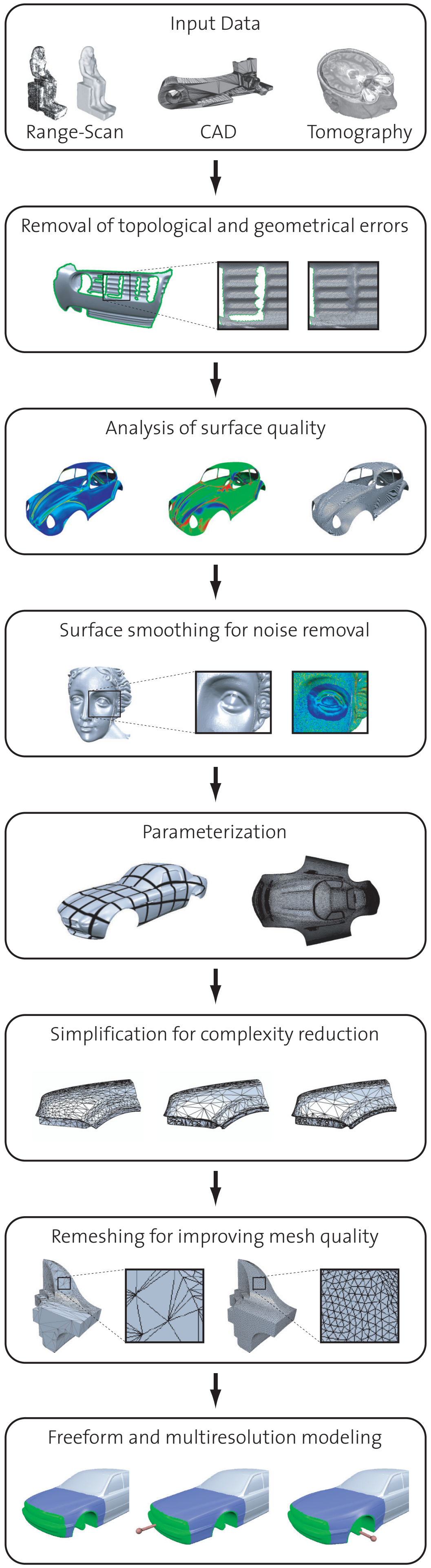
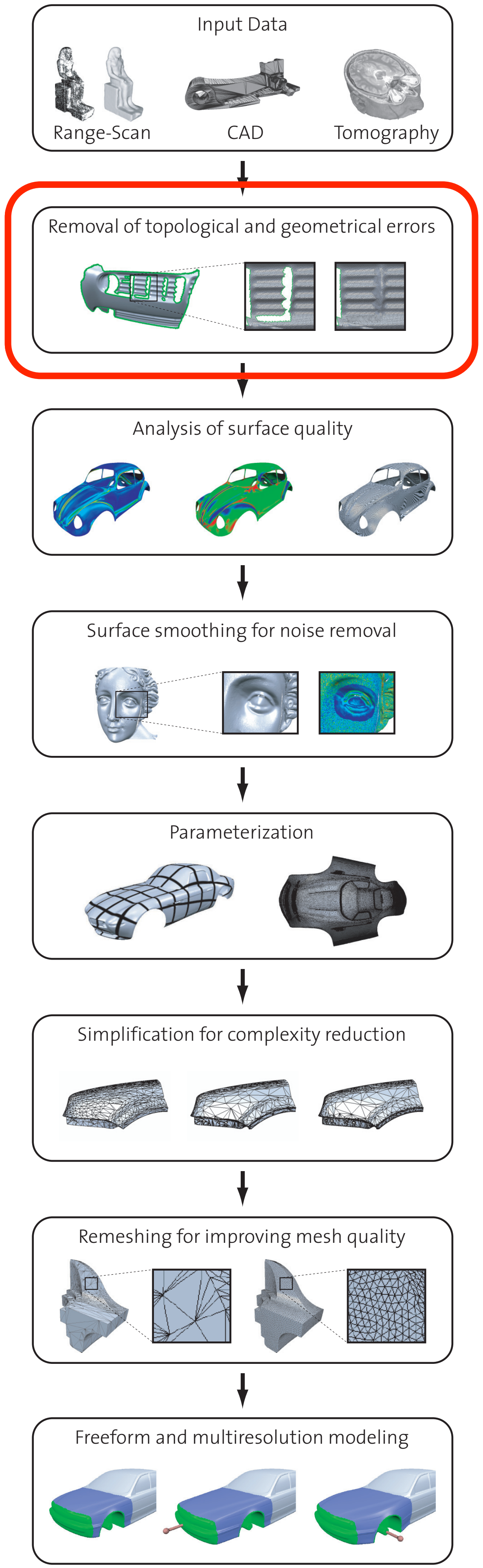


Model Repair

Leif Kobbelt

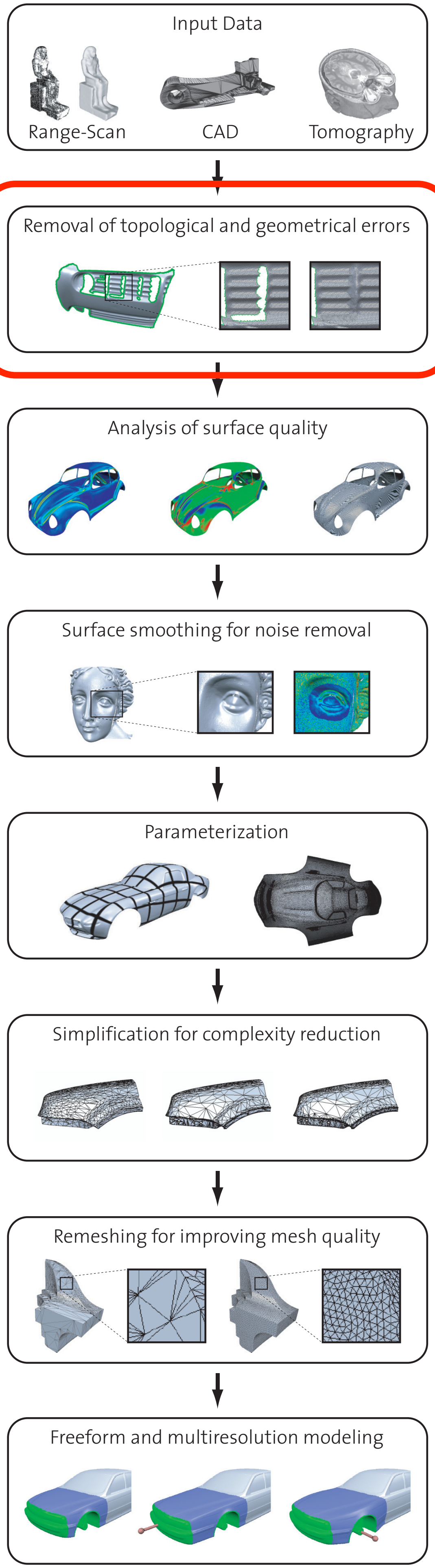
RWTH Aachen University



Model Repair

- model repair is the removal of artifacts from a geometric model such that it becomes suitable for further processing.

- produce a nice, manifold triangle mesh
  – with boundary or
  – without boundary (watertight)

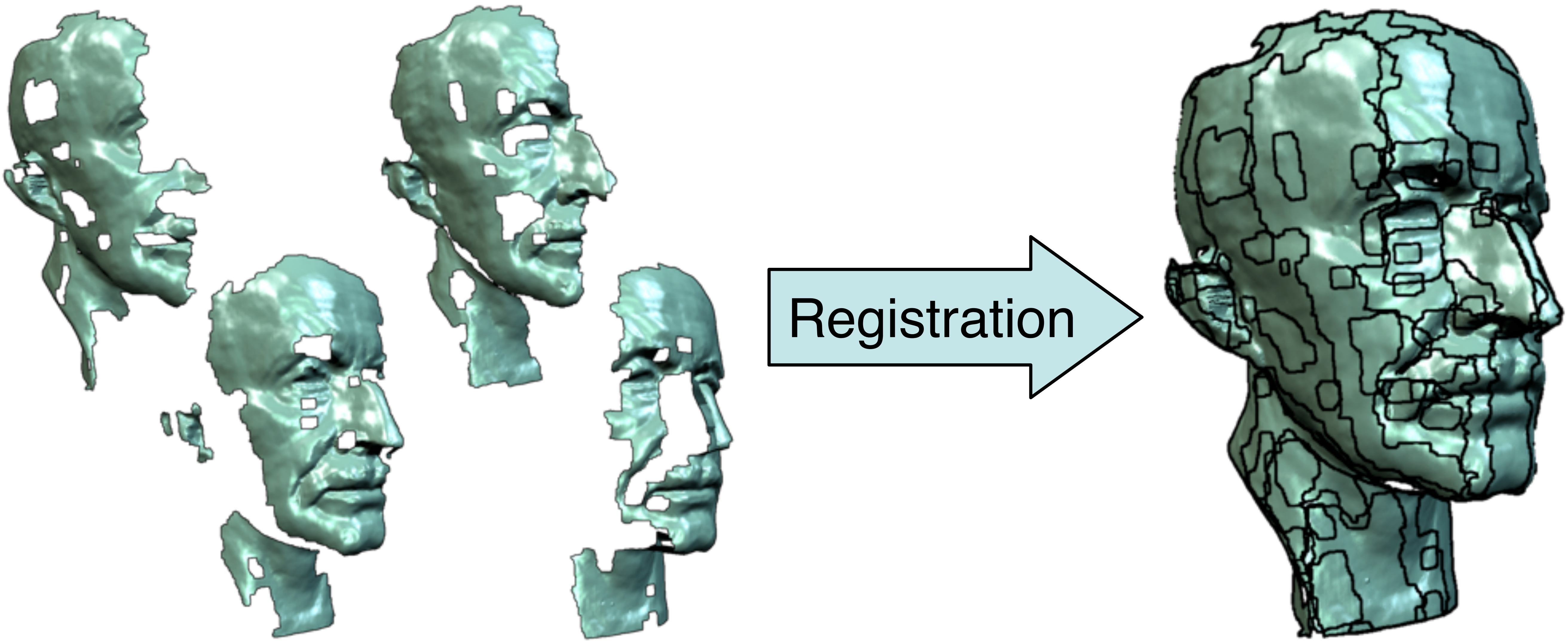


Model Repair

- **types of input**
- surface-oriented algorithms
  - Filling holes in meshes [Liepa 2003]
- volumetric algorithms
  - Simplification and repair of polygonal models using volumetric techniques [Nooruddin and Turk 2003]
  - Automatic restoration of polygon models [Bischoff, Pavic, Kobbelt 2005]
- conclusion & outlook

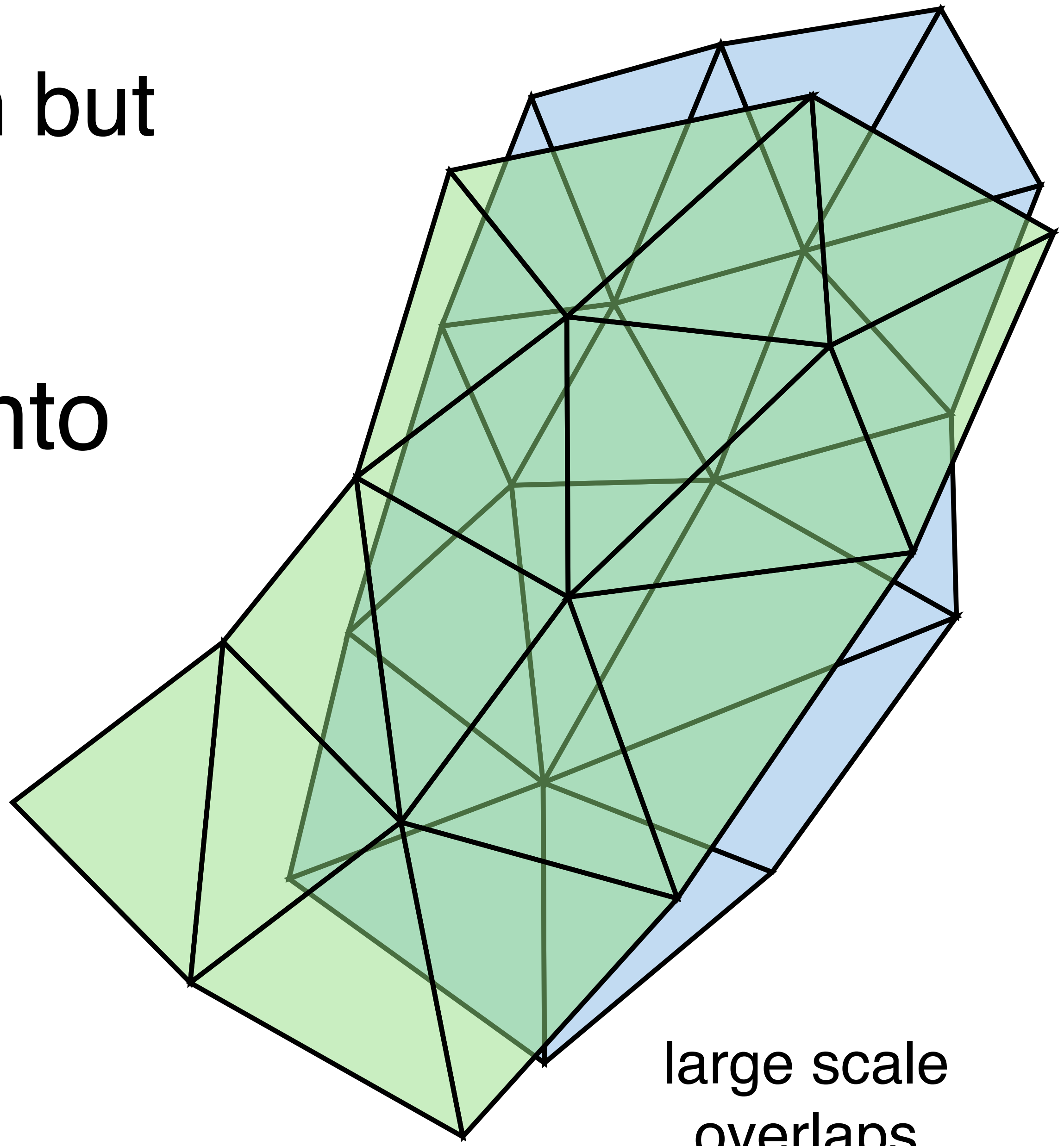
Range Images

- registered range images are a set of patches that describe different parts of an object.



Range Images

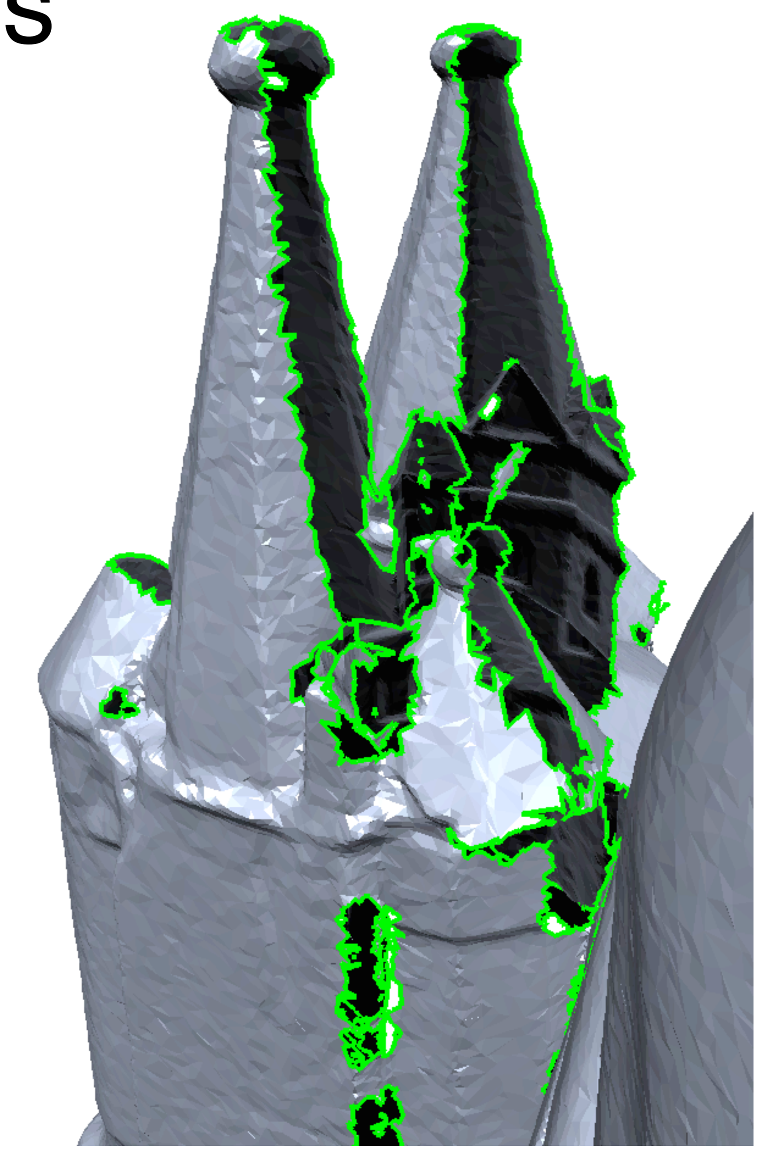
- large areas of overlap are ...
  - ... necessary for registration but
  - ... bad for consistency
- how to merge the patches into a single mesh?
  - inconsistent geometry
  - incompatible connectivities

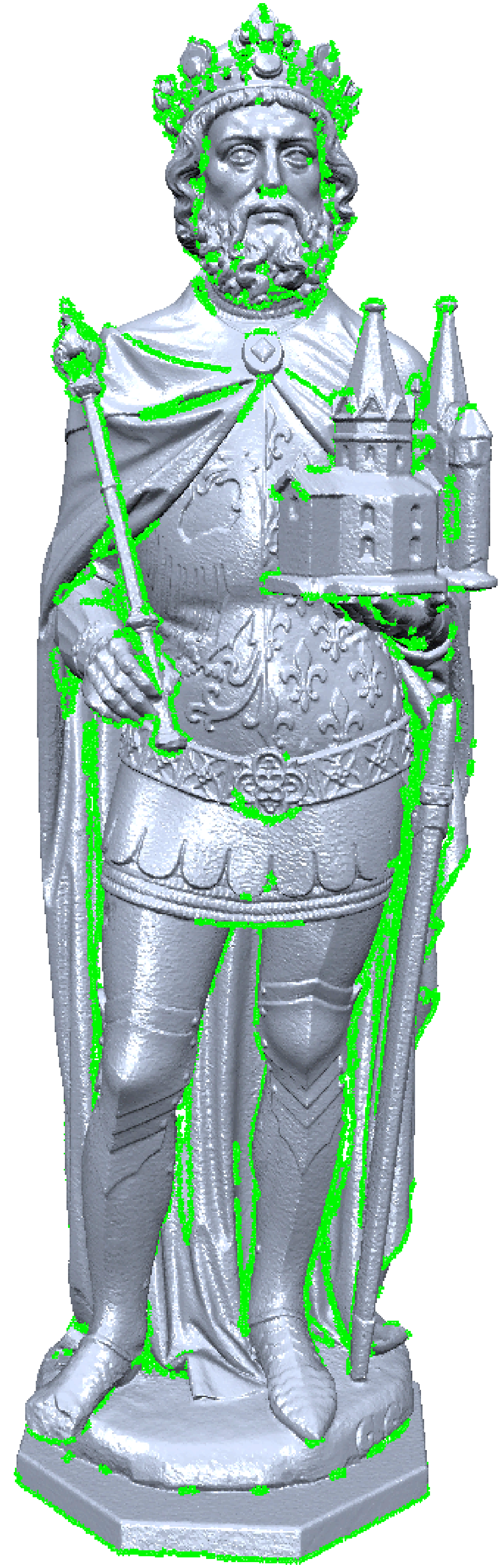


large scale overlaps

Range Images

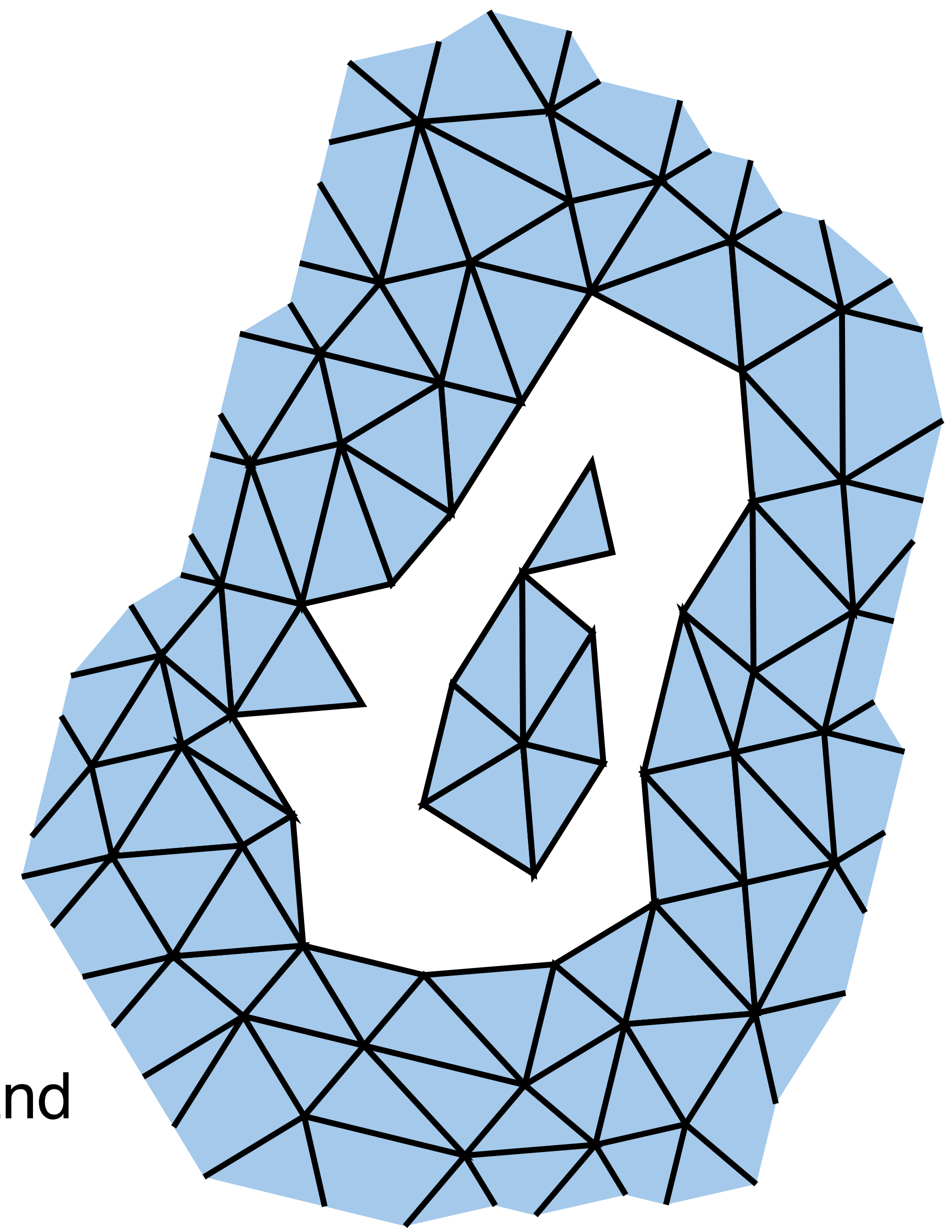
- successfully merged range images are manifold meshes with holes and islands (i.e. boundaries)





Range Images

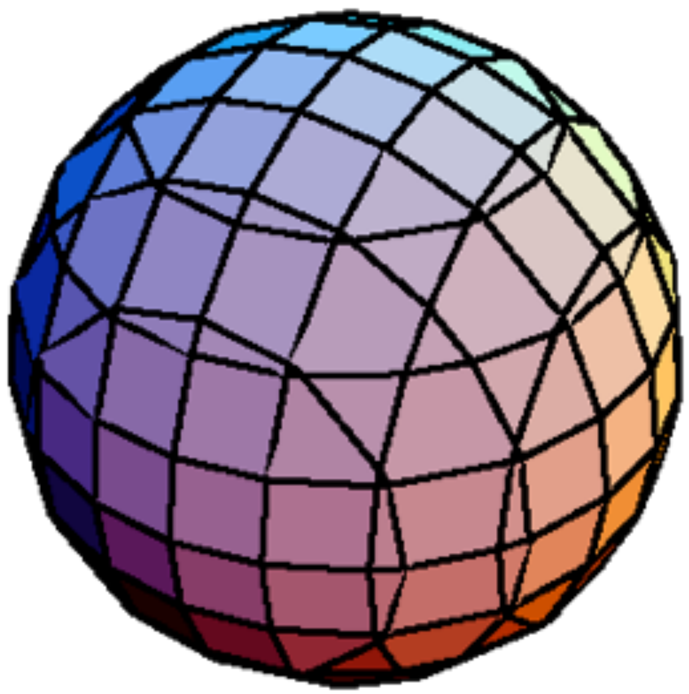
- holes and islands are due to obstructions in the line of sight of the scanner
- identify correspondences between holes and islands
- fill holes
  - smoothly
  - geometry transfer/synthesis
- avoid intersections



holes and isles

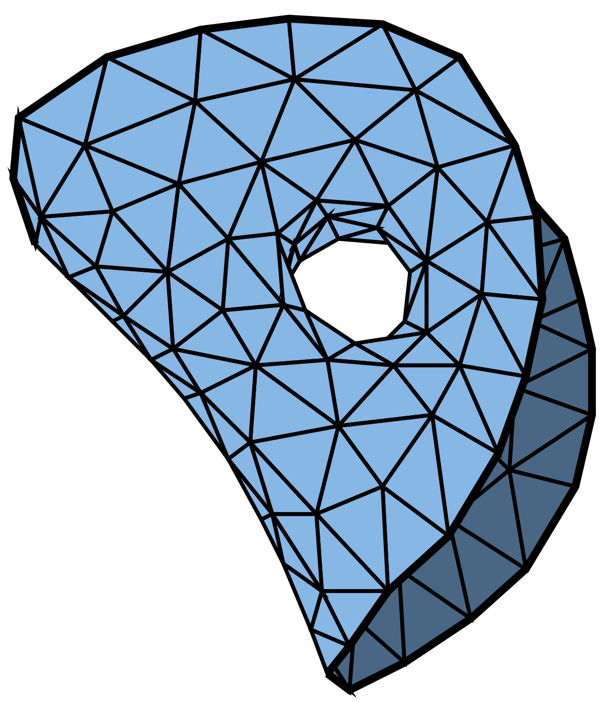
Contoured Meshes

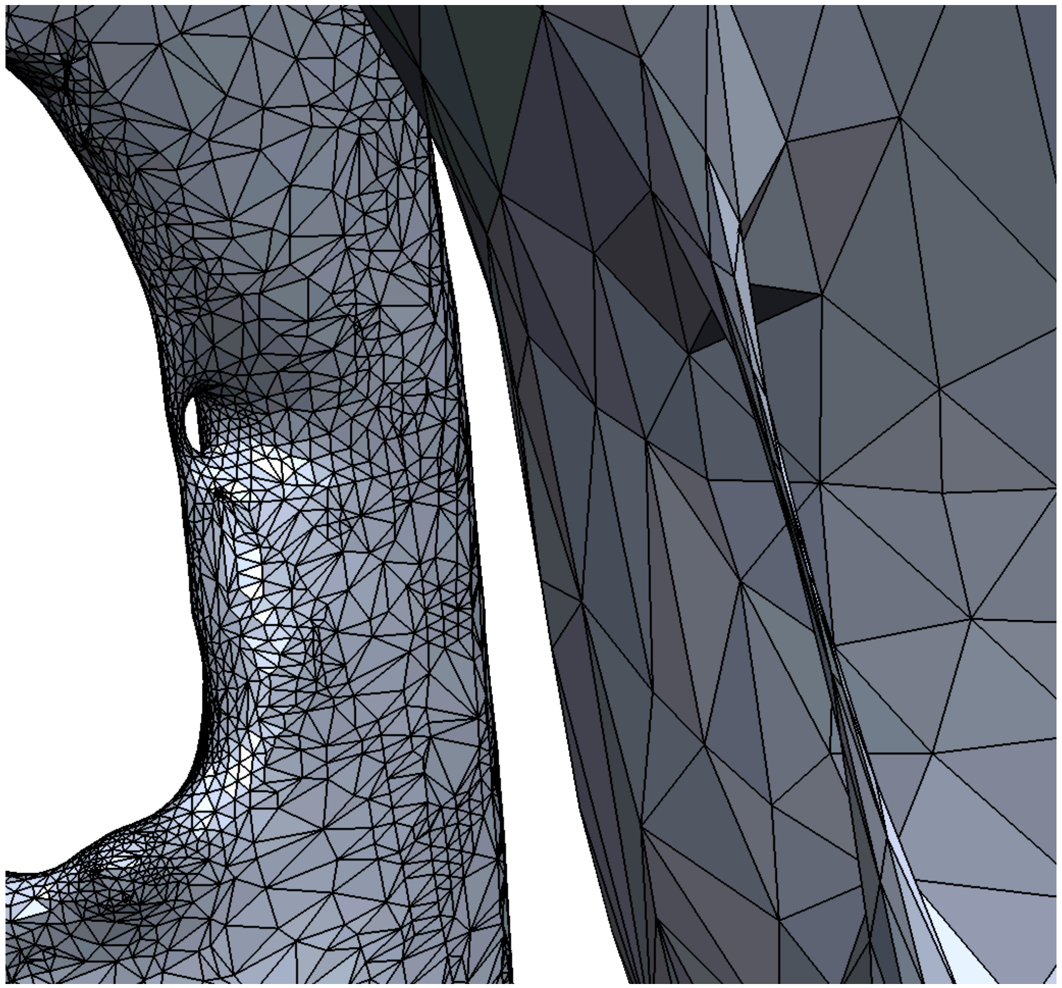
- contoured meshes have been extracted from a volumetric representation (e.g. by marching cubes)



Contoured Meshes

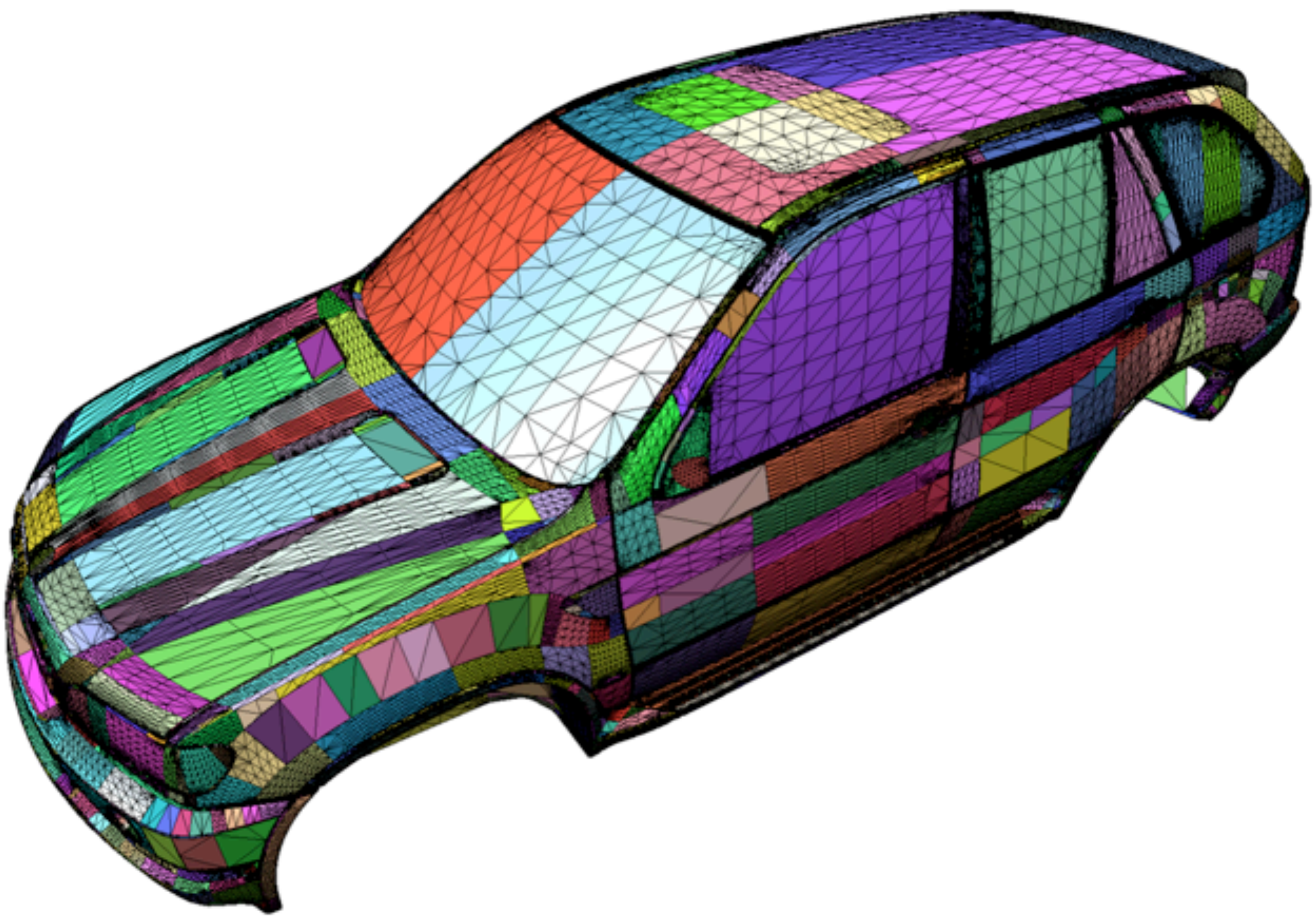
- contoured meshes are usually manifold and closed, but may contain topological noise
  - disconnected components
  - spurious handles
  - cavities





