Procedural Function-based Spatial Microstructures

http://hm.softalliance.net/

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Outline

- Heterogeneous objects modelling
- Natural and artificial microstructures
- Problems with surfaces & voxels
- Using real functions
- Regular and non-regular procedural microstructures
- Direct rendering and fabrication

Function Representation FRep

- Uniform representation of multidimensional point sets as
$$F(X) \geq 0$$
- Function $F(X)$ evaluation procedure traversing the construction tree structure
- Leaves: primitives
- Nodes: operations + relations

Visual Computer, 1995

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

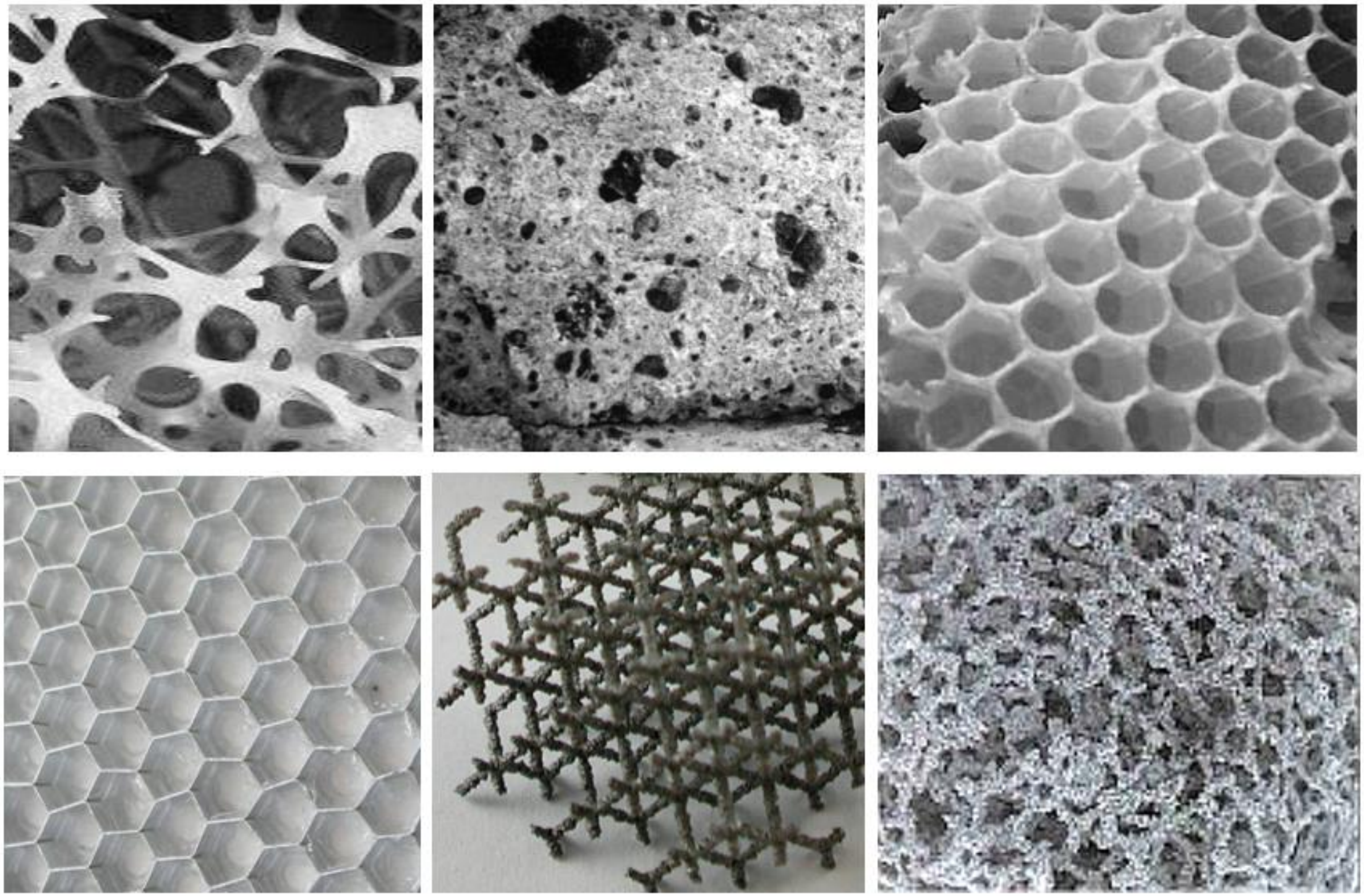
$S_i (X)$ – attributes based on FRep space partitions

Graphical Models, 2001

Heterogeneous objects

- Internal structure with non-uniform volumetric distribution of properties (density, color, transparency, etc.)
- Entities of different dimensionalities
- Gradually varying material distribution in CAD/CAM and fabrication
- Physical simulations, geological and medical modeling and rendering

Natural and artificial microstructures



Problems with surfaces & voxels

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

Procedural microstructures

- Procedural generation of the defining function $F(X)$ value at the given point such that geometry of the entire microstructure is described as

$$F(X) \geq 0$$

- Constructive model based on R-functions:

$$f_3 = f_1 \vee_\alpha f_2 \quad \text{for the union;}$$

$$f_3 = f_1 \wedge_\alpha f_2 \quad \text{for the intersection;}$$

Regular infinite lattices

Periodic infinite slabs

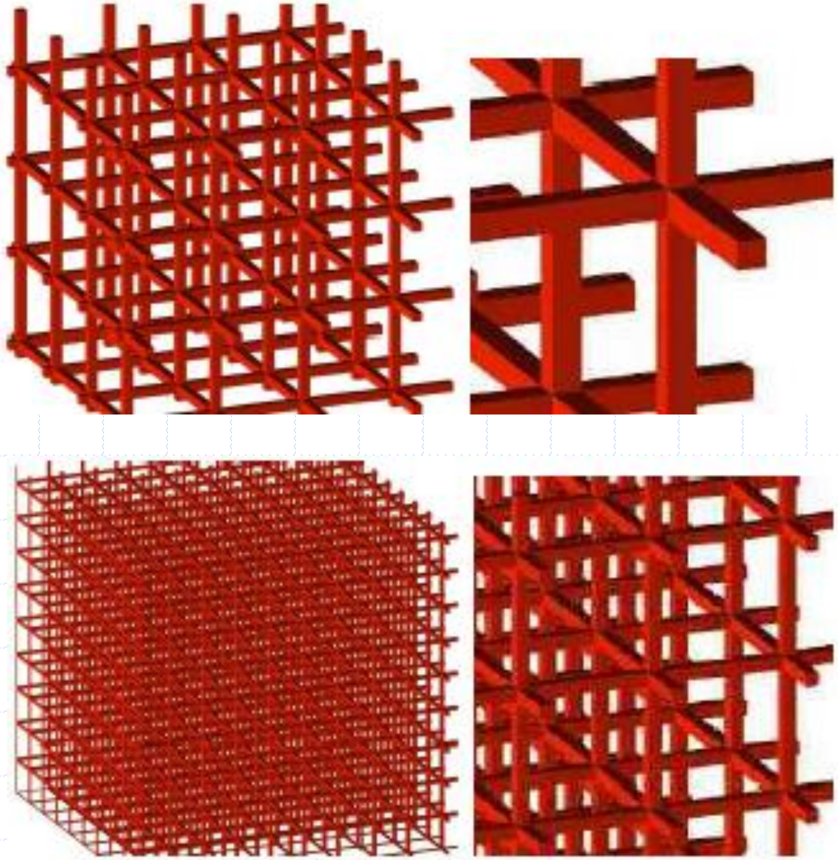
$$s_x(x, y, z) = \sin(q_x x + p_x) - l_x$$

