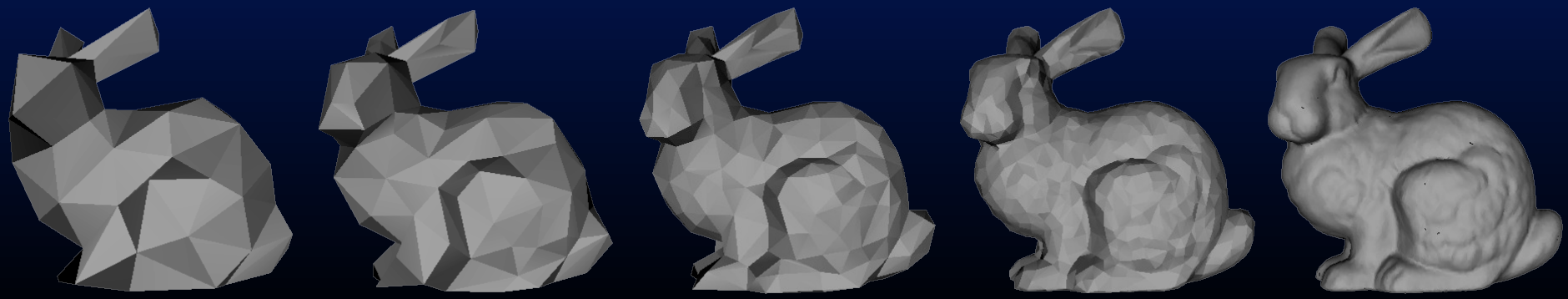
SAN ANTONIO

SIGGRAPH

2002

Advanced Issues In Level Of Detail



Course Introduction

- *Level of detail* (*LOD*) methods provide a powerful way to manage scene complexity
- A standard tool for the graphics developer to control rendering speed
- This course will adress advanced issues in using and developing LOD algorithms, with a focus on polygonal mesh simplification

Course Prerequisites

- We assume
  - Knowledge of the basic LOD concept
  - Experience with interactive graphics
- Target audience
  - Developers wishing to become sophisticated LOD users
  - Researchers wishing to broaden their knowledge of the field

Course Topics

- Generation

  LOD frameworks & creation

- Theory

  Measuring & controlling fidelity

- Applications

  Important real-world applications

Course Schedule

8:30	Welcome, Introductions	Luebke
8:50	Frameworks	Luebke
	Discrete, continuous, & view-dependent LOD	
10:15	Break	
10:30	Algorithms	Varshney, Cohen
	Algorithms and approaches for simplification	
	Appearance-preserving simplification	
12:15	Lunch	

Course Schedule

1:30	Fidelity	Cohen, Reddy, Watson

Measuring geometric and attribute error
Understanding and applying visual perception
Balancing fidelity and performance

3:15	Break	
3:30	Applications	Huebner, Reddy, Watson

Gaming optimizations
Terrain visualization
Out-of-core simplification

5	Conclusion	Luebke

Speakers
In Order of Appearance

- David Luebke, University of Virginia
- Jon Cohen, Johns Hopkins University
- Amitabh Varshney, University of Maryland
- Martin Reddy, SRI International
- Ben Watson, Northwestern University
- Rob Huebner, Nihilistic Software

Frameworks for LOD

- I will discuss 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
- I will focus on view-dependent LOD

Frameworks for LOD

- Questions I will address:
  - *What is view-dependent simplification?*
  - *Why is it better than traditional simplification? When is it worse?*
  - *How is it implemented efficiently?*
- Questions I will leave for the others:
  - *How can we control visual fidelity?*
  - *How much simplification is appropriate?*

Motivation:
Preaching To The Choir

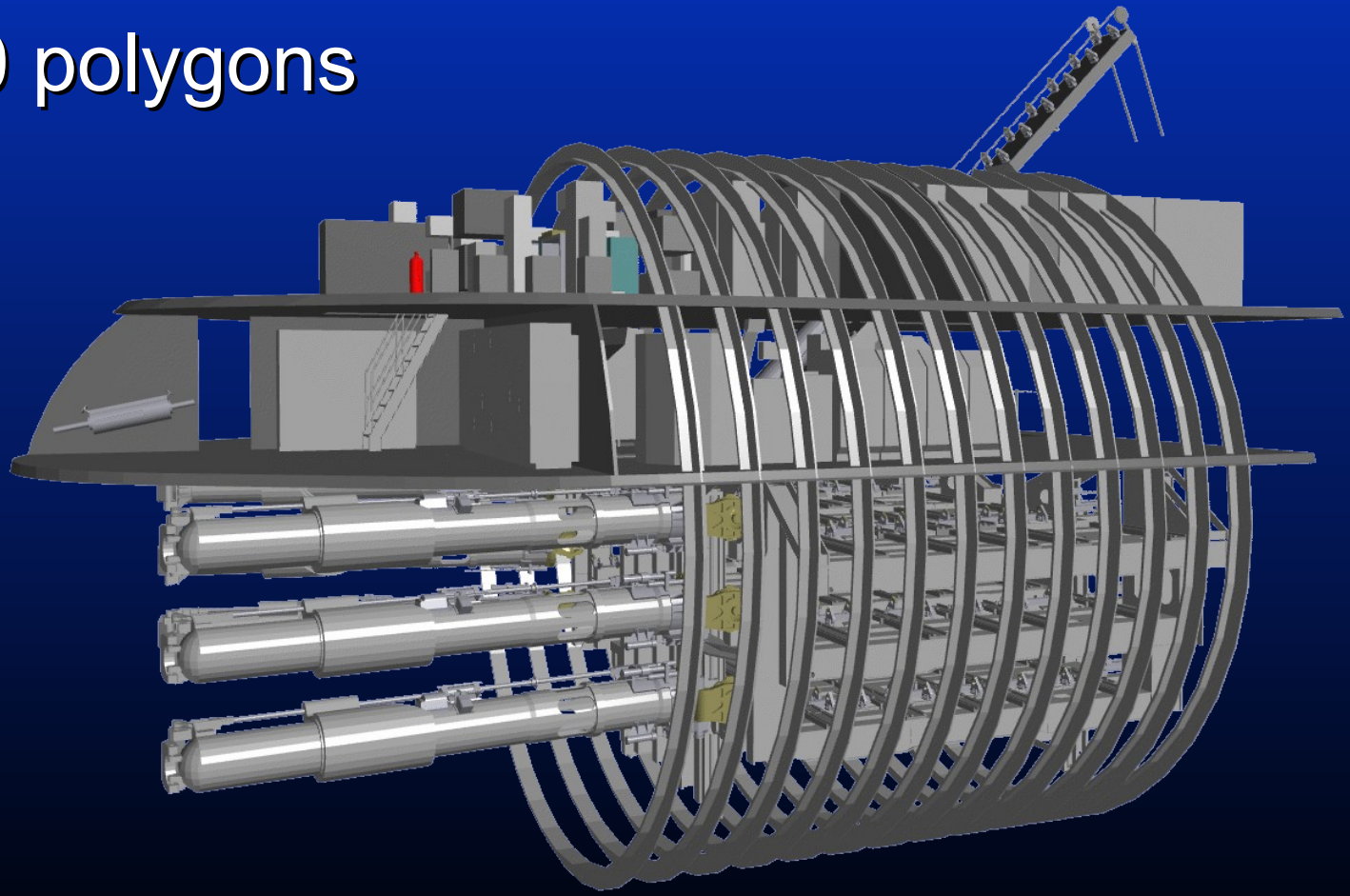
- Interactive rendering of large-scale geometric datasets is important
  - Scientific and medical visualization
  - Architectural and industrial CAD
  - Training (military and otherwise)
  - Entertainment

Motivation:
Big Models

- The problem:
  - Polygonal models are often too complex to render at interactive rates
- Even worse:
  - Incredibly, models are getting bigger as fast as hardware is getting faster…

Big Models:
Submarine Torpedo Room

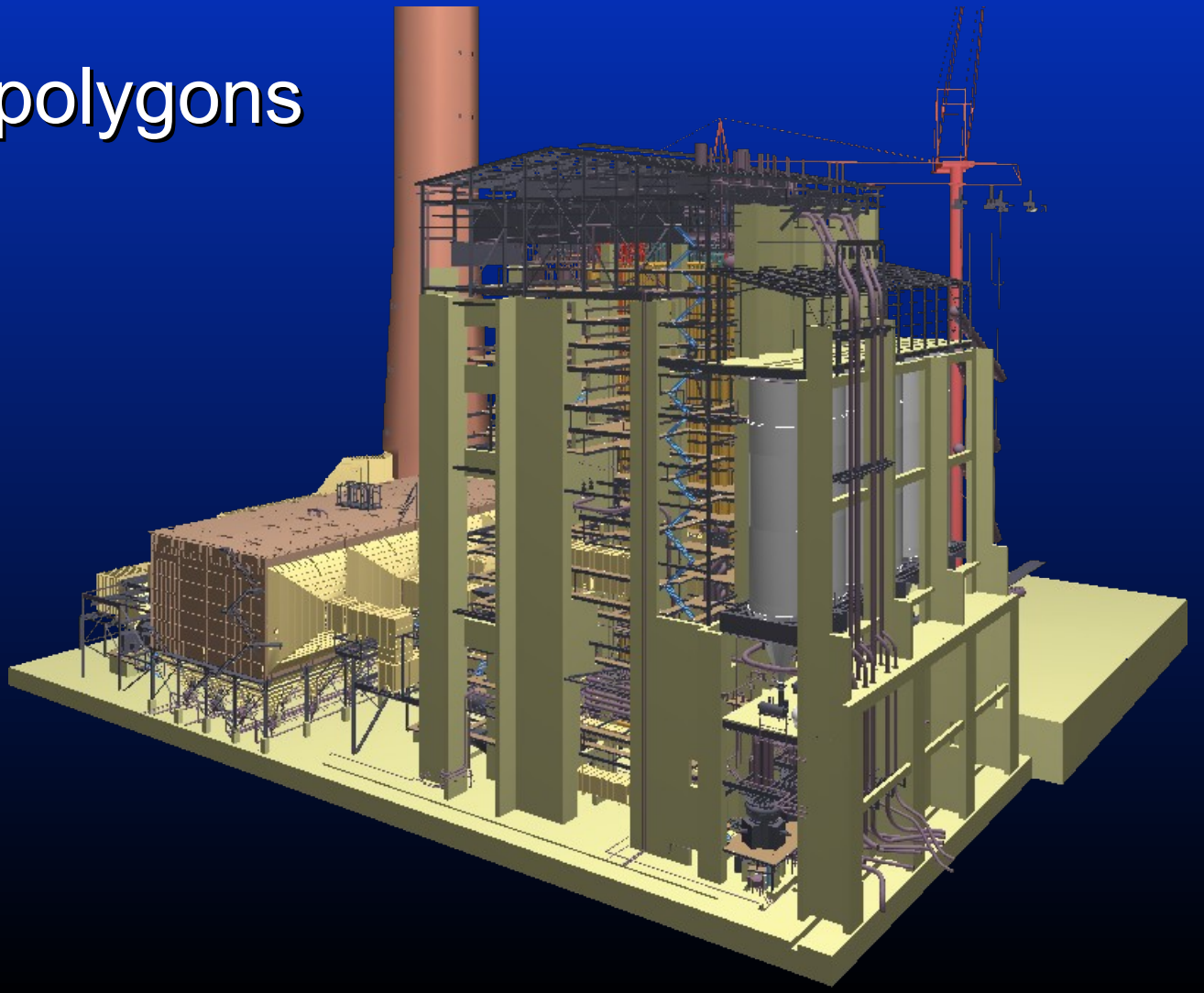
- 700,000 polygons



Courtesy General Dynamics, Electric Boat Div.

Big Models:
Coal-fired Power Plant

- 13 million polygons



(Anonymous)

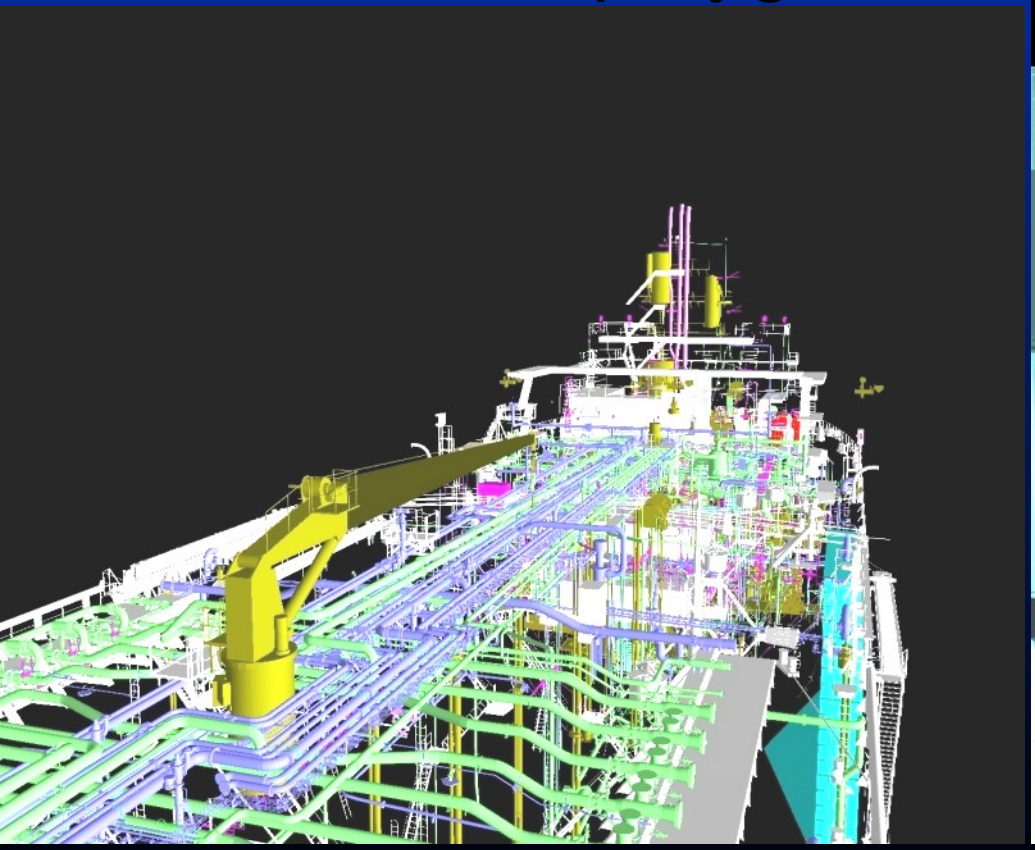
Big Models:
Plant Ecosystem Simulation

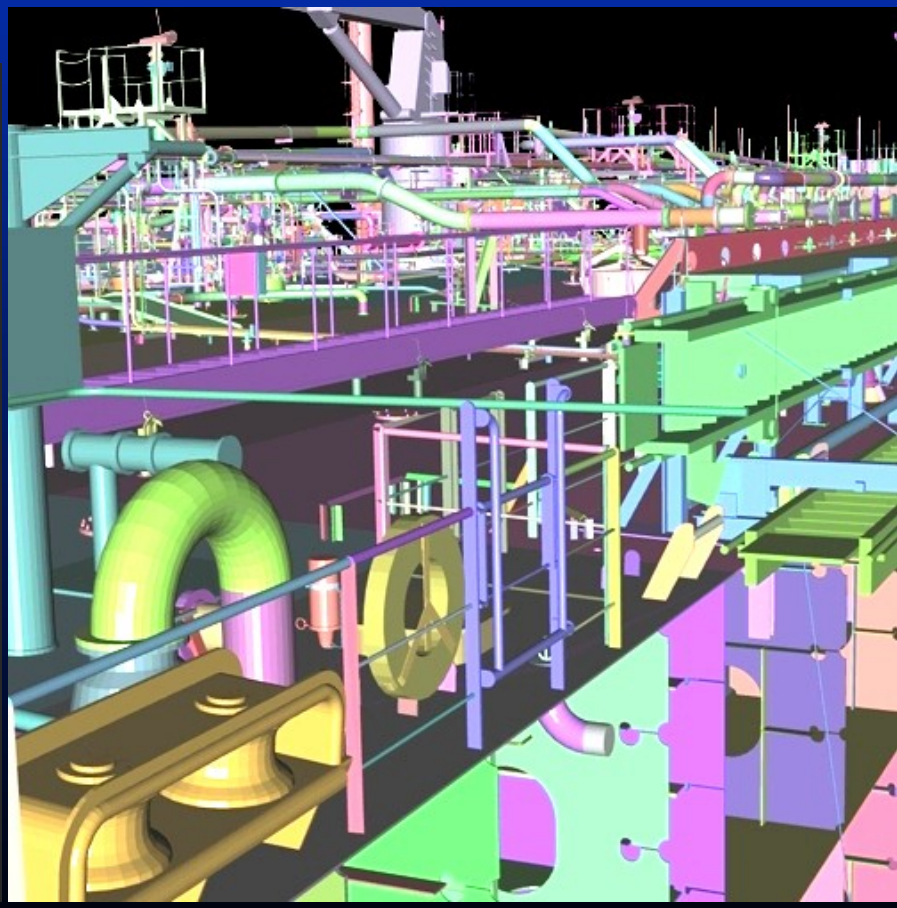
- 16.7 million polygons (sort of)

Deussen et al: *Realistic Modeling of Plant Ecosystems*

Big Models:
Double Eagle Container Ship

- 82 million polygons





Courtesy Newport News Shipbuilding

Big Models:
The Digital Michelangelo Project

- David:
  56,230,343 polygons
- St. Matthew:
  372,422,615 polygons

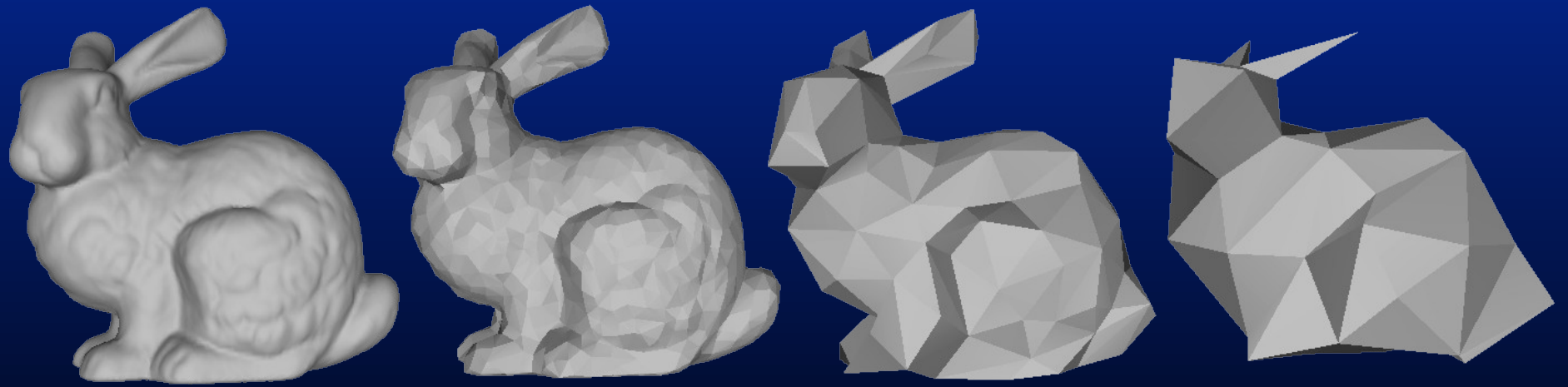
Courtesy Digital Michelangelo Project, Stanford University

