Level of Detail: A Brief Overview

Fall 2010

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(slides based on those of David Luebke @ NVIDIA)

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Introduction

• Geometric simplification/Level of detail (LOD) management are important tools for maintaining interactivity during 3D rendering
  – Focuses on the fidelity / performance tradeoff
  – Not the only tool! Complementary with:
    • Parallel rendering
    • Occlusion culling/visibility culling
    • Out-of-core rendering
    • Image-based rendering [etc]
Level of Detail: The Basic Idea

- The problem:
  - Geometric datasets can be too complex to render at interactive rates

- 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, decimation, multiresolution modeling, …
Level of Detail: Traditional LOD In A Nutshell

- 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 LOD In A Nutshell

- Distant objects use coarser LODs:
Level of Detail: The Big Questions

- How to represent and generate simpler versions of a complex model?

- Courtesy Stanford 3D Scanning Repository

- 69,451 polys
- 2,502 polys
- 251 polys
- 76 polys
Level of Detail: The Big Questions

- How to evaluate the fidelity of the simplified models?

![Image of rabbit models with varying levels of detail]

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

Courtesy Stanford 3D Scanning Repository
Level of Detail: The Big Questions

- *When to use which LOD of an object?*

![Rabbit models with different LODs]( Courtesy Stanford 3D Scanning Repository)

- 69,451 polys
- 2,502 polys
- 251 polys
- 76 polys
Some Background

• History of LOD techniques
  – Early history: Clark (1976), flight simulators
  – Handmade LODs $\rightarrow$ automatic LODs
  – LOD run-time management:
    reactive $\rightarrow$ predictive (Funkhouser)

• LOD frameworks
  – Discrete (1976)
  – Continuous (1996)
  – View-dependent (1997)
  – GPU-based (200X)
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, we call this *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 triangles 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 discrete approach:
  – Discrete LOD: create individual levels of detail in a preprocess
  – Continuous LOD: create data structure from which a desired level of detail can be extracted *at run time.*
Continuous LOD:
Advantages

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

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

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

- 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
Summary: LOD Frameworks

- **Discrete LOD**
  - Generate a handful of LODs for each object

- **Continuous LOD (CLOD)**
  - Generate data structure for each object from which a spectrum of detail can be extracted

- **View-dependent LOD**
  - Generate data structure from which an LOD specialized to the current view parameters can be generated on the fly.
  - One object may span multiple levels of detail

- **(Hierarchical LOD)**
  - Aggregate objects into assemblies with their own LODs
Choosing LODs:
LOD Run-Time Management

• Fundamental LOD issue: where in the scene to allocate detail?
  – For discrete LOD this equates to choosing which LOD will represent each object
  – Run every frame on every object; keep it fast
Choosing LODs

• *Describe a simple method for the system to choose LODs*
  – Assign each LOD a range of distances
  – Calculate distance from viewer to object
  – Use corresponding LOD
Choosing LODs

• *What’s wrong with this simple approach?*
  – Visual “pop” when switching LODs can be disconcerting
  – Doesn’t maintain constant frame rate; lots of objects still means slow frame times
  – Requires someone to assign switching distances by hand
  – Correct switching distance may vary with field of view, resolution, etc.

• *What can we do about each of these?*
Choosing LODs
Maintaining constant frame rate

- One solution: scale LOD switching distances by a “bias”
  - Implement a feedback mechanism:
    - If last frame took too long, decrease bias
    - If last frame took too little time, increase bias
  
  - Dangers:
    - Oscillation caused by overly aggressive feedback
    - Sudden change in rendering load can still cause overly long frame times
Choosing LODs: Maintaining constant frame rate

• A better (but harder) solution: predictive LOD selection

• For each LOD estimate:
  – Cost (rendering time)
  – Benefit (importance to the image)
Choosing LODs: Maintaining constant frame rate

• A better (but harder) solution: predictive LOD selection

• For each LOD estimate:
  – *Cost* (rendering time)
    • # of polygons
    • How large on screen
    • Vertex processing load (e.g., lighting) OR
    • Fragment processing load (e.g., texturing)
  – *Benefit* (importance to the image)
Choosing LODs: Maintaining constant frame rate

• A better (but harder) solution: predictive LOD selection

• For each LOD estimate:
  – *Cost* (rendering time)
  – *Benefit* (importance to the image)
    • Size: larger objects contribute more to image
    • Accuracy: no of verts/polys, shading model, etc.
    • Priority: account for inherent importance
    • Eccentricity: peripheral objects harder to see
    • Velocity: fast-moving objects harder to see
    • Hysteresis: avoid flicker; use previous frame state
Choosing LODs:

- Given a fixed time budget, select LODs to maximize benefit within a cost constraint
  - Variation of the knapsack problem
  - *What do you think the complexity is?*
    - A: NP-Complete (like the 0-1 knapsack problem)
  - In practice, use a greedy algorithm
    - Sort objects by benefit/cost ratio, pick in sorted order until budget is exceeded
    - Guaranteed to achieve at least 50% optimal sol’n
    - Time: $O(n \log n)$
    - Can use incremental algorithm to exploit coherence
Level of Detail:
Generating LODs
Generating LODs

• Simplification Operator

• Measuring Error
Generating LODs

• Simplification Operator

• Measuring Error
Generating LODs

• Simplification Operator:
  – Cell collapse
  – Vertex removal
  – Edge collapse
Generating LODs

• Simplification operator:
  – Cell collapse
  – Vertex removal
  – Edge collapse
    • Full edge collapse
      – + Better fidelity
    • Half edge collapse
      – + Less memory
      – - Quality
    • Vertex-pair merge a.k.a. “virtual edge collapse”
      – - Merges separate objects
Edge Collapse Algorithm
Edge Collapse Benefits

• Edge collapse operation is simple
• Supports non-manifold topology:
Edge Collapse vs. Vertex-Pair Merging

• Even better: *vertex-pair merging* merges two vertices that:
  – Share an edge, or
  – Are within some threshold distance $t$

• Q: *What does vertex-pair merging enable over edge collapse?*
Generating LODs

• Simplification Operator

• Measuring Error
Measuring Error

• Most LOD algorithms measure error geometrically
  – What is the *distance* between the original and simplified surface?
  – What is the *volume* between the surfaces?

• Really this is just an approximation to the actual *visual* error, which includes:
  – Color, normal, & texture distortion
  – Importance of silhouettes, background illumination, semantic importance, etc.
Measuring Visual Error

- Measuring error
  - Image-based ideas
  - Lindstrom & Turk, SIGGRAPH 2000
  - Perceptually-based ideas
  - Luebke & Hallen, EGRW 2001
  - Williams, Luebke, Cohen, Kelley & Schubert, I3D 2003
Measuring Geometric Error

• Measuring error
  – Hausdorff distance
    • One-sided: \( h(A, B) = \max_{a \in A} \min_{b \in B} \|a - b\| \)
    • Two-sided: \( H(A, B) = \max \left( h(A, B), h(B, A) \right) \)
  – Common approximations:
    • Measure vertex-vertex distance, vertex-plane distance
    • METRO: Sample \( H(A,B) \) by sprinkling points on triangles
    • *Quadric Error Metrics*: a variation of vertex-plane distance that works well in practice
Measuring Perceptual Error

• Idea:
  – Measure local simplification operations against a perceptual model to predict whether the user can see the effect of simplification

• Model
  – Use a contrast sensitivity function
Perception 101: Contrast Sensitivity Function

• Contrast grating tests produce a contrast sensitivity function
  – Threshold contrast vs. spatial frequency
  – CSF predicts the minimum detectable static stimuli
Your Personal CSF
Level of Detail:
View-Dependent Simplification
View-Dependent LOD: Algorithms

• Many good published algorithms:
  – Progressive Meshes
  – Hierarchical Dynamic Simplification
  – Multitriangulation
  – Others...
Overview: The VDS Algorithm

• Overview of the VDS algorithm:
  – A preprocess builds the *vertex hierarchy*, 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: Folding And Unfolding

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

Triangles in active list

Vertex hierarchy
Vertex Tree Example

Triangles in active list

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Vertex hierarchy
Vertex Tree Example

Triangles in active list

Vertex hierarchy
The Vertex Tree

- At runtime, folds and unfolds create a cut or boundary across the vertex tree:

This part of the model is represented at high detail

This part in low detail
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
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
Asynchronous Simplification

• Algorithm partitions into two tasks:
  - Run them in parallel
    - Simplify Task
    - Render Task
    - Active Triangle List

- Vertex Tree
Asynchronous Simplification

- If $S = \text{time to simplify}$, $R = \text{time to render}$:
  - Single process $= S + R$
  - Pipelined $= \max(S, R)$
  - Asynchronous $= R$

- The goal: efficient utilization of GPU/CPU
Temporal Coherence

• Exploit the fact that frame-to-frame changes are small

• Three examples:
  – Active triangle list
  – Vertex tree
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
LOD Book

- http://lodbook.com/source/
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](http://vdslib.virginia.edu)
GLOD

• An easy-to-use library for level of detail in OpenGL
  – LOD generation
  – LOD run-time management
  – View-dependent LOD (using VDSlib)

http://www.cs.jhu.edu/~graphics/GLOD