Surface Discretization of Multi-material Heterogeneous Volume Objects

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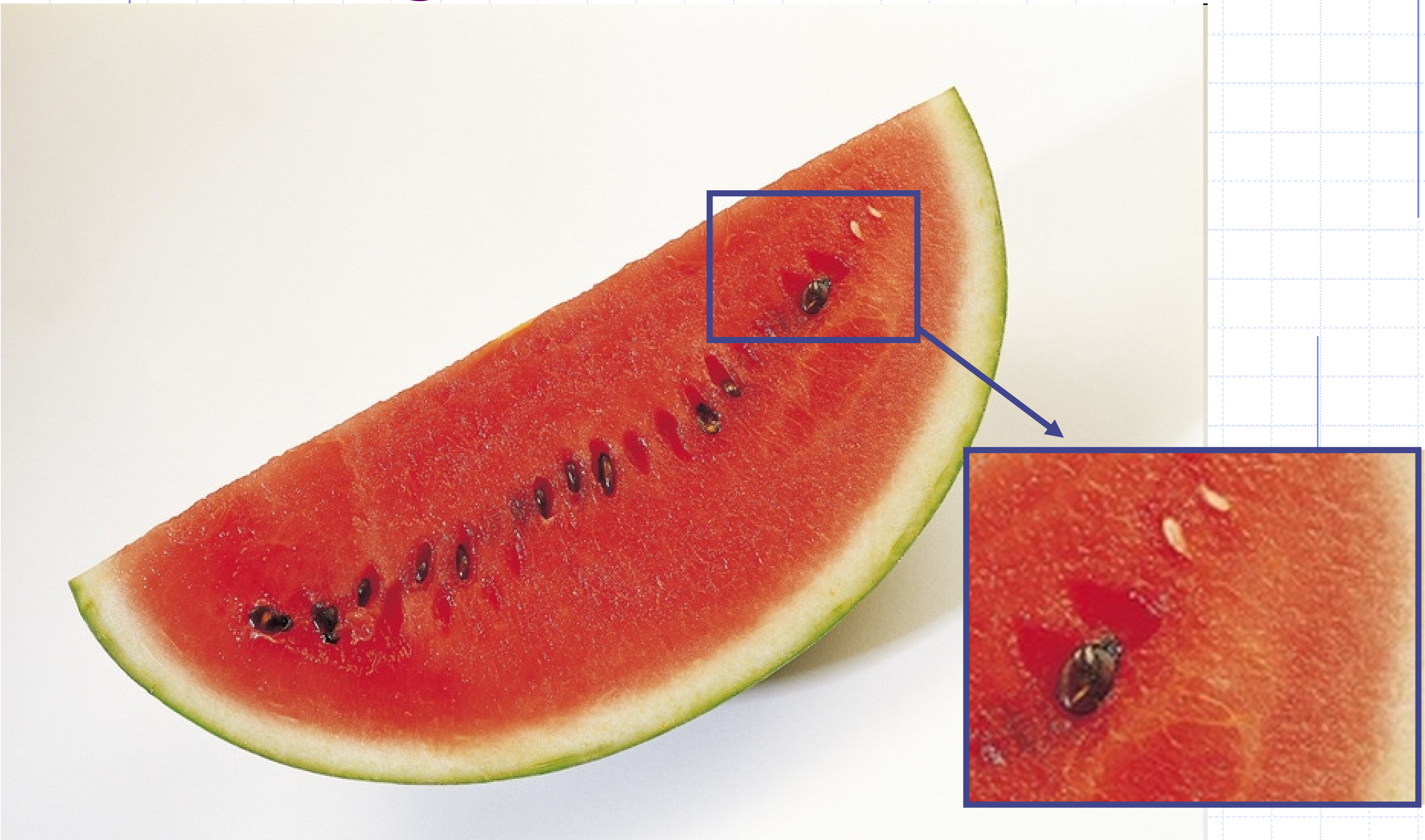
Challenge of Nature



Modelling, Rendering, Fabrication & Consumption

State of the Art

- Complex geometry model
- Simple or no material

Computer-Aided Design

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Heterogeneous Volume Modeling

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Computational Material Science

- Complex material model
- Simple or no geometry

Heterogeneous volume objects

- **Volumetric material distribution -** non-uniform gradually varying materials
- **Multi-scale microstructures** - internal spatial geometric structures with size of details orders of magnitude smaller than the overall size of the object
- Areas: biological and medical research, bio-engineering, composite materials in design and fabrication, mechanical engineering, physical simulations

Problems with surfaces & voxels

- **Size and processing time**
  - 100s Mb polygons, $>10^{10}$ voxels
- **Validity and precision**
  - approximations, surface defects
- **Parameterization and operability**
  - blends, offsets, deformations
- **Manufacturability**
  - STL problems are amplified by the geometric complexity of microstructures

Function Representation FRep

- Uniform represenation of multidimensional shapes defined as

$$F(x, y, z, \ldots) \geq 0$$

- $F=0$ defines a surface (isosurface)
- Function F procedural evaluation traversing the construction tree structure
- Leaves: primitives
- Nodes: operations + relations
- FRep modeling is supported by HyperFun language and software tools

