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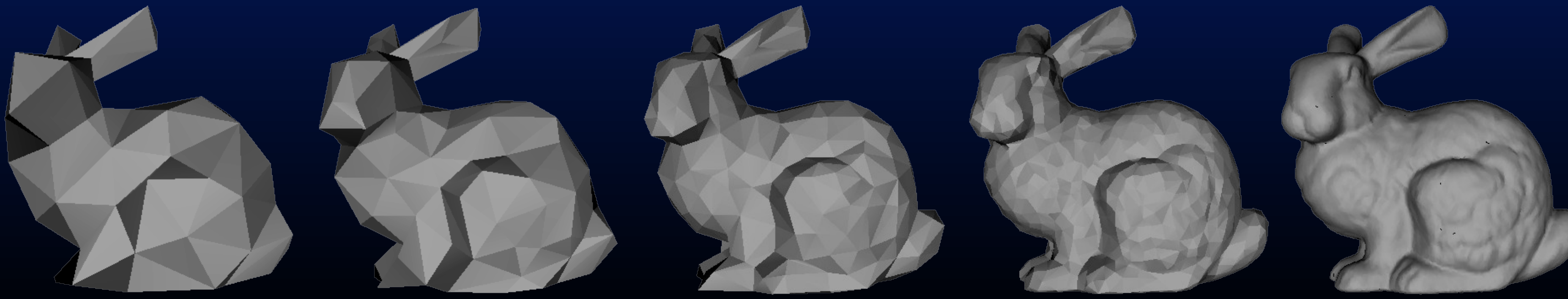
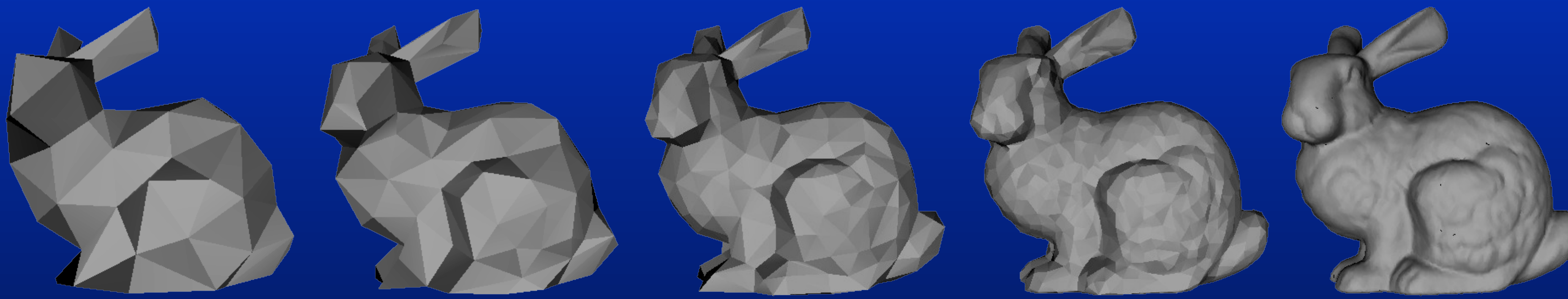
SIGGRAPH 2002

Advanced Issues In Level Of Detail



Algorithms for Generalized LODs



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http://www.cs.umd.edu/gvil

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LOD Algorithms Classification

	View-Independent	View-Dependent
Topology Preserving	Turk 92 Schroeder et al 92 Cohen et al 96 Hoppe 96 Cignoni et al 98 Lindstrom & Turk 99	Xia & Varshney 96 Hoppe 97 De Floriani et al 98 Gueziec et al 98 Klein et al 98
Topology Simplifying	Rossignac & Borrel 93 He et al 96 El-Sana & Varshney 97 Schroeder 97 Garland & Heckbert 97	Luebke & Erikson 97 El-Sana & Varshney 99

Geometry & Topology Simplifications

- Geometry Simplification
  - Reducing the number of geometric primitives (vertices, edges, triangles)
- Topology Simplification
  - Reducing the number of holes, tunnels, cavities
- Geometry + Topology Simplification
  - Aggressive simplifications
  - May not be suitable for some applications

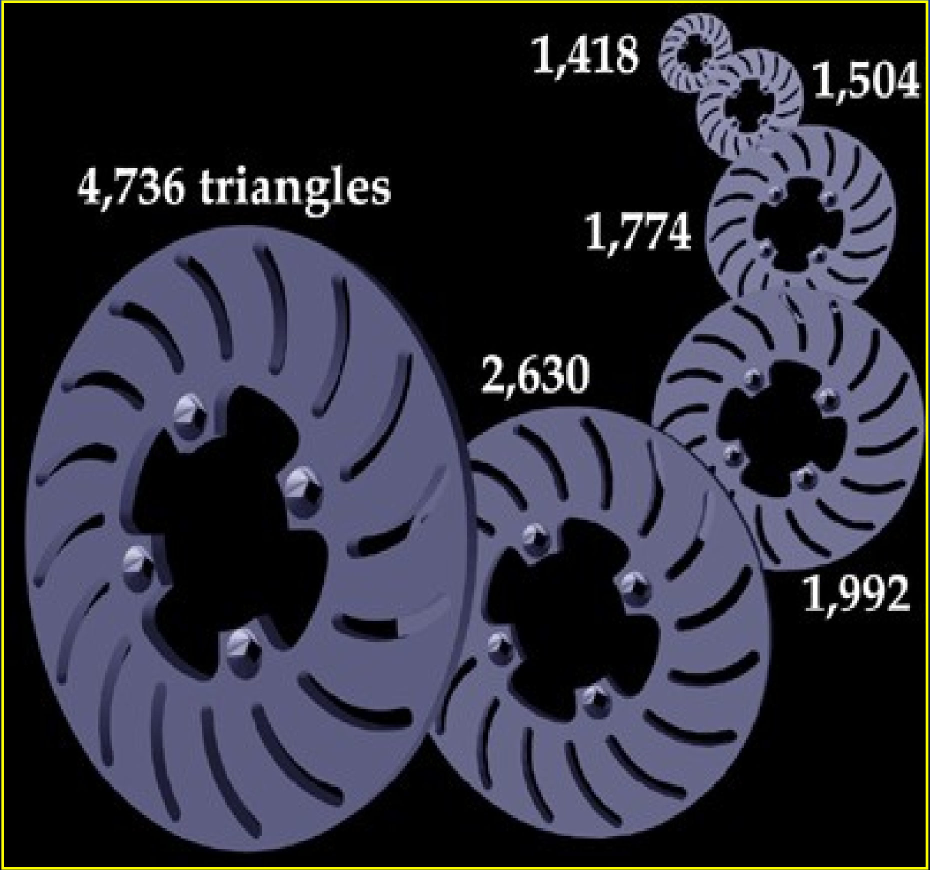
Outline

- Geometry and Topology Simplifications
- Implementing View-dependent LODs
- Variable-Precision Rendering

Outline

- Geometry and Topology Simplifications
  - **View-Independent (Discrete) Simplification of Topology**
  - View-dependent Simplification of Topology
- Implementing View-dependent LODs
- Variable-Precision Rendering

Why Discrete Simplification of Topology?



Discrete Simplification of Topology

Local Algorithms

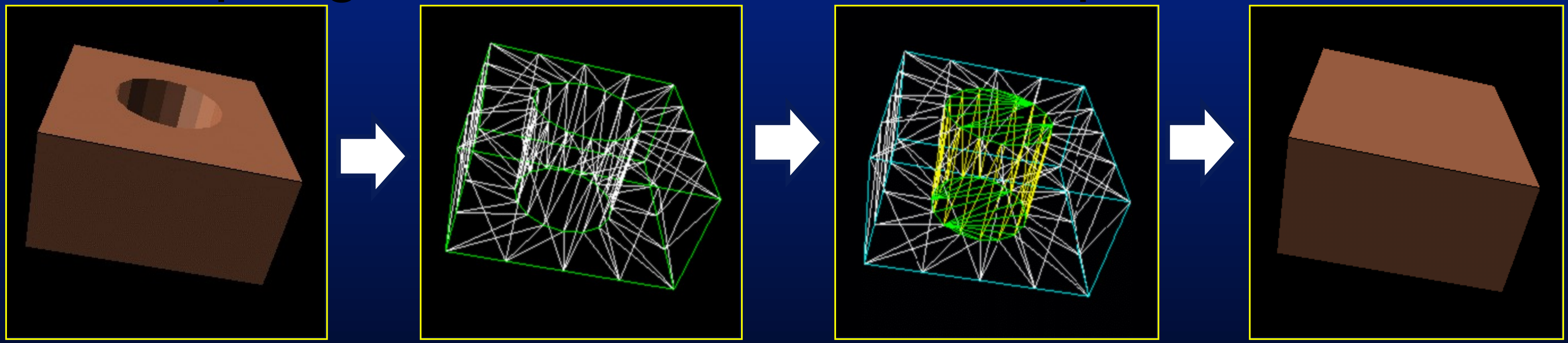
- Collapsing vertex pairs / virtual edges
  – Schroeder, *Visualization 97*
  – Popovic and Hoppe, *Siggraph 97*
  – Garland and Heckbert, *Siggraph 97*
- Collapsing primitives in a cell
  – Rossignac and Borrel, *Modeling in Comp. Graphics 93*
  – Luebke and Erikson, *Siggraph 97*

Global Algorithms

- Low-pass filtering in Volumetric domain
  - He *et al.*, *Visualization 95*
- Rolling a sphere (L_2), cube (L_1, L_∞)
  - El-Sana and Varshney, *Visualization 97*

Our Approach to Discrete Topology Simplification

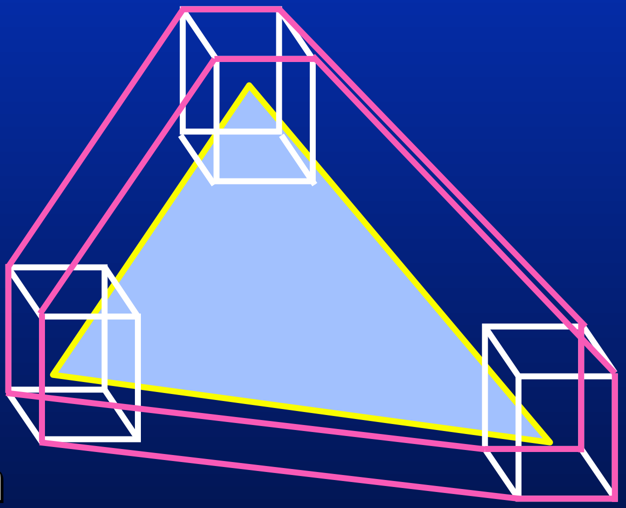
- Similar to α-Hulls
- Roll a sphere of radius α over the object
- Fill-up regions inaccessible to the sphere



El-Sana and Varshney, Visualization 97, IEEE TVCG 98

Alpha Prisms

- Alpha prism
  - Convolve triangle with α-side cube (L_∞ metric)
  - Convex polyhedron
- Compute union of α prisms
  - Fills-up all features less than α
- Generate the surface from the union



GVIL

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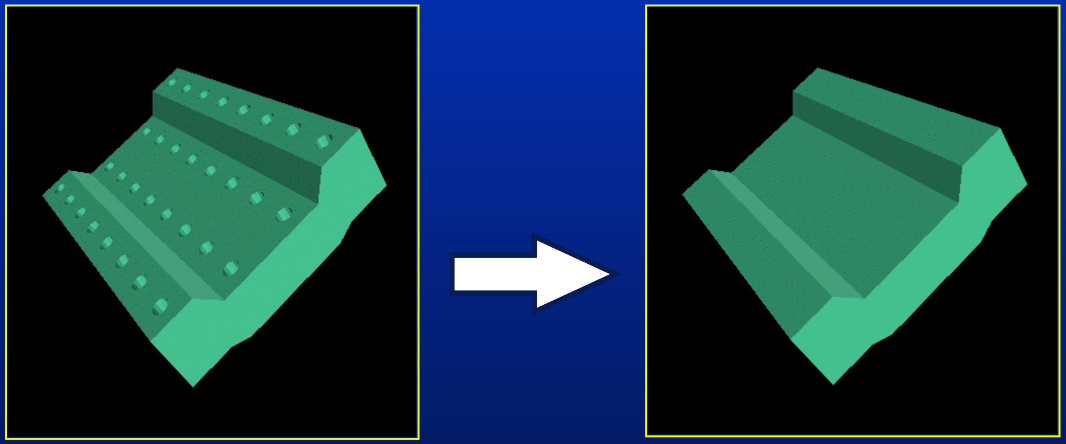
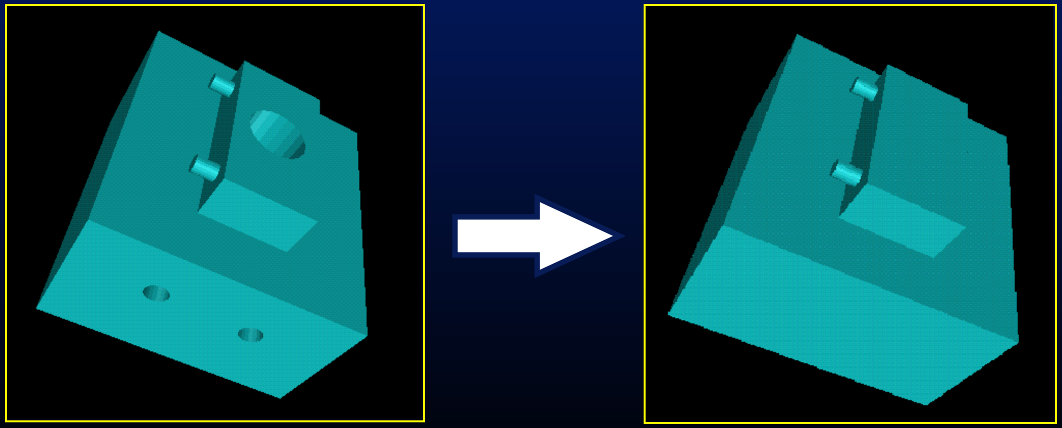
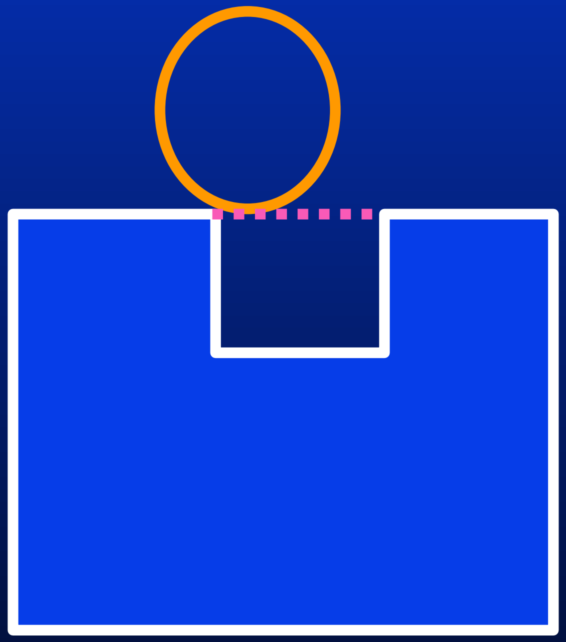
Results

