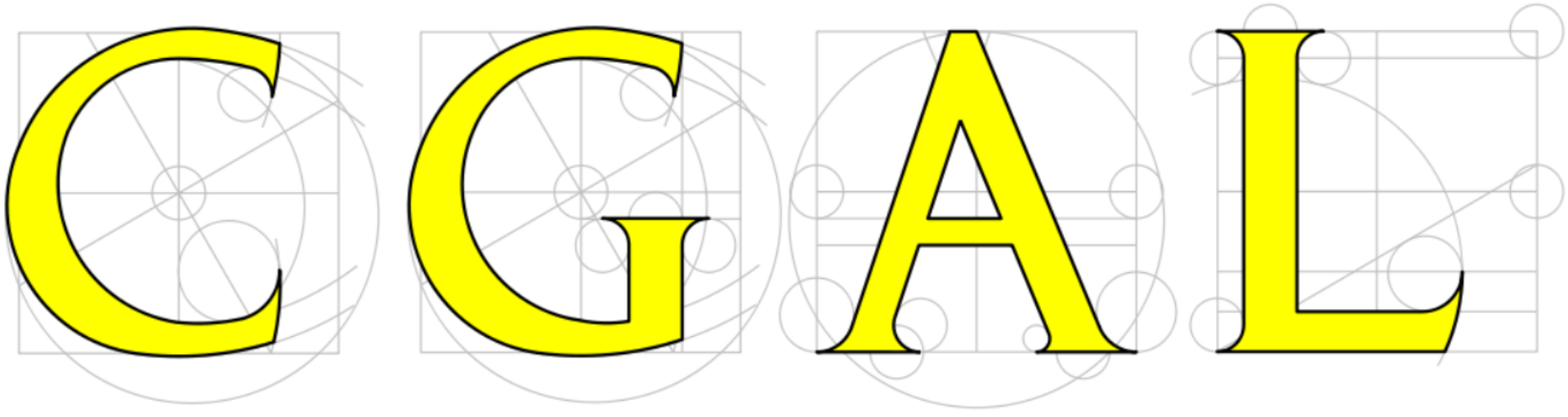


Polygon Mesh Processing in CGAL

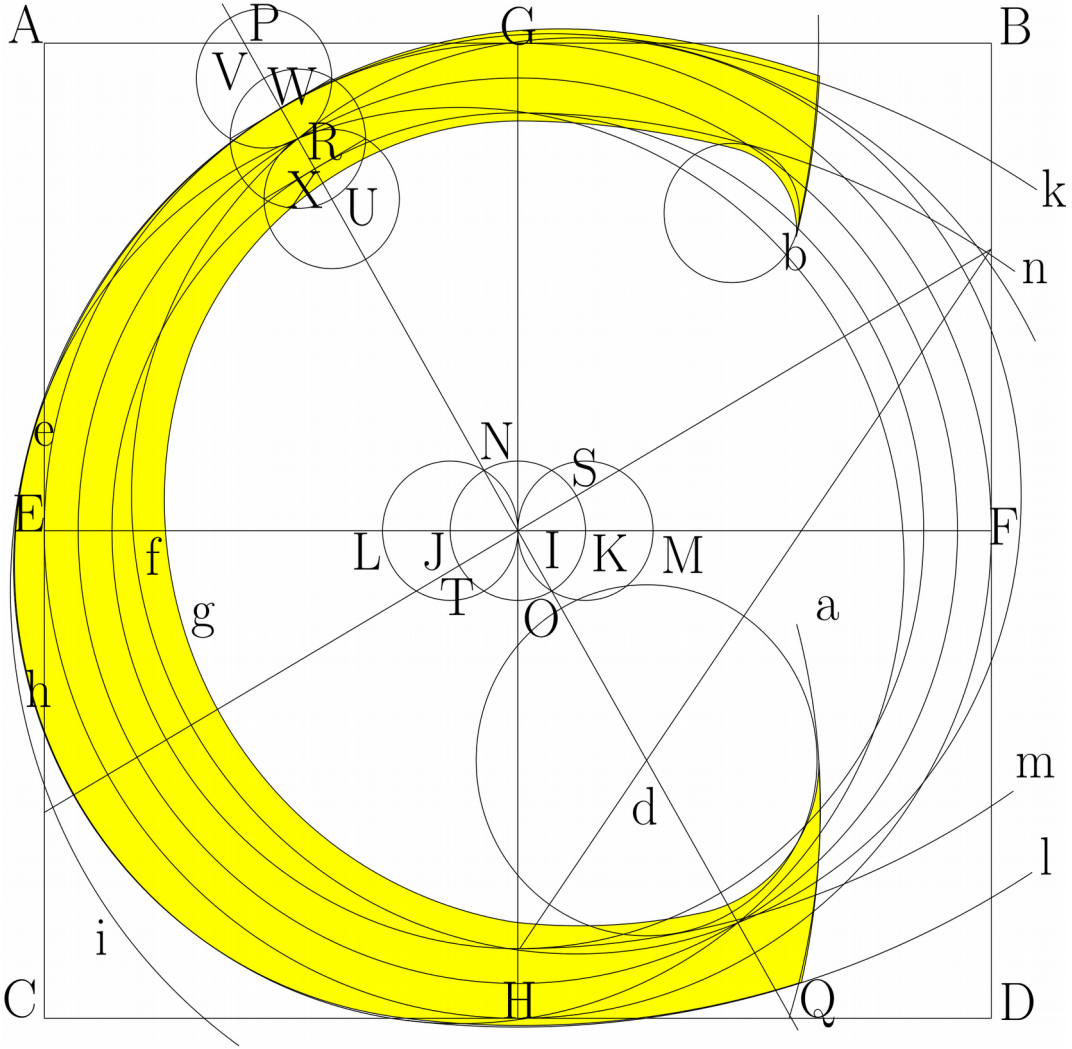
Sébastien Loriot
GeometryFactory

TAU
2017/05/29

GeometryFactory

- 7 engineers (6 PhD, produced by INRIA)
- Actively involved in the CGAL Project (reviews, release management, ...)
- License contracts with the academic partners

- Sales of CGAL software components
- Support to increase customer productivity
- Improve components for customers
- Development of new components for customers



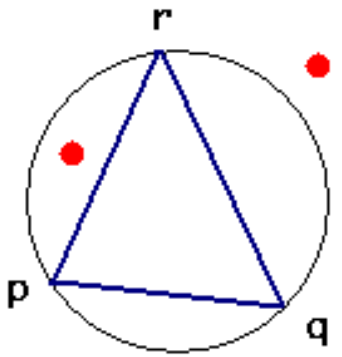
Generic Programming

STL Genericity

```
template <class Key, class Less>
class set {
  Less less;

  insert(Key k)
  {
     if (less(k, treenode.key))
       insertLeft(k);
     else
       insertRight(k);
  }
};
```

CGAL Genericity

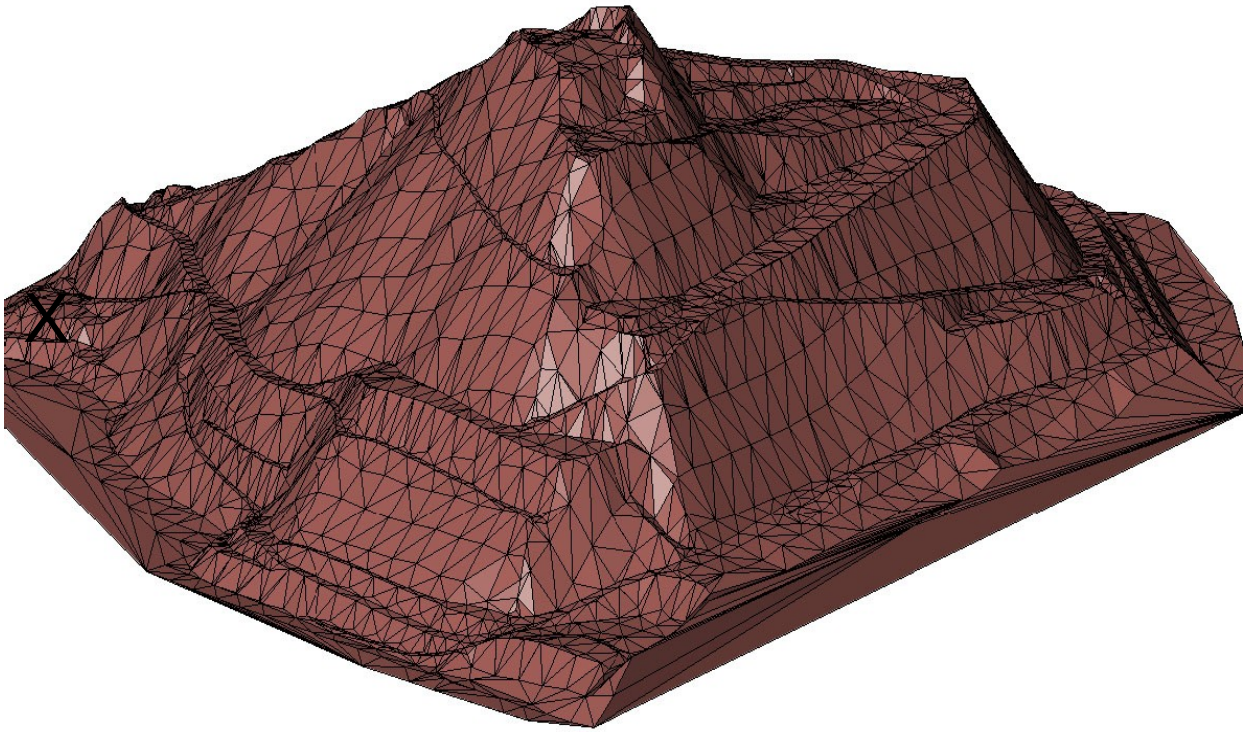
```
template < class Geometry >
class Delaunay_triangulation_2 {
    Geometry::Orientation orientation;
    Geometry::In_circle in_circle;

    void insert(Geometry::Point t) {
       ...
       if(in_circle(p,q,r,t)) {...}
       ...
       if(orientation(p,q,r){...}
    }
};
```



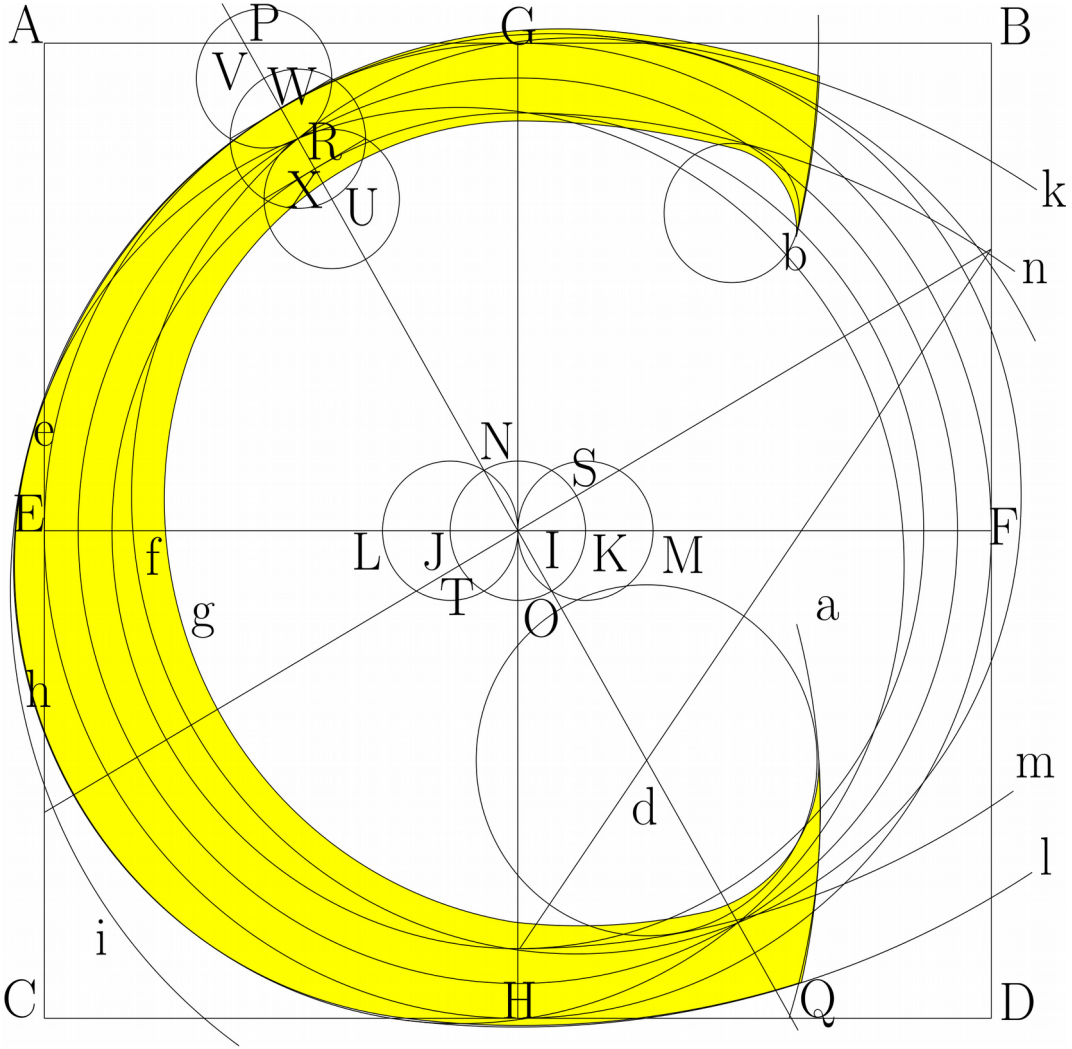
CGAL Genericity

Without explicit conversion to points in the plane

- Triangulate the terrain in an xy-plane
- Triangulate the faces of a Polyhedron



Courtesy: IPF,Vienna University of Technology & Inpho GmbH



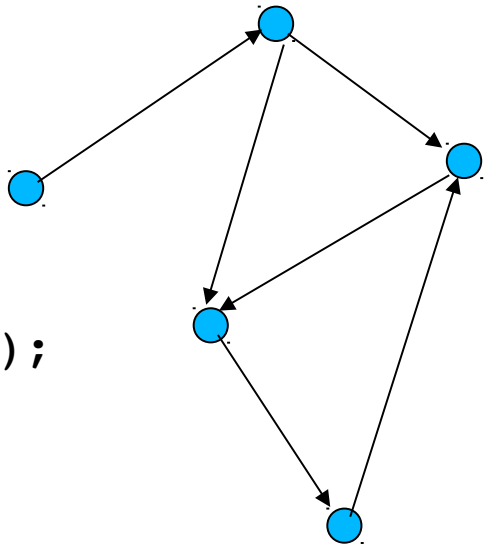
CGAL and the Boost Graph Library

Boost Graph Library (BGL)

- Rich collection of graph algorithms:
  shortest paths, minimum spanning tree, flow, etc.
- A set of concepts to define an abstraction layer for manipulating a graph:

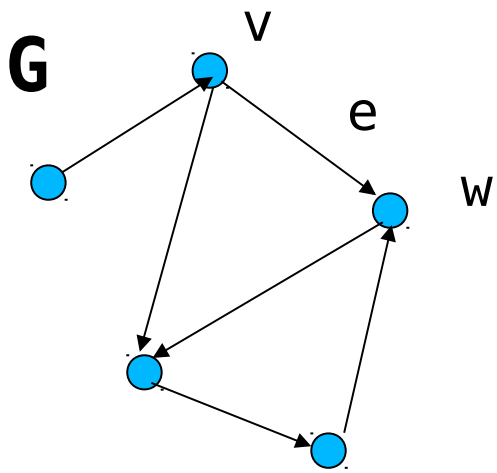
  → algorithms are independant from the data structure

```
boost::dijkstra_shortest_paths(g, source ,
                distance_map(distance_pmap)
                .predecessor_map(predecessor_pmap));
```



Boost Graph Library (BGL)

```
template <typename Graph>
struct graph_traits {
  typedef ... vertex_descriptor;
  typedef ... edge_descriptor;
  typedef ... vertex_iterator;
    ...
};
```




```
vertex_descriptor v, w;
edge_descriptor e;

v = source(e,G);
w = target(e,G);

BOOST_FOREACH(vertex_descriptor v, vertices(G))
{
  ...
}
```

Boost Graph Library (BGL)

BGL and CGAL

- Glue layer for triangulations, arrangements, HDS, Surface_mesh, Polyhedron_3, OpenMesh, …

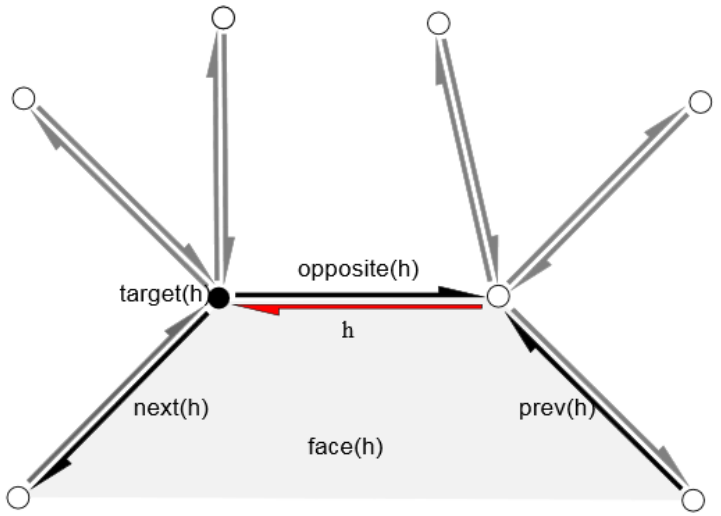
  → We can call dijkstra directly on a CGAL triangulation

- Extension to halfedge and face graphs to implement generic algorithm on polyhedral surfaces
- Most CGAL algorithms are using this API (all in a near future)
- Useful also for having wrappers (`Face_filtered_graph`, ...)

