A Framework for Streaming Geometry in VRML

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We introduce a framework for streaming geometry in VRML that eliminates the need to perform complete downloads of geometric models before starting to display them.

Several factors currently limit the size of Virtual Reality Modeling Language (VRML) models that can be effectively visualized over the Web. Principal factors include network bandwidth limitations and inefficient encoding schemes for geometry and associated properties. The delays caused by these factors reduce the attractiveness of using VRML for a large range of virtual reality models, CAD data, and scientific visualizations. The Moving Pictures Expert Group's MPEG-4 addresses the problem of efficiently encoding VRML scene graphs. MPEG-4 version 2 contains a 3D mesh coding toolkit to compress `IndexedFaceSet` and `LOD` nodes, featuring progressive transmission.[1]

In this article we propose a framework to mitigate the effects on users of long delays in delivering VRML content. Our solution is general and can work independently of VRML. We exploit the powerful prototyping mechanisms in VRML[2] to illustrate how our techniques might be used to stream geometric content in a VRML environment.

Our framework for the progressive transmission of geometry has three main parts, as follows:

1. a process to generate multiple levels-of-detail (LODs),
2. a transmission process (preferably in compressed form), and
3. a data structure for receiving and exploiting the LODs generated in the first part and transmitted in the second.

The processes in parts 1 and 2 have already received considerable attention (see below and the sidebars). In this article we'll concentrate on a solution for part 3.

Our basic contribution in this article is a flexible LOD storage scheme, which we refer to as a *progressive multilevel mesh*. This scheme, primarily intended as a data structure in memory, has a low memory footprint and provides easy access to the various LODs (thus suitable for efficient rendering). This representation is not tied to a particular automated polygon reduction tool. In fact, we can use the output of any polygon reduction algorithm based on vertex clustering (including the edge collapse operations used in several algorithms).

The progressive multilevel mesh complements compression techniques such as those developed by Deering,[3] Hoppe,[4] Taubin et al.,[5] or Gumbold and Strasser.[6] We discuss the integration of some of these compression techniques. However, for the sake of simplicity, we use a simple file format to describe the algorithm, which we'll explain later. Transmitting or storing a mesh in this file format (or compressing it with standard tools such as gzip) proves useful only in situations where no available geometric compression methods will serve. (For instance, when encoding arbitrary vertex clusterings that change the topology and introduce a nonmanifold connectivity).

In our approach, we partition the vertices and triangles of the mesh into several LODs by assigning an integer level to each vertex and triangle. We define and use vertex *representatives* to cause certain vertices—depending on the selected LOD—to be represented by another, substitute vertex. Not all vertices have representatives. Or, more precisely, a vertex may be represented by itself. Representatives can be stored in a single array with one entry per vertex.

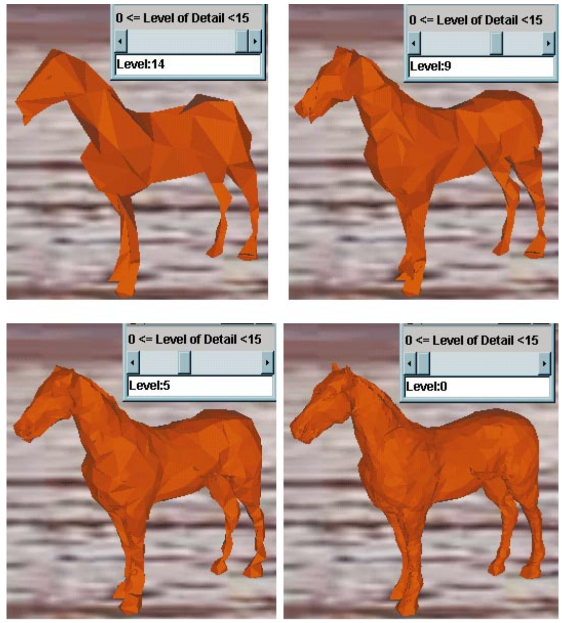
Using the PROTO mechanism of VRML and a script node executing Java code, we implemented a new VRML node to support this representation. A live demo is currently available on the Web at http://www.research.ibm.com/people/g/gueziec (where you can access relevant VRML files and Java bytecode). Figure 1 shows snapshots of our VRML implementation (an earlier version of this demo appeared at VRML 98[7]). Note the LOD can be changed interactively after (and even during) progressive loading.

When restricting ourselves to LODs produced using the familiar edge-collapse operations (as Ronfard and

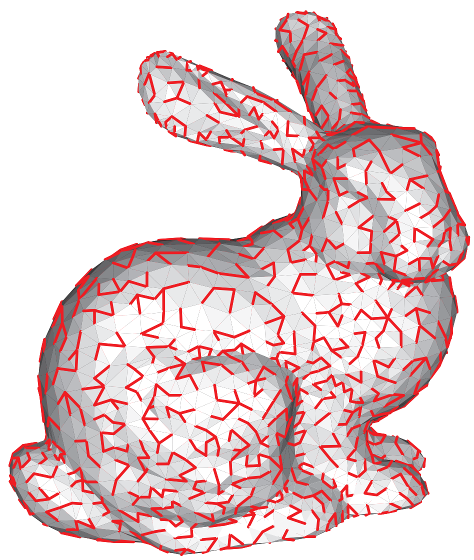
Triangular Meshes, LODs, and Edge Collapses

A polygonal surface is often represented with a *triangular mesh*, composed of a set of vertices and a set of triangles, each triangle being a triplet of vertex references. In addition, triangular meshes have a number of vertex or triangle properties such as color, normal, or texture coordinates. A *corner* is a couple (triangle, vertex of triangle). An *edge* is a pair of vertices, called *endpoints*, used in a triangle. An *edge collapse* consists of bringing both endpoints of an edge to the same position, thereby eliminating two triangles (or one triangle at the boundary of the surface). The edge collapse has an inverse operation, often called *vertex split*.

A significant number of automated methods for producing LOD hierarchies of a triangular mesh rely on edge collapses or on clustering vertices connected by edges, corresponding to applying several edge collapses in sequence. Methods differ in the particular strategy used for collapsing edges. For instance, Ronfard and Rossignac,[8] Guéziec,[12] and Garland and Heckbert[13] ordered the potential collapses according to different measures of the deviation from the original surface that results. Hoppe's[4] approach minimizes a surface energy (based on pairwise vertex distances) and other criteria. Guéziec,[12] Bajaj and Schikore,[14] and Cohen, Manocha, and Olano,[15] bound the maximum deviation from the simplified surface to the original. Note that many very effective simplification techniques work without collapsing edges (notably triangle collapses,[16] vertex removals,[17,18] and the Superfaces method[19]).