www.hyperfun.org

The Visual Computer, 1995

Function-based Heterogeneous Volume Model

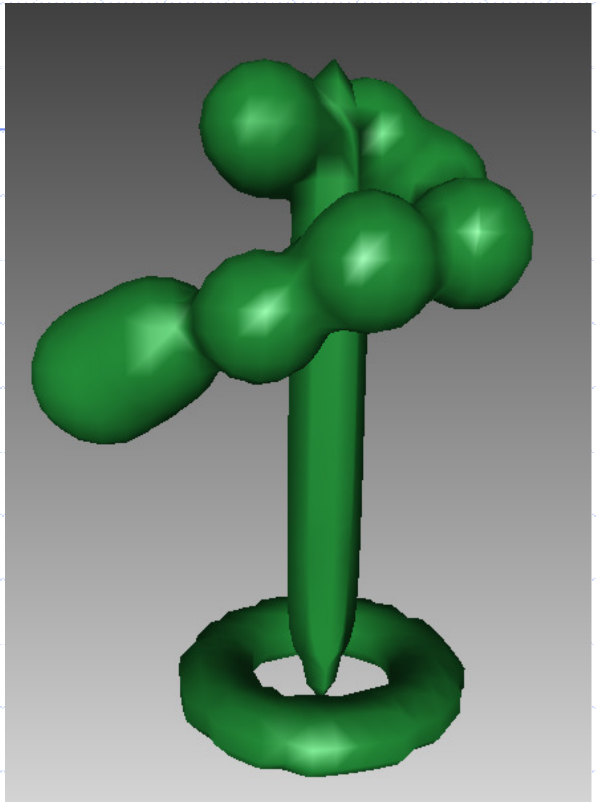
$$o = (F(X), S_1 (X), \ldots, S_k (X))$$

$F(X)$ – geometric function