Boost Graph Library (BGL)

```
template <typename FaceGraph >
struct boost::graph_traits {
    typedef ... vertex_descriptor;
    typedef ... edge_descriptor;
    typedef ... halfedge_descriptor;
    typedef ... face_descriptor;
};
```

```
h_opp = opposite(h,G);
h_next = next(h,G);

h = halfedge(e,G);
e = edge(h,G);

f = face(h,G);
h = halfedge(f,G);
```



Property Maps :

A generic way to associate properties to an object

```
template <class PMap>
struct property_traits {
    typename Pmap::key_type key_type;
    typename Pmap::value_type value_type;
    typename Pmap::reference reference;
    typename Pmap::category category;
};
```

Concepts:

- **ReadablePropertyMap**

  ```
  reference get(key_type key, PMap pmap);
  ```

- **WritablePropertyMap**

  ```
  void put(key_type key, PMap pmap, value_type value);
  ```

- **ReadWritePropertyMap** refines **ReadablePropertyMap** and **WritablePropertyMap**

- **Non-mutable LvaluePropertyMap** refines **ReadablePropertyMap**

  ```
  const value_type& v = pmap[k]
  ```

- **Mutable LvaluePropertyMap** refines **ReadablePropertyMap**

  ```
  value_type& v = pmap[k]
  ```

Property Maps

```
// defining a property map with Point_3 as value type and unsigned int as key
std::vector<Point_3> points;
CGAL::Pointer_property_map<Point_3> pmap(points);

// turning a std::map into a property map
std::map<vertex_descriptor, bool> std_map;
boost::associative_property_map< std::map<vertex_descriptor, bool> >pmap(std_map);

// User defined property map creating a CGAL point on the fly
struct MyPoint{ double x,y,z; };
struct My_pmap
{
  typedef MyPoint key_type;
  typedef boost::readable_property_map_tag category;
  typedef K::Point_3 value_type;
  Typedef value_type reference;

  friend reference get(const key_type& k, My_pmap) { return K::Point_3(k.x, k.y, k.z); }
};
```

Property Tags in BGL API

Tags enable generic code to define and get a property map.

```
typedef boost::property_map<PropertyGraph,
                            boost::vertex_index_t>::type PMap;

boost::property_traits<PMap>::key_type    k;
boost::property_traits<PMap>::value_type  v;

PropertyGraph graph;
PMap pm = get(boost::vertex_index,graph) ;

vi = get(pm,v);
put(pm, v, vi);
```

Dynamic Properties using Surface_mesh

```
typedef CGAL::Surface_mesh<K::Point_3> Mesh;
typedef Mesh::Face_index Face_index;
Mesh m;

Mesh::Property_map<Face_index,std::size_t> cc_ids =
   m.add_property_map<Face_index,std::size_t>("f:cc_ids").first;
// extract the connected component id of each face
PMP::connected_components(m, cc_ids);

for(Face_index f : faces(m))
   std::cout << f  << " " << cc_ids[f] << "\n";
```

Named Parameters

Optional parameters for polygon mesh processing algorithms are provided as named parameters.

template<typename PolygonMesh , typename FaceRange , typename NamedParameters >

void CGAL::Polygon_mesh_processing::isotropic_remeshing (
const FaceRange & faces,
const double & target_edge_length,
PolygonMesh & pmesh,
const NamedParameters & np
)

remeshes a triangulated region of a polygon mesh.

This operation sequentially performs edge splits, edge collapses, edge flips, tangential relaxation and projection to the initial surface to generate a smooth mesh with a prescribed edge length.

Template Parameters

PolygonMesh	model of `MutableFaceGraph` that has an internal property map for `CGAL::vertex_point_t`. The descriptor types `boost::graph_traits<PolygonMesh>::face_descriptor` and `boost::graph_traits<PolygonMesh>::halfedge_descriptor` must be models of `Hashable`. If `PolygonMesh`has an internal property map for `CGAL::face_index_t`, then it should be initialized
FaceRange	range of `boost::graph_traits<PolygonMesh>::face_descriptor`, model of `Range`. Its iterator type is `InputIterator`.
NamedParameters	a sequence of Named Parameters

Parameters

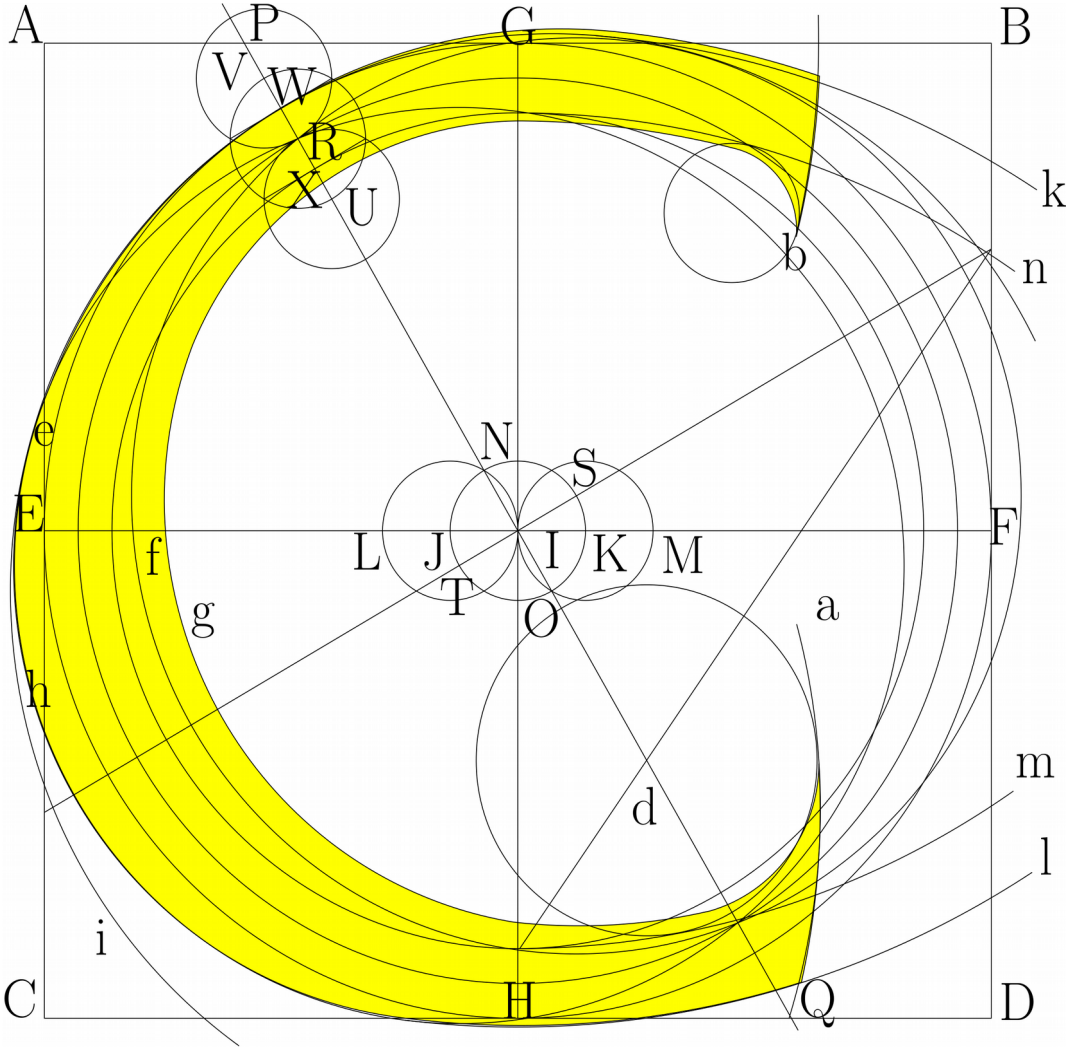
pmesh	a polygon mesh with triangulated surface patches to be remeshed
faces	the range of triangular faces defining one or several surface patches to be remeshed
target_edge_length	the edge length that is targetted in the remeshed patch
np	optional sequence of Named Parameters among the ones listed below

Named Parameters

Named Parameters

geom_traits	a geometric traits class instance, model of Kernel. Exact constructions kernels are not supported by this function.
vertex_point_map	the property map with the points associated to the vertices of pmesh. Instance of a class model of ReadWritePropertyMap.
number_of_iterations	the number of iterations for the sequence of atomic operations performed (listed in the above description)
edge_is_constrained_map	a property map containing the constrained-or-not status of each edge of pmesh. A constrained edge can be splitted or collapsed, but not flipped, nor its endpoints moved by smoothing. Note that patch boundary edges (i.e. incident to only one face in the range) are always considered as constrained edges.
vertex_is_constrained_map	a property map containing the constrained-or-not status of each vertex of pmesh. A constrained vertex cannot be modified at all during remeshing
protect_constraints	If true, the edges set as constrained in edge_is_constrained_map (or by default the boundary edges) are not splitted nor collapsed during remeshing. Note that around constrained edges that have their length higher than twice target_edge_length, remeshing will fail to provide good quality results. It can even fail to terminate because of cascading vertex insertions.
face_patch_map	a property map with the patch id's associated to the faces of faces. Instance of a class model of ReadWritePropertyMap. It gets updated during the remeshing process while new faces are created.
number_of_relaxation_steps	the number of iterations of tangential relaxation that are performed at each iteration of the remeshing process
relax_constraints	If true, the end vertices of the edges set as constrained in edge_is_constrained_map and boundary edges move along the constrained polylines they belong to.

```
PMP::isotropic_remeshing(faces(mesh),
  target_edge_length,
  mesh,
  PMP::parameters::number_of_iterations(10)
    .protect-constraints(true)
    .edge_is_constrained_map(constrained_edges_map)
    .vertex_is_constrained_map(constrained_vertices_map)
    .number_of_relaxation_iterations(5)
);
```

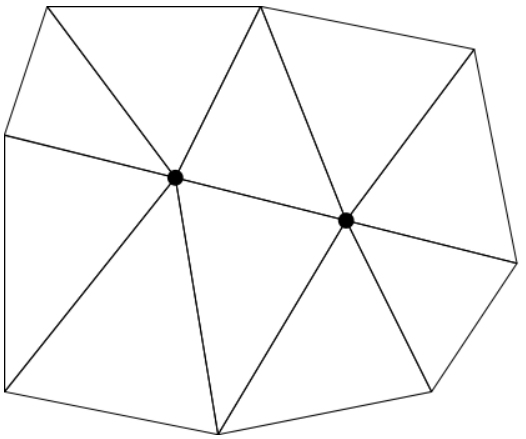


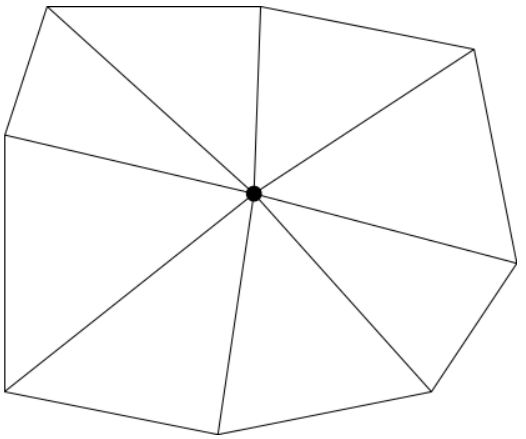
Examples

Surface Mesh Simplification

Surface Mesh Simplification

- Iterative edge collapse preserving the topology of the input model
  - Edges are sorted using a **cost** function
  - Each edge collapsed becomes a point which position is computed using a **placement** function.
  - The algorithm stops when no futher collapse is possible without changing the topology or when a **stop** function indicates to.





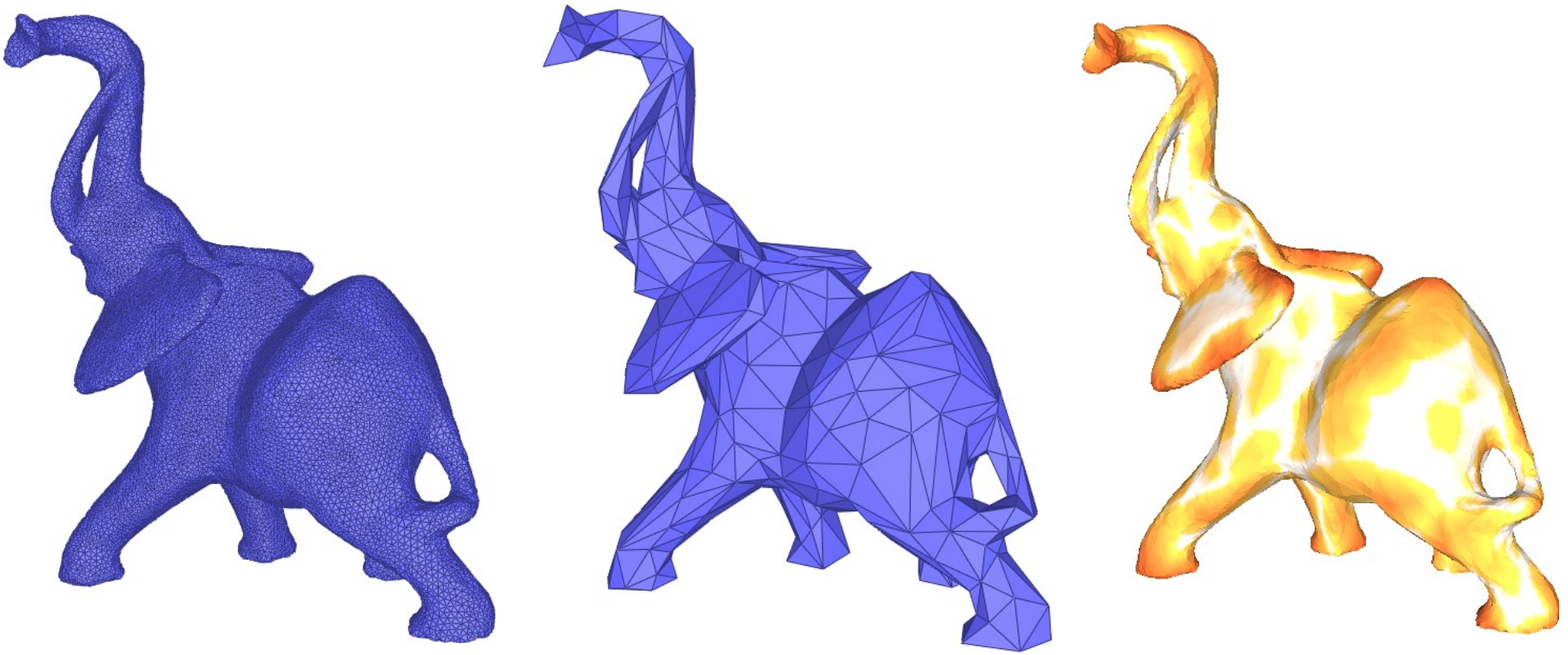
Surface Mesh Simplification

- The cost, placement, and stop functions can be provided to the main function using named parameters:
  - Several classes are provided in CGAL.
  - User can provide his own custom classes by following the **`GetCost`**, **`GetPlacement`**, and **`StopPredicate`** concepts
- User can also mark edges as non-collapsable
- Placement and cost functions can prevent the collapse of an edge (for example when the placement cannot be computed or is invalid)