1 Snapshots of our VRML implementation using a horse model (original model provided by Rhythm & Hues Studios). LODs with (a) 247, (b) 665, (c) 1,519 and (d) 4,350 triangles are accessed interactively on a Pentium 133-MHz laptop PC using a VRML browser.



2 Forest of collapsed edges obtained using a simplification algorithm.[12] Vertices connected by marked edges collapse to the same location.

Rossignac,[8] Xia and Varshney,[9] and Hoppe[10] did), we can use a directed acyclic graph (DAG) to represent a partial ordering among the edge collapses, allowing for local (possibly view dependent) LOD control of a given shape (similar to deFloriani[11]).

Edge collapses

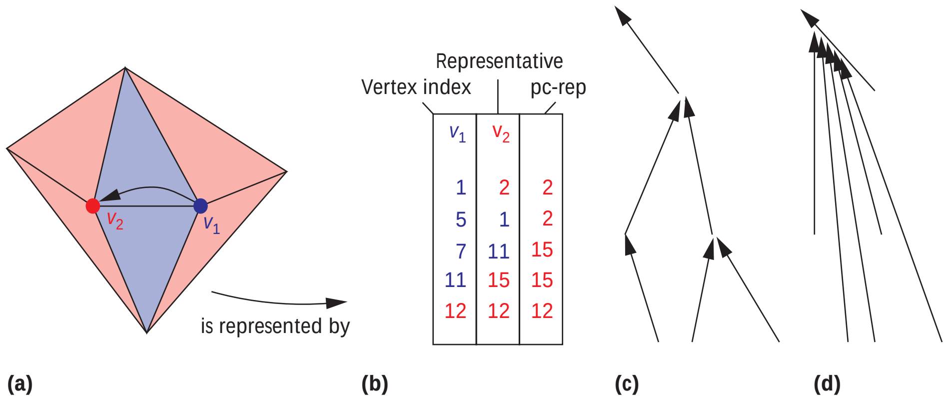
A variety of polygon reduction techniques[4,8,9] use edge collapses to create intermediate LODs. As Figure 2 shows, applying such a polygon reduction technique creates a forest (set of disjoint trees) of collapsed edges. Individual trees can be partially collapsed, with each partial collapse corresponding to an intermediate LOD.

Vertex representatives

A sequence of edge collapses creates a surjective map from the original surface to a simplified surface. With this technique, we don't have to create new triangles. Instead, we use the surjective map to modify triangles from the original surface. To construct the surjective map, we assign a representative for each surface vertex. In the beginning of the process, each vertex represents itself. As edges collapse, the process removes some vertices and chooses representatives for them among the remaining vertices.

It helps to use colors to illustrate this process. In the beginning, every vertex and triangle is red. We use blue for vertices and triangles that are gradually removed from the mesh. We give the edge collapse a direction: one endpoint is removed and painted blue; the other endpoint stays red (until a subsequent collapse removes it) and remains in the mesh (note that its actual coordinates may be modified, but it keeps its index). The triangles removed during the edge collapse are blue. Figure 3 (next page) illustrates the (directed) collapse of an edge $v_1 \rightarrow v_2$. The red vertex v_2 becomes the representative of the blue vertex v_1. A one-to-one correspondence exists between the blue vertices and edge collapses.

The representatives are preferably stored using an array, with one entry per vertex (red vertices are represented by themselves). To build the simplified surface,

