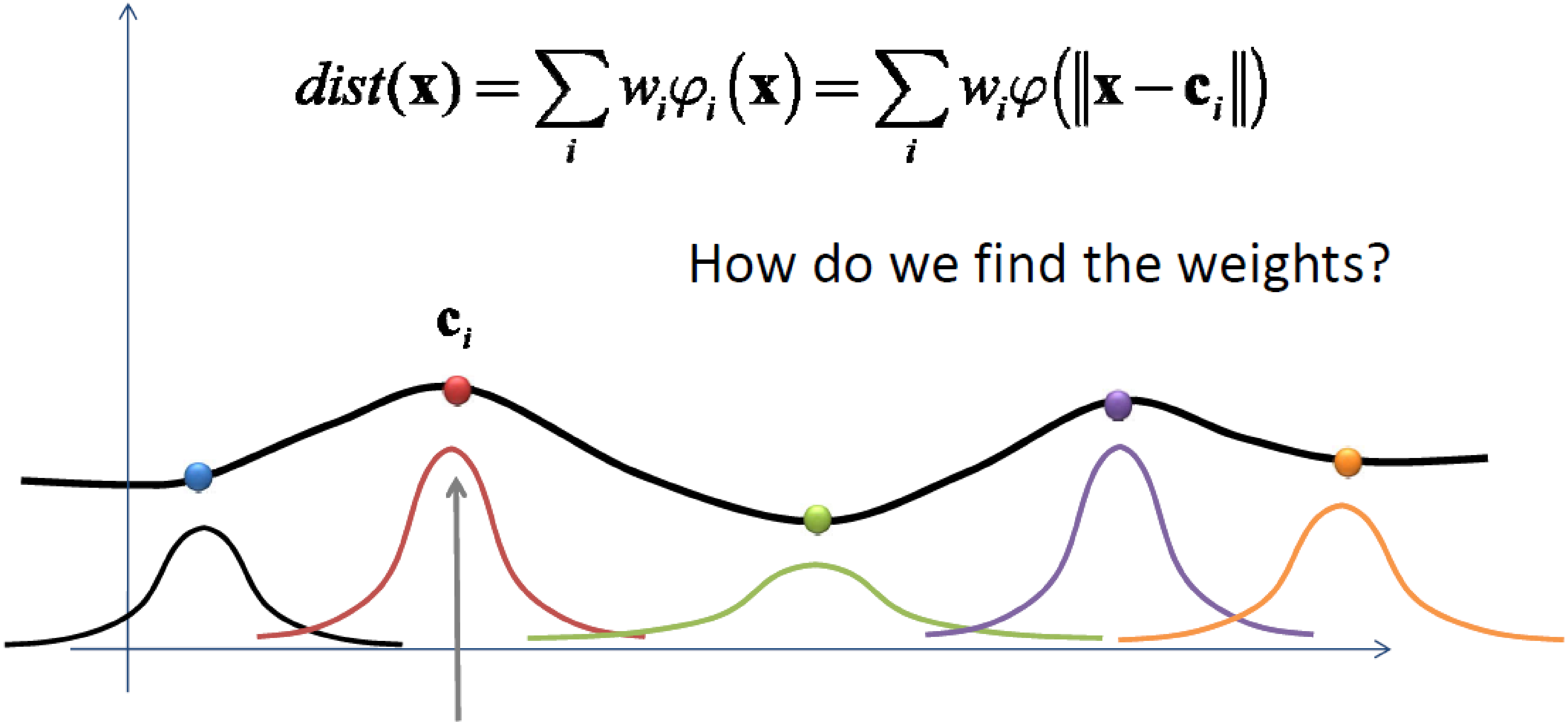
Input



Implicit

Reconstruction from Pointsets

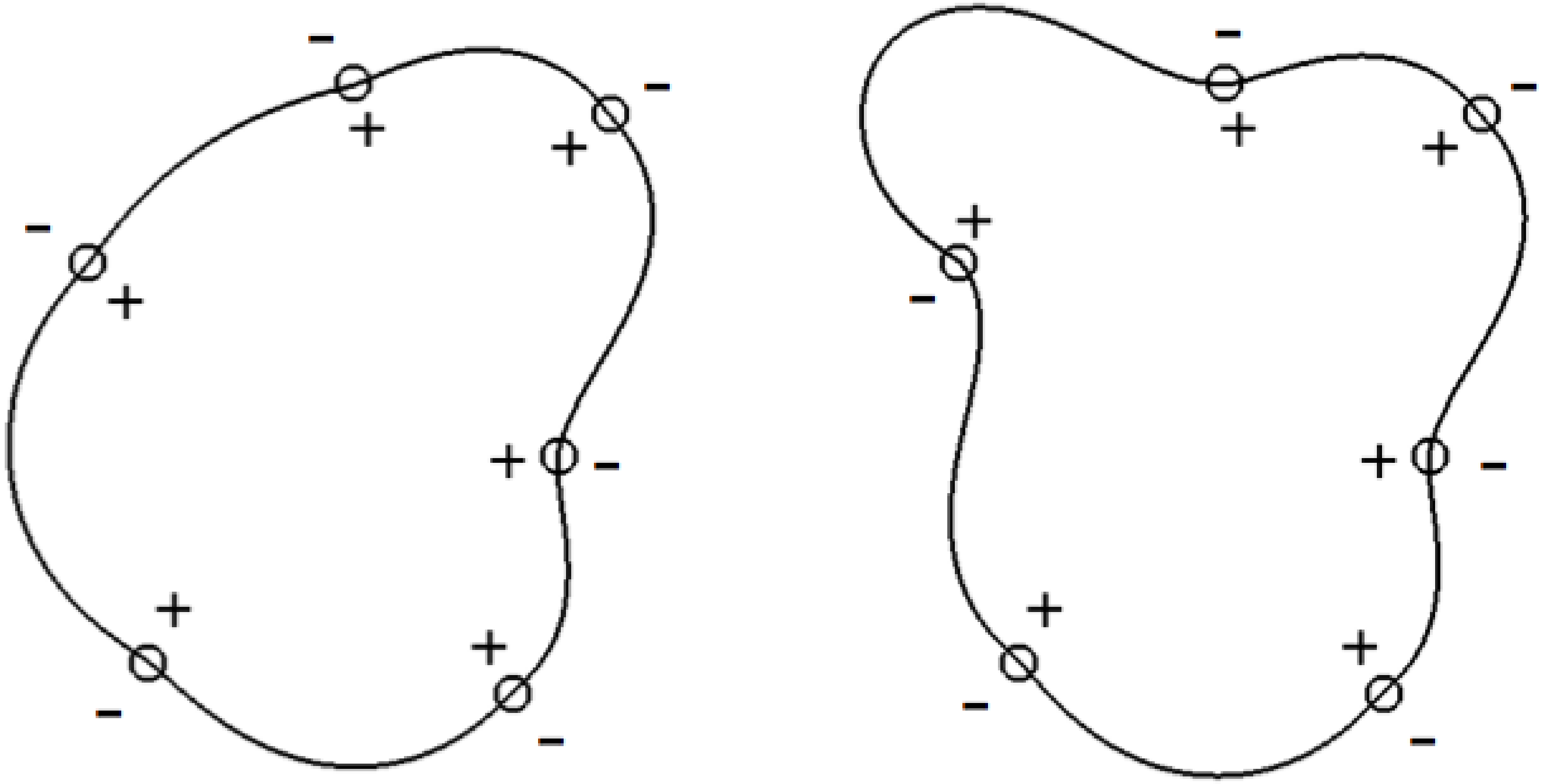
- Implicit function is sum of basis functions



$$dist(\mathbf{x}) = \sum_i w_i \varphi_i(\mathbf{x}) = \sum_i w_i \varphi(\|\mathbf{x} - \mathbf{c}_i\|)$$

How do we find the weights?

Reconstruction from Pointsets



Turk

Reconstruction from Pointsets

- Implicit function is sum of basis functions

$$dist(\mathbf{p}_j) = \sum_i w_i \varphi_i(\mathbf{p}_j) = \sum_i w_i \varphi\left(\left\|\mathbf{p}_j - \mathbf{c}_i\right\|\right) = 0$$

$$dist(\mathbf{p}_j + \varepsilon \mathbf{n}_j) = \sum_i w_i \varphi\left(\left\|\left(\mathbf{p}_j + \varepsilon \mathbf{n}_j\right) - \mathbf{c}_i\right\|\right) = \varepsilon$$