Rods: intersection of slabs

$$r_x(x, y, z) = s_y \wedge_\alpha s_z$$

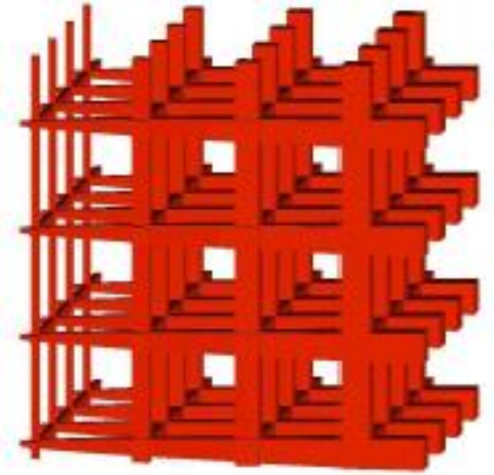
Lattice: union of rods

$$g(x, y, z) = r_x \vee_\alpha r_y \vee_\alpha r_z$$

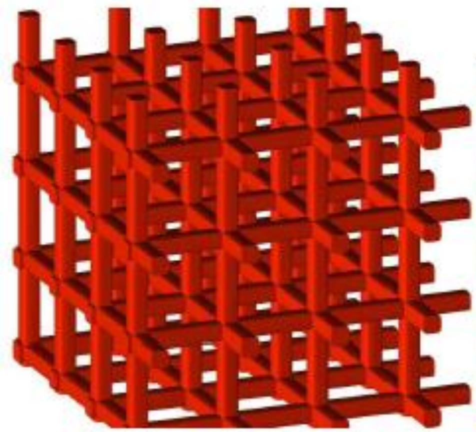


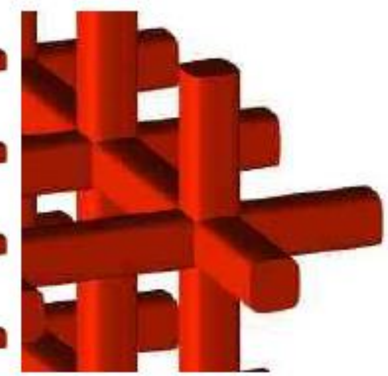
$$g(x, y, z) = (s_y \wedge_\alpha s_z) \vee_\alpha (s_x \wedge_\alpha s_z) \vee_\alpha (s_x \wedge_\alpha s_y)$$

Variations of lattices



- Variable rod thickness

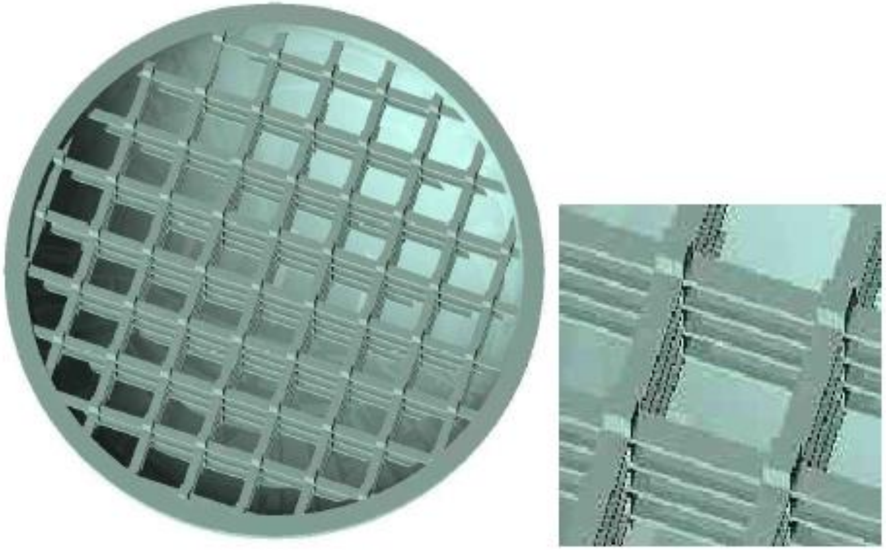




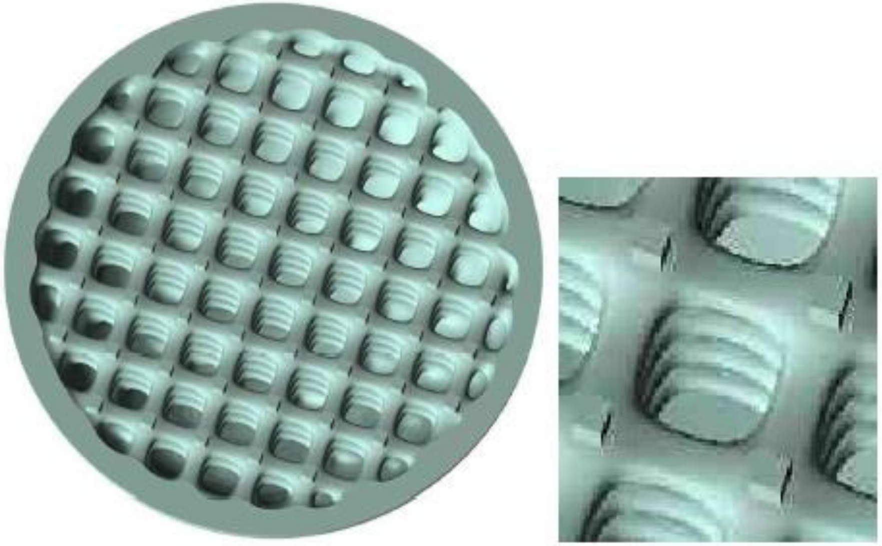
- Smoothed rods

$$f_1 \wedge_b f_2 = (f_1 \wedge_\alpha f_2) + \frac{a_0}{1 + \left(\frac{f_1}{a_1}\right)^2 + \left(\frac{f_2}{a_2}\right)^2}$$

