中国科学技术大学
University of Science and Technology of China

GAMES102

GAMES 102在线课程

几何建模与处理基础

刘利刚

中国科学技术大学

中国科学技术大学
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GAMES 102在线课程：几何建模与处理基础

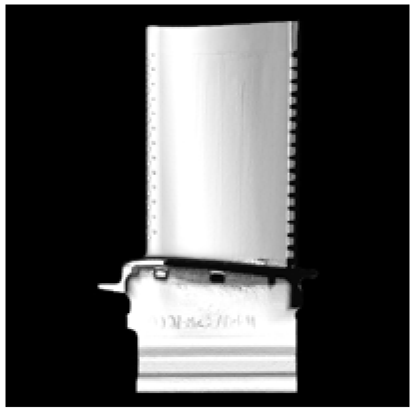
曲面简化

挑战：大规模网格数据

- 存储
- 传输
- 处理
- 渲染

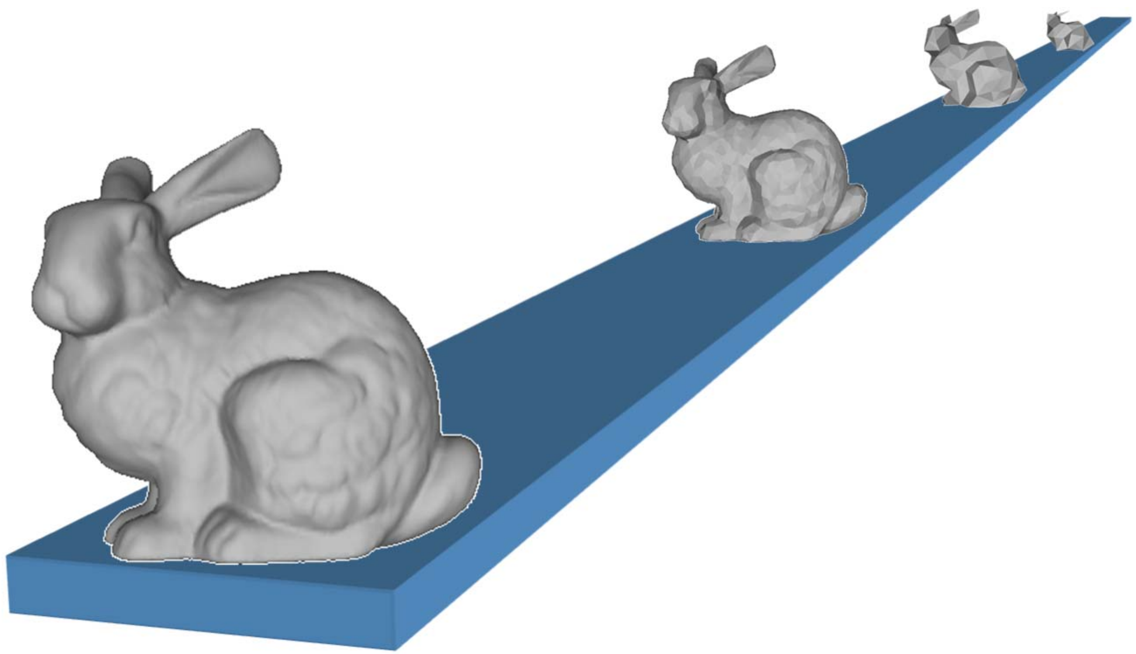
1087716 faces
543652 vertices

1765388 faces
882954 vertices



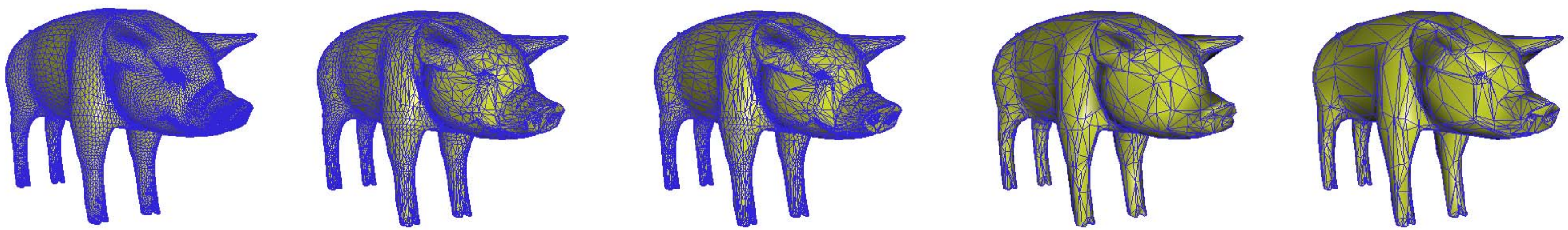
挑战：大规模网格数据

- 冗余数据：信息熵
- 在不损失视觉效果的情况下减少数据量
- Level of details (LOD)



Simplification Examples

69,451 polys   2,502 polys   251 polys   76 polys

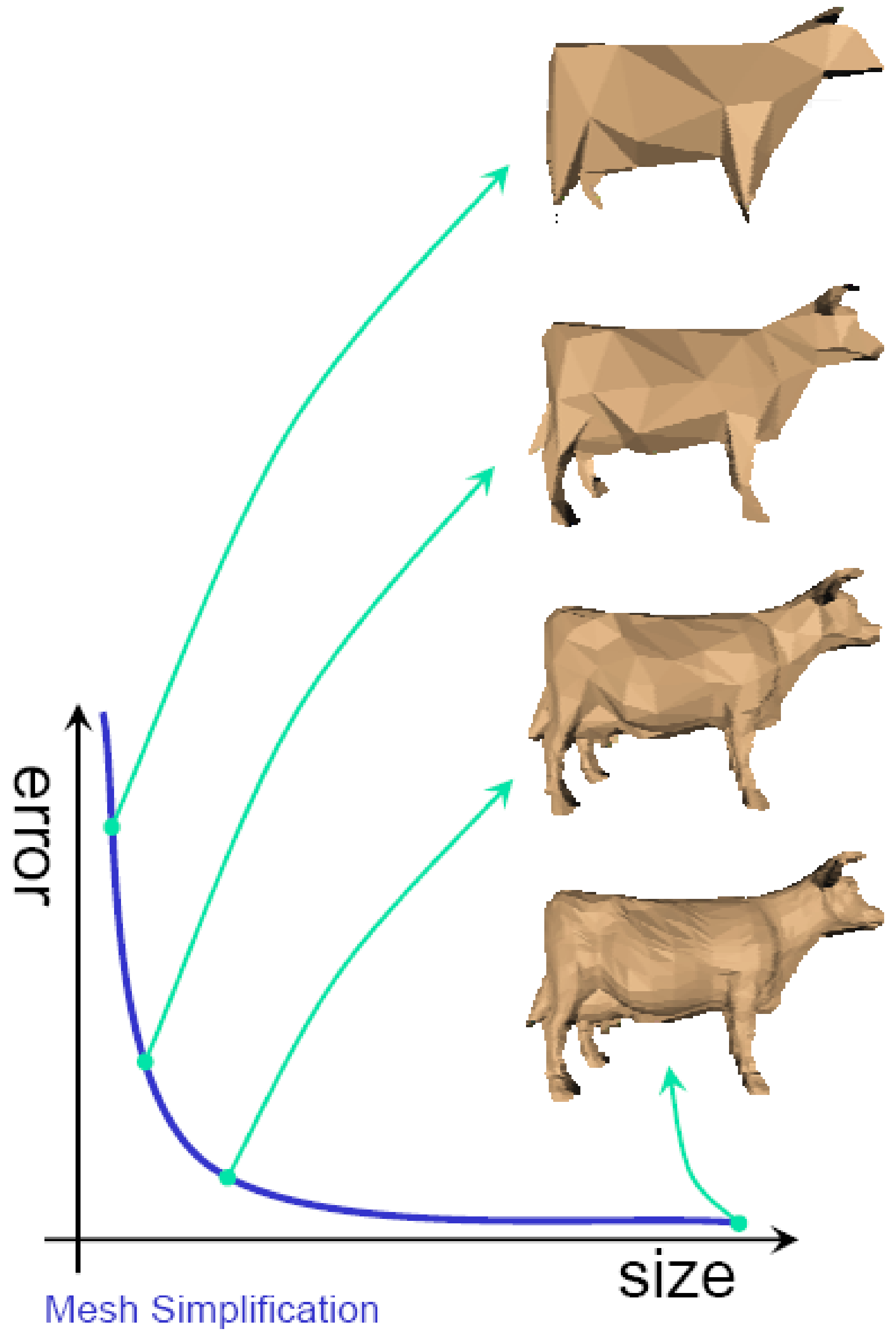


Simplification Applications

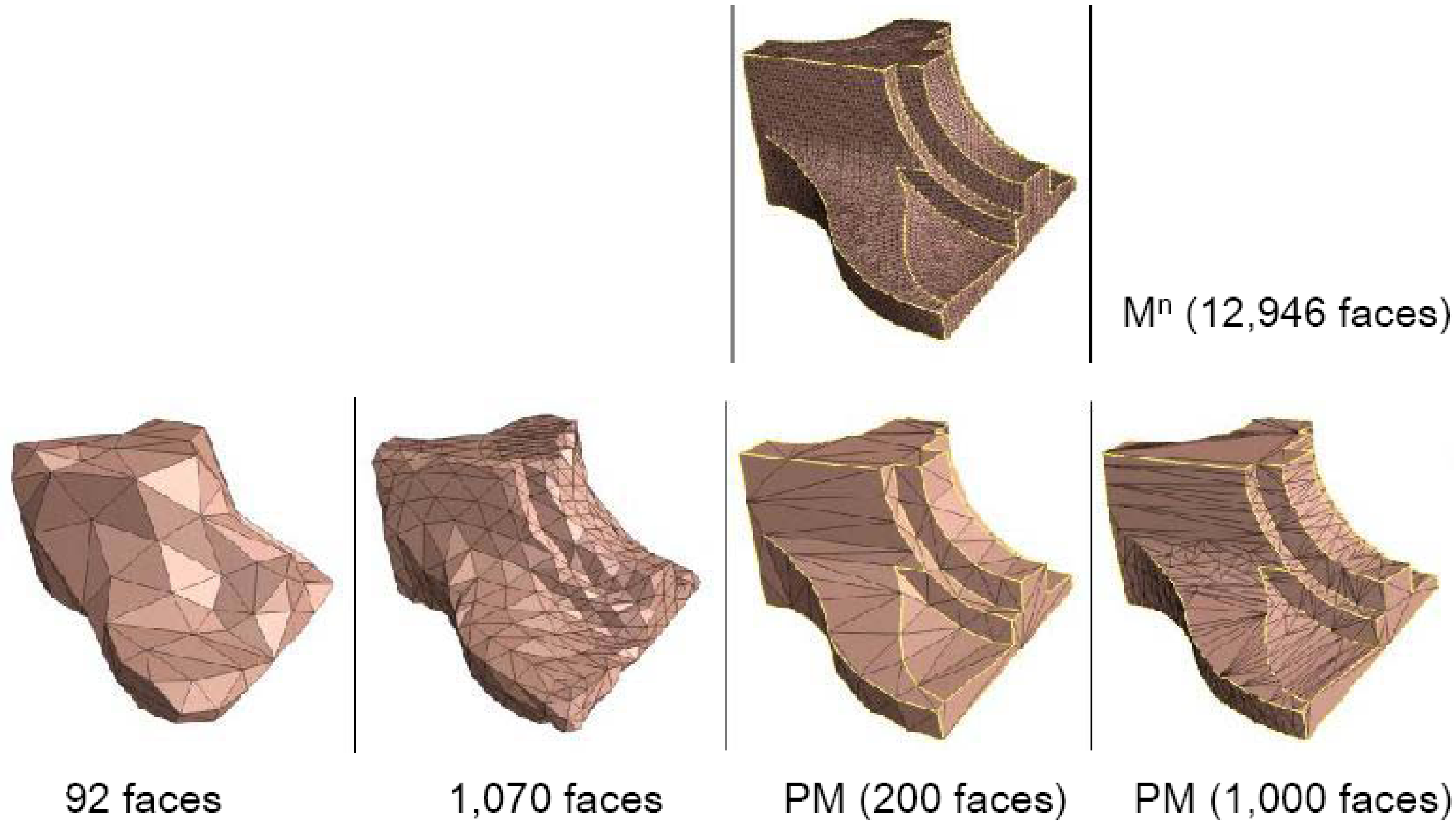
- Level-of-detail modeling
  - Generate a family of models for the same object with different polygon counts
  - Select the appropriate model based on estimates of the object's projected size
- Simulation proxies
  - Run the simulation on a simplified model
  - Interpolate results across a more complicated model to be used for rendering

Tradeoff

- Size
- Error



Quality



Performance Requirements

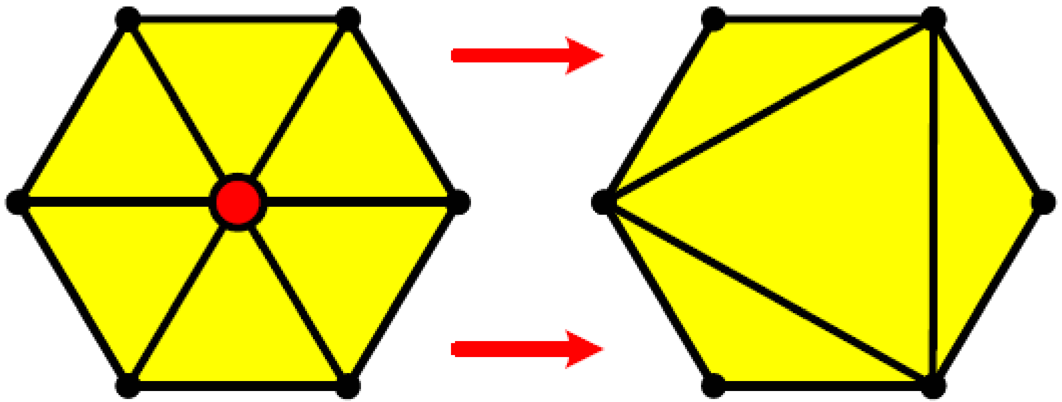
- Offline
  - Generate model at given level(s) of detail
  - Focus on quality
- Real-time
  - Generate model at given level(s) of detail
  - Focus on speed
  - Requires preprocessing
  - Time/space/quality tradeoff

简化方法

- 几何对象
  - 顶点
  - 边
  - 面
- 简化度量
  - 几何
  - 视觉：纹理、材质、法向...