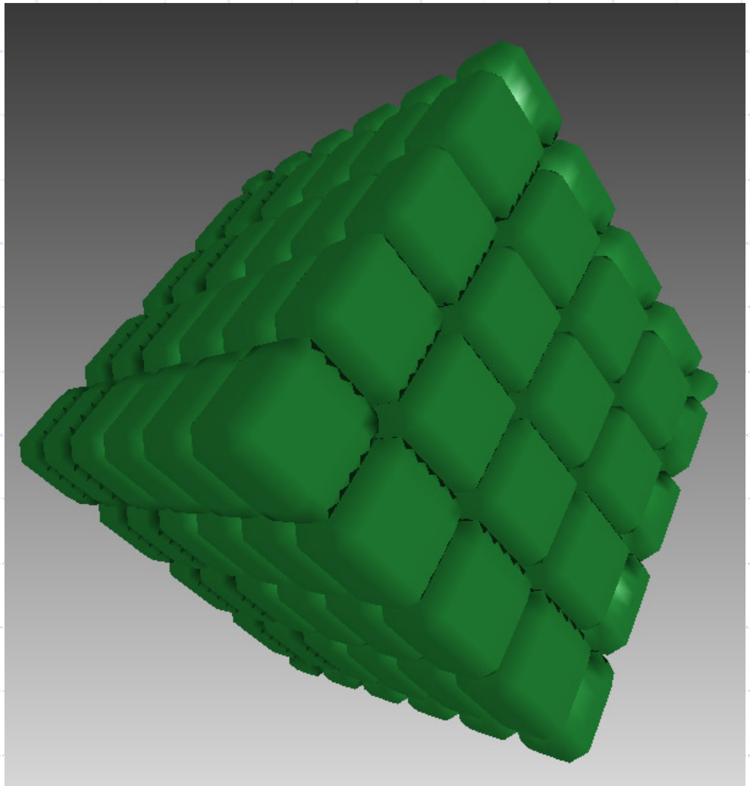
$S_i (X)$ – attribute functions based on

space partitions

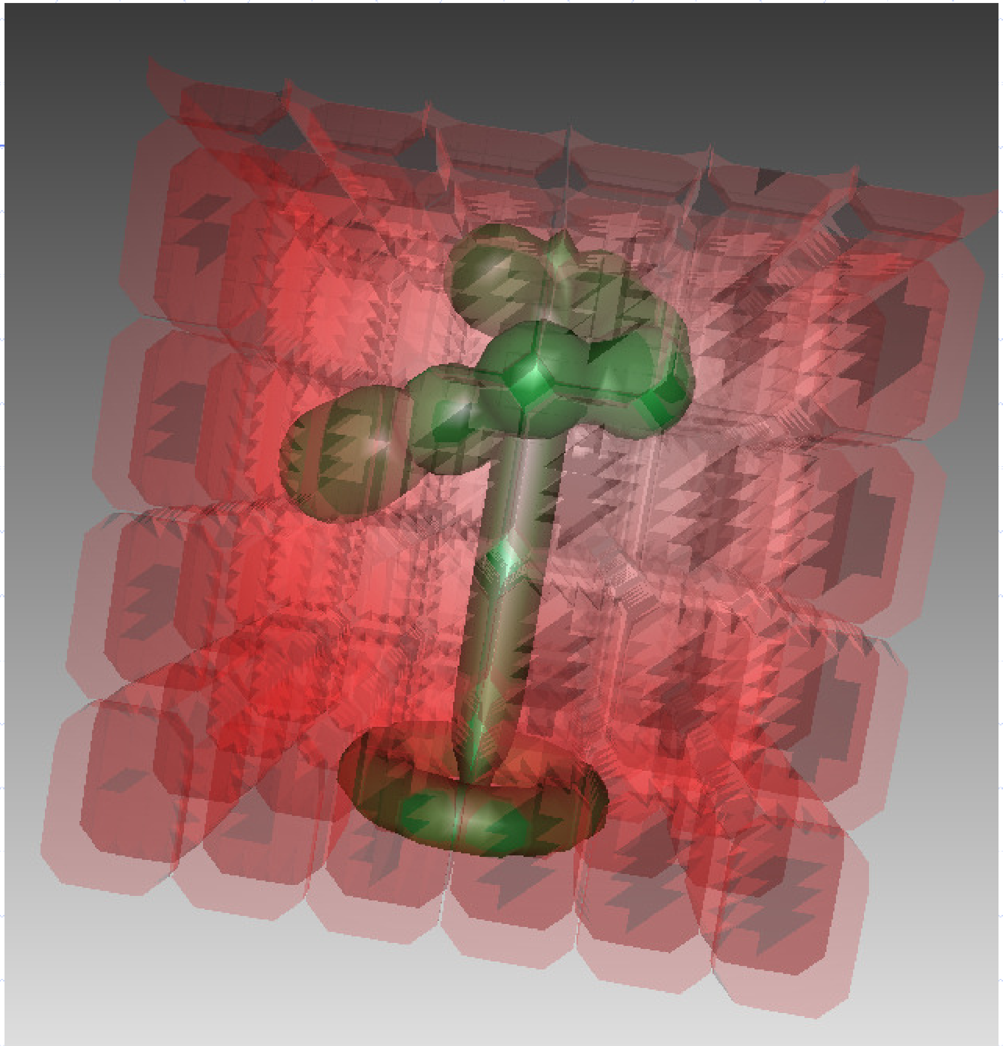
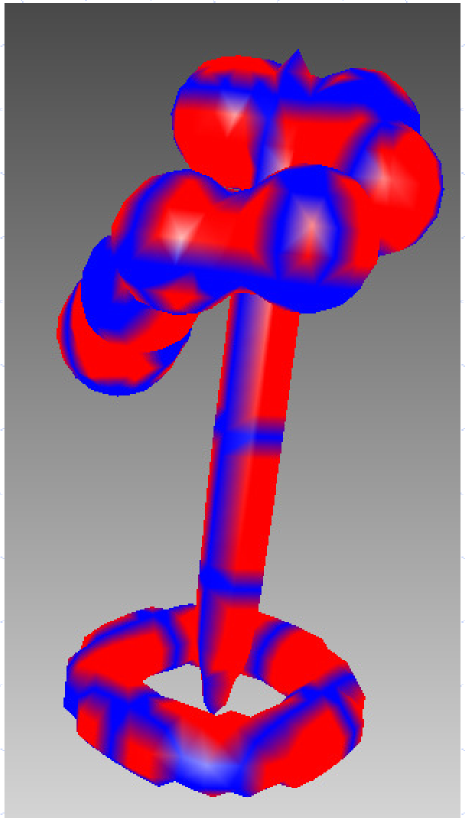
Graphical Models, 2001



