Real-Time Rendering (Echtzeitgraphik)

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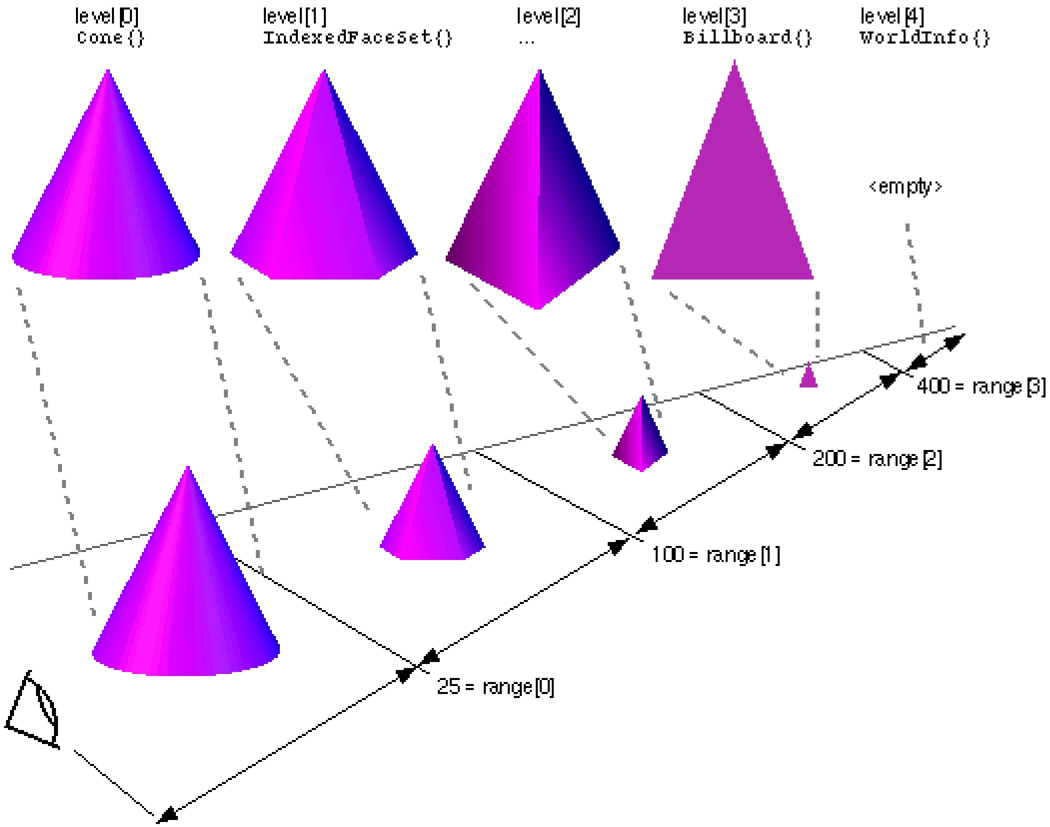
Levels of Detail



Basic Idea

- Problem: even after visibility, model may contain too many polygons
- Idea: Simplify the amount of detail used to render small or distant objects
- Known as
  - Multiresolution modeling, polygonal simplification, geometric simplification, mesh reduction, decimation, multiresolution modeling, …

Definition

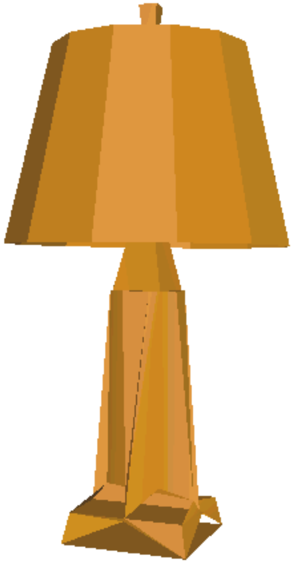
- Polygonal simplification methods simplify the polygonal geometry of small or distant objects
- Does not change rasterization
  - Fragment count remains roughly identical
- Note:
  - Levels of detail, but:
  - Level-of-detail rendering
  - NOT: level of details!

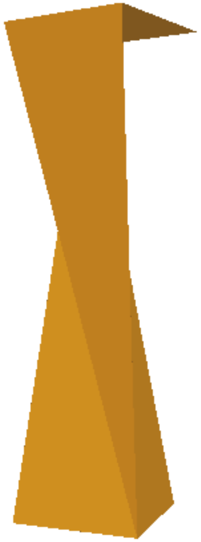
Traditional Approach

- Create *levels of detail* (LODs) for each object in a preprocess (or by hand):


10,108 polys

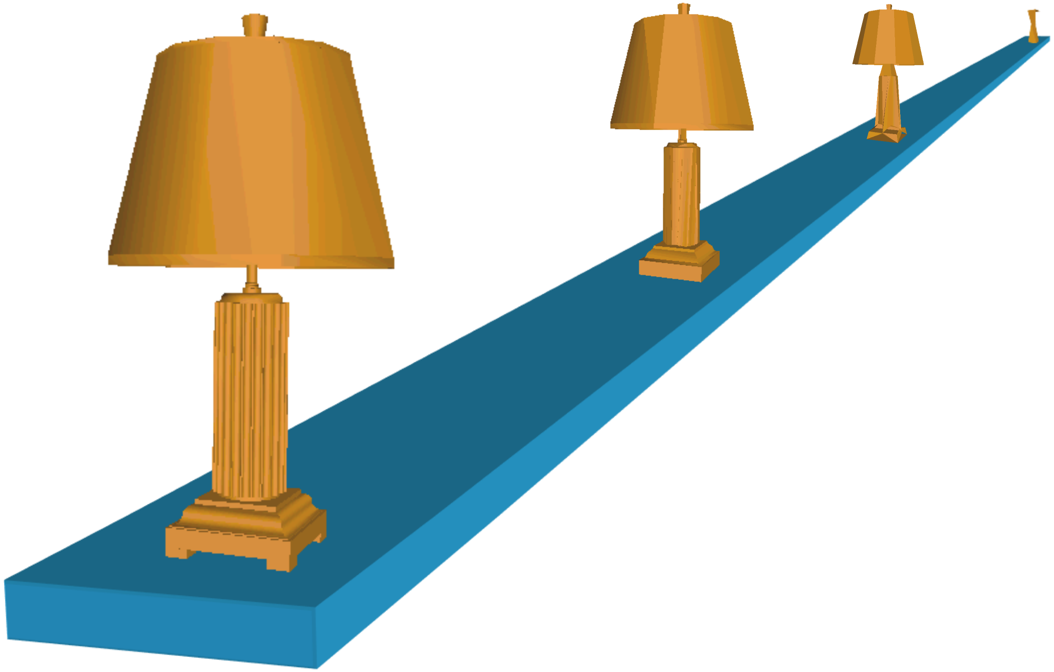

1,383 polys


474 polys


46 polys

Traditional Approach

- At runtime, distant objects use coarser LODs:



LOD Issues

- LOD generation
  - Simplification methods
    - How to reduce polygons
  - Error measures
    - Which polygons to reduce
- Runtime system
  - LOD framework
    - Which LODs are eligible
  - LOD selection
    - Criteria for which LODs are selected
  - LOD switching
    - How to avoid artifacts

Runtime system

- LOD framework
  - Discrete
  - Continuous (a.k.a. progressive)
  - View-dependent
- LOD selection
  - Static (distance/projected area-based)
  - Reactive (react to last frames rendering time)
  - Predictive (cost/benefit model)
- LOD switching
  - Hard switching (popping artifacts!)
  - Blending (ill-defined because of z-buffer!)
  - Geomorph

Creating LODs

- Main topic of this lecture!
- Simplification methods (“operators”)
  - Geometry
    - Edge collapse
    - …
  - Topology
- What criteria to guide simplification?
  - Visual/perceptual criteria are hard
  - Geometric criteria are more common

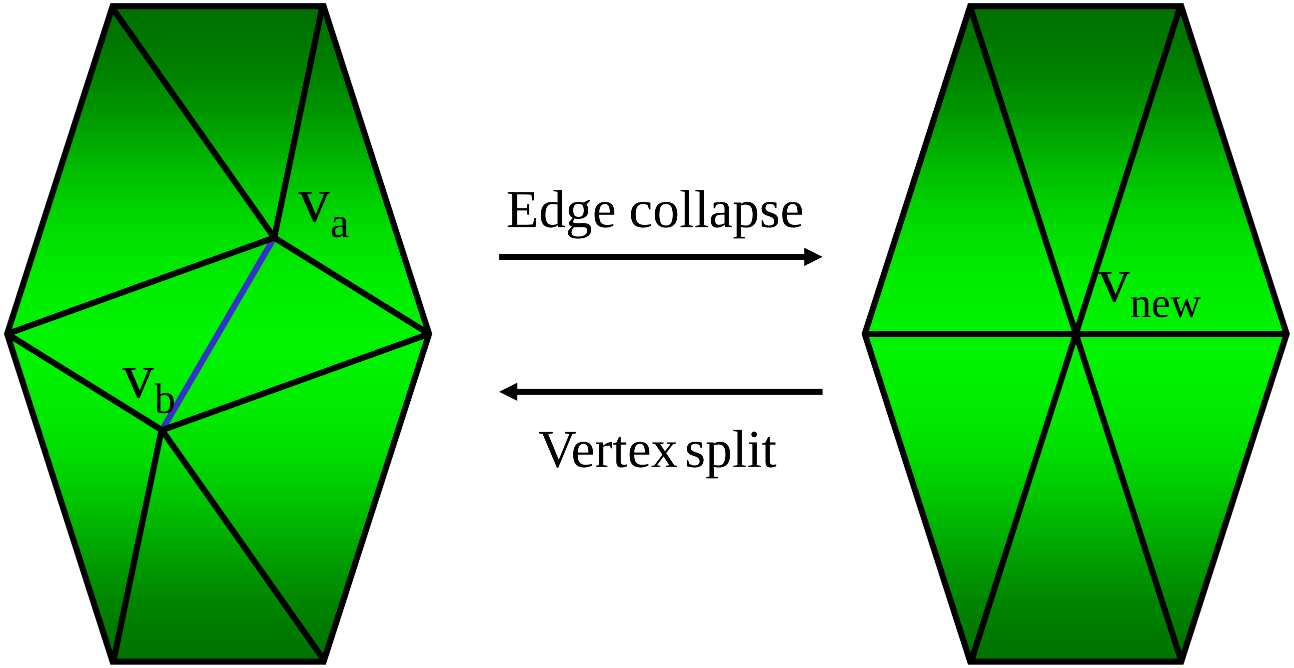
Simplification Operators

- Local geometry simplification
  - Iteratively reduce number of geometric primitives (vertices, edges, triangles)
- Topology simplification
  - Reducing number of holes, tunnels, cavities
- Global geometry simplification