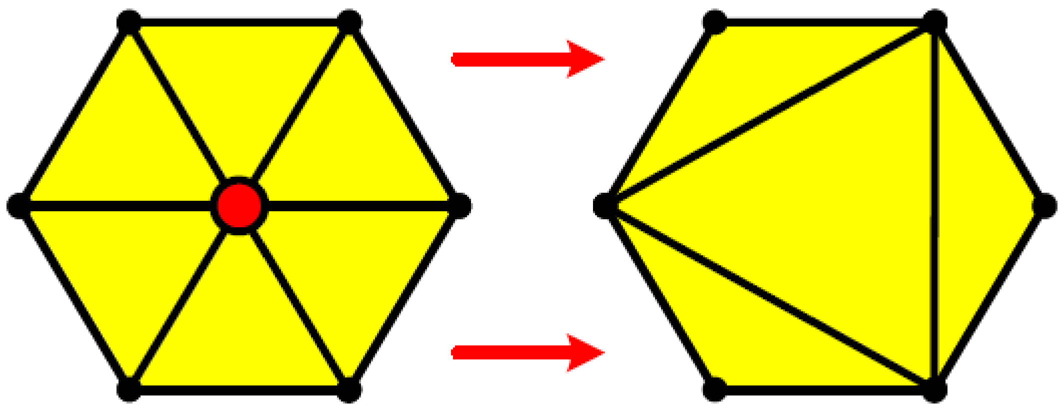
Methodology

- Sequence of local operations
  - Involve near neighbors - only small patch affected in each operation
  - Each operation introduces error
  - Find and apply operation which introduces the least error



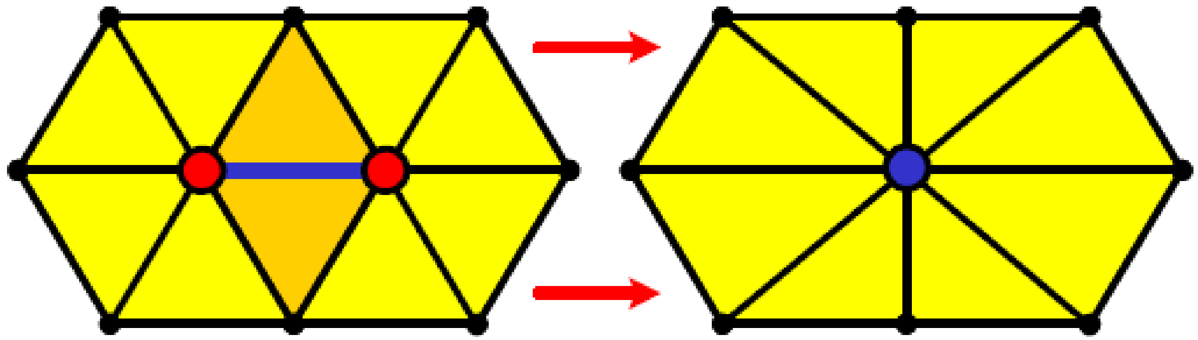
Simplification Operations (1)

- Decimation
  - Vertex removal:
    - v ← v-1
    - f ← f-2
- Remaining vertices - subset of original vertex set



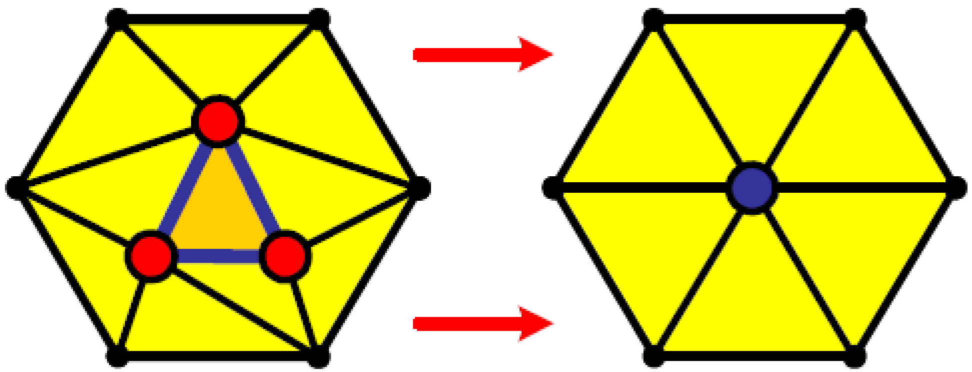
Simplification Operations (2)

- Decimation
  - Edge collapse
    - v ← v-1
    - f ← f-2
- Vertices may move



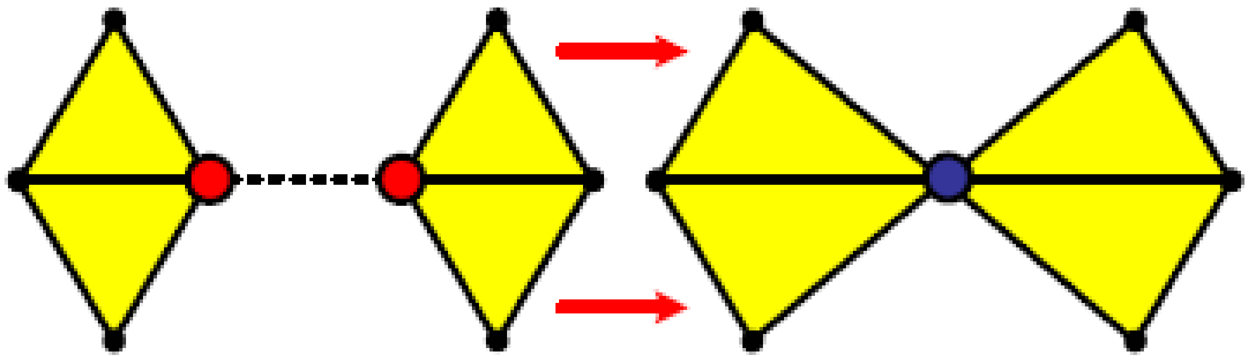
Simplification Operations (3)

- Decimation
  - Triangle collapse
    - v ← v-2
    - f ← f-4
- Vertices may move



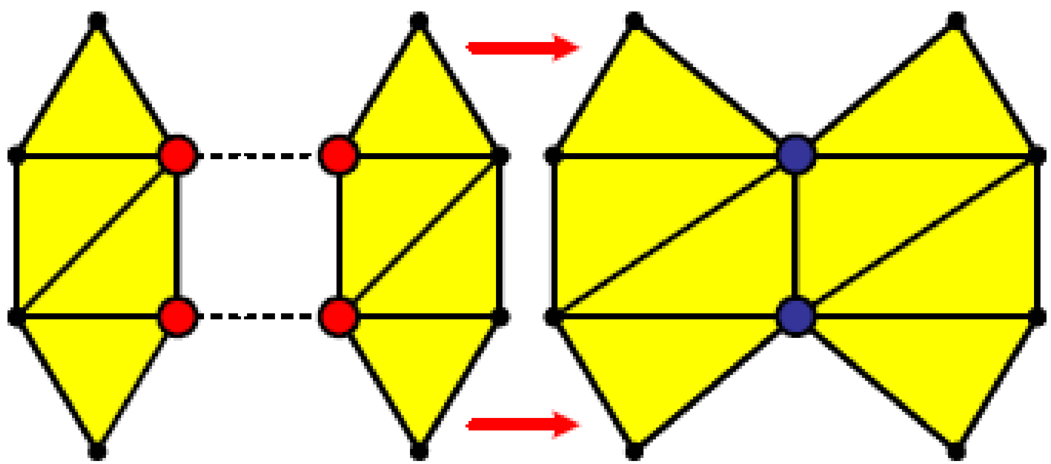
Simplification Operations (4)

- Contraction
  - Pair contraction (cluster of two vertices)
- Vertices may move



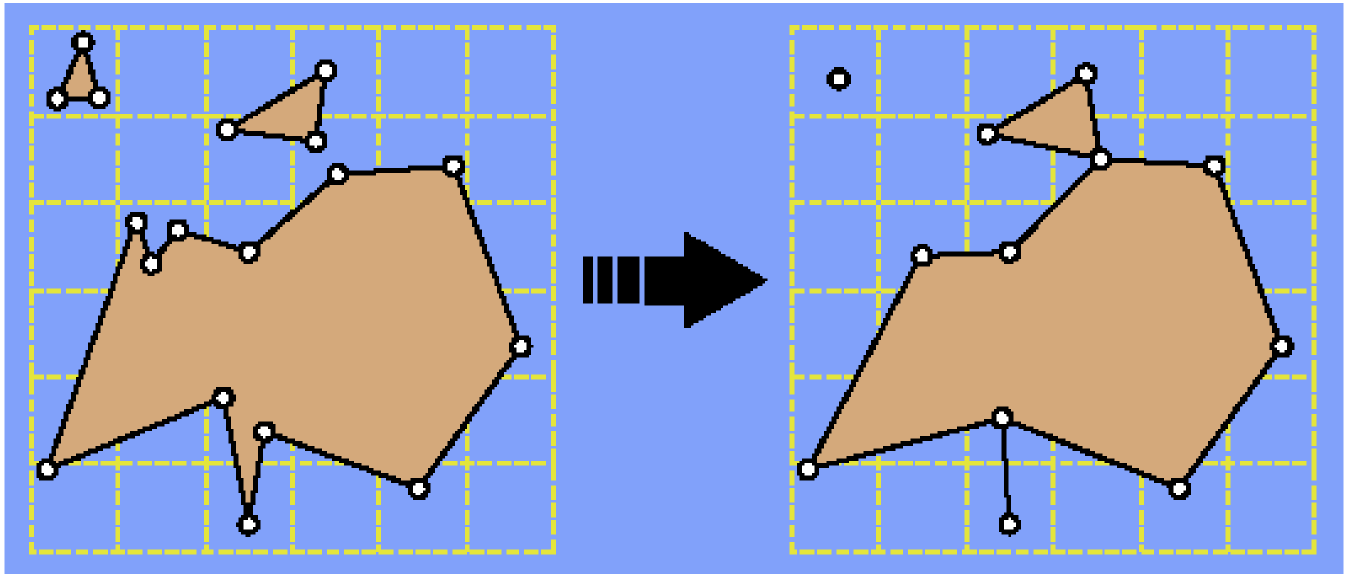
Simplification Operations (5)

- Contraction
  - Cluster contraction (set of vertices)
- Vertices may move



Simplification Operations: Vertex Clustering

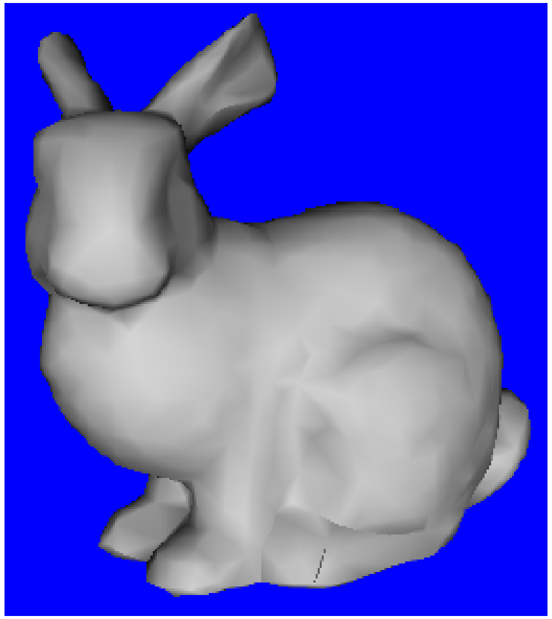
- Merge all vertices within the same cell



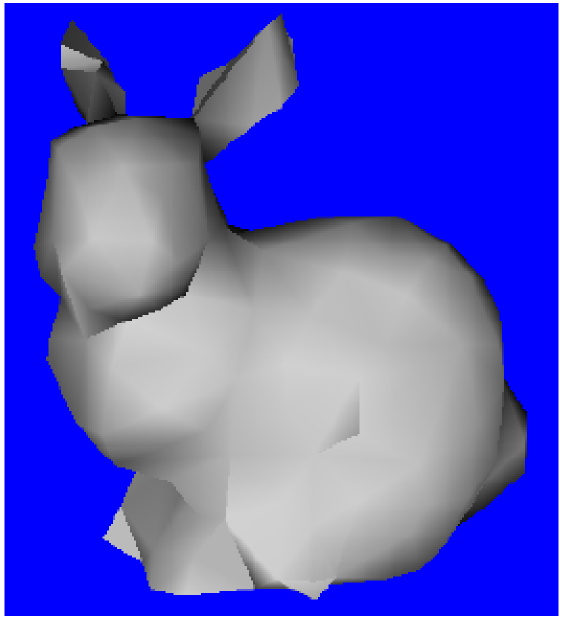
Error Control

- Local error: Compare new patch with previous iteration
  - Fast
  - Accumulates error
  - Memory-less
- Global error: Compare new patch with original mesh
  - Slow
  - Better quality control
  - Can be used as termination condition
  - Must remember the original mesh throughout the algorithm

