Topology Optimization for Computational Fabrication

Jun Wu, Niels Aage, Sylvain Lefebvre, Charlie Wang

EUROGRAPHICS2017
The 38th annual conference of the
EUROPEAN ASSOCIATION FOR COMPUTER GRAPHICS

TU Delft

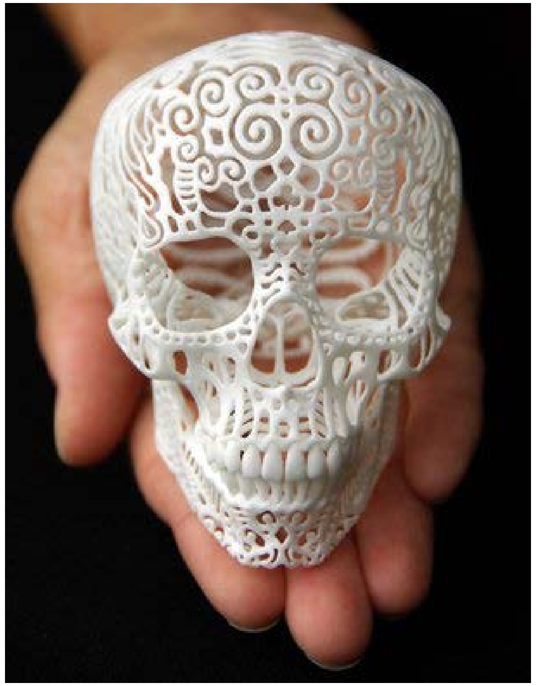
Topology Optimization for Computational Fabrication

Part 3: Controllable Topology Optimization – Geometric Features

Dr. Jun Wu
TU Delft

Complexity is free

TU Delft & MX3D, 2015

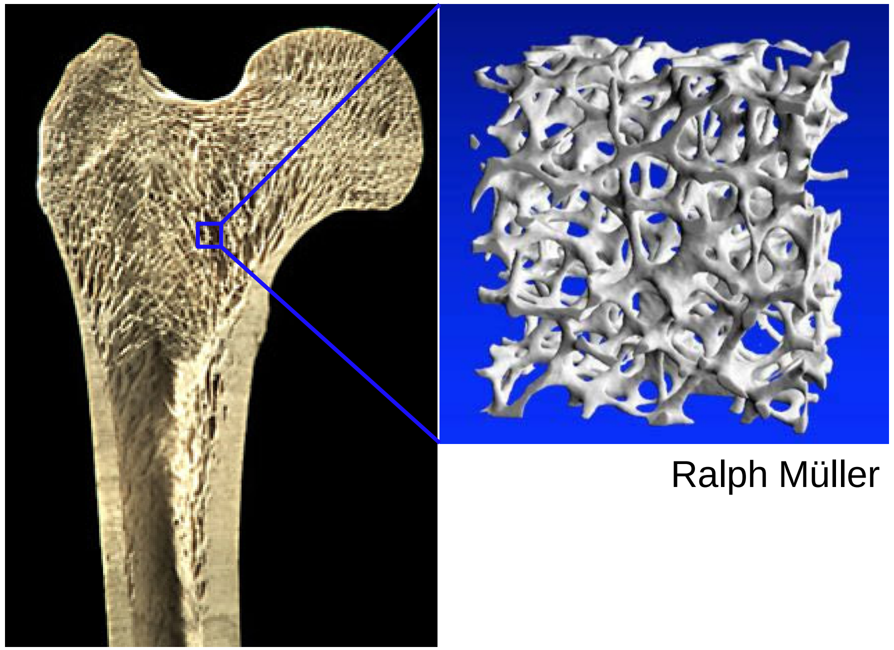


Joshua Harker

Scott Summit

Complexity is free? … Not really!

Tiny details



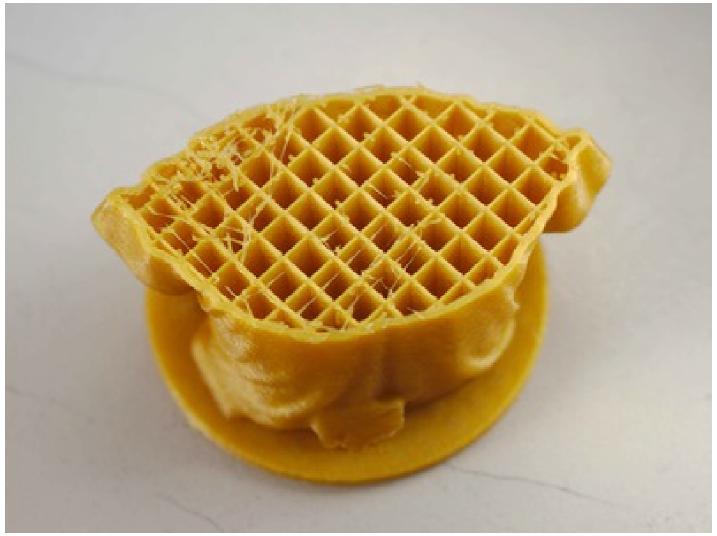
Ralph Müller

Paul Crompton

Supports

Concept Laser GmhH

Infill



mpi.fs.tum.de

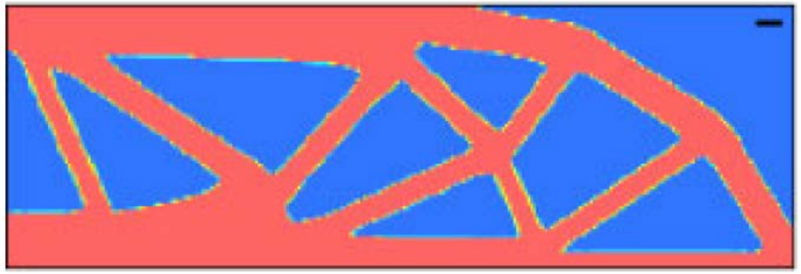
Outline

- Geometric feature control by **density filters**
- Geometric feature control by **alternative parameterizations**

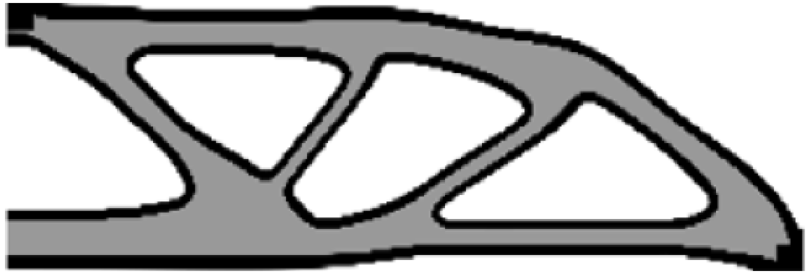
Geometric feature control by density filters
(An incomplete list)

Reference

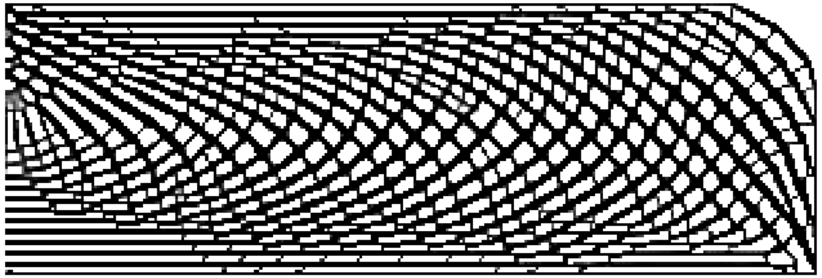
Minimum feature size, Guest'04



Coating structure, Clausen'15

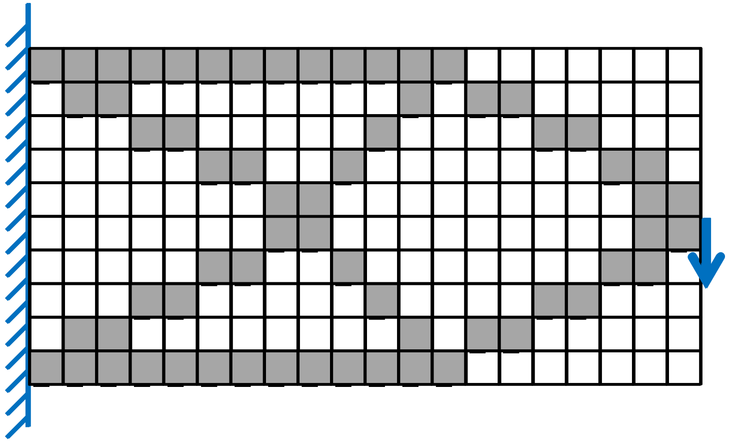


Self-supporting design, Langelaar'16



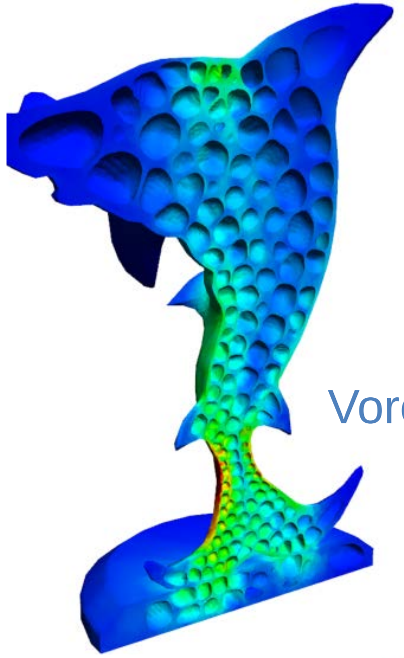
Porous infill, Wu'16

Geometric feature control by alternative parameterizations (An incomplete list)

