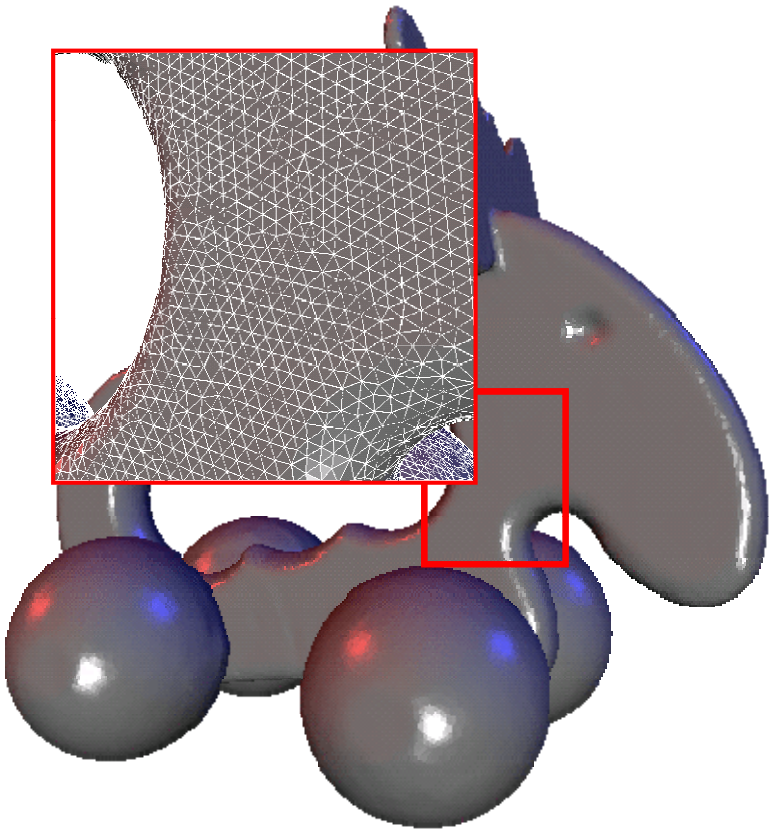
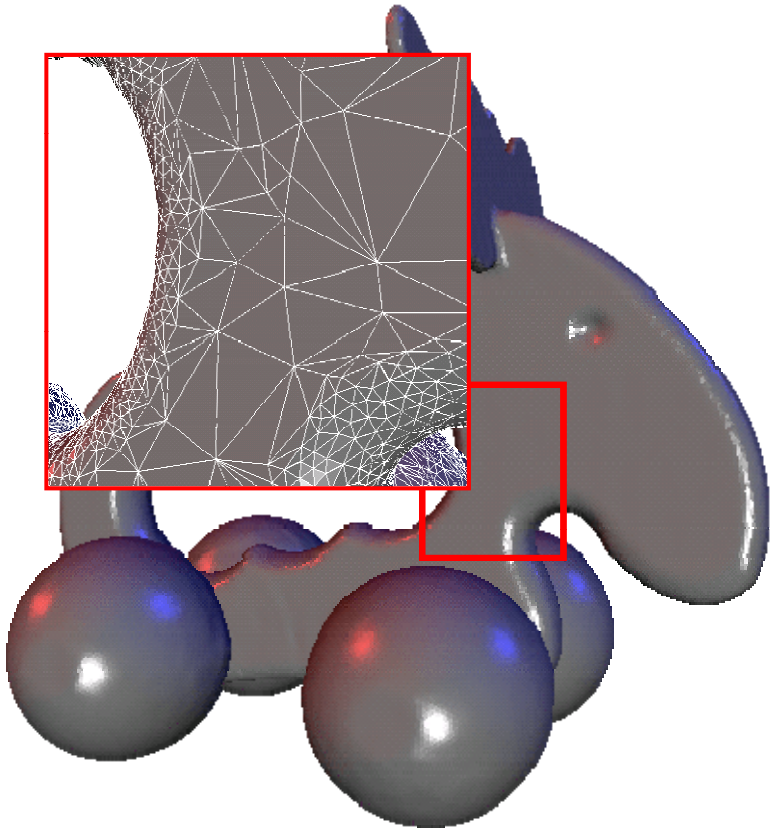
Mesh Simplification

Applications

- Oversampled 3D scan data



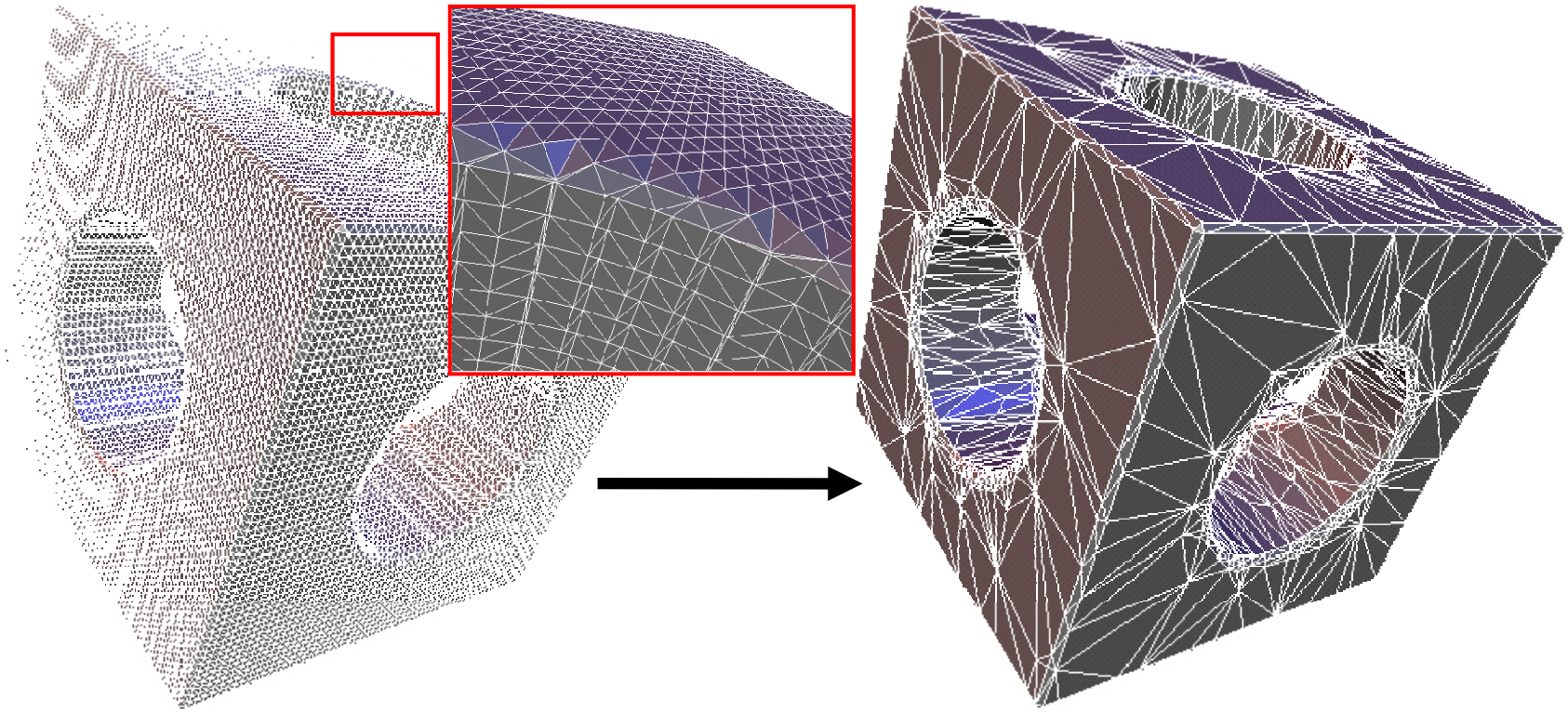
~150k triangles



~80k triangles

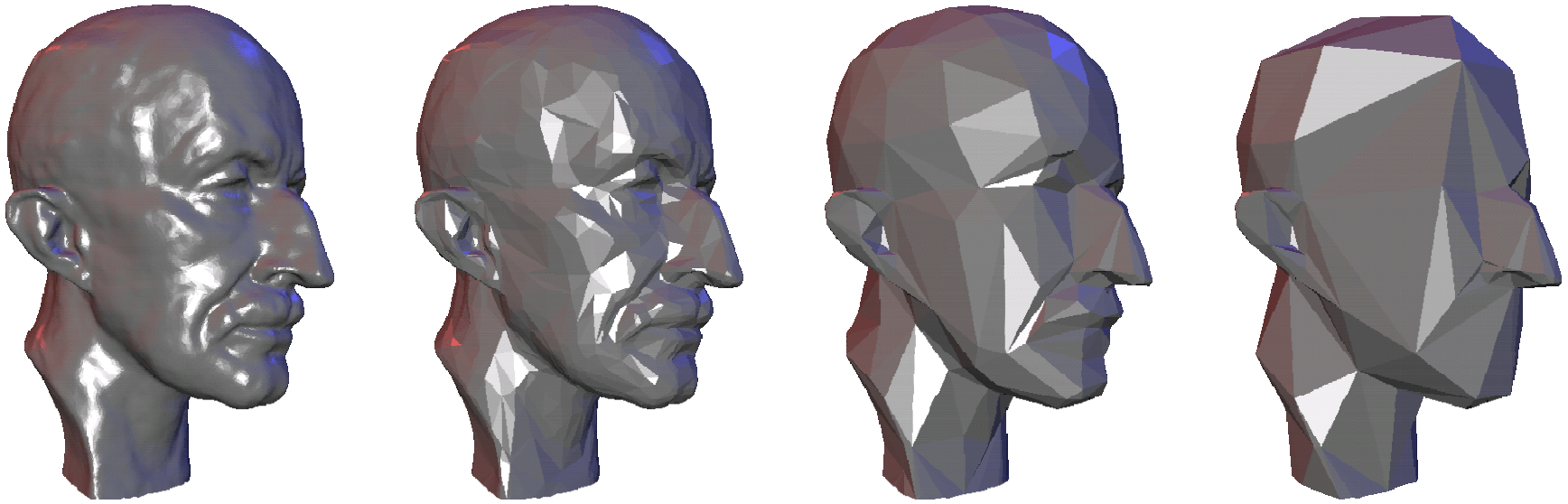
Applications

- Overtessellation: E.g. iso-surface extraction



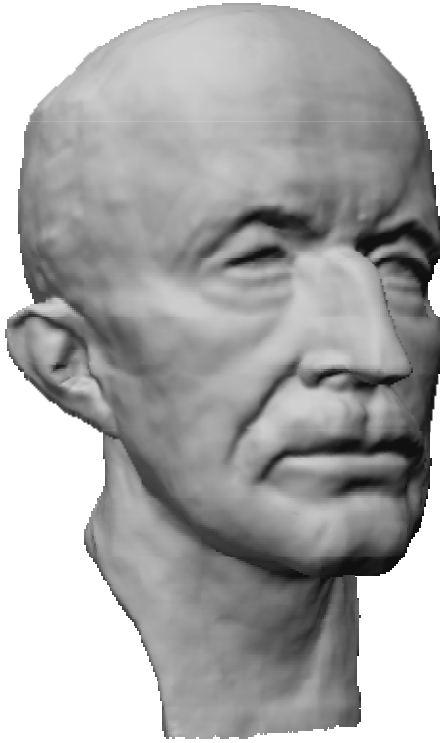
Applications

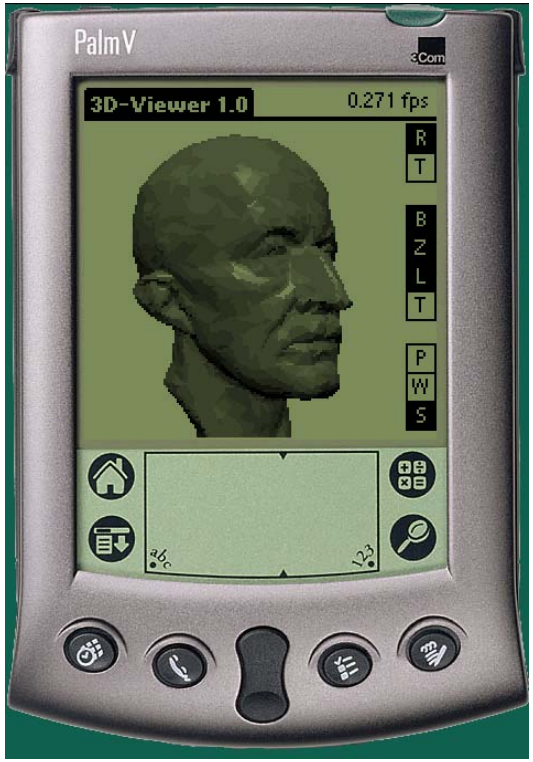
- Multi-resolution hierarchies for
  - efficient geometry processing
  - level-of-detail (LOD) rendering