Triangulated NURBS

- set of patches that contain small scale gaps and overlaps



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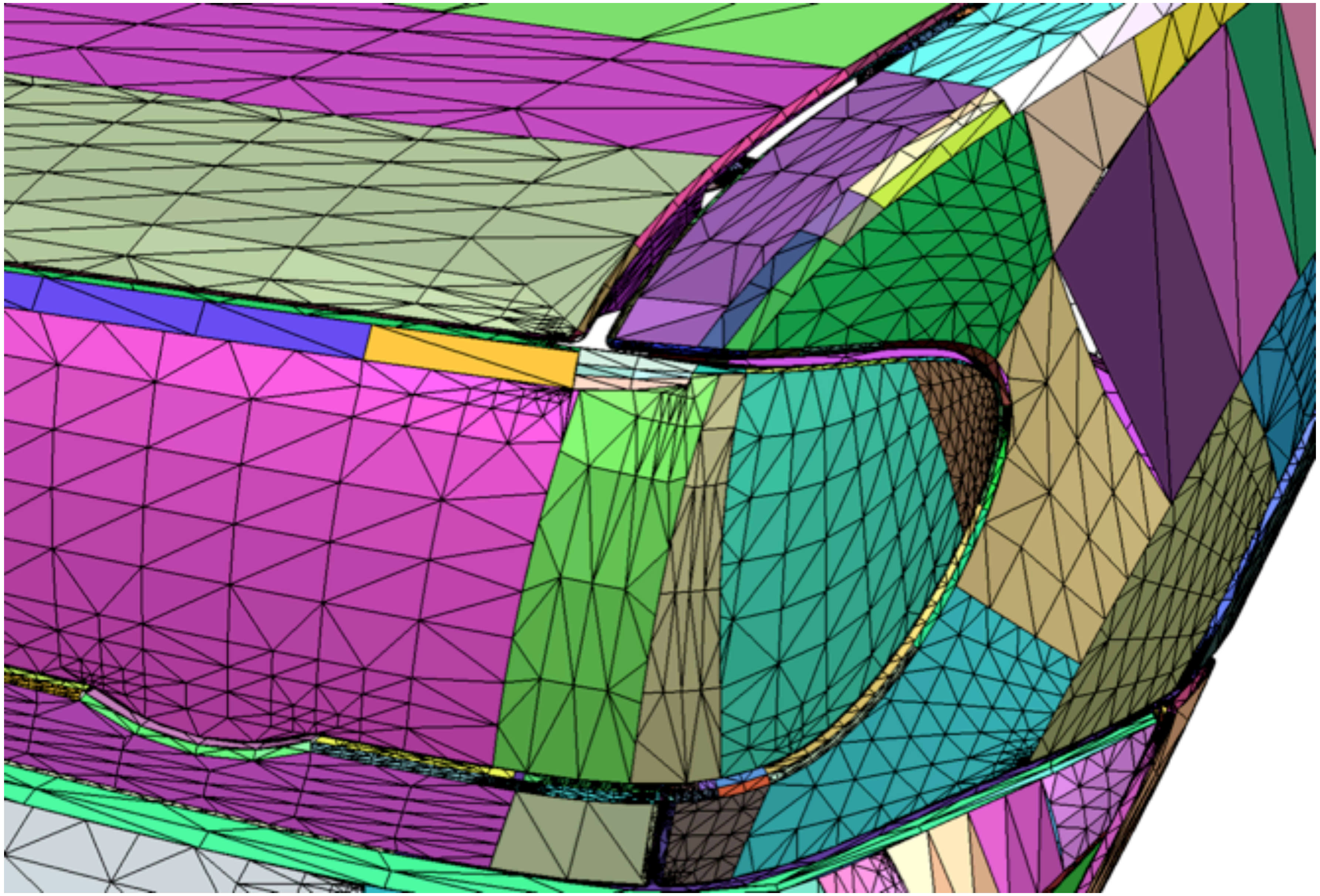
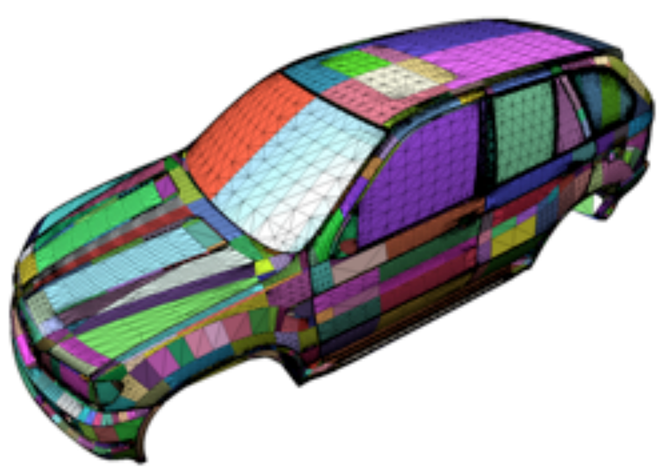
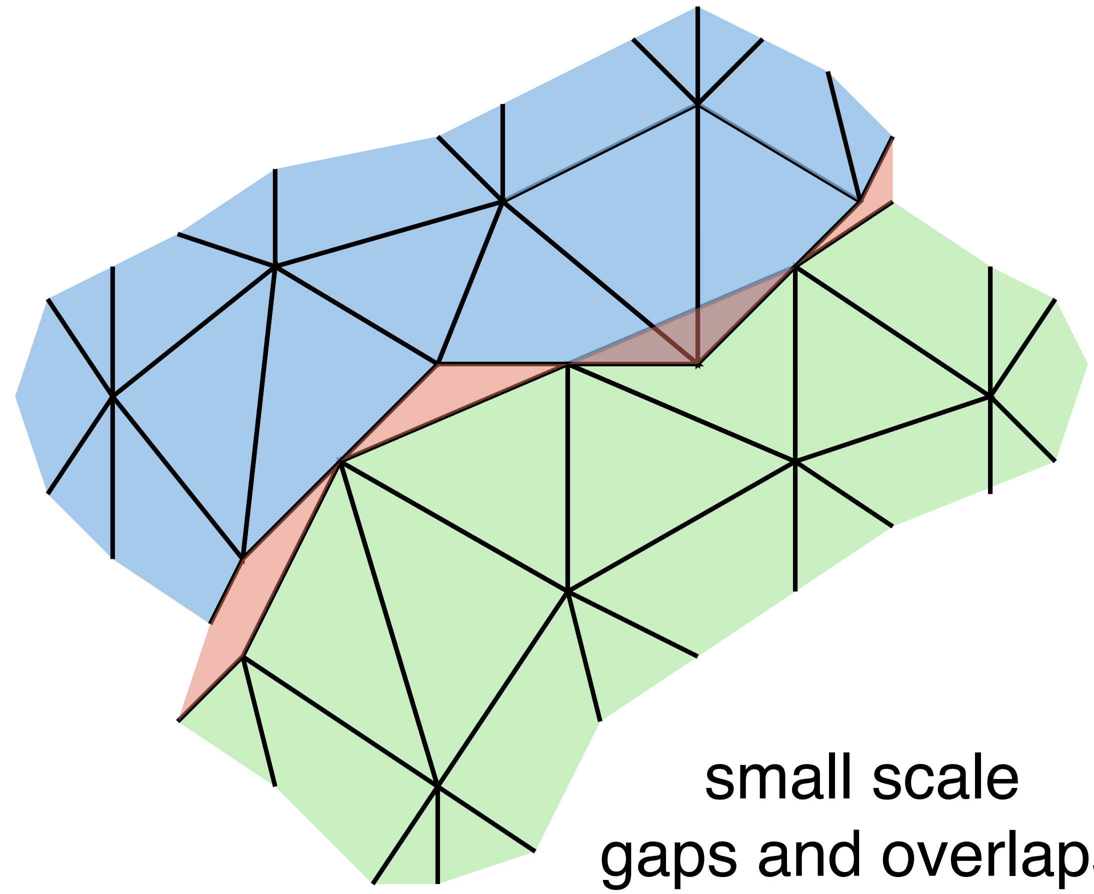


Triangulated NURBS

- gaps and overlaps are due to triangulating a common (trimmed) patch boundary differently from both sides
- issues
  - consistent orientation
  - structure preservation

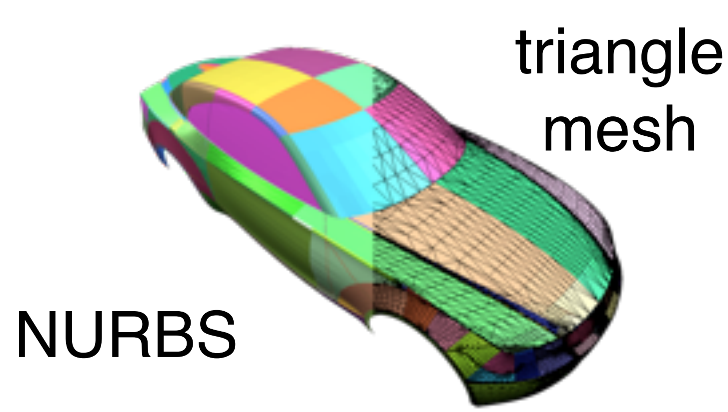


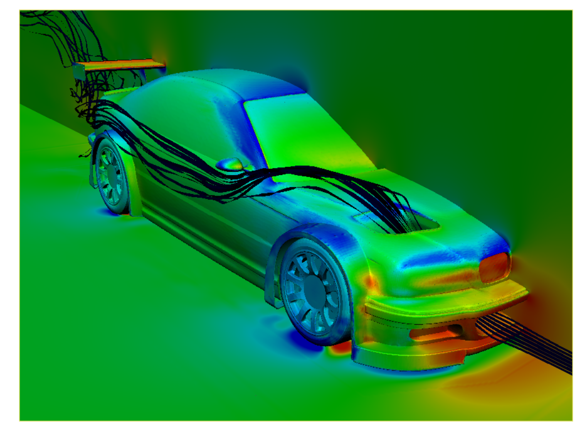


small scale
gaps and overlaps

Triangulated NURBS

- typical workflow, e.g., in CAD/CAM:





Editing → Repair → Simulation

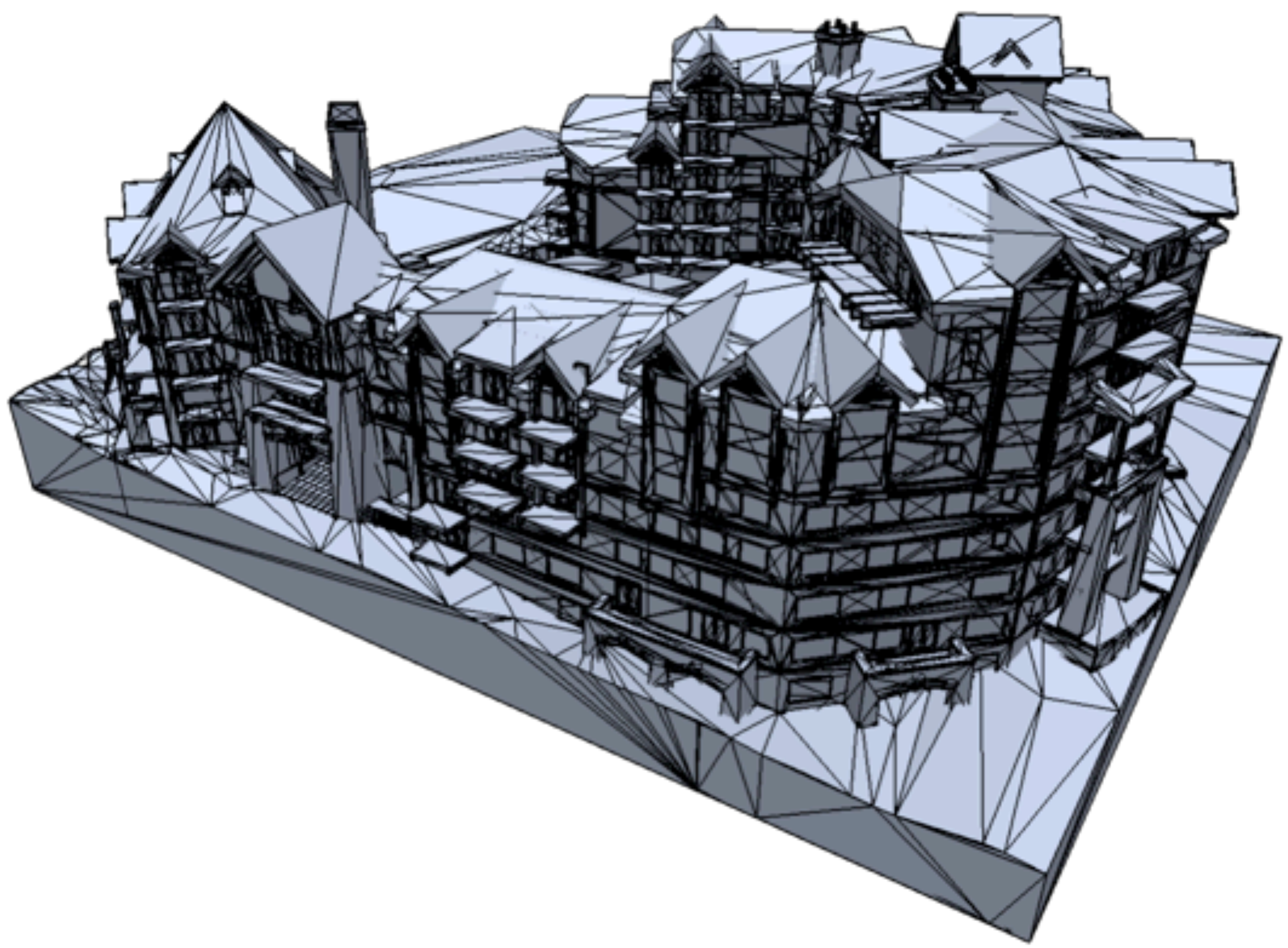
manual

often:manu
al(!)

automatic

Triangle Soups

- a triangle soup is a set of triangles without connectivity information



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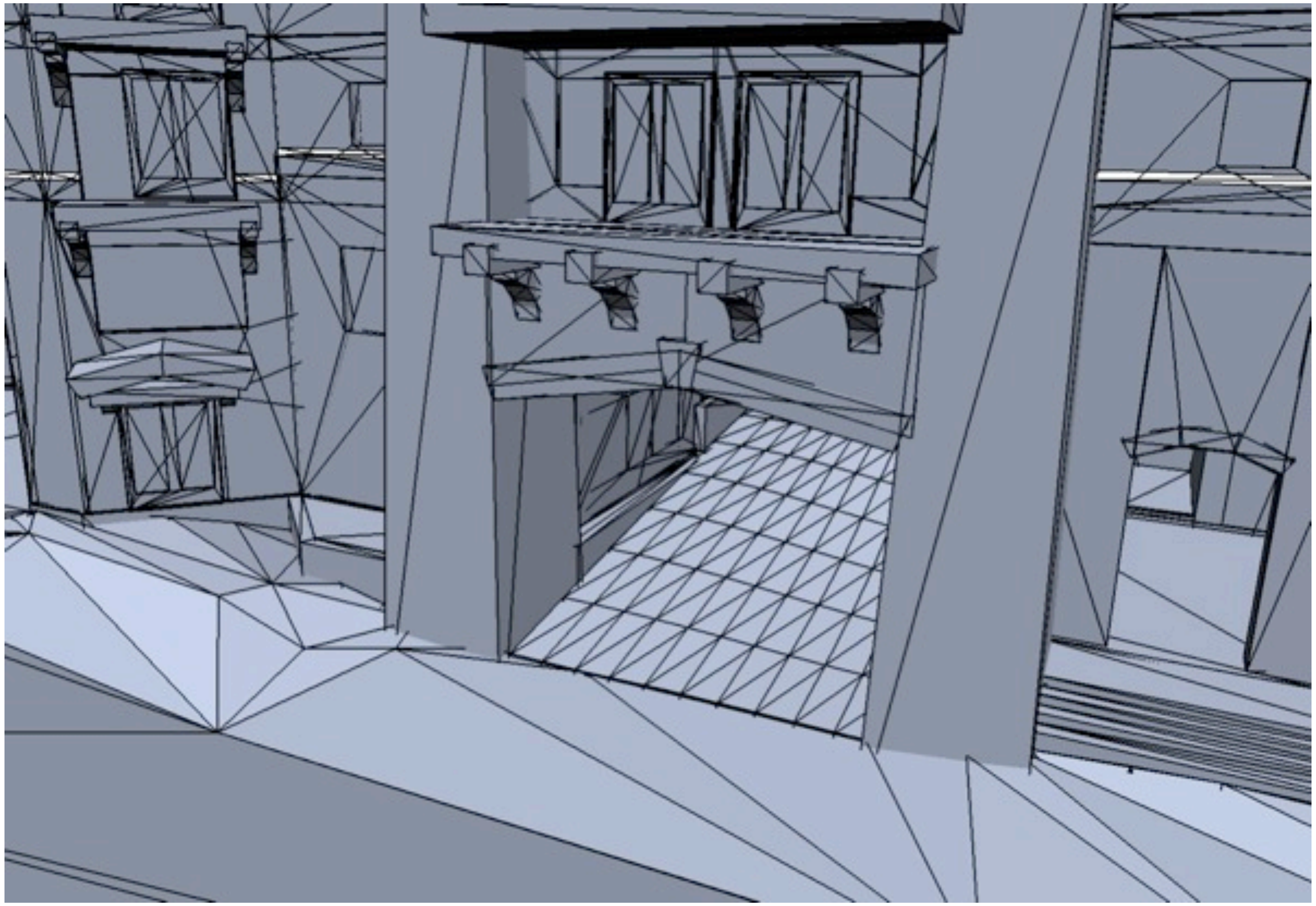
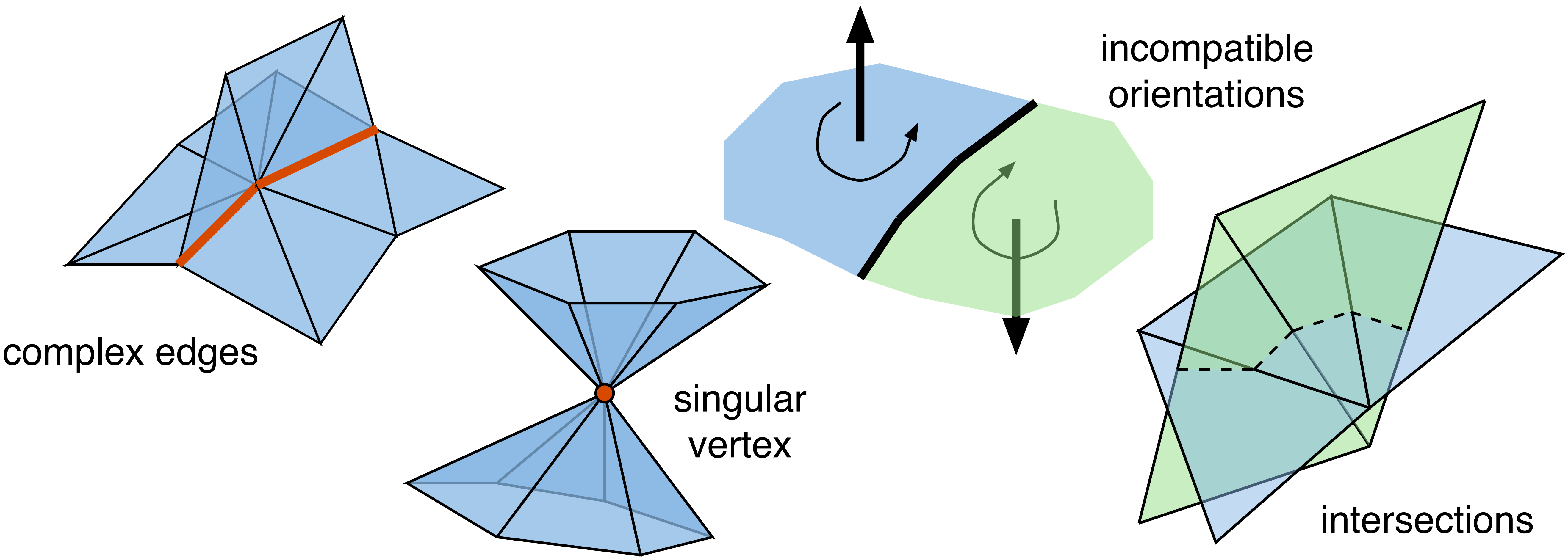


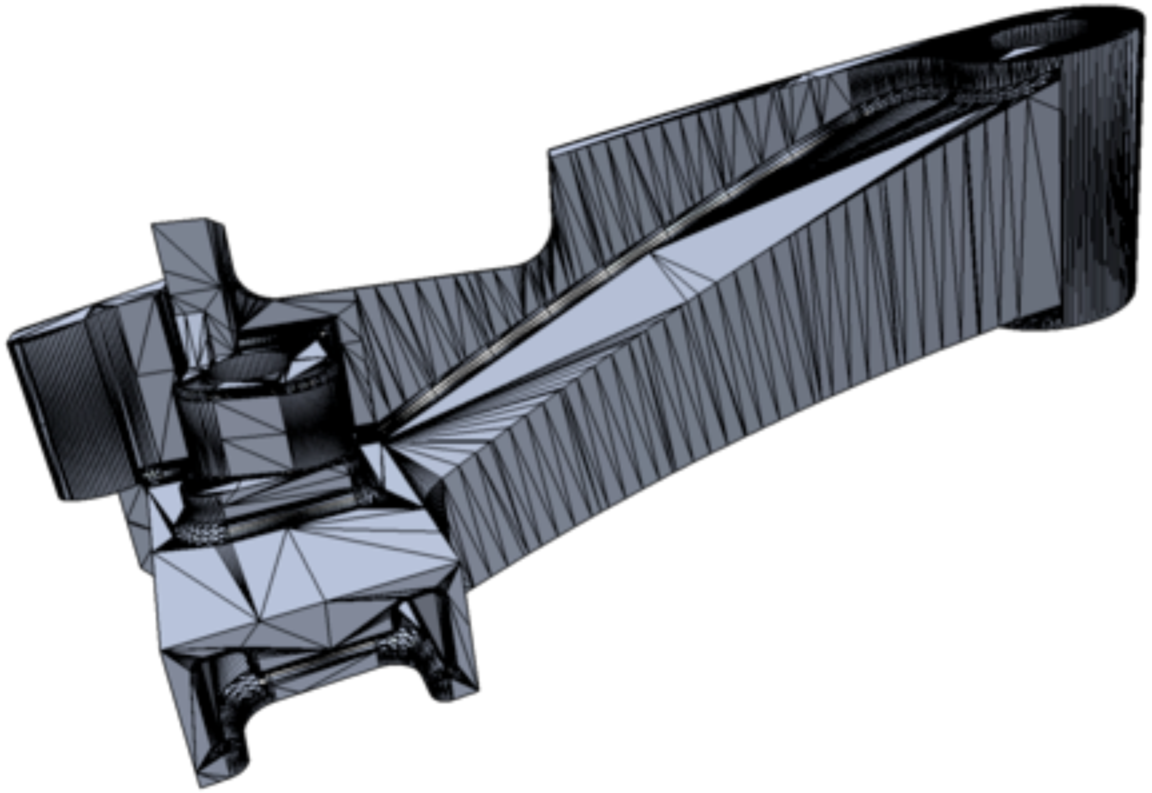
Triangle Soups

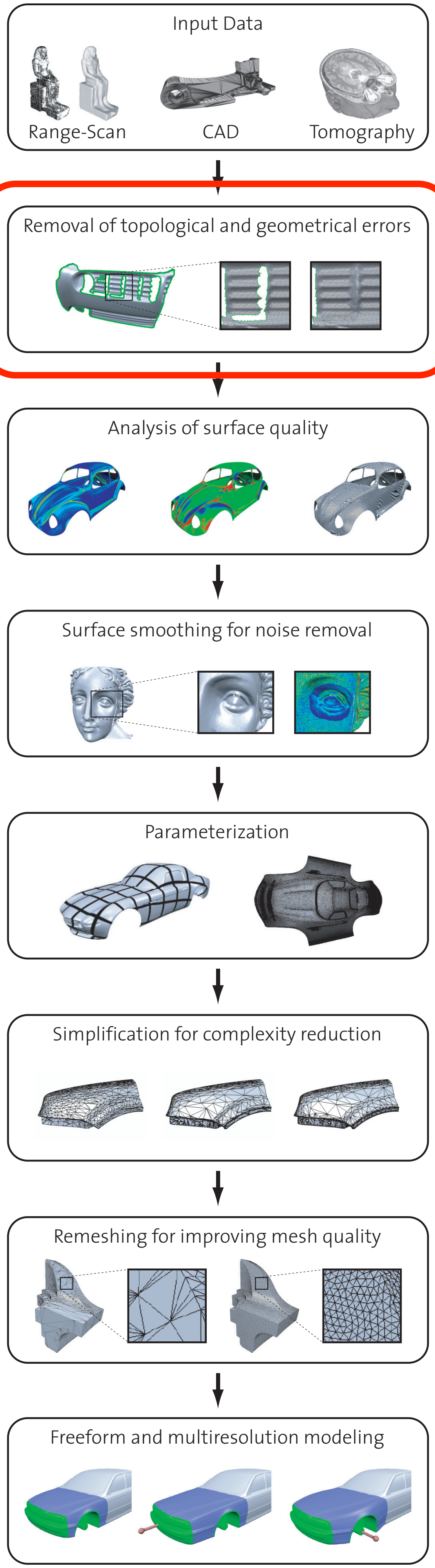
- good for visualization but bad for downstream applications that require manifold meshes
- in addition to the artifacts we already encountered:



Not Covered In *This* Lecture ...

- geometrical noise
  ➞ smoothing (Mark)
- badly meshed manifolds
  ➞ remeshing (Pierre)





Model Repair

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- **surface-oriented algorithms**
  - Filling holes in meshes [Liepa 2003]
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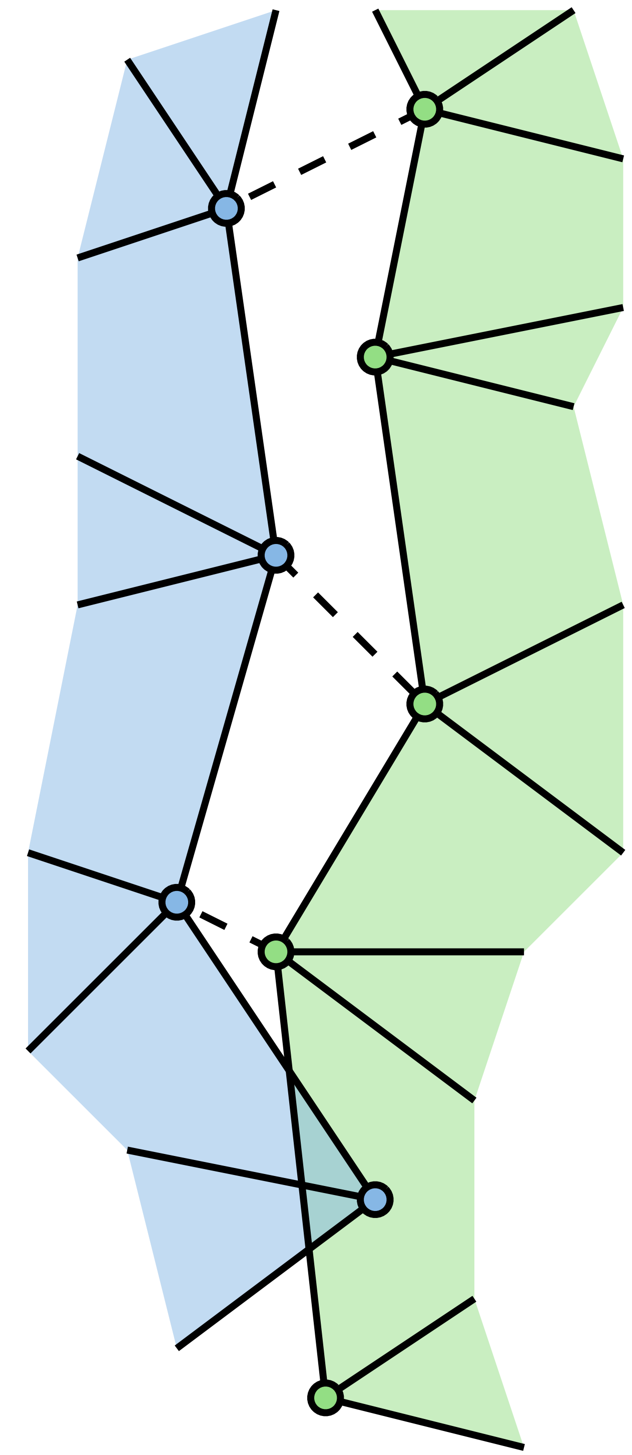
- conclusion & outlook

Surface-Oriented Algorithms

- surface oriented approaches explicitly identify and resolve artifacts
- methods
  - snapping
  - splitting
  - stitching
  - ...

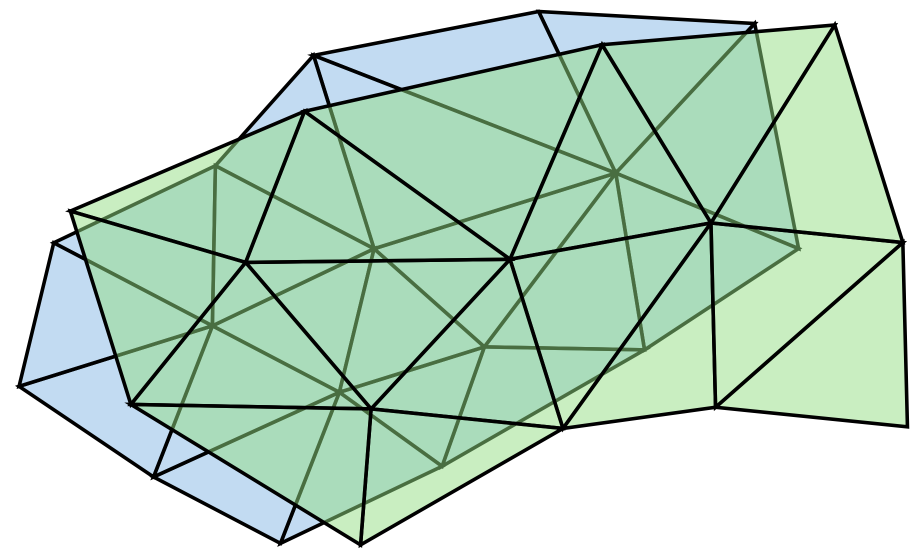


Surface-Oriented Algorithms

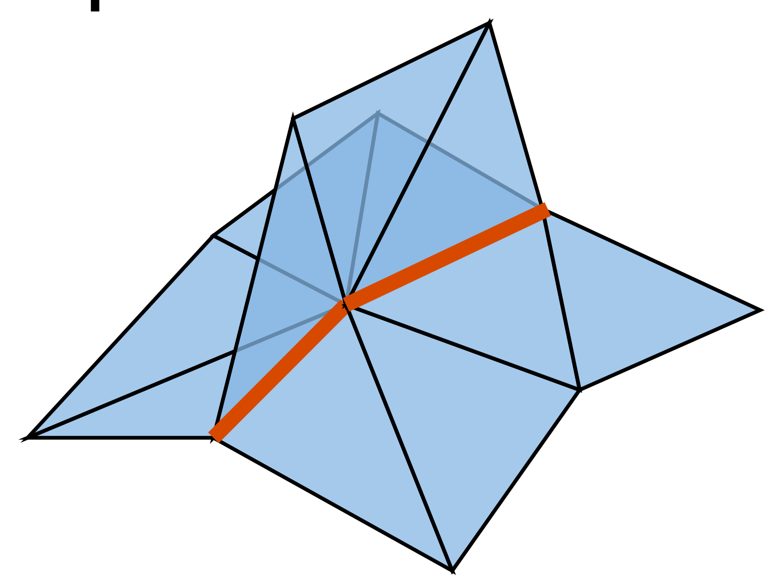
- advantages
  - fast
  - conceptually easy
  - memory friendly
  - structure preserving, minimal modification of the input

Surface-Oriented Algorithms

- problems
  - not robust
    - numerical issues
    - inherent non-robustness



  - no quality guarantees on the output



Example Algorithm

- algorithm for filling holes

  Peter Liepa

  Filling Holes in Meshes

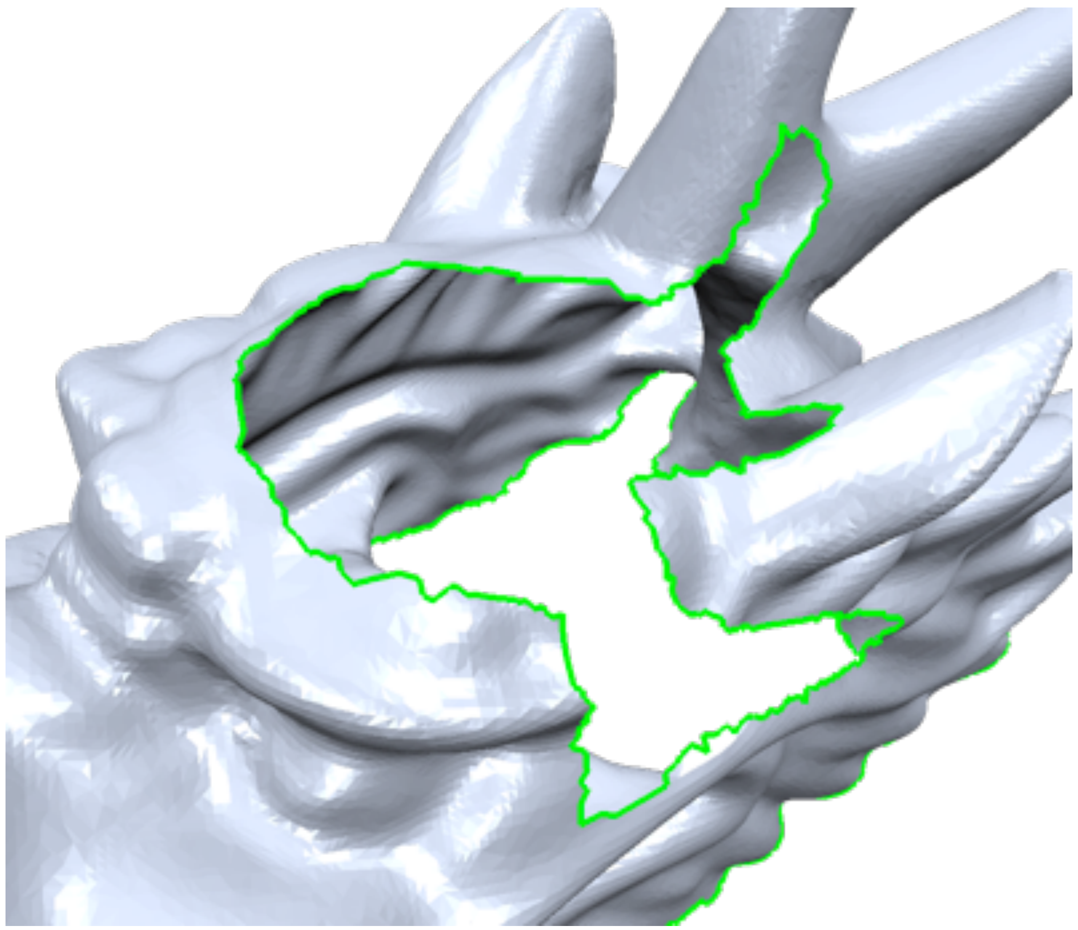
  In Proc. Symposium on Geometry Processing 2003

