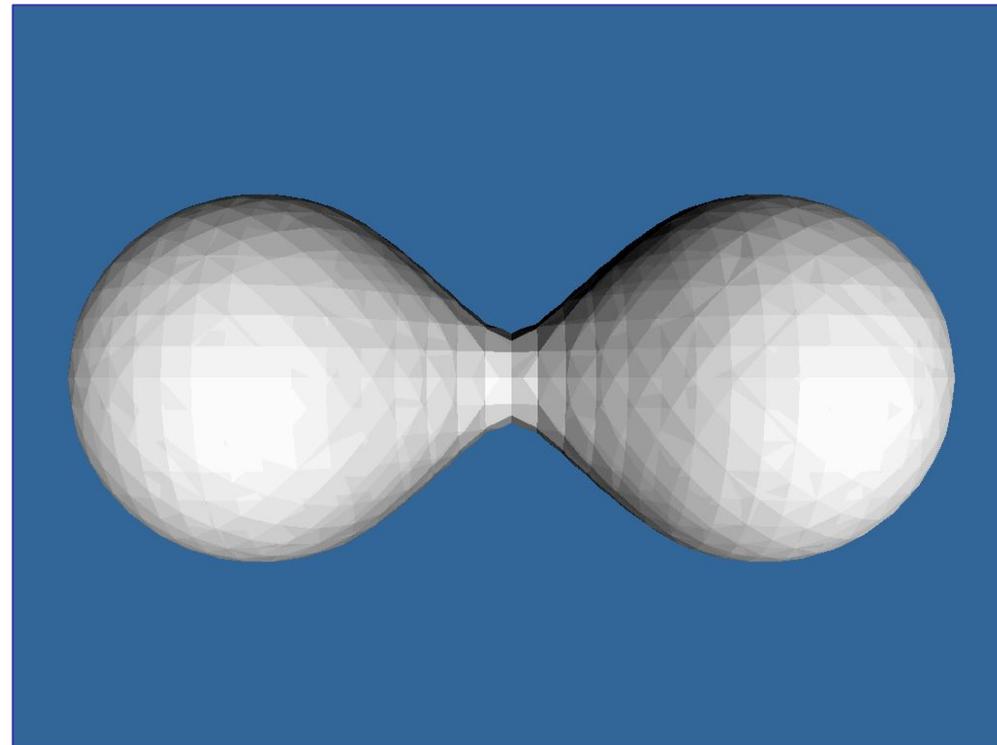
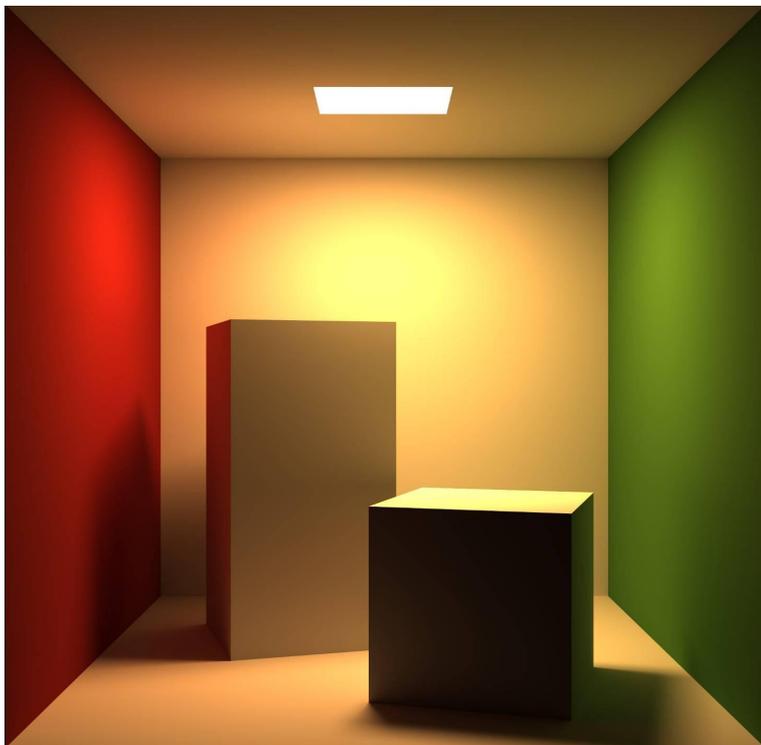


Further Graphics

Improved ray casting *Generalized Implicit Surfaces*



Left: “*Cornell Box*” by Steven Parker, University of Utah.

A tera-ray monte-carlo rendering of the Cornell Box, generated in 2 CPU years on an Origin 2000. The full image contains 2048 x 2048 pixels with over 100,000 primary rays per pixel (317 x 317 jittered samples). Over one trillion rays were traced in the generation of this image.

Right: Animated polygonization of two metaballs dynamically generating an implicit surface at 5 levels of octree recursion (~3200 polygons per frame)

Alex Benton, University of Cambridge – alex@bentonian.com

Supported in part by Google UK, Ltd

Speed things up!

Bounding volumes

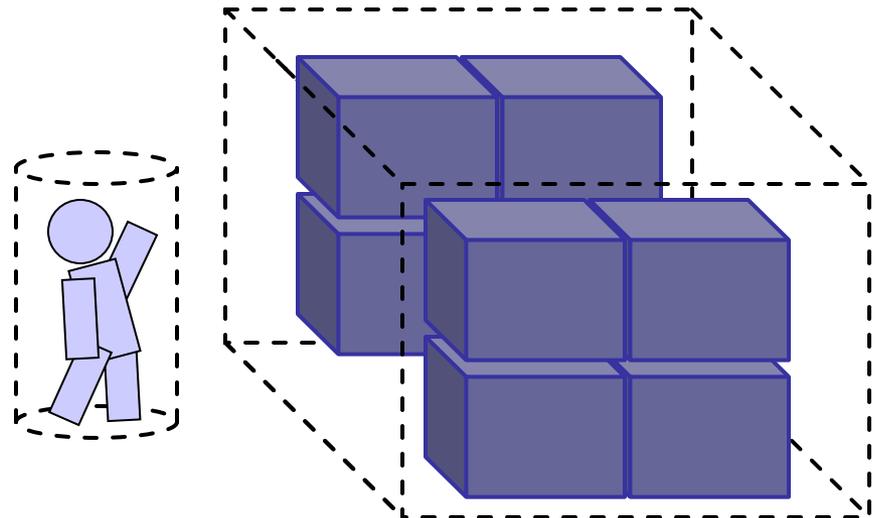
A common optimization method for ray-based rendering is the use of *bounding volumes*.

Nested bounding volumes allow the rapid culling of large portions of geometry

- Test against the bounding volume of the top of the scene graph and then work down.

Great for...