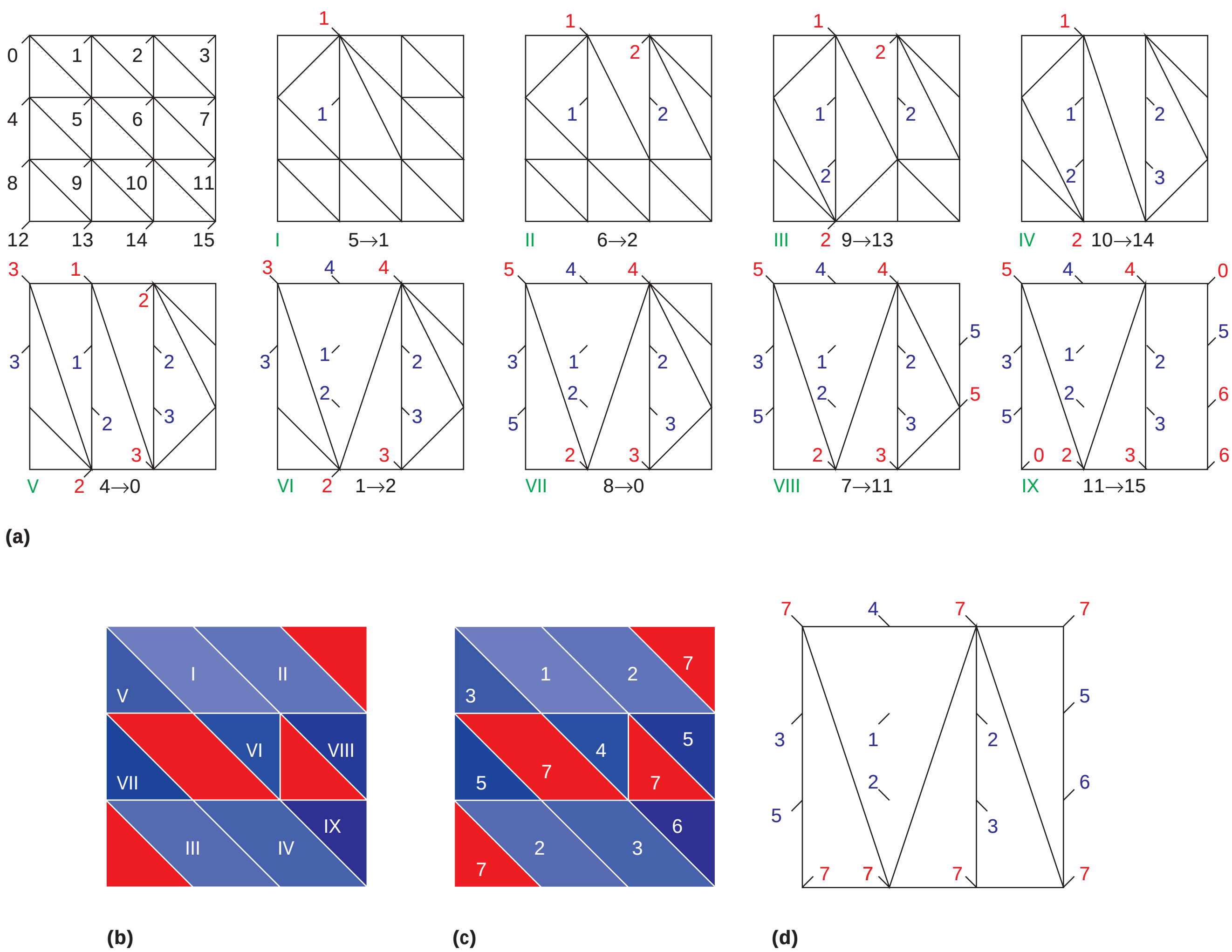


3 **(a) During an edge collapse, the blue vertex v_1 and blue triangles are removed. The arrow indicates a vertex representative assignment. (b) A vertex representative array and path-compressed representative (pc-rep) array. (c) Tree of representatives before path compression. (d) After path compression.**

we path-compress the vertex representatives array as shown in Figures 3b and 3d. We refer to the resultant array as the *pc-rep* array. To perform the path compression, we follow the representative hierarchy until we find a root and make each element in the path point directly to the root.[20] Triangles are stored using the original vertex indices and, for a particular LOD, they're rendered using the pc-rep array.

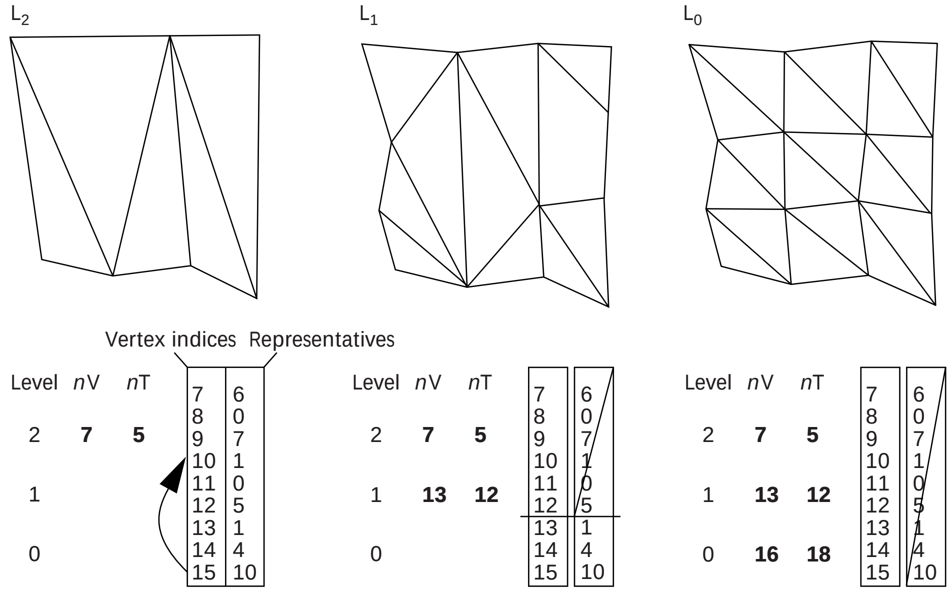
Vertex and triangle levels

Now we'll explain how to assign levels to vertices and triangles as edges collapse. In what follows, we'll write that a vertex is in the *star* of an edge if it's either an endpoint of the edge or adjacent to an endpoint.



4 **(a) A simple mesh. Nine edge collapses, numbered I through IX, affect the levels of the red and blue vertices as shown (numbers in black indicate the vertex identifiers; numbers in blue and red indicate the levels assigned to vertices during edge collapses). (b) Labeling the blue triangles according to the edge collapse number (I through IX) that eliminates them. (c) and (d) Partitioning the surface in seven LODs. The *i*th LOD uses vertices and triangles with labels *i*, *i* + 1. . . ., 7.**

Consider the model of Figure 4, called the simple mesh, with 16 vertices and 18 triangles. We used nine edge collapses to simplify the mesh. We assigned levels to vertices as follows: at the start all vertices are red with Level 0. When an edge collapses, we compute the maximum Level l in vertices of the edge star and assign Level $l + 1$ to both the red and blue edge endpoints. $L + 1$ is also the level assigned to the triangles that become blue during the collapse. We used levels of blue vertices and triangles to generate LODs. Levels of red vertices are used only temporarily for computing levels of blue vertices. To become familiar with this process, examine Figure 4 carefully—it provides the complete details of the edge collapses. In the end of the simplification process, we incremented the highest level and assigned it to all red vertices and triangles (this is Level 7 in Figure 4).



5 Accessing different LODs of the progressive multilevel representation: Level 2 (left), Level 1 (middle), and Level 0 (right).

Partitioning a surface into LODs

Once we've produced a partition of the vertices and the triangles in levels (Figures 4c and 4d illustrate this for the simple surface), we can define the surface LODs. The *i*th LOD consists of all vertices and triangles of a level greater or equal to i. In Figure 4 the coarsest surface level is 7 and the finest is 1. To evolve from surface LOD i to $j < i$, we simply provide vertex and triangles of levels j to $i - 1$. If a high granularity isn't required, we can create fewer levels by merging any number of consecutive levels in a single level. (In fact, we reduced the number of levels to three from the same data in Figure 5.)

Figure 5 shows how to access different LODs of the progressive multilevel representation. For Level 2 (left), which has five triangles, follow the representatives hierarchy toward the roots until the representative indices fall below 7 (the current number of vertices). For Level 1 (middle), which has 12 triangles (and 13 vertices), follow the representatives until they fall below 13 (representatives for vertices below index 13 can be ignored and thus crossed out). Level 0 (right) shows 16 vertices and 18 triangles. All representatives can be ignored.

We next sort the vertices and triangles according to their level, starting from the highest to the lowest level (red vertices and triangles have the highest level), and update the triangle vertex indices and the vertex representatives to reflect the permutation (sorting) on the vertices. This results in a progressive multilevel mesh as defined in the next section.