Combining with a shell



Truncation of a lattice by a solid and union with its shell



Blending union between rods and with a shell

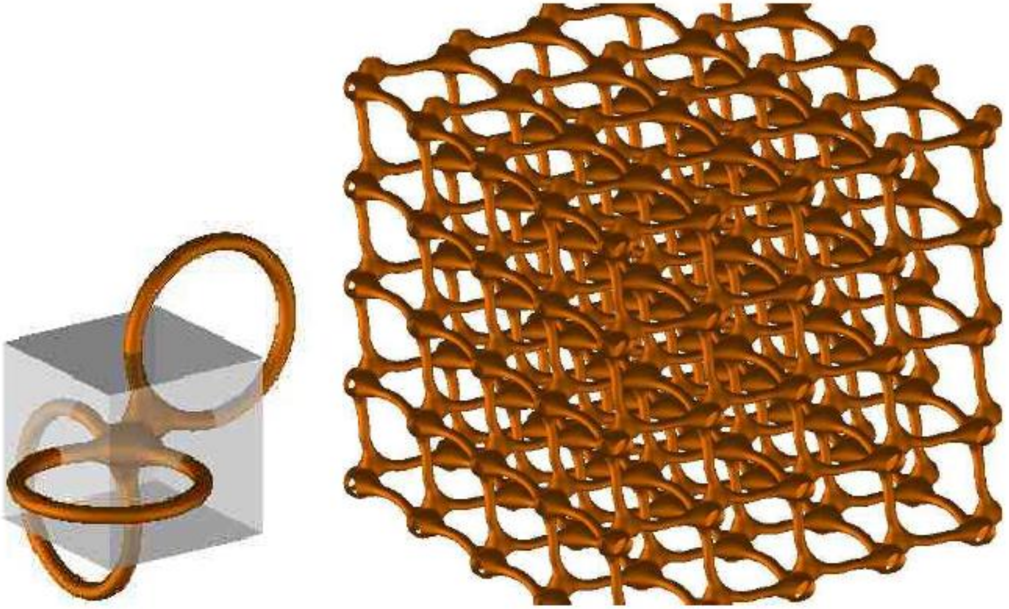
Parameterization by distance

Lattice step decreases closer to the surface

Cellular microstructures

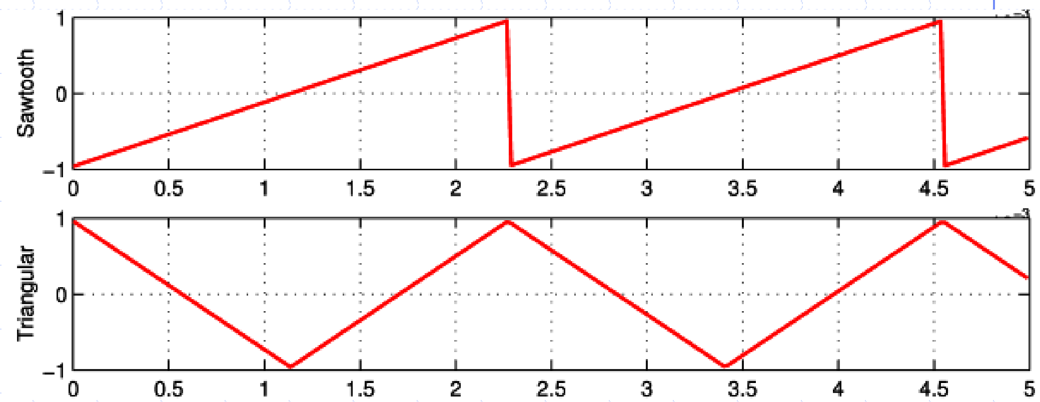
Replication of a unit cell with periodic space mapping:

$$x' = perodic(x)$$



Cellular microstructures

- Non-symmetric cell - sawtooth
- Symmetric cell – triangular



Sawtooth

$$g(t) = \frac{1}{2} + \left(\frac{t}{a} - \text{floor}\left(\frac{t}{a} + \frac{1}{2}\right)\right)$$

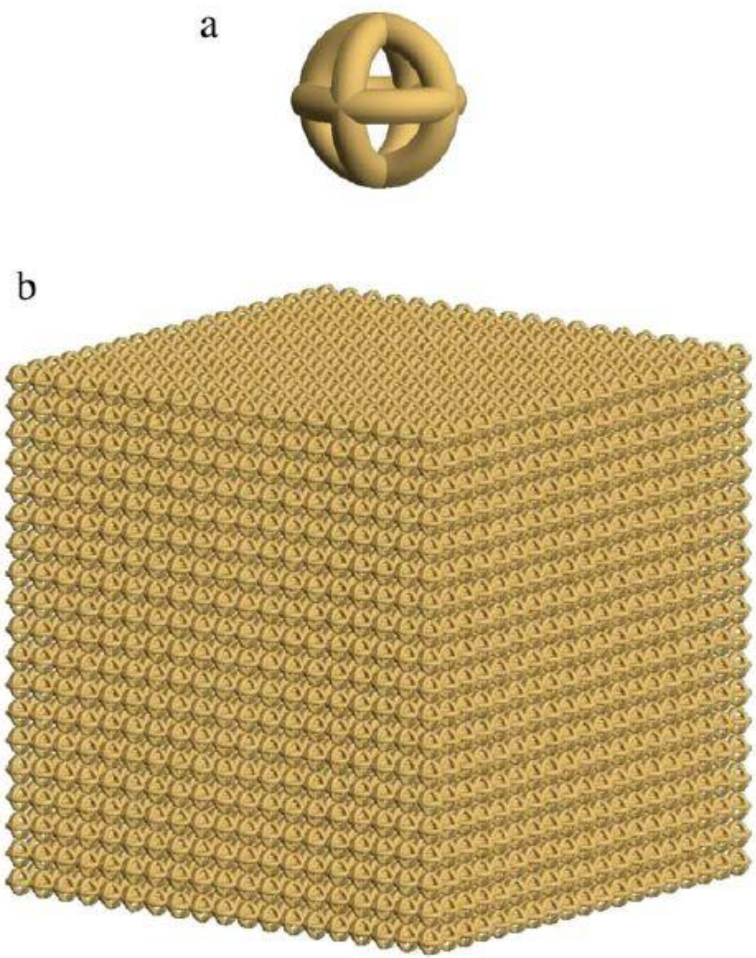
Triangular

$$g(t) = \frac{1}{2} + \frac{1}{\pi}\sin^{-1}\left[\sin\left(\pi\frac{t}{a}\right)\right]$$