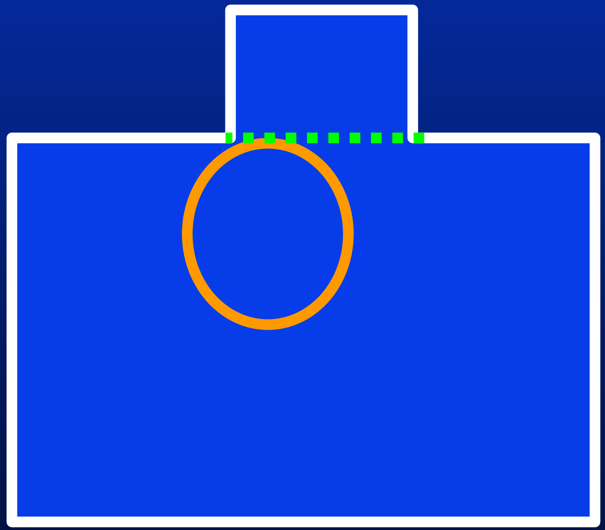




Concavities and Convexities

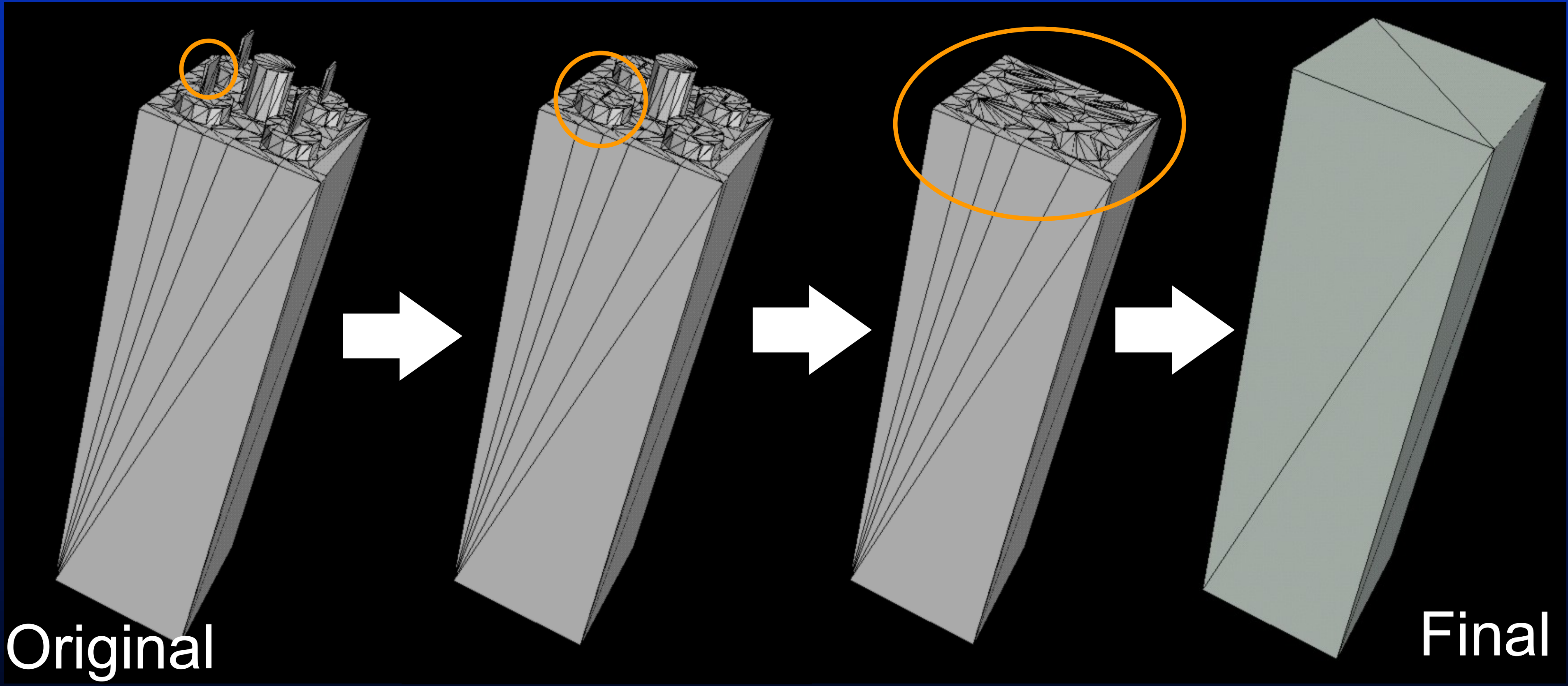


Concavity



Convexity

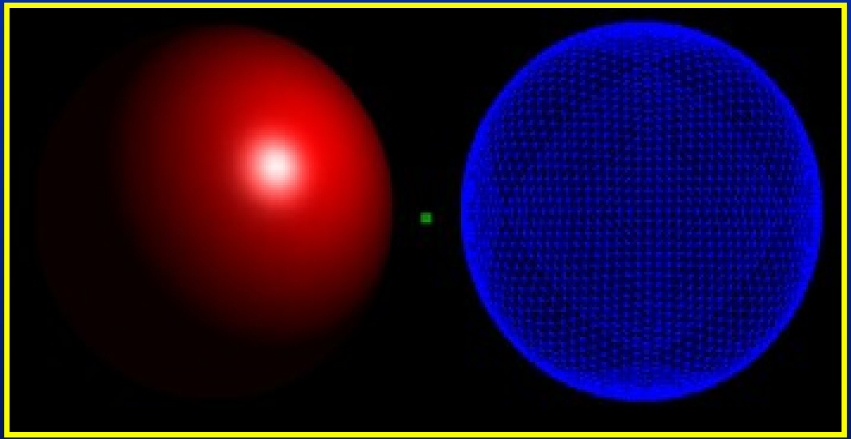
Results



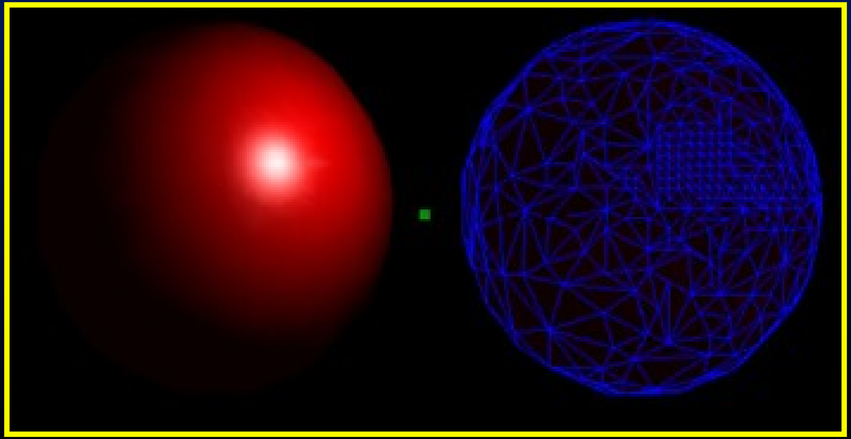
Outline

- Geometry and Topology Simplifications
  - Discrete Simplification of Topology
  - **View-dependent Simplification of Topology**
- Implementing View-dependent LODs
- Variable-Precision Rendering

Illumination- and View-Dependent Detail



8192 triangles



537 triangles

View-Dependent Topology Simplification

- Aggressive simplification
- Varied topology simplification
- Connect different objects
- Efficient fold-over prevention policy
- Real-time

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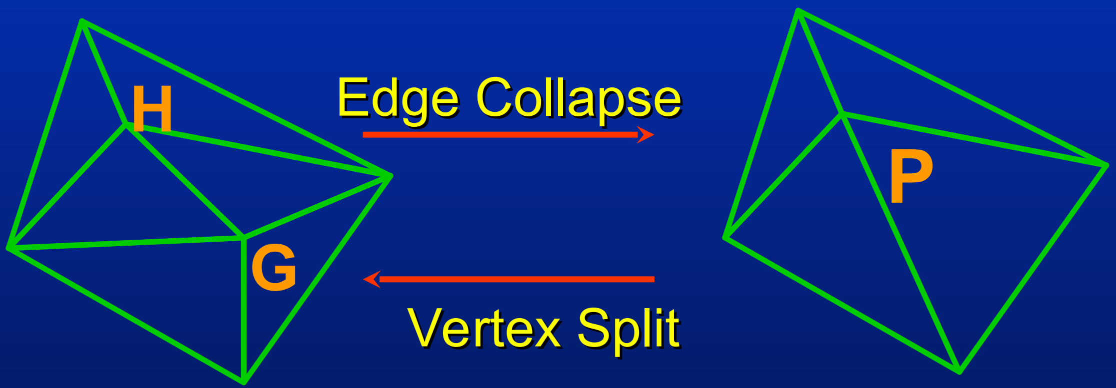
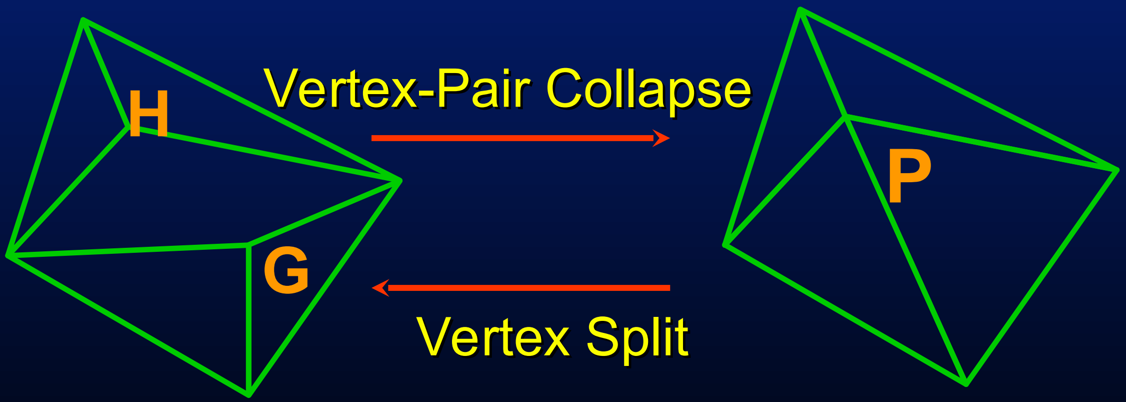
Edge and Vertex-Pair Collapses

Edge Collapse



Vertex-Pair Collapse
(Virtual Edge)



Simplifying Genus

- Allow virtual edge collapses
- Limit potentially $O(n^2)$ virtual edges
- Typical constraints:
  - Delaunay edges
  - Edges that span neighboring cells in a spatial subdivision: octree, grids, etc.
  - Maximum edge length

Virtual Edges

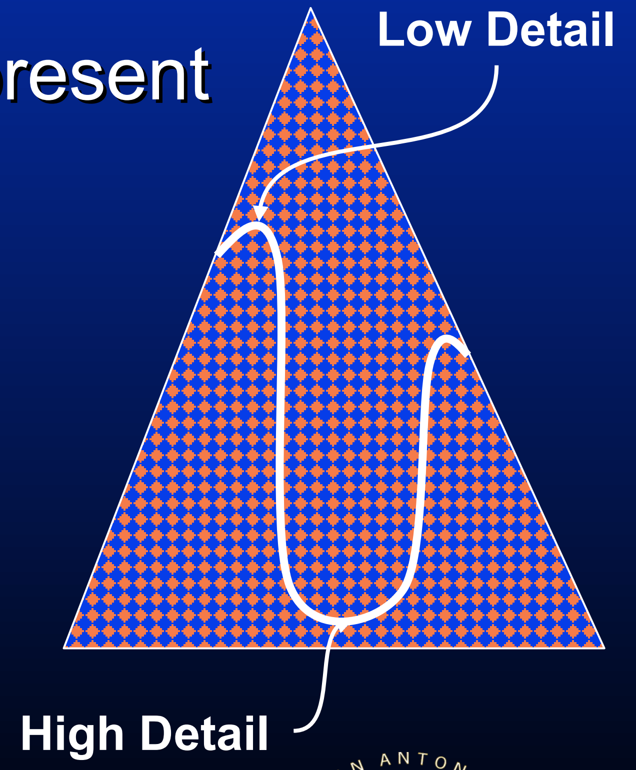
- Subdivide the dataset into patches
  - Initialize each triangle to a patch
  - Merge two patches that:
    - **Share at least one edge**
    - **Their normals differ less than threshold**
- Construct Delaunay triangulation using only the vertices on patch boundaries

View Dependence Tree

- Use an appropriate distance metric
- Construct the set of virtual edges
- Build a heap of all the edges (virtual and real) using the given metric.
- While not empty (heap)
  - Extract (minimum) edge
  - Collapse its two vertices

View Dependence Tree

- Hierarchy of vertex-pair collapses
- Different levels in this hierarchy represent different levels of detail
- Construct the hierarchy offline
- Run-time navigation involves:
  - Vertex split: Refinement
  - Vertex collapse: Simplification



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Run-time Traversal

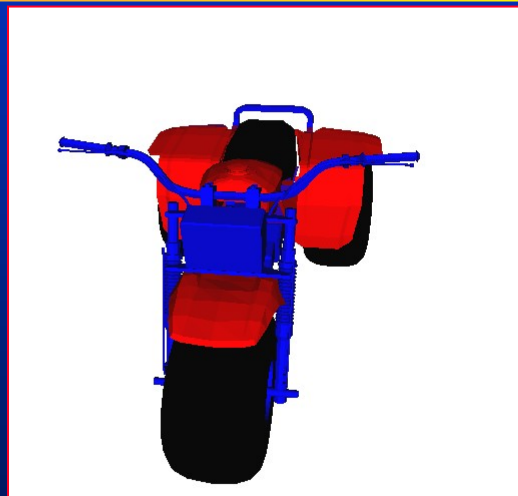
```
for each active node n do
  switch(NextStat(n)){
    case SPLIT   : if ( CanSplit(n))
                         Split(n);
    case MERGE: if ( CanMerge(n) &&
                         CanMerge(Sibling(n))
                         Merge(n);
    case STAY    : // No Change on the active-nodes list }
```

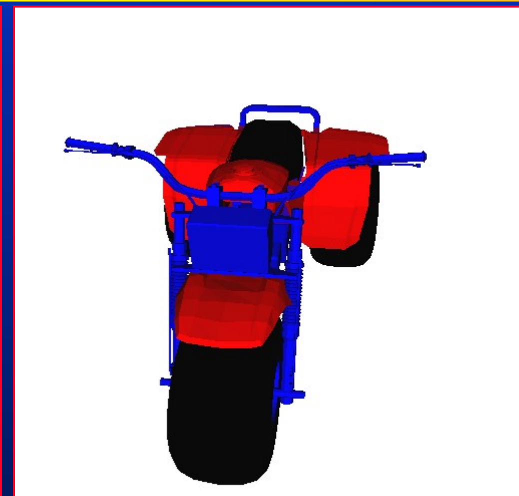
Simplification Factors

- Screen-space projection
- Local illumination
- Visibility culling
- Silhouette boundaries
- Object Speed
- LOD transfer function
- Prevent fold-overs
  - Implicit Dependencies