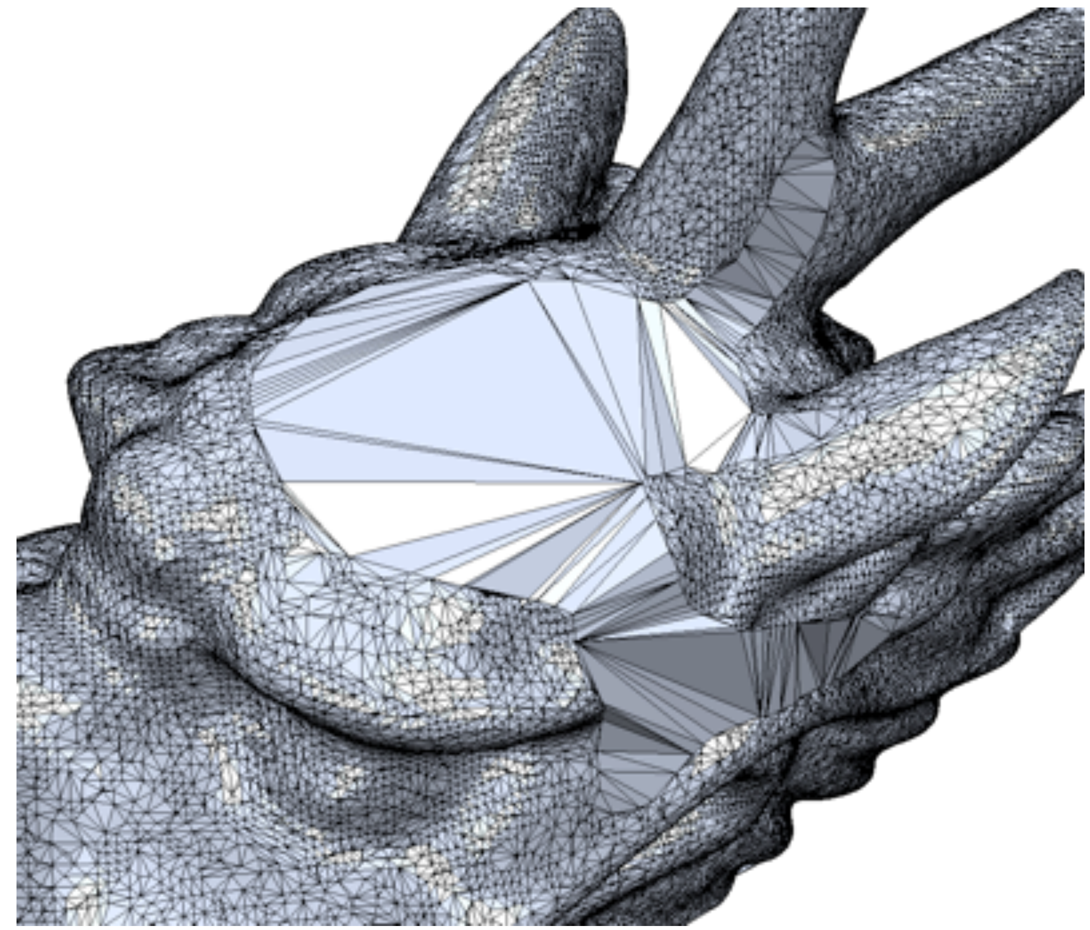
- three stages

  1. compute a coarse triangulation T to fill a hole
  2. refine the triangulation, T → T', to match the vertex densities of the surrounding area
  3. smooth the triangulation T' to match the geometry of the surrounding

Filling Holes in Meshes - 1

- compute a coarse triangulation T

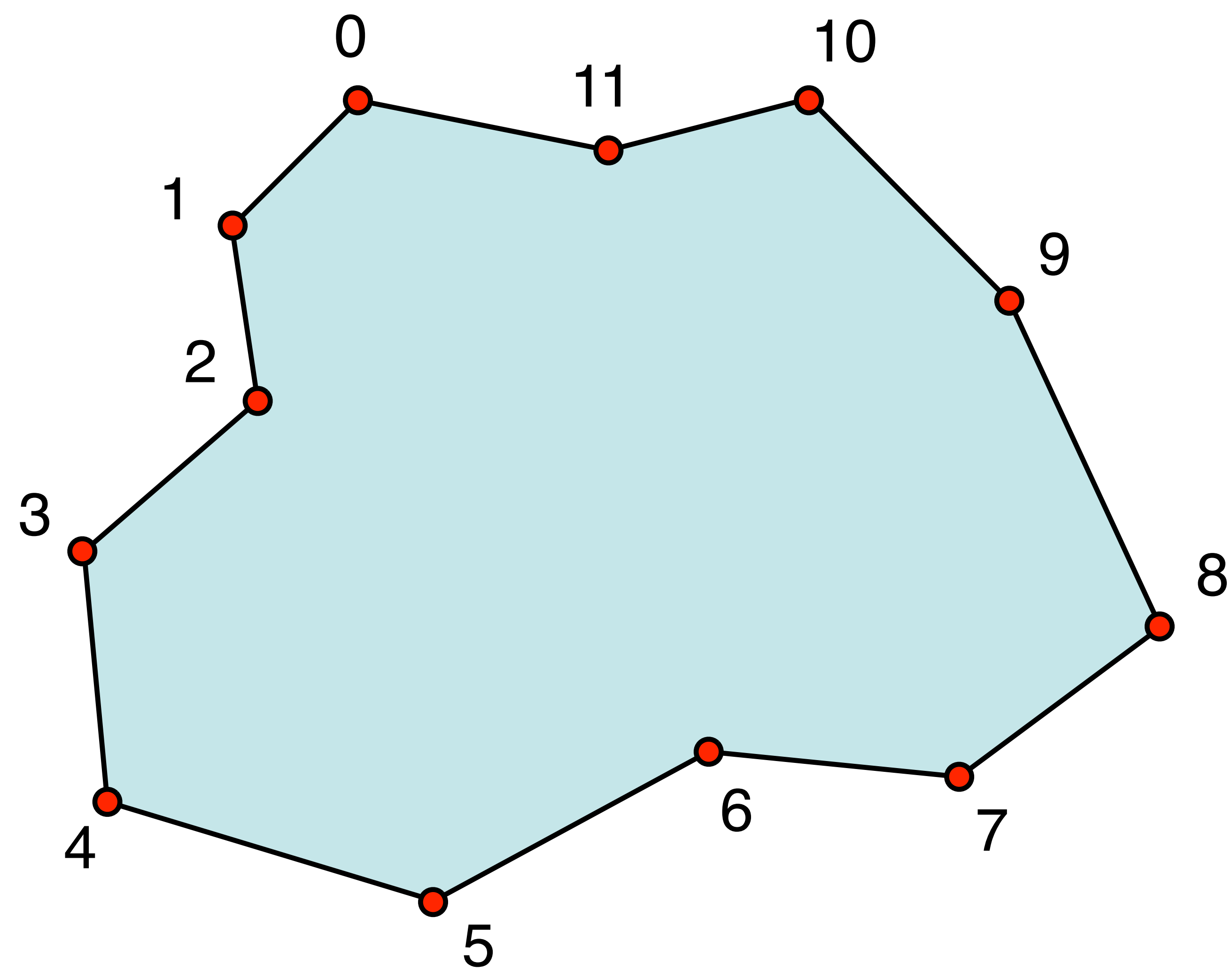




Filling Holes in Meshes - 1

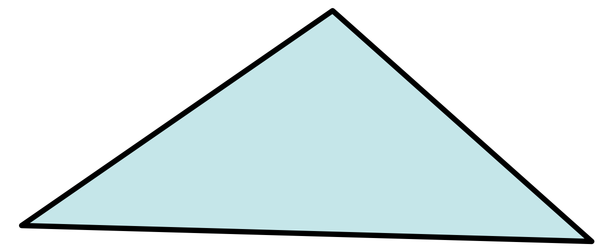
- compute a coarse triangulation T of minimal weight w(T)

n vertices,
n–2 triangles

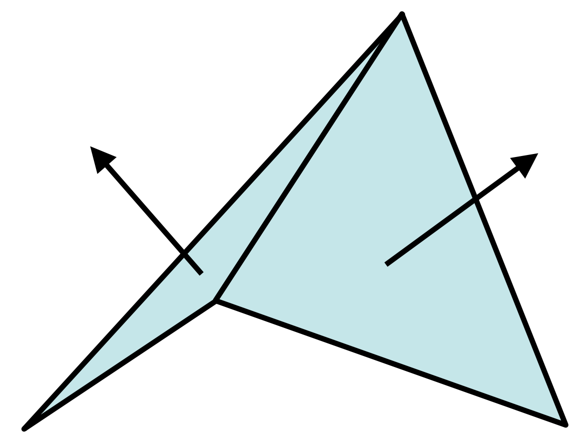


Filling Holes in Meshes - 1

- weight w(T) is a mixture of
  - $\text{area}(T) = \sum_{\Delta \in T} \text{area}(\Delta)$



  - maximum dihedral angle in T

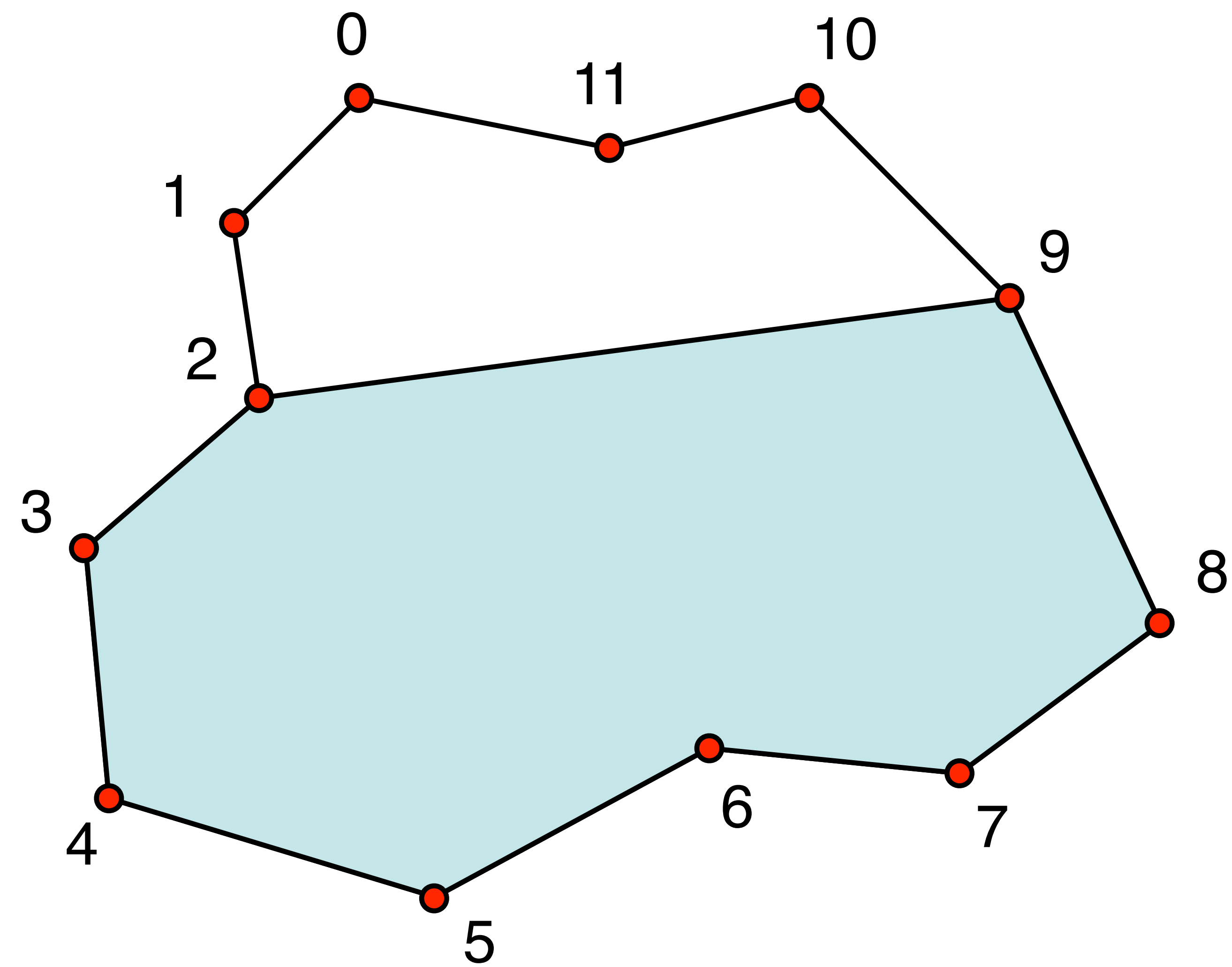


- thus, we favour triangulations of low area and low normal variation

Filling Holes in Meshes - 1

- let w[a,c] be the minimal weight that can be achieved in triangulating the polygon a,a+1,...,c

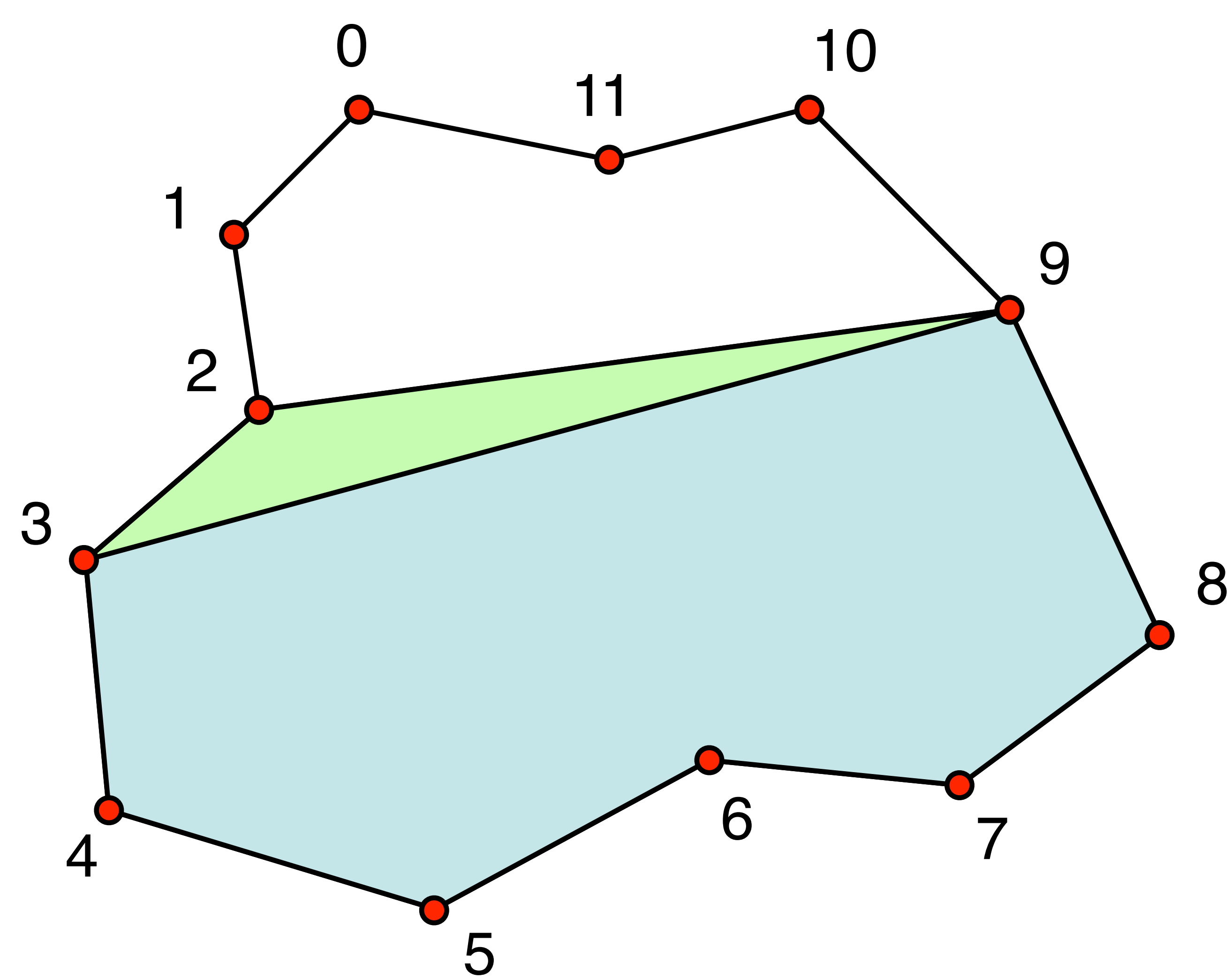
w[2,9] = ?



Filling Holes in Meshes - 1

- let w[a,c] be the minimal weight that can be achieved in triangulating the polygon a,a+1,...,c

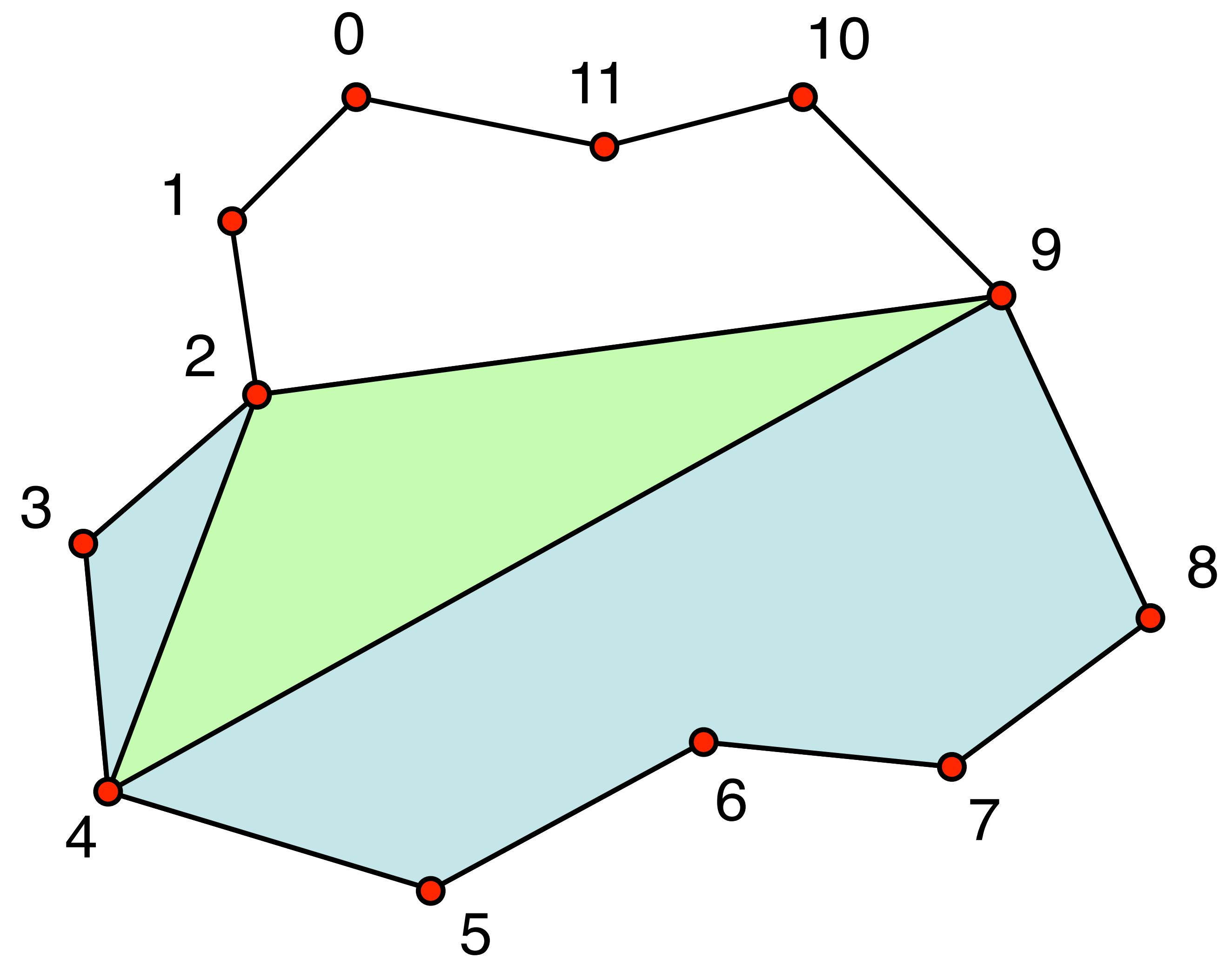
w[2,9] = min(
  w(Δ(2,3,9)) + w[3,9],



Filling Holes in Meshes - 1

- let w[a,c] be the minimal weight that can be achieved in triangulating the polygon a,a+1,...,c

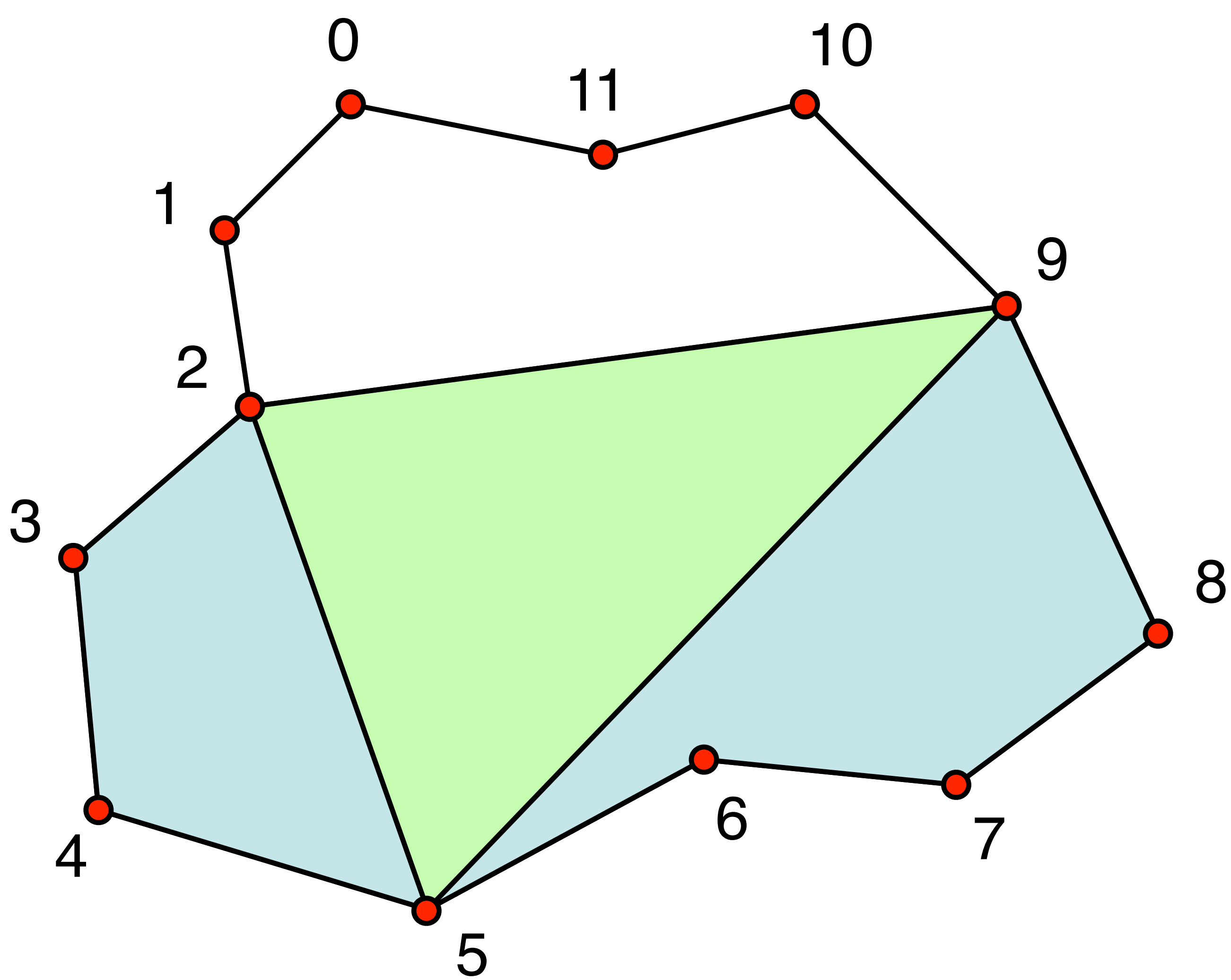
w[2,9] = min(
w(Δ(2,3,9)) + w[3,9],
w[2,4] + w(Δ(2,4,9)) + w[4,9],



Filling Holes in Meshes - 1

- let w[a,c] be the minimal weight that can be achieved in triangulating the polygon a,a+1,...,c

$$
\begin{aligned}
w[2,9] = \min(& \\
& w(\Delta(2,3,9)) + w[3,9], \\
w[2,4] + & w(\Delta(2,4,9)) + w[4,9], \\
w[2,5] + & w(\Delta(2,5,9)) + w[5,9],
\end{aligned}
$$



Filling Holes in Meshes - 1

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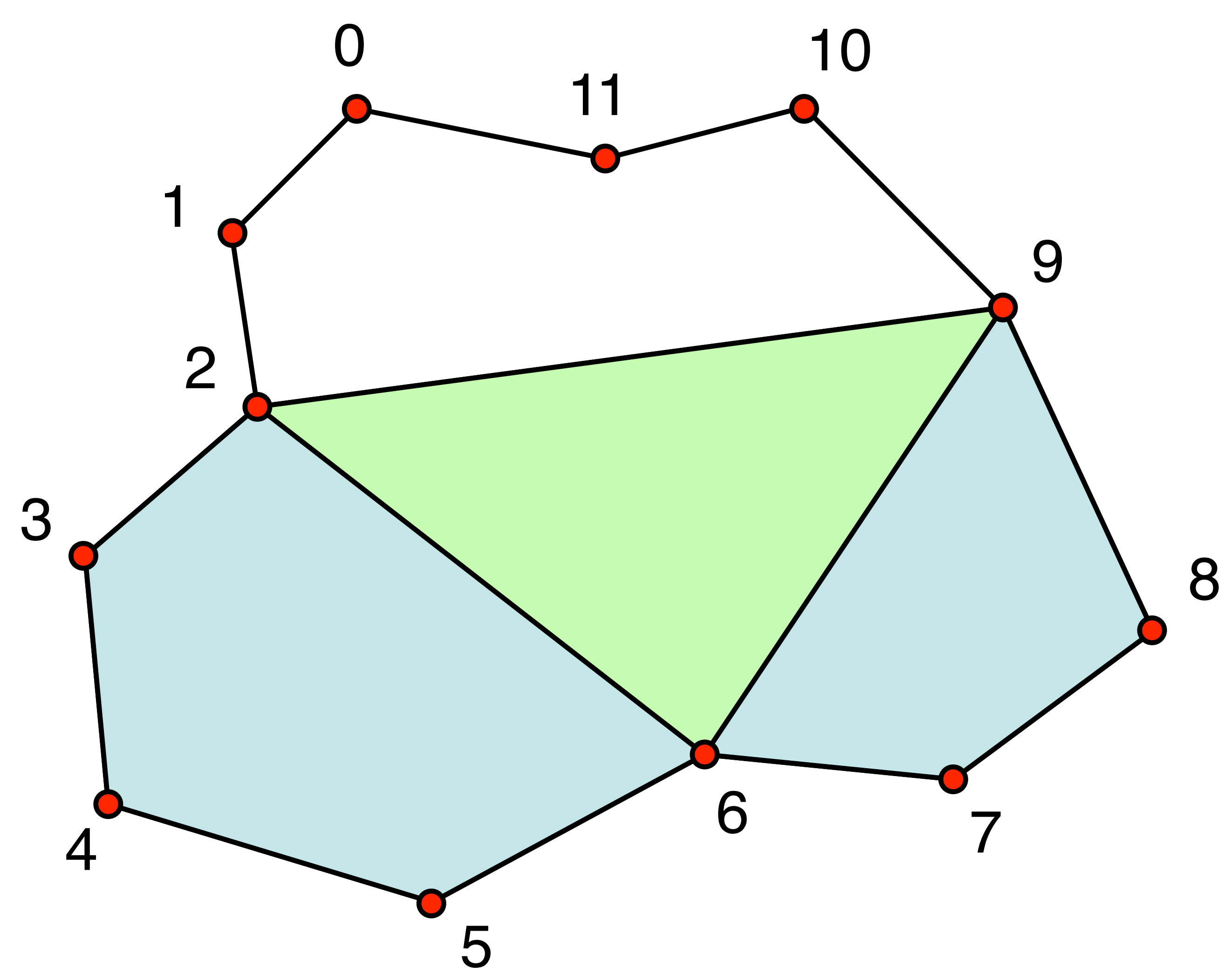
\begin{aligned}
w[2,9] = \min(& \\
& w(\Delta(2,3,9)) + w[3,9], \\
& w[2,4] + w(\Delta(2,4,9)) + w[4,9], \\
& w[2,5] + w(\Delta(2,5,9)) + w[5,9], \\
& w[2,6] + w(\Delta(2,6,9)) + w[6,9],
\end{aligned}
$$



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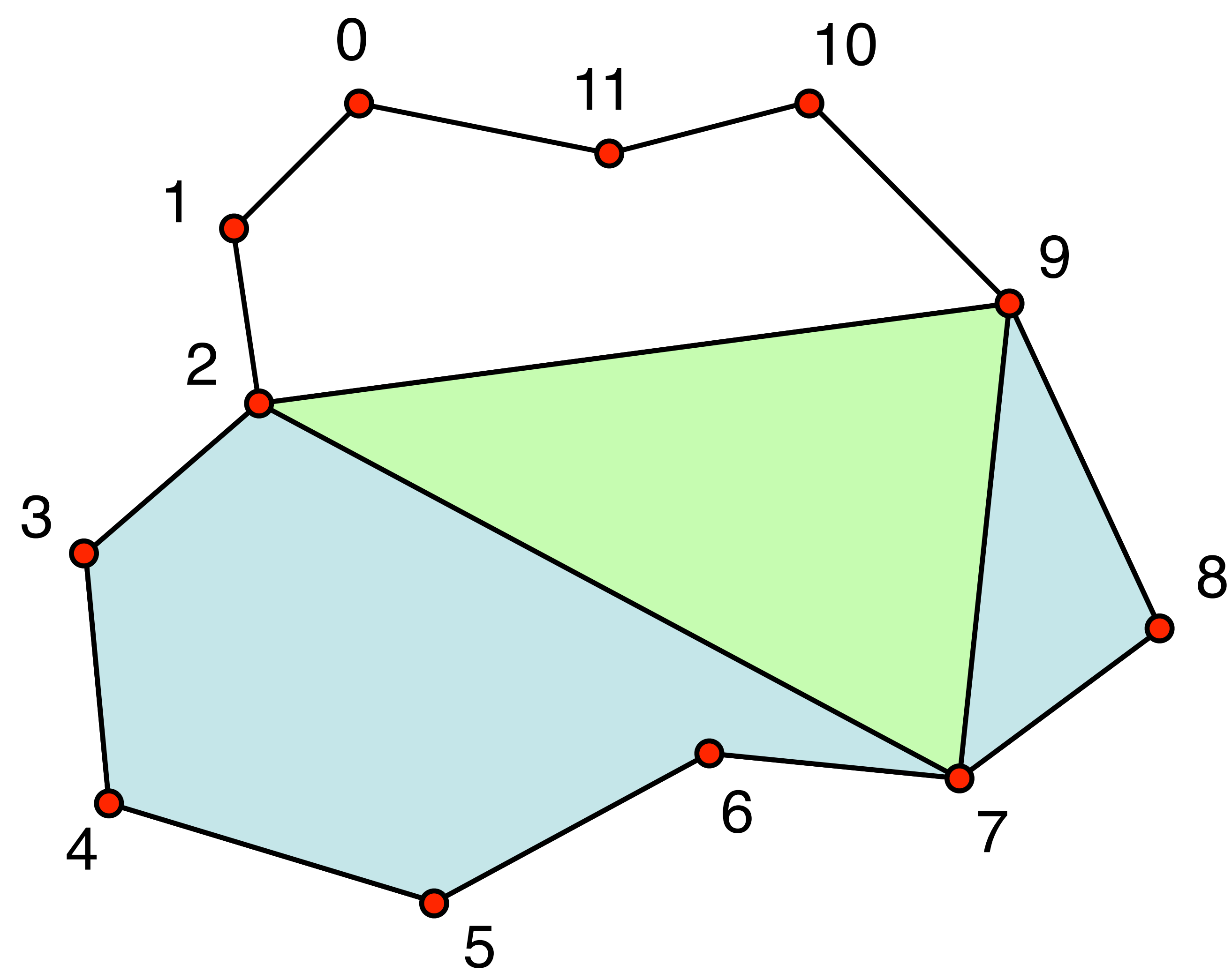
w[2,4] + & w(\Delta(2,4,9)) + w[4,9], \\
w[2,5] + & w(\Delta(2,5,9)) + w[5,9], \\
w[2,6] + & w(\Delta(2,6,9)) + w[6,9], \\
w[2,7] + & w(\Delta(2,7,9)) + w[7,9],
\end{aligned}
$$