Level of Detail:
The Basic Idea

- One solution:
  - Simplify the polygonal geometry of small or distant objects
  - Known as *Level of Detail* or *LOD*
    - A.k.a. polygonal simplification, geometric simplification, mesh reduction, multiresolution modeling, …

Level of Detail: Traditional Approach

- Create *levels of detail* (*LODs*) of objects:

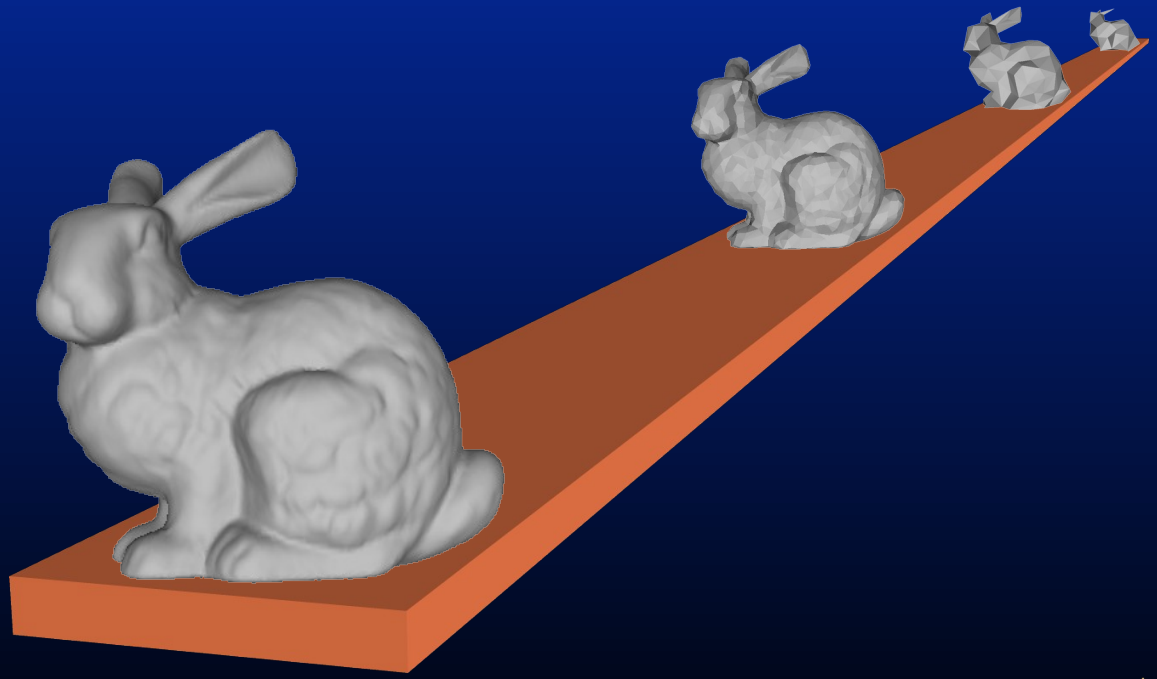


69,451 polys 2,502 polys 251 polys 76 polys

Courtesy Stanford 3D Scanning Repository

Level of Detail: Traditional Approach

- Distant objects use coarser LODs:



Traditional Approach:
Discrete Level of Detail

- Traditional LOD in a nutshell:
  - Create LODs for each object separately in a preprocess
  - At run-time, pick each object's LOD according to the object's distance (or similar criterion)
- Since LODs are created offline at fixed resolutions, I refer to this as *Discrete LOD*

Discrete LOD:
Advantages

- Simplest programming model; decouples simplification and rendering
  - LOD creation need not address real-time rendering constraints
  - Run-time rendering need only pick LODs

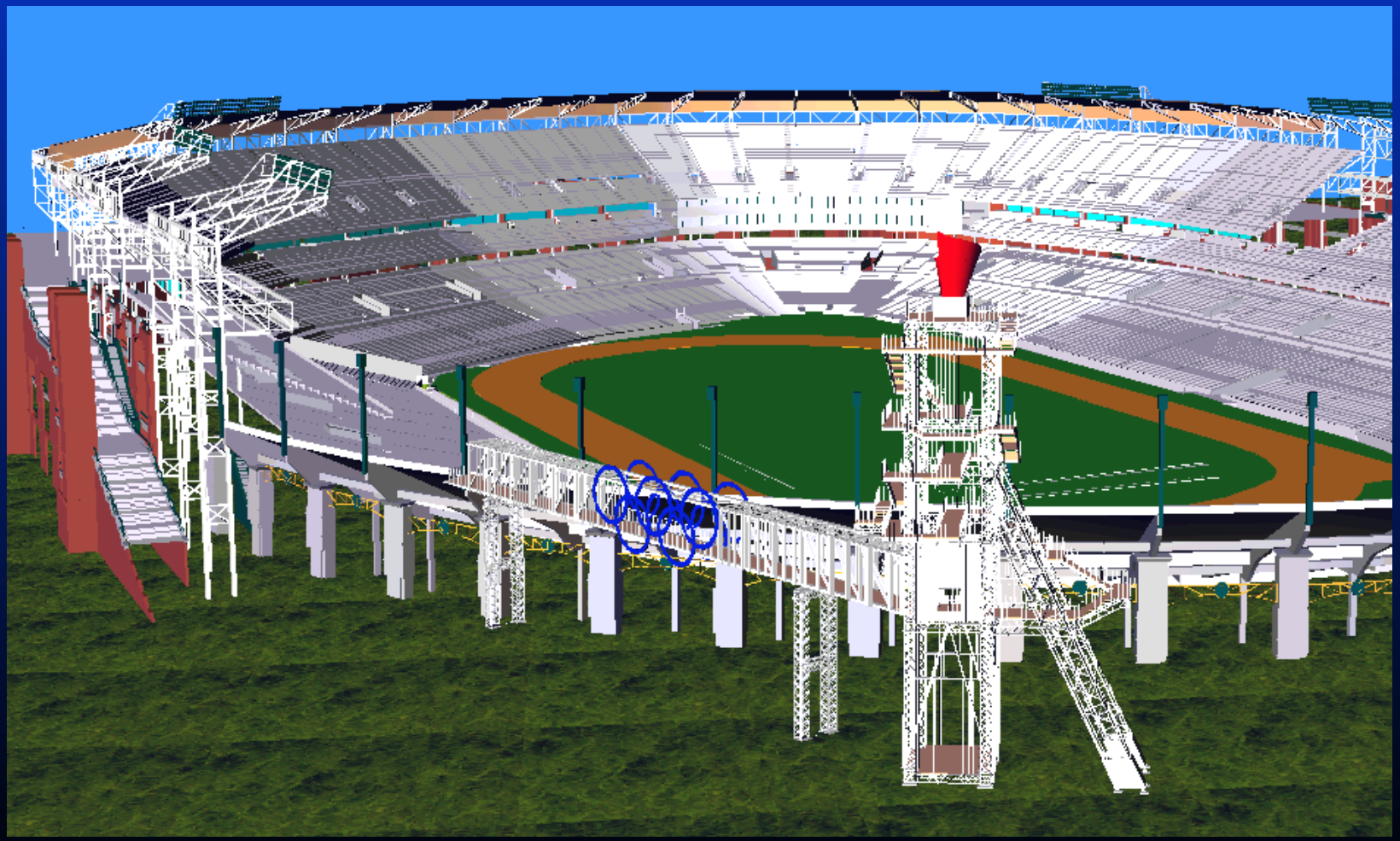
Discrete LOD:
Advantages

- Fits modern graphics hardware well
  - Easy to compile each LOD into triangle strips, display lists, vertex arrays, …
  - These render *much* faster than unorganized polygons on today's hardware (3-5 x)

Discrete LOD: Disadvantages

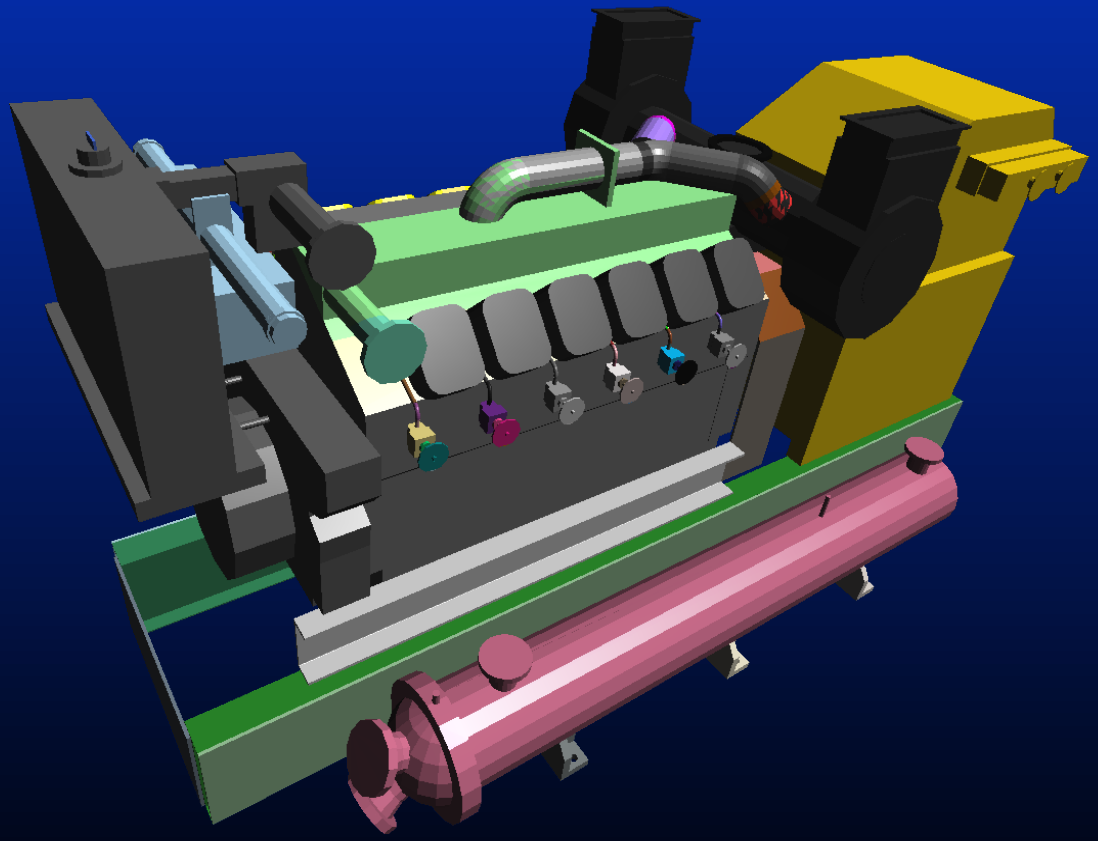
- So why use anything but discrete LOD?
- Answer: sometimes discrete LOD not suited for *drastic simplification*
- Some problem cases:
  - Terrain flyovers
  - Volumetric isosurfaces
  - Super-detailed range scans
  - Massive CAD models

Drastic Simplification:
The Problem With Large Objects



Courtesy IBM and ACOG

Drastic Simplification:
The Problem With Small Objects



Courtesy Electric Boat

Drastic Simplification

- For drastic simplification:
  - Large objects must be subdivided
  - Small objects must be combined
- Difficult or impossible with discrete LOD
- *So what can we do?*

Continuous Level of Detail

- A departure from the traditional static approach:
  - Discrete LOD: create individual LODs 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

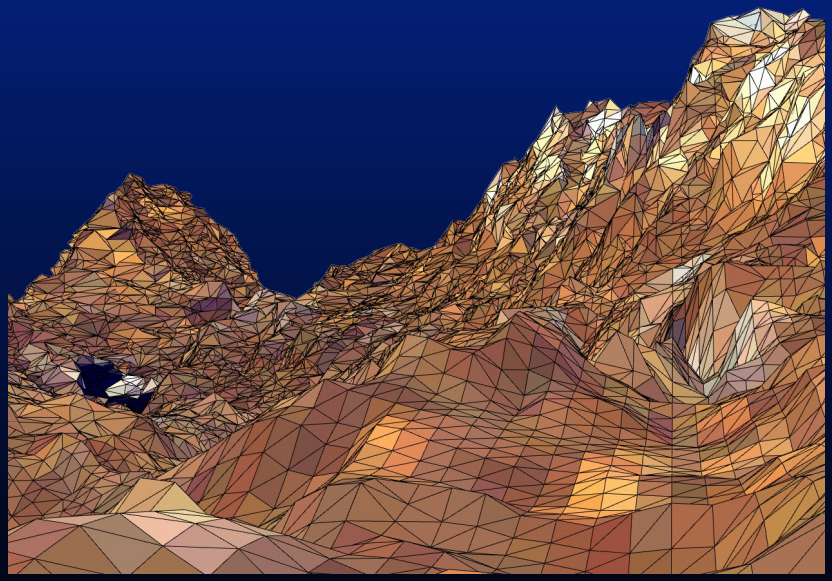
- Better granularity → smoother transitions
  - Switching between traditional LODs can introduce visual “popping” effect
  - Continuous LOD can adjust detail gradually and incrementally, reducing visual pops
    - Can even *geomorph* the fine-grained simplification operations over several frames to eliminate pops [Hoppe 96, 98]

Continuous LOD: Advantages

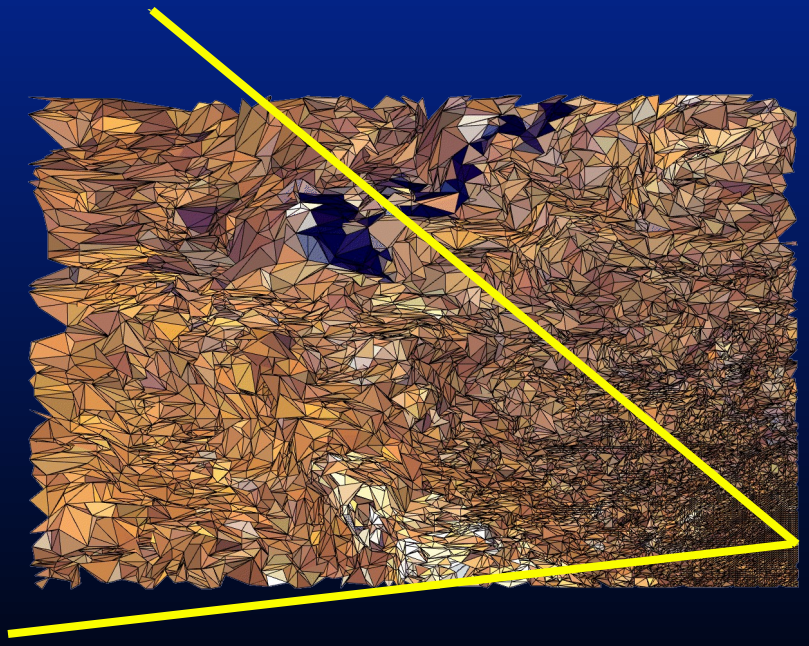
- Supports progressive transmission
  - *Progressive Meshes [Hoppe 97]*
  - *Progressive Forest Split Compression [Taubin 98]*
- Leads to *view-dependent LOD*
  - Use current view parameters to select best representation *for the current view*
  - Single objects may thus span several levels of detail

View-Dependent LOD: Examples

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



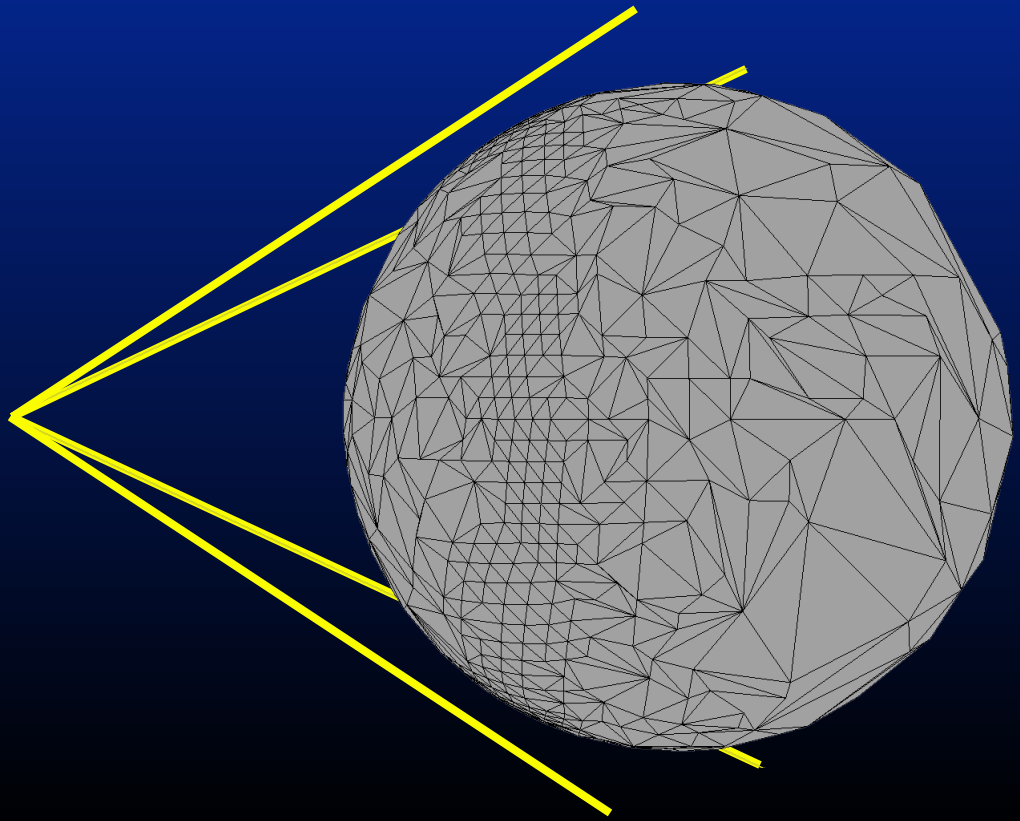
View from eyepoint



Birds-eye view

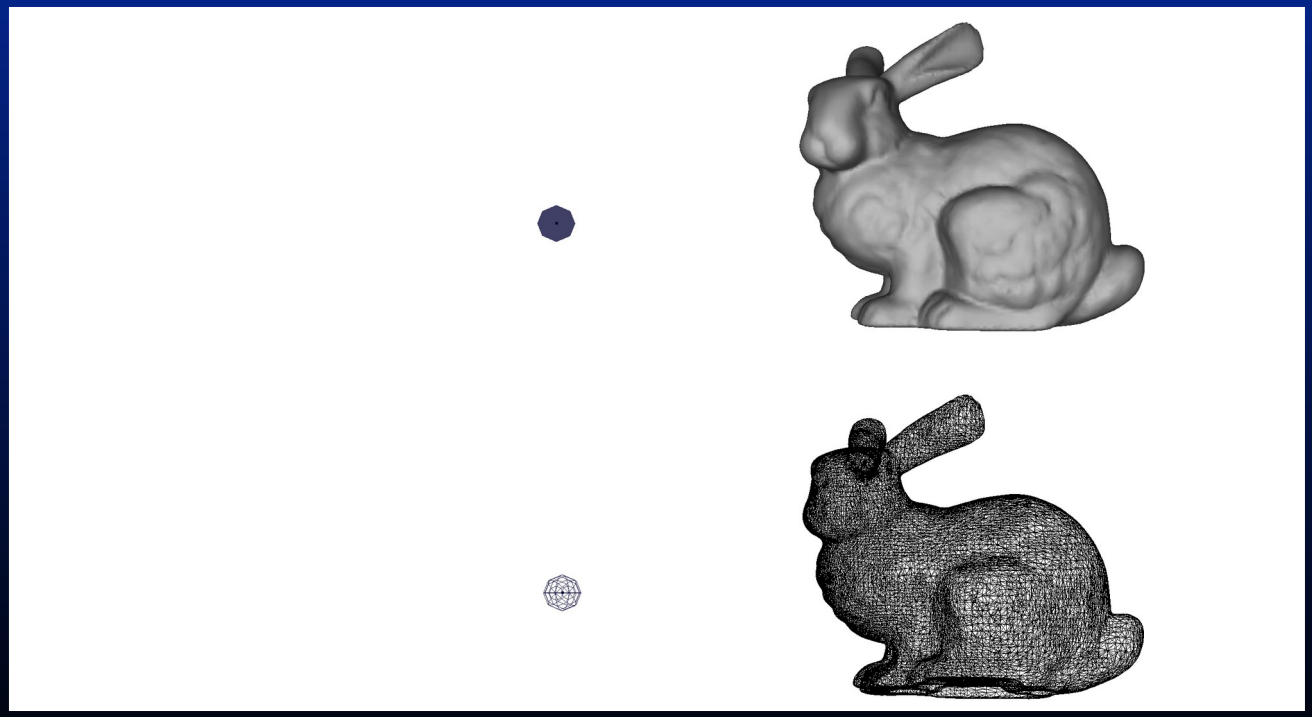
View-Dependent LOD: Examples

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



View-Dependent LOD: Examples

- Show more detail where the user is looking than in their peripheral vision:



34,321 triangles

View-Dependent LOD: Examples

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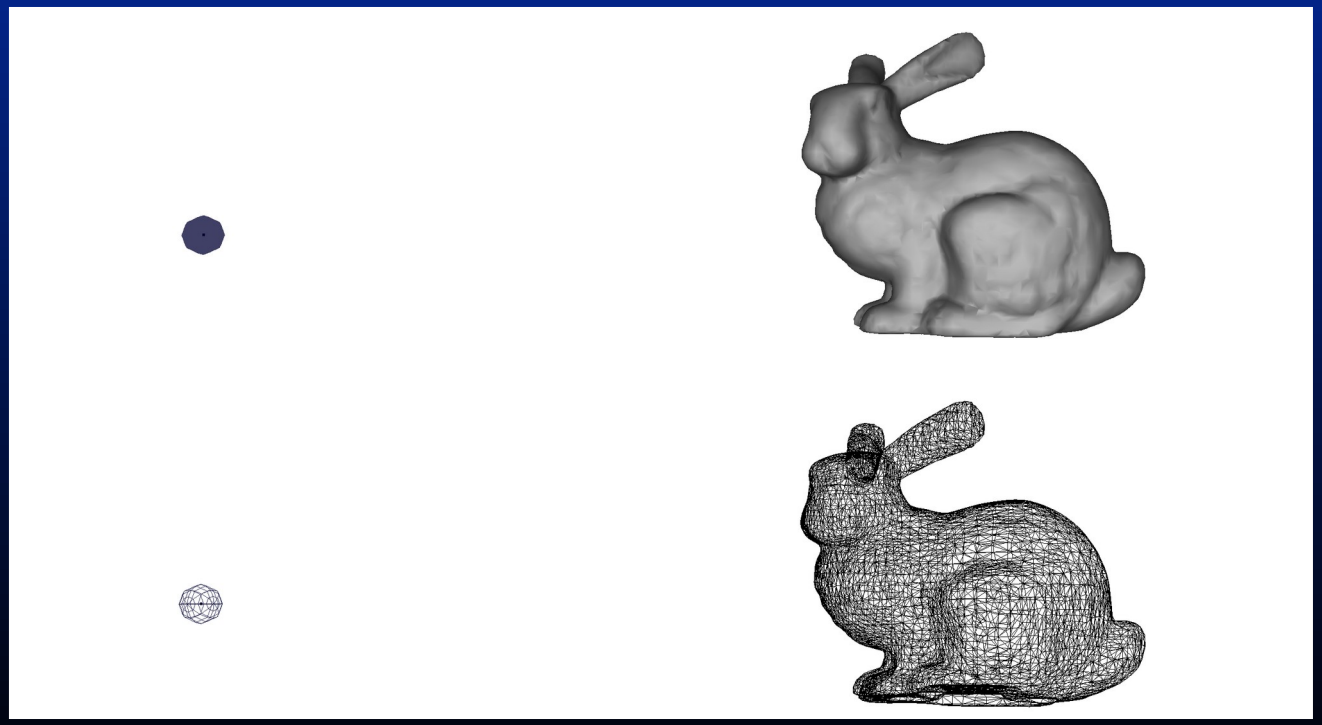


11,726 triangles

View-Dependent LOD: Advantages

- Even better granularity
  - Allocates polygons where they are most needed, within as well as among objects
  - Enables even better overall fidelity
- Enables drastic simplification of very large objects
  - Example: stadium model
  - Example: terrain flyover

An Aside: Hierarchical LOD

- View-dependent LOD solves the Problem With Large Objects
- *Hierarchical LOD* can solve the Problem With Small Objects
  - Merge objects into assemblies
  - At sufficient distances, simplify assemblies, not individual objects
- Note that hierarchical LOD implies a topology-modifying algorithm

An Aside: Hierarchical LOD

- Hierarchical LOD dovetails nicely with view-dependent LOD
  - Treat the *entire scene* as a single object to be simplified in view-dependent fashion
- Hierarchical LOD can also sit atop traditional discrete LOD schemes
  - *Imposters [Maciel 95]*
  - *HLODs [Erikson 01]*

View-Dependent LOD: Algorithms

- Many good published algorithms:
  - *Progressive Meshes* by Hoppe [SIGGRAPH 96, SIGGRAPH 97, …]
  - *Merge Trees* by Xia & Varshney [Visualization 96]
  - *Hierarchical Dynamic Simplification* by Luebke & Erikson [SIGGRAPH 97]
  - *Multitriangulation* by DeFloriani et al
  - Others…

Overview:
The VDS Algorithm

- I'll mostly describe my own work
  - Algorithm: *VDS* Implementation: *VDSlib*
  - Similar in concept to most other algorithms
- Amitabh will give his take on some related issues later

Overview:
The VDS Algorithm

- Overview of the VDS algorithm:
  - A preprocess builds the *vertex tree*, a hierarchical clustering of vertices
  - At run time, clusters appear to grow and shrink as the viewpoint moves
  - Clusters that become too small are collapsed, filtering out some triangles

Data Structures

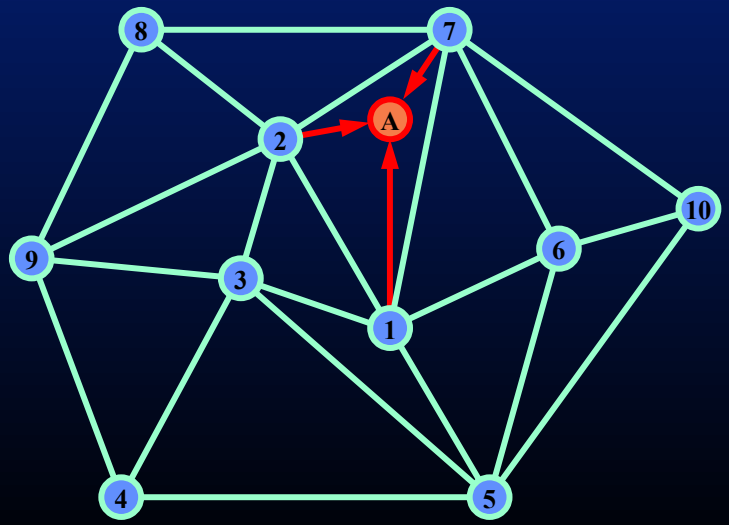
- The *vertex tree*
  - Represents the entire model
  - Hierarchy of all vertices in model
  - Queried each frame for updated scene
- The *active triangle list*
  - Represents the current simplification
  - List of triangles to be displayed
  - Triangles added and deleted by operations on vertex tree

The Vertex Tree

- Each vertex tree node *supports* a subset of the model vertices
  - Leaf nodes support a single vertex from the original full-resoluton model
  - The root node supports all vertices
- For each node we also assign a representative vertex or *proxy*

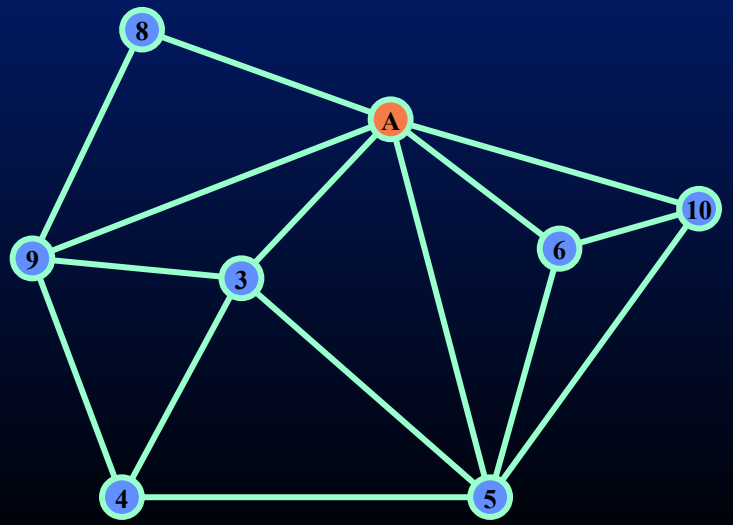
The Vertex Tree:
Folding And Unfolding

- *Folding* a node collapses its vertices to the proxy
- *Unfolding* the node splits the proxy back into vertices

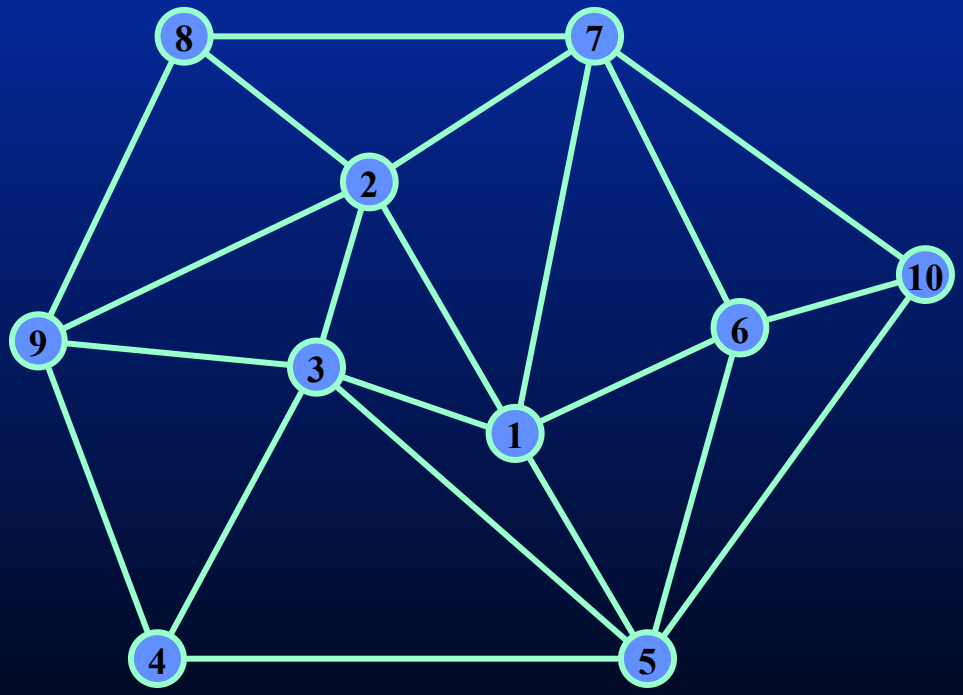


Fold Node A

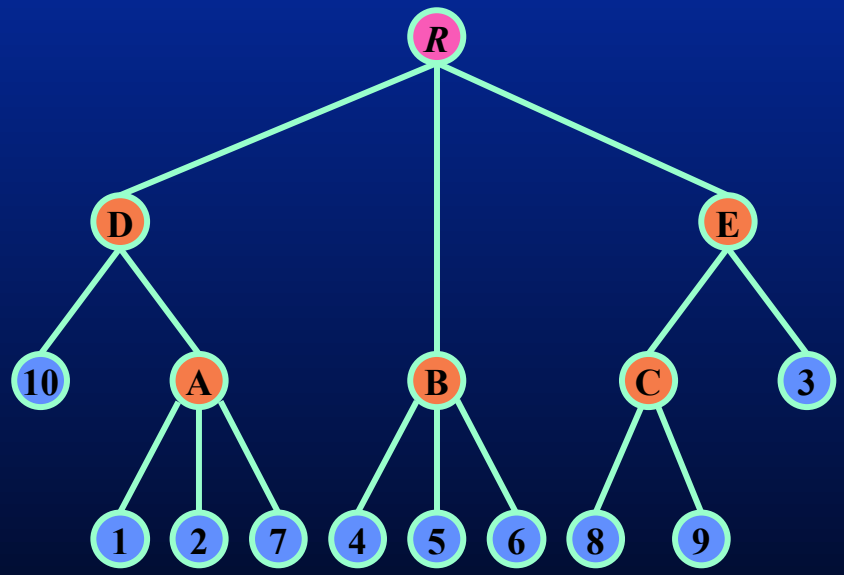
Unfold Node A



Vertex Tree Example

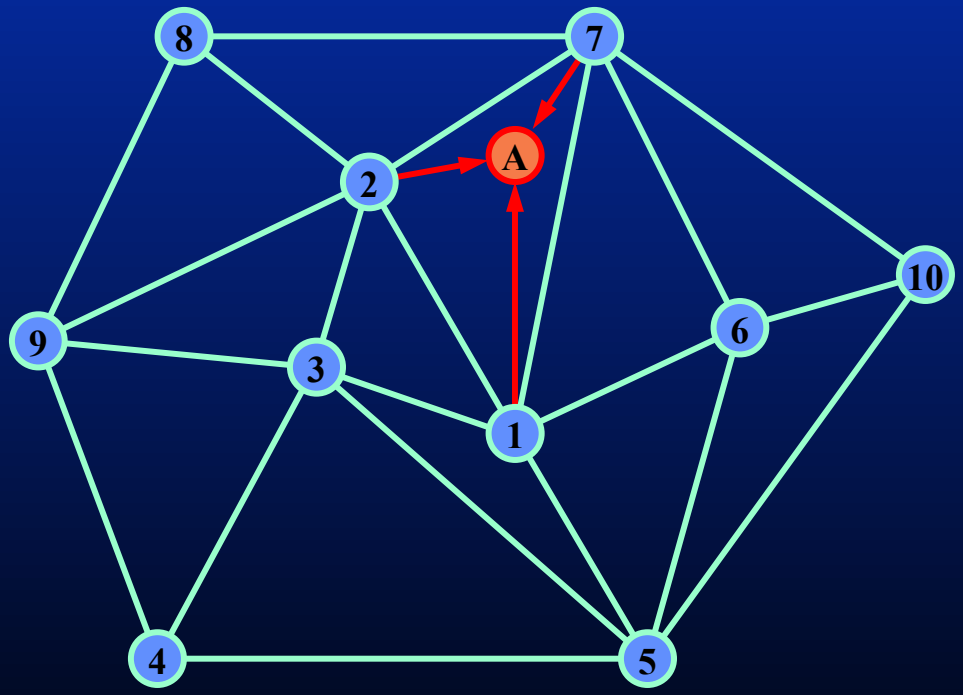


Triangles in active list



Vertex tree

Vertex Tree Example



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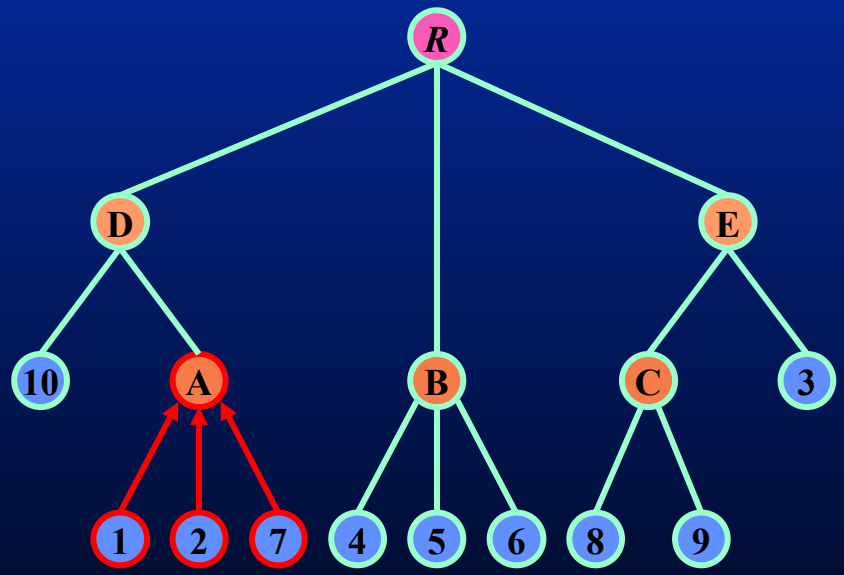