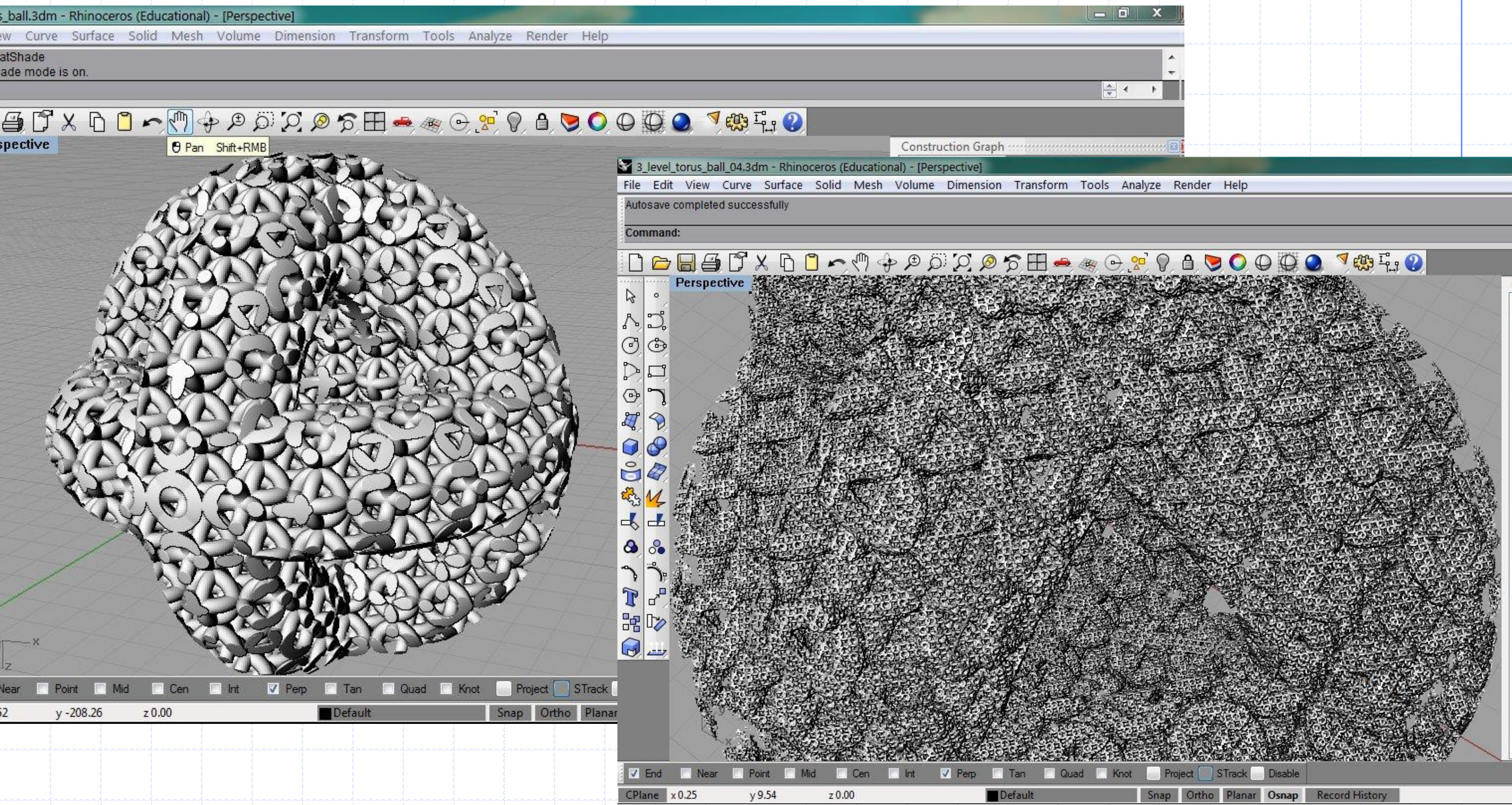
where *a* is a period of the function.

Cellular microstructures

Replication of a unit cell (a: union of three tori) with periodic space mapping (b: sawtooth or triangle)



Multi-scale nested FRep structures

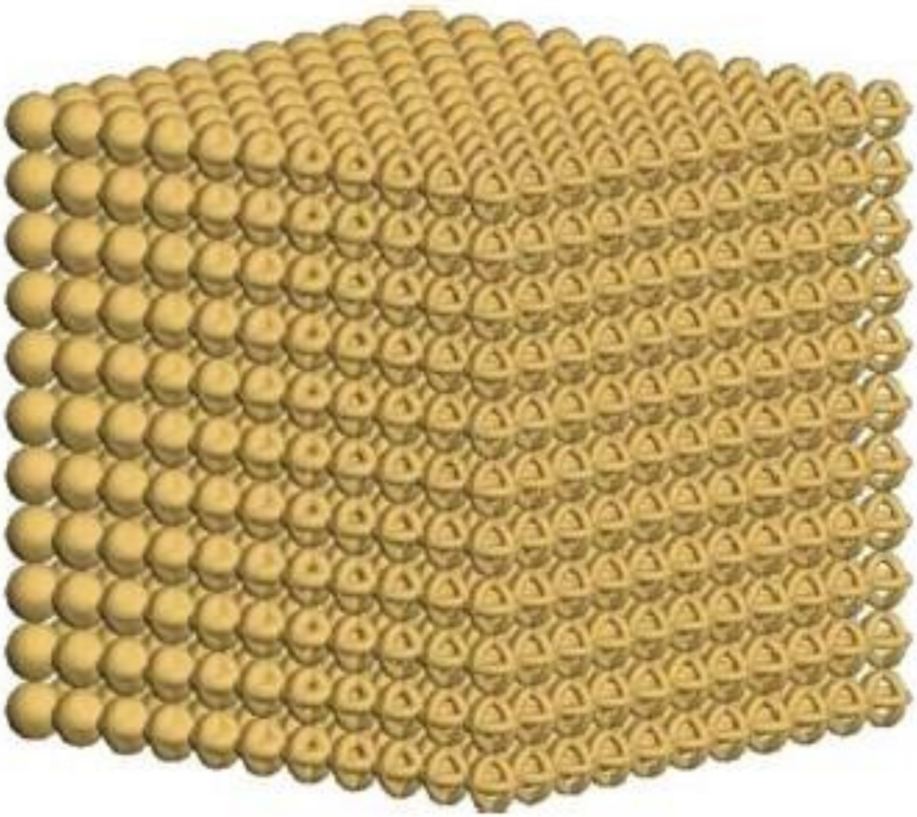


3 levels of nested tori balls

Metamorphosis

- Spatial metamorphois from a ball to a union of three tori:

$f = f_1(1-t) + f_2 t$
$t \in [0,1]$
f_1 is a ball
f_2 is a union of three tori

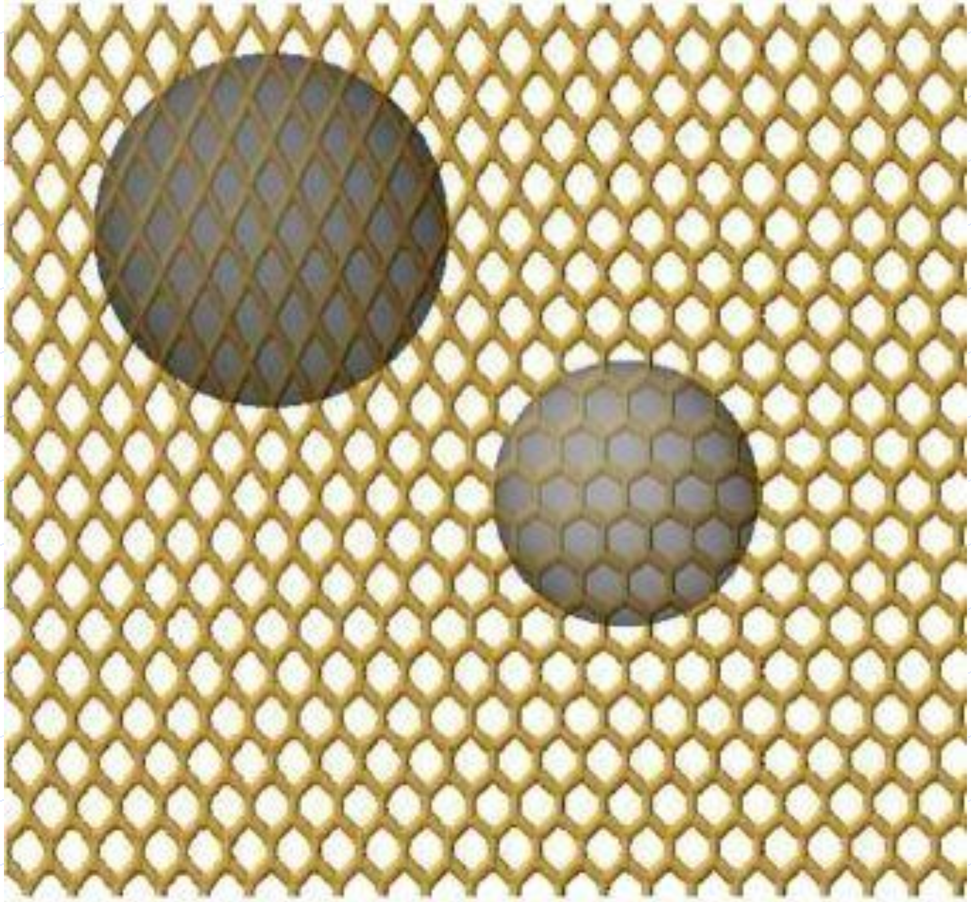


Spatial interpolation

Cell metamorphosis:

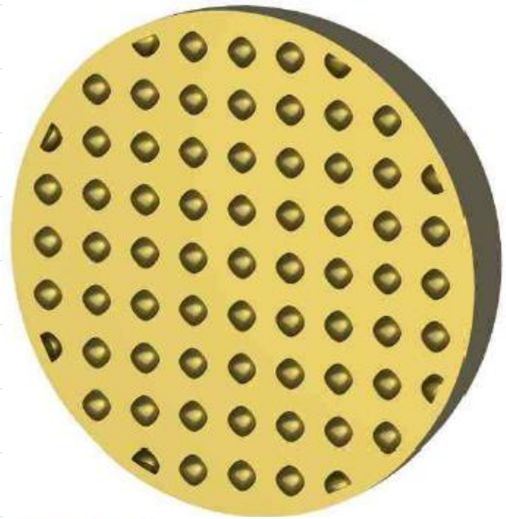
$f = f_1(1-t) + f_2 t$
$t \in [0,1]$
f_1 is a rhomboid
f_2 is a hexagonal lattice