Surface Mesh Simplification

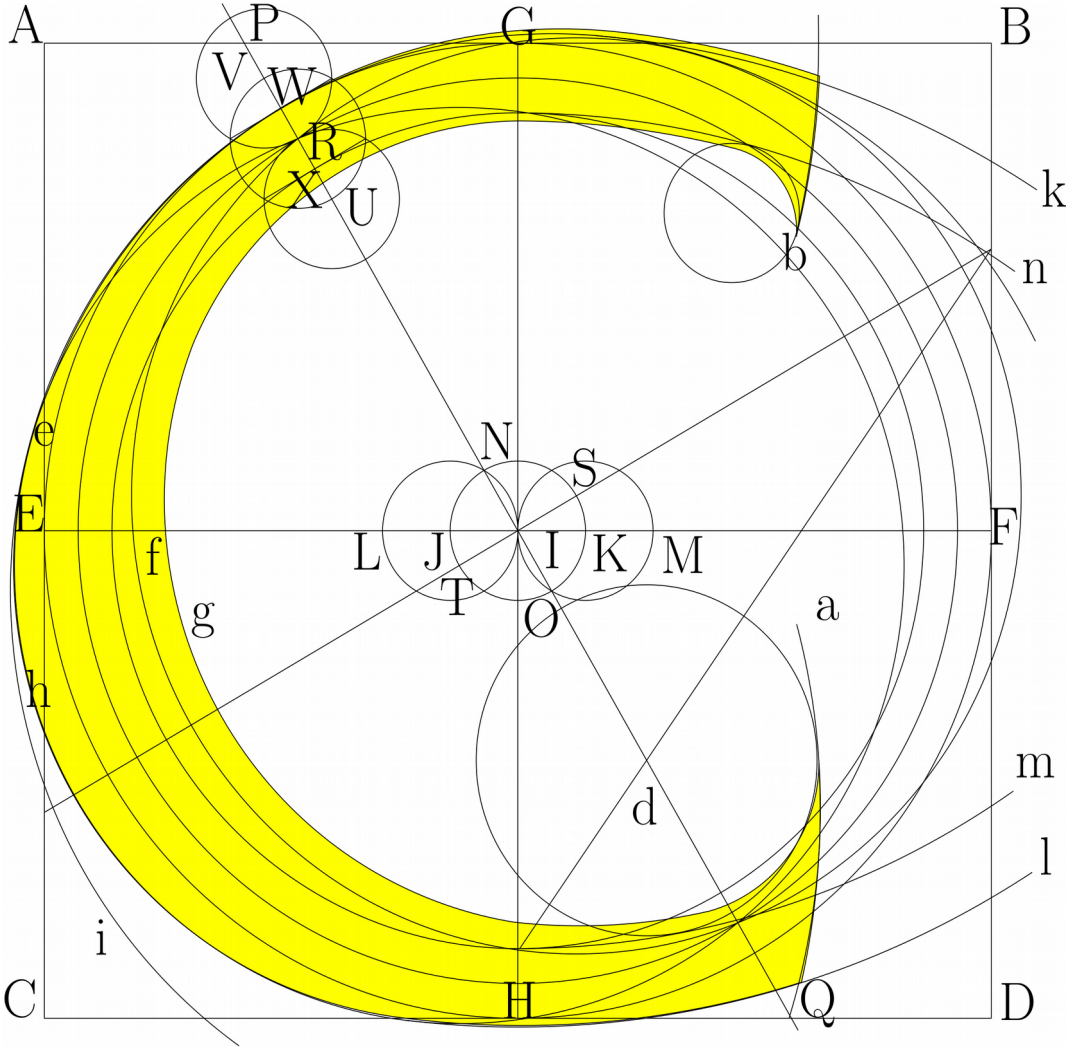
```
namespace SMS = CGAL::Surface_mesh_simplification;
namespace params = CGAL::parameters;

SMS::edge_collapse(surface_mesh,
                   stop,
                   params::edge_is_constrained_map(bem)
                     .get_placement(Placement(bem))
                     .get_cost(Cost())
);
```

Approximated Hausdorff Distance
(Polygon Mesh Processing – CGAL 4.10)



Approximated Hausdorff Distance
(Polygon Mesh Processing – CGAL 4.10)

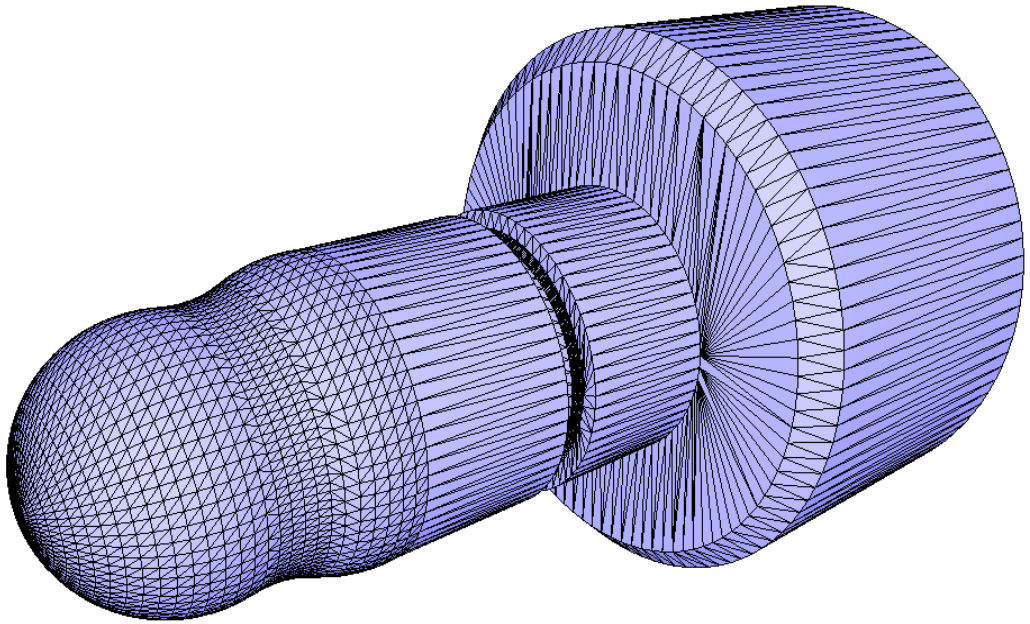
- Approximation (lower bound) of the distance from surface A to surface B
  - Points are taken on the surface of A
  - An AABB-tree of the faces of B is used to get the distance of each sample point to B
- A template parameter allows to do the queries in parallel
- The sampling method and the quality of the sampling is controlled using named-parameters

