Repairing

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Outlines

- Definitions
- Defects and flaws
- Upstream and Downstream applications
- Types of input
- Approaches

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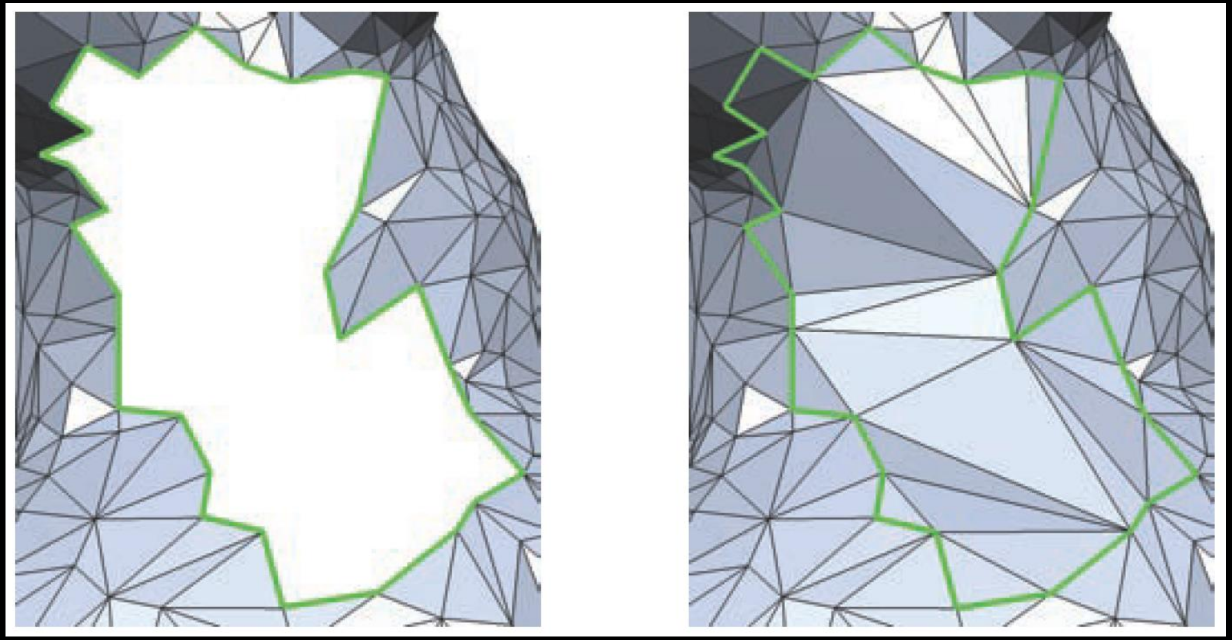
Problem Statement

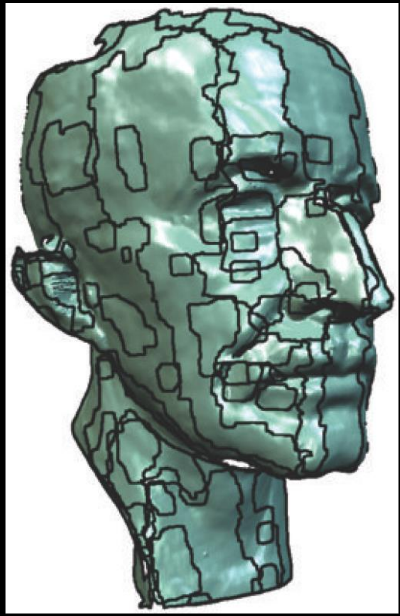
- Model repair is the process of removing artifacts from a geometric model in order to generate an output model suitable for further processing by downstream applications that require certain quality guarantees for their input.



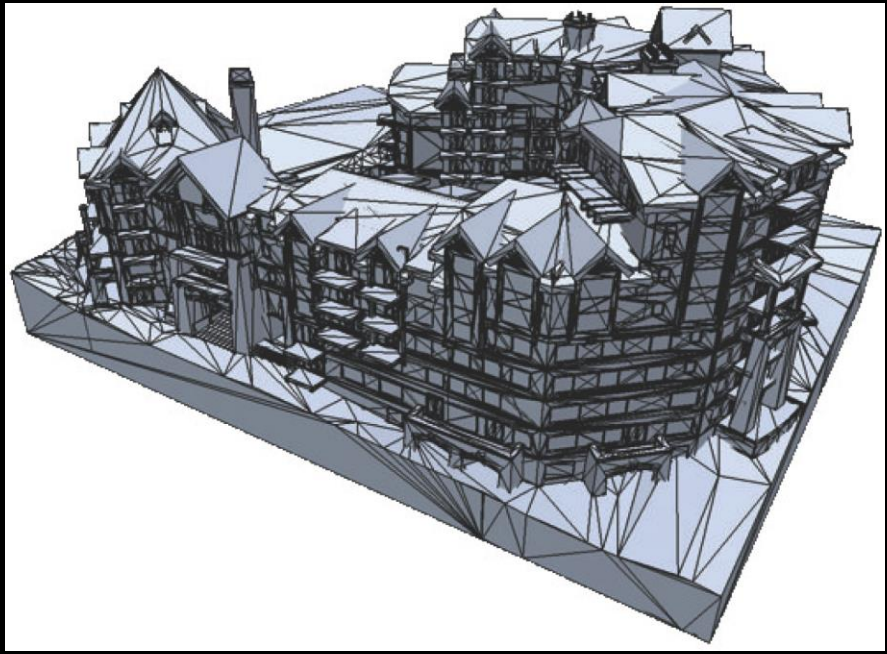
Hole filling

Application dependent

- Depends on the particular application scenario:
  - what kind of “models” are considered,
  - what exactly constitutes an “artifact,”
  - what is meant by “suitable for further processing”



Registered range scans from scanners



Triangle soups
from CAD models

One application

- The design cycle encountered in automotive CAD/CAM.
- Models are typically manually designed in CAD systems that use trimmed NURBS surfaces as the underlying data structure for representing freeform surface geometry.
- However, numerical fluid simulations for shape analysis and optimization cannot handle such NURBS patches directly but rather need a watertight, manifold triangle mesh as input.
- Thus, there is a need for an intermediate stage that converts the NURBS model into a triangle mesh.
- Unfortunately, this conversion process is prone to producing meshing artifacts that cannot be handled by simulation packages.
- Thus, the converted model has to be repaired—usually in a tedious manual post-process, which often takes longer than the simulation itself.

Repairing Guidelines

- What is the upstream application? (trimmed NURBS surfaces)
  - Determines characteristics and defects of input
- What is the downstream application? (manifold triangle meshes for FEM)
  - Determines requirements on output
- Based on this information,
  - is it necessary to repair the input?
- If repairing is necessary,
  - is there an algorithm that does it directly?
- If direct repair is not possible,
  - can several algorithms be used in sequence?
- If not,
  - there is a gap in the state-of-the-art.

