Budapesti Műszaki- és Gazdaságtudományi Egyetem
Villamosmérnöki és Informatikai Kar
Automatizálási és Alkalmazott Informatika Tanszék

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REAL-TIME VISUALIZATION OF DETAILED TERRAIN

KONZULENS

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BUDAPEST, 2003

HALLGATÓI NYILATKOZAT

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Kelt: Budapest, 2003. 05. 16.

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Balogh András

Összefoglaló

A nagy kiterjedésű, részletdús felületek valósidejű megjelenítése a számítógépes grafika egyik alapvető problémája. A téma fontosságát az is mutatja, hogy a hosszú évek óta tartó folyamatos kutatások eredményeképpen mára számtalan algoritmus látott napvilágot. Azonban az egyre növekvő követelmények újabb módszerek kifejlesztését igénylik. Munkámban megoldást keresek a domborzat felbontásának futásidejű növelésére procedúrális geometria hozzáadásával. Természetesen az ilyen procedúrális részlet valósidejű beillesztése a domborzatba nem egyszerű feladat. A legtöbb algoritmus az előfeldolgozási feltételei miatt egyáltalán nem képes az ilyen típusú felületek megjelenítésére.

Dolgozatomban először röviden elemzem, és összehasonlítom az eddig kifejlesztett legsikeresebb terepmegjelenítő algoritmusokat, rámutatok azok előnyeire és korlátaira egyaránt, majd az egyik legújabb és leghatékonyabb algoritmust alapul véve kifejlesztek egy olyan módszert, ami alkalmassá teszi tetszőleges felbontású, procedúrális geometriával dúsított domborzatok valósidejű megjelenítésére. Mindemellett bemutatok egy olyan árnyalási technikát is, ami a legmodernebb grafikus hardverek tudását maximálisan kihasználva lehetővé teszi az ilyen részletes domborzatok valósághű, pixel pontos megvilágítását is.

Abstract

This thesis focuses on real-time displaying of large scale, detail rich terrains. Although terrain rendering algorithms have been studied for a long time, it is still a very active field in computer graphics. The growing requirements and changing conditions always call for new solutions. In this work I explore possible methods to increase the perceived resolution of the surface by adding extra procedural detail to the terrain geometry at run-time. This is not an easy task, as it can be seen by the lack of available algorithms supporting it. High performace terrain rendering techniques all depend on special precomputed data for a fixed size, static terrain, which makes them unable to deal with such detailed surfaces generated at run-time.

I start out with describing and comparing several well known algorithms, that take different approaches to terrain visualization. Then, based on one of these algorithms, I introduce a novel method to extend the algorithm to support real-time visualization of high resolution terrain surfaces with extra detail geometry. To complement the geometry with a decent lighting solution, I also develop a robust technique to perform accurate per pixel shading of such a detailed terrain, using the latest crop of graphics hardware.

Table of Contents

1 Introduction

1.1 Overview

One of the most important use case of computers is simulation. It allows us to do things that would not be possible (or would be too dangerous, or just too expensive) otherways. Simulation is a very wide concept. Whether we are simulating the collision of entire galaxies, or some tiny particles in a cyclotron, or the efficiency and behaviour of a jet engine under various circumstances, or the view from an airplane 10'000 feet above, it is all the same. Simulation mimics reality[1]. Thus, we call the result Virtual Reality (VR), where everything seems and works like in reality, except that it is not real[2]. A VR system has lots of components, the one responsible for creating audiovisual stimuli is one of the most important ones, since humans can comprehend this kind of information the most. Here we will be concerned exlusively with the visualization part. More specifically the visualization of large scale, detailed terrain surfaces.

Applications ranging from aerial and land traffic training and control software, to entertaining computer games, all require detailed, consistent views of massive terrain surfaces. There are a lot of issues involved in terrain visualization. Most important ones are the compact, yet accurate representation of the terrain model (describing its geometry, material properties and such), efficient management (i.e. paging from mass storage devices) of this dataset, and displaying the geometry extracted from this model, so that the result is comparable to what one would see in reality.