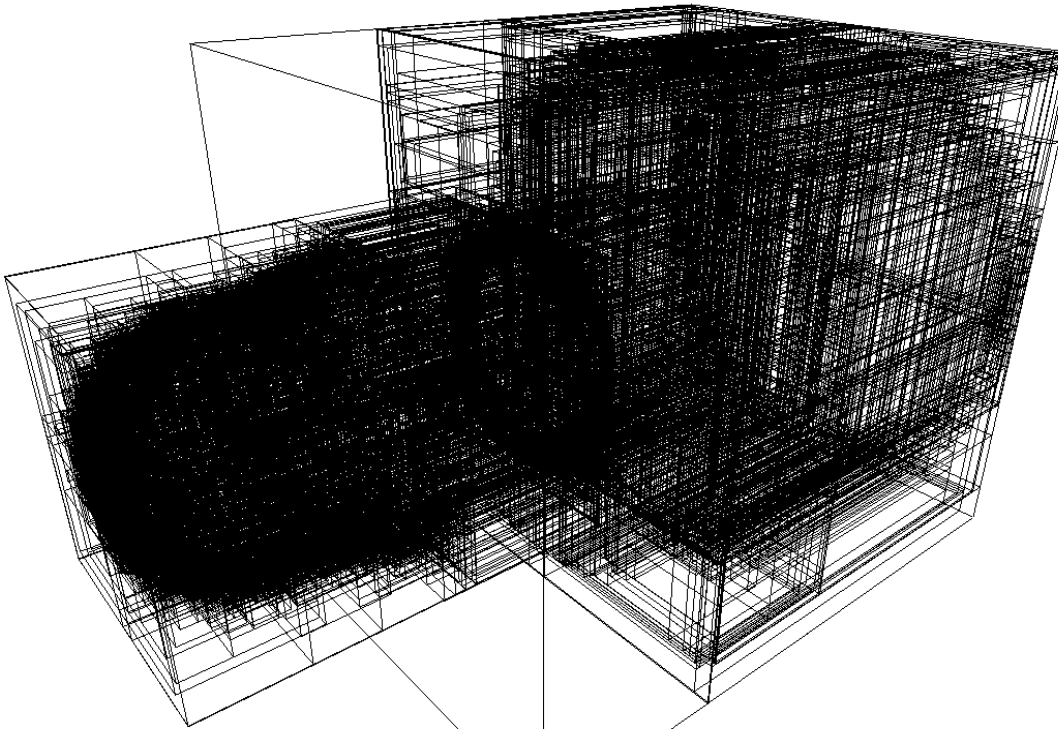


Quick Tour

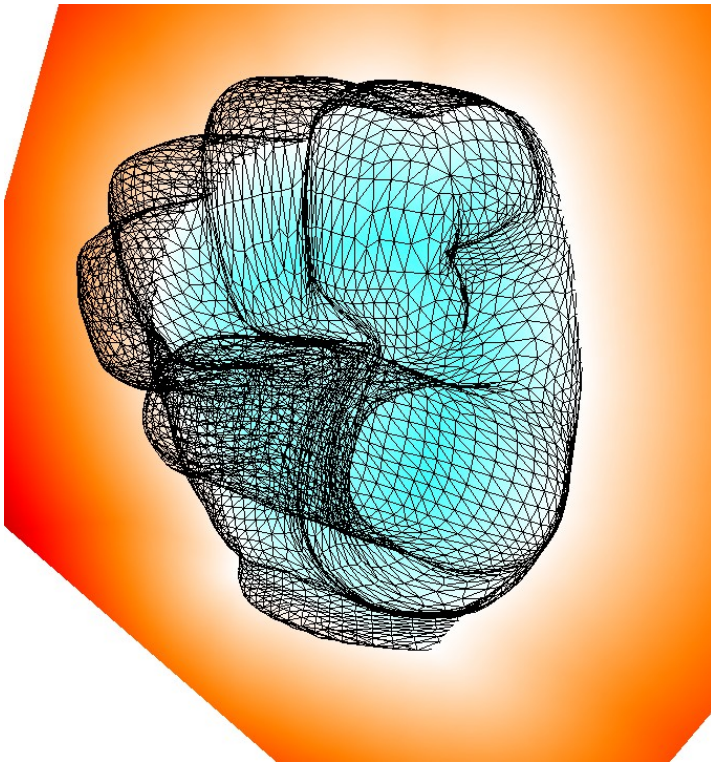
Distances and Intersections

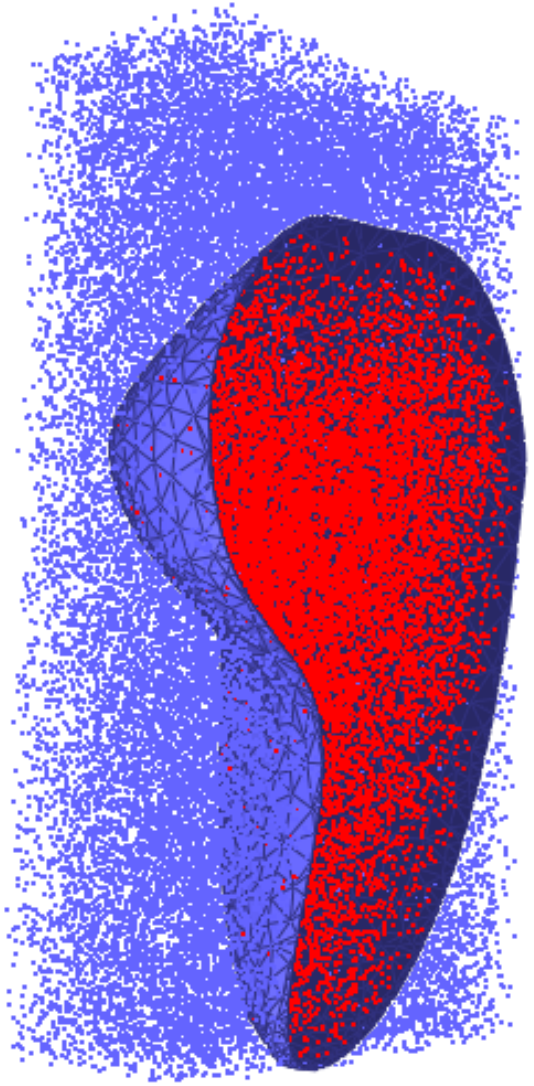
Based on CGAL::AABB_tree

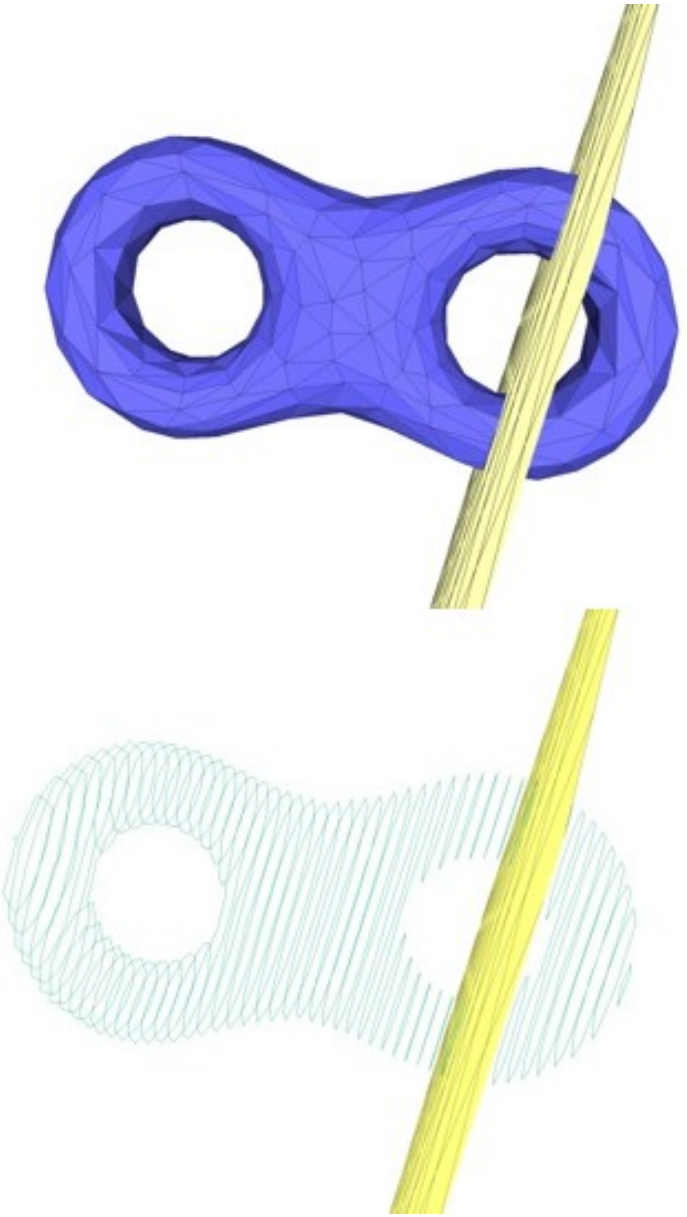




Distance and Intersection Computation

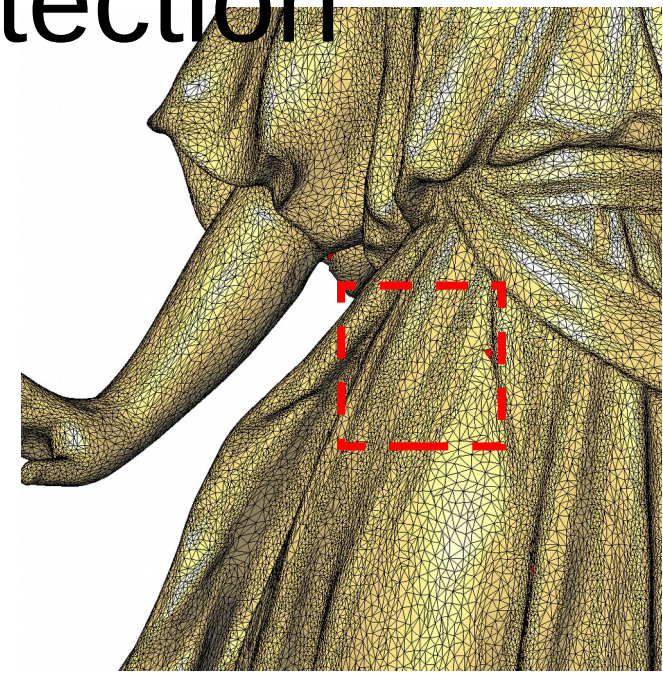


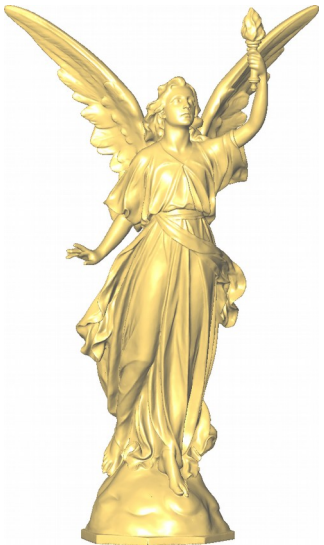


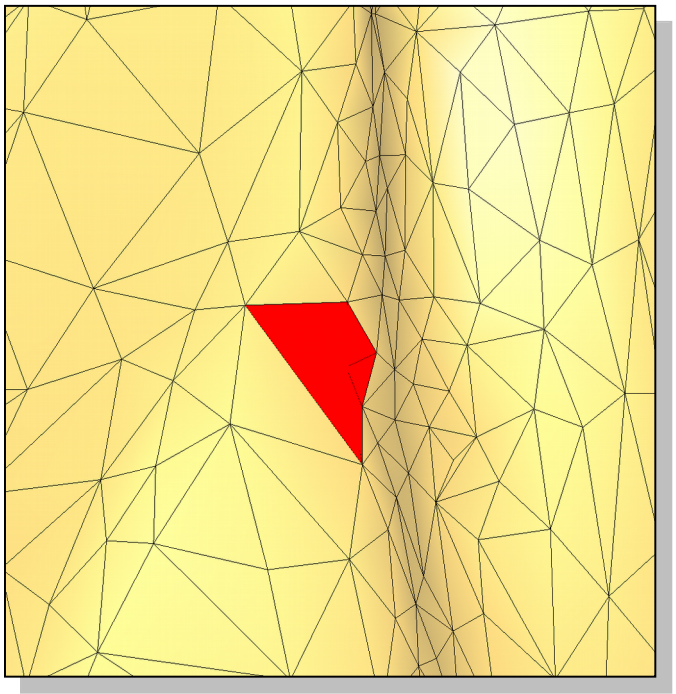


Box Intersection Detection

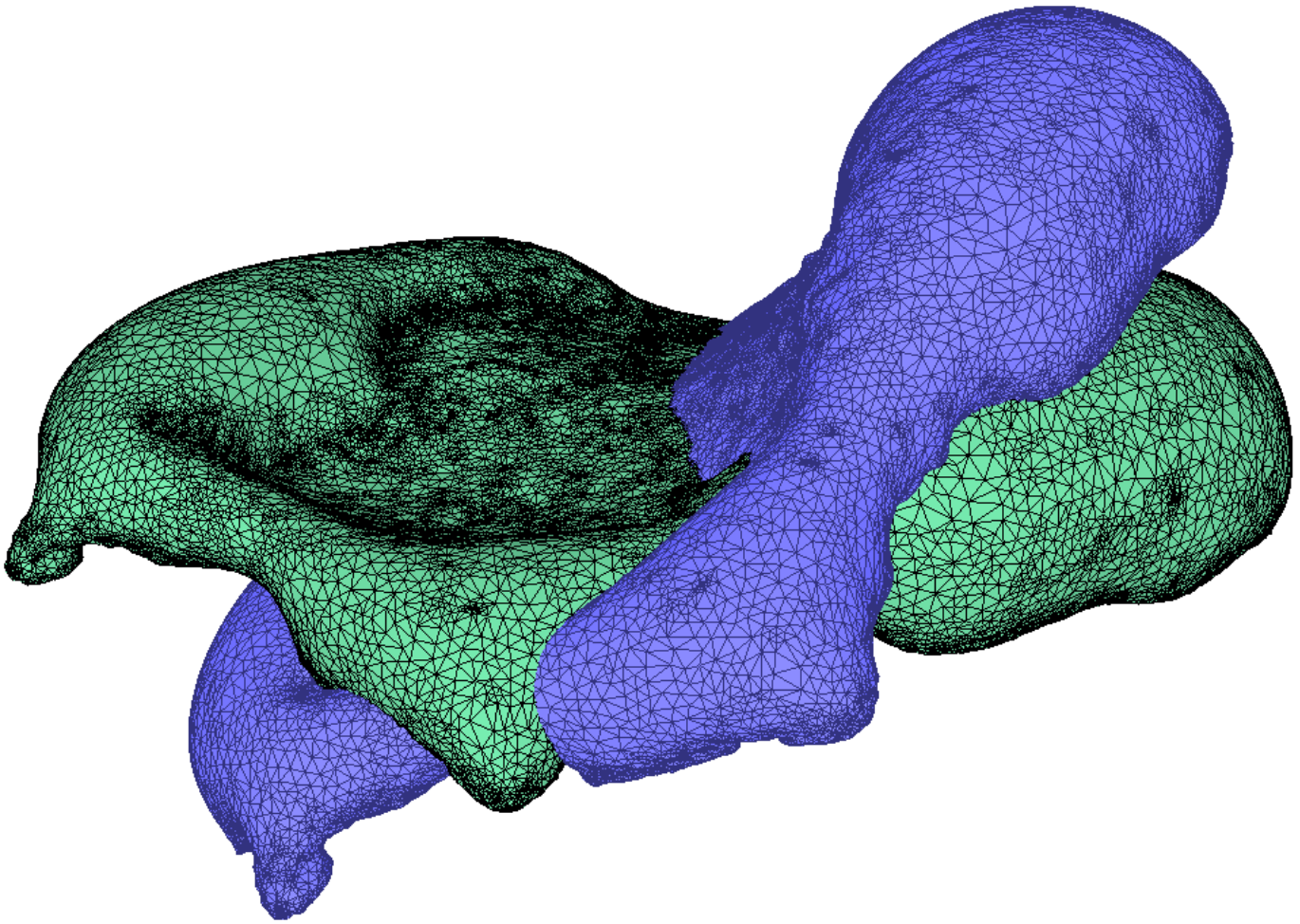
- CGAL::Box_intersection_d
  Algorithm for finding all intersecting pairs for large numbers of axis-aligned bounding boxes.



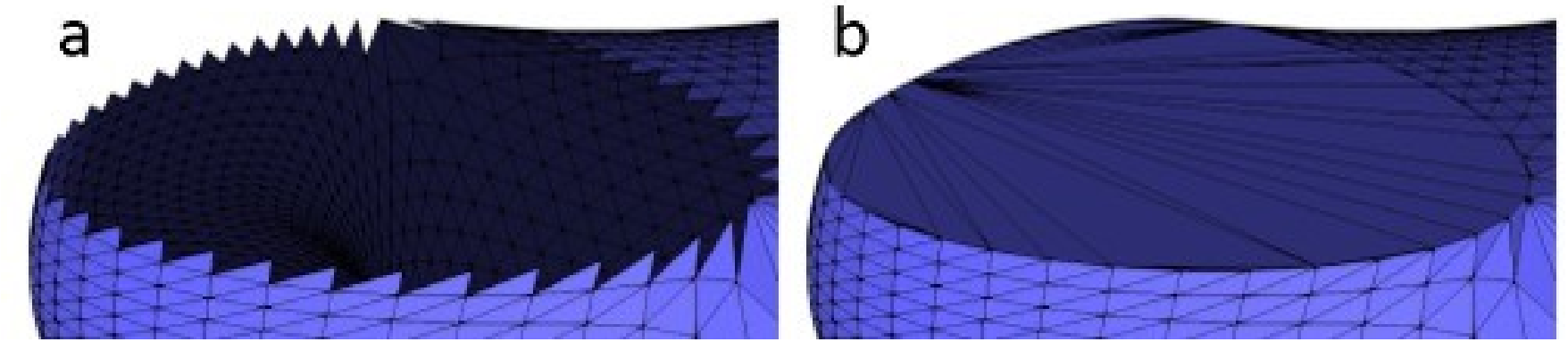




Intersection Test

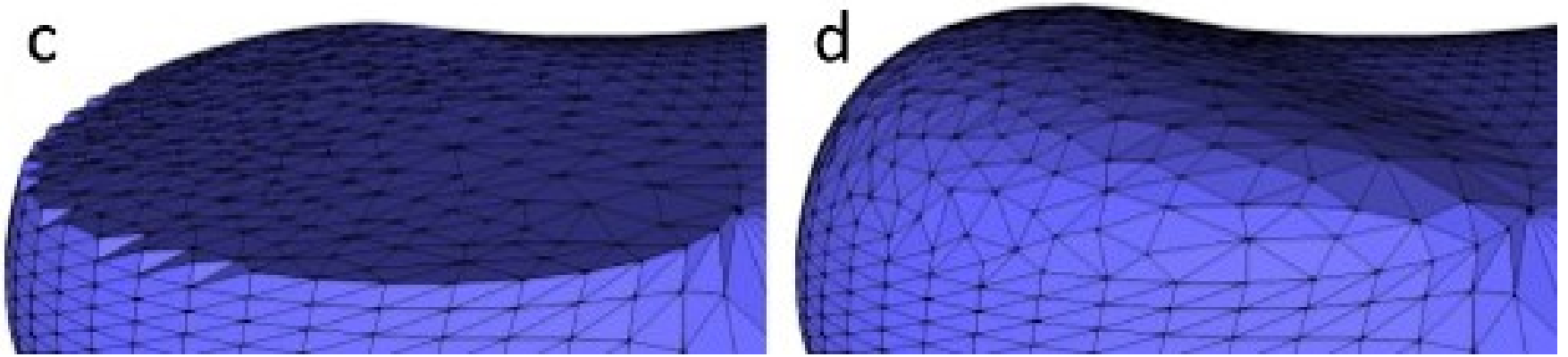


Hole filling [Liepa 2003], [Zou et al. 2013]



Hole

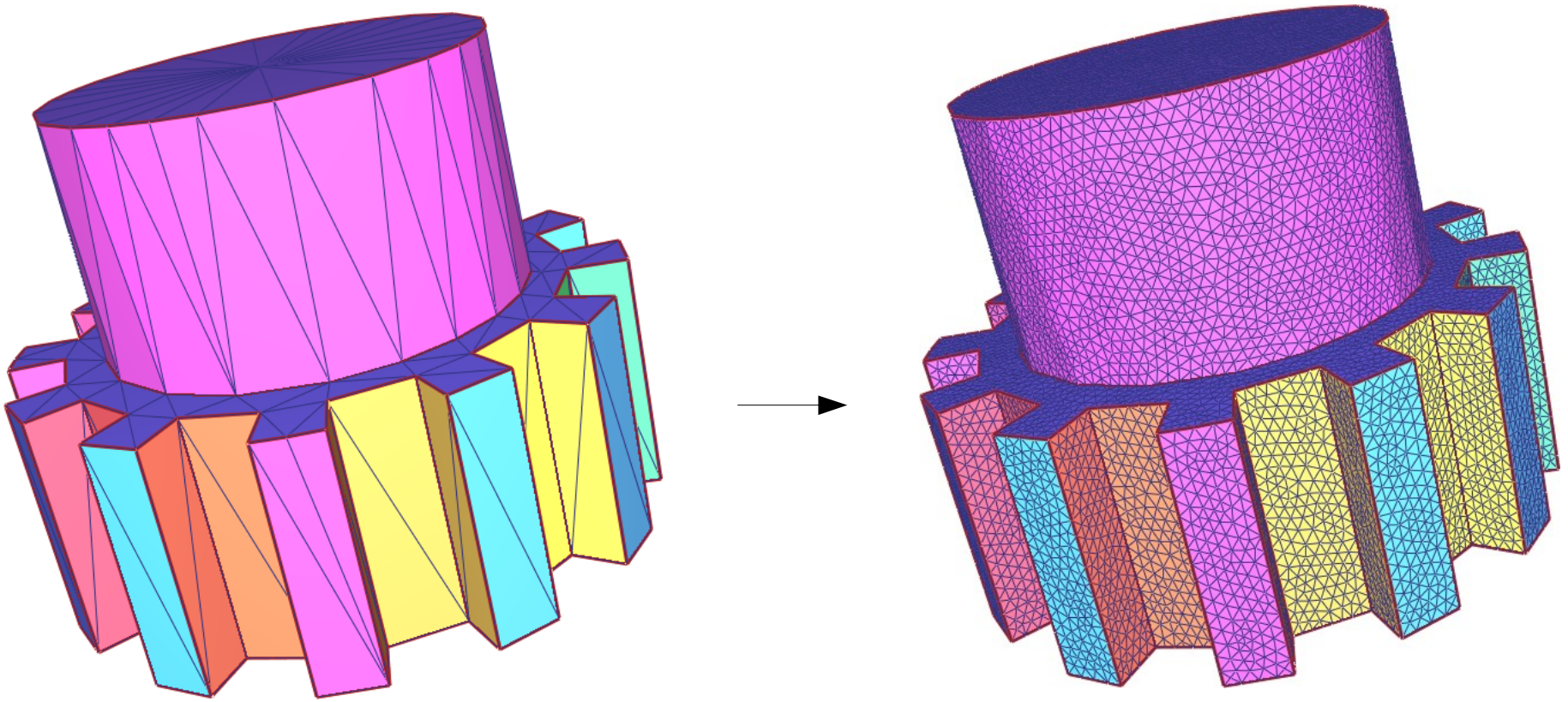
Triangulate



Refine

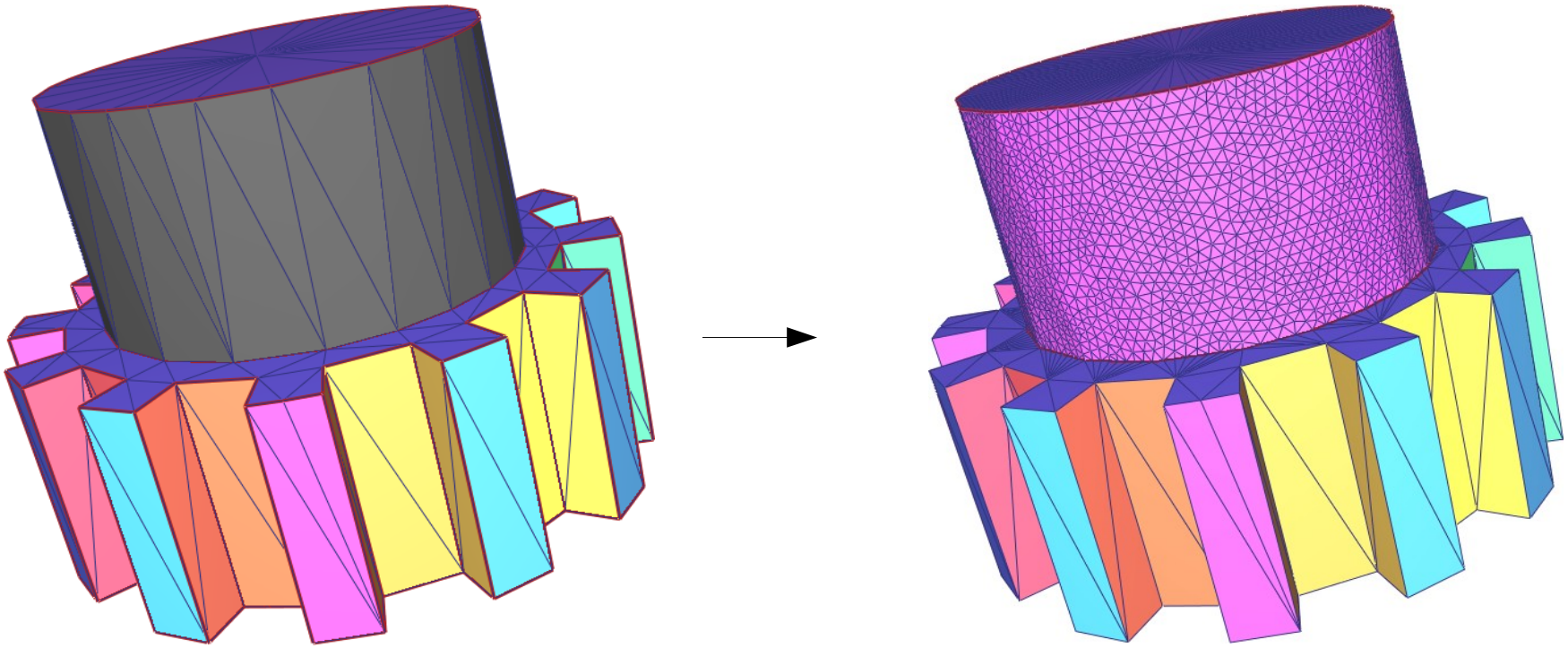
Fair

Isotropic Remeshing [Botsch-Kobbelt 2004]



