Multi-material Modeling

http://hm.softalliance.net/

Alexander Pasko, Evgenii Maltsev

State of the Art

- Complex geometry model
- Simple or no material

Computer-Aided Design

↓

Heterogeneous Volume Modeling and Volume CAD

↑

Computational Material Science

- Complex material model
- Simple or no geometry

Heterogeneous volume objects

- **Object shape** – geometric point set
- **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

Constructive Hypervolume Model

Hypervolume is a multidimensional point set with multiple attributes

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

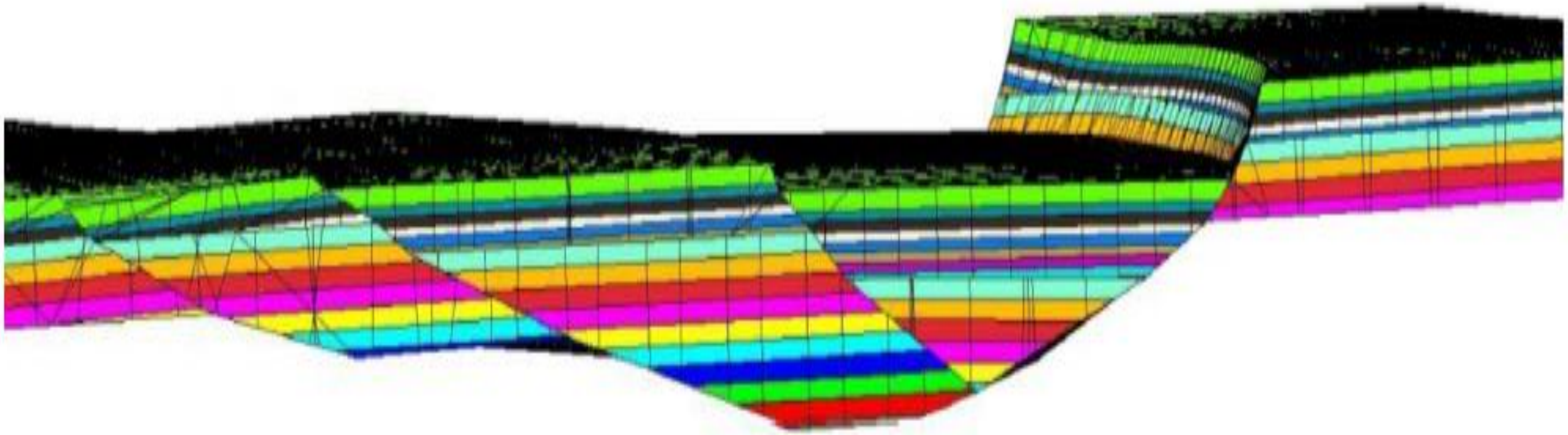
$F(X)$ – FRep of geometry

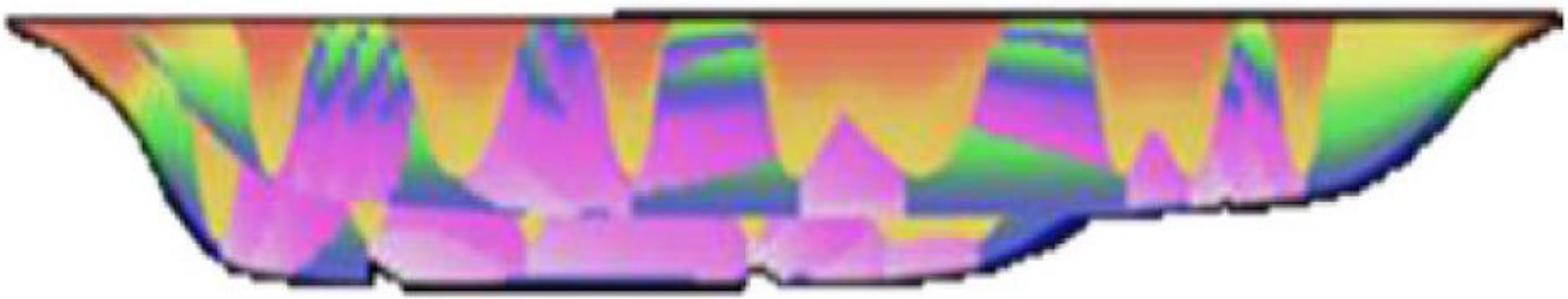
$S_i(X)$ – attributes based on FRep

space partitions (for example, volumetric material distribution)

Graphical Models, 2001

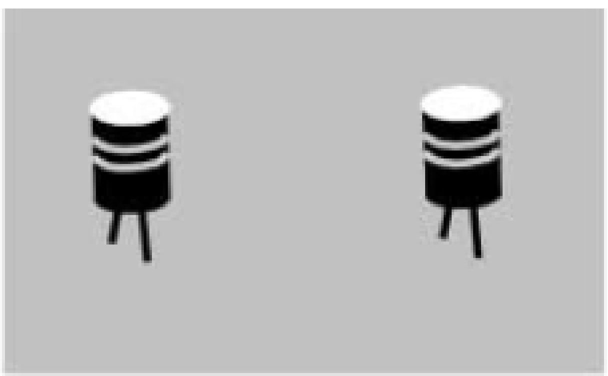
Heterogeneous Materials in Nature - Geology