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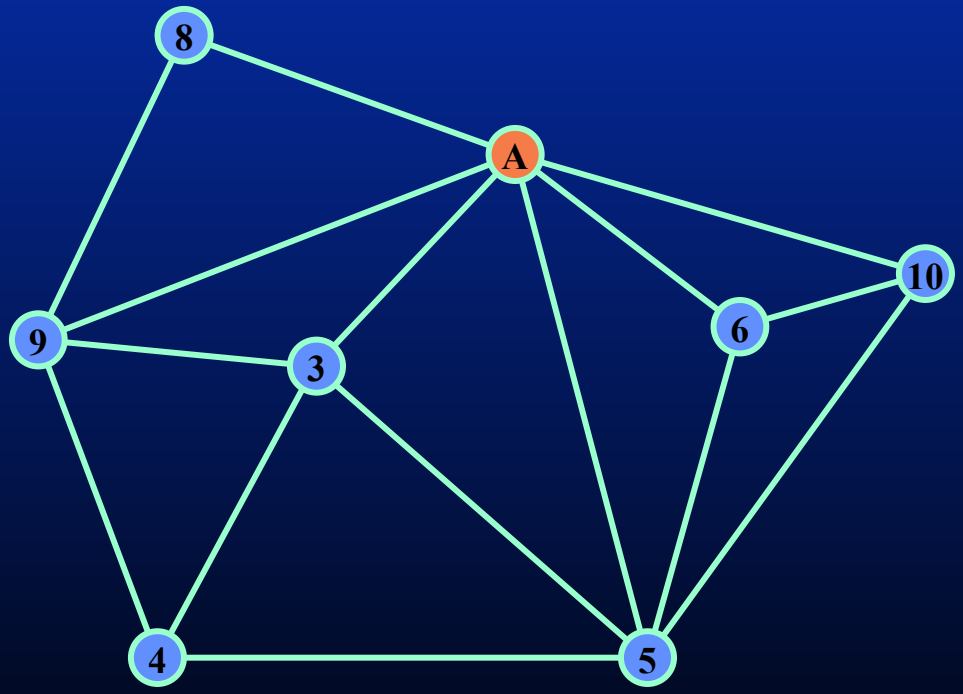

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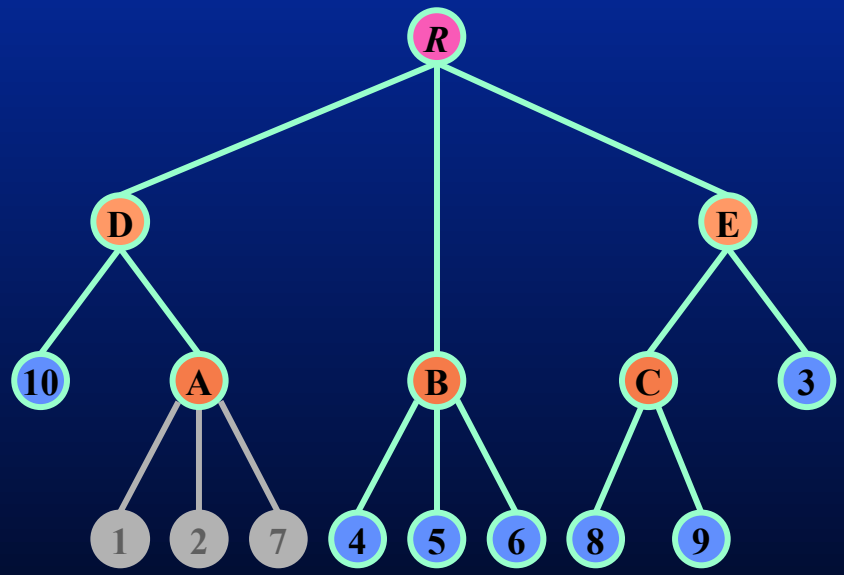

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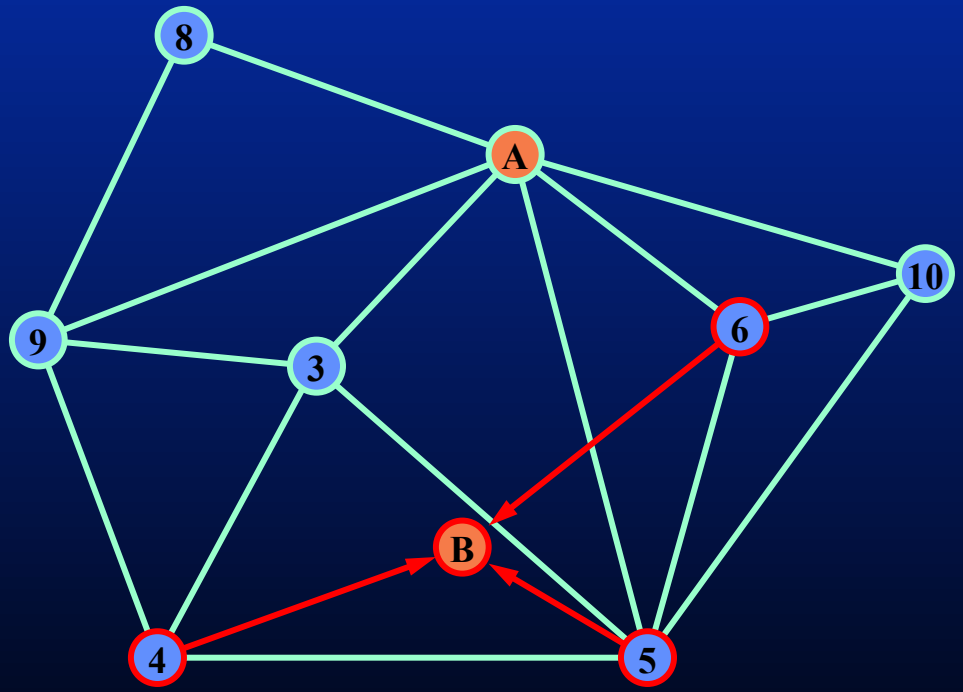

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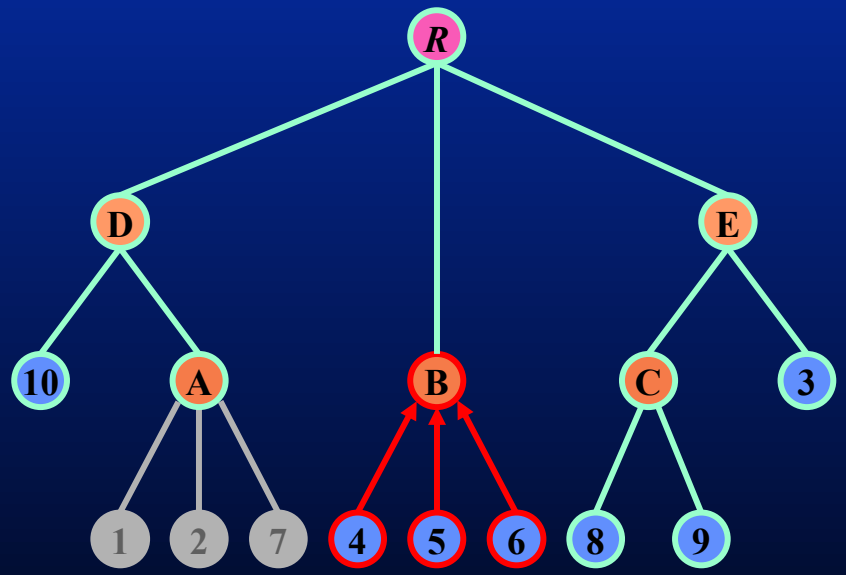

Vertex tree

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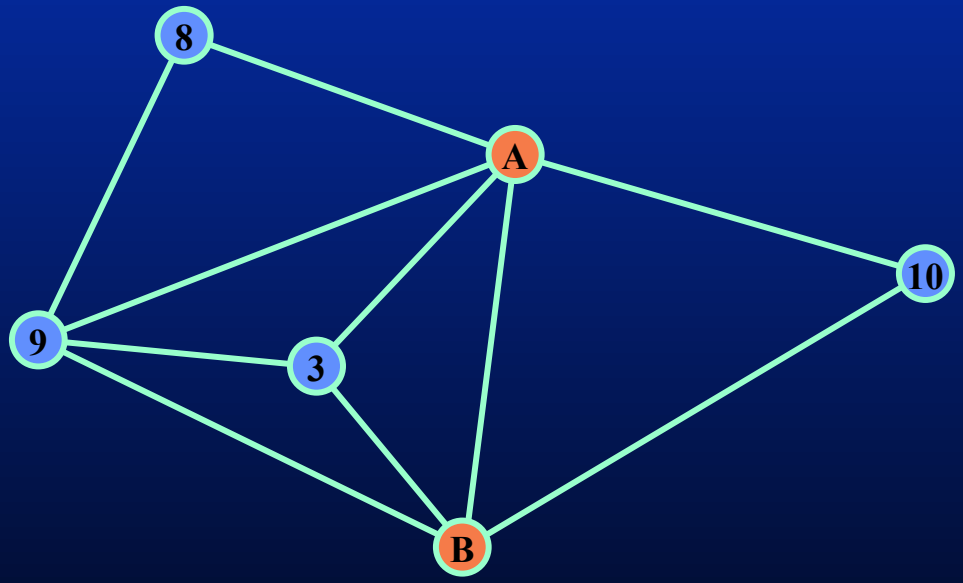

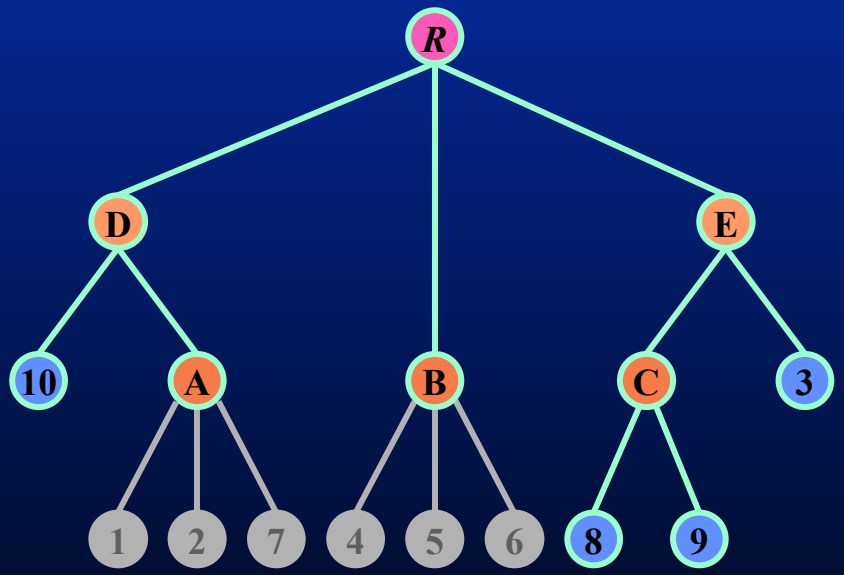

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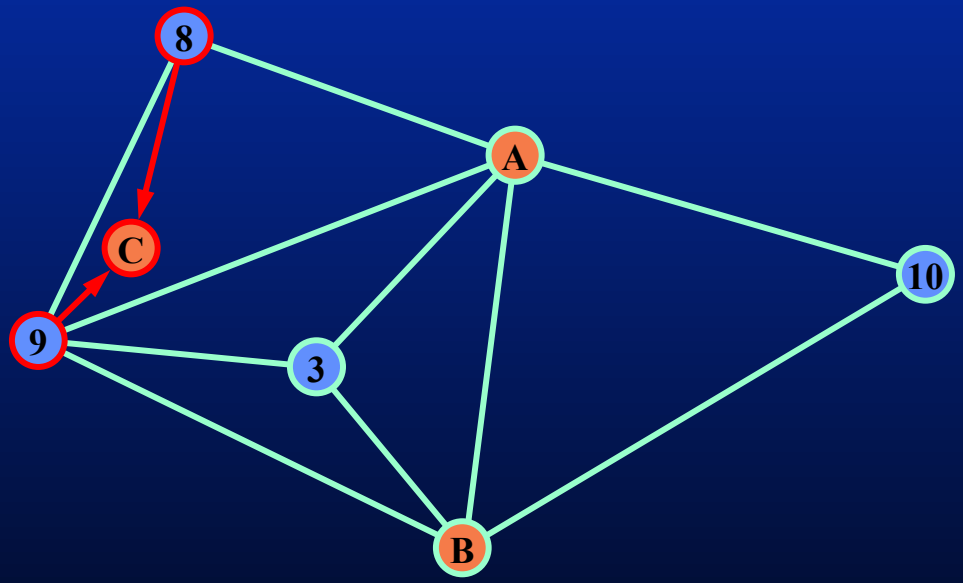

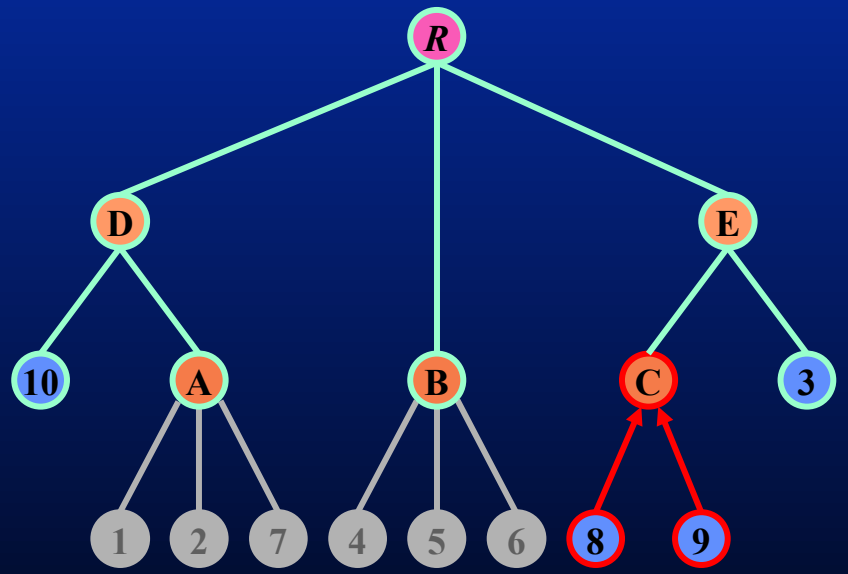

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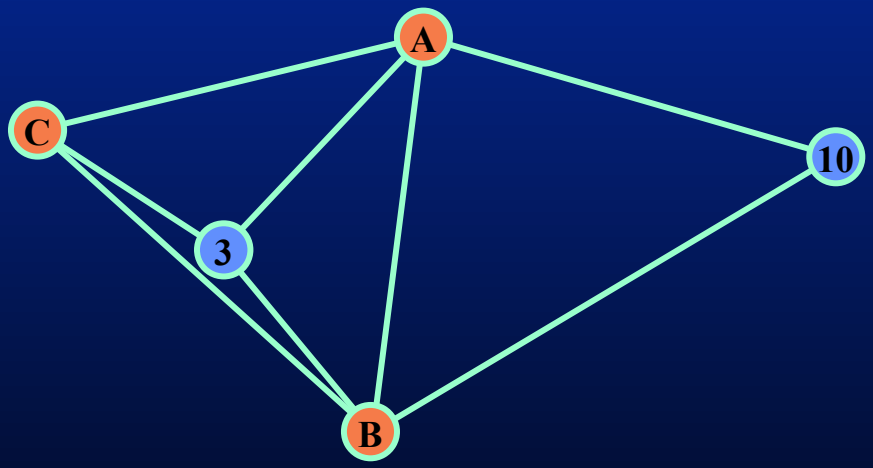

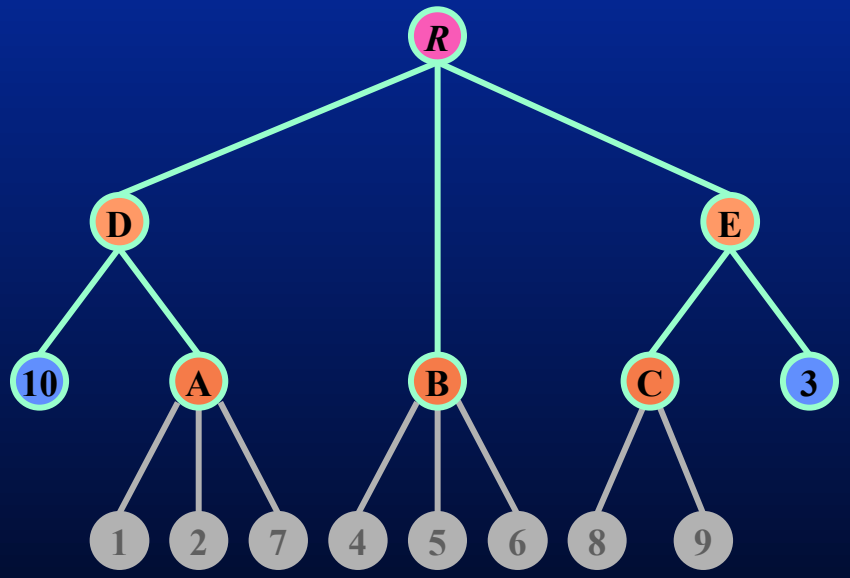

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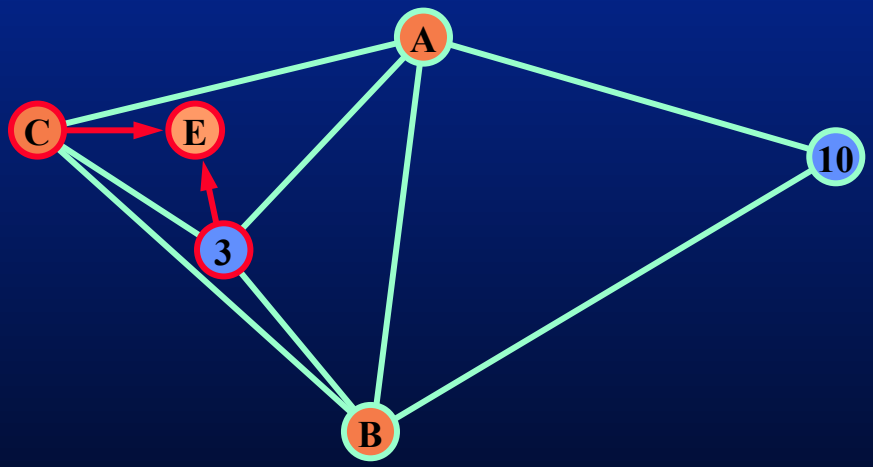