Local Geometry Simplification

- Edge collapse
- Vertex-pair collapse
- Triangle collapse
- Cell collapse
- Vertex removal
- General geometric replacement

Edge Collapse

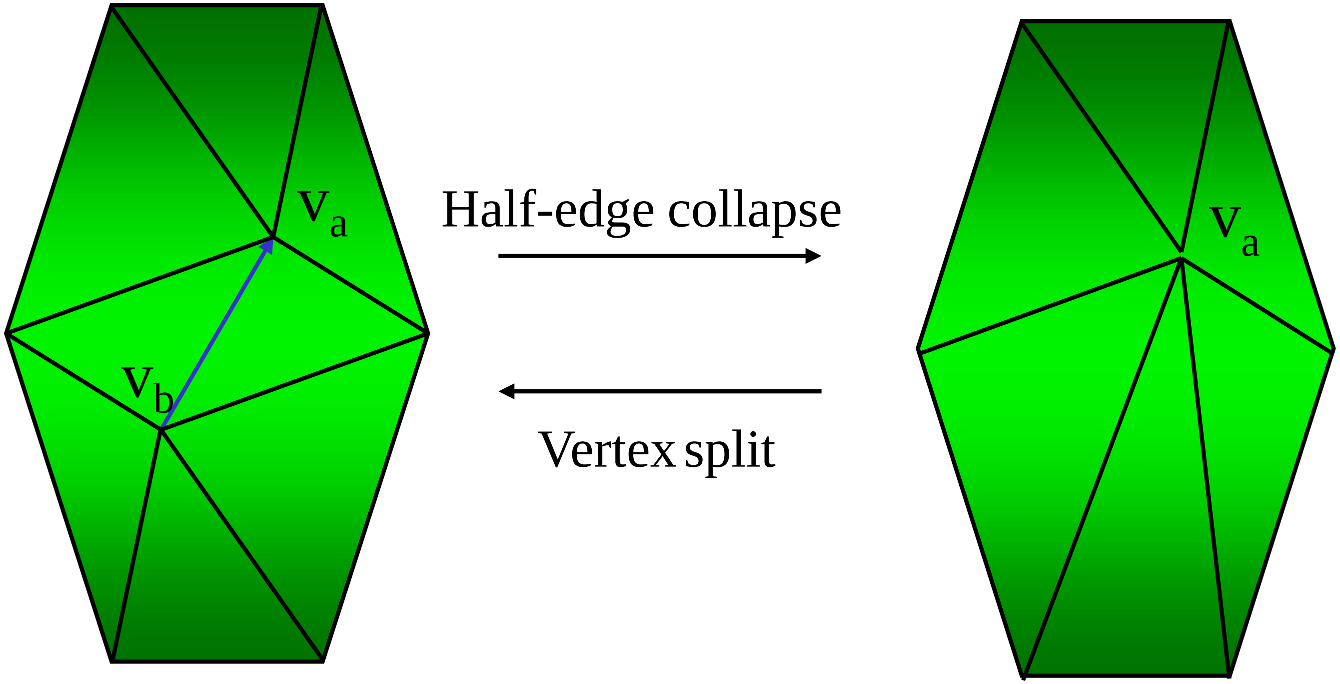


Edge collapse

Vertex split

Hoppe, *SIGGRAPH 96*; Xia *et al.*, *Visualization 96*; Hoppe, *SIGGRAPH 97*; Bajaj *et al.*, *Visualization 99*; Gueziec *et al.*, *CG&A 99*; …