- Collision detection between scene elements
- Culling before rendering
- Accelerating ray-tracing, -marching



Types of bounding volumes

The goal is to accelerate volumetric tests, such as “does the ray hit the cow?” → *speed* trumps *precision*

- choose fast hit testing over accuracy
- ‘bboxes’ don’t have to be tight

Axis-aligned bounding boxes

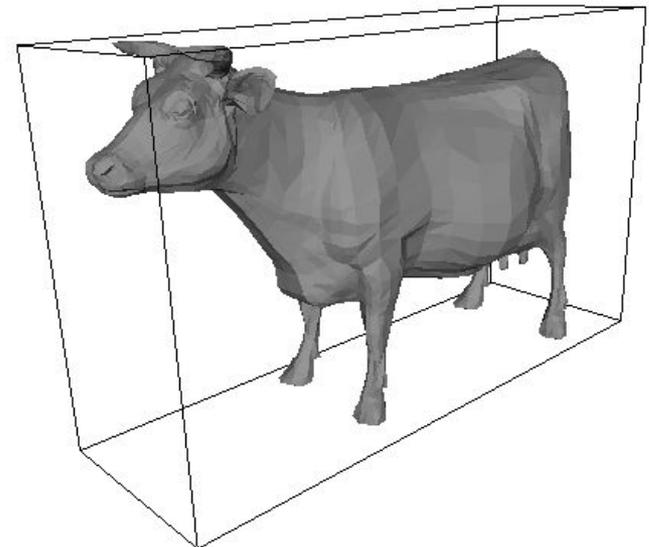
- max and min of x/y/z.

Bounding spheres

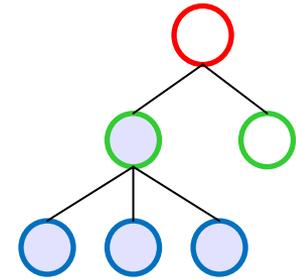
- max of radius from some rough center

Bounding cylinders

- common in early FPS games

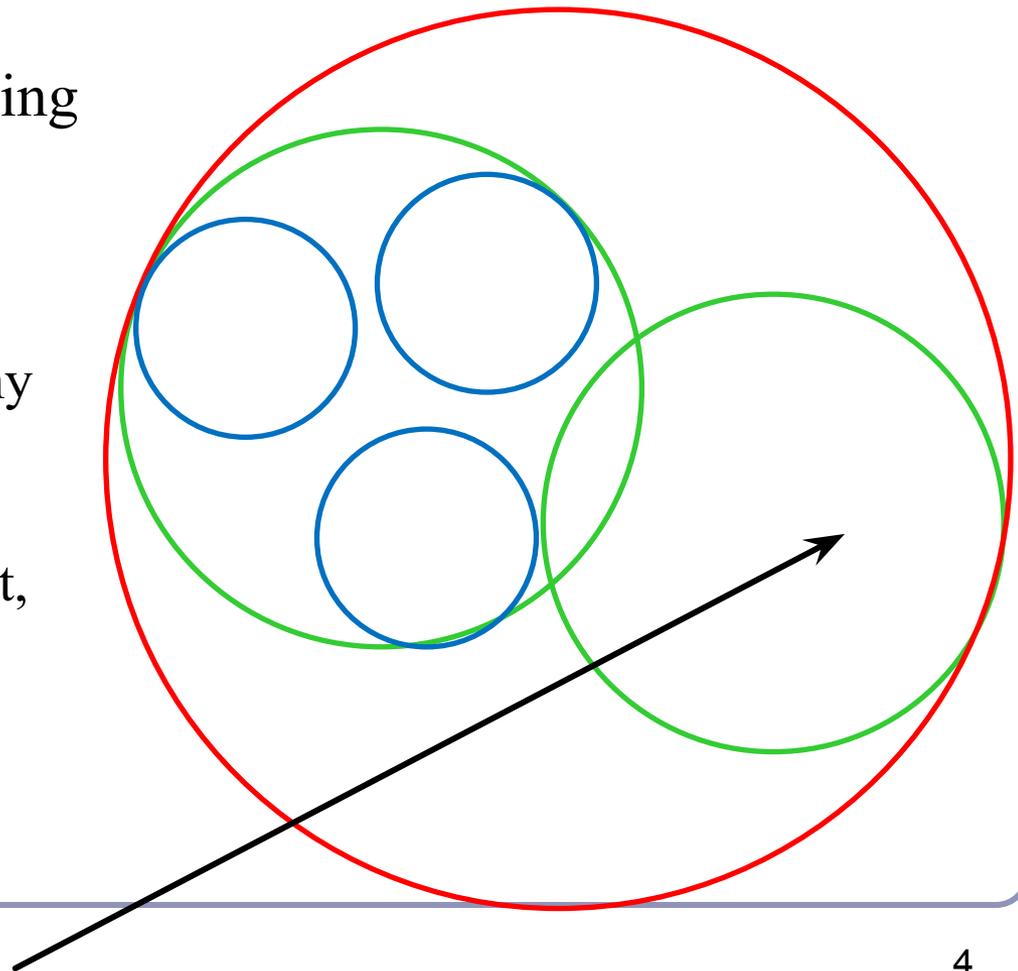


Bounding volumes in hierarchy



Hierarchies of bounding volumes allow early discarding of rays that won't hit large parts of the scene.

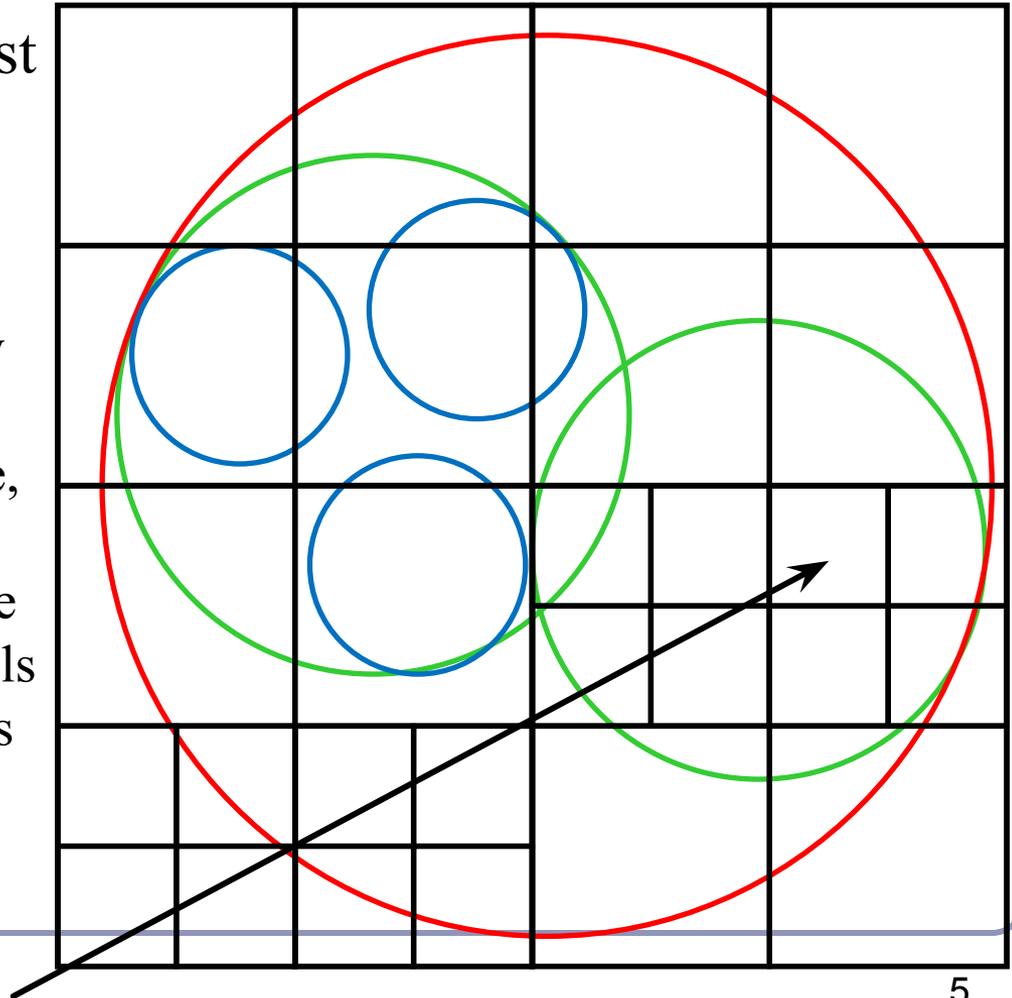
- Pro: Rays can skip subsections of the hierarchy
- Con: Without spatial coherence ordering the objects in a volume you hit, you'll still have to hit-test every object