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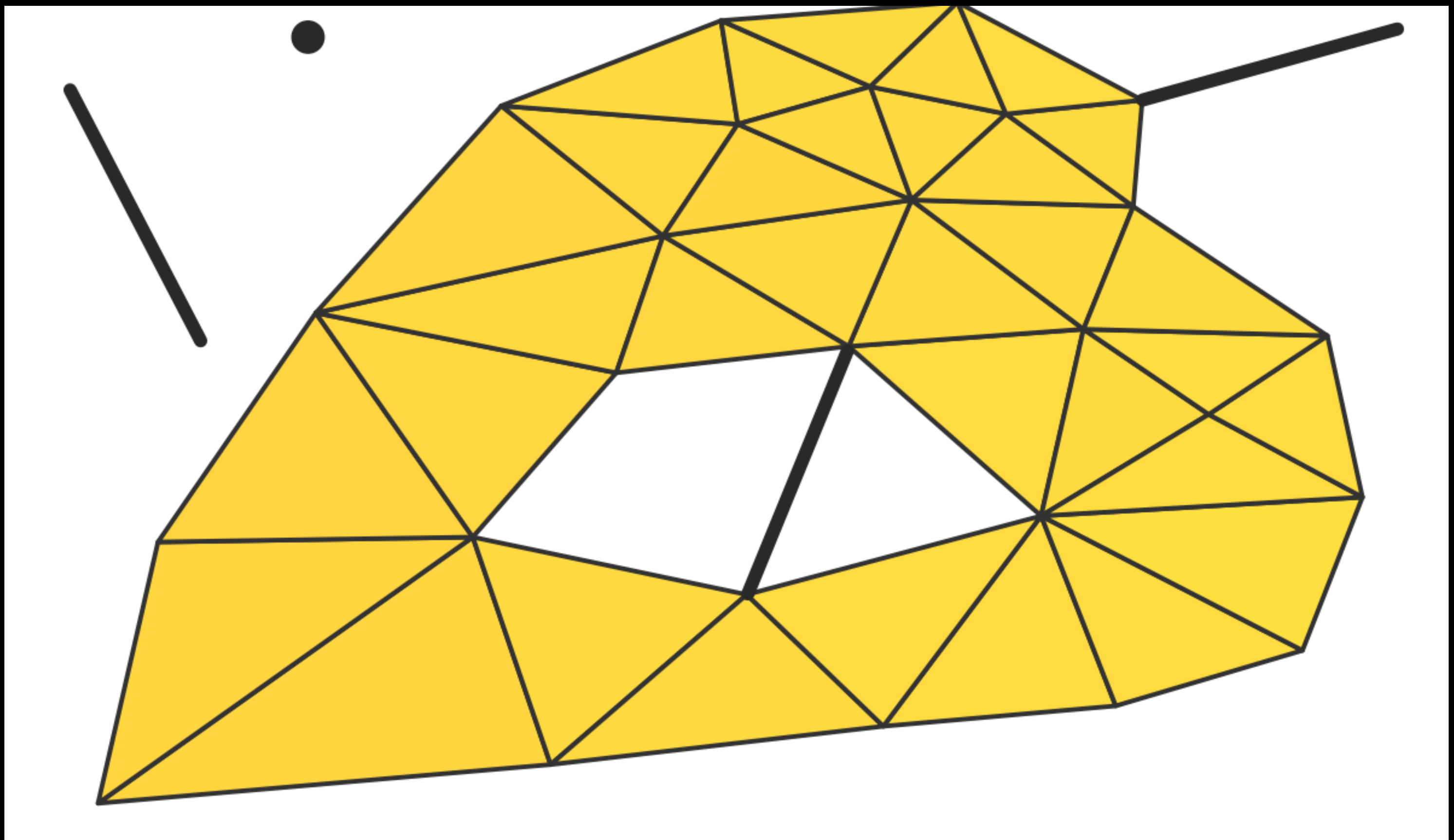
Isolated Vertices and Dangling Edges

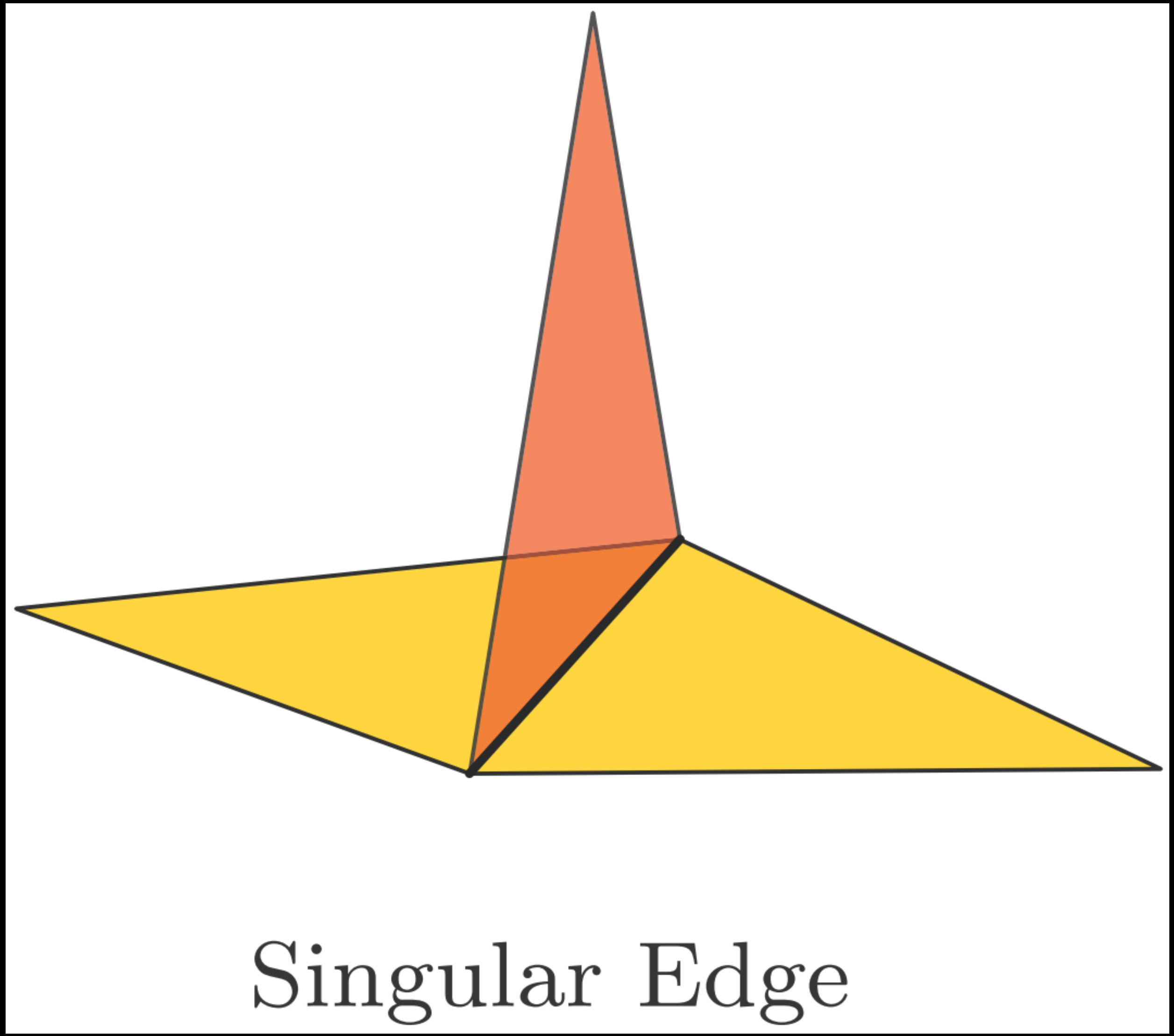


Isolated & Dangling Elements

Singular Edges

- When more than two polygons share a common edge, then such an edge is said to be singular, complex, or nonmanifold.

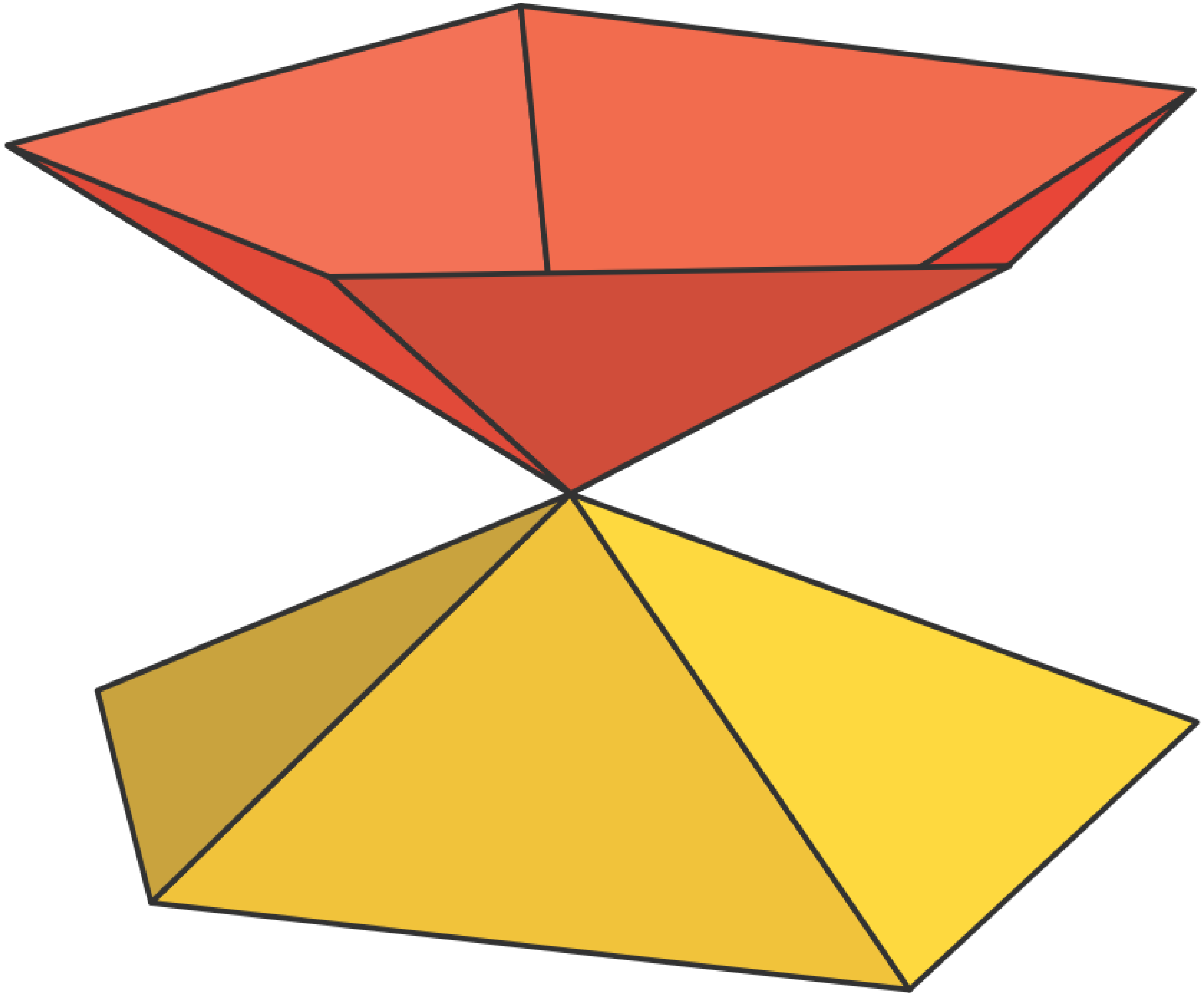
- Detection
  - count the number of incident triangles



