Mesh Optimization

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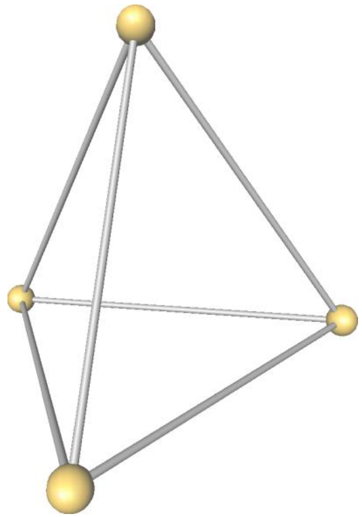
Goals

- 3D simplicial mesh generation
- optimize shape of elements
  - for matrix conditioning
  - isotropic
- control over sizing
  - dictated by simulation
  - constrained by boundary
  - low number of elements desired
    - more elements = slower solution time



Popular Meshing Approaches

- advancing front
- specific subdivision
  - octree
  - lattice (e.g. body centered cubic)
- Delaunay
  - refinement
  - sphere packing

combined with local optimizations

- spring energy
  - Laplacian
  - non-zero rest length
- aspect / radius ratios
- dihedral / solid angles
- max-min/min-max
  - volumes
  - edge lengths
  - containing sphere radii

[Freitag Amenta Bern Eppstein]

- sliver exudation

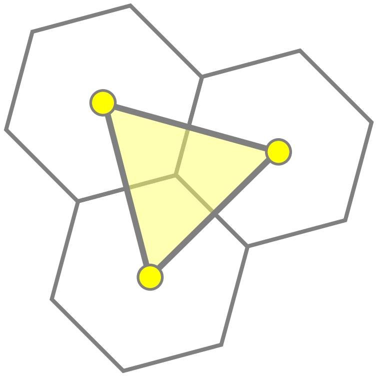
[Edelsbrunner Goy]

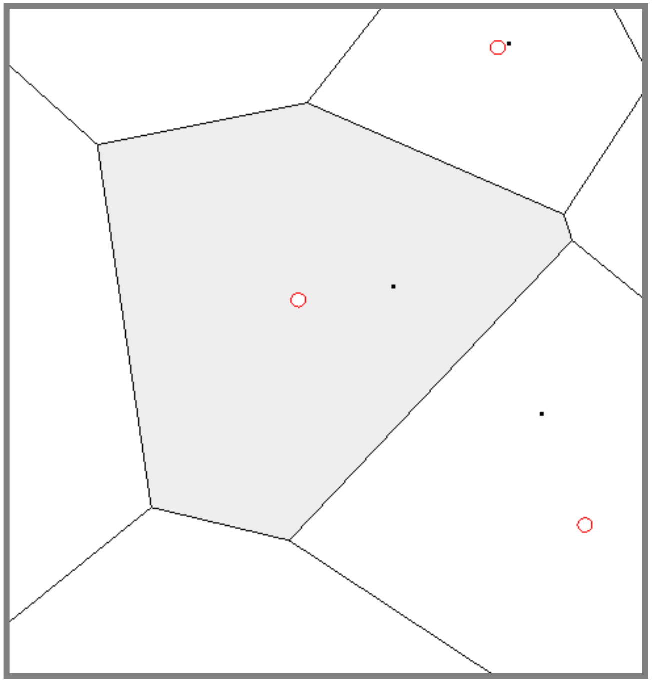
Variational?

- Design one energy function such that good solutions correspond to low energy ones (global minimum in general a mirage).
- Solutions found by optimization techniques.

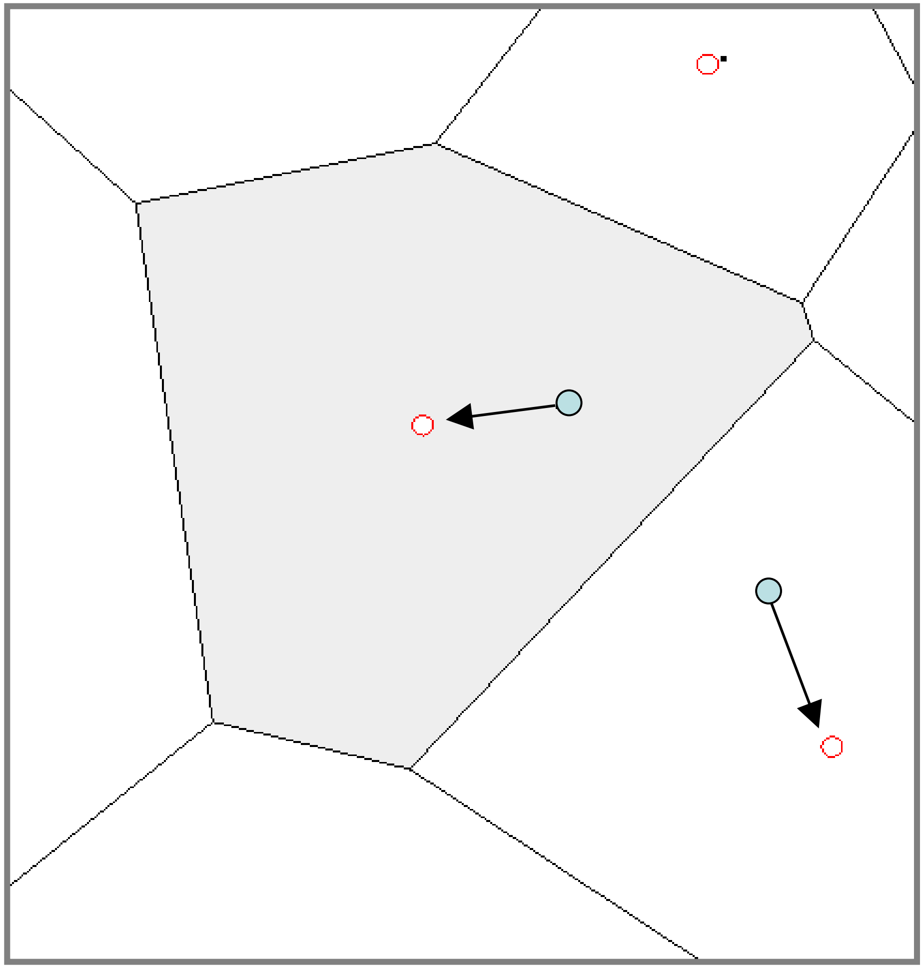
Example Energy in 2D

$$E = \sum_{j=1..k} \int_{x \in R_j} \| x - x_j \|^2 \, dx$$



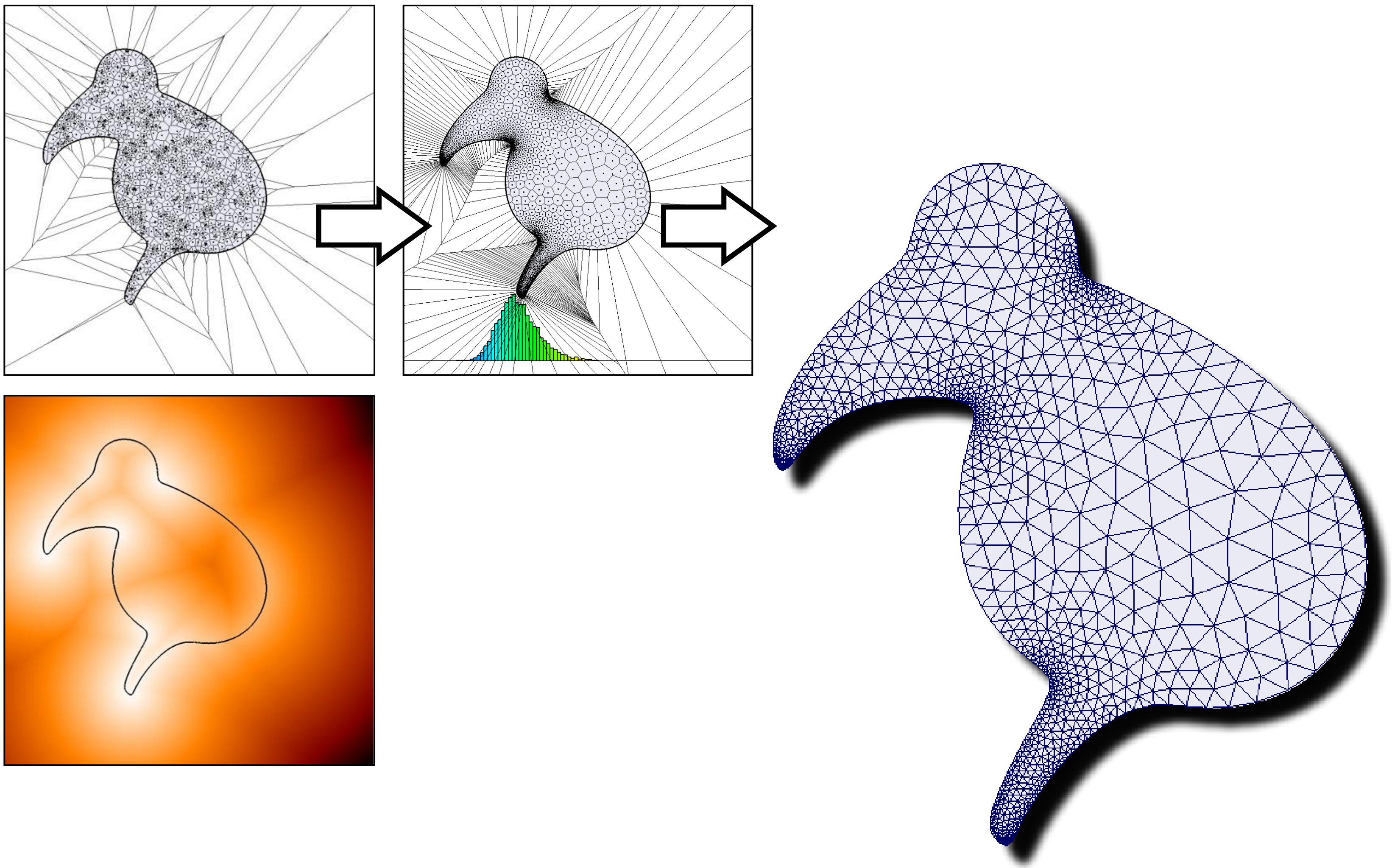


Lloyd Iteration

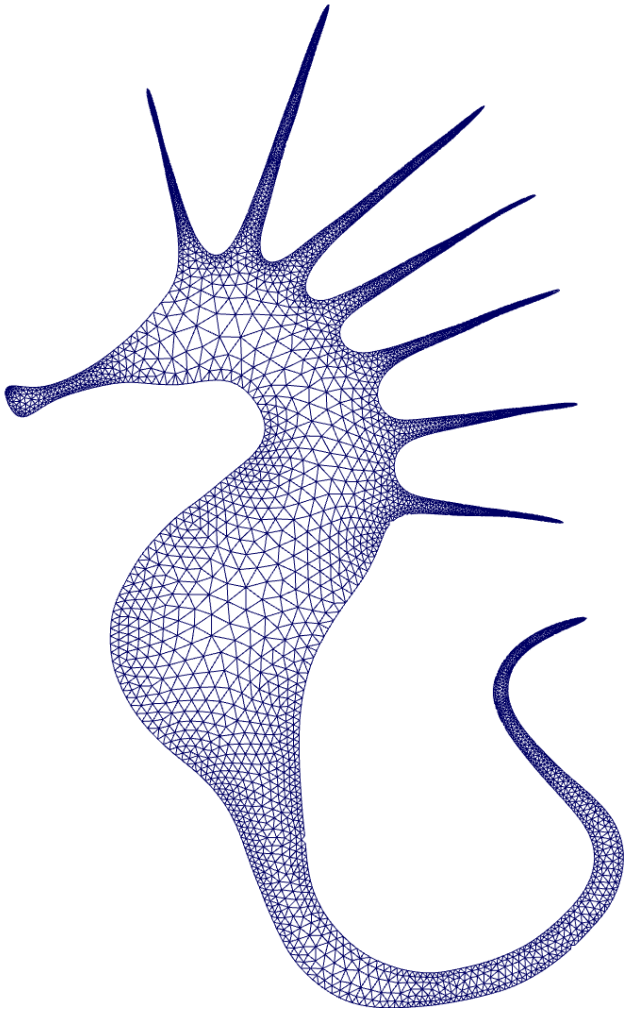


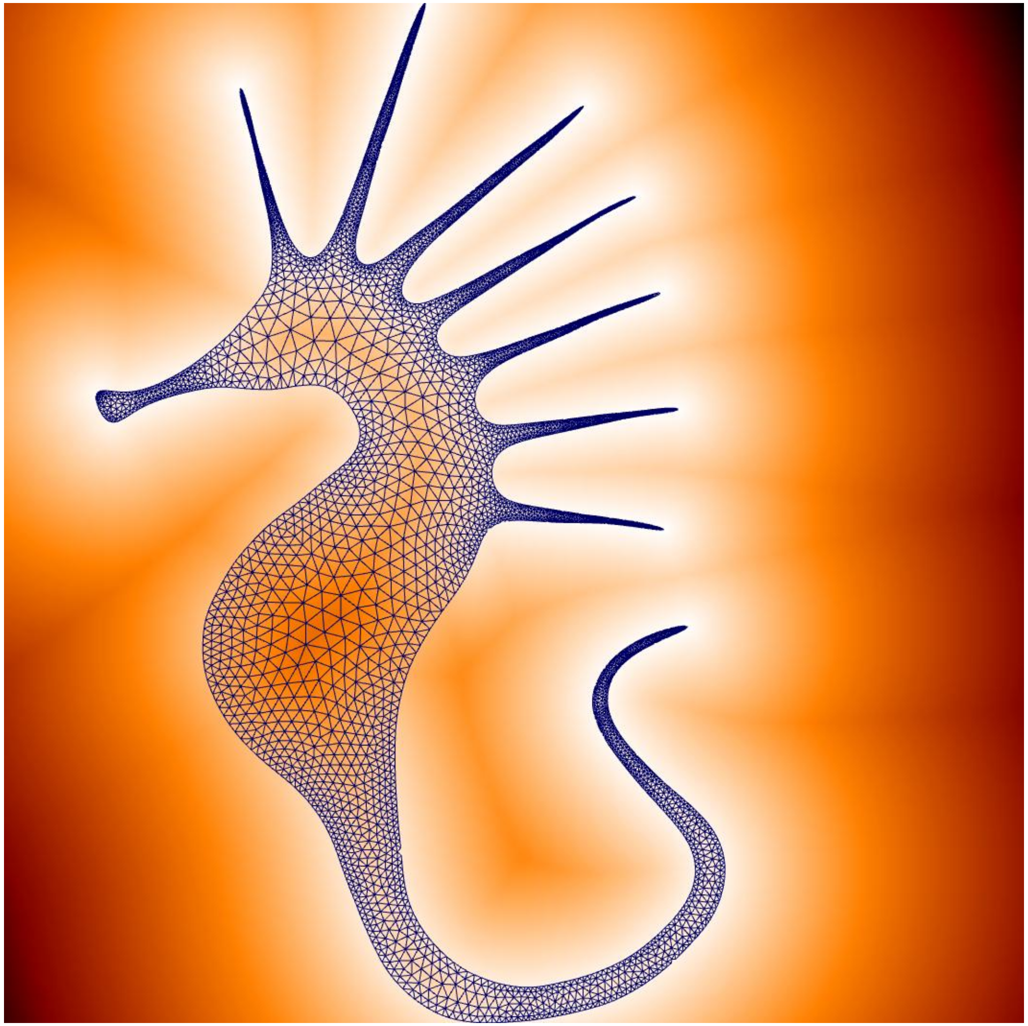
demo

2D Optimized Triangle Meshing



2D Optimized Triangle Meshing



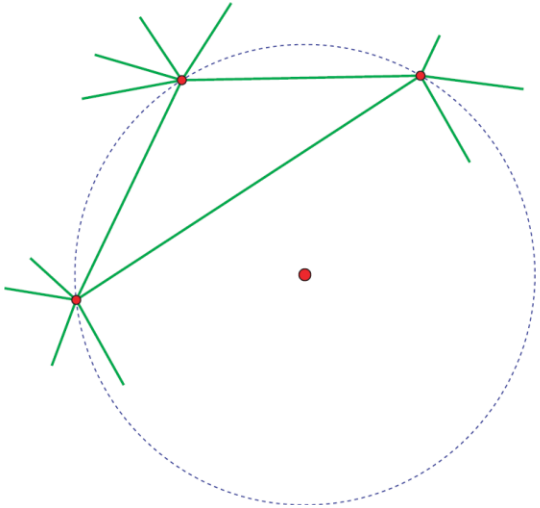


Delaunay refinement

Termination

- shape criterion: radius-edge ratio
- in 2D: max $\sqrt{2}$ (implies min 20.7°)
- in 3D: max 2 (nothing similar on dihedral angles)

[Chew, Ruppert, Shewchuk, ...]



Delaunay refinement

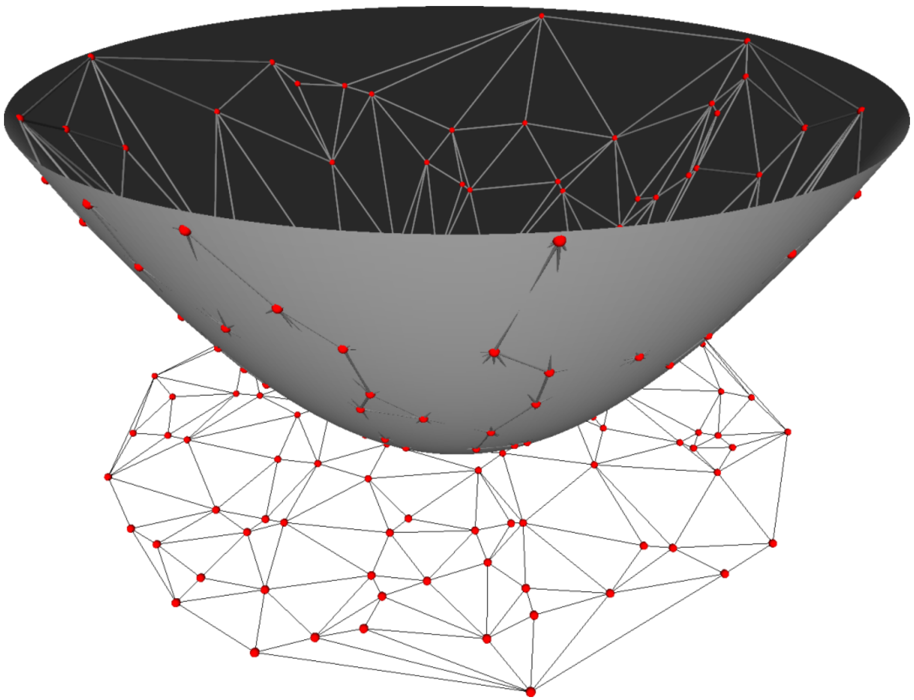
+ greedy (fast)
+ easy incorporation of sizing field
+ allows boundary conforming
  - possibly with Steiner points
  - even for sharp angles on boundary [Teng]
+ guaranteed bounds on radius-edge ratio

- blind to slivers
  - and experimentally...produces slivers

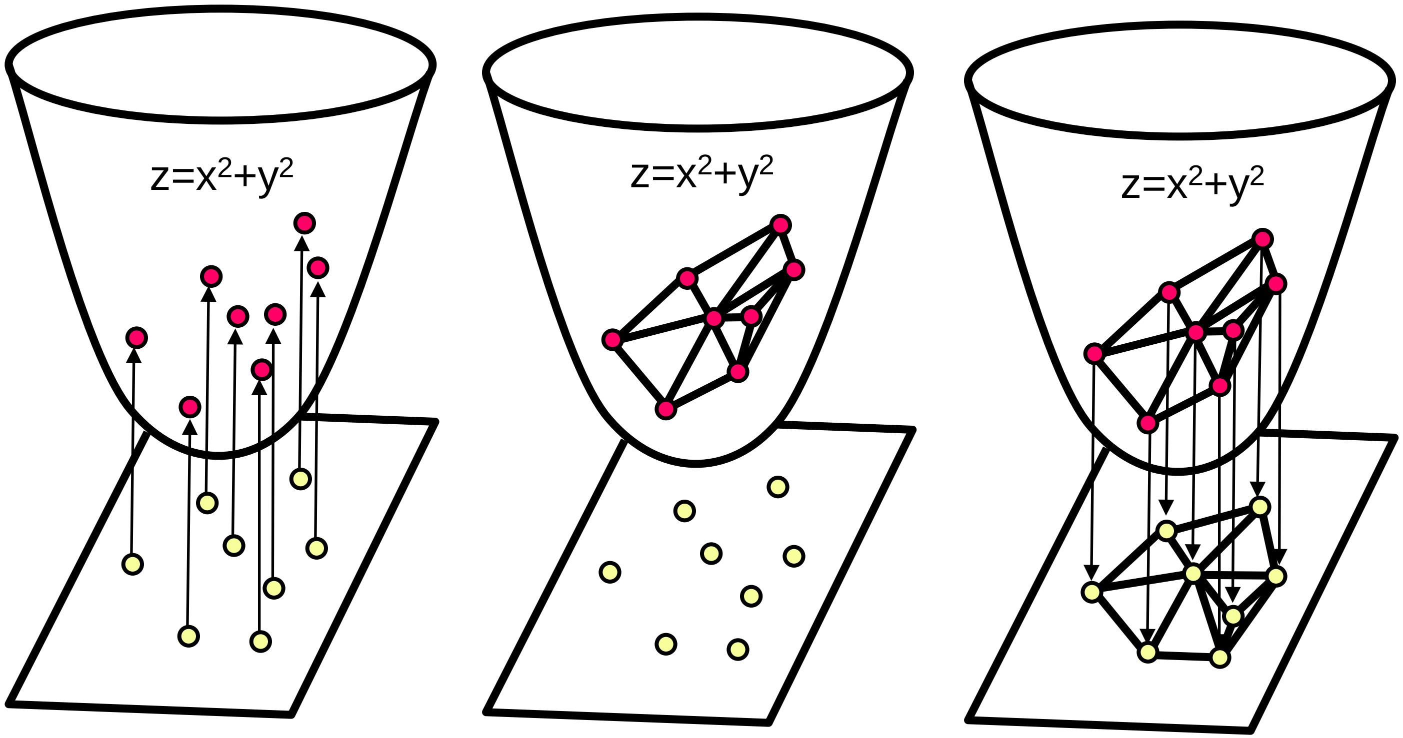
Background

Delaunay Triangulation

- **Duality on the paraboloid**: Delaunay triangulation obtained by projecting the lower part of the convex hull.



Delaunay Triangulation

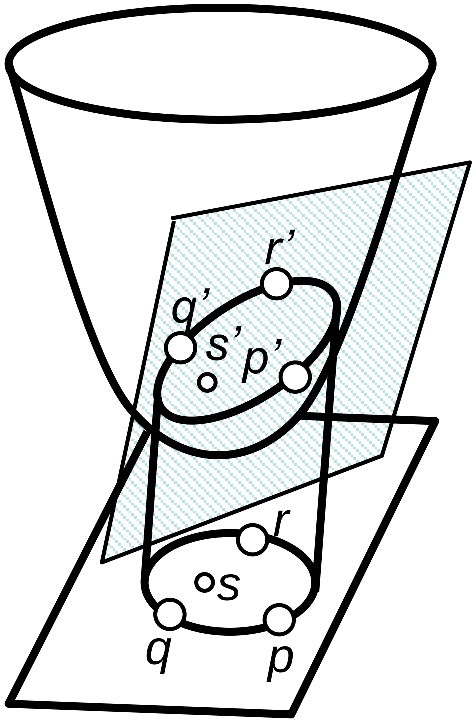


Project the 2D point set onto the 3D paraboloid → Compute the 3D lower convex hull → Project the 3D facets back to the plane.

Proof

- The intersection of a plane with the paraboloid is an ellipse whose projection to the plane is a circle.
- *s* lies within the circumcircle of *p*, *q*, *r* iff *s'* lies on the lower side of the plane passing through *p'*, *q'*, *r'*.

- *p*, *q*, *r* $\in$ *S* form a Delaunay triangle iff *p'*, *q'*, *r'* form a face of the convex hull of *S'*.