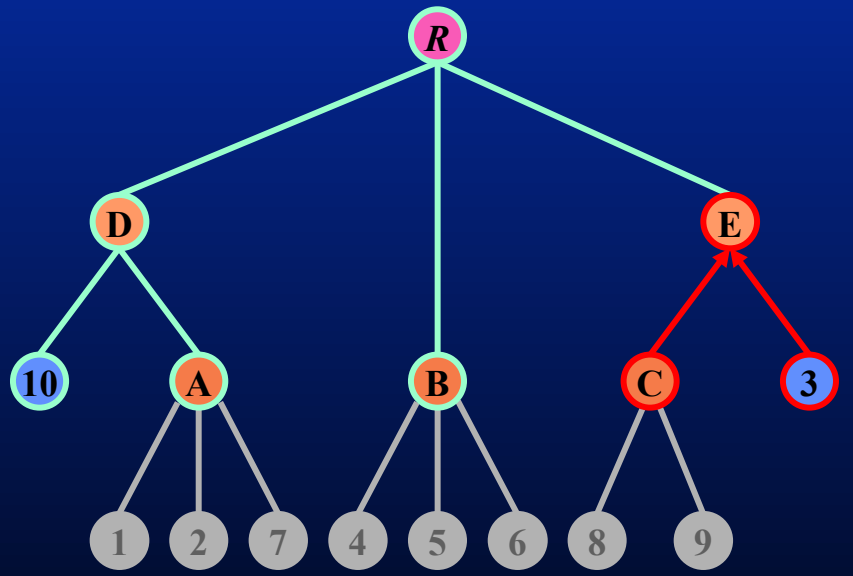

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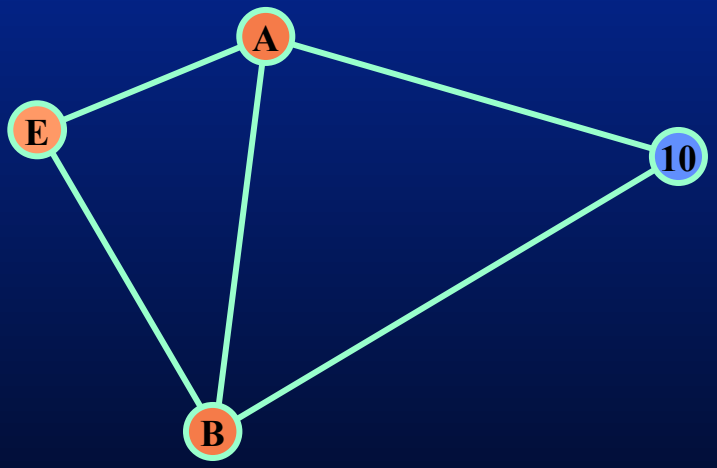

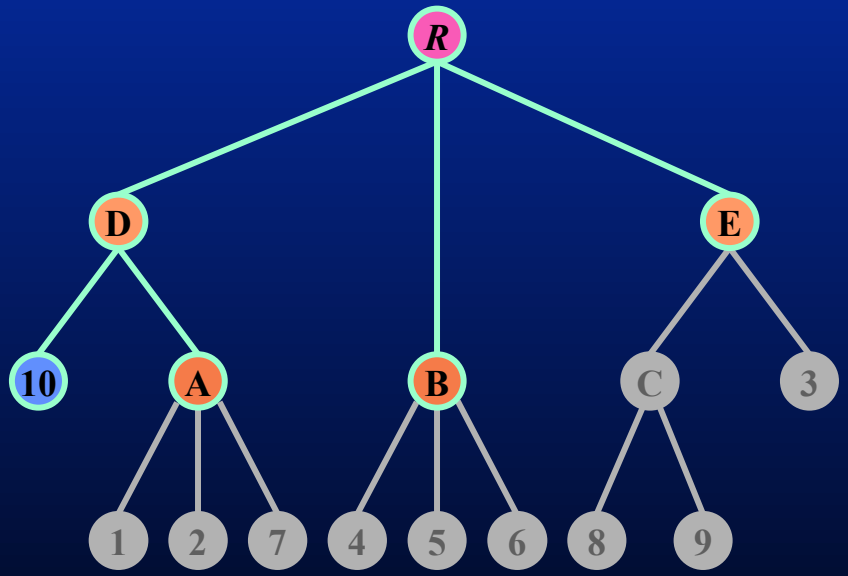

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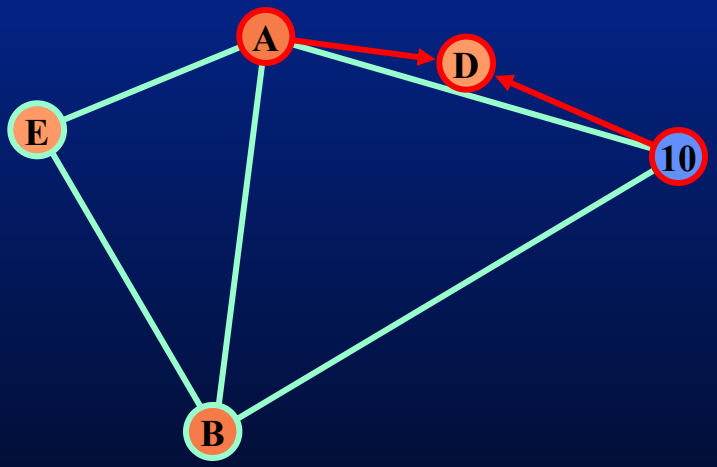

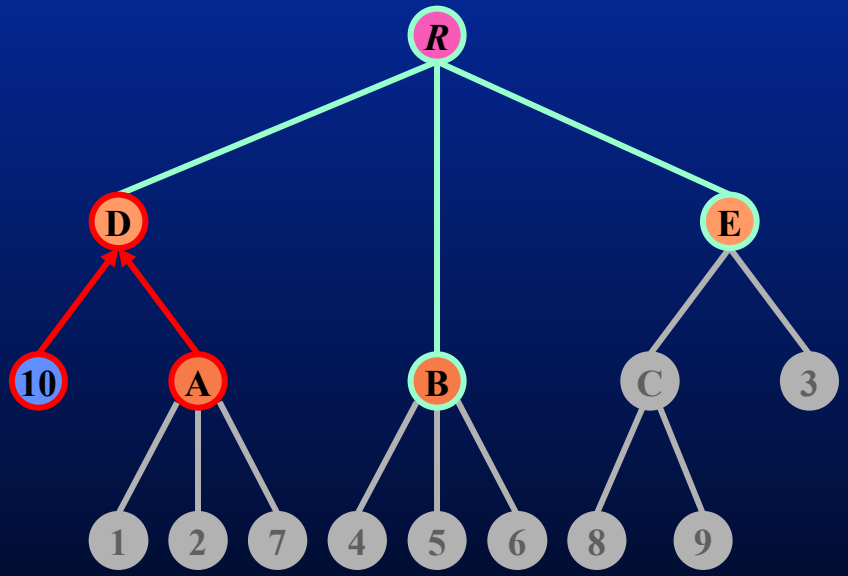

Triangles in active list

Vertex tree

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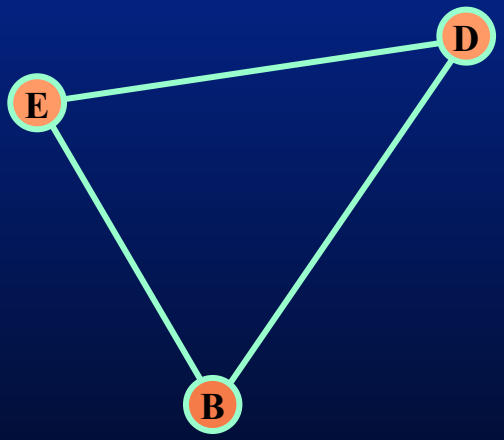

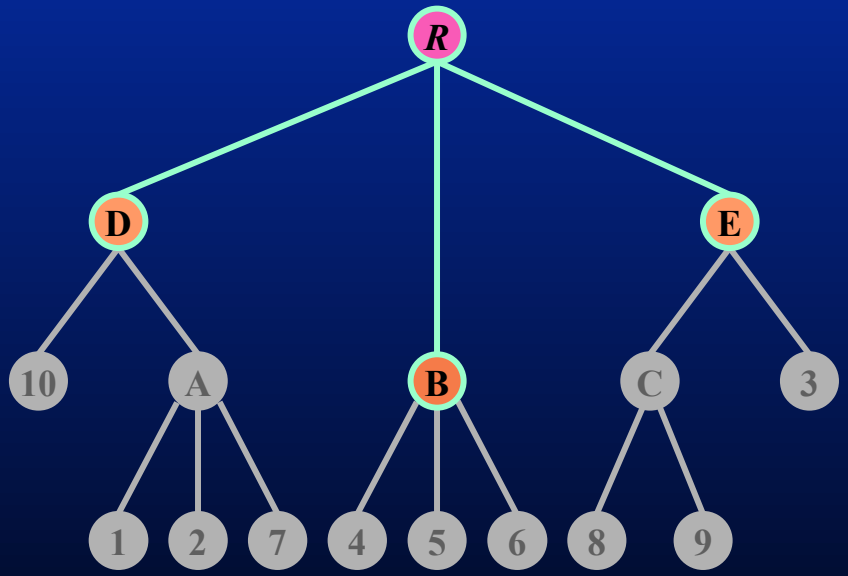

Triangles in active list

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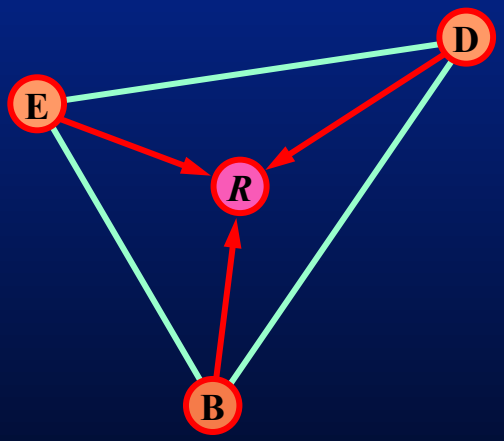

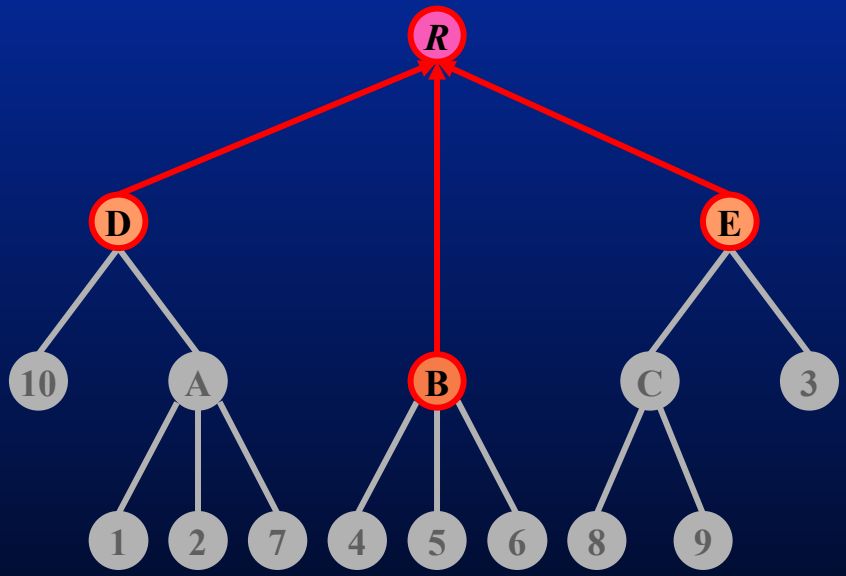

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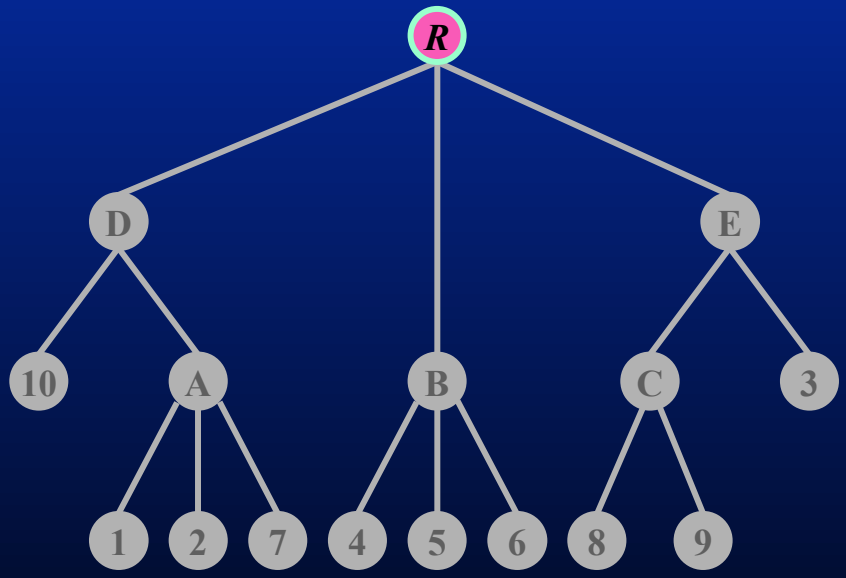
Vertex Tree Example

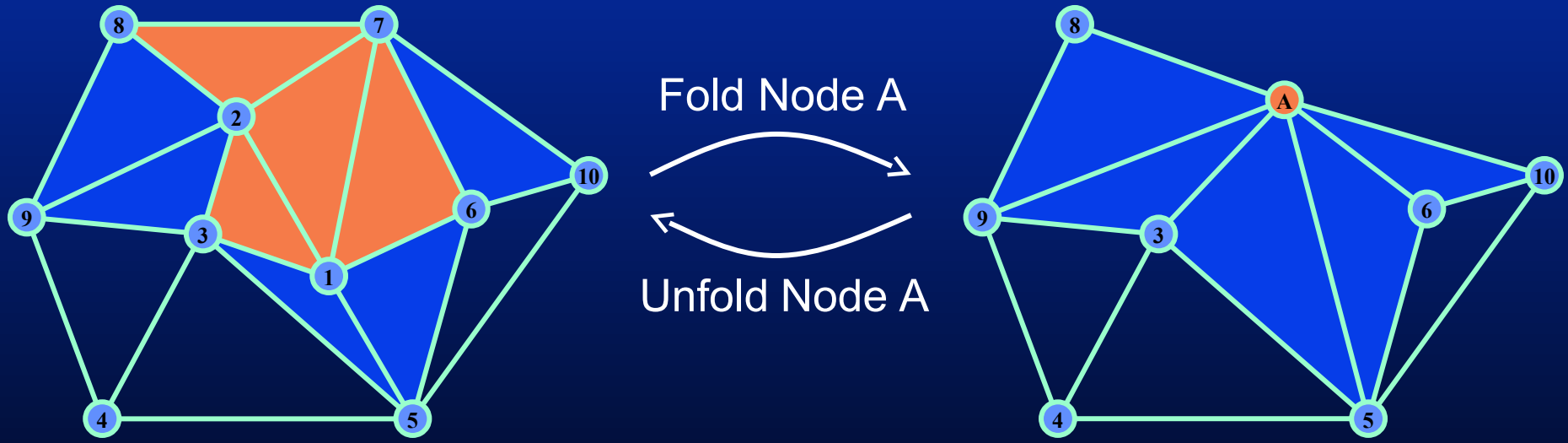


Triangles in active list

Vertex tree

The Vertex Tree:
Livetris and Subtris

- Two categories of triangles affected:



Node->Subtris: triangles that disappear upon folding

Node->Livetris: triangles that just change shape

The Vertex Tree:
Livetris and Subtris

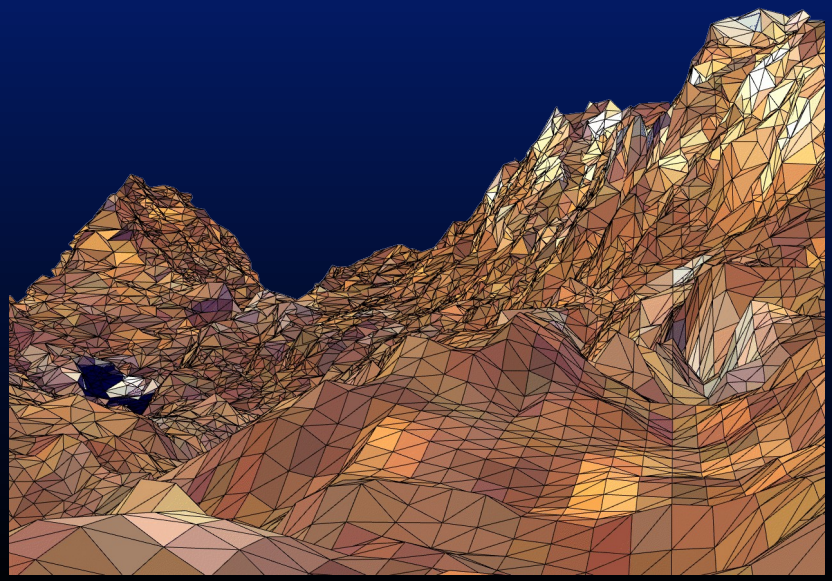
- The *key observation*:
  - Each node's subtris can be computed offline to be accessed quickly at run time
  - Each node's livetris can be maintained at run time, or lazily evaluated upon rendering

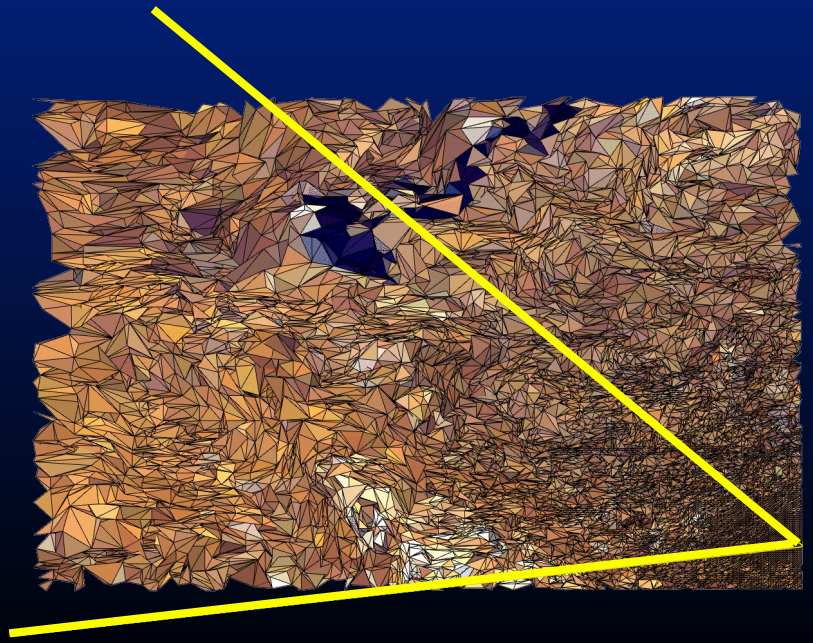
View-Dependent Simplification

- Any run-time criterion for folding and unfolding nodes may be used
- Examples of view-dependent simplification criteria:
  - Screenspace error threshold
  - Silhouette preservation
  - Triangle budget simplification
  - Gaze-directed perceptual simplification (discussed by Martin later)