Filling Holes in Meshes - 1

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\begin{aligned}
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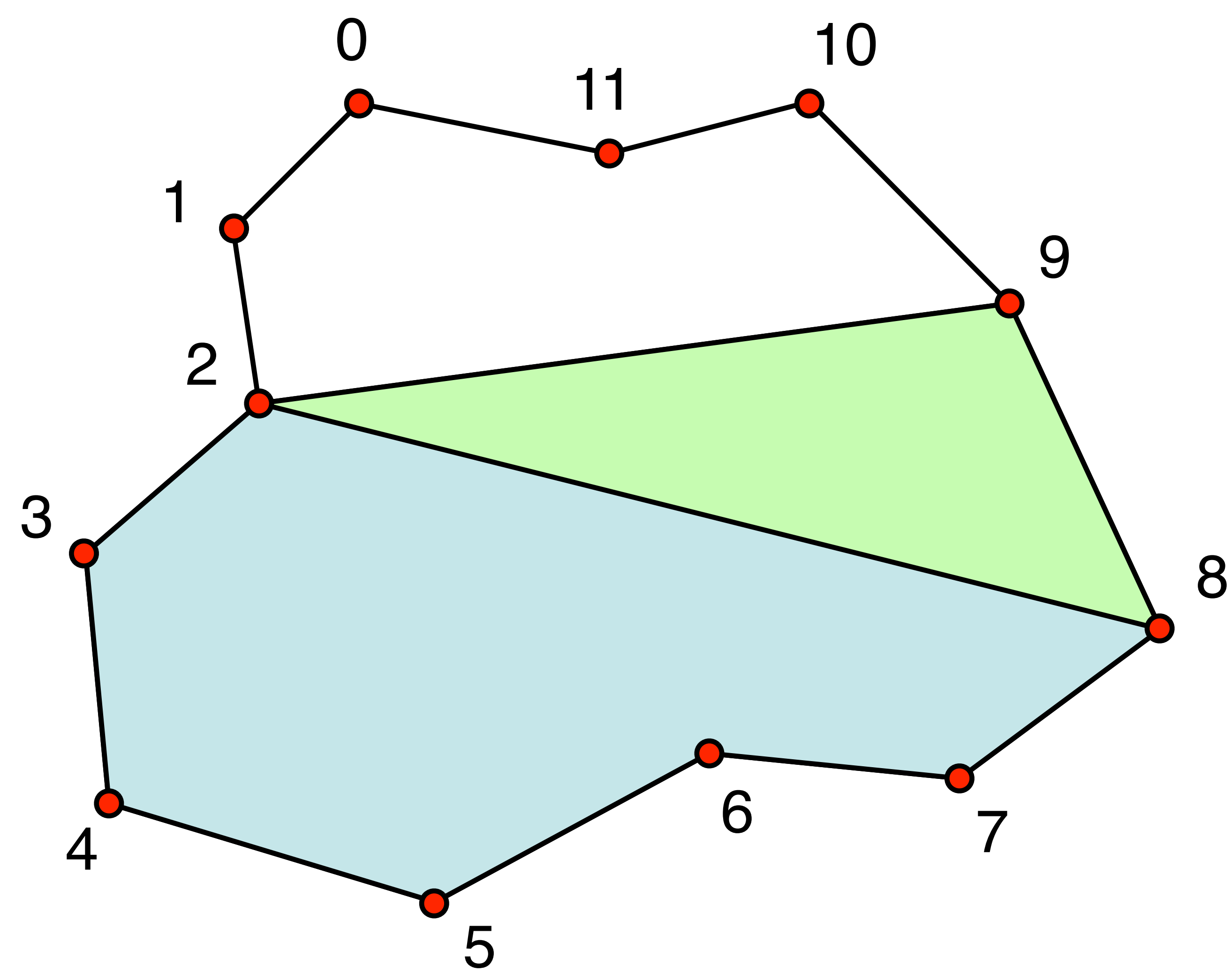
&w(\Delta(2,3,9)) + w[3,9],\\
&w[2,4] + w(\Delta(2,4,9)) + w[4,9],\\
&w[2,5] + w(\Delta(2,5,9)) + w[5,9],\\
&w[2,6] + w(\Delta(2,6,9)) + w[6,9],\\
&w[2,7] + w(\Delta(2,7,9)) + w[7,9],\\
&w[2,8] + w(\Delta(2,8,9))\\
)&
\end{aligned}
$$



Filling Holes in Meshes - 1

- let w[a,c] be the minimal weight that can be achieved in triangulating the polygon a,a+1,...,c
- recursion formula

$$w[a,c] = \min_{a<b<c} w[a,b] + w(\Delta(a,b,c)) + w[b,c]$$

$$w[x,x+1] = 0$$

- dynamic programming leads to an $O(n^3)$ algorithm

Filling Holes in Meshes - 2+3

- refine the triangulation such that its vertex density matches that of the surrounding area

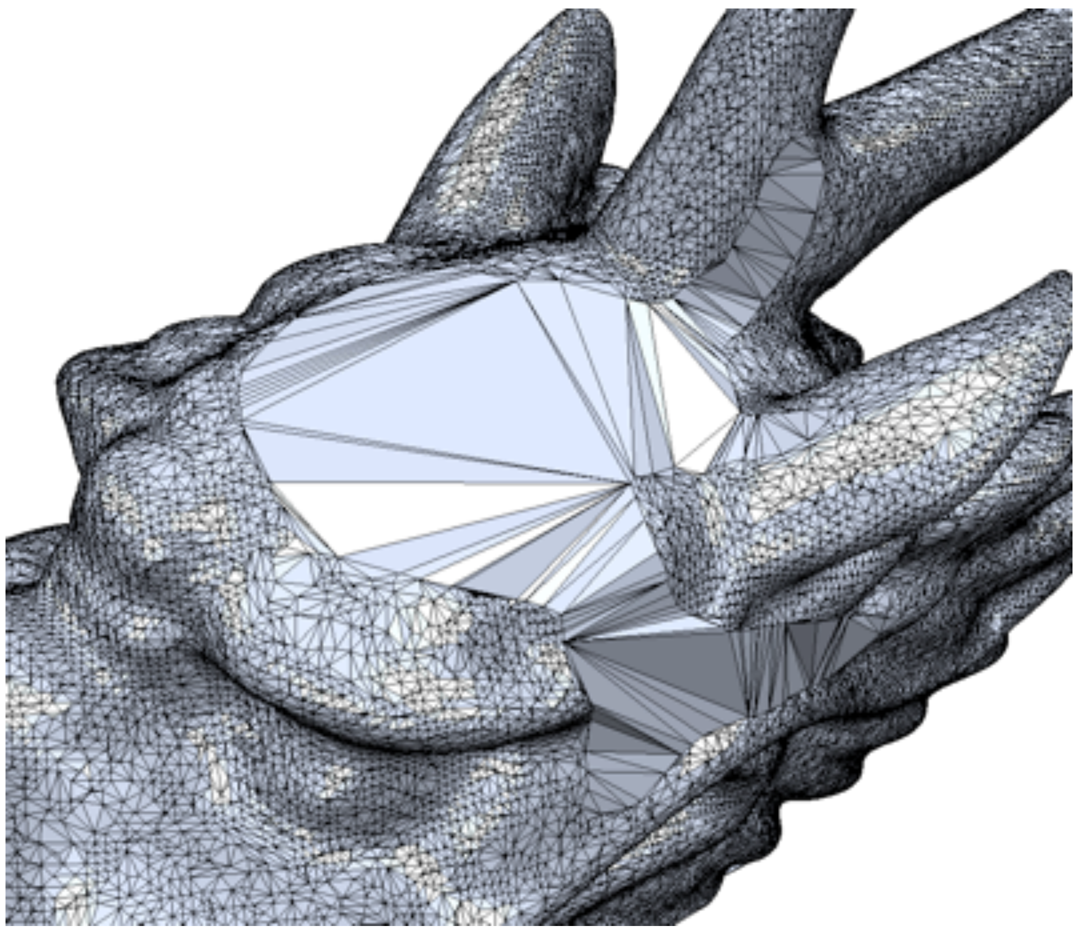
➡ Pierre's talk about remeshing

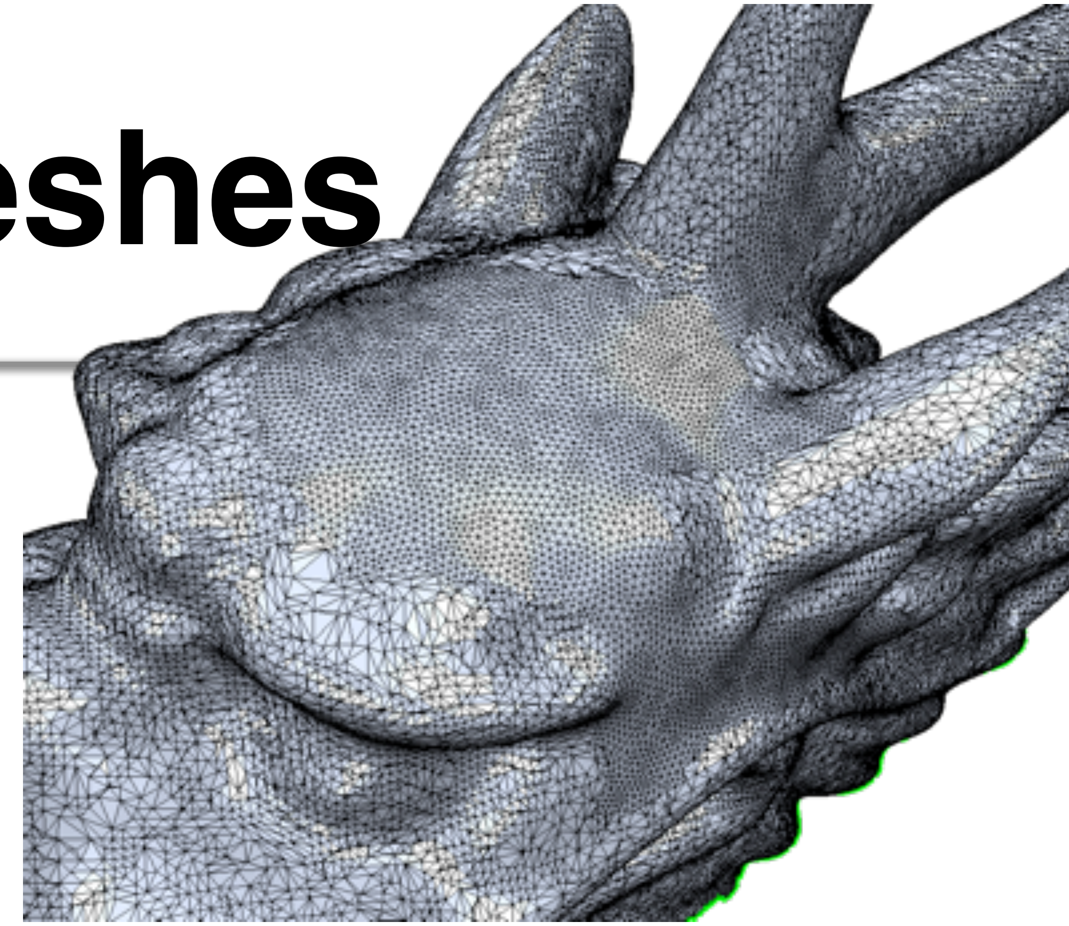
- smooth the filling such that its geometry matches that of the surrounding area

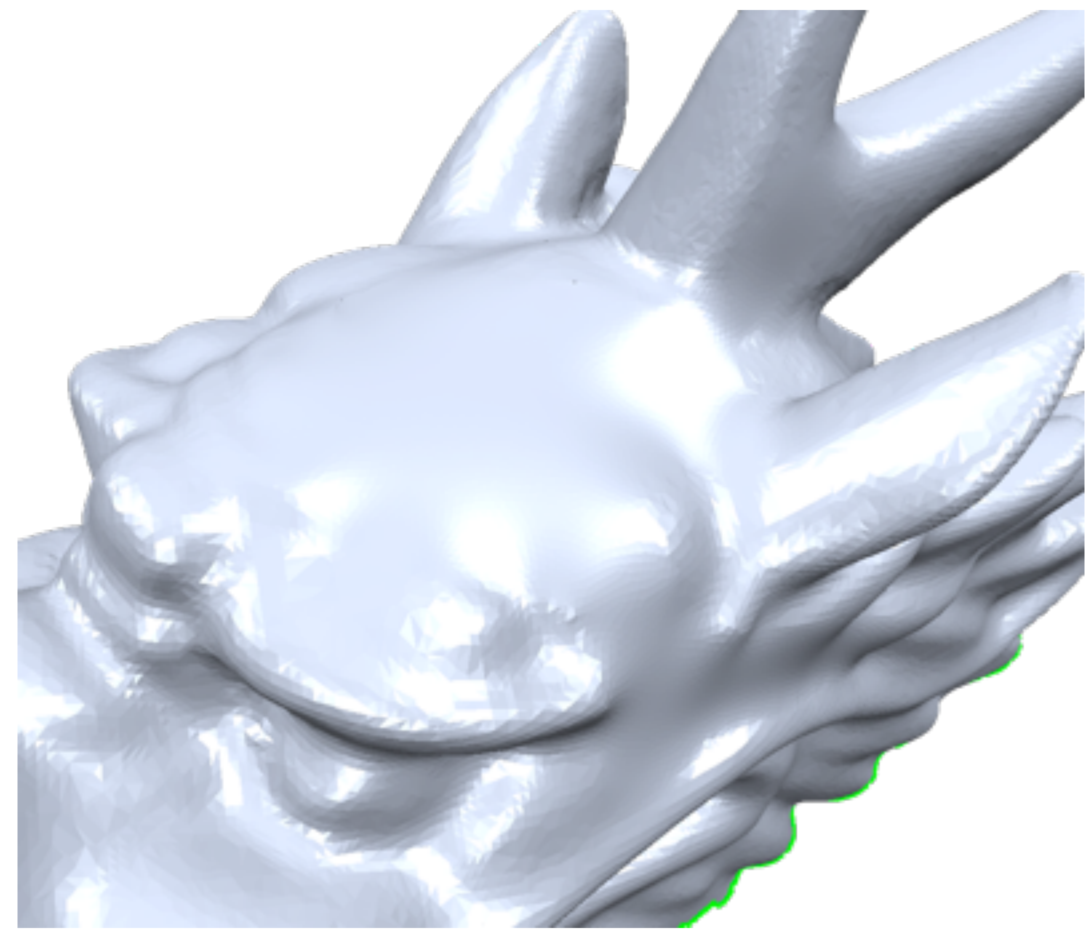
➡ Mark's talk about mesh smoothing

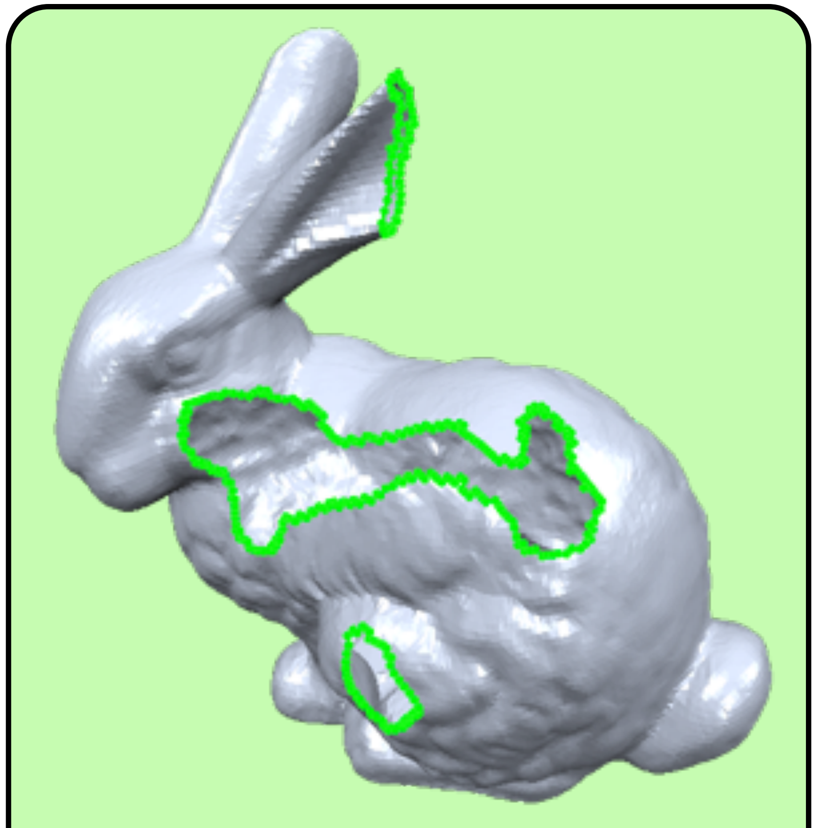
Filling Holes in Meshes

- refinement and smoothing

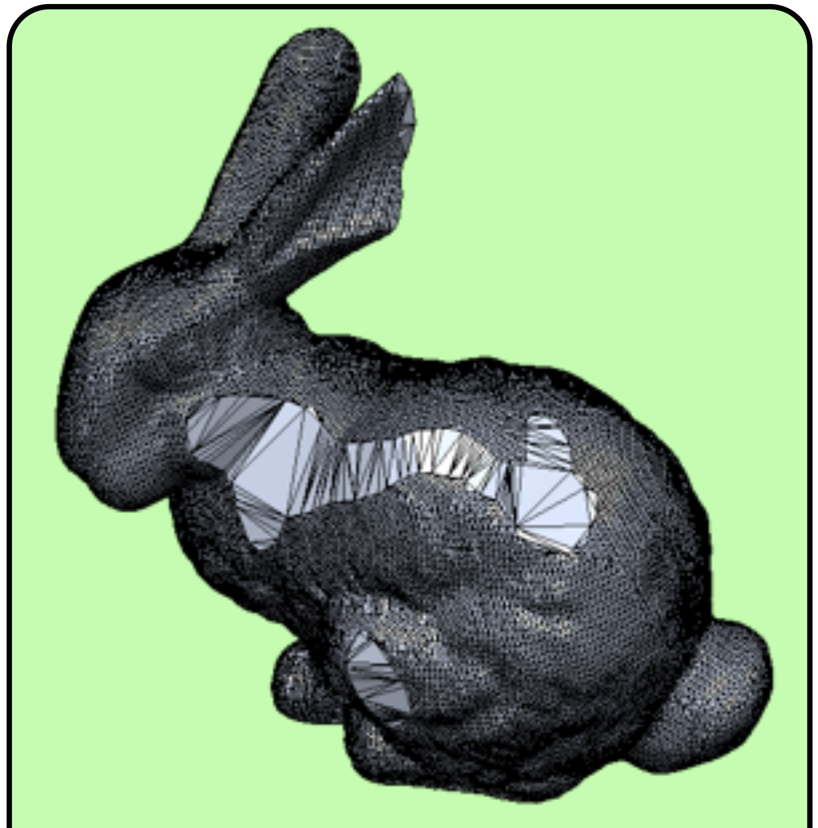




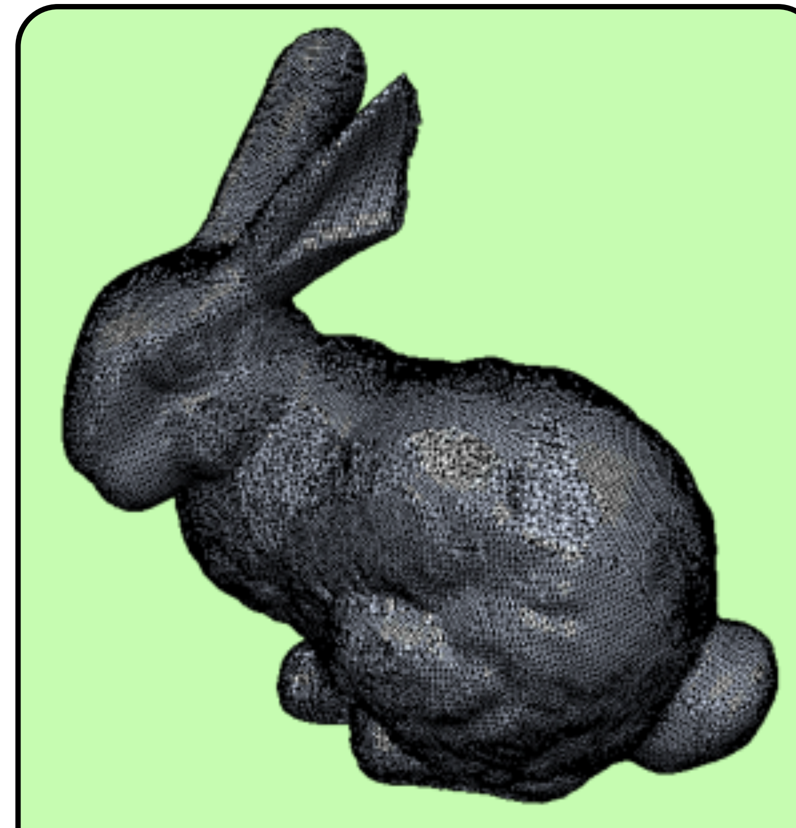




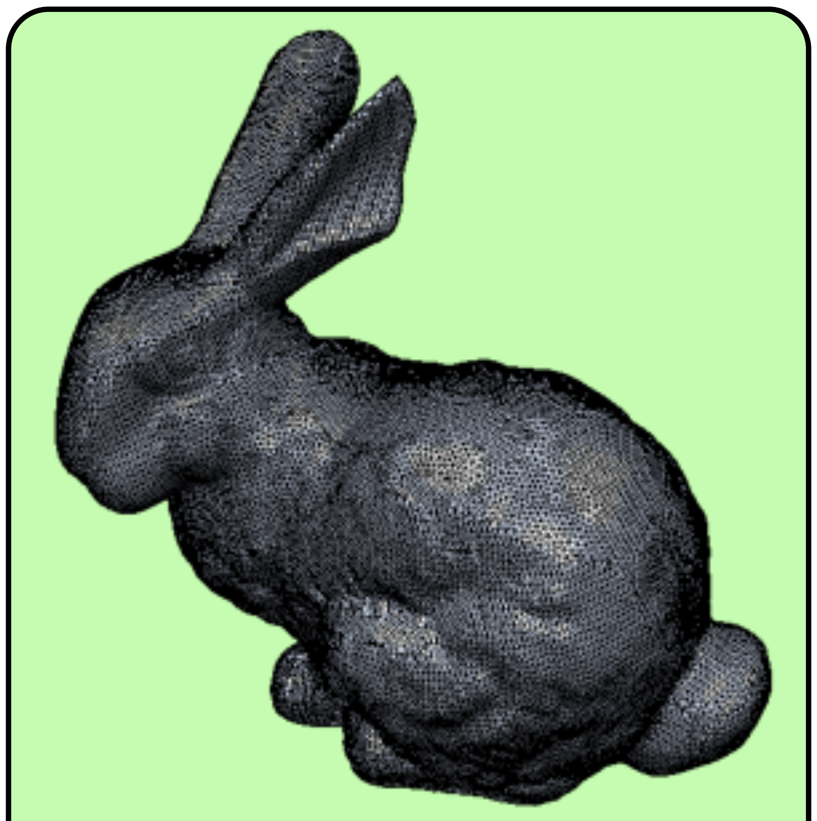
Input model



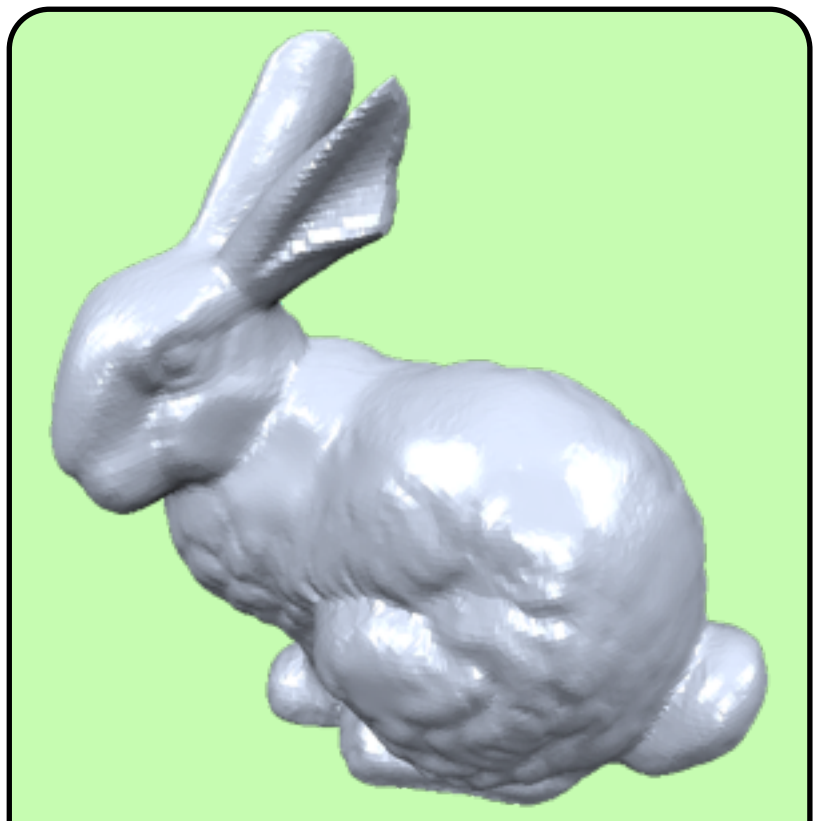
Minimal triangulation



Refined triangulation



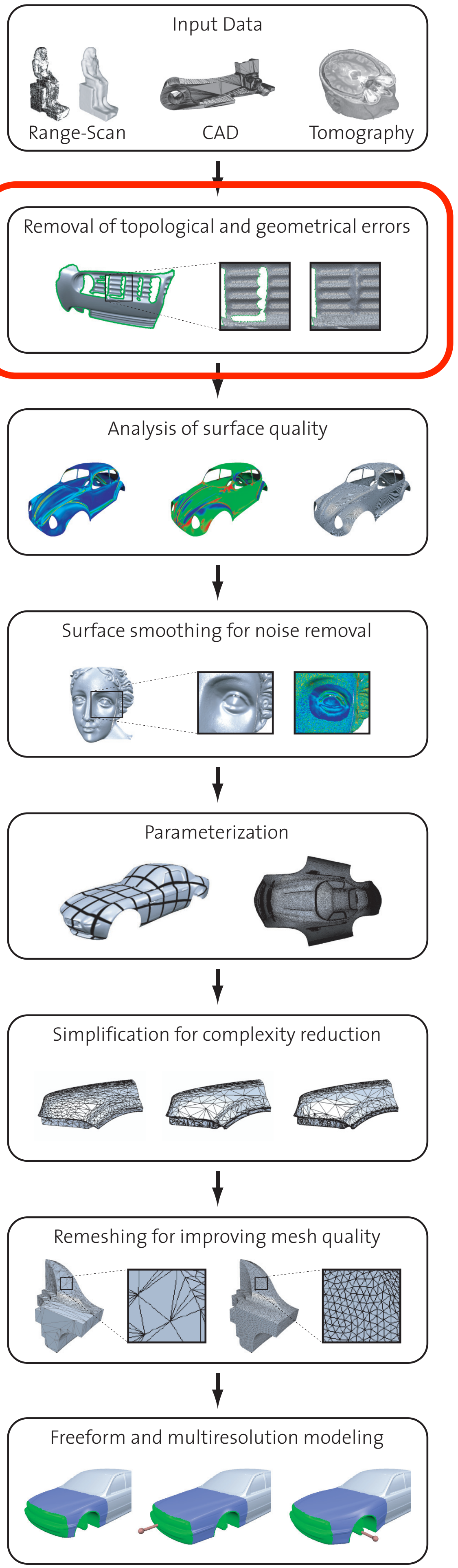
Output model



Output model

Filling Holes in Meshes

- what problems do we encounter?
  - islands are not incorporated
  - self-intersections cannot be excluded
  - quality depends on boundary distortion



Model Repair

- types of input
- surface-oriented algorithms
  - Filling holes in meshes [Liepa 2003]
- **volumetric algorithms**
  - Simplification and repair of polygonal models using volumetric techniques [Nooruddin and Turk 2003]
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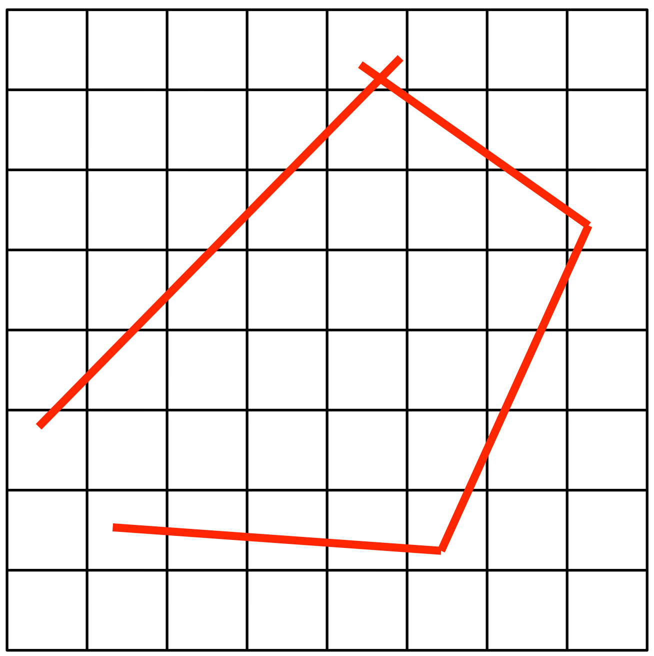
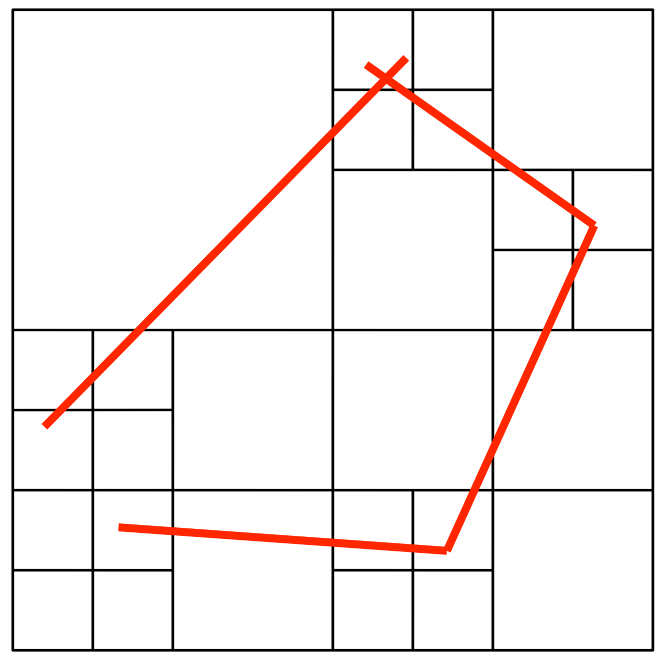
Volumetric Algorithms

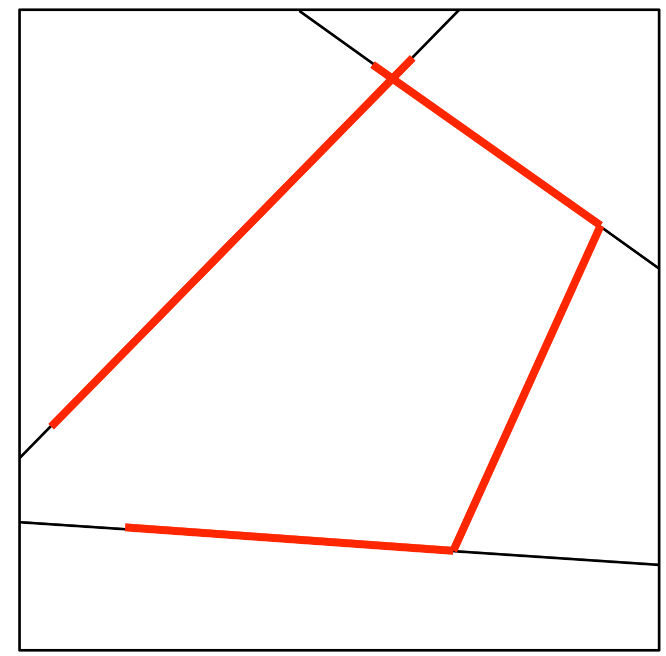
1. convert the input model into an intermediate volumetric representation ➙ loss of information



voxel grid



adaptive octree



BSP tree

Volumetric Algorithms

1. convert the input model into an intermediate volumetric representation ➙ loss of information
2. discrete volumetric representation ➙ robust and reliable processing
   – morphological operators (dilation, erosion)
   – smoothing
   – flood-fill to determine interior/exterior
   – ...