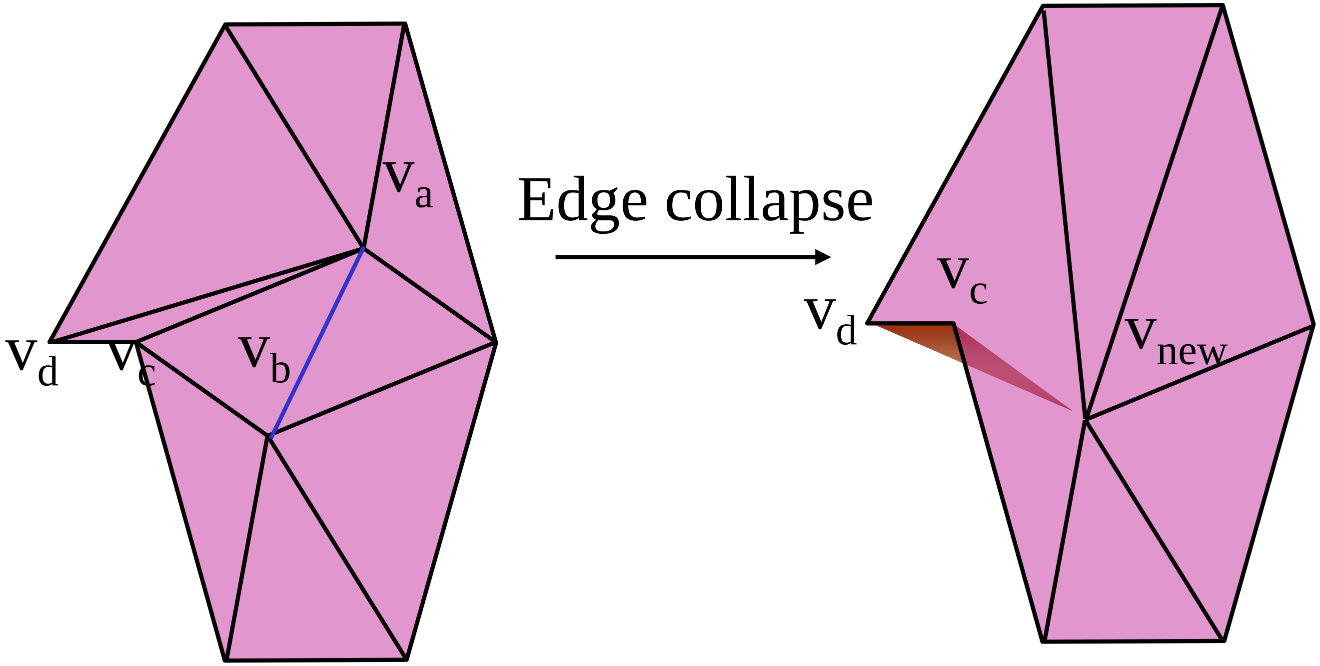
Half-Edge Collapse



Half-edge collapse

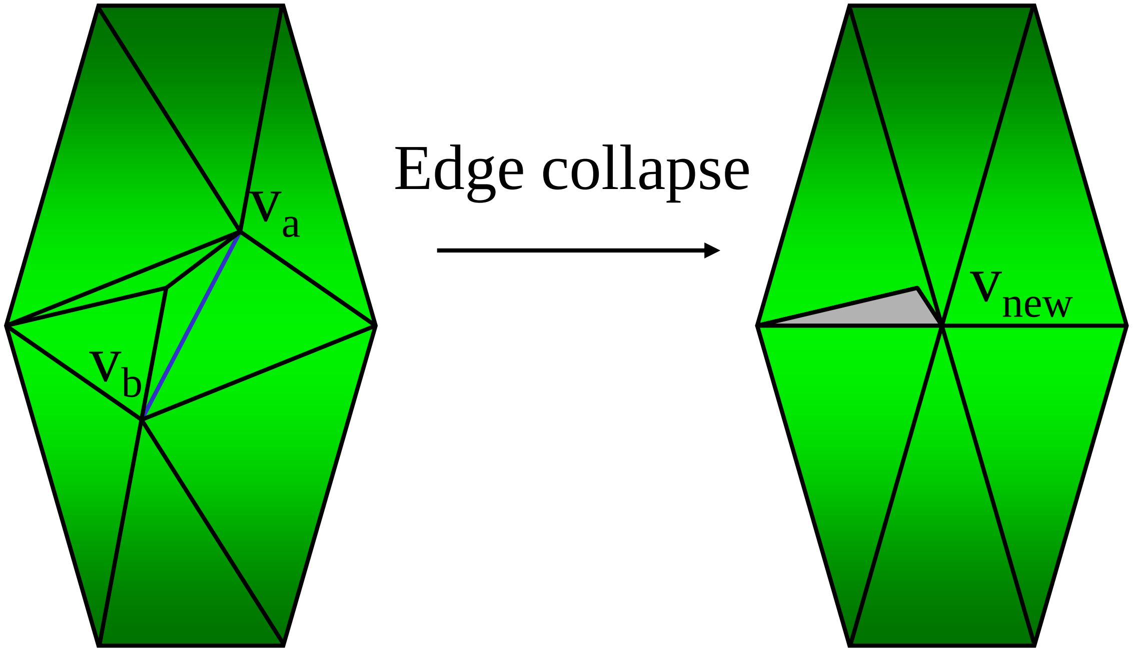
Vertex split

Watch for Mesh Foldovers

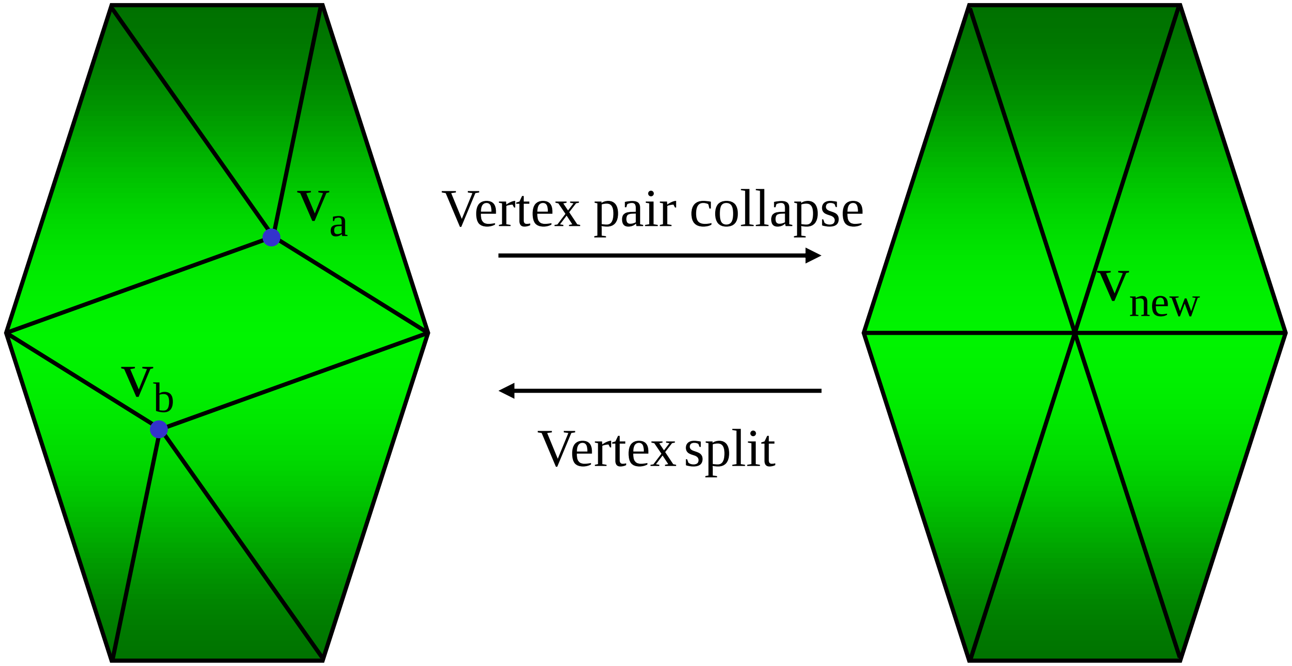


- Calculate the adjacent face normals, then test if they would flip after simplification
- If so, that simplification can be weighted heavier or disallowed

Implementation: Watch for Identical / Non-Manifold Tris

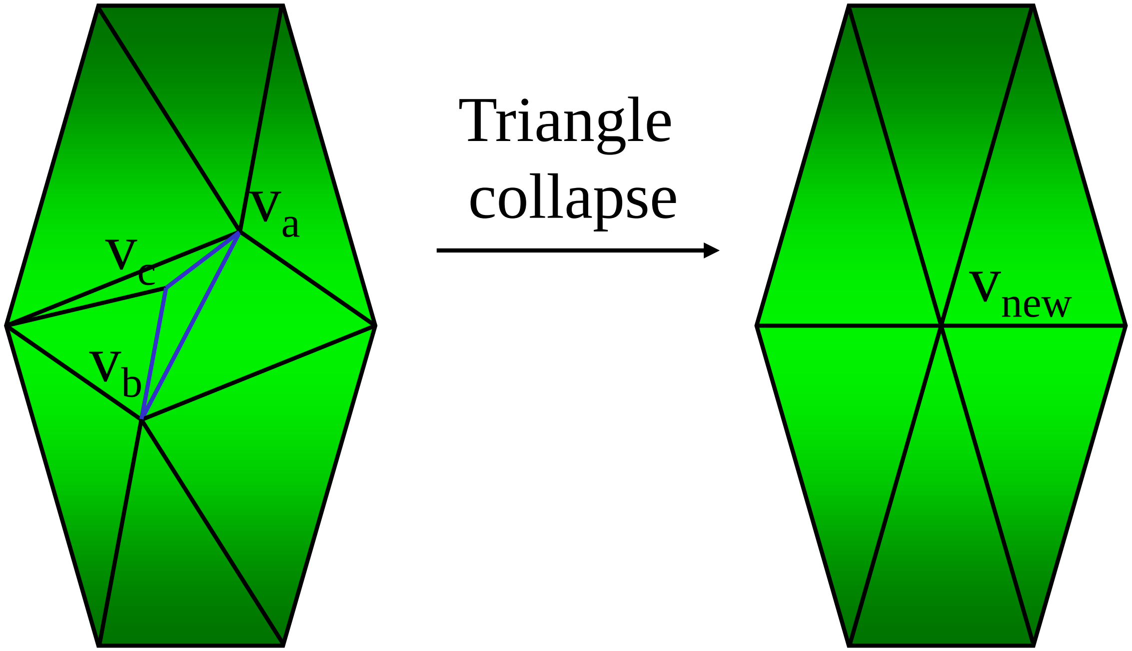


Vertex-Pair Collapse



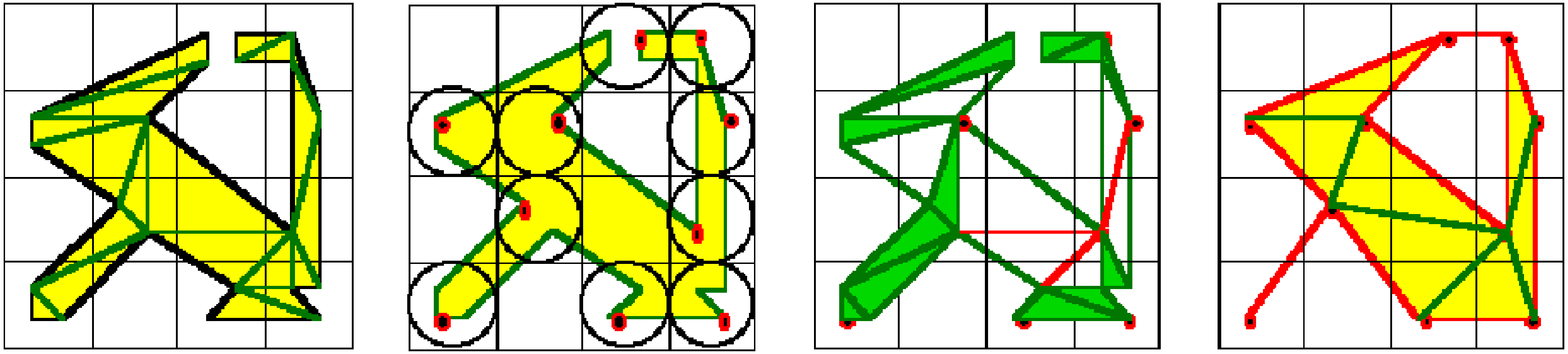
Schroeder, *Visualization 97*; Garland & Heckbert, *SIGGRAPH 97*;
Popovic & Hoppe, *SIGGRAPH 97*; El-Sana & Varshney, *Eurographics 99*; …

Triangle Collapse



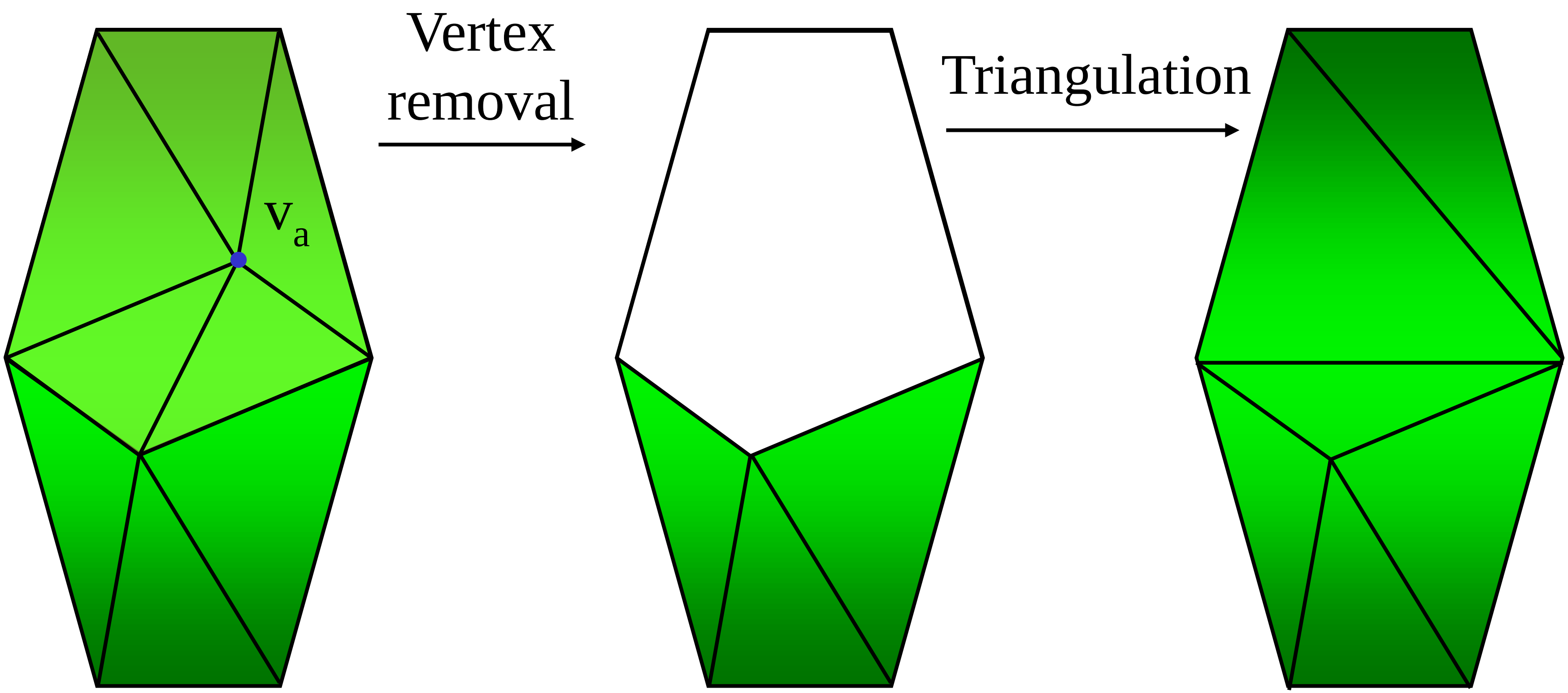
Hamann, *CAGD 94*; Gieng *et al*., *IEEE TVCG 98*