Applications

- Adaptation to hardware capabilities

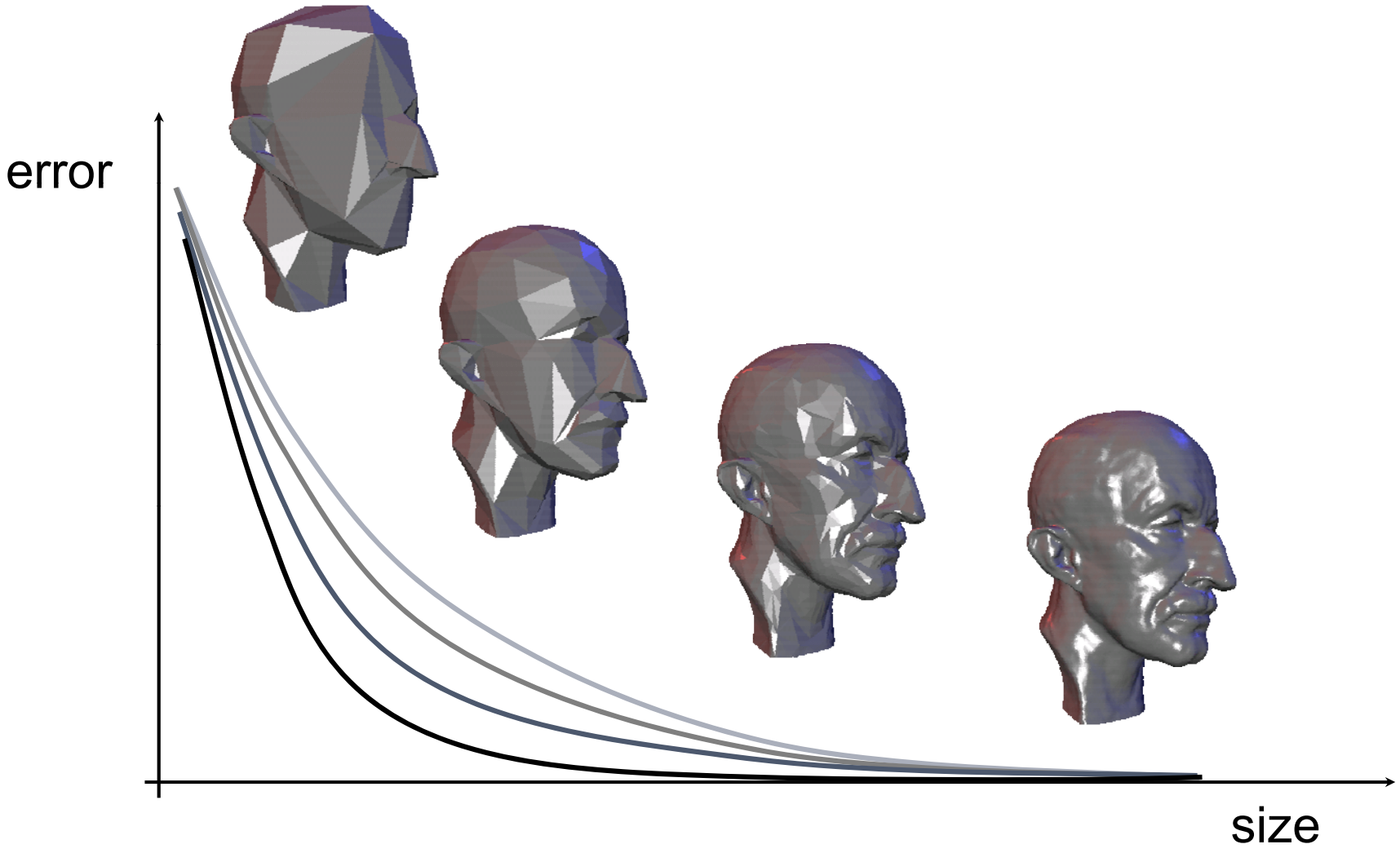




1999

2012

Size-Quality Tradeoff

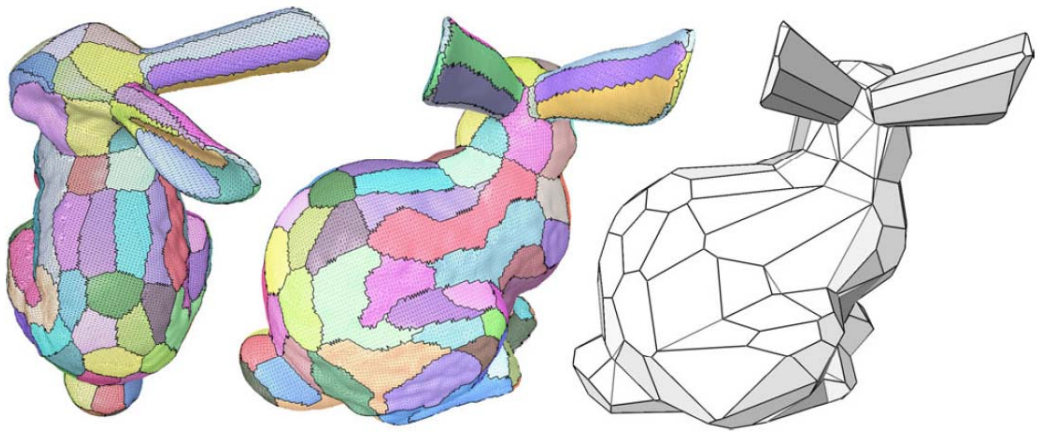


Problem Statement

- Given: $\mathcal{M} = (\mathcal{V}, \mathcal{F})$
- Find: $\mathcal{M}' = (\mathcal{V}', \mathcal{F}')$ such that
  1. $|\mathcal{V}'| = n < |\mathcal{V}|$ and $\|\mathcal{M} - \mathcal{M}'\|$ is minimal, or
  2. $\|\mathcal{M} - \mathcal{M}'\| < \epsilon$ and $|\mathcal{V}'|$ is minimal
- Respect additional fairness criteria
  – normal deviation, triangle shape, scalar attributes, etc.

Mesh Decimation Methods

- **Vertex clustering**
- **Incremental decimation**
- Resampling
- Mesh approximation

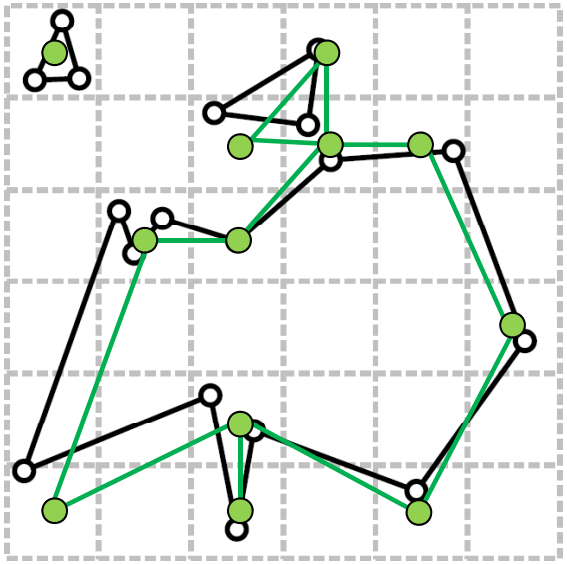


Vertex Clustering

- Cluster Generation
- Computing a representative
- Mesh generation
- Topology changes

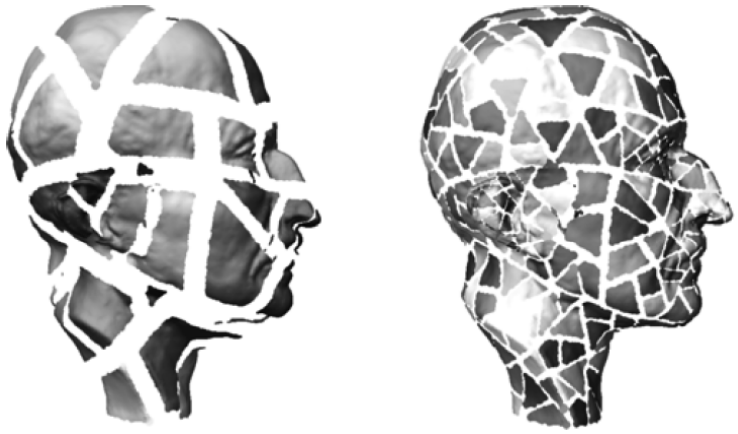
Vertex Clustering

- Cluster Generation
  - Uniform 3D grid
  - Map vertices to cluster cells
- Computing a representative
- Mesh generation
- Topology changes



Vertex Clustering

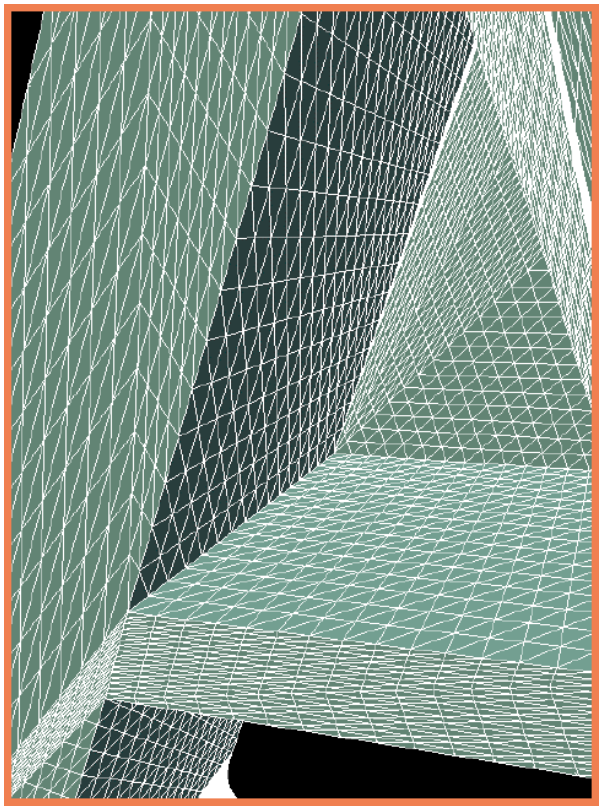
- Cluster Generation
  - Hierarchical approach
  - Top-down or bottom-up
- Computing a representative
- Mesh generation
- Topology changes

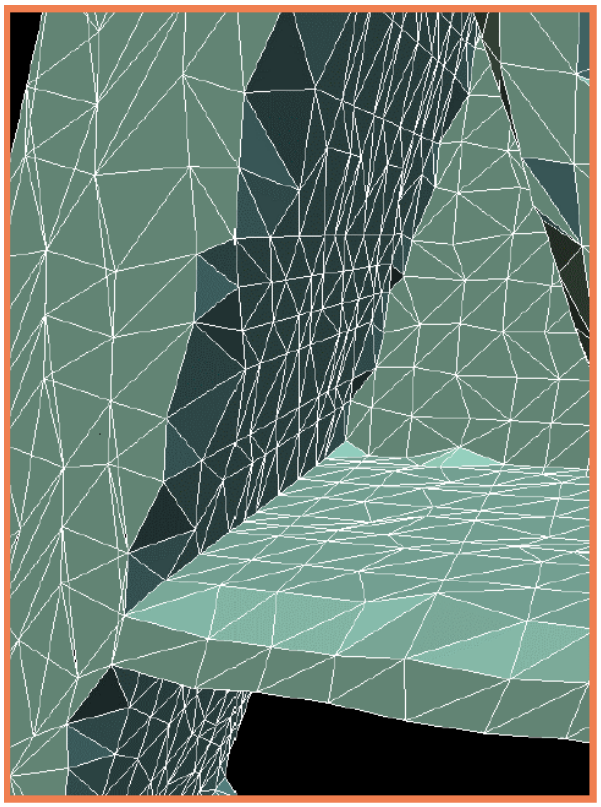


Vertex Clustering

- Cluster Generation
- Computing a representative
  - Average/median vertex position
  - Error quadrics
- Mesh generation
- Topology changes