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3. extract the surface of a solid object from the volume ➙ manifold and watertight

Volumetric Algorithms

- advantages
  - fully automatic
  - few (intuitive) user parameters
  - robust
  - guaranteed manifold output

Volumetric Algorithms

- problems
  - slow and memory intensive
    ➙ adaptive data structures
  - aliasing and loss of features
    ➙ feature sensitive reconstruction (EMC, DC)
  - loss of mesh structure
    ➙ bad luck (... hybrid approaches)
  - large output
    ➙ mesh decimation (Mark's talk)

Example 1

- example algorithm 1

  F. S. Nooruddin and G. Turk

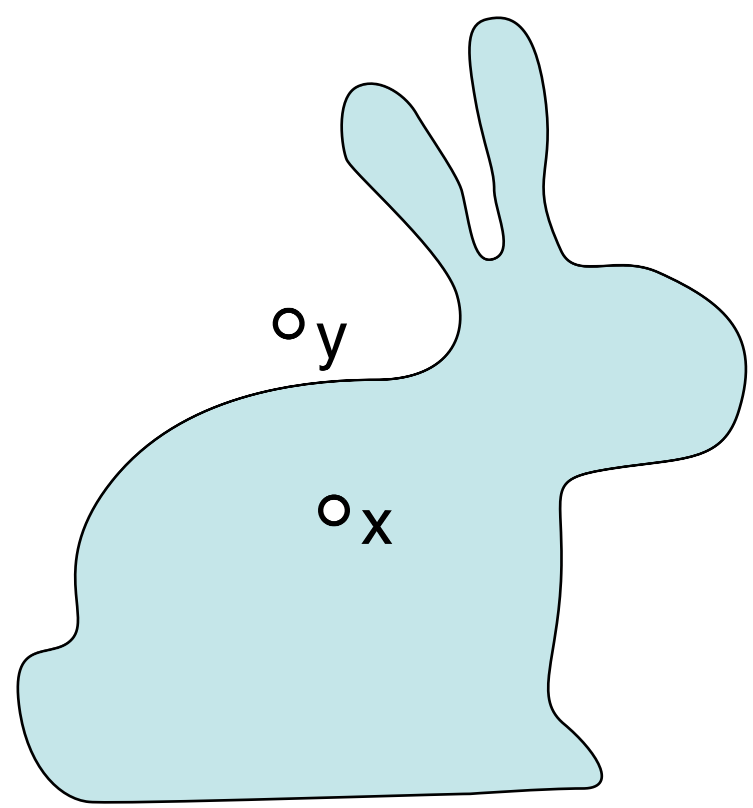
  Simplification and Repair of Polygonal Models Using Volumetric Techniques

  IEEE Transactions on Visualization and Computer Graphics 2003

- issues
  - classification of sample points as being *inside* or *outside* of the object (parity count, ray stabbing)
  - sampling the volume
  - extracting the mesh

Nooruddin and Turk's Method

- point classification: Layered depth images (LDI)



Nooruddin and Turk's Method

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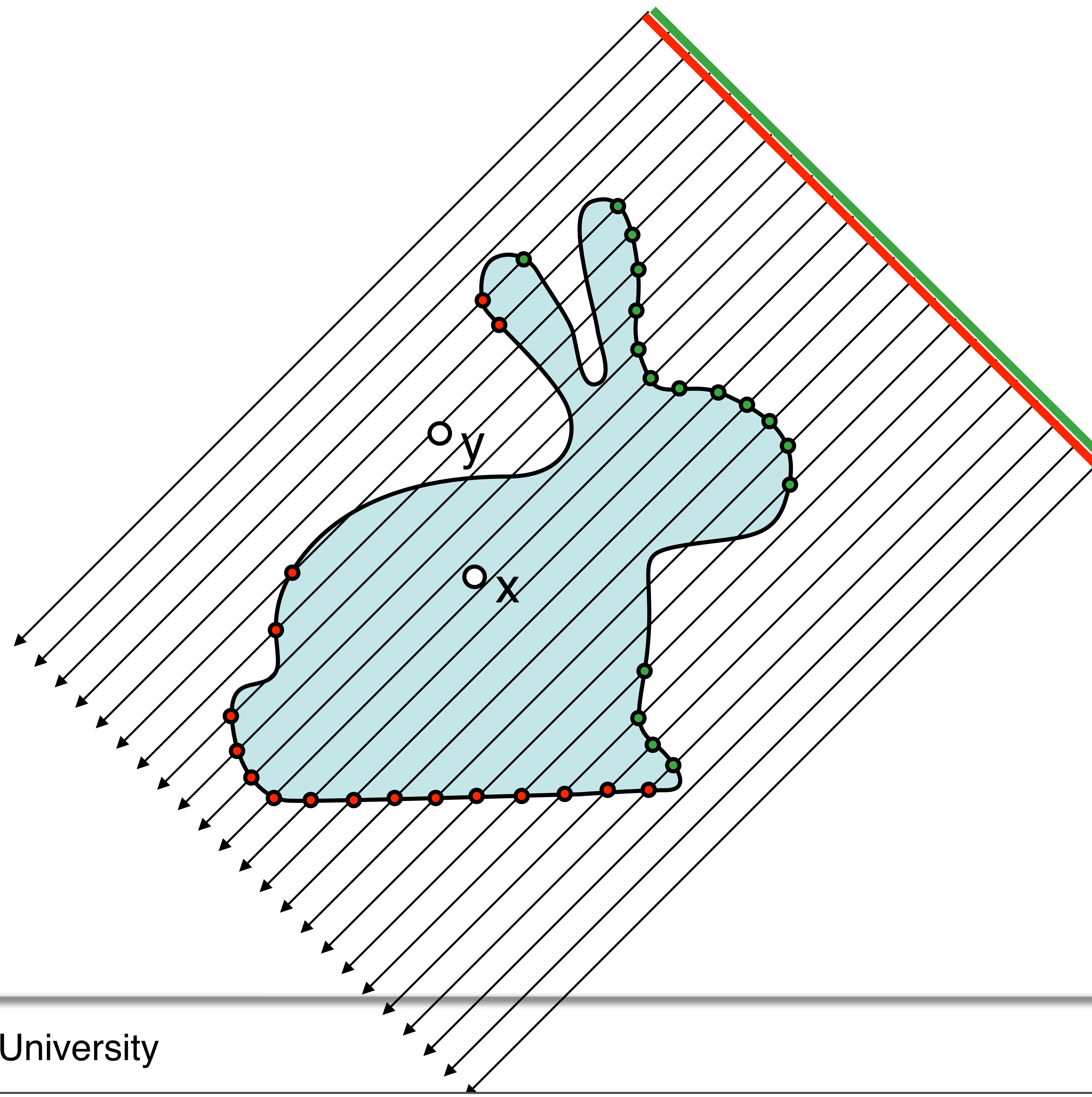

Nooruddin and Turk's Method

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Nooruddin and Turk's Method

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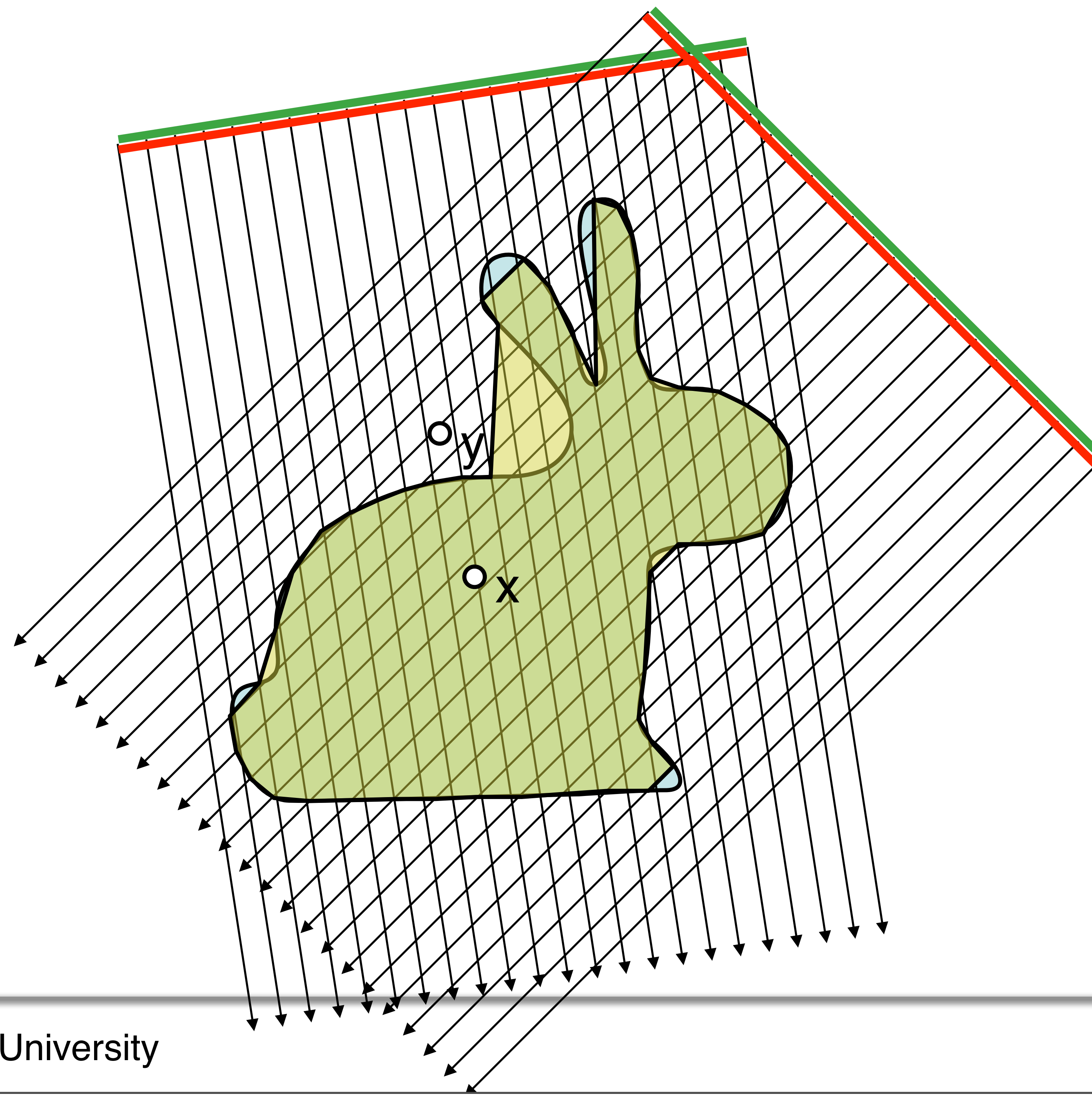
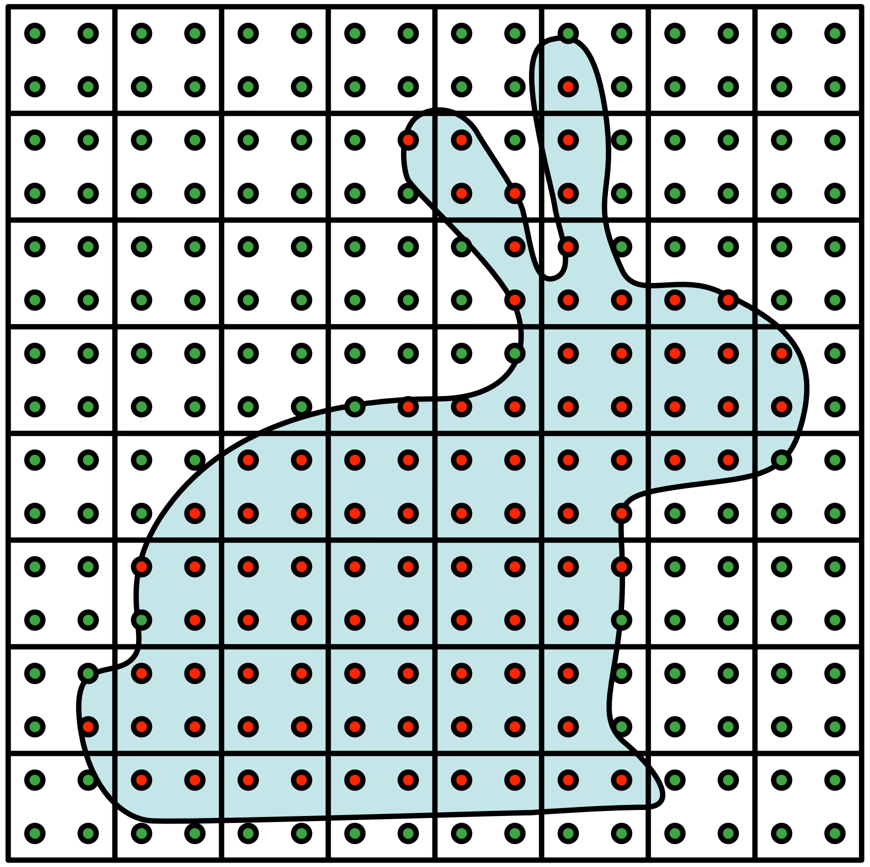


Nooruddin and Turk's Method

- point classification: Layered depth images (LDI)
  1. record n layered depth images
  2. project the query point x into each depth image
  3. if any of the images classifies x as exterior, then x is globally classified as exterior else as interior

Nooruddin and Turk's Method

- supersampling
- filtering
  - Gaussian
  - morphological filters (dilation, erosion)
    - model simplification
    - reduction of topological noise
- marching cubes



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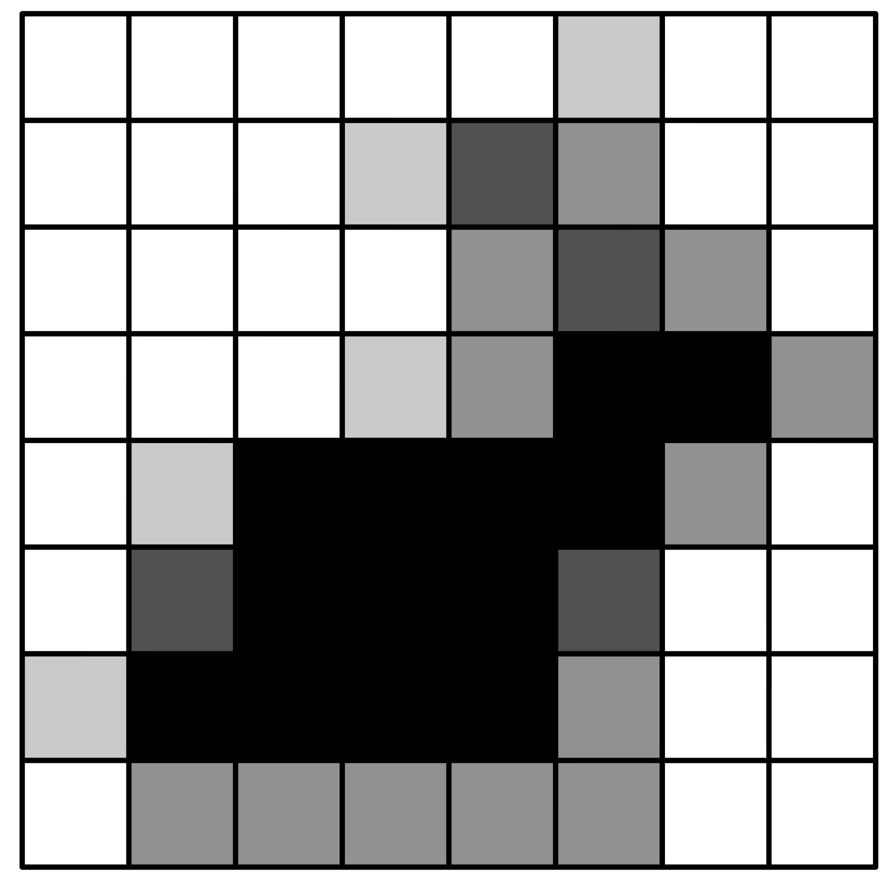

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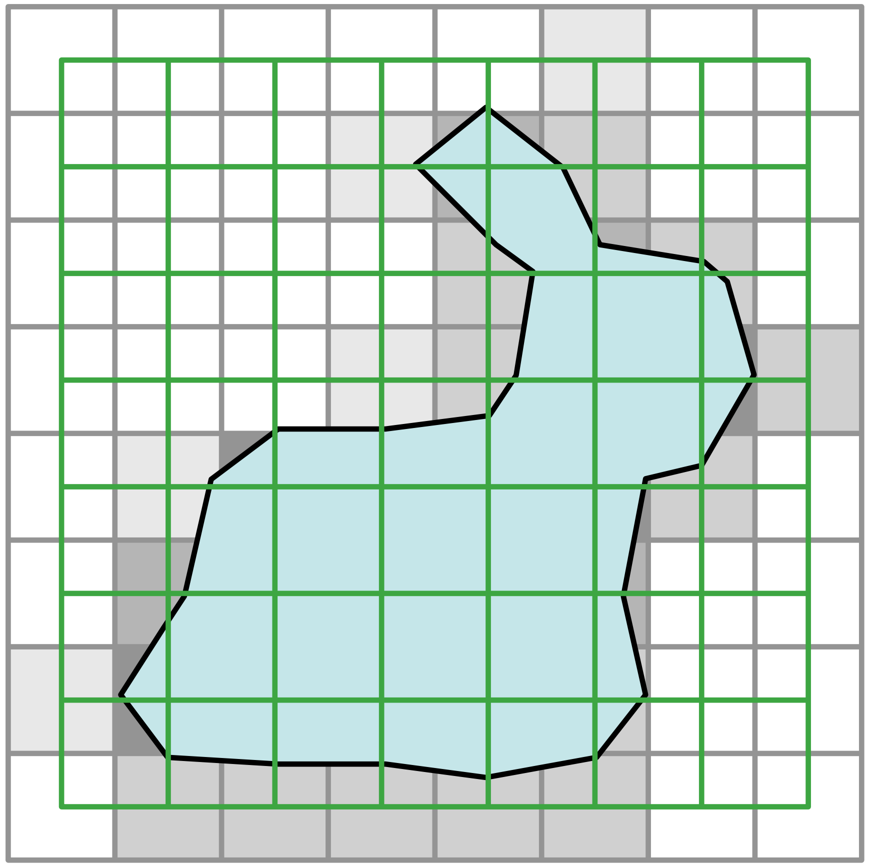
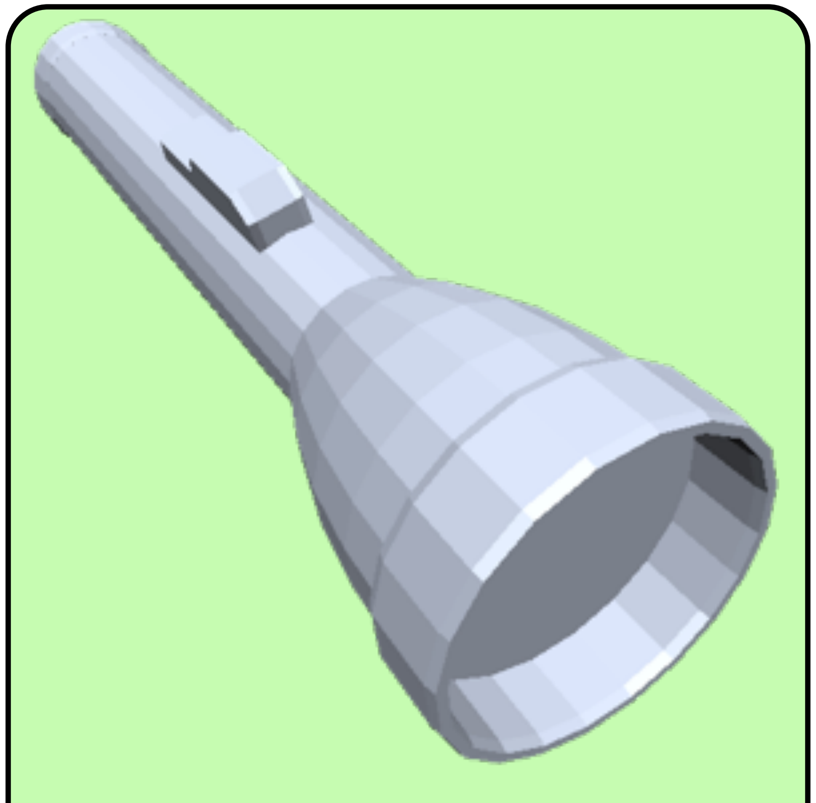
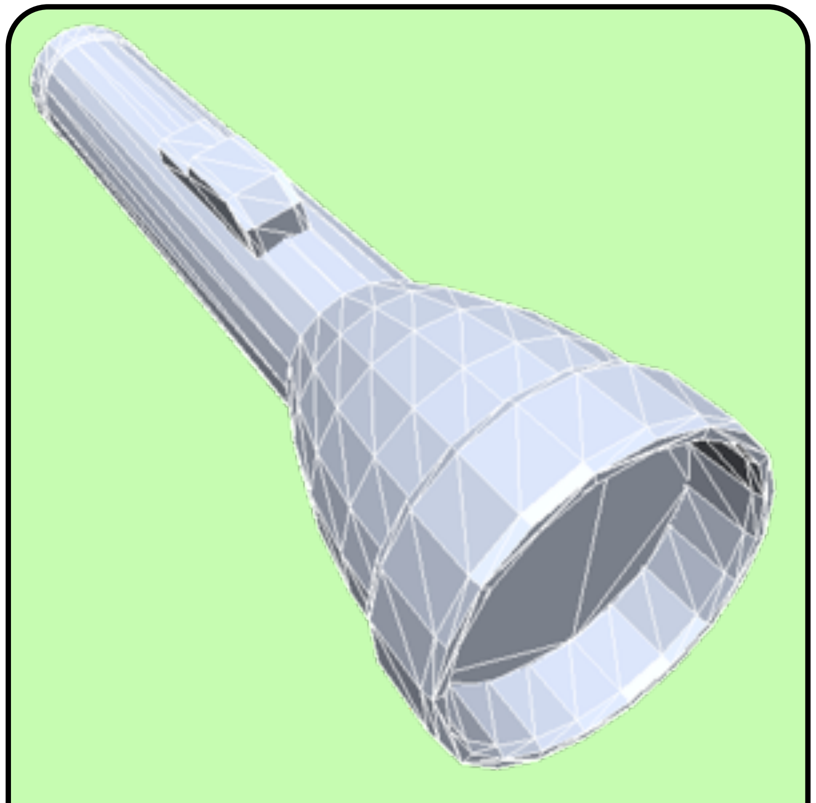
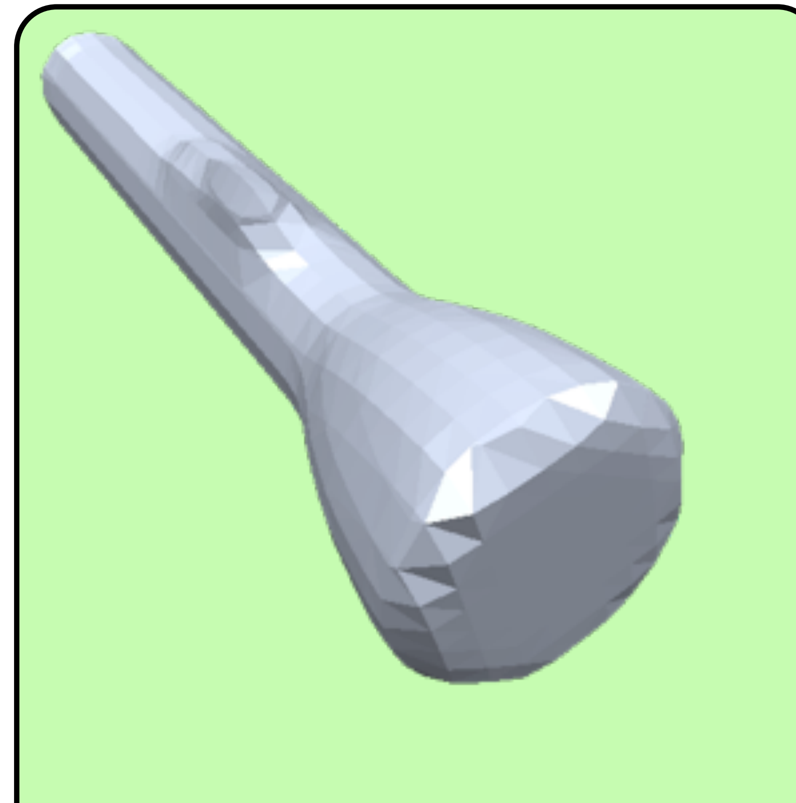




Input model



Input model



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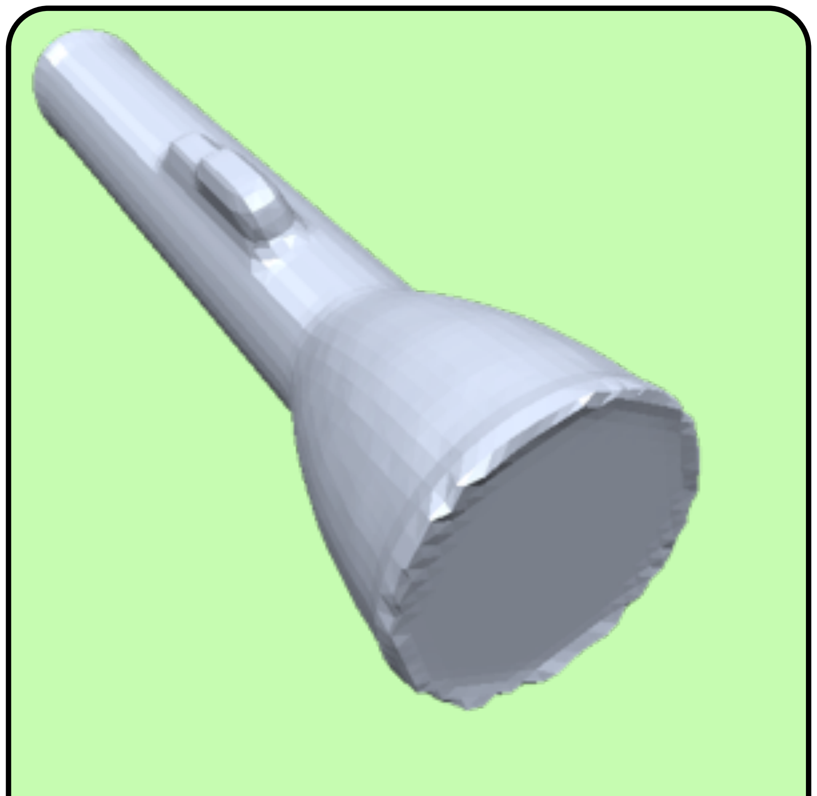
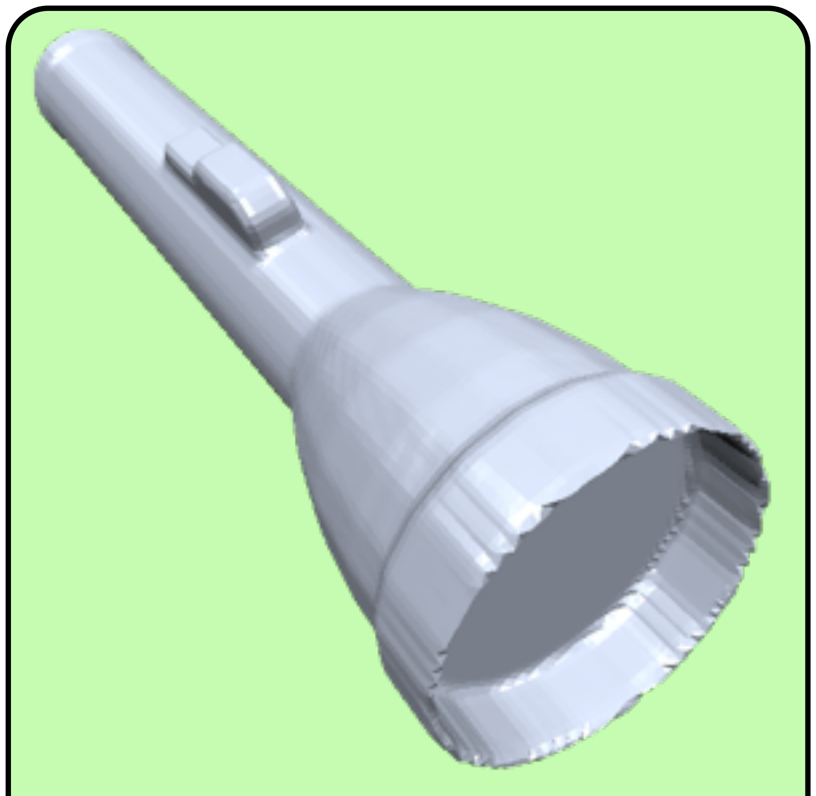


100×100×100



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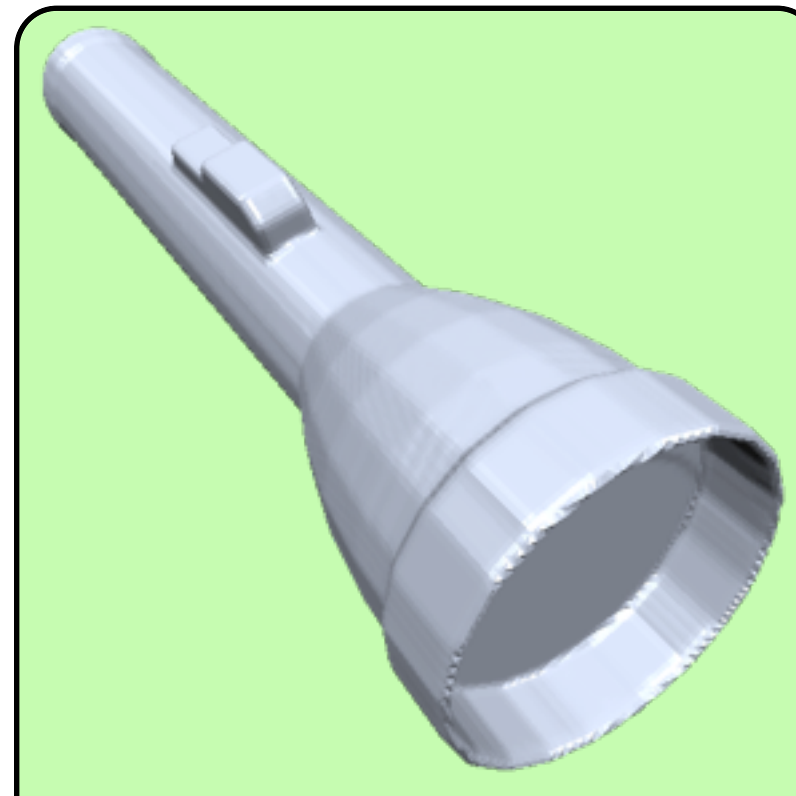
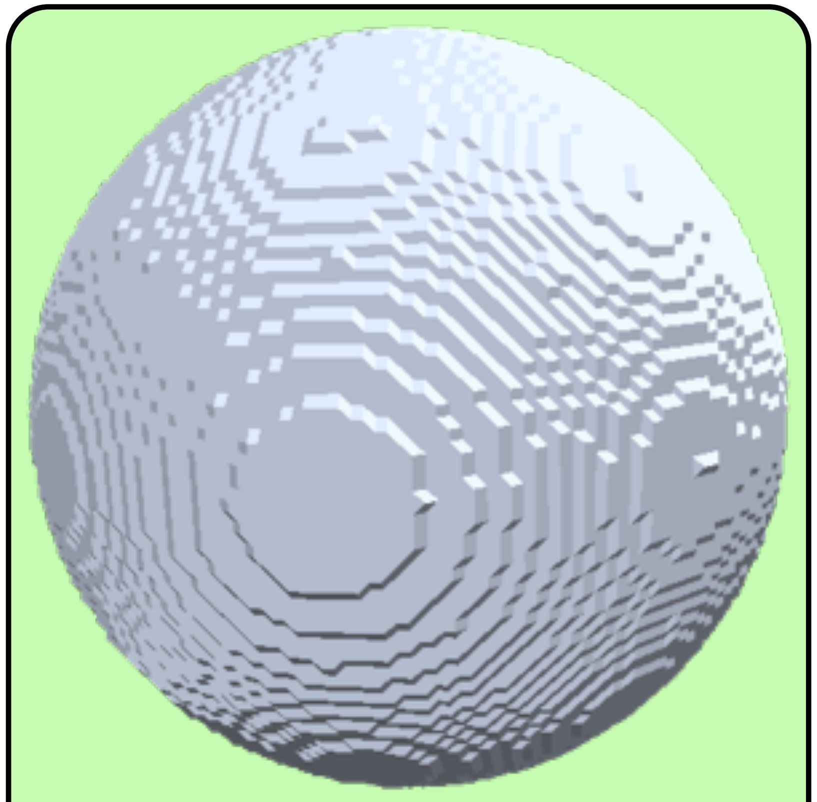
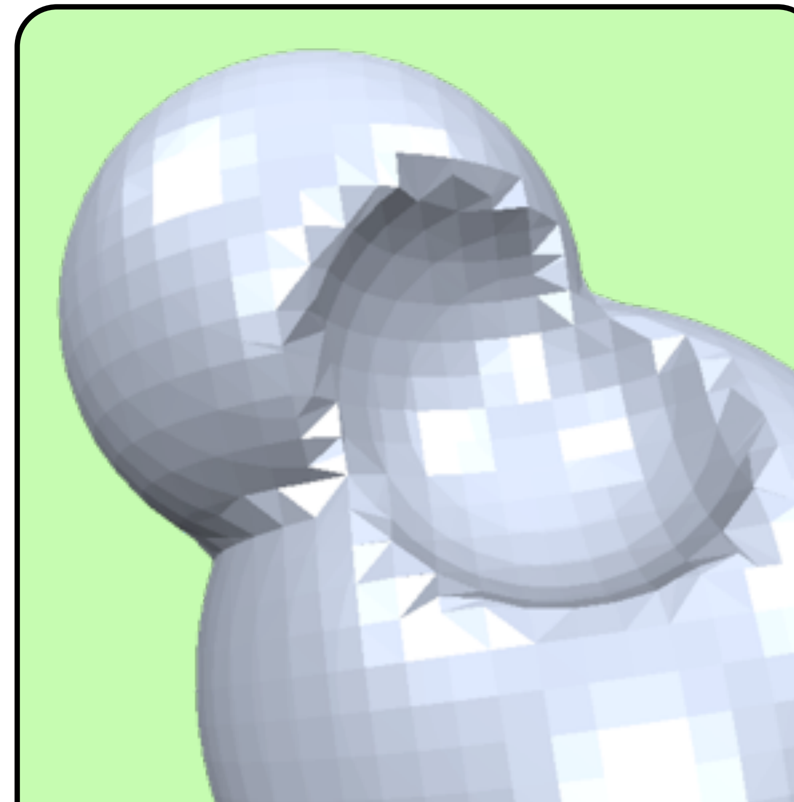


300×300×300

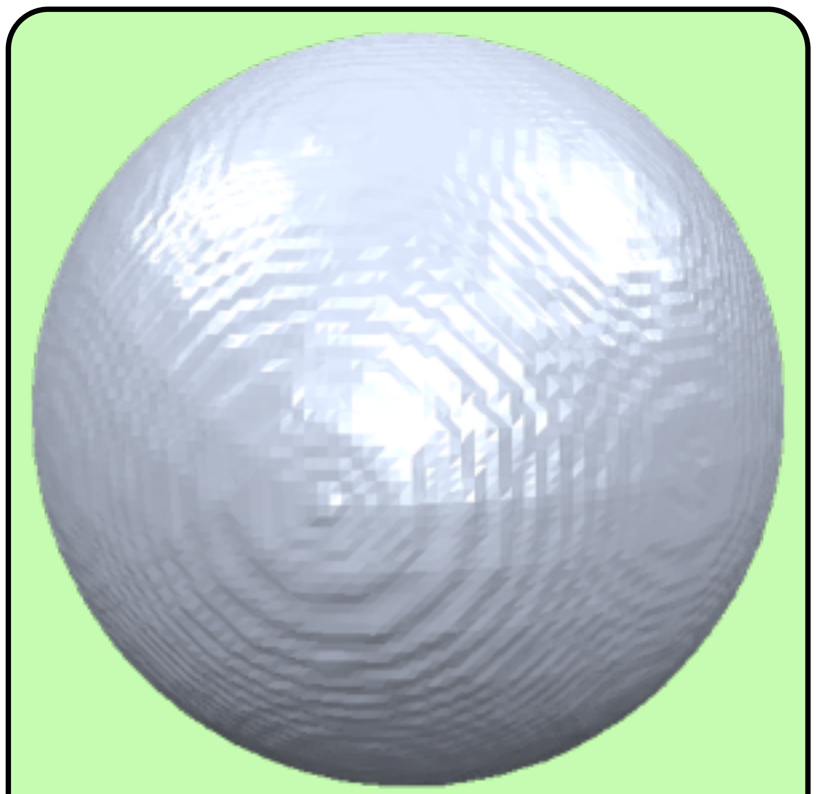


Raw

Smoothing



Marching Cubes



Supersampling

Supersampling + smoothing

Nooruddin and Turk’s Method

- voxelization
  - characteristic function / signed distance function
  - cannot handle all kinds of inconsistencies
- repair
  - uniform treatment of voxel
  - cannot exploit local shape information
- extraction
  - thresholding
  - sampling artifacts