Progressive multilevel mesh

A progressive multilevel mesh with L different levels is a particular triangular mesh as follows (instead of enumerating levels from 1 through L, we enumerate them from 0 through $L - 1$ for easier translation to a C- or Java-type array):

- Vertices and triangles are assigned a level starting from 0 (the most detailed level) to $L - 1$ (coarsest level). Both are enumerated in order of decreasing level, and the maximum index n_l for a vertex of a given level l is stored.
- For each vertex v with a level less than $L - 1$, a representative may be supplied. A representative references another vertex, with a higher level (and lower vertex number) substituted for the vertex v whenever v is missing from the current mesh. Representatives define a graph called a forest, which can be conveniently stored using an array with one entry per vertex.
- From this information, we can efficiently compute L LODs: each LOD l, $0 \le l \le L - 1$ uses vertices and triangles of levels $l, l + 1, \ldots, L - 1$. For each such triangle, if a vertex reference exceeds n_l, we follow the forest of representatives as shown in Figure 5 until we fall below n_l. For speed-up we path-compress the forest of representatives. The cost of pointing directly to the roots from each node is slightly superlinear in terms of the number of nodes (see Tarjan[20]). By substituting vertex references in triangles with their corresponding forest root, we can switch directly from any level to any other level without explicitly building intermediate levels. Path compression is performed on a temporary copy of the representatives array (to preserve the forest hierarchy for subsequent use) every time the LOD changes.
- Vertices of the LODs don't have to be a proper subset of the original vertices (although it's more convenient). When evolving from Level l of the triangular mesh to Level $l - 1$ (increasing the resolution), the positions and properties (color, texture coordinates, surface normal) of the representatives of Level $l - 1$ vertices may be changed by reading them from a secondary array (or list). The primary array stores the original values.

```
#3-level progressive mesh
{#level 2 vertices       (4)
-3.0,  3.0,  3.0,  3.0,  -3.0, -3.0
3.0.  -3.0}
{#level 2 triangles (2), followed with
 #                   representatives
6,   2,   8,           0, 1,
3,   8,   2}
{#level 1 vertices       (3)
-2.3,  3.0,-3.0, 2.3,     2.3, 2.3}
{#level 1 triangles      (4)
4,   6,   7,     1,
5,   2,   6,
6,   4,   5,
4,   0,   5}
{#level 0 vertices       (3)
2.3,   3.0, 2.3, 2.3,     3.0, 2.3}
{#level 0 triangles (no representatives
 #necessary)
8,   3,   9,
9,   1,   8,
7,   8,   1,
8,   7,   6}
```

6 **Exemplary ASCII file for storing a mesh with three progressive LODs. This example is 2D. (# signs precede comments.)**

```
PROTO MultiLevelProgIfs
[
  field       SFString urlData  ""
  field       SFBool   debug    FALSE
]
{
  DEF ifs IndexedFaceSet {
    coordIndex []
    coord Coordinate { point [ ] }
  }
  DEF script Script {
    url               "ProgIfs.class"
    directOutput      TRUE
    mustEvaluate      TRUE

    field             SFString urlData IS urlData
    field             SFNode   ifs     USE ifs
    eventIn  SFBool   update
    eventOut SFBool   isReady
  }
ROUTE script.isReady TO script.update
}
```

7 **The file "ProgIfs.wrl" defining a PROTO for an IndexedFaceSet that can be streamed and whose LOD can be changed interactively.**

- Potentially, vertices can be added in a level without adding corresponding triangles, thus allowing additional freedom for changing the topology.

Figure 6 shows a simple file format that summarizes the information required in a progressive multilevel mesh. (Recall that a progressive multilevel mesh is primarily a data structure. Files such as the one in Figure 6 should be used in practice for transmission and storage only if no geometry compression method is available.) Batches of vertices and triangles are specified similarly to a typical triangular mesh, with the difference that some triangles use vertex indices that potentially can refer to vertices in missing batches. In Figure 6, the line `6,2,8,   0,1,` should be interpreted as follows: when the system reads triangle (6,2,8) from the storage or network, only vertices 0 to 3 can be referenced (this single vertex batch was read so far). Vertex 6 requires a representative (this is 0) as well as vertex 8 (1). The next time the system reads 8, this vertex's representative is not specified again.

Low memory footprint

We perform a simple byte count for specifying a generic mesh—ignoring vertex and triangle properties—and assume that n vertices and approximately $2n$ triangles exist (this depends on the surface genus and number of boundaries; it's exact for a torus). We also assume that the system uses 4 bytes to store each vertex coordinate (typically a 4-byte `float`) and vertex index (a 4-byte `int`). A generic mesh would be stored using $36n$ bytes. Our representation would use less than $40n$ bytes, since vertex representatives—the sole addition—aren't supplied for all vertices (the additional cost factor is at most $40/36 \cong 1.1$).

Support for smooth transitions

When we add detail to the triangular mesh by lowering the level from l to $l-1$, we introduce the vertices of Level $l-1$ in the mesh. The new triangles are determined as explained above, but for the new vertices, the coordinates of their representative are used first, resulting in a mesh that remains geometrically the same as the Level l mesh (when all added vertices have a representative in Level l). Then, gradually, the coordinates are interpolated linearly from that position to the new coordinates using a parameter λ that varies between 0 and 1.

VRML implementation

In this section we describe our VRML 2.0 implementation, based on defining a new node using the `PROTO` mechanism and Java in the script node for the logic. Figure 7 shows the PROTO that we defined and Figure 8 shows a sample VRML file using the PROTO. The new node behaves as an **IndexedFaceSet**, has the **URL** of the file containing the data as the only **field** (instance variable) to be set up when the node is instantiated, and has one **eventIn** that the browser uses to request an update.

The Java program in the script node implements two fundamental functions. One function, called **addLevel()**, appends a new level to the data structure after it's read and thus implements progressive loading. The other, called **setLevel(int level)**, implements fast switching between LODs, potentially setting a fractional level for a geomorph using **setLevel(float level)**.

The code has two threads: upon instantiation, a thread downloads the data from the **URL** provided in the **urlData** field, immediately returning control to the browser. Then, whenever a level is completely downloaded and ready for display, Java notifies the VRML browser by sending an **isReady** event. After the browser regains control, it decides when to paint the new levels by sending an **update** event to the node. The main thread of the Java program handles the changes in LOD of the **IndexedFaceSet** node.

