Measuring Simplification Error

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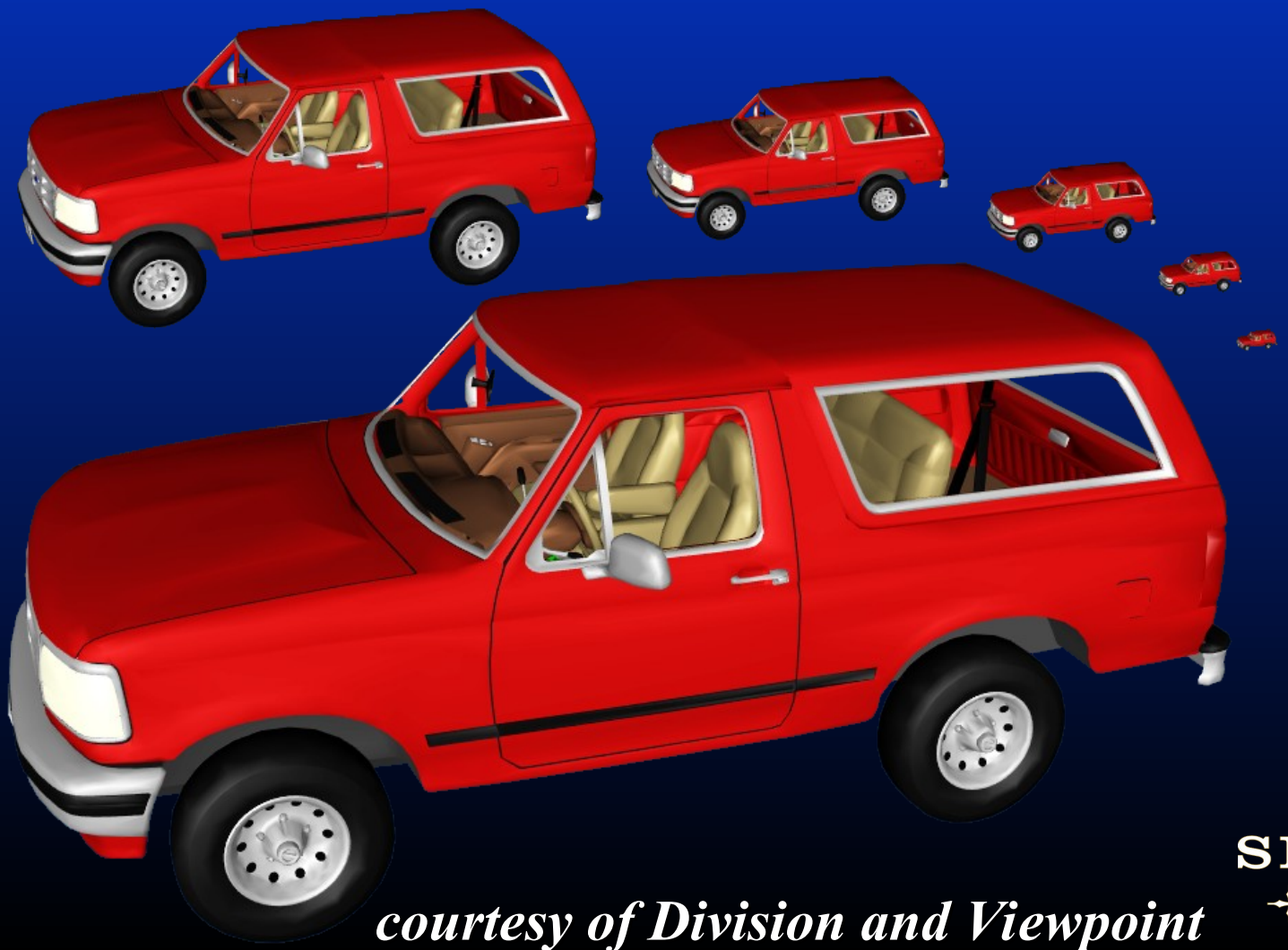
What I'll Talk About

- Introduction
- Geometric Error
- Attribute Error
- Hybrid Simplification

Why Measure Error?

- Guide simplification process
  - Making better choices produces better simplifications
- Know quality of results
  - Object-space error bounds describes quality
- Know when to show a particular LOD
  - Which LOD for a given screen-space error
- Balance quality for large environments
  - What error bound for a given polygon count