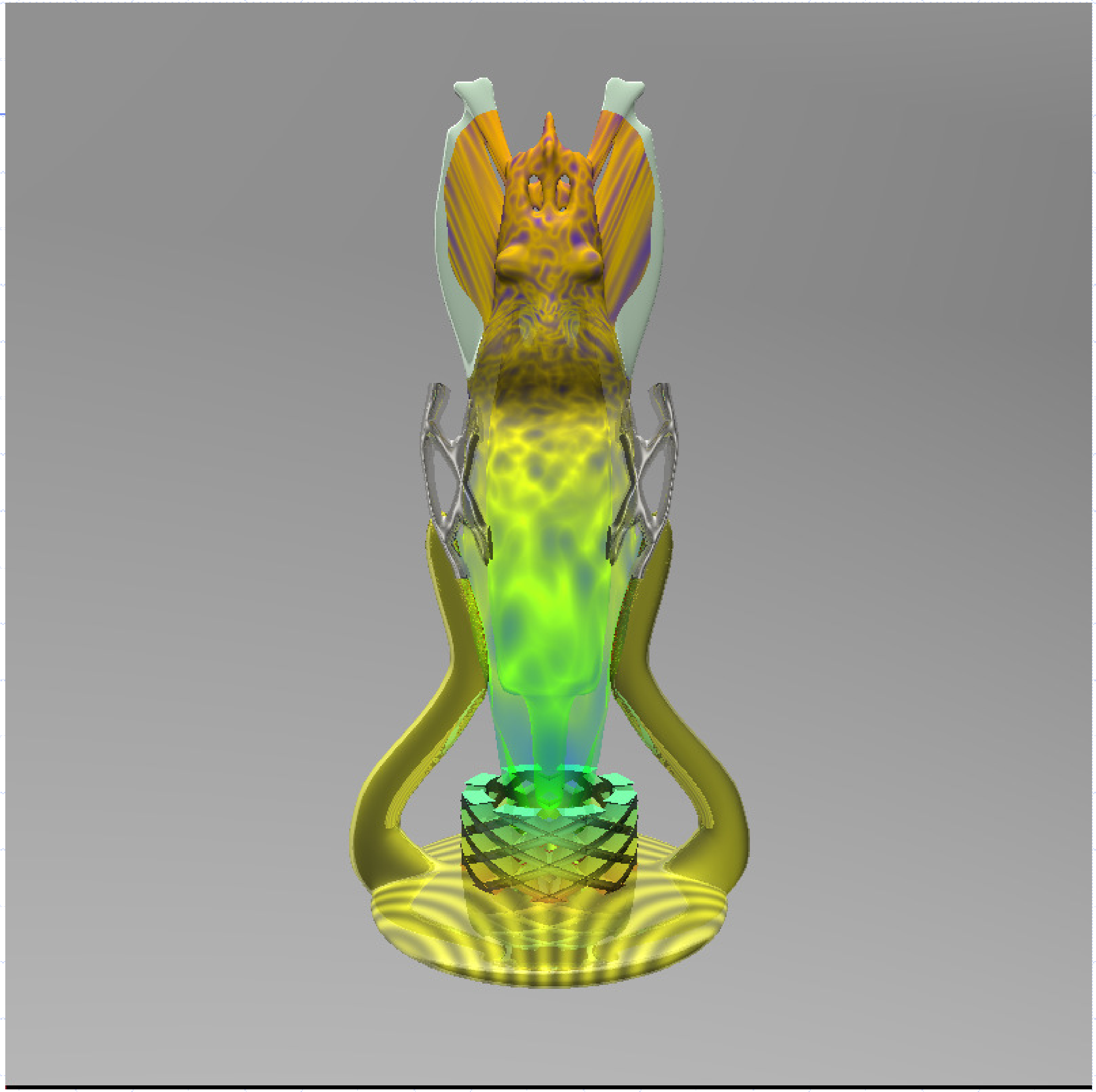
Geometry



Attribute
space partitioning

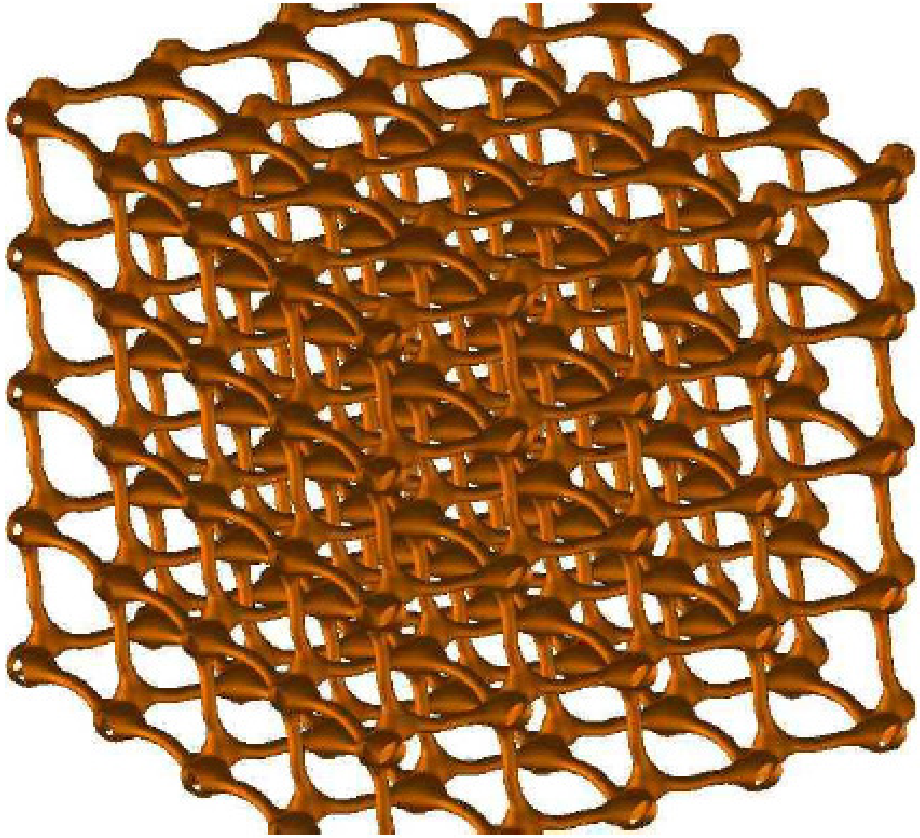



Procedural volumetric materials

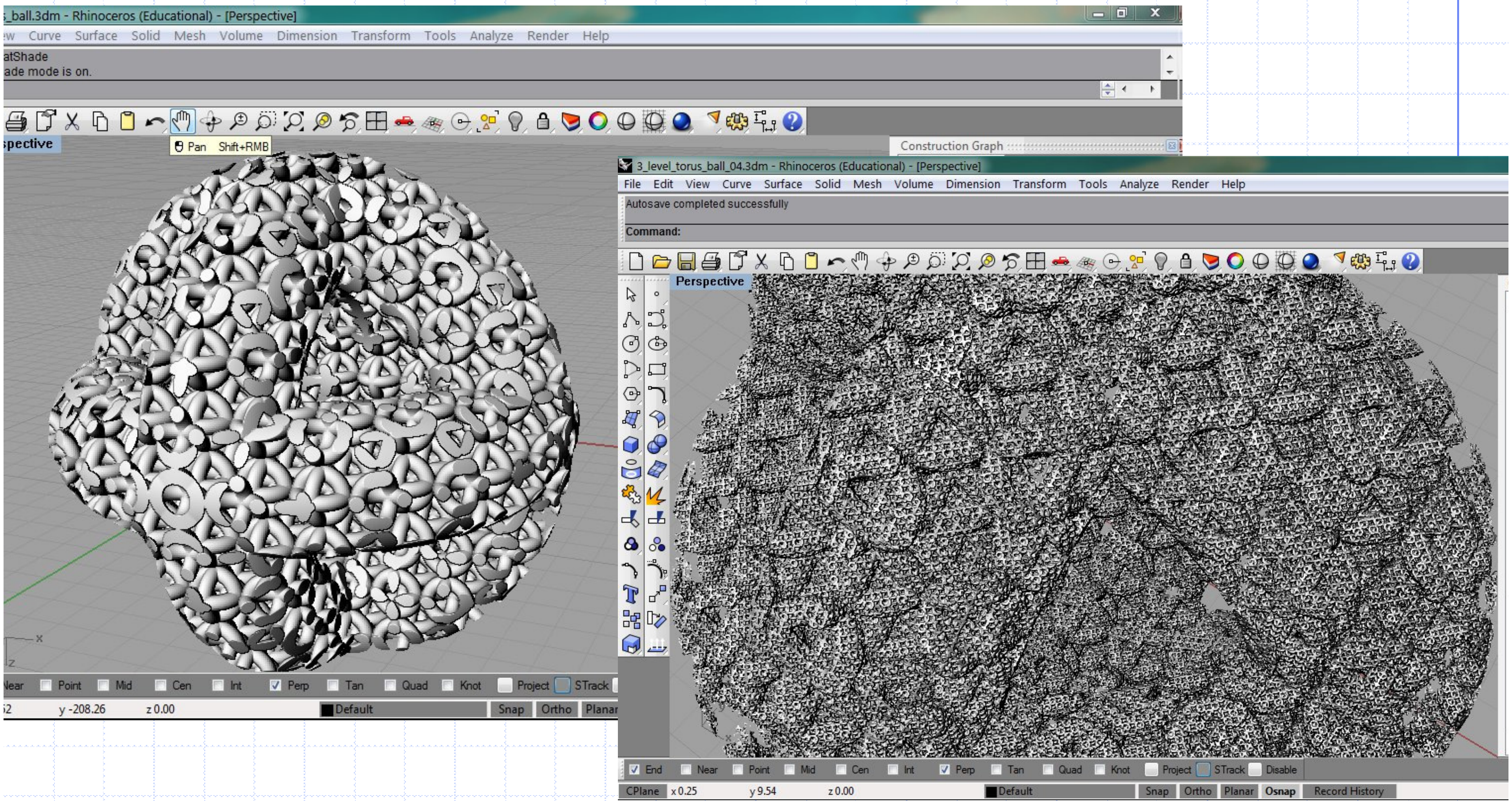


Cellular microstructures