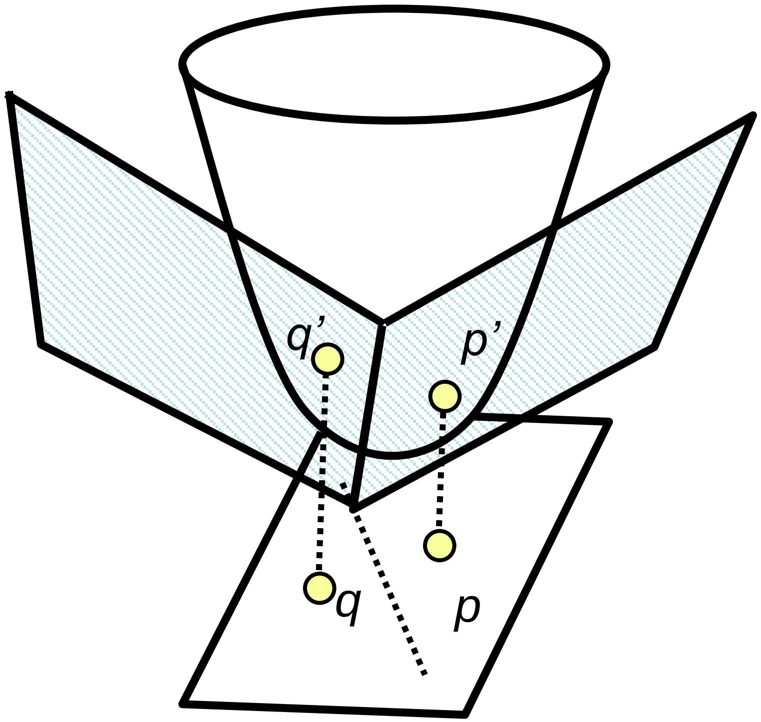


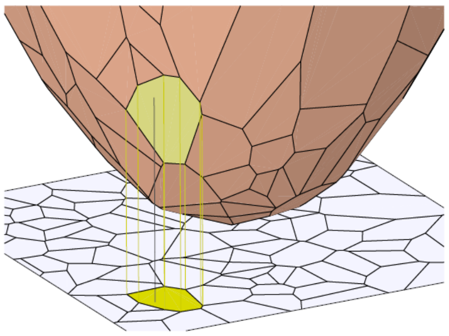
Voronoi Diagram

- Given a set *S* of points in the plane, associate with each point $p=(a,b) \in S$ the plane tangent to the paraboloid at *p*:

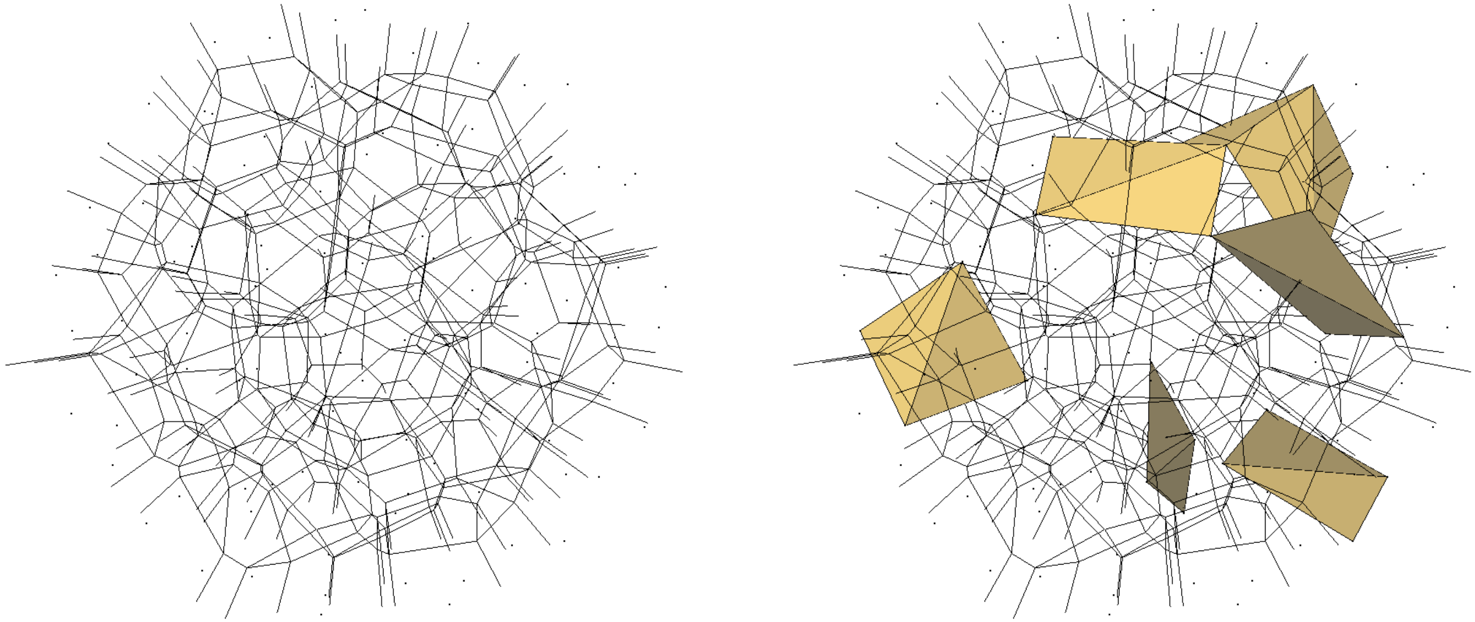
$$z = 2ax+2by-(a2+b2).$$

- VD(*S*) is the projection to the (x,y) plane of the 1-skeleton of the convex polyhedron formed from the intersection of the halfspaces above these planes.





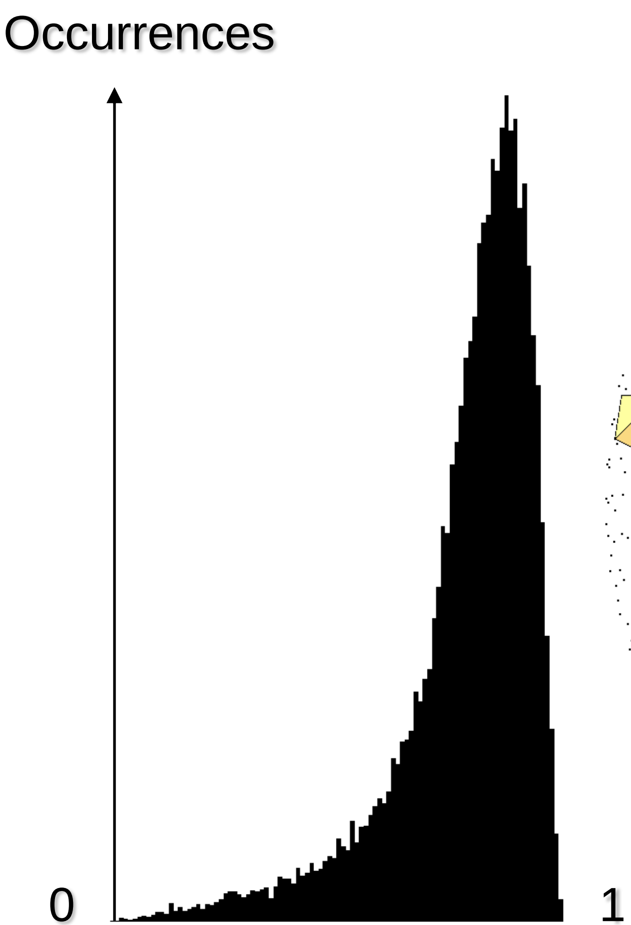
First Idea: Lloyd Algorithm



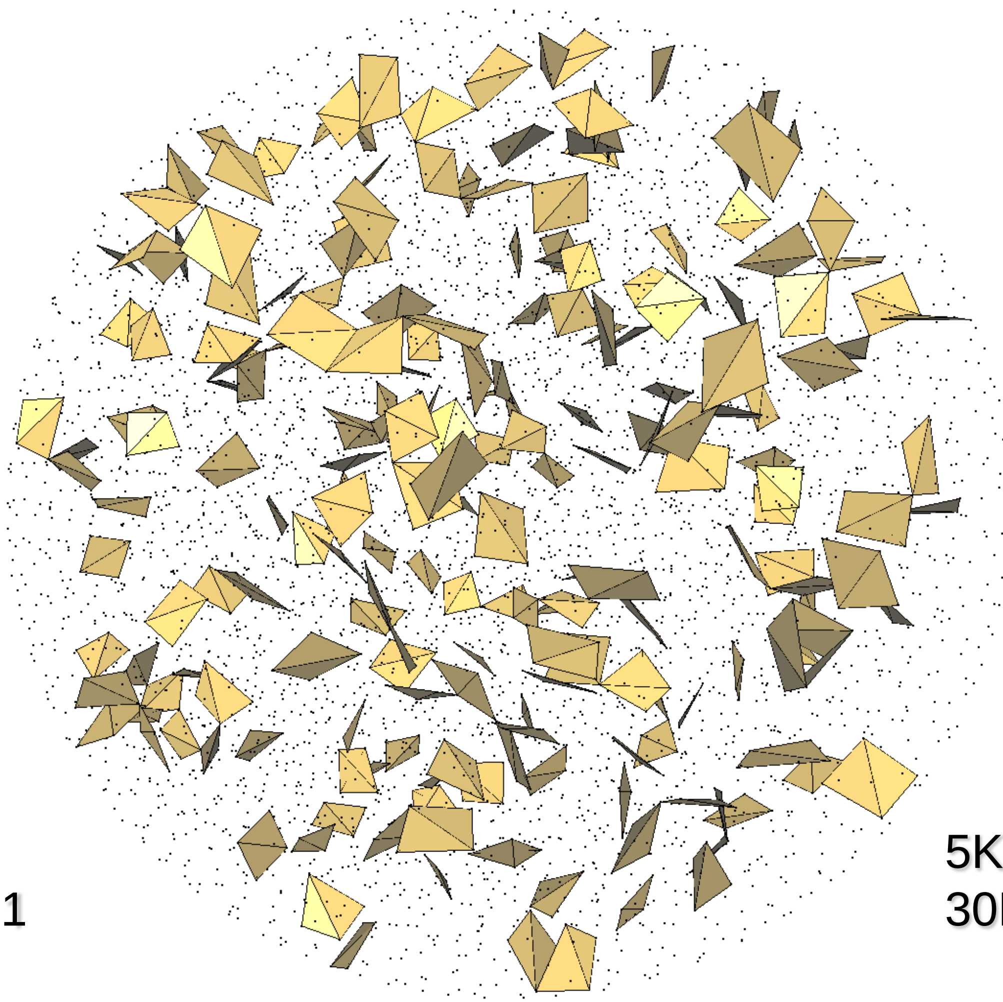
(after Lloyd relaxation)

...back to primal ?

Centroidal Voronoi Tessellation



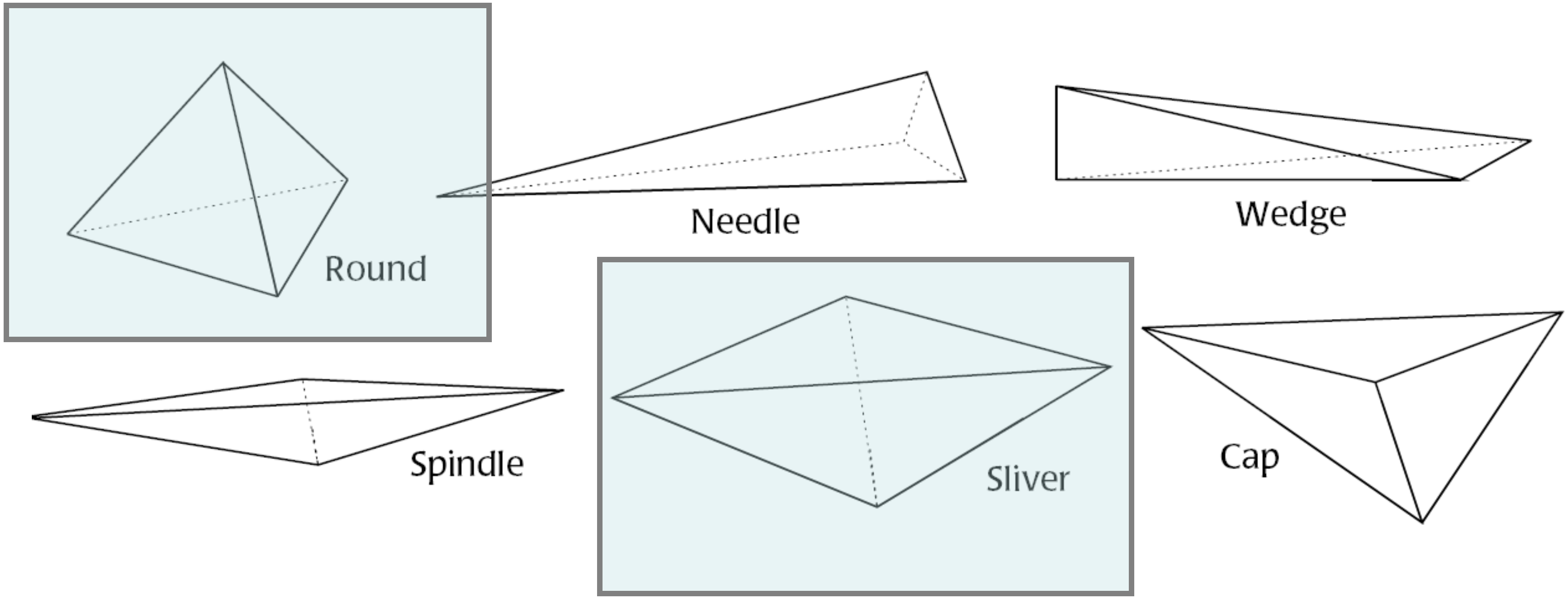
distribution of radius ratios



5K sites
30K tets

220 “slivers” (tets with radius ratio < 0.2)

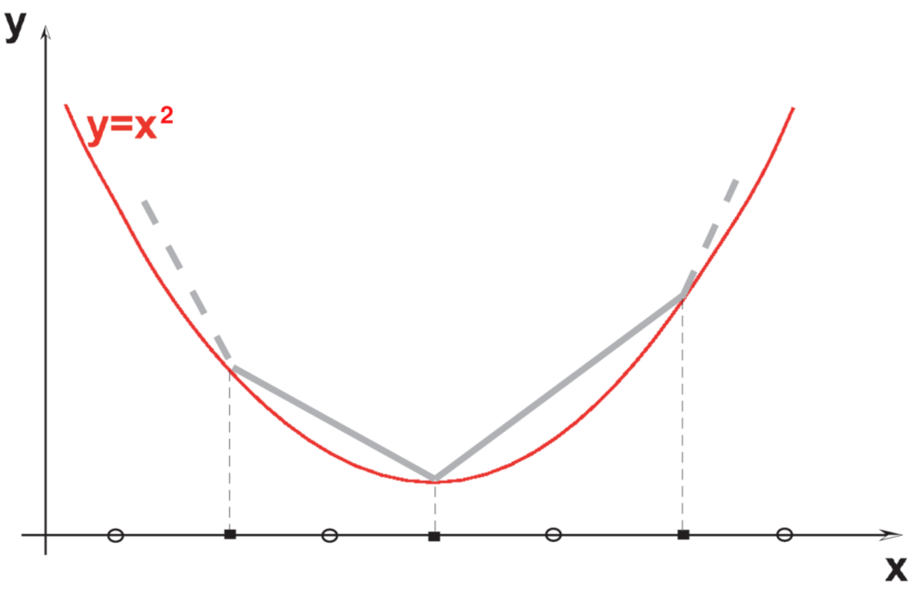
Tetrahedra Zoo



well-spaced points generate only **round** or **sliver** tetrahedra

Key Idea

- adopt the "function approximation" point of view **[Chen 04]** *Optimal Delaunay Triangulation*
- 1D: $f(x)=x^2$ centered at any vertex
- minimize the L^1 norm between f and PWL interpolation



Key Idea

- 3D: $||x||^2$ (graph in $\mathbb{R}^4$)
- approximation theory:
  - linear interpolation: optimal shape of the element related to the Hessian of f **[Shewchuk]**
- Hessian($||x||^2$) = Id
  - regular tetrahedron best
- note: FE ~ mesh that best *interpolates* a function + matrix conditioning

Key Question

- which mesh best approximates the paraboloid?
  - (PWL interpolates)

- Answers:
  - for **fixed point locations**
    - Delaunay (lifts to lower facets of convex hull)
  - for **fixed connectivity**
    - quadratic energy
    - closed form for local optimum

Function Approximation

- Given:
  - triangulation T
  - bounded domain Ω in IR^n

- Consider function approximation error:

$$Q(T, f, p) = \| f - f_{I,T} \|_{L^p,\Omega}$$

linear interpolation

Function Approximation

Theorem [Chen 04]:

$$Q(DT, \| x \|^2, p) = \min_{T \in P_V} Q(T, \| x \|^2, p), 1 \le p \le \infty$$

set of all triangulations with a **given set** V

▪ = convex hull of V

Isotropic function

[d'Azevedo-Simpson 89] in IR^2, $p = \infty$

[Rippa 92] in IR^2, $1 \le p \le \infty$

[Melissaratos 93] in IR^D, $1 \le p \le \infty$

Function Approximation

Let us V vary

Problem:

- find triangulation T^* such that:

$$Q(T^*, f, p) = \inf_{T \in P_N} Q(T, f, p), 1 \le p \le \infty$$

set of all triangulations with a **at most N vertices**

Proof:

- existence
- necessary condition for $p=1$

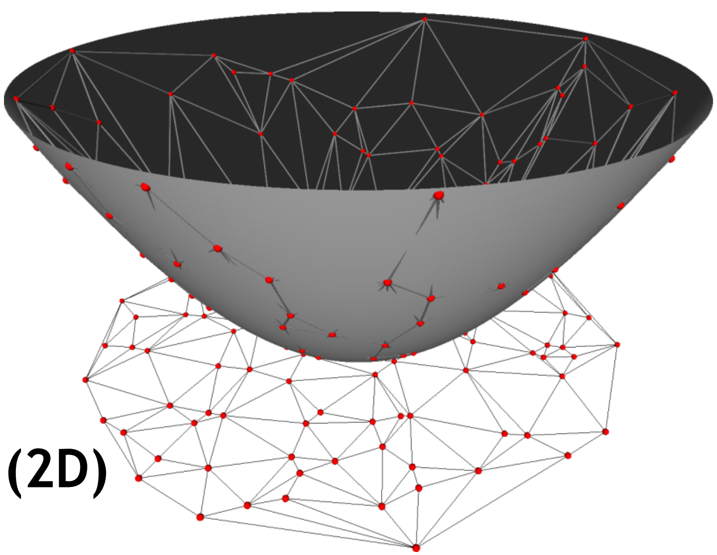
Function Approximation

$$Q(DT, \| x \|^2, p) = \min_{T \in P_V} Q(T, \| x \|^2, p), 1 \le p \le \infty$$

Isotropic function

set of all triangulations with a **given set** V

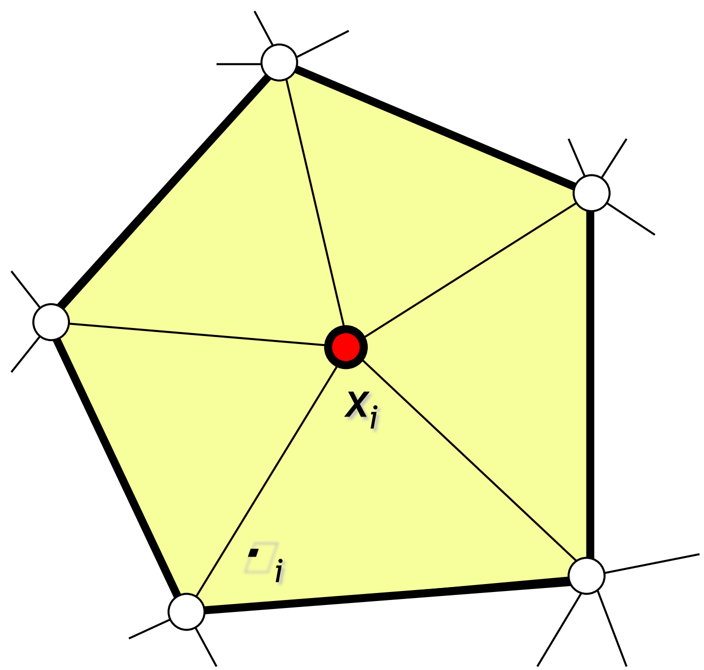
▪ = convex hull of V



(2D)

Function Approximation

- x_i: vertex
- Ω_i: *union of simplices incident to* x_i
- $|A|$: *Lebesgue measure of set A in* IR^n



Function Approximation

$$Q(T, f, p) = \| f_{I,T} - f \|_{L^p,\Omega}$$

$$Q(T, f, p) = \left[\int_{\Omega} | f_{I,T}(x) - f(x) |^p dx \right]^{1/p}$$

$$Q(T, f, 1) = \int_{\Omega} (f_{I,T}(x) - f(x)) dx$$

f **convex,** $\boldsymbol{f_{I,T}}$ **PWL interpolant**

$$Q(T, f, 1) = \int_{\Omega} f_{I,T}(x) dx - \int_{\Omega} f(x) dx$$

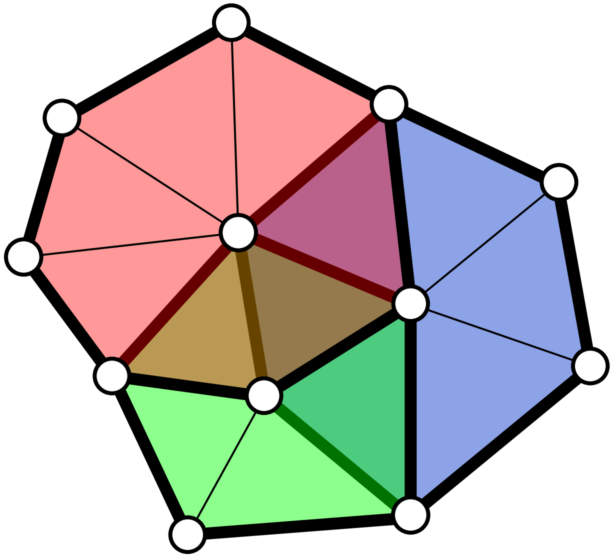
Function Approximation

$$Q(T, f, 1) = \int_{\Omega} f_{I,T}(x)dx - \int_{\Omega} f(x)dx$$

$$= \sum_{\tau \in T} \int_{\tau} f_{I,T}(x)dx - \int_{\Omega} f(x)dx$$

$$= \frac{1}{n+1} \sum_{\tau \in T} \left(|\tau| \sum_{k=1}^{n+1} f(x_{\tau}, k) \right) - \int_{\Omega} f(x)dx$$

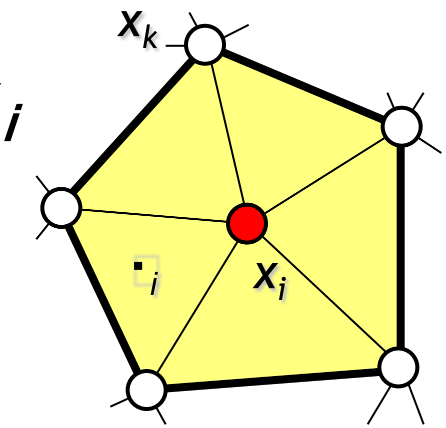
$$= \frac{1}{n+1} \sum_{x_i \in T} f(x_i) |\Omega_i| - \int_{\Omega} f(x)dx$$



n+1 overlaps

Function Approximation

restrict to patch Ω_i incident to vertex x_i



$$Q(\Omega_i, f, 1) = \frac{1}{n+1} \sum_{x_i \in \Omega_i} f(x_i) |\Omega_i| - \int_{\Omega_i} f(x)dx$$

$$= \frac{1}{n+1} \sum_{\tau_j \in \Omega_i} \left(|\tau_j(x)| \sum_{x_k \in \tau_j, x_k \neq x_i} f(x_k) \right) + \frac{|\Omega_i|}{n+1} f(x_i) - \int_{\Omega_i} f(x)dx$$

constant

minimize

$$E_{ODT} \equiv \sum_{\tau_j \in \Omega_i} \left(|\tau_j(x)| \sum_{x_k \in \tau_j, x_k \neq x_i} f(x_k) \right) + |\Omega_i| f(x_i)$$

Function Approximation

$$E_{ODT} \equiv \sum_{\tau_j \in \Omega_i} (|\tau_j(x)| \sum_{x_k \in \tau_j, x_k \neq x_i} f(x_k)) + |\Omega_i| f(x_i)$$

minimum if $\nabla E_{ODT} = 0$

$$\nabla f(x_i^*) = -\frac{1}{|\Omega_i|} \sum_{\tau_j \in \Omega_i} \left(\nabla |\tau_j|(x_i) \sum_{x_k \in \tau_j, x_k \neq x_i} f(x_k) \right)$$

if $f(x) = \| x \|^2$

$$\boxed{x_i^* = -\frac{1}{2|\Omega_i|} \sum_{\tau_j \in \Omega_i} \left(\nabla |\tau_j|(x_i) \sum_{x_k \in \tau_j, x_k \neq x_i} \| x_k \|^2 \right)}$$

Geometric Interpretation

$$x_i^* = \frac{1}{|\Omega_i|} \sum_{\tau_j \in \Omega_i} |\tau_j| c_j$$

circumcenter

demo

- **Note**: optimal location depends only on the 1-ring neighbors, not on the current location. If all incident vertices lie on a common sphere, optimal location is at sphere center.