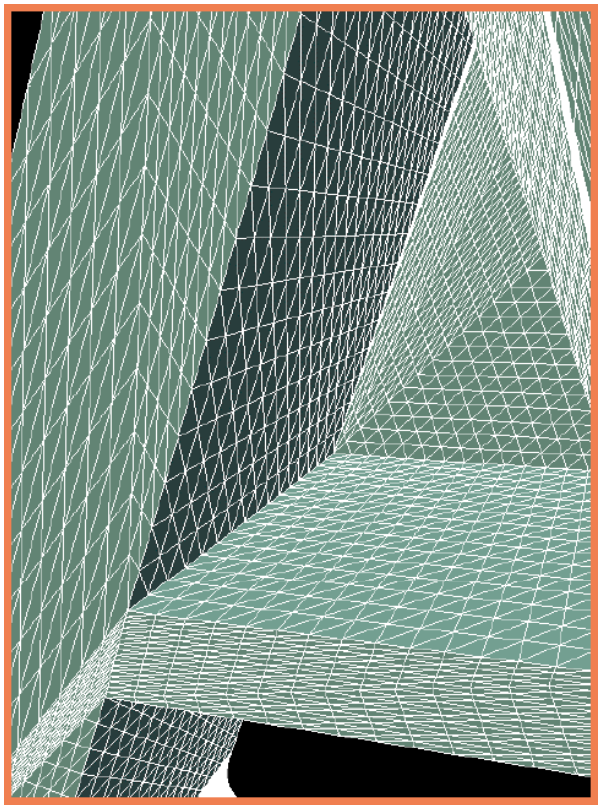
Computing a Representative

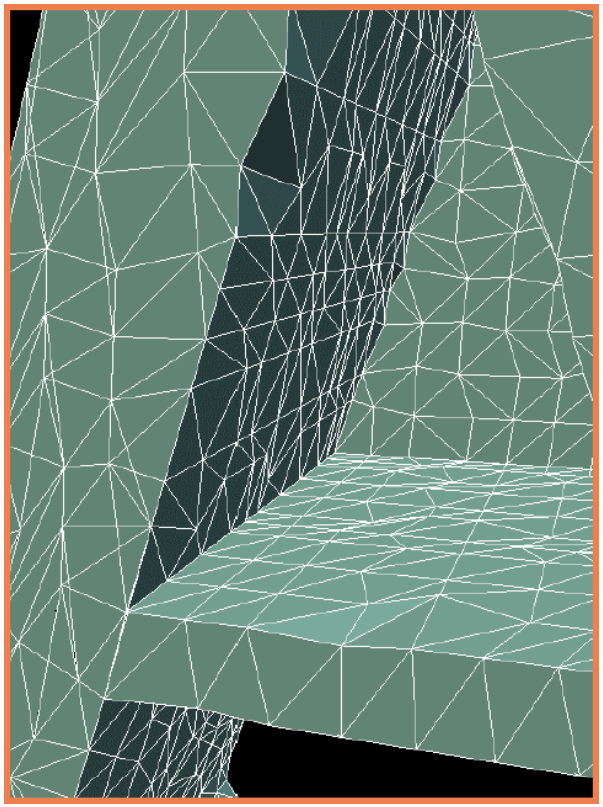




Average vertex position

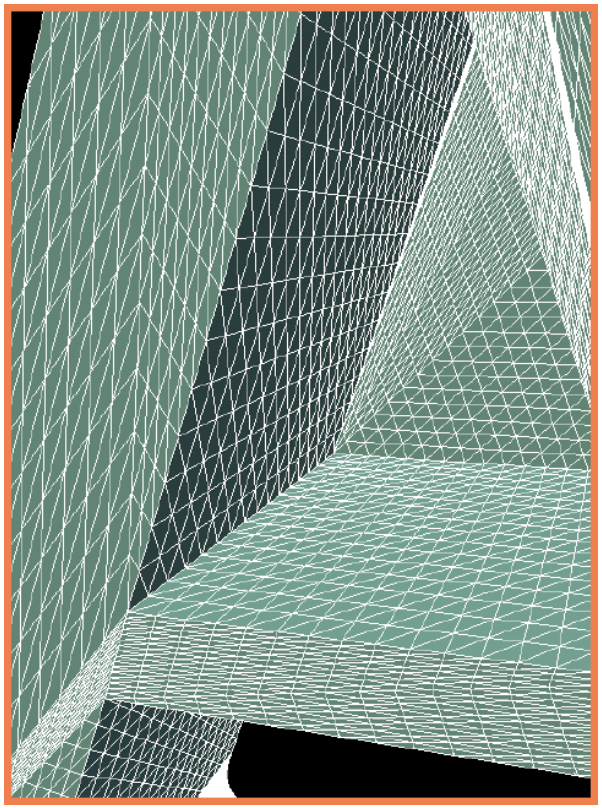
Computing a Representative

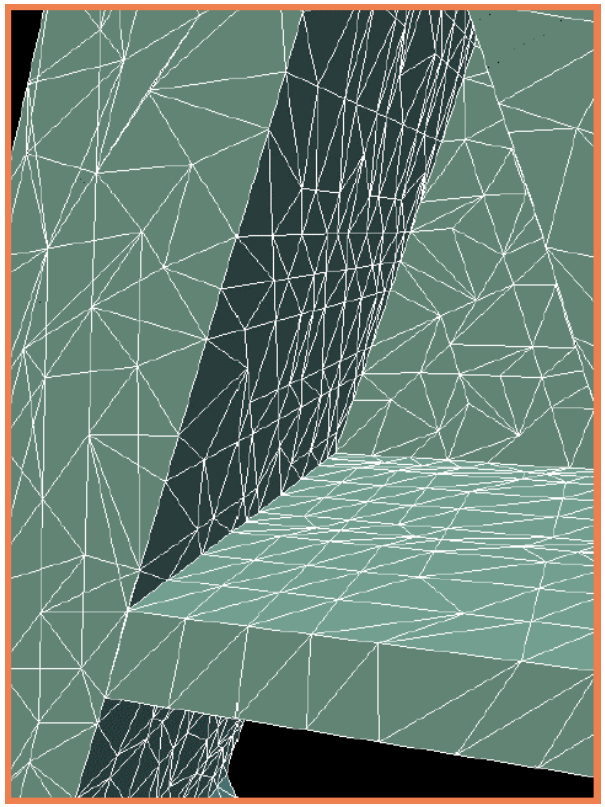




Median vertex position

Computing a Representative

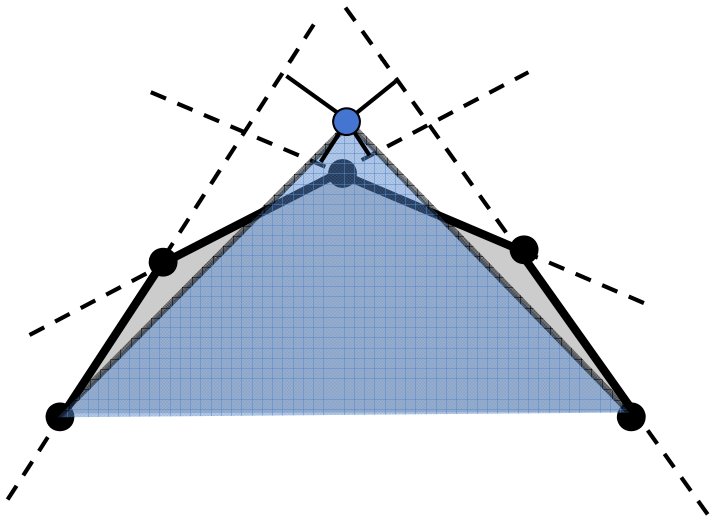




Error quadrics

Error Quadrics

- Patch is expected to be piecewise flat
- Minimize distance to neighboring triangles' planes



Error Quadrics

- Squared distance of point *p* to plane *q*:

$$p = (x, y, z, 1)^T, \quad q = (a, b, c, d)^T$$

$$dist(q, p)^2 = (q^T p)^2 = p^T (q q^T) p =: p^T Q_q p$$

$$Q_q = \begin{bmatrix} a^2 & ab & ac & ad \\ ab & b^2 & bc & bd \\ ac & bc & c^2 & cd \\ ad & bd & cd & d^2 \end{bmatrix}$$

Error Quadrics

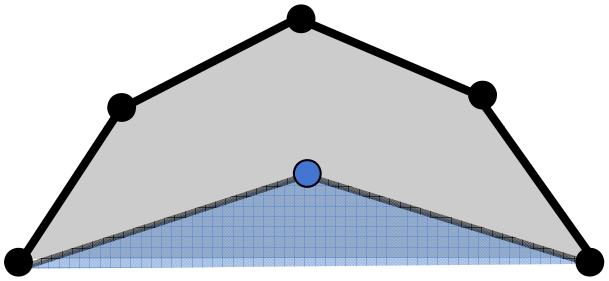
- Sum distances to planes q_i of vertex' neighboring triangles:

$$\sum_i dist(q_i, p)^2 = \sum_i p^T Q_{q_i} p = p^T \left(\sum_i Q_{q_i} \right) p =: p^T Q_p p$$

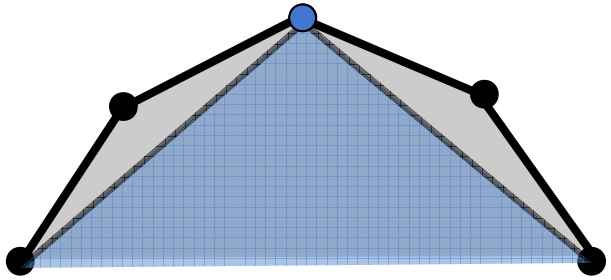
- Point p^* that minimizes the error satisfies:

$$\begin{bmatrix} q_{11} & q_{12} & q_{13} & q_{14} \\ q_{21} & q_{22} & q_{23} & q_{24} \\ q_{31} & q_{32} & q_{33} & q_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} p^* = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

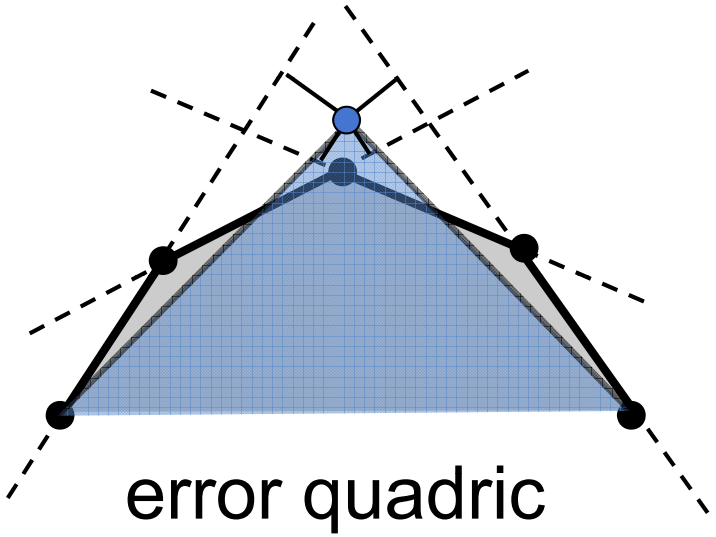
Comparison



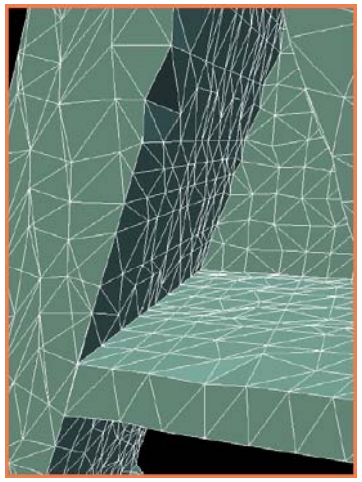
average

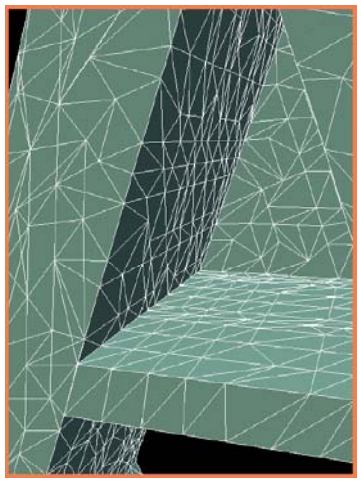


median



error quadric





Vertex Clustering

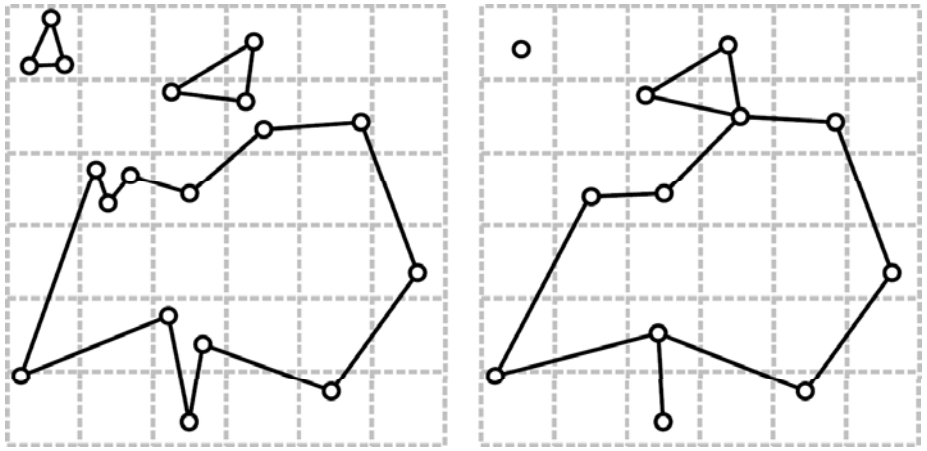
- Cluster Generation
- Computing a representative
- Mesh generation
  - Clusters $p \leftrightarrow \{p_0,\ldots,p_n\}$, $q \leftrightarrow \{q_0,\ldots,q_m\}$
- Topology changes

Vertex Clustering

- Cluster Generation
- Computing a representative
- Mesh generation
  - Clusters $p \leftrightarrow \{p_0,\ldots,p_n\}$, $q \leftrightarrow \{q_0,\ldots,q_m\}$
  - Connect (p,q) if there was an edge (p_i,q_j)
- Topology changes

Vertex Clustering

- Cluster Generation
- Computing a representative
- Mesh generation
- Topology changes
  - If different sheets pass through one cell
  - Can be non-manifold



Outline

- Applications
- Problem Statement
- Mesh Decimation Methods
  - Vertex Clustering
  - **Incremental Decimation**
  - Extensions

Incremental Decimation

500K

50K

5K

0.5K

Incremental Decimation

- General Setup
- Decimation operators
- Error metrics
- Fairness criteria
- Topology changes

General Setup

- Repeat:
- pick mesh region
- apply decimation operator
- Until no further reduction possible

Greedy Optimization

- For each region
- evaluate quality after decimation
- enqeue(quality, region)

- Repeat:
- get best mesh region from queue
- apply decimation operator
- update queue
- Until no further reduction possible

Global Error Control

- For each region
- evaluate quality after decimation
- enqeue(quality, region)

- Repeat:
- get best mesh region from queue
- if error < ε
- apply decimation operator
- update queue
- Until no further reduction possible