Ford Bronco Model



Triangles
: 41,855
27,970
20,922
12,939
8,385
4,766

courtesy of Division and Viewpoint

SAN ANTONIO SIGGRAPH 2002

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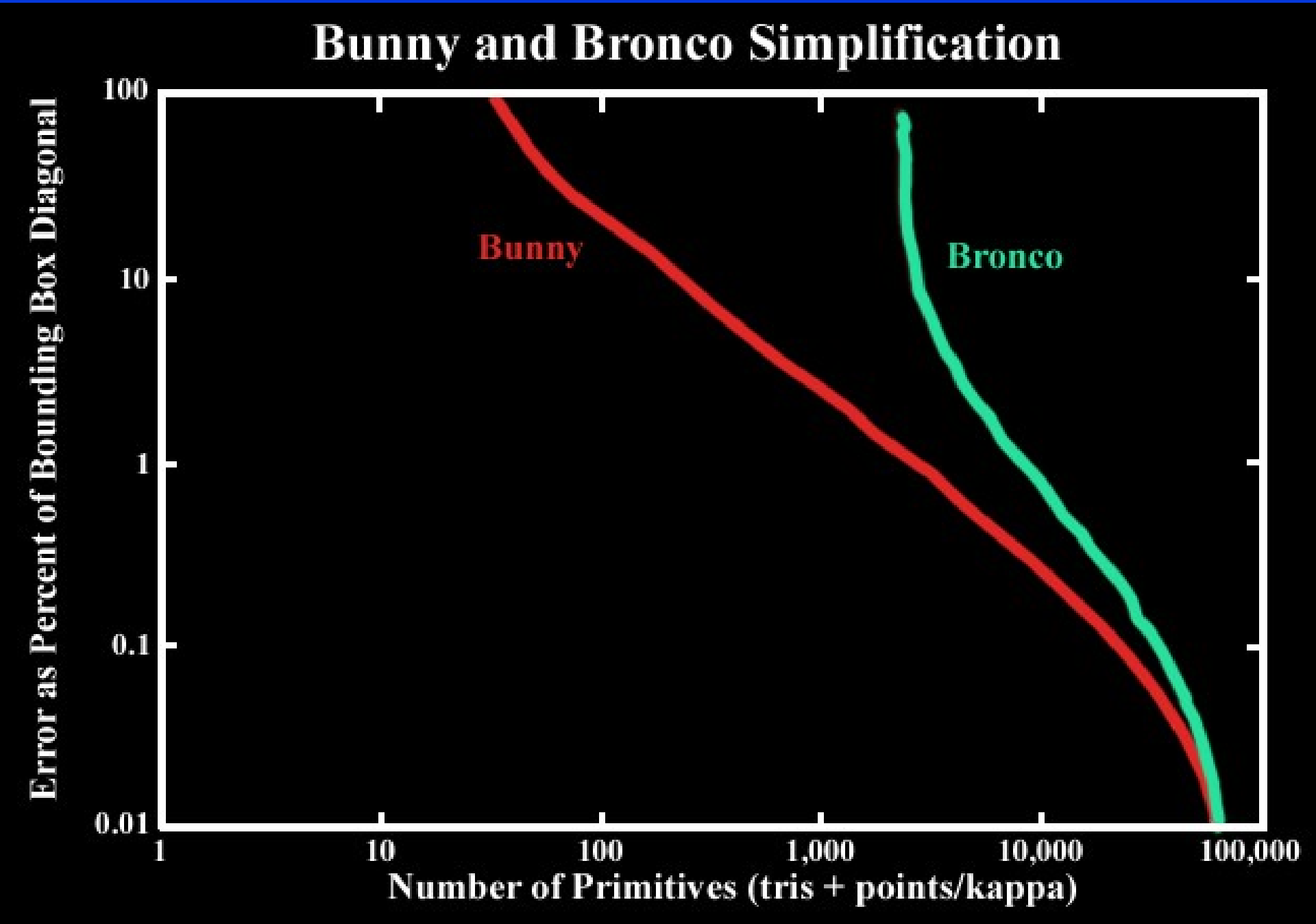
Geometric Error Measures

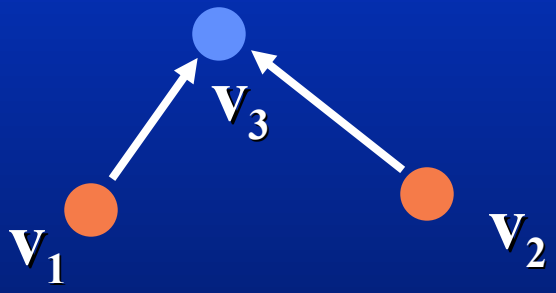
- Promote accurate 3D shape preservation
- Also preserves screen-space shape
  - Silhouettes
  - Pixel coverage


Bunny and Bronco Simplification
Error as Percent of Bounding Box Diagonal
100
10
1
0.1
0.01
Bunny
Bronco
1
10
100
1,000
10,000
100,000
Number of Primitives (tris + points/kappa)

Classifying Geometric Error Metrics

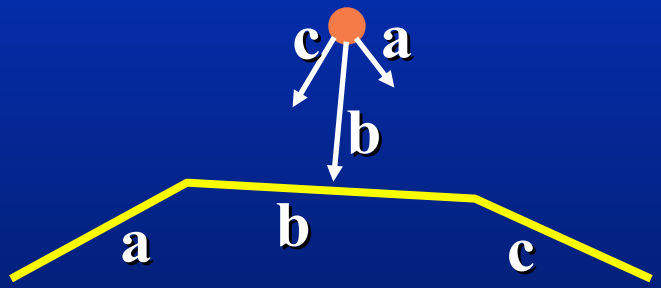
- Vertex-Vertex Distance
- Vertex-Plane Distance
- Point-Surface Distance
- Surface-Surface Distance