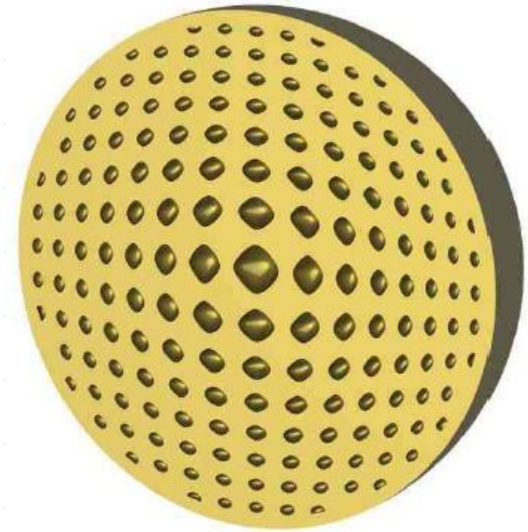
or transfinite interpolation



Porous media

1. Basic pore replication
2. Distance dependency
3. Adding noise



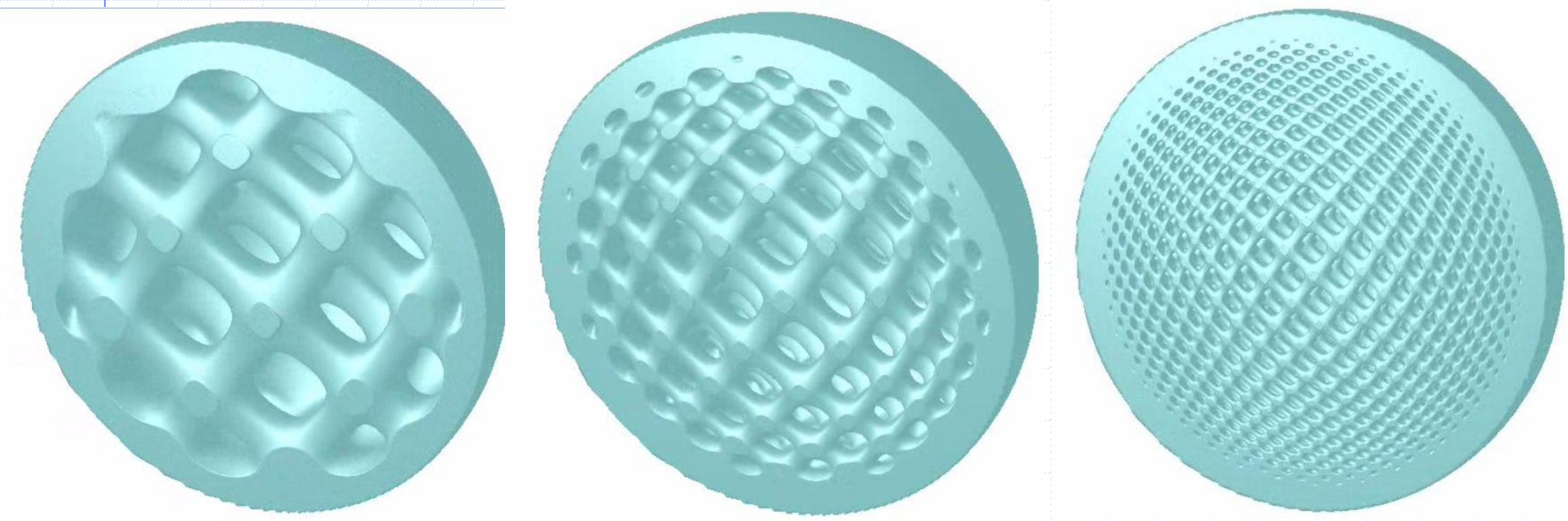


Direct rendering

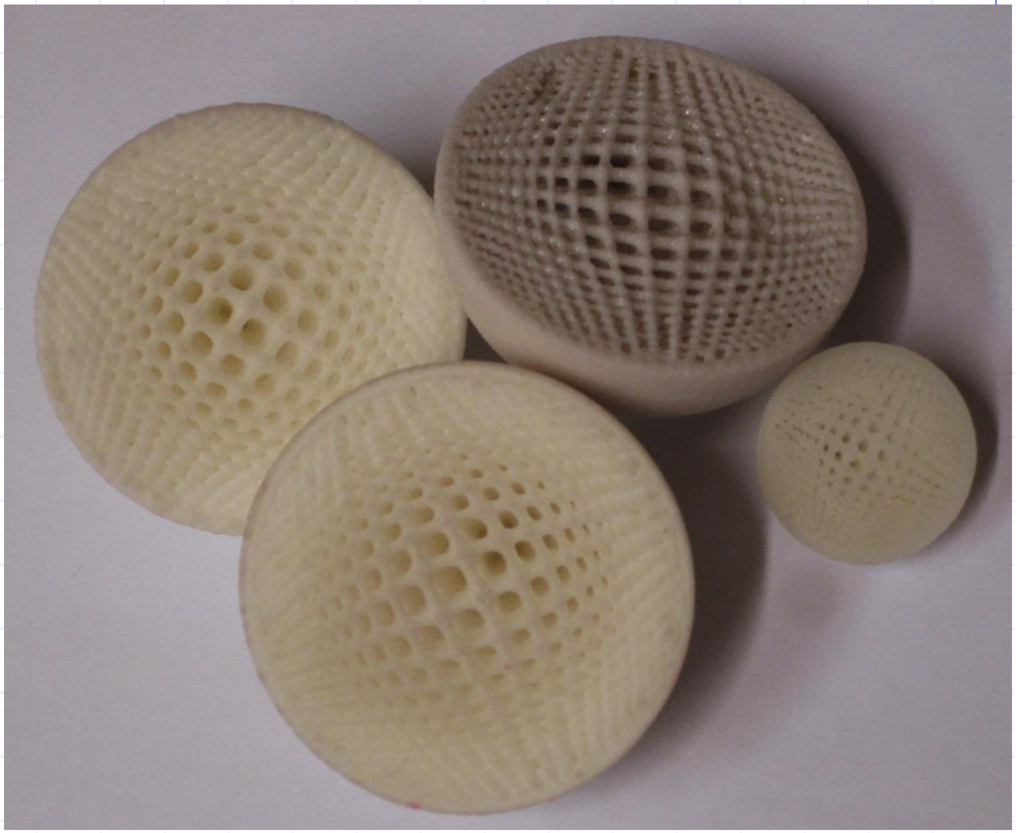
- Real-time ray-tracing on GPU
- independent of the microstructure density

Direct rendering

with blending to the shell and between rods



Towards direct fabrication



- 3D Systems Sinterstation
- ZCorp 3D printer
- Stratasys Dimension
    - STL problems
    - Proprietary protocols

3D prints by the Centro de Tecnologia da Informao, CTI, Brasil

Applications

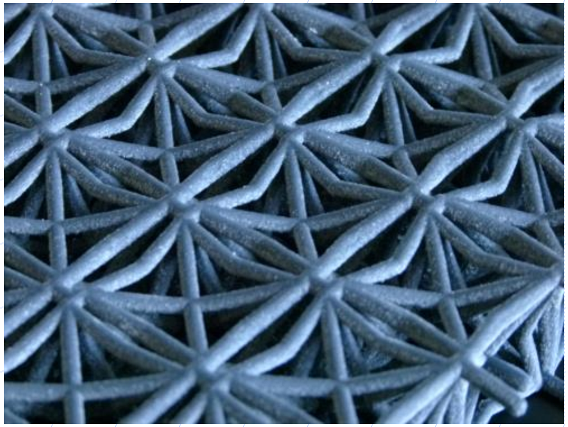
- Additive manufacturing / 3D printing
- Mechanical and bio-engineering
- Geological exploration
- Medicine
- Digital art and entertainment
- Creativity for disabled children - SHIVA project

Applications in 3D Printing

Chess pieces (resin & stereolithography)

Solver pendant (3D printed wax, casting)

Pavilion (concrete 3D print, D-shape)



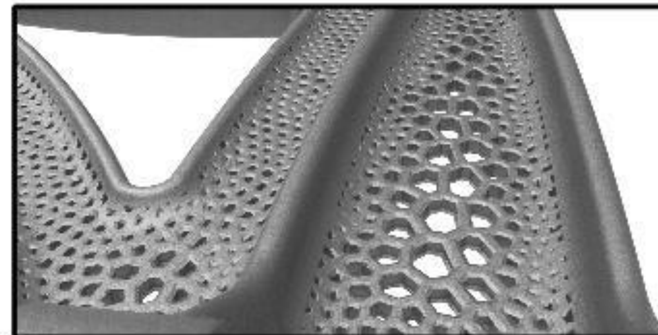
Construction pattern (plastic, ZCorp)