Singular Vertices

- When a vertex is not manifold in the topology of the abstract simplicial complex, it is called a combinatorially singular vertex.

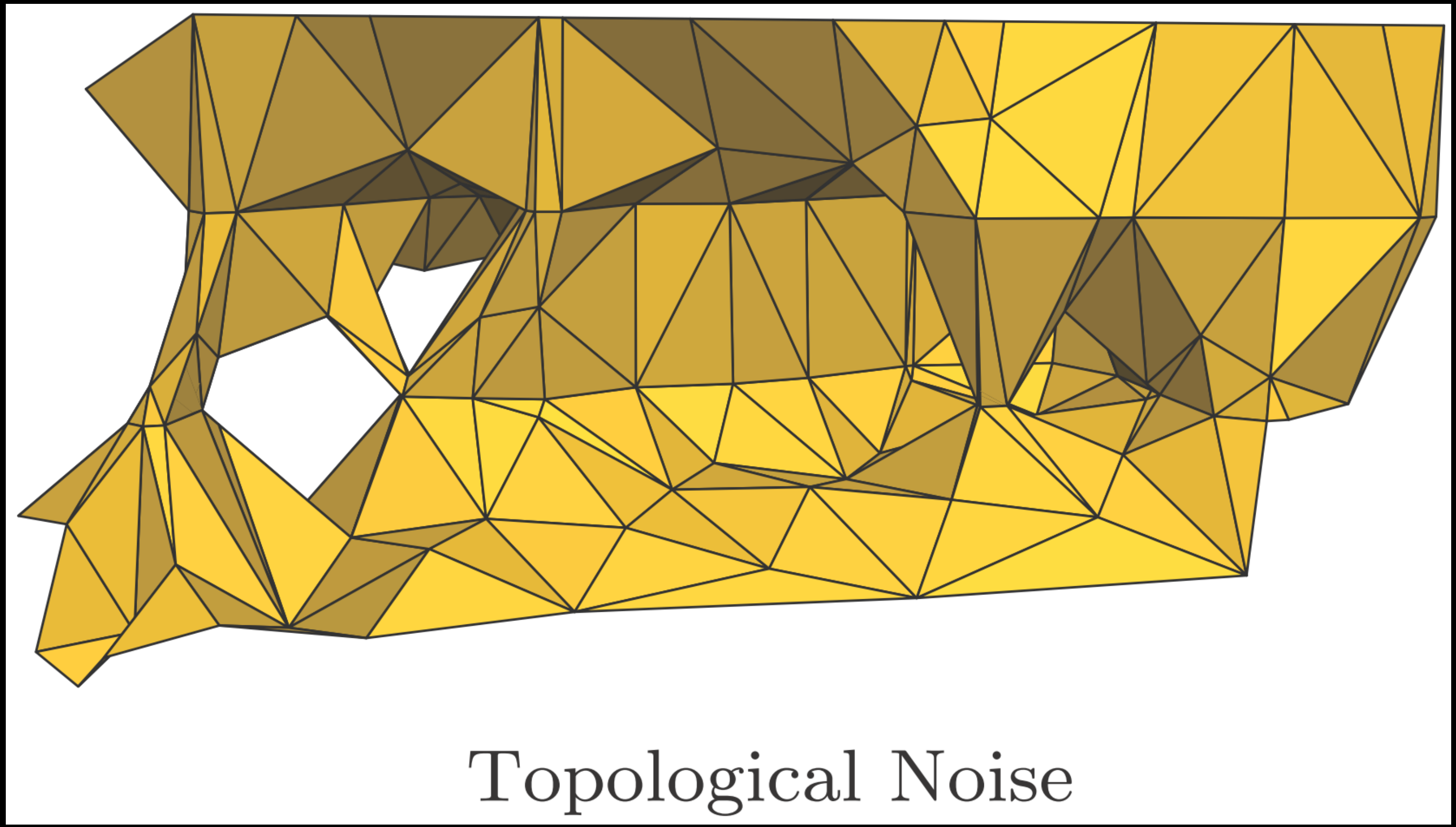
- Detection
  - count the number of connected components in the neighborhood



Singular Vertex

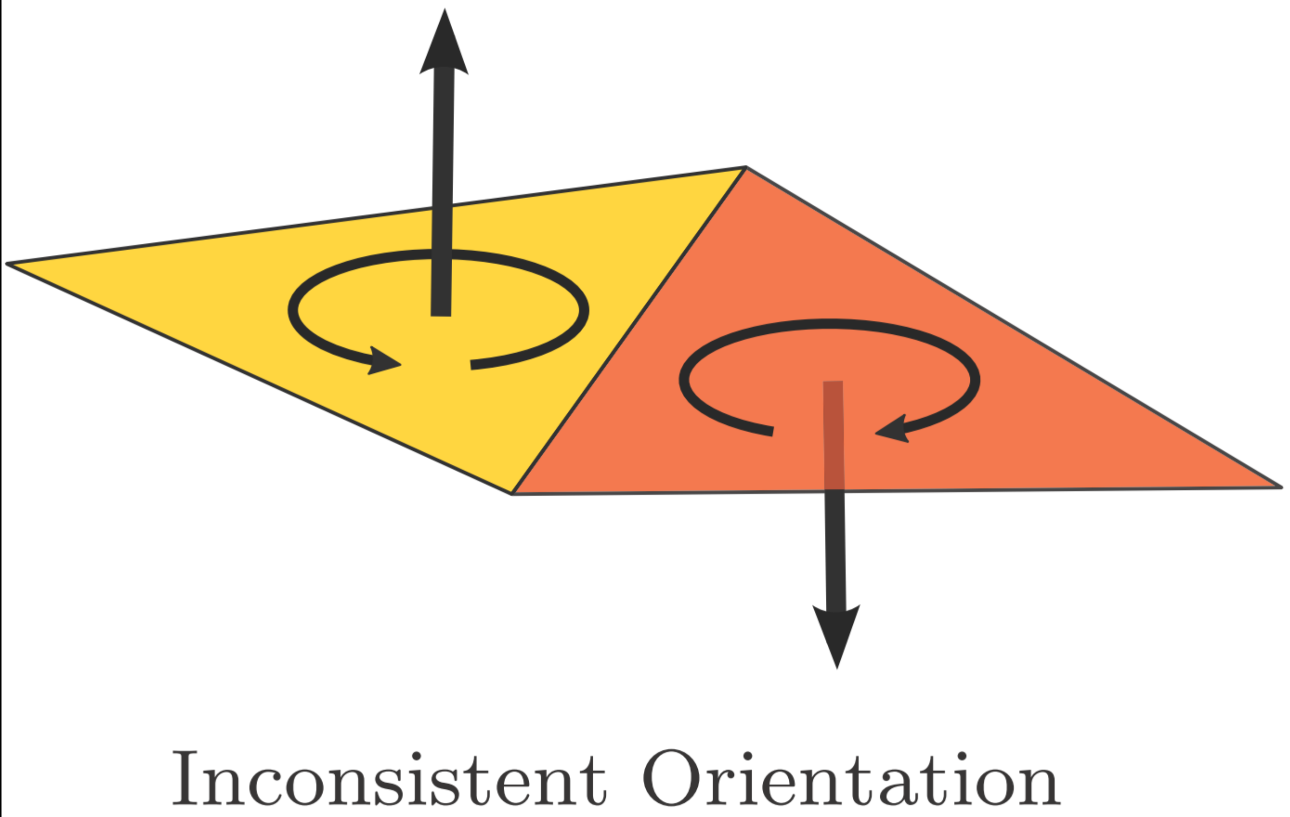
Topological Noise

- Often, in these processes tiny handles or tunnels, which were not present in the original object, are introduced in the constructed digital model due to aliasing effects or noise in the discrete underlying data.