Vertex-Vertex Distance



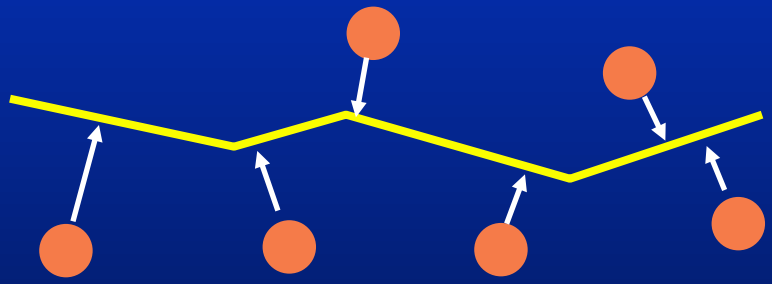
- $E = \max(\| v_3 - v_1 \|, \| v_3 - v_2 \|)$
- Appropriate during topology changes
  - Rossignac and Borrel 93
  - Luebke and Erikson 97
- Loose for topology-preserving collapses

Vertex-Plane Distance



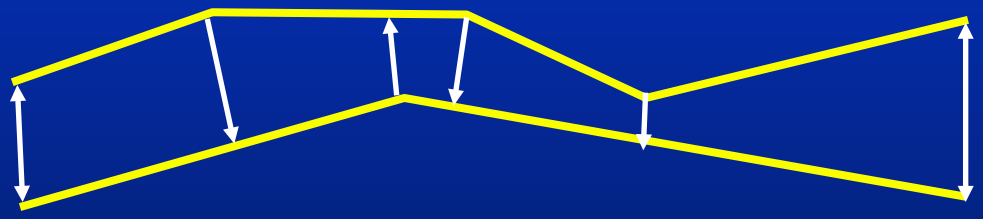
- Store set of planes with each vertex
  - Error based on distance from vertex to planes
  - When vertices are merged, merge sets
- Ronfard and Rossignac 96
  - Store plane sets, compute max distance
- *Error Quadrics* - Garland and Heckbert 96
  - Store quadratic form, compute sum of square distances

Point-Surface Distance



- Used in Hoppe 93 and 96
- Map point set to closest points on simplified surface
- Compute sum of square distances

Surface-Surface Distance



- Bound maximum distance between input and simplified surfaces
  - Tolerance Volumes - Guéziec 96
  - Simplification Envelopes - Cohen/Varshney 96
  - Hausdorf Distance - Klein 96
  - Mapping Distance - Bajaj/Schikore 96, Cohen et al. 97