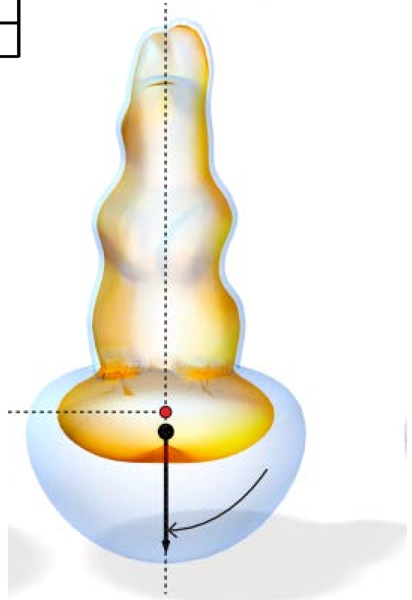


Reference: Voxel discretization

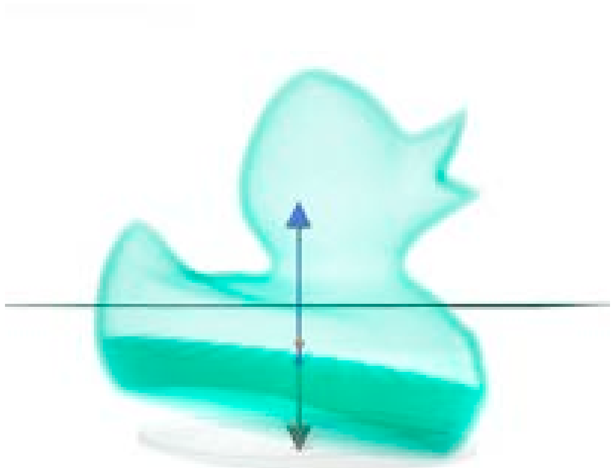
Skin-frame, Wang'13



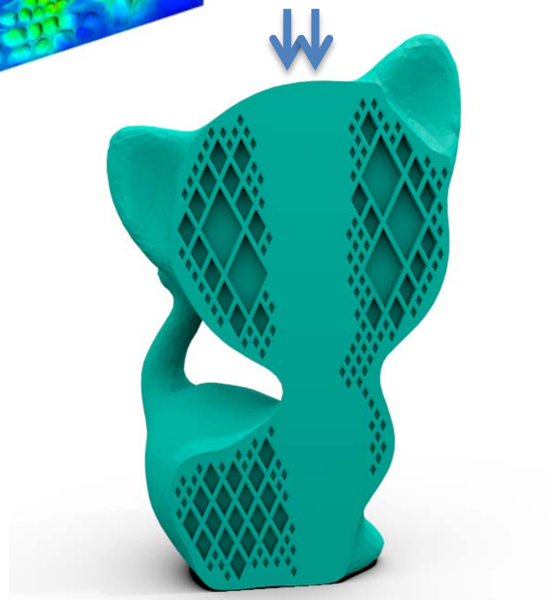
Voronoi cells, Lu'14



Offset surfaces, Musialski'15



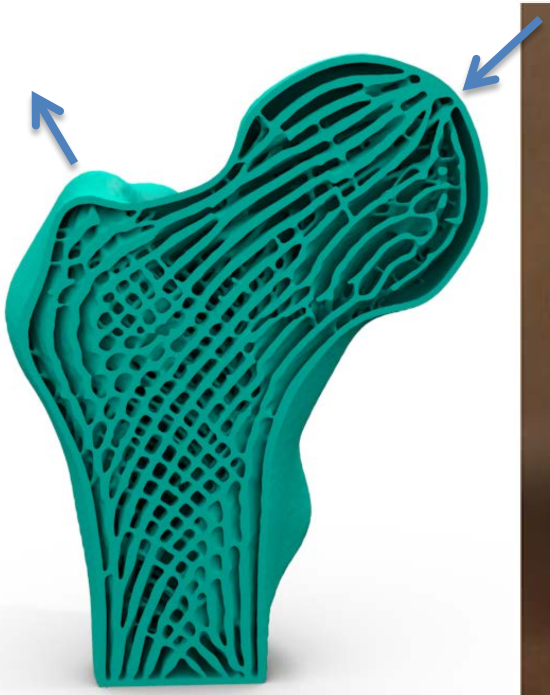
Ray representation, Wu'16



Adaptive rhombic, Wu'16

Outline

- Geometric feature control by **density filters**
- Geometric feature control by **alternative parameterizations**

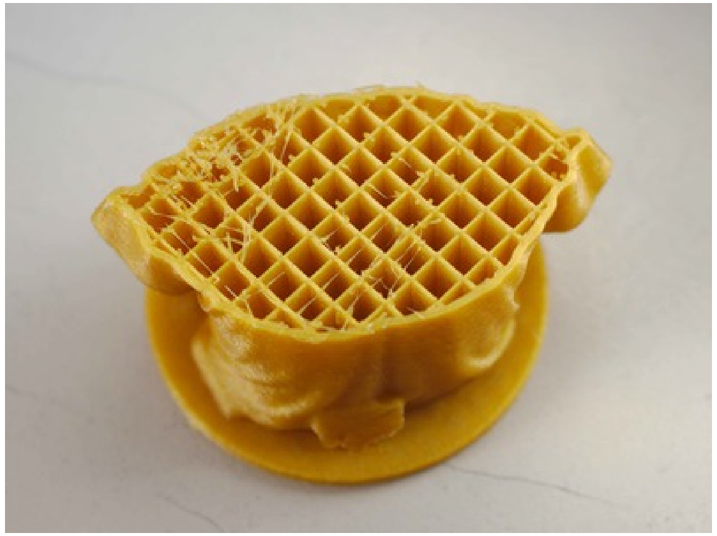



Bone-inspired infill

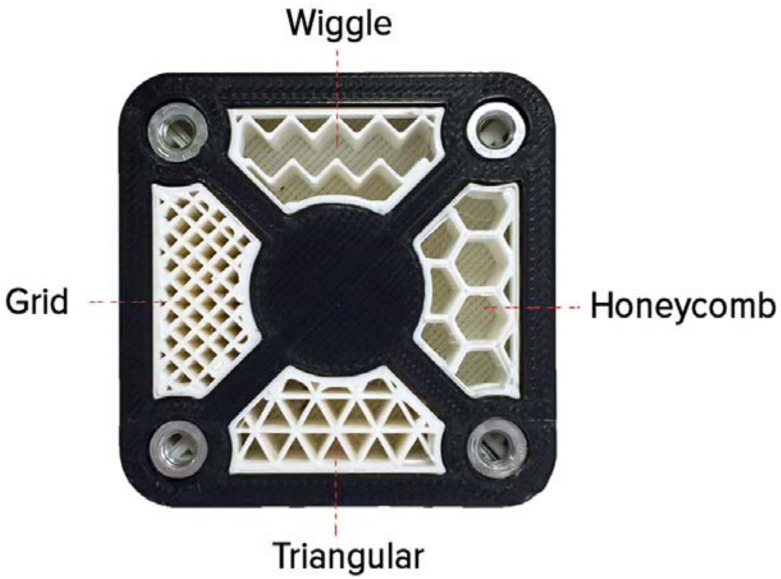

Self-supporting infill

Infill in 3D Printing

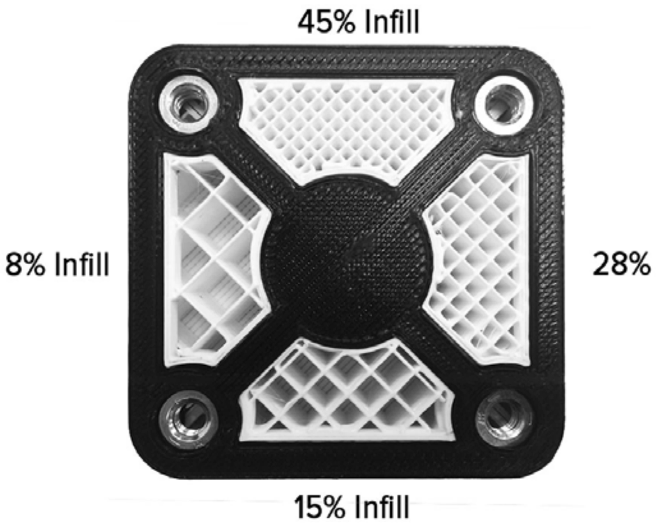
- A user-selected regular pattern, with a volume percentage
- A rough balance between
  - Physical properties (mass, strength), and
  - Cost (material usage, print time)



Infill



Different infill patterns

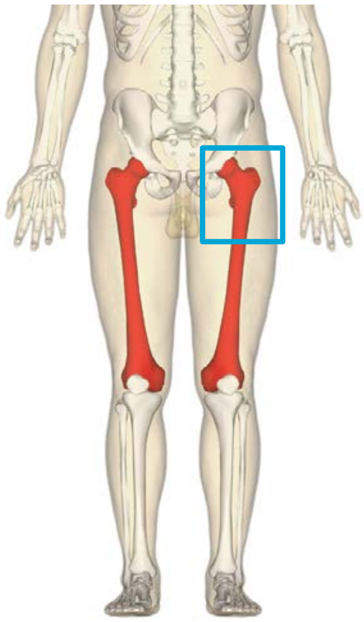


Different infill percentages

https://3dplatform.com/3d-printing-tips-infill-percentage-and-pattern-explained/

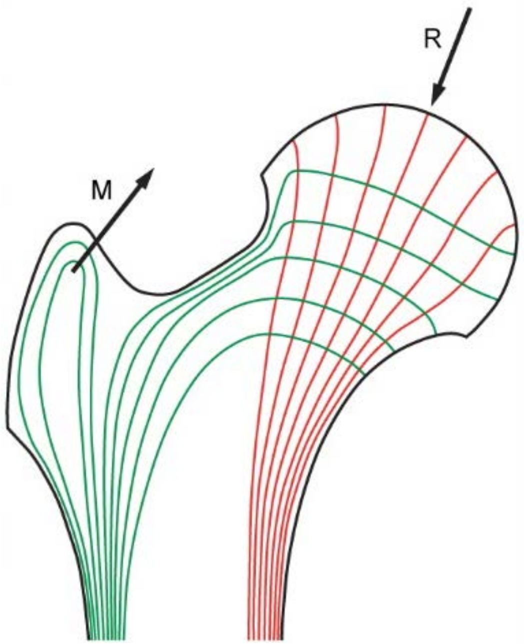
Infill in Nature

- Trabecular bone
  - Porous structures, oriented with the principle stress direction
  - Resulted from a natural optimization process
  - Light-weight-high-resistant