Results

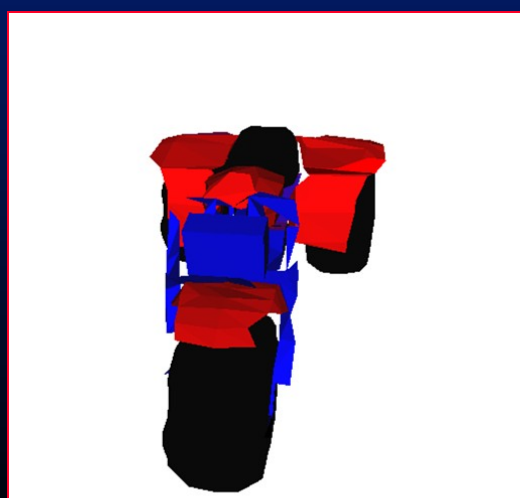
13.5K tris

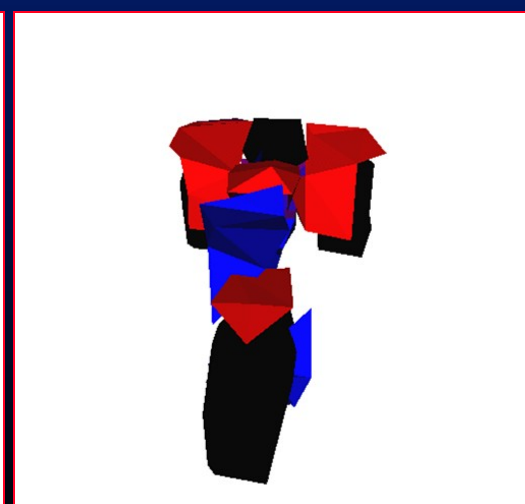




8.2K tris

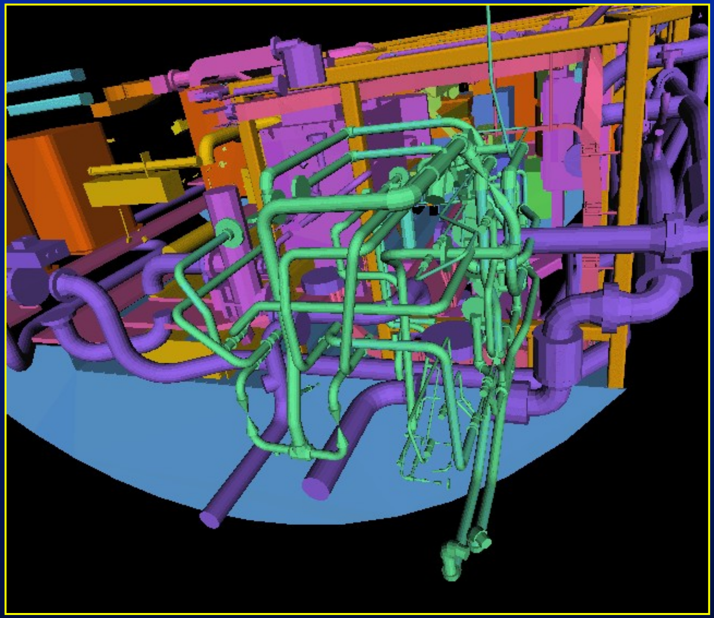
2.0K tris

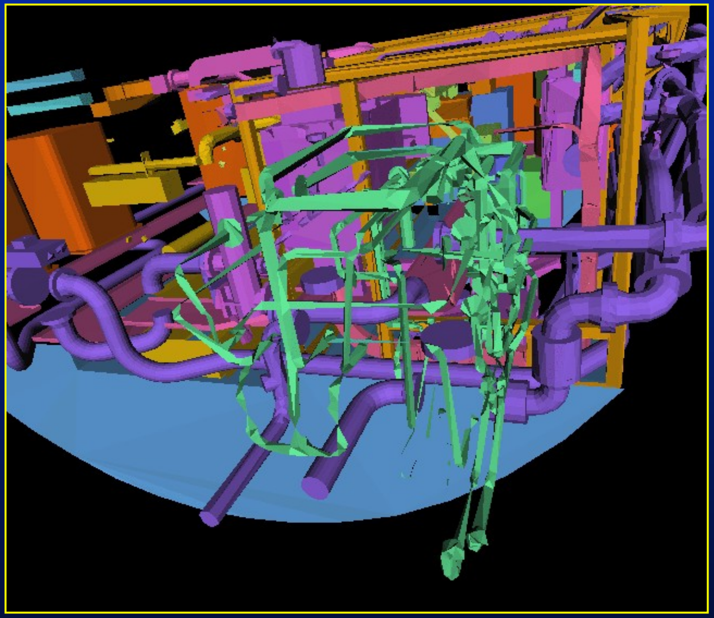




200 tris

Results



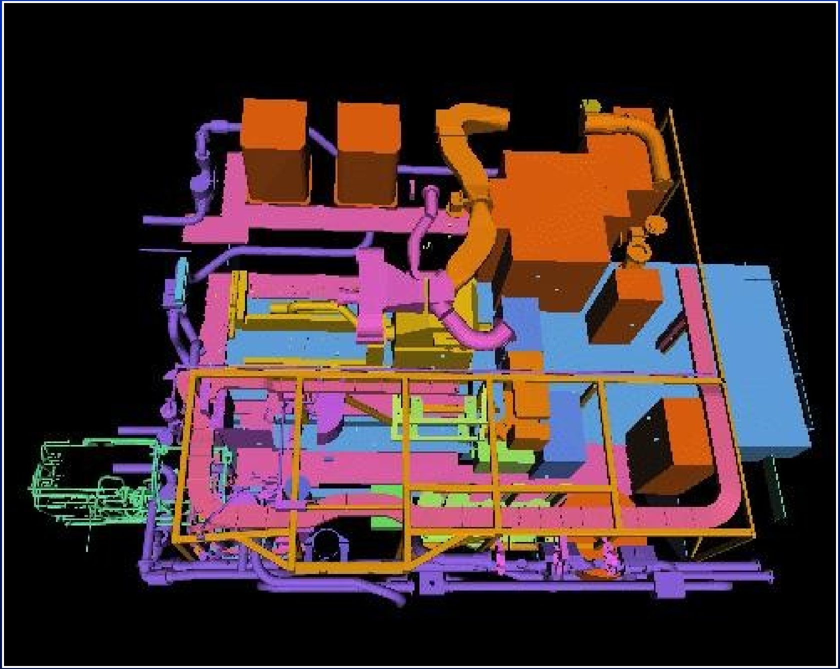


Close

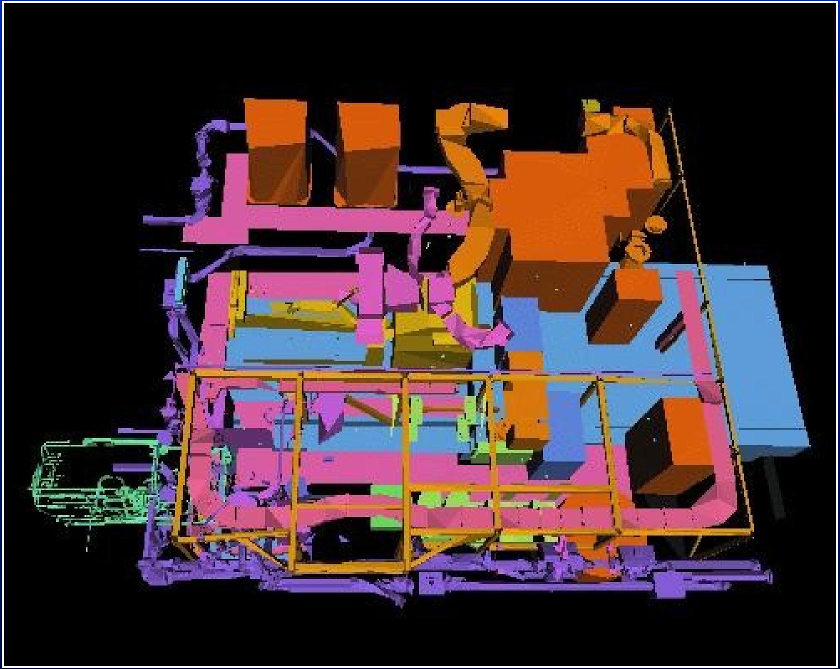
Far

El-Sana and Varshney, Eurographics 99

Results



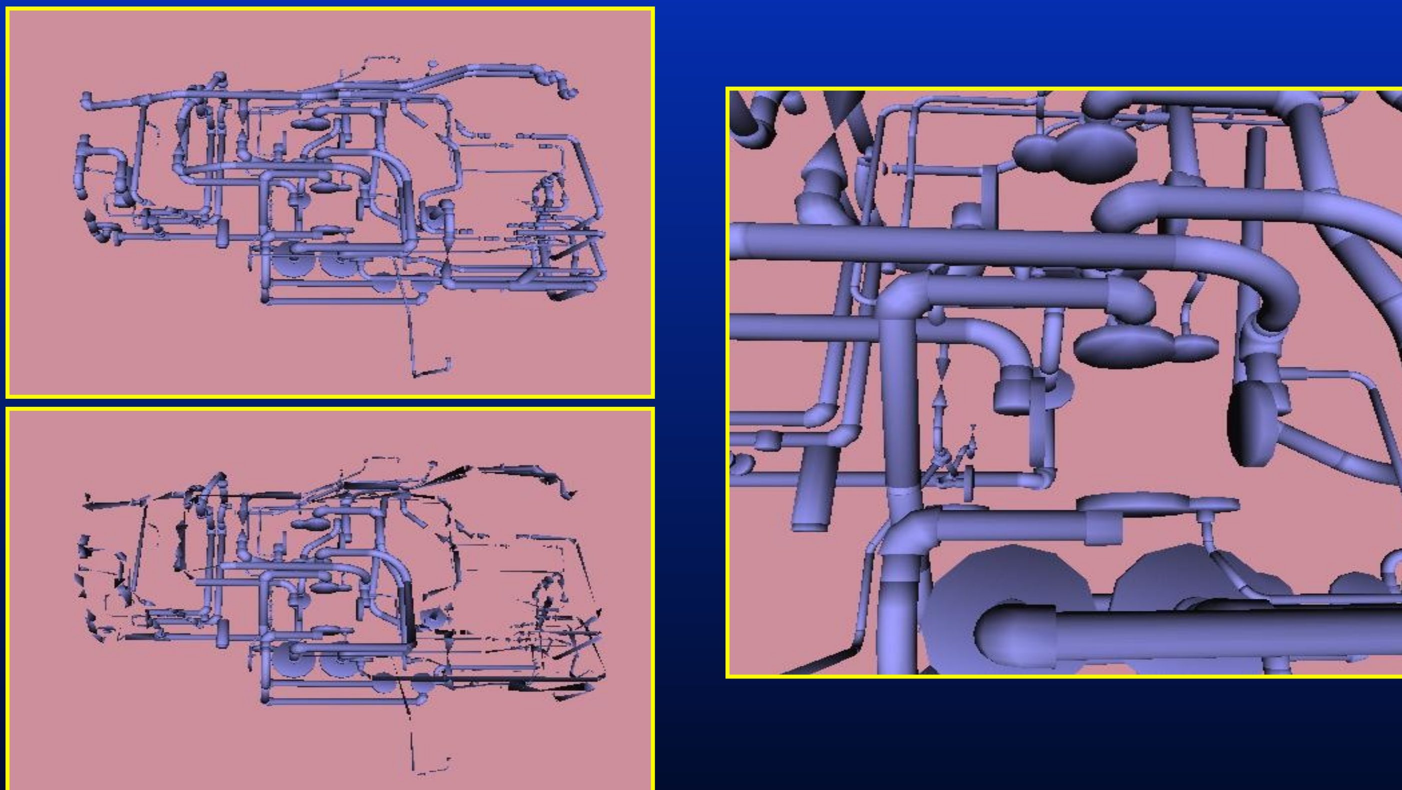
Original (340K tris)



Simplified (49K tris)

Auxilliary Machine Room Dataset

Foveation Results



El-Sana and Varshney, Eurographics 99

Outline

- Geometry and Topology Simplifications
- Implementing View-dependent LODs
  - Explicit and Implicit Dependencies
  - Maintaining triangle strips
- Variable-Precision Rendering

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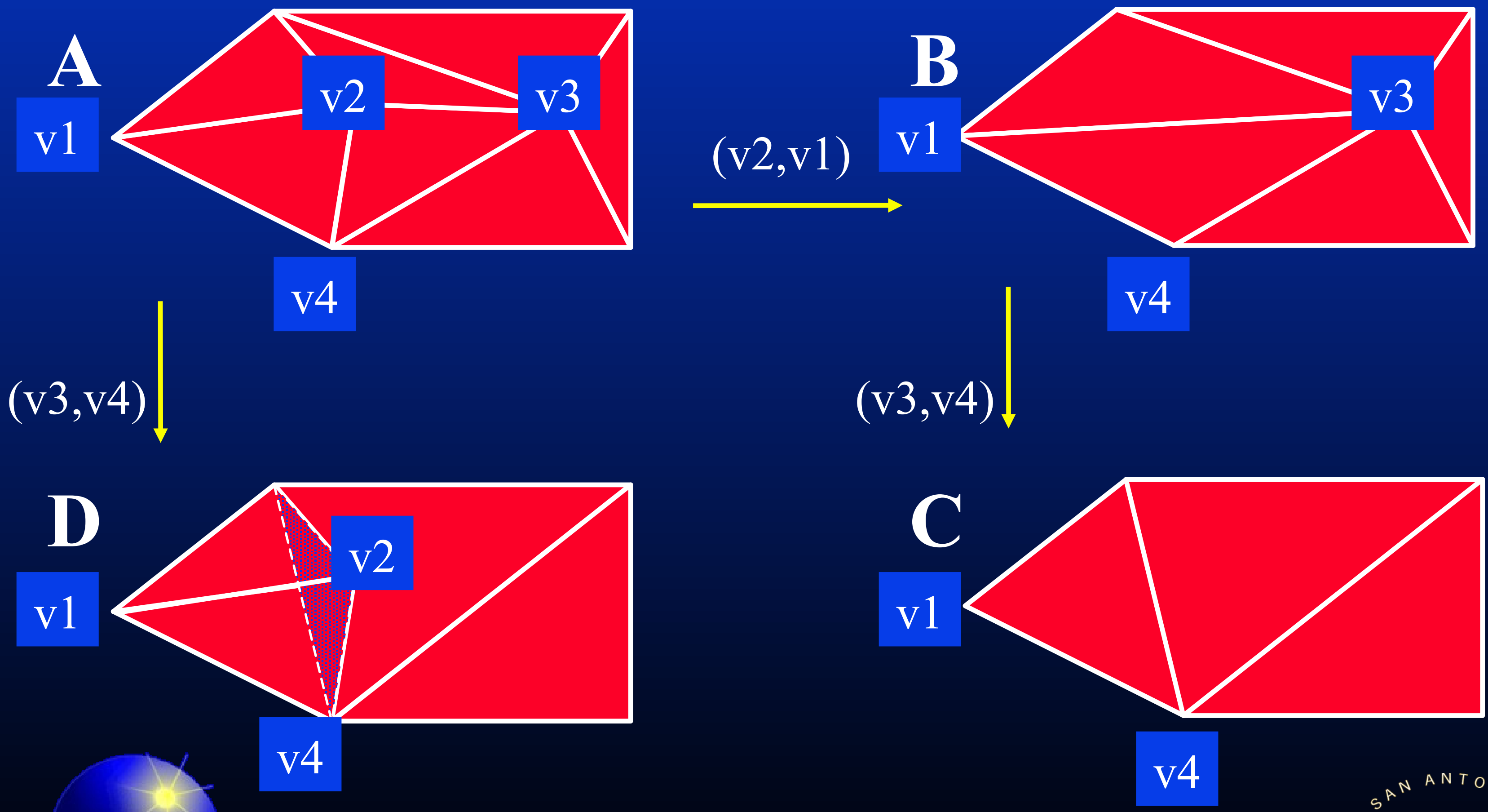
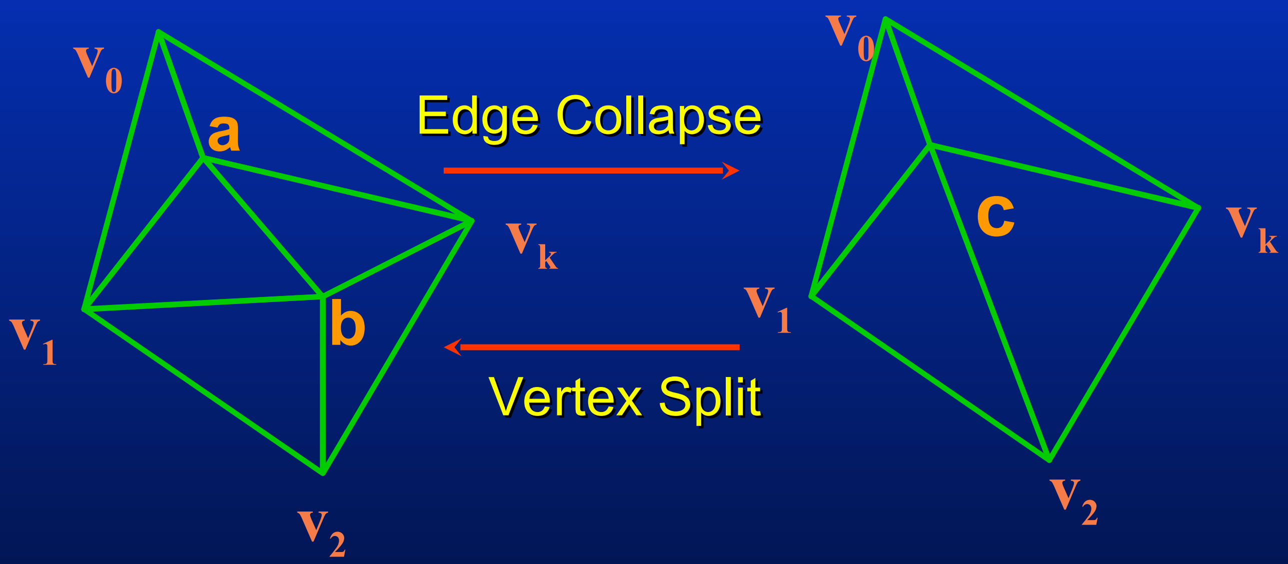
Mesh Folding Problem