Screenspace Error Threshold

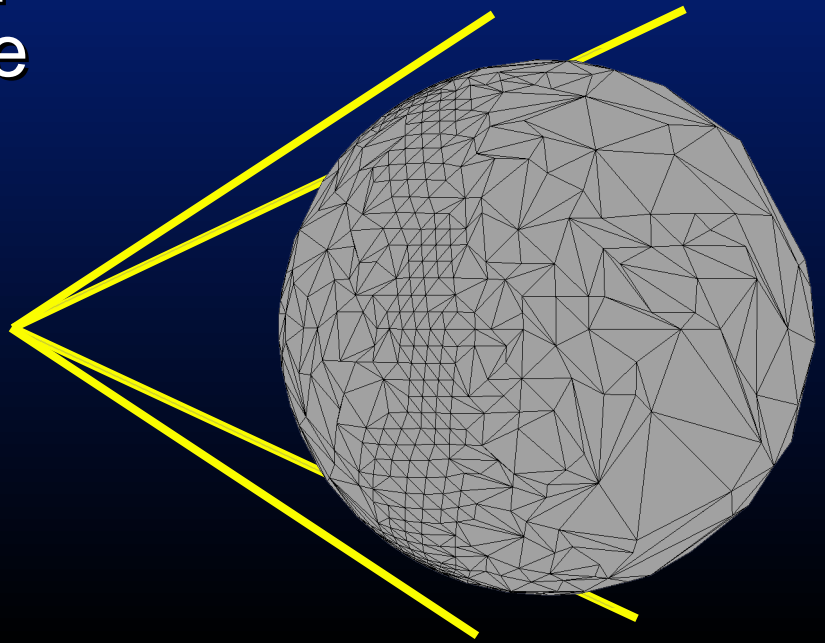
- Nodes chosen by projected area
  - User sets screenspace size threshold
  - Nodes which grow larger than threshold are unfolded





Silhouette Preservation

- Retain more detail near silhouettes
  - A *silhouette node* supports triangles on the visual contour
  - Use tighter screenspace thresholds when examining silhouette nodes



Triangle Budget Simplification

- Minimize error within specified number of triangles
  - Sort nodes by screenspace error
  - Unfold node with greatest error, putting children into sorted list
  - Repeat until budget is reached

View-Dependent Criteria:
Other Possibilities

- *Specular highlights*: Xia describes a fast test to unfold likely nodes
- *Surface deviation*: Hoppe uses an elegant surface deviation metric that combines silhouette preservation and screenspace error threshold

View-Dependent Criteria:
Other Possibilities

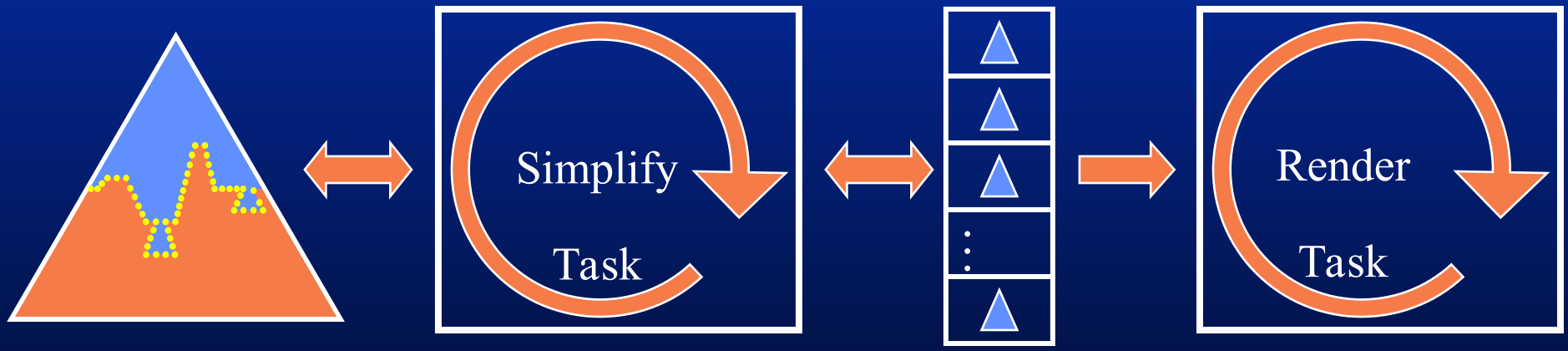
- *Sophisticated surface deviation metrics:*
  See Jon's talk!
- *Sophisticated perceptual criteria*:
  See Martin's talk!
- *Sophisticated temporal criteria*:
  See Ben's talk!

Implementing VDS:
Optimizations

- Asynchronous simplification
  - Parallelize the algorithm
- Exploiting temporal coherence
  - Scene changes slowly over time
- Maintain memory coherent geometry
  - Optimize for rendering
  - Support for out-of-core rendering

Asynchronous Simplification

- Algorithm partitions into two tasks:



Vertex Tree

Active Triangle List

- Run them in parallel

Asynchronous Simplification

- If *S* = time to simplify, *R* = time to render:
  - Single process = (*S* + *R*)
  - Pipelined = **max**(*S*, *R*)
  - Asynchronous = *R*
- The goal: efficient utilization of GPU/CPU
  - e.g., NV Vertex Array Range (VAR) rendering

Temporal Coherence

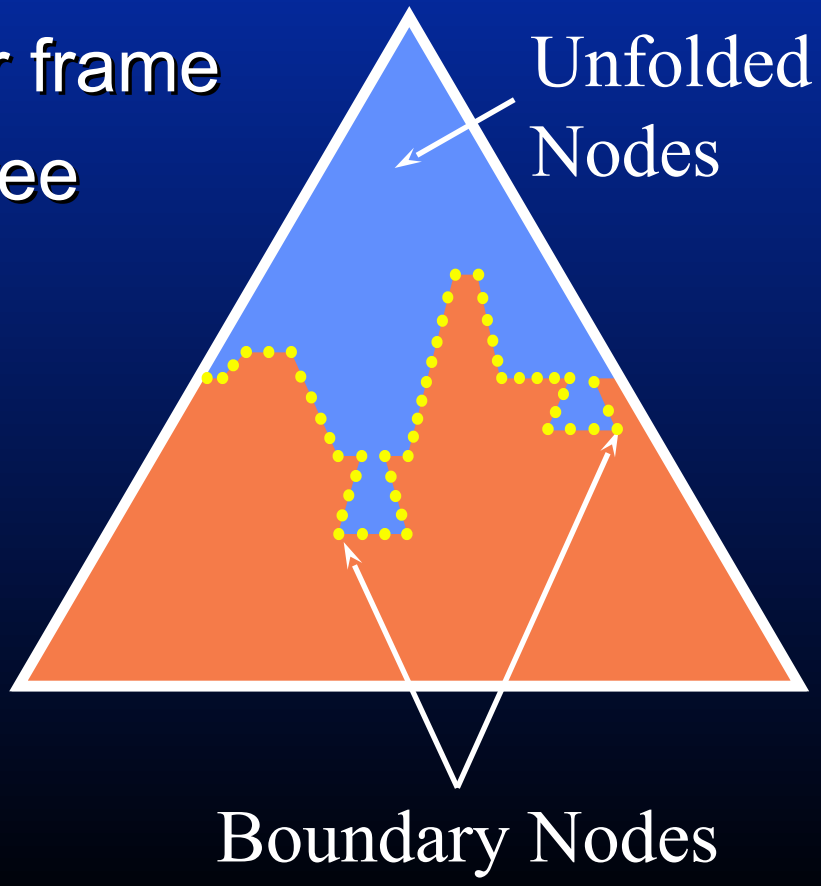
- Exploit the fact that frame-to-frame changes are small
- Three examples:
  - Active triangle list
  - Vertex tree
  - Budget-based simplification

Exploiting Temporal Coherence

- Active triangle list
  - Could calculate active triangles every frame
  - But…few triangles are added or deleted each frame
  - Idea: make only incremental changes to an *active triangle list*
    - Simple approach: doubly-linked list of triangles
    - Better: maintain coherent arrays with swapping

Exploiting Temporal Coherence

- Vertex Tree
  - Few nodes change per frame
  - Don’t traverse whole tree
  - Do local updates only at *boundary nodes*



Temporal Coherence: Triangle Budget Simplification

- Exploiting temporal coherence in budget-based simplification
  - Introduced by ROAM [Duchaineau 97]
  - Start with tree from last frame, recalculate error for relevant nodes
  - Sort into two priority queues
    - One for potential unfolds, sorted on max error
    - One for potential folds, sorted on min error

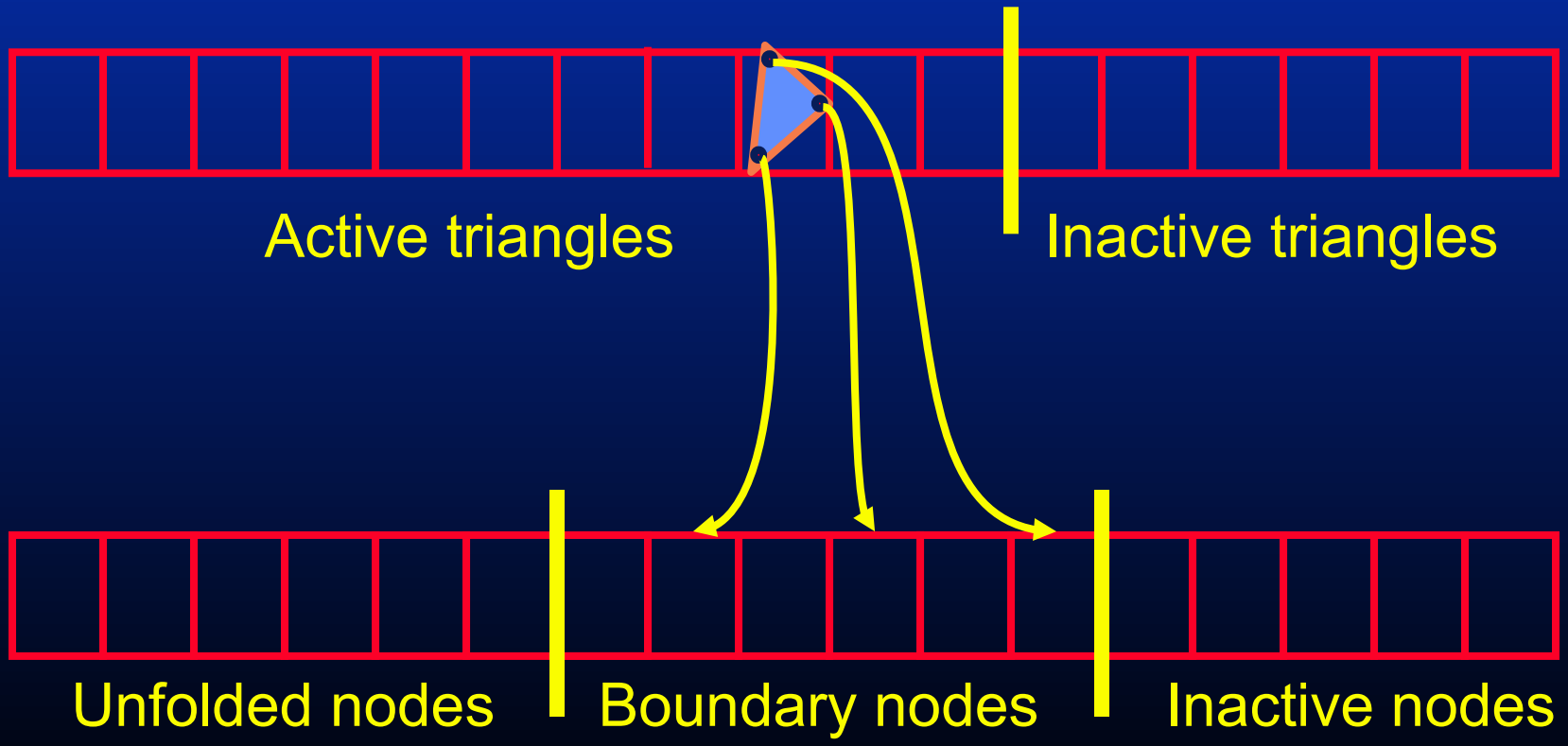
Temporal Coherence: Triangle Budget Simplification

- Then simplify:
  - While budget is met, unfold max node
    - This is the node whose folding has created the most error in the model
  - While budget is exceeded, fold min node
    - This is the node that introduces the least error when folded
  - Insert parents and children into queues

  Repeat until $error_{max} < error_{min}$

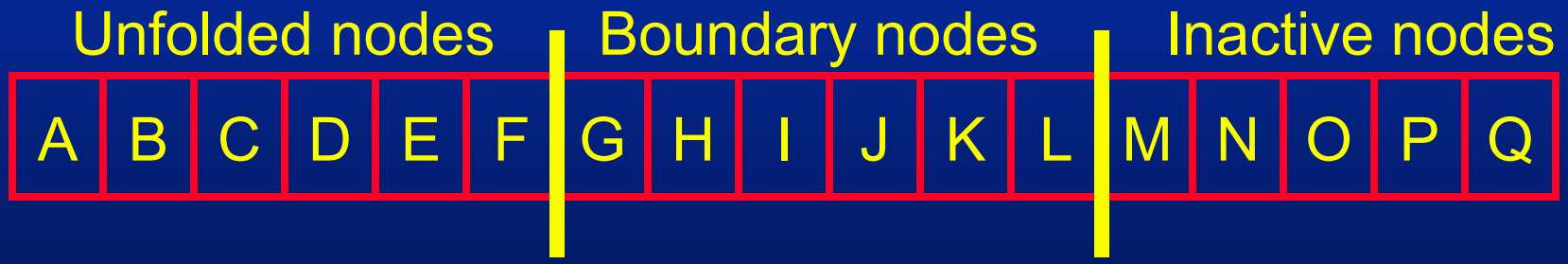
Optimizing For Rendering

- Idea: maintain geometry in coherent arrays



Optimizing For Rendering

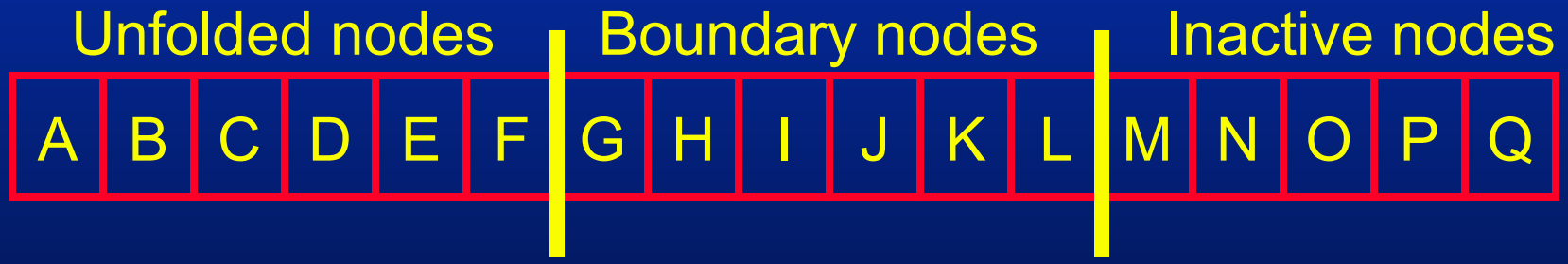
- Idea: use swaps to maintain coherence



Fold node D:

Optimizing For Rendering

- Idea: use swaps to maintain coherence

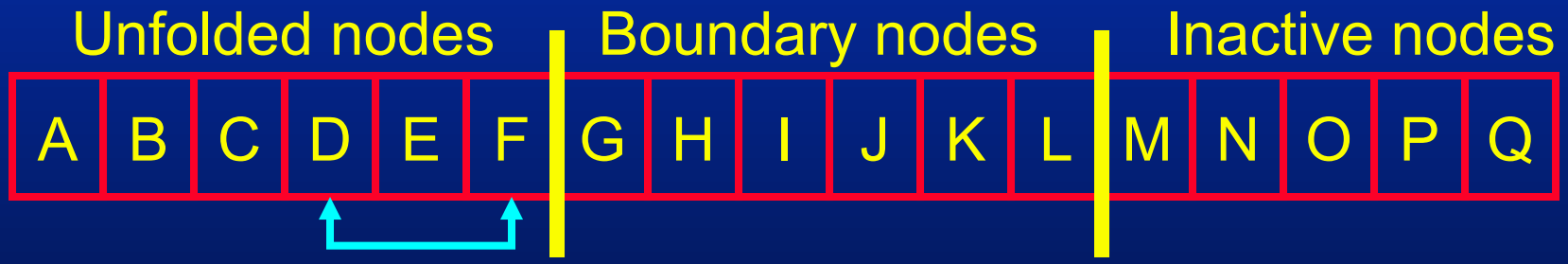


Fold node D:

Swap D with F

Optimizing For Rendering

- Idea: use swaps to maintain coherence



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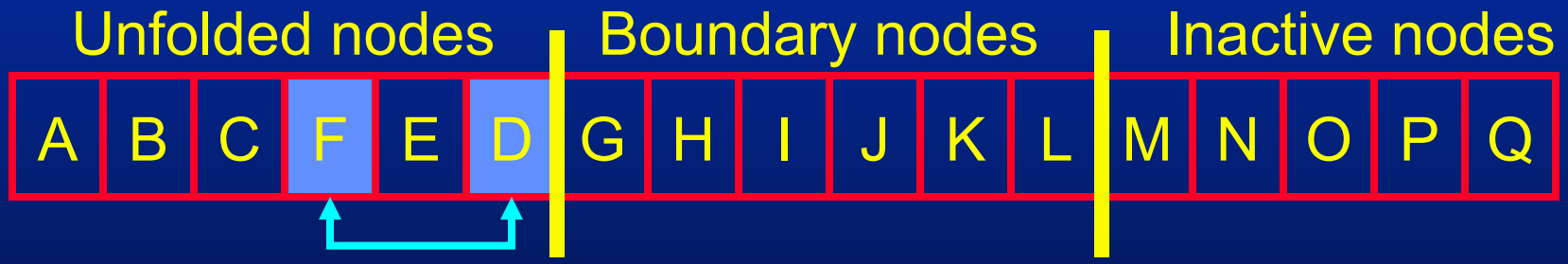

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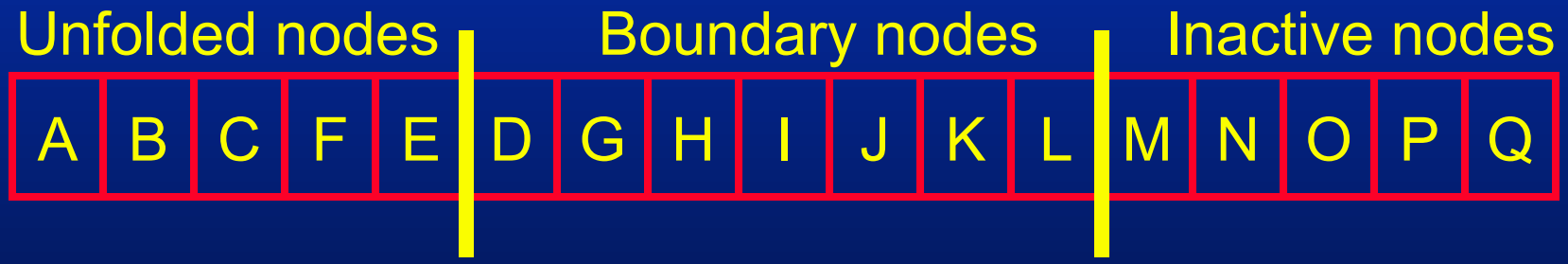
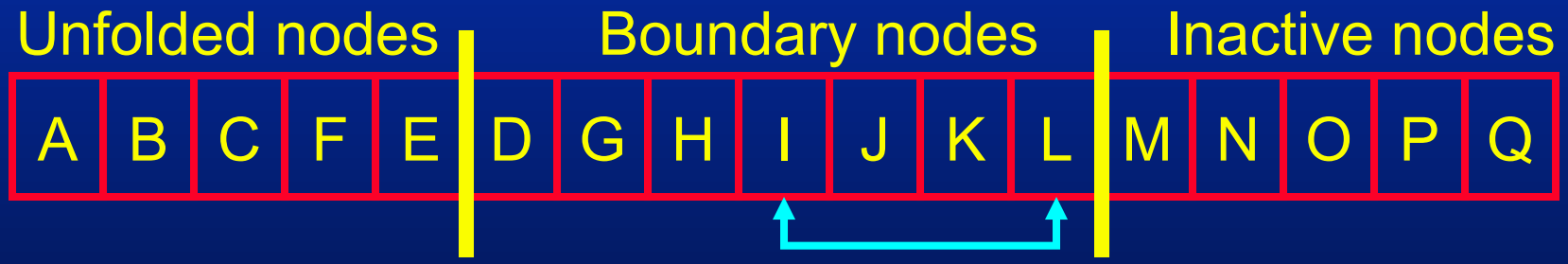