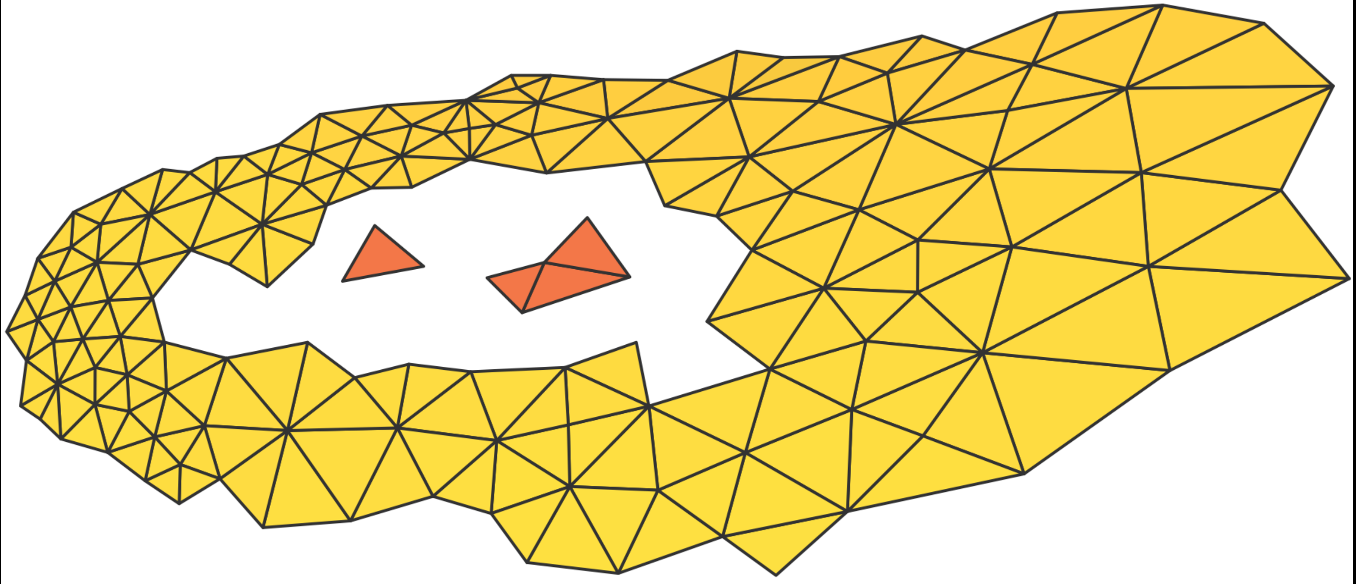
Orientation

- Polygons in an indexed face set are represented through sequences of vertex indices.
- This is typically achieved by selecting a seed face and by propagating the orientation to neighboring faces.
- Nevertheless, some configurations are intrinsically not orientable.



Surface Holes

- When digitizing a real-world object through standard laser range scanners, it is usual to encouter occluded parts which cannot be captured because the laser beam is shadowed by other parts of the object.
- A hole is an undesirably missing piece of surface within a triangulated patch.



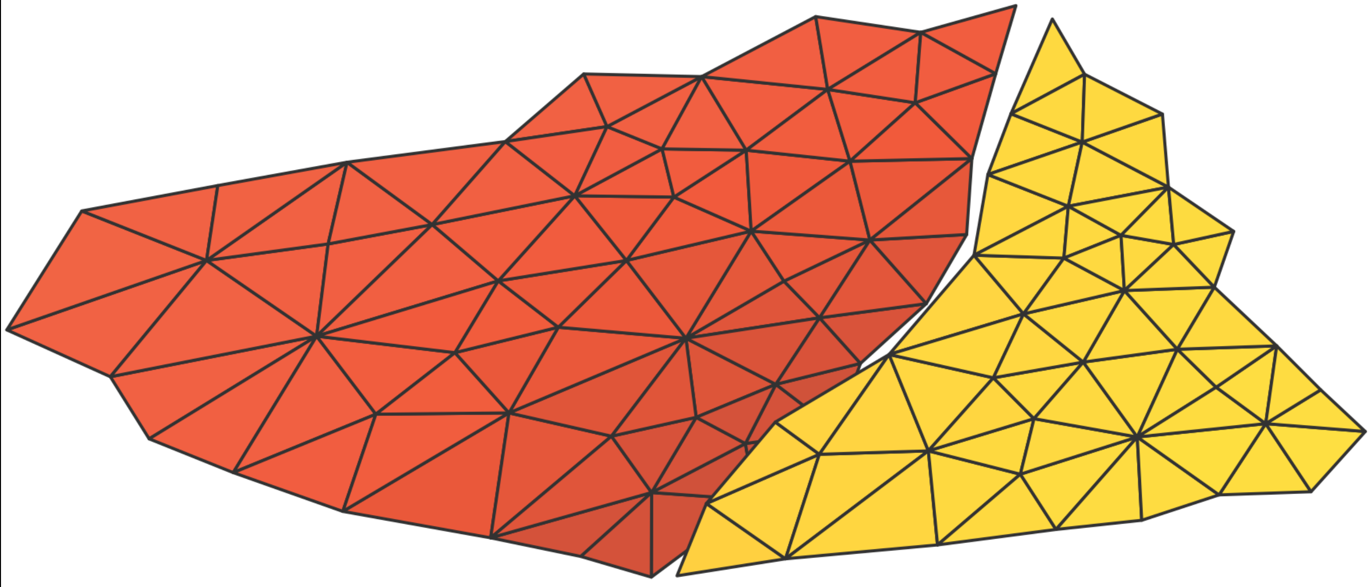
Hole (with Islands)

Surfaces holes

- The boundary of a hole normally consists of one or more closed edge loops.
- Holes might represent larger areas of missing data.
  - Challenge of conceiving a plausible geometry to fill the holes
- May contain so-called islands.

Gaps

- When designing a surface through standard CAD systems, the various tessellated patches are typically slightly displaced in a way that—though the intention of the designer was to construct a continuous surface—adjacent patches are separated by undesired gaps.



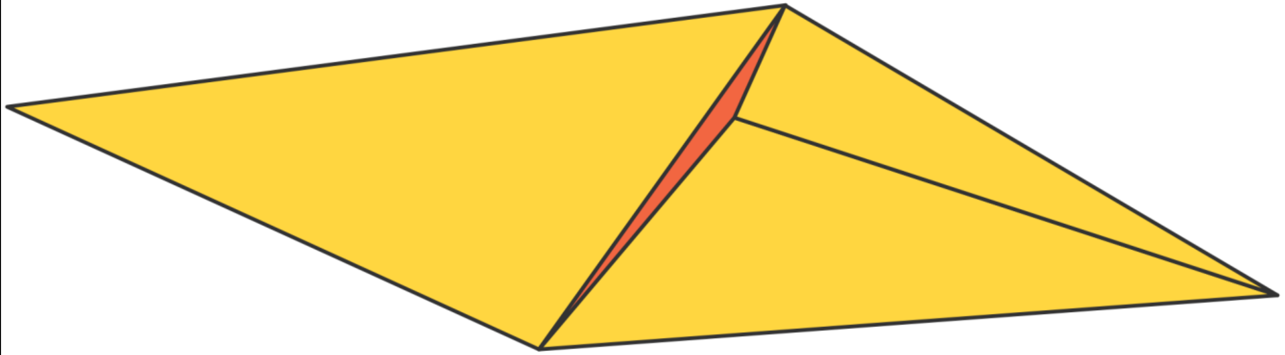
Gap (with partial Overlap)

Gaps

- A gap is defined as the empty region between two triangulated surface patches that should be continuously connected but are not due to the gap.
- The boundary of a gap, indeed, is typically made of two (or more) disconnected chains of edges.
- Quite narrow.