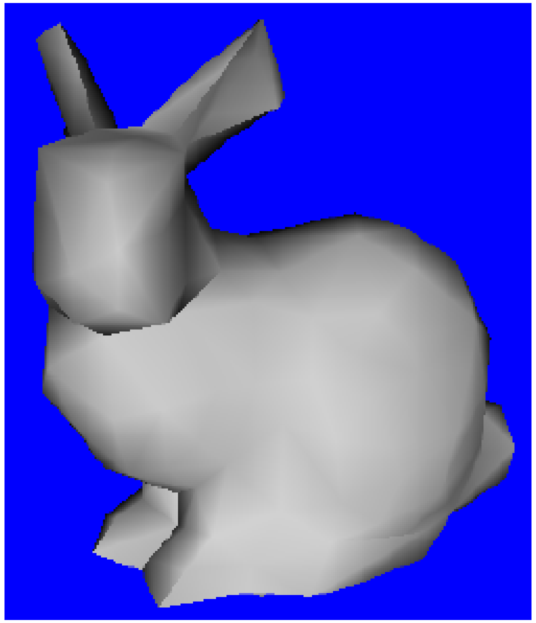
Local vs. Global Error



2000 faces



488 faces



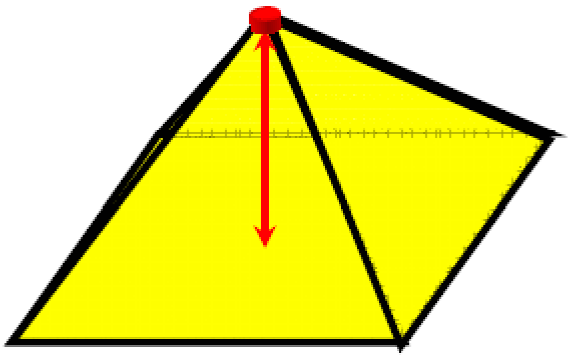
488 faces

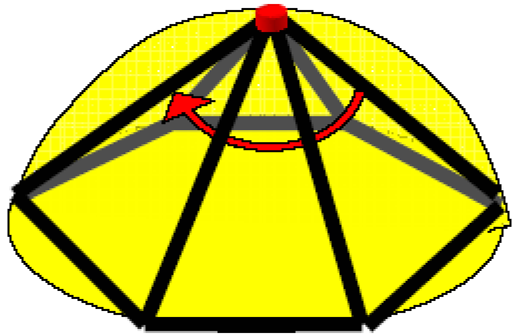
1. Local Simplification Strategies

The Basic Algorithm

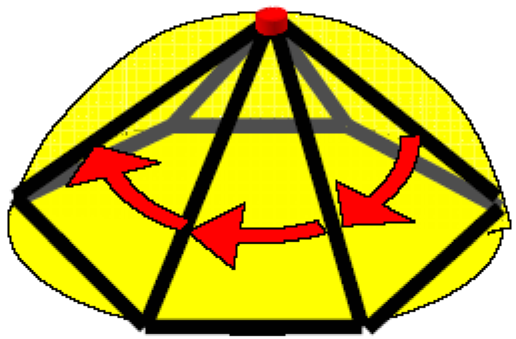
- Repeat
  - Select the element with minimal error
  - Perform simplification operation (remove/contract)
  - Update error (local/global)
- Until mesh size / quality is achieved

Simplification Error Metrics





- Measures
  - Distance to plane
  - Curvature
- Usually approximated
  - Average plane
  - Discrete curvature



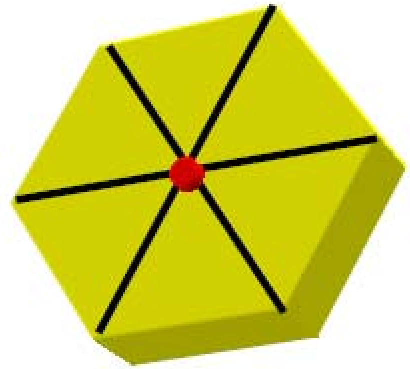
$\Sigma\alpha / 2\pi$

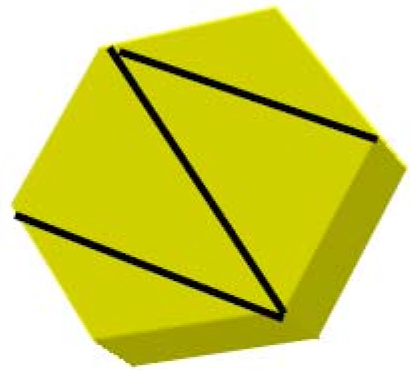
Implementation Details

- Vertices/Edges/Faces data structure
  - Easy access from each element to neighboring elements
- Use priority queue (e.g. heap)
  - Fast access to element with minimal error
  - Fast update

1.1 Vertex Removal [Schroeder et al 92]

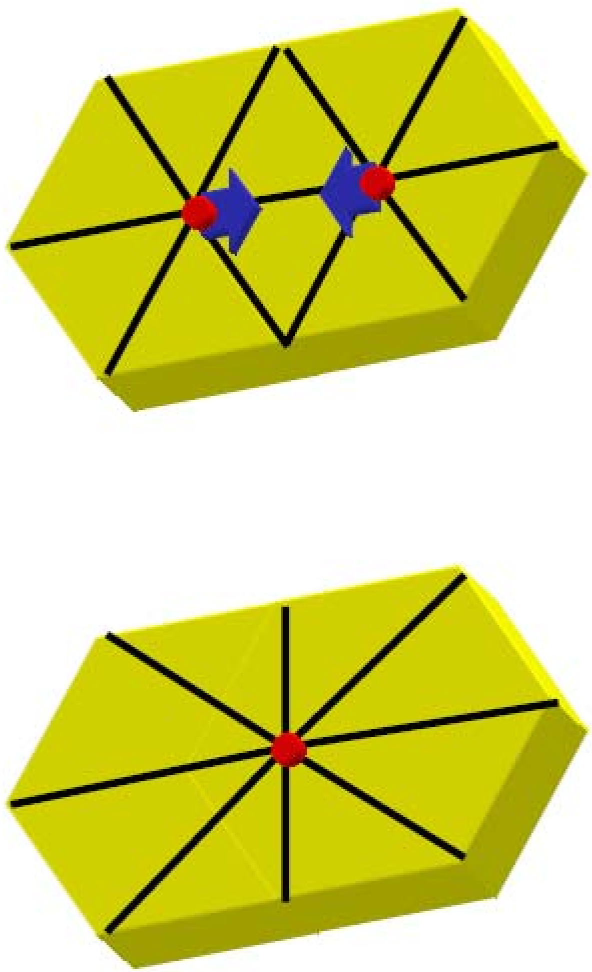
- Simplification operation: Vertex removal
- Error metric: Distance to average plane
- May preserve mesh features (creases)





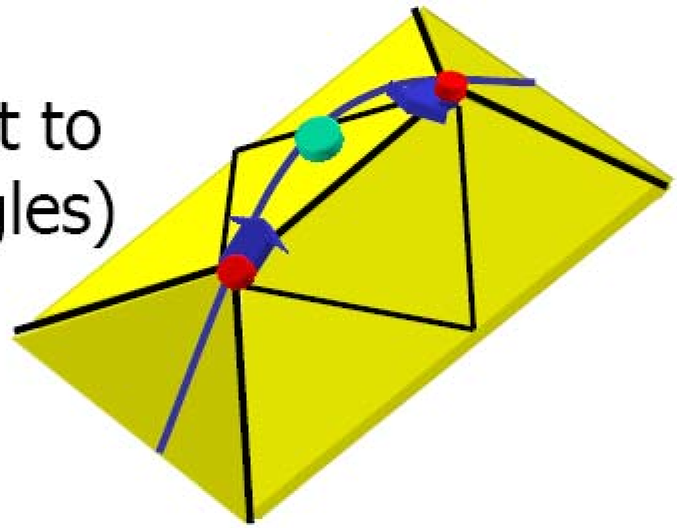
1.2 Edge Collapse [Hoppe el al 93]

- Simplification operation:
  Pair contraction
- Error metric:
  distance, pseudo-global
- Simplifies also topology

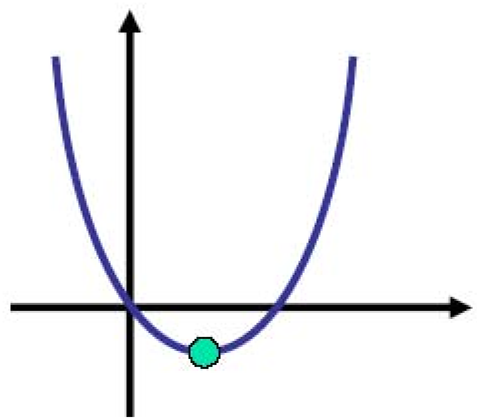


Distance Metric: Quadrics

- Choose point closest to set of planes (triangles)



- Sum of squared distances to set of planes is quadratic ⇒ has a minimum



The Quadric Error Metric (QEM)

[Garland & Heckbert 1997]

- Given a plane, we can define a quadric Q

$$Q = (\mathbf{A}, \mathbf{b}, c) = (\mathbf{n}\mathbf{n}^T, d\mathbf{n}, d^2)$$

measuring squared distance to the plane as

$$Q(\mathbf{v}) = \mathbf{v}^T \mathbf{A} \mathbf{v} + 2\mathbf{b}^T \mathbf{v} + c$$

$$Q(\mathbf{v}) = \begin{bmatrix} x & y & z \end{bmatrix} \begin{bmatrix} a^2 & ab & ac \\ ab & b^2 & bc \\ ac & bc & c^2 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} + 2\begin{bmatrix} ad & bd & cd \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} + d^2$$

Garland and Heckbert. Surface Simplification Using Quadric Error Metrics. Siggraph 1997.

The Quadric Error Metric

- Sum of quadrics represents set of planes

$$\sum_i (\mathbf{n}_i^T \mathbf{v} + d_i)^2 = \sum_i Q_i(\mathbf{v}) = \left(\sum_i Q_i \right)(\mathbf{v})$$

- Each vertex has an associated quadric
  - Error(v_i) = $Q_i(v_i)$
  - Sum quadrics when contracting $(v_i, v_j) \rightarrow v'$
  - Cost of contraction is $Q(v')$

$$Q = Q_i + Q_j = (\mathbf{A}_i + \mathbf{A}_j, \mathbf{b}_i + \mathbf{b}_j, c_i + c_j)$$

The Quadric Error Metric

- Sum of endpoint quadrics determines v'
  - Fixed placement: select v_1 or v_2
  - Optimal placement: choose *v'* minimizing ***Q*(*v'*)**

$$\nabla Q(\mathbf{v'}) = 0 \Rightarrow \mathbf{v'} = -\mathbf{A}^{-1}\mathbf{b}$$

  - Fixed placement is faster but lower quality
  - But it also gives smaller progressive meshes
  - Fallback to fixed placement if A is non-invertible

Contracting Two Vertices

- **Goal**: Given edge $e = (v_1, v_2)$, find contracted

  $v = (x,y,z)$ that minimizes $\Delta(v)$:

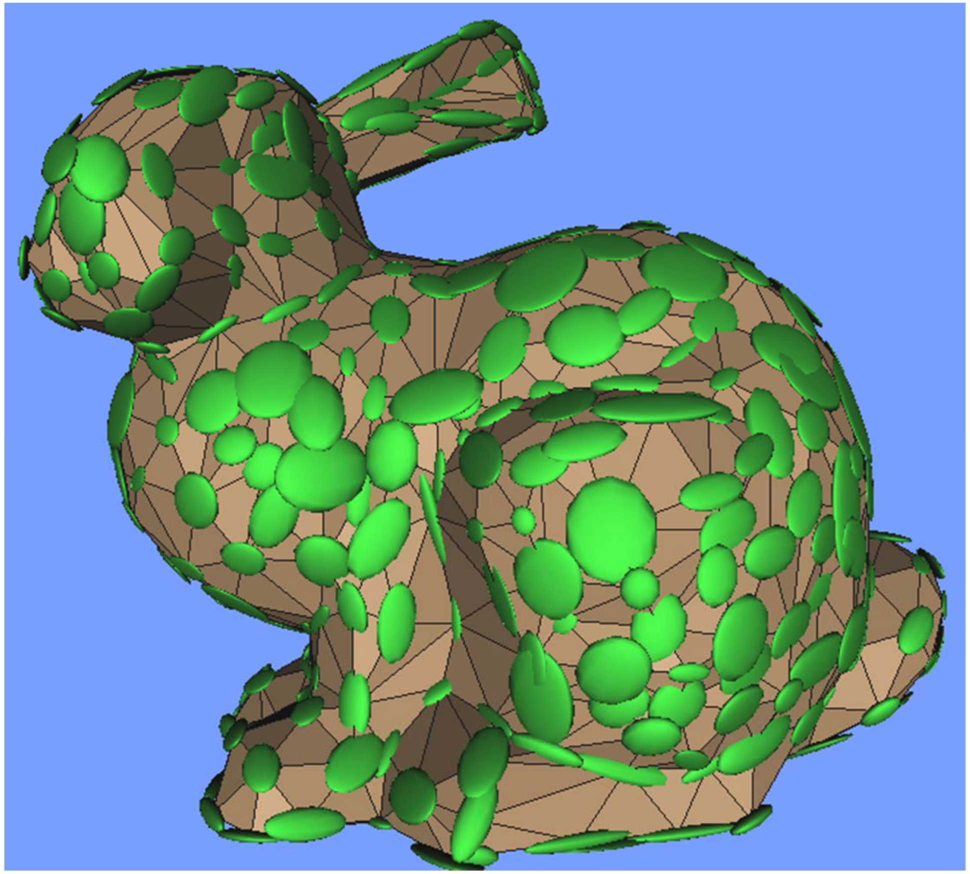
  $\partial\Delta/\partial x = \partial\Delta/\partial y = \partial\Delta/\partial z = 0$

- Solve system of linear *normal equations*:

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

If no solution - select the edge midpoint

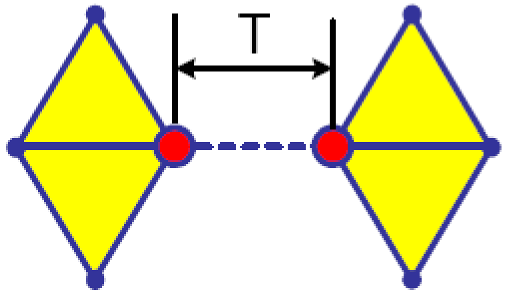
Visualizing Quadrics



- Quadric isosurfaces
  - Are ellipsoids (maybe degenerate)
  - Centered around vertices
  - Characterize shape
  - Stretch in least-curved directions

Selecting Valid Pairs for Contraction

- Edges:
  $\{(v_1,v_2) : (v_1v_2) \text{ is in the mesh}\}$

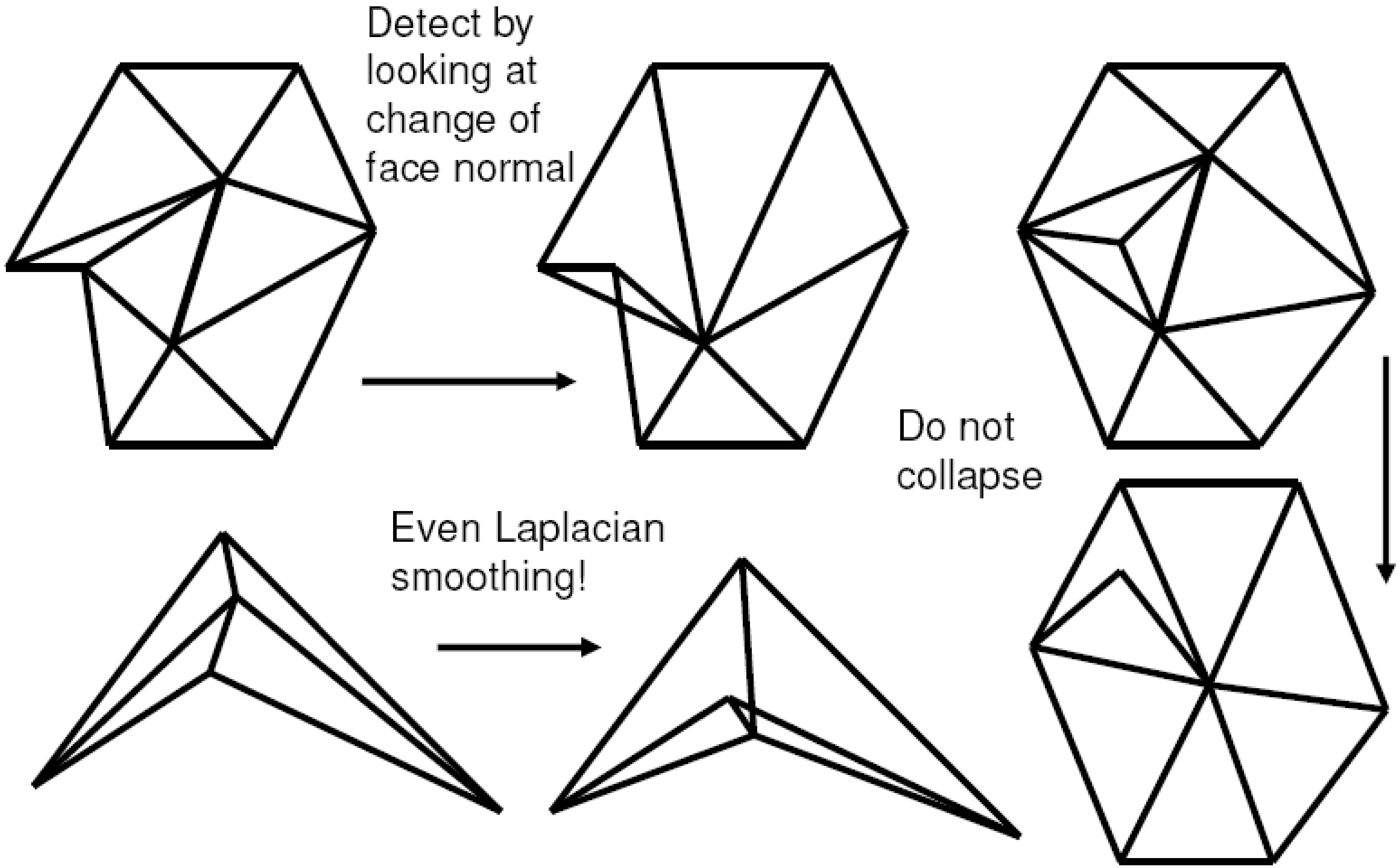


- Close vertices:
  $\{(v_1,v_2) : ||v_1 - v_2|| < T\}$
  - Threshold T is input parameter

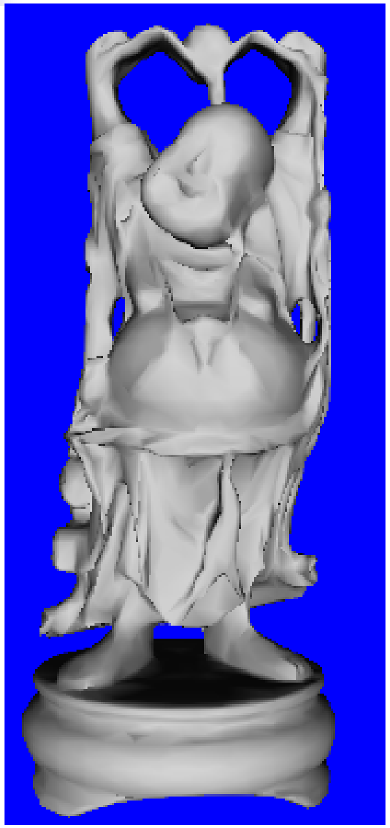
Algorithm

- Compute Q_V for all the mesh vertices
- Identify all valid pairs
- Compute for each valid pair (v_1, v_2) the contracted vertex v and its error $\Delta(v)$
- Store all valid pairs in a priority queue (according to $\Delta(v)$)
- While reduction goal not met
  - Contract edge (v_1, v_2) with the smallest error to v
  - Update the priority queue with new valid pairs

Artifacts by Edge Collapse

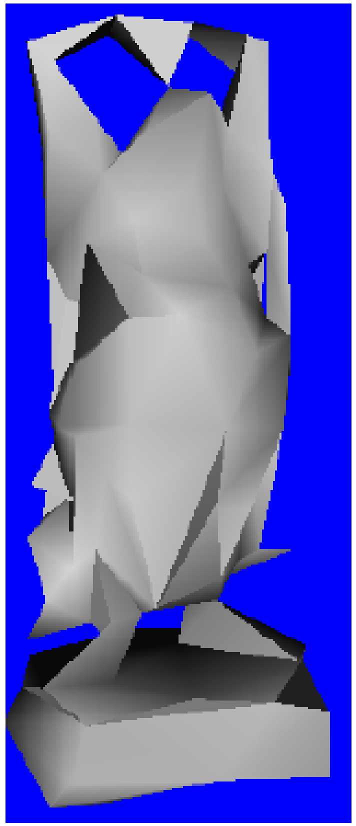


Examples



Original - 12,000

2,000 faces



298 faces (140 vertices)

Pros and Cons

- Pros
  - Error is bounded
  - Allows topology simplification
  - High quality result
  - Quite efficient
- Cons
  - Difficulties along boundaries
  - Difficulties with coplanar planes
  - Introduces new vertices not present in the original mesh

1.3 Appearance-based metrics

- Generalization required to handle appearance properties
  - color
  - texture
  - normals
  - etc.
- Treat each vertex as a 6-vector [x,y,z,r,g,b]
  - Assume this 6D space is Euclidean
    - Of course, color space is only roughly Euclidean
  - Scale xyz space to unit cube for consistency

Generalized Quadric Metric

	Vertex	Dimension
Color	[x y z r g b]	6x6 quadrics
Texture	[x y z s t]	5x5 quadrics
Normal	[x y z u v w]	6x6 quadrics
Color+Normal	[x y z r g b u v w]	9x9 quadrics

$$Q(\mathbf{v}) = \mathbf{v}^T \mathbf{A} \mathbf{v} + 2\mathbf{b}^T \mathbf{v} + c$$

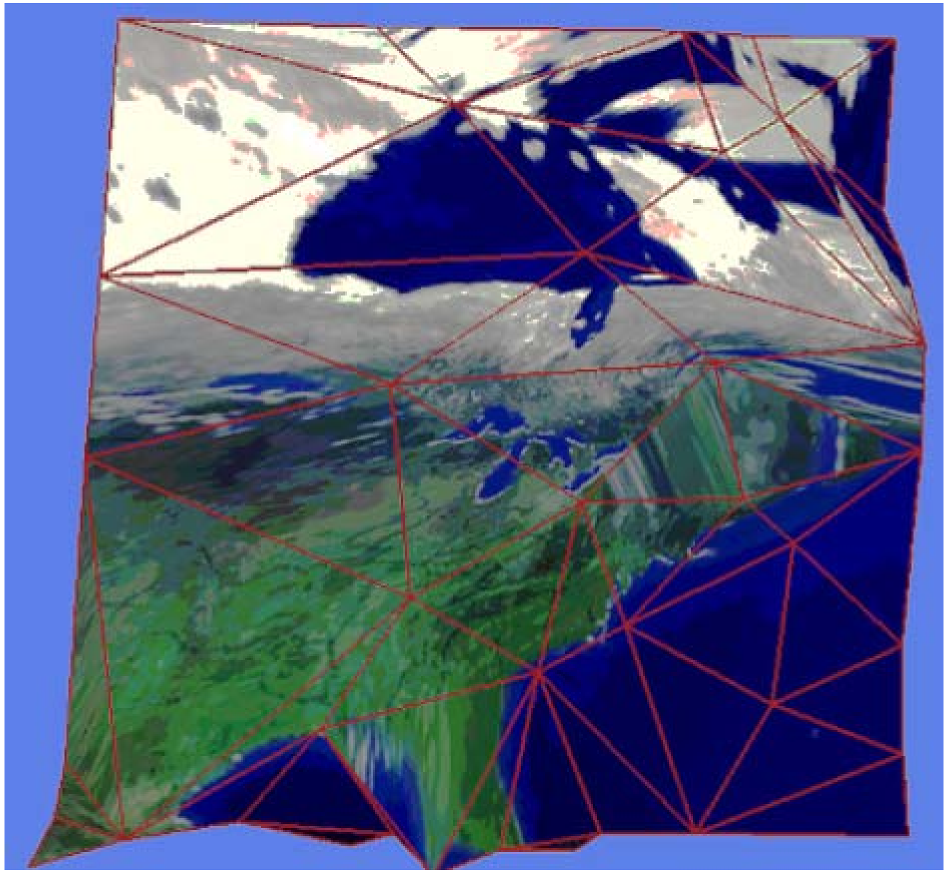
Example

50761 triangles

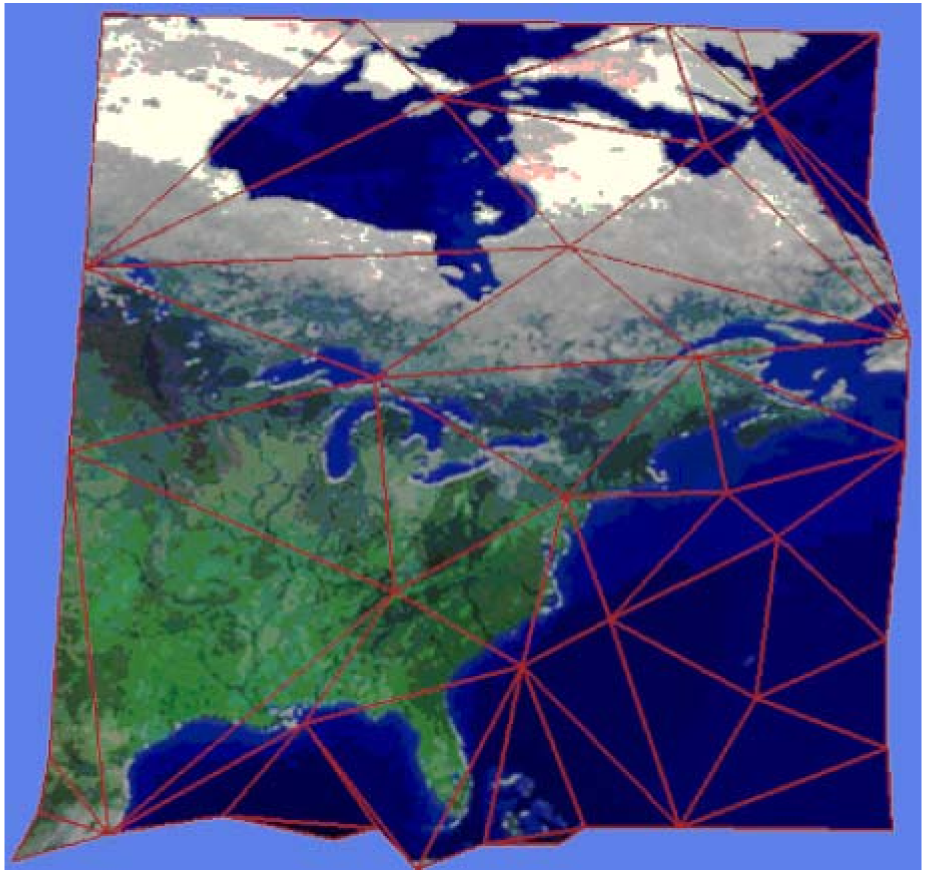
1500 triangles

A Sample Textured Surface

Comparison



Simplifying geometry only



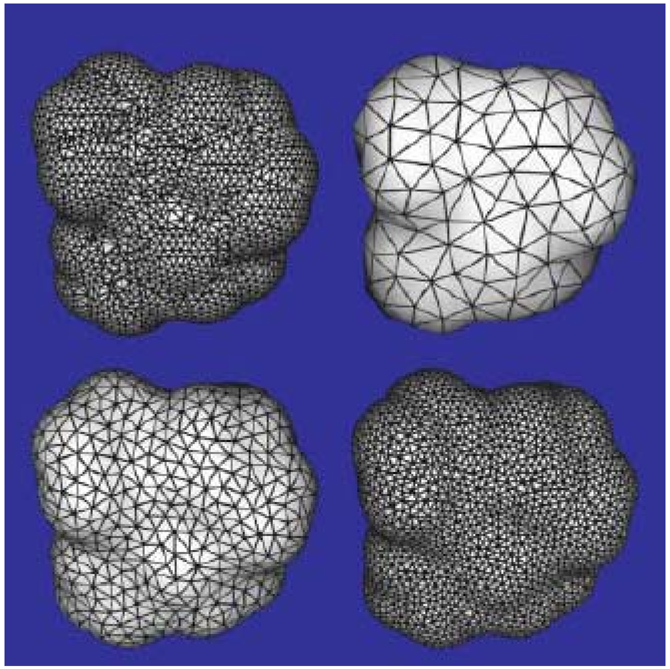
Simplifying geometry + texture coordinates