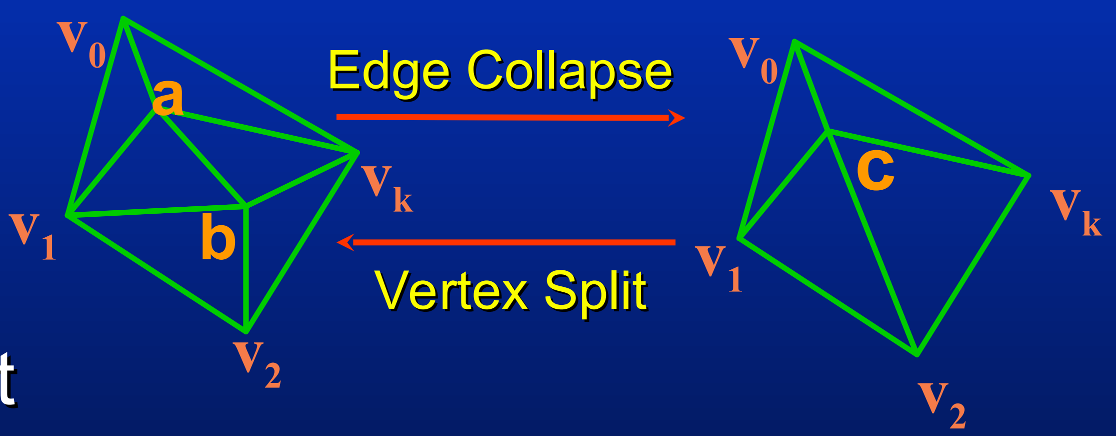


Explicit Dependencies



Neighborhood of an edge collapse is determined and fixed during preprocessing and used for validity checks at run-time

Explicit Dependencies



- Vertex split
  - Vertex *c* can split to *(a, b)* only if vertices v_0 , v_1 , … v_k are present and adjacent to *c* at run-time.
- Vertex-pair collapse
  - Vertex-pair *(a, b)* can collapse to vertex *c* only when all the vertices v_0 , v_1 , … v_k are present and adjacent to *(a, b)*.

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Implicit Dependencies

- Observations
  - Collapsibility graph is a Directed Acyclic Graph
  - Validity check involves determining the age of a node relative to its neighbors
- Solution
  - Each node is assigned a unique integer as *id*
  - Assign new nodes progressively increasing id-number

Implicit Dependencies

- Vertex ***v*** can split if:
  - Its *id* is greater than the *id* of all its neighbors

- Vertex-pair ***(u, v)*** can collapse to ***w*** if:
  - ***w*** 's *id* is less than the *id* of the parents of the neighbors of the two vertices (*u*,*v*)

Implicit Dependencies

- Vertex needs to maintain only two values:
  - Max ID of all its neighbors
  - Min ID of parents of all its neighbors
- Run-time checks become constant time
  - check against the above two values instead of all neighbors
- Localized memory accesses
  - Eg: Stanford Dragon (871K triangles, 874K nodes)
    - avg memory access distance for dependency checks comes down to ~1 byte from 14 MB

Outline

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  - Maintaining triangle strips
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Recent Research on Triangle Strips

Akeley, Haeberli, Burns, *1990*

Arkin et al. Visual Computer 96

Evans, Skiena, Varshney, *Visualization 96*

Duchaineau et al., Visualization 97

Gumhold & Strasser, *Siggraph 98*

El-Sana, Azanli, Varshney, Visualization 99

Xiang, Held, Mitchell, I3D *99*

Deering, *Siggraph 95*

Bar-Yehuda & Gotsman, ACM TOG 96

Chow, *Visualization 97*

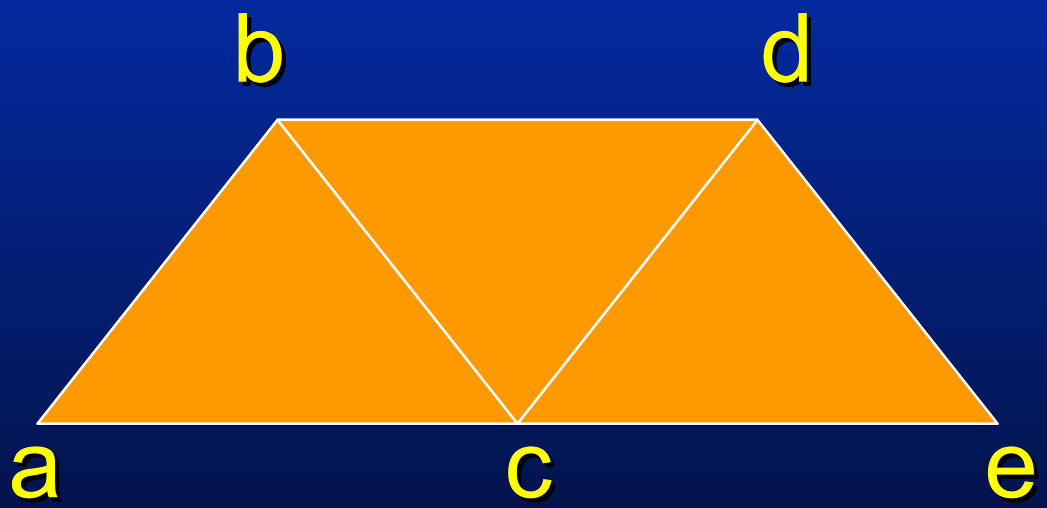
Speckmann & Snoeyink, *CCCG 97*

Taubin et al., *Siggraph 98*

Hoppe, *Siggraph 99*

Velho et al., Visual Computer 99

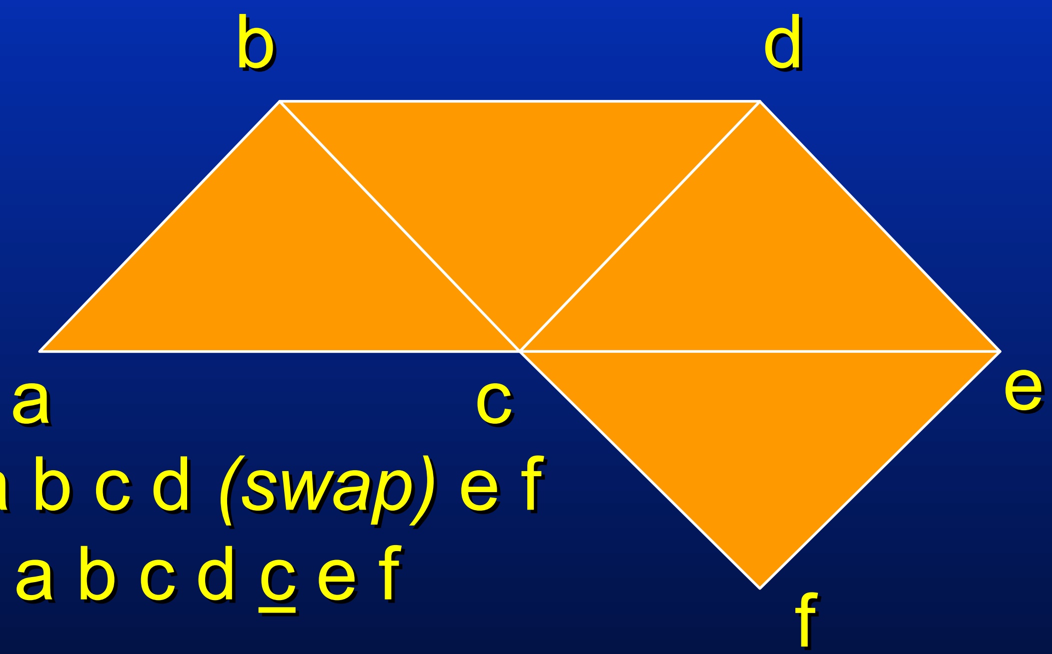
Triangle Strip



Triangles: (abc), (bcd), (cde)

Triangle Strip: abcde

Generalized Triangle Strips



Triangle Strip: a b c d *(swap)* e f

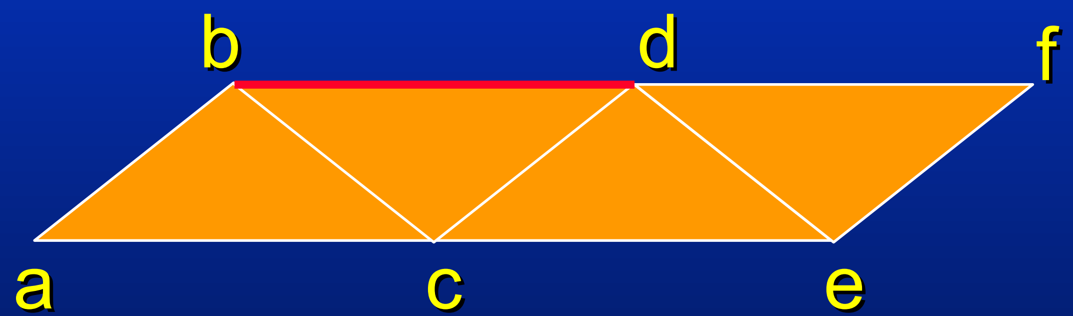
a b c d <u>c</u> e f

Repeating vertices changes direction

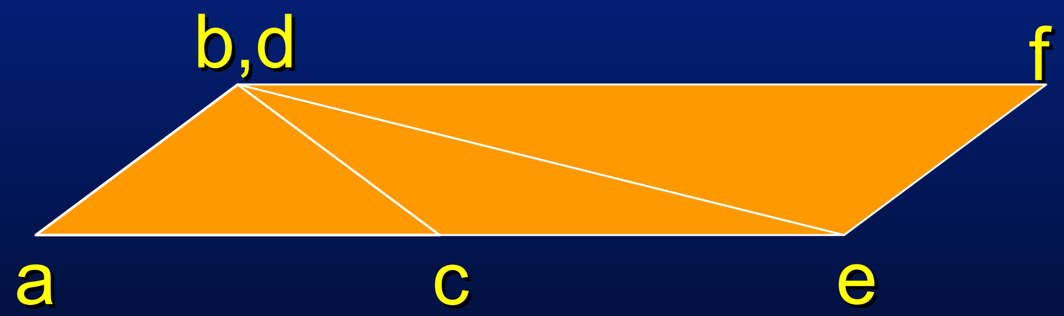
Triangle Strips with LODs

- Triangle strips
  - 2X speedup
  - Hardware / Software support
- Discrete LODs
  - Off-line computation of triangle strips per LOD
- View-dependent simplification
  - Connectivity changes every frame
  - Requires run-time update of triangle strips

Edge Collapse in a Triangle Strip



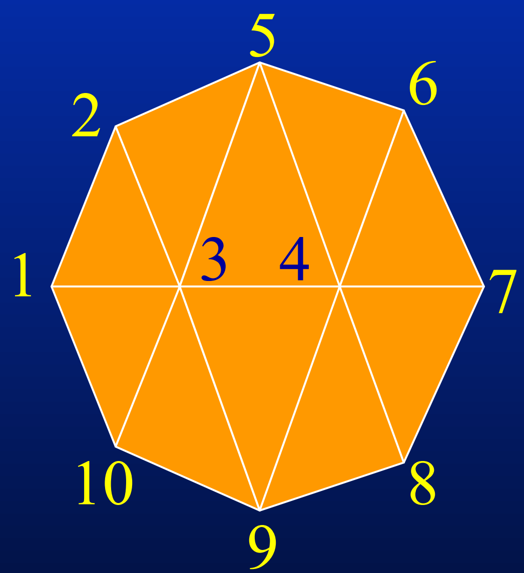
(abcdef)