Degenerate Elements

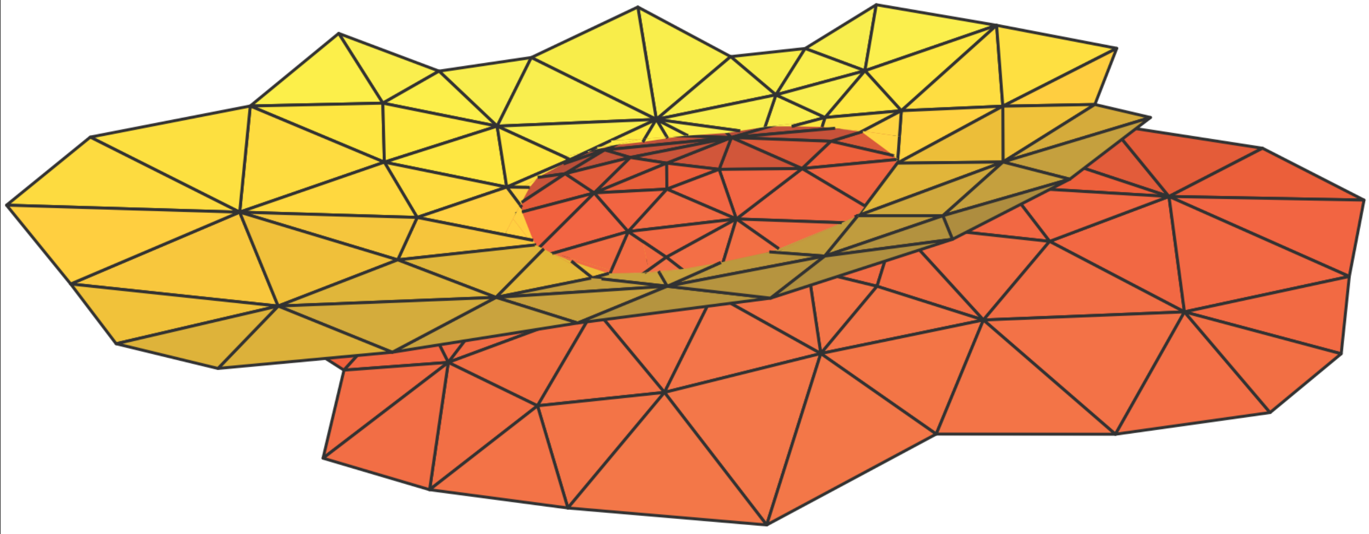
- Degenerate triangles are triangles with zero area.
- These elements are the source of several problems for numerous applications, since many useful entities cannot be computed on such triangles (normal vectors, circumscribing circles, barycentric coordinates, etc).



(Near) Degeneracy

Self-Intersections

- Self-intersecting meshes are typically generated
  - by tessellation of multipatch CAD models,
  - by deformation of mesh models,
  - by composing models out of multiple parts without care,
  - or when merging patches reconstructed from partial scans of a 3D object.
- Due to the ambiguities, there is no common strategy to tackle this problem.



(Self-)Intersection

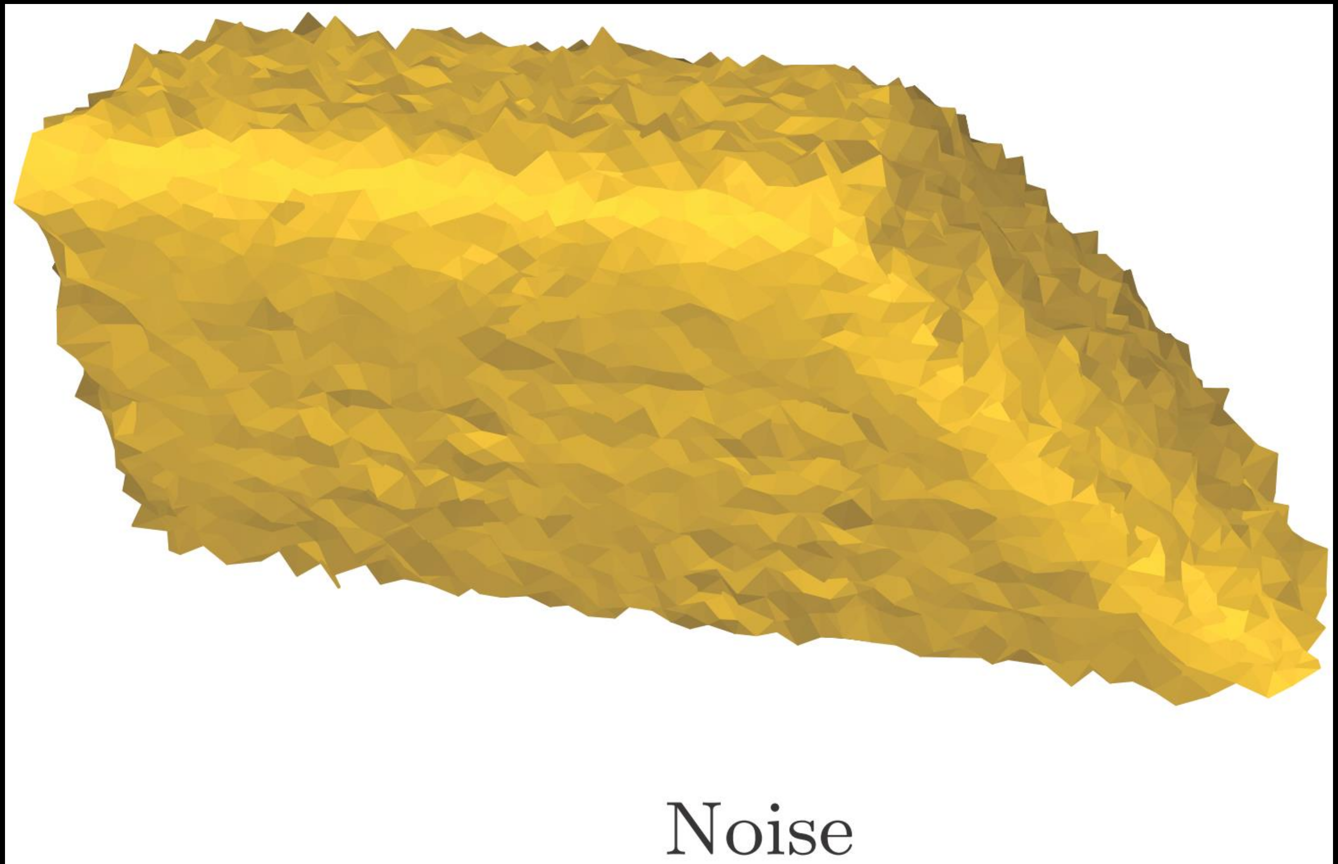
Sharp Feature Chamfering

- The sharp edges and corners of the original shape are removed by the sampling process and replaced by irregularly triangulated chamfers.
- Having such well-defined sharp features has clear advantages for both visualization and reverse engineering.

Feature Chamfering/Aliasing

Data Noise

- Every digitization tool has a finite precision.
- Thus, the acquired raw data of the sampled model contains additive noise from various sources.
- A main challenge is to remove the noise while preserving the main morphology of the underlying sampled surface.



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Upstream applications

- Determines characteristics and defects of input
- The origin of defects in a mesh: Nature and Approach
- Nature of the data modeled
  - (physical) real-world data
  - (virtual) concepts
- Approach employed to convert such data into polygon meshes

Nature

- If a model is designed, the basic concept is typically an abstraction.
- Downstream applications may face problems such as nonmanifoldness, gaps, and intersections.
- These defects are either caused by inaccuracies in modeling or produced by description processes that are often based on surface representations although solids are meant to be created.

Nature

- if the model is digitized, problems are mostly in the measured data.
- May include noise, holes, chamfered features, and topological noise
- Due to limitations of the measurement process employed for digitization.

Approach

- Such abstraction/data is converted into a polygon mesh (if not originally designed in polygonal form).

- The conversion itself can be the source of further flaws that depend on the specific approach used.
  - For example, a CAD model, gaps and intersections might arise due to the necessarily occurring deviation of each triangulated patch from the original curved surface.
  - Depending on the quality of the tessellation algorithm also (near-)degenerate polygons might be created.

Downstream applications

- Determines requirements on output

- Visualization
  - only the existence of significant holes is generally deemed unacceptable; all other types of defects can often be neglected.
  - To achieve pleasing renderings of a certain visual quality, however, also noise, gaps, and chamfered features can be adverse.

Downstream applications

- Modeling
  - Connected surfaces without degeneracies are usually required.
  - Intersections are often acceptable in the case of surface-based methods.
  - Singularities and topological noise do not cause problems for some methods, others require or prefer clean manifold meshes.