2. Global Simplification Strategies

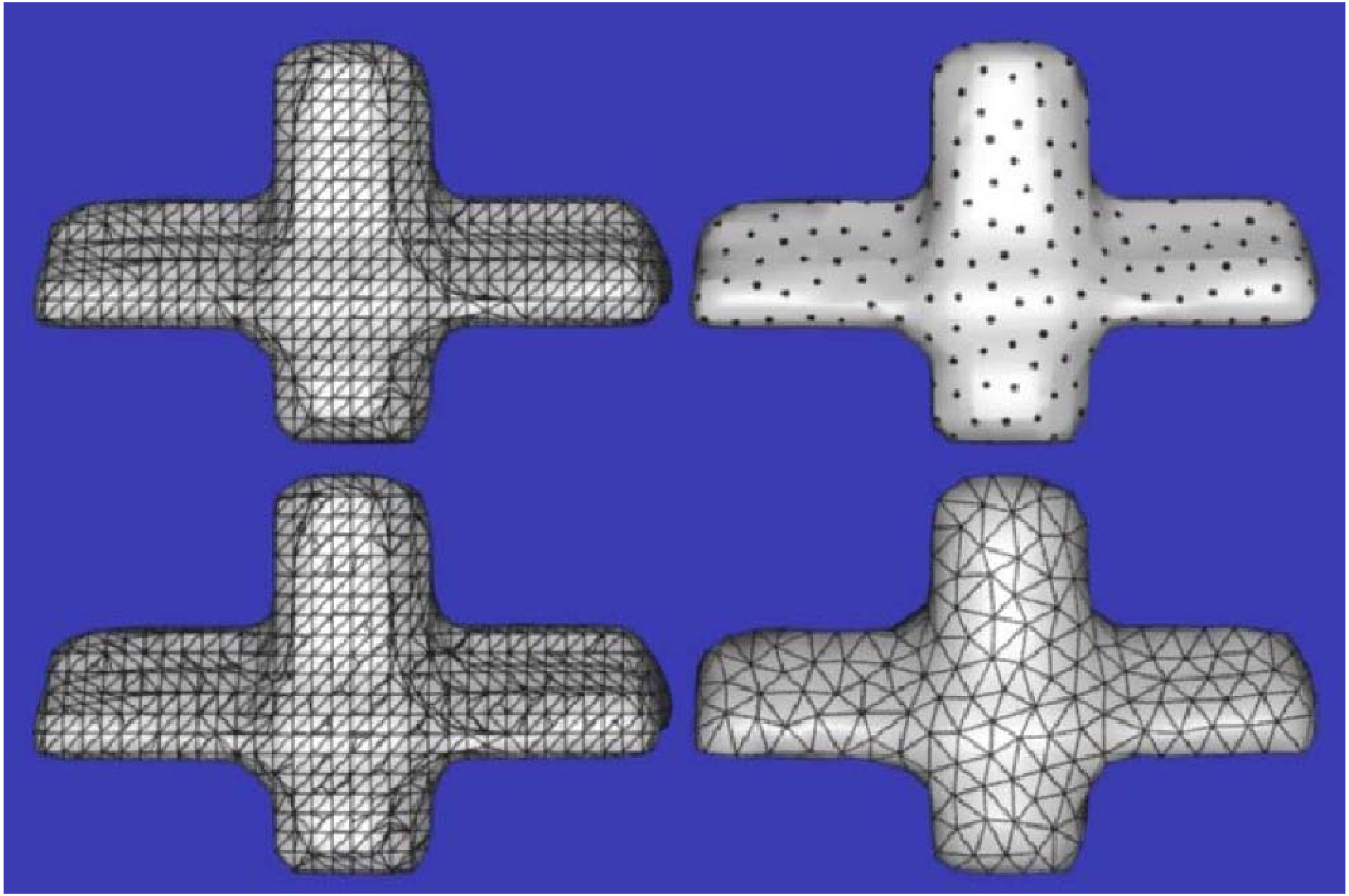
Resampling

2.1 Mesh Re-Tiling [Turk 92]

- Re-tiling attempts to simplify as well as improve meshing by introducing new “uniformly spaced” vertices



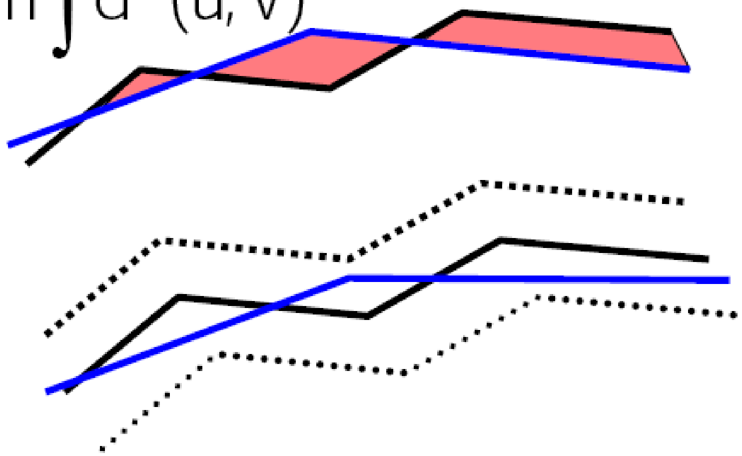
Re-Tiling Example



2.2 Mesh Optimization [Hoppe et al 93]

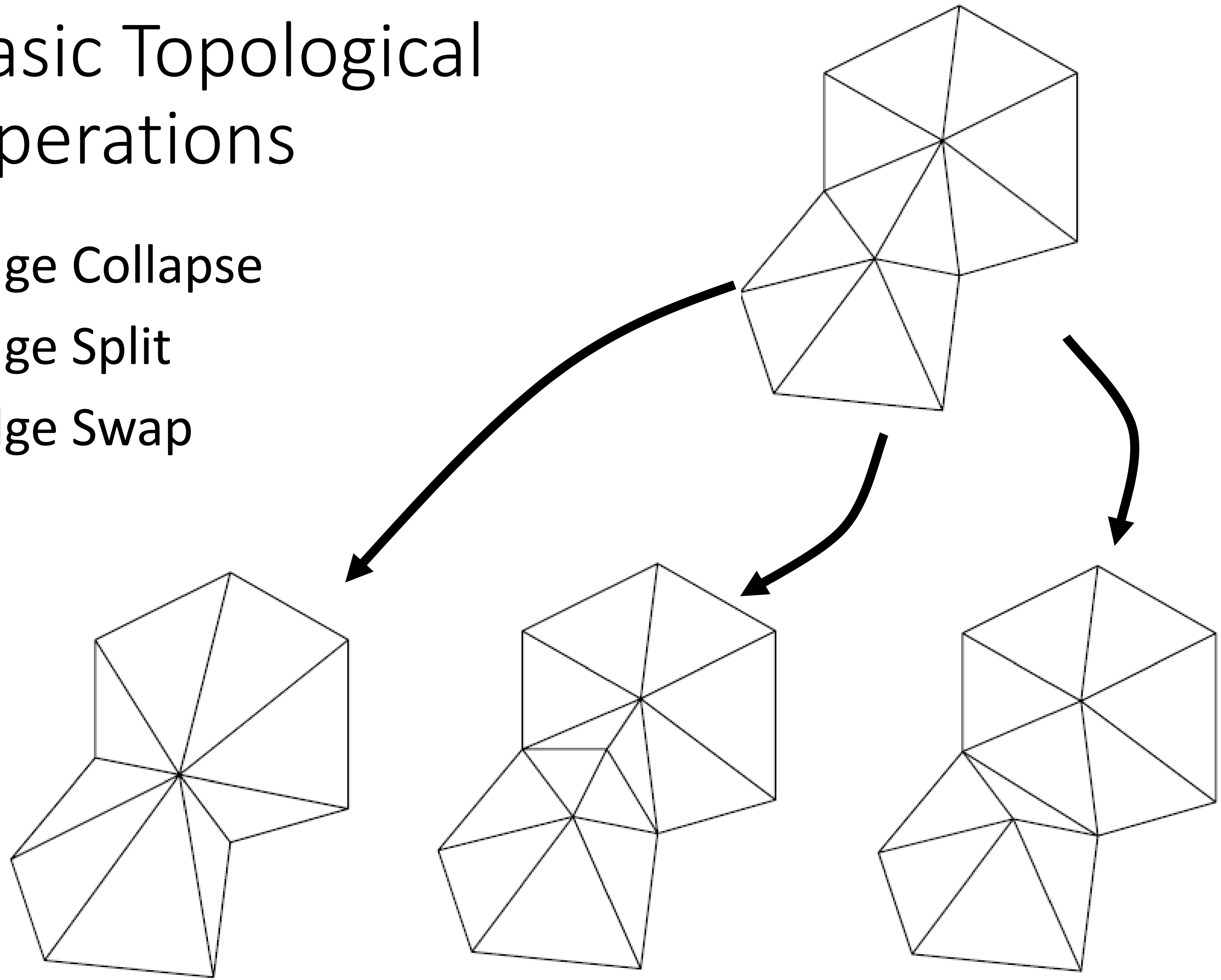
- Frames simplification as an optimization problem
  - Minimizes some energy function
  - Make simple changes to the topology of the mesh
  - Evaluate the energy before and after the change
  - Accept any change that reduces the energy

$$\min \int d^2(u, v)$$

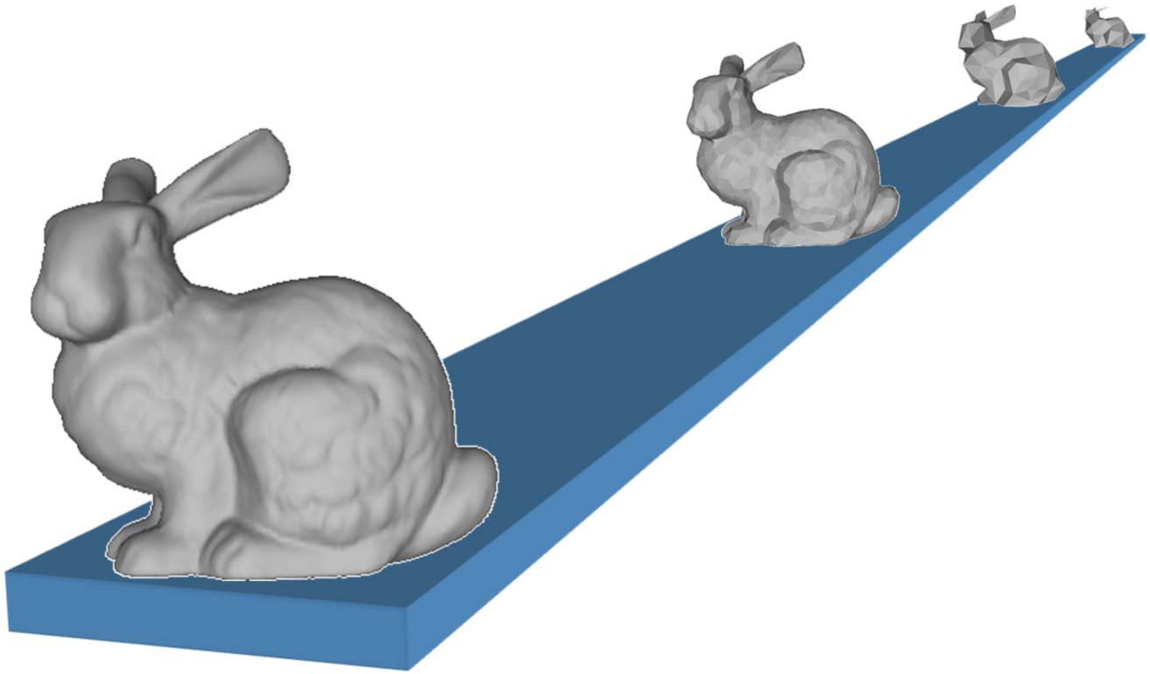


Basic Topological Operations

- Edge Collapse
- Edge Split
- Edge Swap



Level of Detail (LOD)