We must not forget that simulation is always an approximation. Even if we make some very exact and precise calculations, we do them with regards to a model. A simplified model of the part of the real world we are interested in. It is very important to have a firm grasp on these concepts, because it is essential when one has to make important decisions and balance tradeoffs during engineering some kind of simulation application.

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[1] Or, perhaps, unreality. One could simulate an imagined world, where one could bend the rules of physics.

[2] Well, what is real, and what is not is really a question of philosophy. According to Platon, one cannot talk about things that do not exist.

1.2 Computer graphics

Computer Graphics (CG for short) is in itself a very diverse field. There are a number of very good textbooks on the topic [11][12] and I very much recommend reading at least one of them to get familiar with the concepts. Although I will do my best to make this paper easy to understand for everyone, I will still assume some basic knowledge in the field of computer graphics.

There are some very different methods for photorealistic versus non-photorealistic (like an illustration), and real-time versus off-line rendering. The main goal is of course to display some kind of image on the screen. Even this simple task of displaying an already calculated image has its problems. Today's computer displays have severe limitations, most importantly that they lack the dynamic range of the human eye. We could (and should) use higher internal precision for our calculations (this is called HDR (High Dynamic Range) rendering) to achieve more realistic reflections and other effects (like the specular bloom), but we still should not forget that ultimately it will be displayed on a device with reduced dynamic range. That is a limitation we have to live with[1]. There are some image processing methods, like adaptive contrast enhancement, that tries to bring detail into the compressed dynamic range to make the image more enjoyable, but it is really just cheating the eye by distorting the source range. This technique is mainly used as a post processing operation on commercials or movies. It is too expensive for real-time visualization, however.

There are many ways to display a scene in computer graphics. What is common is that for each pixel on the screen, we have to determine a color value that represents the incoming light from that direction. The difference is how the light contributions are calculated for each pixel. Global illumination methods, like radiosity and raytracing are physically most accurate, but they are very expensive in terms of required calculations. Since we are aiming at real-time visualization, they are not appropriate for our purposes. Incremental image synthesis on the other hand uses a local illumination model, meaning that each object is displayed as a set of primitives (points, lines or triangles) and each primitive is shaded independently of other parts of the scene. Thus it is possible to build special, heavily pipelined hardware accelerators capable to process geometry and fragments (pixel data) at an incredible speed, but this comes at a price. Shadows, and

[1] Some military flight simulators utilize special display devices that are capable of displaying very bright spots (simulating mainly ground lights), but they are expensive and still limited to points.

inter-object reflections that are handled elegantly by the global lighting solutions, have to be added using various tricks and hacks. Although these tricks are not always perfectly accurate, they do not have to be. In our case it is enough to give the user an illusion of reality. Also, some techniques from raytracing and radiosity can be used directly in the local lighting solution. Eventually it turns out that near raytraced quality images can be rendered in real-time using cheap, consumer level hardware accelelrators.

In the rest of this document we will be concerned solely with using hardware accelerated rendering techniques for real-time visualization of large-scale detailed terrains.

2 Modelling the terrain

2.1 Geometrical description of the surface

Before we could delve into the details of how a terrain is actually rendered on the screen, we have to look at how terrain data is given. From a geometric point of view, a terrain can be described by a generic three dimensional surface. We could define such a surface explicitly with a bivariate vector function $p: R^2 \to R^3$ like $p(i,j) = [x(i,j), y(i,j), z(i,j)]$ where the two parameters (i and j) drive each component of the p vector. Usually these functions are not defined analytically, but rather their domain and range are quantized at discrete intervals, and the functions are given numerically as one big multi-dimensional array. This means that we will have a set of points instead of a truly continuous surface. In order to preserve the surface's C^0 continuity in R, we need to utilize interpolation methods. One of the simplest form of interpolation is the linear one, that is patching the hole between three neighboring points with a triangle. This will fit very nicely for hardware assisted rendering. Also, one triangle could be subdivided into many more smaller triangles, enabling effective simulation of nonlinear interpolation by displacing them.