- Rapid prototyping
  - The mesh model naturally needs to be convertible to a solid model, that is, it has to well-define an interior and exterior volume
  - So the mesh definitely has to be closed and free of intersections and singular non-manifold configurations that would prevent an unambiguous volume classification.

Downstream applications

- Geometry processing
  - The input mesh is additionally required to be free of degeneracies and noise in order to allow for the computation of element properties and discrete differential quantities in a reasonable way.
  - Aliasing effects like topological noise and chamfered features negatively affect and disturb several of these methods.
- Simulation (FEM) of real-world phenomena on digital models
  - The highest (all) requirements on the model's quality in order to be able to achieve reliable results.

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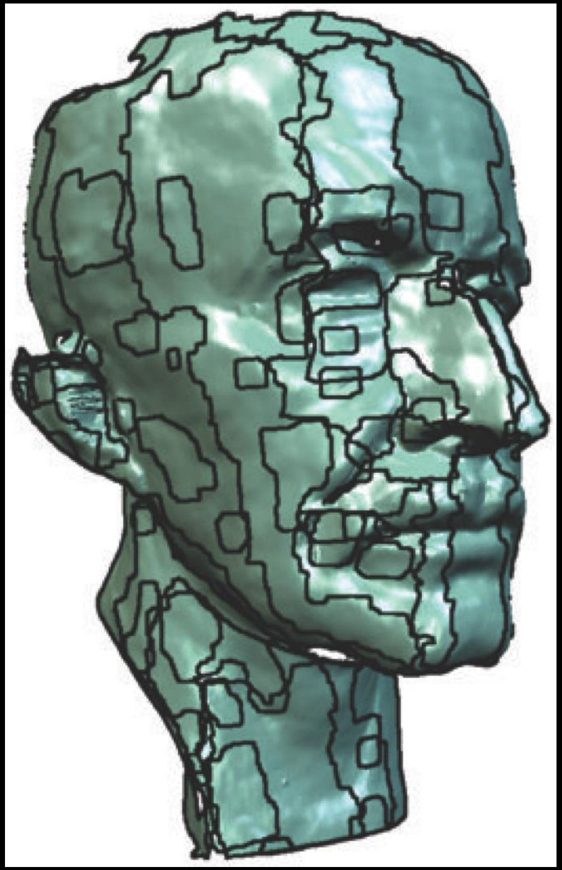
Registered range scans

- A set of patches (usually triangle meshes) that represent overlapping parts of the surface S of a scanned object.

- The main geometric problem in this setup is the potentially very large overlap of the scans.
  - a point x on S is often described by multiple patches

- Each patch has its own connectivity that is usually not compatible to the connectivity of the other patches.



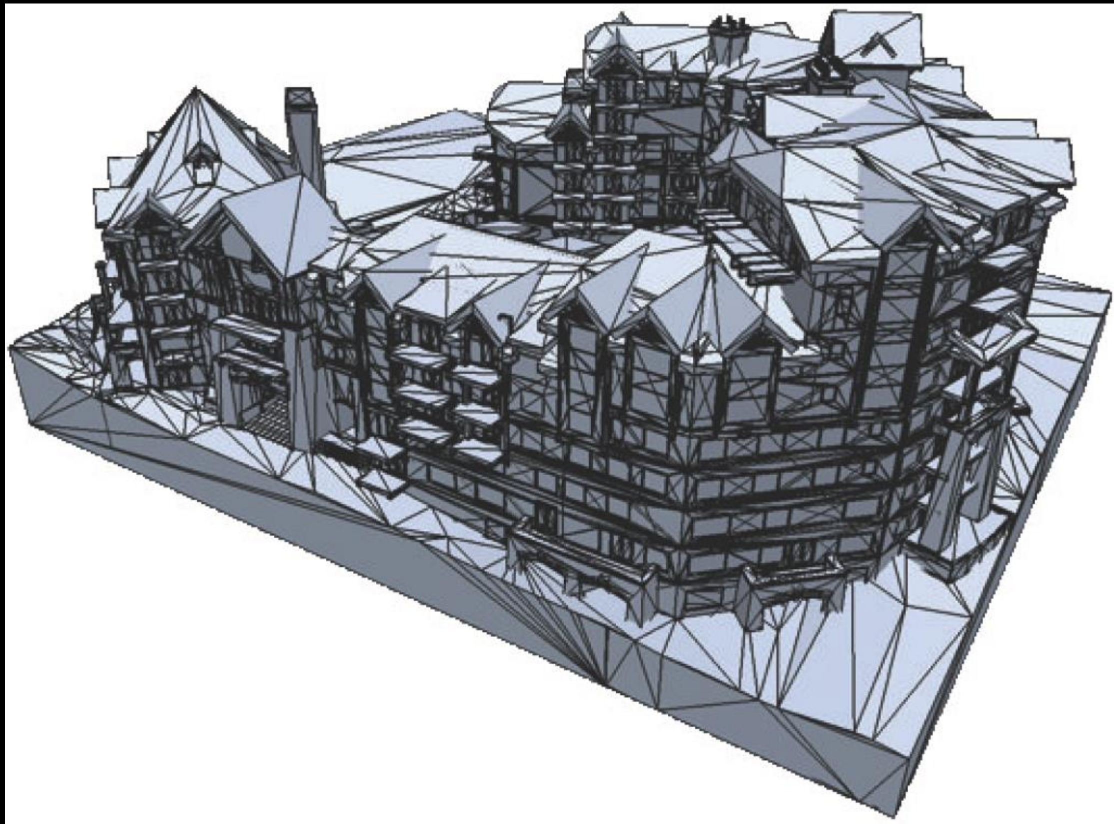
Fused range scans

- Manifold meshes with boundaries (i.e., gaps, holes, and islands).

- Either these artifacts are due to obstructions in the line of sight of the scanner
- Or they result from bad surface properties of the scanned model, such as transparency or glossiness.

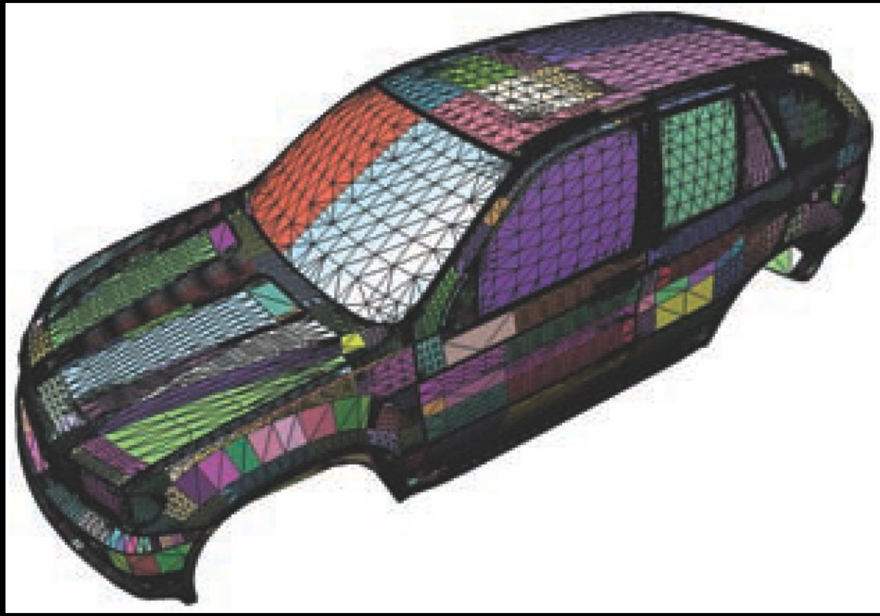
Triangle soups

- Mere sets of triangles with little or no connectivity information.
- They most often arise in CAD models
  - manually created in a boundary representation where users typically assemble predefined elements (taken from a library) without bothering about consistency constraints.
- Due to the manual layout, these models typically are made of only a few thousands triangles, but they may contain all kinds of artifacts.