Example 2

- example algorithm 2

  S. Bischoff, D. Pavic, L. Kobbelt

  Automatic Restoration of Polygon Models

  Transactions on Graphics 2005

Overview

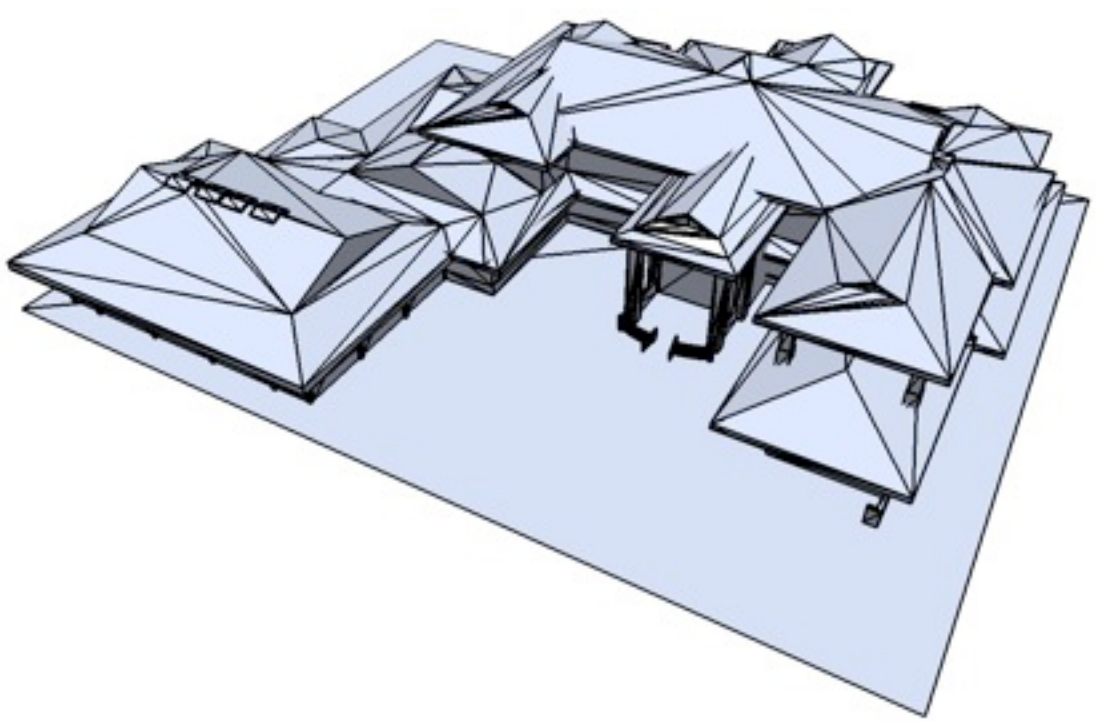
volumetric representation

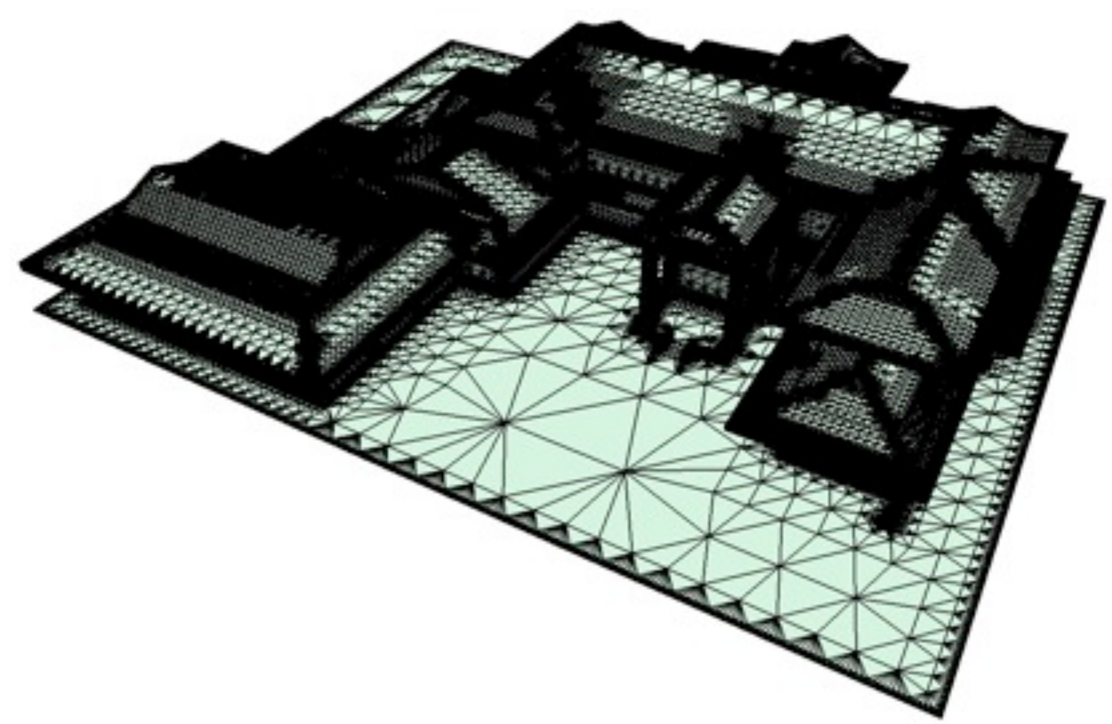
gap filling, removal of interior geometry

volumetric representation

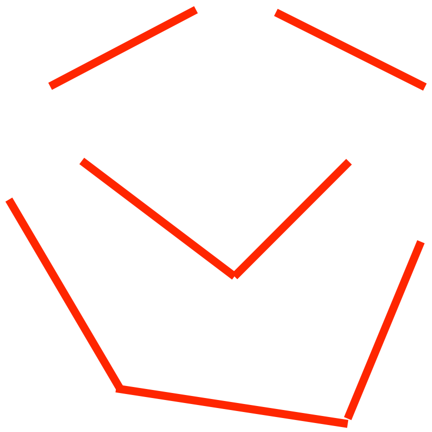
voxelization

manifold mesh extraction

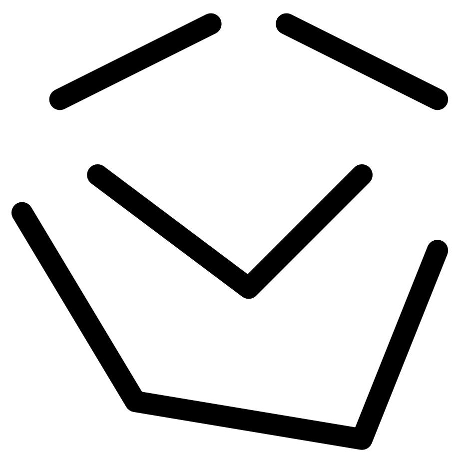




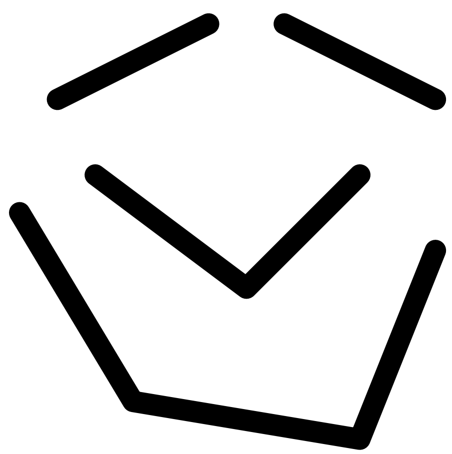
Overview

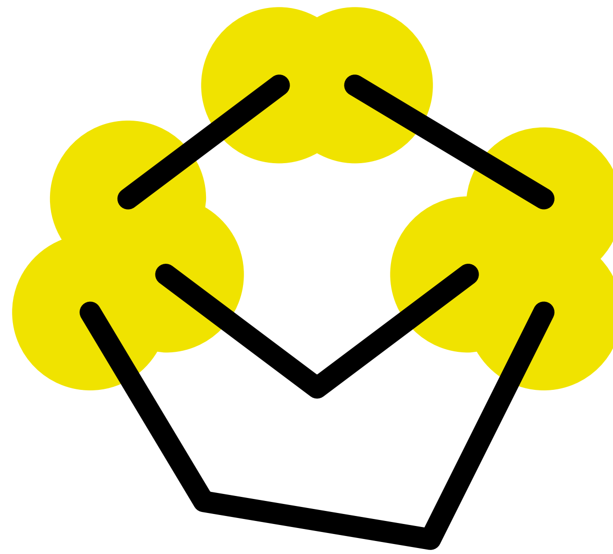


Overview

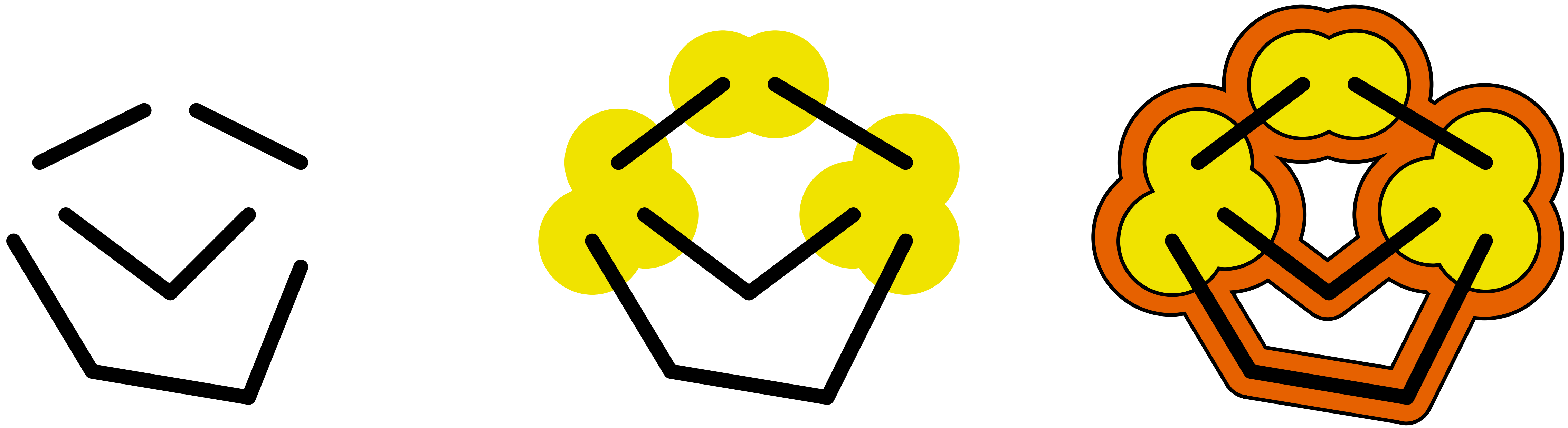


Overview

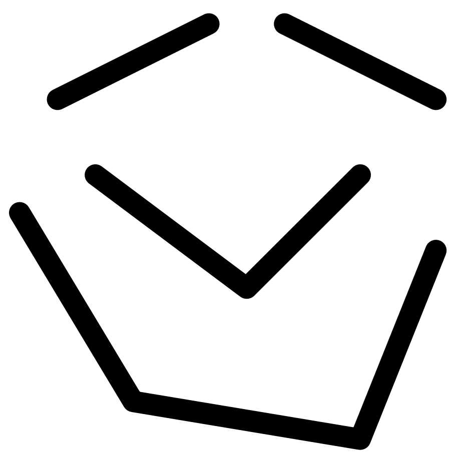


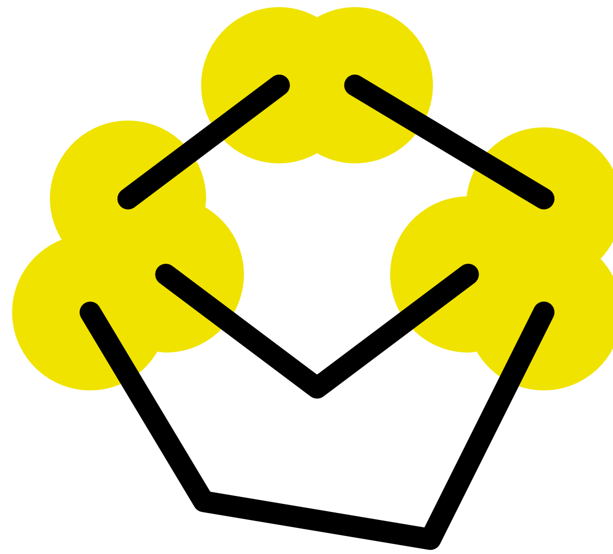


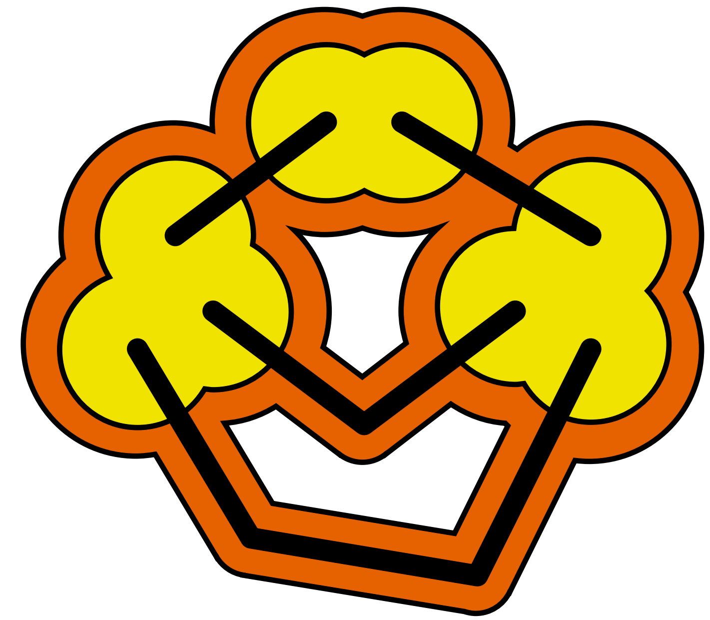
Overview



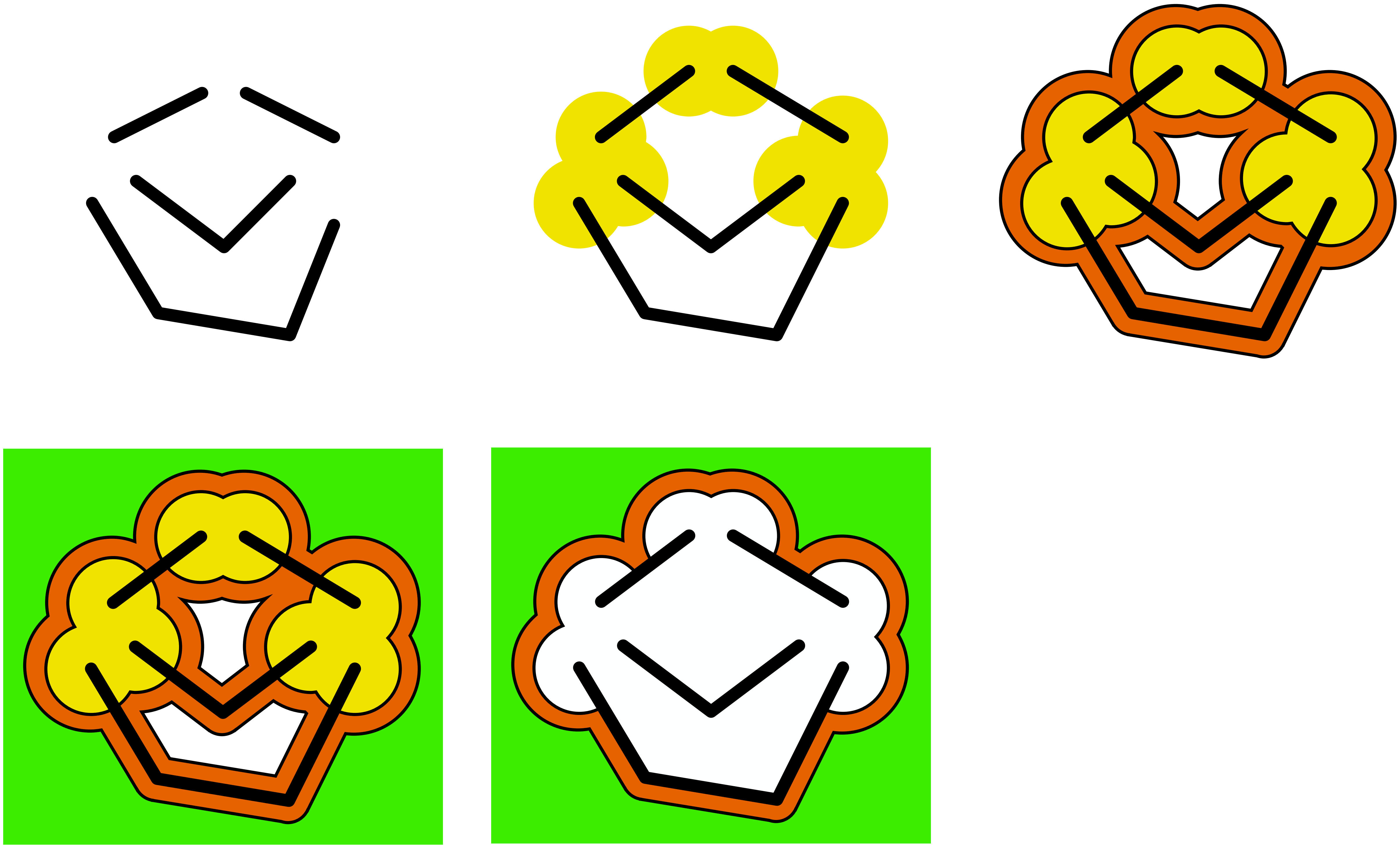
Overview



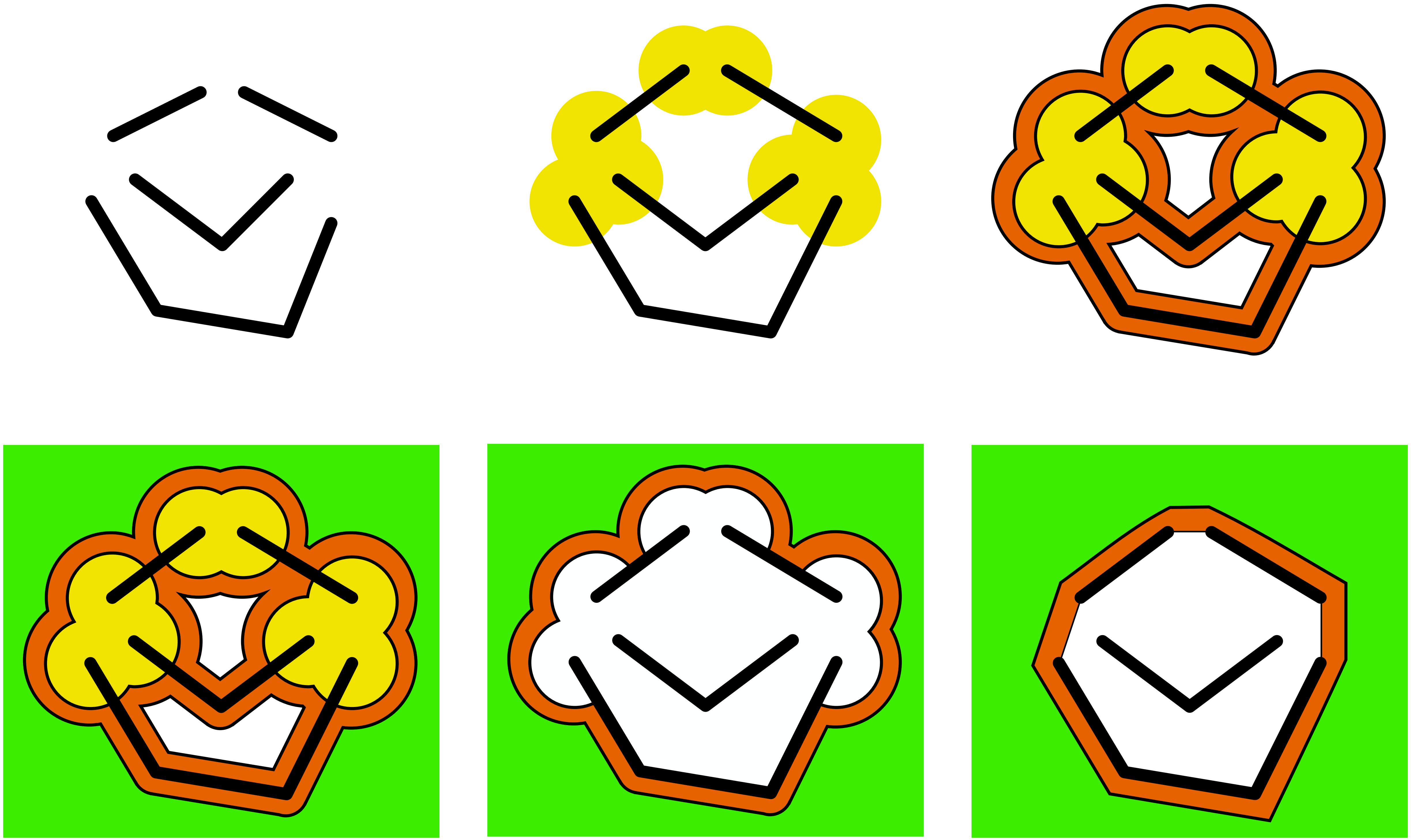




Overview



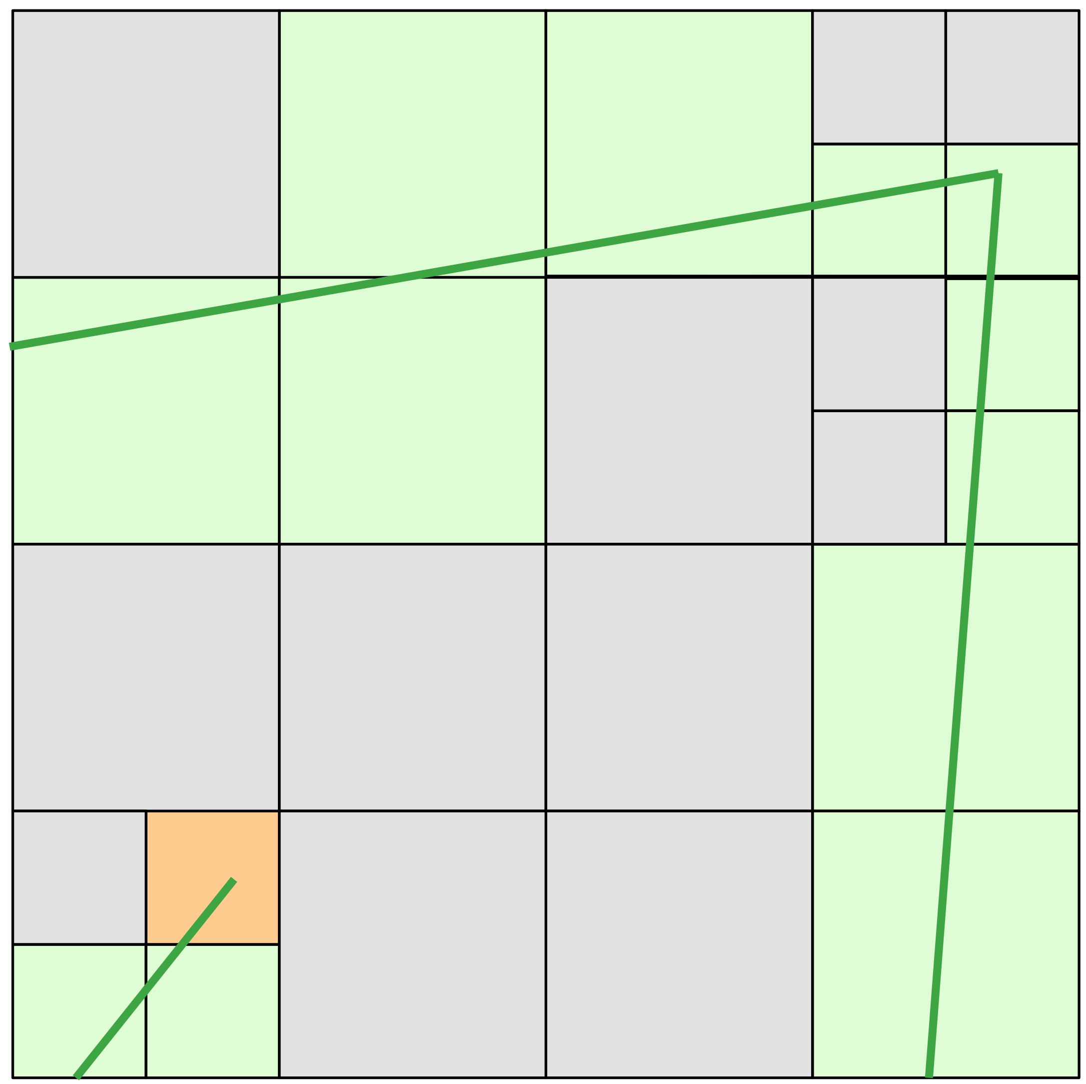
Overview



Conversion

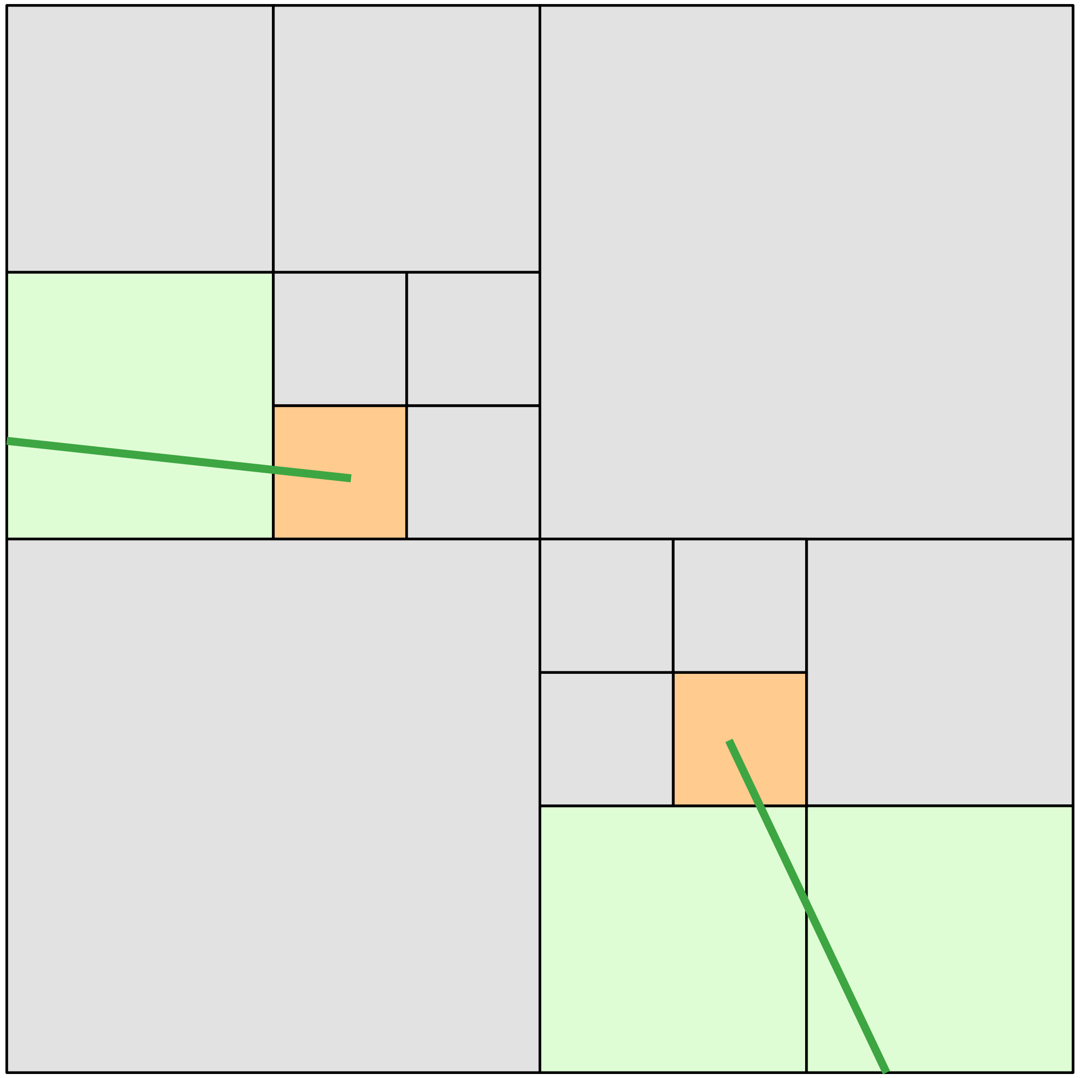
- adaptive octree: subdivide a cell, if it contains multiple planes or a boundary

voxel topology
=
polygon topology



Closing Gaps

- close gaps by dilating the boundary voxels



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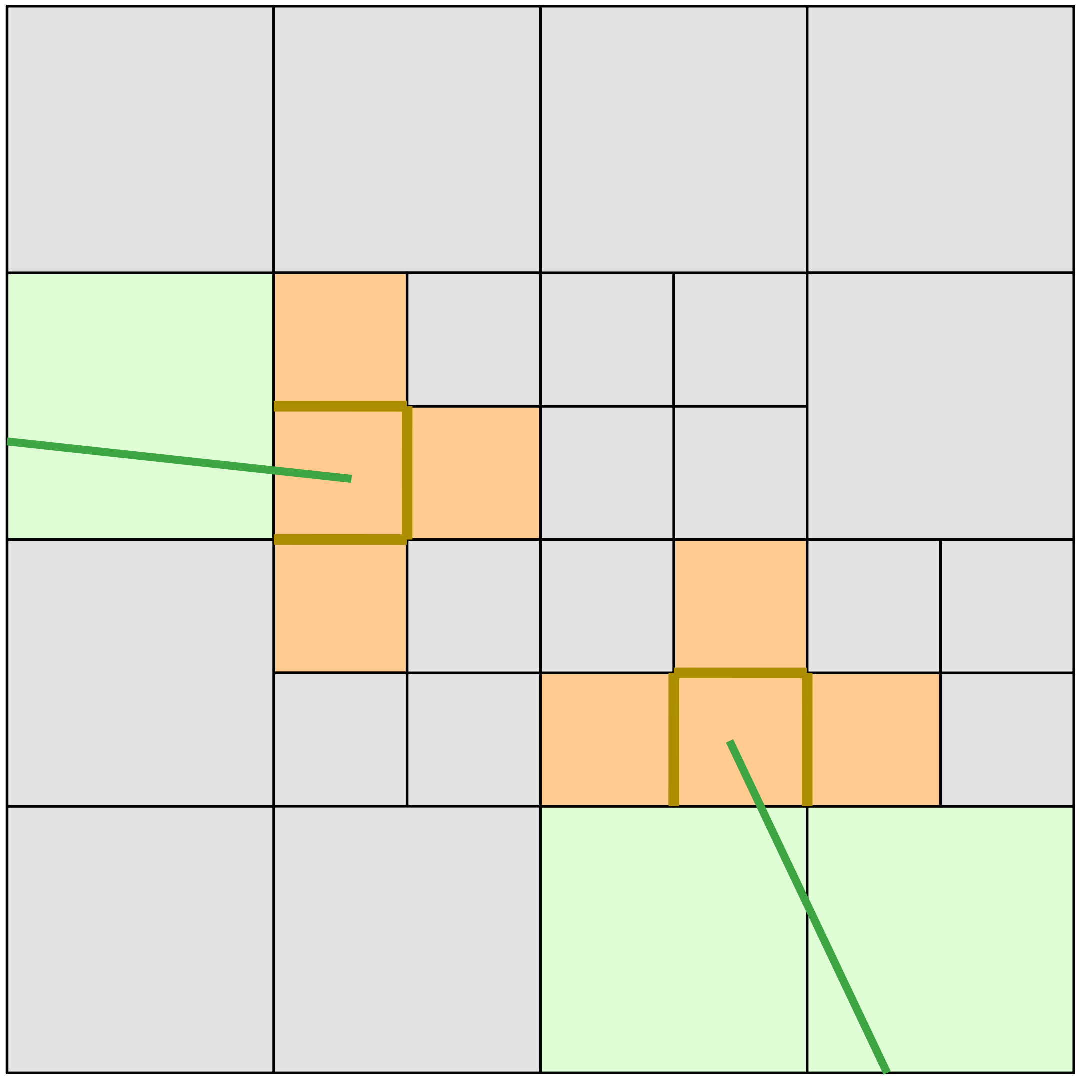