The download thread progressively downloads the total number of LODs, vertex, triangle, and properties data, and periodically updates the corresponding arrays (triangle, vertex pc-rep, vertex representative, and, optionally, property arrays). These arrays—which are private to the script code but persist after the download thread finishes—are used later by the script code's main thread to update the **IndexedFaceSet** fields responding to browser requests. The main thread does this by setting and changing values of the **coord** and **coordIndex** fields (and optionally of the other property fields) as a function of the data downloaded by the download thread and the requested LOD. Typically, the download thread automatically updates the **IndexedFaceSet** fields with the highest resolution LOD available as soon as all the data associated with it finishes downloading.

Note that we decided not to show the VRML logic necessary to trigger the change in LODs in Figure 7. This can be done in many different ways. For instance, as shown in Figures 1, 9, 10, and 11 (next page), a simple user interface (including a slider) can be spawned to interactively change the LOD. Another possibility is to maintain a triangle budget in the VRML scene and change it using a **Script** (for simplicity, using JavaScript) depending on the object's relative position in the scene. This triangle budget can be a **field** of the PROTO that the Java code handles.

In Figure 9, texture coordinates are specified for each vertex. A file specifying this model must thus provide texture coordinates in addition to the vertex positions (Figure 6 doesn't show this).

```
#VRML V2.0 utf8

EXTERNPROTO MultiLevelProgIfs
[
  field   SFString  urlData
]
["ProgIfs.wrl"]

Shape {
    geometry MultiLevelProgIfs{
    urlData    "horse.lod.gz"
    }
}
```

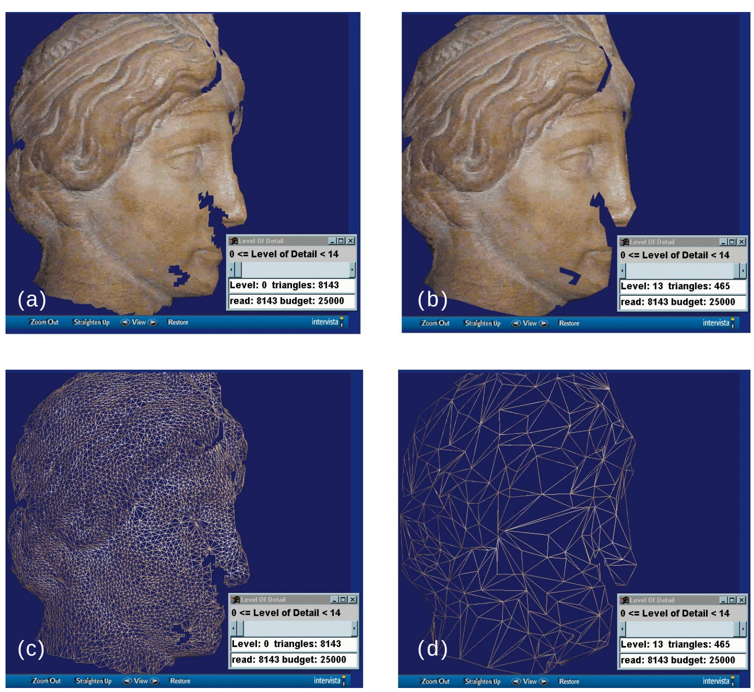
8 **A simple VRML file using the PROTO defined in "ProgIfs.wrl." Using a VRML browser when adding a Background node and some Appearance information, we can produce the pictures shown in Figure 1.**

Figure 11 shows a progressive multilevel mesh obtained by clustering vertices and exhibiting topological changes. Figure 11 also shows a geomorph between two levels of the model. As we'll discuss in the next section, we use representatives only for a selected number of clustered vertices. Accordingly, when performing a geomorph, we generally don't have a complete mapping between vertices of the higher and lower levels, unless more representatives are supplied than those required strictly for discrete levels. As illustrated in Figure 11 geomorphs are nonetheless possible without this additional information. The results may sometimes be less visually pleasing.

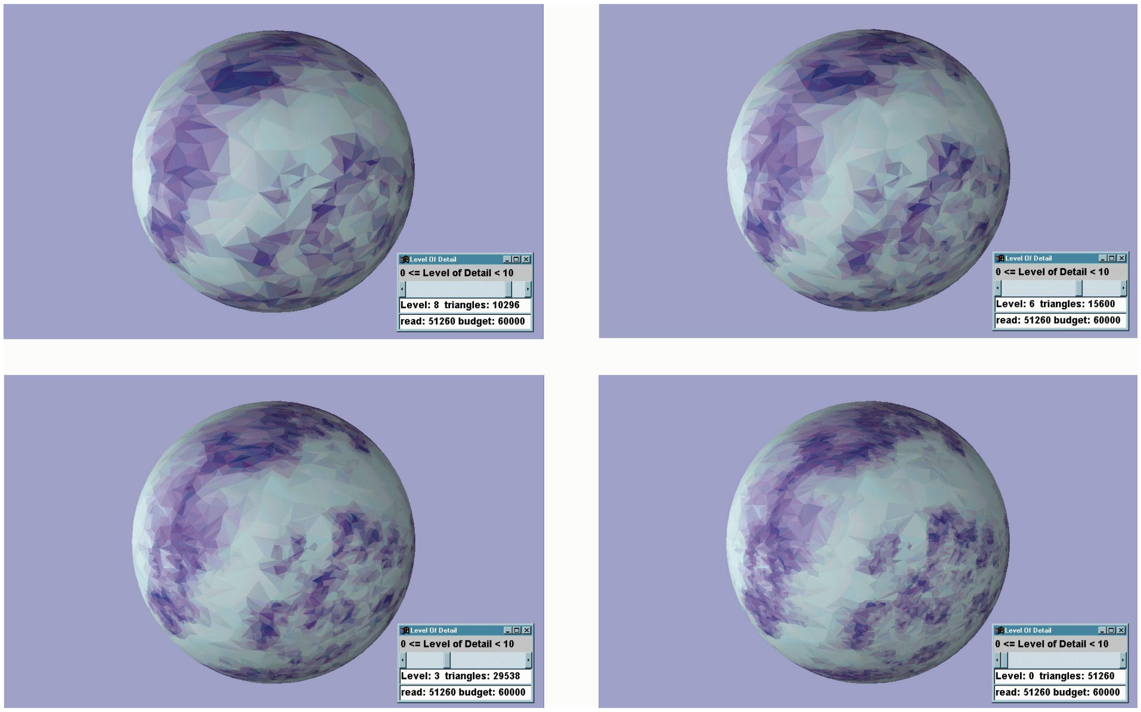
Vertex clustering

Although it was convenient in the section "Edge collapses" to start with the specification of a sequence of edge collapses on a given mesh to build a progressive multilevel mesh, we can use more general input.