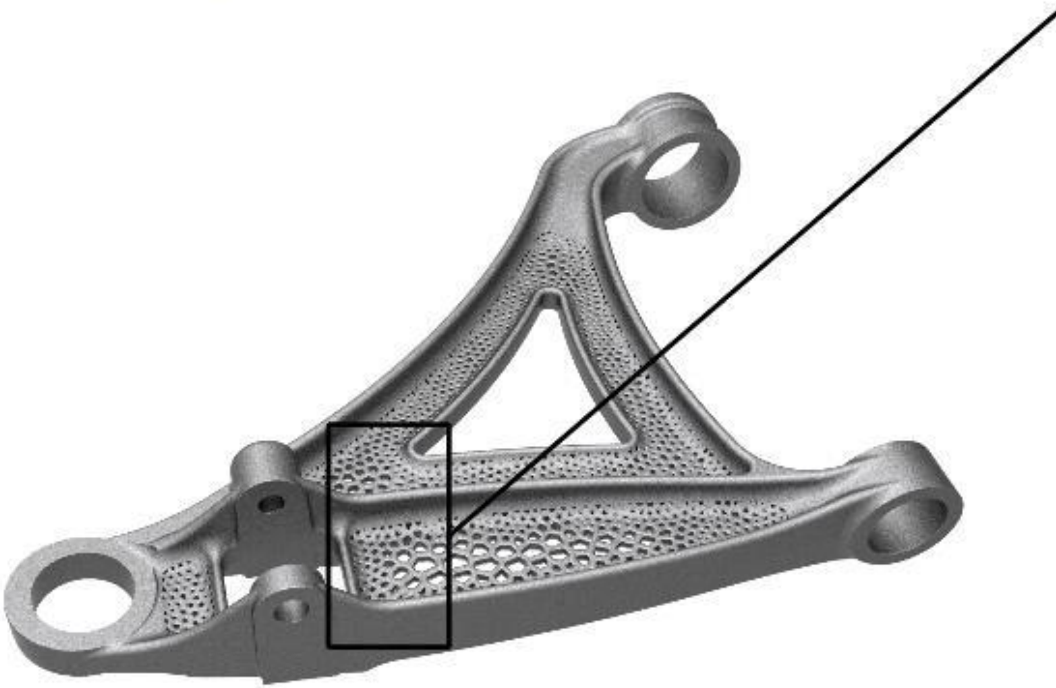
Bonbonniere (wood, milling machine)

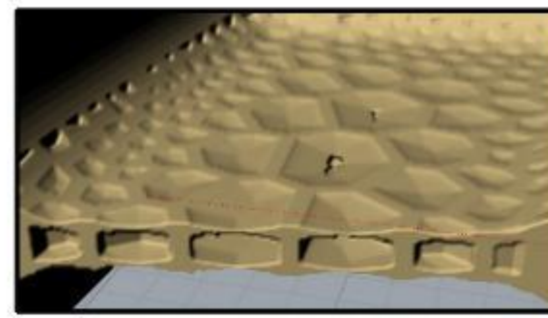
Next Steps – Advanced Designs w/ Automatic Closed Loop Simulation Feedback

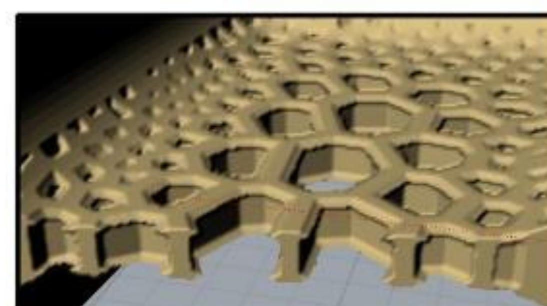
Adaptive variable cellular and internal structures based on direct FEA and simulation feedback linked to dynamic generative parameters.

Ex 1: Simulation optimized & parameterized cellular structure with porous skin.









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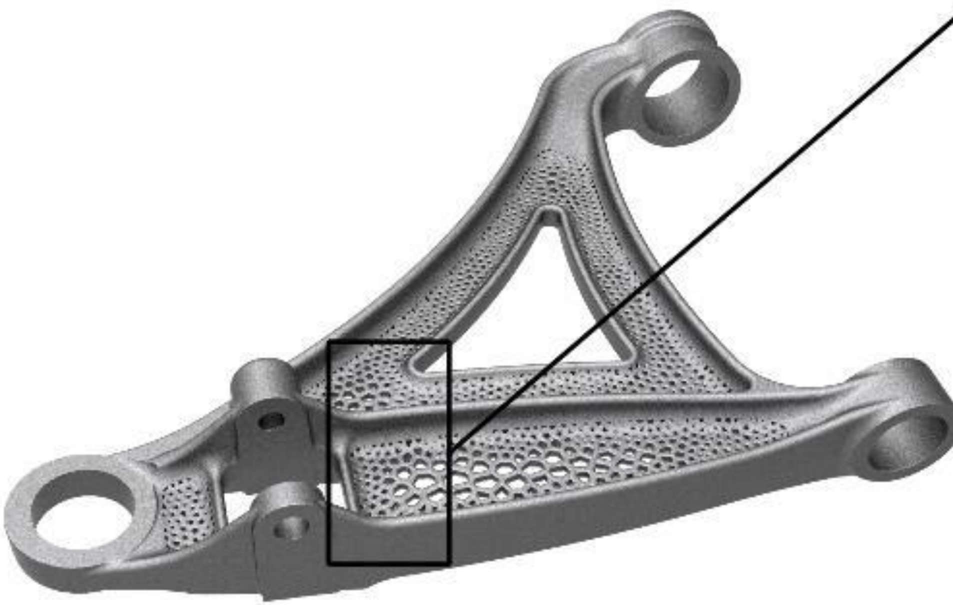
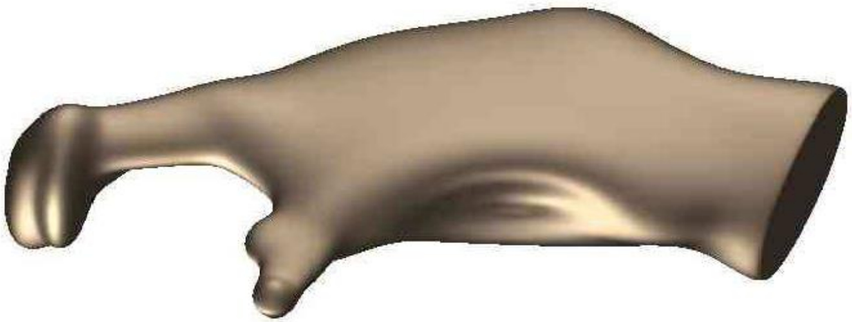