Cell Collapse



Grid based: Rossignac & Borrel, *Modeling in Computer Graphics 93*
Octree-based: Luebke & Erikson, *SIGGRAPH 98*

Vertex Removal



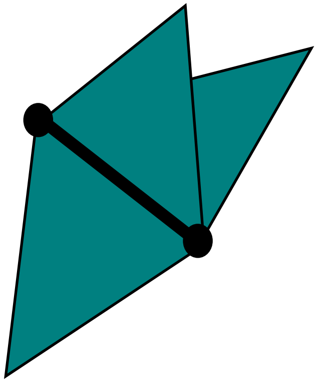
Schroeder *et al.*, *SIGGRAPH 92*;
Klein & Kramer, *Spring Conf. On Comp. Graphics 97*

General Geometric Replacement

- Replace a subset of adjacent triangles by a simplified set with
- “*Multi-triangulation*”
- Fairly general: can encode edge collapses, vertex removals, and edge flips

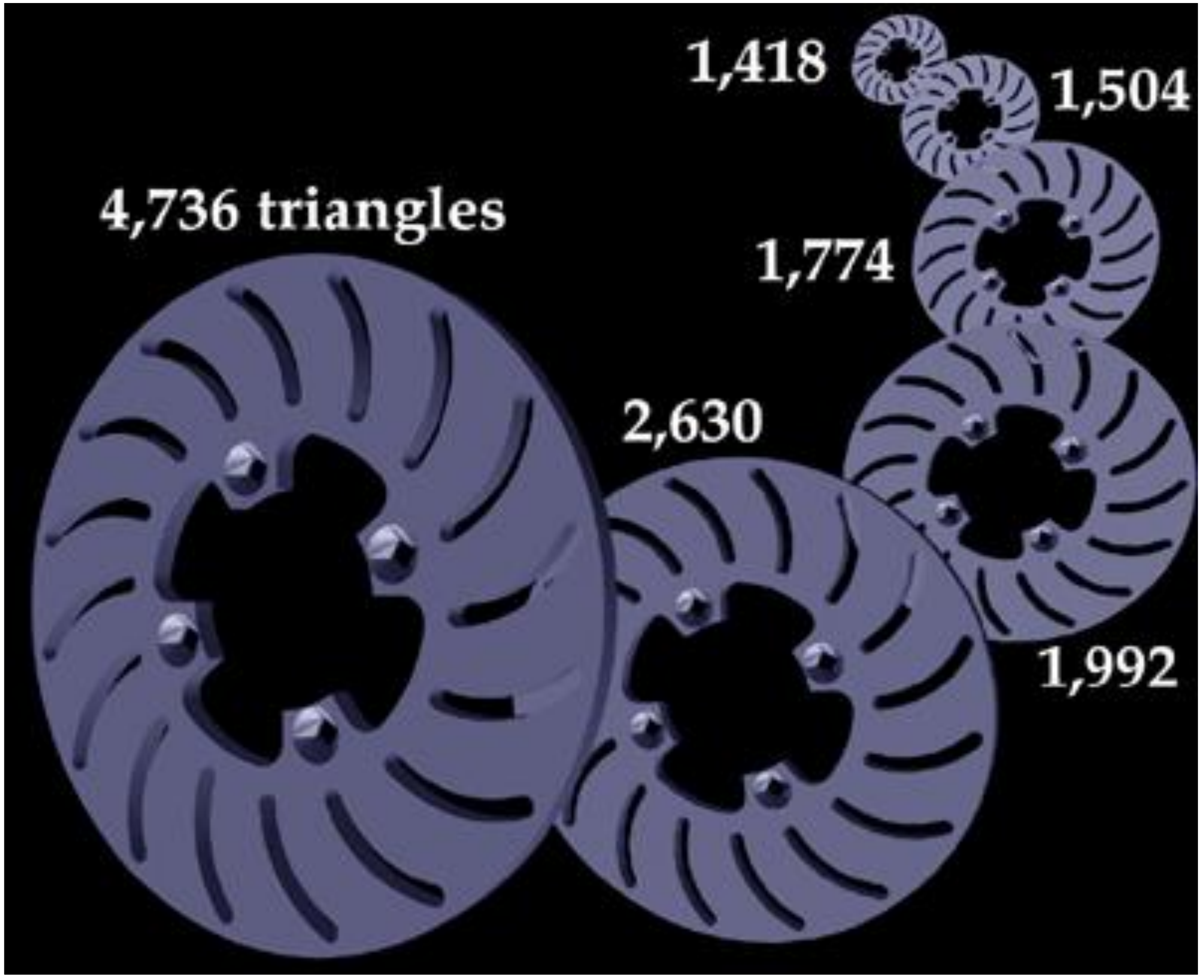
Discussion / Comparison

- Edge collapse and triangle collapse:
  - Simplest to implement
  - Support geometric morphing across levels of detail
  - Support non-manifold geometry
- Full-edge vs. half-edge collapses:
  - Full edge represents better simplifications
  - Half-edge is more efficient in incremental encoding
- Cell collapse:
  - Simple, robust
  - Varies with rotation/translation of grid
- Vertex removal vs edge collapse
  - Hole retriangulation is not as simple as edge collapse
  - Smaller number of triangles affected in vertex removal



Simplifying Geometry vs Topology

- Pure geometric simplification not enough



Local Topology Simplification

- Collapsing vertex pairs ("pair contraction") / virtual edges
  - Schroeder, *Visualization 97*
  - Popovic and Hoppe, *SIGGRAPH 97*
  - Garland and Heckbert, *SIGGRAPH 97*
- Collapsing primitives in a cell
  - Rossignac and Borrel, *Modeling in Comp. Graphics 93*
  - Luebke and Erikson, *SIGGRAPH 97*

Virtual Edge Collapse

- Allow virtual edge collapses
- Limit no. of virtual edges (potentially $O(n^2)$)
- Typical constraints:
  - Delaunay edges
  - Edges that span neighboring cells in a spatial subdivision: octree, grids, etc.
  - Maximum edge length

Global Geometry Simplification

- Sample and reconstruct
- Adaptive subdivision

Sample and Reconstruct

- Scatter surface with sample points
  - Randomly
  - Let them repel each other
- Reduce sample points
- Reconstruct surface

Adaptive Subdivision

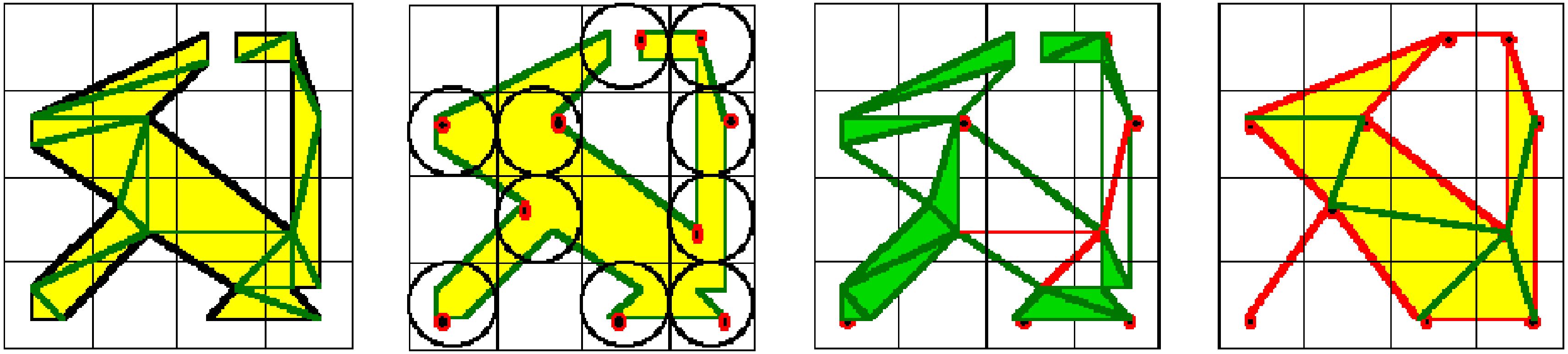
- Create a very simple *base model* that represents the model
- Selectively subdivide faces of base model until fidelity criterion met (draw)
- Big potential application: *multiresolution modeling*

Example 1: Vertex Clustering

- Rossignac and Borrel, 1992
- Operator: cell collapse

- Apply a uniform 3D grid to the object
- Collapse all vertices in each grid cell to single *most important* vertex, defined by:
  - Curvature (1 / maximum edge angle)
  - Size of polygons (edge length)
- Filter out degenerate polygons

Example 1: Vertex Clustering



- Apply a uniform 3D grid to the object
- Collapse all vertices in each grid cell to single *most important* vertex, defined by:
  - Curvature (1 / maximum edge angle)
  - Size of polygons (edge length)
- Filter out degenerate polygons

Vertex Clustering

- Resolution of grid determines degree of simplification

- Representing degenerate triangles
  - Edges: OpenGL line primitive
  - Points: OpenGL point primitive

Vertex Clustering

- Pros
  - Very fast
  - Robust (topology-insensitive)
- Cons
  - Difficult to specify simplification degree
  - Low fidelity (topology-insensitive)
  - Underlying grid creates sensitivity to model orientation