Types of multi-material objects

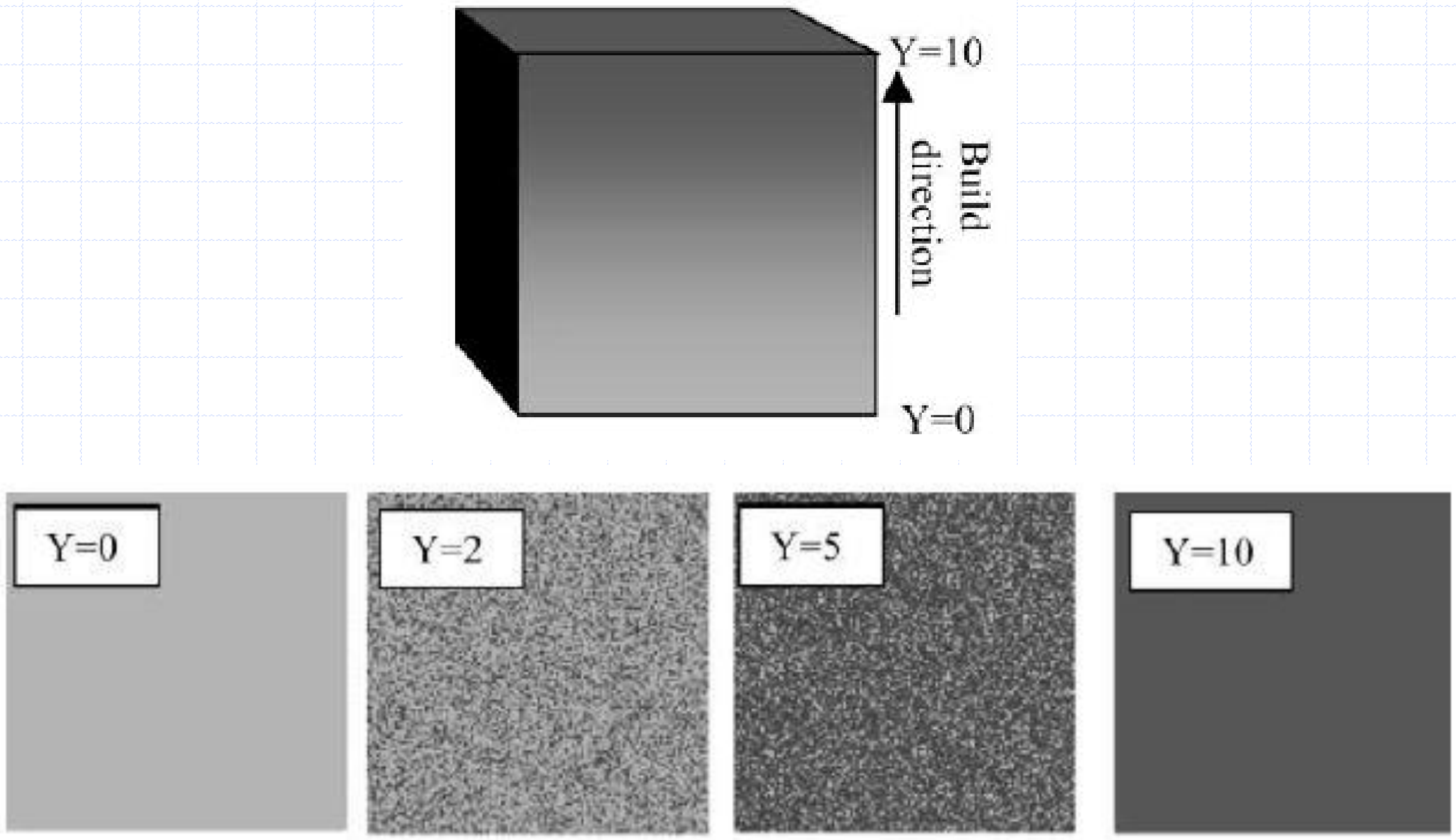
- Multiple homogeneous materials



- Composite material

- Functionally graded material (FGM)

Sliced patterns of heterogeneous object



Material modelling with scalar fields

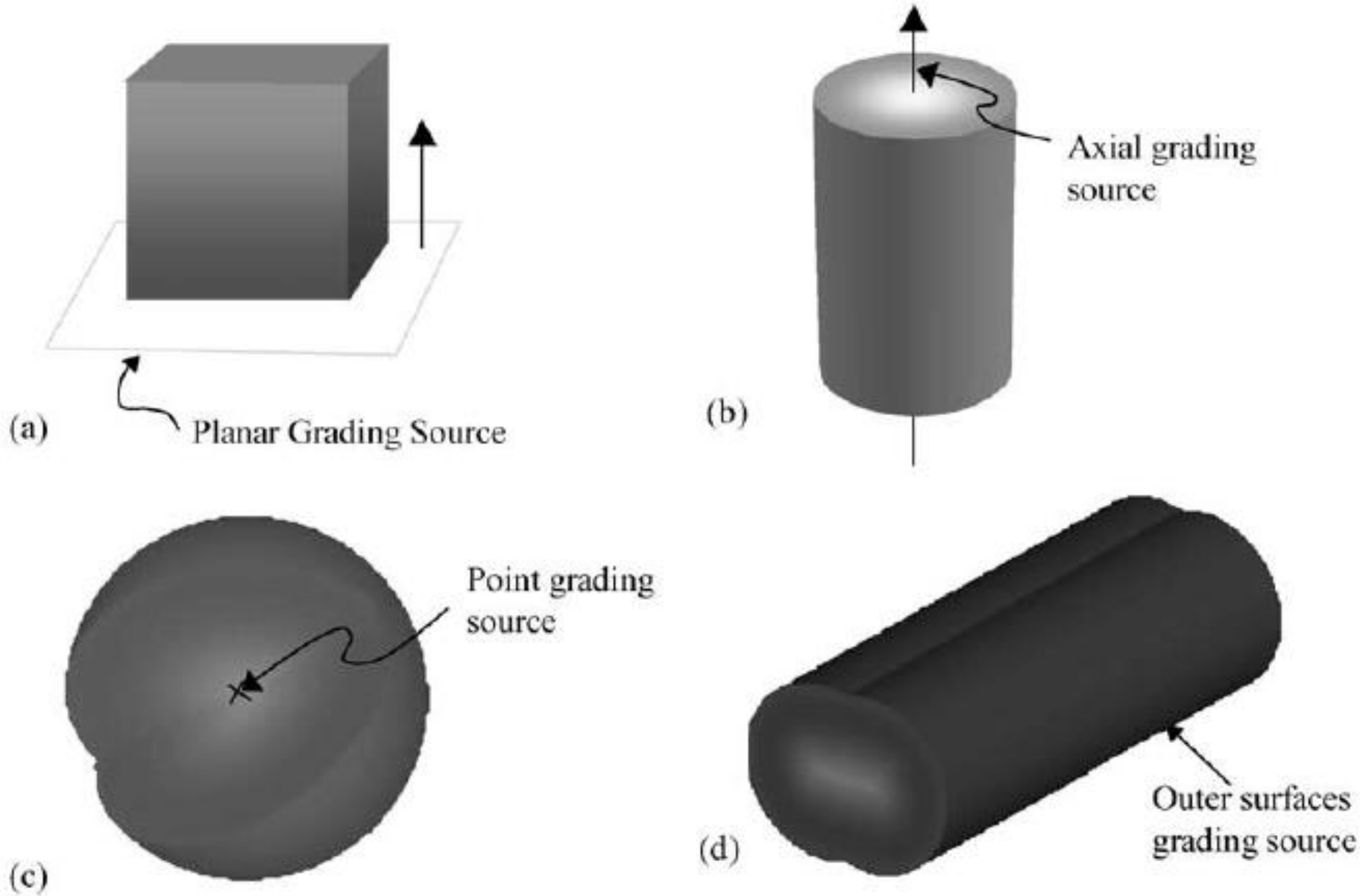
- Analytical
- Sampled
- Simulation and optimization
- Spline-based
- Source-based
- Feature-based
- Shape-conforming
- Compound / constructive
- Procedural

Computer-Aided Design, 2019 (in progress)

Source-based material modelling

1. Introduce material sources with single uniform material
2. Assign material sources with distance fields – **points, lines, planes, outer surface boundaries**
3. Apply some interpolation to define material at any point

Source-based material modelling



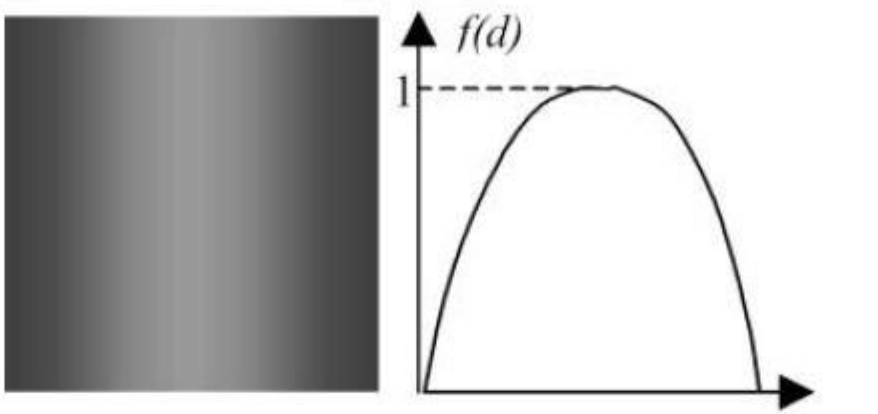
Y.K. Siu, S.T. Tan / Computer-Aided Design 34 (2002) 41–55