Subdivision of space

Split space into cells and list in each cell every object in the scene that overlaps that cell.

- Pro: The ray can skip empty cells
- Con: Depending on cell size, objects may overlap many filled cells or you may waste memory on many empty cells
- Popular for voxelized games (ex: *Minecraft*)



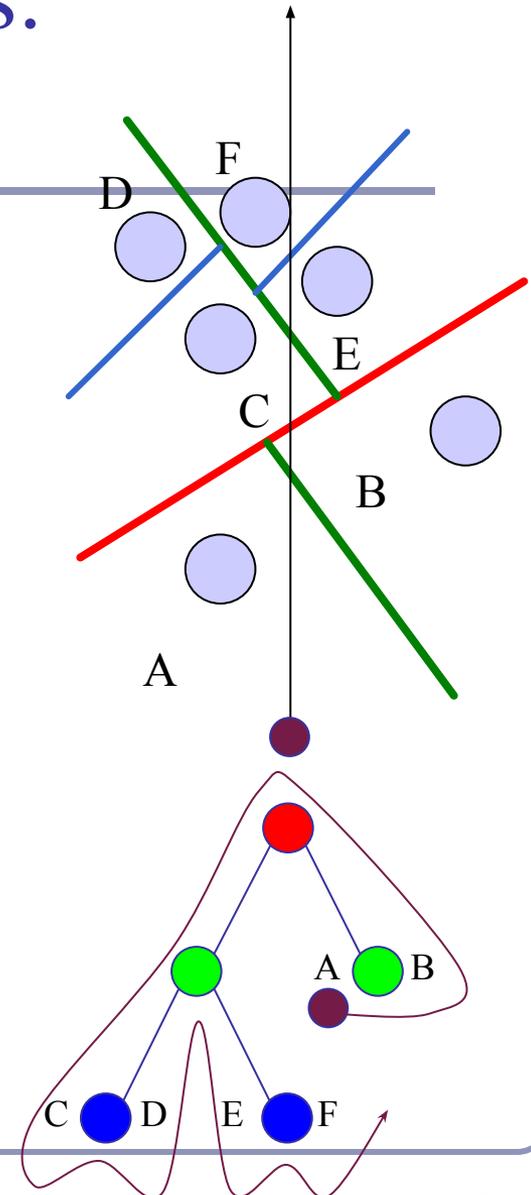
Popular acceleration structures: BSP Trees

The *BSP tree* **pre-partitions** the scene into objects in front of, on, and behind a tree of planes.

- This gives an ordering in which to test scene objects against your ray
- When you fire a ray into the scene, you test all near-side objects before testing far-side objects.

Challenges:

- requires slow pre-processing step
- strongly favors static scenes
- choice of planes is hard to optimize



Popular acceleration structures: *kd-trees*

The *kd-tree* is a simplification of the BSP Tree data structure

- Space is recursively subdivided by axis-aligned planes and points on either side of each plane are separated in the tree.
- The *kd-tree* has $O(n \log n)$ insertion time (but this is very optimizable by domain knowledge) and $O(n^{2/3})$ search time.
- *kd-trees* don't suffer from the mathematical slowdowns of BSPs because their planes are always axis-aligned.

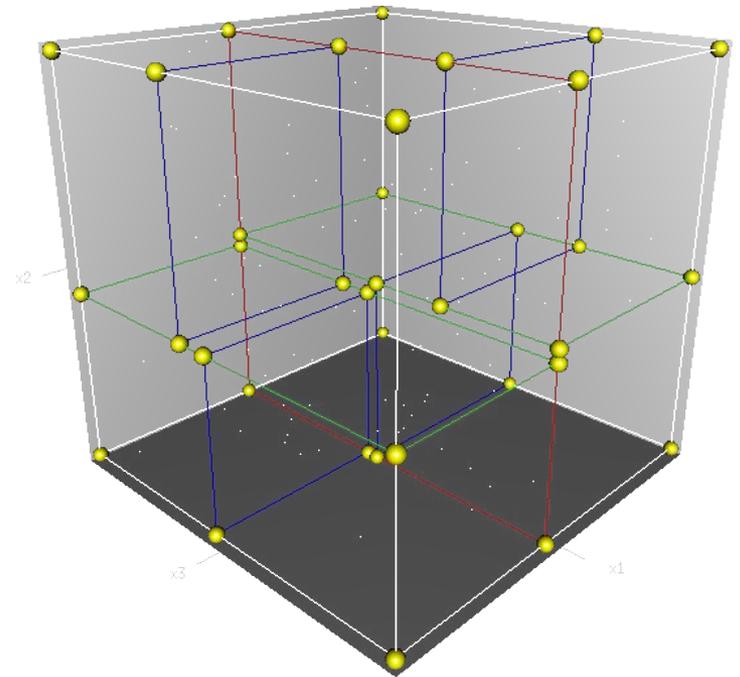


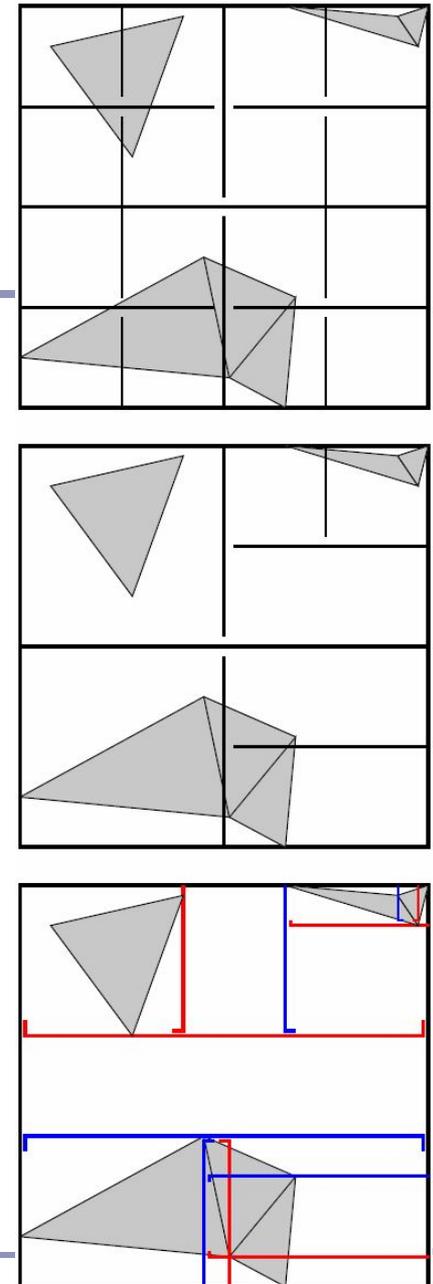
Image from Wikipedia, bless their hearts.