Optimization

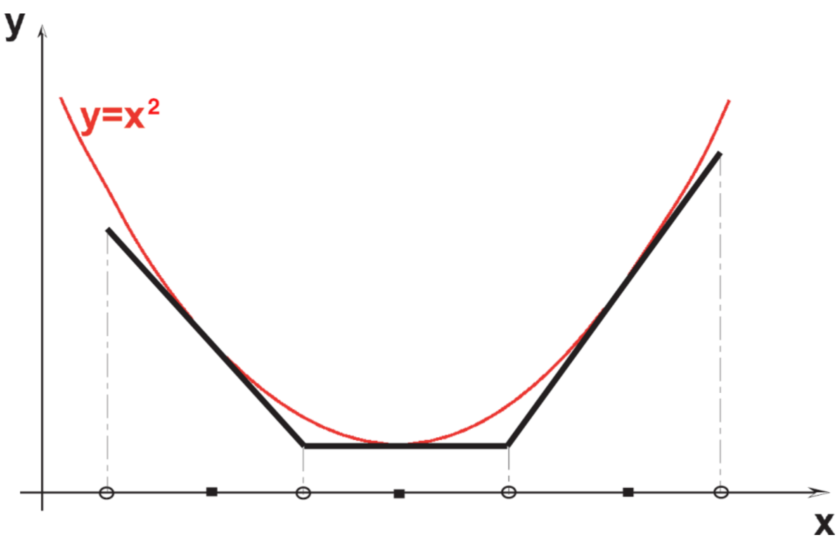
- alternate updates of
  - connectivity
  - vertex location

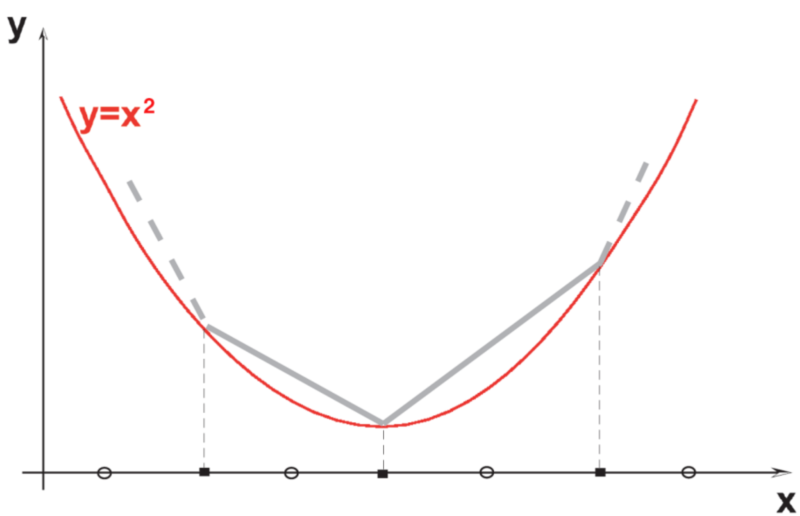
- both steps minimize the same energy
  - as for Lloyd iteration

- for convex fixed boundary
  - energy monotonically decreases
  - convergence to a (local) minimum

Underlaid *vs* Overlaid Approximant

- CVT
  - partition
  - approximant
  - compact Voronoi **cells**
  - isotropic **sampling**
- ODT
  - overlapping decomposition
  - PWL interpolant
  - compact **simplices**
  - isotropic **meshing**



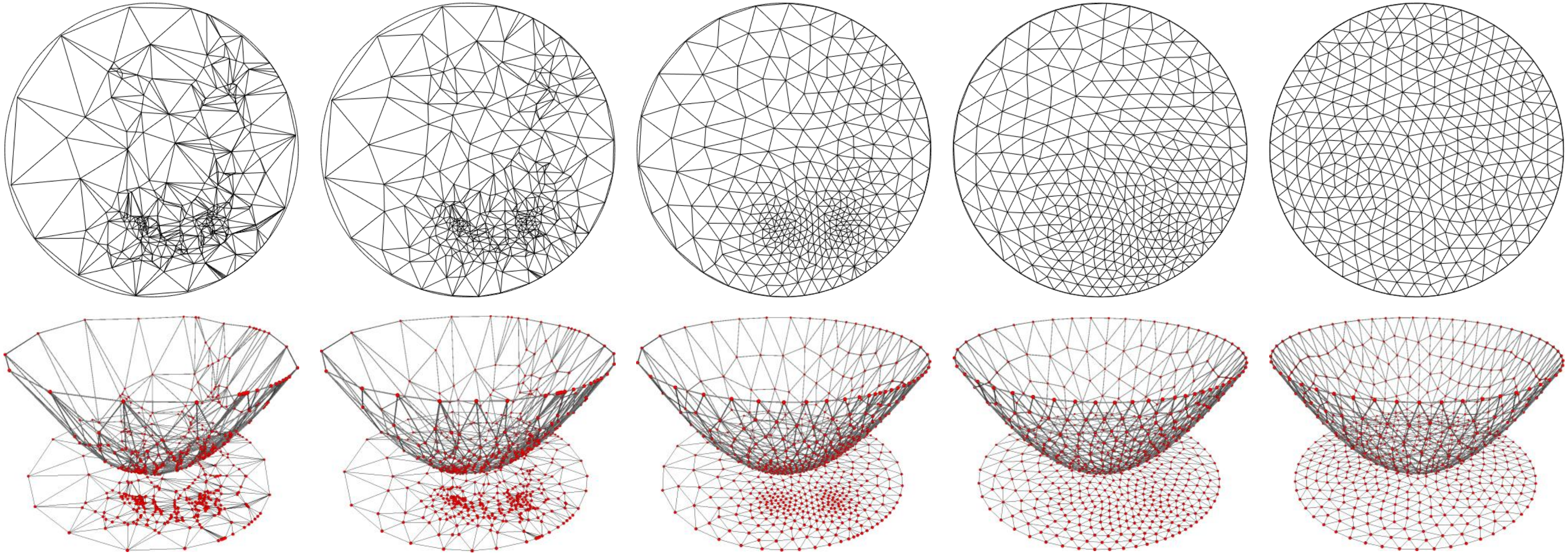


Optimization

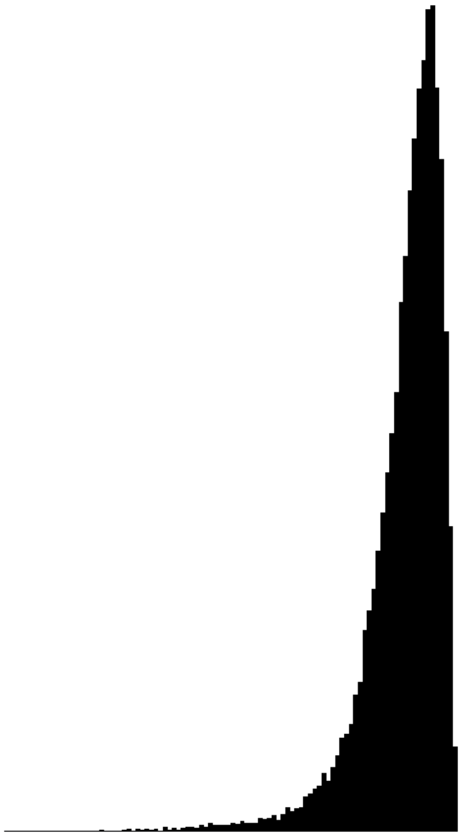
Alternate updates of

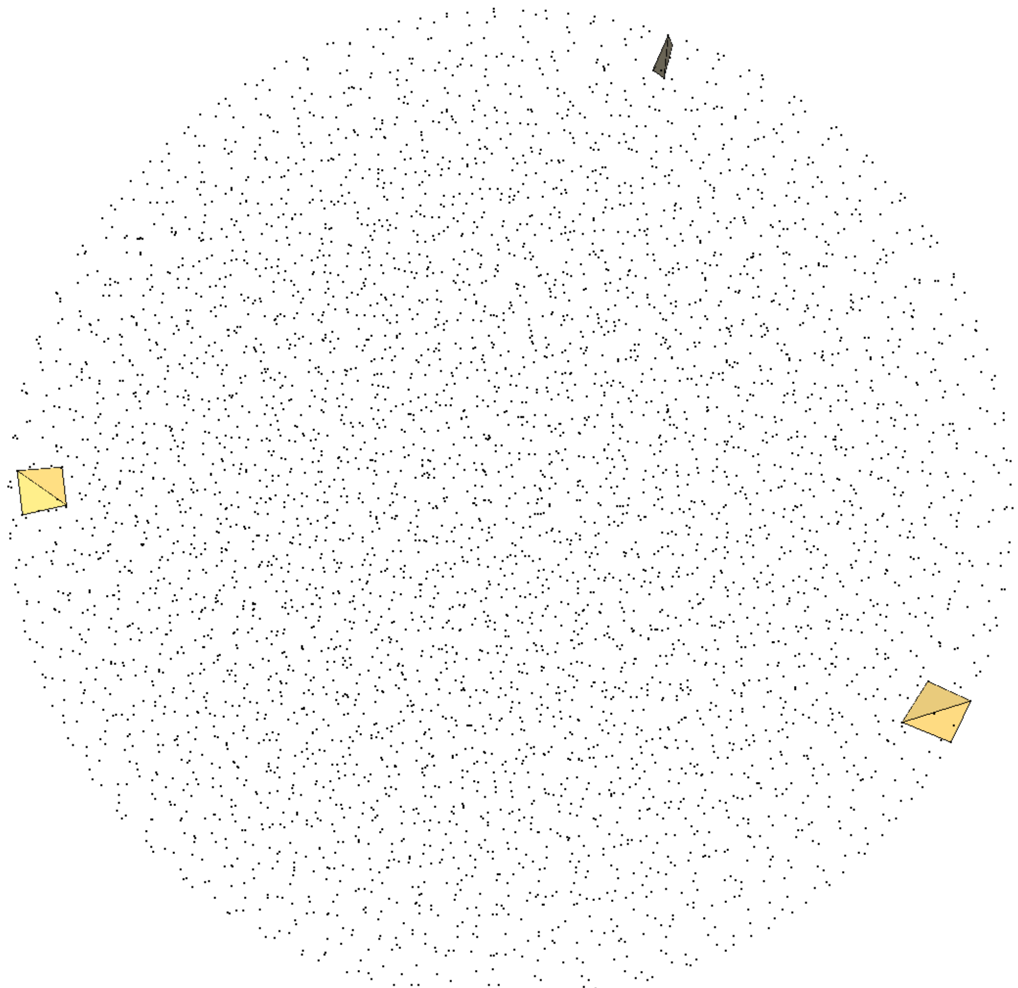
- connectivity (Delaunay triangulation)
- vertex locations

demo



Optimal Delaunay Triangulation





distribution of radius ratios

3 “slivers”, each with two vertices on boundary

Sizing Field

Goal reminder:

- shape of elements
- boundary approximation
- minimize #elements
- *note: not independent (well-shape elements force K-Lipschitz sizing field* **[Ruppert, Miller et al.]***)*

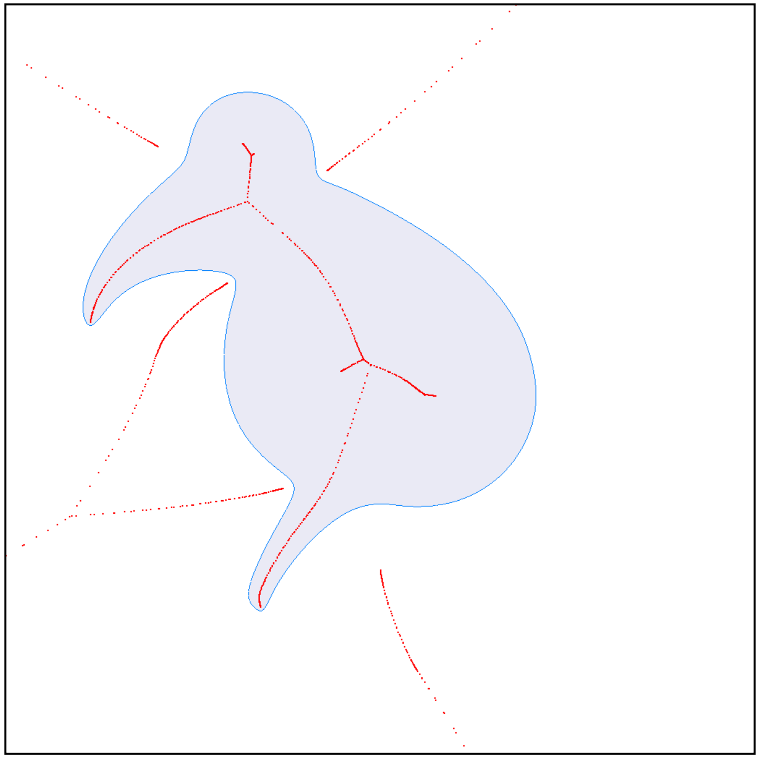
Proposal:

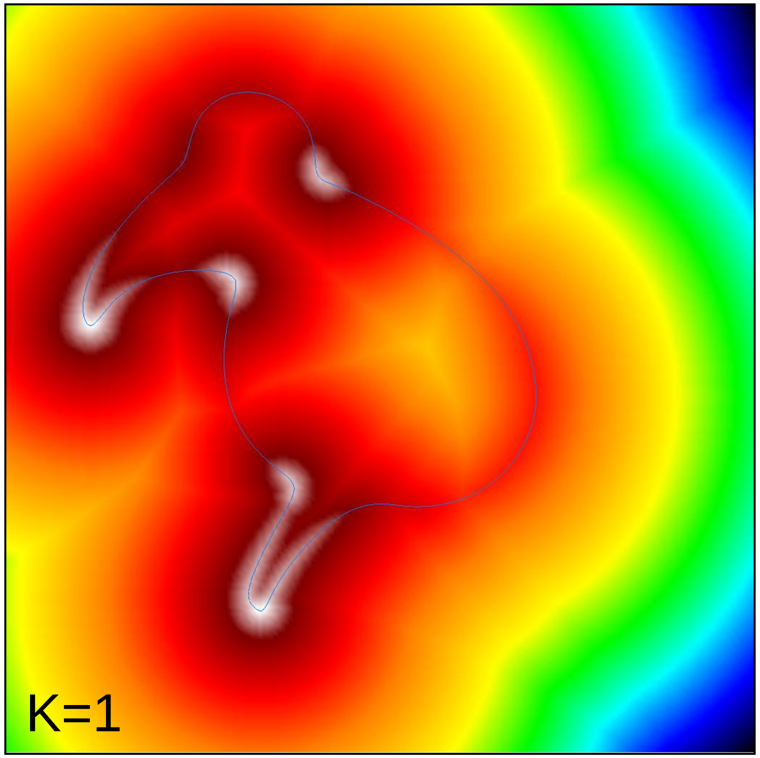
- size <= *lfs* (local feature size) on boundary
- sizing field = maximal K-Lipschitz

$$\boxed{\mu(x) = \inf_{y \in \partial\Omega} \left[K \| x - y \| + lfs(y) \right]}$$

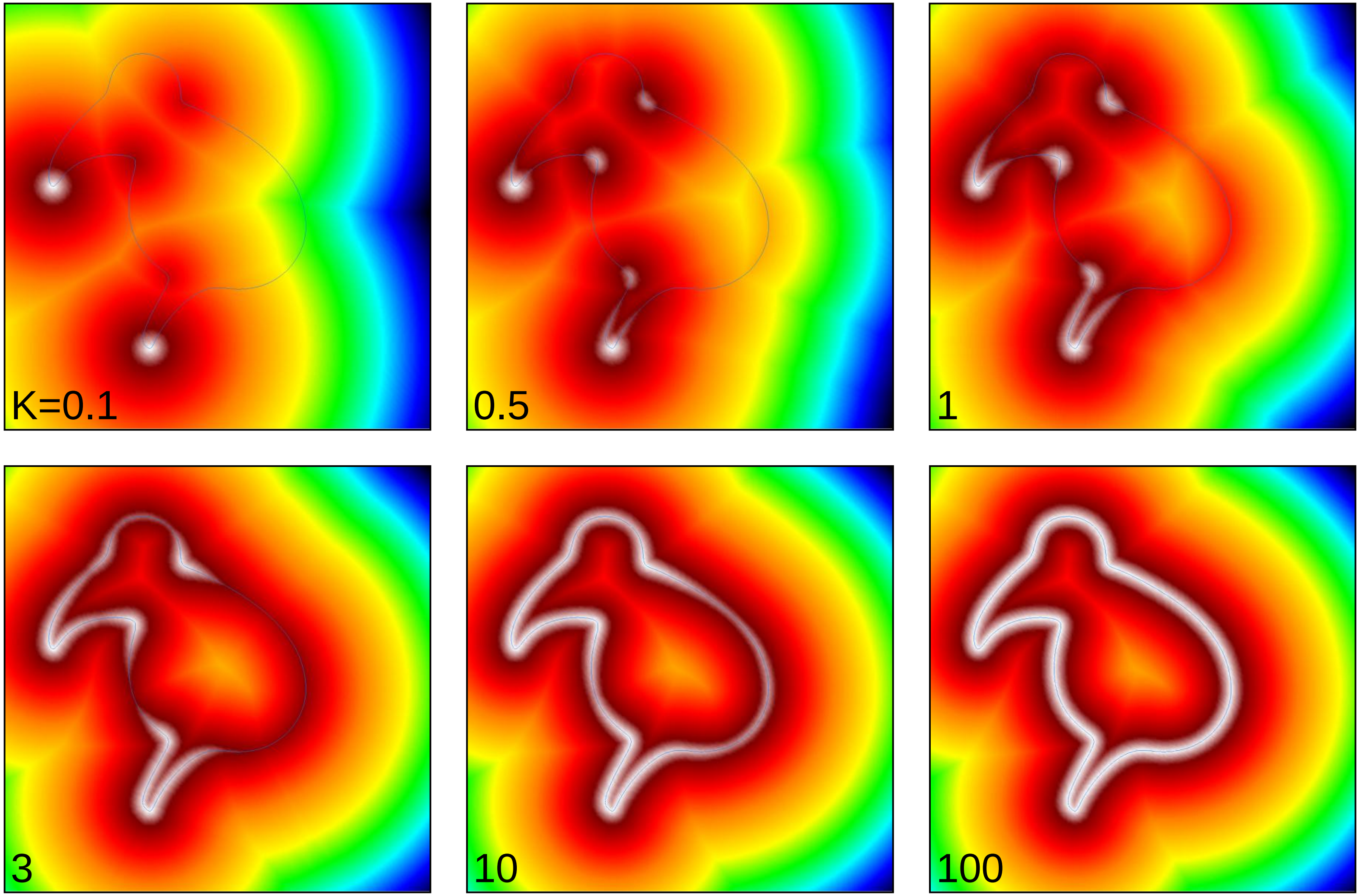
Sizing Field

$$\mu(x) = \inf_{y \in \partial\Omega} \left[K \| x - y \| + lfs(y) \right]$$





Sizing Field: Examples



Algorithm

- read input boundary $\partial\Omega$
- setup data structure & preprocessing
- compute sizing field
- generate initial sites inside Ω
- do
  - Delaunay triangulation of $\{x_i\}$
  - move sites to optimal locations $\{x_i^*\}$

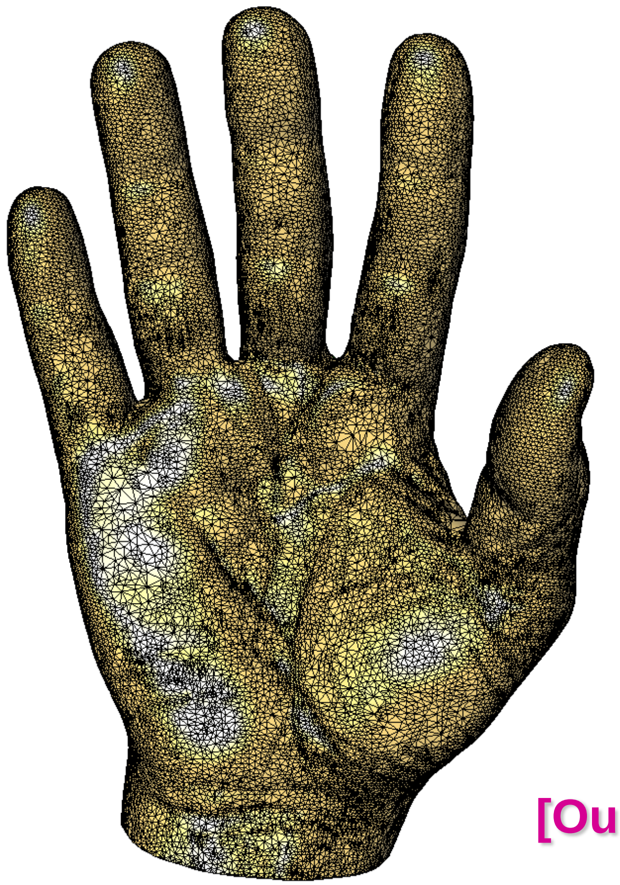
  until convergence or stopping criterion
- extract interior mesh

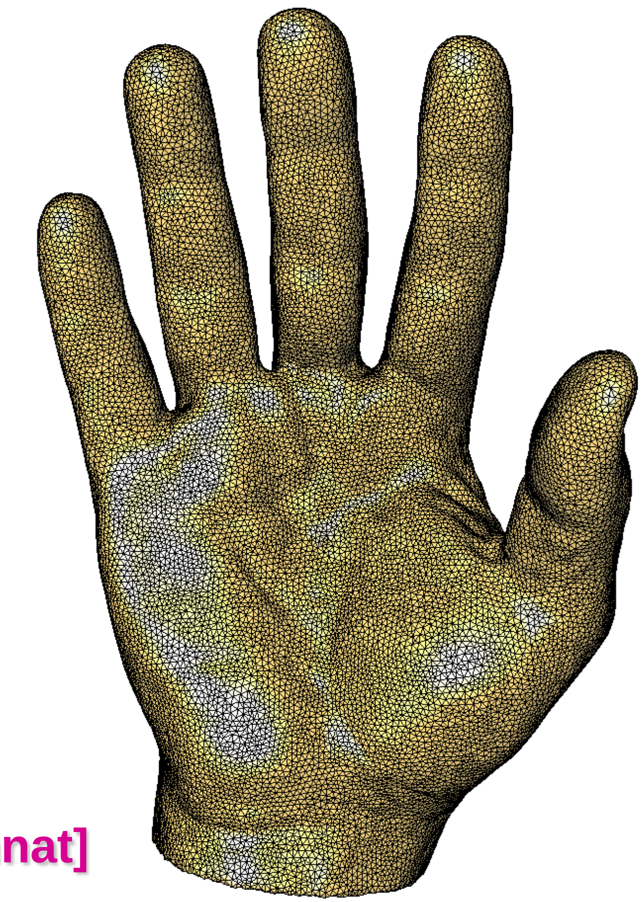
Input Boundary $\partial\Omega$

- surface triangle mesh

- **Requirements:**
  - intersection free
  - closed
  - restricted Delaunay triangulation of the input vertices [Oudot-Boissonnat, Cohen-Steiner et al.]