Source-based material modelling

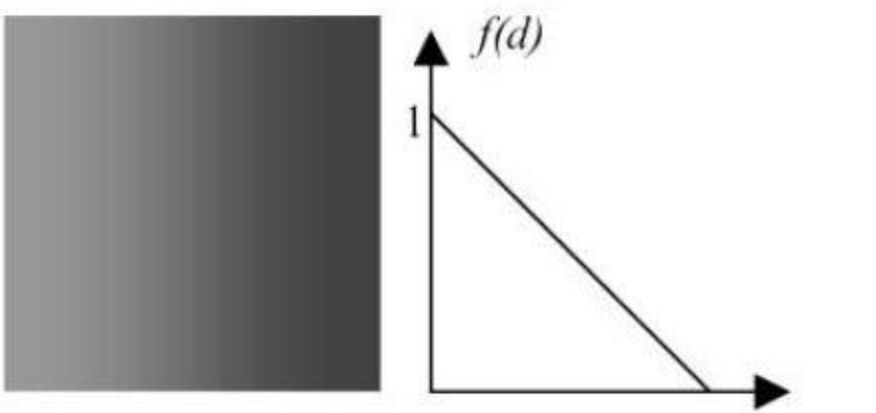
$$\sum_{j=1}^{n} M_{sj} = 1$$

$$n = 3,\ M_s = (0.7,\ 0,\ 0.3),\ M_e = (0,\ 0.7,\ 0.3)$$

$$f(d) = \left(\frac{d}{r}\right)^2 - 2\left(\frac{d}{r}\right) + 1$$

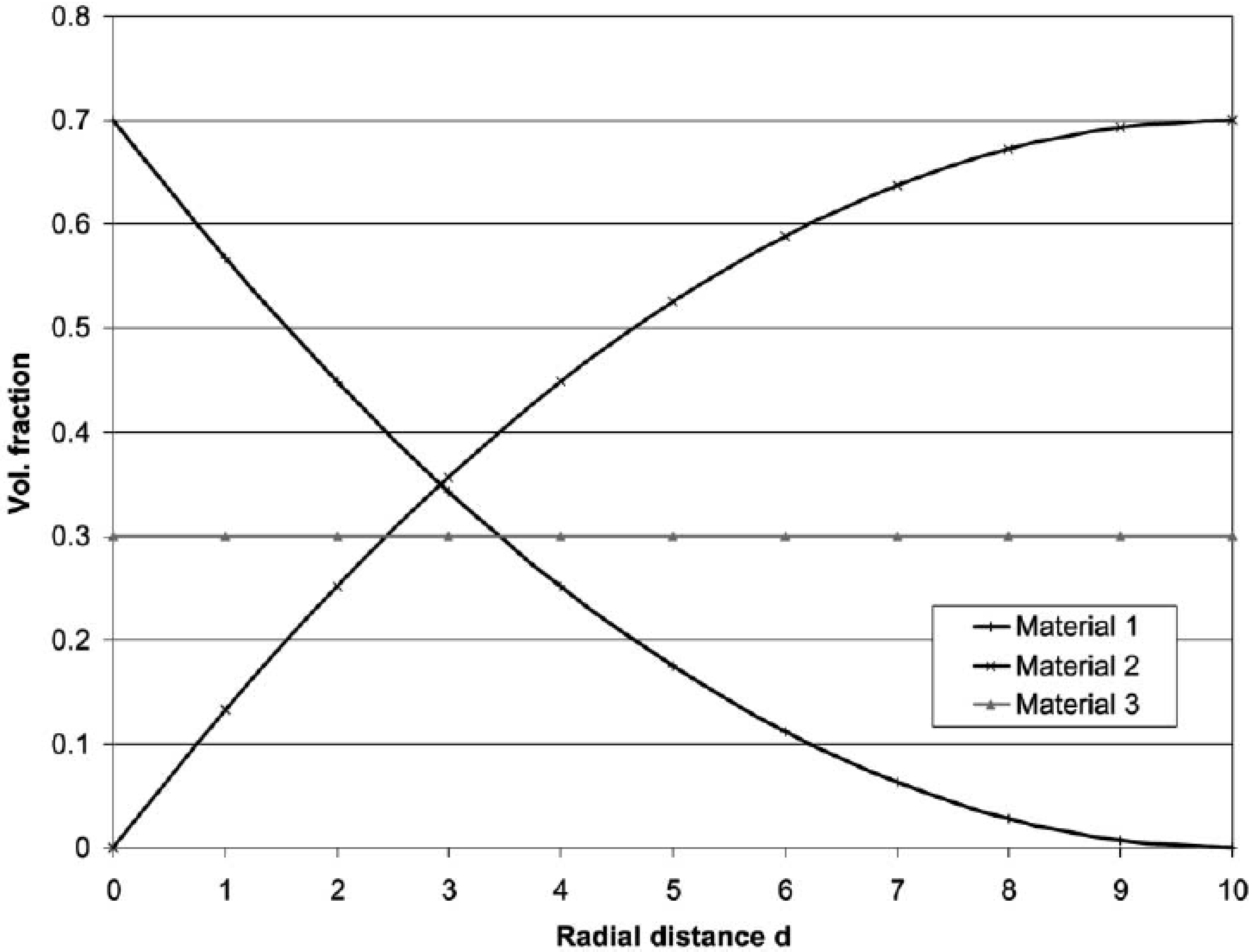


$f(d) = \sin(\pi d)$



$f(d) = 1 - d$

Source-based material modelling

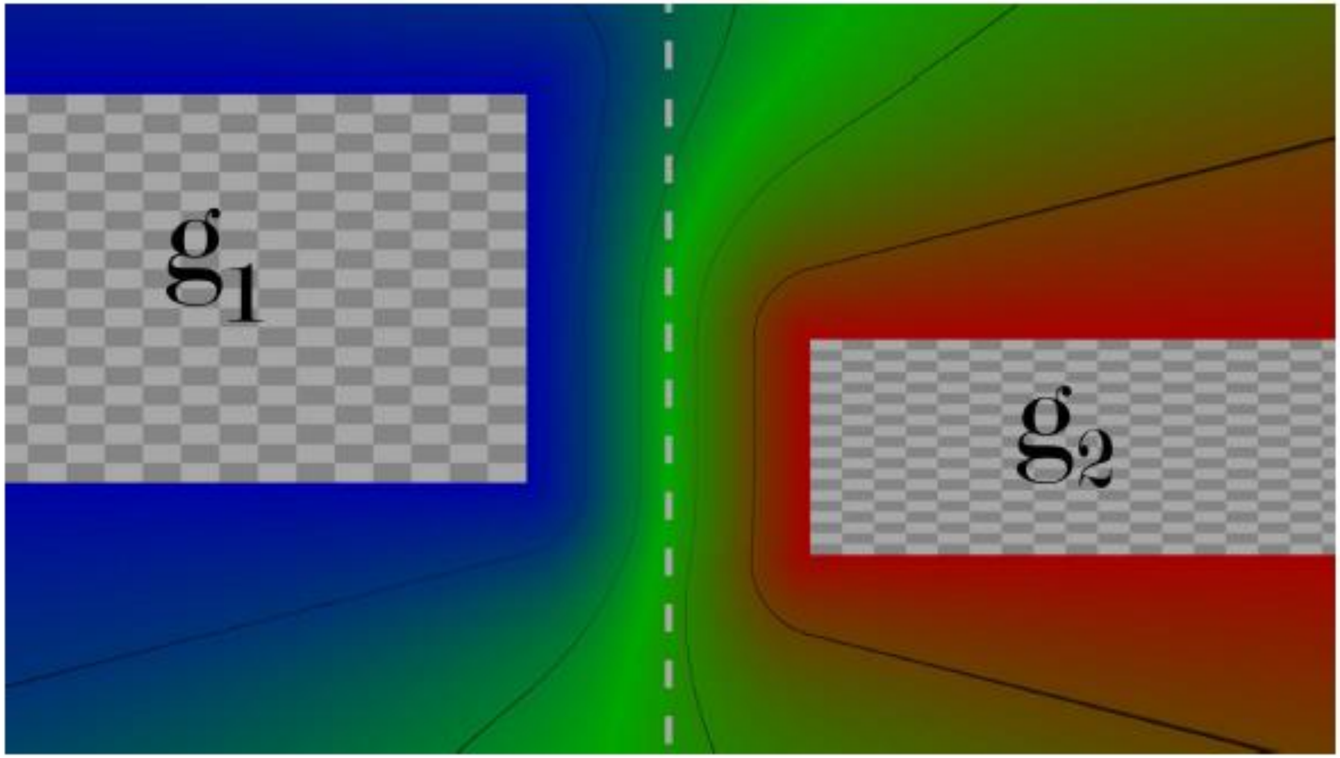


Y.K. Siu, S.T. Tan / Computer-Aided Design 34 (2002) 41–55

Feature-based material modelling