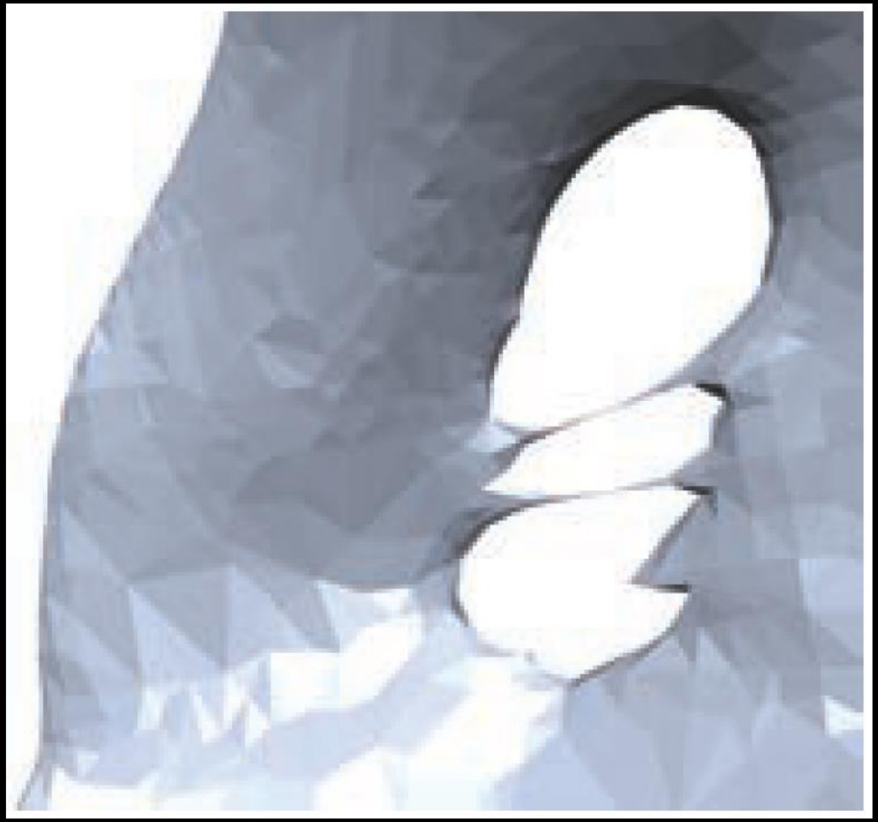
Triangulated NURBS patches

- A set of connected triangle mesh patches that contain gaps and small overlaps along the boundaries of the patches.
  - intersecting patches and inconsistent normal orientations.
- These artifacts arise when triangulating two or more trimmed NURBS patches that join at a common boundary curve.
- Usually, each patch is triangulated separately; thus the common boundary is sampled differently from each side.



Contoured meshes

- Meshes have been extracted from a volumetric dataset by Marching Cubes, Dual Contouring, or other polygon mesh extraction algorithms.
  - signed distance field
- These meshes often contain other topological artifacts, such as small spurious handles.
- Due to the finite resolution of the underlying grid, voxels are often classified incorrectly, leading to the so-called partial volume effect.

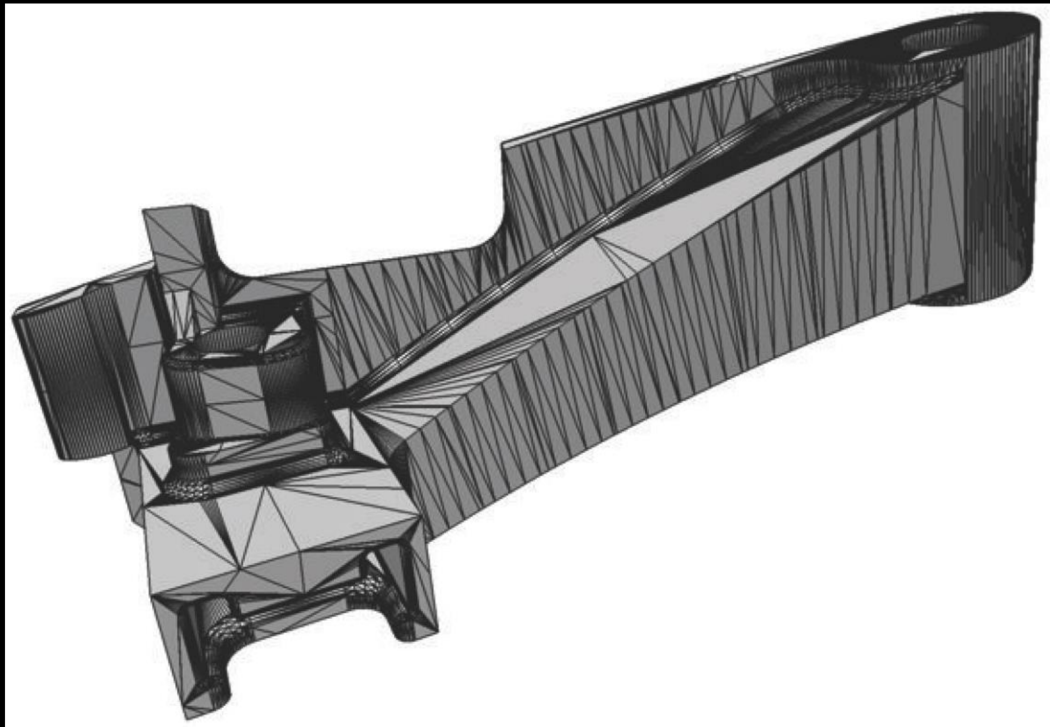


Badly meshed manifolds

- Degenerate elements such as triangles with zero area, caps (one inner angle close to π), needles (one edge length close to zero), and triangle flips (normal jump between adjacent faces close to π).

- From the tessellation of CAD models
- Output of Marching Cubes
  - in particular if they are enhanced by feature-preserving techniques

- The degenerate shapes of the elements prevent further processing and lead to instabilities in numerical simulations.



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Surface-oriented algorithms

- operate directly on the input data and try to explicitly identify and resolve artifacts on the surface.
- only minimally perturb the input model and are able to preserve the polygonal mesh structure in areas that are not in the direct vicinity of artifacts.
- Gaps could be removed by snapping boundary elements (vertices and edges) onto each other or by stitching triangle strips in between the gap.
- Holes can be closed by filling in a triangulated patch that is optimal with respect to some surface quality functional.
- Intersections could be located and resolved by explicitly splitting edges and triangles.

Surface-oriented algorithms (downside)

- To guarantee a valid output, surface-oriented repair algorithms usually require that the input model already satisfy certain quality requirements
  - Often enough these requirements cannot be guaranteed nor even be checked automatically, so these algorithms are rarely fully automatic but instead need user interaction and manual post-processing.
- Due to numerical inaccuracies, certain types of artifacts (like intersections or large overlaps) cannot be resolved robustly.
- Other artifacts, like gaps between two separate solids that are geometrically close to each other, cannot even be identified.

Consistent Normal Orientation

- Consistently orienting the normals of an input model is part of most surface-oriented repair algorithms
- Can even improve the performance of volumetric algorithms.

- Usually the orientation of the normals is propagated along a minimum spanning tree between neighboring patches.

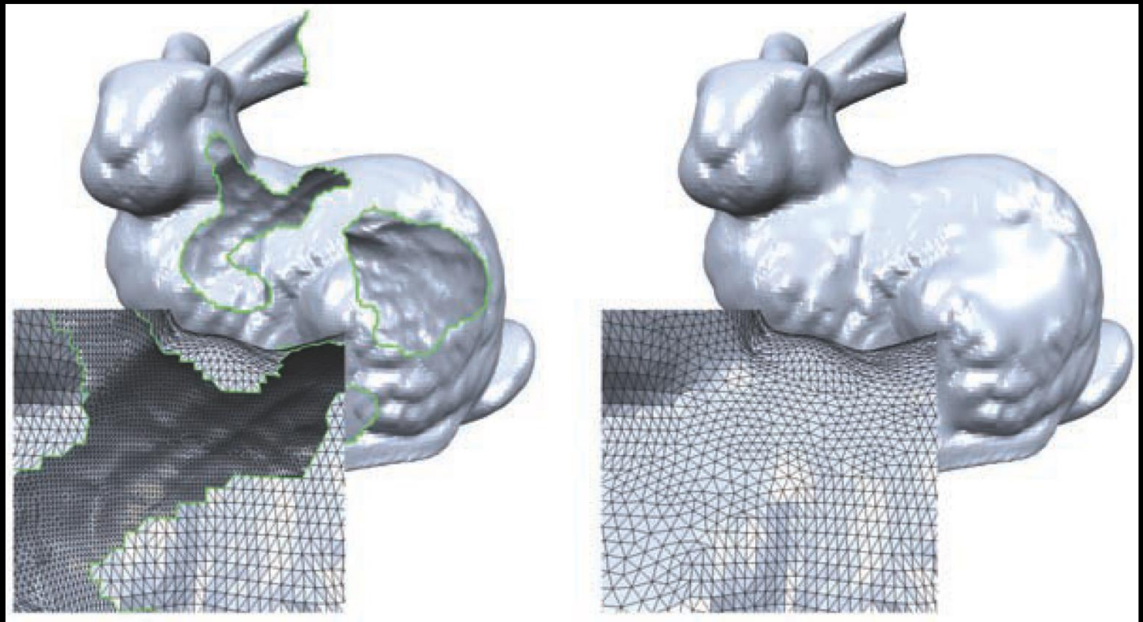
Surface-Based Hole Filling

- Describe an algorithm for computing a smooth triangulation of a hole.