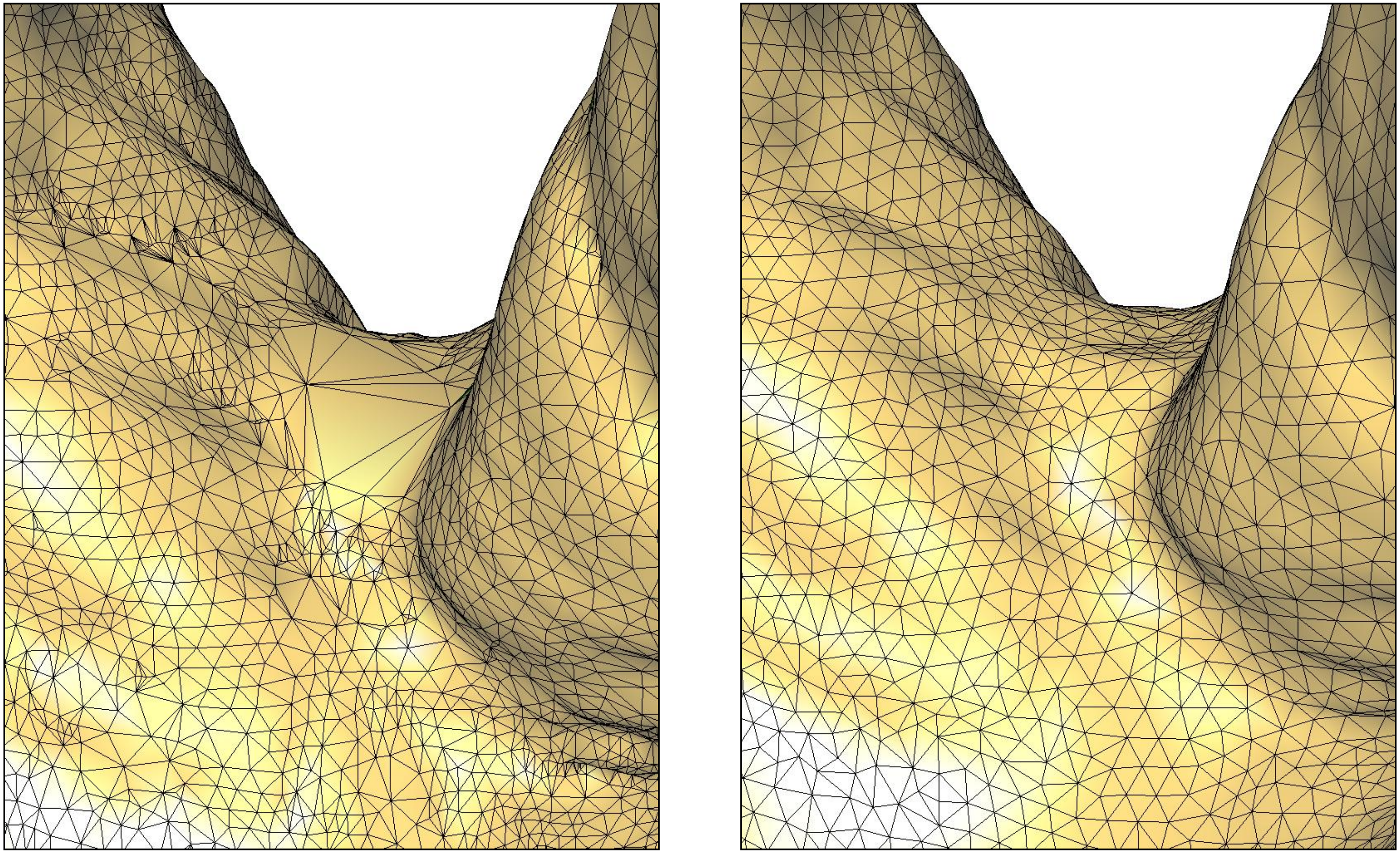
Input Boundary $\partial\Omega$





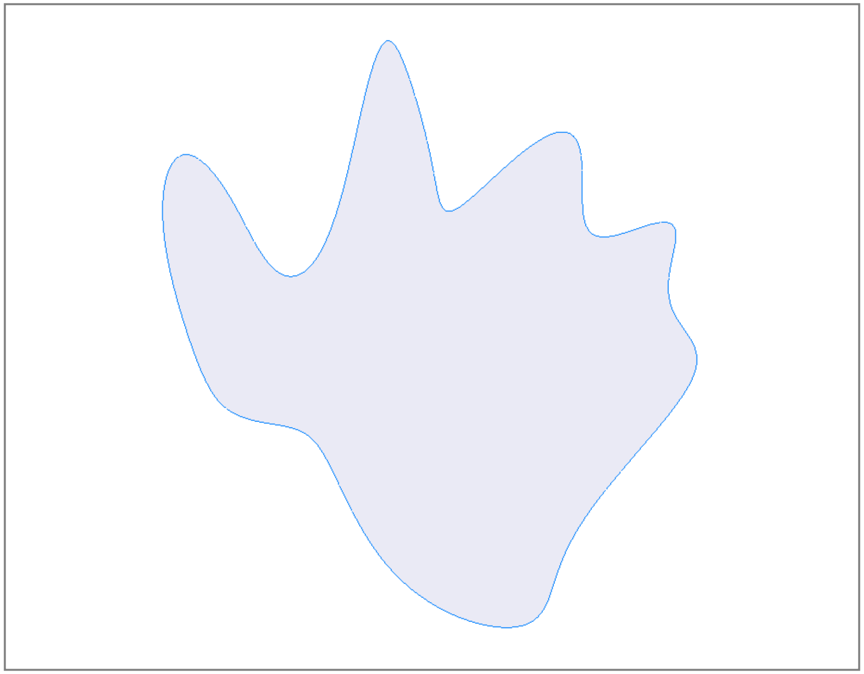
[Oudot-Boissonnat]

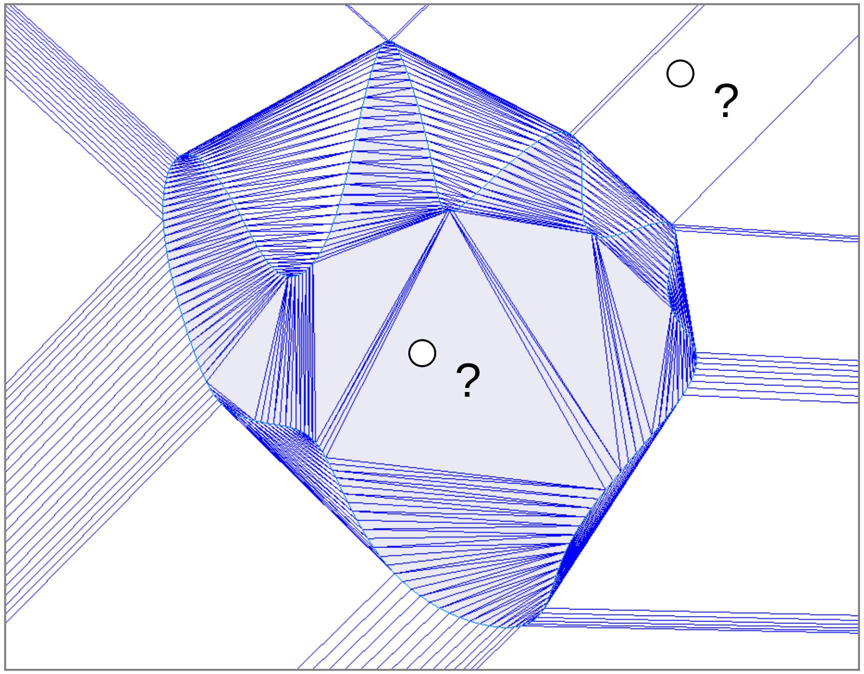
Input Boundary $\partial\Omega$



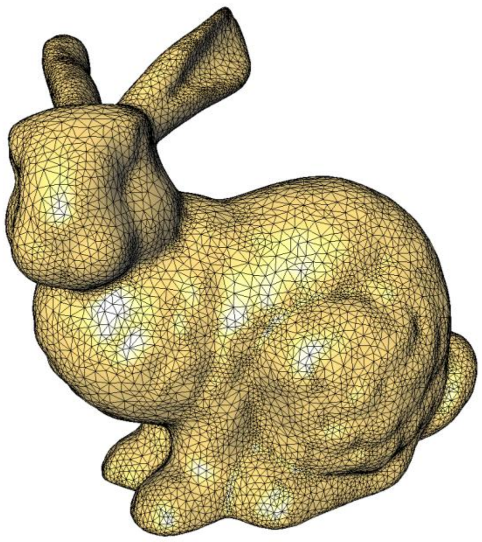
Setup & Preprocessing

- Insertion of input mesh vertices to a 3D Delaunay triangulation
  - **control mesh**
  - used to answer inside/outside queries

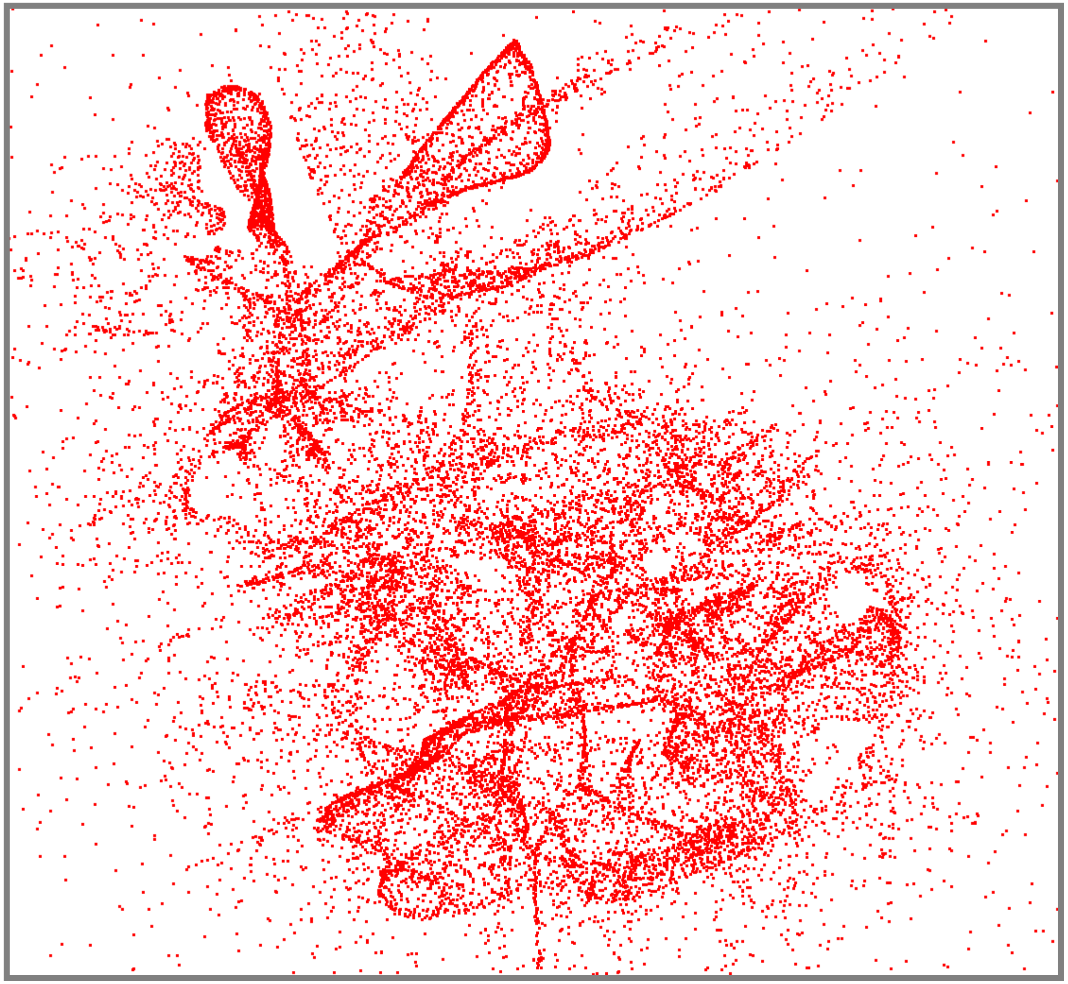




Sizing Field: Poles



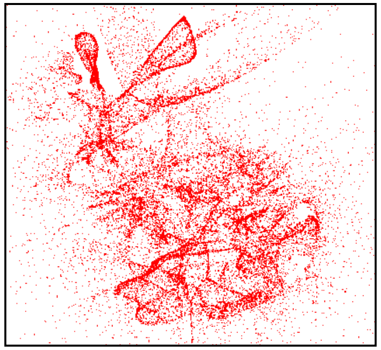
control mesh

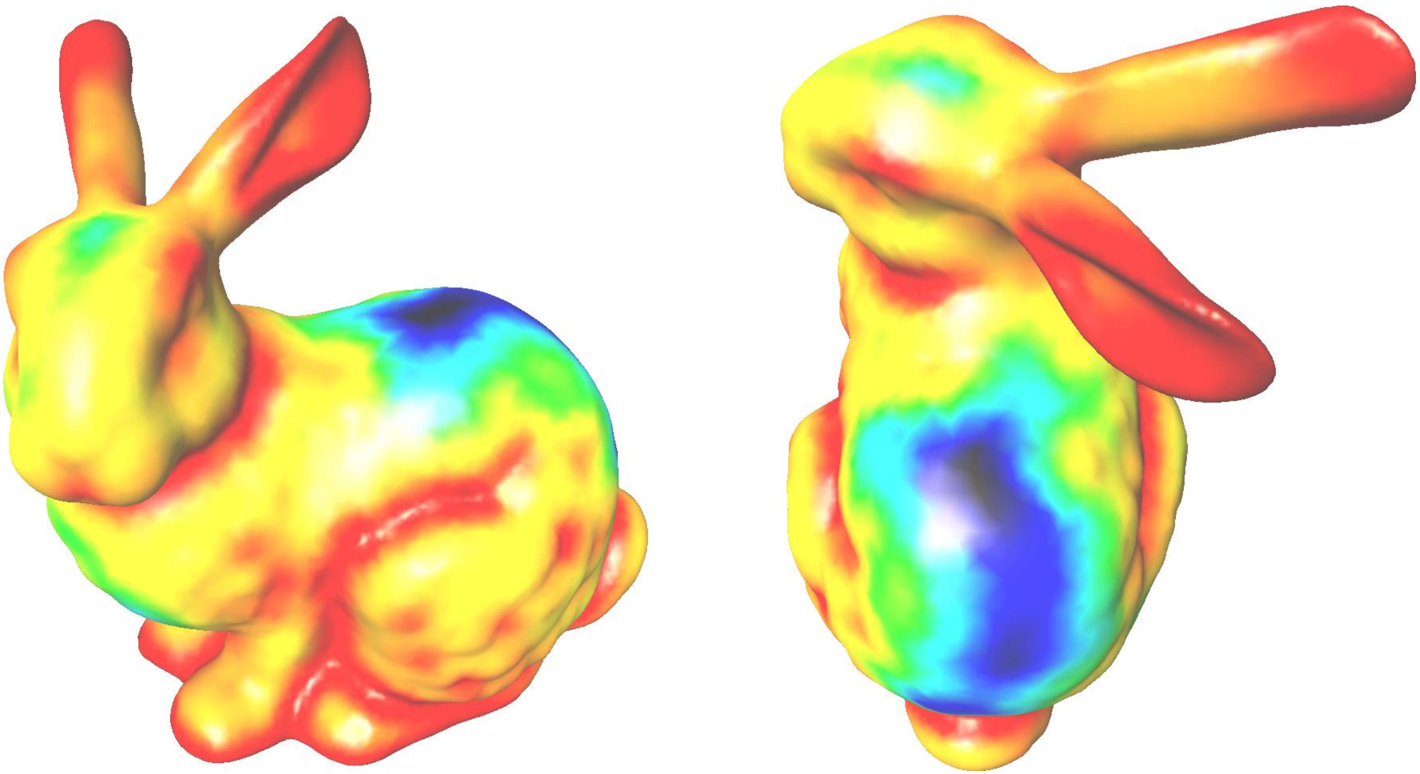


poles

[Amenta-Bern 98]

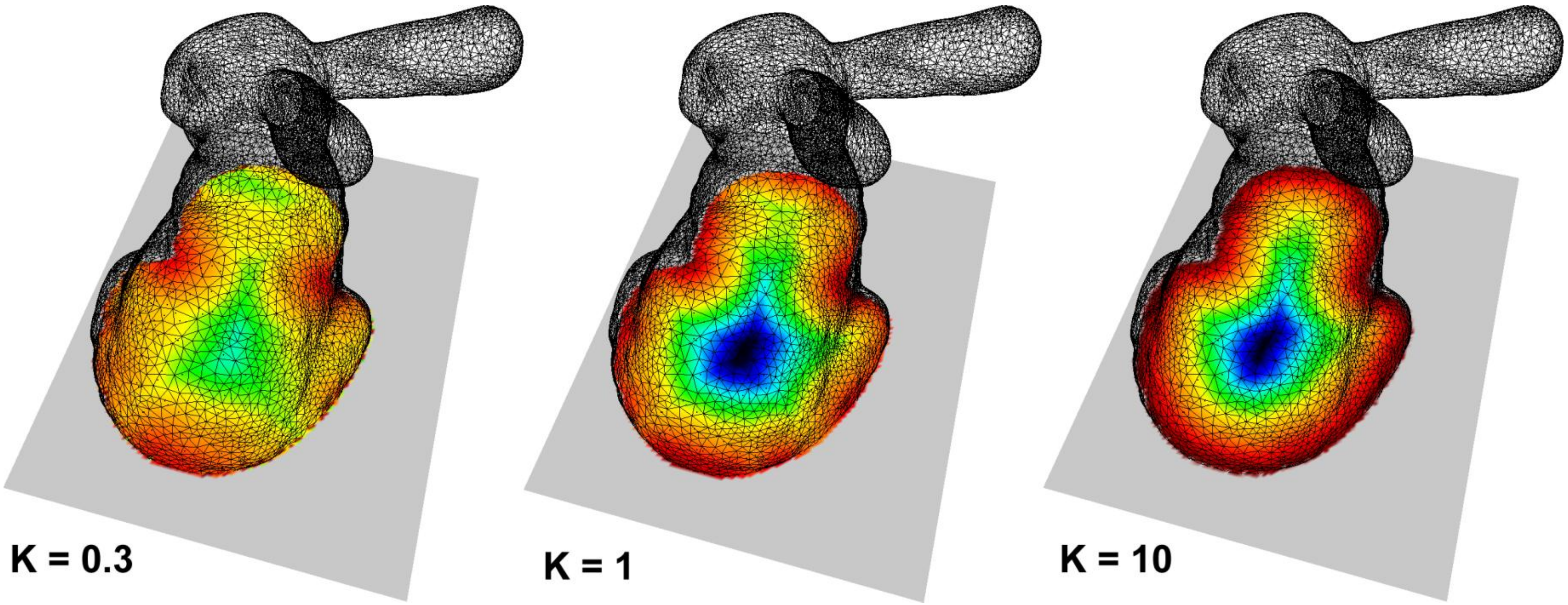
Sizing Field: lfs





Approximation: distance to set of poles
CGAL orthogonal search in a kD-tree [Tangelder-Fabri]

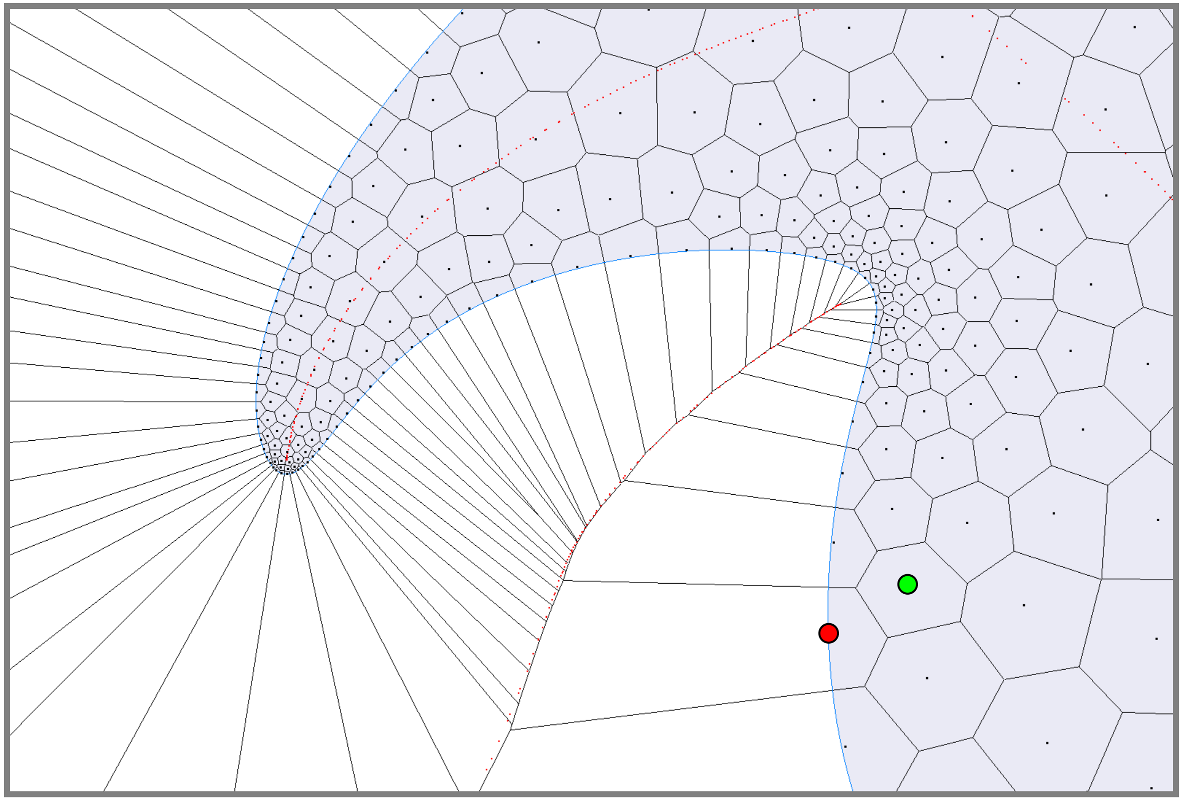
Sizing Field: Examples



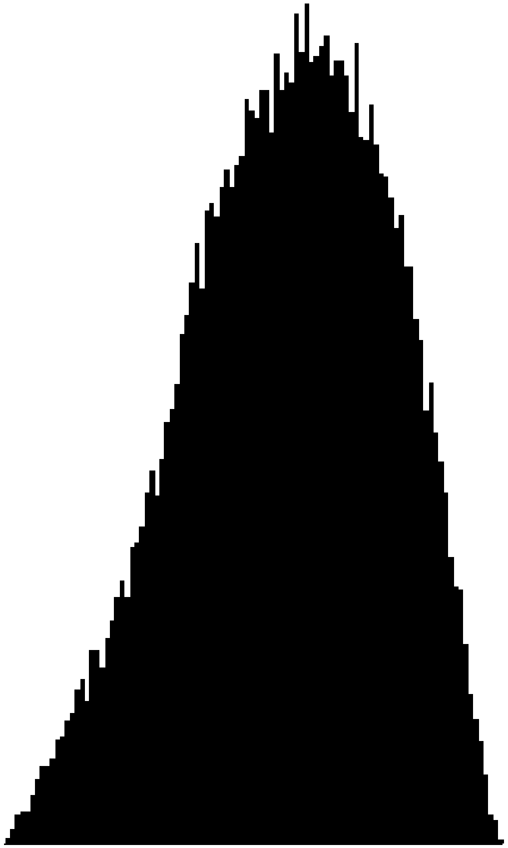
Approximation: fast marching from boundary
Representation: regular grid or balanced octree

Optimization

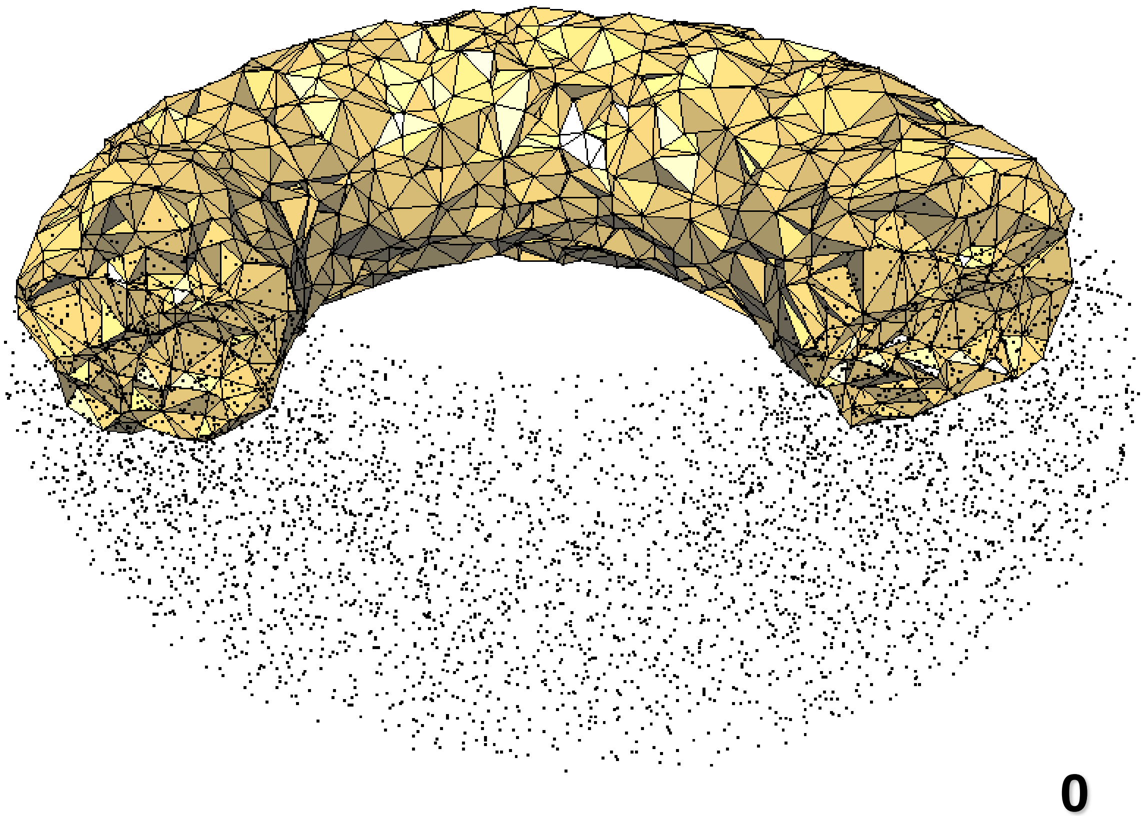
- classification boundary/interior vertices by localization of boundary in Voronoi cells
  - CVT on boundary
  - ODT inside