1. Introduce material features with single uniform material
2. Represent material features with scalar fields or obtain "smooth" approximation of distance fields
3. Apply the **transfinite interpolation** to define material at any point

Feature-based material modelling

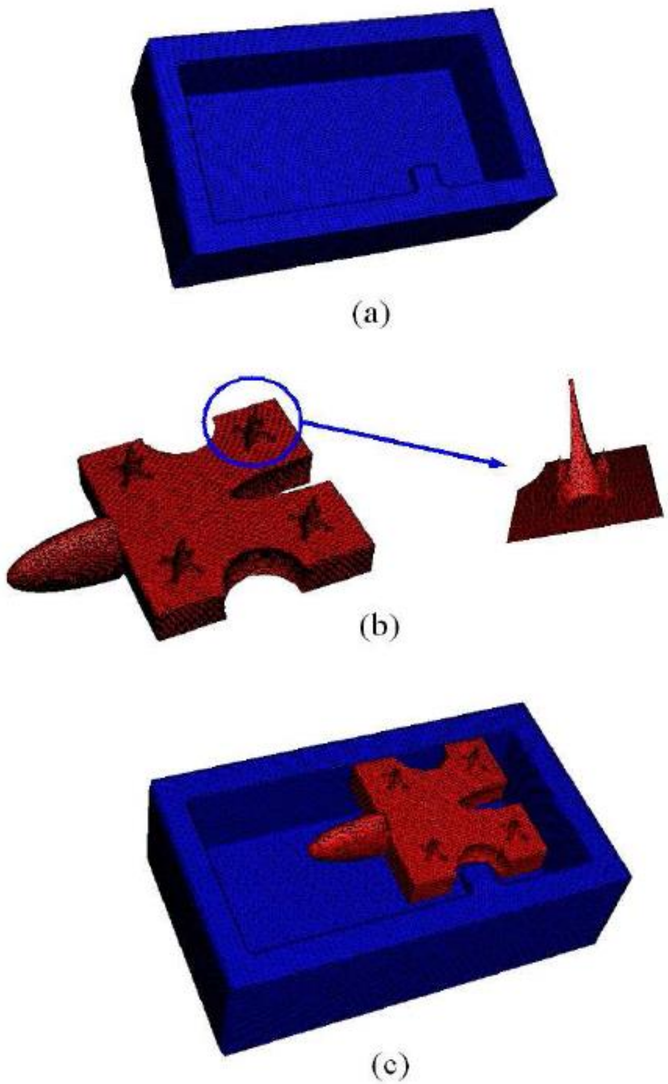


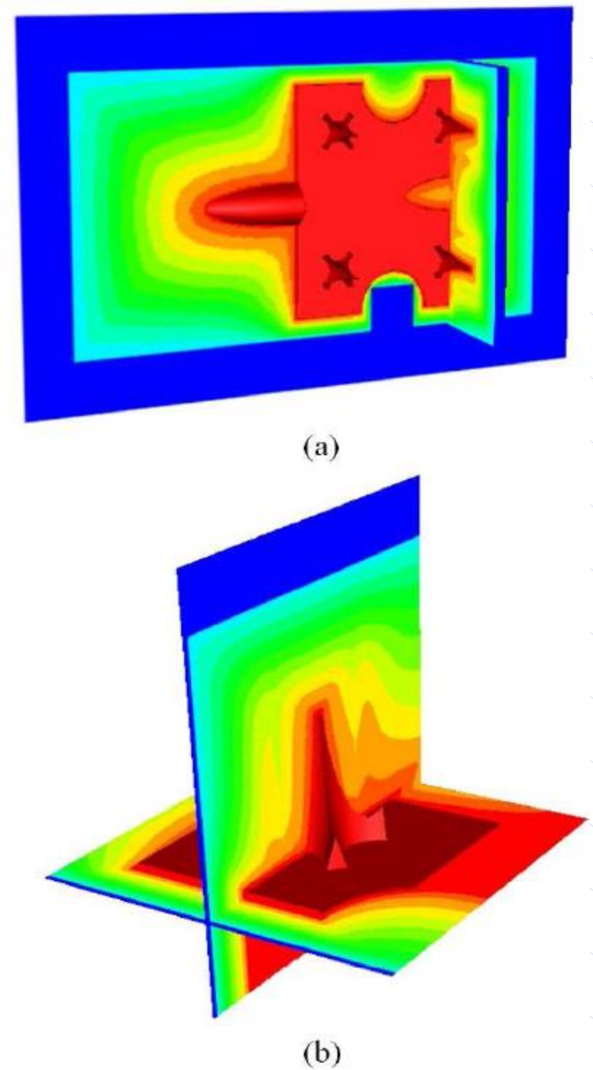
$$\mathbf{c}(\mathbf{p}) = \frac{\sum_{k=1}^{n} w_k(\mathbf{p})\tilde{\mathbf{c}}_k}{\sum_{k=1}^{n} w_k(\mathbf{p})}$$