wikipedia.org

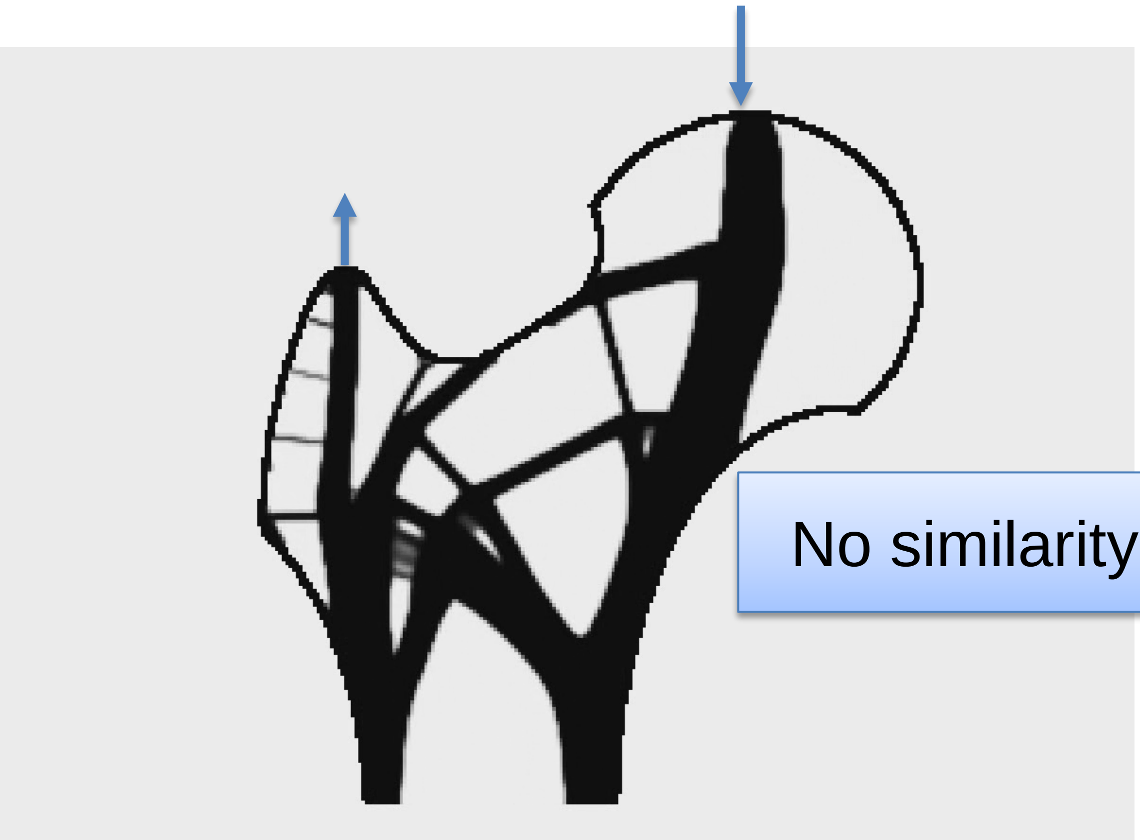
Cross-section of
a human femur



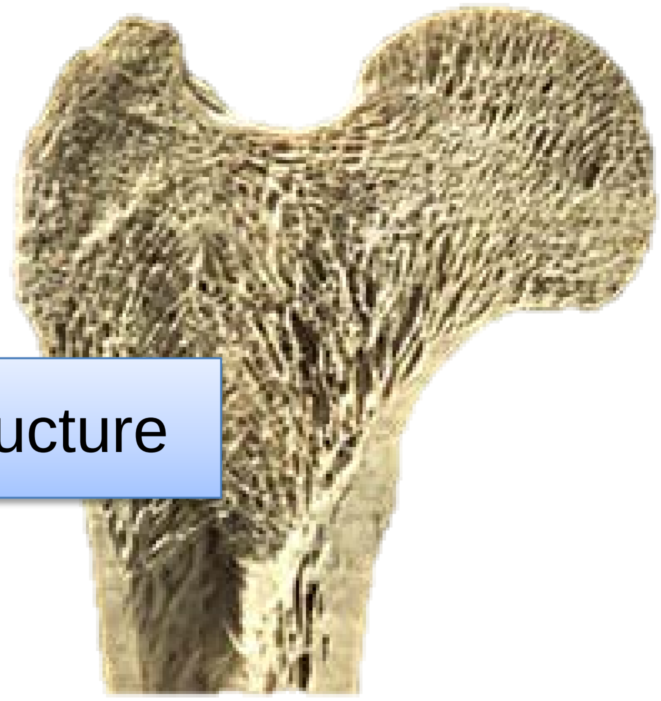
Principle stress directions

Optimize bone-like structures as infill for AM?

Topology Optimization Applied to Design Infill



Topology optimization

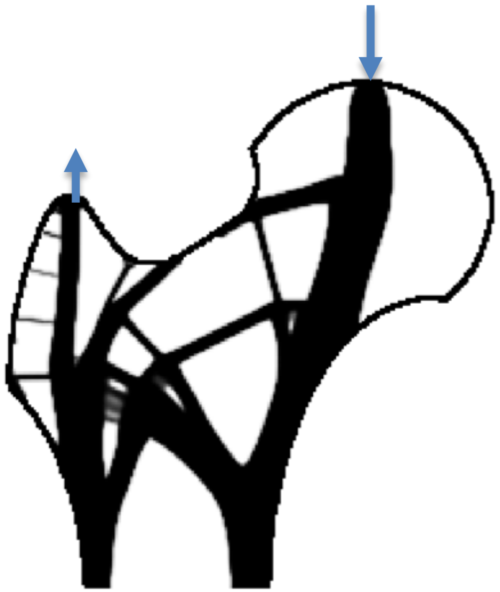


Infill in the bone

No similarity in structure

Topology Optimization Applied to Design Infill

- Materials accumulate to “important” regions
- The total volume $\sum_i \rho_i v_i \leq V_0$ does not restrict local material distribution



Infill by standard topology optimization

Infill in the bone

Approaching Bone-like Structures: The Idea

- Impose **local constraints** to avoid fully solid regions

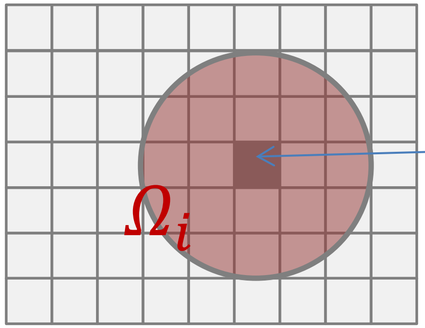
Min: $c = \frac{1}{2} U^T K U$

s.t. : $KU = F$

$\rho_i \in [0,1], \forall i$

~~$\sum_i \rho_i \le V_0$~~

$\hat{\rho}_i \le \alpha, \forall i$



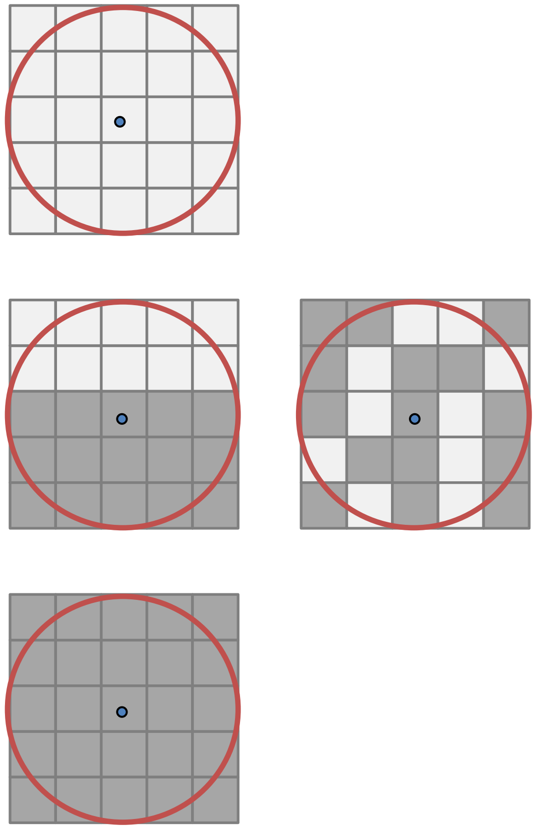
$$\hat{\rho}_i = \frac{\sum_{j \in \Omega_i} \rho_j}{\sum_{j \in \Omega_i} 1}$$

Local-volume measure

$\hat{\rho}_i = 0.0$

$\hat{\rho}_i = 0.6$

$\hat{\rho}_i = 1.0$



Constraints Aggregation (Reduce the Number of Constraints)

$\hat{\rho}_i \leq \alpha, \forall i$ ⟺ $\max_{i=1,\ldots,n} |\hat{\rho}_i| \leq \alpha$ ⟺ $\lim_{p \to \infty} \|\rho\|_p = \left(\sum_i (\hat{\rho}_i)^p\right)^{\frac{1}{p}} \leq \alpha$

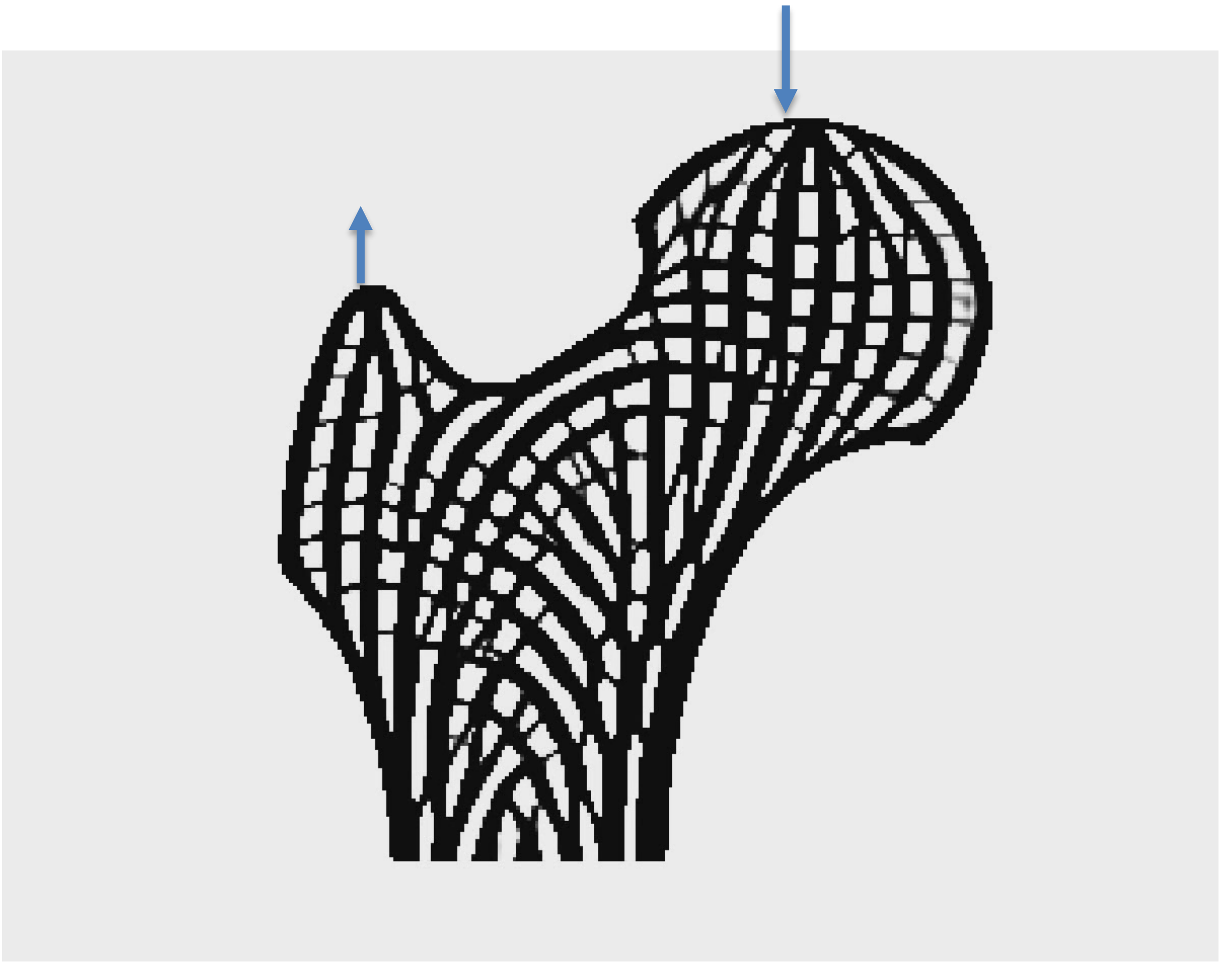
Too many constraints!