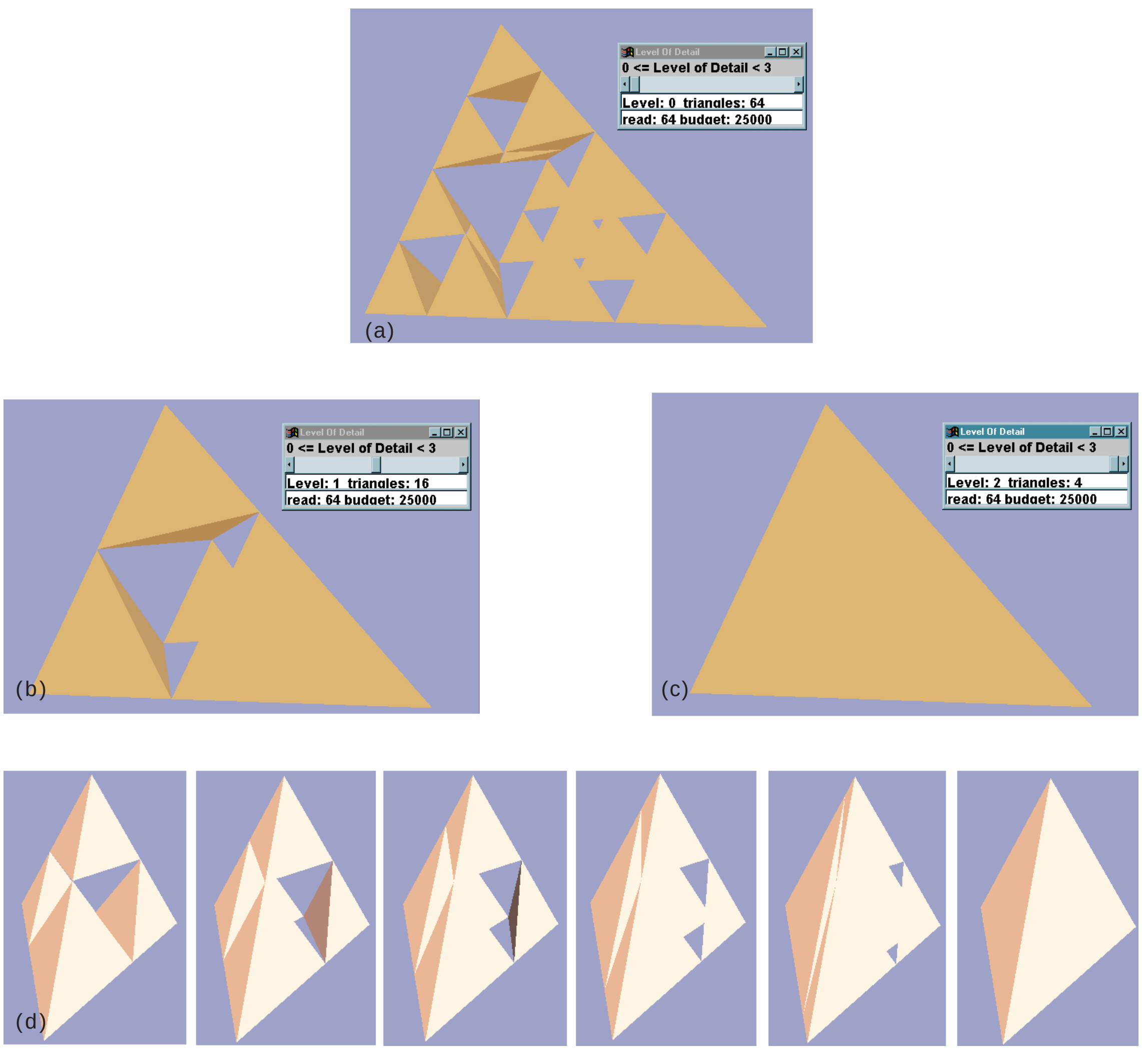
We can easily build a progressive multilevel mesh



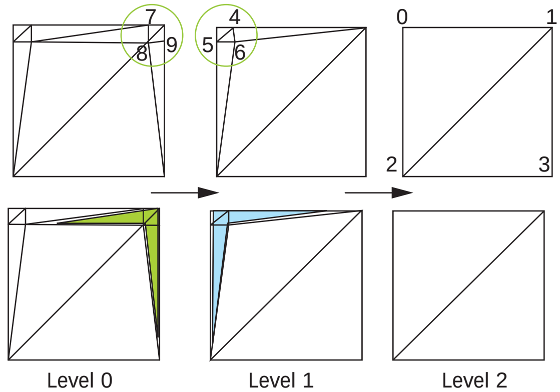
9 **A model with texture coordinates per vertex at the highest (a) and lowest (b) LOD. Corresponding wireframe models are shown in Figures 9c and 9d. We can switch between them in real time on a Pentium 133-MHz laptop computer.**



10 **A model of marble using colors per vertices with 50,000 triangles at the highest resolution.**



11 **Nonmanifold model with levels of (a) 64, (b) 16, and (c) 4 triangles. Topological changes, obtained by vertex clusterings, can be represented in a progressive multilevel mesh. (d) A geomorph between two levels of the model.**



12 **Building a progressive multilevel mesh from two vertex clusterings (circles show which vertices are clustered). The vertices are enumerated according to the level at which they appear or disappear (top row). The system identifies and enumerates the triangles that collapsed as a result of the clustering (bottom row). The first clustering is shown in green, while the second is shown in blue.**

using the vertex clustering information provided by any polygon reduction tool. To do this, we need the vertices and triangles of the most detailed mesh and, for each clustering, a new set of vertices (of the mesh after clustering) and a mapping between the vertices of the previous mesh and the new vertices.

Figure 12 illustrates this process and shows a model for which two successive clustering operations were applied.

We'll now explain how we obtained the resulting progressive multilevel mesh shown in Figure 6. Vertices and triangles are assigned levels and re-enumerated. For each remaining vertex after clustering, we identify its ancestors in the previous mesh using the mapping provided. Among its ancestors, we select one vertex as a "preferred" ancestor based on geometric proximity. (Other criteria are possible.) We assign the remaining vertices to Level 0 and the largest indices (for example, 7, 8, and 9 in Figure 12). We also identify the triangles that become degenerate during the clustering and assign them to Level 0 as well. Then we assign the largest triangle indices to these degenerate triangles. (To avoid visual clutter, Figure 12 doesn't show this.)