Feature Preserving

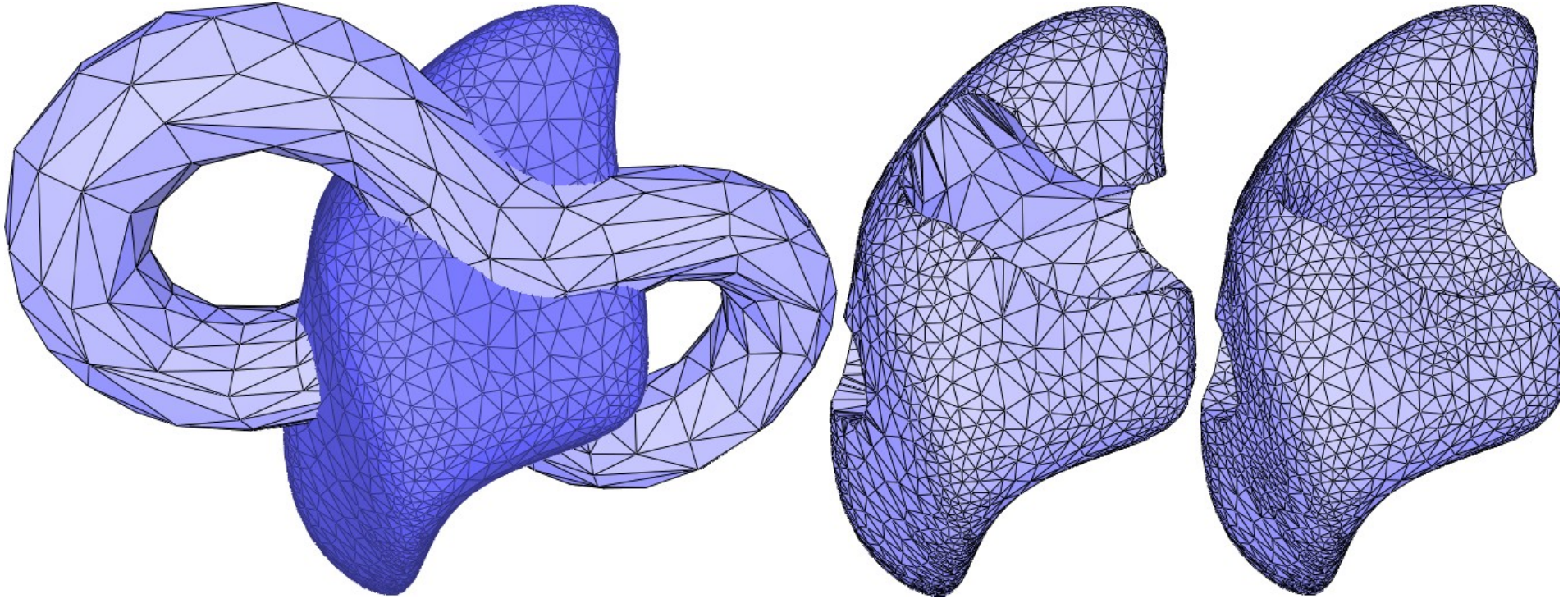
Isotropic Remeshing



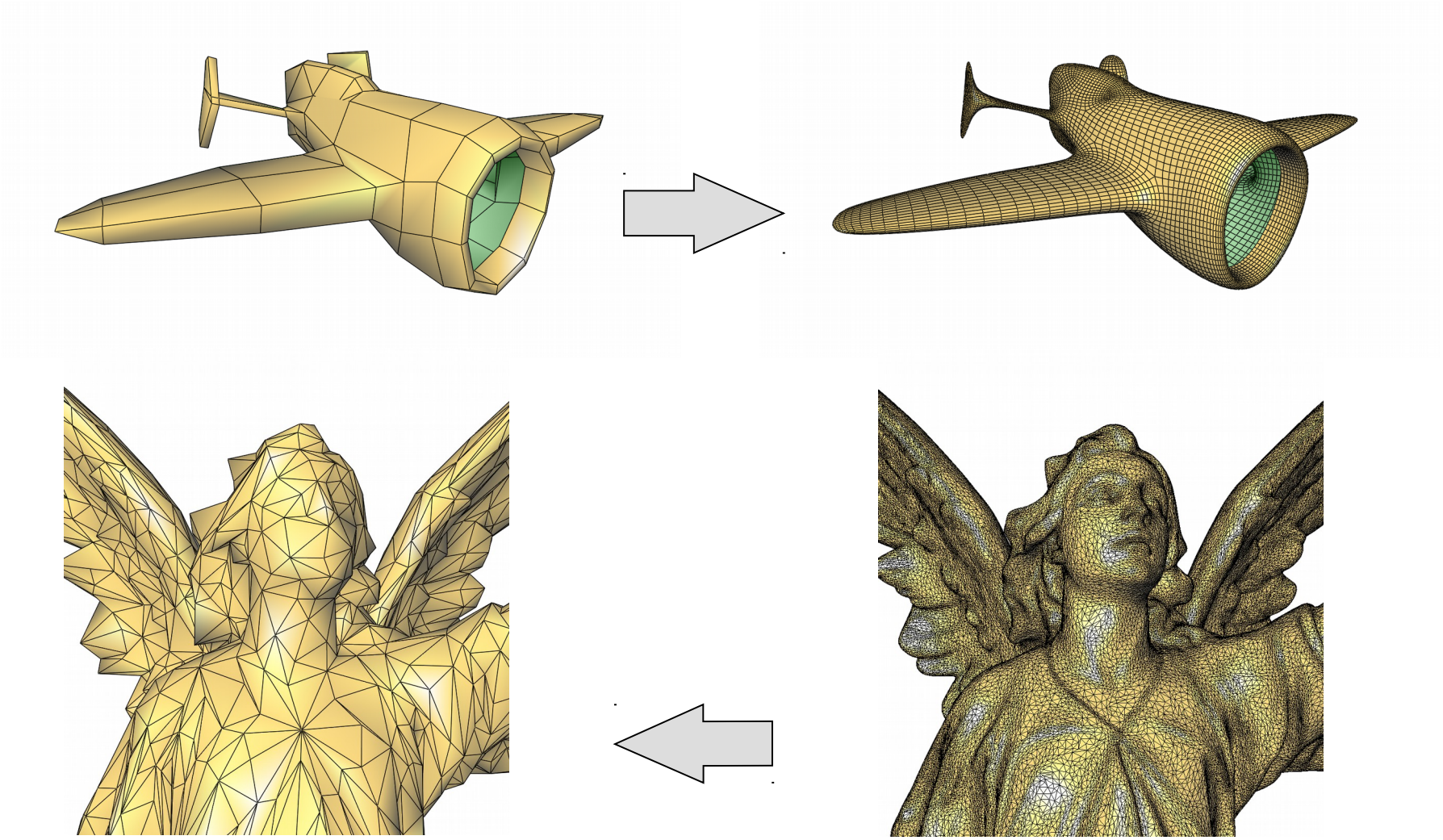
Apply on Selection

3D Boolean Operations using Corefinement

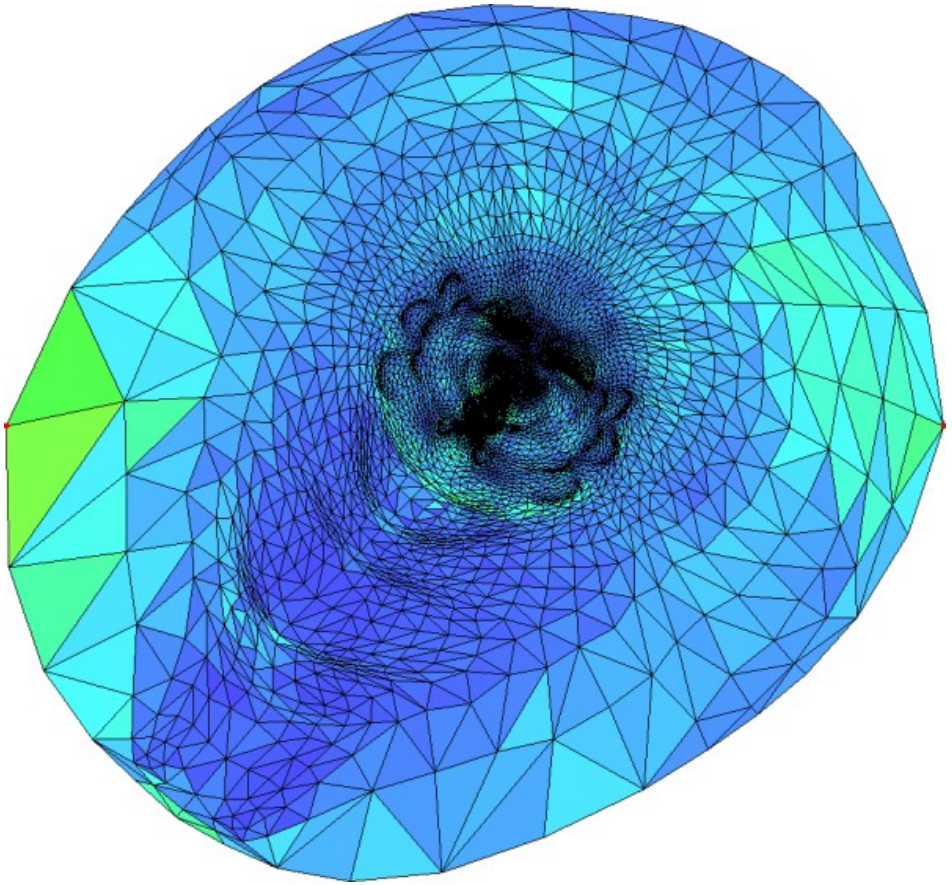
- Fast version but restricted to surface meshes
- Various applications: attribute preservation, mesh clipping, ...



Subdivision and Simplification

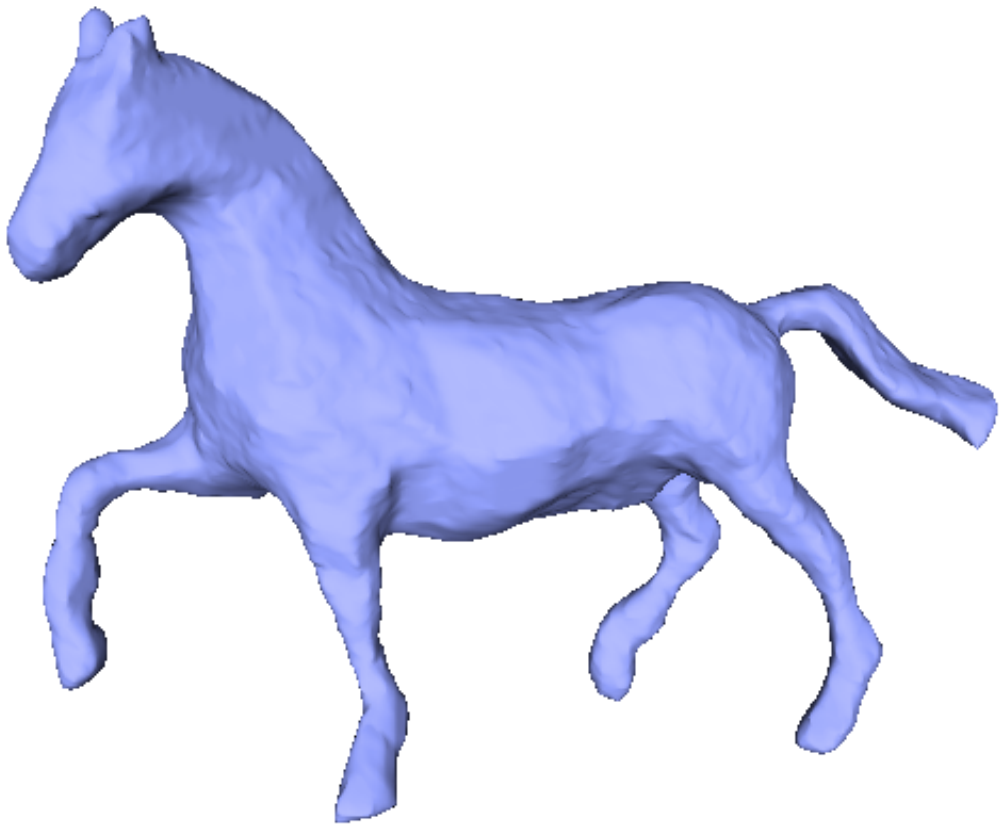


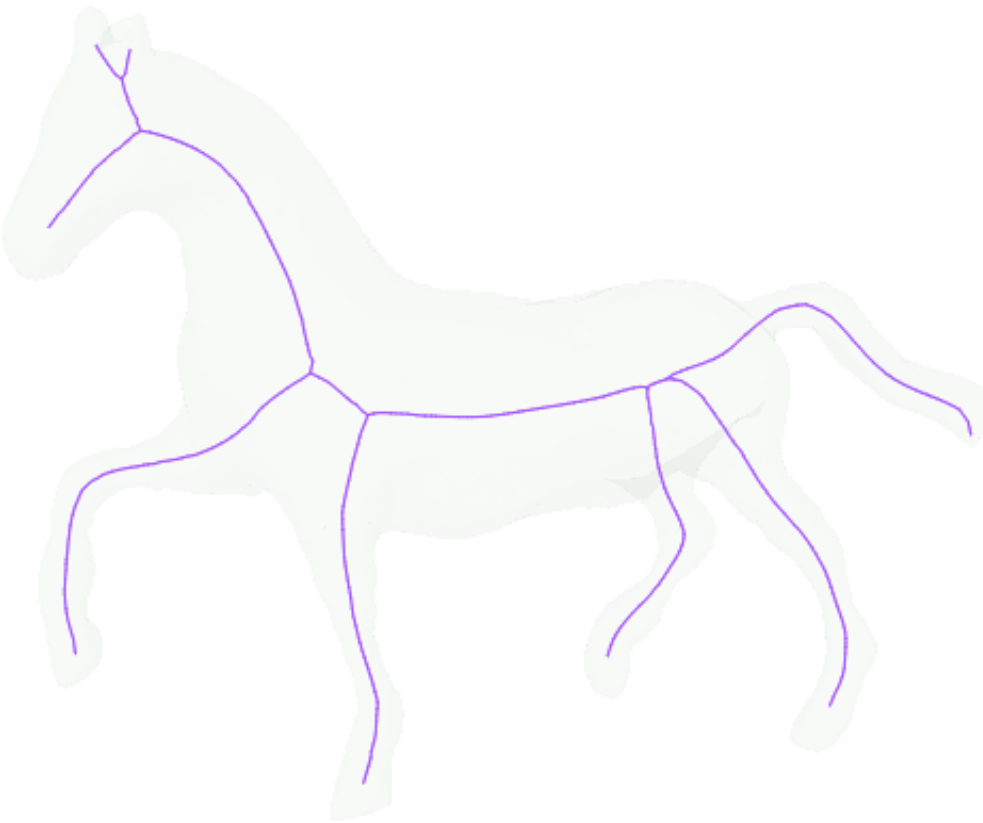
Parameterization



Skeletonization [Tagliasacchi et al.]