Multiresolution Representation

Multiresolution Representation of M

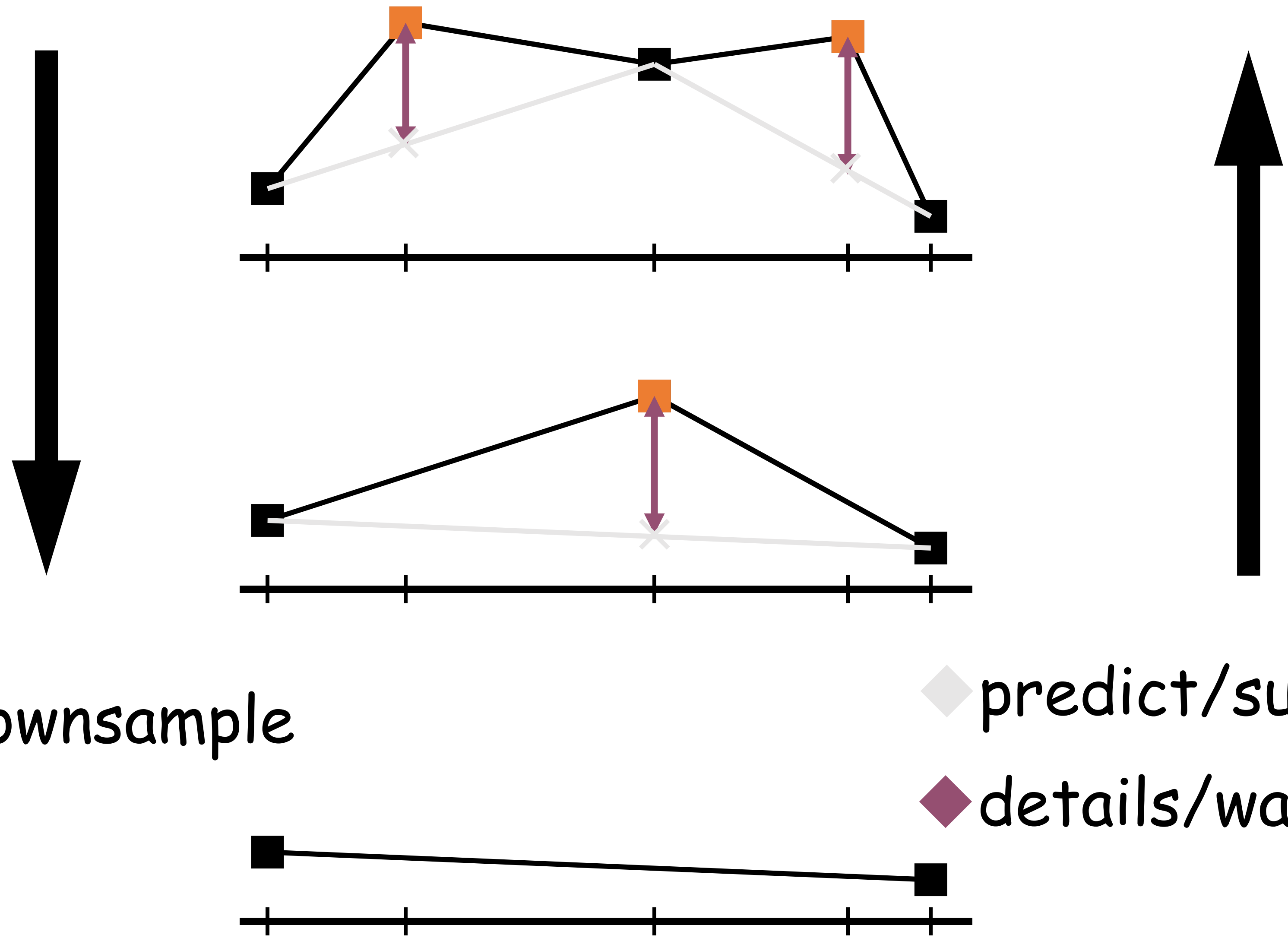
=

Base mesh M^0

+

A sequence of refinements M^i

Multiresolution



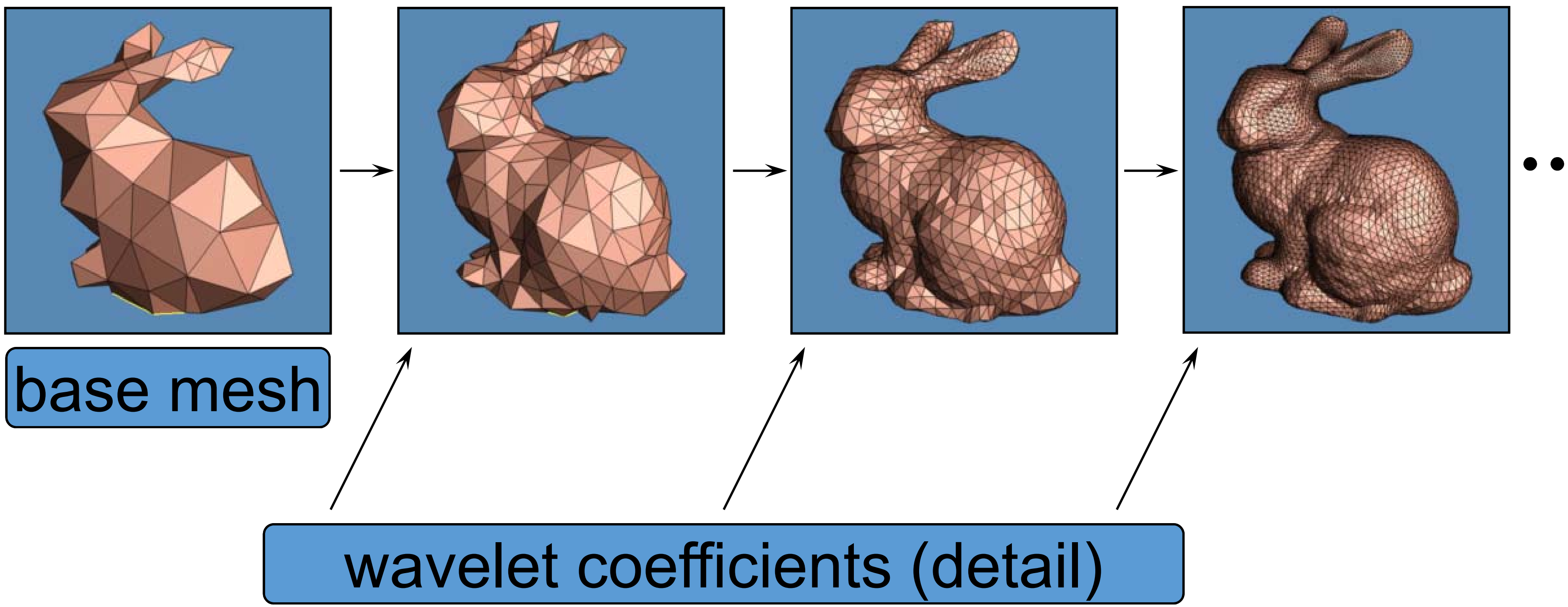
downsample

predict/subdivide

details/wavelets

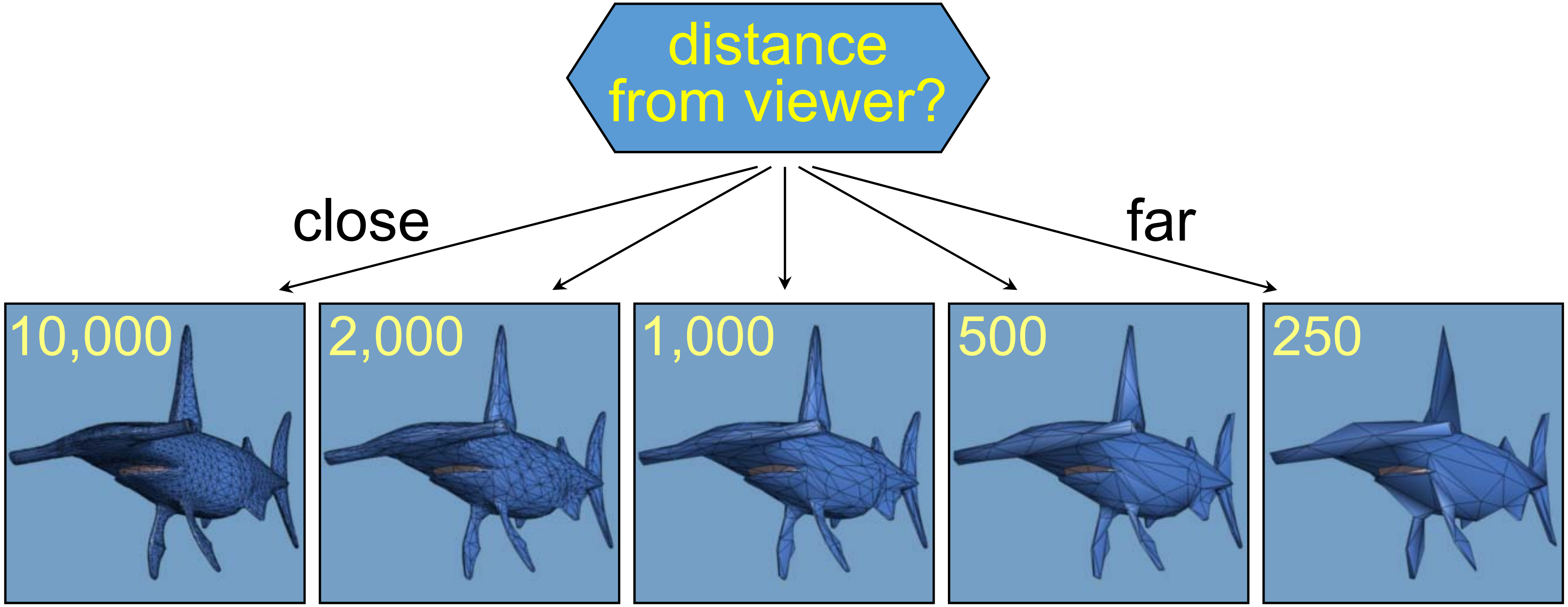
Multiresolution Analysis

[Lounsbery-etal93] [Eck-etal95] [Certain-etal96]



1. Discrete LOD

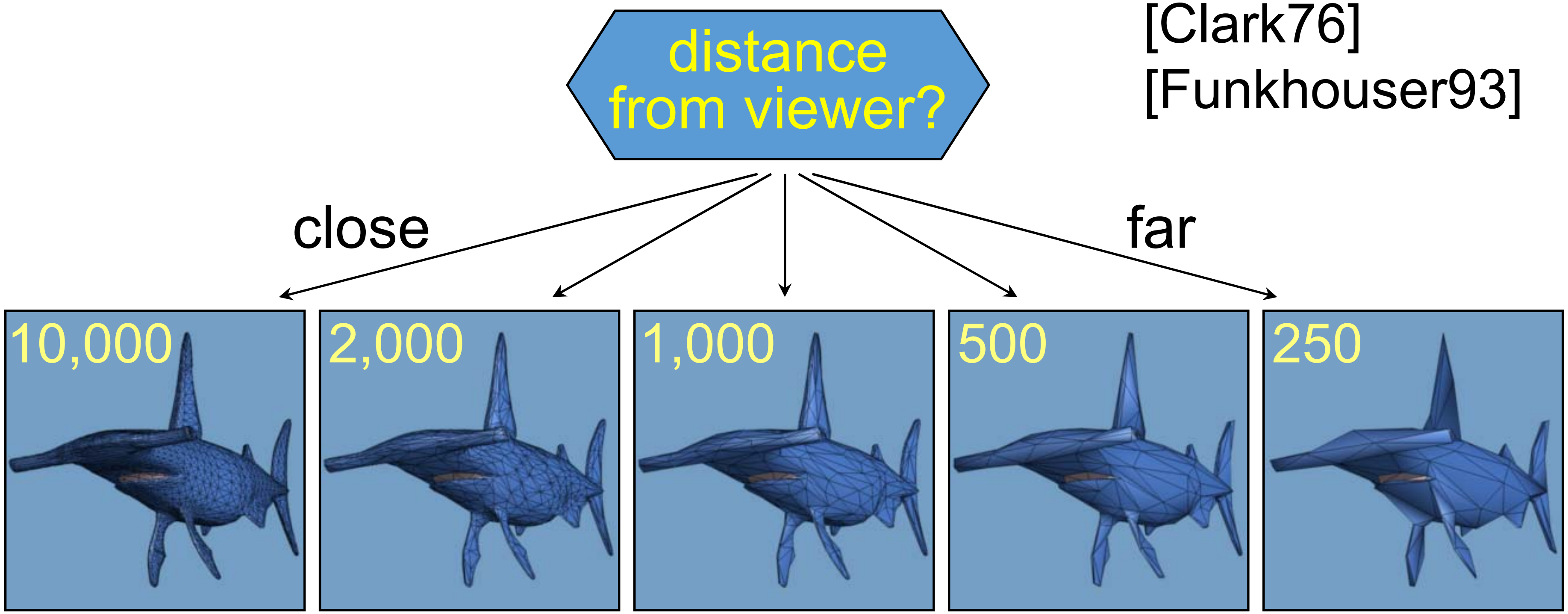
- "Pop" discontinuity



Concern: transitions may "pop"

2. Continuous LOD

[Clark76]
[Funkhouser93]