Popular acceleration structures: *Bounding Interval Hierarchies*

The *Bounding Interval Hierarchy* subdivides space around the volumes of objects and shrinks each volume to remove unused space.

- Think of this as a “best-fit” *kd*-tree
- Can be built dynamically as each ray is fired into the scene

Image from Wächter and Keller's paper,
Instant Ray Tracing: The Bounding Interval Hierarchy, Eurographics (2006)

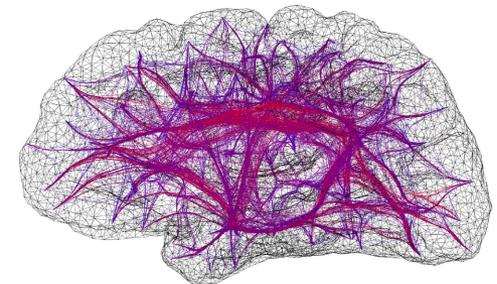
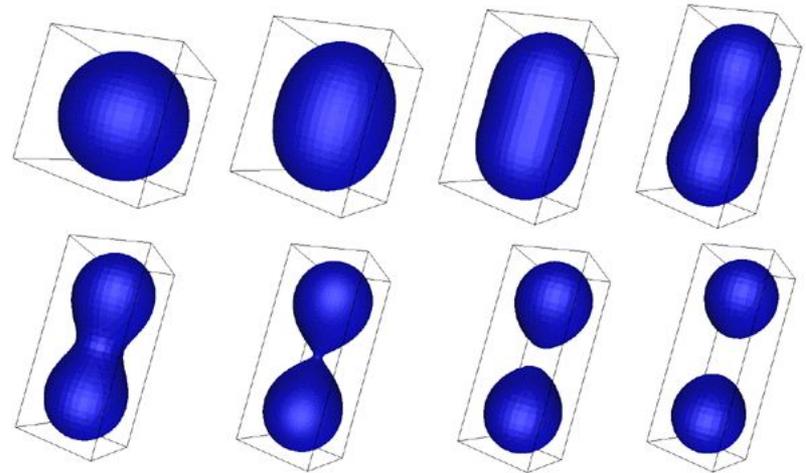


Implicit surfaces

Implicit surface modeling⁽¹⁾ is a way to produce very ‘organic’ or ‘bulbous’ surfaces very quickly without subdivision or NURBS.

Uses of implicit surface modelling:

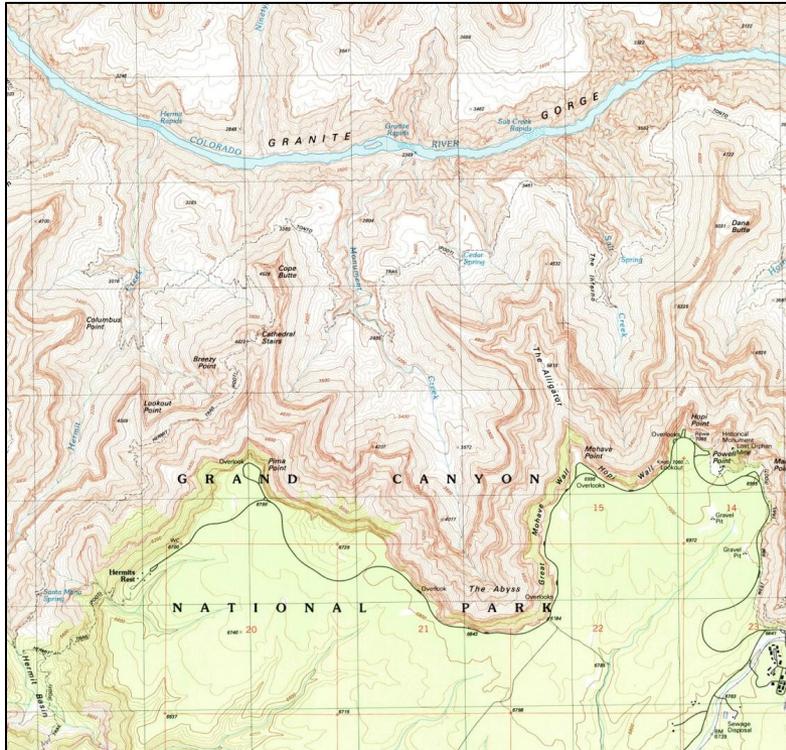
- Organic forms and nonlinear shapes
- Scientific modeling (electron orbitals, gravity shells in space, some medical imaging)
- Muscles and joints with skin
- Rapid prototyping
- CAD/CAM solid geometry



⁽¹⁾ AKA “metaball modeling”, “force functions”, “blobby modeling”...

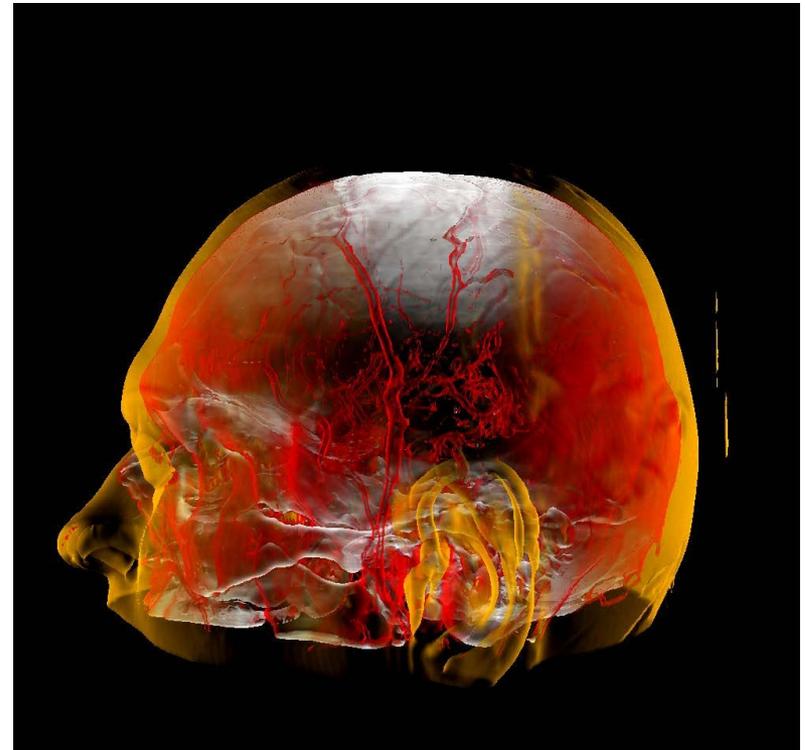
Terminology

Isoclines



Grand Canyon Quadrangle
Arizona-Coconino Co.
7.5 minute series (topographic)
Courtesy of [National Park Maps](http://NationalParkMaps.com) (npmaps.com)

Isosurfaces



Balázs Csebfalvi, Balázs Tóth, Stefan Bruckner, Meister Eduard Gröller
[Illumination-Driven Opacity Modulation for Expressive Volume Rendering](#), *Proceedings of Vision, Modeling & Visualization 2012*, pages 103-109. November 2012.