$2n$ equations

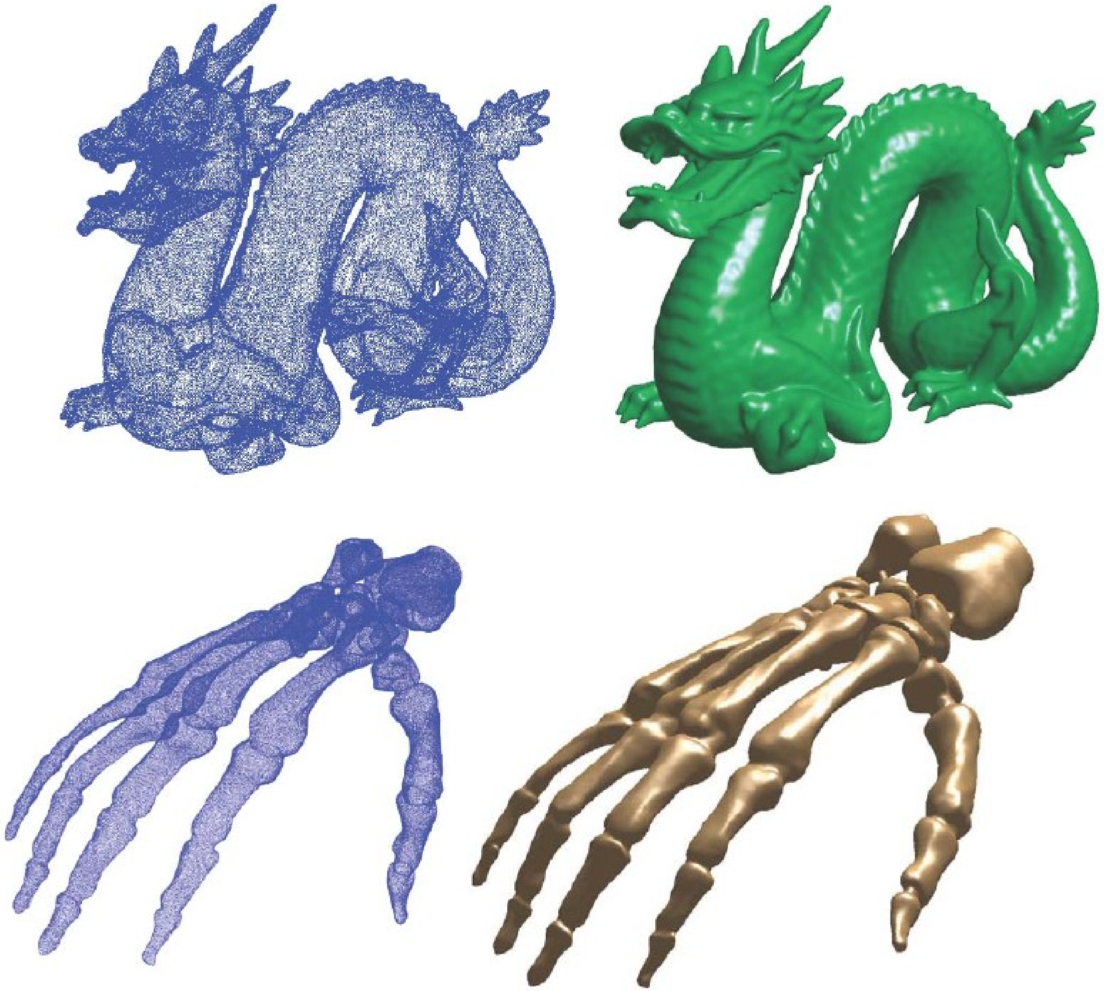
$2n$ variables

The on- and off-surface points are the centers $\mathbf{c}_i$

$$\underbrace{\begin{pmatrix} \phi(\|\mathbf{x}_1 - \mathbf{x}_1\|) & \cdots & \phi(\|\mathbf{x}_1 - (\mathbf{x}_n + \varepsilon \mathbf{n}_n)\|) \\ \vdots & \mathbf{K} & \vdots \\ \phi(\|(\mathbf{x}_n + \varepsilon \mathbf{n}_n) - \mathbf{x}_1\|) & \cdots & \phi(\|(\mathbf{x}_n + \varepsilon \mathbf{n}_n) - (\mathbf{x}_n + \varepsilon \mathbf{n}_n)\|) \end{pmatrix}}_{\mathbf{K}} \underbrace{\begin{pmatrix} w_1 \\ \vdots \\ w_n \\ w_n \\ \vdots \\ w_{2n} \end{pmatrix}}_{\mathbf{w}} = \underbrace{\begin{pmatrix} 0 \\ \vdots \\ 0 \\ \varepsilon \\ \vdots \\ \varepsilon \end{pmatrix}}_{\mathbf{d}}$$

Reconstruction from Pointsets

Examples



Implicit Surface Summary

- Advantages:
    - Easy to test if point is on surface
    - Easy to compute intersections/unions/differences
    - Easy to handle topological changes
- Disadvantages:
    - Indirect specification of surface
    - Hard to describe sharp features
    - Hard to enumerate points on surface
        - Slow rendering

Summary

Feature	Polygonal Mesh	Implicit Surface	Parametric Surface	Subdivision Surface
Accurate	No	Yes	Yes	Yes
Concise	No	Yes	Yes	Yes
Intuitive specification	No	No	Yes	No
Local support	Yes	No	Yes	Yes
Affine invariant	Yes	Yes	Yes	Yes
Arbitrary topology	Yes	No	No	Yes
Guaranteed continuity	No	Yes	Yes	Yes
Natural parameterization	No	No	Yes	No
Efficient display	Yes	No	Yes	Yes
Efficient intersections	No	Yes	No	No

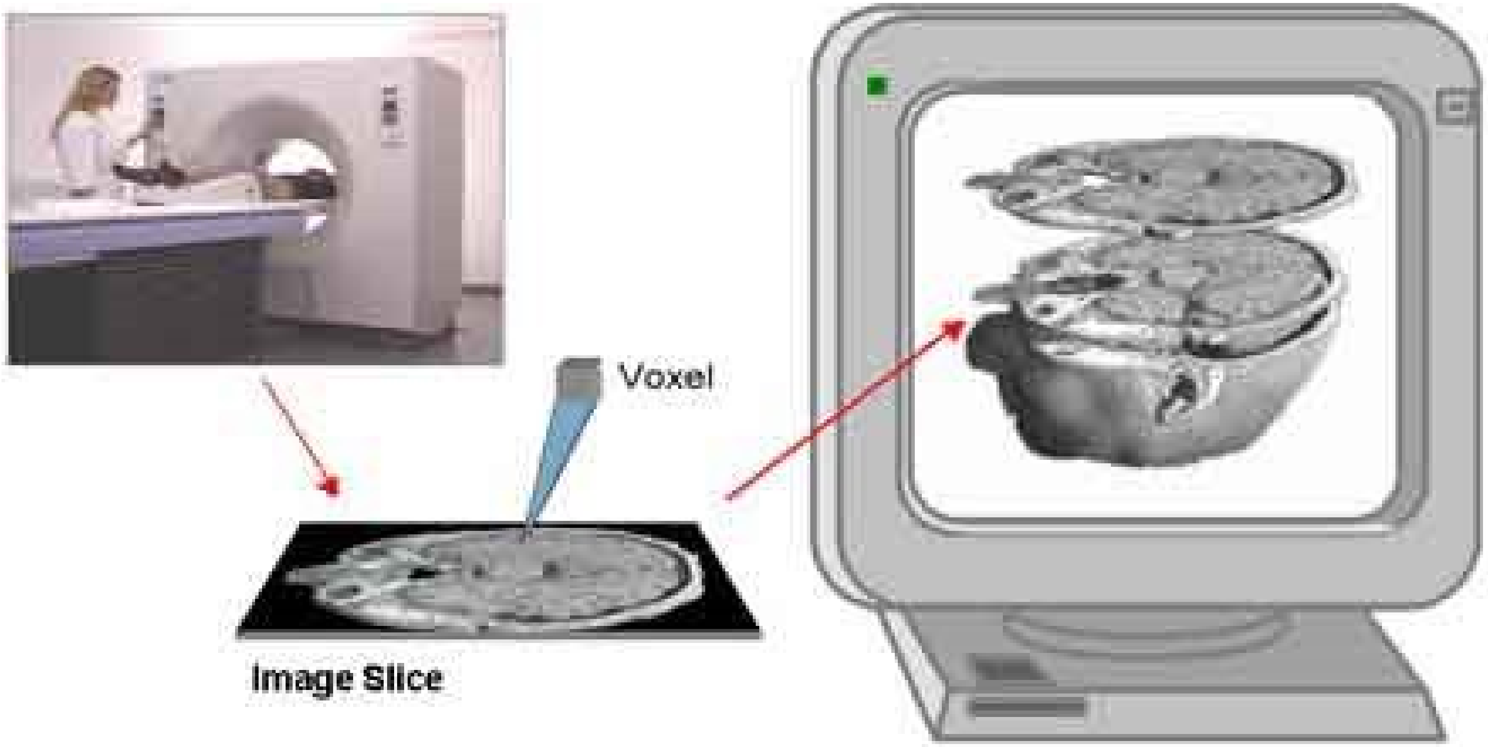
3D Object Representations

- Raw data
  - Range image
  - Point cloud
- Surfaces
  - Polygonal mesh
  - Subdivision
  - Parametric
  - Implicit

- Solids
  - Voxels
  - BSP tree
  - CSG
  - Sweep
- High-level structures
  - Scene graph
  - Application specific

Solid Modeling

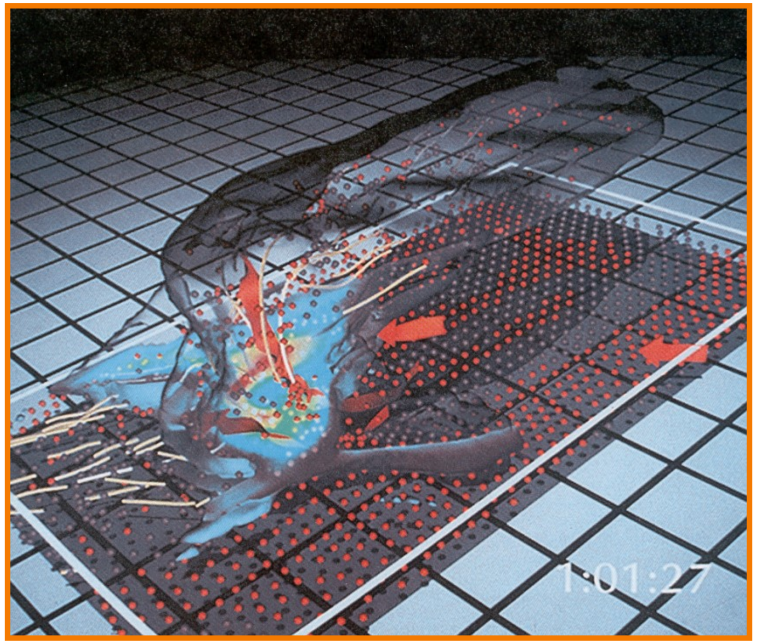
- Represent solid interiors of objects



www.volumegraphics.com

Motivation 1

- Some acquisition methods generate solids



Airflow Inside a Thunderstorm

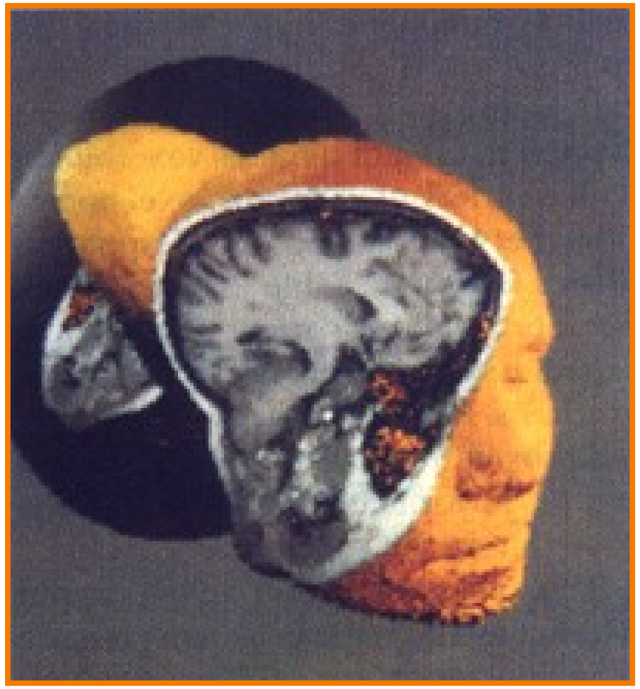
*(Bob Wilhelmson,
University of Illinois at Urbana-Champaign)*