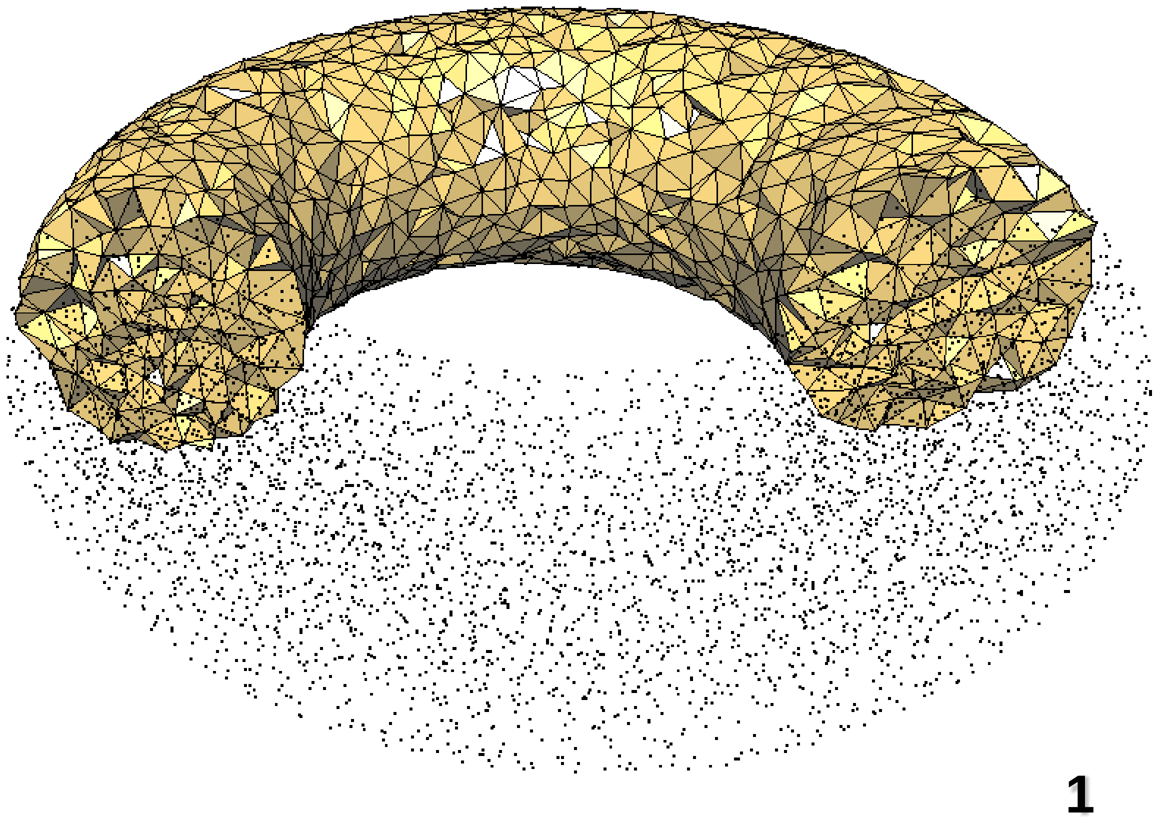
Optimization: init



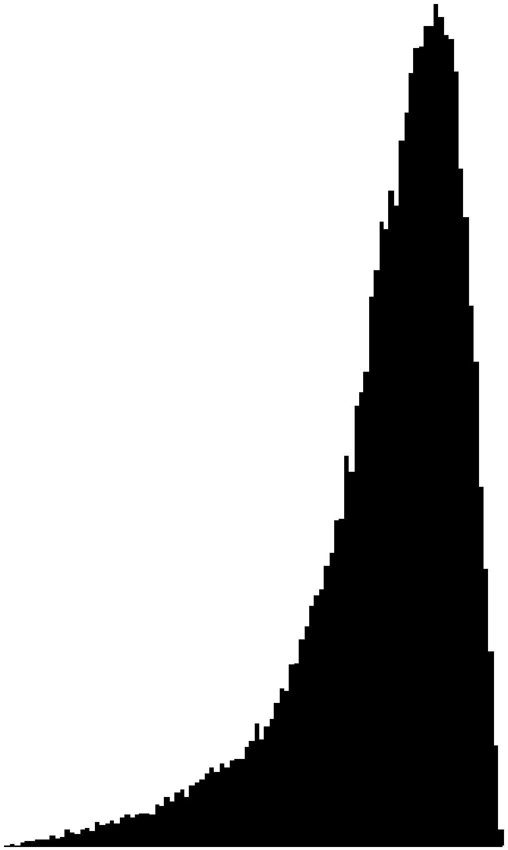
Distribution of radius ratios

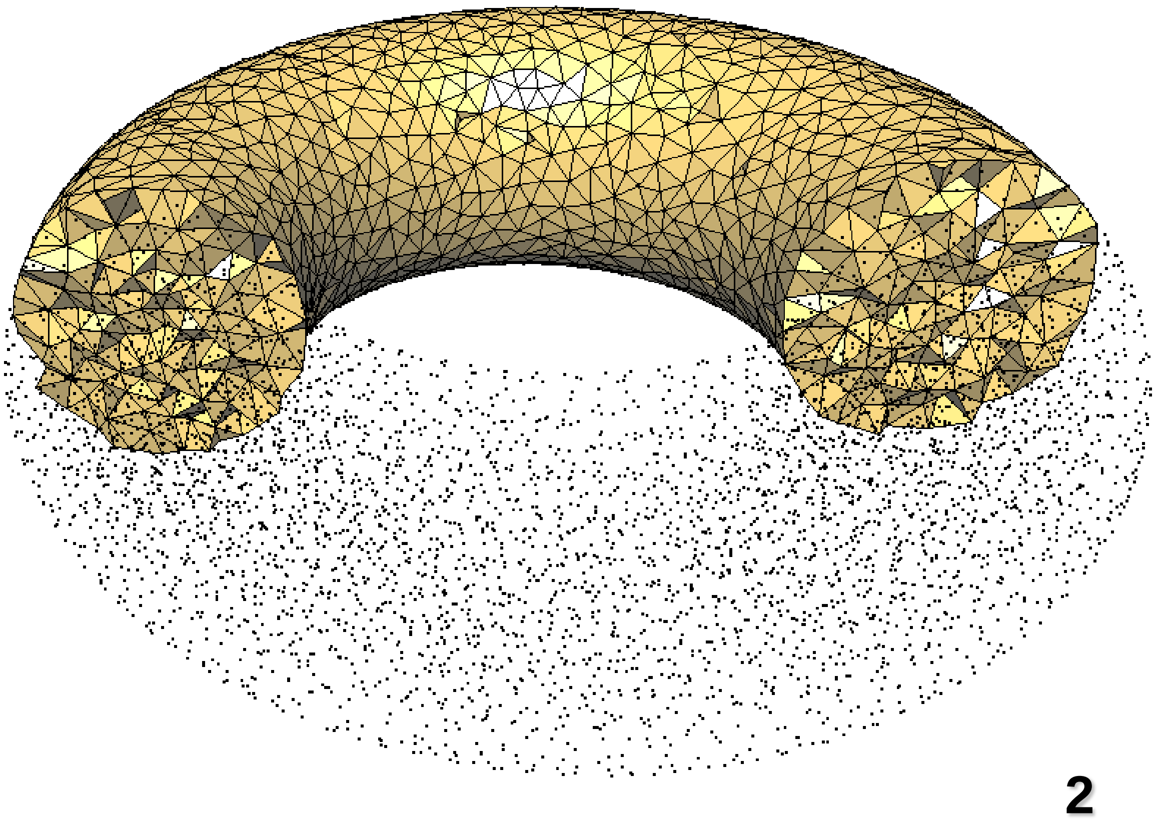


Optimization: step 1

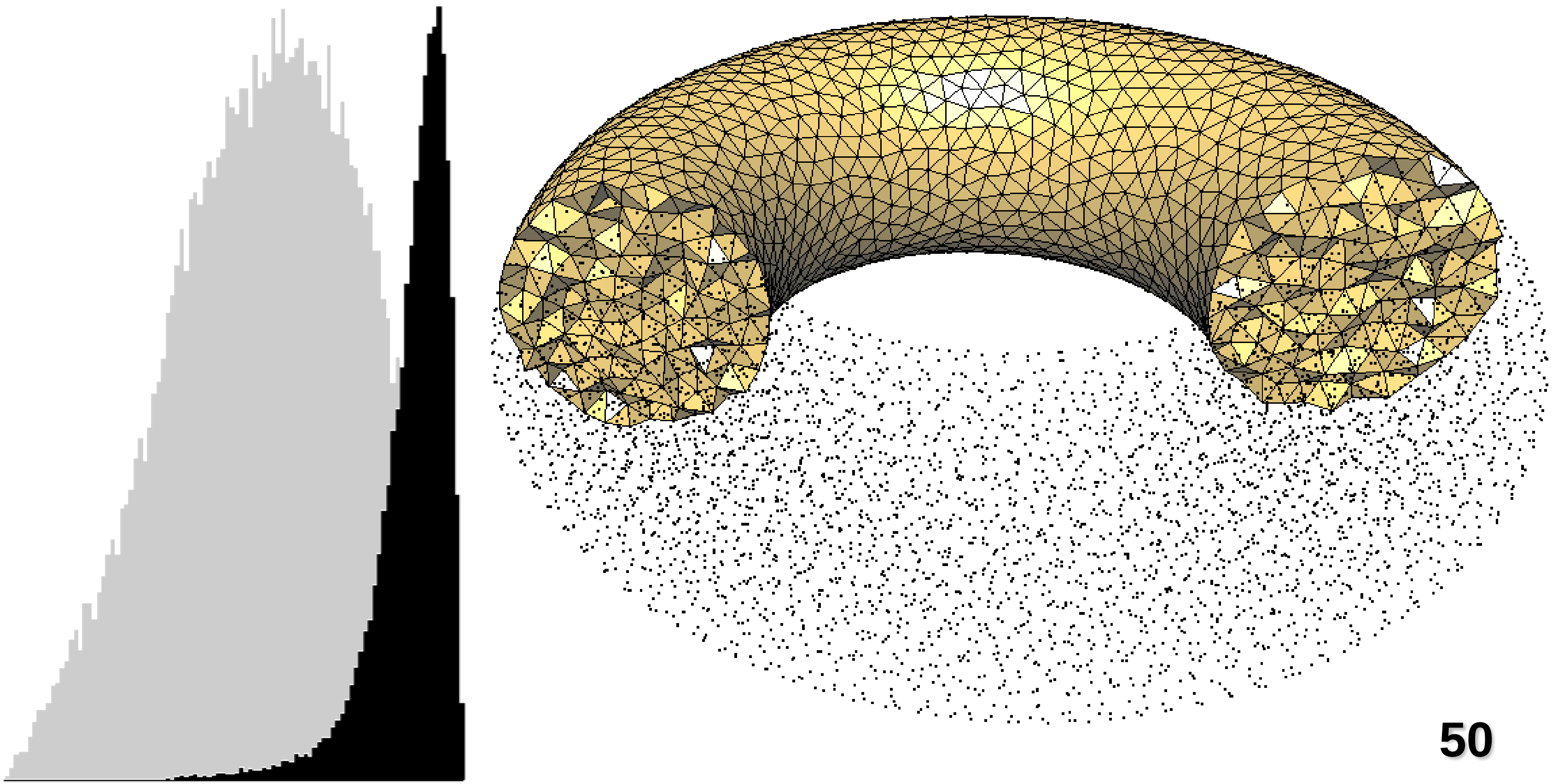


Optimization: step 2

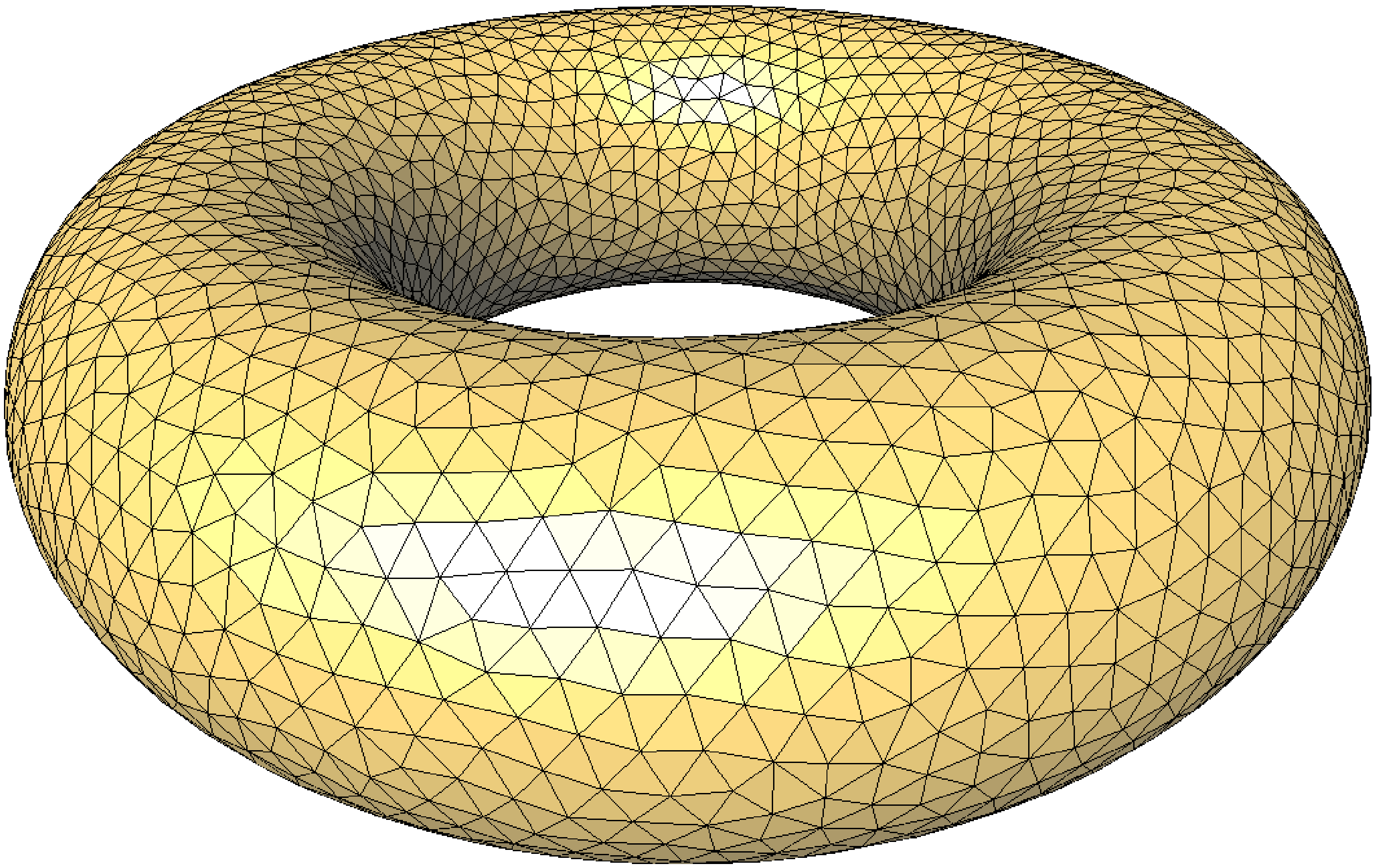




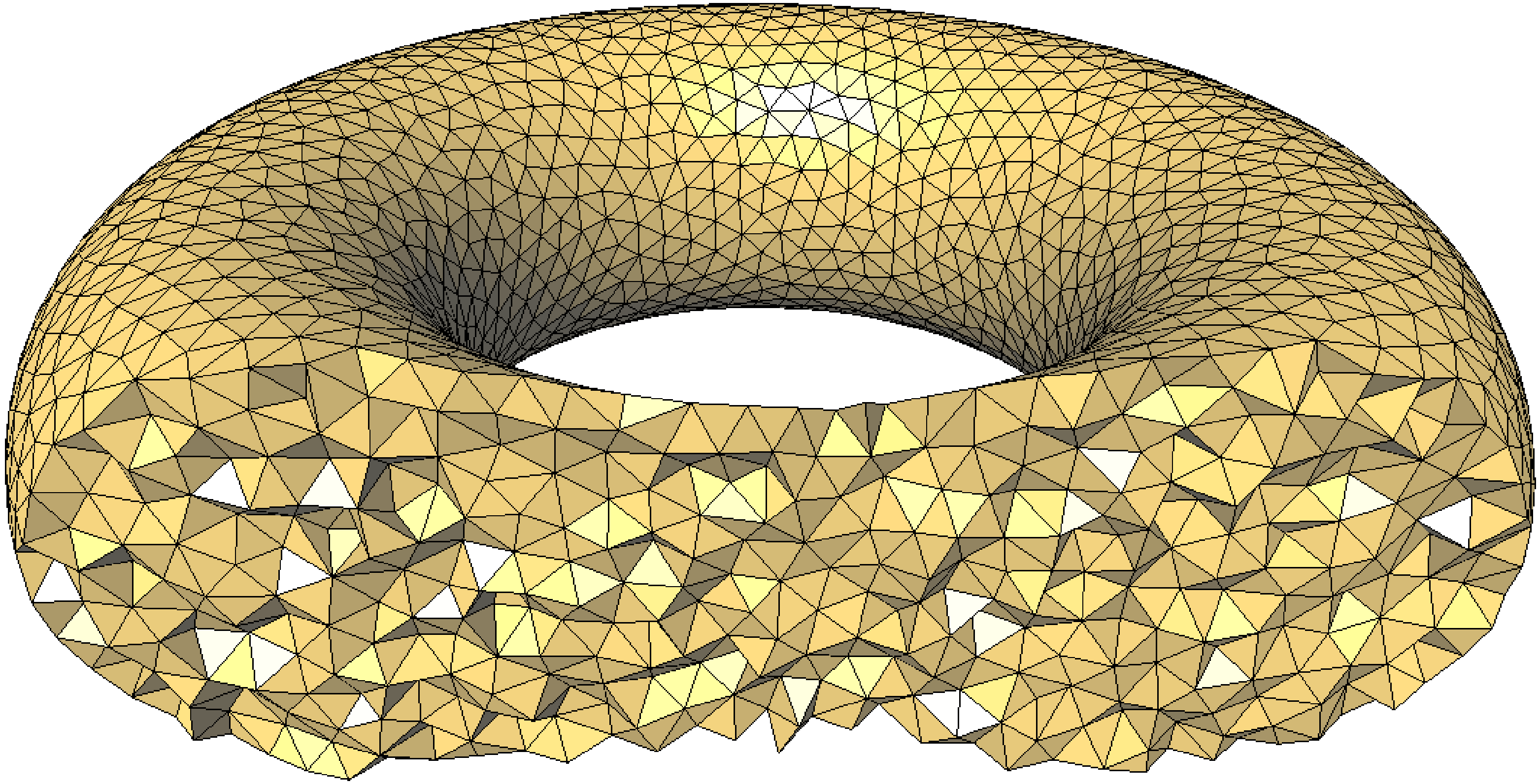
Optimization: step 50



Optimization: step 50

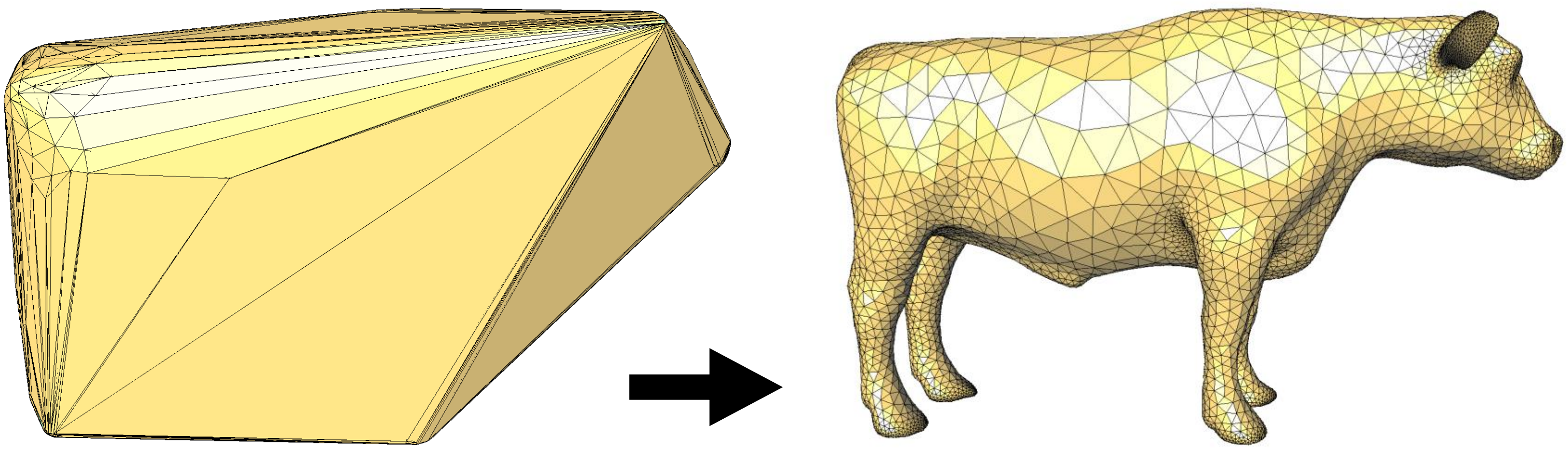


Optimization: step 50

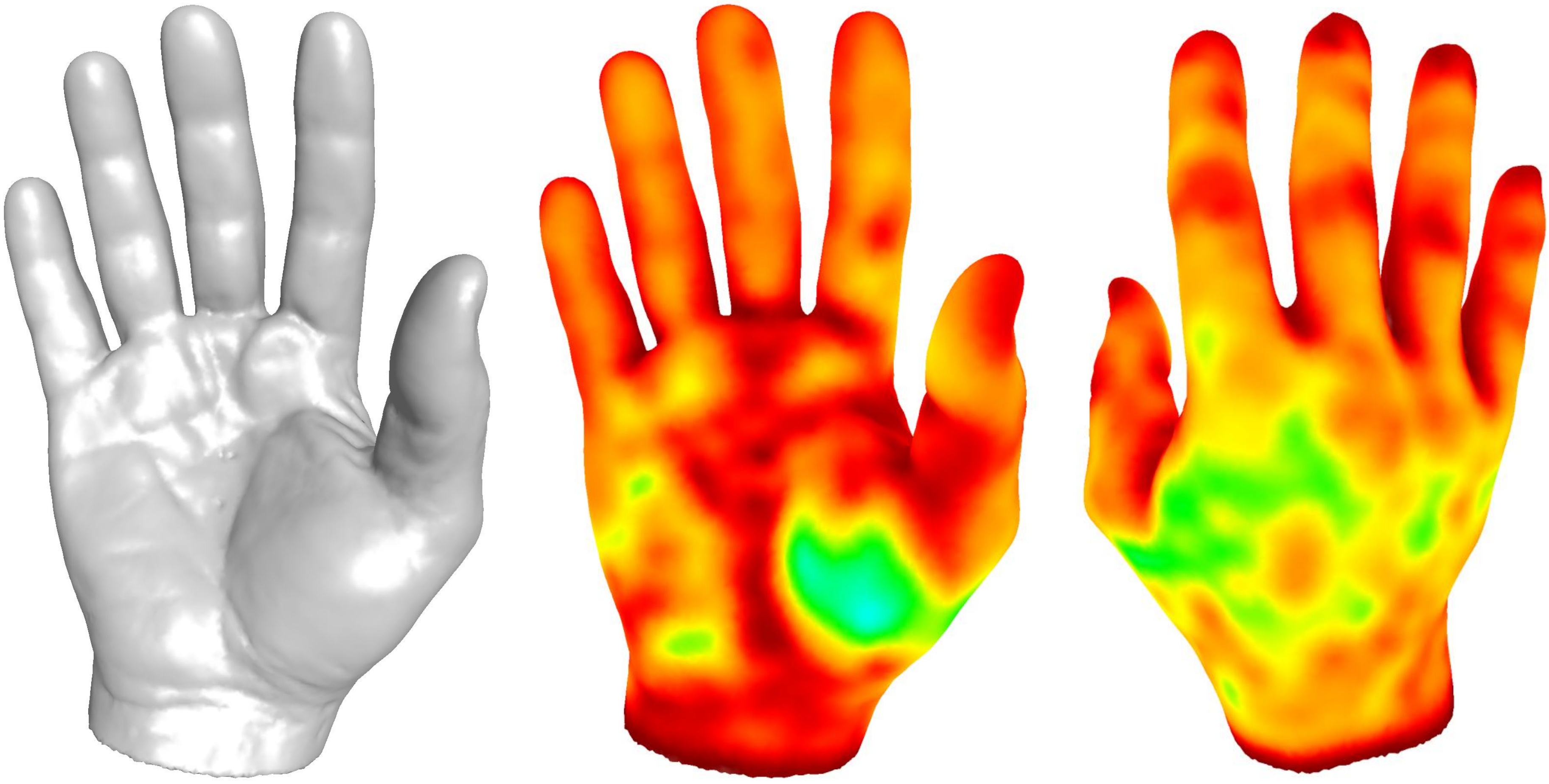


Interior Mesh Extraction

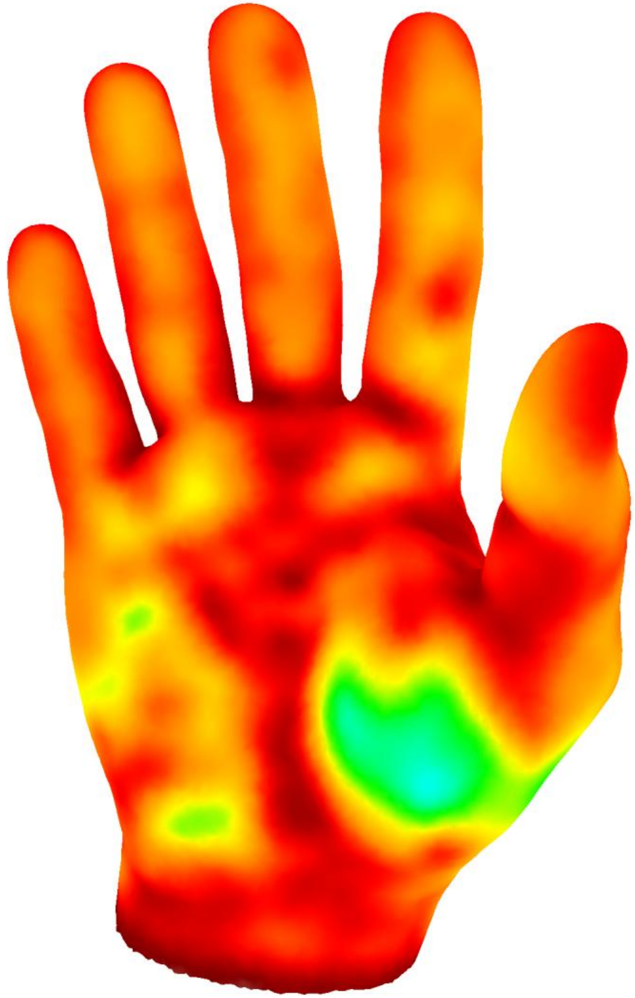
- Delaunay triangulation tessellates the convex hull