Implicit surface modeling

The user controls a set of *control points* or *primitives*. Each point generates a field of force, which drops off as a function of distance from the point (like gravity weakening with distance.)

$$F(r) = \text{“The force at distance } r\text{”}$$

For any real value τ , the set of all points in space where the sum of forces equals τ is an isosurface: an *implicit surface*.

$$S = \{x \in \mathbb{R}^3 \mid \sum_p F(|xp|) = \tau\}$$

...or, more prosaically, solve:

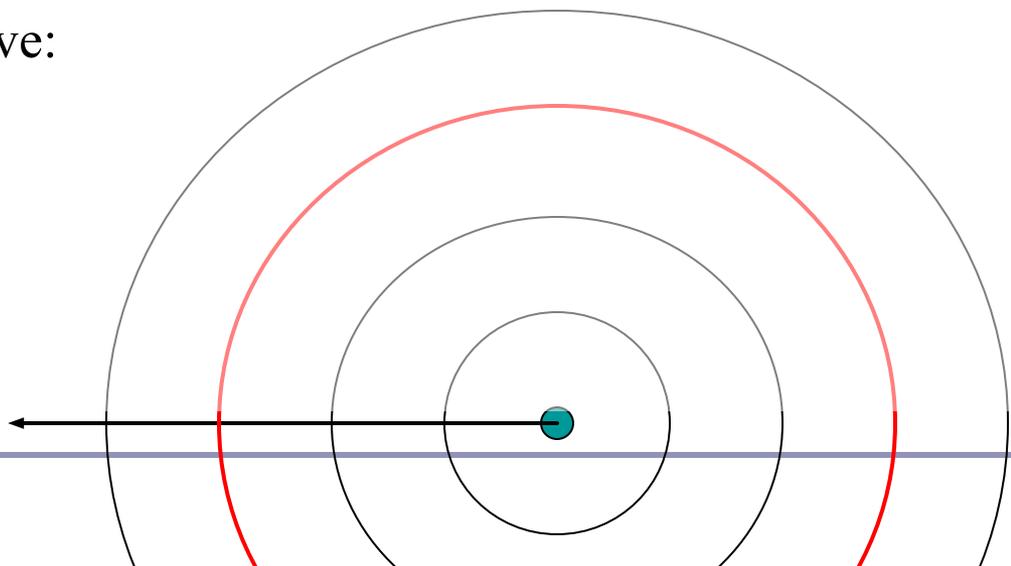
$$\sum_p F(|xp|) - \tau = 0$$

Force = 2

1

0.5

0.25 ...



Force functions

A few popular force field functions:

- “Blobby Molecules” – Jim Blinn

$$F(r) = a e^{-br^2}$$

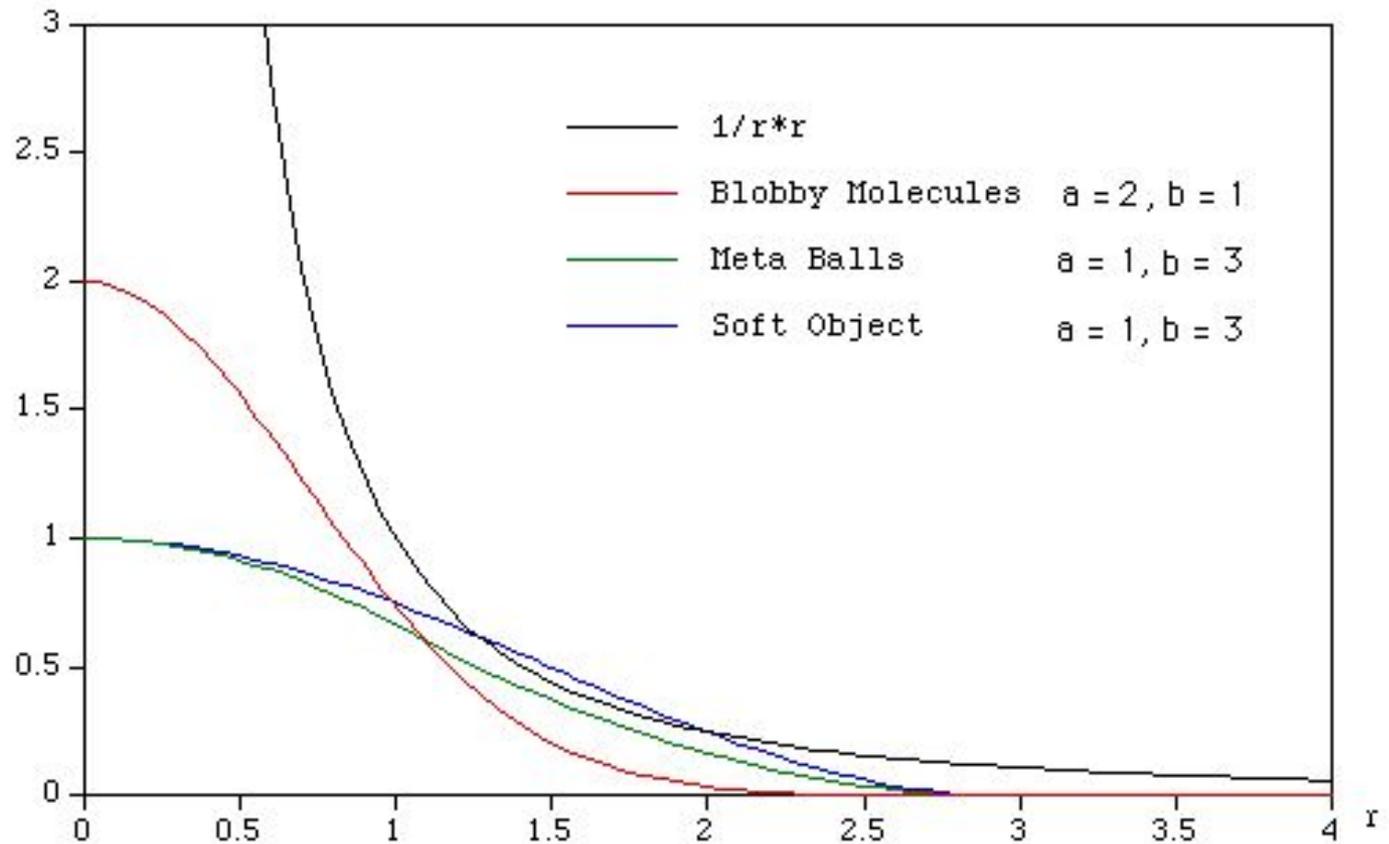
- “Metaballs” – Jim Blinn

$$F(r) = \begin{cases} a(1 - 3r^2 / b^2) & 0 \leq r < b/3 \\ (3a/2)(1 - r/b)^2 & b/3 \leq r < b \\ 0 & b \leq r \end{cases}$$