Visible Human

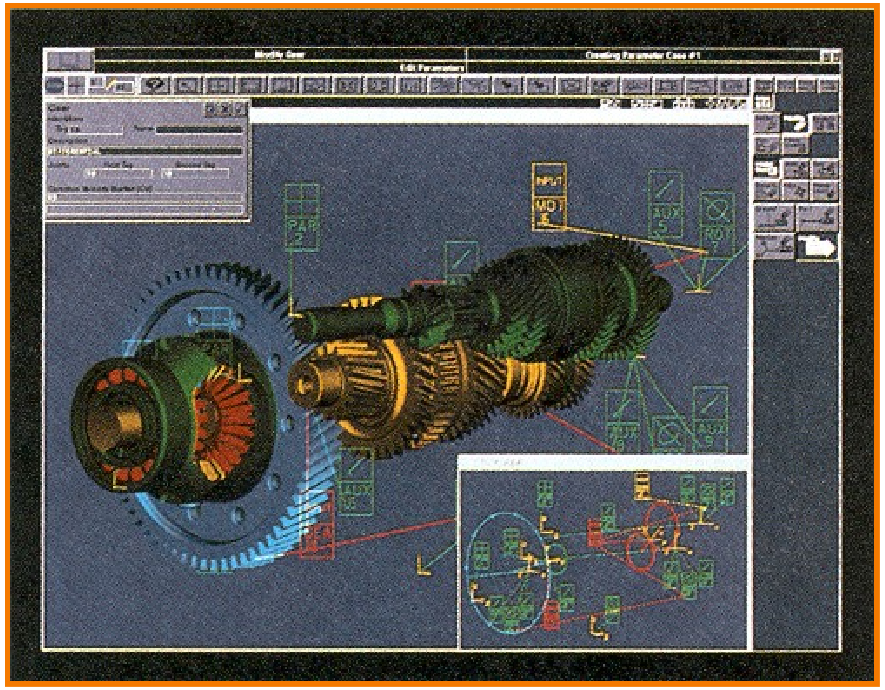
(National Library of Medicine)

Motivation 2

- Some applications require solids
  - Examples: medicine, CAD/CAM



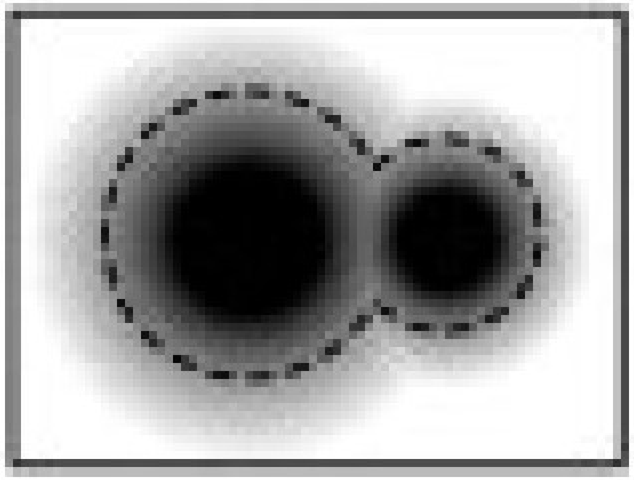
SUNY Stoney Brook



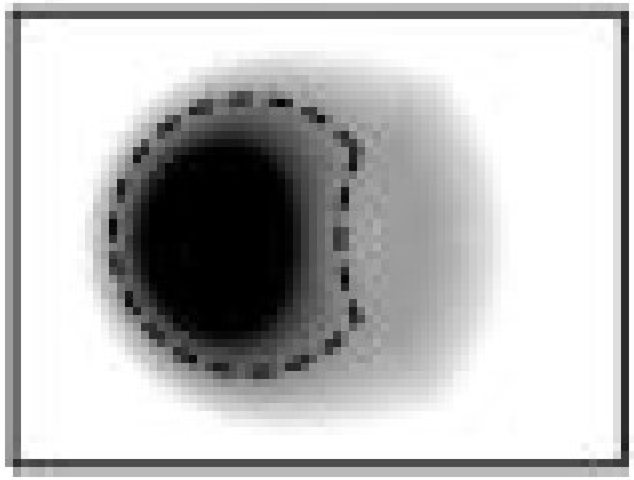
Intergraph Corporation

Motivation 3

- Some operations are easier with solids
    - Example: union, difference, intersection



Union



Difference

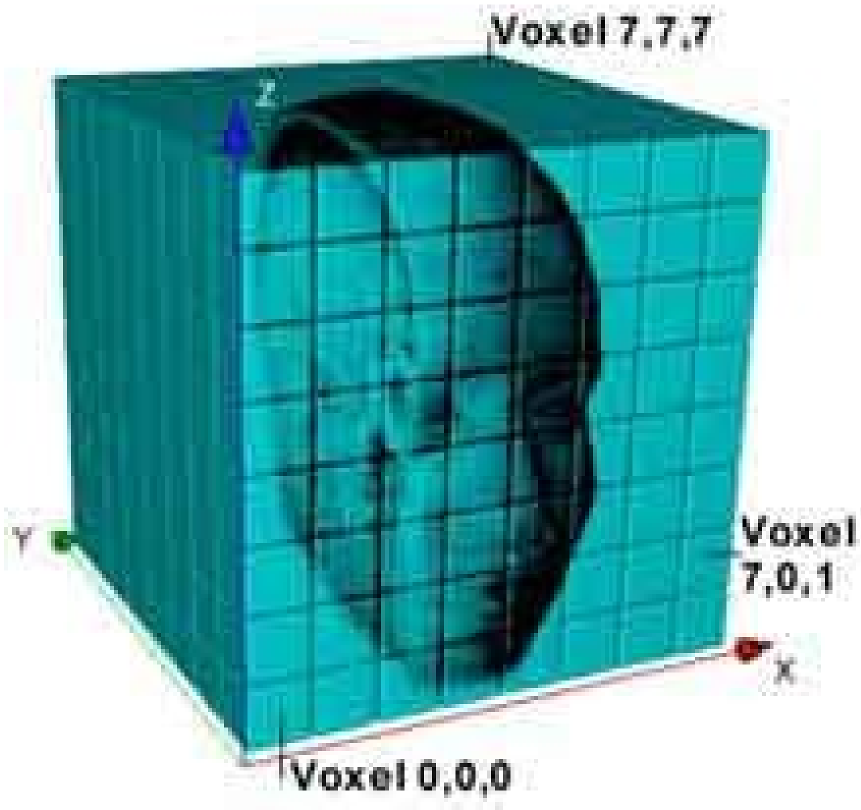
Bloomenthal

3D Object Representations

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

Return to Voxels

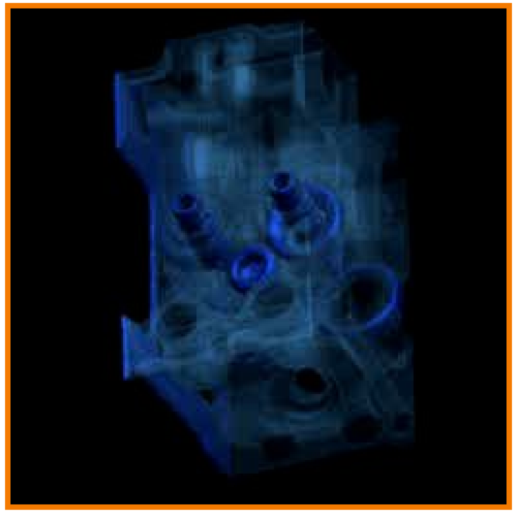
- Regular array of 3D samples (like image)



www.volumegraphics.com

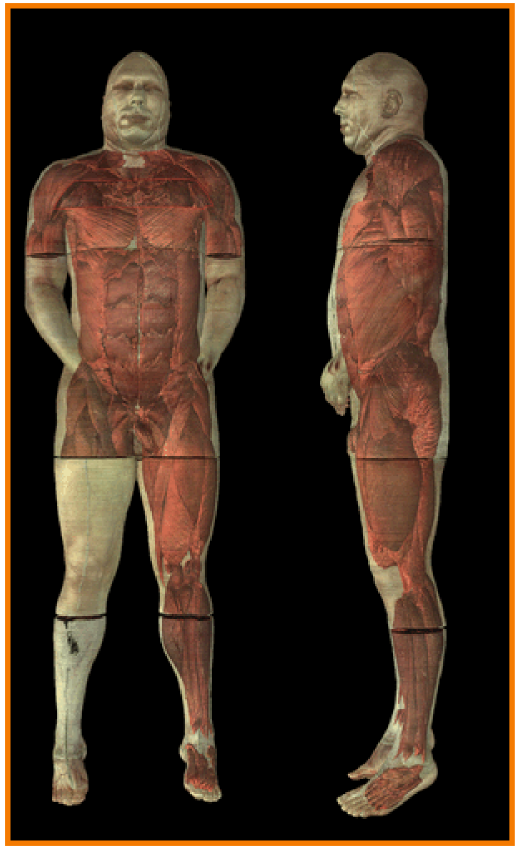
Voxels

- Store properties of solid object with each voxel
  - Occupancy
  - Color
  - Density
  - Temperature
  - etc.



Engine Block

Stanford University

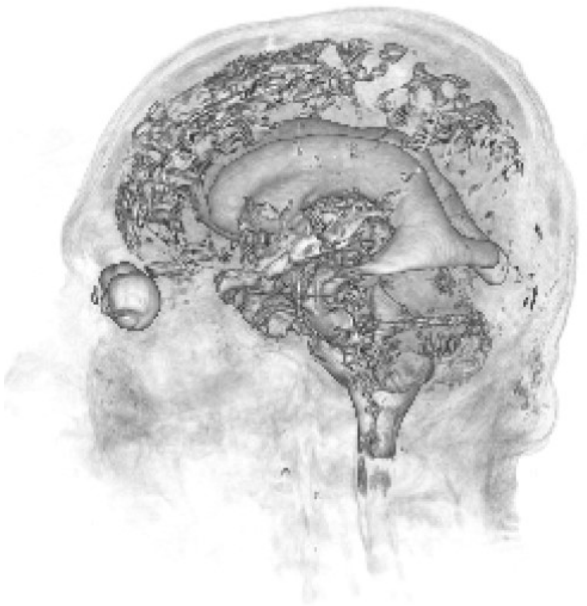


Visible Human

(National Library of Medicine)