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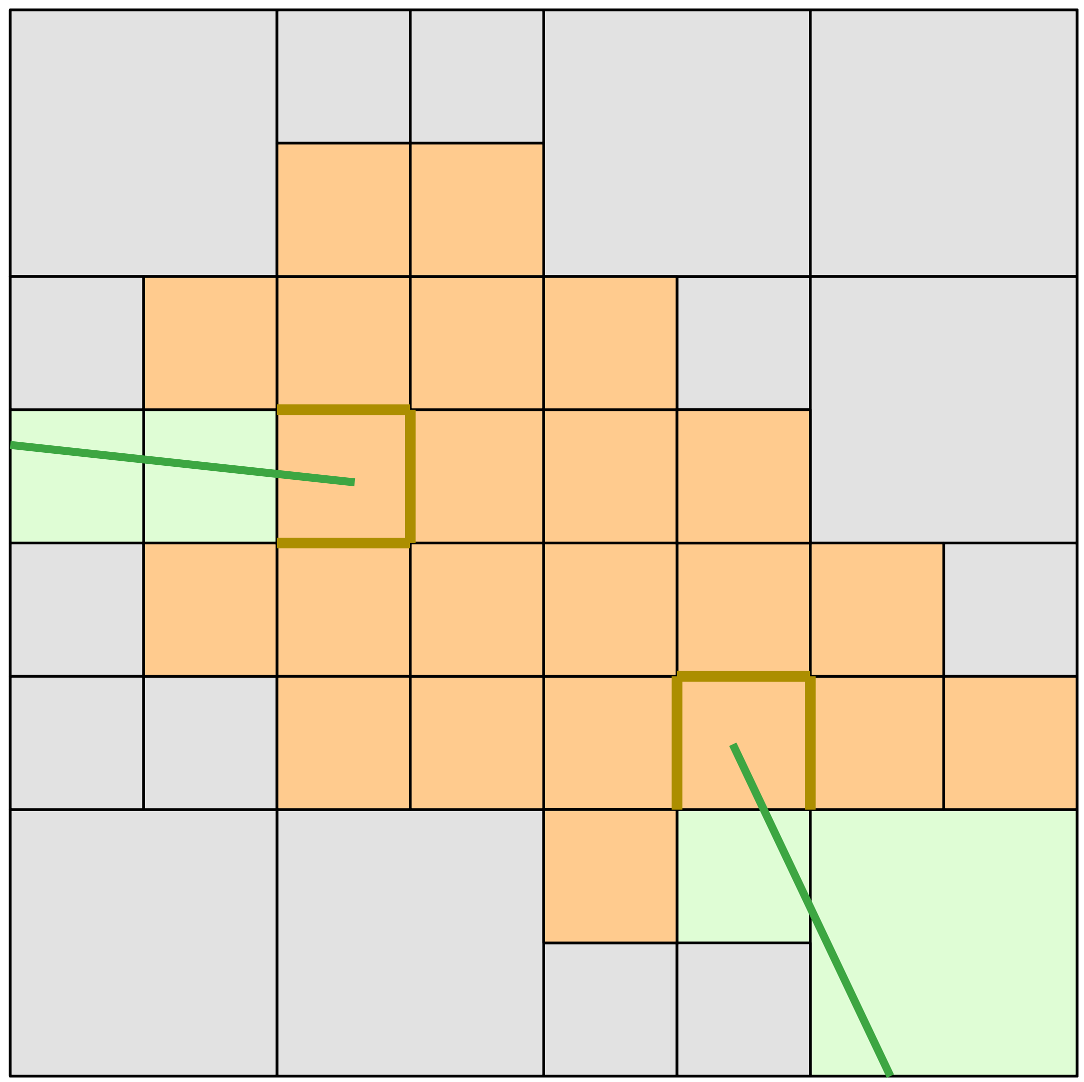
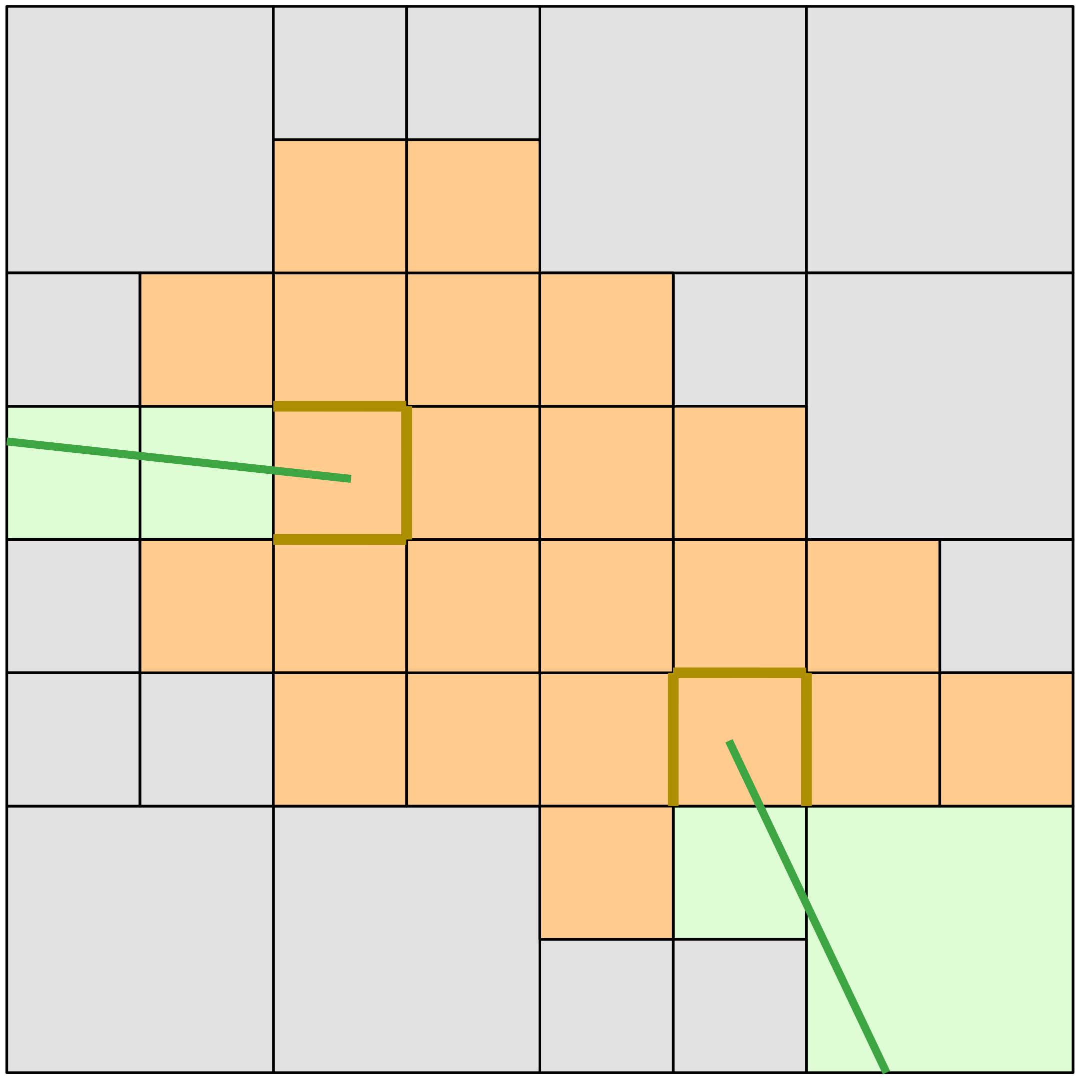


Determine Exterior

- determine the exterior by flood filling & dilation



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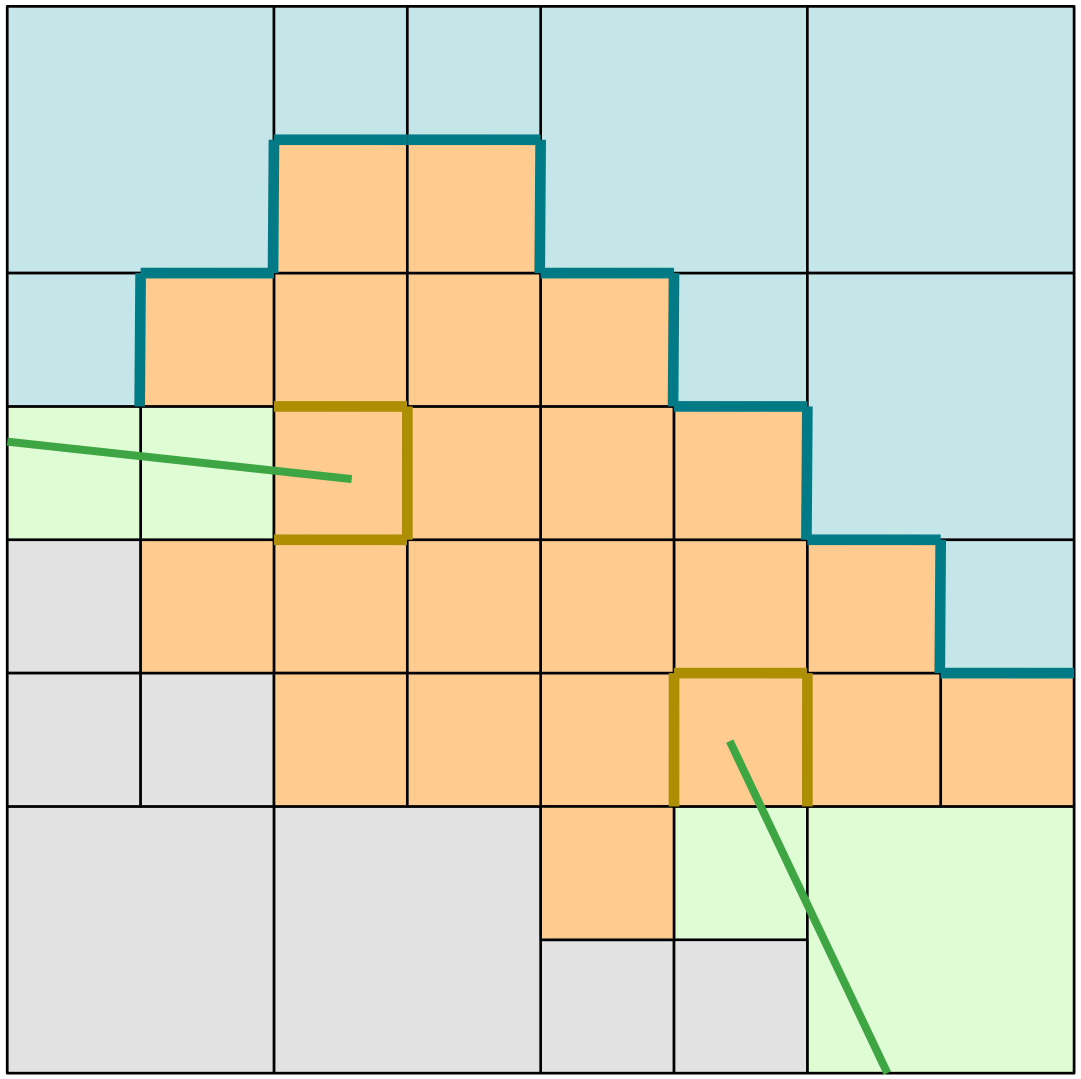

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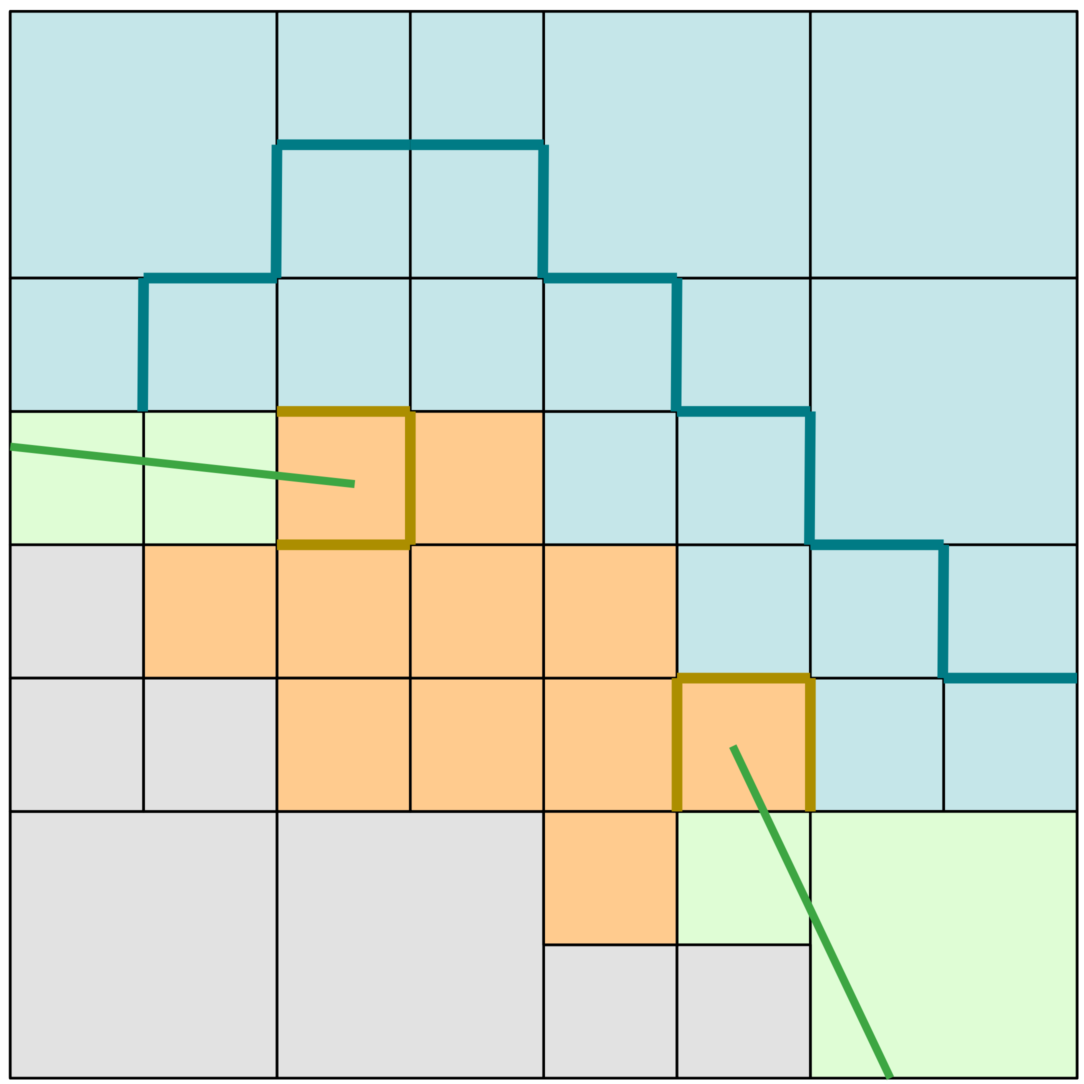

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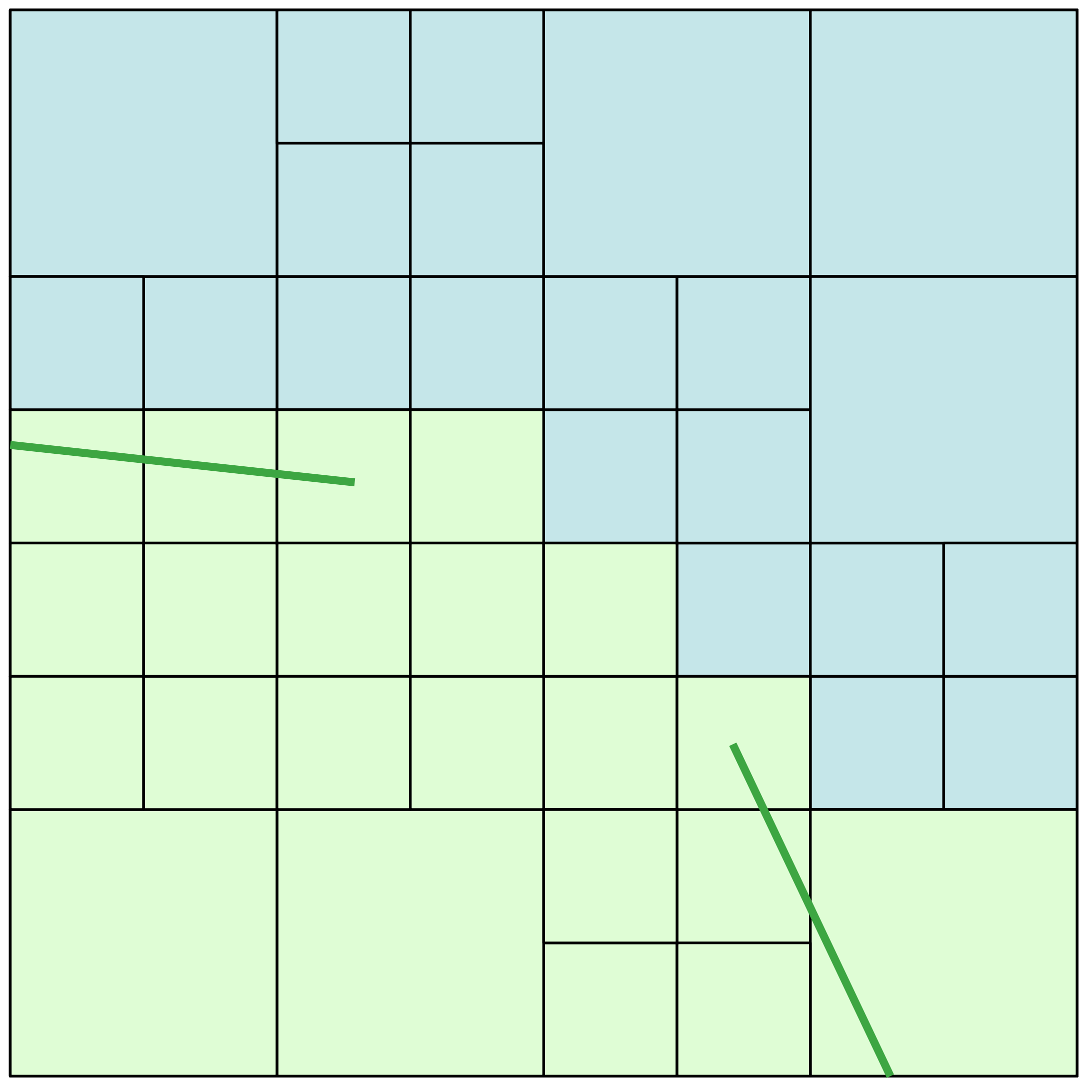
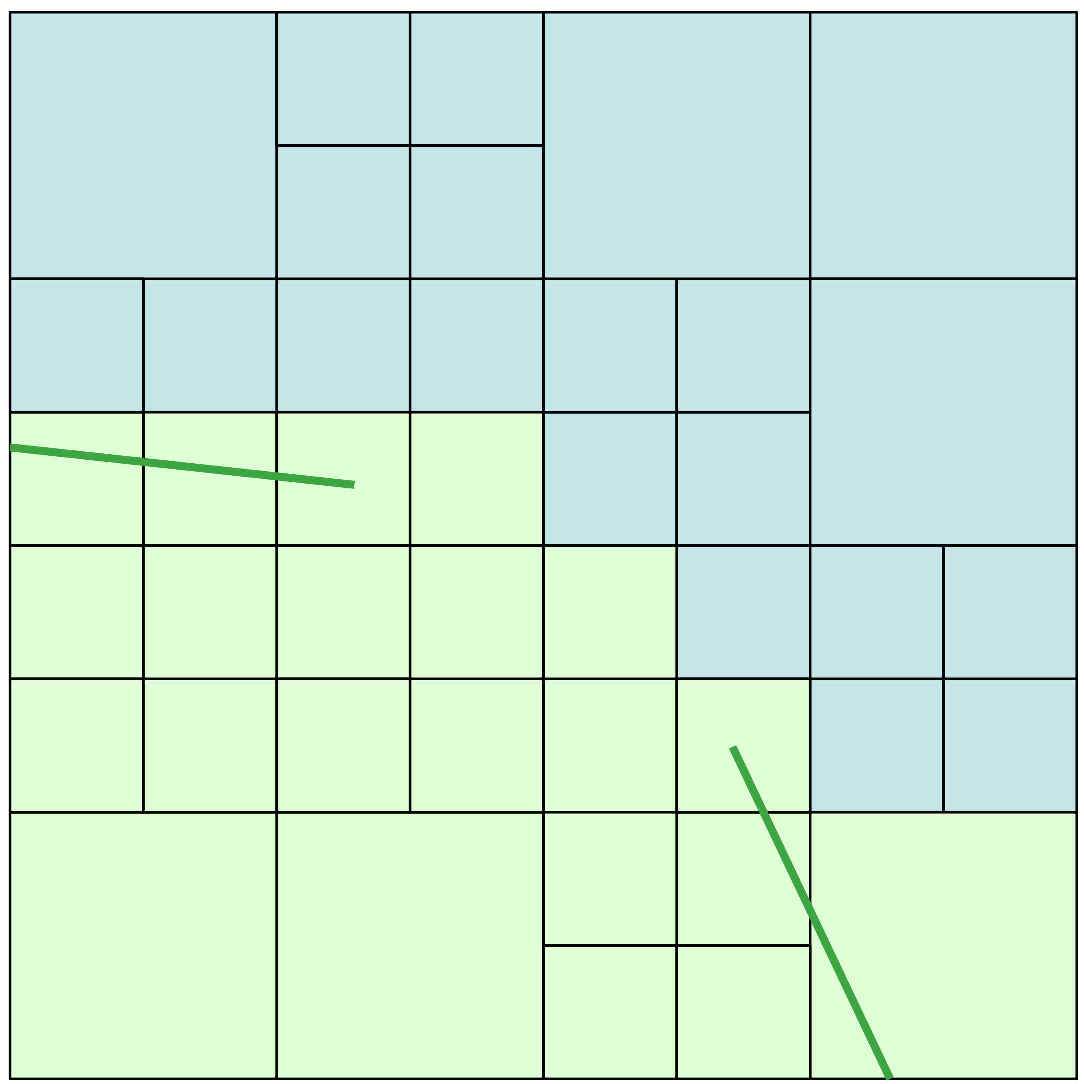


Extract the Surface

- extract the surface by a variant of Dual Contouring



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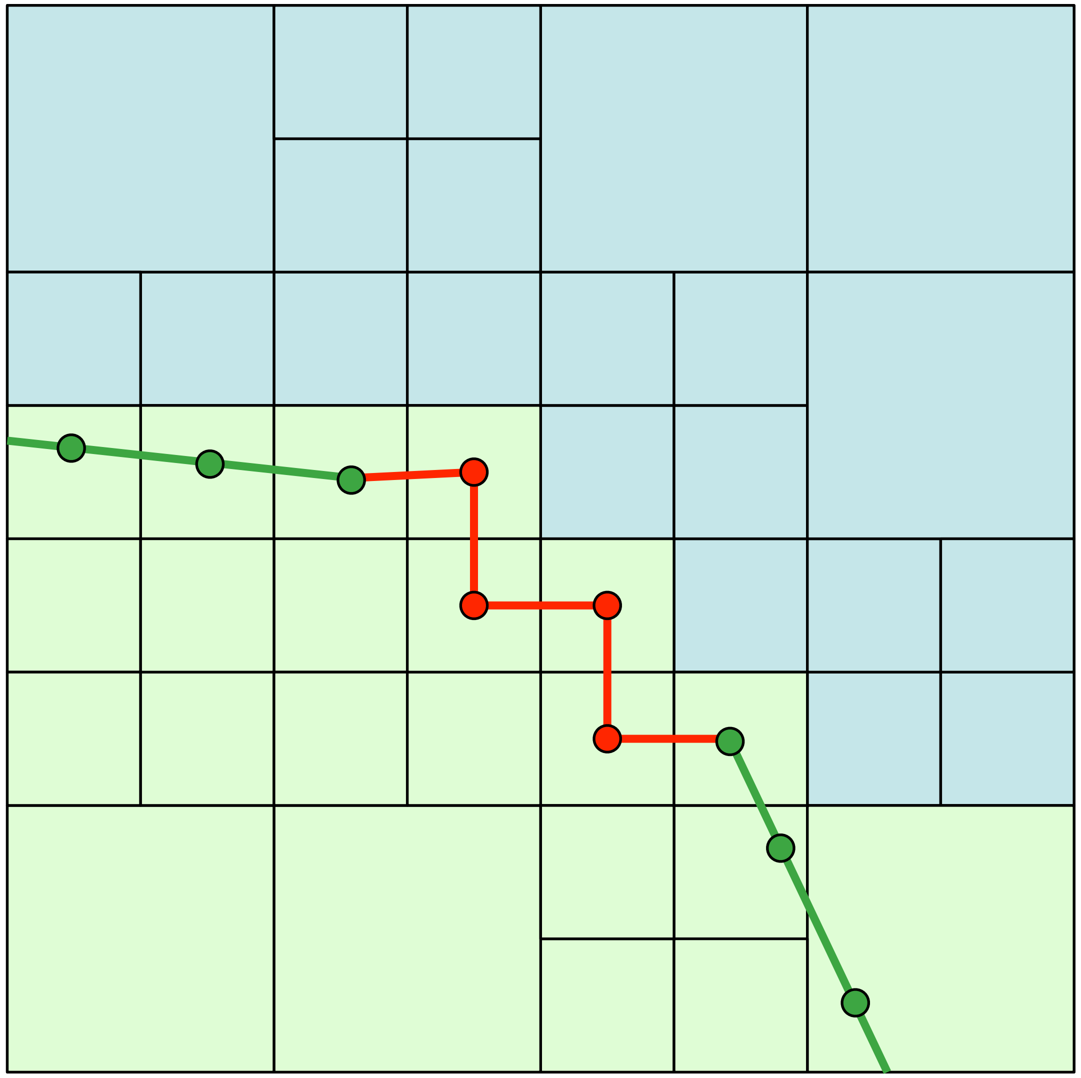

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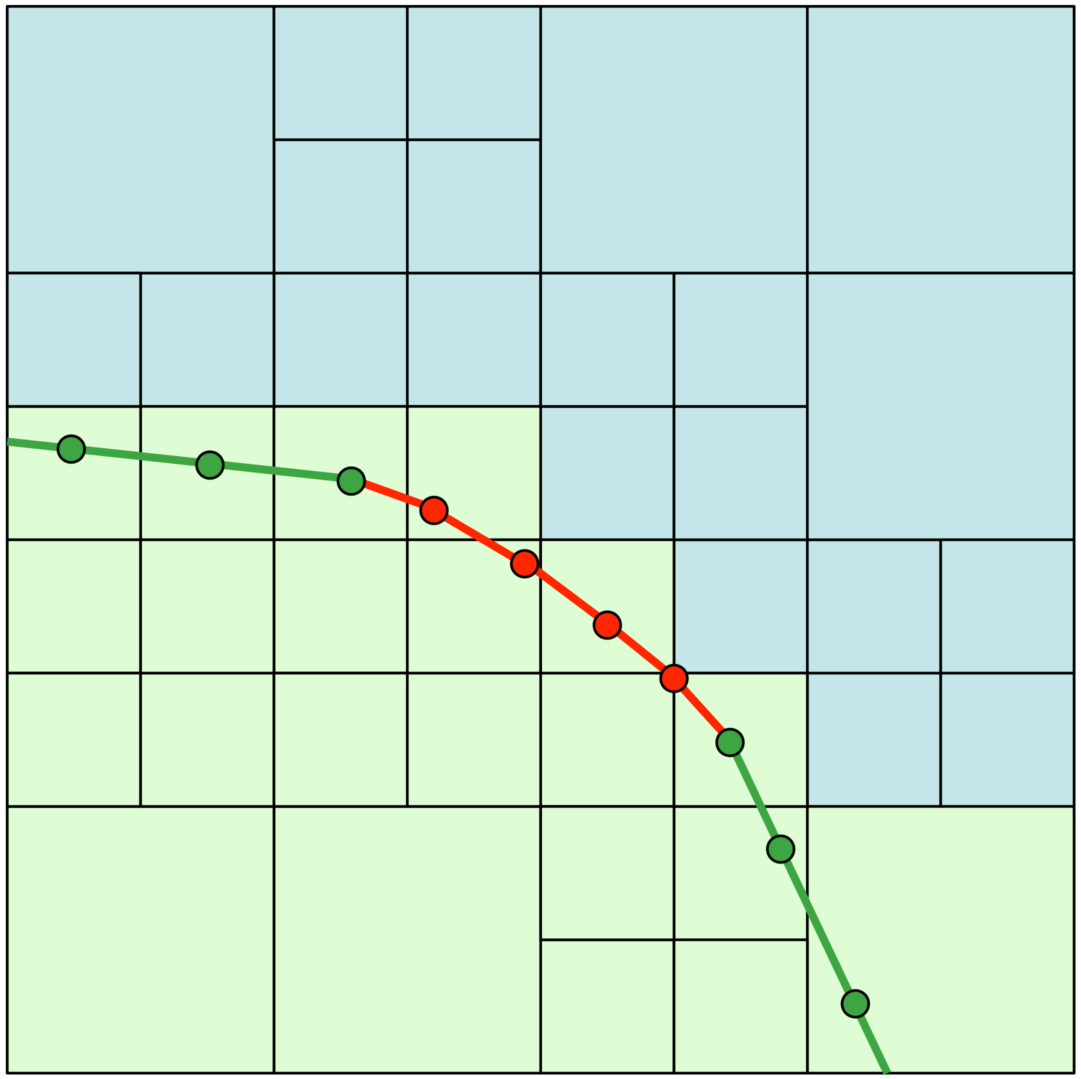
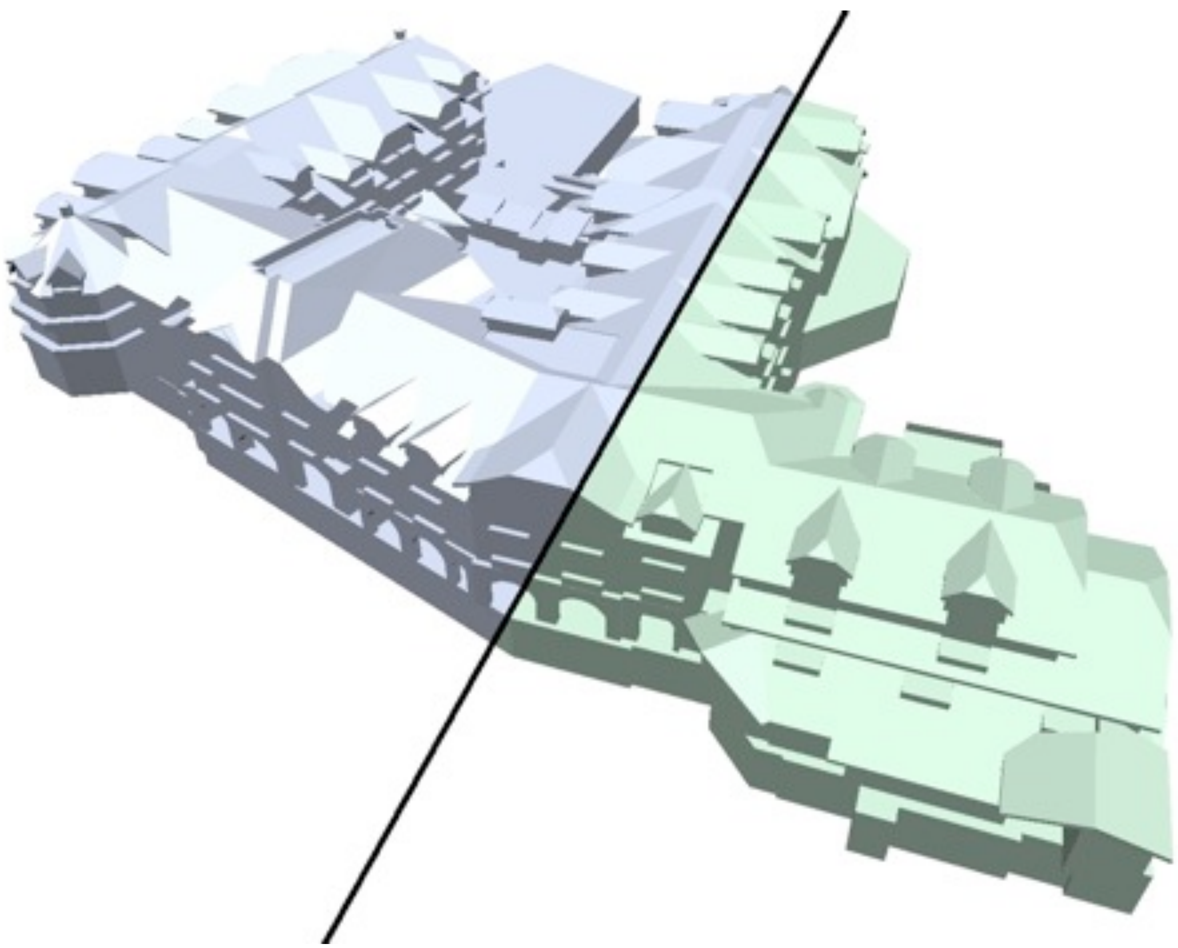
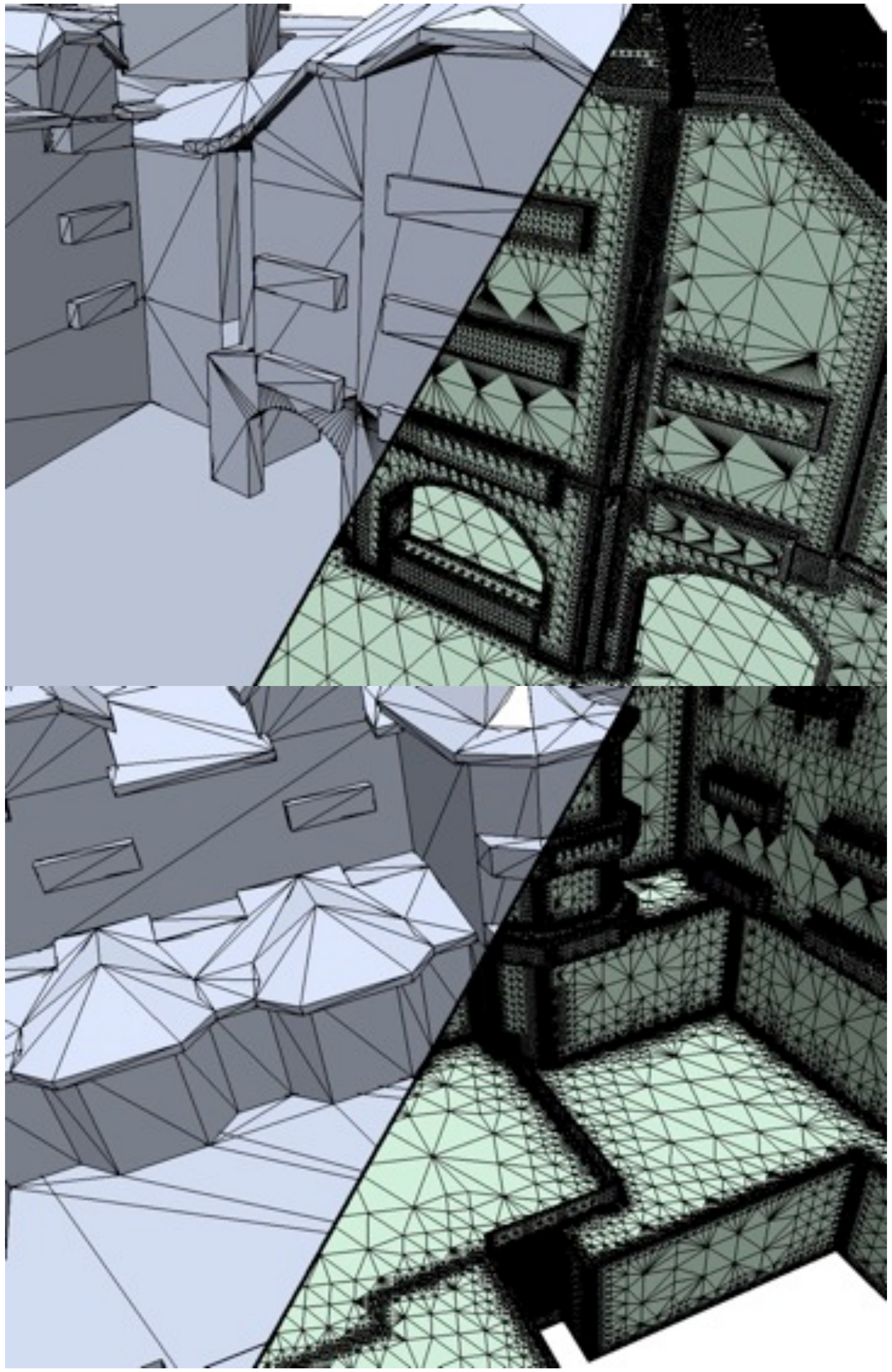