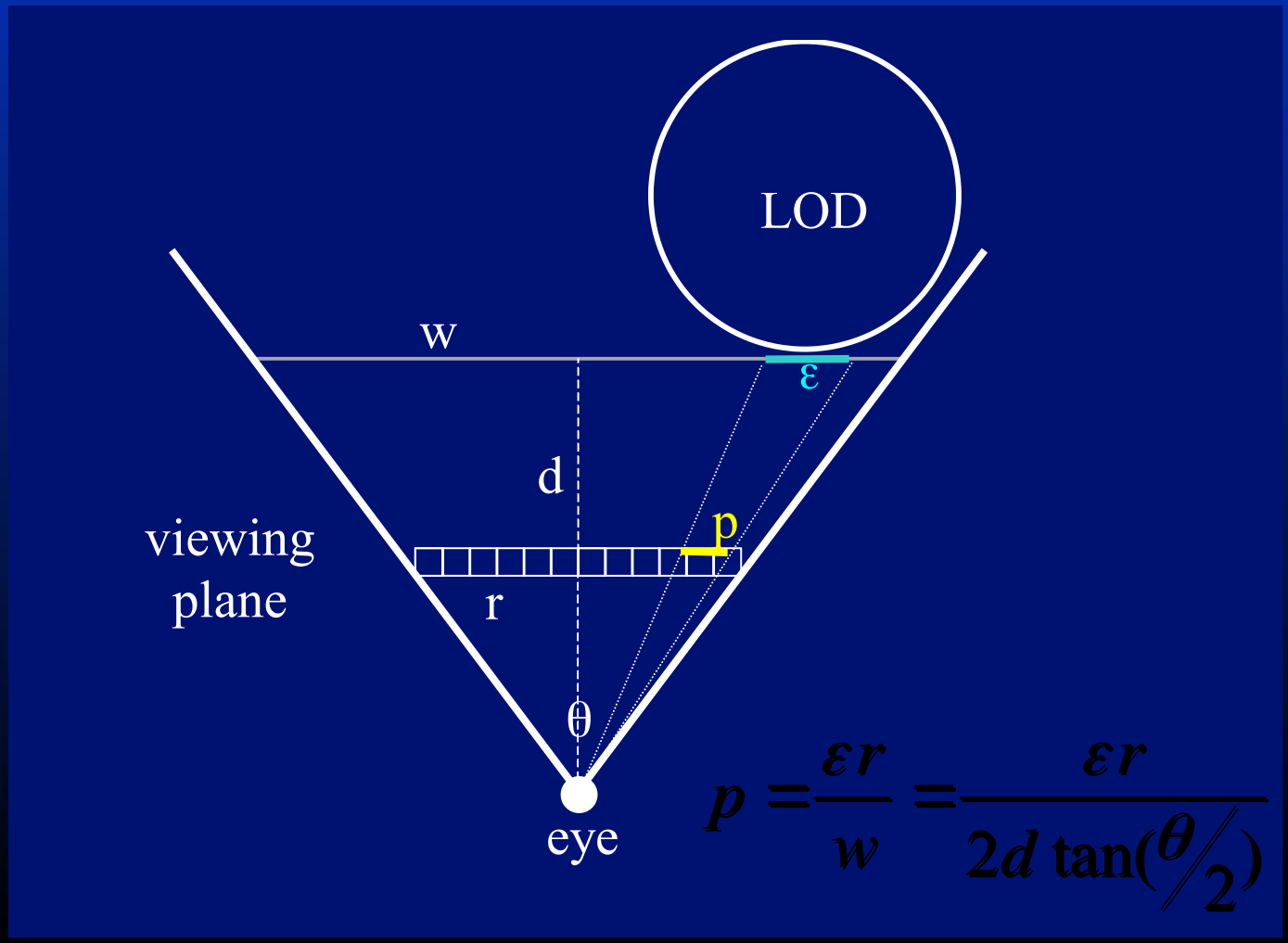
Vertex-Vertex != Surface-Surface

- Error is zero at vertices and exterior edges
- Error is non-zero everywhere else
  - not captured by vertex-vertex or vertex-plane metrics

Memoryless Simplification

- Lindstrom/Turk 98
- No measure of error from original mesh
  - *Incremental* rather than total error
- Preserve volume and area as simplification progresses
- Low error demonstrated after-the-fact
  - Metro - Cignoni et al. 96

Screen-space Geometric Error



$$p = \frac{\varepsilon r}{w} = \frac{\varepsilon r}{2d \tan(\theta/2)}$$

Geometric Error Observations

- Vertex-vertex and vertex-plane distance
  - Fast
  - Low error shown after-the-fact, but not guaranteed by metric
- Cannot guarantee quality without surface-surface distance bound
- Hoppe's point-surface approximates one-sided surface-surface
- Good error measures useful at run-time
  - 3D average or maximum error distance

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Attribute Error Metrics

- Attributes include colors, normals, and texture coordinates
- Promote accuracy of final pixel colors

Classifying Attribute Error Metrics

- Vertex-Vertex Distance
- Vertex-Plane Distance
- Point-Surface Distance
- Surface-Surface Distance

Vertex-Vertex Distance

- GAPS point clouds - Erikson/Manocha 98
  - Measure sum of square distances from vertex to its constituent vertices (area-weighted)
  - Used for colors, normals, and texture coordinates
  - Stored as 5 floats for 3D attributes (e.g. rgb)
- Normal cones
  - Luebke/Erikson 97, Xia et al. 97

Vertex-Plane Distance

- Higher-dimensional error quadrics
  - Garland and Heckbert 98
  - Vertices live in higher-dimensional position + attribute space
  - Planes defined in this space
- Multiple attribute quadrics
  - Hoppe 99
  - Decouples affects of position and attributes
  - Reduces storage and computational complexity

Point-Surface Distance

- Extension of geometric point-surface distance
  - Hoppe 96
- Geometric correspondences found between original surface samples and simplified surface
- Sum of square attribute distances minimized
- Used primarily for vertex colors

Surface-Surface Distance

- Bajaj / Schikore 96
  - Geometric projections provide local mappings
  - Maximum distance of scalar attributes measured over surface

Screen-space Attribute Error

- Texture coordinates work like geometric error
  - Cohen et al. 98
- Normal error controls dynamic refinement around highlights
  - Xia et al. 97, Klein 98
  - Doesn't allow more simplification as objects recede
- Color control?

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Hybrid Simplification

- Integrates multi-resolution polygon and point rendering into single hierarchy
  - Based on *Multi-triangulation* data structure of DeFloriani et al ‘97
- Optimizes hierarchy based on primitives for a given error bound
- full paper - *IEEE Visualization 2001*