Voxel Processing

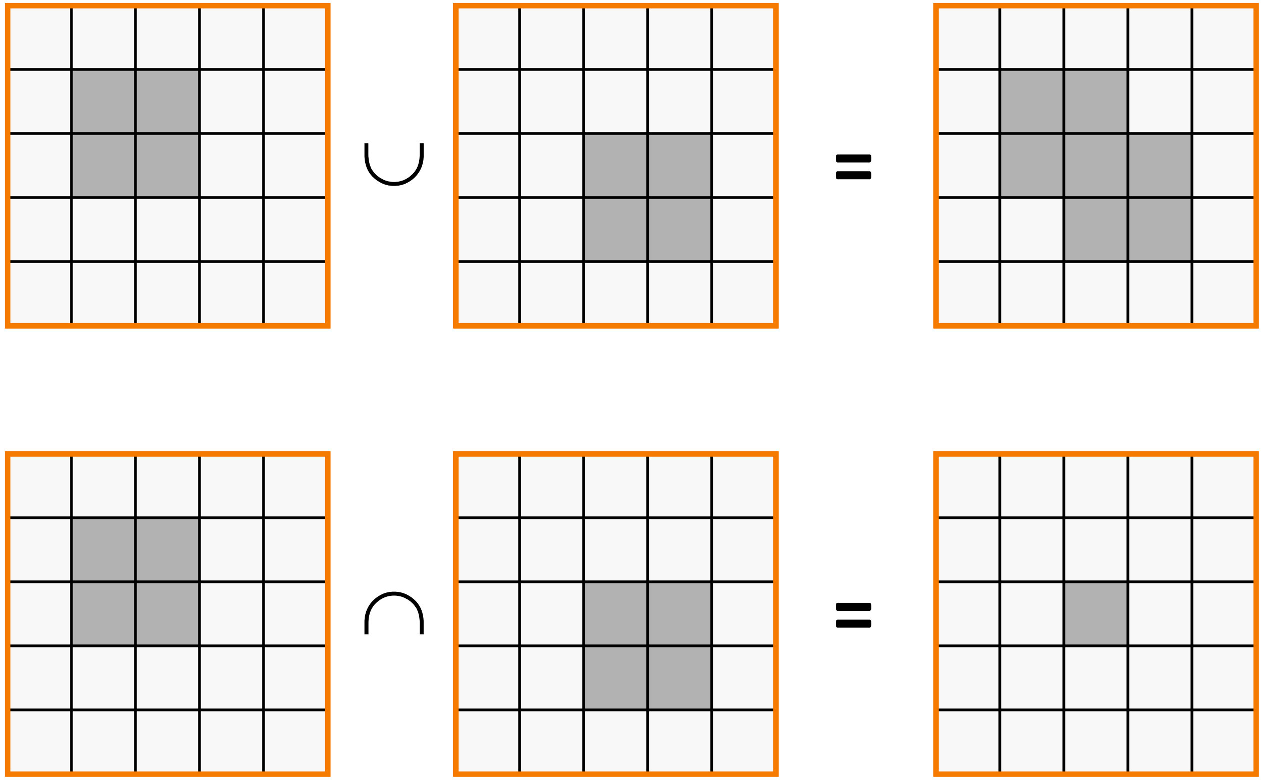
- Signal processing (just like images)
  - Reconstruction
  - Resampling
- Typical operations
  - Blur
  - Edge detect
  - Warp
  - etc.
- Often fully analogous to image processing



www.volumegraphics.com

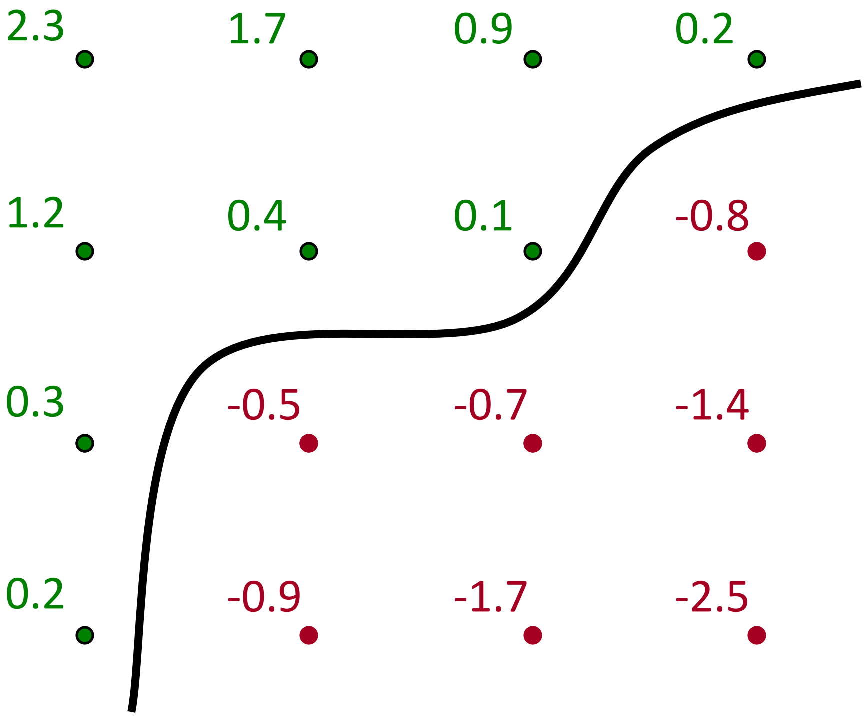
Voxel Boolean Operations

- Compare objects voxel by voxel
  - Trivial



Voxel Display

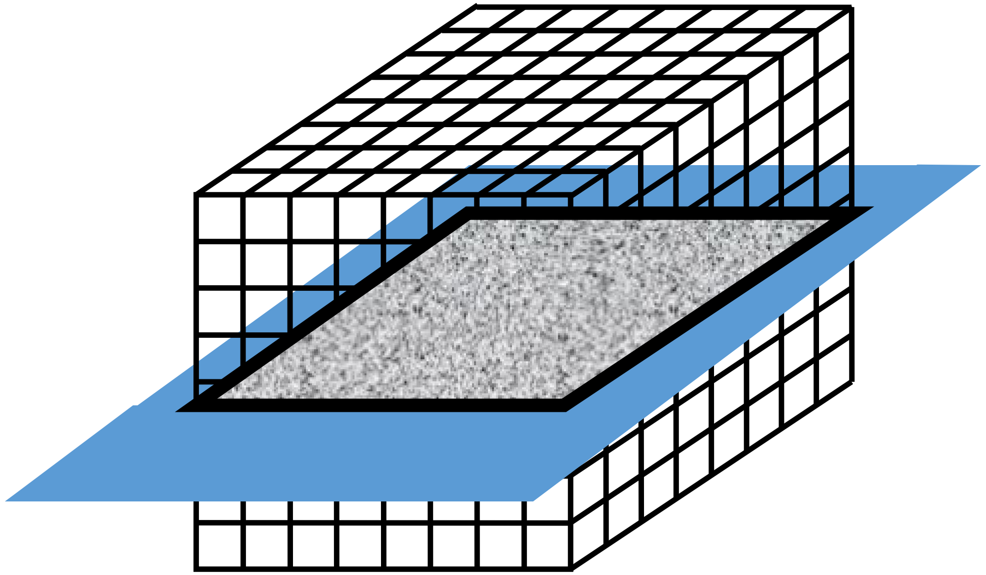
- Isosurface rendering
  - Interpolate samples stored on regular grid
  - Isosurface at f(x,y,z) = 0 defines surface

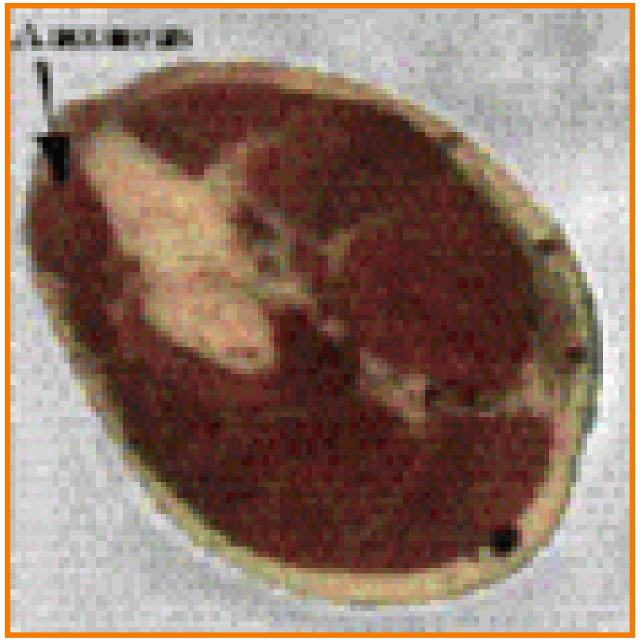


2.3	1.7	0.9	0.2
1.2	0.4	0.1	-0.8
0.3	-0.5	-0.7	-1.4
0.2	-0.9	-1.7	-2.5

Voxel Display

- Slicing
  - Draw 2D image resulting from intersecting voxels with a plane



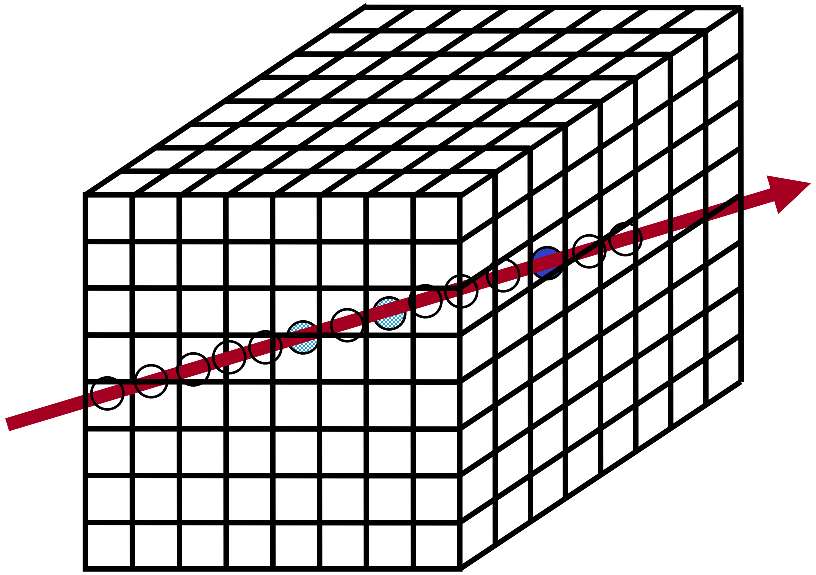


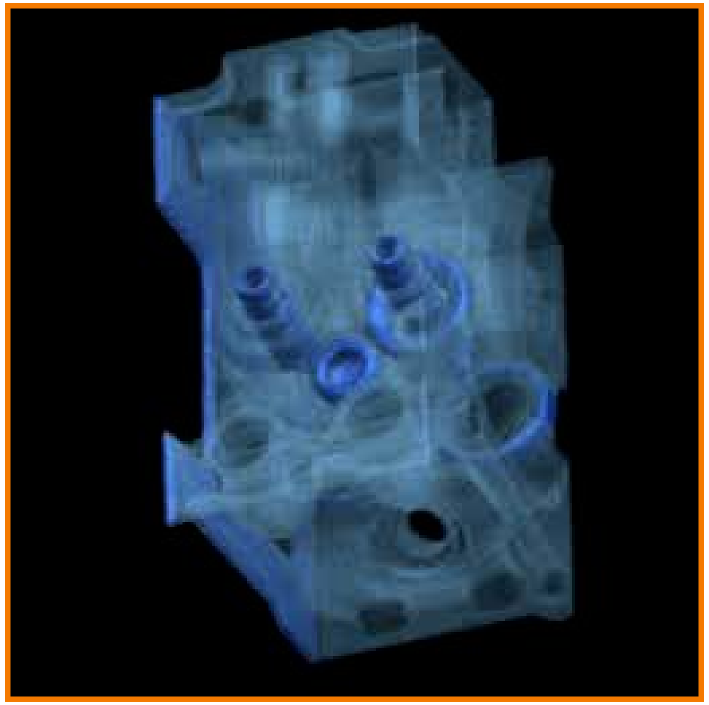
Visible Human

(National Library of Medicine)

Voxel Display

- Ray casting
  - Integrate density along rays: compositing!