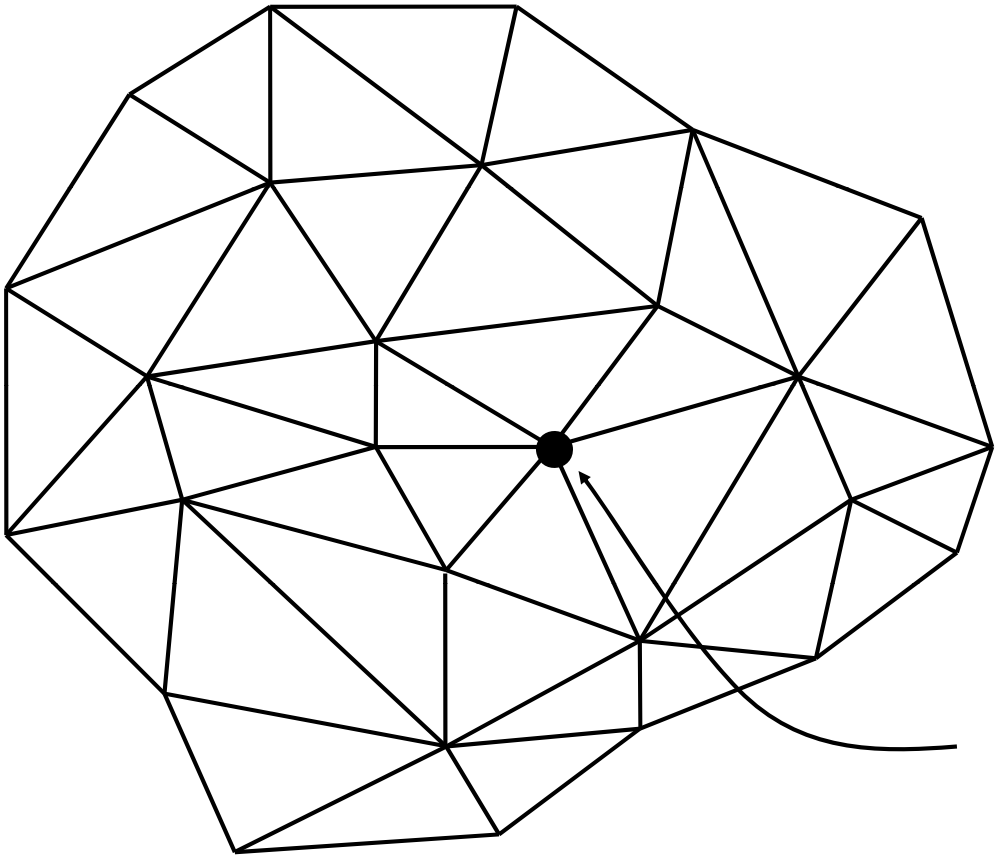
Incremental Decimation

- General Setup
- Decimation operators
- Error metrics
- Fairness criteria
- Topology changes

Decimation Operators

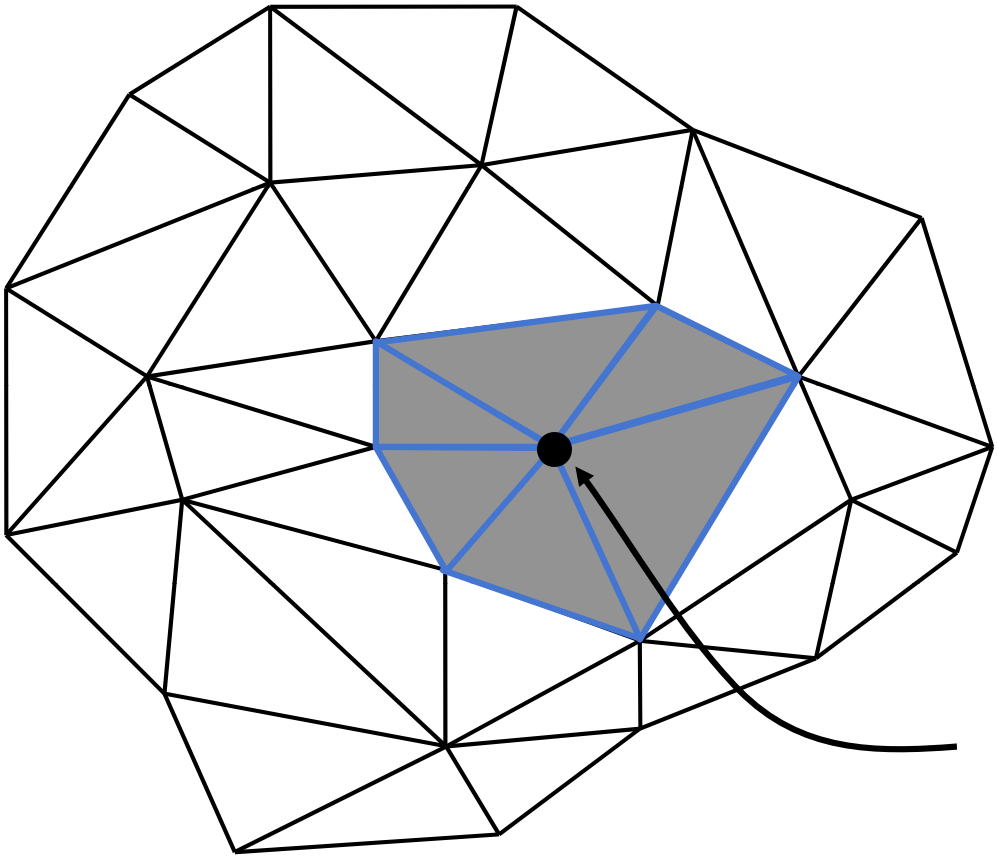
- What is a "region" ?
- What are the DOF for re-triangulation?
- Classification
  - Topology-changing vs. topology-preserving
  - Subsampling vs. filtering
  - Inverse operation → progressive meshes

Vertex Removal



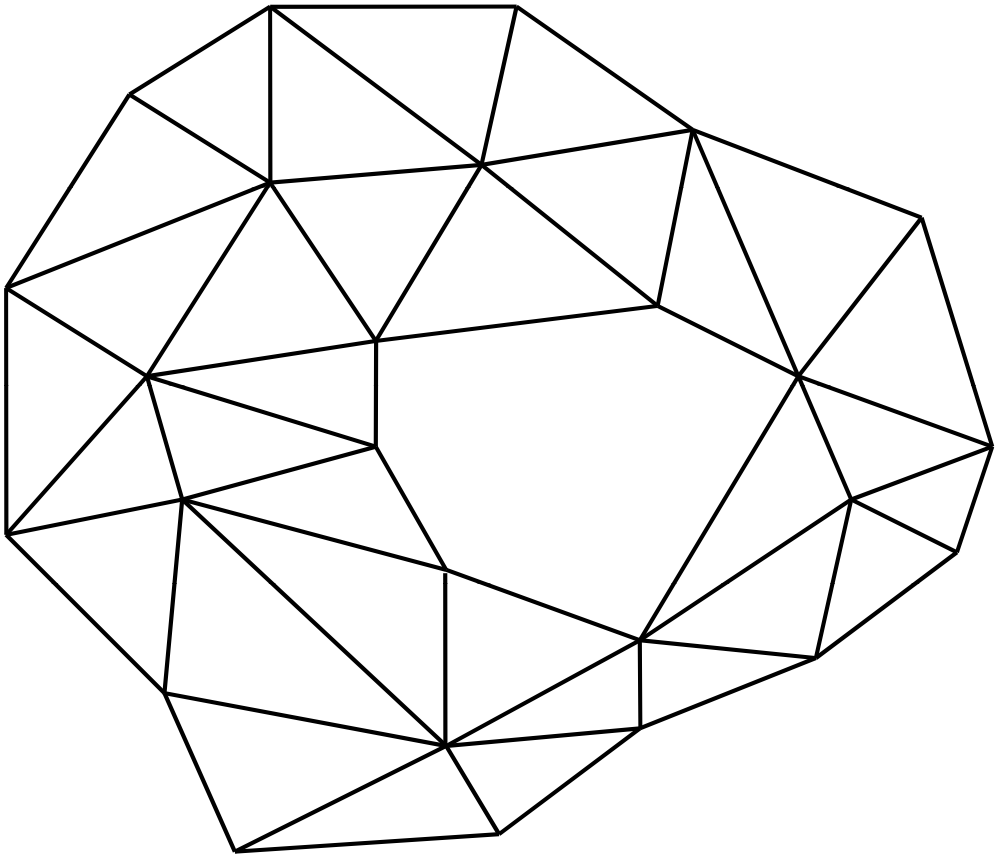
Select a vertex to be eliminated

Vertex Removal



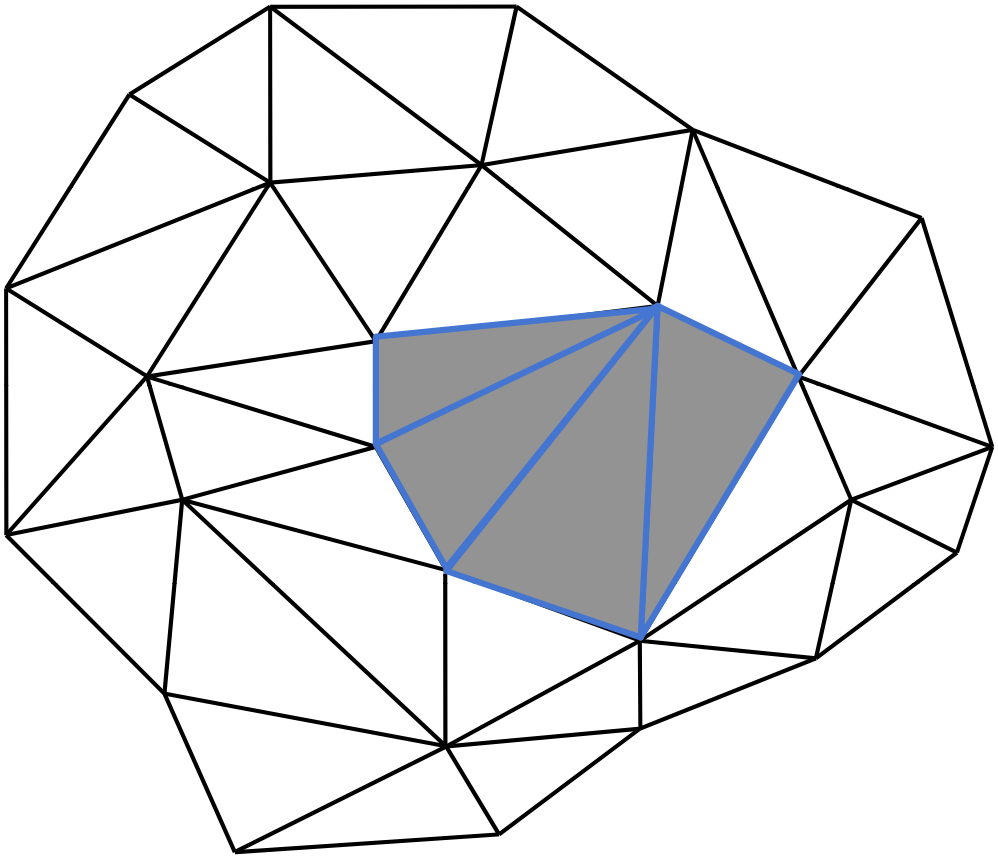
Select all triangles
sharing this vertex

Vertex Removal



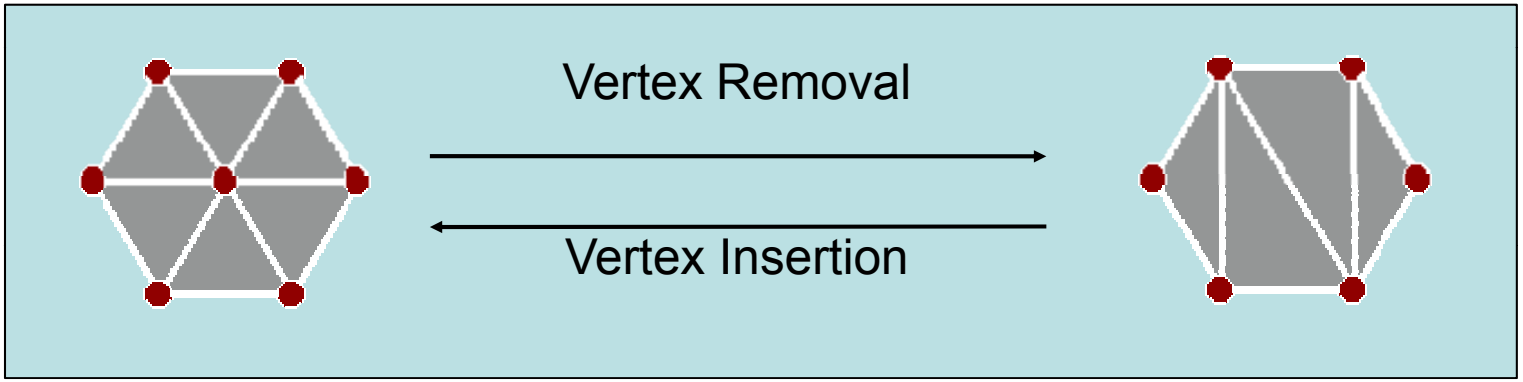
Remove the selected triangles, creating the hole