Fold node D:

Move Unfolded/Boundary Marker

Optimizing For Rendering

- Idea: use swaps to maintain coherence

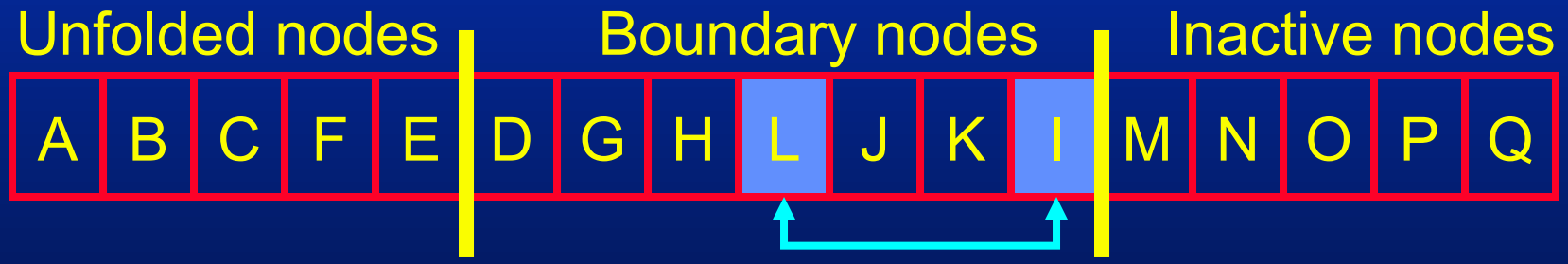


Fold node D:

Deactivate D's children (swap w/ last boundary node)

Optimizing For Rendering

- Idea: use swaps to maintain coherence

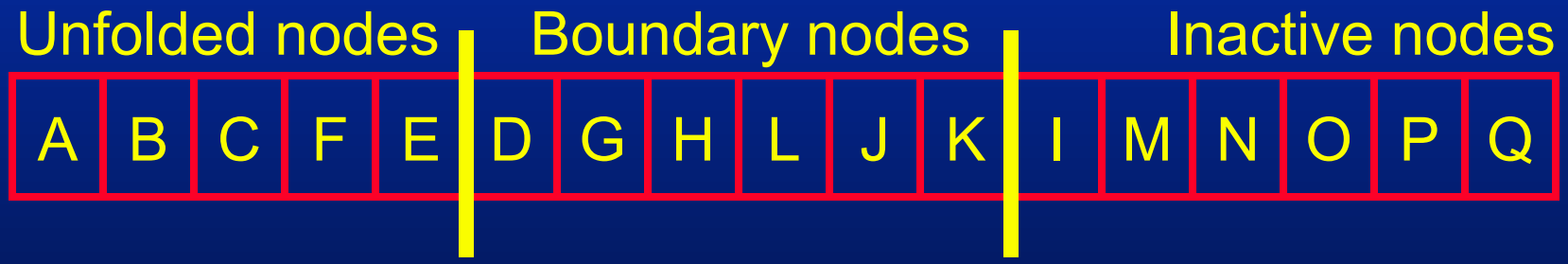


Fold node D:

Deactivate D's children (swap w/ last boundary node)

Optimizing For Rendering

- Idea: use swaps to maintain coherence



Fold node D:

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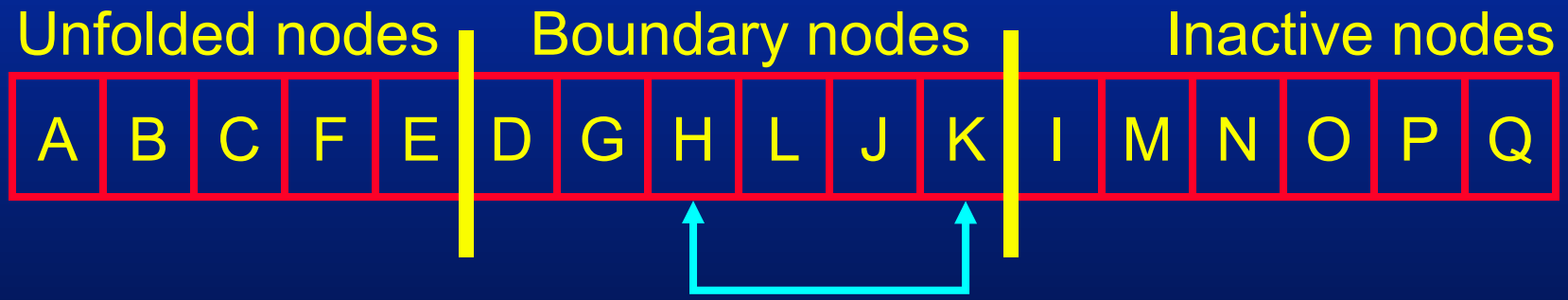
Optimizing For Rendering

- Idea: use swaps to maintain coherence



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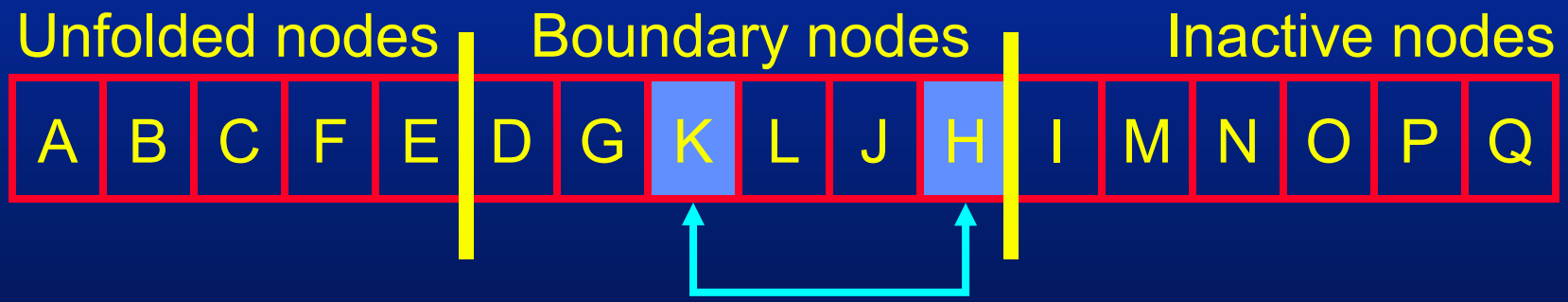
Optimizing For Rendering

- Idea: use swaps to maintain coherence

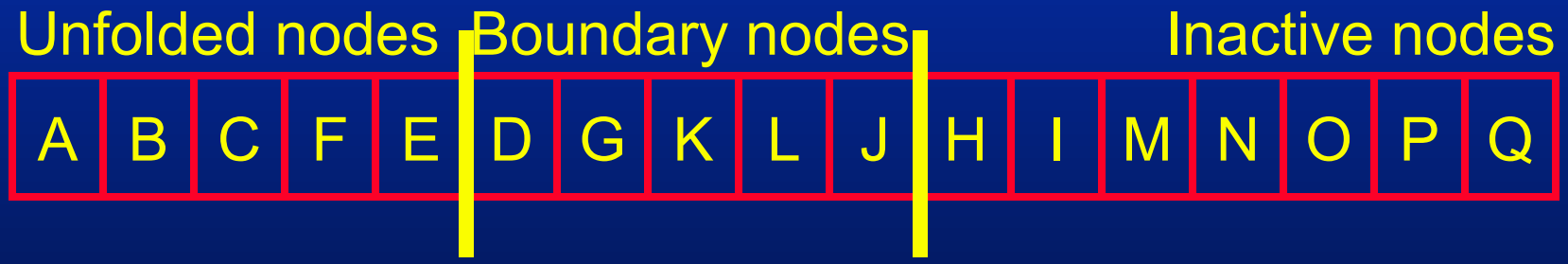


Fold node D:

Deactivate D's children (swap w/ last boundary node)

Optimizing For Rendering

- Idea: use swaps to maintain coherence

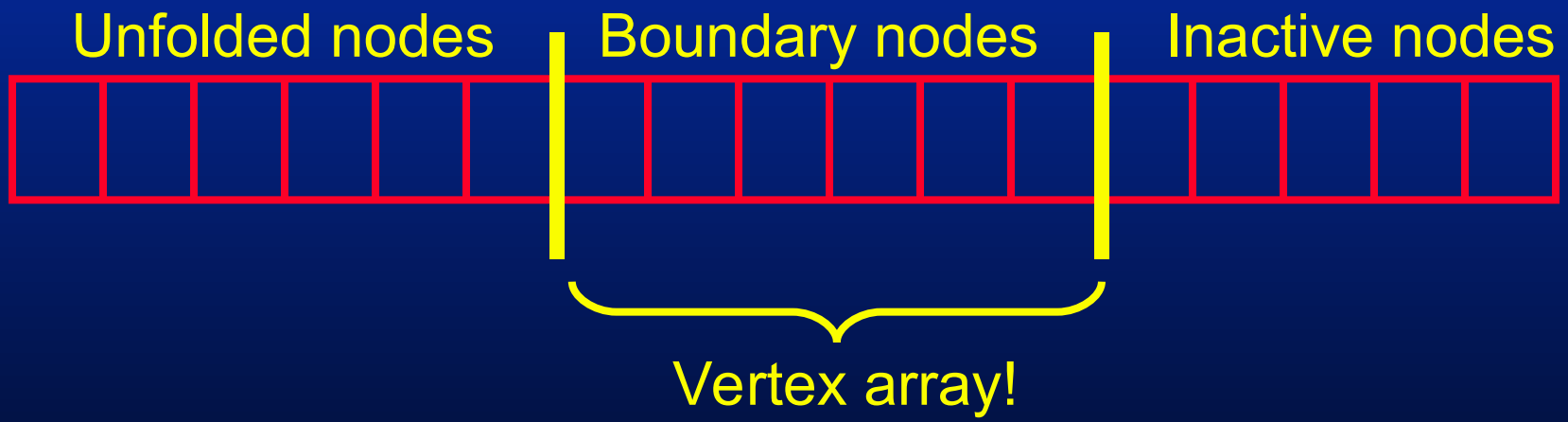


Fold node D:

Deactivate D's children (swap w/ last boundary node)

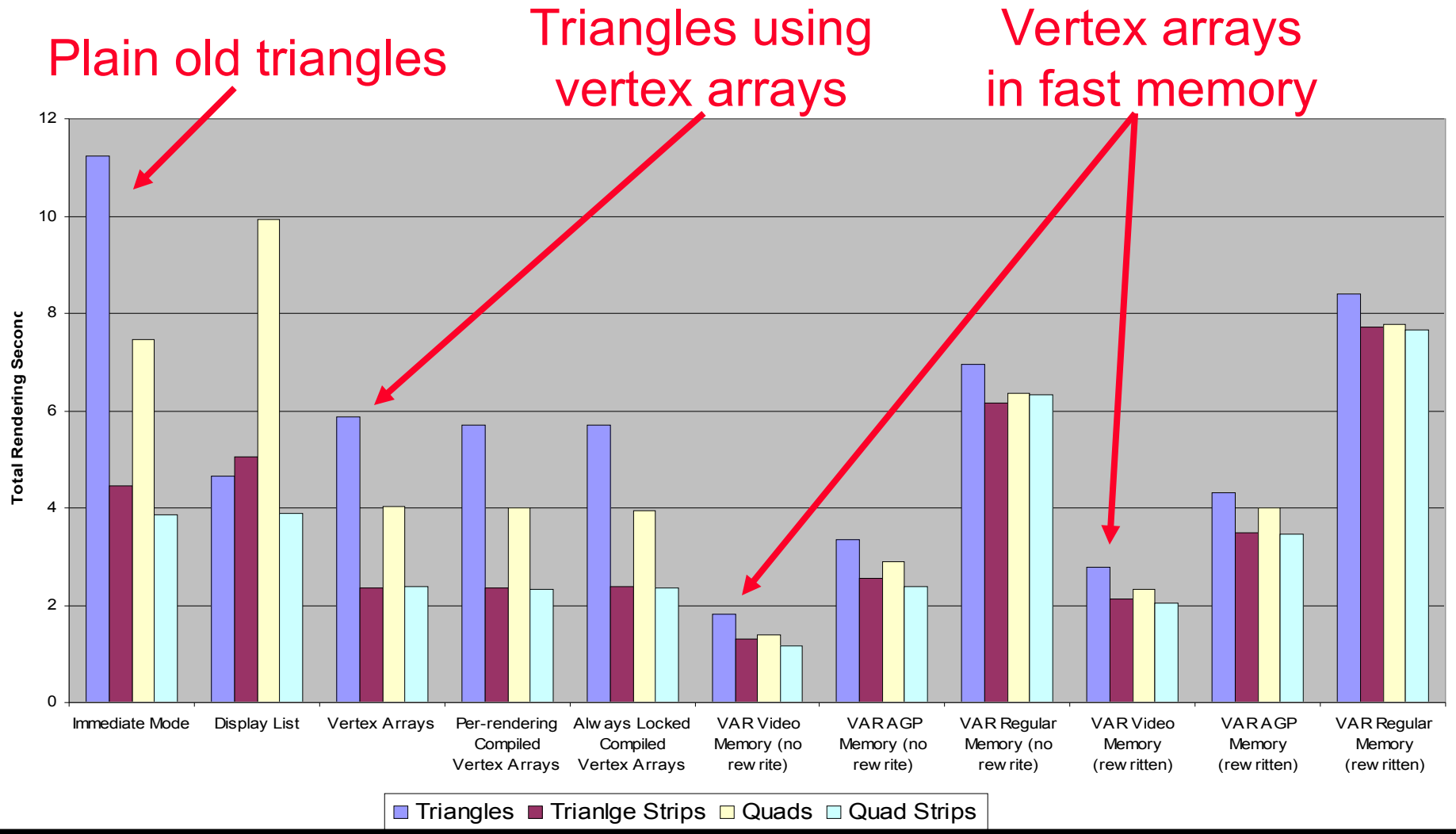
Optimizing For Rendering: Vertex Arrays

- Biggest win: vertex arrays



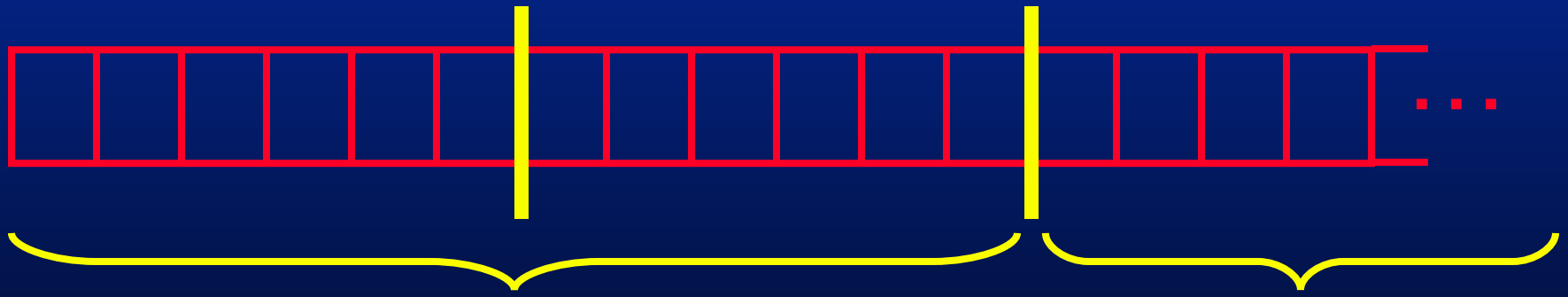
  - Actually, keep separate parallel arrays for rendering data (coords, colors, etc)

Optimizing For Rendering:
Vertex Arrays on GeForce2



Out-of-core Rendering

- Coherent arrays lend themselves to out-of-core simplification and rendering:



Out-of-core Rendering

- Coherent arrays lend themselves to out-of-core simplification and rendering:
  - Only need active portions of triangle and node arrays
  - Implement arrays as memory-mapped files
    - Let virtual memory system manage paging
    - A prefetch thread walks boundary nodes, bringing their children into memory to avoid glitches

Summary:
VDS Pros

- *Supports drastic simplification!*
  - View-dependent; handles the Problem With Large Objects
  - Hierarchical; handles the Problem With Small Objects
  - Robust; does not require (or preserve) mesh topology

Summary:
VDS Pros

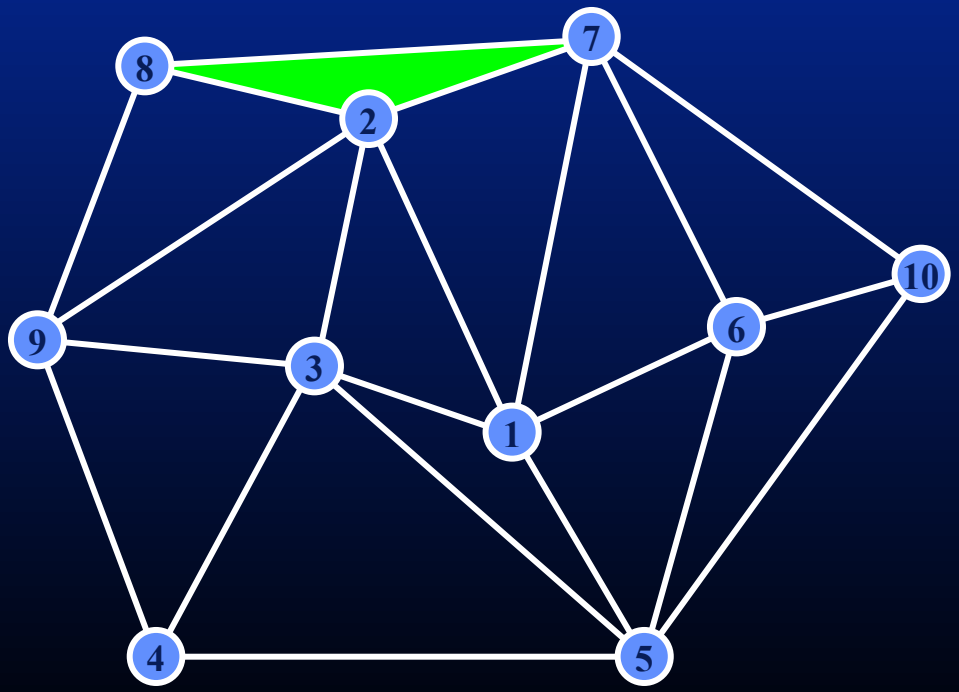
- Rendering can be implemented efficiently using vertex arrays
- Supports rendering of models much larger than main memory