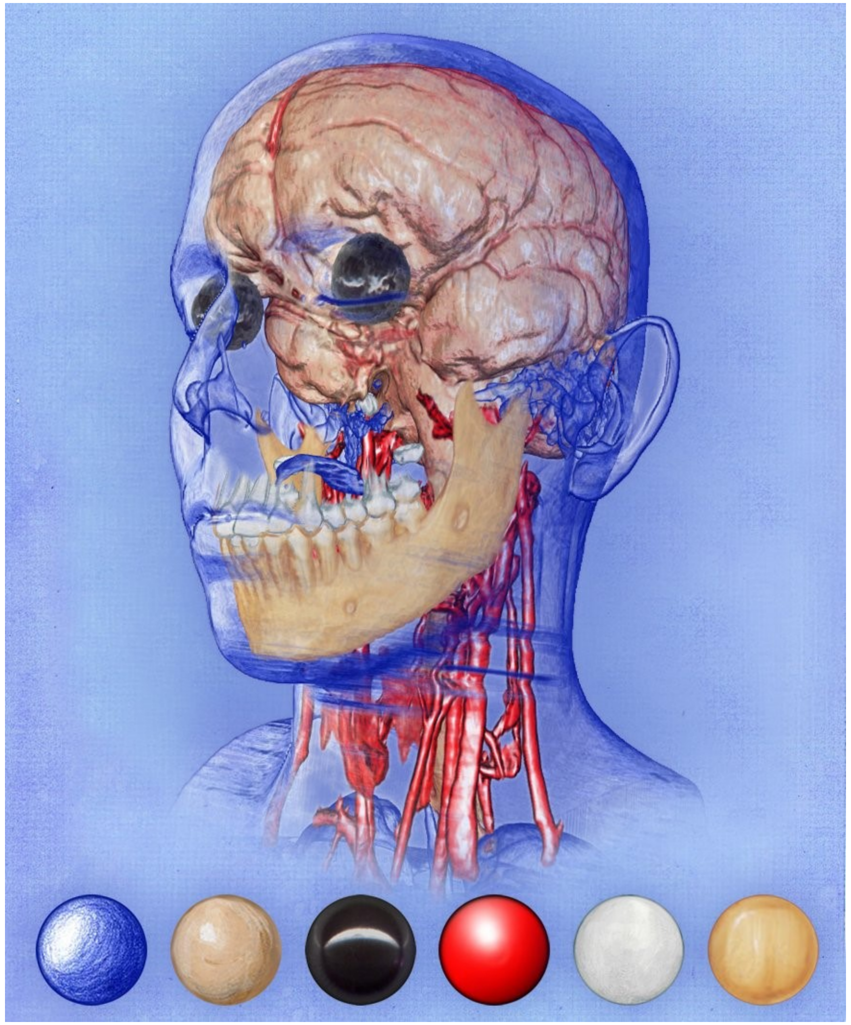




Engine Block
Stanford University

Voxel Display

- Extended ray-casting
  - Transfer functions: Map voxel values to opacity and material
  - Normals (for lighting) from density gradient



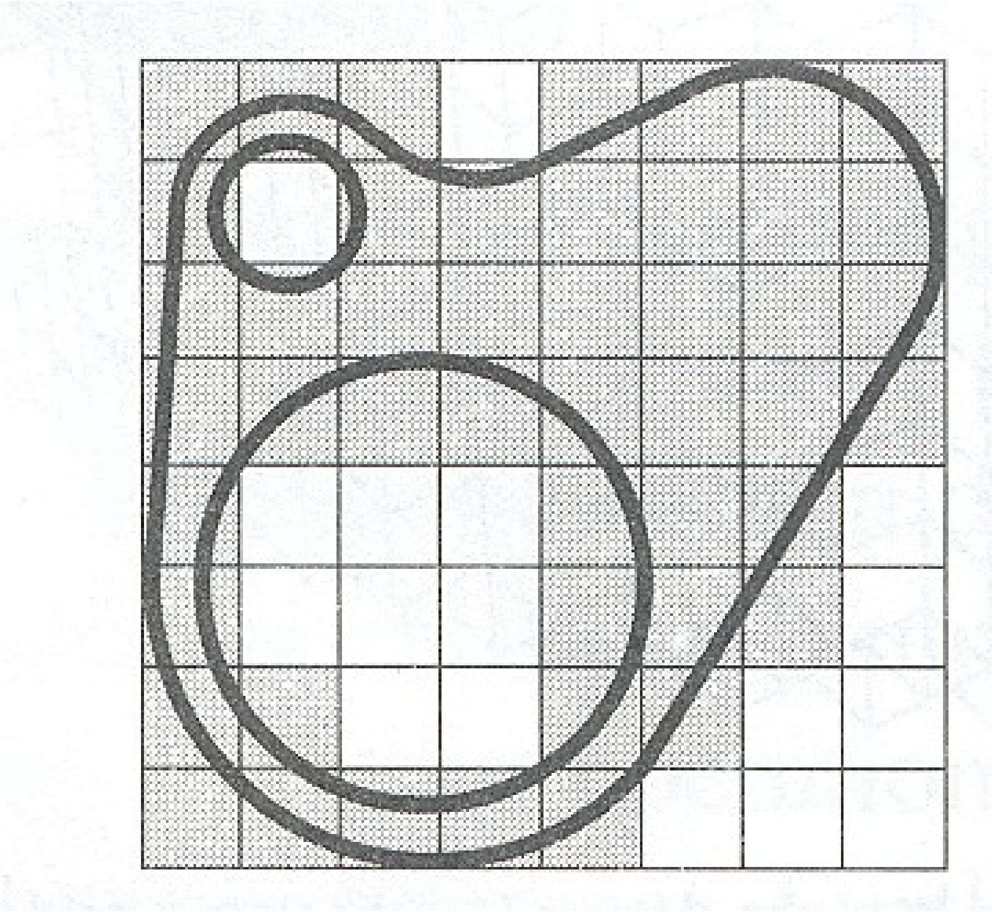
Bruckner et al. 2007

Voxels

- Advantages
  - Simple, intuitive, unambiguous
  - Same complexity for all objects
  - Natural acquisition for some applications
  - Trivial boolean operations
- Disadvantages
  - Approximate
  - Not affine invariant
  - Expensive display
  - Large storage requirements

Voxels

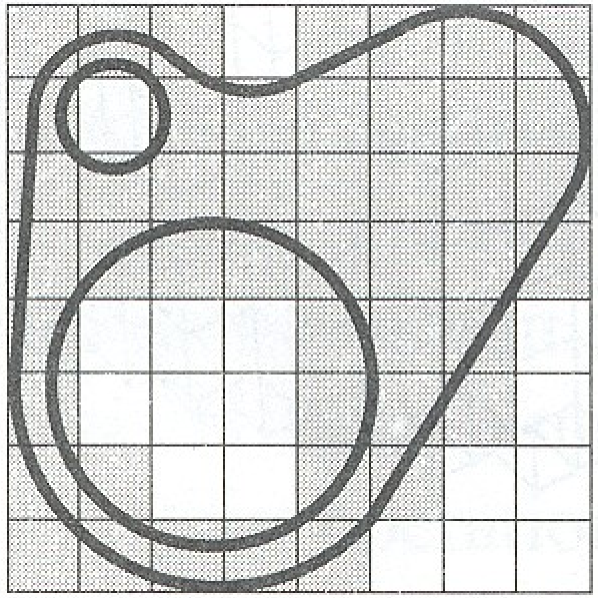
- What resolution should be used?



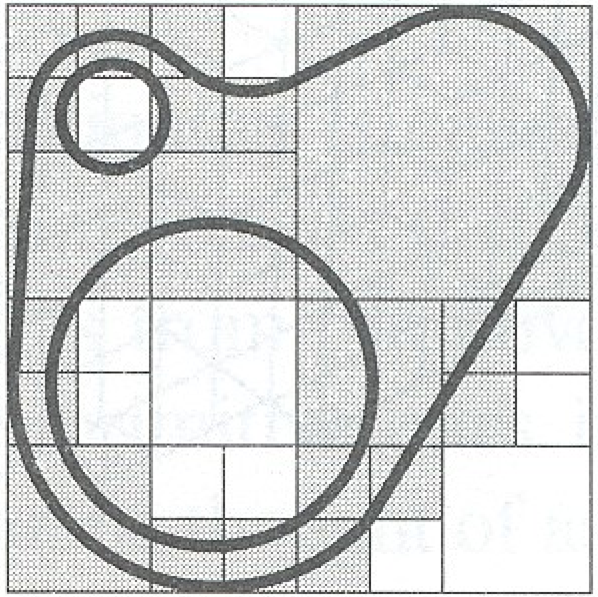
FvDFH Figure 12.21

Quadtrees & Octrees

- Refine resolution of voxels hierarchically
  - More concise and efficient for non-uniform objects