Vertex Removal



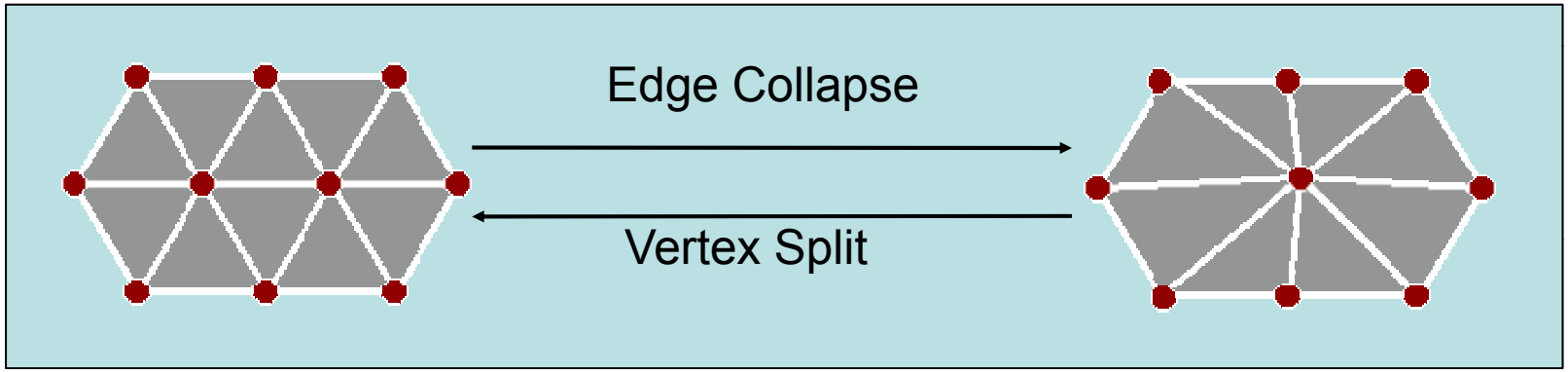
Fill the hole with
new triangles

Decimation Operators



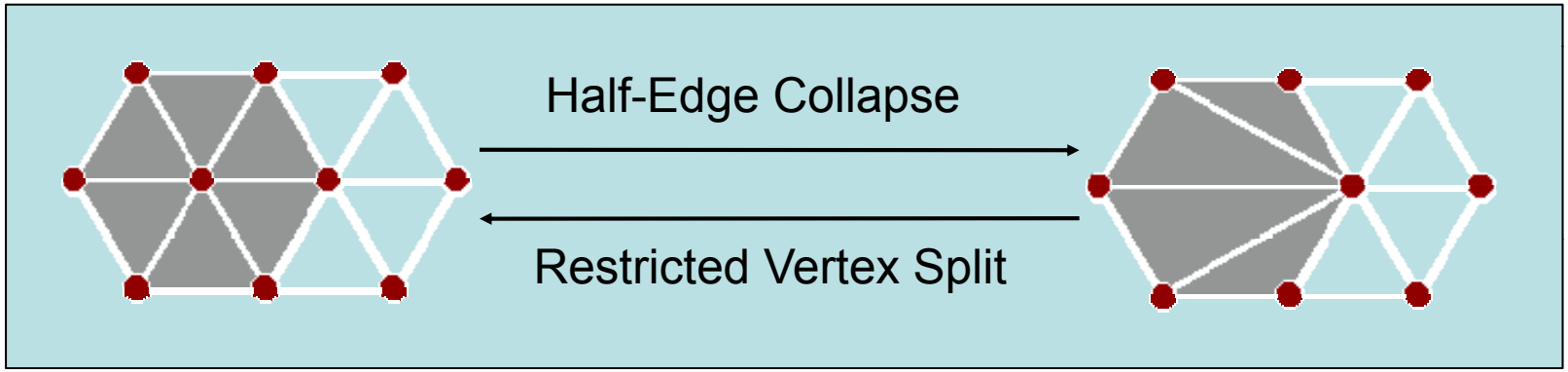
- Remove vertex
- Re-triangulate hole
  - Combinatorial degrees of freedom

Decimation Operators



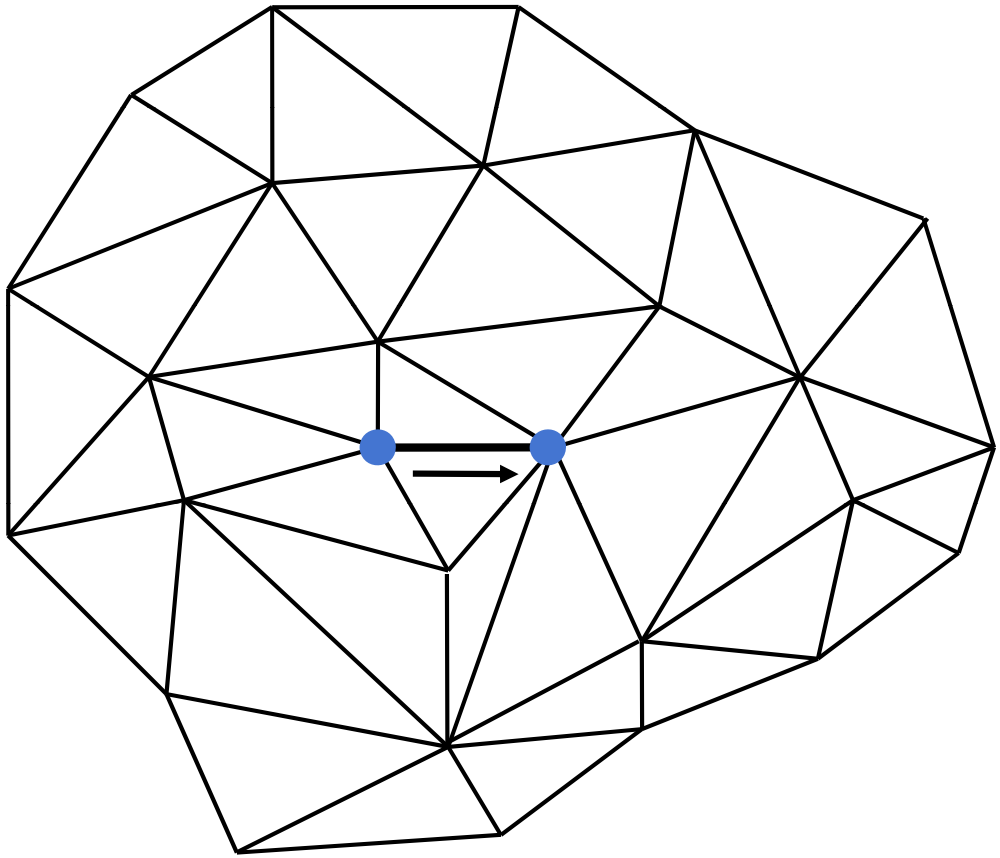
- Merge two adjacent vertices
- Define new vertex position
  - Continuous degrees of freedom
  - Filter along the way

Decimation Operators

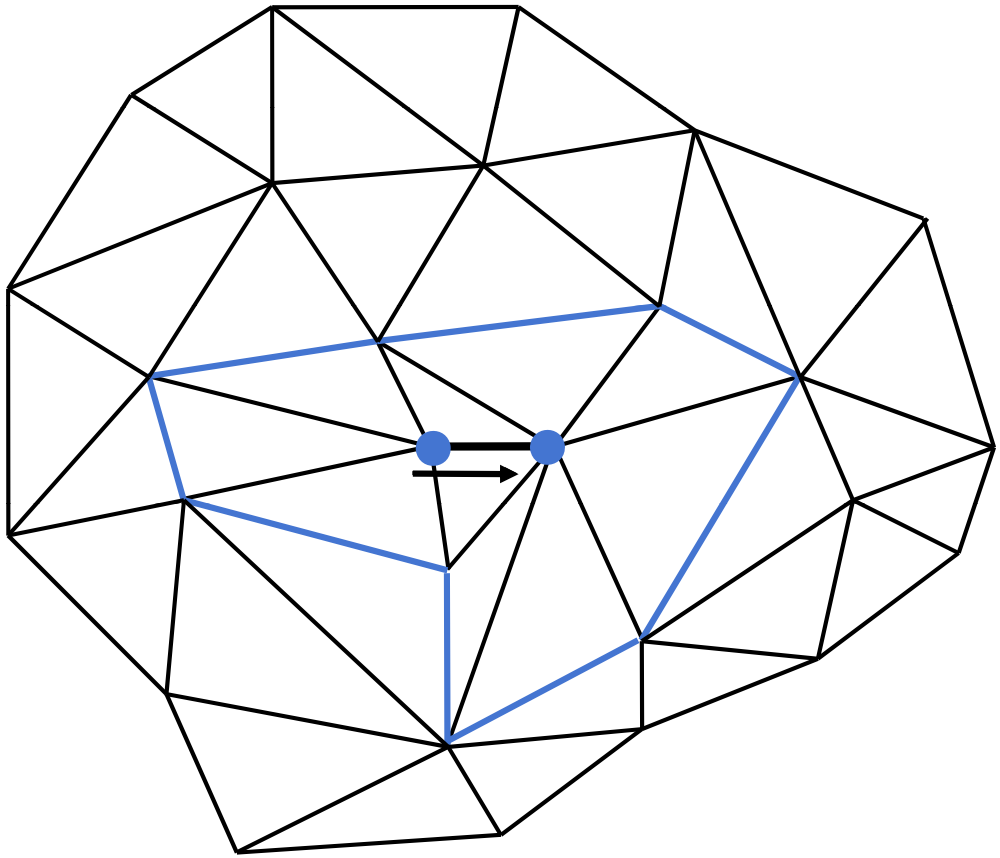


- Collapse edge into one end point
  - Special case of vertex removal
  - Special case of edge collapse
- No degrees of freedom
- Separates global optimization from local optimization