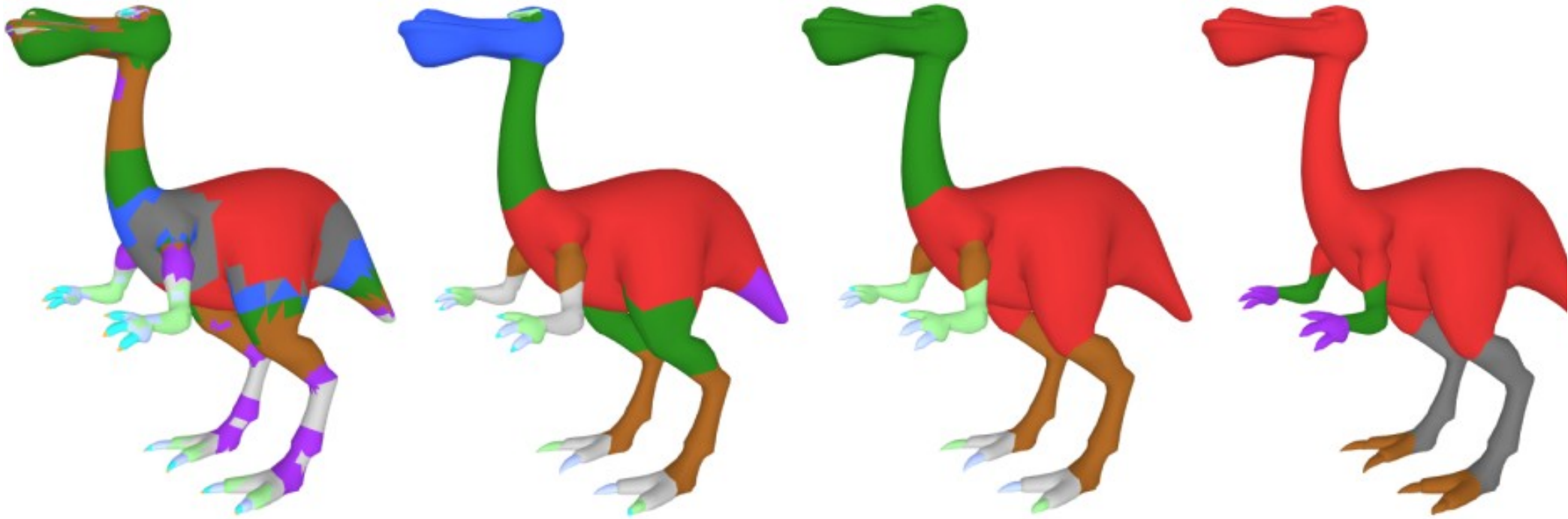
Mean Curvature Flow skeletonization





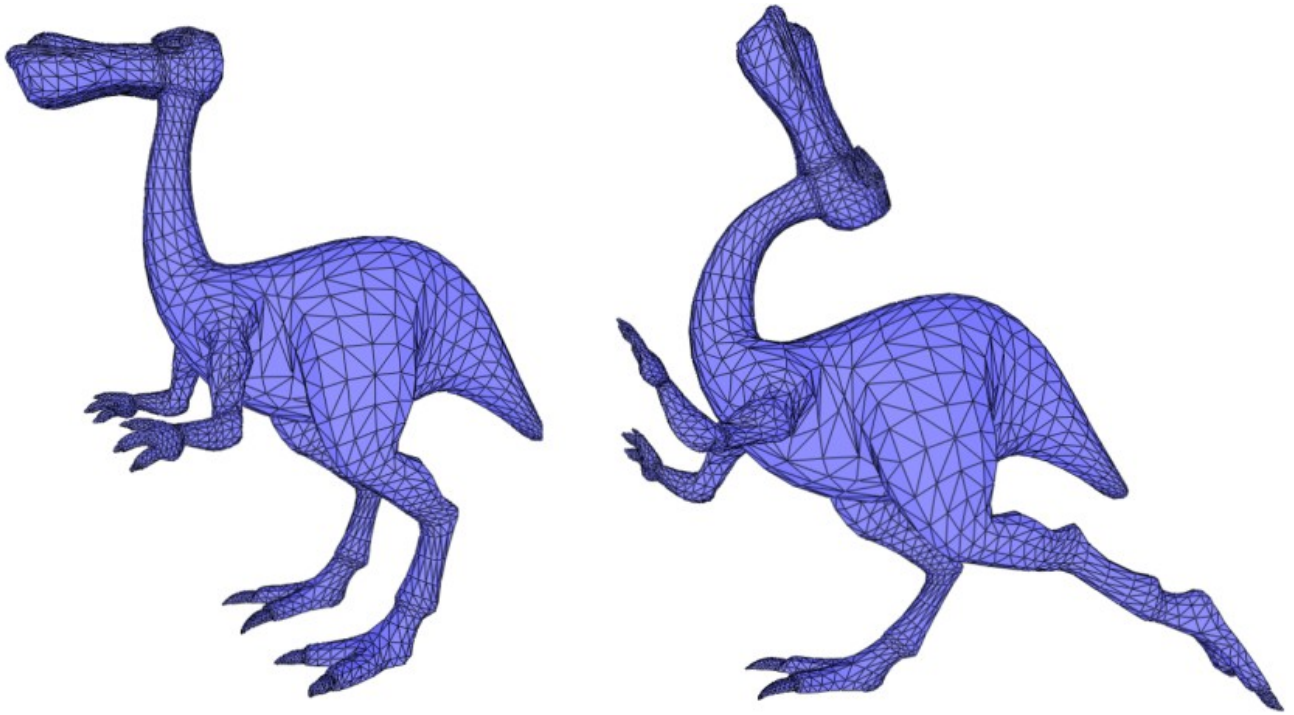
Segmentation [Shapira et al. 2008]

- Segment surface into k patches
- Based on «shape diameter» estimate

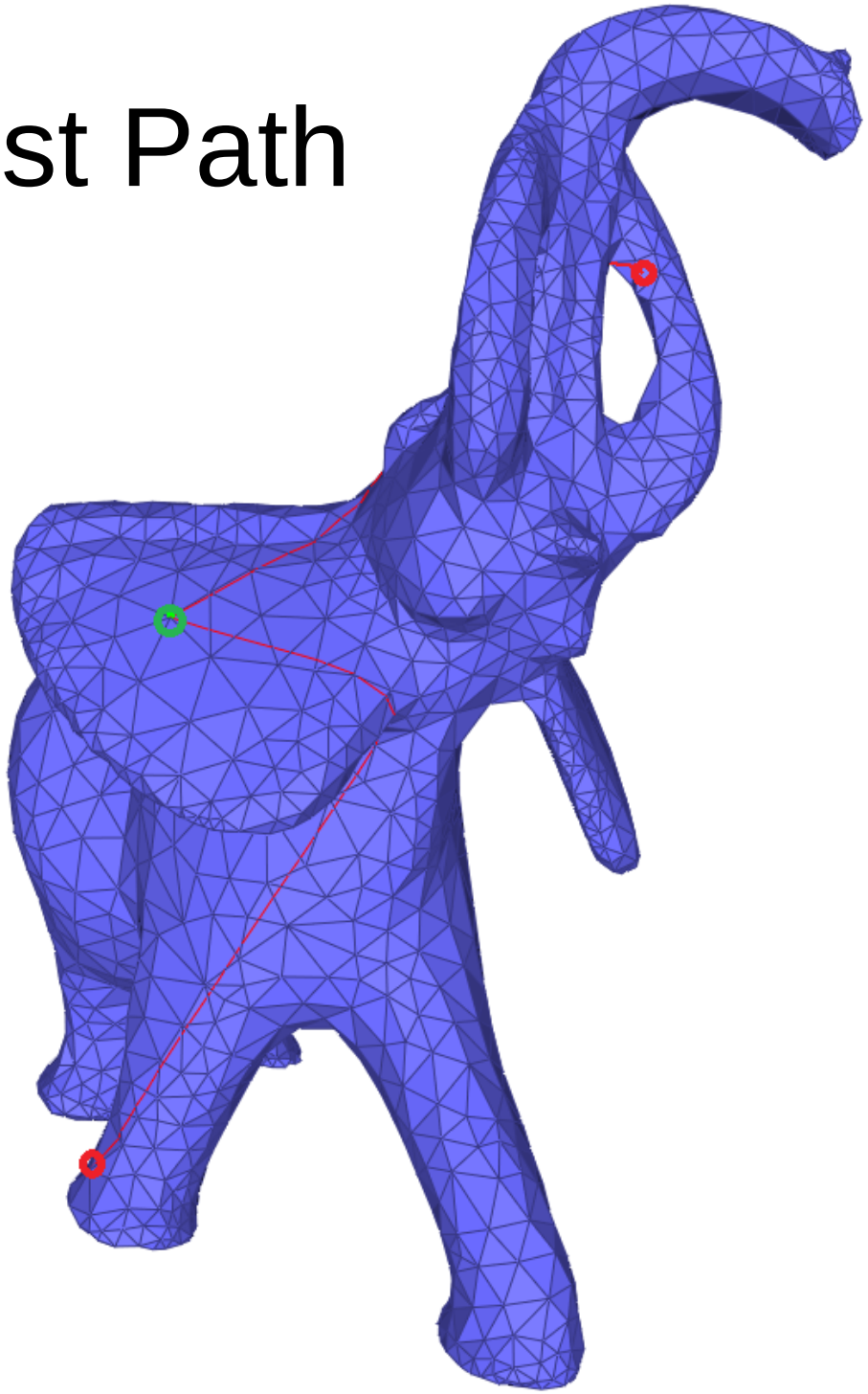


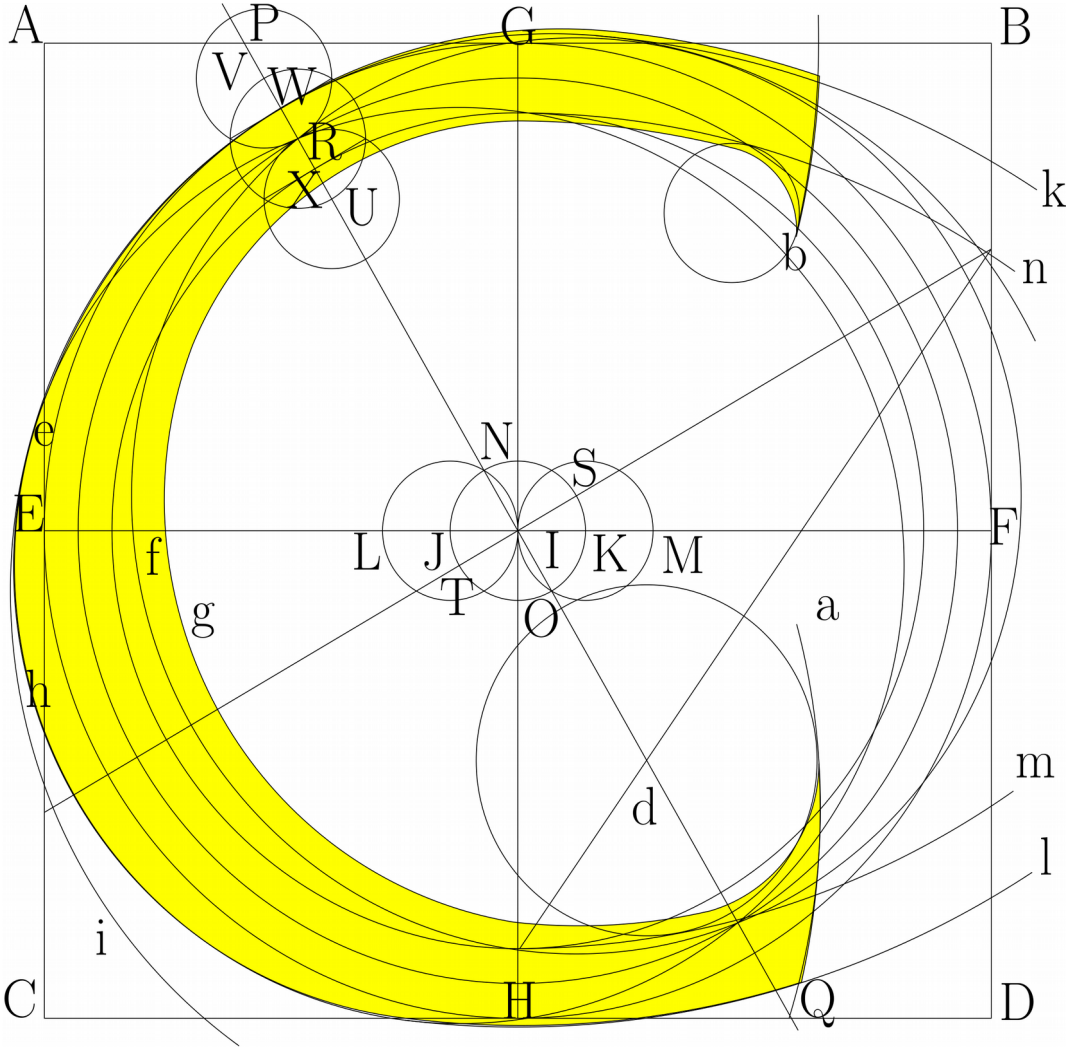
Deformation [Sorkine-Alexa 2007]

As Rigid as Possible (“ARAP”)