Uniform Voxels

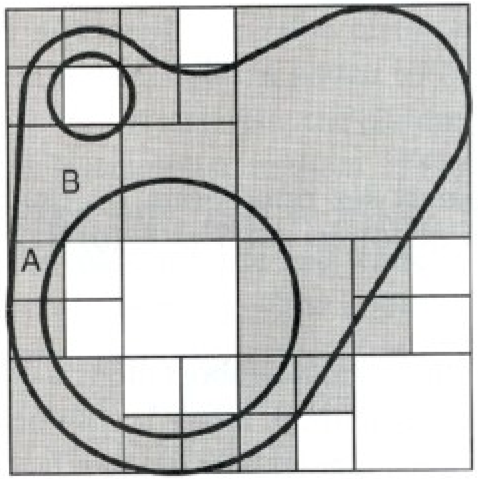


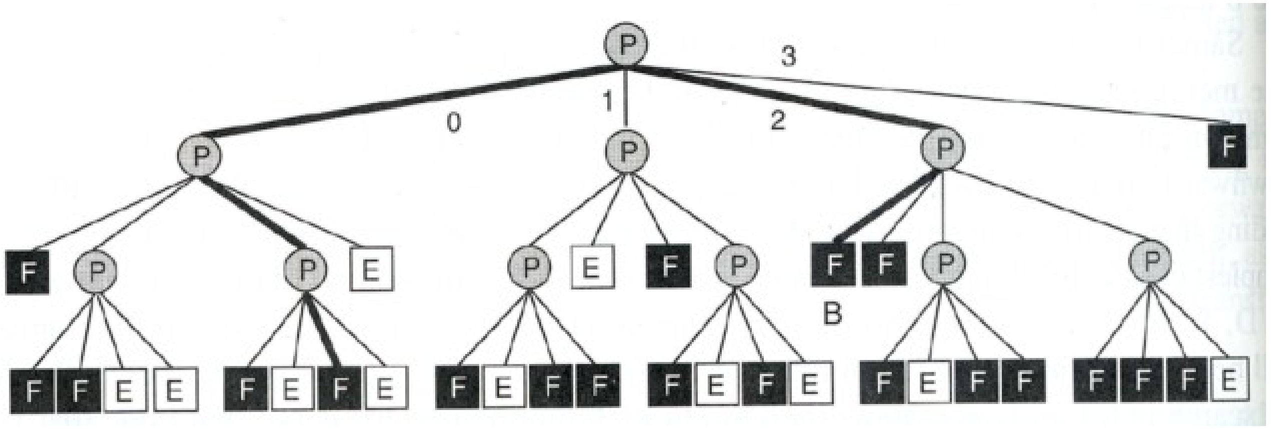
Quadtree (Octree in 3D)

FvDFH Figure 12.21

Quadtree Processing

- Hierarchical versions of voxel methods
  - Finding neighbor cell requires traversal of hierarchy: expected/amortized O(1)



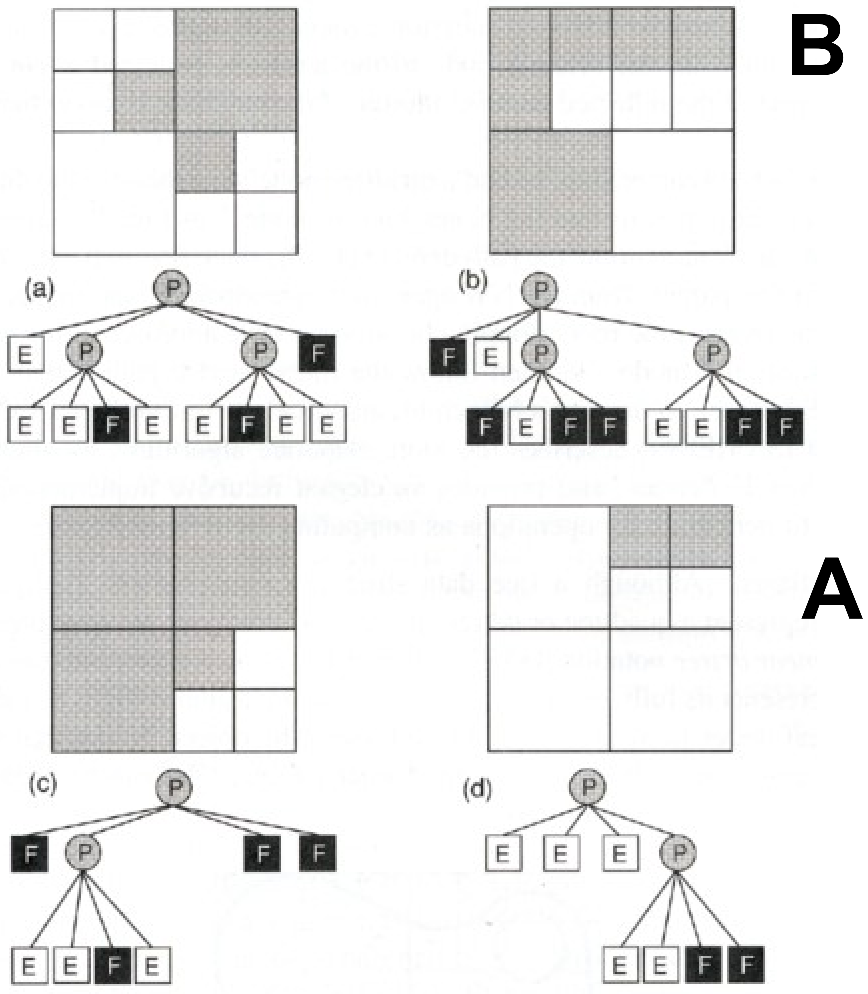


FvDFH Figure 12.25

Quadtree Boolean Operations

A

B



A ∪ B

A ∩ B

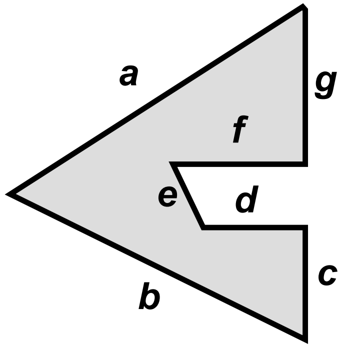
FvDFH Figure 12.24

3D Object Representations

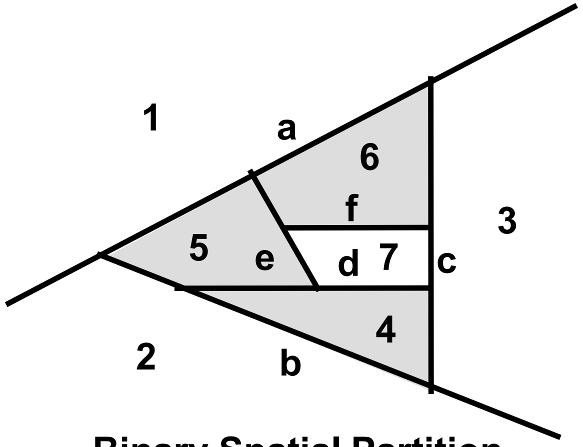
- Raw data
  - Range image
  - Point cloud
- Surfaces
  - Polygonal mesh
  - Subdivision
  - Parametric
  - Implicit

- Solids
  - Voxels
  - ➢ BSP tree
  - CSG
  - Sweep
- High-level structures
  - Scene graph
  - Application specific

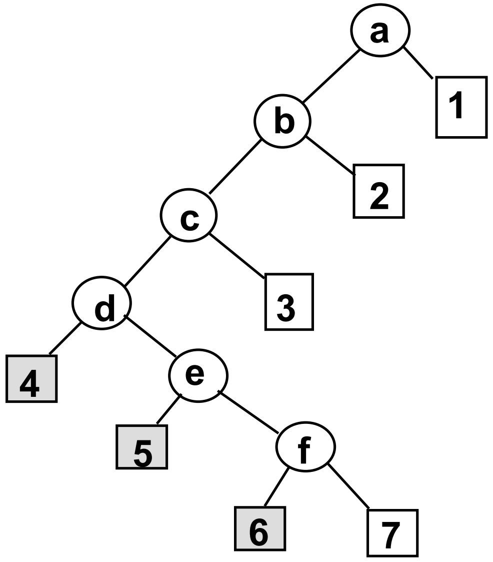
BSP Trees



Object



Binary Spatial Partition

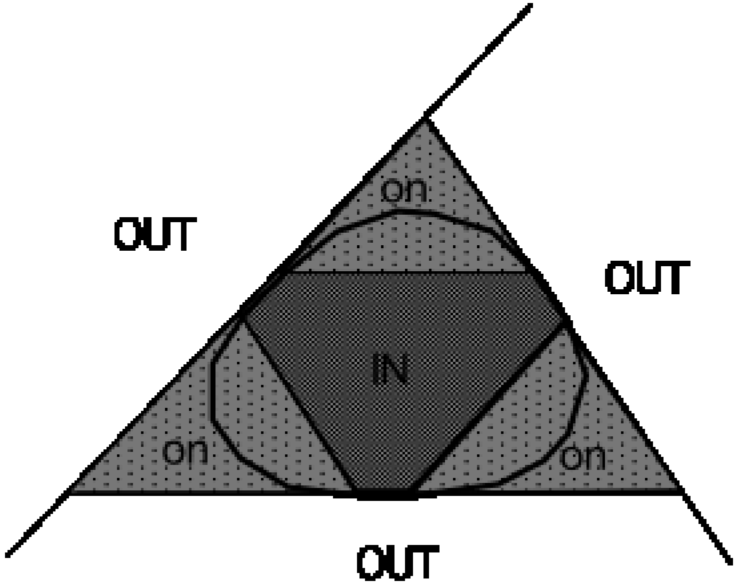


Binary Tree

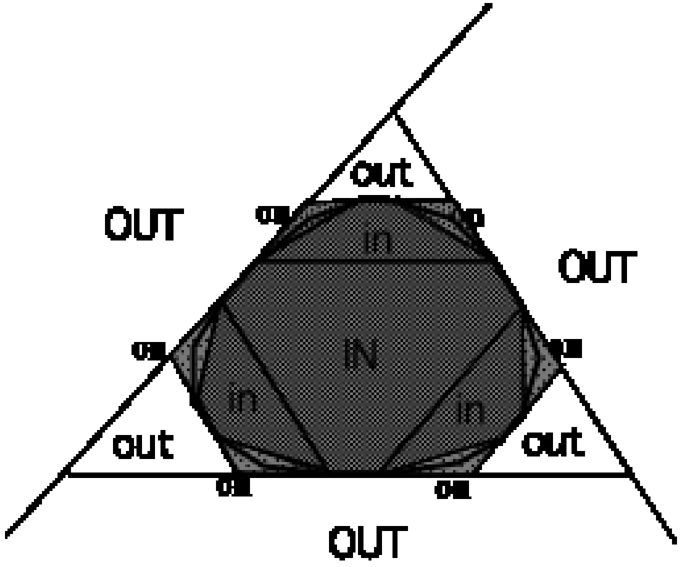
Naylor

BSP Trees

- Key properties
  - visibility ordering (later)
  - hierarchy of convex regions (useful for collision)