A single constraint
But non-differentiable

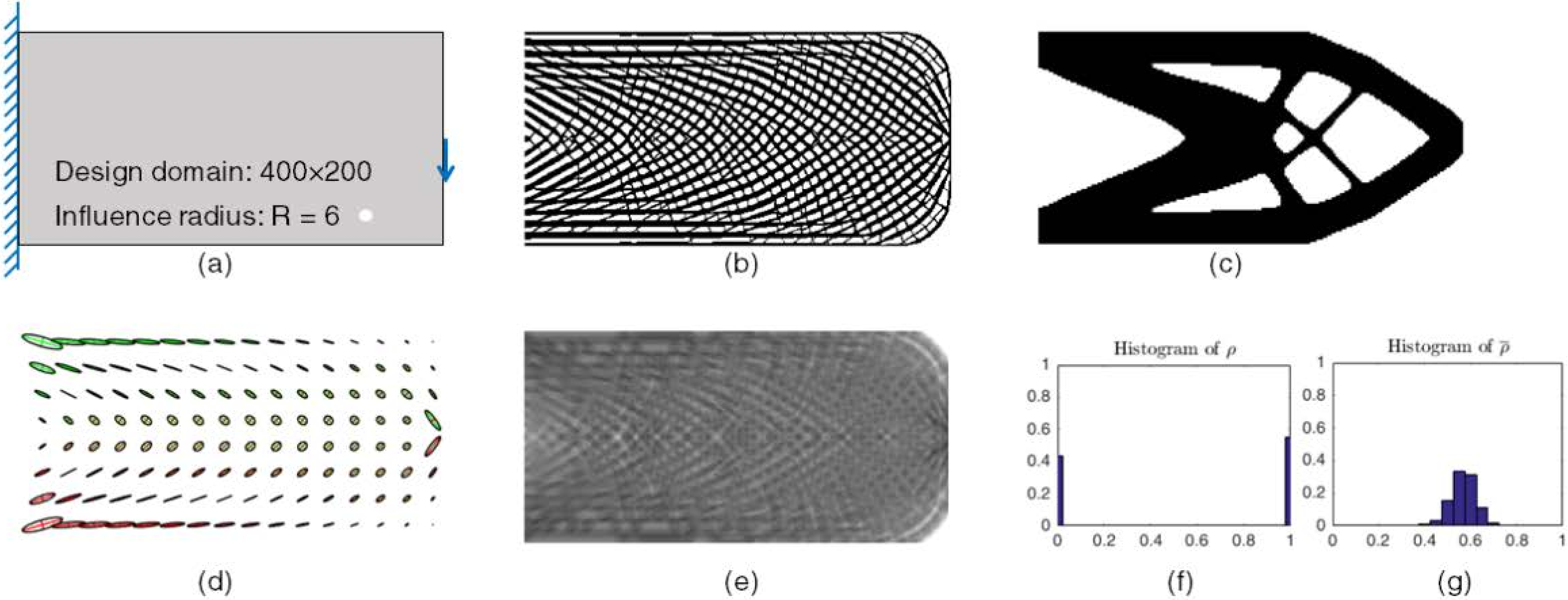
A single constraint
and differentiable
Approximated with p =16

Bone-like Infill in 2D

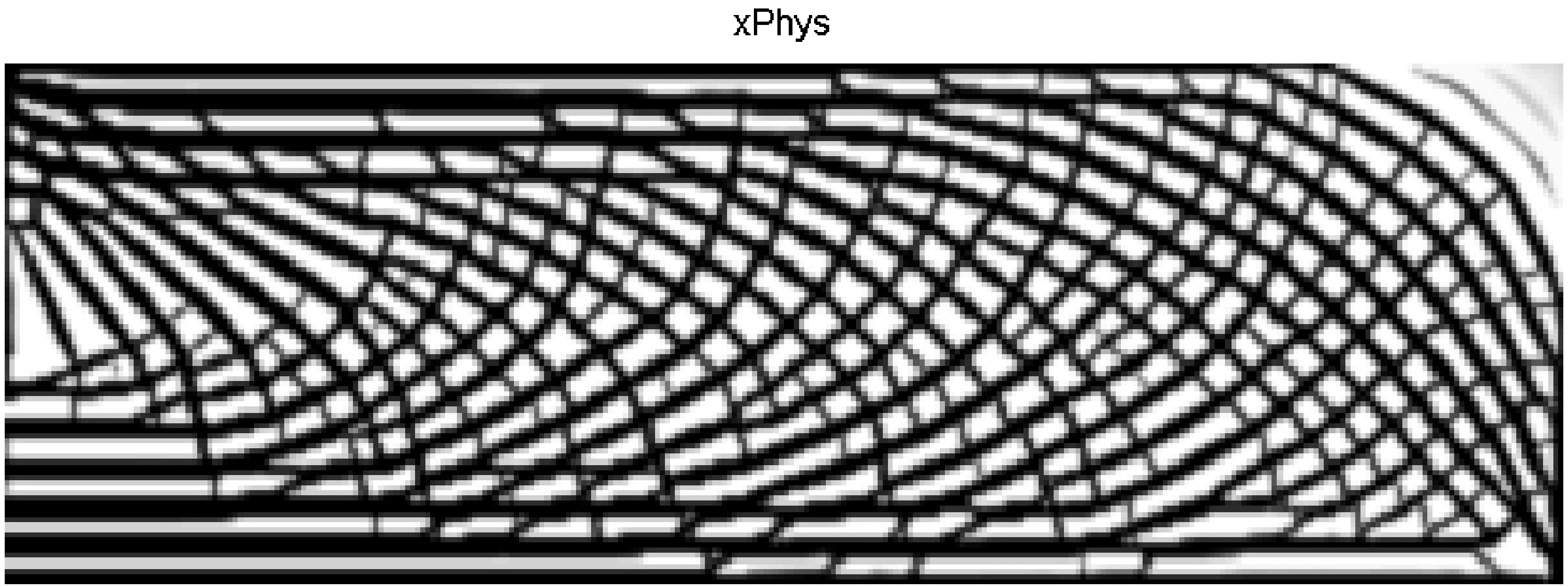
Cross-section of a human femur



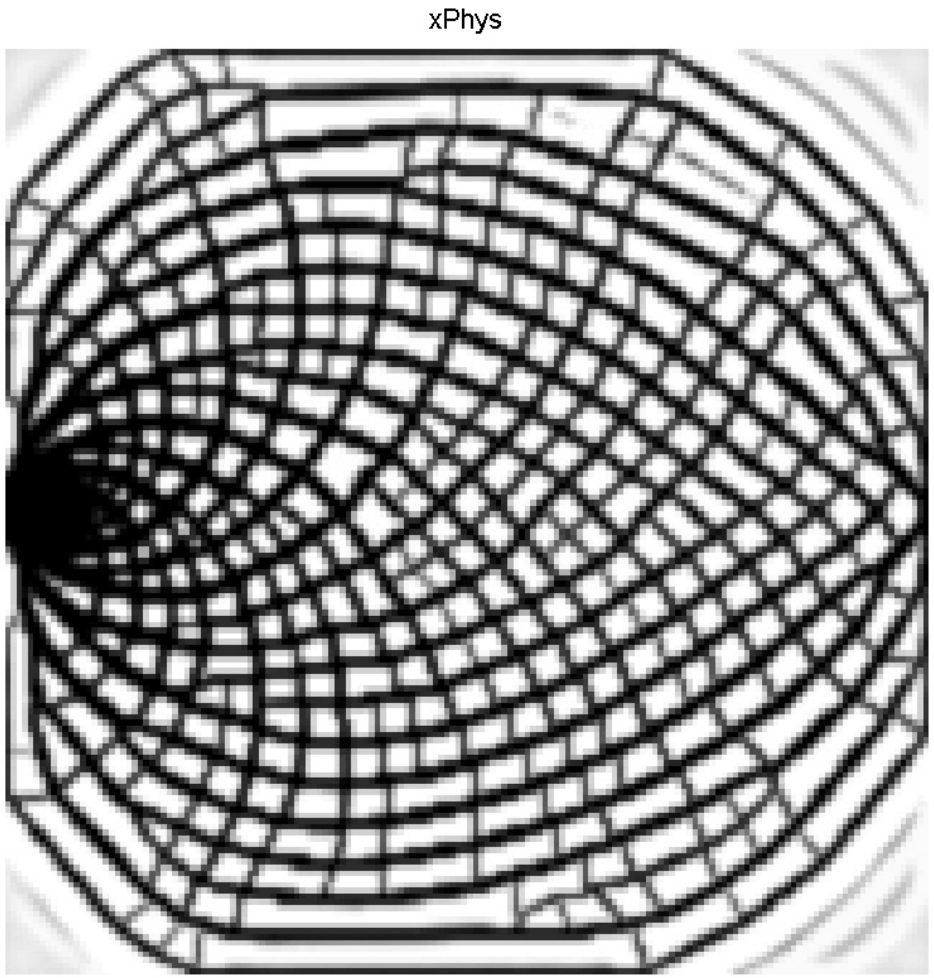
A Test Example



Result: 2D Animation



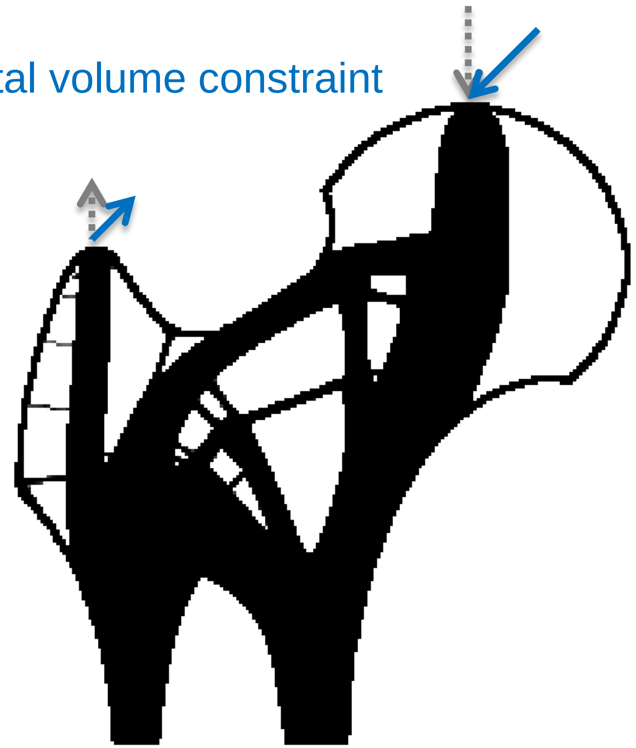
Result: 2D Animation



Robustness wrt. Force Variations

- Bone-like structures are significantly stiffer (126%) in case of force variations