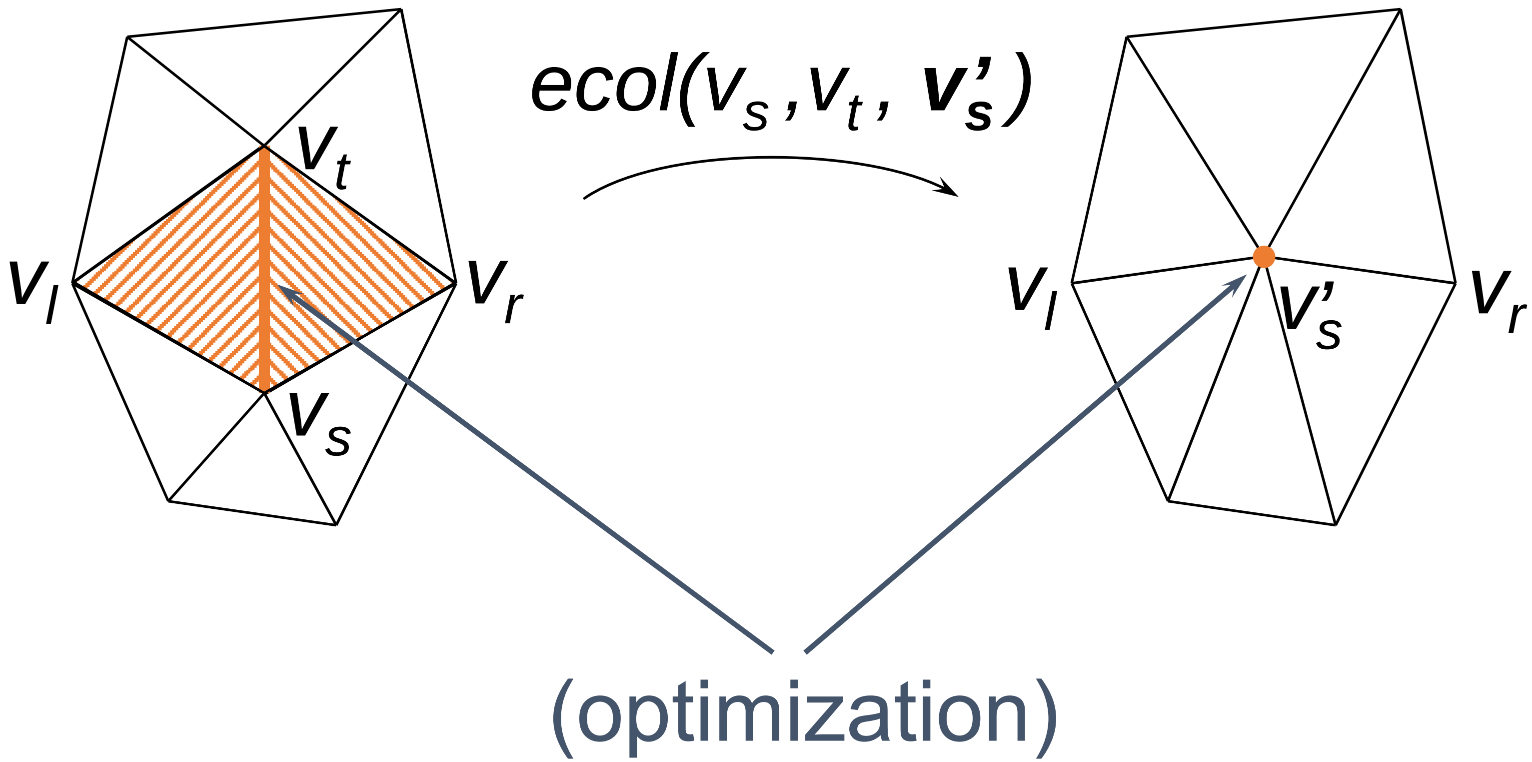


Concern: transitions may “pop”

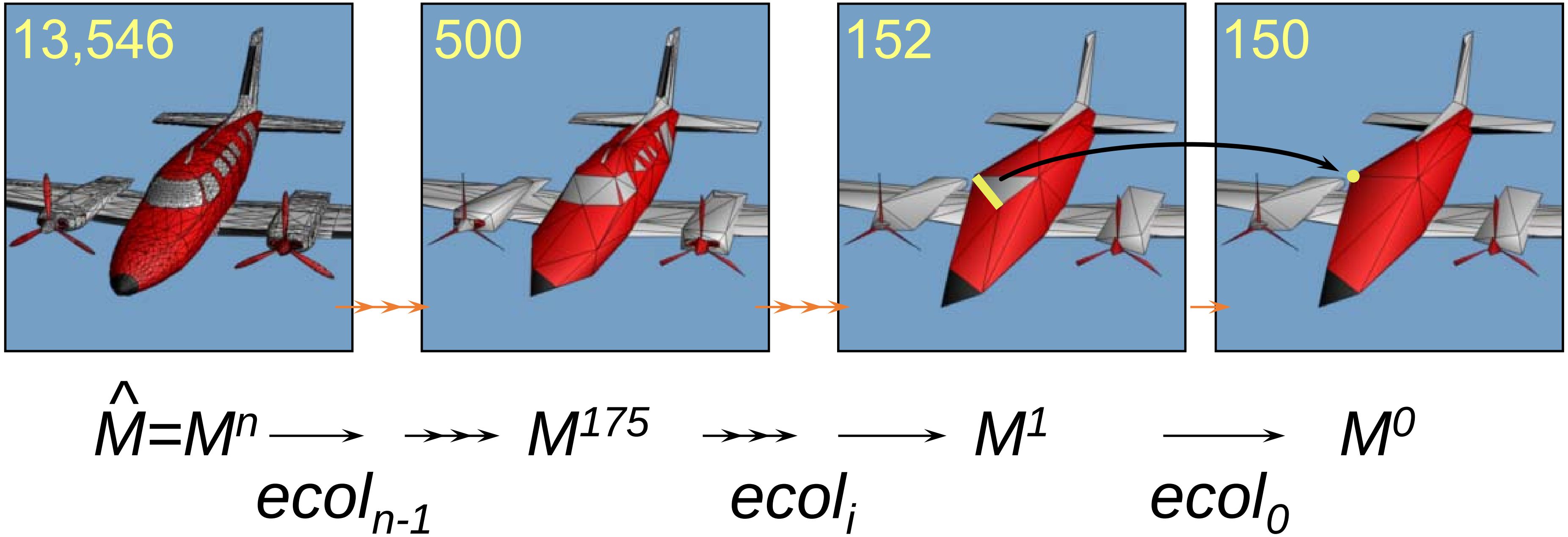
→ would like smooth LOD

Mesh Simplification Procedure

- Idea: recode sequence of edge collapses

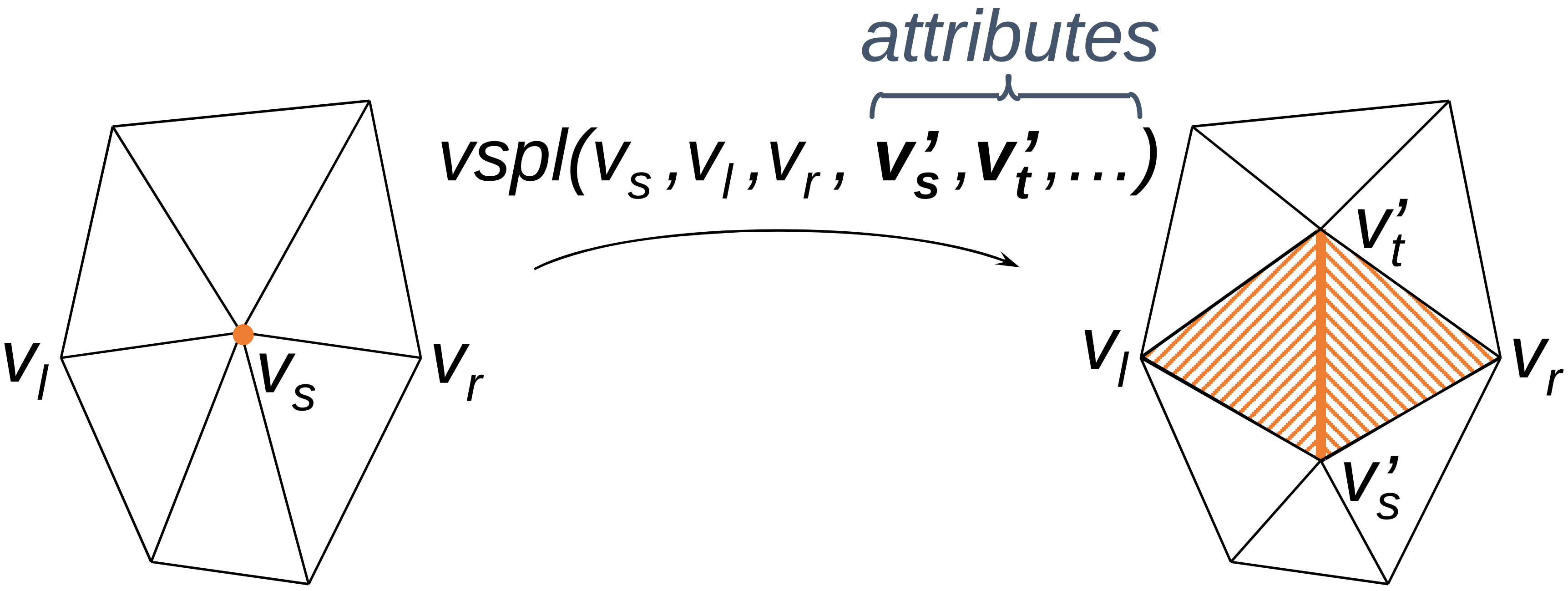


Simplification Process

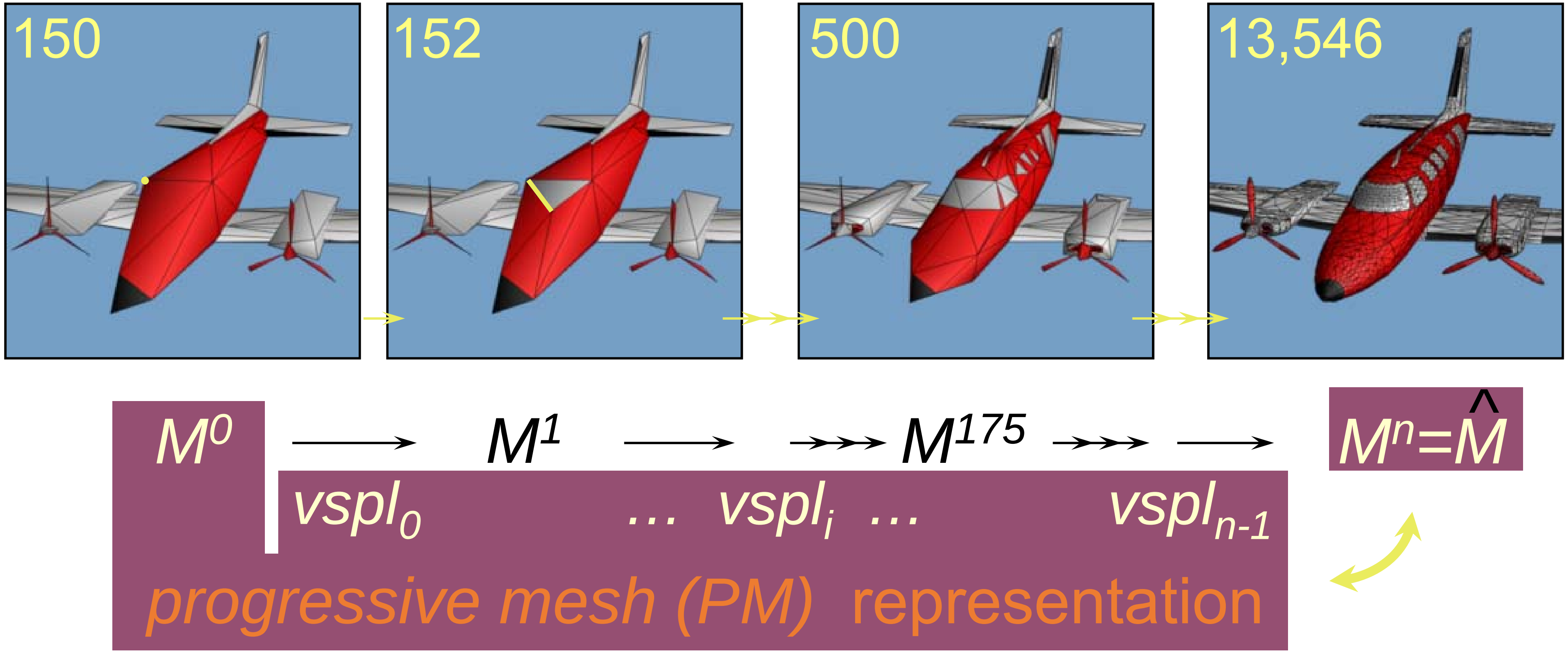


Invertible!

Vertex split transformation:

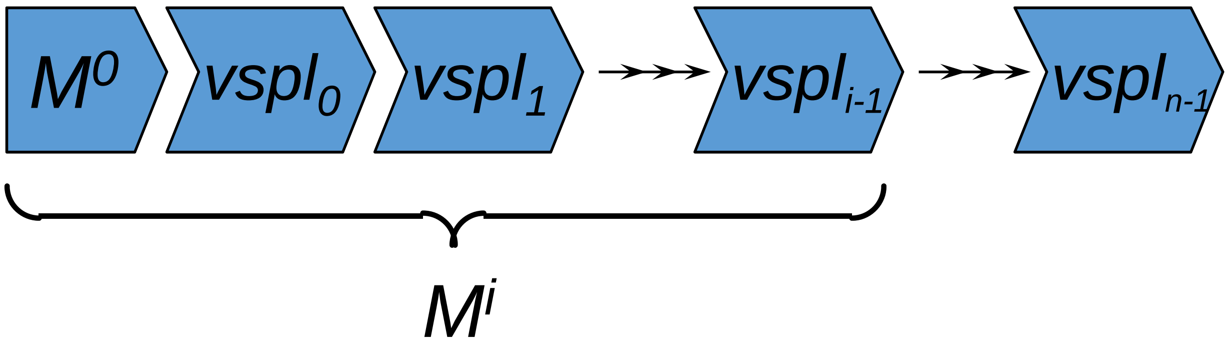


Reconstruction Process

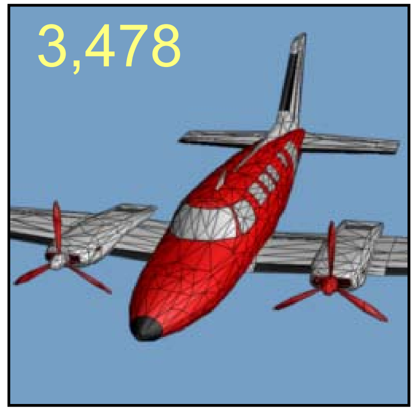


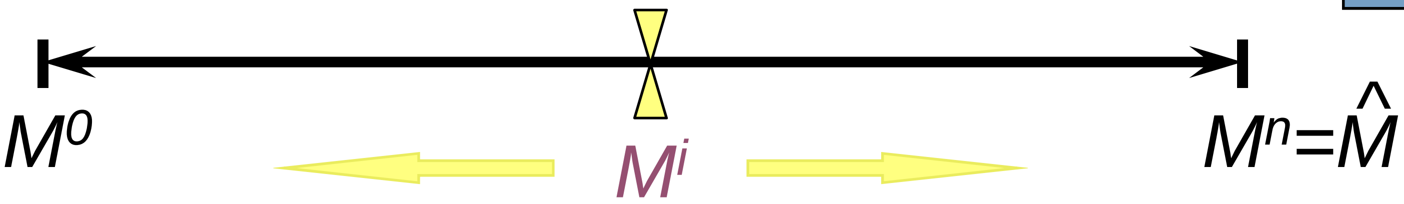
Continuous-resolution LOD

From PM, extract M^i of any desired complexity.