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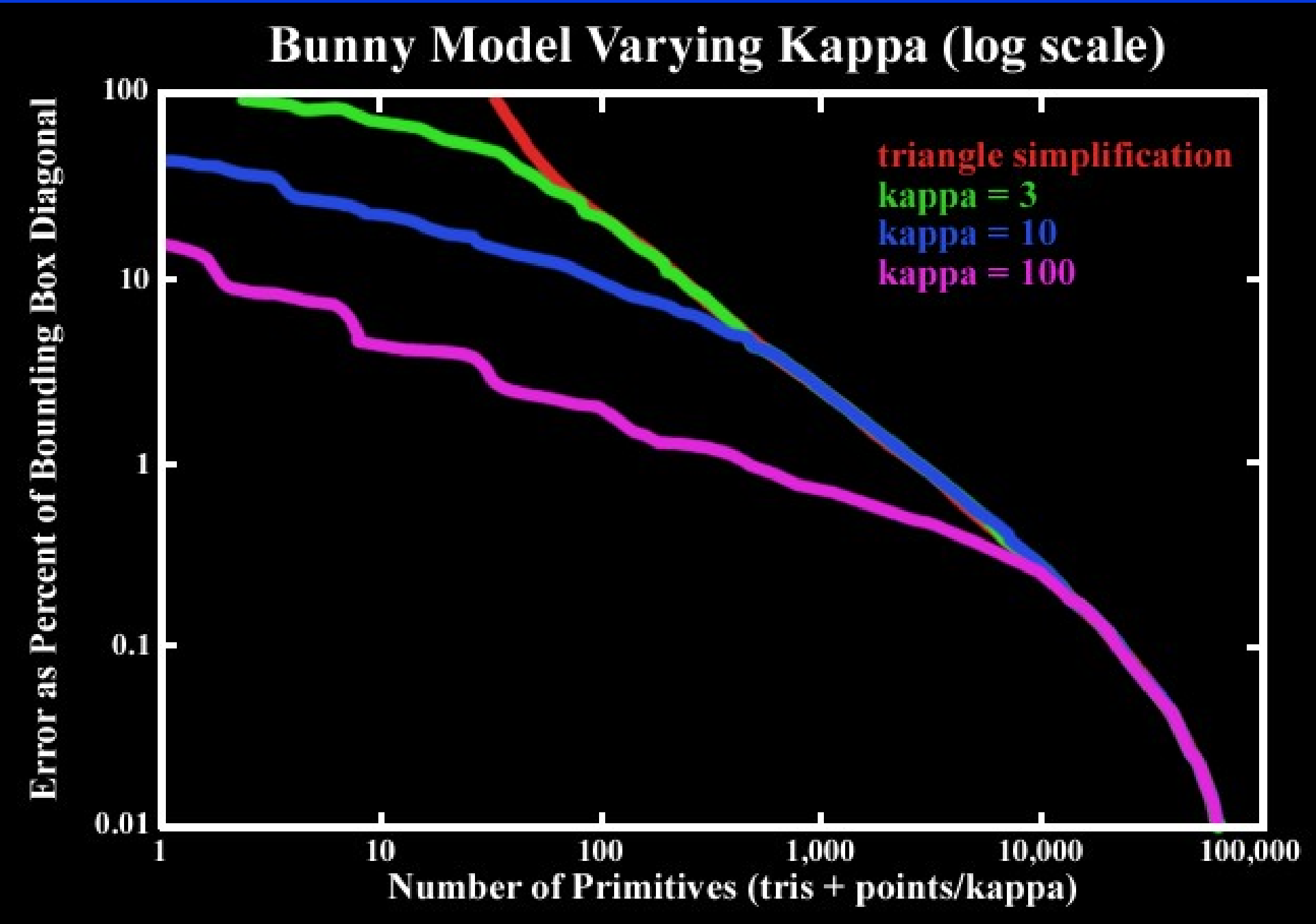
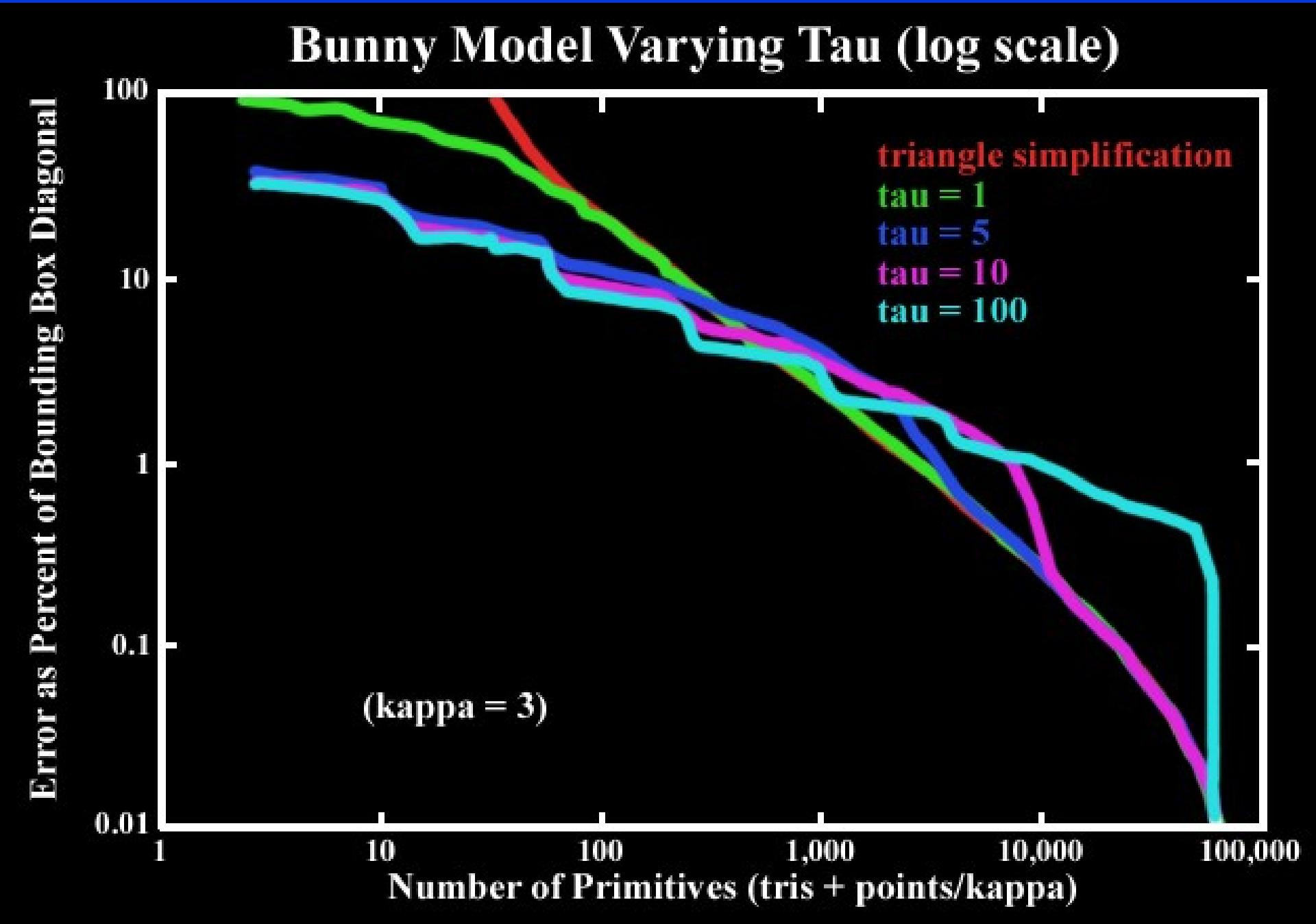
Simplification Operations