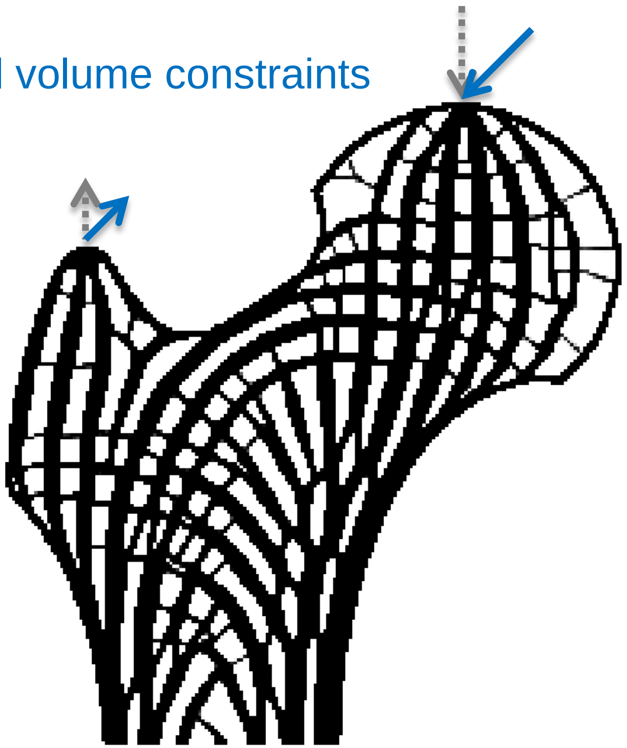
Total volume constraint



c = 30.54

c’= 45.83

Local volume constraints



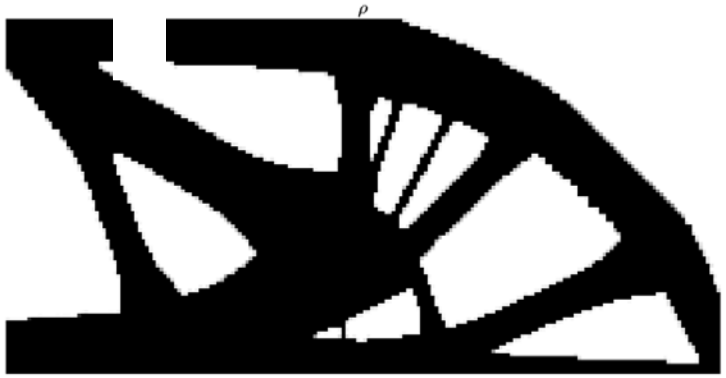
c = 36.72

c’ =36.23

Robustness wrt. Material Deficiency

- Bone-like structures are significantly stiffer (180%) in case of material deficiency

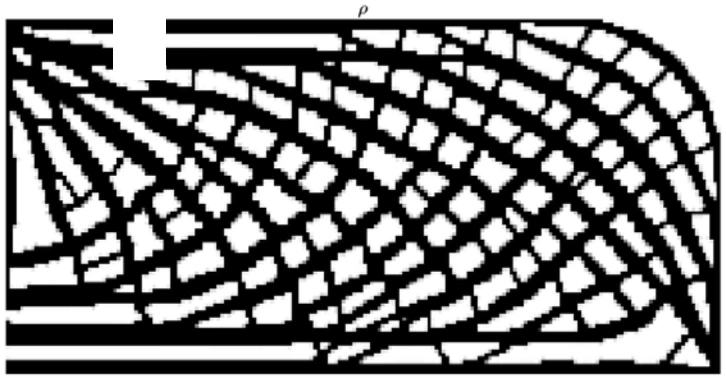
Total volume constraint



c = 76.83

c' =242.77

Local volume constraints

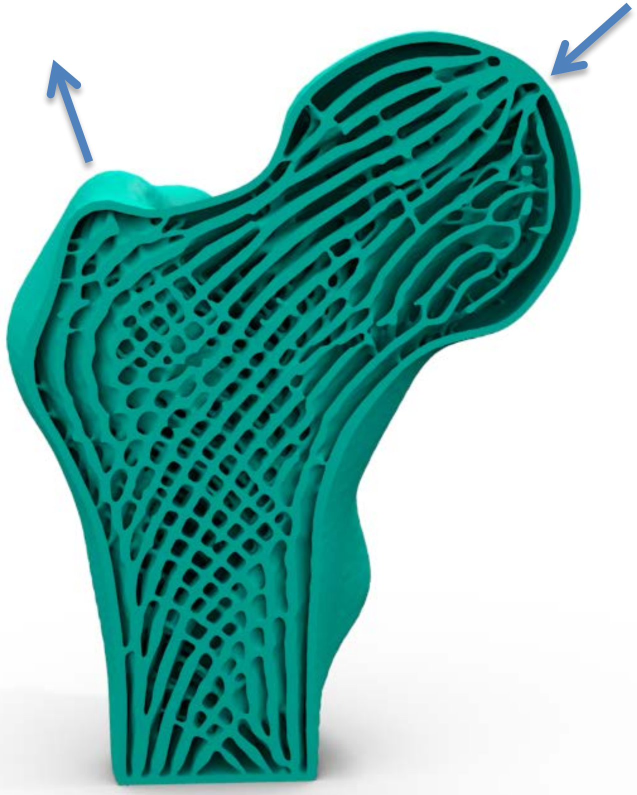


c = 93.48

c'= 134.84

Bone-like Infill in 3D

Infill in the bone

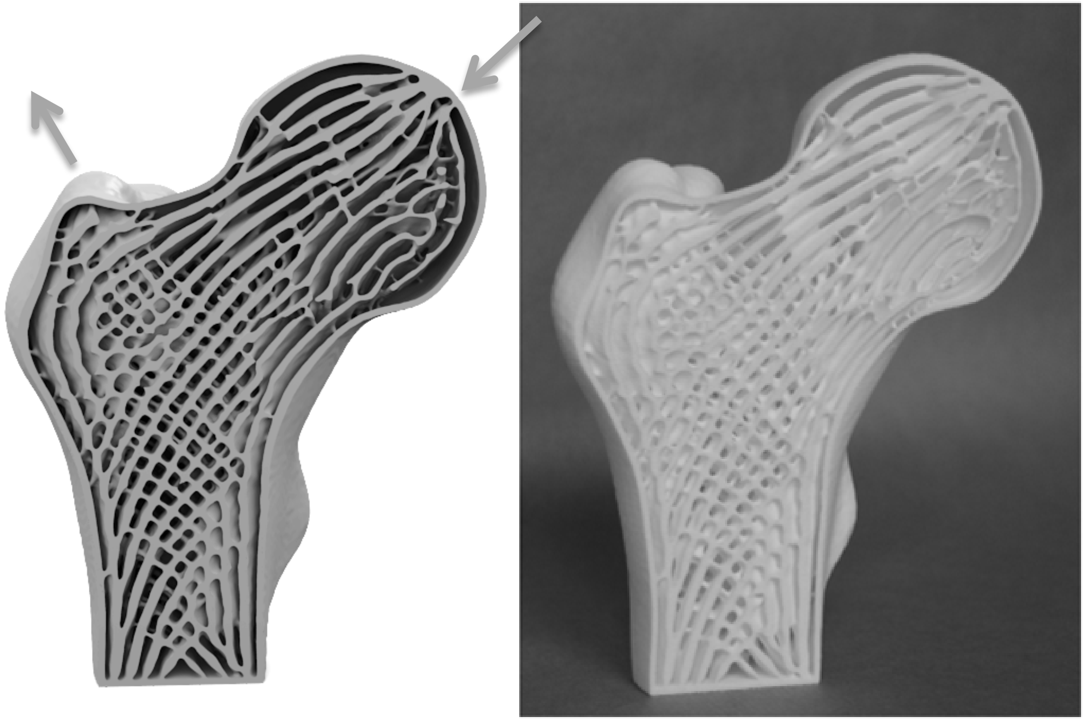


Optimized bone-like infill

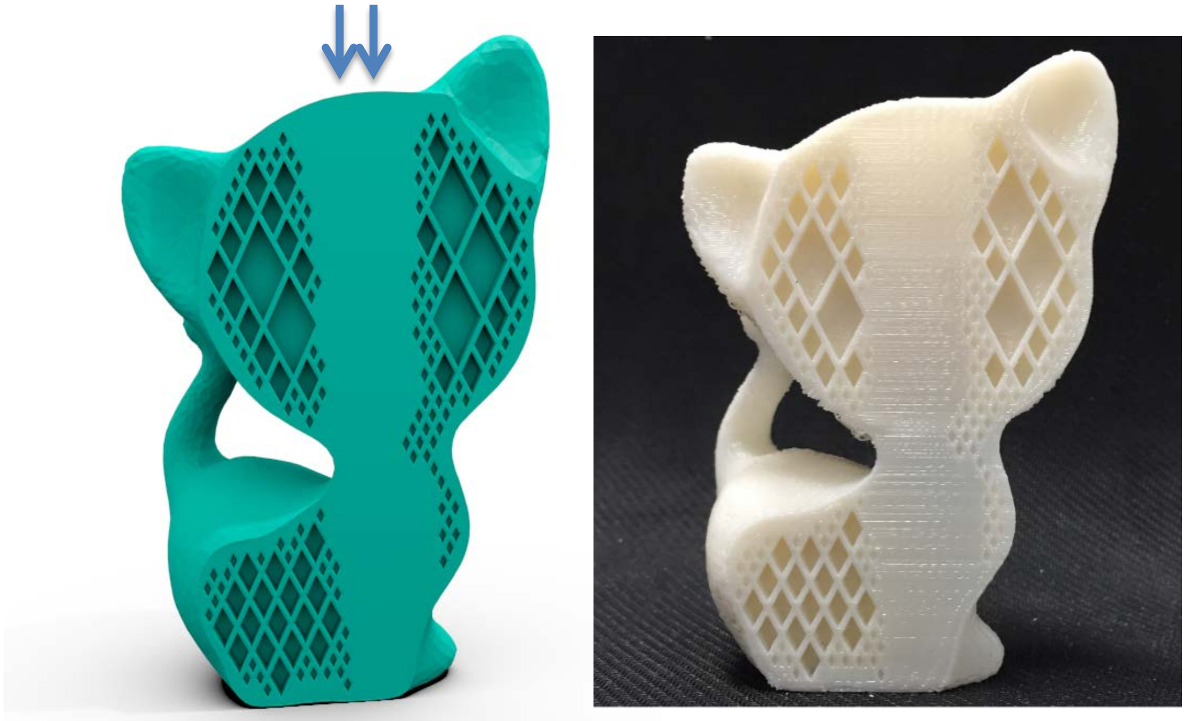
Wu et al., TVCG'2017

Outline

- Geometric feature control by **density filters**
- Geometric feature control by **alternative parameterizations**