Lattice scaffold for a jaw bone



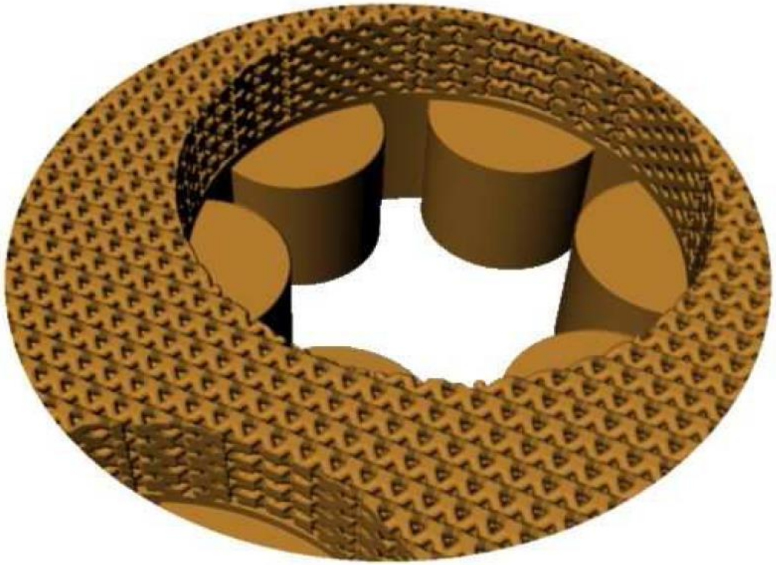
Initial jaw bone model

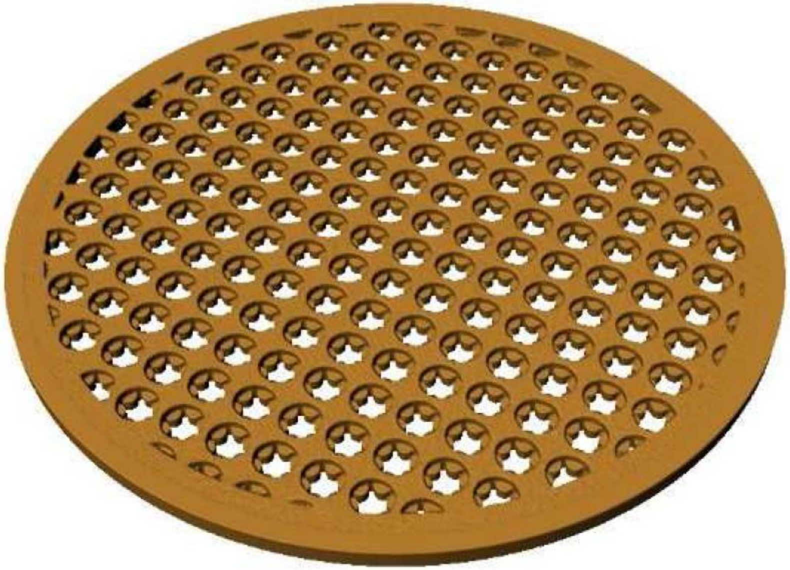
Union of lattice with bone shell

Lattice truncated by bone

Jaw bone model by Denis Kravtsov

Filter design

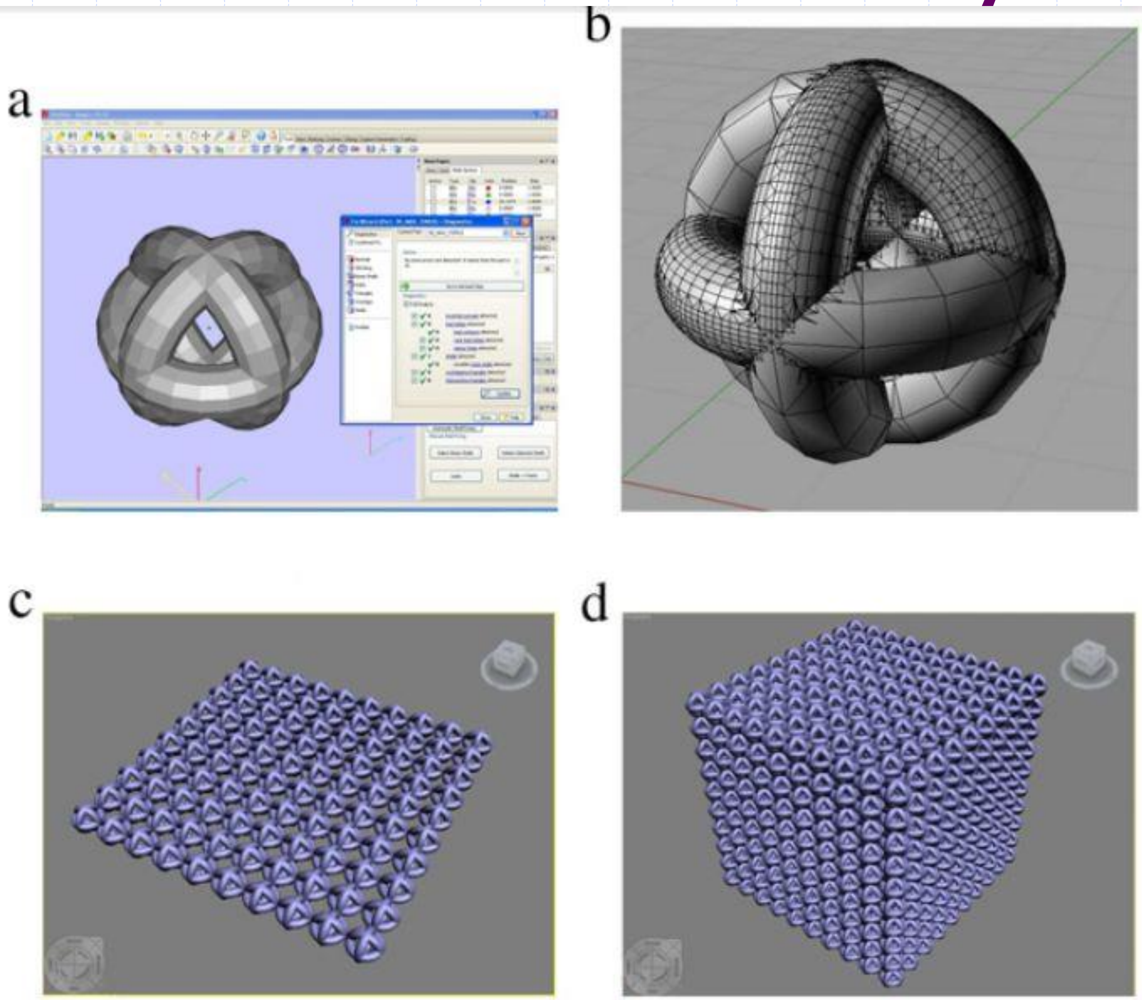




Surface design

Set-theoretic difference between the surface and the volume microstructure

Experiment with CAD systems



All CAD systems have failed the array of 100 tori balls

Conclusions

Polygon-free and voxel-free approach to

- Interactive modeling
- Real-time rendering
- Fabrication (ongoing)
- Fitting and analysis (future work)

Step towards procedural multiresolution modeling on micro- and nano-levels with infinite “zoom”.