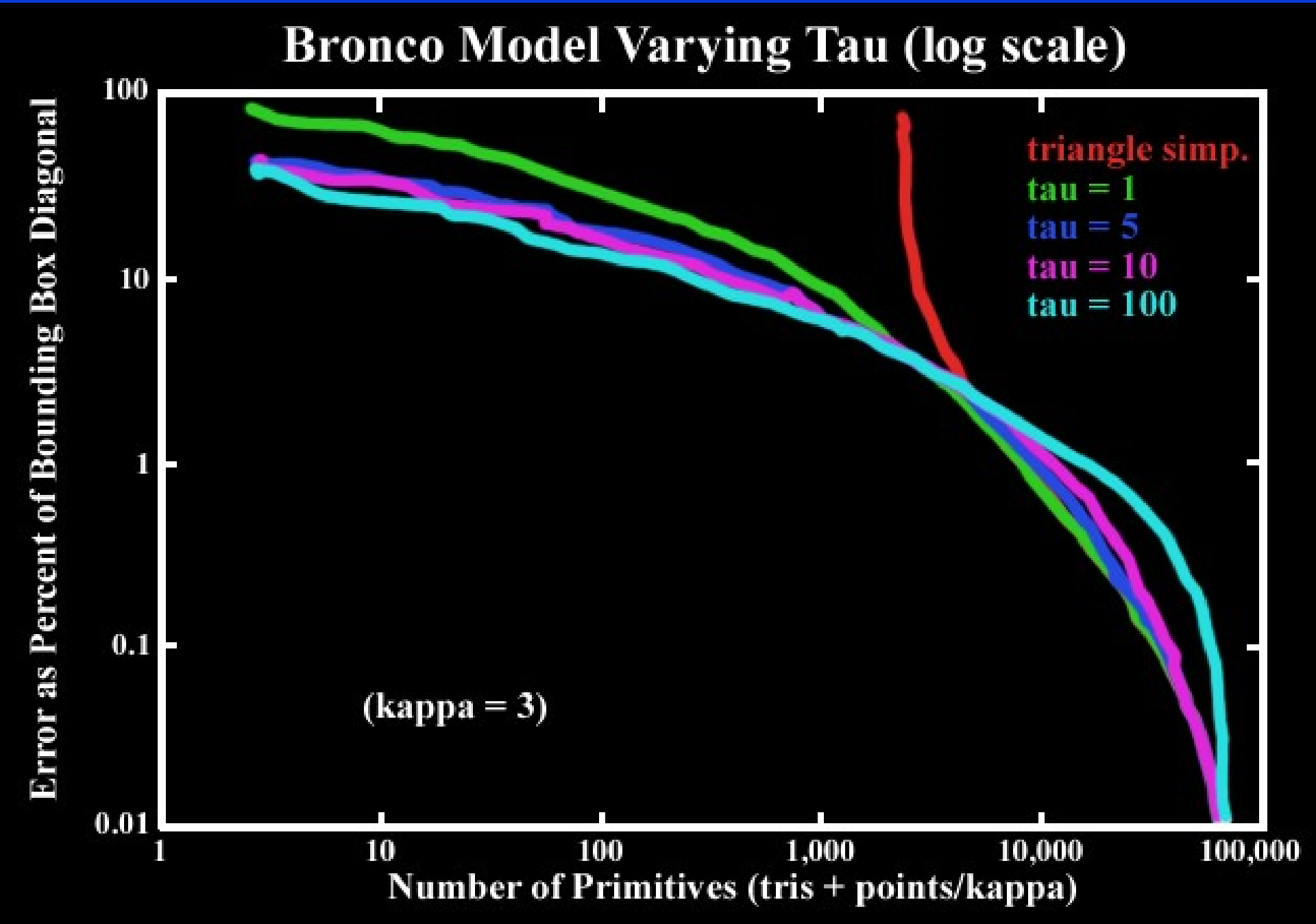
- Polygon simplification (edge collapse)
- Point replacement
  - replace a triangle with fewer than κ points
  - choose points to cover triangle
  - error: triangle error + point radius
- Point simplification
  - merge points (using octree)
  - error: max triangle error + point radius