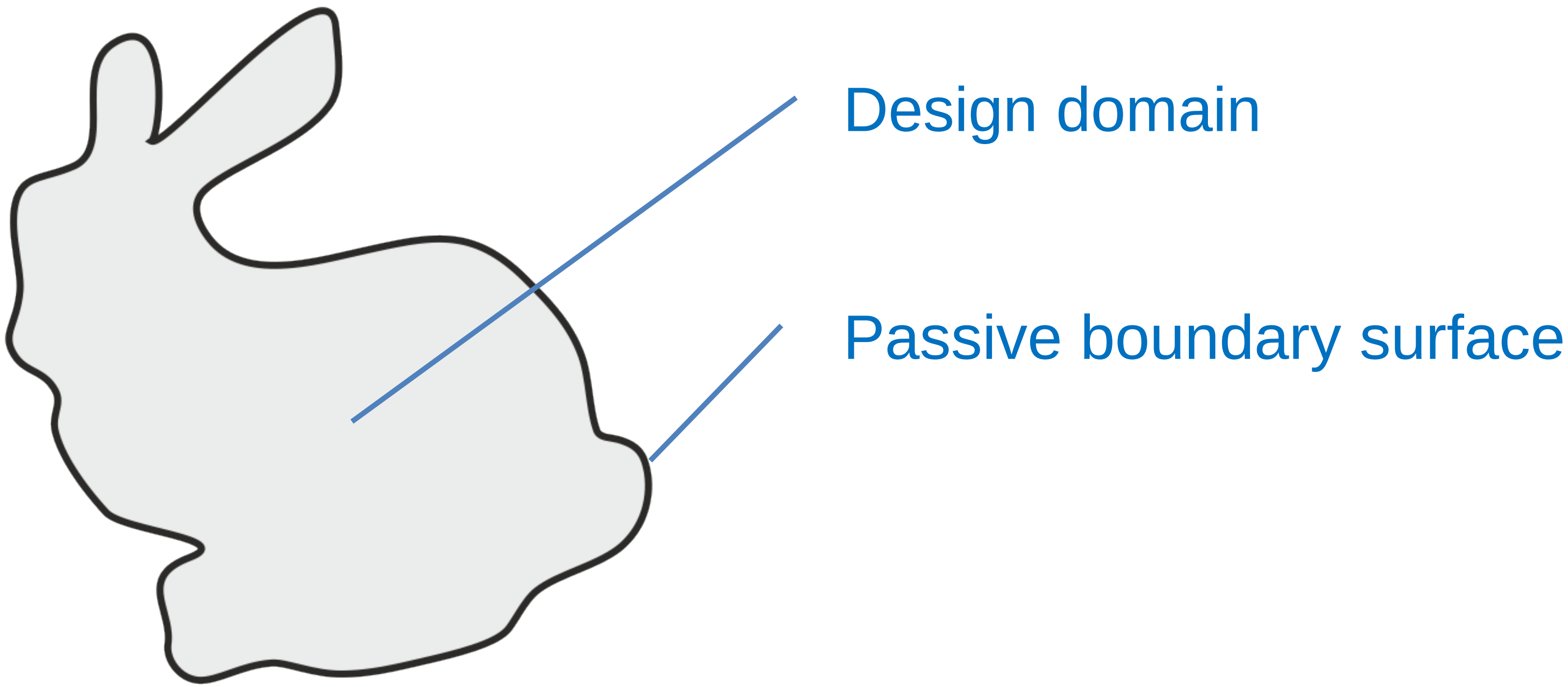
Bone-inspired infill



Self-supporting infill

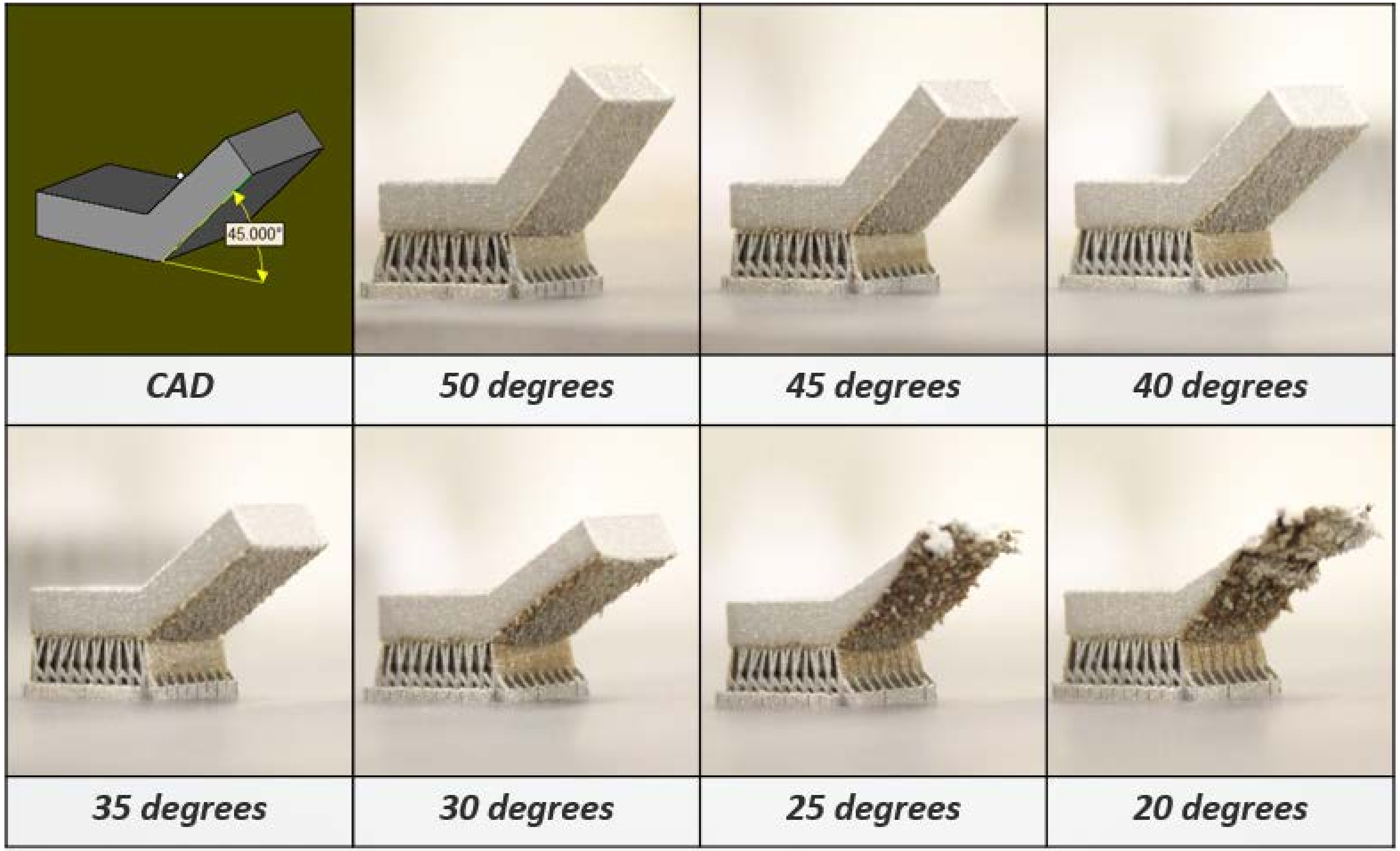
Infill Optimization

- To find the optimal material distribution in the interior of a given shape



Overhang in Additive Manufacturing

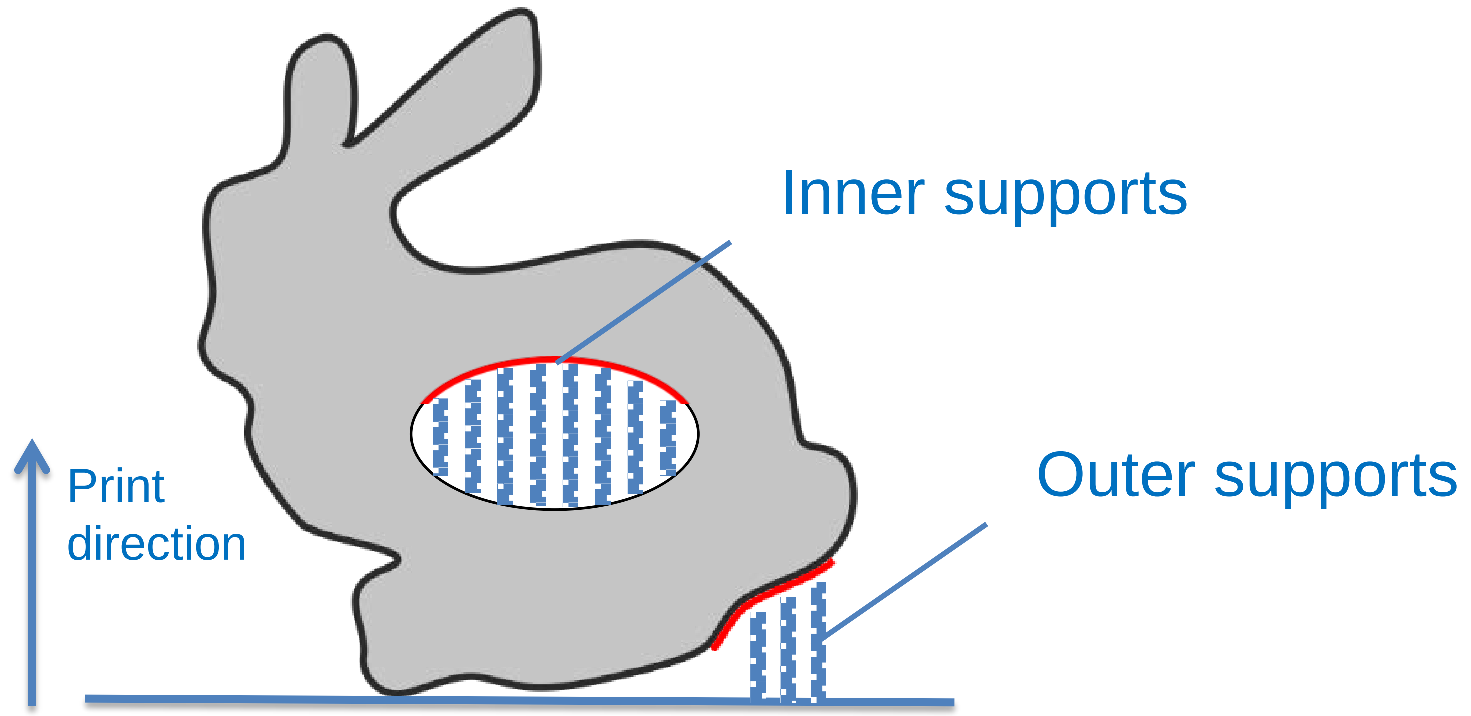
- Support structures are needed beneath overhang surfaces