3,478 faces?





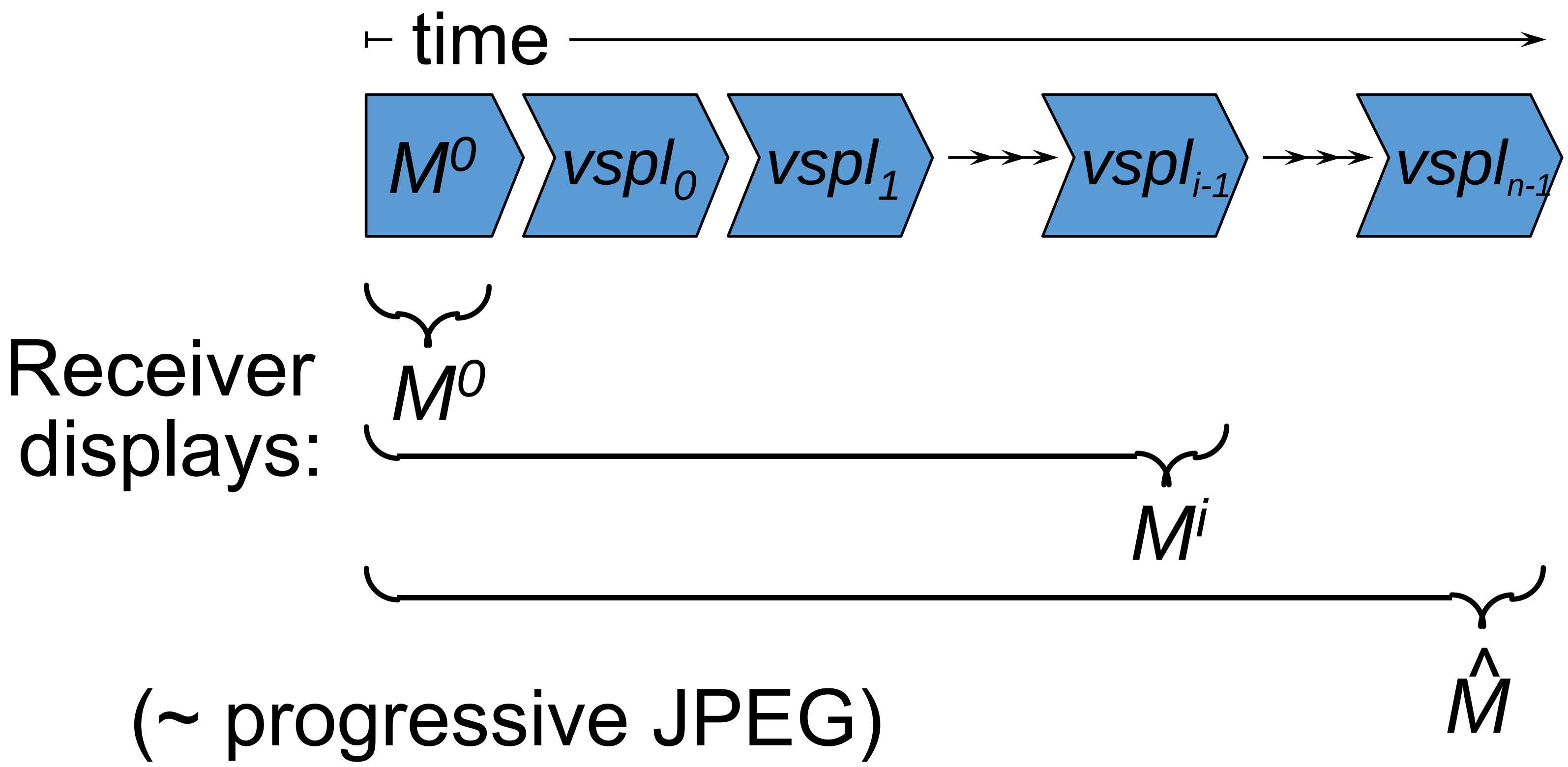
200K faces/sec! 100K faces/sec!

(166 MHz Pentium)

v

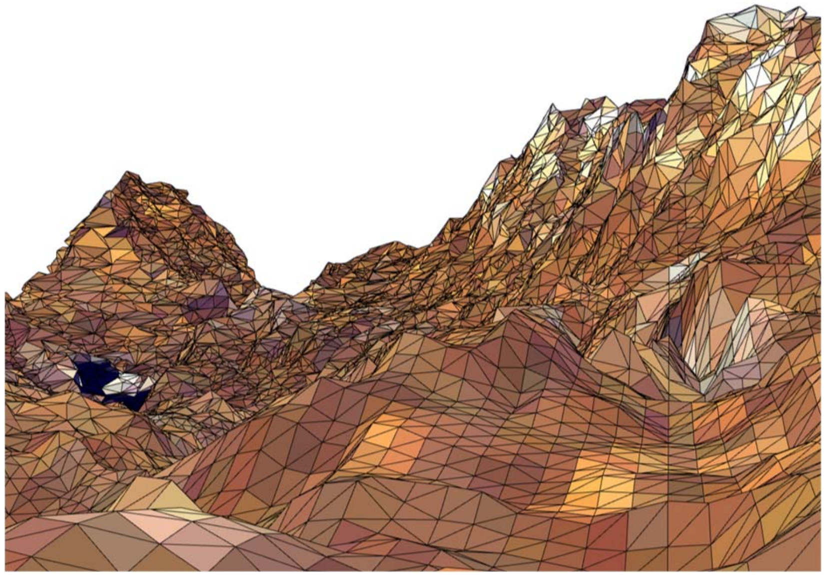
Progressive Transmission

Transmit records progressively:

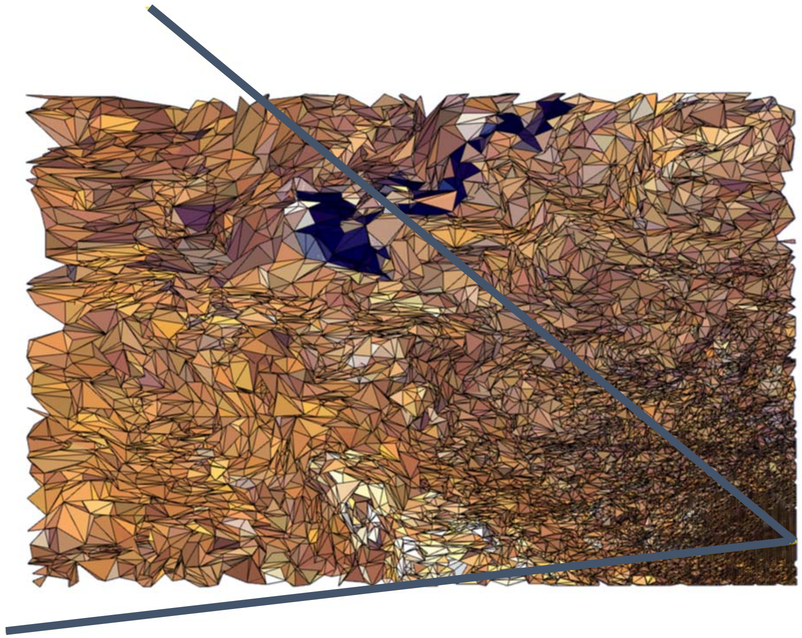


3. View-Dependent LOD

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

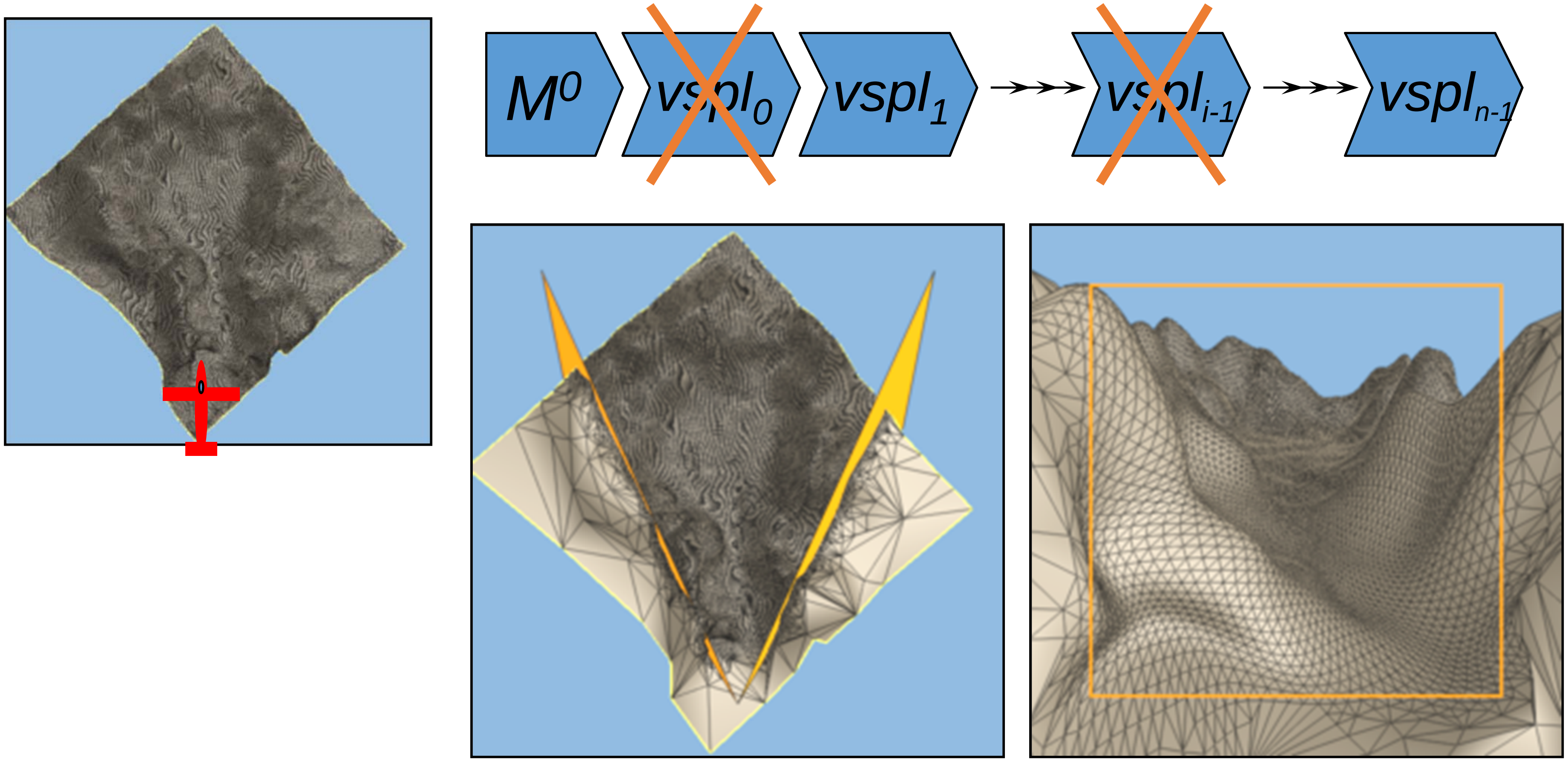


View from eyepoint



Birds-eye view

Selective Refinement



[SIGGRAPH 96]: incremental update not possible

Challenges: Unreal 5 demo

Challenges: Digital Cities

Challenges

- 纹理的简化
  - 熵、保特征…
- 数据组织与调度
  - 虚拟纹理
  - 虚拟几何
- 计算模式
  - Client/Server (CS)
  - Browser/Server (BS)
  - Cloud-Edge-Client computing：云、边、端
- …

Resources

- Internet, Papers, Siggraph courses
- VDSlib - http://vdslib.virginia.edu
  - A public-domain view-dependent simplification and rendering package/library
- Luebke's work on view-dependent simplification:
  - http://www.cs.virginia.edu/~luebke/simplification.html
- Hoppe's work on progressive meshes:
  - http://www.research.microsoft.com/~hhoppe
- Garland's work on quadric error metrics:
  - http://www.uiuc.edu/~garland
  - http://www.cs.cmu.edu/afs/cs/user/garland/www/multires/survey.html
- The Multi-Tesselation (MT) homepage:
  - http://www.disi.unige.it/person/MagilloP/MT

作业9

- 任务：
  - 实现网格简化的QEM方法
    - Garland and Heckbert. Surface Simplification Using Quadric Error Metrics. Siggraph 1997.
    - http://mgarland.org/files/papers/quadrics.pdf
- 目的
  - 学习网格的拓扑关系（点、边、面）更新的维护
- 交互界面（可选）
  - 通过操纵网格顶点个数$n \leq N$(输入网格顶点数)，可以生成简化网格（减少n），也可以回退到原始网格（增加n）
  - 思考：如何记录简化的操作？
- Deadline：2021年1月2日晚

中国科学技术大学
University of Science and Technology of China

谢　谢　！