Note that I have defined the function's domain as being two dimensional. This enables us to interpret the data as points defined over an imaginary grid characterized by the formal parameters i and j. This is important, because the grid gives us connectivity information[1]. This information is required to correctly interpolate between the discrete points.

It would be perfectly valid to include additional input variables, such as time, to the function, to achieve an animated surface. Naturally, these extra variables could be interpolated just like the others.

[1] There are more complex surfaces like TINs (Triangulated Irregular Networks), that cannot be given by such a function. This is because such a network requires special connectivity information.

2.2 Using heightmaps and displacement maps

Despite the fact that the function described in the previous section gives us the most flexibility when defining a surface, in most cases though, terrain is not given as such a generic surface, but as simple elevation data, called a heightmap. This could be described with a simpler $p: R^2 \to R^3$ function, like $p(x,z) = [x, y(x,z), z]$. It is easy to see that this is a special case of the original function. This formula is much more constrained than the previous one, since overhanging surfaces (like the one shown in Figure 2-1) cannot be modelled with it. Still this format is preferred over the generic one, because it is much more efficient in terms of memory usage, since all we need to store is a simple scalar for each point (the other two components are implicitly given by the function definition). Since on most systems usually data throughput is the bottleneck, this is a major win. Generalizing this idea means that we could use a simple vector function that describes the base form of the surface, and then use another compact scalar function that changes the base surface. A very nice example for adding more detail to a surface in such a way is called displacement mapping. Displacement mapping is a technique that displaces each point on the surface in the direction of the normal vector (n) by an amount given by a bivariate scalar function $d: R^2 \to R$. So the final, displaced position is $r(i,j) = p(i,j) + n(i,j)d(i,j)$. Note that the heightmap is really a displacement map defined over a plane. Next generation hardware accelerators will have built-in support for mesh subdivision and displacement, making this technique ideal for adding detail to a smooth surface.

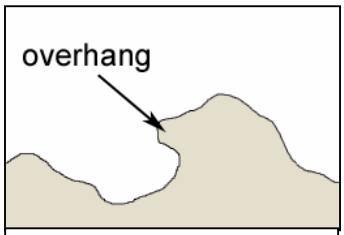


Figure 2-1 Overhangs

Obviously, if the surfaces are given numerically rather than analytically then function interpolation must be used to combine surfaces with different resolutions. Later in this paper (in Chapter 6) I will also use a special kind of surface combining technique to add more detail to a base surface.

2.3 Surface normal and tangent plane

A vector that is perpendicular to the surface at a given point is called a normal. The surface normal has lots of uses. Some of the more important ones are collision detection and response, and lighting calculations. Actually, we are not really interested

in the normal vector itself, but the tangent plane defined by it. It might help to think about the normal, as the representation of the plane. To be exact, the normal vector defines only the facing direction of the plane, not its position, but for most computations that is enough. By defining a point on the plane, we can also pin down the plane's exact location. Note that there are an infinite number of normal vector and point combinations that define the same plane. The normal could be scaled by an arbitrary positive[1] scalar, and any other point on the plane is a good candidate for the plane definition. Most of our calculations require the normal to be unit length, however, making the vector unique to the plane. Such unit length vectors are said to be normalized. We can normalize any vector by dividing each of its components by the length of the vector. Having the unit normal and a point on the plane, we can calculate the distance of any point from the plane as illustrated on Figure 2-2.