$$w_a(\mathbf{p}) = \frac{d_b(\mathbf{p})}{d_a(\mathbf{p}) + d_b(\mathbf{p})}$$

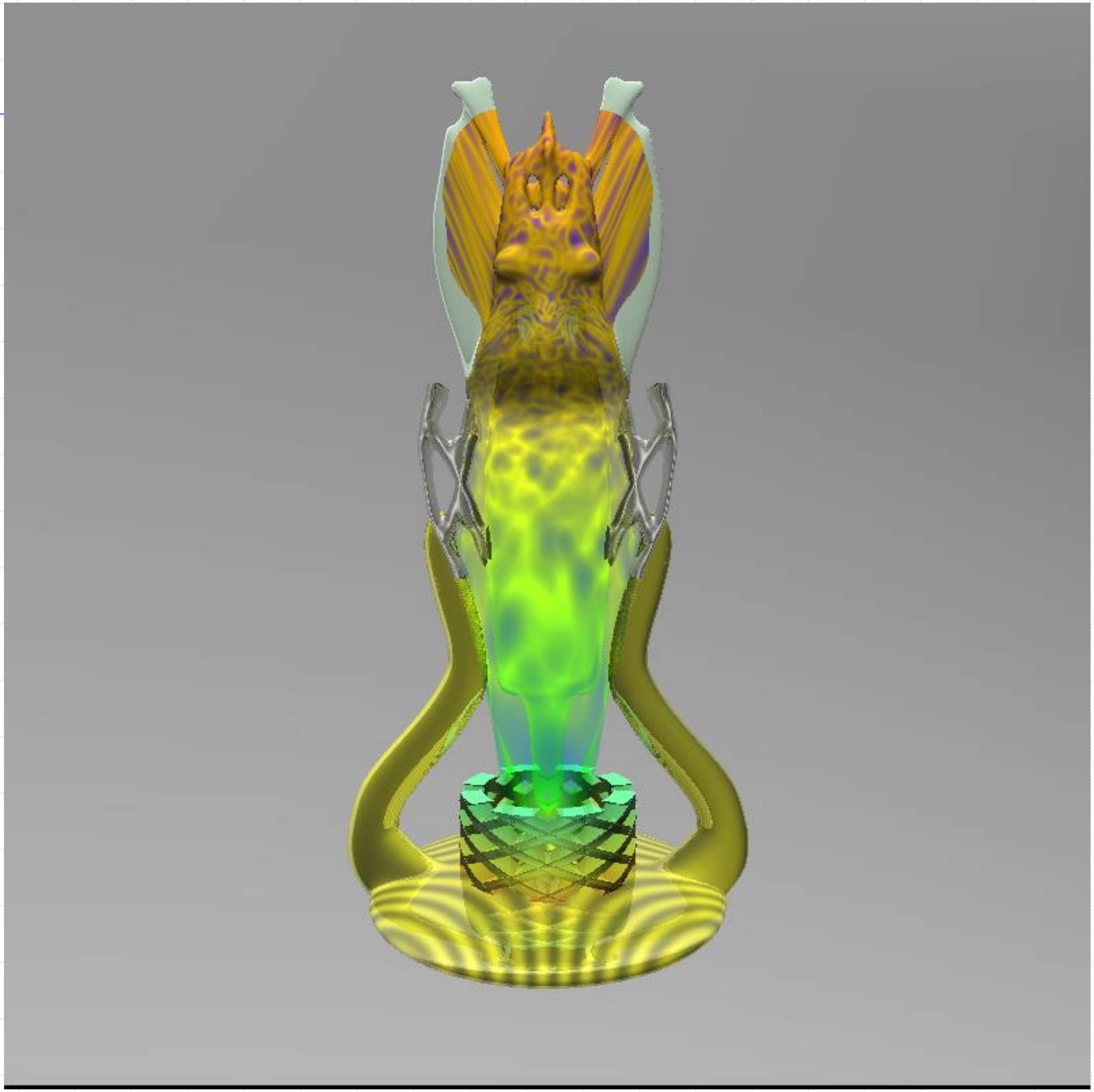
$$w_b(\mathbf{p}) = \frac{d_a(\mathbf{p})}{d_a(\mathbf{p}) + d_b(\mathbf{p})}$$