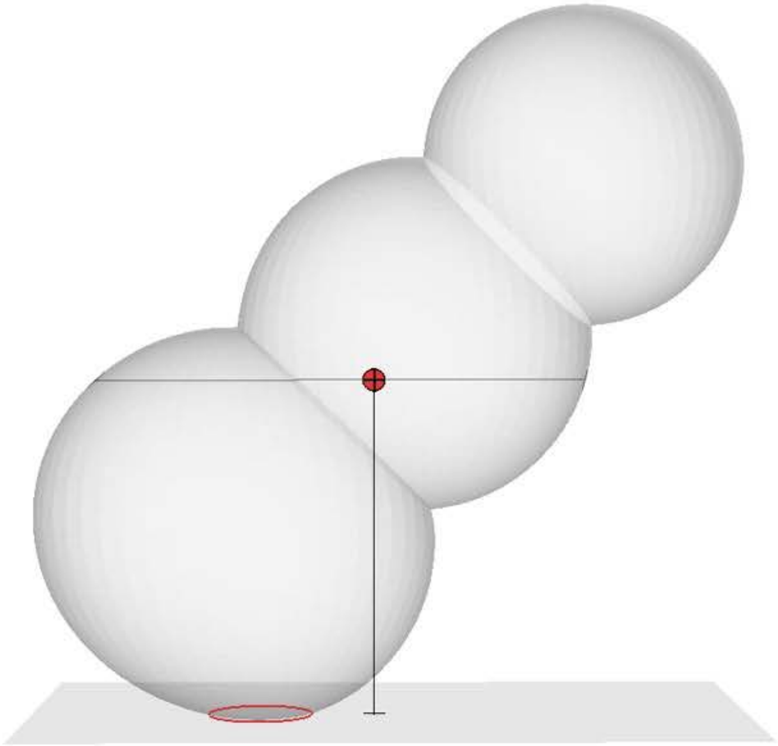
https://www.protolabs.com/blog/tag/direct-metal-laser-sintering/

Support Structures in Cavities

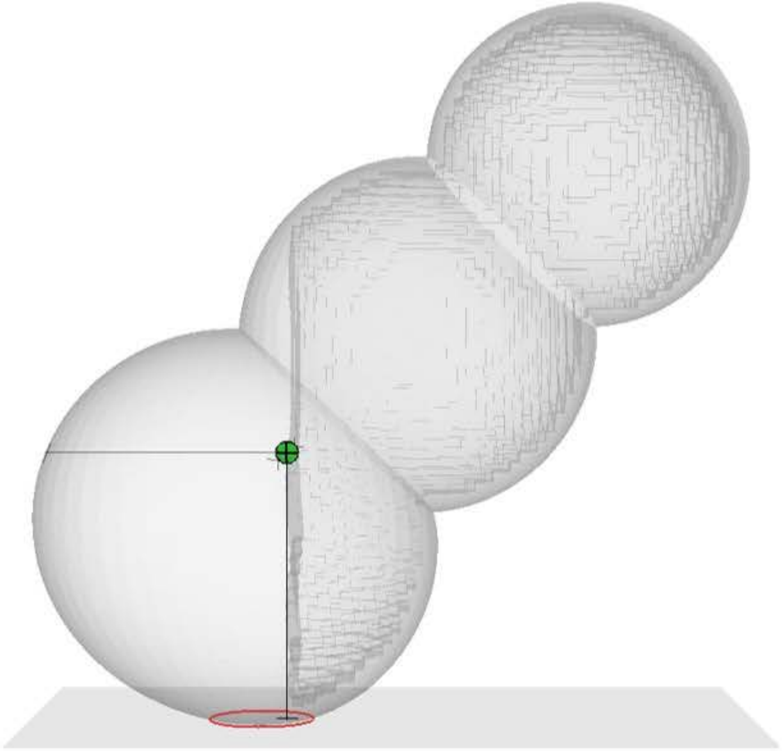
- Post-processing of inner supports is problematic



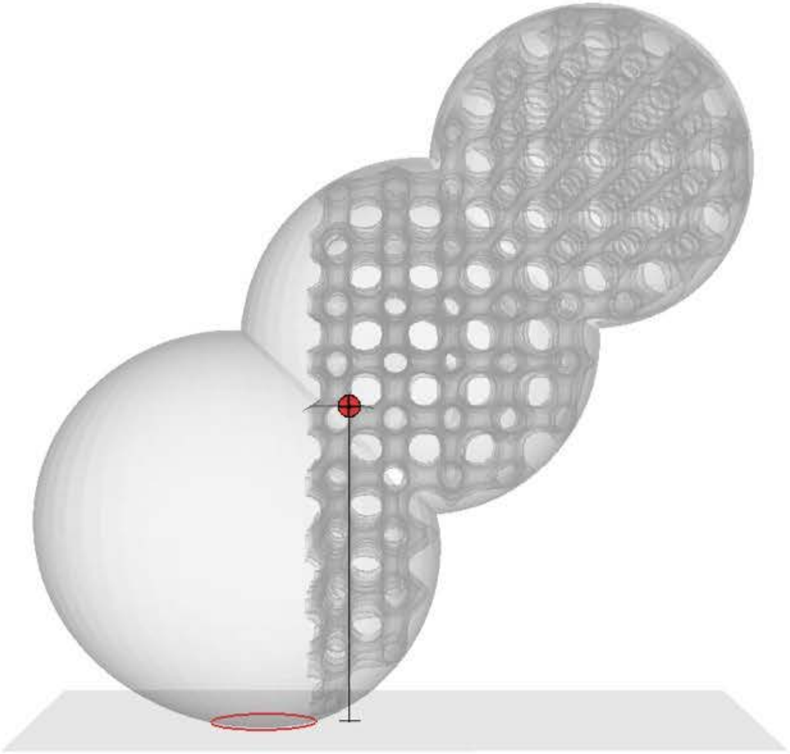
Infill & Optimization Shall Integrate



Solid,
Unbalanced



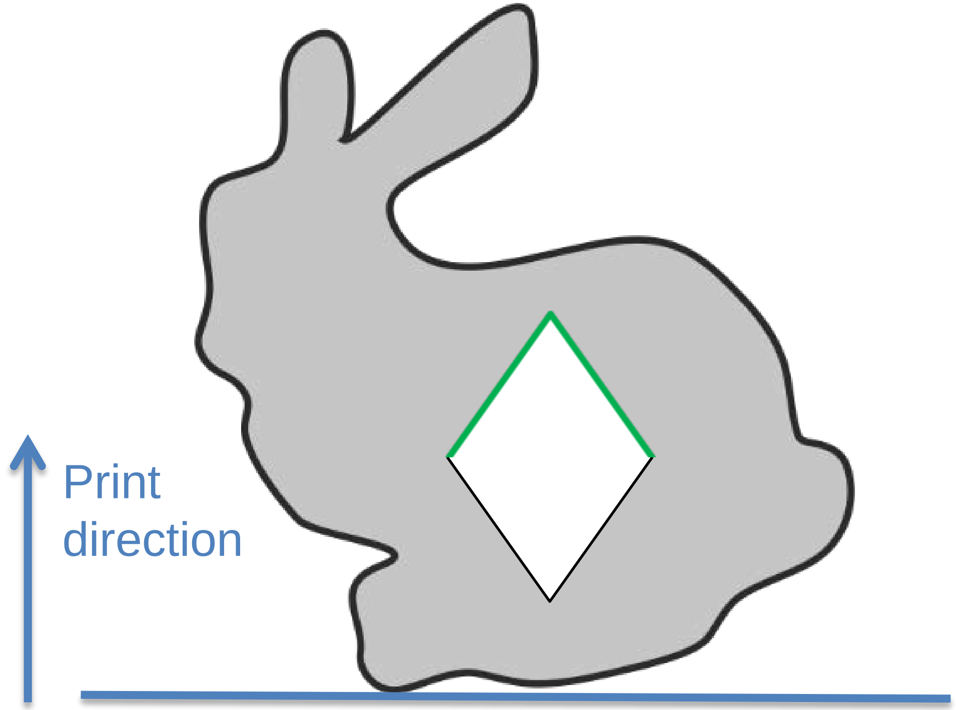
Optimized,
Balanced



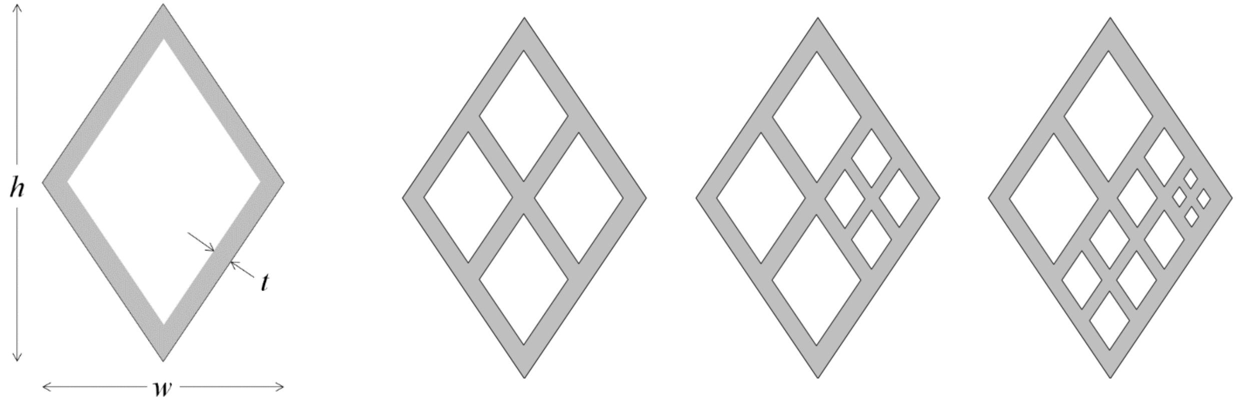
With infill,
Unbalanced

The Idea

- Rhombic cell: to ensure self-supporting
- Adaptive subdivision: as design variable in optimization