The remaining vertices (0 through 6 in Figure 12) and triangles are re-enumerated and the mapping adjusted to take the re-enumeration into account. The operation then repeats for the second clustering, for assignments to Level 1. We stop when all clusterings are processed.

This construction actually demonstrates that nonmanifold models and topological changes can be represented in a progressive multilevel mesh (those obtained by clustering vertices). In fact, Figure 11 shows a nonmanifold mesh whose topology is gradually simplified to that of a sphere (or tetrahedron). Figure 13 shows the corresponding multilevel file.

Returning to Figure 12, to specify the clustering operations, you would naturally specify that four vertices get mapped into one, and that again four vertices get mapped into one. Does this mean that 4 + 4 = 8 representatives should be specified in the multilevel mesh representation (or six, since when a vertex is its own representative, the information is implicitly recorded)? Not so, because representatives are required only when vertices touched by triangles of a given level are missing from the current level. It turns out that the information confined in Figure 6 suffices to encode the LODs of Figure 12, with only three representatives. (You may want to examine which representatives are necessary in Figure 13.)

Local surface refinement

Here we assume again that a suitable algorithm generates a succession of edge collapses to produce LODs. The actual order in which the collapses occur is irrelevant. However, when the algorithm validates a given collapse *i*, the collapsed edge neighborhood is in a particular configuration, resulting from a few identifiable edge collapses, say collapses *j* and *k*. We record that collapse *i* must occur after collapses *j* and *k*, defining a *partial ordering* on the collapses. This partial ordering proves useful in selecting a consistent subset of the collapses for a local simplification or refinement of the surface.

Storing a partial ordering between collapses

Each edge collapse has a status: S stands for "split," meaning that the collapse hasn't occurred yet. C stands for "collapsed," meaning that the collapse has occurred. If performing a certain collapse—for instance in Figure 4 collapse V with blue vertex 4 and red vertex 0 ($4 \rightarrow 0$) —requires that other collapses be performed beforehand—for example, collapse I ($5 \rightarrow 1$) and collapse III ($9 \rightarrow 13$)—we add two edges (V → *I*) and (V → III) to a directed acyclic graph (DAG). This means that situations in which V has status C and I has status S or III has status S are impossible. We can store this DAG in various ways. (Essentially, for each vertex of the DAG, we want to have

```
#2-level progressive mesh
{#level 2 vertices
0, 0, 0,    2, 2, 0,     2, 0, 2,
0, 2, 2}
{#level 2 triangles
0, 4, 5,    1, 2,
5, 4, 6,    3,
6, 0, 5,
4, 0, 6}
{#level 1 vertices
1, 1, 0,    1, 0, 1,     0, 1, 1,
2, 1, 1,    1, 2, 1,     1, 1, 2}
{#level 1 triangles
8, 6, 3,
3, 6, 9,
9, 8, 3,
6, 8, 9,
7, 5, 9,
9, 5, 2,
2, 7, 9,
5, 7, 2,
1, 4, 8,
8, 4, 7,
7, 1, 8,
4, 1, 7}
```

13 **Vertices, triangles, and representatives for the first two levels of the (nonmanifold) mesh of Figure 11. Note that three representatives suffice.**

Related Work on Progressive and View-Dependent Mesh Representations

The progressive meshes method introduced by Hoppe[4] consists of representing a mesh as a base mesh followed with a sequence of vertex splits (defined in the sidebar "Triangular Meshes, LODs, and Edge Collapses"). This permits progressive loading and transmission and view-dependent refinement. Progressive meshes can also be used to obtain a compressed representation of a mesh.

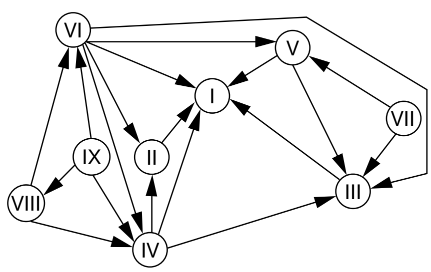
The progressive multilevel meshes introduced here provide freedom on the granularity of LOD changes and permit switching between arbitrary LODs without constructing intermediate levels. Also, arbitrary vertex clusterings can be encoded on manifold or nonmanifold meshes, allowing changes to the topology.

Xia and Varshney[9] applied edge collapses and vertex splits selectively for view-dependent refinement of triangular meshes. In the section "From edge collapses to a progressive multilevel representation," red vertices resemble the "parents" and blue vertices the "children" in Xia and Varshney's method.

De Floriani et al.[11] used a directed acyclic graph (DAG) to represent local mesh updates and their dependencies. In this article, we present a related DAG representation where each node represents an edge collapse and vertex split pair, and directed edges represent dependencies between collapses.

Hoppe defined vertex hierarchies to perform selective, view-dependent refinement of meshes.[10] By querying neighboring faces of a given edge or vertex, he can determine whether a given collapse or split proves feasible in a given configuration.

Luebke and Erikson[21] used an octree to represent vertex hierarchies. Vertex representatives defined here relate to "triangle proxies" in their work.



14 A directed acyclic graph representing the partial ordering of edge collapses corresponding to Figure 4.

a list of all the directed edges that enter the vertex and all the directed edges that exit from the vertex.) For our approach, we chose to use hash tables keyed with the vertex number. We also note that V has two *collapse constraints* and that I and III each have one *split constraint*. When we split V, then we can decrease the number of split constraints of I and III. Similarly, we can increase or decrease the number of collapse constraints. Figure 14 shows the complete DAG for the surface of Figure 4.

The procedure we use for building the DAG is very simple. First we examine the current level of all vertices belonging to the star (1-neighborhood) of the collapsed edge. Each level greater than zero indicates that the corresponding vertex was the outcome of a collapse. Then we determine the collapses that produced that particular vertex (for instance, by recording this information in a list or hash table).

Figure 15 shows how this DAG can locally refine the surface using a consistent subset of vertex splits. You can use various criteria to decide which vertices of the surface should be locally split (based on the distance to the viewpoint or the relation between the surface normal and viewing direction, and so on). Then, using the partial ordering defined above, it's easy to determine which vertex splits must occur and in which sequence they must occur. Performing a topological sort on the DAG's subgraph represented by the vertex splits accomplishes this.