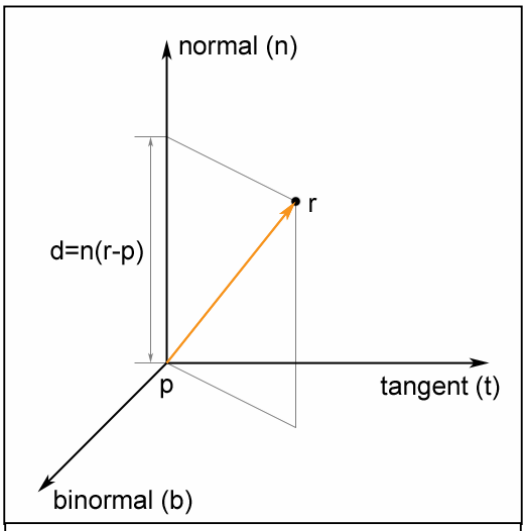


Figure 2-2 Calculating the distance between a point and a plane .

When using homogeneous coordinates, we can express a plane in a much more compact and convenient way. Instead of defining a unit normal vector and a point separately, we can describe the plane with a simple four component vector q, where the first three components represent the facing direction of the plane and the fourth component is the negated distance of the plane from the origo. Using this vector, we can calculate any point's distance from the plane by calculating the dot product between the point and the plane (see equations on the left). The distance is signed, meaning that the plane divides the space into a positive and a negative half space. Moreover, we can use the same dot product operation to calculate the sine of the angle between the plane and a unit length direction vector.

$$
\begin{aligned}
p &= \begin{bmatrix} p_x & p_y & p_z & p_w \end{bmatrix} \\
n &= \begin{bmatrix} n_x & n_y & n_z & 0 \end{bmatrix} \\
r &= \begin{bmatrix} r_x & r_y & r_z & r_w \end{bmatrix} \\
d &= n(r-p) = nr - np = qr \\
q &= \begin{bmatrix} n_x & n_y & n_z & -np \end{bmatrix}
\end{aligned}
$$

[1] Negating the vector will still define the plane with the same set of points but it will have a different facing direction.

Now, that we know how to use the tangent plane, let us see, how to find it for a given point on a surface. For each point on the parametric surface, there is exactly one tangent plane, that can be defined by the contact point and the normal vector of the surface at that point. Using the function from the previous section, the normal vector is defined as follows[1]:

$$n = \frac{\partial p}{\partial i} \times \frac{\partial p}{\partial j}$$

The partial derivatives of the surface lay on the tangent plane, and the cross product is perpendicular to both tangent vectors. Thus the resulting vector is also perpendicular to the tangent plane. Even if the surface is not given analytically, we can still compute an approximation using finite differencing. Note that this formula does not usually result in a unit length normal vector, so we must take care of normalizing it, if necessary. Even if we can skip normalizing, calculating the direction of the normal vector on-the-fly for every point is still a costly operation. So it is recommended to calculate and store them beforehand, if possible. Also, when the surface is given analitically then the normal vectors can also be derived analitically, which might be cheap enough to be evaluated runtime.

[1] Note that the definition is the same for both left and right handed coordinate systems. The results will be different, because the cross product operator is defined differently in the two coordinate systems.

3 Displaying the geometry

3.1 Overview

Assuming we know everything about the surface geometry, displaying it seems like an easy task.. Note that we are not interested in the material properties of the terrain, nor in the characteristics of the environment (like lightsources) for the moment. These topics will be discussed later (in Chapter 7). Right now we are only concerned with pure geometry. Now, all we have to do is walk the surface grid, and build a triangle mesh by connecting neighbouring vertices. Unfortunately this method is not usable in real-time visualizaton. Suppose we have to display a terrain that has an area of a million hectares (100Km * 100Km) at 10cm resolution. In this case we would have to display a triangle mesh consisting of no less than a thousand milliard (10^{12}) vertices. Since for each vertex we need at least a couple of bytes for height information (and in the generic case for two more coordinates), we would have to deal with terrabytes of data. Even if we had the memory and the bandwidth necessary to access all these data, we would still not be able to process this much information in real time.