- “Soft Objects” – Wyvill & Wyvill

$$F(r) = a(1 - 4r^6/9b^6 + 17r^4/9b^4 - 22r^2 / 9b^2)$$

Comparison of force functions



Rendering implicit surfaces

Several choices:

1. Render the surface directly to the GPU
 - + : Realtime lighting, smooth surfaces, looks great
 - : Hard to integrate with other objects in scene
 - : Solve the “intercept surface with ray” problem
2. Convert the surface into a mesh of connected polygons, approximating the surface to a fixed level of precision (“polygon soup”)
 - + : Mesh can be manipulated, interact with scene
 - : Costly setup costs or runtime framerate hit

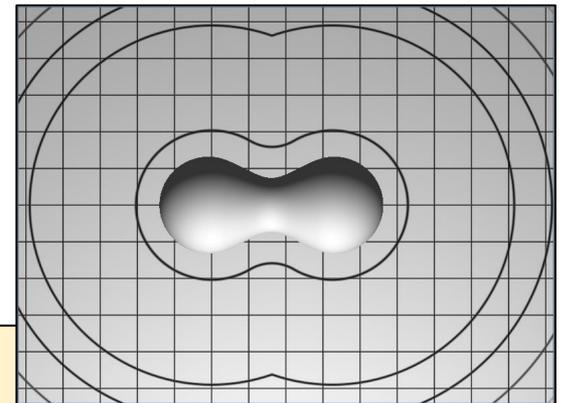
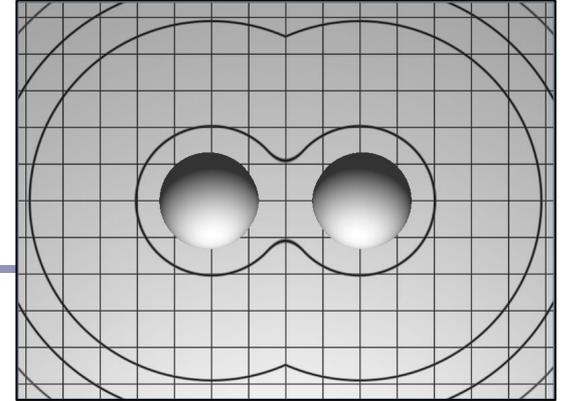
Rendering implicit surfaces with Signed Distance Fields

Blynn's metaballs force function is a piecewise Polynomial:

$$F(r) = \begin{cases} a(1 - 3r^2 / b^2) & 0 \leq r < b/3 \\ (3a/2)(1-r/b)^2 & b/3 \leq r < b \\ 0 & b \leq r \end{cases}$$

GLSL:

```
float getMetaball(vec3 p, vec3 v) {
    float r = length(p - v);
    if (r < b / 3.0) {
        return a * (1.0 - 3.0 * r * r / b * b);
    } else if (r < b) {
        return (3.0 * a / 2.0) * (1.0 - r / b) * (1.0 - r / b);
    } else {
        return 0.0;
    }
}
```



Rendering implicit surfaces with Signed Distance Fields

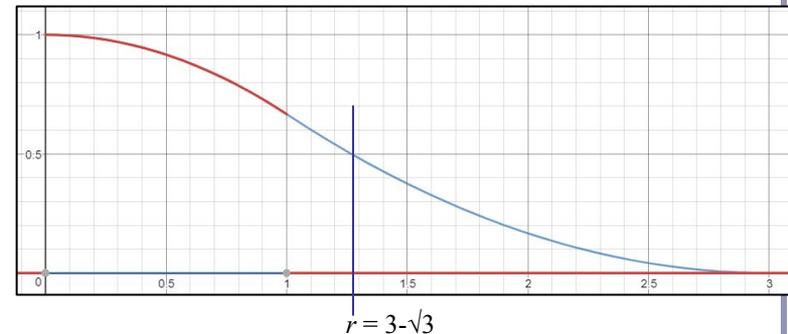
Let's use Blynn's constants: $a=1$, $b=3$

We want to be able to answer the question, “if $F < 0.5$, then we're outside the surface. What is the minimum distance from our current position to $F=0.5$?”

$$\begin{aligned} F &= (3a/2)(1-r/b)^2 \\ &= (3/2)(1-r/3)^2 \\ r^2 - 6r + (9-6F) &= 0 \\ r &= 3 \pm \sqrt{6F} \end{aligned}$$

The square roots yield \pm values, but we can discard the half of the polynomial whose r value is $>b$, leaving us with simply:

$$r = 3 - \sqrt{6F}$$



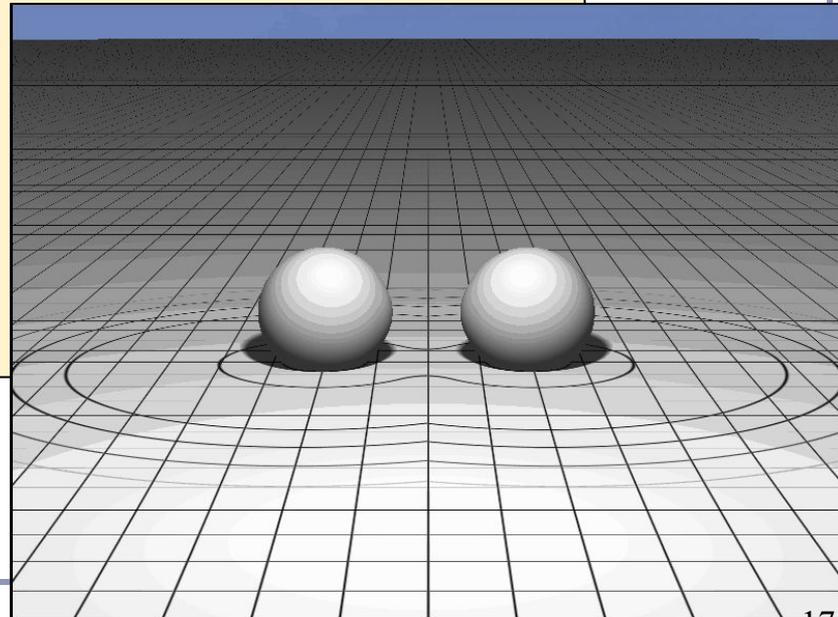
Solve for $F = 0.5$

$$\rightarrow r = 3 - \sqrt{3} = 1.2679529$$

Insight: if we restrict ourselves to metaballs of weight 1, then only Blynn's second polynomial applies outside the isosurface of $F=0.5$

Rendering implicit surfaces with Signed Distance Fields

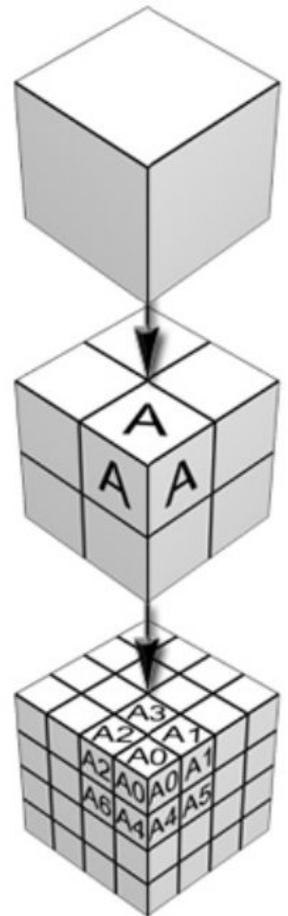
```
float sdImplicitSurface(vec3 p) {  
    float mb = getMetaball(p, BallA) + getMetaball(p, BallB);  
    float minDist = min(length(p - BallA), length(p - BallB));  
  
    // 1.2679529 is the x-intercept of the metaball expression  
    // when force = 0.5  
    float r = 1.2679529;  
  
    float d;  
    if (minDist > 3 /* b=3 */) {  
        return max(minDist - 3, 3 - r);  
    } else {  
        return 3 - sqrt(6.0 * mb) - r;  
    }  
}
```



Rendering implicit surfaces with polygons

An *octree* is a recursive subdivision of space which “homes in” on the surface, from larger to finer detail.