Coupling with a geometry-compression method

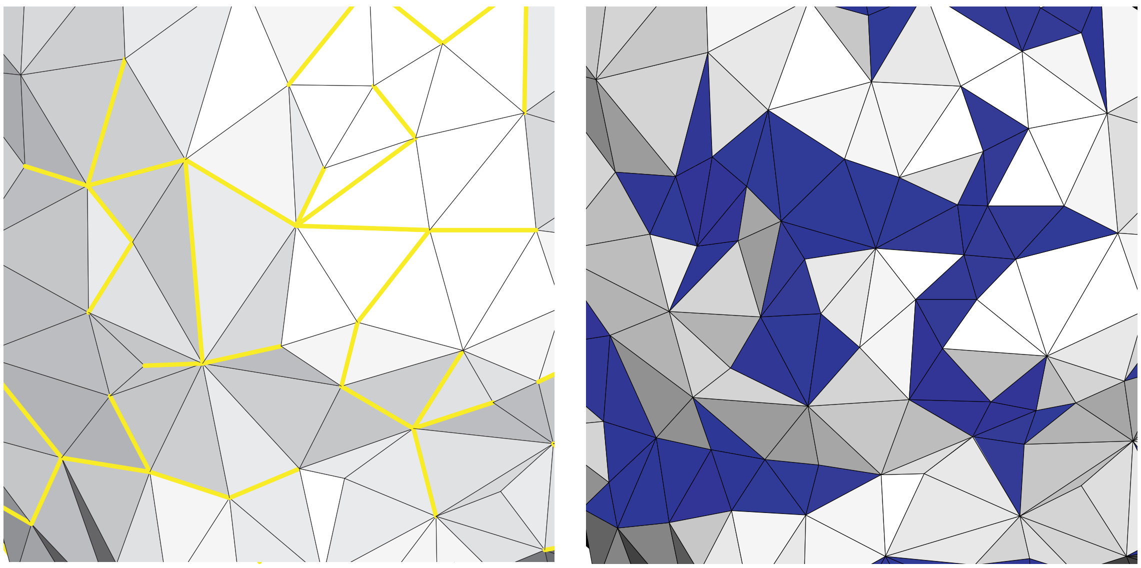
Taubin et al.[5] introduced the progressive forest split compression method, which represents a triangular mesh as a low resolution mesh followed by a sequence of refinements, each one specifying how to add triangles and vertices. Figure 16 shows the basic operation—a forest split. After marking a forest of edges on the lower resolution surface, the surface is cut through the edges and the resulting gap is filled with a forest of triangles. For the added triangles to form a forest, we impose topological constraints on the polygon reduction method. For instance, when using edge collapses, we make sure that after removing the two triangles corresponding to the collapse (of an interior edge), the set of removed triangles still forms a forest (this occurs after the very first edge collapse).

The information to encode this operation can be highly compressed. A simple encoding of the forest of edges requires 1 bit per edge (for example, a value of 1 for the edges belonging to the forest and 0 for the other edges). Since any subset of the forest edges forms a forest, we can determine at a certain point that some edges must have a bit of 0, thus achieving additional savings. The resulting bitstream can be further compressed using arithmetic coding. The triangles for insertion form a forest as well. Various possibilities exist for a compressed encoding of their connectivity. For instance, for each tree of the forest, we can use 2 bits per triangle to indicate whether it's a leaf, has a left or right neighbor, or both.

Overall, a forest split operation doubling the number n of triangles of a mesh requires a maximum of approximately $3.5n$ bits to represent the changes in connectivity. We obtain this bit count by multiplying the number of edges marked (approximately 1.5 times the number of triangles) by 1 bit and the number of triangles added (n) by 2 bits. Note that it's impossible to more than double the number of triangles in a mesh when applying a forest split operation, because we can't mark more edges than what a vertex spanning tree has (one less than the number of vertices, which is approximately half the number n of triangles of the mesh). We can, however, make the encoding of changes in geometry (vertex displacements and new properties) more compact by using efficient prediction methods along the tree of edges or the gap obtained after cutting.

The forest split compression can be coupled with our progressive multilevel representation as follows: As soon as a forest split refinement is transmitted, it can be interpreted as a vertex clustering operation performed on the

15 An example of selective refinement (the original mesh is shown on the left). The partial ordering of edge collapses and vertex splits enables a consistent subset of vertex splits (right) starting from a simplified mesh (middle).



16 The forest split refinement operation: after marking a forest of edges on the lower resolution surface (left), the surface is cut through the edges and the resulting gap is filled with a forest of triangles (right).

refined mesh to obtain the previous mesh (since the correspondence between the vertices before and after the split is implicitly known), and thus be decoded into an additional LOD by building a progressive multilevel mesh from vertex clustering. The `addLevel()` method described in the "VRML implementation" section may then be used to append the new level to the data structure. A similar mechanism could be used to incorporate other geometry compression methods as well.

Conclusion

We've described a framework for streaming polygonal data. Our LOD representation features the following characteristics:

- It can be built from the output of most automated polygon reduction algorithms (using vertex clustering).
- It requires only a 10 percent memory overhead in addition to the full detail mesh.
- LODs can be accessed on-the-fly by manipulating vertex indices.
- Any granularity is possible, from individual vertex splits to, for example, doubling the number of vertices.
- It supports smooth transitions (geomorphs).
- It's complementary to a compression process: the data can be put in our format after it's transmitted in compressed form.

We exploited VRML's capability to create new nodes and implemented our method for streaming geometry in VRML. We used Java in Script nodes to interactively load and change the LODs. Java's performance was very satisfactory. Some of the main difficulties we experienced were related to inconsistent or noncompliant support of Java in Script nodes in VRML browsers. However, we found that Platinum Technology's Worldview 2.1 for Internet Explorer 4.0 is a good environment to work with. When VRML browsers mature, we hope that these issues will be resolved. We believe that we've provided one of the first documented examples of how to use Java in Script nodes to stream 3D geometry content in VRML.

Our work can be extended in many ways. While VRML supports a very general binding model for properties (color, texture coordinates, and so on) of various mesh elements (vertex, face, corner), this article focuses on the geometry and properties bound to vertices—vertex colors in Figure 10 and texture coordinates per vertex in Figure 9. Implementing the selective refinement of the LOD in Java would probably push the limits of Java in script nodes (or the External Authoring Interface), because geometry refinement computations (in Java) and rendering (by the browser) must be tightly coupled and exchange considerable information. ■

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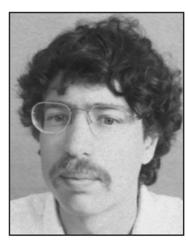

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