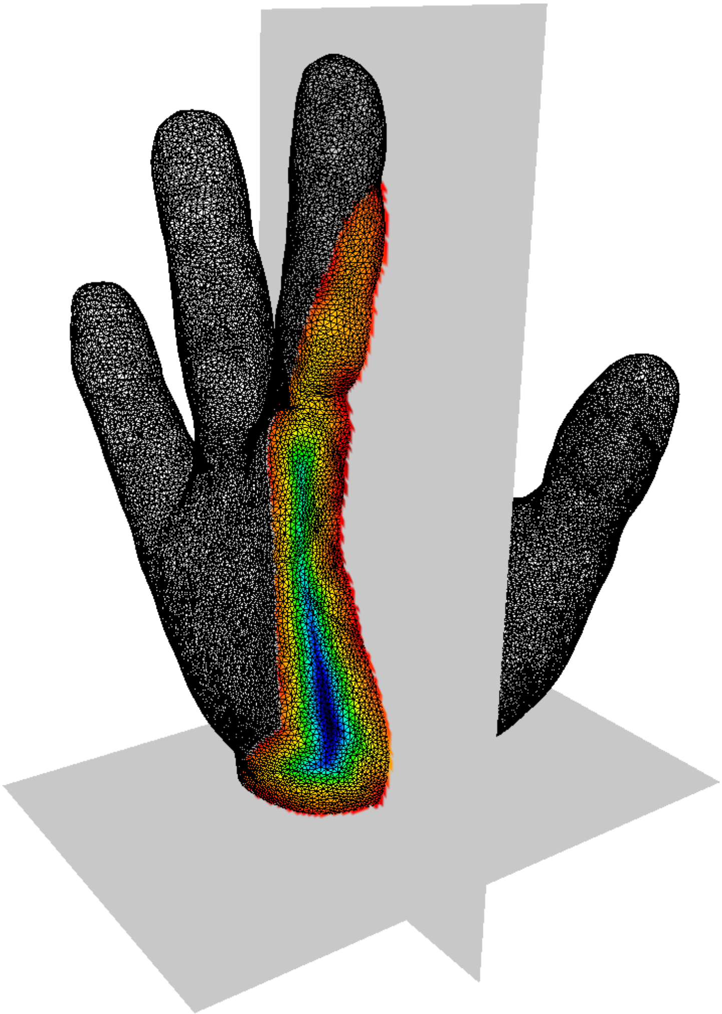


Hand: lfs



Hand: Sizing





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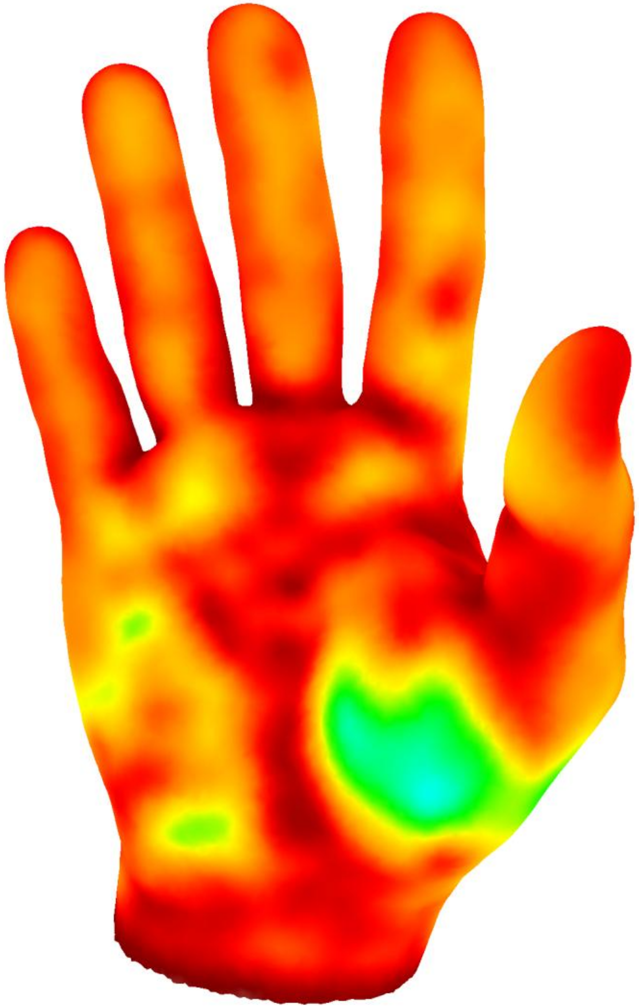

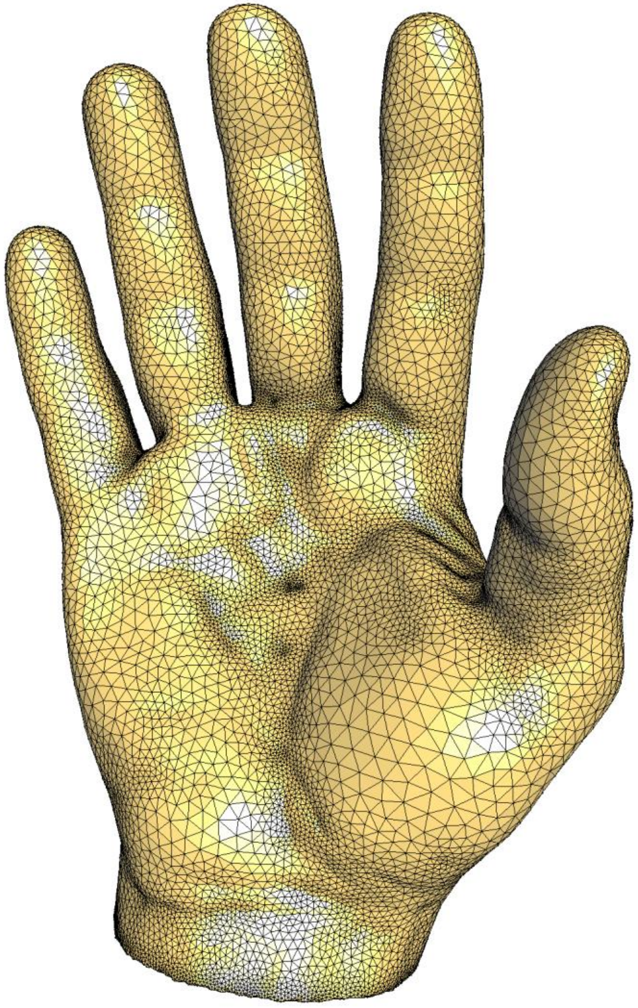

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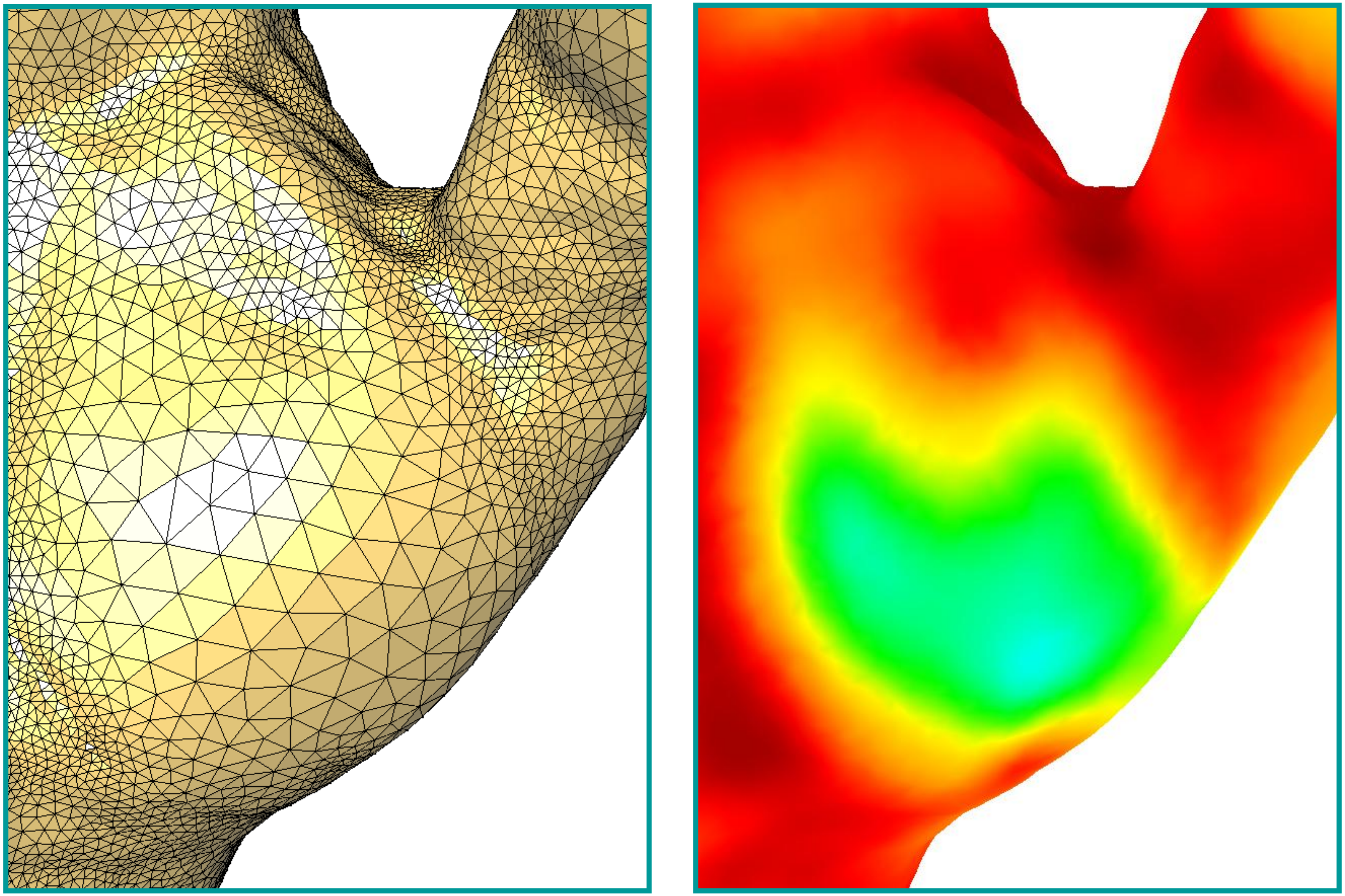
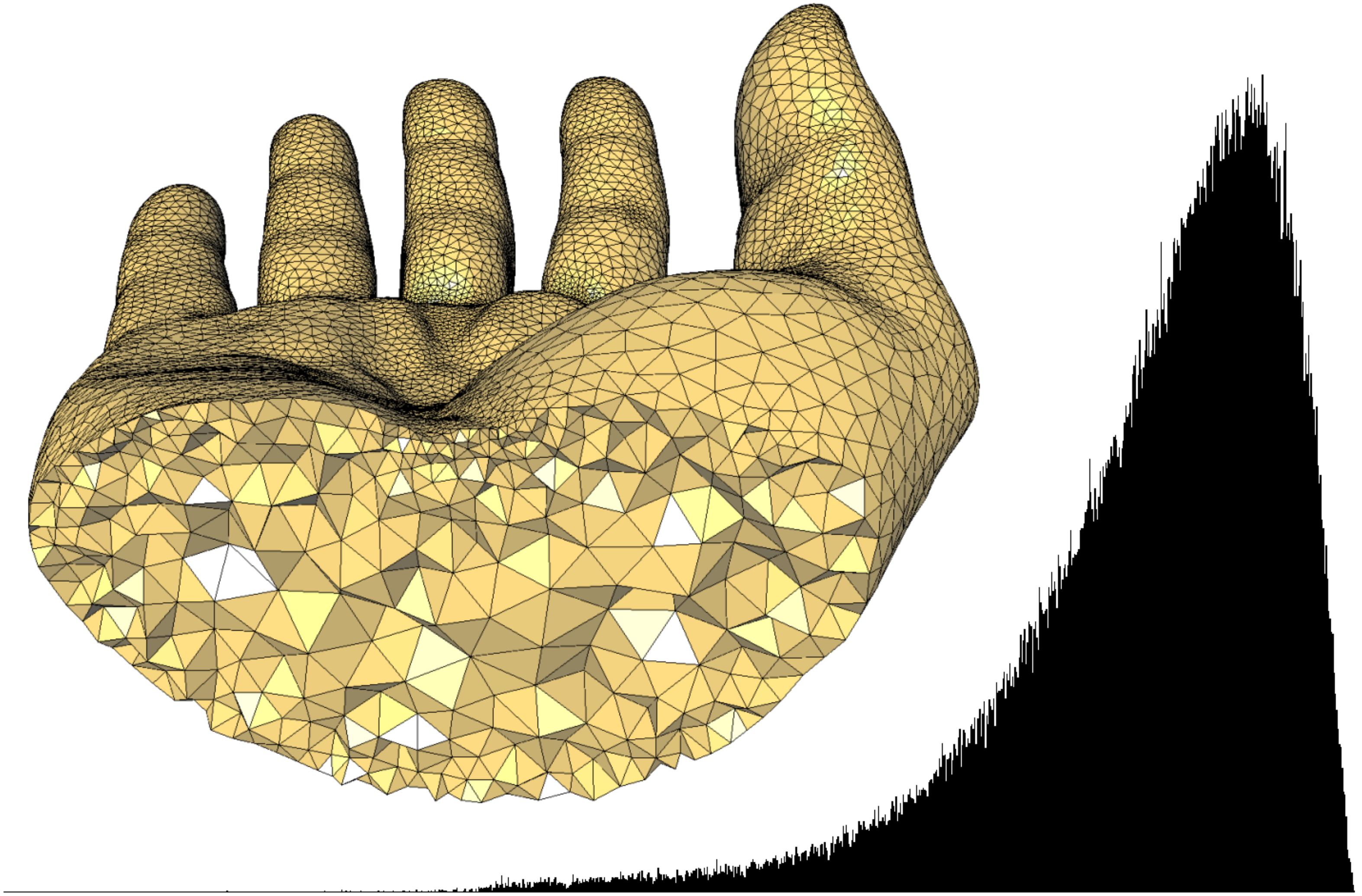
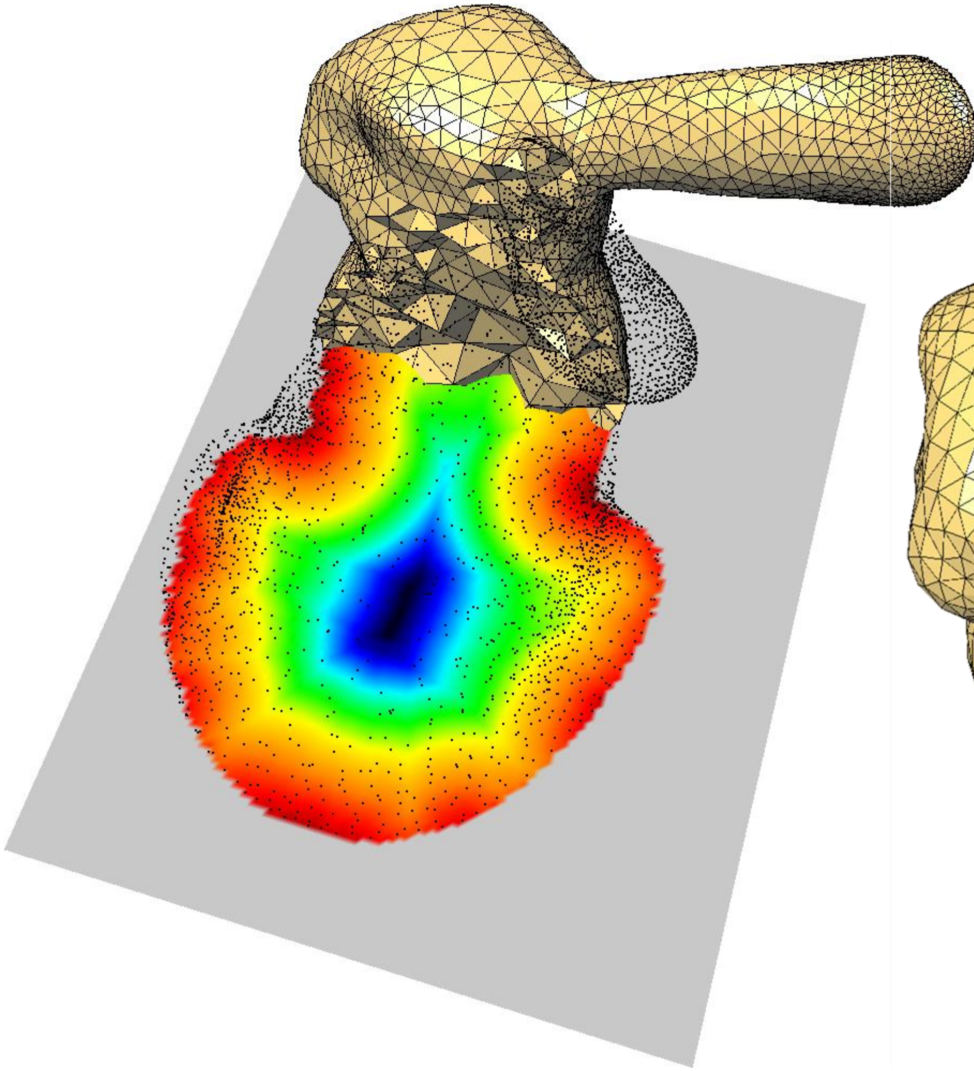
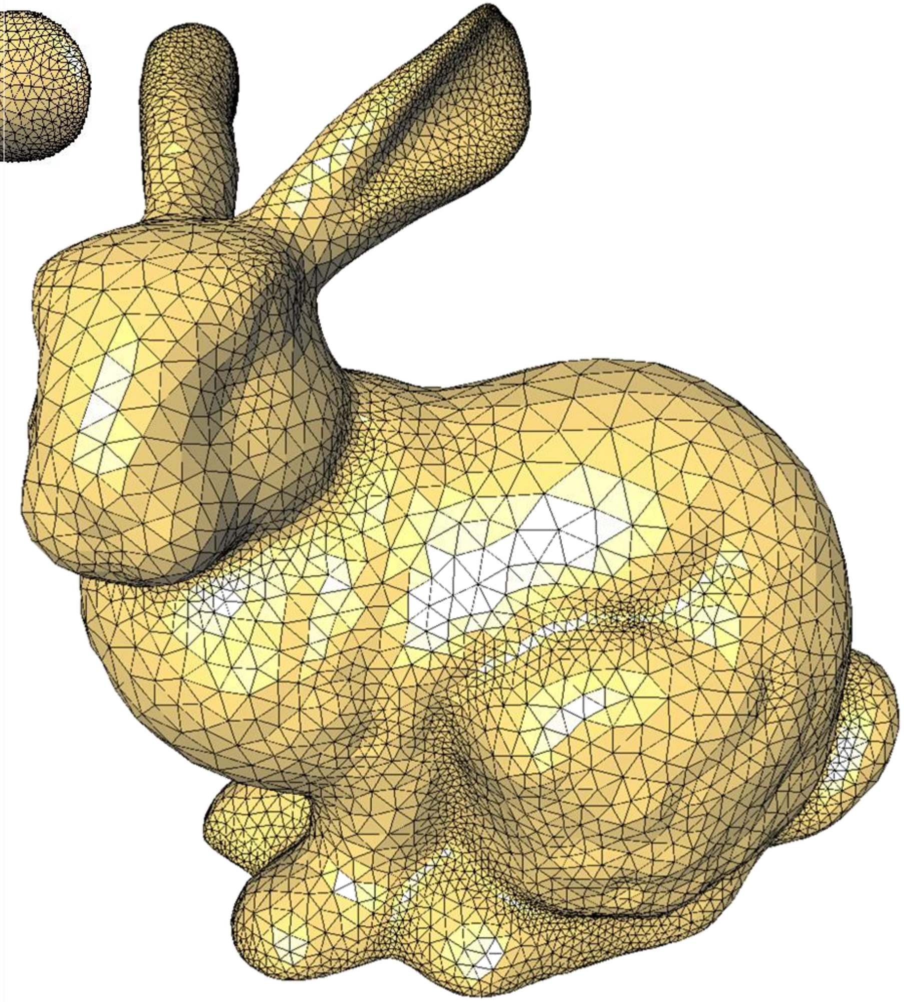