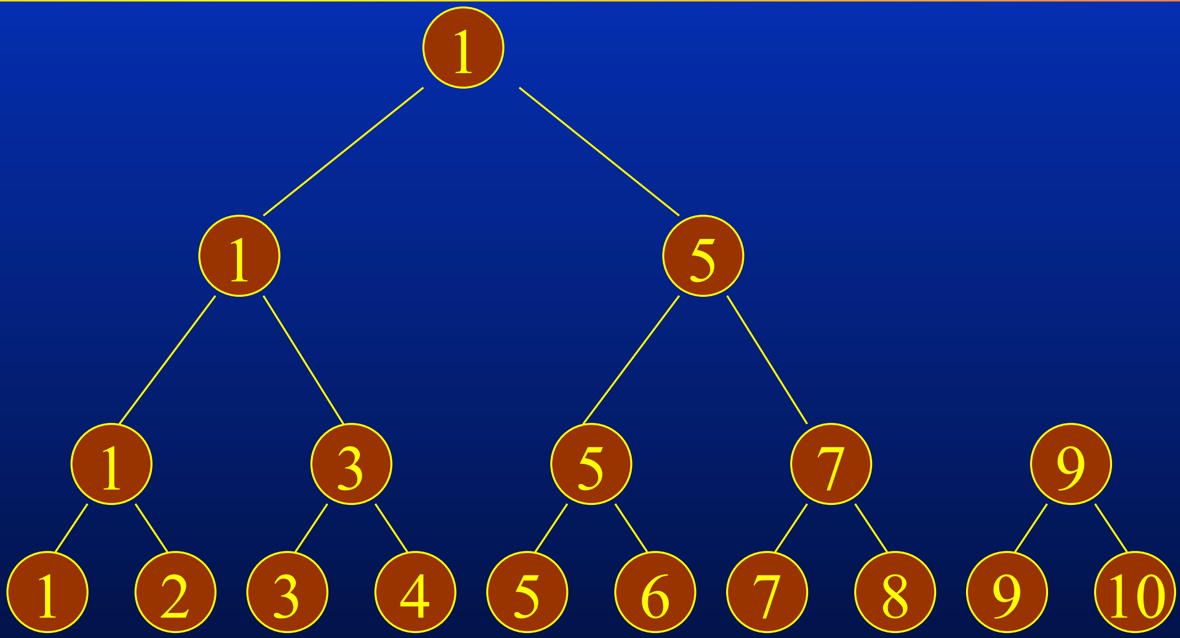
(abcbef)

Repeating vertices can represent edge collapses

Merge Tree

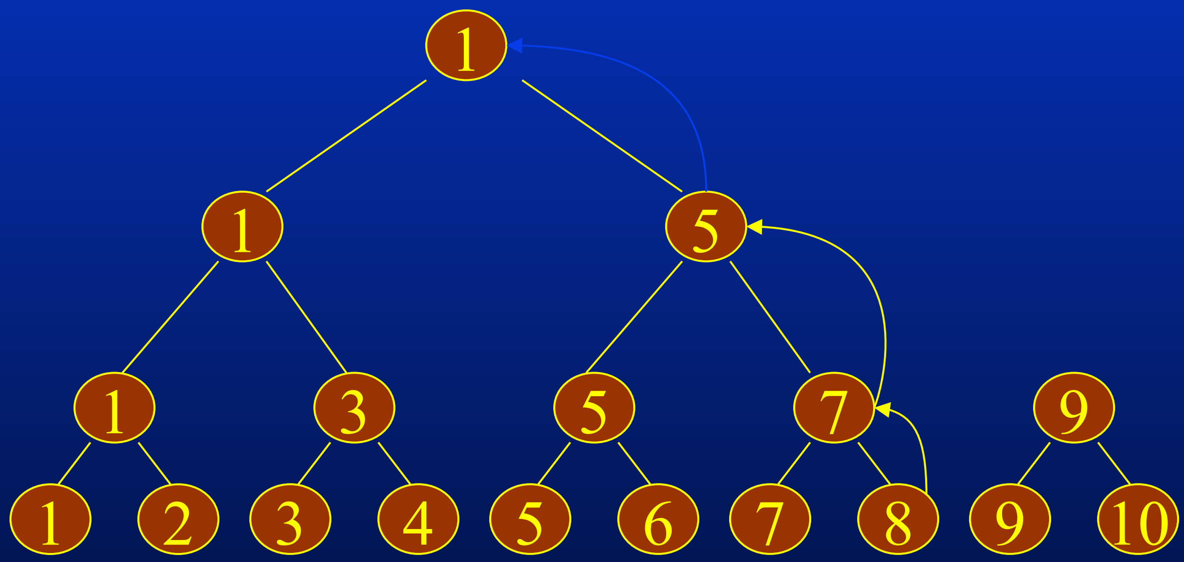


Mesh



Merge Tree

Following Parent Pointers



- Replace each Triangle Strip vertex by its closest active ancestor
- Need efficient pointer hopping

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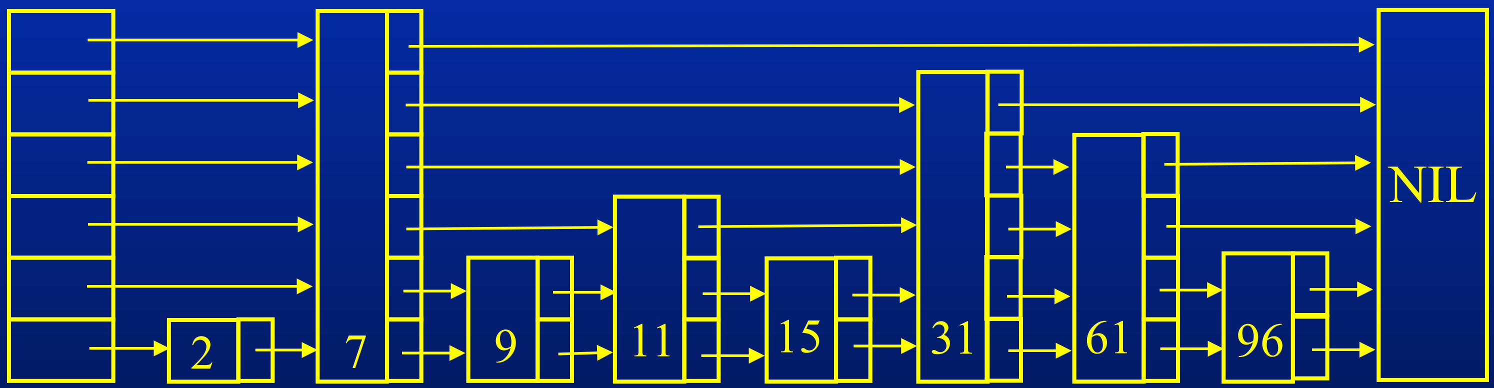
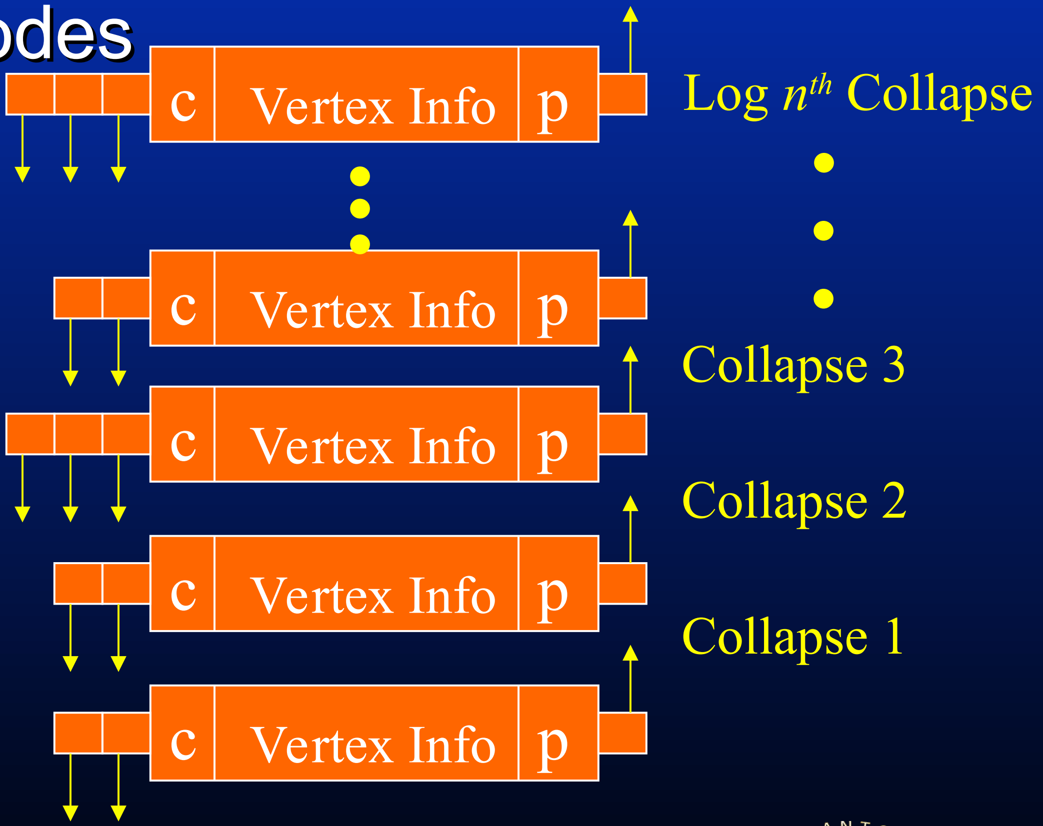
Skip Lists



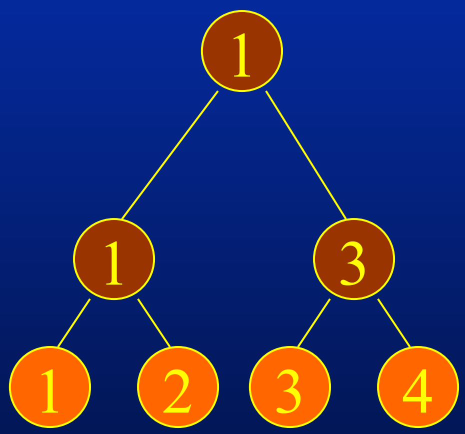
- Pugh [CACM 1990]
- Probabilistic balancing
- Fast searches
- Compressed trees

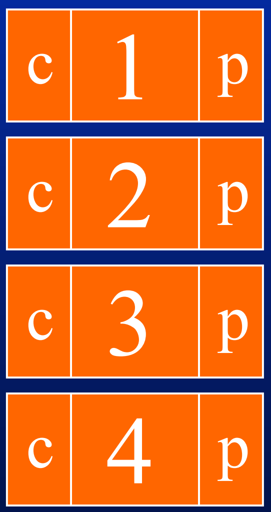
Skip Strip Data Structure

- Array of Skip Strip Nodes
- Merge
  - Increment p
  - Increment c
- Split
  - Decrement p
  - Decrement c



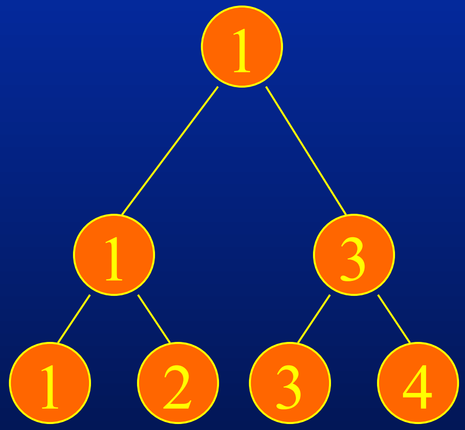
Building a Skip Strip

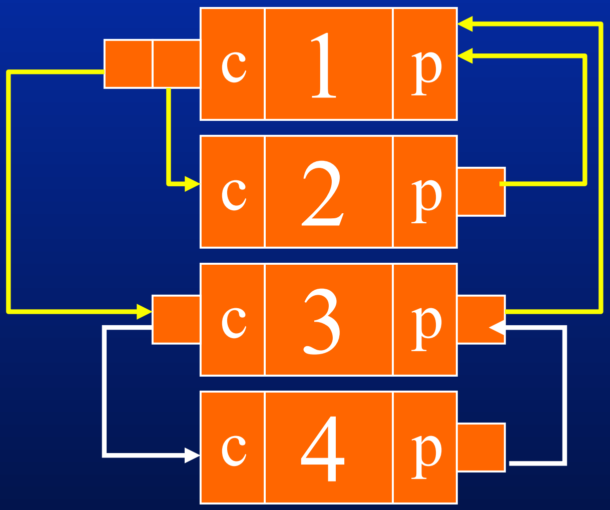




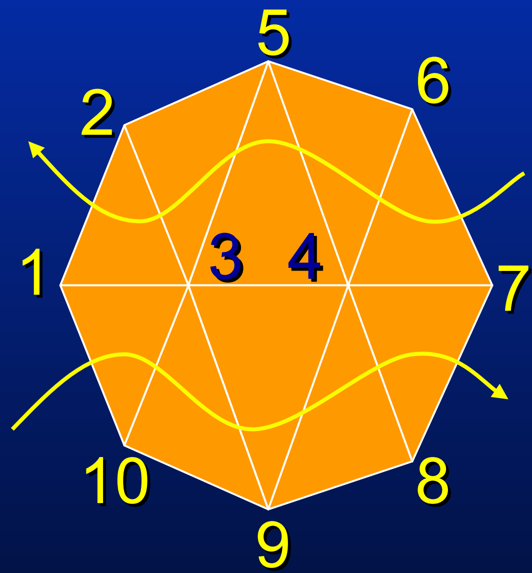
Building a Skip Strip

Building a Skip Strip





Skip Strips with LODs

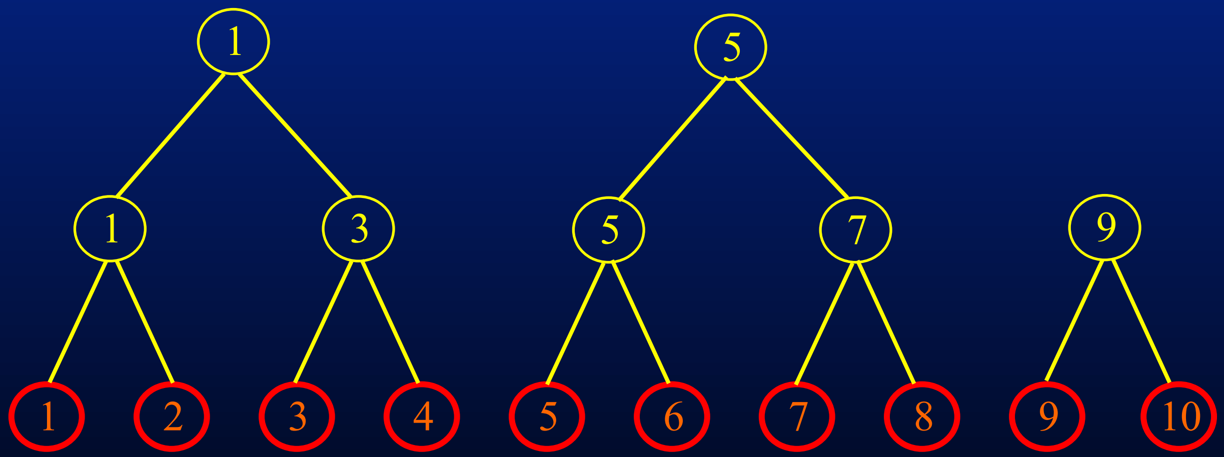


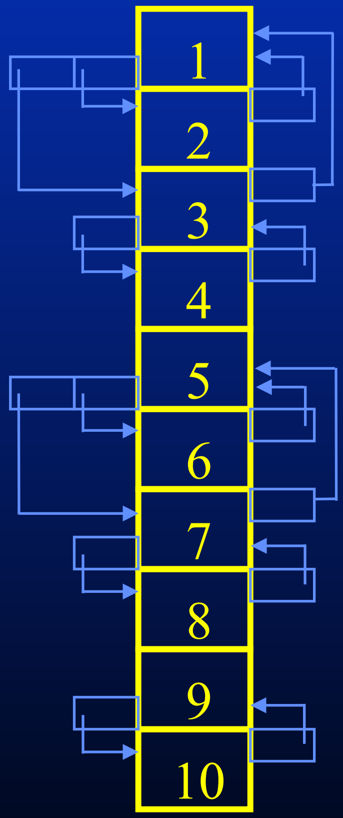
Triangle Strip A (7 6 4 5 3 2 1)