1st level Approximation



2nd level Approximation

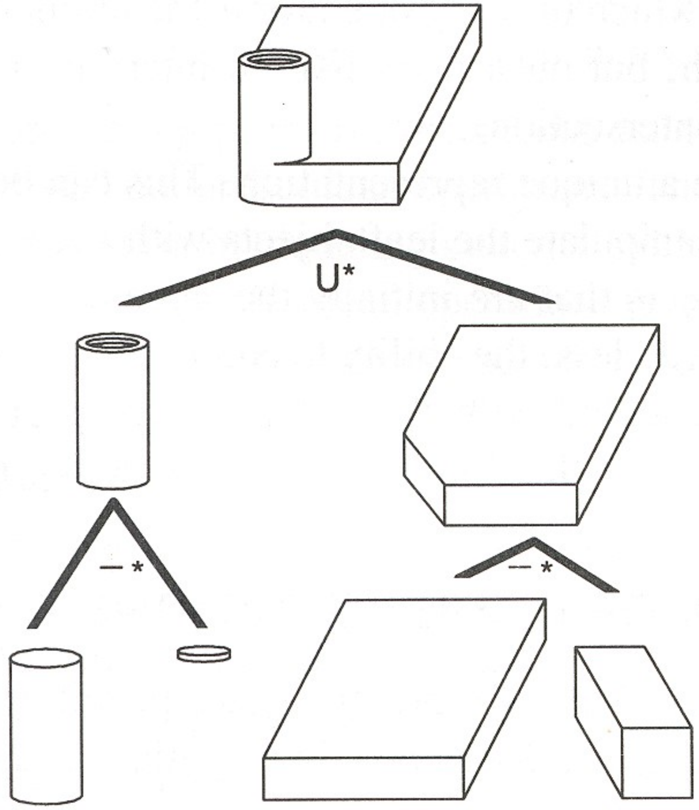
Naylor

3D Object Representations

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

Constructive Solid Geometry (CSG)

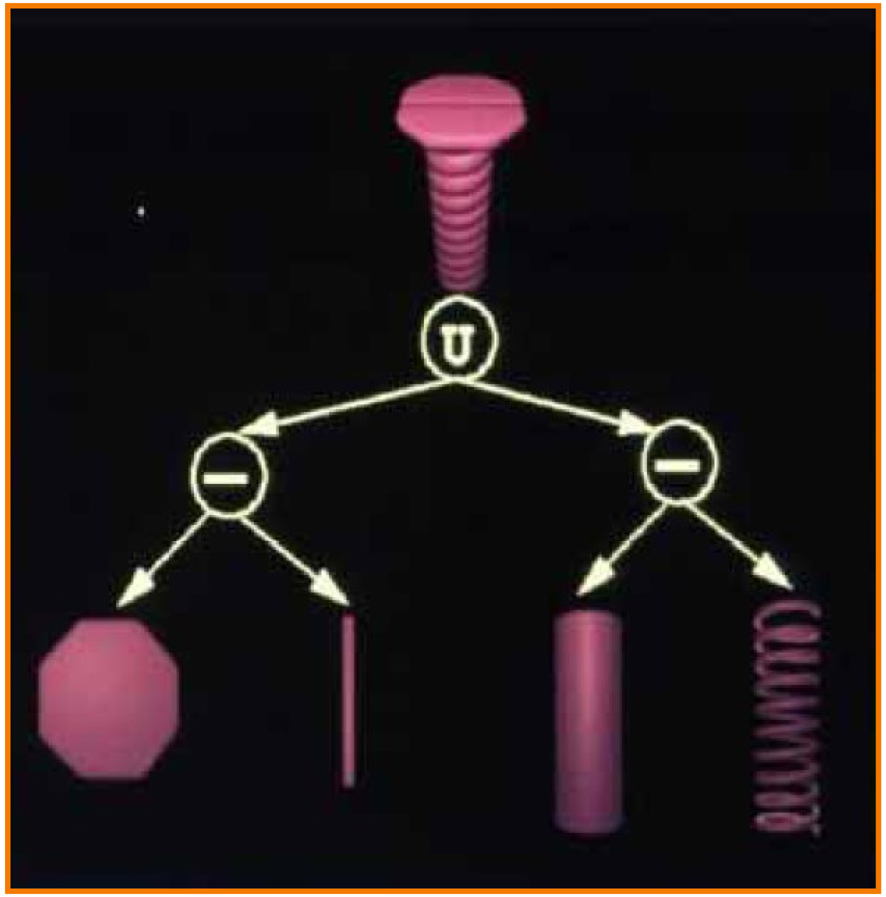
- Represent solid object as hierarchy of boolean operations
  - Union
  - Intersection
  - Difference



FvDFH Figure 12.27

CSG Acquisition

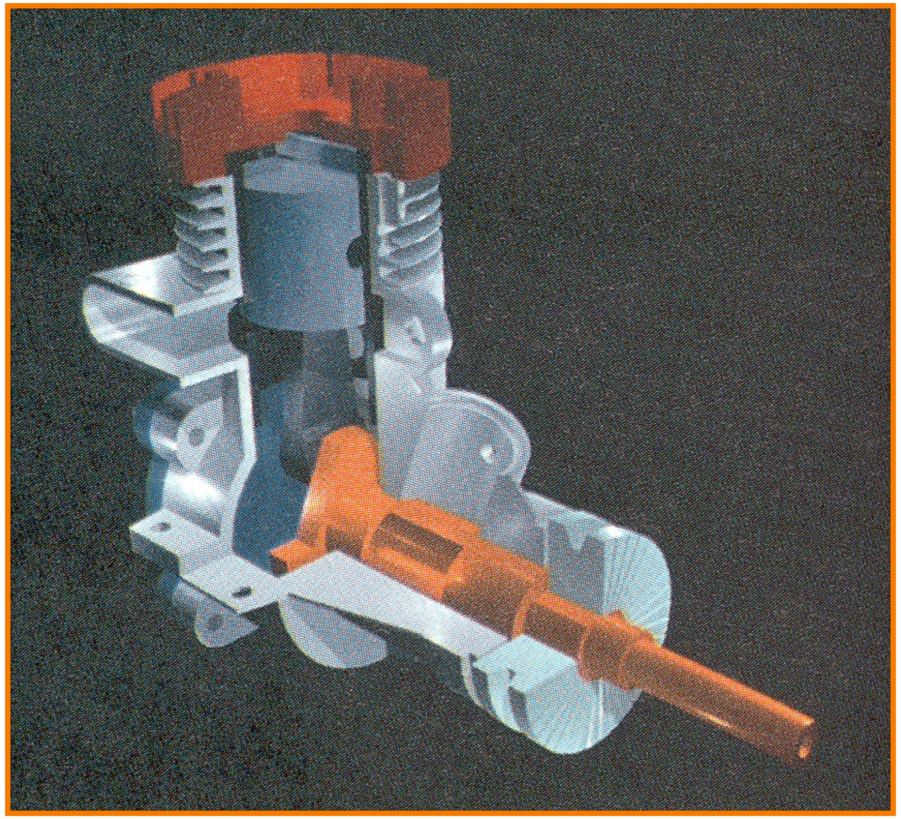
- Interactive modeling programs
  - Intuitive way to design objects



SUNY Stoney Brook

CSG Acquisition

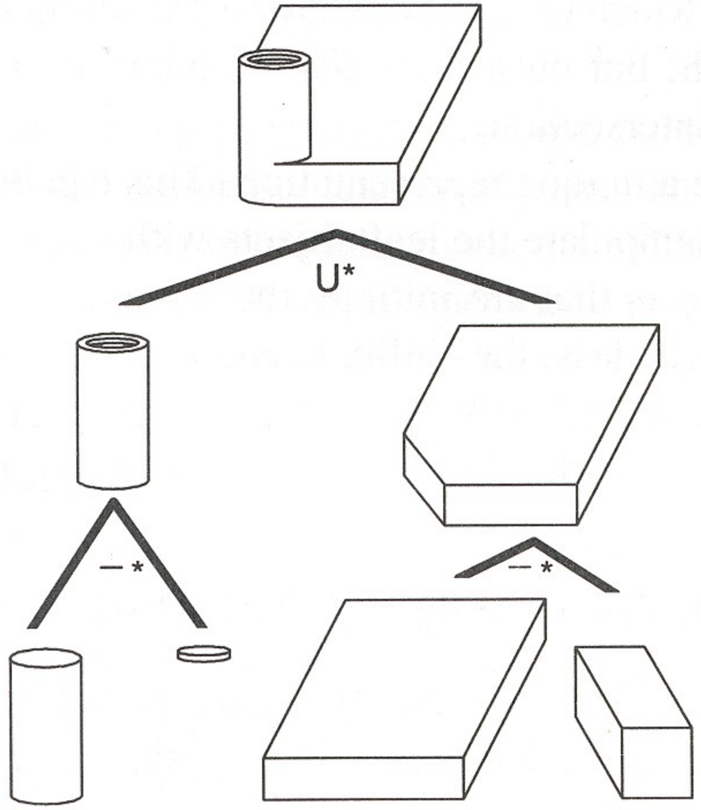
- Interactive modeling programs
  - Intuitive way to design objects



H&B Figure 9.9

CSG Boolean Operations

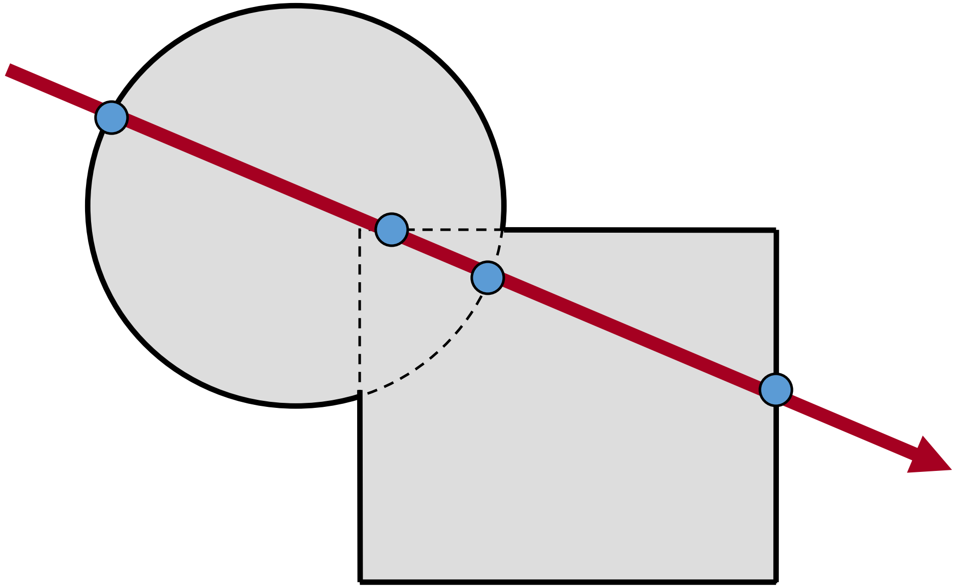
- Create a new CSG node joining subtrees
  - Union
  - Intersection
  - Difference