Summary:
VDS Cons

- Increases CPU, memory overhead
- Fastest rendering mode currently restricted to 65K vertices (April 2001)

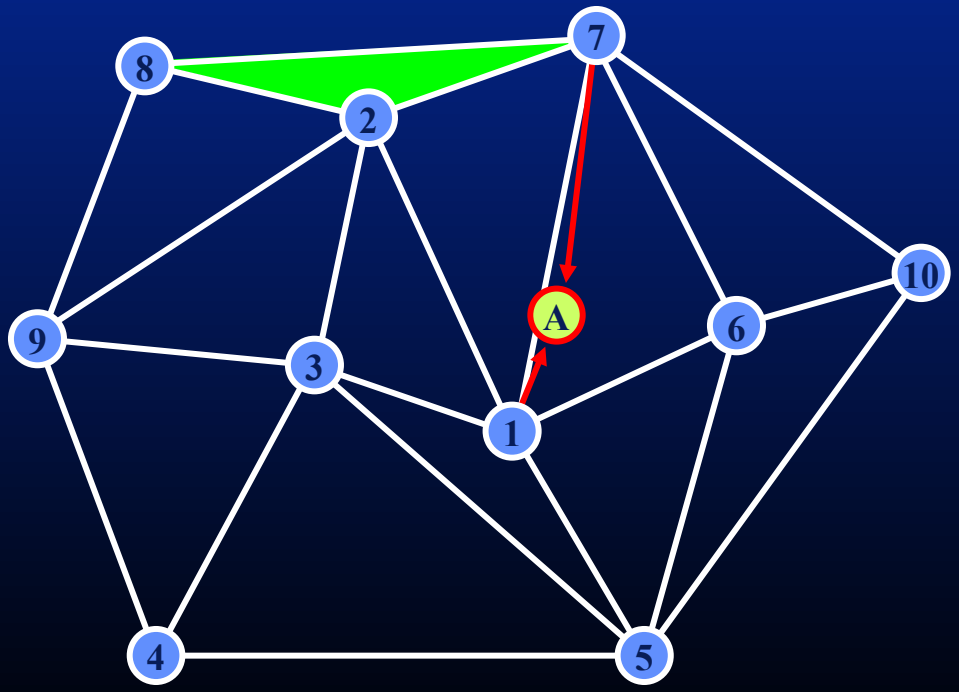
Summary:
VDS Cons

- Be aware of *mesh foldovers:*



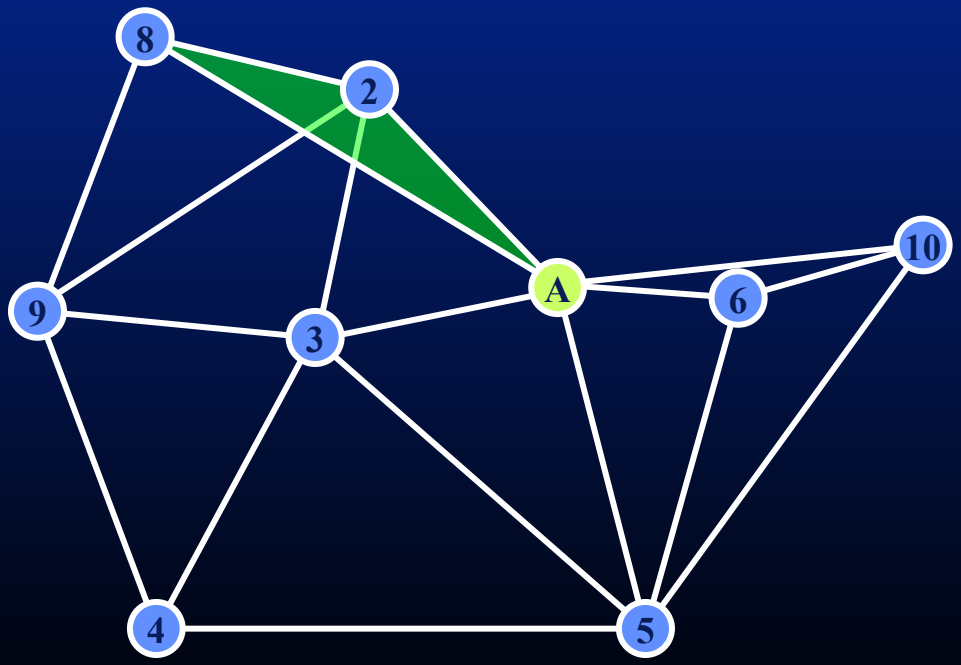
Summary:
VDS Cons

- Be aware of *mesh foldovers:*



Summary:
VDS Cons

- Be aware of *mesh foldovers:*



Summary:
VDS Cons

- Be aware of *mesh foldovers:*
  - These can be very distracting artifacts
  - Amitabh will talk about how to prevent them

View-Dependent Versus Discrete LOD

- View-dependent LOD is superior to traditional discrete LOD when:
  - Models contain very large individual objects (e.g., terrains)
  - Simplification must be completely automatic (e.g., complex CAD models)
  - Experimenting with view-dependent simplification criteria

View-Dependent Versus Discrete LOD

- Discrete LOD is often the better choice:
  - Simplest programming model
  - Reduced run-time CPU load
  - Easier to leverage hardware:
    - Compile LODs into vertex arrays/display lists
    - Stripe LODs into triangle strips
    - Optimize vertex cache utilization and such

View-Dependent Versus Discrete LOD

- Applications that may want to use:
  - Discrete LOD
    - Video games (but much more on this later…)
    - Simulators
    - Many walkthrough-style demos
  - Dynamic and view-dependent LOD
    - CAD design review tools
    - Medical & scientific visualization toolkits
    - Terrain flyovers (much more later…)

Continuous LOD:
The Sweet Spot?

- Continuous LOD may be the right compromise on modern PC hardware
  - Benefits of fine granularity without the cost of view-dependent evaluation
  - Can be implemented efficiently with regard to
    - Memory
    - CPU
    - GPU

VDSlib

- Implementation: *VDSlib*
  - A public-domain view-dependent simplification and rendering package
  - Flexible C++ interface lets users:
    - Construct vertex trees for objects or scenes
    - Specify with callbacks how to simplify, cull, and render them
  - Available at *http://vdslib.virginia.edu*

VDSlib:
Ongoing Work

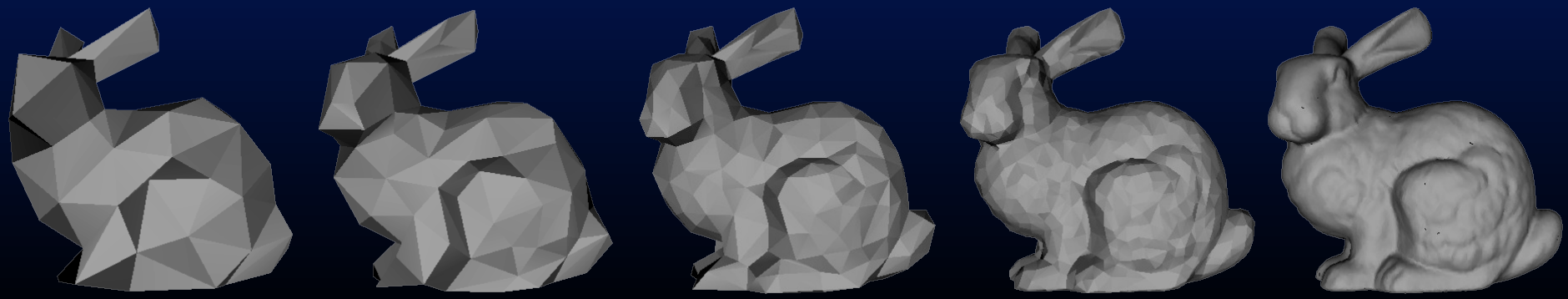
- Ongoing research projects using VDSlib:
  - Out-of-core LOD for interactive rendering of *truly* massive models
  - Perceptually-guided view-dependent LOD, including gaze-directed techniques
  - Non-photorealistic rendering using VDSlib as a framework

SAN ANTONIO

SIGGRAPH

2002

The End



Appendix:
Related Work

- Hoppe: Progressive Meshes (SIGGRAPH 96, SIGGRAPH 97, other papers)
  - Edge collapse vs. vertex merging
  - Pros:
    - Dynamic, view-dependent simplification
    - Elegant scheme for mesh attributes
  - Cons:
    - Requires clean mesh topology
    - Slow preprocess (though not implicit to PM)
    - Still per-object LOD

Appendix:
Web Resources

- VDSlib: *http://vdslib.virginia.edu*
  - A public-domain view-dependent simplification library
- My work on view-dependent simplification:
  http://www.cs.virginia.edu/~luebke/simplification.html
  - A SIGGRAPH paper
  - My dissertation on VDS
  - The attached tech report on VDS for CAD applications
  - A survey of LOD algorithms written for graphics developers

Appendix:
Web Resources

- Hughes Hoppe's work on progressive meshes:
  http://www.research.microsoft.com/~hhoppe
  - 2 SIGGRAPH papers
  - A paper on efficient implementation of progressive meshes
  - A paper on terrain rendering using progressive meshes
  - Much more…
- Michael Garland's work on quadric error metrics:
  http://www.uiuc.edu/~garland
  - A SIGGRAPH paper
  - Garland's dissertation on QEM
  - Follow-up papers, e.g. extending QEM to surface attributes
  - Public domain code for generating LODs with QEM

Appendix:
Web Resources

- The Multi-Tesselation (MT) home page:

  http://www.disi.unige.it/person/MagilloP/MT/

  – A different approach to dynamic and view-dependent simplification by De Floriani, Magillo, and Puppo.

  – Includes code and sample software

Appendix:
Attached Papers

- David Luebke. *Robust View-Dependent Simplification For Very Large-Scale CAD Visualization*, University of Virginia Tech Report CS-99-33.
  - An updated version of the original SIGGRAPH ‘97 paper describing the view-dependent simplification framework presented here.

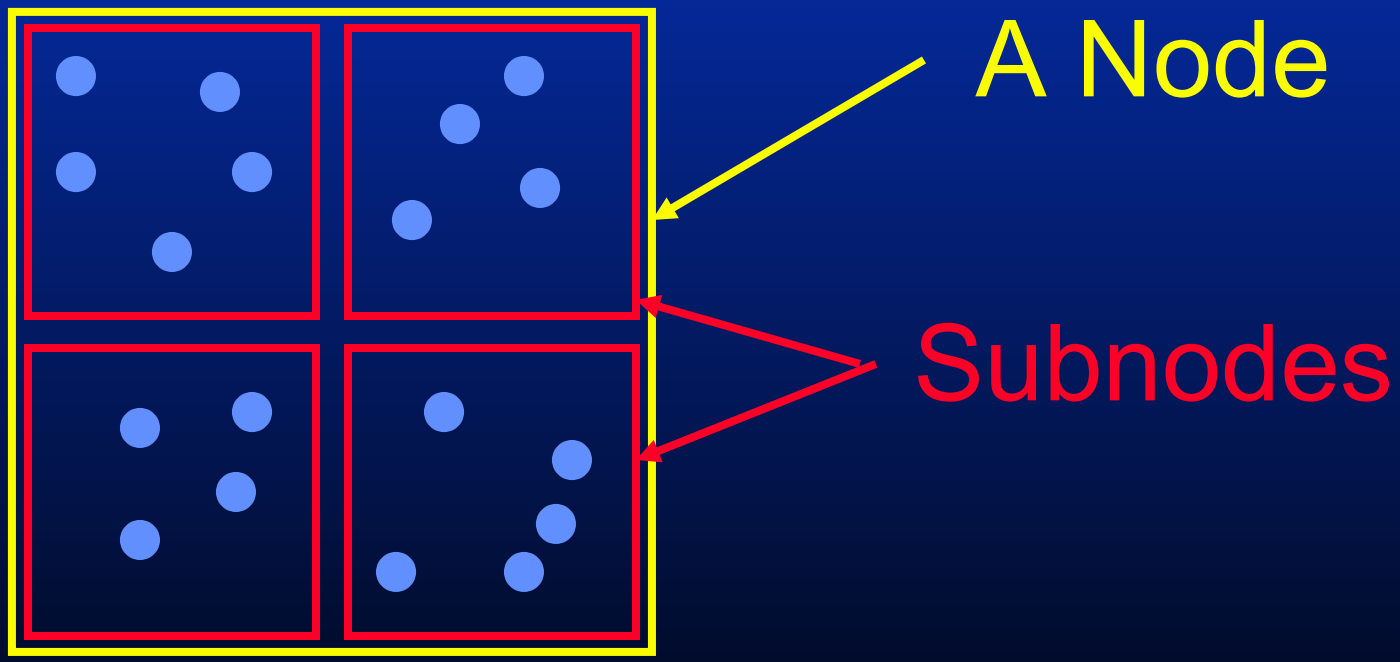
Appendix:
Attached Papers

- David Luebke, Jonathan Cohen,Nathaniel Williams, Mike Kelley, Brenden Schubert . *Perceptually Guided Simplification of Lit, Textured Meshes.* University of Virginia Tech Report CS-2002-07.
  - Describes ongoing work applying perceptual metrics (see Martin's talk) to view-dependent polygonal simplification.

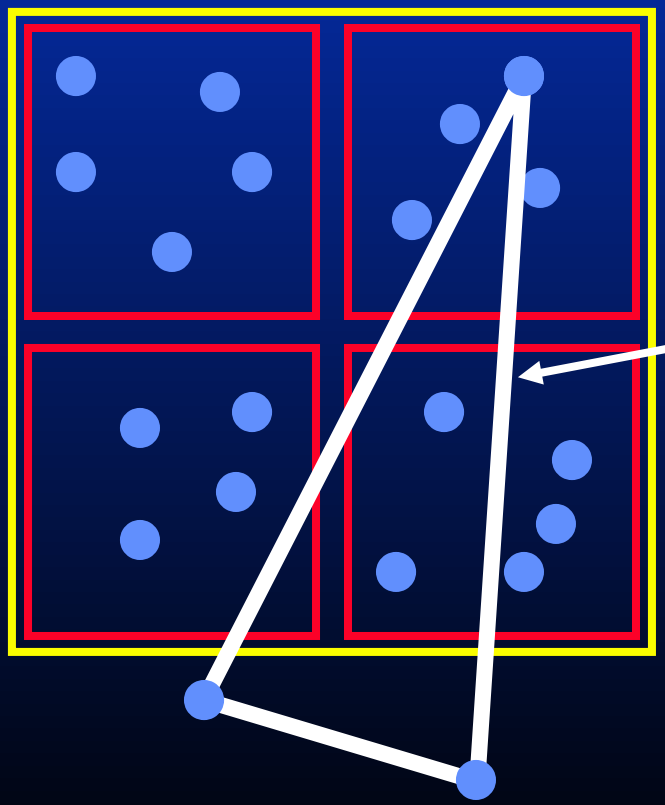
The Vertex Tree:
Livetris and Subtris

- Computing livetris and subtris:
  - `node->livetris` = triangles with exactly one corner vertex supported by node
  - `node->subtris` = triangles with:
    - Two or three corners in different subnodes
    - No two corners in the same subnode

The Vertex Tree:
Livetris and Subtris

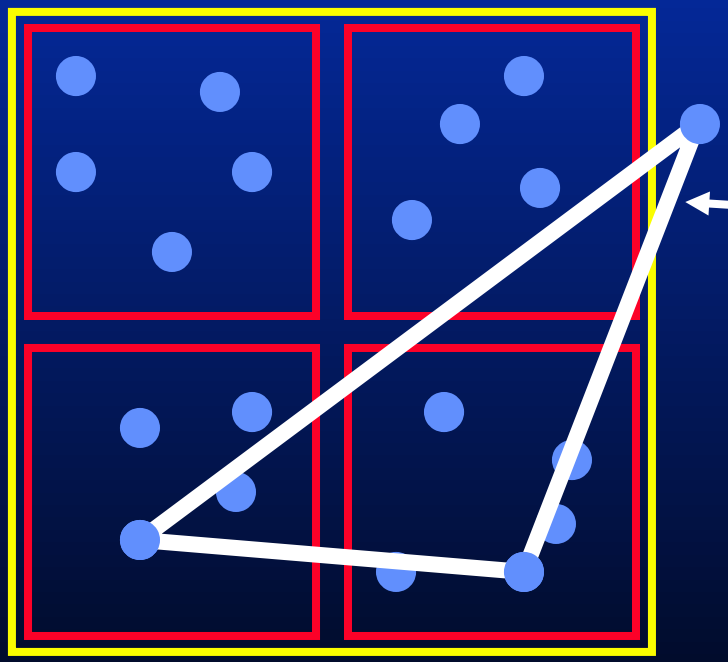


The Vertex Tree:
Livetris and Subtris



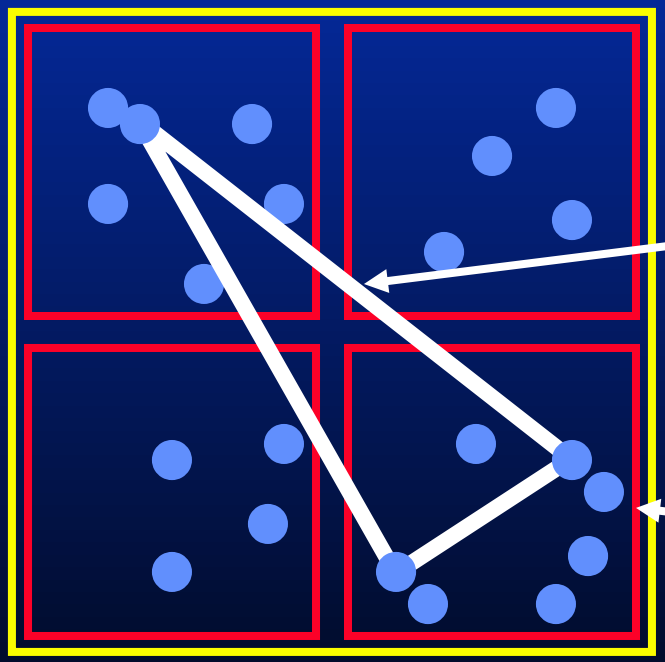
This is a **livetri** of the node

The Vertex Tree:
Livetris and Subtris



This is a **subtri** of the node

The Vertex Tree:
Livetris and Subtris



This is neither.

It's a subtri
of this subnode