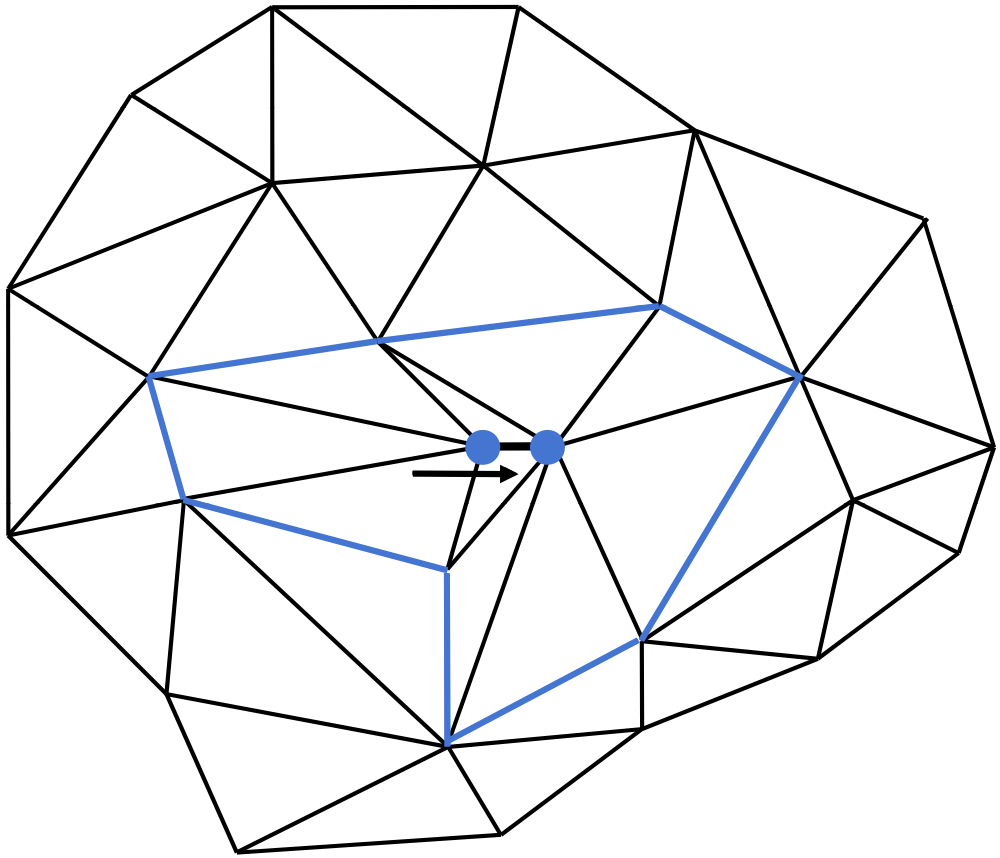
Half-Edge Collapse



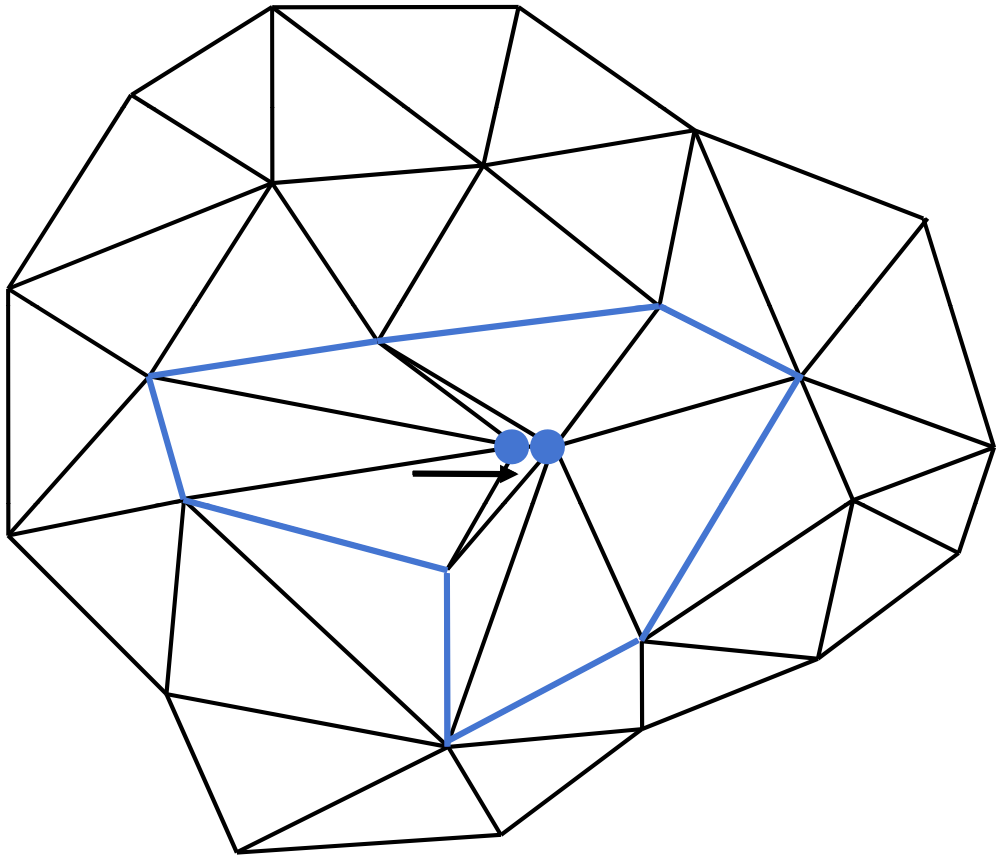
Half-Edge Collapse



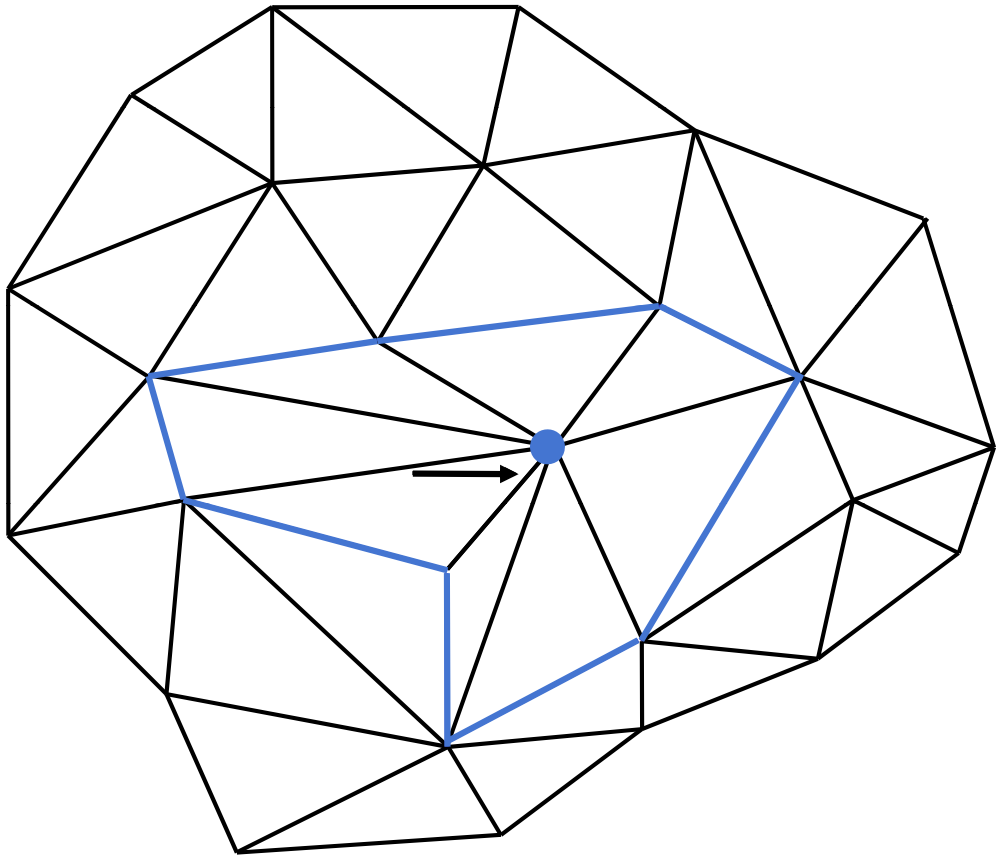
Half-Edge Collapse



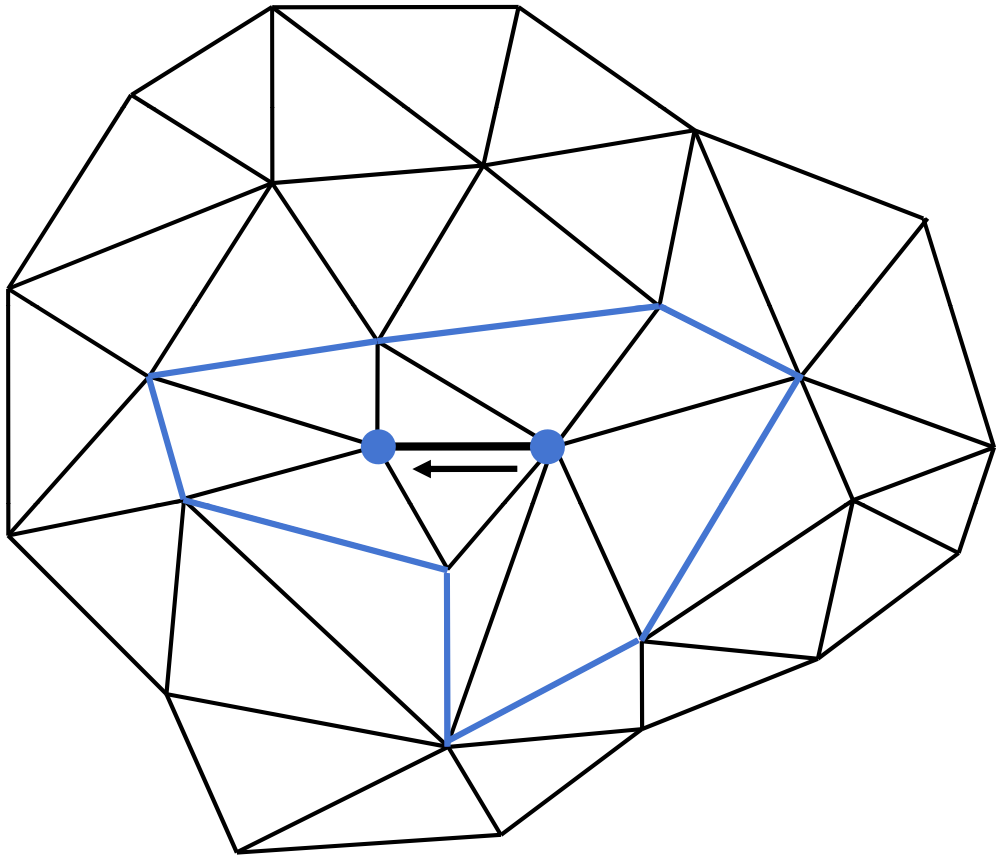
Half-Edge Collapse



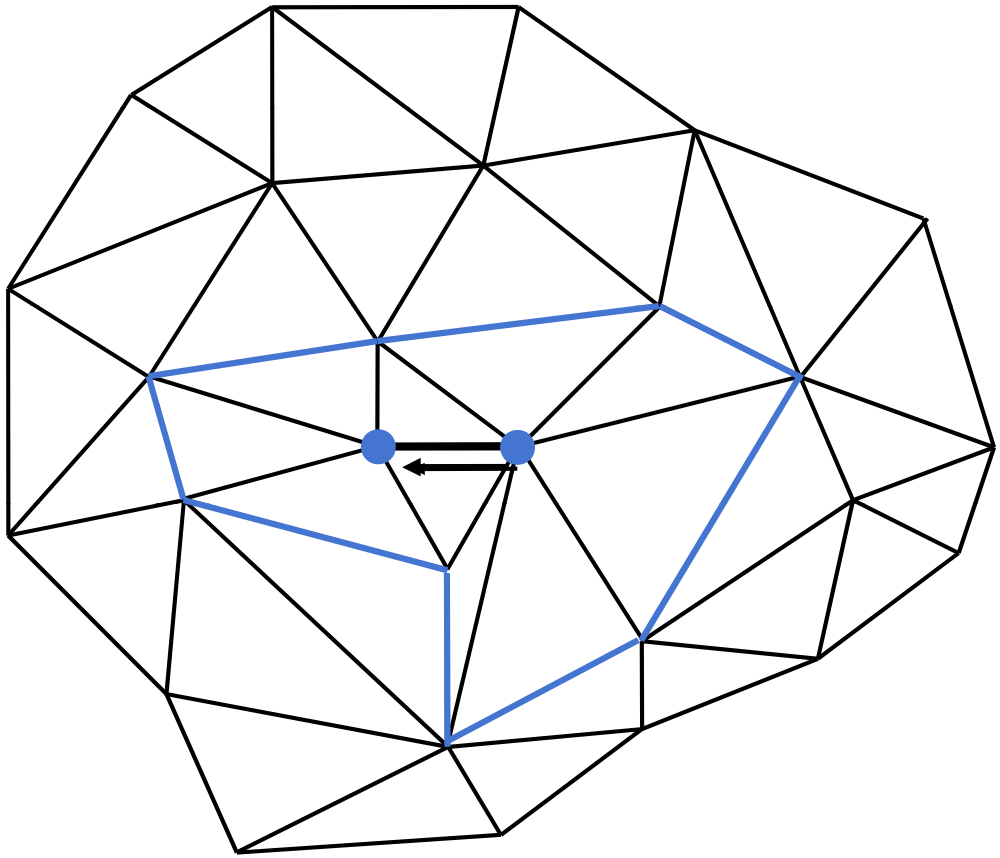
Half-Edge Collapse



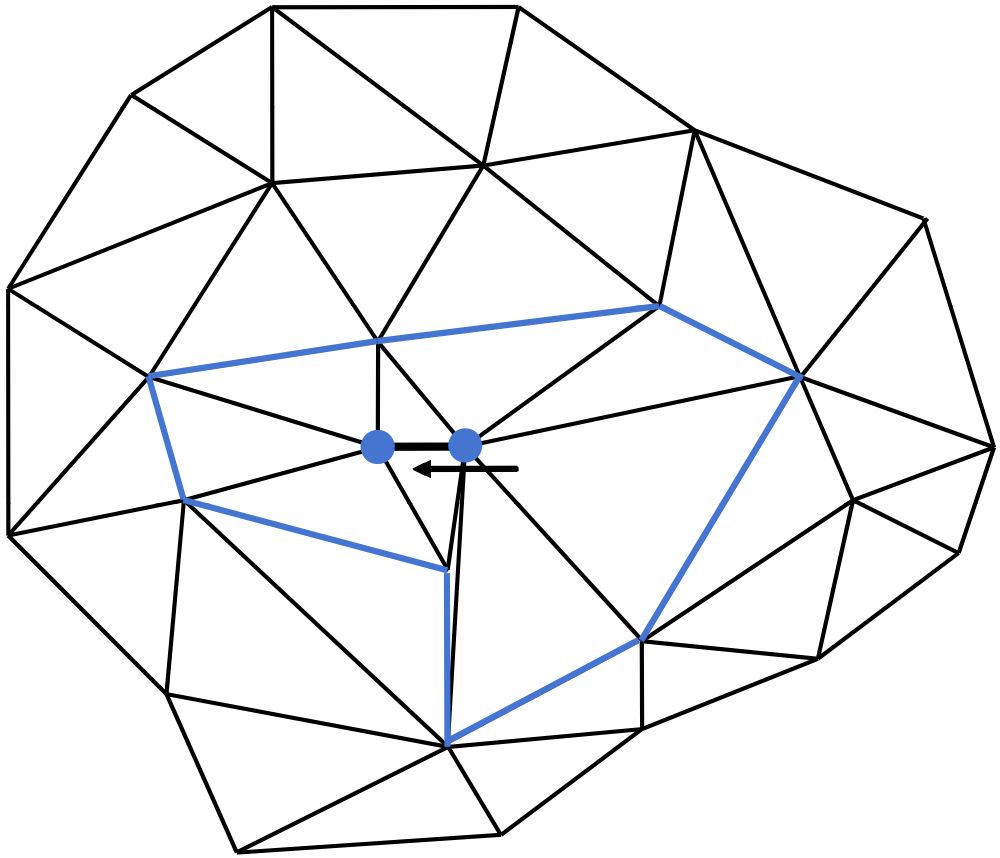
Half-Edge Collapse



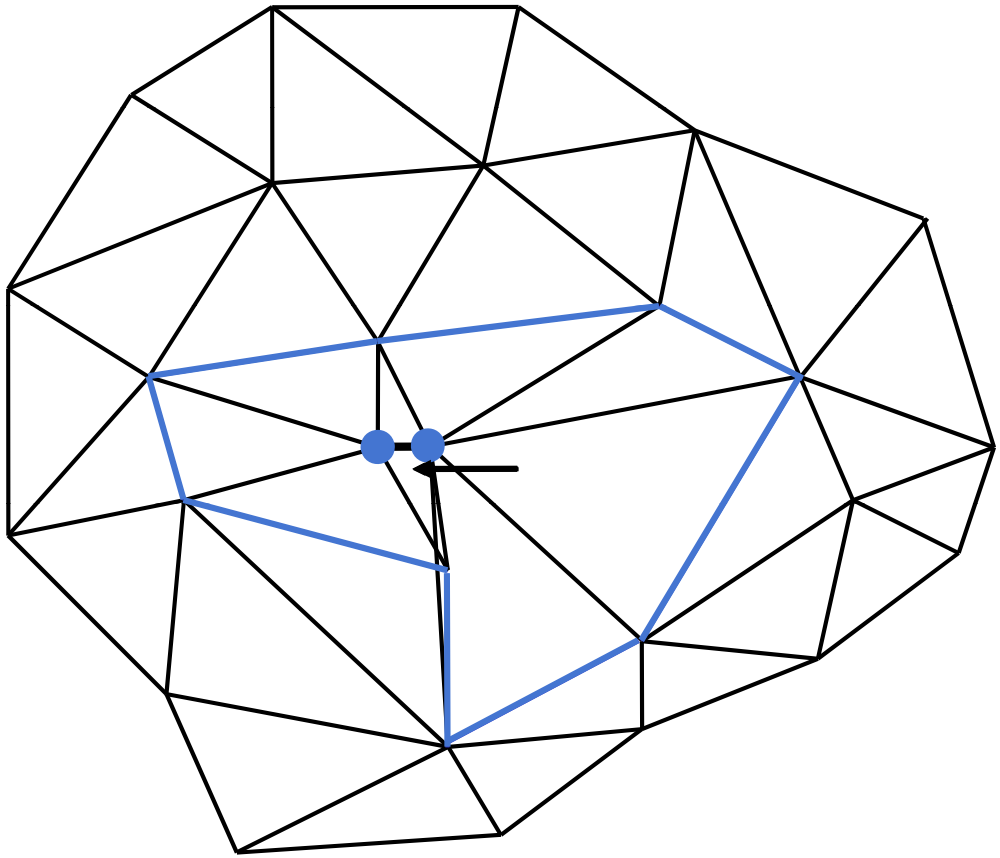
Half-Edge Collapse



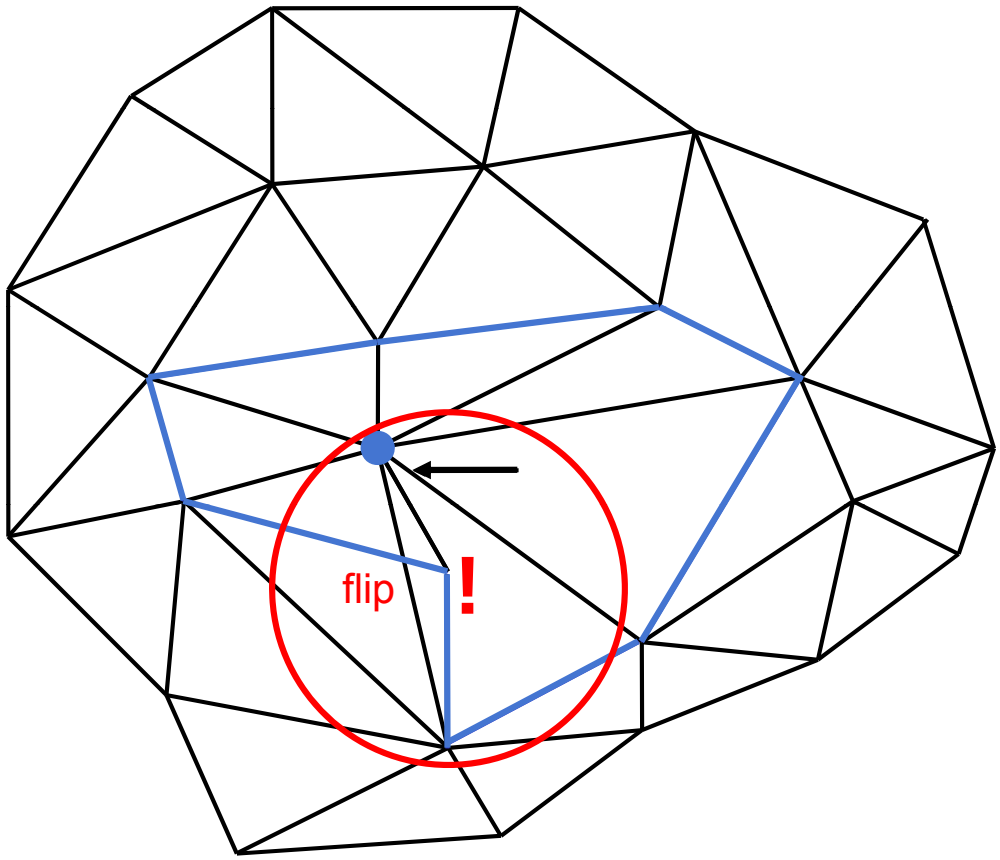
Half-Edge Collapse



Half-Edge Collapse



Half-Edge Collapse

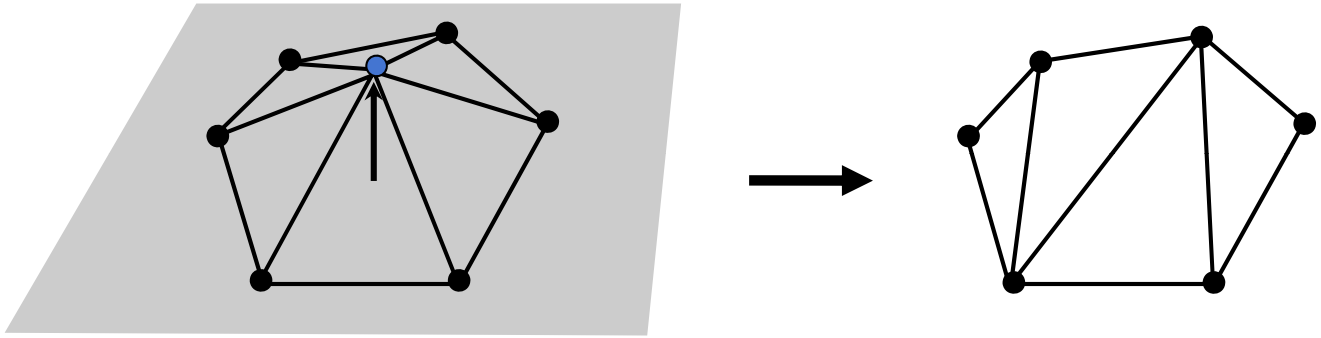


Incremental Decimation

- General Setup
- Decimation operators
- Error metrics
- Fairness criteria
- Topology changes

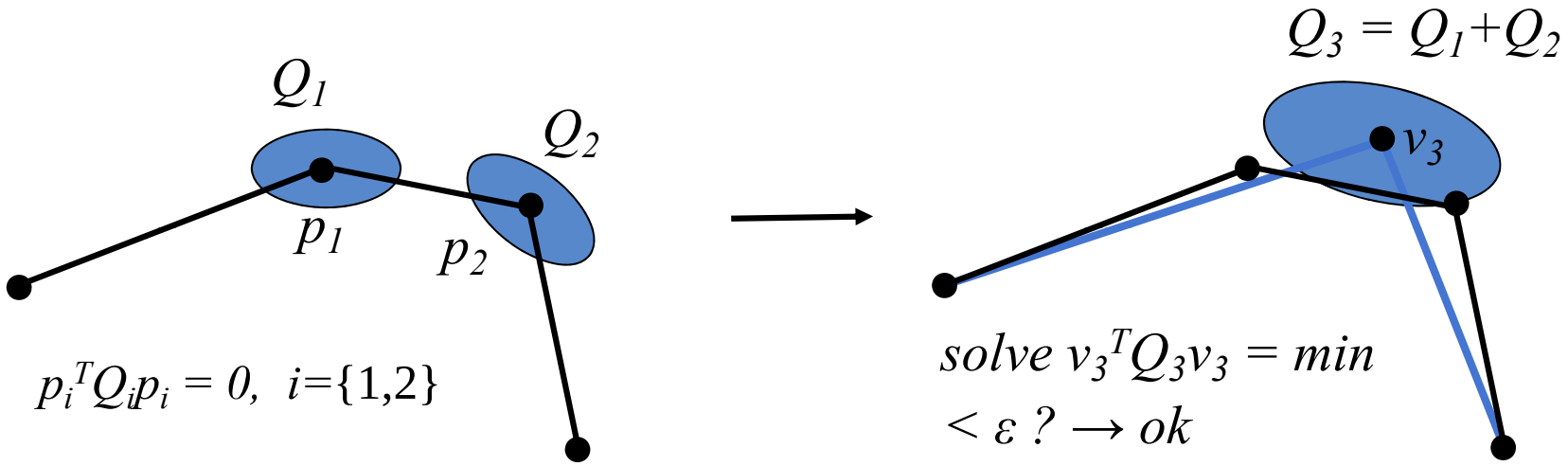
Local Error Metrics

- Local distance to mesh
  - Compute average plane
  - No comparison to *original* geometry



Global Error Metrics