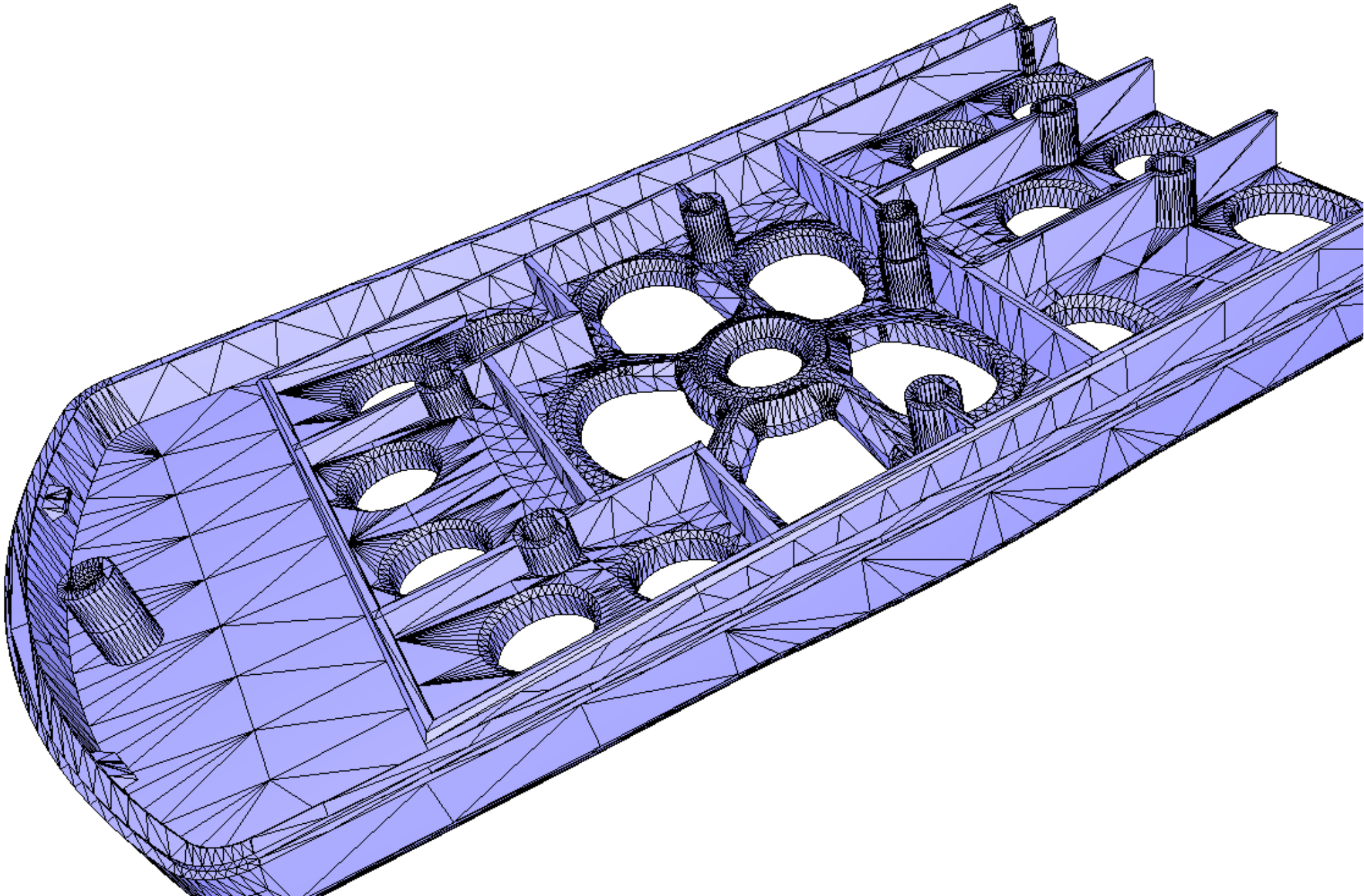
Geodesic Shortest Path



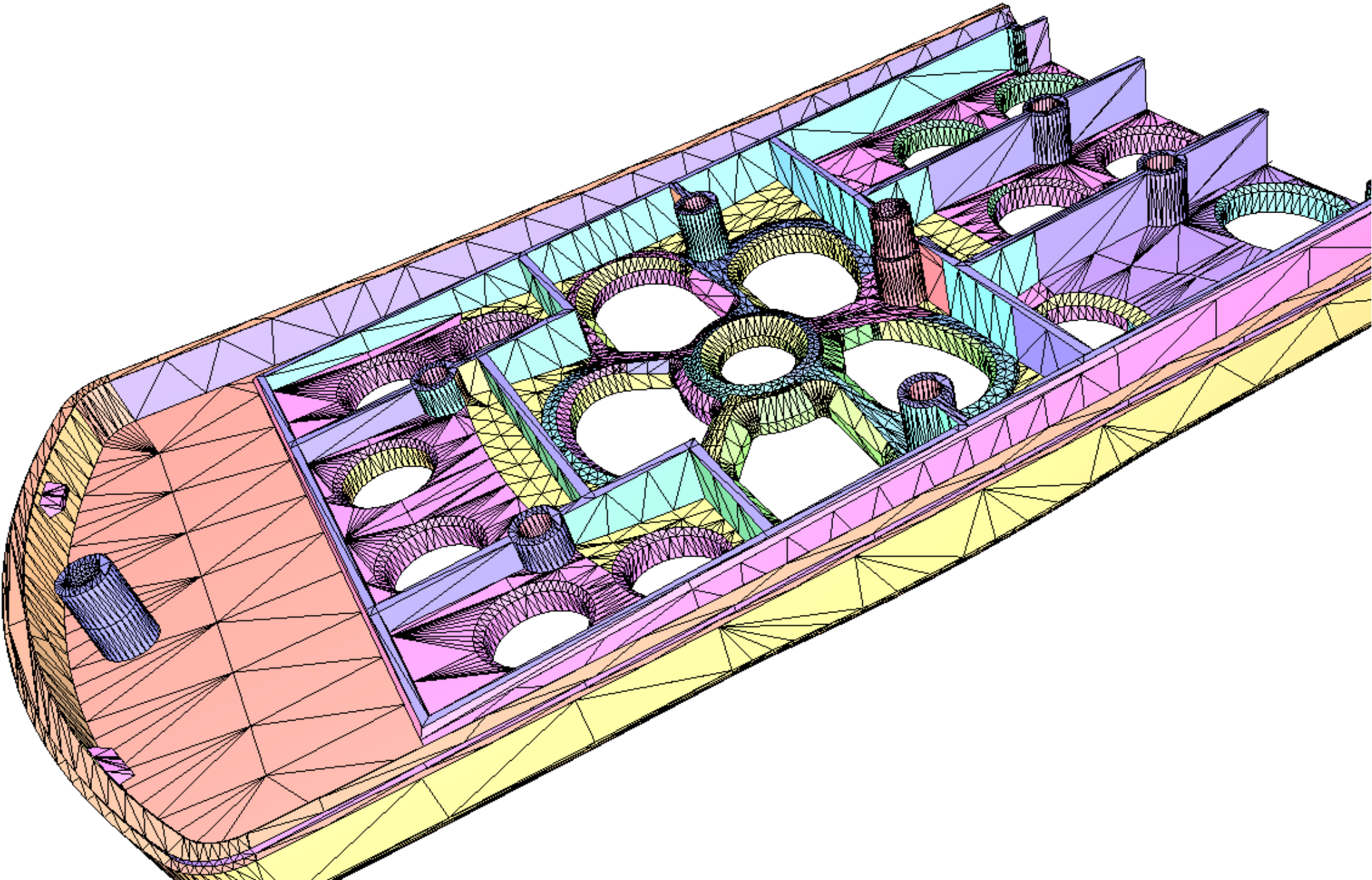


Under Development

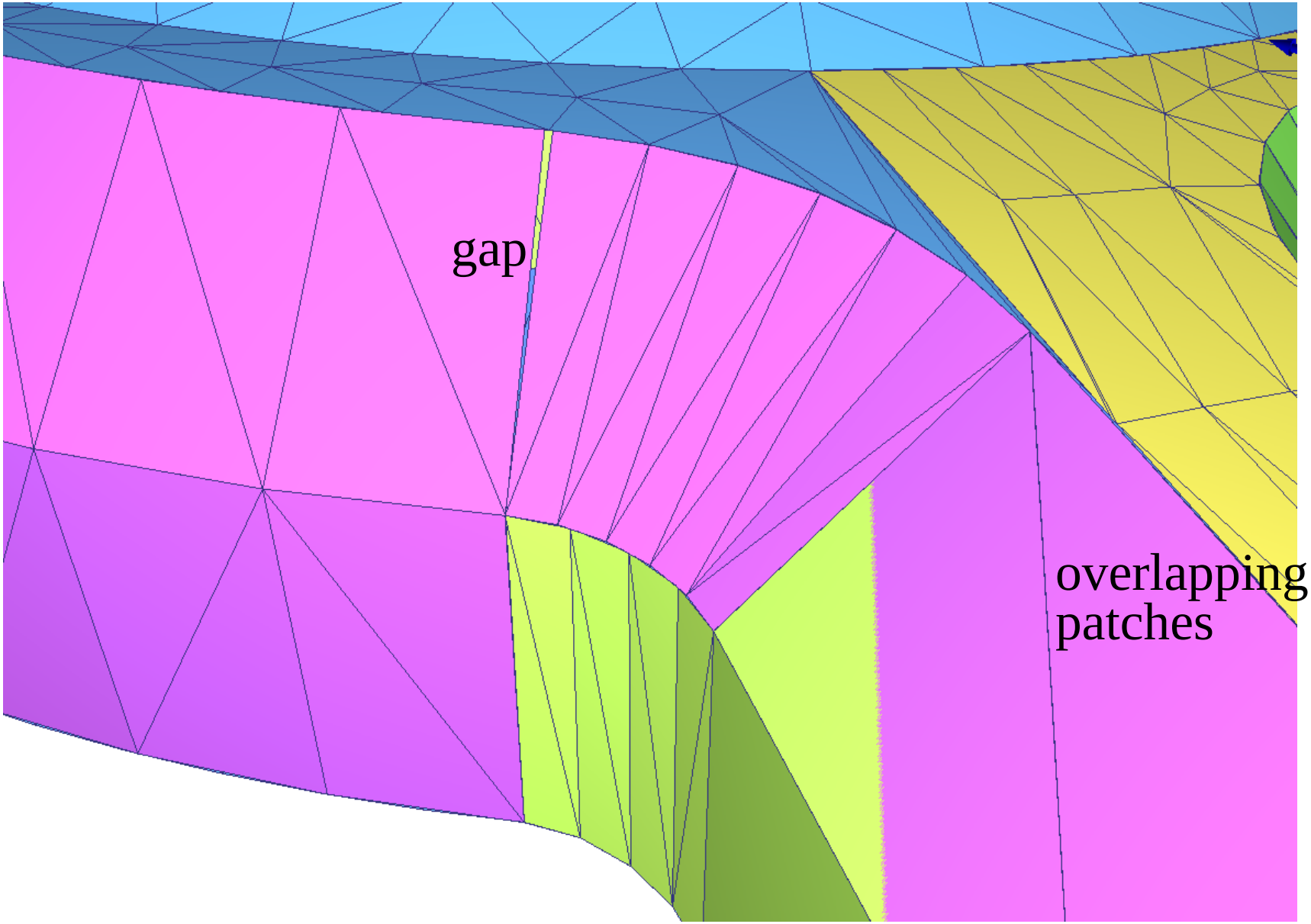
Mesh Repair



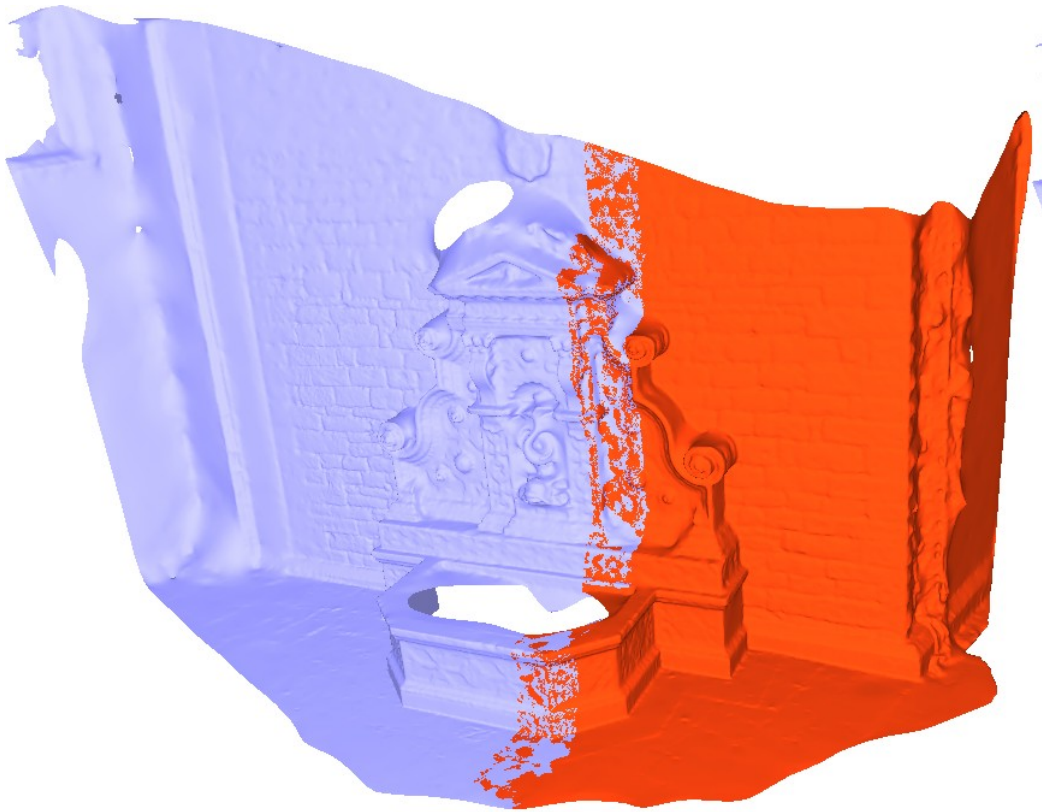
Mesh Repair

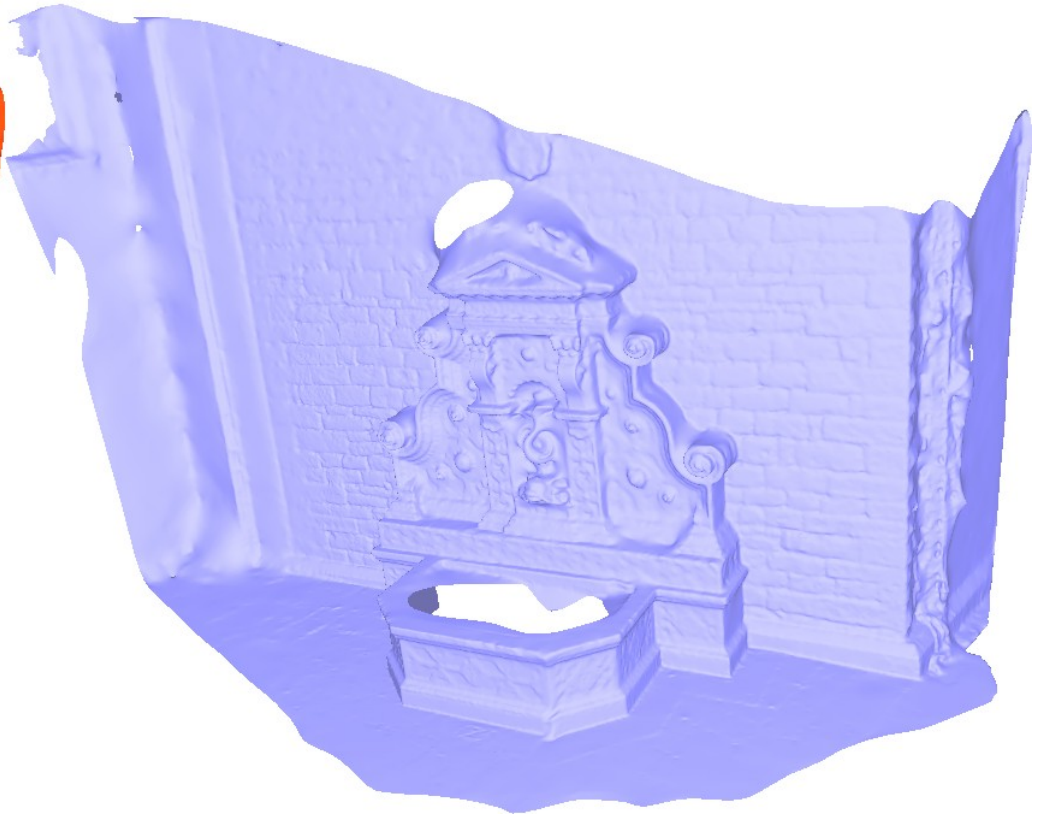


Mesh Repair

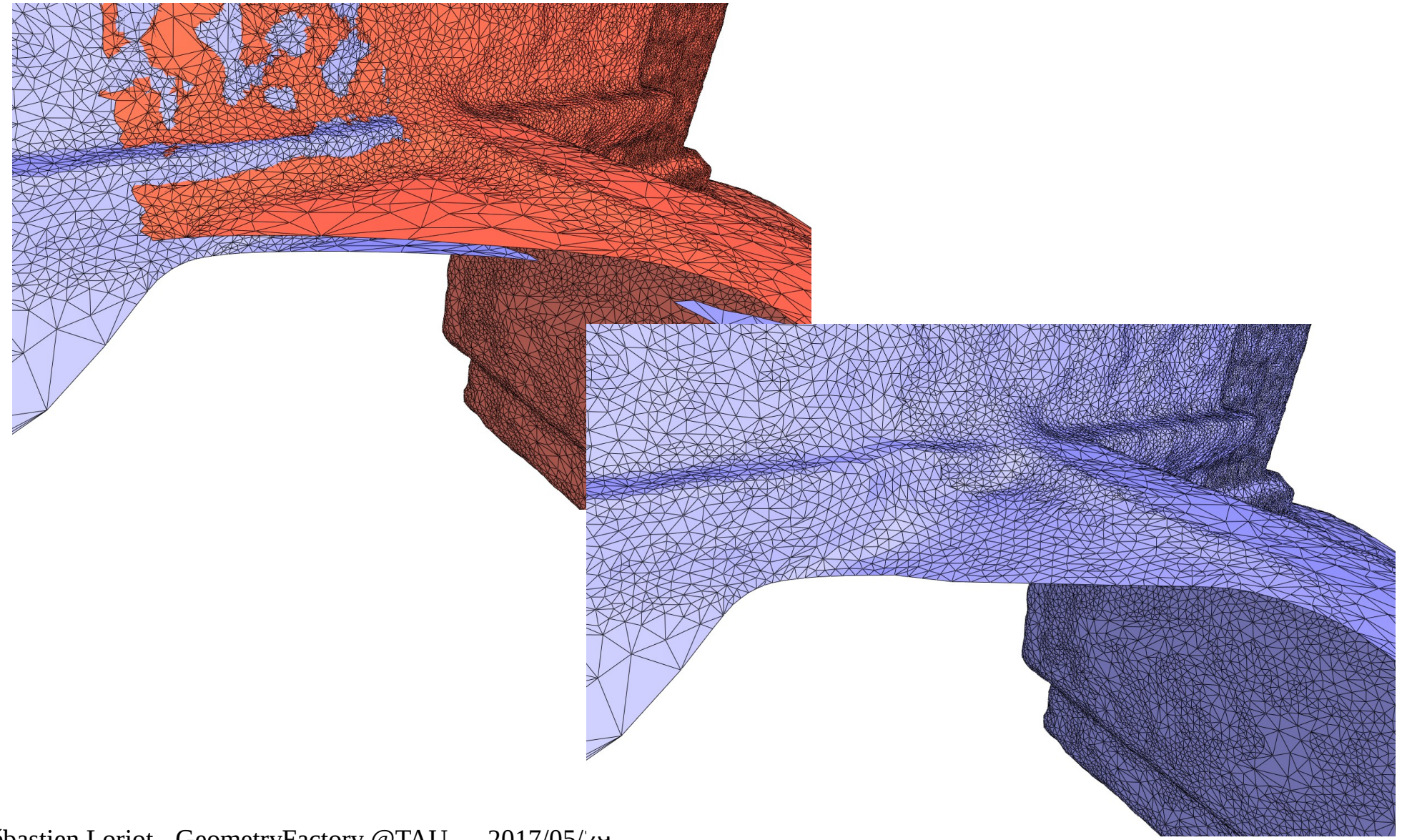


Mesh Fusion

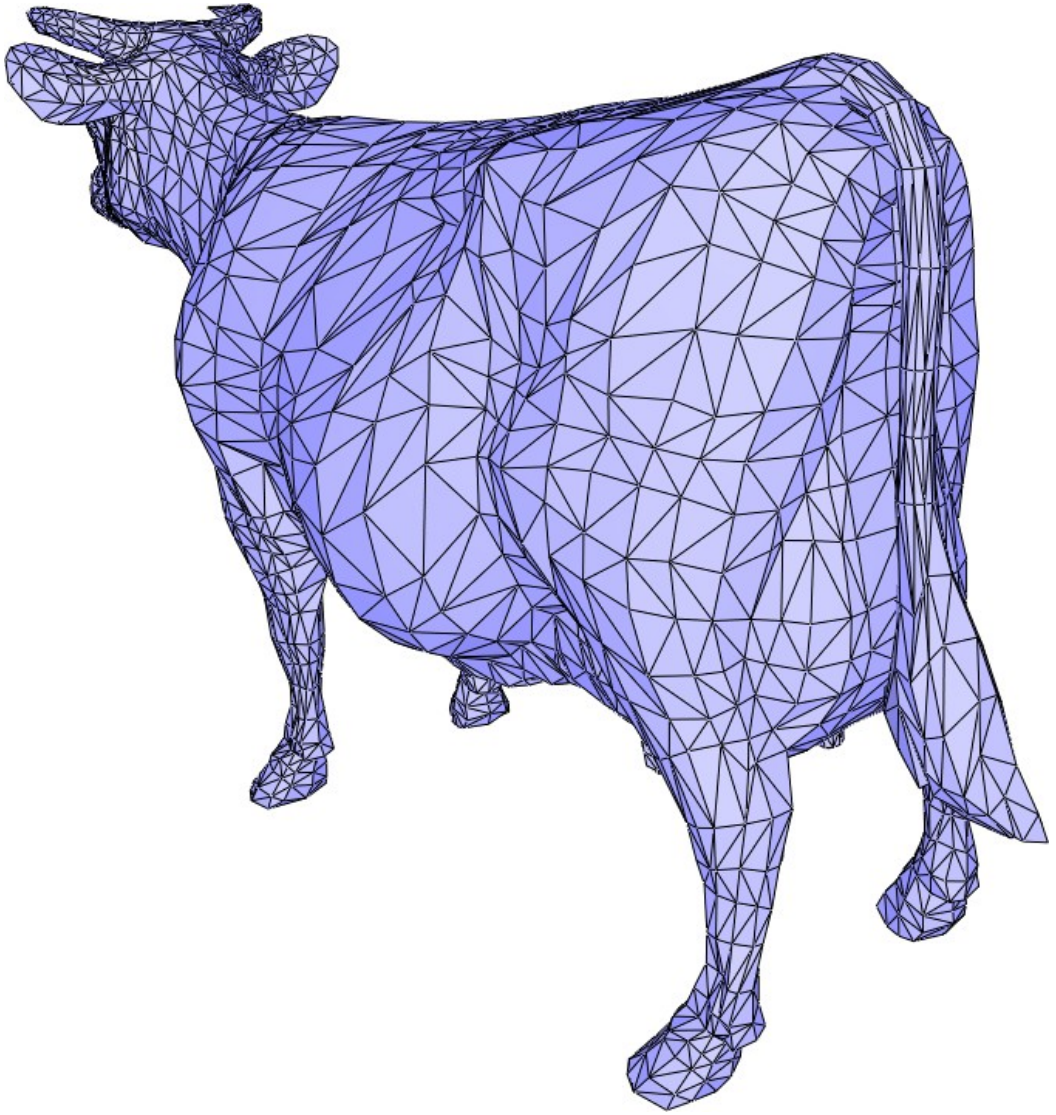




Mesh Fusion