Triangle Strip B (1 10 3 9 4 8 7)

Skip Strip Example

Triangle Strip A: 7 6 4 5 3 2 1
Display Strip A: 7 6 4 5 3 2 1
Triangle Strip B: 1 10 3 9 4 8 7
Display Strip B: 1 10 3 9 4 8 7

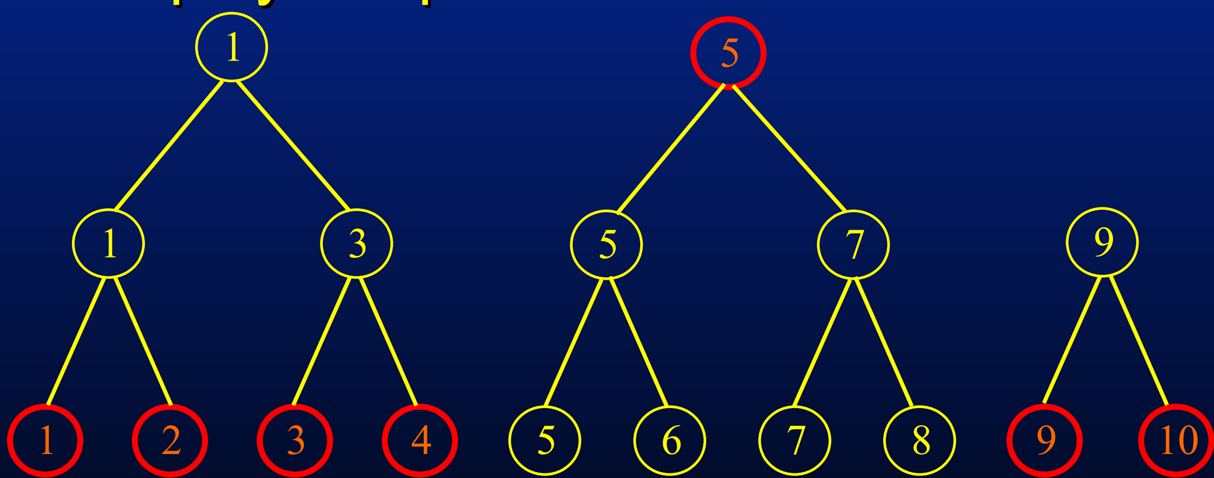




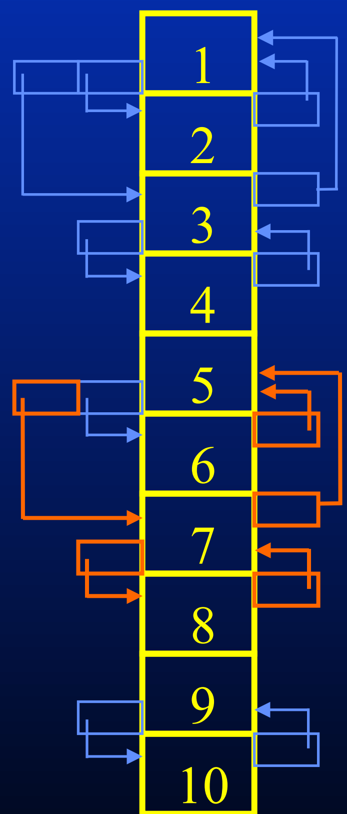
Highest Resolution

Skip Strip Example

Triangle Strip A: 7 6 4 5 3 2 1
Display Strip A: 5 5 4 5 3 2 1
Triangle Strip B: 1 10 3 9 4 8 7
Display Strip B: 1 10 3 9 4 5 5

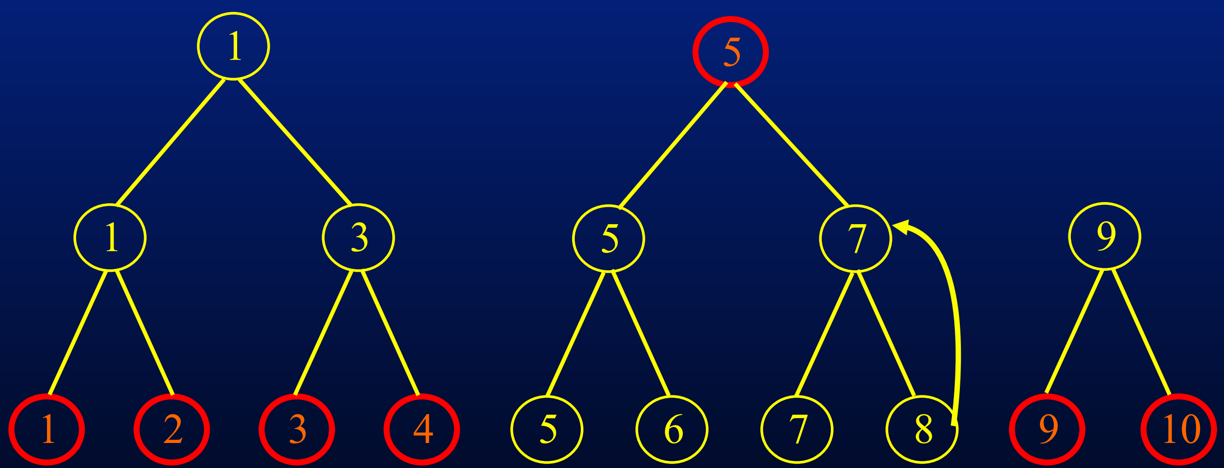


Lower Resolution

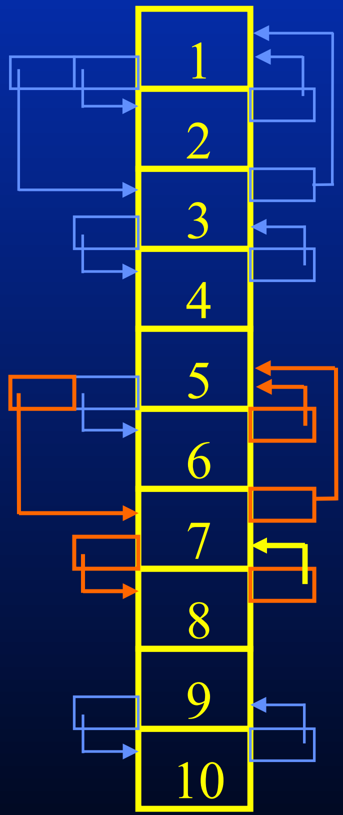


Skip Strip Example

Triangle Strip A: 7 6 4 5 3 2 1
Display Strip A: 5 5 4 5 3 2 1
Triangle Strip B: 1 10 3 9 4 8 7
Display Strip B: 1 10 3 9 4 5 5

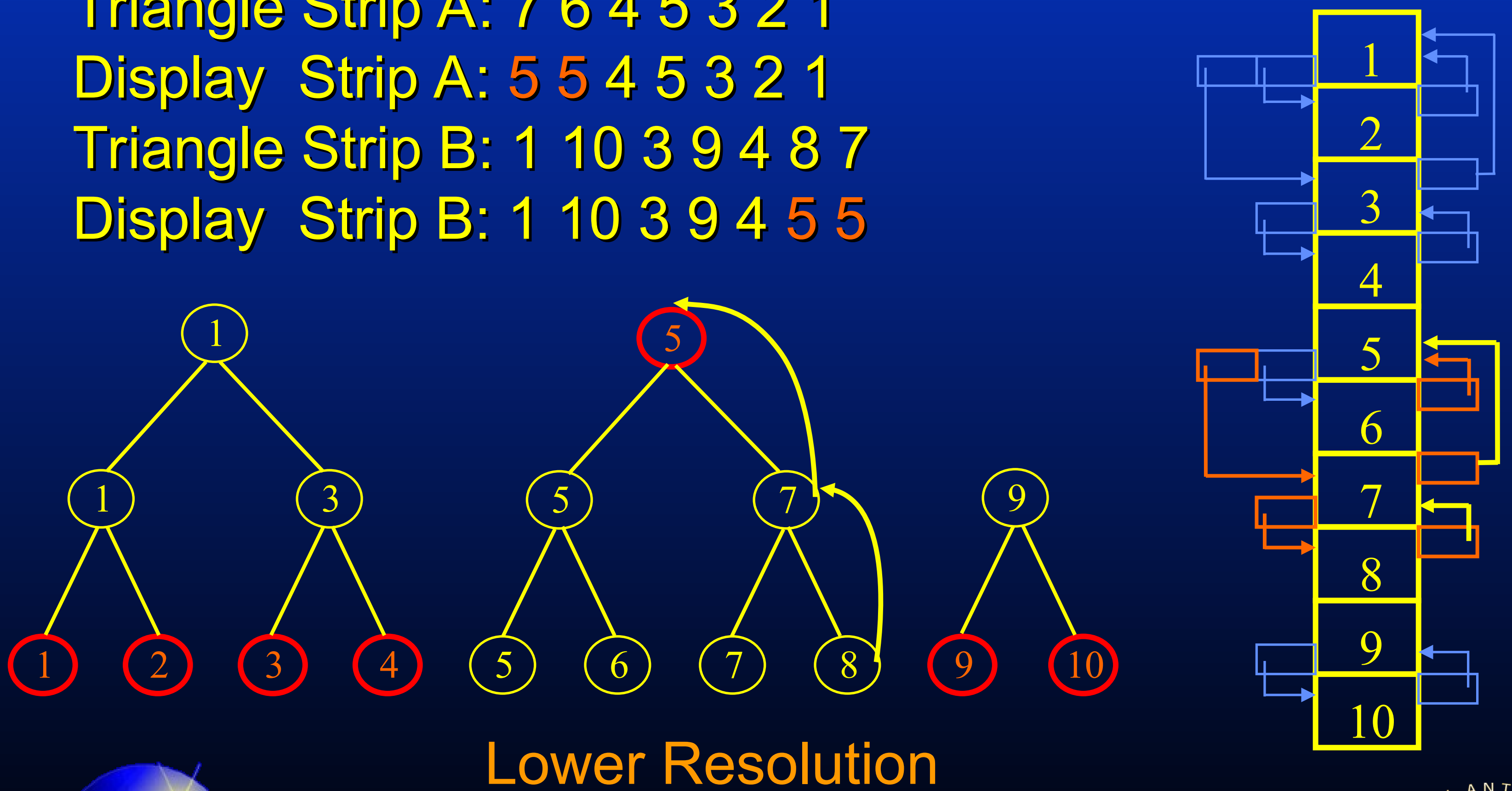


Lower Resolution



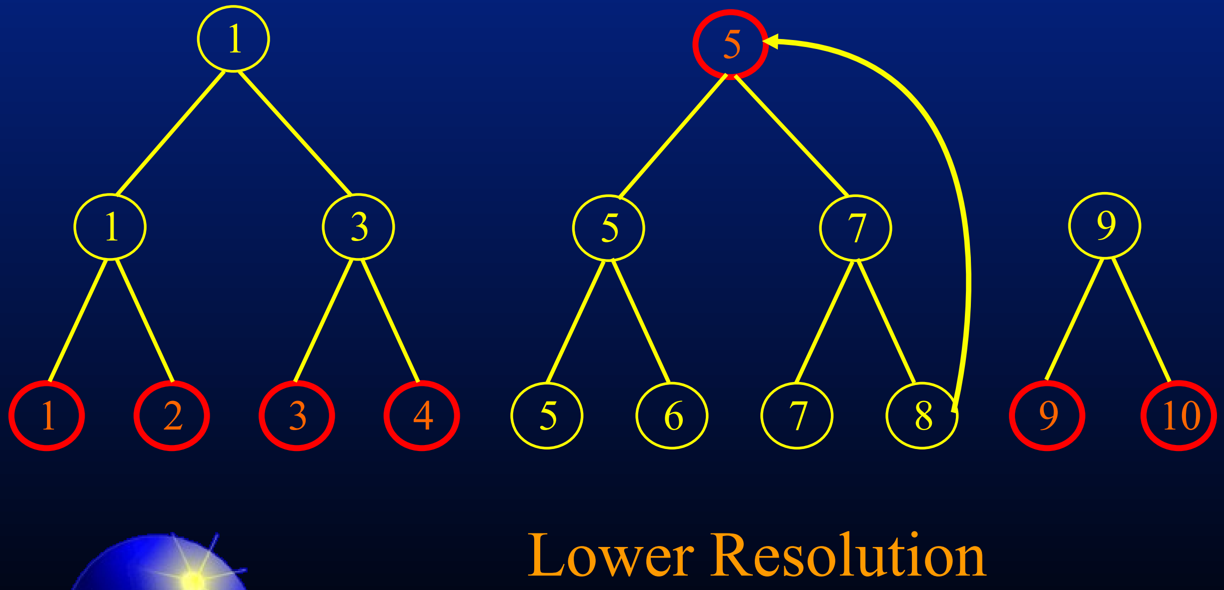
Skip Strip Example

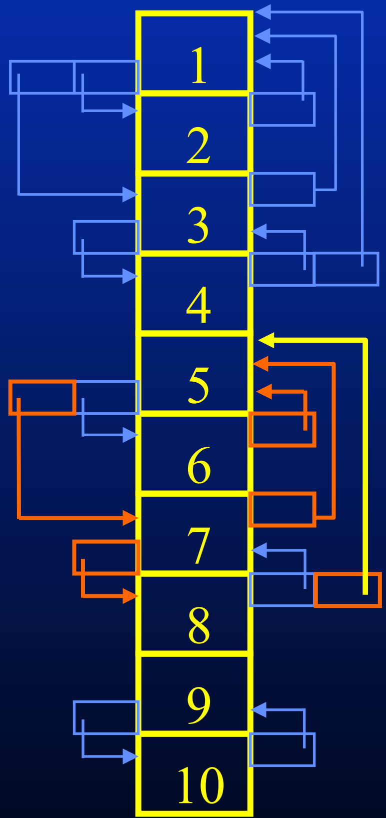
Triangle Strip A: 7 6 4 5 3 2 1
Display Strip A: 5 5 4 5 3 2 1
Triangle Strip B: 1 10 3 9 4 8 7
Display Strip B: 1 10 3 9 4 5 5



Optimized Skip Strip Example

Triangle Strip A: 7 6 4 5 3 2 1
Display Strip A: 5 5 4 5 3 2 1
Triangle Strip B: 1 10 3 9 4 8 7
Display Strip B: 1 10 3 9 4 5 5





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Real-Time Display

- Determine the display vertices
- Determine the display strips
  - Determine which strips have changed
  - Traverse the changed triangle strips
  - Follow Skip Strip pointers to get appropriate ancestors
  - Remove redundant vertices