Replication of a unit cell with periodic space mapping

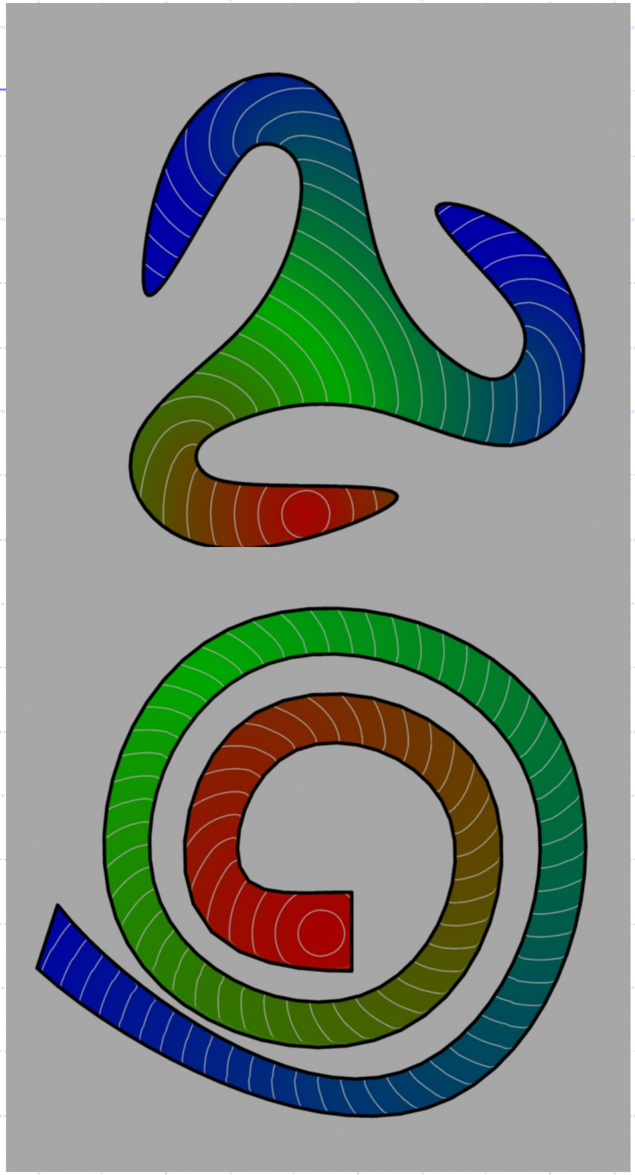


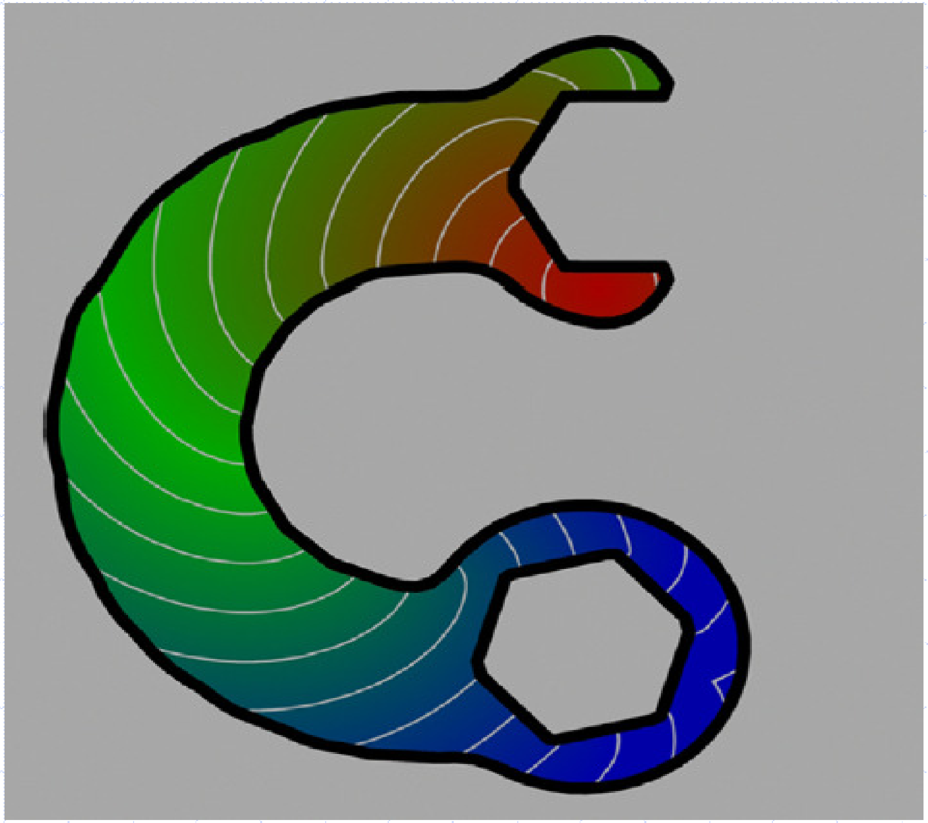
Multi-scale nested FRep structures



3 levels of nested tori balls

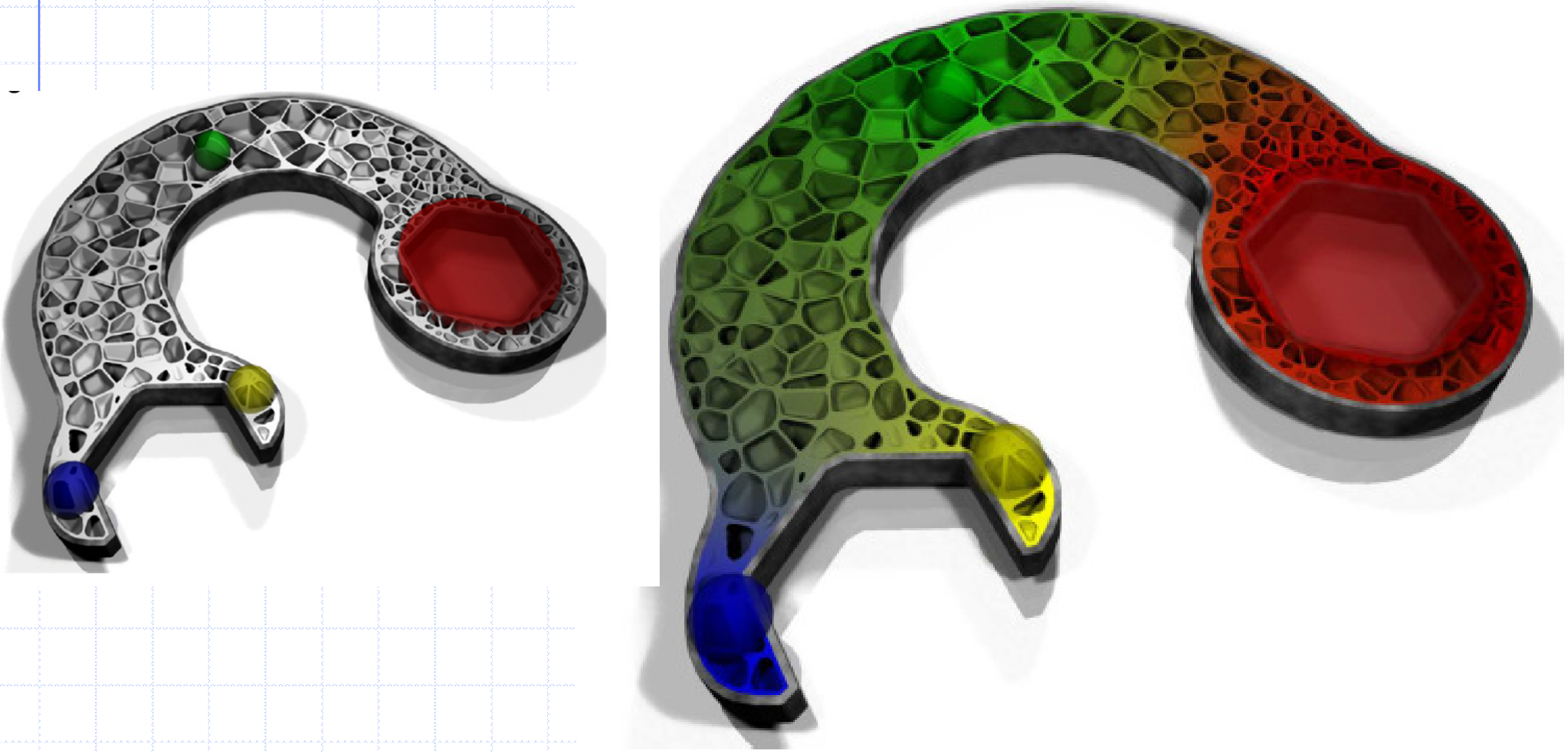
Interior Distance Interpolation





Computers & Graphics, 2013

Microstructures and gradient materials with interior distance



Computers & Graphics, 2013

Multi-material surface discretization

1) Adaptively discretize surfaces for all space partitions (material regions)