Polygons versus Points

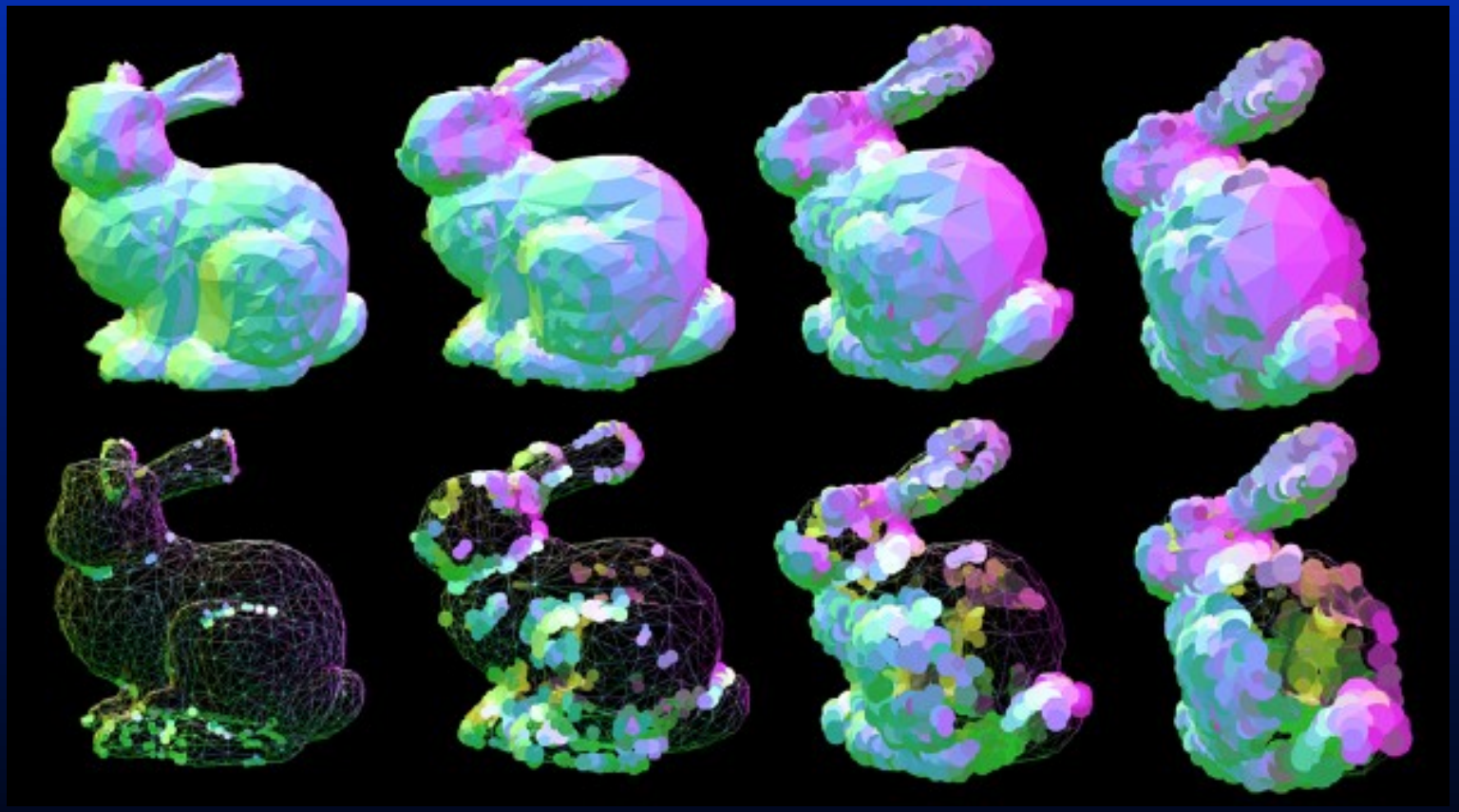
- Each has measurable rendering performance on a given platform
  - Perhaps based on combination of transform rate and fill rate
- Measure ratio of perfomance, κ
  - how many points equals a polygon
- Optimize LOD creation to minimize primitive count for given error bound