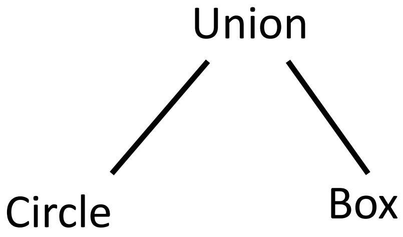


FvDFH Figure 12.27

CSG Display & Analysis

- Ray casting





Union

Circle

Box

3D Object Representations

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  - Implicit
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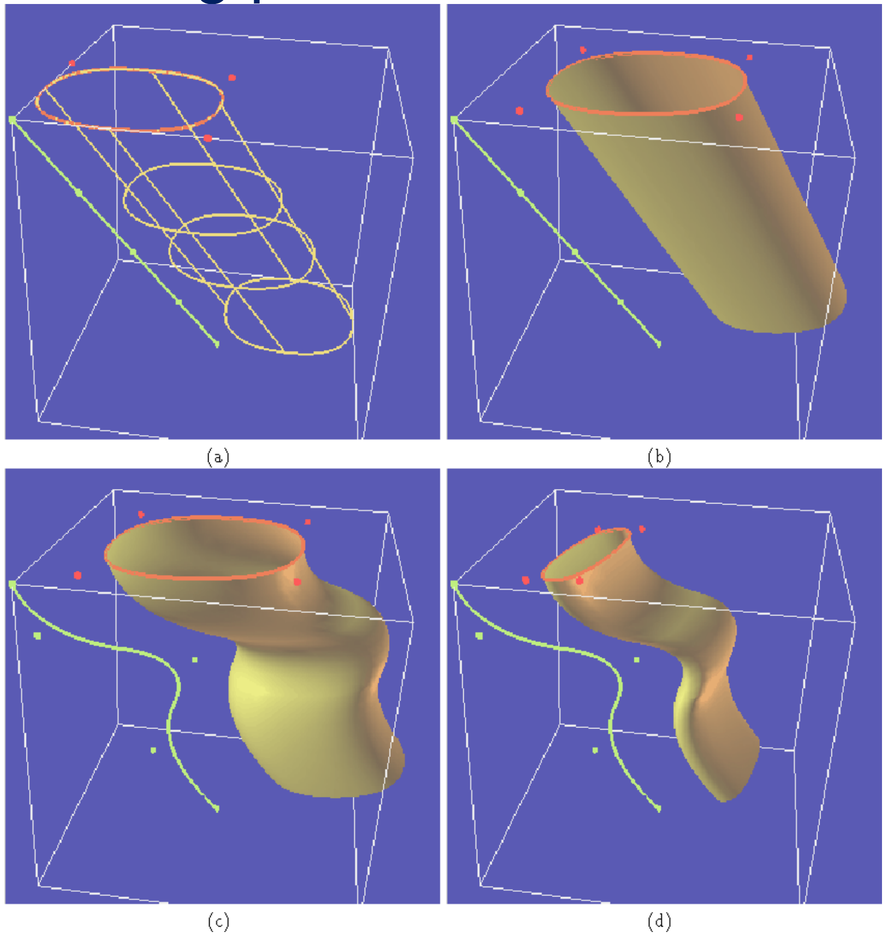
  - Voxels
  - BSP tree
  - CSG
  - ➢ Sweep
- High-level structures
  - Scene graph
  - Application specific

Sweeps

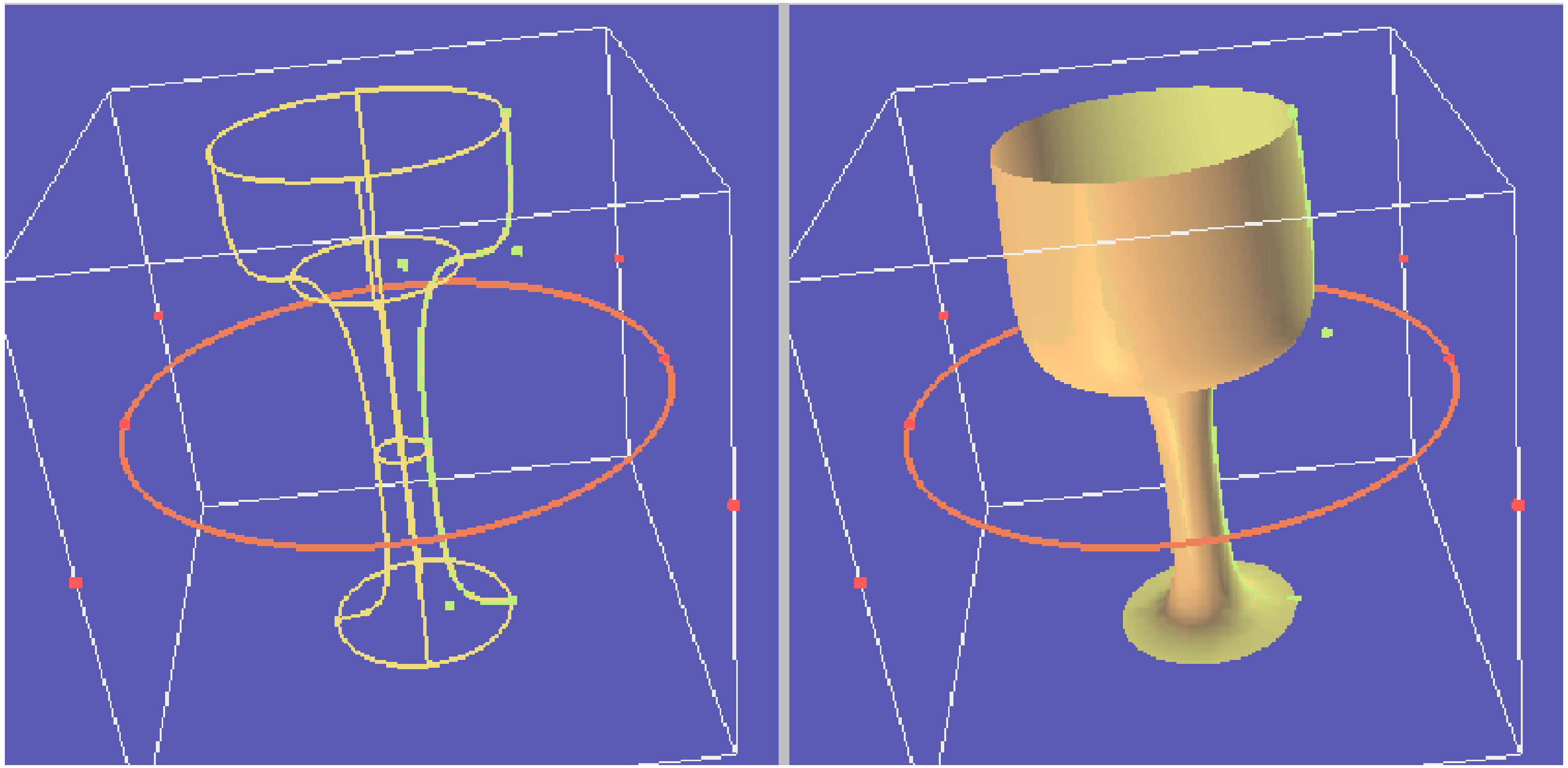
- Swept volume
  - Sweep one curve along path of another curve



Demetri Terzopoulos

Sweeps

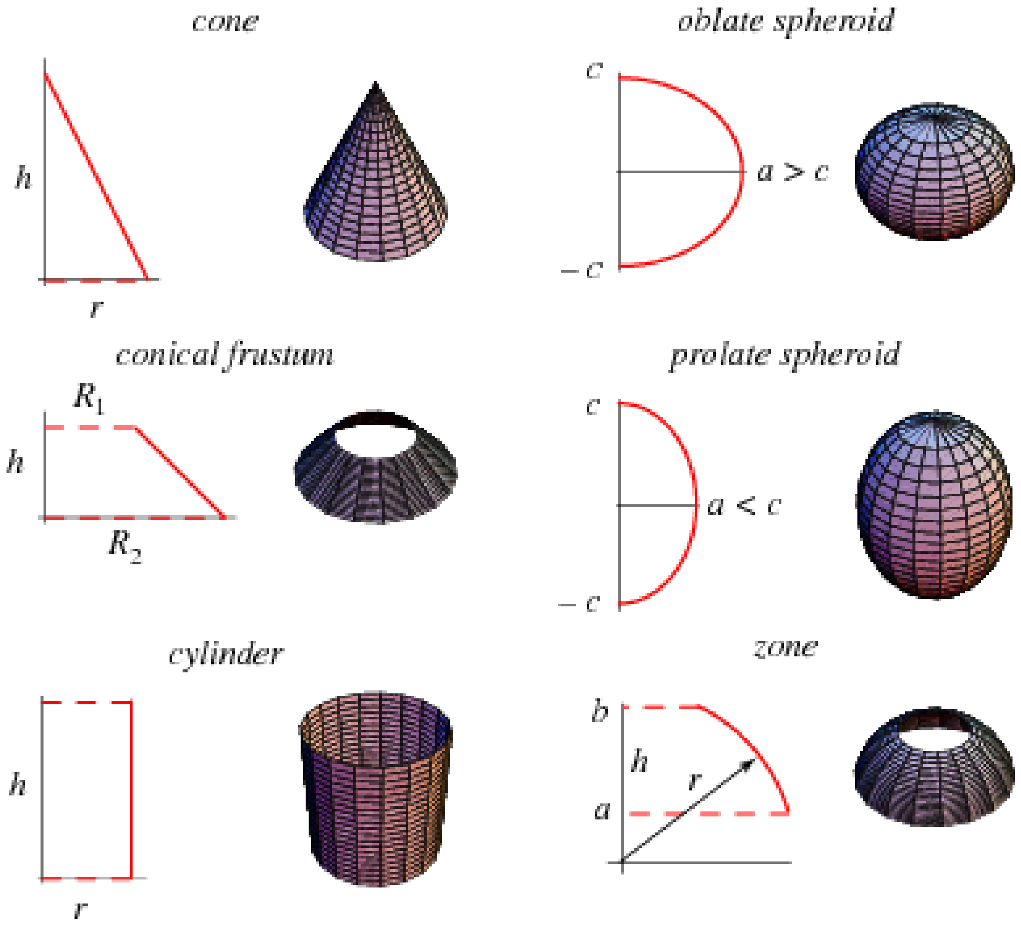
- Surface of revolution
  - Take a curve and rotate it about an axis



Demetri Terzopoulos

Sweeps

- Surface of revolution
  - Take a curve and rotate it about an axis



Wolfram

Summary

Feature	Voxels	Octree	BSP	CSG
Accurate	No	No	Some	Some
Concise	No	No	No	Yes
Affine invariant	No	No	Yes	Yes
Easy acquisition	Some	Some	No	Some
Guaranteed validity	Yes	Yes	Yes	No
Efficient boolean ops	Yes	Yes	Yes	Yes
Efficient display	No	No	Yes	No