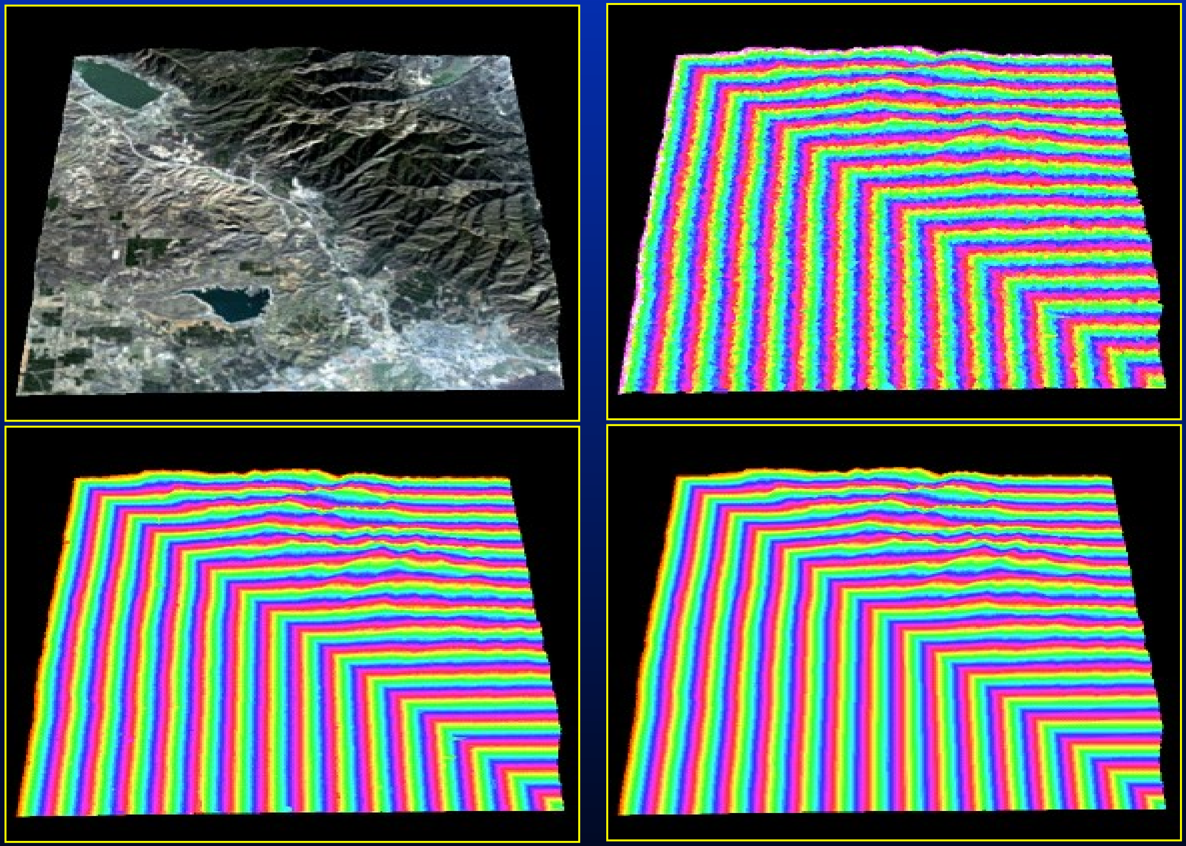
Efficient Skipping

- Reduce the traversed non-active vertices
  - Compress the traversed paths
  - Update the compressed paths in lazy fashion
  - Cache the active path index
- Efficiency
  - We use only *O(log log n)* jumps

Results: Terrain

255K tris

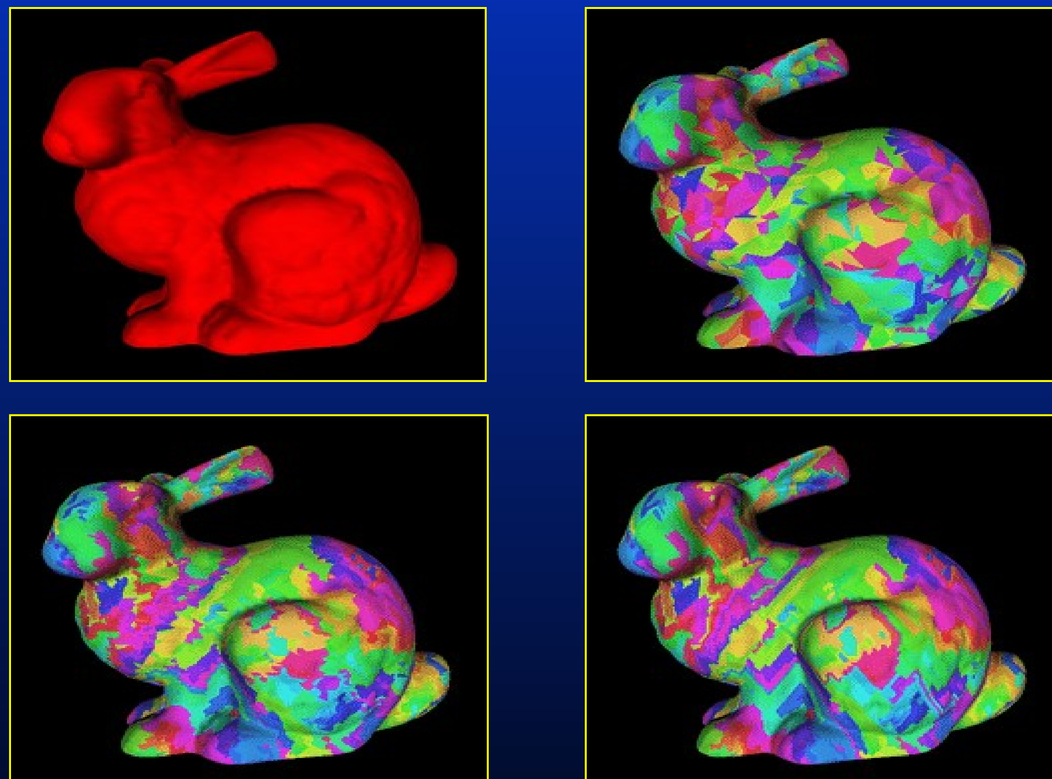
32K tris



255K tris

522K tris

Results: Bunny



30K tris

5K tris

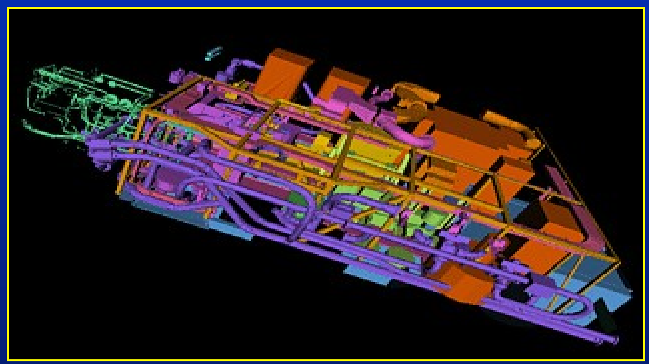
30K tris

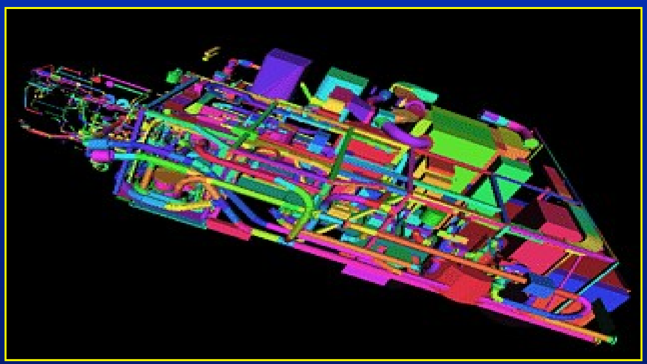
65K tris

El-Sana and Varshney, Visualization 99

Auxiliary Machine Room

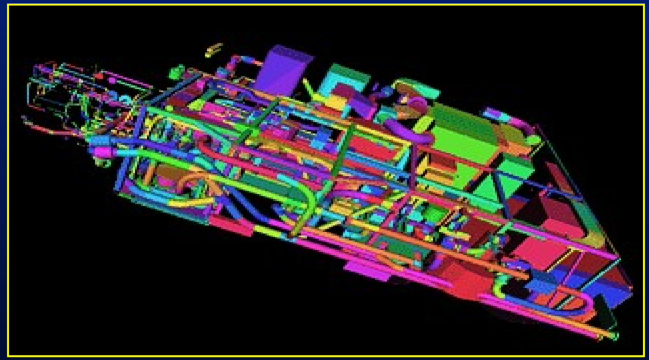
65K tris

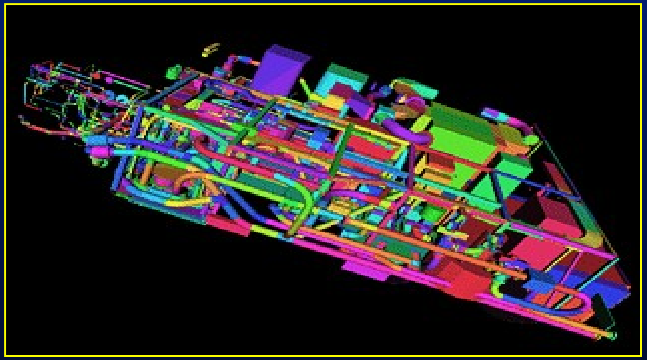




65K tris

170K tris





340K tris

El-Sana and Varshney, Visualization 99

Results

- Skip Strips make execution of split and merge operations more efficient
- Applicable to any hierarchical vertex scheme
- Four our four sample datasets:
  - Skip Strips provided ~ 1.5 to 2.0 X improvement over sending raw view-dependent triangles
  - Skip Strips provided ~ 1.6 to 1.7 X improvement over per-frame greedy triangle strip generation
- *But we have not tested this with video memory …*

Outline

- Geometry and Topology Simplifications
- Implementing View-dependent LODs
- Variable-Precision Rendering

Defining Level of Detail

- *Number* of Primitives
- *Precision* of primitives
  - Colors (Heckbert *82*, Xiang *97*)
  - Normals (Deering *95*, Zhang & Hoff *97*)
  - Vertex coordinates (King & Rossignac *99*)

Variable-Precision Rendering

- Reduce the precision of graphics primitives
- Relate the number of bits of input precision for a given display accuracy
- Speedup 3D transformation and lighting by taking advantage of SIMD parallelism
- Explore spatio-temporal coherence

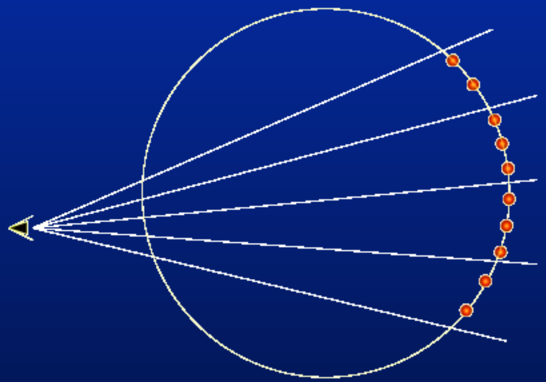
Related Work

Sugihara *89*
Milenkovic & Nackman *90*
Rossignac & Borrel *93*
Deering *95*
Fortune & Van Wyk *96*
Chow *97*
Luebke & Erikson *97*
Fortune *98*

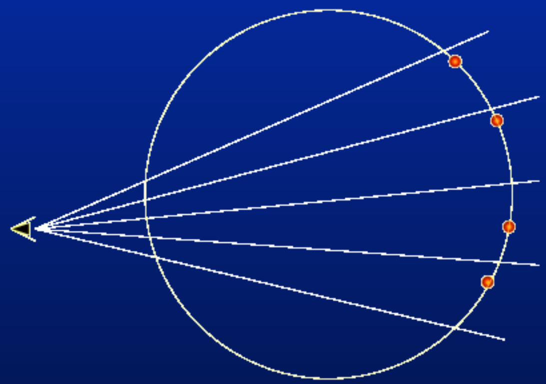
Taubin & Rossignac *98*
Taubin et al. *98*
Li & Kuo *98*
Cohen-Or et al. *99*
- Bajaj et al. *99*
- King & Rossignac *99*

Bajaj et al. *2000*
Pajarola & Rossignac *2000*

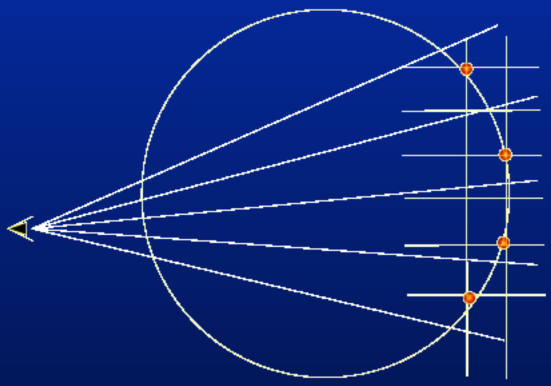
Variable-Precision vs. Multiresolution



Original



Multiresolution



Variable Precision

Assumptions

- Minimum-sized cube covering the object
  - x, y, z normalized to range [-1.0, 1.0]
- N-bit fixed-point representation of operands
- Rounding to the nearest integer
- Worst-case study

Error Analysis

- Representation error of a
  - Half bit, i.e., $\varepsilon_a \le \frac{1}{2}$
- Addition error of $(a+b)$

$$\varepsilon_{(a+b)} \le \varepsilon_a + \varepsilon_b \le \frac{1}{2} + \frac{1}{2} = 1, \text{ i.e., lose one bit of accuracy}$$

- Multiplication error of $(a \times b)$

$$\varepsilon_{(a \times b)} \le \left| a\varepsilon_b + b\varepsilon_a \right| \le \frac{1}{2} + \frac{1}{2} = 1, \text{ i.e., lose one bit of accuracy}$$

Error Analysis

- Division error of (a/b)

Generated error $\varepsilon_{(a/b)}^{gen} < 1$ due to truncation

Propagated error $\varepsilon_{(a/b)}^{prop} = \frac{\partial}{\partial a}\left(\frac{a}{b}\right)\varepsilon_a + \frac{\partial}{\partial b}\left(\frac{a}{b}\right)\varepsilon_b$

$$= \frac{\varepsilon_a}{b} + \frac{a}{b^2}\varepsilon_b \le \frac{1}{b} \qquad \left(\begin{array}{c}\varepsilon_a, \varepsilon_b < 1/2 \\ a < b\end{array}\right)$$

$$\varepsilon_{(a/b)} = \varepsilon_{(a/b)}^{gen} + \varepsilon_{(a/b)}^{prop} < 1 + \frac{\text{distance of far plane from eye}}{\text{distance of scene vertex to eye}}$$

Putting it all together

$$m = n + 3 + \left\lceil \log_2 \left(1 + \frac{\text{distance of far plane from eye}}{\text{distance of scene vertex to eye}} \right) \right\rceil$$

m is number of bits of input data

n is output accuracy after transformation

e.g., 1024×1024 window with pixel-level accuracy

object half-way across the view volume

$$n = 10$$

$$m = 10 + 3 + \lceil \log_2 (1 + 2) \rceil = 15$$

View-dependent Transformation

- Construct bounding volume hierarchy
- Find the projected size of the object
- Determine the nearest visible vertex accuracy

$$near\_bits = m - \left\lfloor \left| \log_2\left(\frac{\text{projected range}}{2}\right) \right| \right\rfloor$$

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View-dependent Transformation

Accuracy needed for each vertex:

$$vertex\_bits = near\_bits - \left\lfloor \log_2\left(\frac{\text{transformed W of the vertex}}{\text{distance of nearest vertex to eye}}\right) \right\rfloor$$

Compute by using bounding volume hierarchy

Spatio-temporal Coherence

- Spatial coherence
  - Using differences in neighboring vertices
  - $M\,x' = M\,(x + \Delta x) = M\,x + M\,\Delta x$
  - Top-down octree traversal
- Temporal Coherence
  - Frame-to-frame
  - $M'\,x = (M + \Delta M)\,x = M\,x + \Delta M\,x$
  - Can be combined with spatial coherence

Transformation Result

Floating Point
(32 bits/vertex coordinate)

Variable Precision
(7.9 bits/vertex coordinate)

Variable-Precision Lighting

$$
\begin{aligned}
Color = {} & emission_{mat} + ambient_{model} \times ambient_{mat} + \\
& \sum_{i=0}^{m-1} \left(\frac{1}{k_c + k_l d + k_q d^2}\right)_i \times (spotlight\_effect)_i \times \\
& (ambient_{light} \times ambient_{mat} + \\
& (\max\{\mathbf{L} \cdot \mathbf{N}, 0\}) \times diffuse_{light} \times diffuse_{mat} + \\
& (\max\{\mathbf{H} \cdot \mathbf{N}, 0\})^{shin} \times specular_{light} \times specular_{mat})_i
\end{aligned}
$$

Sources of Illumination Errors

- Operands with different accuracy
- Square-root operation error
- Specular exponentiation error

Illumination Errors

Operands a and b with different bits of accuracy: n (for a) and n' (for b) and $n > n'$

- Addition error of $(a+b)$

$$\varepsilon_{(a+b)} \le \varepsilon_a + \varepsilon_b \le 2^{-(n+1)} + 2^{-(n'+1)} \approx 2^{-(n'+1)}$$

i.e. same accuracy as the less accurate operand

- Multiplication error of $(a \times b)$

$$\varepsilon_{(a\times b)} \le \left| a\varepsilon_b + b\varepsilon_a \right| \le 2^{-(n+1)} \times 1 + 2^{-(n'+1)} \times 1 \approx 2^{-(n'+1)}$$

Same as in the addition case

Illumination Errors

Square-root operation error

- Fixed-point operation ⇒ table lookup
- 2n bits operand
- Most significant n bits as index

Illumination Errors

Specular exponentiation error of (a^{shin})

- Operand a with n bits accuracy, $shin < 128$
- Error maximized by large a, ε_a, and $shin$

$$(a+\varepsilon_a)^{shin} \approx a^{shin} + a\varepsilon_a \times shin \quad (if\ \varepsilon_a << a)$$

$$\varepsilon_{(a^{shin})} \approx a\varepsilon_a \times shin < 1\times 2^{-(n+1)} \times 128 = 2^{-(n-6)}$$

i.e., lose 6 bits of accuracy at most.