- First, the holes are identified and filled by a coarse triangulation.
- These patches are then refined such that their vertex densities and average edge lengths match those of the mesh surrounding the holes.
- Finally, the patch is smoothed so as to blend with the geometry of the surrounding mesh.

Surface-Based Hole Filling

- This algorithm reliably fills holes in models with smooth patches.
- The density of the vertices matches that of the surrounding surface.
- does not check or avoid geometric self-intersections
- does not detect or incorporate islands into the filling patch



Conversion to Manifolds

- All complex edges and singular vertices are identified by counting the number of adjacent faces.
- The input is then cut along these complex edges into separate manifold patches.
- Finally, pairs of matching edges (i.e., edges that have geometrically the same endpoints) are identified and merged, if possible, in a topologically consistent manner.

- This, however, is done efficiently and robustly.

Gap Closing

- Typical for triangulated NURBS models.

- For each pair of boundary edges, the area between the two edges normalized by the edge lengths is computed.
- This score measures the geometric error that would be introduced by merging the two edges.
- Pairs of boundary edges are then iteratively merged in order of increasing score.

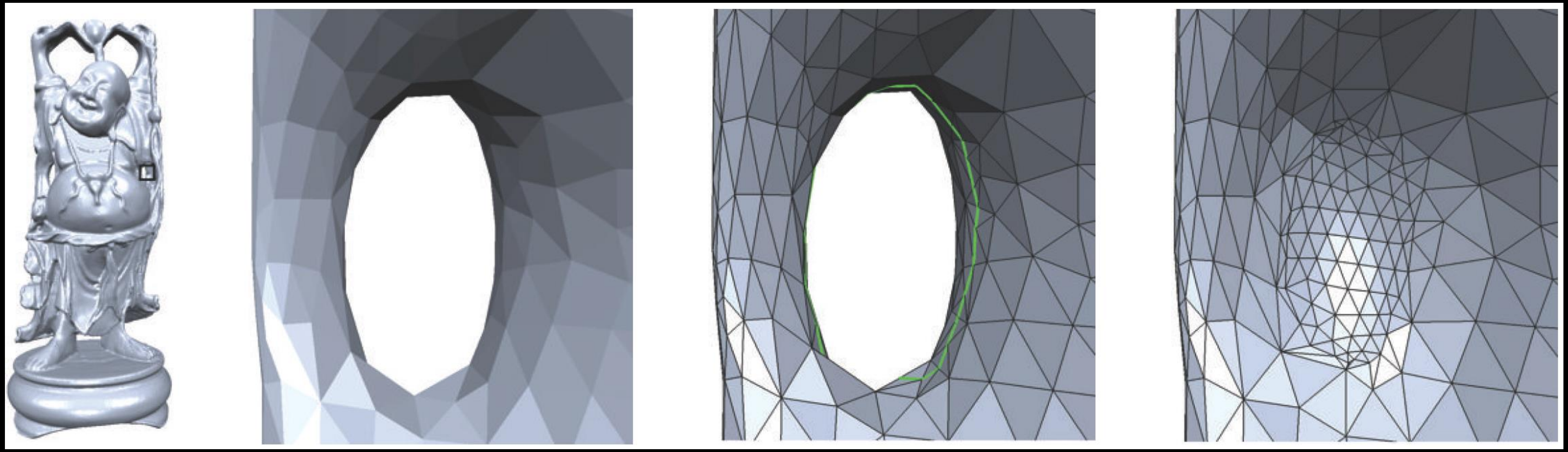
Gap Closing

- Usually easy to implement
- If the input data is well behaved and the user parameters are chosen in accordance with the error that was accepted during triangulation, they manage to produce satisfying results.

- However, there are no guarantees on the quality of the output.
- Allows the user to override the decisions towards the expected result.

Topology Simplification

- Detects and resolves all handles up to a given size ε in a manifold triangle mesh.
- Handles are removed by cutting the input along a non-separating closed path and sealing the two resulting holes by triangle patches



Topology Simplification

- Detection
  - Dijkstra's algorithm on the dual graph from a seed triangle
  - When two different loops touch along a common, a handle is detected
  - To detect all handles of the input mesh, one has to perform the region growing for every triangle.
  - Downside
    - cannot guarantee that no geometric self-intersections are created after a handle is removed.

Volumetric algorithms

- Convert the input model into an intermediate volumetric representation from which the output model is then extracted.
  - fully automatic and produce guaranteed watertight models
- A volumetric representation can be any kind of partitioning of the embedding space into cells such that each cell can be classified as being inside, outside, or intersected by the surface.
- Volumetric representations: regular Cartesian grids, adaptive octrees, kd-trees, BSP-trees, and Delaunay triangulations.
- Do not allow for artifacts like intersections, holes, gaps, overlaps, or inconsistent normal orientations.
- Often also guarantee the absence of complex edges and singular vertices
- Spurious handles, however, might still be present.

Volumetric algorithms (downside)

- The conversion to and from a volume leads to a resampling of the model
  - Introduces aliasing artifacts and loss of model features
  - destroys any structure that might have been present in the connectivity of the input model.
- The number of triangles in the output of a volumetric algorithm is usually much higher than that of the input model
  - thus has to be decimated in a post-processing step.
- The quality of the output triangles often degrades and has to be improved afterwards.
- Volumetric representations are quite memory-intensive so it is hard to run them at very high resolutions.

Volumetric Repair on Adaptive Grids

- The algorithm first creates an adaptive octree representation of the input model where each cell stores the triangles intersecting with it.
  - Cells that are not yet on maximum depth are recursively split if they either contain a boundary edge or if the triangles within the cell deviate too much from a common regression plane.
  - From these triangles a feature-sensitive sample point can be computed for each cell.
- Then, a sequence of morphological operations is applied to the octree to determine the topology of the model.
- Finally, the connectivity and geometry of the reconstruction are derived from the octree structure and samples, respectively.
  - A Dual Contouring

Volumetric Repair on Adaptive Grids

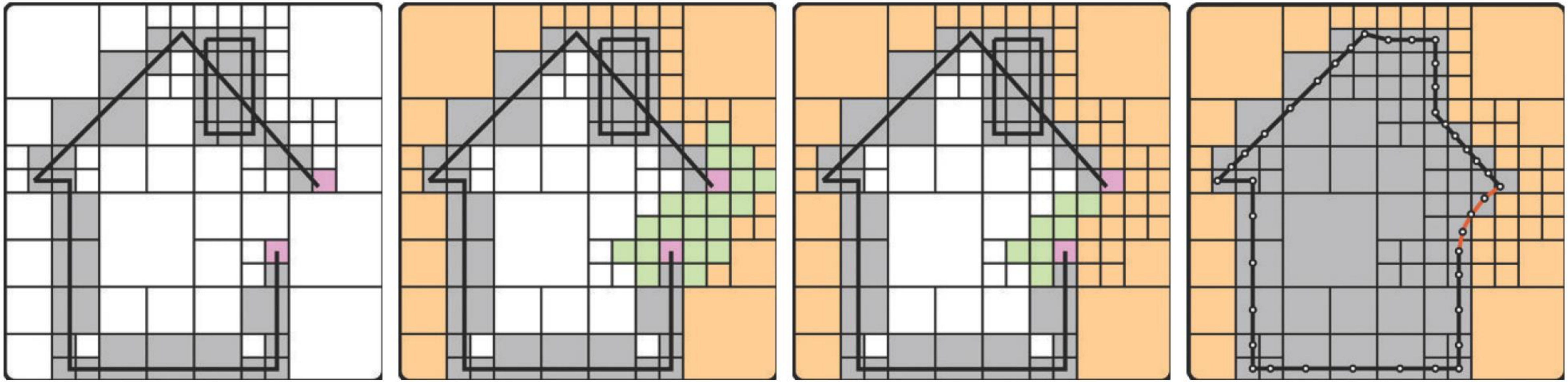


Figure 8.7. From left to right: Adaptive octree (boundary cells are marked red). Dilated boundary (green) and outside component (orange). Outside component dilated back into the boundary cells. Final reconstruction. (Image taken from [Botsch et al. 06b]. ©2006 ACM, Inc. Included here by permission.)