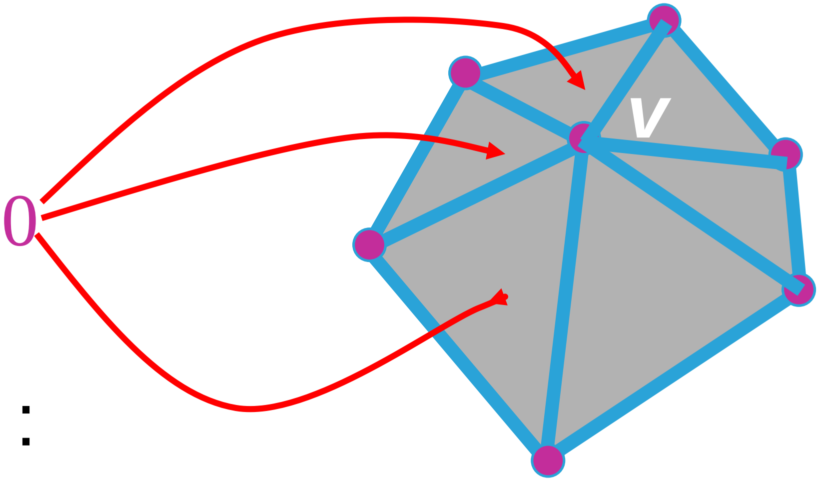
Creating LODs: Error Measures

- What criteria to guide simplification?
  - Visual/perceptual criteria are hard
  - Geometric criteria are more common
- Examples:
  - Vertex-vertex distance
  - Vertex-plane distance
  - Point-surface distance
  - Surface-surface distance
  - Image-driven
- Issues:
  - Error propagation?
  - Need to include attributes (tex coords, …)

Quadric Error Metric

- Vertex-plane distance
- Minimize distance to all planes at a vertex
- Plane equation for each face:

$$p: \quad Ax + By + Cz + D = 0$$



- Distance to vertex ***v*** :

$$p^T \cdot v = \begin{bmatrix} A & B & C & D \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

Squared Distance at a Vertex

$$\Delta(v) = \sum_{p \in planes(v)} (p^T v)^2$$

$$= \sum_{p \in planes(v)} (v^T p)(p^T v)$$

$$= \sum_{p \in planes(v)} v^T (pp^T) v$$

$$= v^T \left(\sum_{p \in planes(v)} pp^T \right) v$$

Quadric Derivation (cont'd)

- pp^T is simply the plane equation squared:

$$pp^T = \begin{bmatrix} A^2 & AB & AC & AD \\ AB & B^2 & BC & BD \\ AC & BC & C^2 & CD \\ AD & BD & CD & D^2 \end{bmatrix}$$

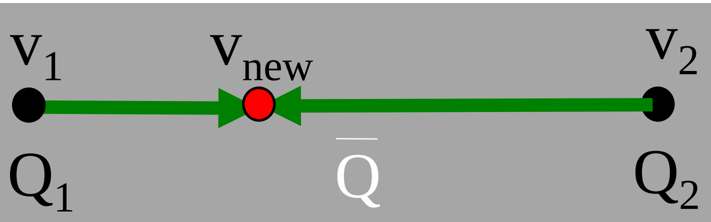
- *The pp^T sum at a vertex v is a matrix, Q:*

$$\Delta(v) = v^T (Q) v$$

Using Quadrics

- Construct a quadric Q for every vertex

The *edge quadric*:



$$\bar{Q} = Q_1 + Q_2$$

- Sort edges based on edge cost
  - Suppose we contract to v_{new}:
    - Edge cost = $V_{new}^T \, \bar{\mathbf{Q}} \, V_{new}$
  - V_{new}'s new quadric is simply **Q**

Optimal Vertex Placement

- Each vertex has a quadric error metric Q associated with it
  - Error is zero for original vertices
  - Error nonzero for vertices created by merge operation(s)
- Minimize Q to calculate optimal coordinates for placing new vertex
  - Details in paper
  - Authors claim 40-50% less error

Boundary Preservation

- To preserve important boundaries, label edges as normal or *discontinuity*
- For each face with a discontinuity, a plane perpendicular intersecting the discontinuous edge is formed.
- These planes are then converted into quadrics, and can be weighted more heavily with respect to error value.

Quadric Error Metric

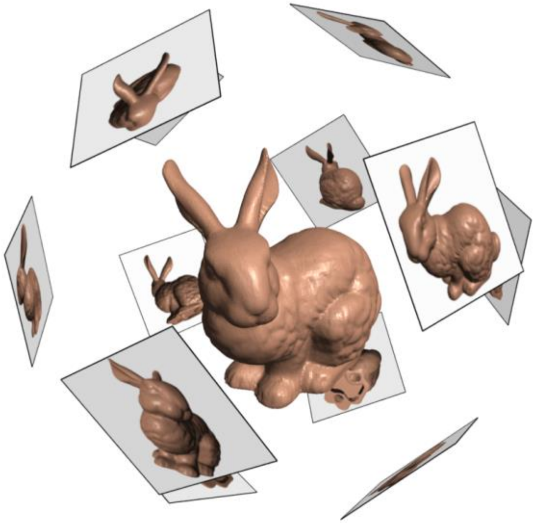
- Pros:
  - Fast! (bunny to 100 polygons: 15 sec)
  - Good fidelity even for drastic reduction
  - Robust -- handles non-manifold surfaces
  - Aggregation -- can merge objects

Quadric Error Metric

- Cons:
  - Introduces non-manifold surfaces

  - Tweak factor *t* is ugly
    - Too large: O(n^2) running time
    - Correct value varies with model density
  - Needs further extension to handle color (7x7 matrices)

Image-Driven Simplification

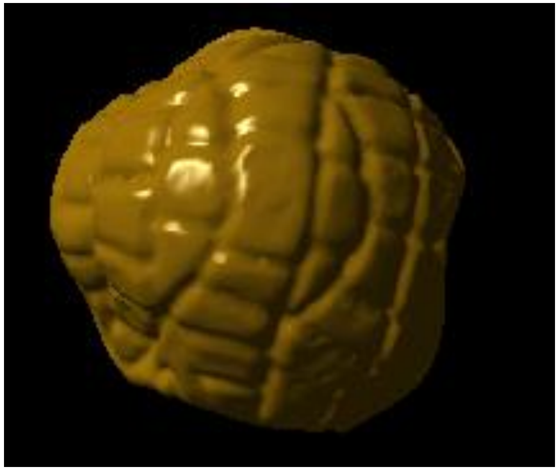


12 cameras used to capture quality of bunny simplification (Lindstrom/Turk 2000)

- Measure error by rendering
  - Compare resulting images
  - Lindstrom/Turk 2000
- Captures attribute and shading error, as well as texture content

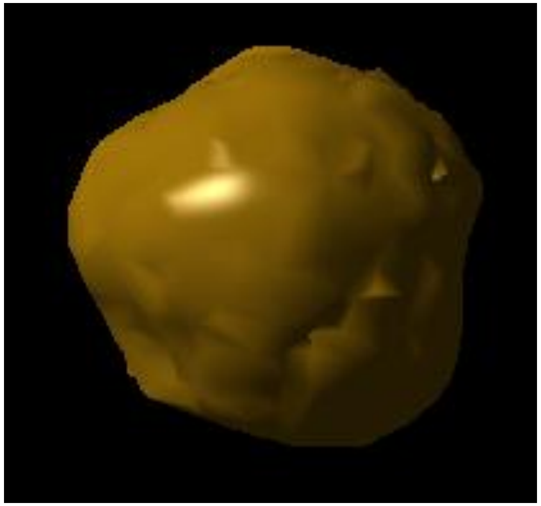
Appearance-Preserving Simplification

- Reduce drastically
- Simulate lost geometry using bump maps
- NVIDIA/ATI tools available



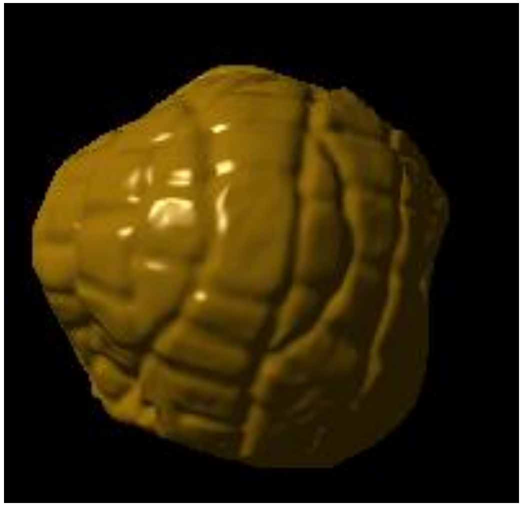
original

13.000 tris



simplification

1700 tris



normal-mapped

1700 tris

Frameworks for LOD

- Three basic LOD frameworks:
    - *Discrete LOD*: the traditional approach
    - *Continuous LOD*: encoding a continuous spectrum of detail from coarse to fine
    - *View-dependent LOD*: adjusting detail across the model in response to viewpoint

Discrete LOD: Advantages

- Simplest programming model; decouples simplification and rendering
  - LOD creation need not address real-time rendering constraints
  - Run-time rendering engine need only pick LODs
- Fits modern graphics hardware well
  - Easy to compile each LOD into triangle strips, cache-aware vertex arrays, etc.
  - These render *much* faster than immediate-mode triangles on today’s hardware

Discrete LOD: Disadvantages

- So why use anything but discrete LOD?
  - Reason 1: sometimes discrete LOD not suited for drastic simplification
  - Reason 2: in theory, can get better fidelity/polygon with other approaches

Continuous Level of Detail

- A departure from the traditional discrete approach:
  - Discrete LOD: create individual levels of detail in a preprocess
  - Continuous LOD: create data structure from which a desired level of detail can be extracted *at run time*.