Illumination Errors

- Dot-product of vectors lose 2 bits accuracy
- Putting it all together
  - Specular (least accurate) decides the overall accuracy
  - lose 1 bit for normalization, 2 bits for dot product, 6 bits for exponentiation
  - Total loss of accuracy: 9 bits
  - So: $m = n+9$ *(n = output accuracy, m = input accuracy)*

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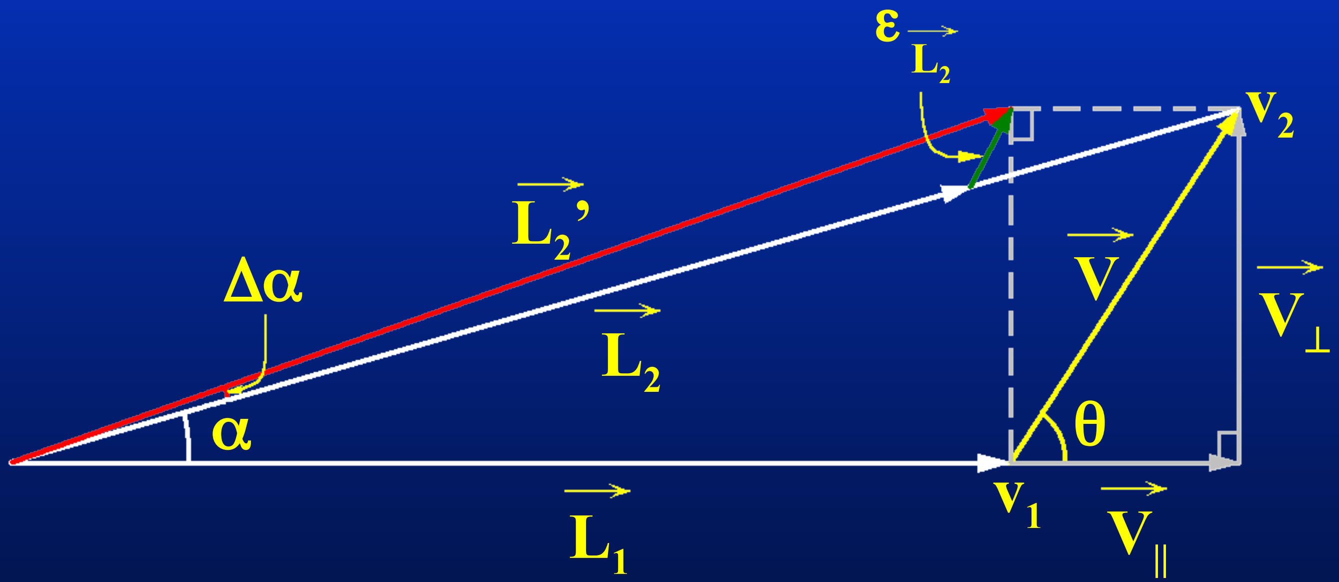
Incremental Lighting



The error of using L_2' as an estimate of L_2 is in the order of $\left(\left\| \vec{V} \right\|^2 \Big/ 2 \left\| \vec{L_1} \right\|^2 \right)$

Implementation Notes

- Vertices processed in groups as a tradeoff between
  - L2 cache size
  - Expensive cost of resetting MMX register flag between changes in operand types
- Avoid error buildup
  - Matrix setup and composition per frame is full precision
  - Transformations are variable precision
  - Computation cost is negligible

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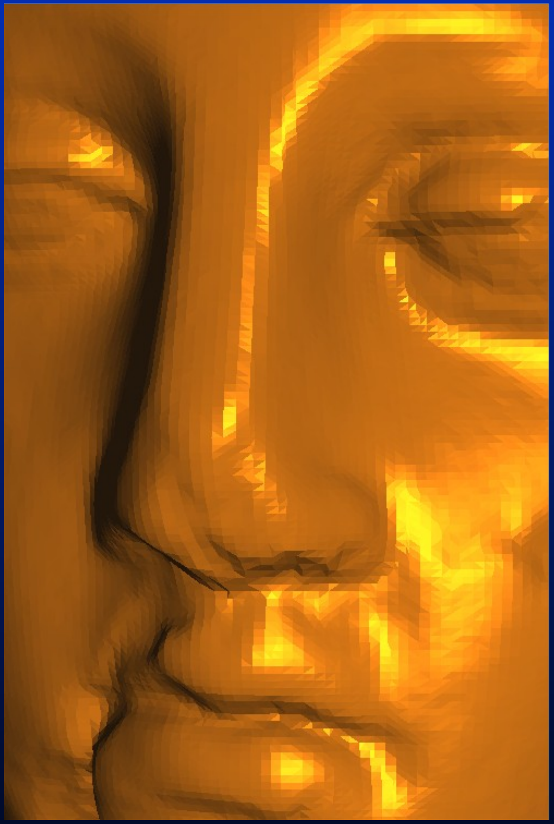
Results: Venus

Floating Point

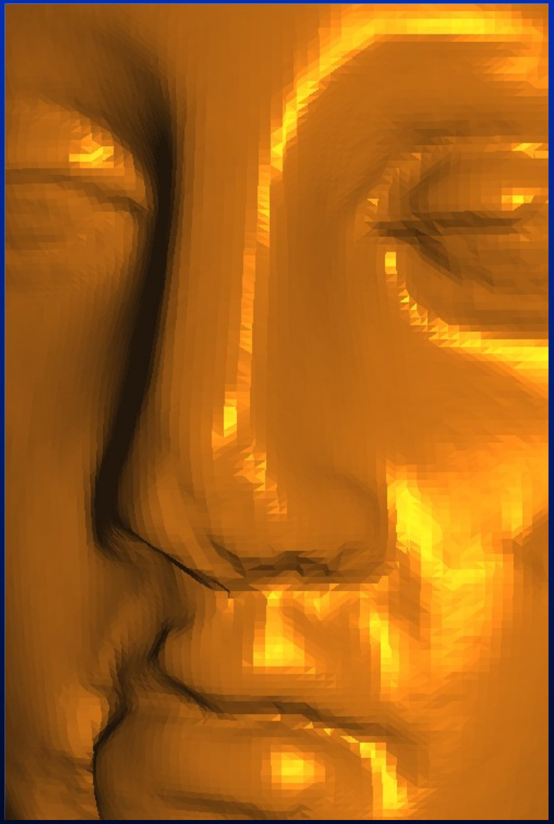
Variable Precision

Hao and Varshney, ACM I3D 2001

Results: Venus

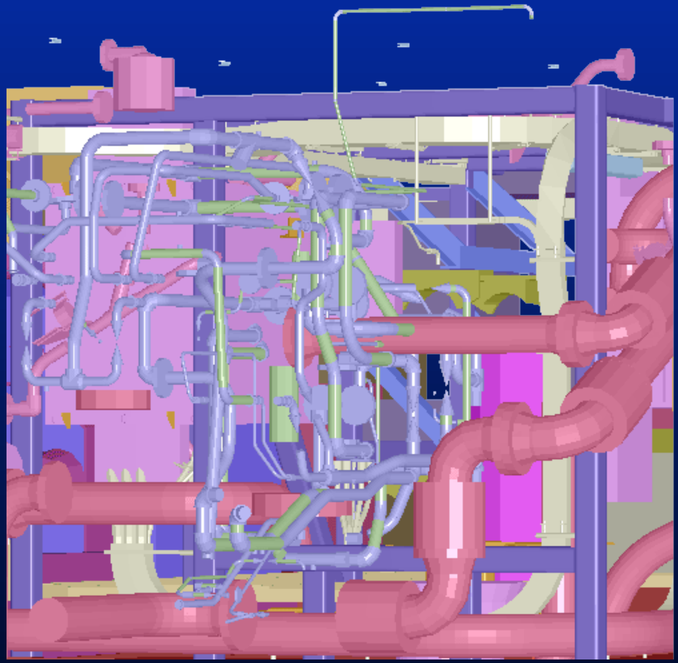


Floating Point

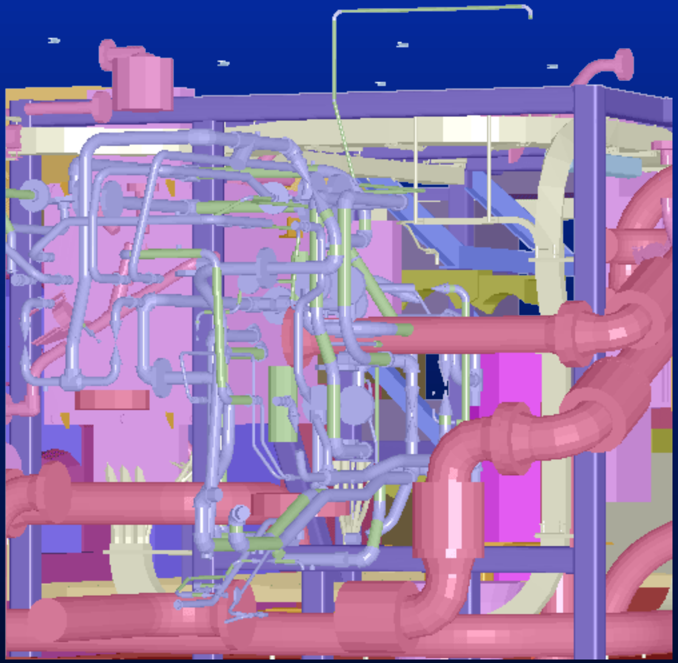


Variable Precision

Results
Auxiliary Machine Room



Floating Point



Variable Precision

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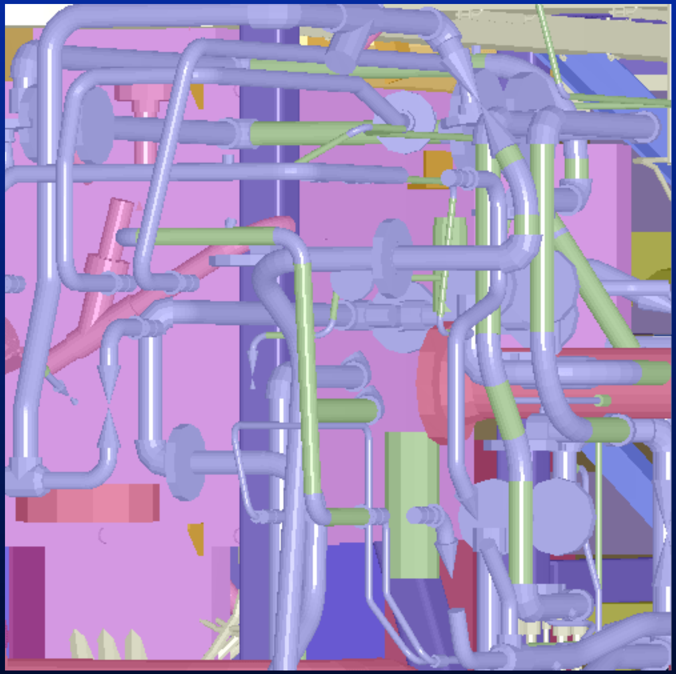
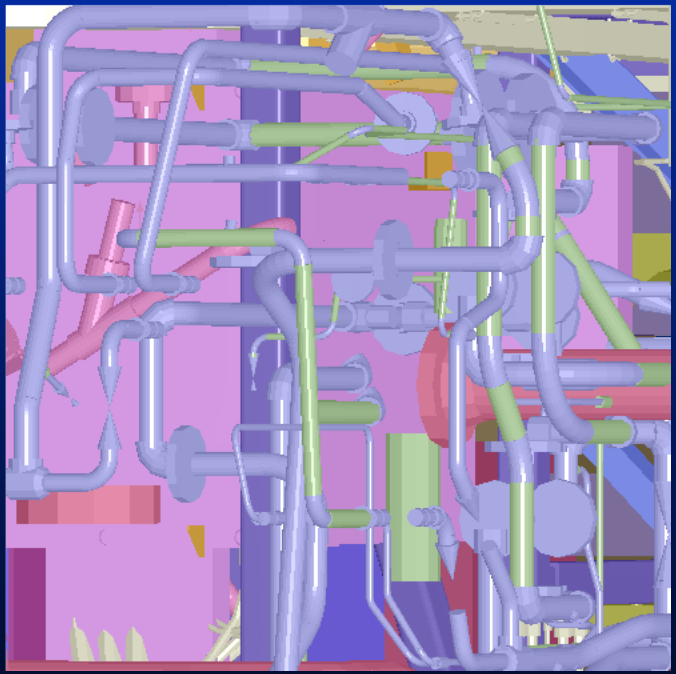
Results
Auxiliary Machine Room



Floating Point
Close-up



Variable Precision
Close-up

Conclusions

- More efficient transformation and lighting
- Complementary to multiresolution approaches
- For the datasets we tested
  - Using PII 400MHz PC with 128M RAM
  - Voodoo3 3500 graphics card and Glide API
  - Provides a factor of 4 or more speedup

Software

- http://www.cs.umd.edu/gvil/vpr.html
- Download free for non-commercial use

Conclusions

- Discrete and View-dependent LODs for simplifications of geometry and topology
- Implicit Dependencies for localizing data accesses
- Skip Strips: Updating triangle strips with view-dependent LODs
- Variable-Precision transformations and lighting

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