For interactive display, we need to render an image at minimum 15 fps (frames per second). For the illusion of continuous animation at least 24 fps is required[1], but 60-80 fps is much more plausible to the human brain. Today's state of the art workstations are capable of processing about a 100 million vertices per second. This means that if we are to achieve an enjoyable framerate, we have to live with 4 million vertices per frame. Note that these are theoretical peak rates. In practice this means a lot less, about 200 thousand triangles per frame. Of course these are just raw numbers, real performance depends on the complexity of the vertex and fragment programs used, the number of state changes required (which causes expensive pipeline stalling), the number of pixels rendered (depth complexity), and so on...

[1] Movie films are played back at 24fps, but sometimes it's rather unconvincing (e.g. when the camera is turning around in a small room, the motion feels jerky).

3.2 Introducing Level of Detail

As we can see, the brute force method proposed in the previous section is not going to suffice. We have to find a way to display that huge dataset by accessing and using a limited number of vertices. This inevitably means that we have to drop detail. Of course it is up to the application to decide how much detail should be dropped, and where. The ultimate goal is to drop as much unnecessary detail as possible while still preserving a good level of perceived image quality. In general, these kinds of algorithms are collectively called LOD (Level of Detail) algorithms.

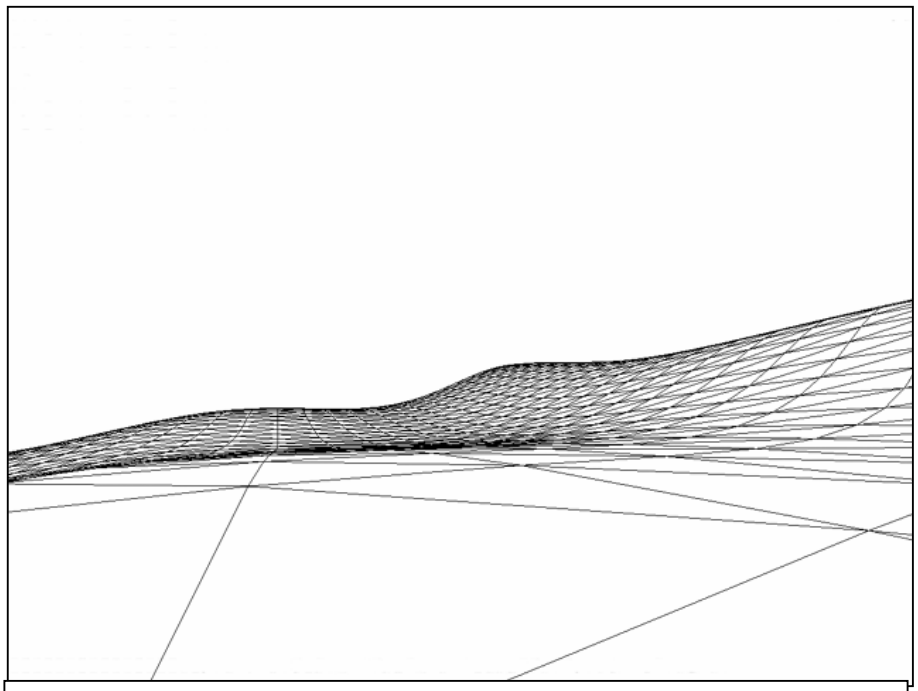


Figure 3-1 A wireframe rendering of a terrain without LOD

Looking at Figure 3-1 immediately demonstrates the problems caused by the lack of LOD. Every triangle on the screen have approximately the same size in world space. The nearby regions (which make up the majority of the pixels on the screen) are made up of only a couple of triangles, clearly missing every kind of detail. A little farther away, there is a sudden density change (thick black), where the terrain surface is almost parallel to the viewing plane (i.e. the surface normal is perpendicular to the viewing vector, as is the case with silhouette edges), thus triangles there will be very small when projected to screen space and so have a minimal contribution to the final

image. Still a bit farther, projected triangles will be also very small, as a result of perspective.