Self-intersections Removal using Refinement



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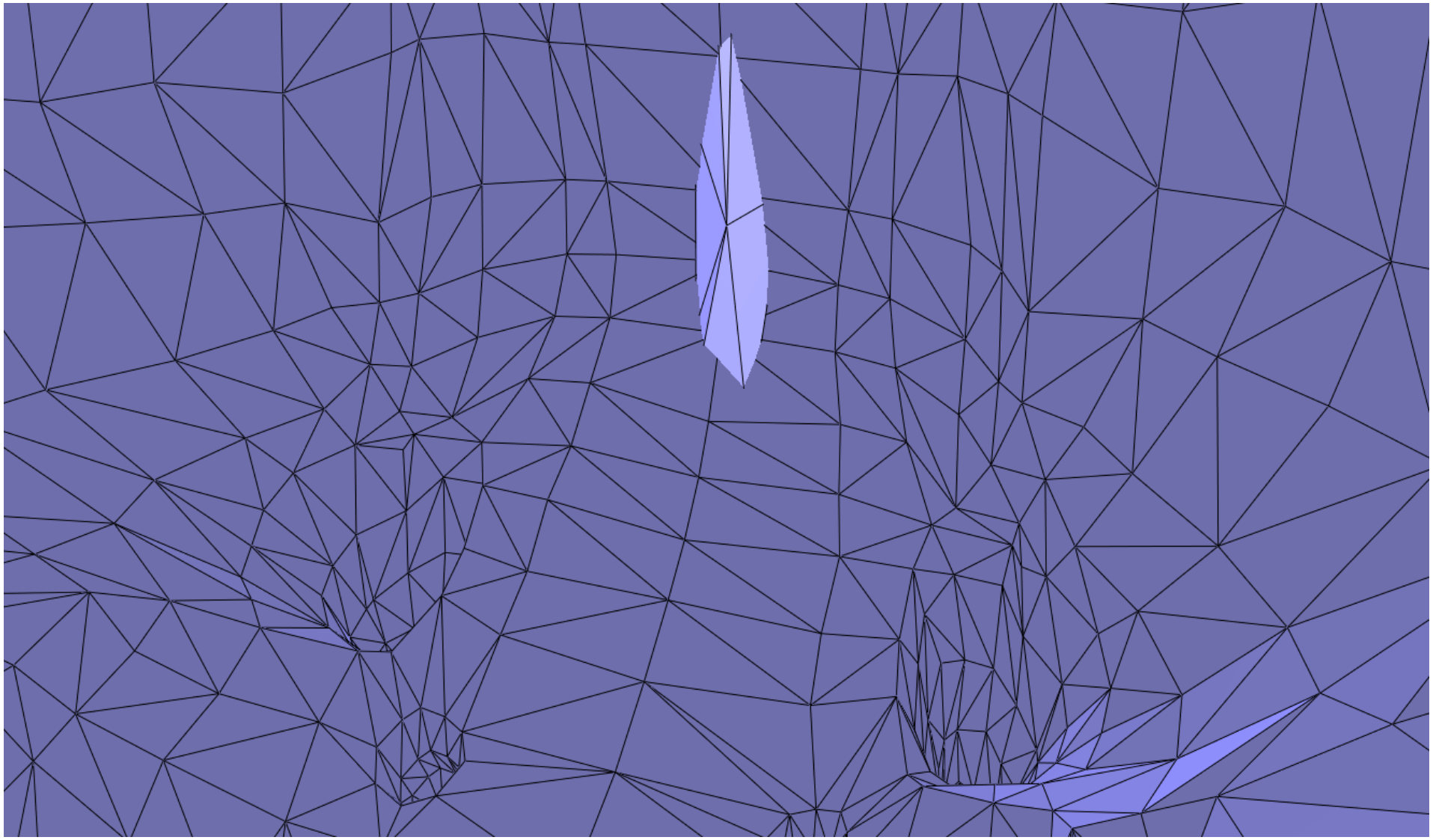

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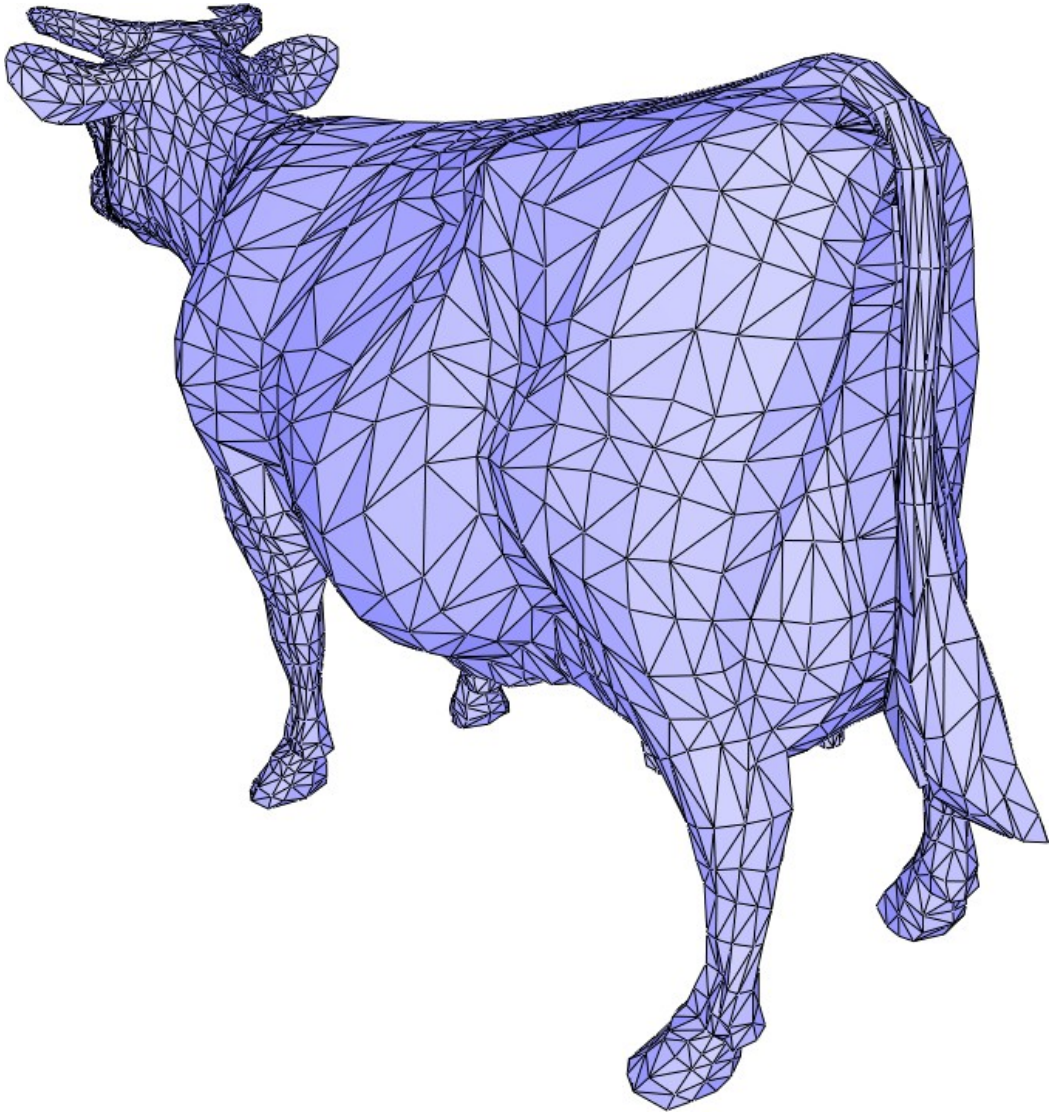
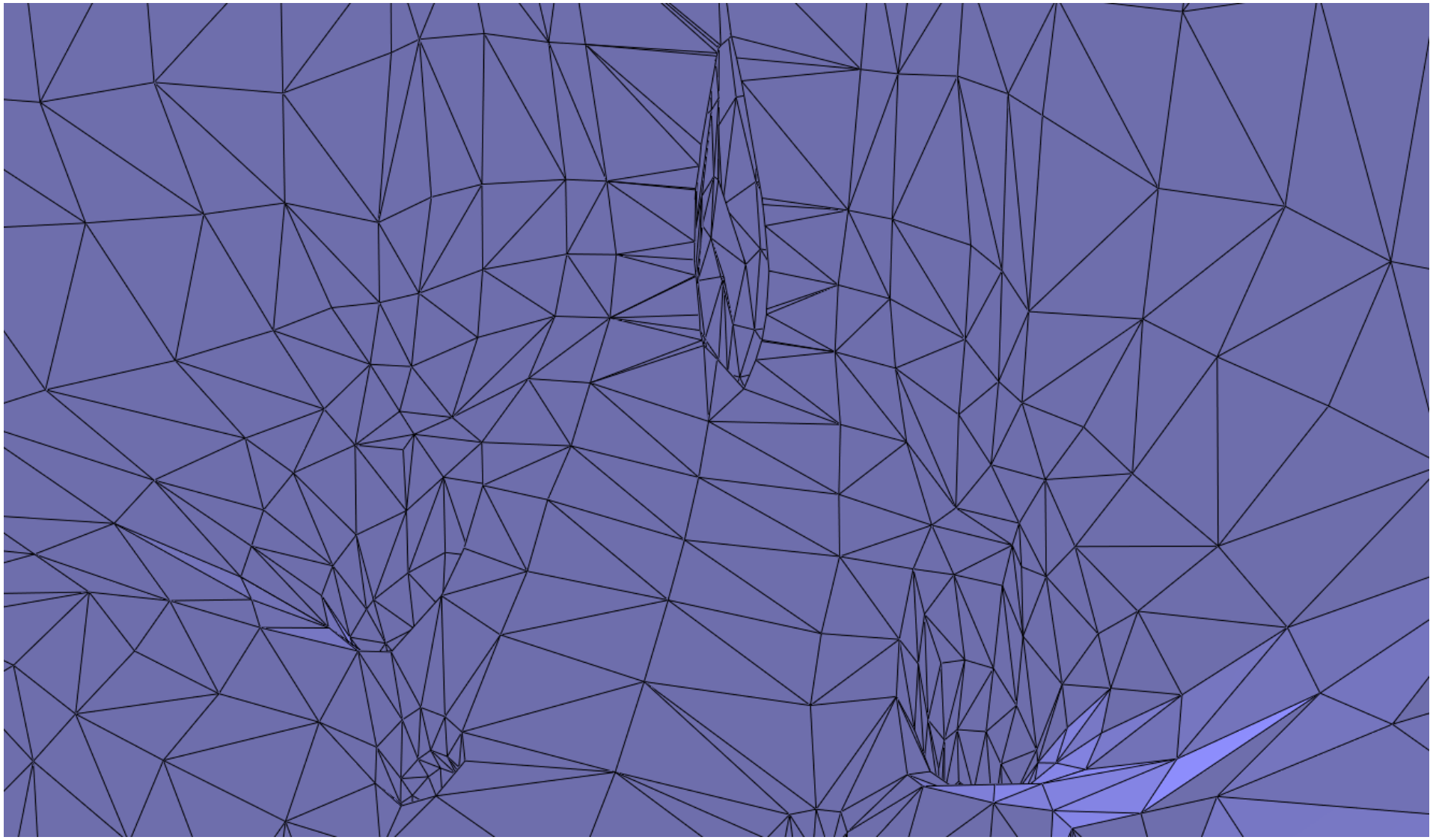
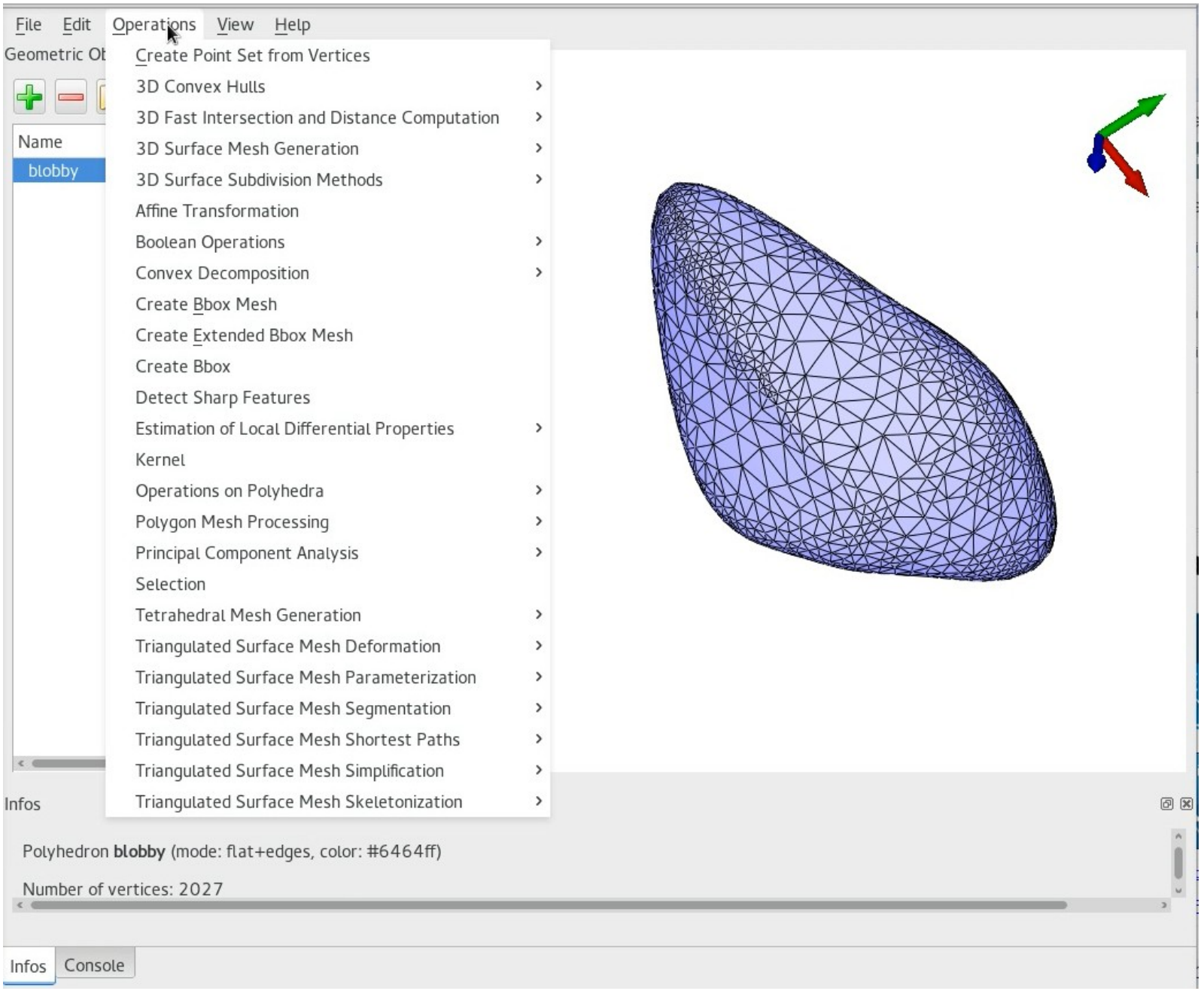


Self-intersections Removal using Refinement



Polyhedron Demo



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