Continuous LOD: Advantages

- Better granularity → better fidelity
  - LOD is specified exactly, not chosen from a few pre-created options
  - Thus objects use no more polygons than necessary, which frees up polygons for other objects
  - Net result: better resource utilization, leading to better overall fidelity/polygon

Continuous LOD: Advantages

- Better granularity → smoother transitions
  - Switching between traditional LODs can introduce visual “popping” effect
  - Continuous LOD can adjust detail gradually and incrementally, reducing visual pops
    - Can even *geomorph* the fine-grained simplification operations over several frames to eliminate pops (e.g., w/ a vertex shader)

Continuous LOD: Advantages

- Supports progressive transmission (*streaming*)
    - *Progressive Meshes [Hoppe 97]*
    - *Progressive Forest Split Compression [Taubin 98]*
- Leads to
    - Use current view parameters to select best representation *for the current view*
    - Single objects may thus span several levels of detail

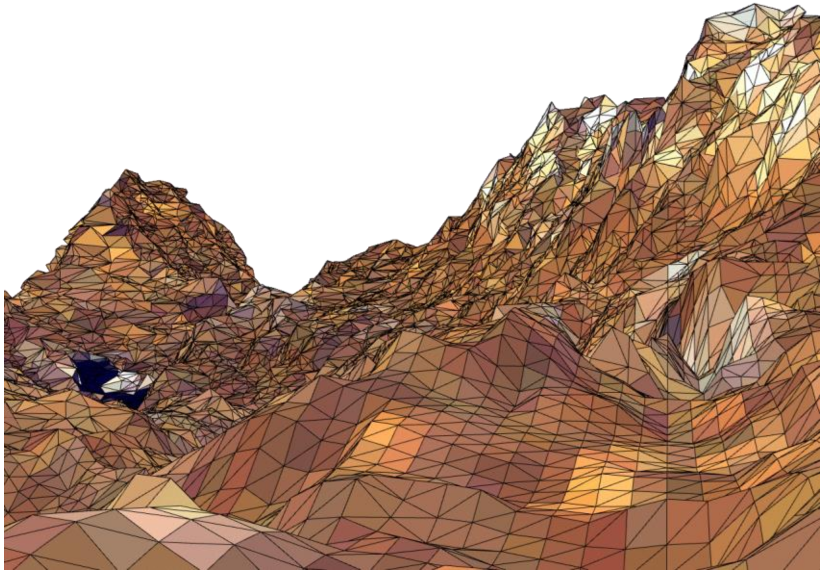
Continuous LOD Algorithm

- “Progressive meshes”
- Iteratively apply local simplification operator
    - Until base mesh
- Entity = edge or vertex or triangle …

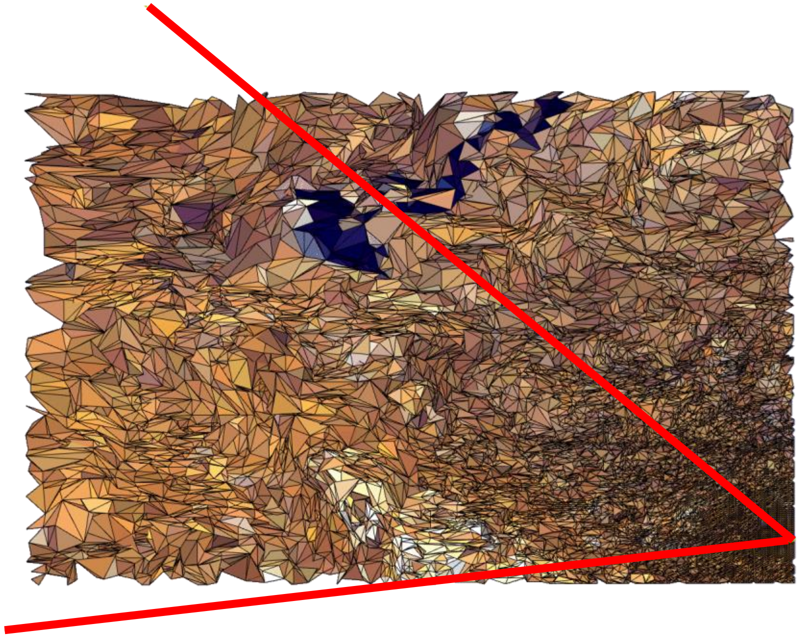
```
Sort all entities (by some metric)
repeat
   Apply local simplification operator:
     remove entity
     Fix-up topology
until (no entities left)
```

View-Dependent LOD: Examples

- Show nearby portions of object at higher resolution than distant portions



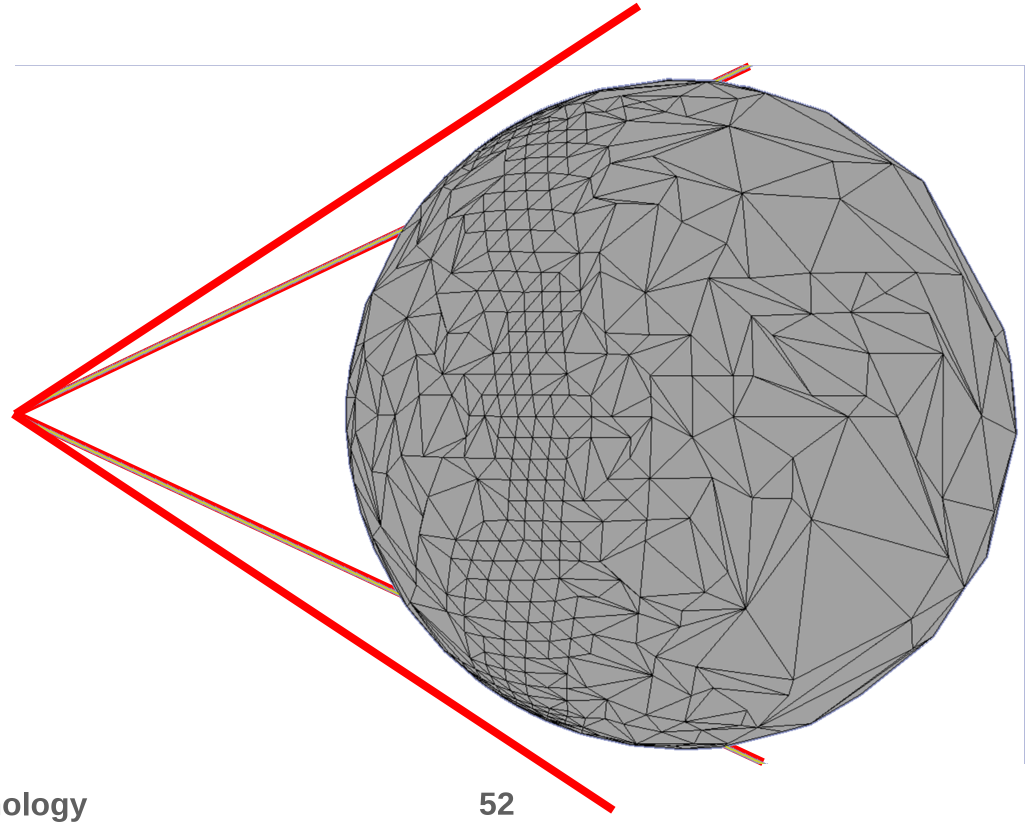
View from eyepoint



Birds-eye view

View-Dependent LOD: Examples

- Show silhouette regions of object at higher resolution than interior regions

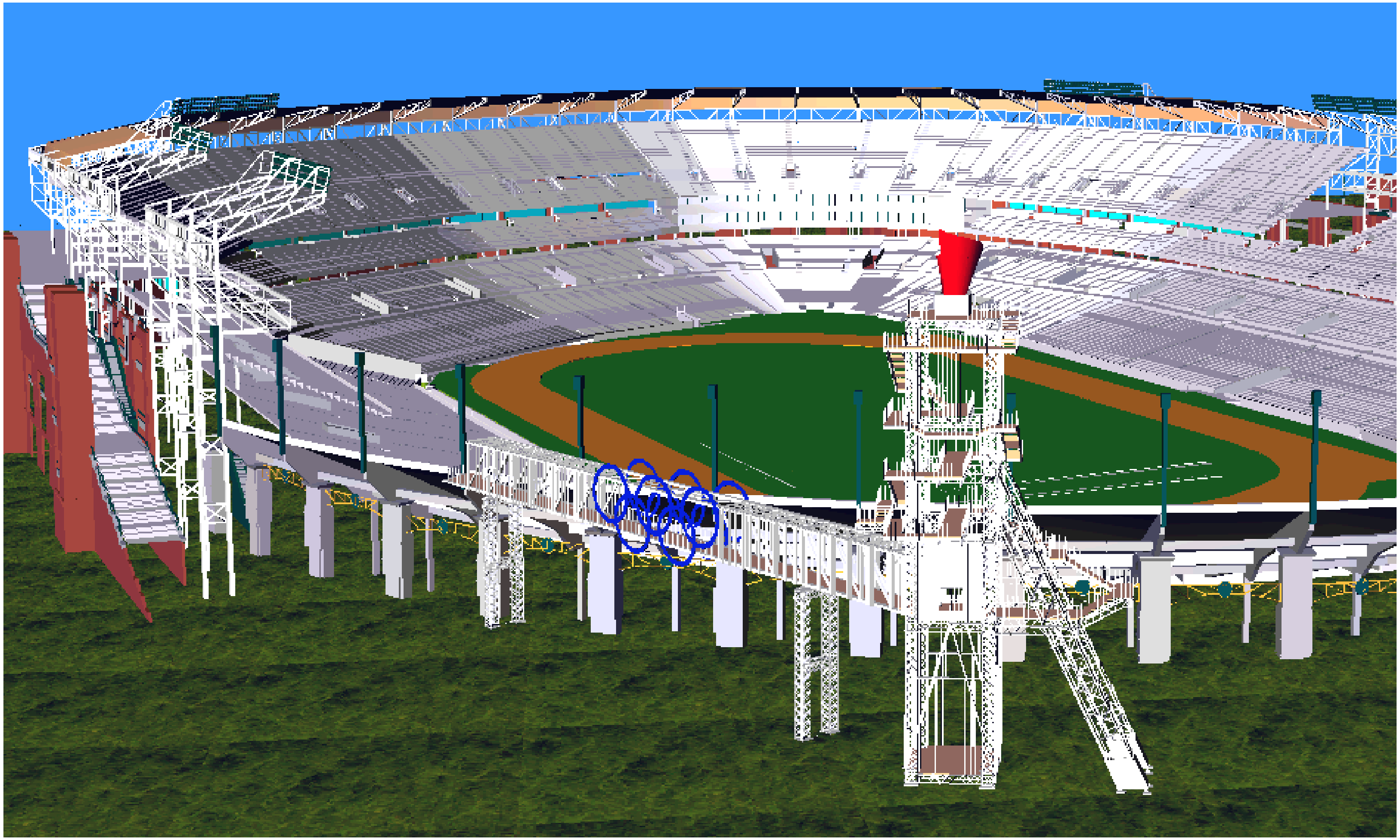


Advantages of View-Dependent LOD

- Even better granularity
- Enables drastic simplification of very large objects
  - Example: stadium model
  - Example: terrain flyover

Drastic Simplification:

The Problem With Large Objects



Terrain LOD

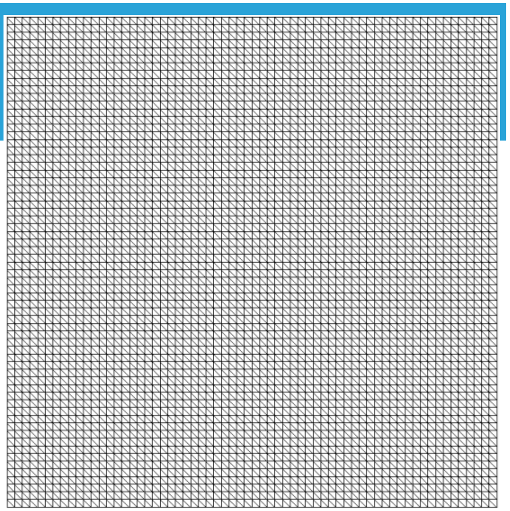
- Has been around for long (flight simulators, GIS, games …)
- Geometry is more constrained

  → Specialized solutions

- Properties
  - Simultaneously very near and very far

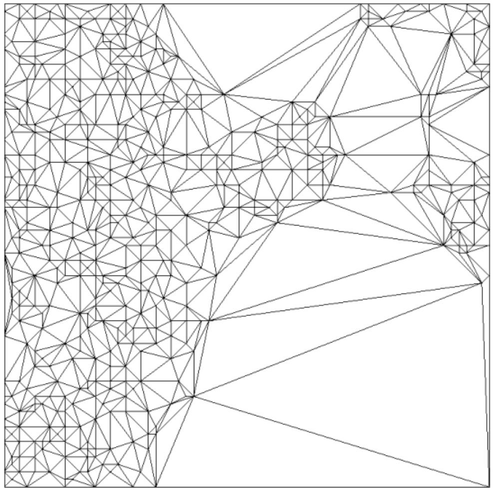
    → Requires progressive/view-dependent LOD!
  - Very large terrains → out-of-core
- Problems:
  - Dynamic modification of terrain data
  - Fast rotation

Regular Grids



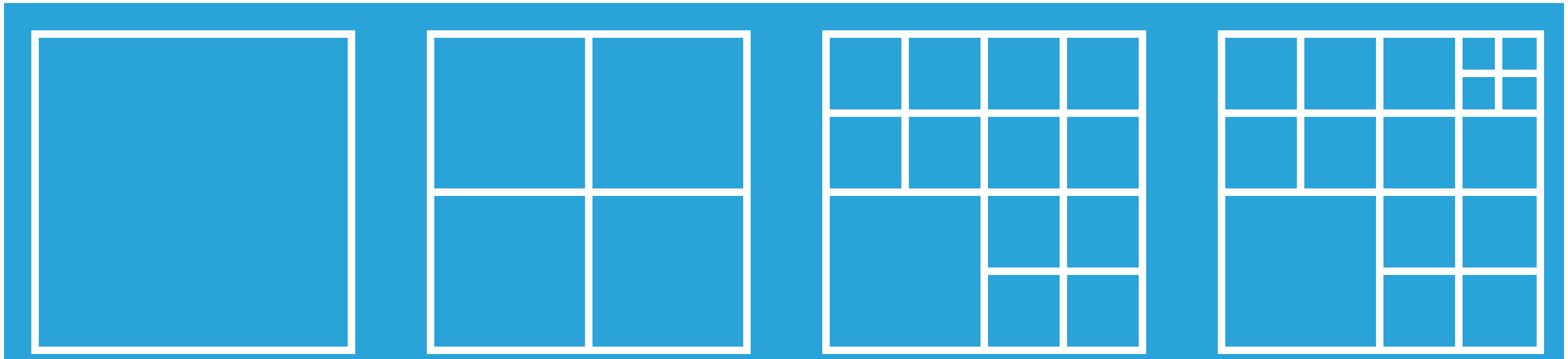
- Uniform array of height values
- Simple to store and manipulate
- Easy to interpolate to find elevations
- Less disk/memory (only store z value)
- Easy view culling and collision detection
- Used by most implementers

TINs

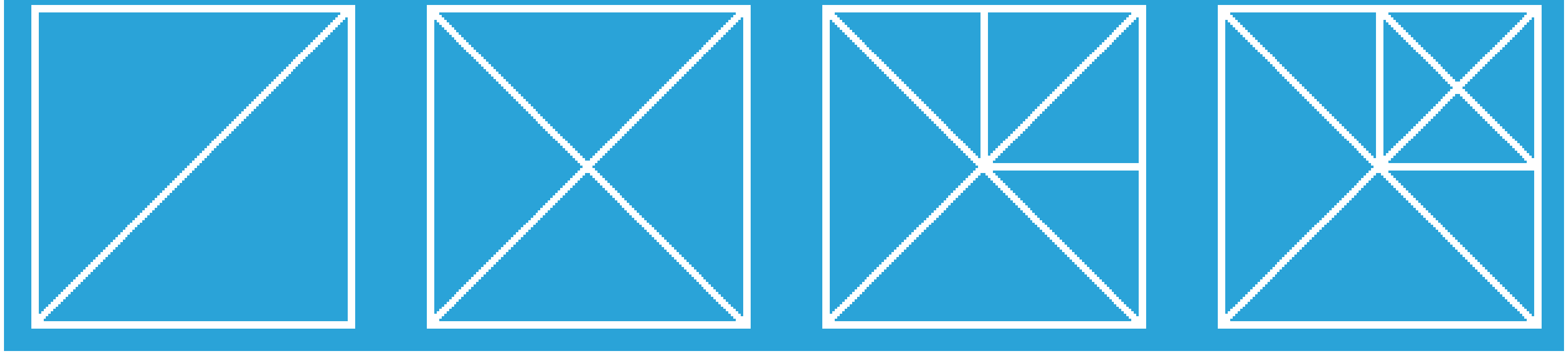


- Triangulated Irregular Networks
- Fewer polygons needed to attain required accuracy
- Higher sampling in bumpy regions and coarser in flat ones
- Can model maxima, minima, ridges, valleys, overhangs, caves

LOD Hierarchy Structures



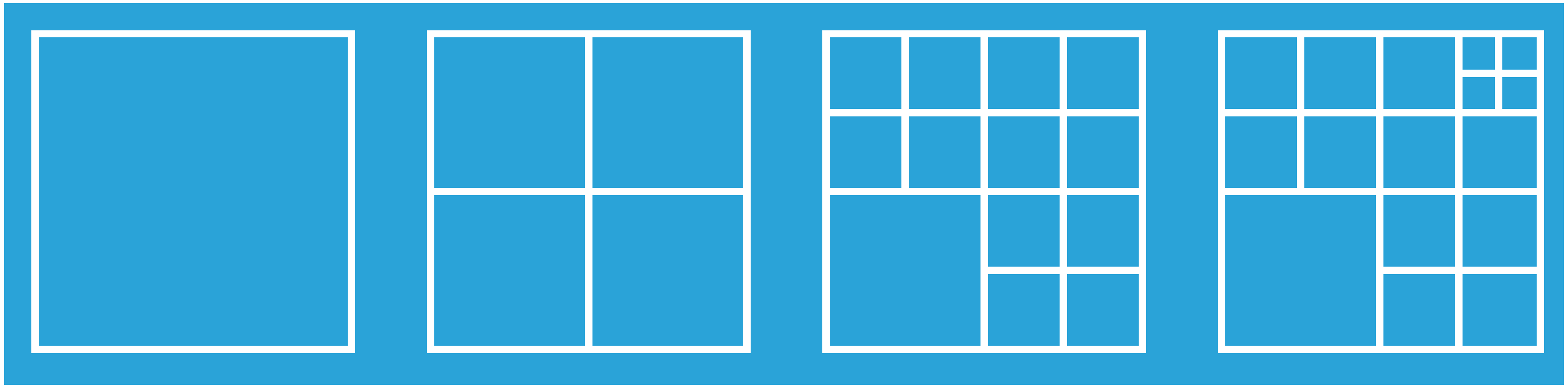
QuadTree Hierarchy



BinTree Hierarchy

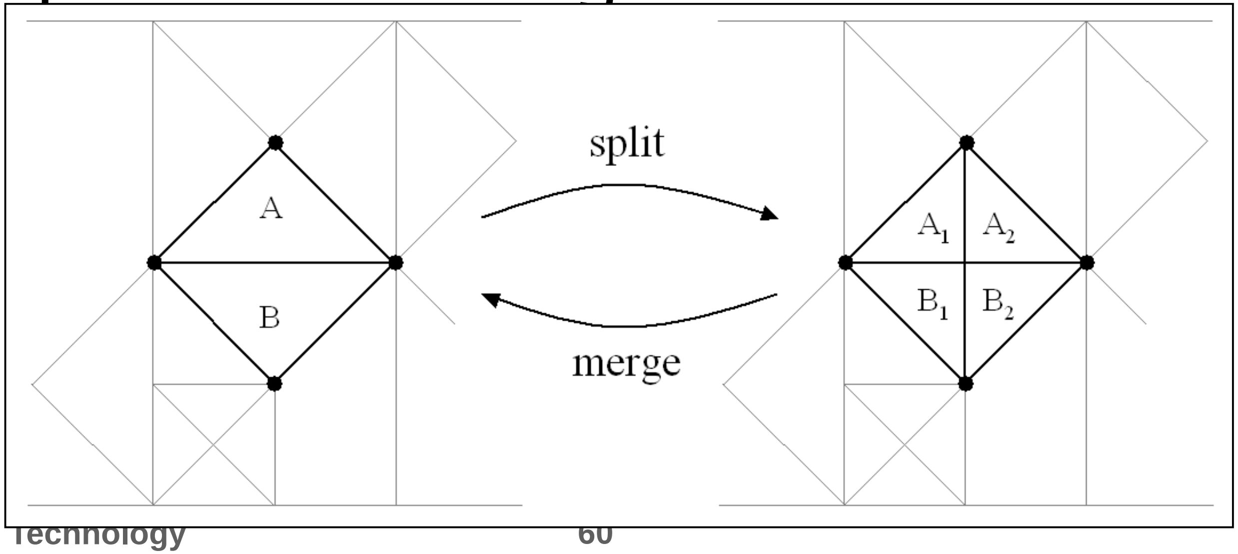
Quadtrees

- Each quad is actually two triangles
- Produces cracks and T-junctions
- Easy to implement
- Good for out-of-core operation