Feature-based gradient volumetric materials

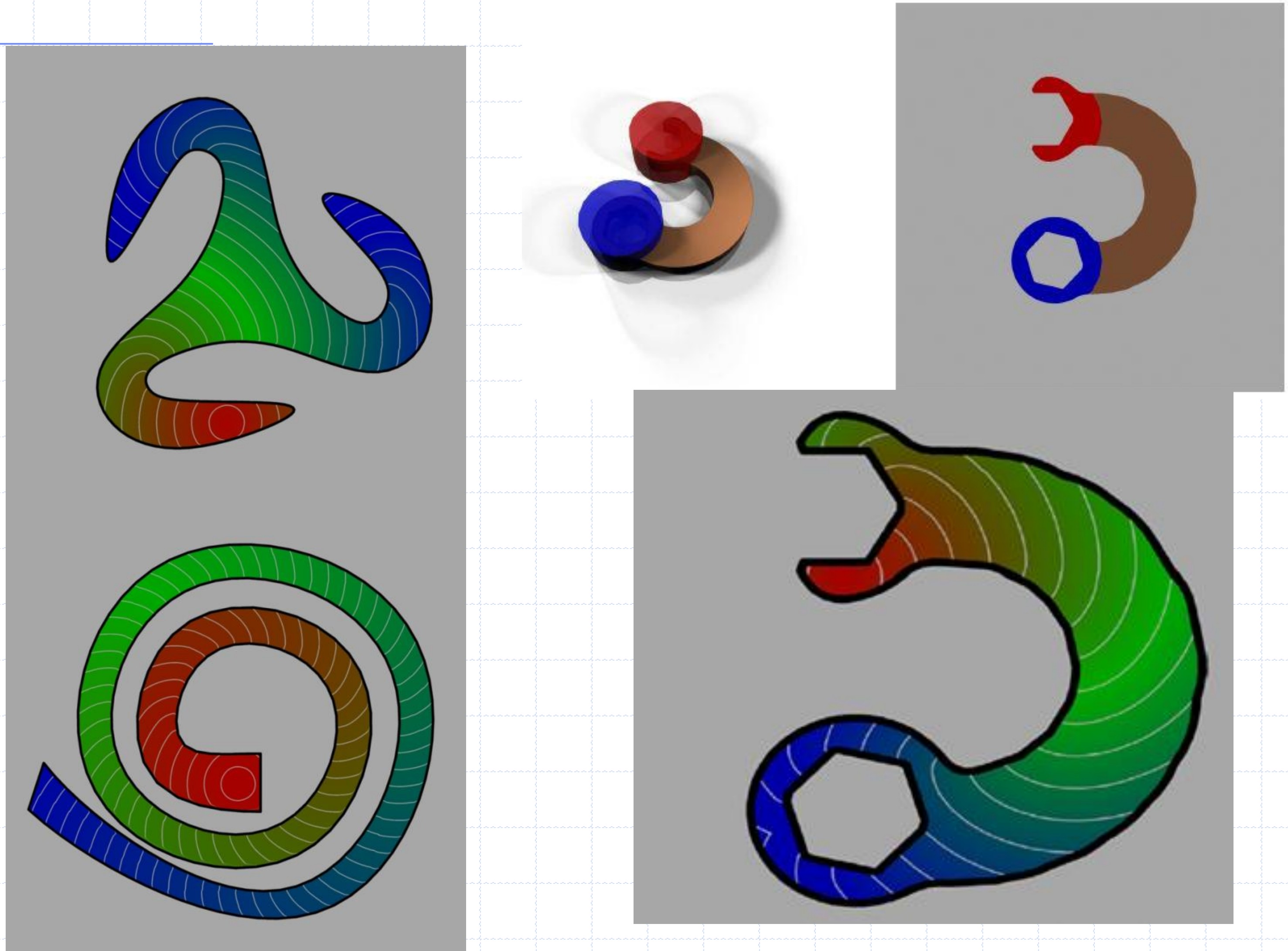




Procedural volumetric materials

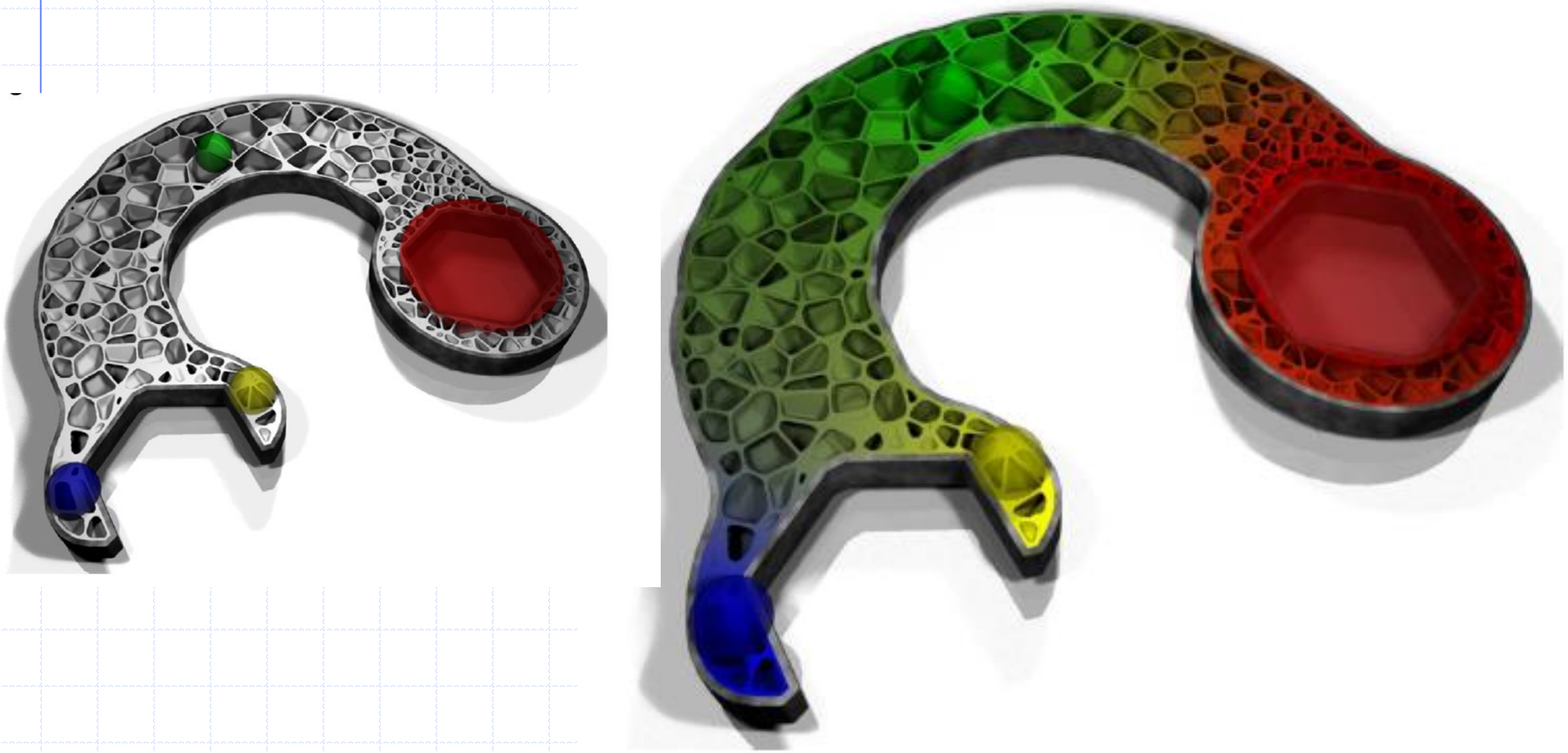


Shape-aware Material Distribution: Interior Distance Interpolation



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

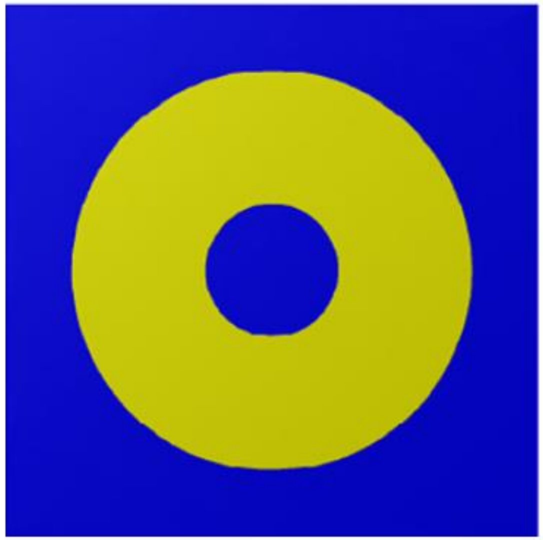
Step 1. Surface discretization for space partitions

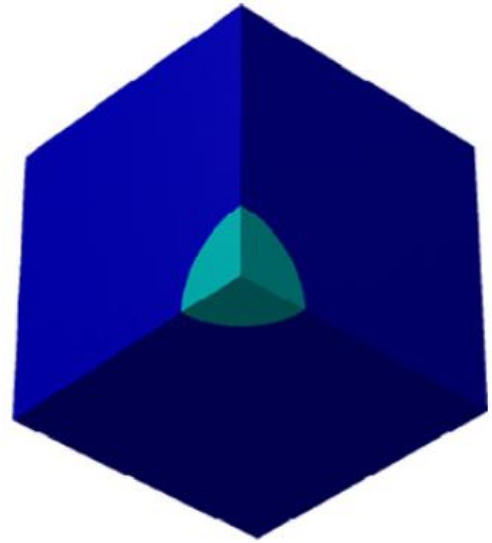
- Generate random points and project them on the surface *f=0*