- Error quadrics
  - Squared distance to planes at vertex
  - No bound on true error

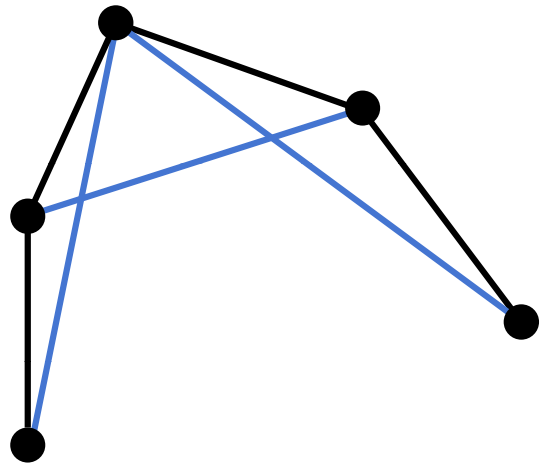


Incremental Decimation

- General Setup
- Decimation operators
- Error metrics
- Fairness criteria
- Topology changes

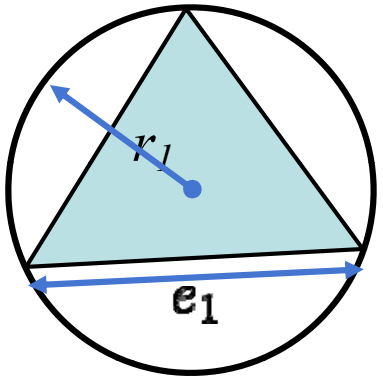
Fairness Criteria

- Rate quality of decimation operation
  - Approximation error
  - Triangle shape
  - Dihedral angles
  - Valence balance
  - ...

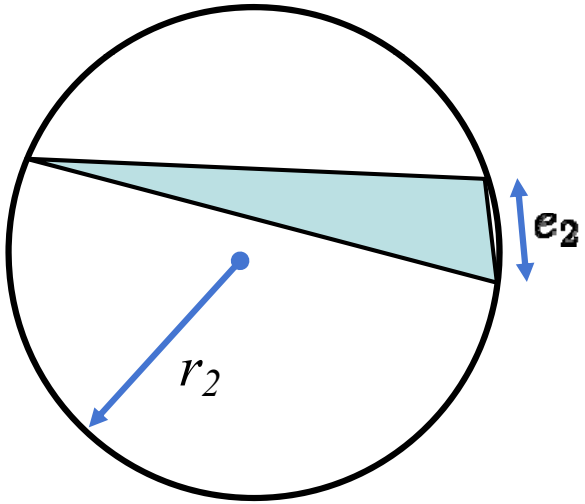


Fairness Criteria

- Rate quality after decimation
  - Approximation error
  - Triangle shape
  - Dihedral angles
  - Valence balance
  - ...

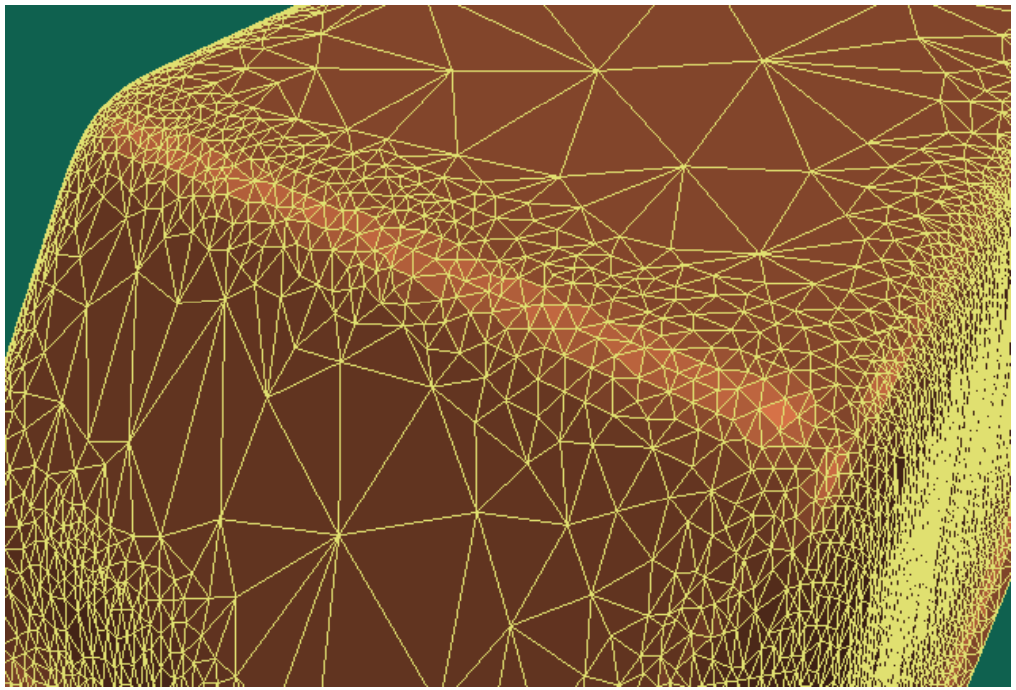


$$\frac{r_1}{e_1} < \frac{r_2}{e_2}$$



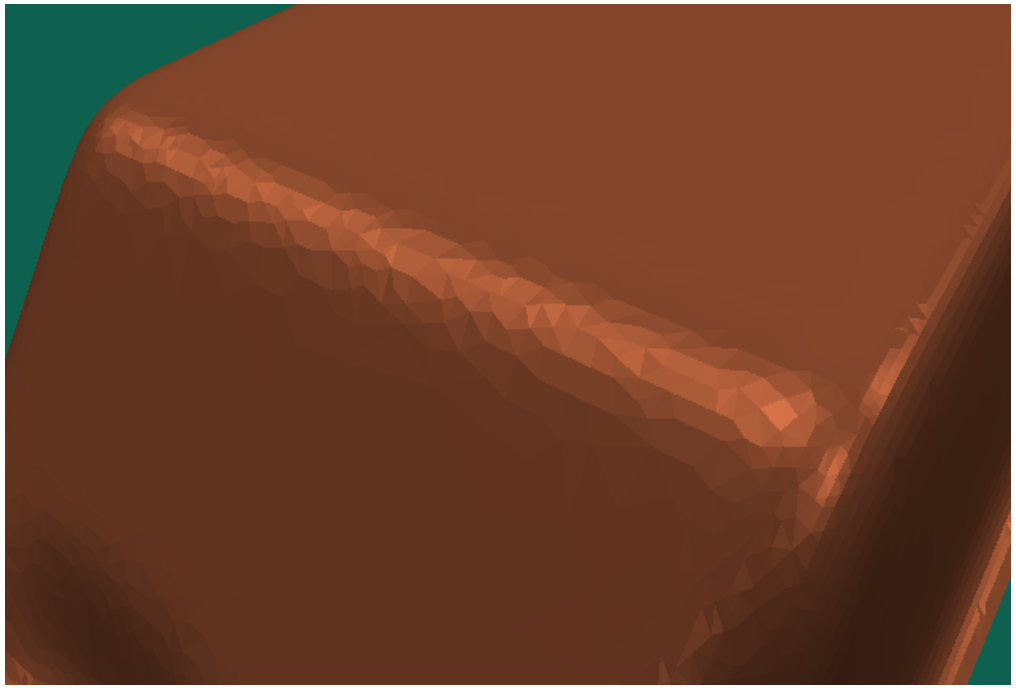
Fairness Criteria

- Rate quality after decimation
  - Approximation error
  - Triangle shape
  - Dihedral angles
  - Valence balance
  - ...