By using an error metric, we can measure how good the approximation is for some part of the scene. Based on this error we can decide if we need to drop or add some more detail. There are a lot of ways to measure error, and which one is most appropriate usually depends on the application. One simple to calculate example is a vertex's object space relative error, that is, the difference vector between two consecutive LODs in object space. Object space errors do not take perspective into account. To do this, the object space error have to be projected to screen space. The resulting screen space error effectively tells us how different the final image would be, if we would have included that vertex, or not. Projections fall into two main types: isotropic projection does not depend on viewing direction, while anisotropic does. Obviously, anisotropic projection yields more accurate results, but is usually more expensive to compute. Evaluating the error term for every vertex is not always practical. Sometimes it might be better to calculate the errors for triangles or even for whole meshes. Which one should be used really depends on the actual context. So our goal is to meet a given threshold of error, using as few triangles as possible.

There are two main kinds of LOD schemes: discrete and continuous. Discrete LODs have (as the name suggests) a fixed number of static meshes with different resolutions. During rendering, we choose an appropriate level based on some error metrics, and draw it. The main advantage is that these static meshes can be precalculated up-front, allowing for mesh optimizations. Also, they can be uploaded to the GPU's local memory for faster access. Discrete LOD is simple and fast. It works well for objects that are relatively far away from the viewer, since the distance makes level selection practically view independent. It does not, however, work well for close-up views. Such cases would require different tessellation levels at different parts of the mesh, depending on the view. Supporting view dependent meshes with discrete LOD would require storing so many different static meshes that it would make this method impractical. Since terrain rendering requires close-up views of huge datasets, discrete LODs might seem to be a bad choice. It is possible, however, to partition an object into smaller parts, with view independent LODs, and render those separately. This technique has a couple of issues though. Joining neighbouring parts seamlessly is problematic, and finding the balance between the number of levels, and mesh resolution is not easy (and

is probably very application specific). Although discrete LOD schemes are quite rigid, we will see some examples of efficient terrain rendering methods that use discrete LOD.

On the contrary, continuous LOD (also called CLOD) schemes offer a vast (practically unlimited) number of different meshes, without requiring additional storage space for each of them. These algorithms assemble the approximating mesh at runtime, giving the application much finer control over mesh approximation. This means that these methods require less triangles to achieve the same image quality. The downside is that these CLOD algorithms are usually quite complex, the cost of building and maintaining the mesh is high. Also, since the mesh is dynamic, it must reside in system memory and sent over to the GPU every frame[1]. Most terrain rendering algorithms (including the one my work is based upon) are based on CLOD schemes, because it is more flexible and scalable then discrete LOD.

3.3 View-dependent refinement

For continuous level of detail we need algorithms that construct a triangle mesh that approximates the terrain as it would be seen from a particular location. In our case this means that only vertices that are visible and play a significant role in forming the shape of the terrain should be selected into the mesh. Finer tesselation occurs in nearby terrain and at terrain features. These kind of algorithms use a so called view-dependent refinement method. The result is a mesh that is more detailed in the areas of interest, and less detailed everywhere else. Refinement methods can be grouped into two main categories. The first one is bottom-up refinement (also called decimation), which starts from the highest resolution mesh, and reduces its complexity, until an error metric is met. The other one is called top-down refinement, which starts from a very low resolution base mesh, and adds detail only where necessary. The bottom-up method gives more optimal triangulations (that is, a better approximation, given the same triangle budget), but the calculations required are proportional to the size of the input data. The top-down method, on the other hand, while results in a slightly less optimal triangulation, is insensitive to the size of the input data. Its calculation requirements depend only on the size of the output mesh, which in our case is much lower than the input. Legacy algorithms, like [3], were based on the bottom up method, because input data was small, and rendering was expensive. Today almost every algorithm is based on

[1] With fast AGP (Accelerated Graphics Port) bus, this is usually not a bottleneck.

the top-down scheme, since the size of input datasets have increased by some orders of magnitude, while rendering performance is much higher (so rendering a couple of more triangles than necessary will not hurt overall performance).