Hand: Radius Ratios

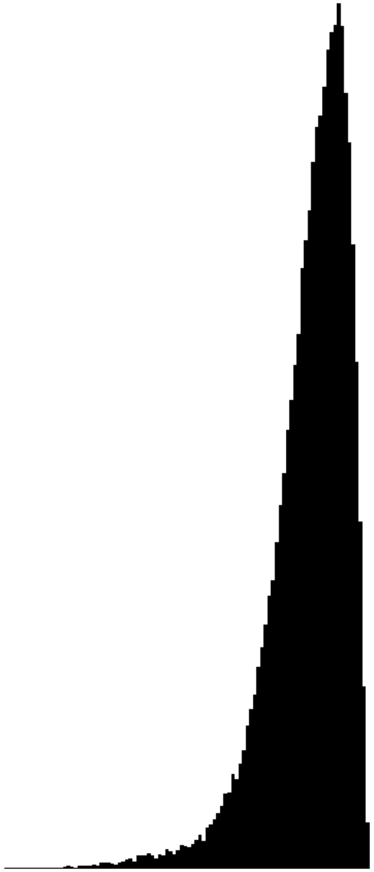


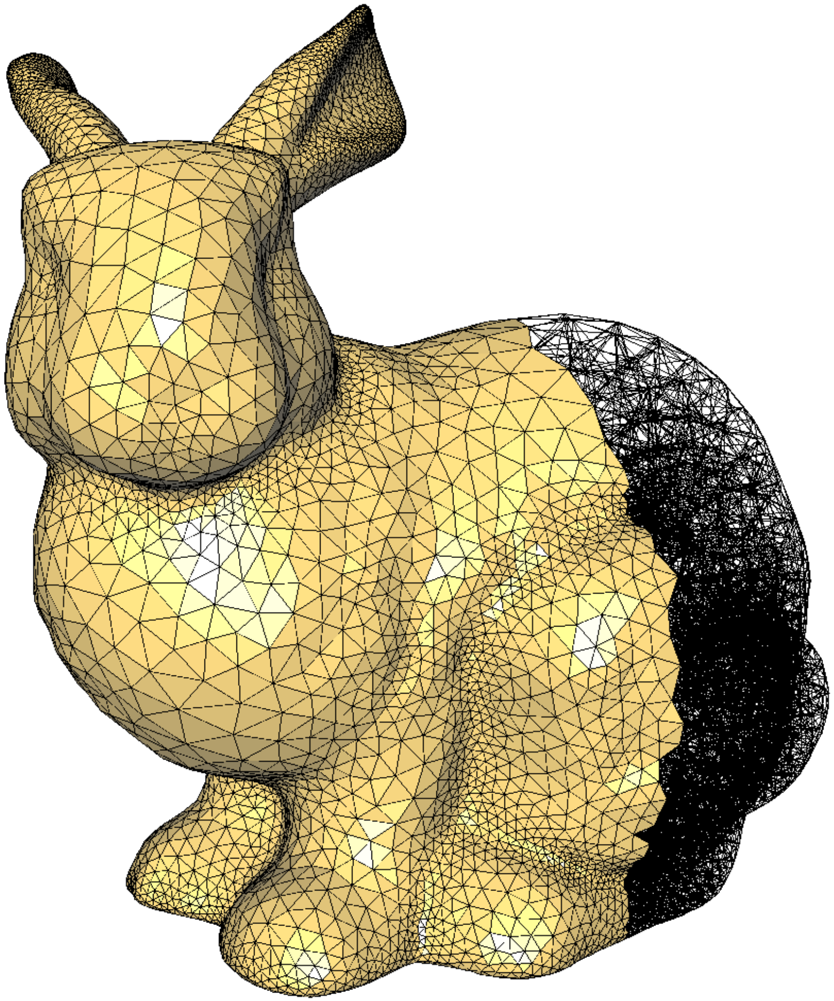
Stanford Bunny



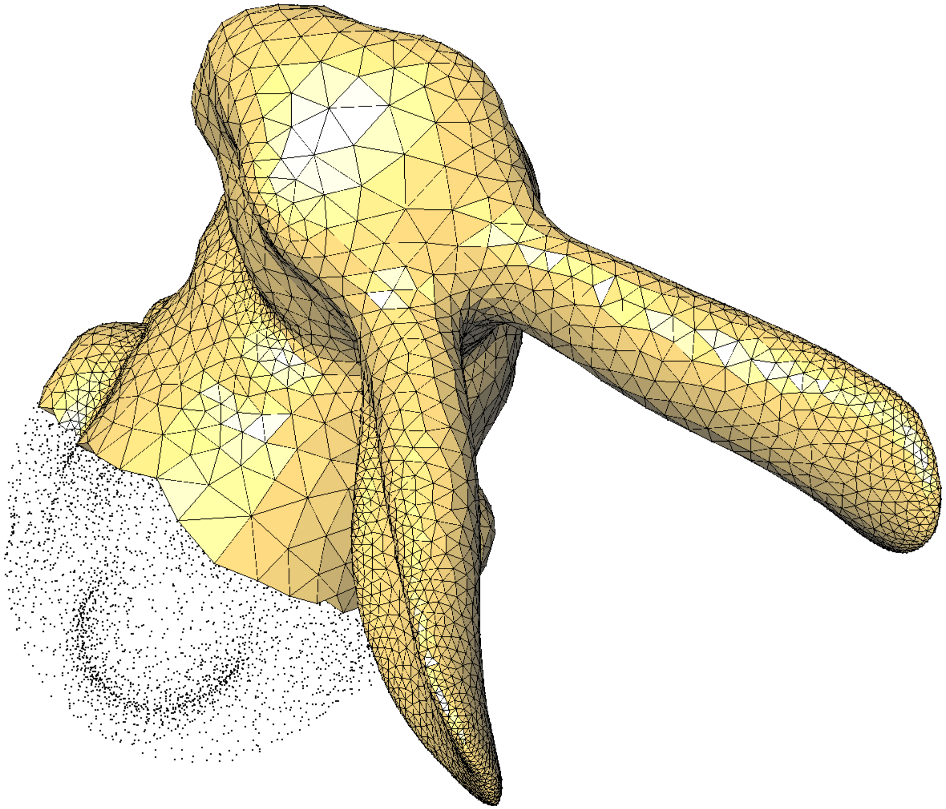


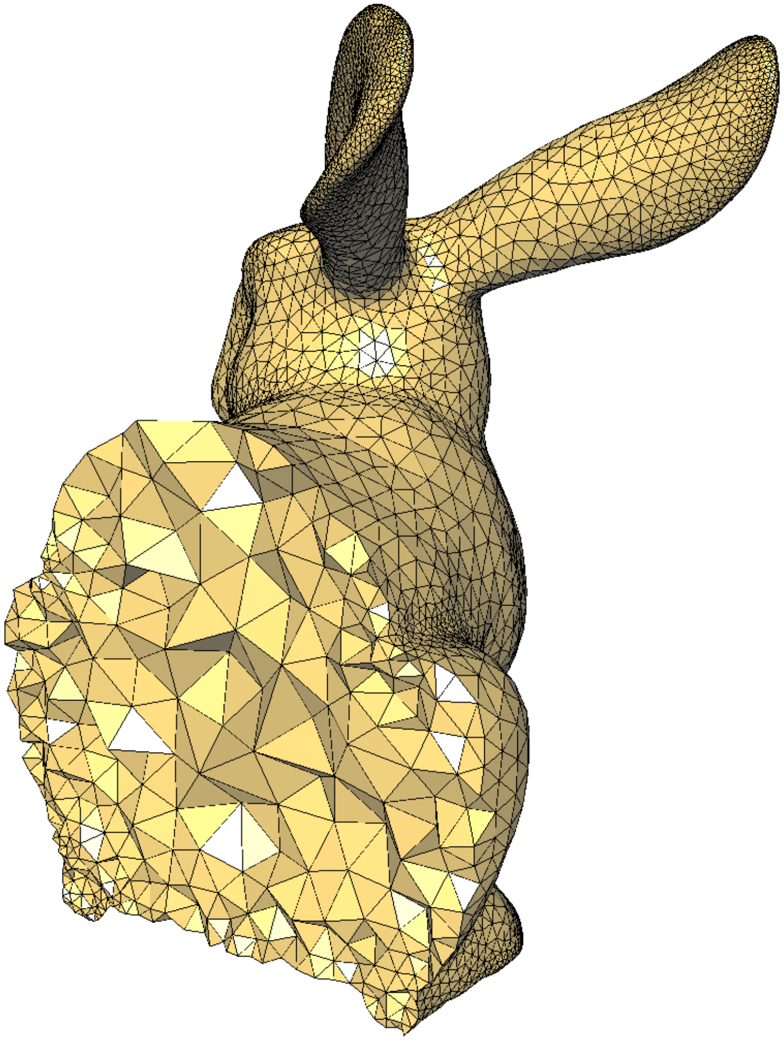
Stanford Bunny



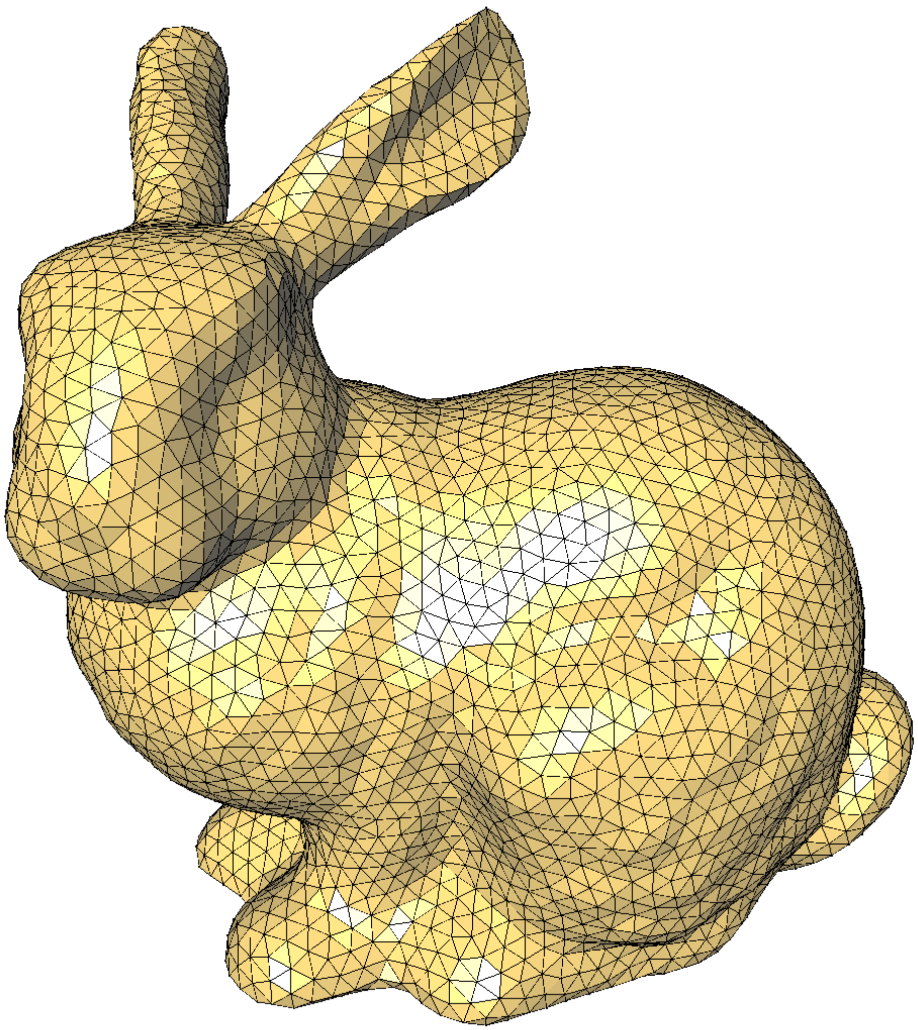


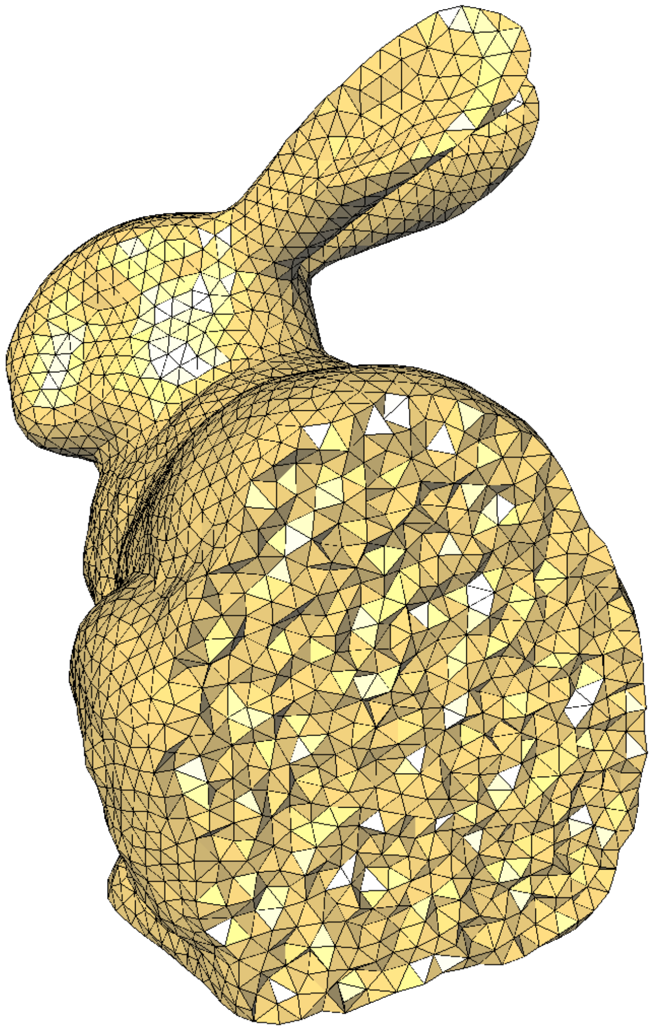
Stanford Bunny



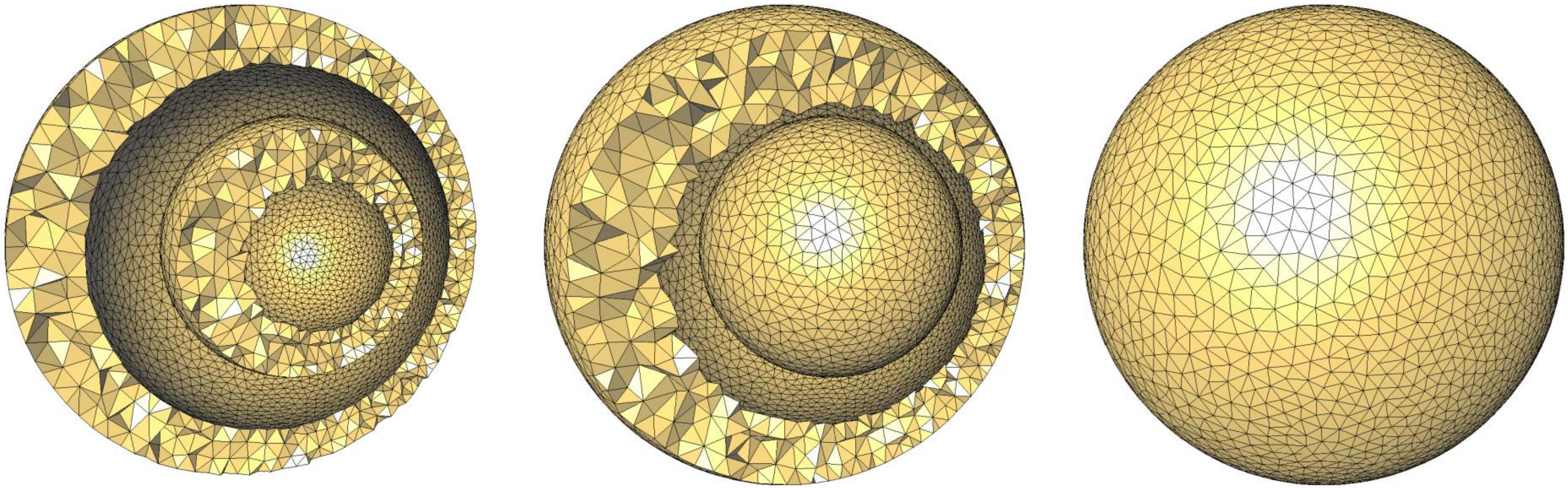


Stanford Bunny (uniform)

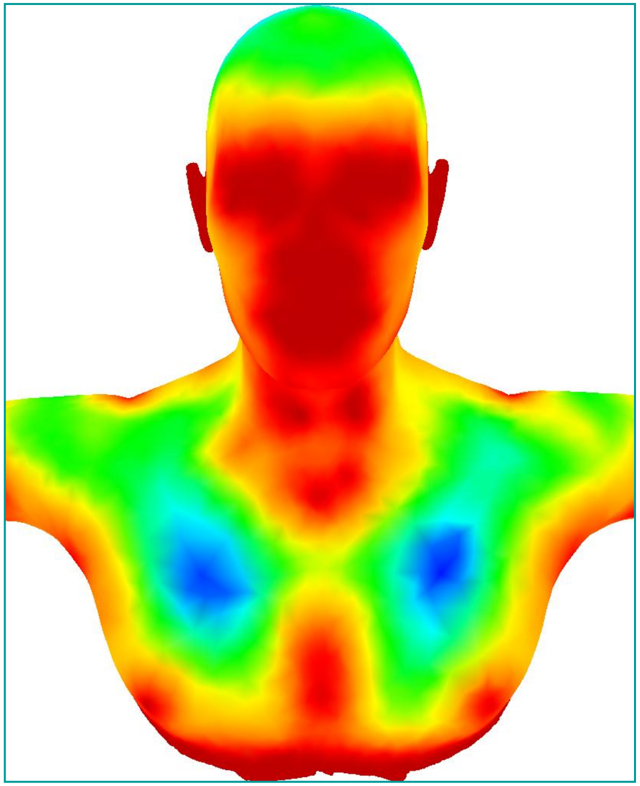


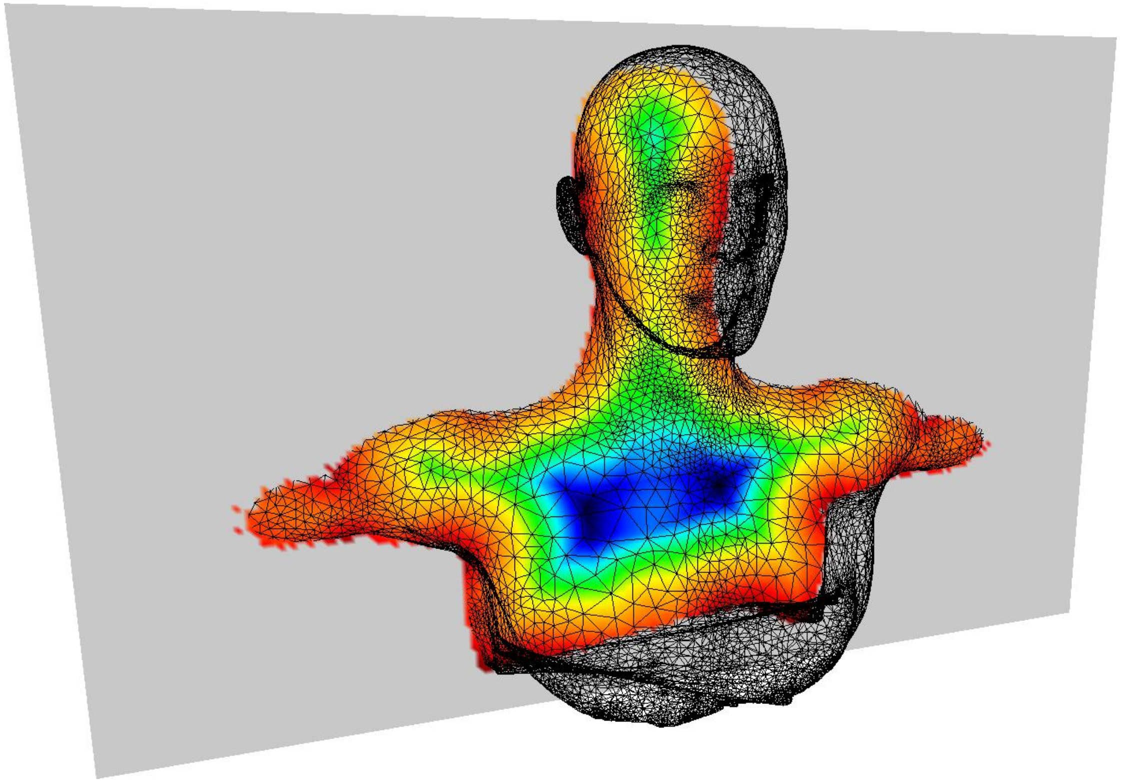


Nested Spheres



Torso





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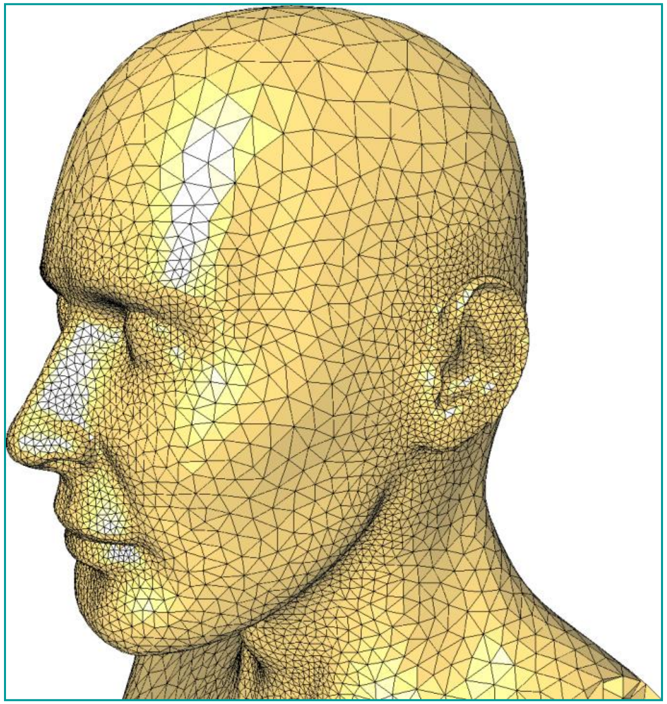

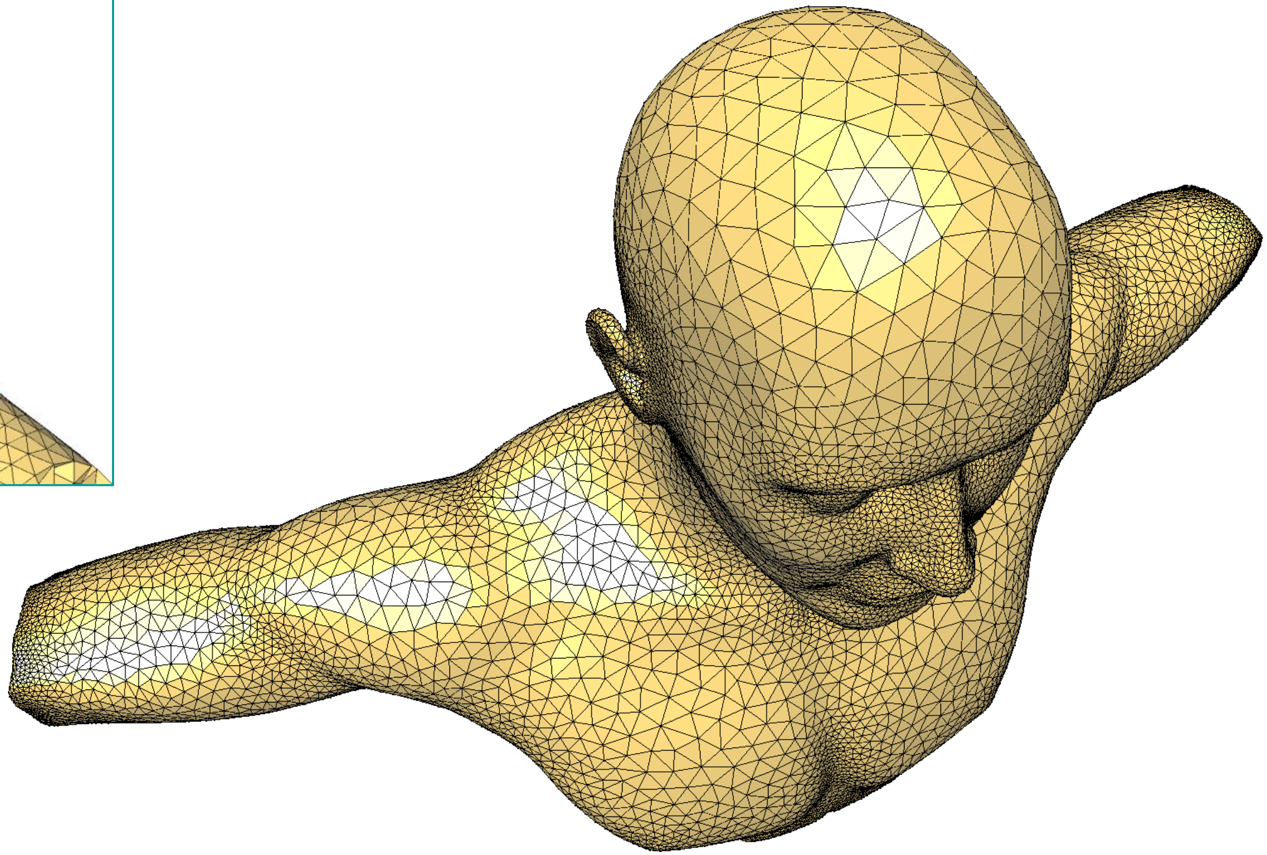

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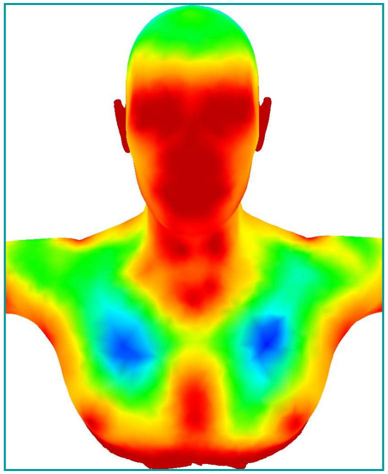