- An octree encloses a cubical volume in space. You evaluate the force function $F(v)$ at each vertex v of the cube.
- As the octree subdivides and splits into smaller octrees, only the octrees which contain some of the surface are processed; empty octrees are discarded.

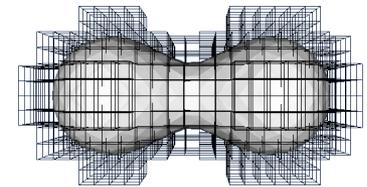
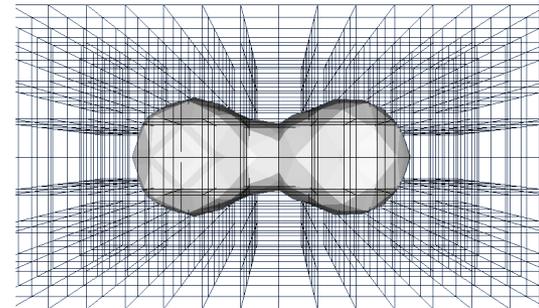
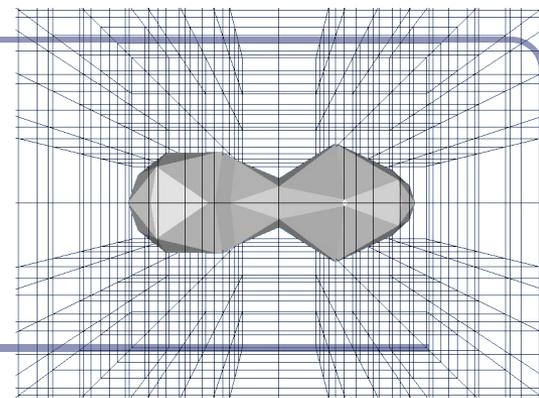


Polygonizing the surface

To display a set of octrees, convert the octrees into polygons.

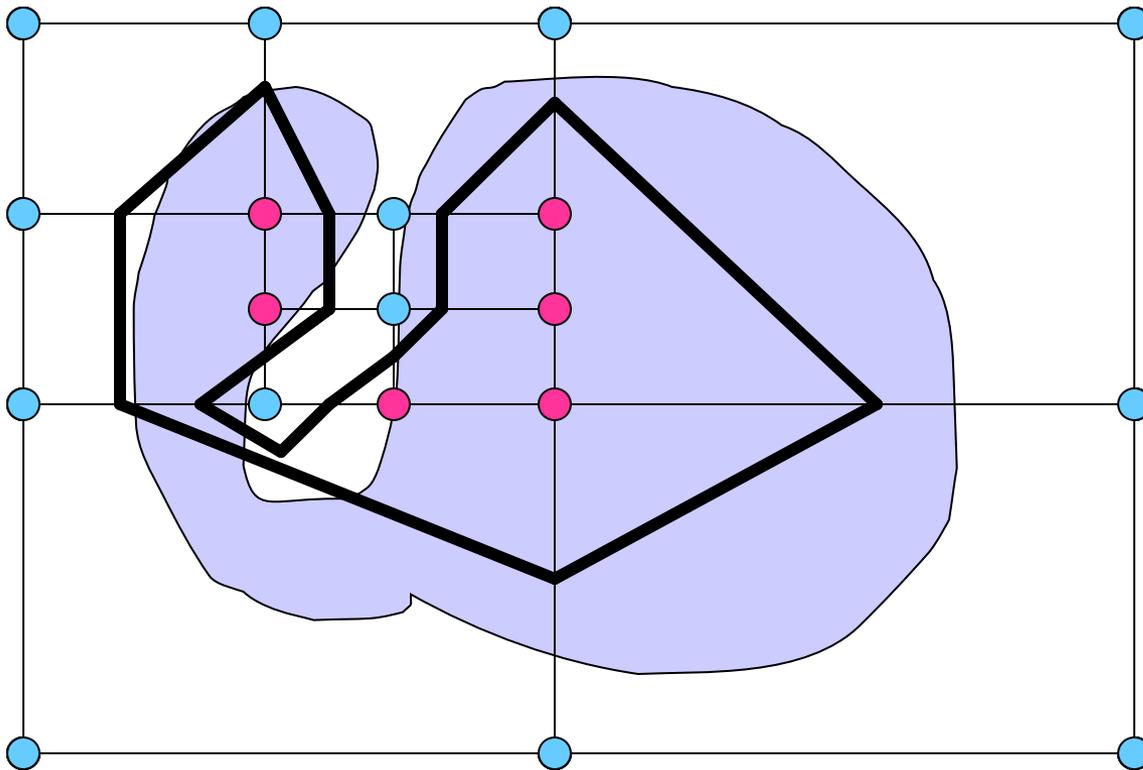
- If some corners are “hot” (above the force limit) and others are “cold” (below the force limit) then the isosurface must cross the cube edges in between.
- The set of midpoints of adjacent crossed edges forms one or more rings, which can be triangulated. The normal is known from the hot/cold direction on the edges.

To refine the polygonization, subdivide recursively; discard any child whose vertices are all hot or all cold.



Polygonizing the surface

Recursive subdivision (on a quadtree):

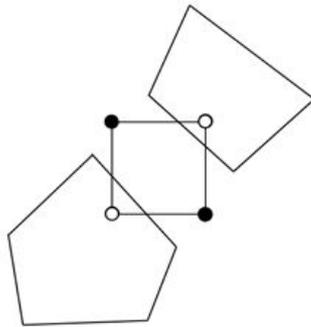


Polygonizing the surface

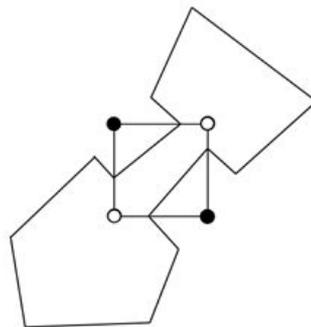
There are fifteen possible configurations (up to symmetry) of hot/cold vertices in the cube. →

- With rotations, that's 256 cases.