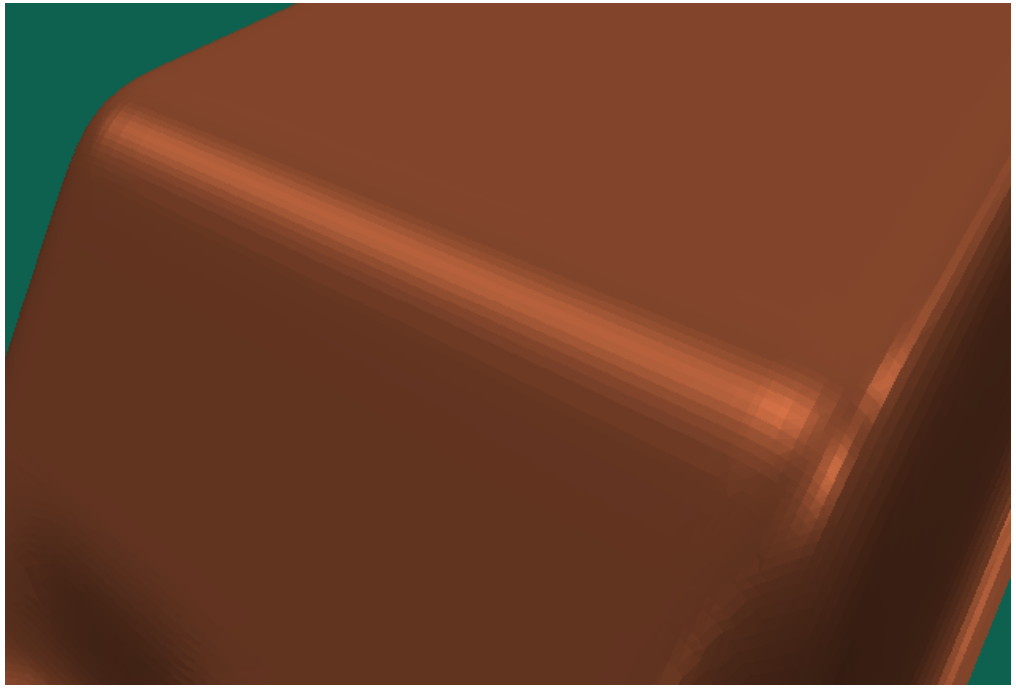
Fairness Criteria

- Rate quality after decimation
  - Approximation error
  - Triangle shape
  - Dihedral angles
  - Valence balance
  - Color differences
  - ...



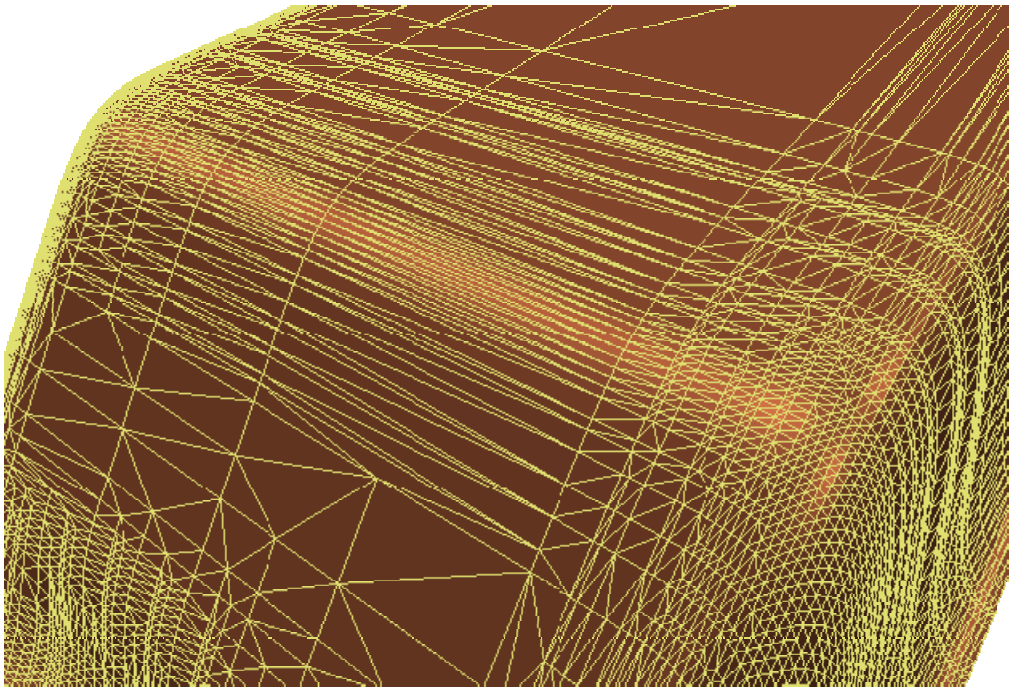
Fairness Criteria

- Rate quality after decimation
  - Approximation error
  - Triangle shape
  - Dihedral angles
  - Valence balance
  - Color differences
  - ...



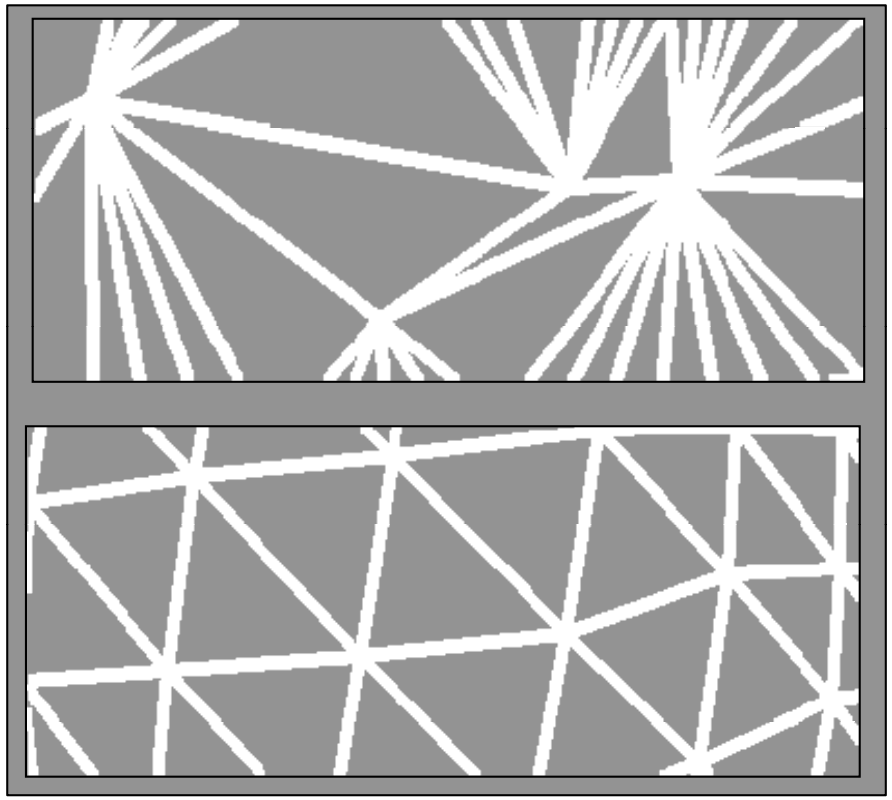
Fairness Criteria

- Rate quality after decimation
  - Approximation error
  - Triangle shape
  - Dihedral angles
  - Valence balance
  - Color differences
  - ...



Fairness Criteria

- Rate quality after decimation
  - Approximation error
  - Triangle shape
  - Dihedral angles
  - Valence balance
  - Color differences
  - ...

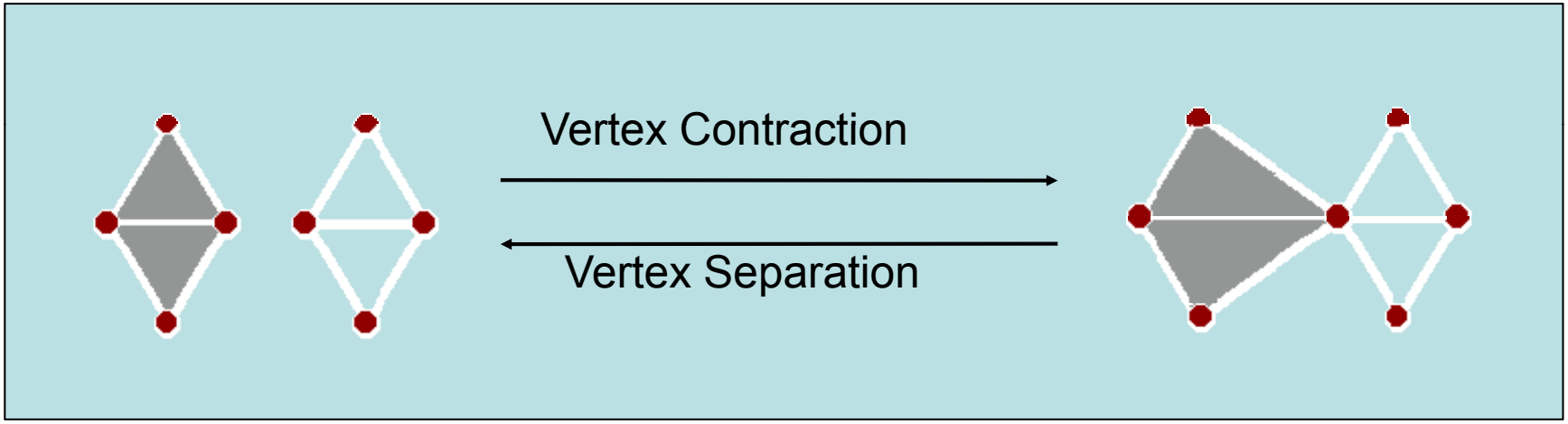


Incremental Decimation

- General Setup
- Decimation operators
- Error metrics
- Fairness criteria
- Topology changes

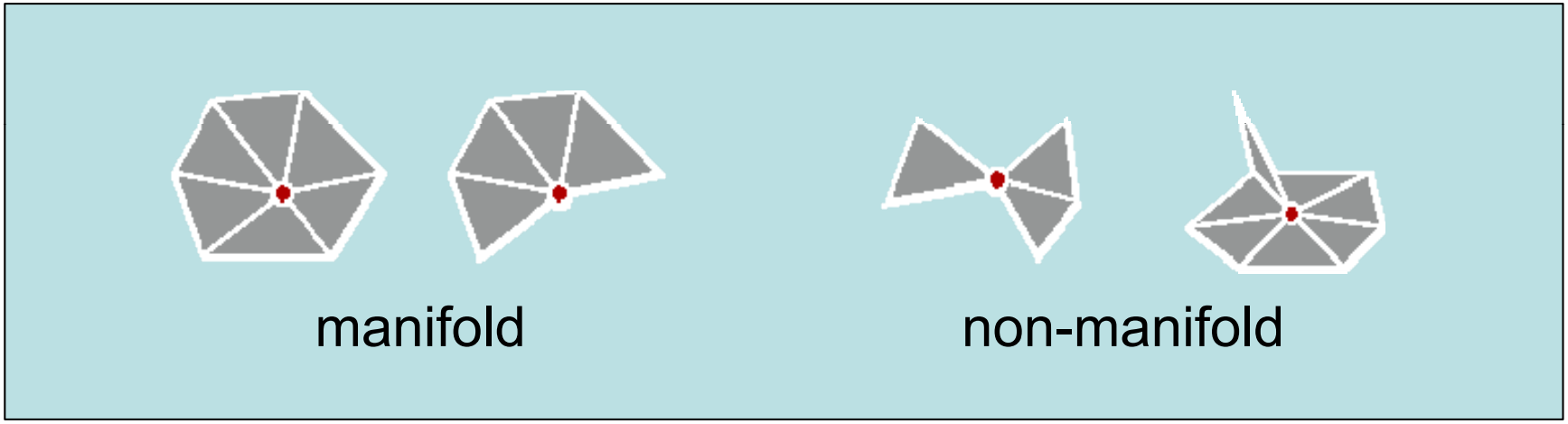
Topology Changes ?

- Merge vertices across non-edges
  - Changes mesh topology
  - Need *spatial neighborhood* information
  - Generates *non-manifold* meshes



Topology Changes ?

- Merge vertices across non-edges
  - Changes mesh topology
  - Need *spatial neighborhood* information
  - Generates *non-manifold* meshes



Comparison

- Vertex clustering
  - fast, but difficult to control simplified mesh
  - topology changes, non-manifold meshes
  - global error bound, but often not close to optimum
- Incremental decimation with quadric error metrics
  - good trade-off between mesh quality and speed
  - explicit control over mesh topology
  - restricting normal deviation improves mesh quality