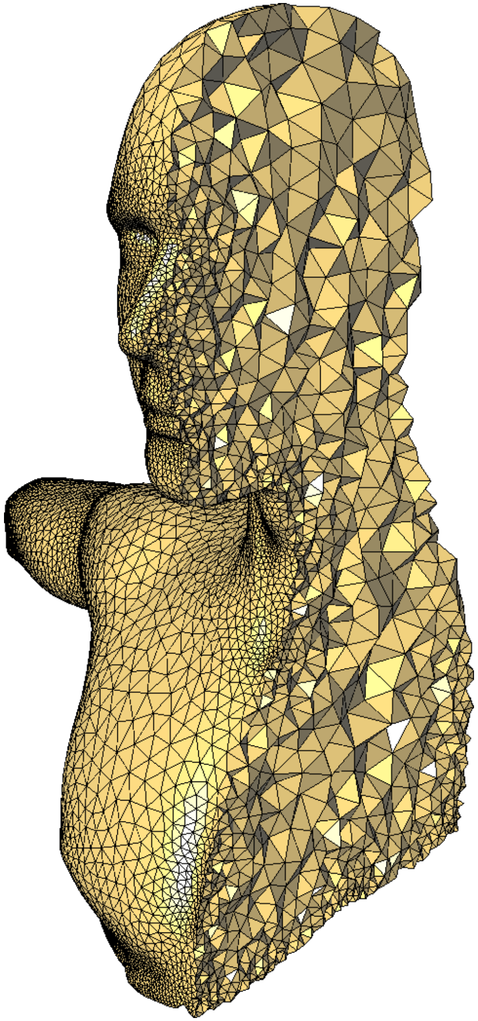

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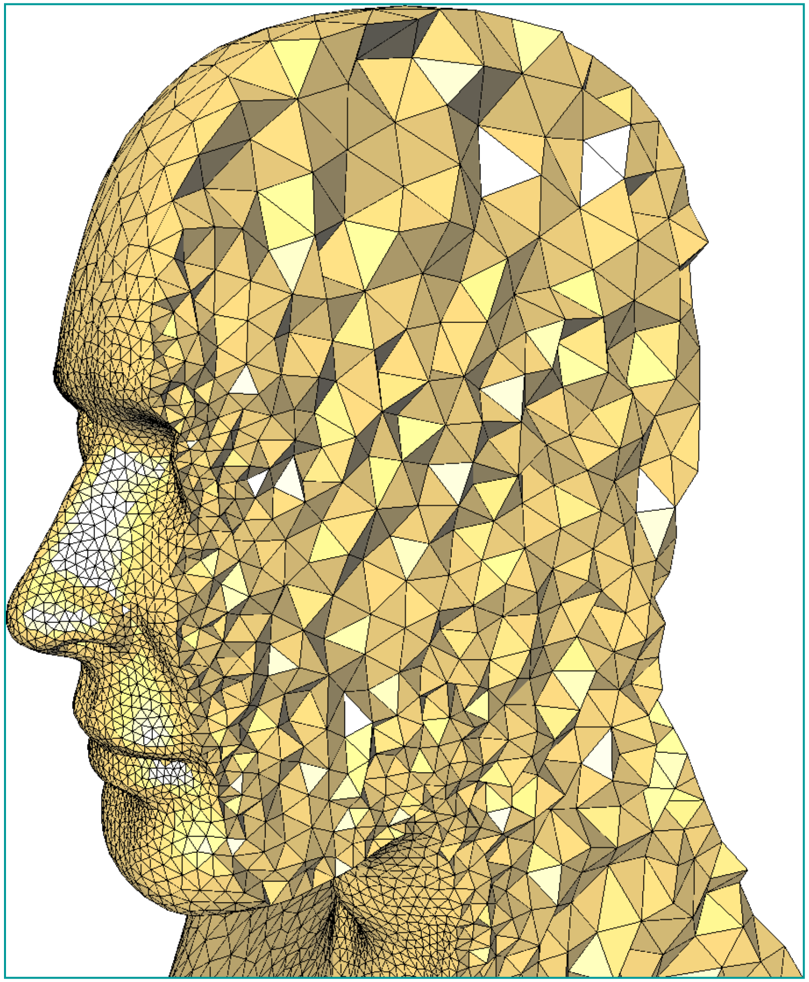

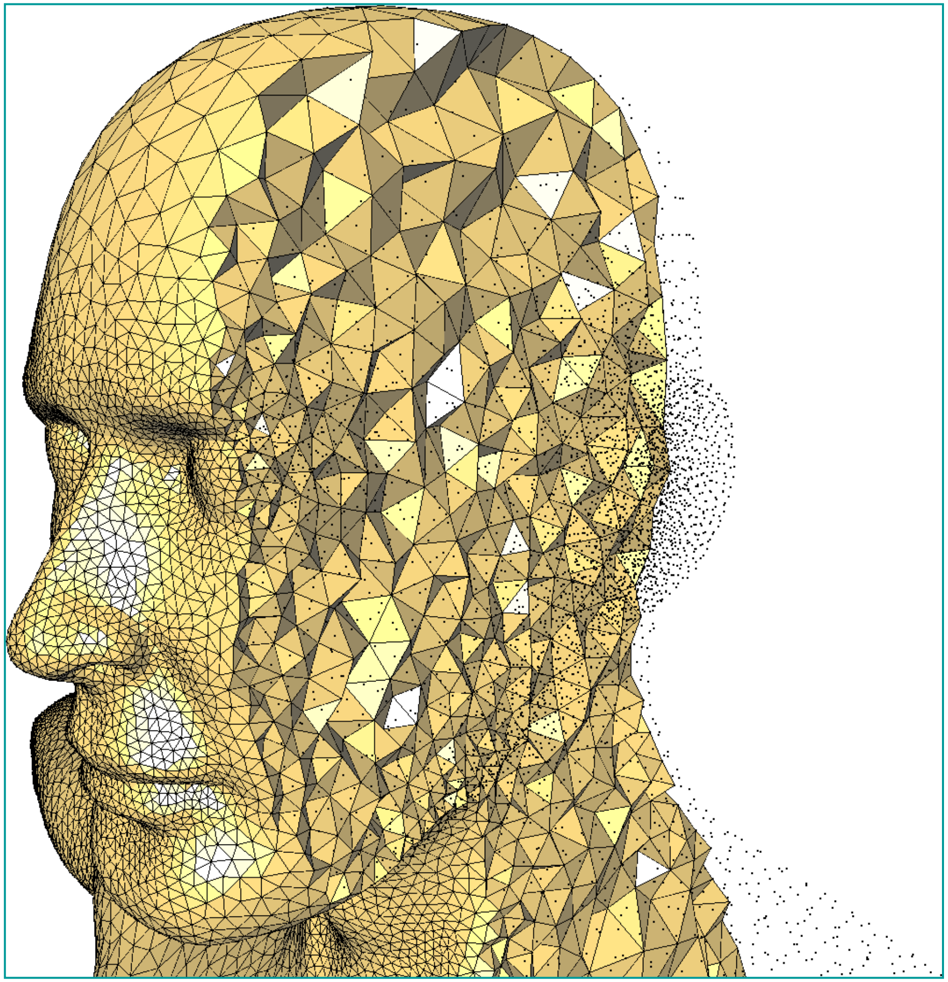

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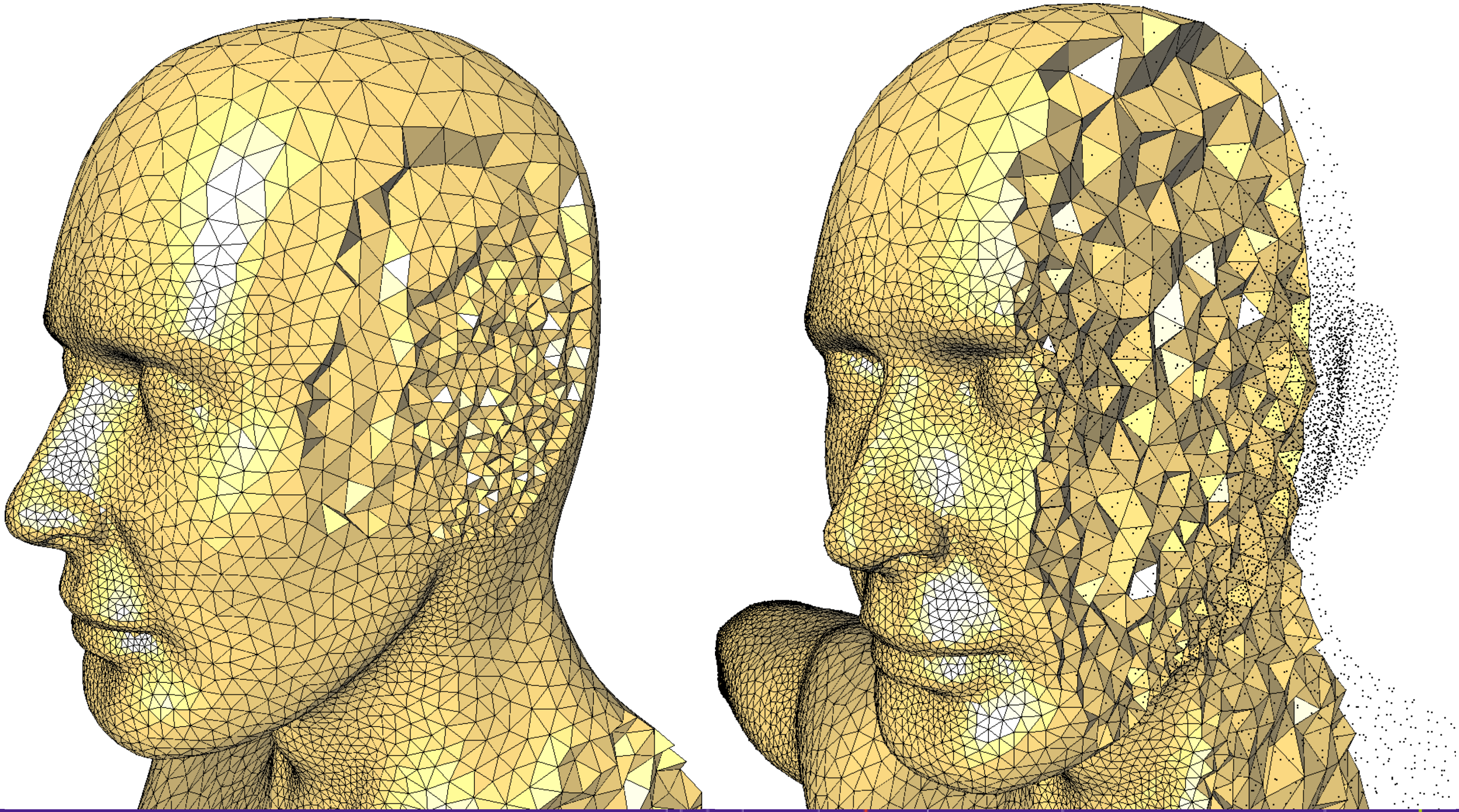
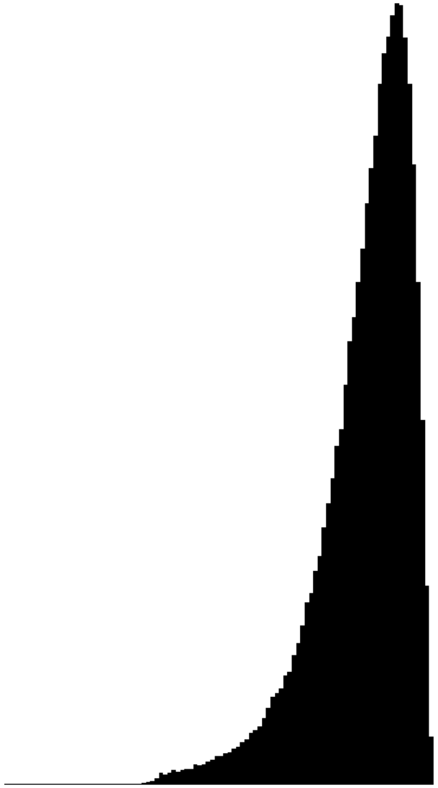
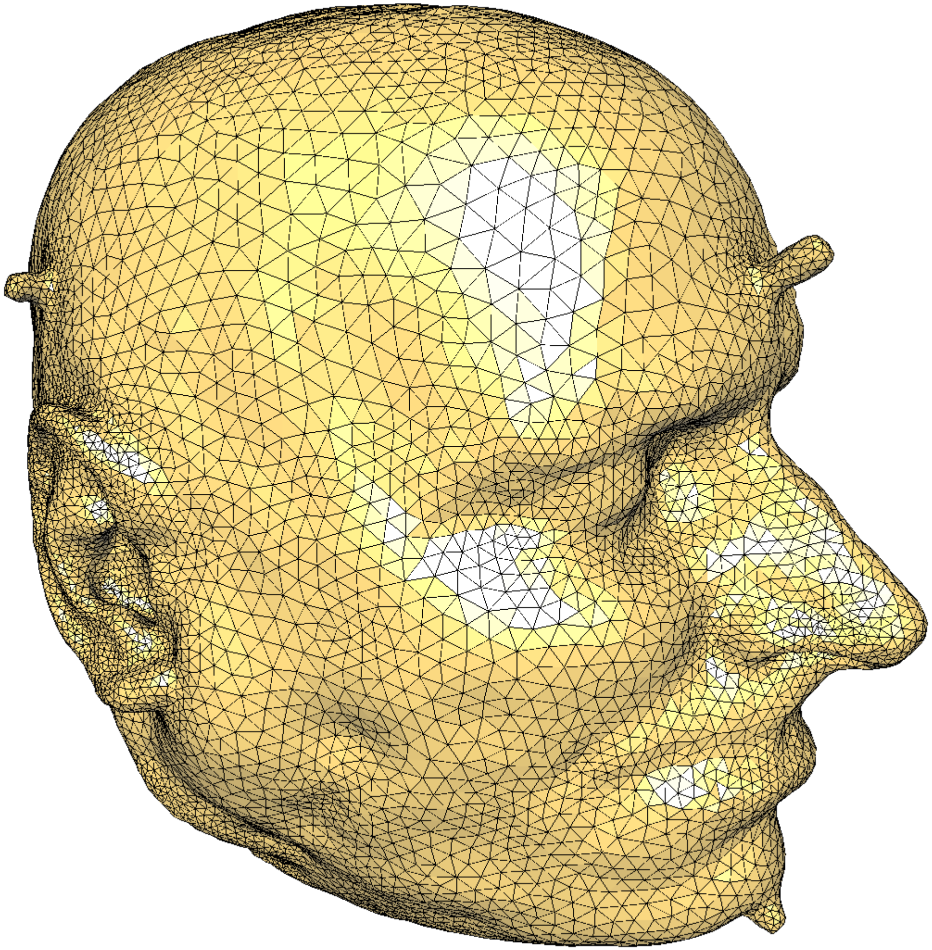
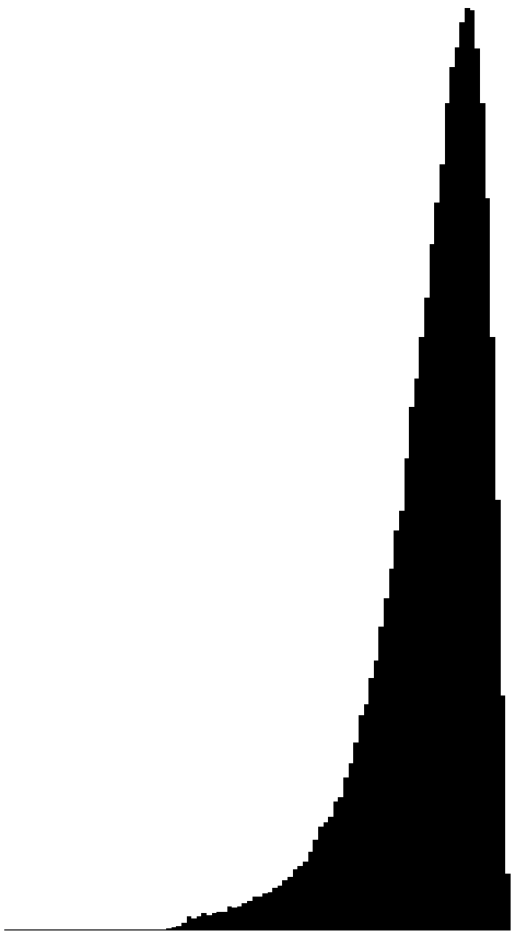
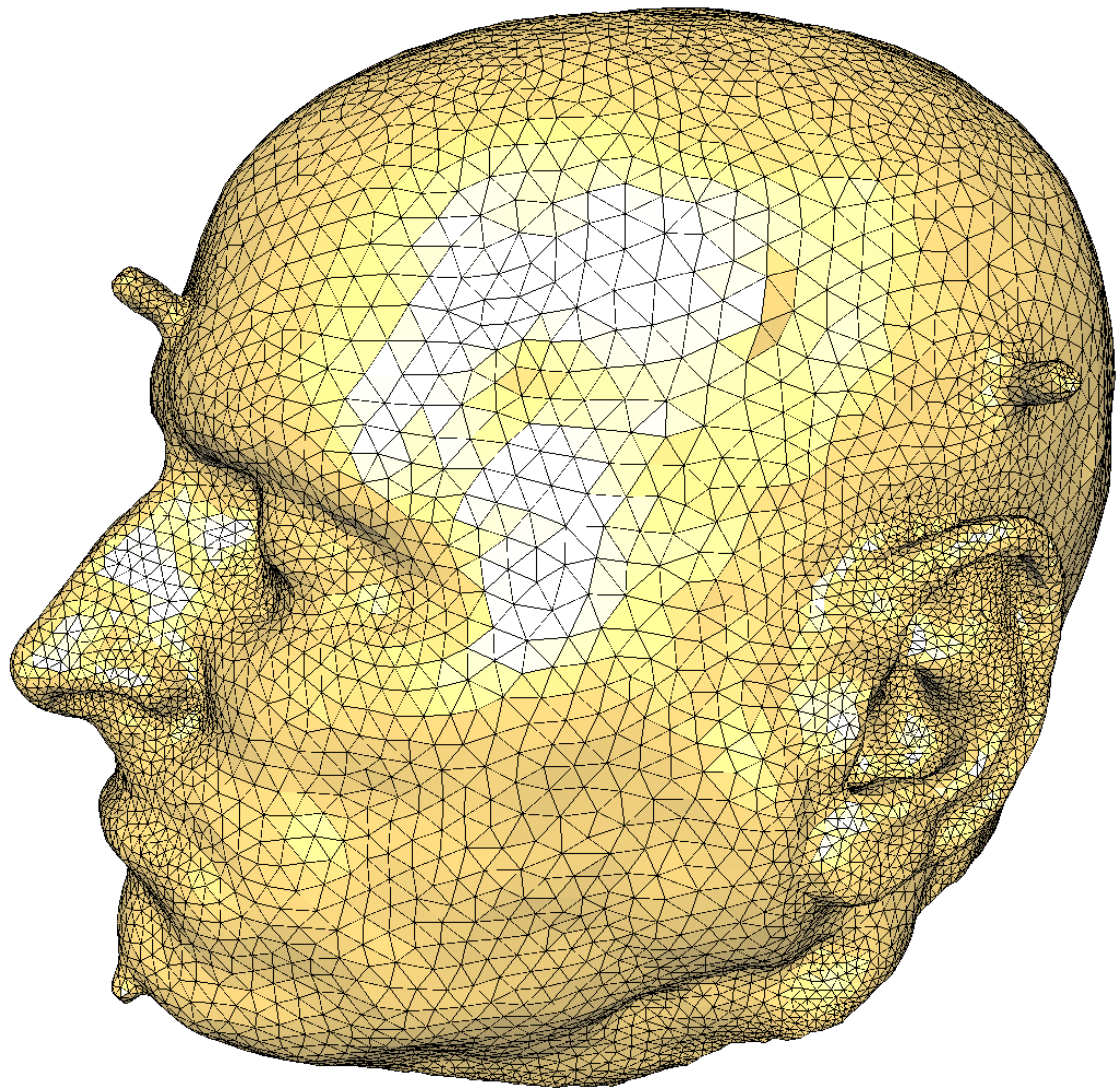


The Visible Human

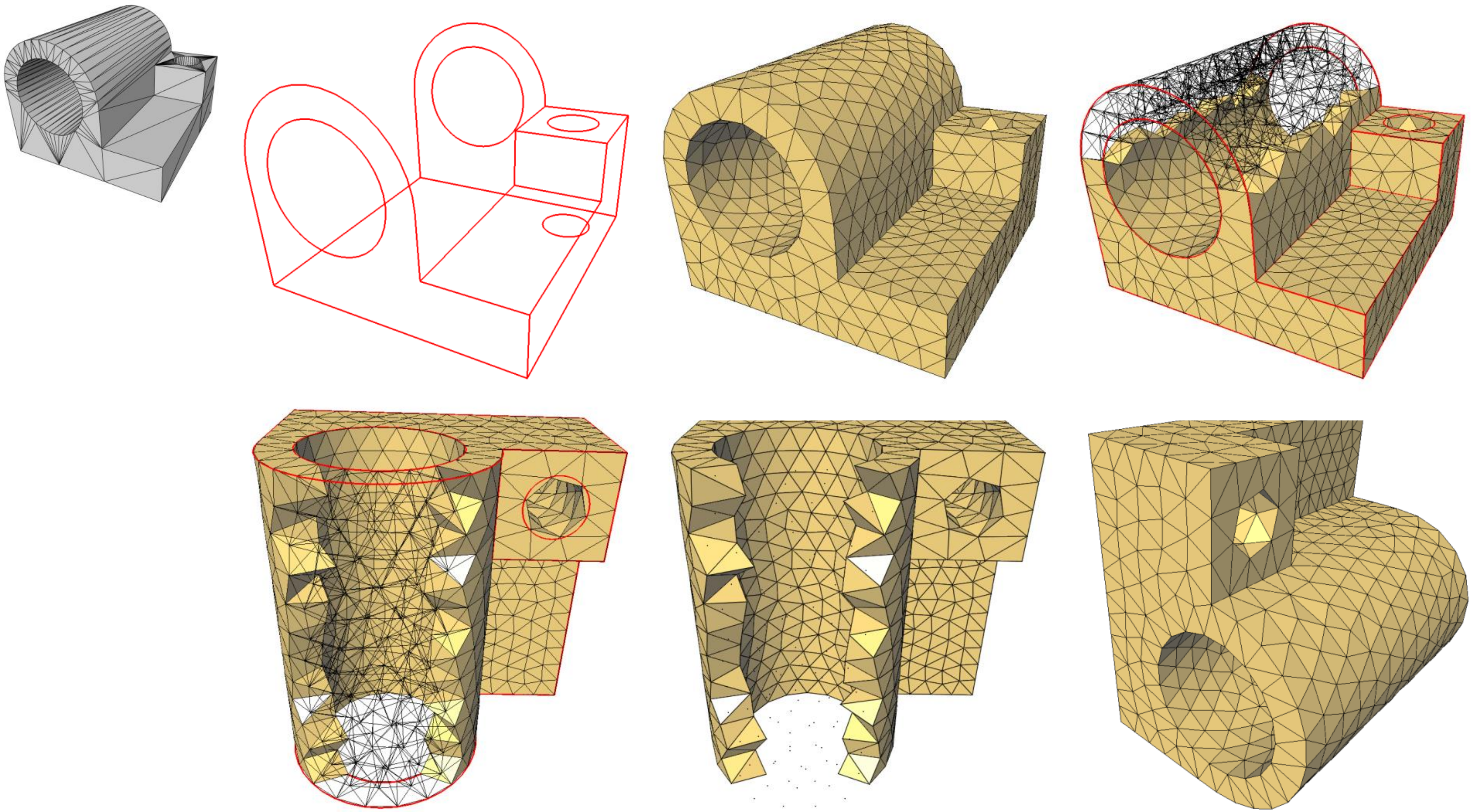




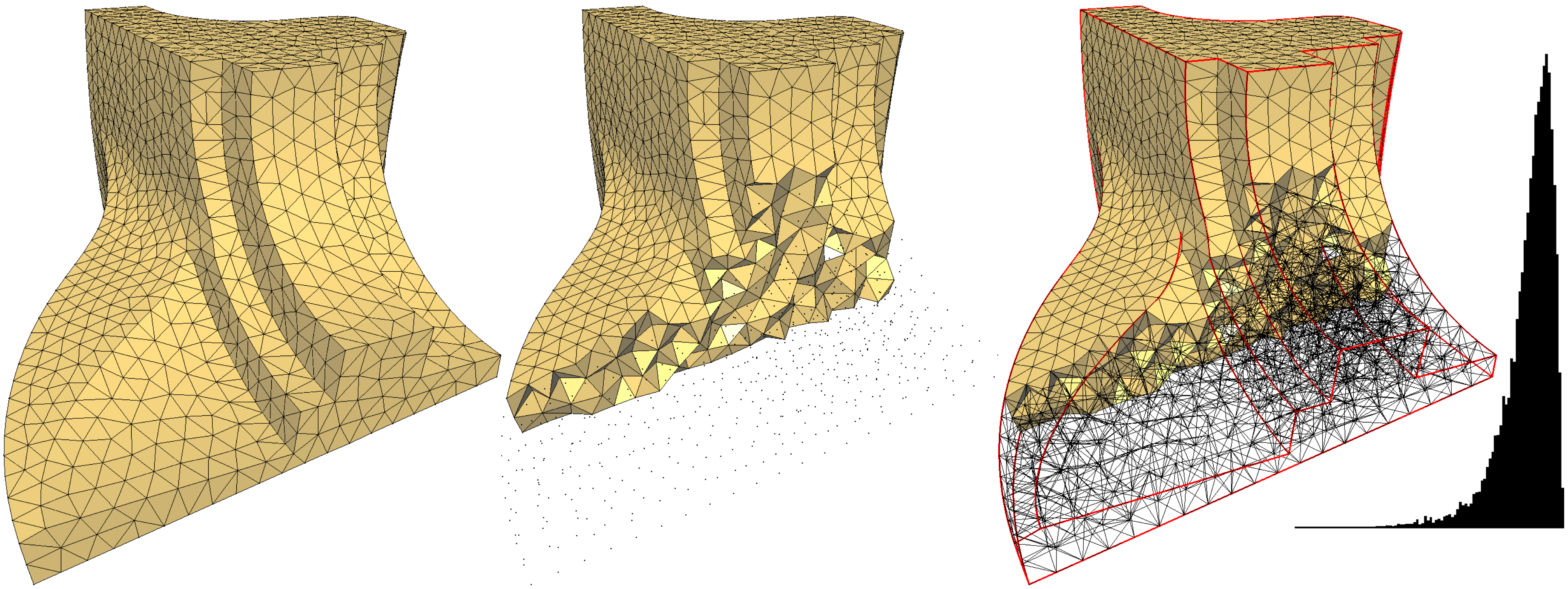




Joint



Fandisk



Conclusion

- Meshes
  - Definition, variety
  - Background
    - Voronoi
    - Delaunay
    - constrained Delaunay
    - restricted Delaunay
  - Optimization
    - 2D, 3D
    - Lloyd iteration, function approximation approach