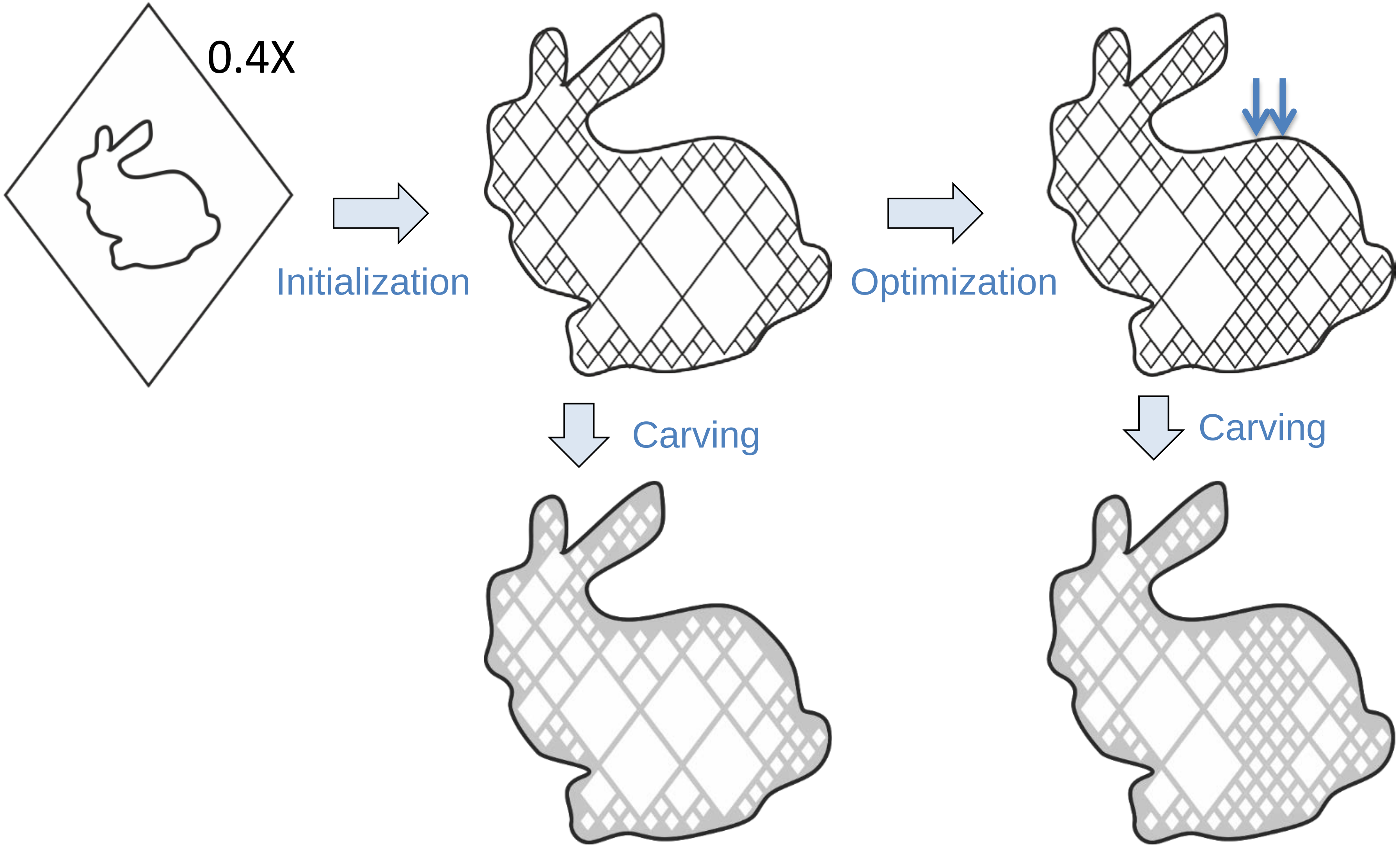


Rhombic cell



Adaptive subdivision

Self-Supporting Rhombic Infill: Workflow



Self-Supporting Rhombic Infill: Subdivision Criteria

- Min: $c = \frac{1}{2} U^T K U$ Subject to: $KU = F; V = \sum_i \rho_i \leq V_0$

Voxel-wise topology optimization

Per-voxel density as variable

$$\rho_i \in \{0.0, 1.0\}, \forall i$$

Per-voxel sensitivity: $G_i = -\frac{\partial c / \partial \rho_i}{\partial V / \partial \rho_i}$

Subdivision-based topology optimization

Per-subdivision as variable

$$\beta_c \in \{0, 1\}, \forall c$$

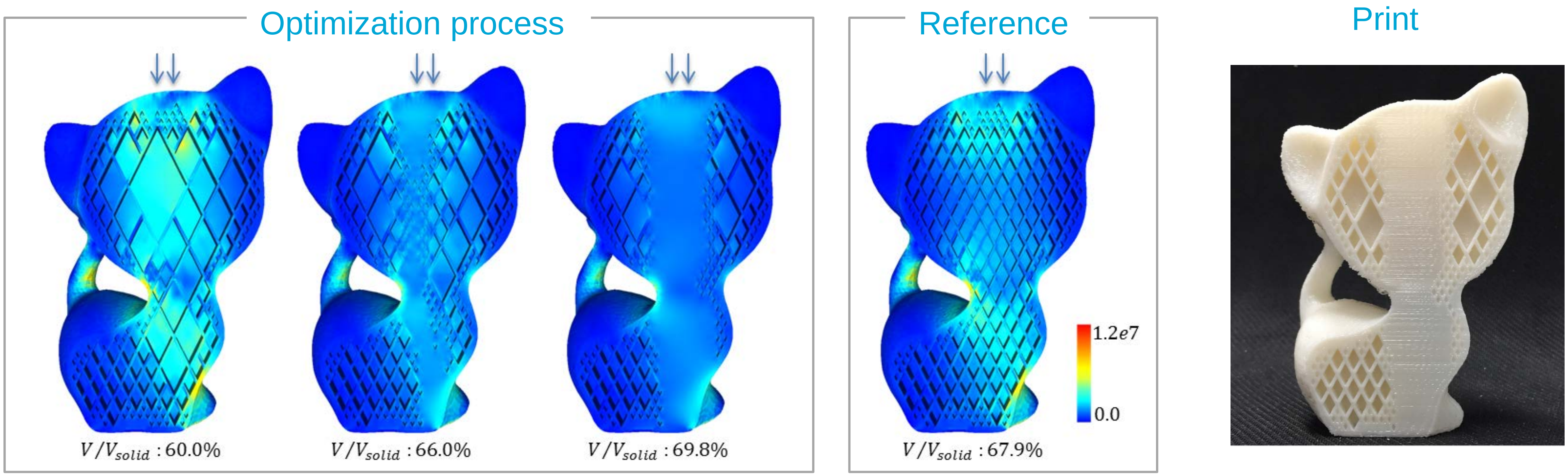
Per-voxel density assigned by subdivision

$$\rho_i(\beta) = \begin{cases} 1.0 & i \text{ covered by walls} \\ 0.0 & \text{otherwise} \end{cases}$$

Per-subdivision sensitivity: $G_c = -\frac{\partial c / \partial \beta_c}{\partial V / \partial \beta_c}$

Self-Supporting Rhombic Infill: Results

- Optimized mechanical properties, compared to regular infill
- No additional inner supports needed

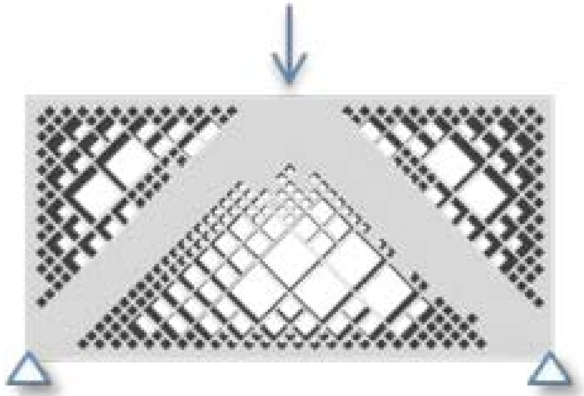


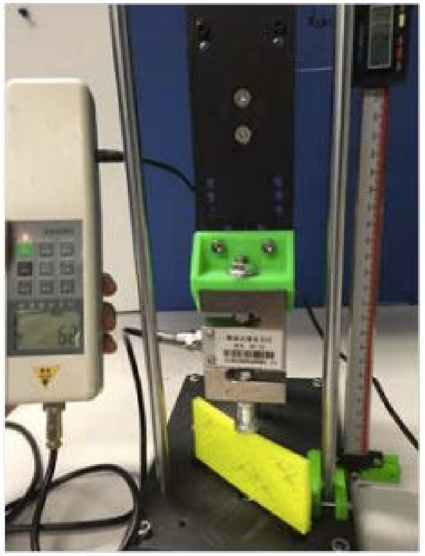
Wu et al., CAD’2016

Mechanical Tests

Under same force (62 N)

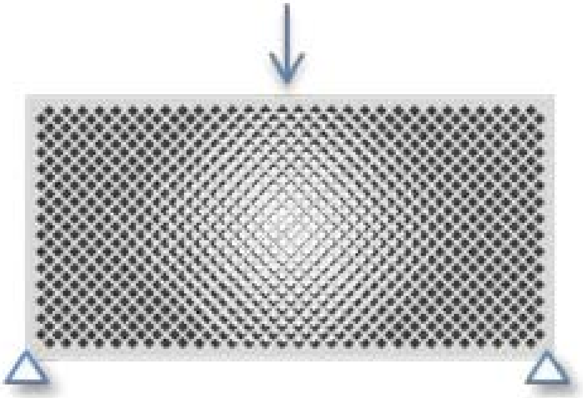
Under same displacement (3.0 mm)





Dis.
2.11 mm

Force
90 N



Dis.
4.08 mm

Force
58 N

Summary

- Geometric feature control by **density filters**
- Geometric feature control by **alternative parameterizations**

Thank you for your attention!

Questions?

Dr. Jun Wu
j.wu-1@tudelft.nl
Depart. of Design Engineering, TU Delft

Incomplete references: Density filters

- Guest, James K., Jean H. Prévost, and T. Belytschko. "Achieving minimum length scale in topology optimization using nodal design variables and projection functions." International journal for numerical methods in engineering 61, no. 2 (2004): 238-254.
- Wang, Fengwen, Boyan Stefanov Lazarov, and Ole Sigmund. "On projection methods, convergence and robust formulations in topology optimization." Structural and Multidisciplinary Optimization 43, no. 6 (2011): 767-784.
- Clausen, Anders, Niels Aage, and Ole Sigmund. "Topology optimization of coated structures and material interface problems." Computer Methods in Applied Mechanics and Engineering 290 (2015): 524-541.
- Langelaar, Matthijs. "An additive manufacturing filter for topology optimization of print-ready designs." Structural and Multidisciplinary Optimization (2016): 1-13.
- Wu, Jun, Niels Aage, Ruediger Westermann, and Ole Sigmund. "Infill Optimization for Additive Manufacturing--Approaching Bone-like Porous Structures." IEEE Transactions on Visualization and Computer Graphics, 2016.

Incomplete references: Alternative parameterizations

- Wang, Weiming, Tuanfeng Y. Wang, Zhouwang Yang, Ligang Liu, Xin Tong, Weihua Tong, Jiansong Deng, Falai Chen, and Xiuping Liu. "Cost-effective printing of 3D objects with skin-frame structures." ACM Transactions on Graphics (TOG) 32, no. 6 (2013): 177.
- Lu, Lin, Andrei Sharf, Haisen Zhao, Yuan Wei, Qingnan Fan, Xuelin Chen, Yann Savoye, Changhe Tu, Daniel Cohen-Or, and Baoquan Chen. "Build-to-last: Strength to weight 3d printed objects." ACM Transactions on Graphics (TOG) 33, no. 4 (2014): 97.
- Musialski, Przemyslaw, Thomas Auzinger, Michael Birsak, Michael Wimmer, and Leif Kobbelt. "Reduced-order shape optimization using offset surfaces." ACM Trans. Graph. 34, no. 4 (2015): 102.
- Wu, Jun, Lou Kramer, and Rüdiger Westermann. "Shape interior modeling and mass property optimization using ray-reps." Computers & Graphics 58 (2016): 66-72.
- Wu, Jun, Charlie CL Wang, Xiaoting Zhang, and Rüdiger Westermann. "Self-supporting rhombic infill structures for additive manufacturing." Computer-Aided Design 80 (2016): 32-42.

Topology Optimization

Minimize: $c = \frac{1}{2} U^T K U$

Subject to: $KU = F$

$\rho_i \in [0,1], \forall i$

$\sum_i \rho_i \leq V_0$