Bunny Model Varying Kappa (log scale)
Error as Percent of Bounding Box Diagonal
100
10
1
0.1
0.01
1
10
100
1,000
10,000
100,000
Number of Primitives (tris + points/kappa)
triangle simplification
kappa = 3
kappa = 10
kappa = 100

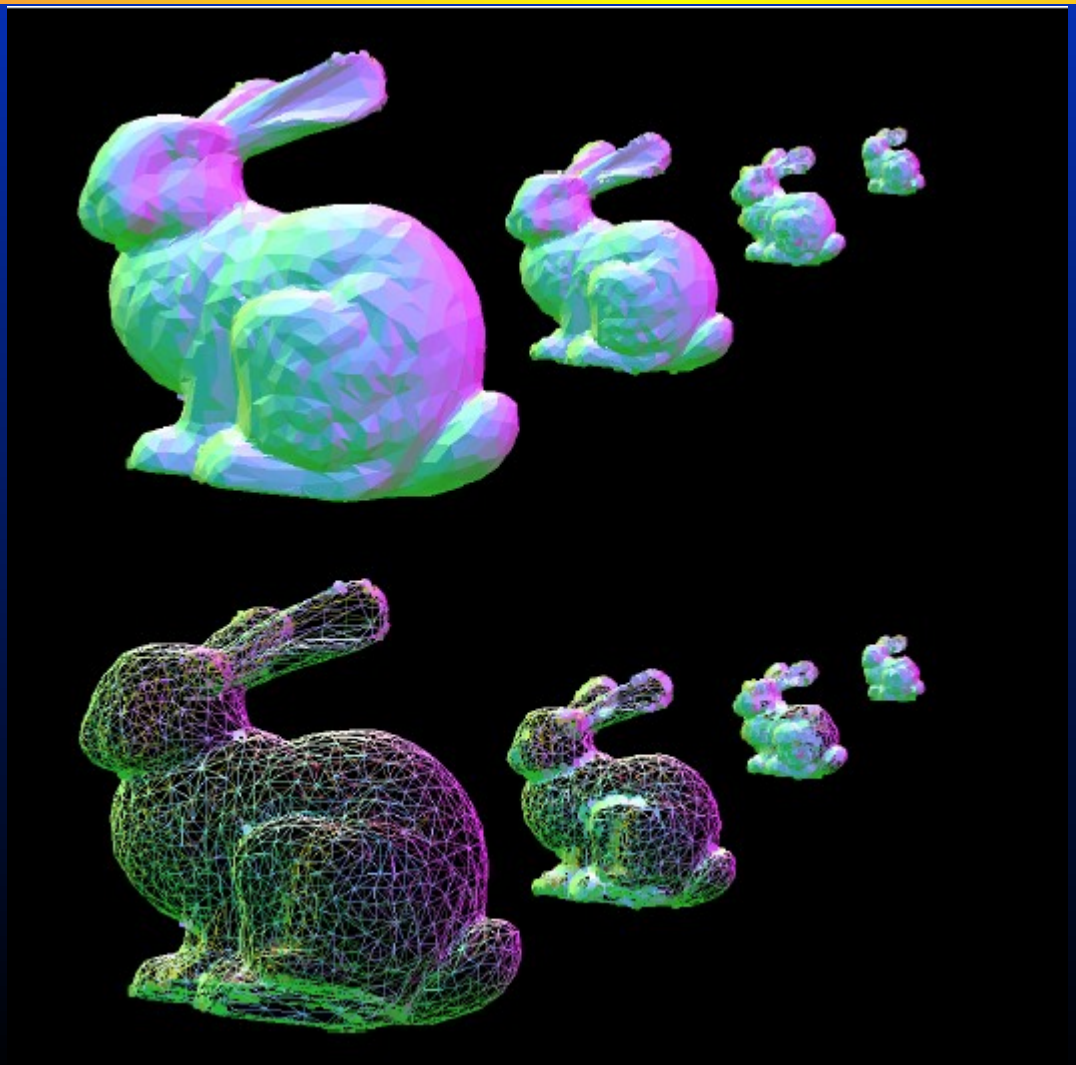

Bunny Model Varying Tau (log scale)
Error as Percent of Bounding Box Diagonal
100
10
1
0.1
0.01
triangle simplification
tau = 1
tau = 5
tau = 10
tau = 100
(kappa = 3)
1
10
100
1,000
10,000
100,000
Number of Primitives (tris + points/kappa)


Bronco Model Varying Tau (log scale)
Error as Percent of Bounding Box Diagonal
100
10
1
0.1
0.01
1
10
100
1,000
10,000
100,000
Number of Primitives (tris + points/kappa)
triangle simp.
tau = 1
tau = 5
tau = 10
tau = 100
(kappa = 3)

Bunny - 1,2,3,4% object-space deviation



Bunny - 5 pixels of deviation



Hybrid Armadillo

Conclusions

- Variety of approaches to bounding object and attribute space errors
- Screen-space geometric error known
- Screen-space texture error known
- Screen-space color and normal error still have room for improvement
  - Employ bounds on color and normal deviation at run-time
  - Guarantee appearance, but simplify more as objects recede
  - Texture and normal map approach requires parameterization, texture management, and advanced shading functions

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