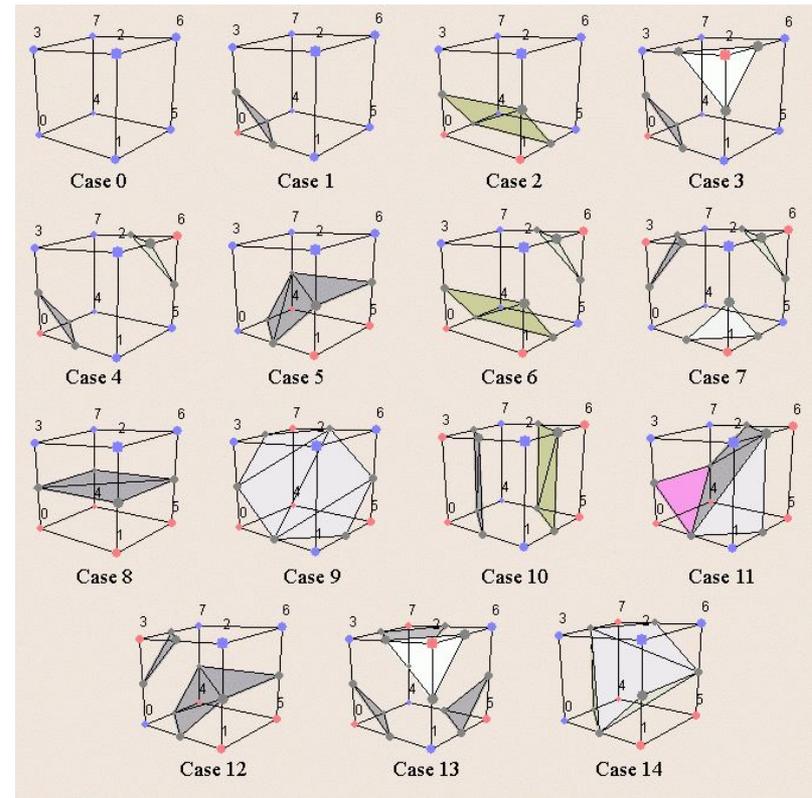
Beware: there are *ambiguous cases* in the polygonization which must be addressed separately. ↓



Break contour



Join contour



Images courtesy of [Diane Lingrand](#)

Polygonizing the surface

One way to overcome the ambiguities that arise with the cube method is to decompose the cube into tetrahedra.

- A common decomposition is into five tetrahedra. →
- Caveat: need to flip every other cube. (Why?)
- Can also split into six.

Another way is to do the subdivision itself on tetrahedra—no cubes at all.

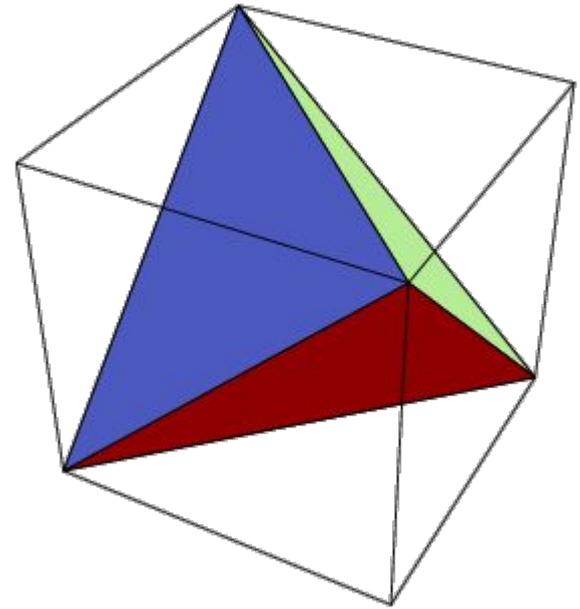
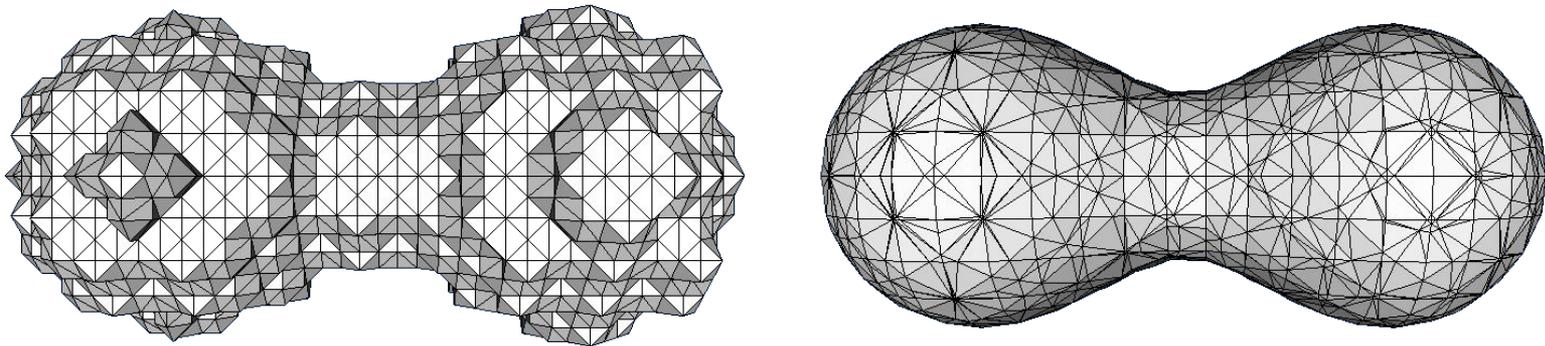


Image from the [Open Problem Garden](#)

Smoothing the polygonization

Improved edge vertices

- The naïve implementation builds polygons whose vertices are the midpoints of the edges which lie between hot and cold vertices.
- The vertices of the implicit surface can be more closely approximated by points linearly interpolated along the edges of the cube by the weights of the relative values of the force function.
 - $t = (0.5 - F(P1)) / (F(P2) - F(P1))$
 - $P = P1 + t (P2 - P1)$



Same force points

Marching cubes

An alternative to octrees if you only want to compute the final stage is the *marching cubes* algorithm (Lorensen & Cline, 1985):

- Fire a ray from any point known to be inside the surface.
- Using Newton's method or binary search, find where the ray crosses the surface.
 - Newton: derivative estimated from discrete local sampling
 - There may be many crossings
- Drop a cube around the intersection point: it will have some vertices hot, some cold.
- While there exists a cube which has at least one hot vertex and at least one cold vertex on a side and no neighbor on that side, create a neighboring cube on that side. Repeat.



Marching cubes is common in medical imaging such as MRI scans. It was first demonstrated (and patented!) by researchers at GE in 1984, modeling a human spine.

References

Implicit modelling:

D. Ricci, *A Constructive Geometry for Computer Graphics*, Computer Journal, May 1973

J Bloomenthal, *Polygonization of Implicit Surfaces*, Computer Aided Geometric Design, Issue 5, 1988

B Wyvill, C McPheeters, G Wyvill, *Soft Objects*, Advanced Computer Graphics (Proc. CG Tokyo 1986)

B Wyvill, C McPheeters, G Wyvill, *Animating Soft Objects*, The Visual Computer, Issue 4 1986

<http://astronomy.swin.edu.au/~pbourke/modelling/implicitsurf/>

<http://www.cs.berkeley.edu/~job/Papers/turk-2002-MIS.pdf>

<http://www.unchainedgeometry.com/jbloom/papers/interactive.pdf>

<http://www-courses.cs.uiuc.edu/~cs319/polygonization.pdf>