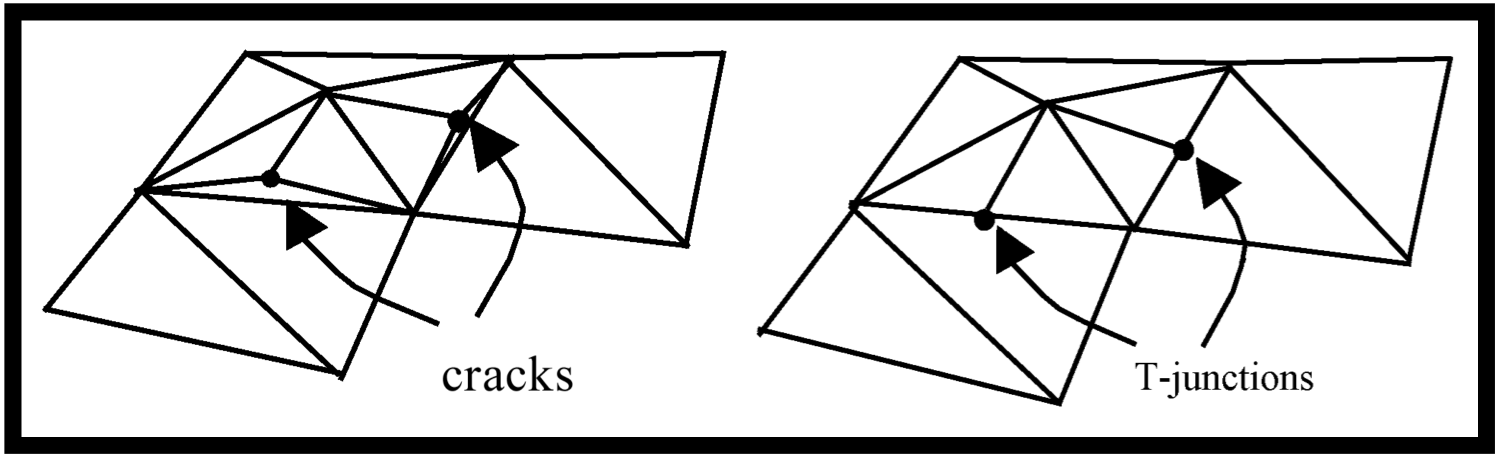


Bintrees

- Terminology
  - Binary triangle tree (bintree, bintritree, BTT)
  - Right triangular irregular networks (RTIN)
  - Longest edge bisection
- Easier to avoid cracks and T-junctions
- Neighbor is never more than 1 level away
- Very popular “ROAM” algorithm



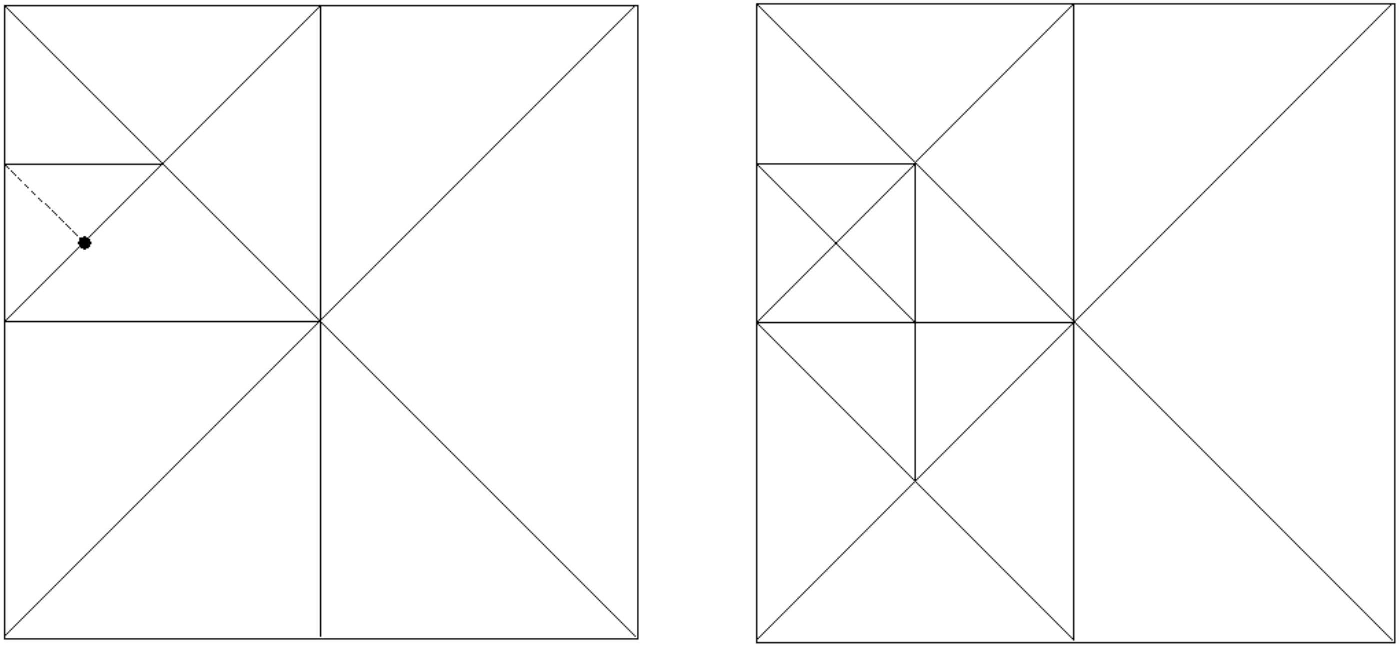
Cracks and T-Junctions



- Avoid cracks:
  - Force cracks into T-junctions / remove floating vertex
  - Fill cracks with extra triangles
- Avoid T-junctions:
  - Continue to simplify ...

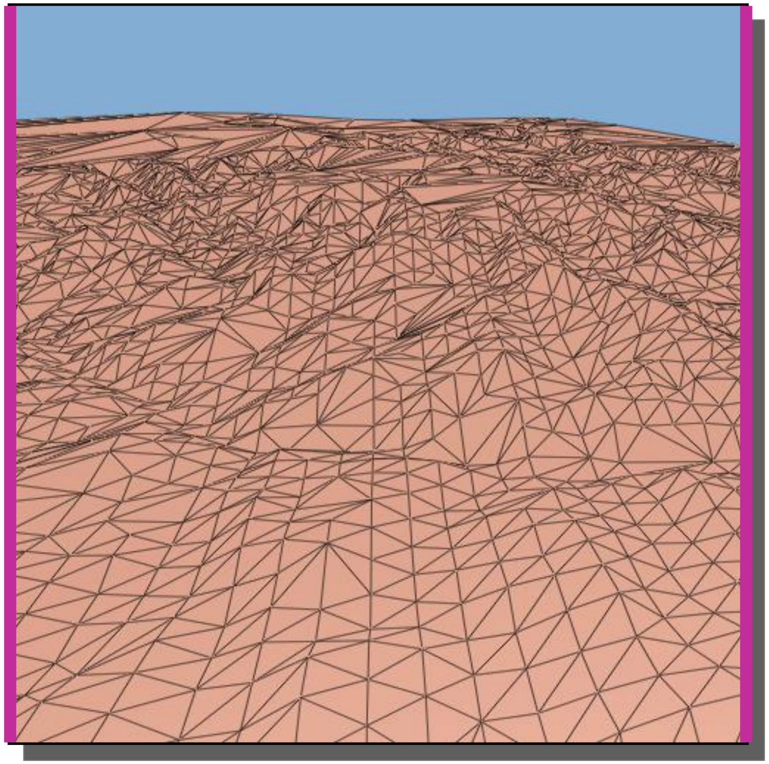
Avoiding T-junctions

- In bintrees:

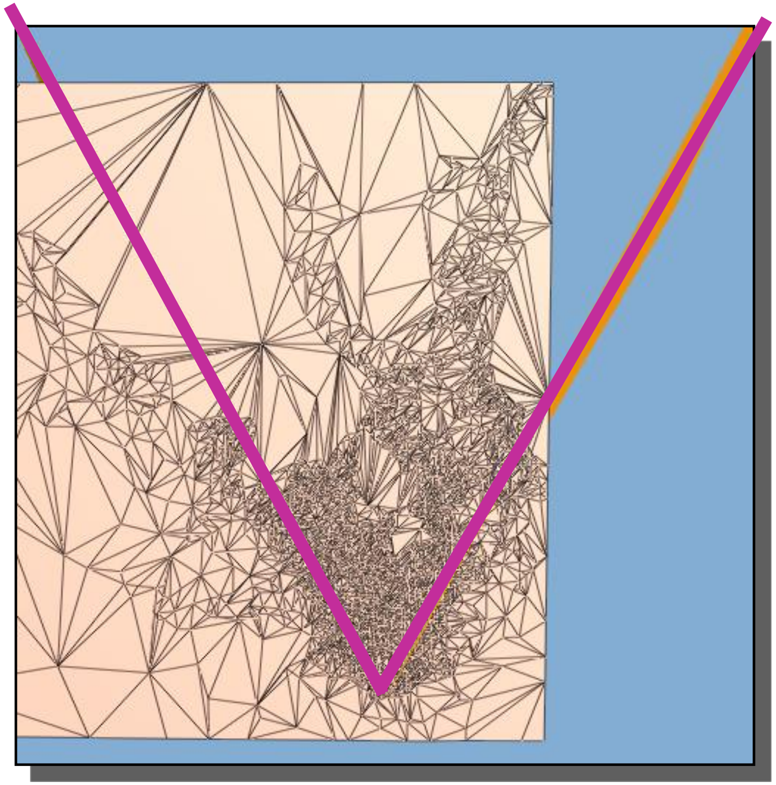


View-Dependent Terrain LOD

- Hoppe et al.



actual view



overhead view