Results





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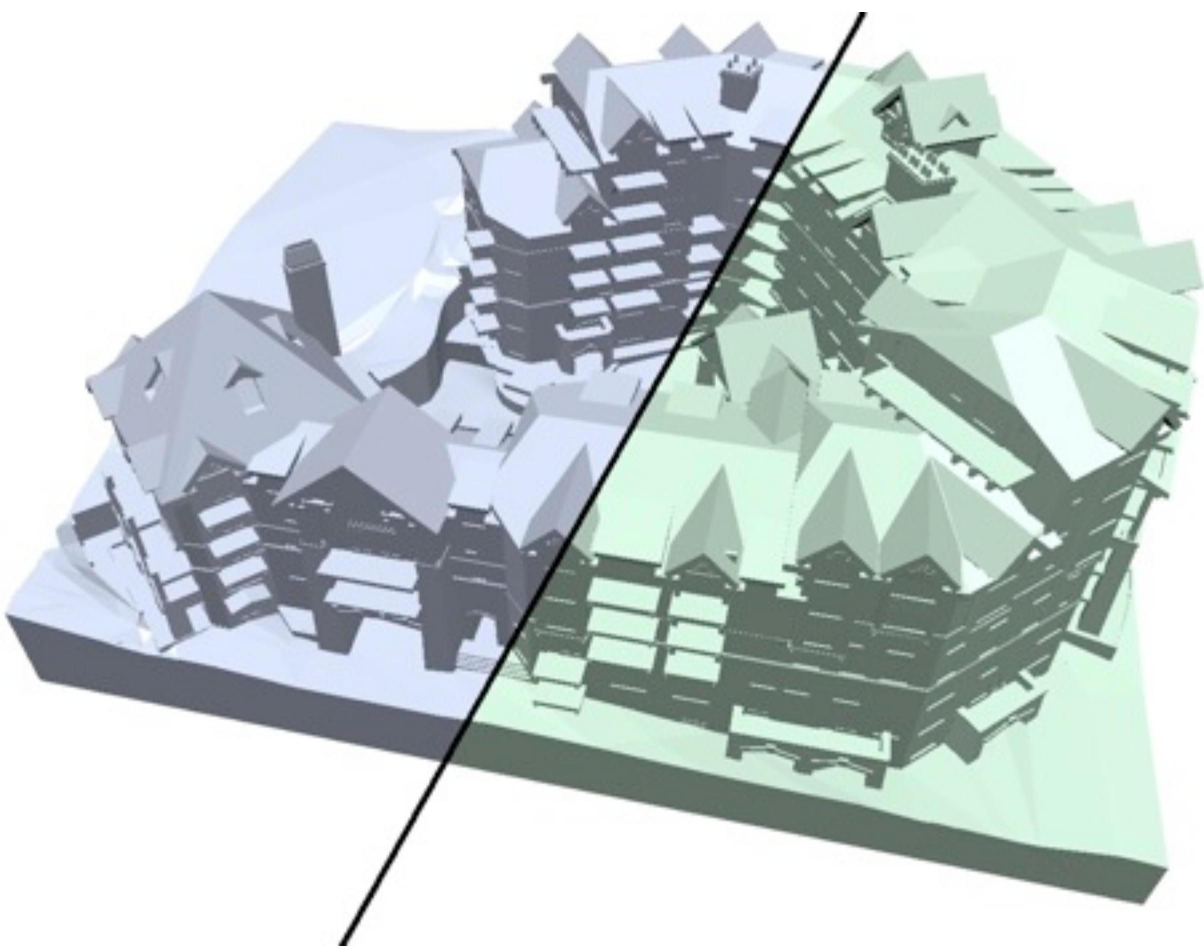

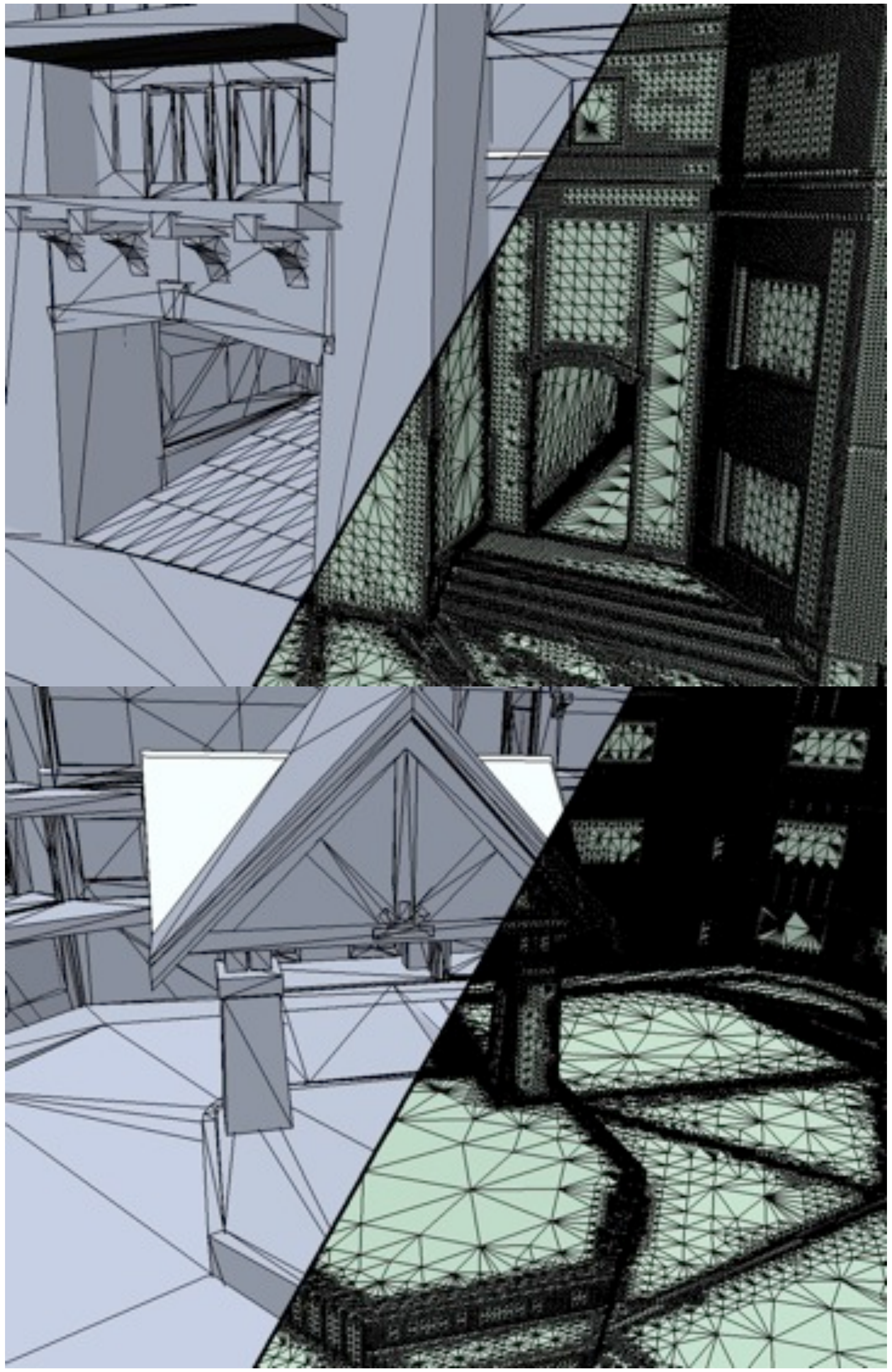

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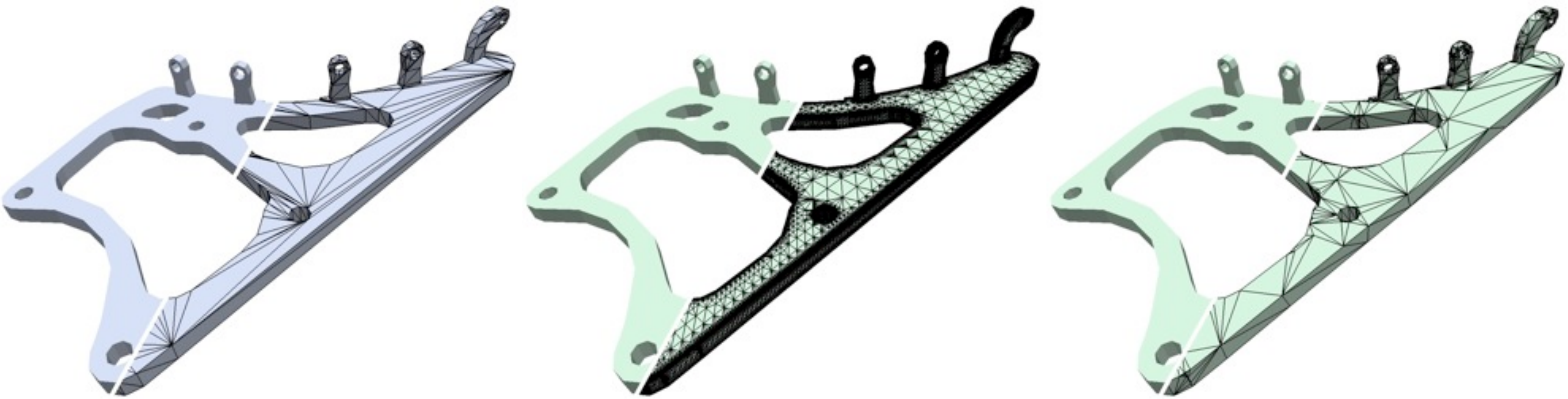
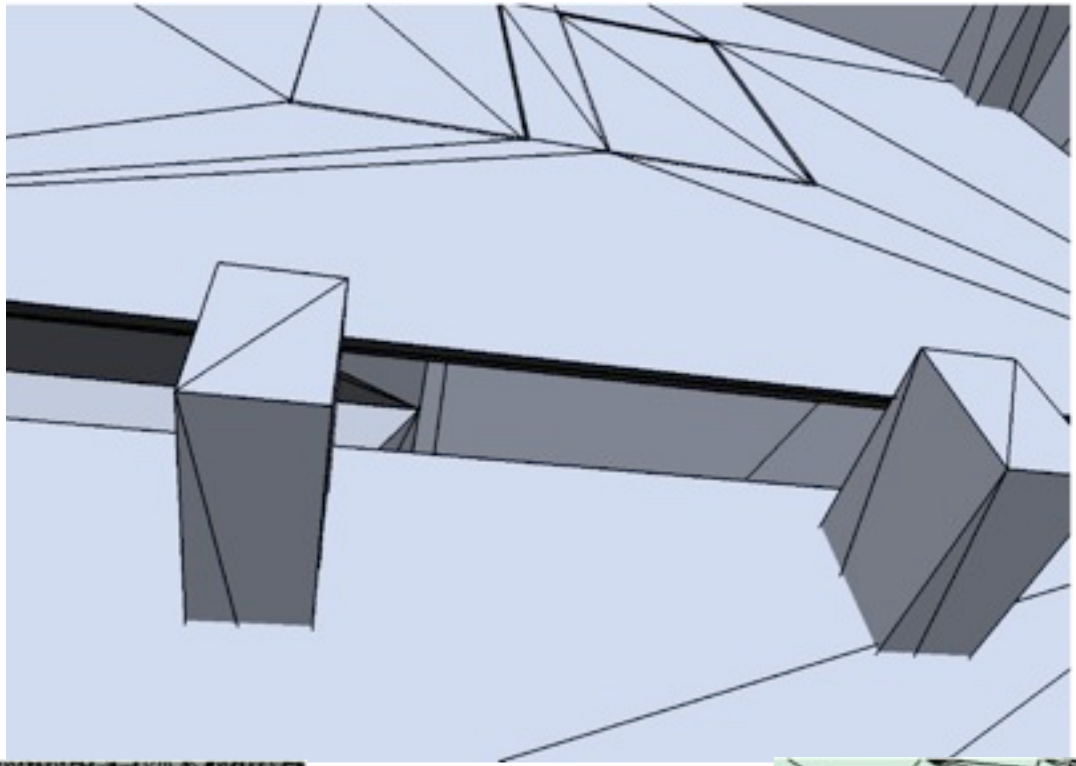


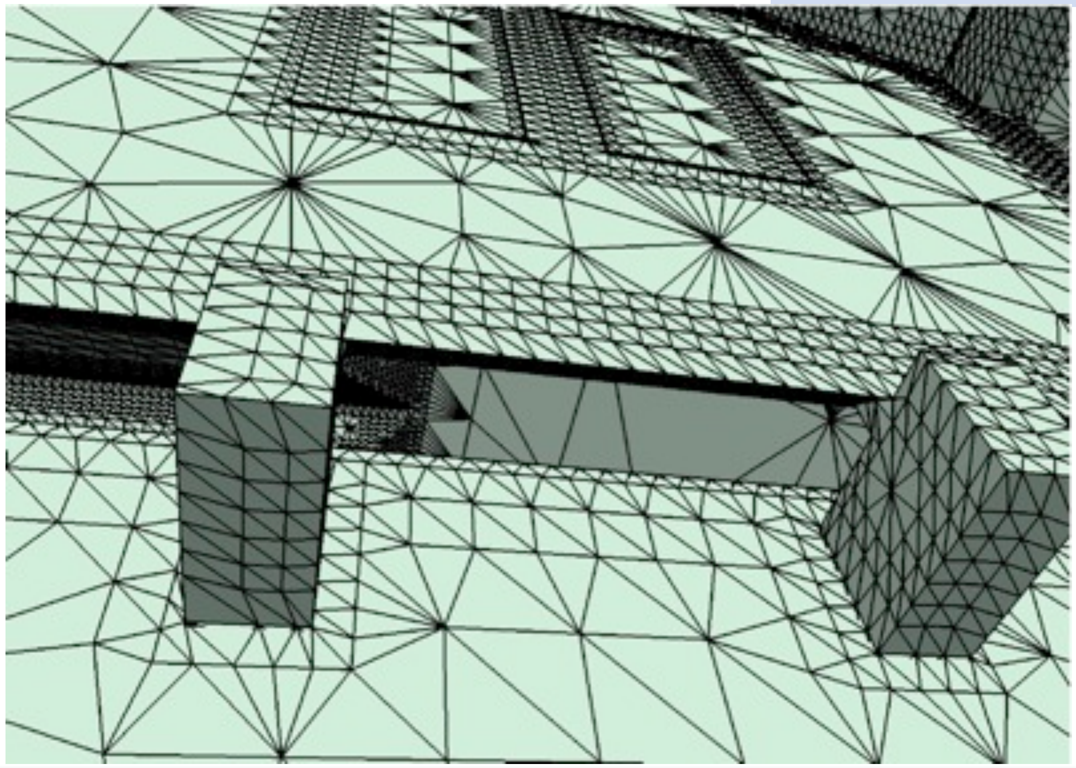
original	reconstruction	decimated
1124 triangles	279892 triangles (at 1000^3)	7018 triangles

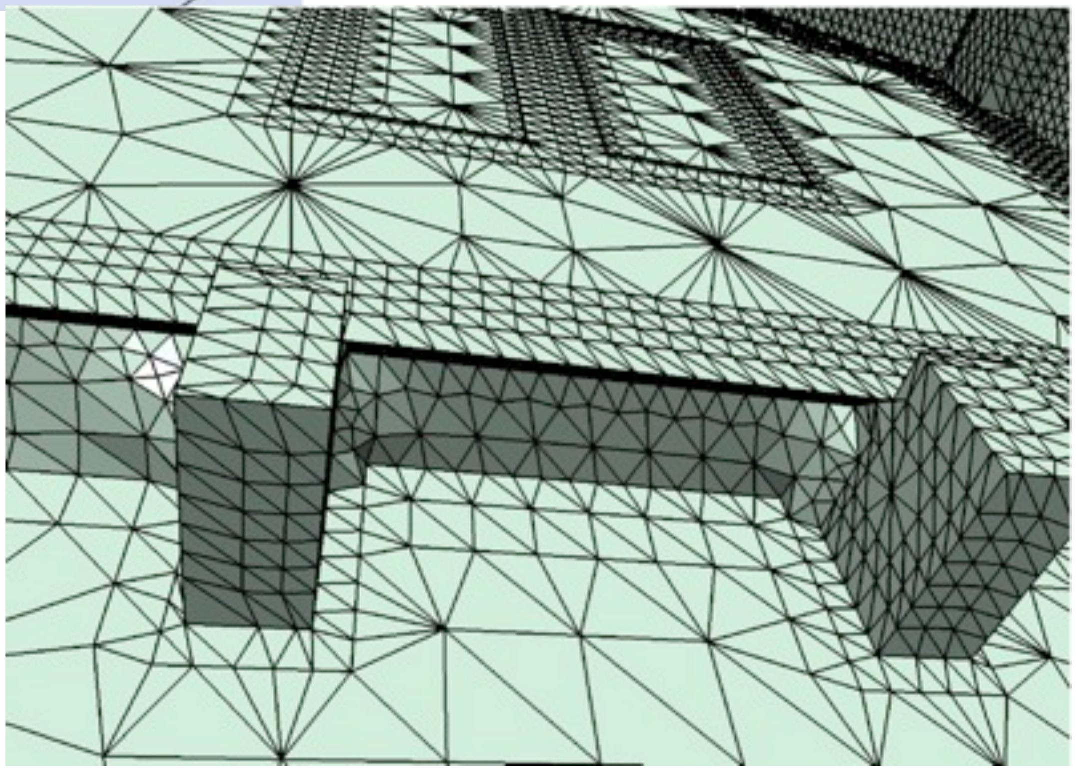
Results

without
gap filling

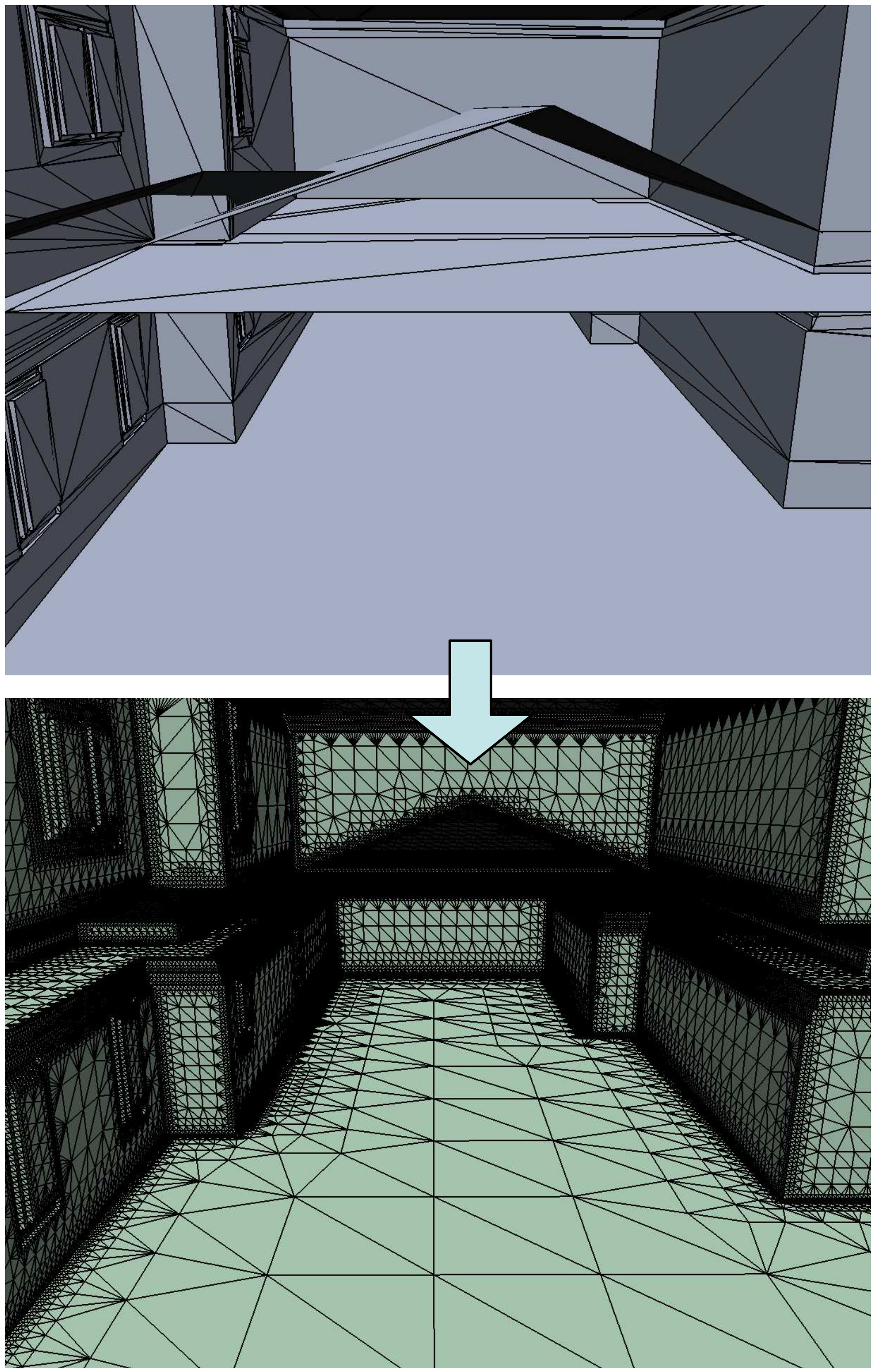


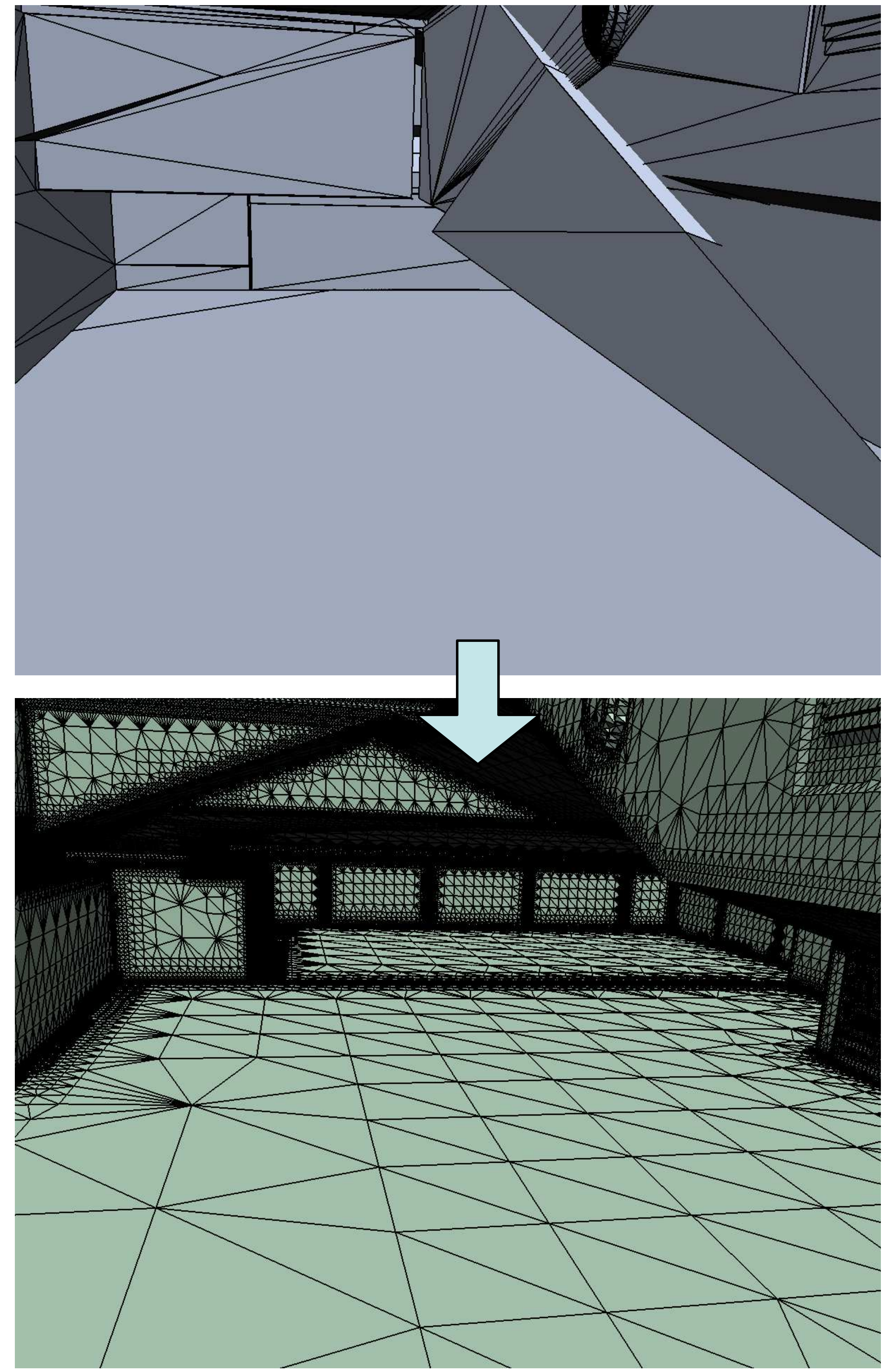
with
gap filling

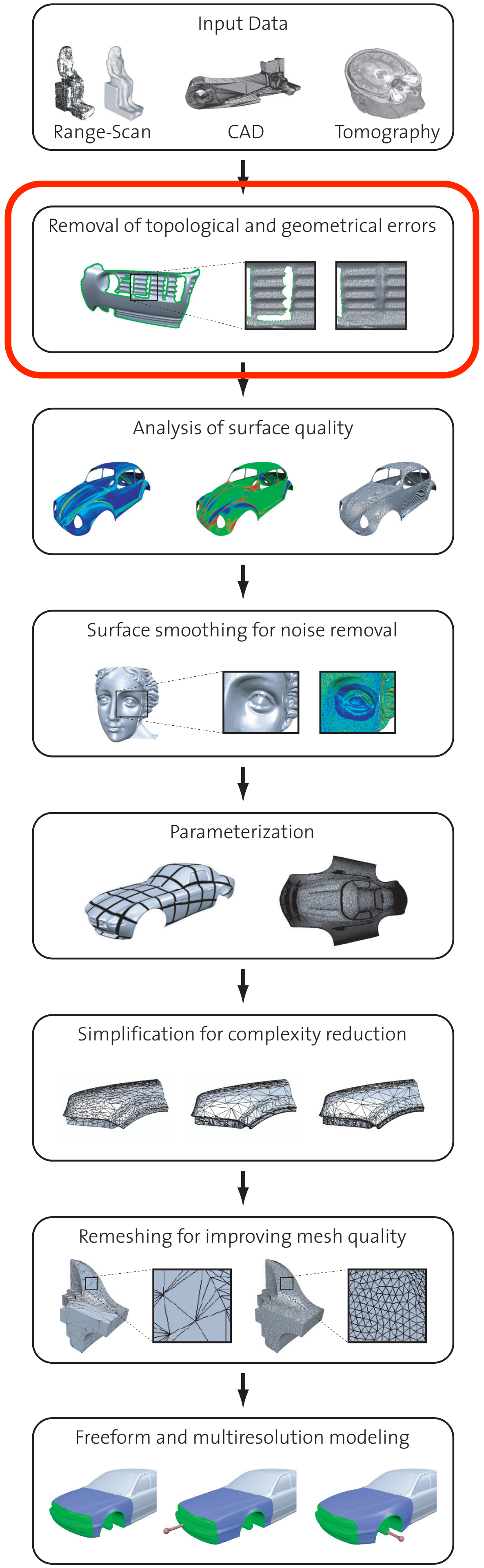




Results





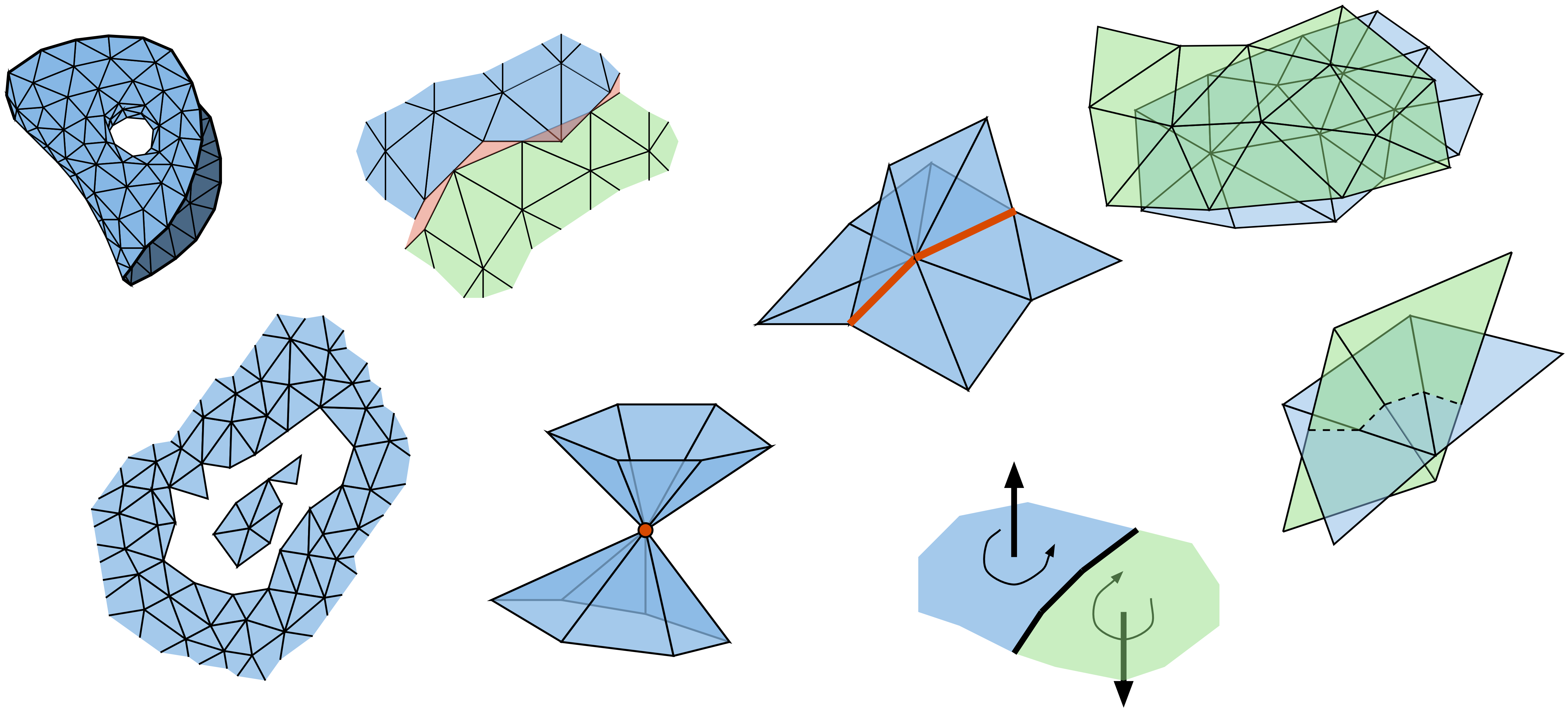


Model Repair

- types of input
- surface-oriented algorithms
  - Filling holes in meshes [Liepa 2003]
- volumetric algorithms
  - Simplification and repair of polygonal models using volumetric techniques [Nooruddin and Turk 2003]
  - Automatic restoration of polygon models [Bischoff, Pavic, Kobbelt 2005]
- **conclusion & outlook**

Conclusion

- mesh repair to remove artifacts that arise in various types of input models



Conclusion

- surface-oriented algorithms ...
  - fast, structure preserving
  - often not robust, need user interaction and cannot give quality guarantees on the output
- volumetric algorithms ...
  - use an intermediate volumetric representation and thus produce guaranteed watertight meshes
  - suffer from (topological) sampling problems

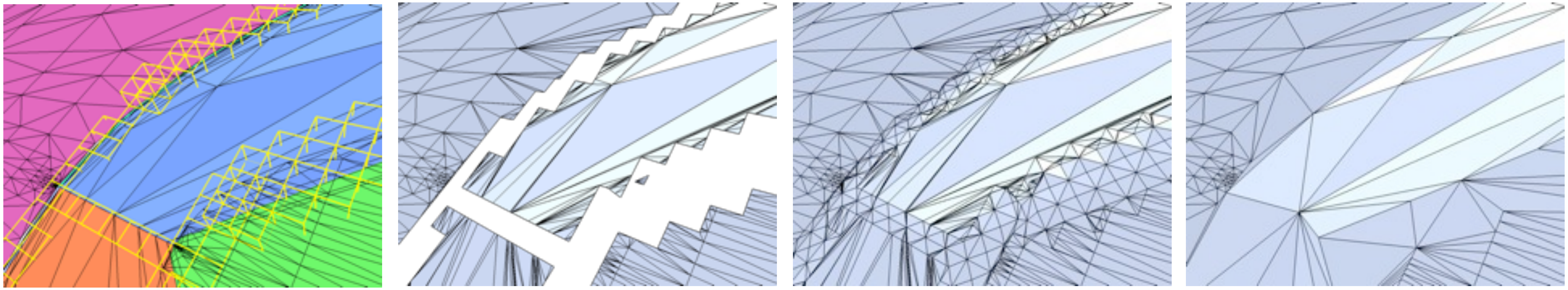
History of Mesh Repair

- Surface-oriented
- Volumetric

- Bøhn, Wozny: Automatic CAD Model Repair: Shell-Closure. 1992
- Mäkelä, Dolenc: Some Efficient Procedures for Correcting Triangulated Models. 1993
- Turk, Levoy: Zippered Polygon Meshes from Range Images. 1994
- Barequet, Sharir: Filling Gaps in the Boundary of a Polyhedron. 1995
- Curless, Levoy: A Volumetric Method for Building Complex Models from Range Images. 1996
- Barequet, Kumar: Repairing CAD Models. 1997
- Murali, Funkhouser. Consistent Solid and Boundary Representations. 1997
- Guéziec, Taubin, Lazarus, Horn: Cutting and Stitching: [...] 2001
- Guskov, Wood: Topological Noise Removal. 2001
- Borodin, Novotni, Klein: Progressive Gap Closing for Mesh Repairing. 2002
- Davis, Marschner, Garr, Levoy: Filling Holes in Complex Surfaces Using Volumetric Diffusion. 2002
- Liepa: Filling Holes in Meshes. 2003
- Greß, Klein: Efficient Representation and Extraction of 2-Manifold Isosurfaces Using kd-Trees. 2003
- Nooruddin, Turk: Simplification and Repair of Polygonal Models Using Volumetric Techniques. 2003
- Borodin, Zachmann Klein: Consistent Normal Orientation for Polygonal Meshes. 2004
- Ju: Robust Repair of Polygonal Models. 2004
- Bischoff, Pavic, Kobbelt: Automatic Restoration of Polygon Models. 2005
- Podolak, Rusinkiewicz: Atomic Volumes for Mesh Completion. 2005
- Shen, O'Brien, Shewchuk: Interpolating and Approximating Implicit Surfaces from Polygon Soup. 2005

Outlook

- ***hybrid*** algorithms that are ...
  - ... robust and
  - ... structure preserving



- Bischoff, Kobbelt: *Structure Preserving CAD Model Repair*. Eurographics 2005