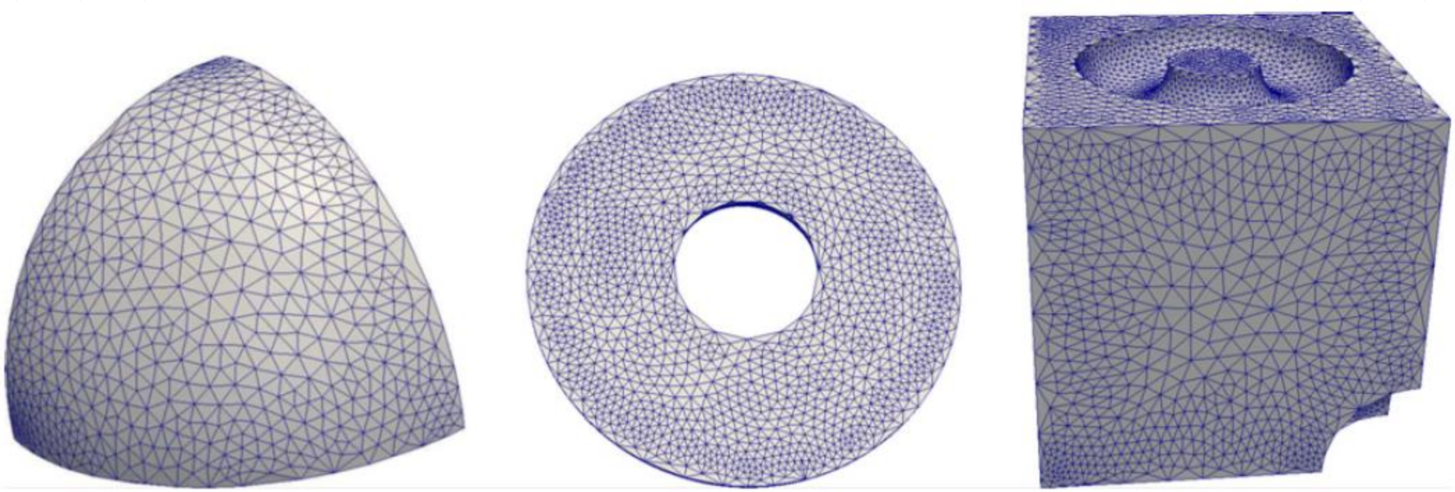
$$\mathbf{p} \leftarrow \mathbf{p} - f(\mathbf{p}) \frac{\nabla f(\mathbf{p})}{\|\nabla f(\mathbf{p})\|^2}$$

- 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

Mesh optimization

- Criteria:

  - regularized shape and size of mesh triangles,
  - retrieved sharp features
  - minimized approximation error

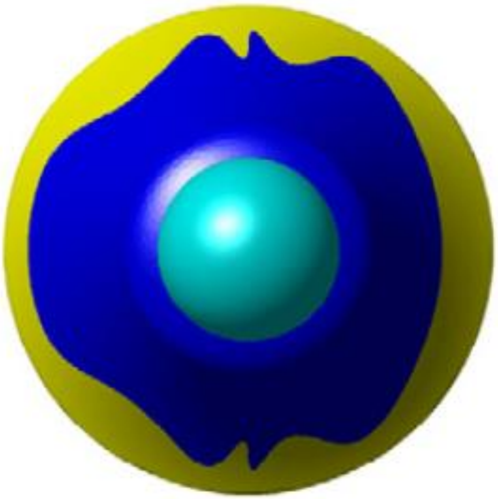
- Algorithm:

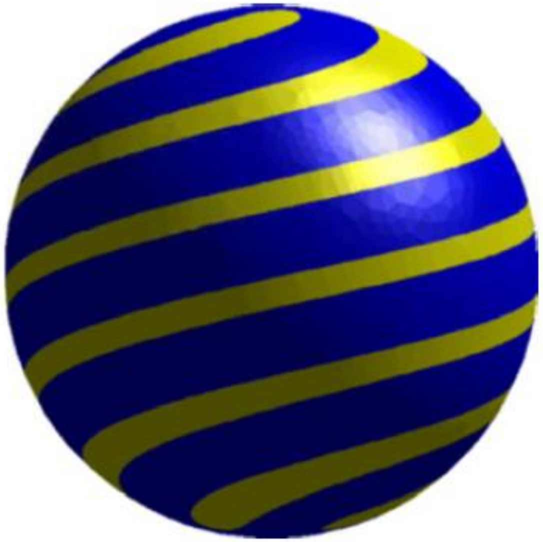
  1: Move the triangle vertices to align the triangle normal with the gradient of f

  2: Regularize the shape of the triangles by vertex relocation

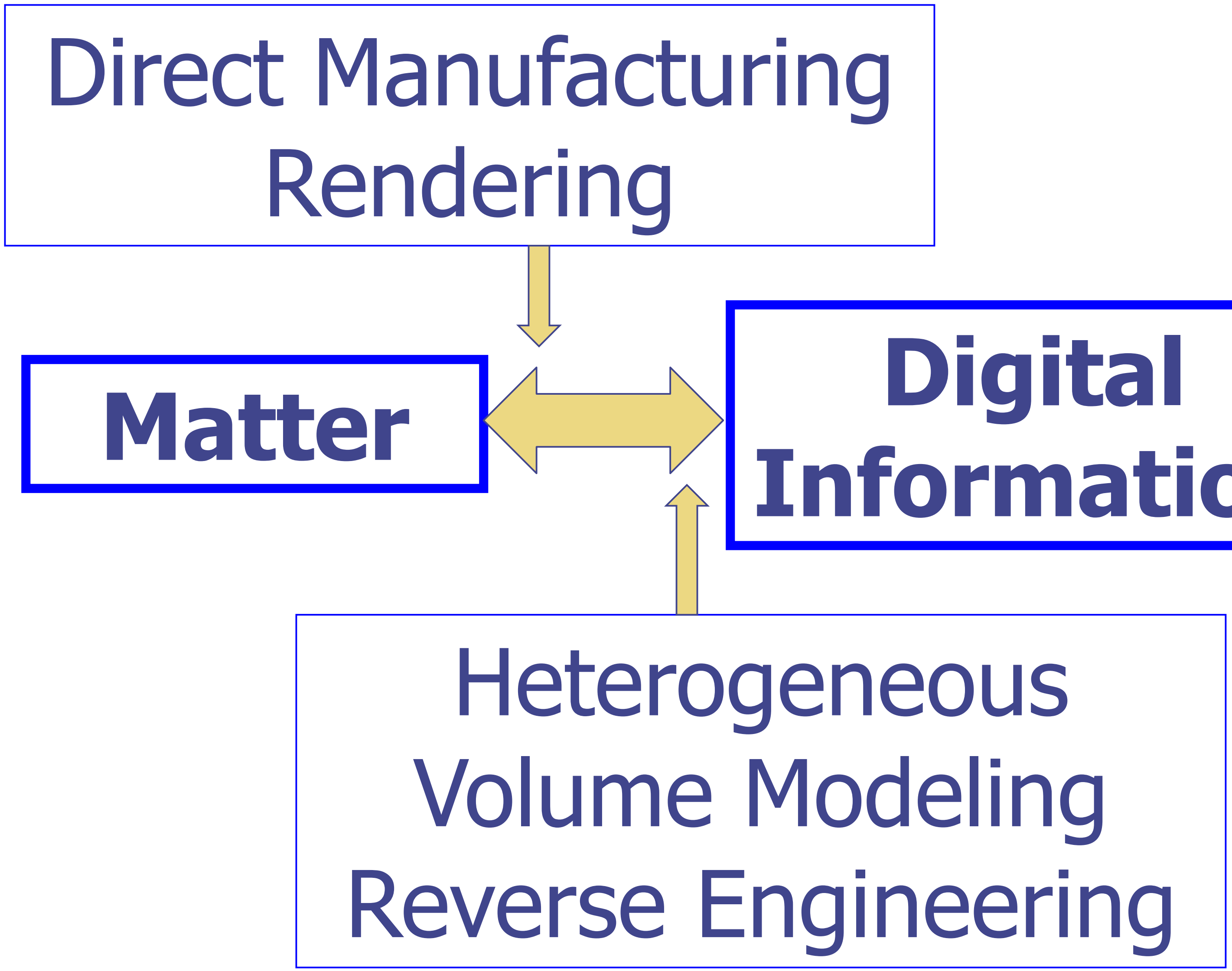
  3: Project the vertices back on the surface