This is a perfect example of the precious balancing required when engineering performance critical applications. One has to balance carefully, and make important tradeoffs. With today's hardware, it is cheaper to send a little more triangles than spending long CPU cycles just to decide that a few of those triangles were unnecessary. It is always very important to identify the bottleneck in the processing pipeline. It is safe to say, that today's GPUs (Graphic Processing Unit) can process as many vertices as it is possible to send down the bus[1]. With time, bottlenecks move from one part of the processing pipeline to another. Thus every so often these methods must be revisited and evaluated.

It is also very important, that the resulting mesh is continuous, so it must not have T-junctions (also called T-vertices), where cracks might appear. There are a number of ways to avoid such cracks, but these depend on the exact algorithm used.

3.4 Data management

Of course with huge terrains there is still the problem of accessing the data. If the surface data has to be paged in from an external storage device, it is called out-of-core refinement. Mass storage devices usually have very poor random access characteristics, but have an acceptable performance for linear data access. By reordering the dataset in a way, that a more linear access pattern is used, we can achieve much better performance. Also, spatial locality means better cache usage, and thus improves overall performance. There are many ways to deal with this problem. In this paper I will only briefly introduce the method used by the SOAR algorithm.

[1] Assuming a standard transform stage setup.

4 A survey of algorithms

4.1 Overview

In the last decade there have been some very intense work in the field of terrain rendering. Today, there exist a lot of different algorithms, each having its own strengths and drawbacks. In this survey I am going to briefly describe some of the more successful ideas. They will also serve as a reference, so my work can be compared against previous results.

Most algorithms described here render terrains described by heightfields. These heightfields are usually defined over a square grid (if it is not square, then a tight bounding square could be used instead). One of the most straightforward method for partitioning such a grid into smaller parts is by means of a quadtree. A quadtree is a datastructure, where each node has four children. When used in terrain rendering, the root node represents the whole surface, and the child nodes subdivide the parent into four smaller partitions, and so on. Figure 4-1 shows quadtree partitioning. Some early terrain rendering techniques use this spatial partitioning only to perform fast gross culling against the viewing frustum. In this case the algorithm always have to subdivide to the lowest level for rendering, but large blocks can be culled away easily if outside the frustum. It is very easy to add some LOD to this method by subdividing deeper in branches with a higher error. Of course this kind of subdivision does not guarantee that the resulting mesh will be free of T-junctions. The mesh will likely to have cracks where different level of detail parts connect. The restricted quadtree triangulation (RQT) can solve this problem. Such a restricted triangulation can be ensured by walking in a dependency graph defined over a grid (see [6] for example), and adding the necessary extra vertices. Figure 4-2 illustrates this method:

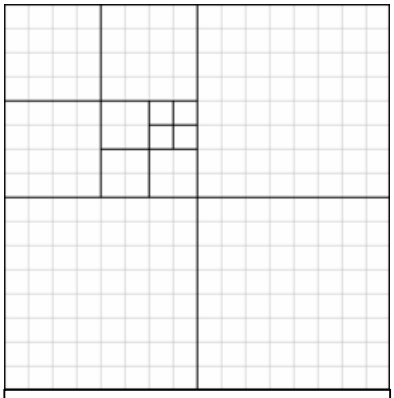


Figure 4-1 Quadtree hierarchy

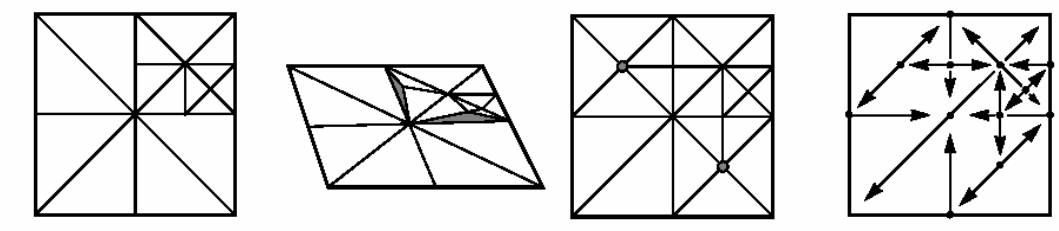


Figure 4-2 Walking the dependency graph, and adding extra vertices where necessary results in a restricted quadtree triangulation (Illustration by Renato Pajarola).