2) Define and sample the boundary curves between each pair of materials

3) Assemble meshes together while protecting the material boundary curves

Advances in Engineering Software, 2012

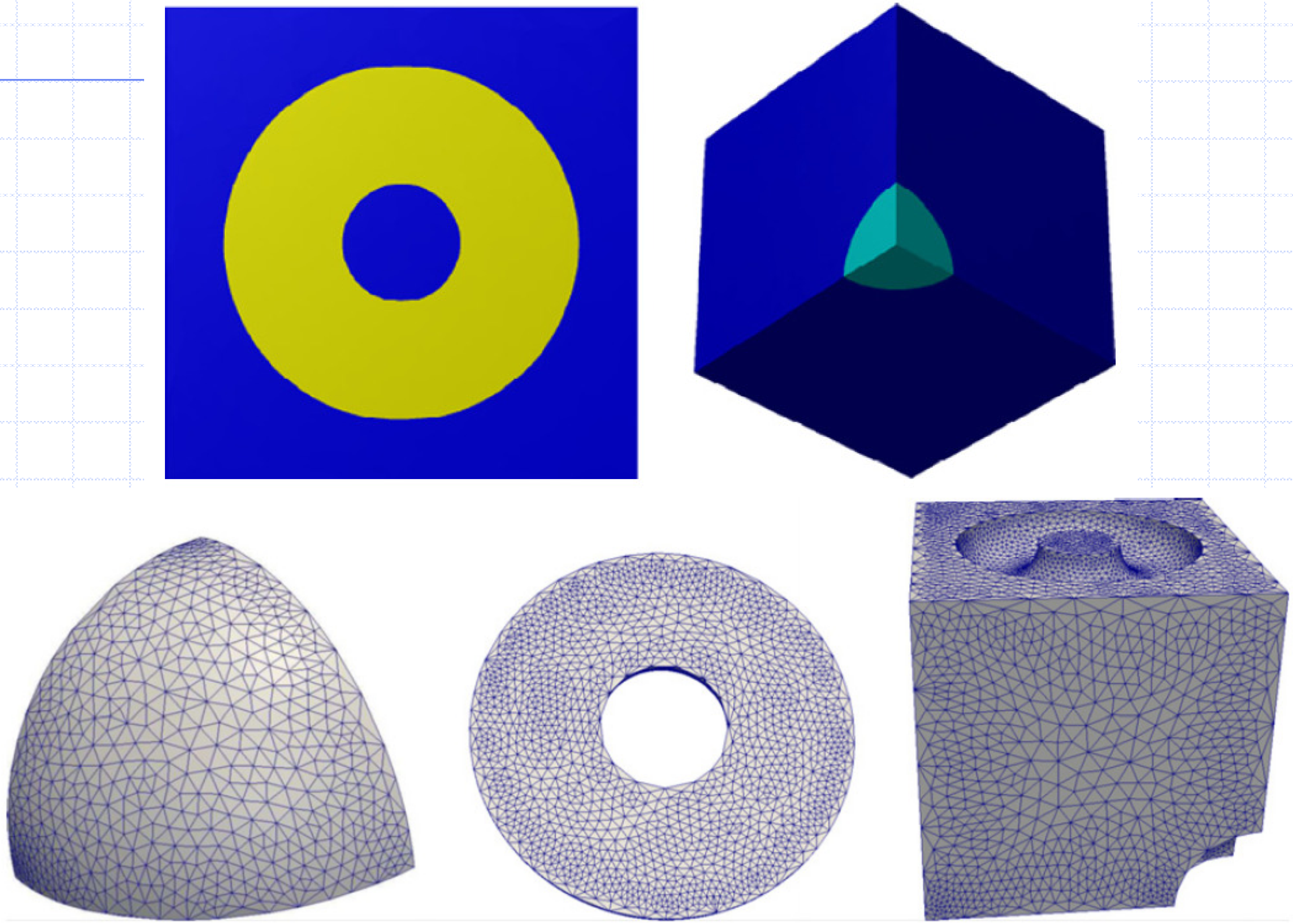
Step 1. Surface discretization for space partitions

- Generate random points and project them on the surface *f=0*

$$\mathbf{p} \leftarrow \mathbf{p} - f(\mathbf{p}) \frac{\nabla f(\mathbf{p})}{\|\nabla f(\mathbf{p})\|^2}$$

- Adding ghost points from the bounding box
- Compute the Delaunay tetrahedralization of the obtained point-set
- Find the set of triangles on the surface
- Subdivide triangles with high surface curvature
- Optimize the mesh (moving vertices, etc.)

Example for Step 1



Surfaces for three space partitions

Step 2. Material boundary curves

- For adjacent partitions A_i and A_j of the entire object G, the material boundary curve is

$$c_{i,j} = \partial A_i \wedge \partial A_j \wedge \partial G$$

- Select from mesh vertices those with

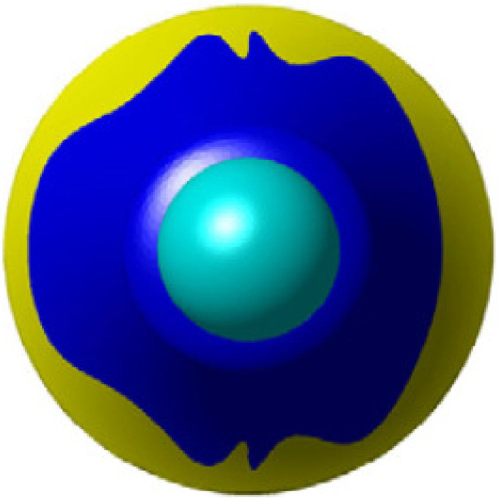
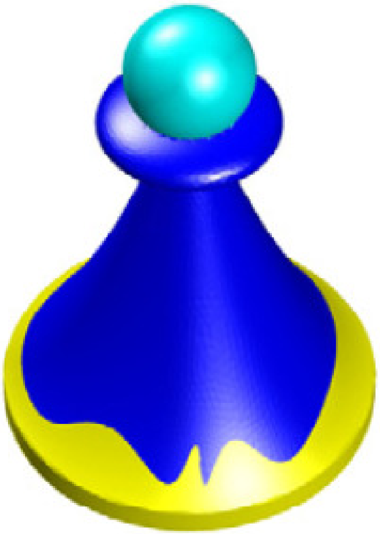
$$F = S_i = S_j = 0$$

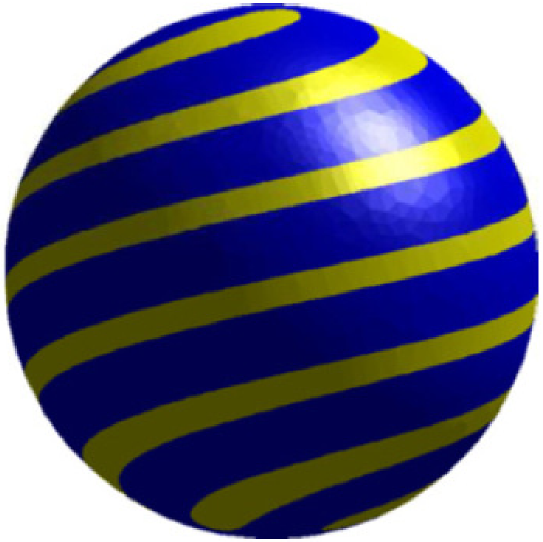
- Subdivide edges between selected vertices.
- Project new vertices back to the surface.