Examples

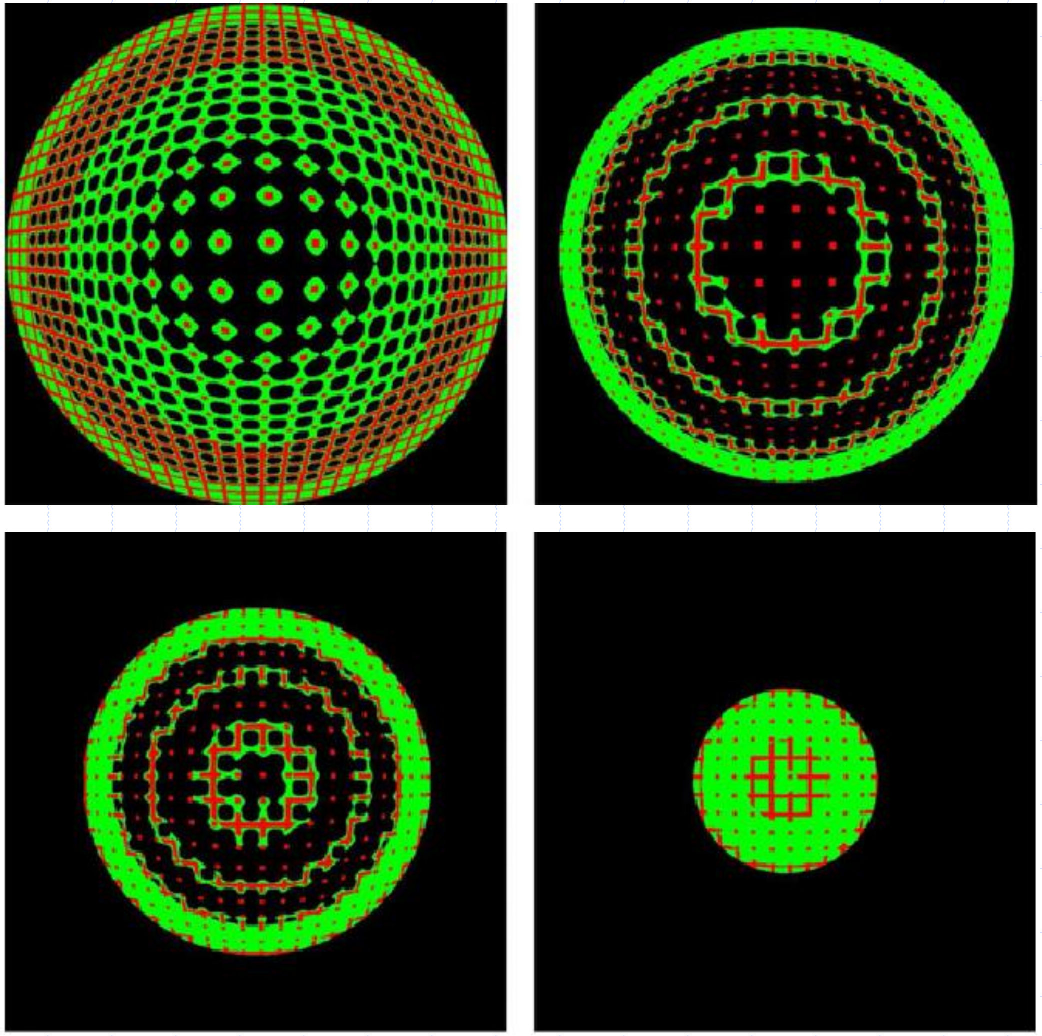




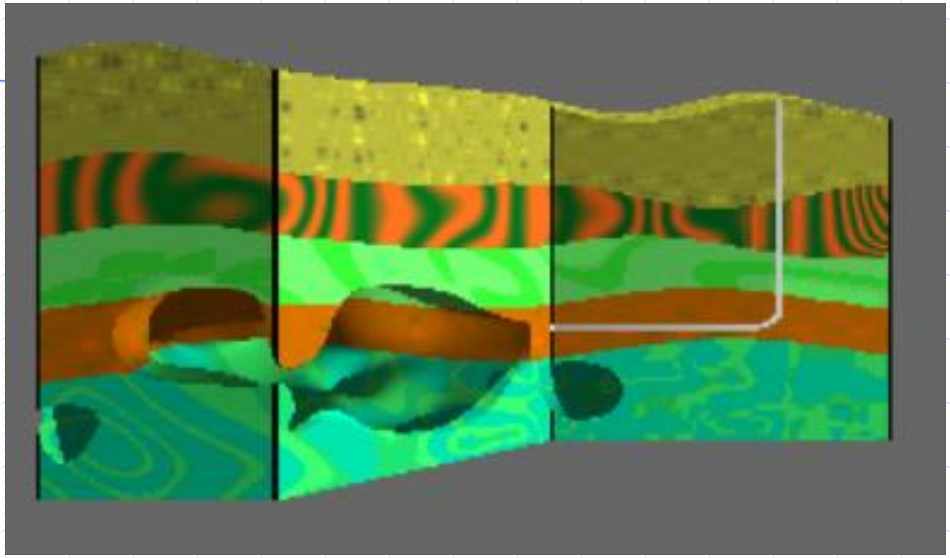
DM: Direct Manufacturing



Direct multi-material 3D printing



Geological Model

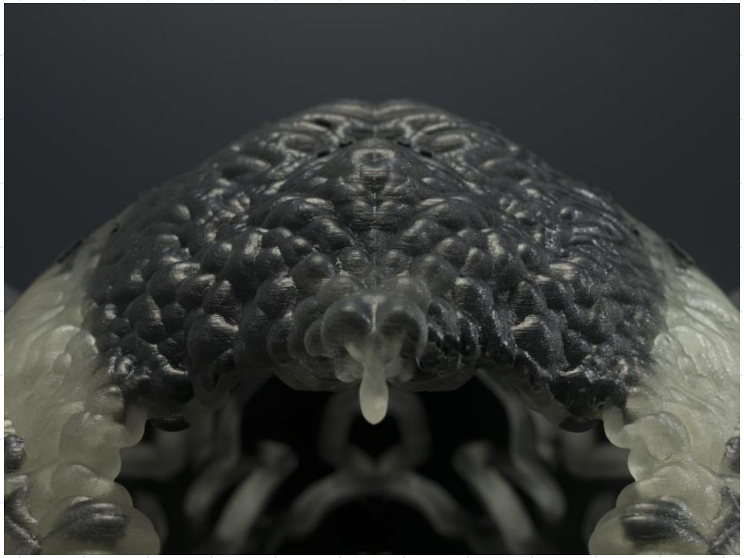


- Several homogeneous layers of different materials
- A point set is a full block between the flat bottom and the top surface
- Layers a modeled as discontinuous attribute function
- Set operations: the complex cut and the well
- Attributes are redefined in the well and along the edges

ZCorp Color 3D Print

HyperFun – VRML – surface colors

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

Multi-material corset

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