Step 3. Assembly of meshes and boundary curves

- Make a union of balls B with radius r centered at boundary curve vertices $c_{i,j}$
- Remove mesh vertices inside B
- Compute the Delaunay tetrahedralization of remaining mesh vertices and boundary curves
- Find the set of triangles on the surface

Examples

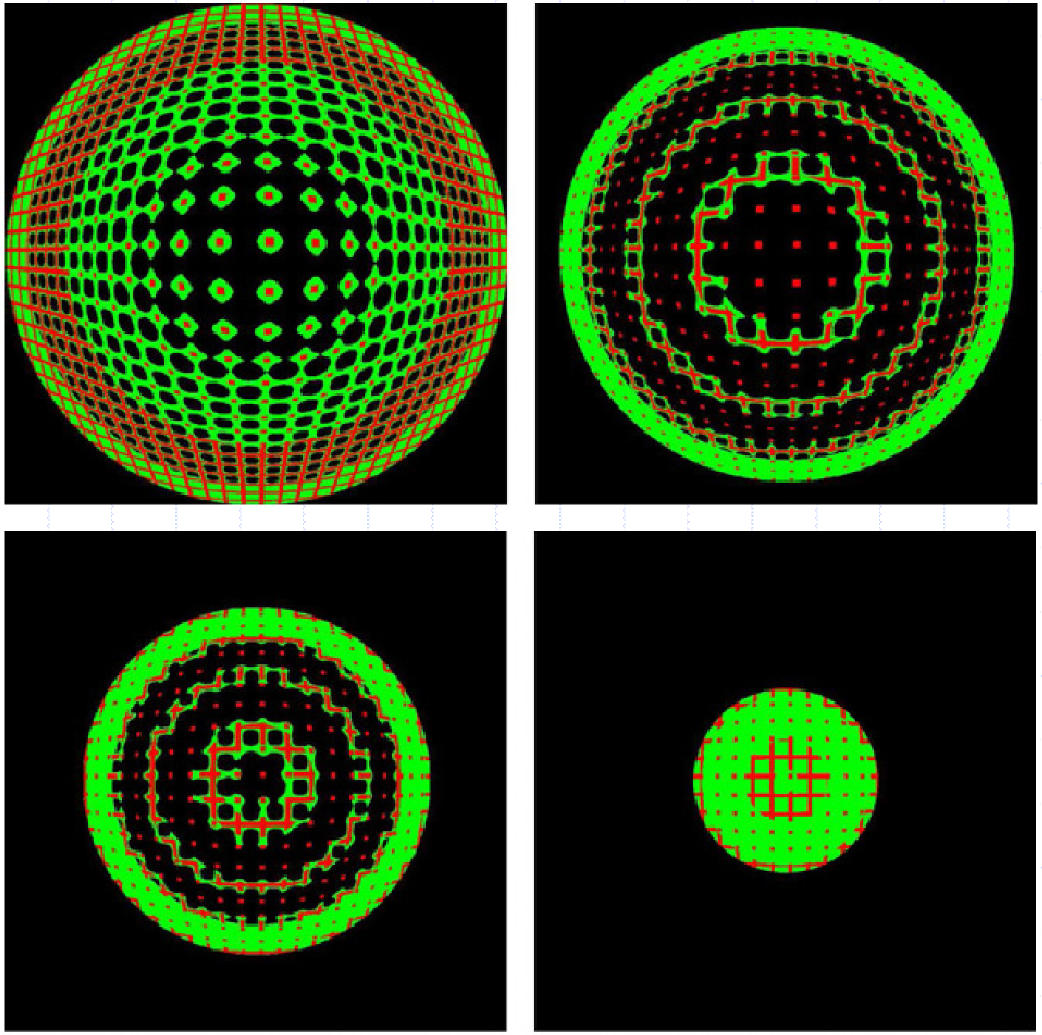



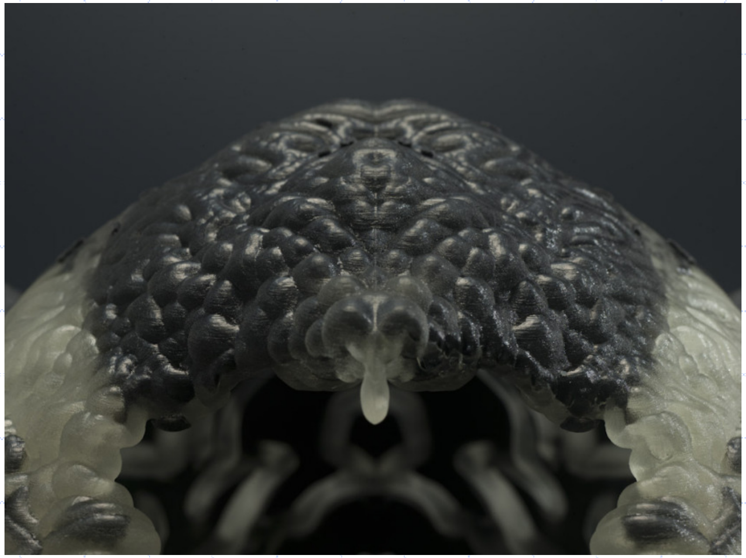
Multi-material corset

Tools: Symvol API & Objet Connex multi-material 3D printer

Direct multi-material 3D printing



Multi-material helmet

Model: Neri Oxman, MIT & Uformia, Norway
Tools: Symvol API & Objet Connex multi-material 3D printer
Exhibitions: Centre Pompidou, Paris & 3D Printshow, London

Questions ?