There are a couple of issues with this technique, though. This explicit dependency walk is quite expensive, especially when dealing with lots of vertices. Also, it only adds vertices, not triangles, and it is not trivial how to build a new triangulation for the resulting set of vertices. Now that we have seen a basic approach and its problems, let us investigate some more sophisticated techniques.

4.2 Chunked LOD

Thatcher Ulrich's work [7] is a relatively simple, yet very effective terrain rendering technique based on discrete level of detail. Contrary to other, more complicated algorithms, its aim is not to achieve an optimal triangulation, but to maximize triangle throughput, while minimizing CPU usage. As it has been discussed in the previous chapter, it builds on the fact, that today's graphics subsystems are so fast, that it is usually cheaper to render a bit more triangles than to spend a lot of CPU cycles to drop some of the unnecessary ones. Of course, level of detail management is still required, but at a much coarser level. So the idea is to apply view dependent LOD management not to single vertices, but to bigger chunks of geometry.

As a preprocessing step, a quadtree of terrain chunks is built (see Figure 4-3). Every node is assigned a chunk, not just the leaves. Each chunk can contain an arbitrary mesh, enabling very effective mesh optimization in the preprocessing step. The meshes on different levels in the tree have different size in world space. The tree does not have to be full, nor balanced, making adaptive detail possible. Each chunk is self contained (the mesh and the texture maps are all packed together), making out-of-core data management and rendering easy and efficient. During rendering the quadtree nodes are culled against the viewing frustum as usual. The visible nodes are then split recursively, until the chunk's projected error falls below a threshold.

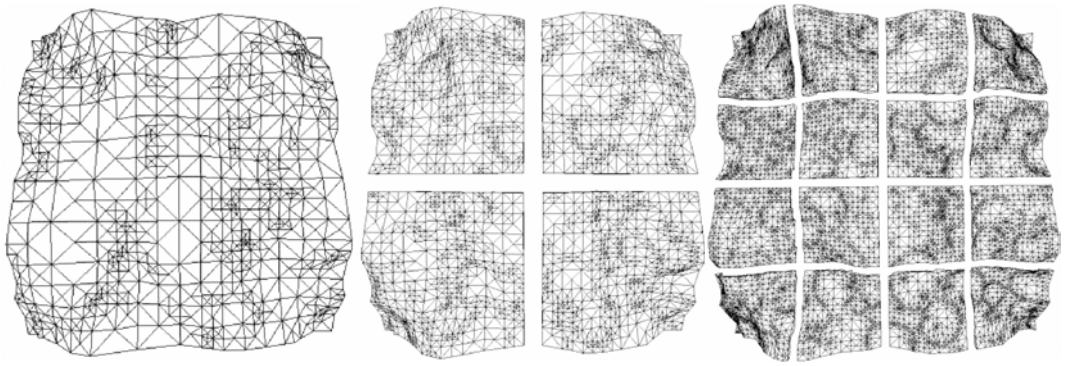


Figure 4-3 The first three levels of the quadtree (Illustration by Thatcher Ulrich).

Since the terrain is assembled from separate chunks, there will be cracks in the geometry between different LODs in the hierarchy. In ordert to minimize these artifacts, Ulrich uses a technique called skirting. Skirting basically means, that on the edges of the mesh, there are extra triangles extending downwards, effectively hiding the gaps. One must be careful when selecting skirt height, though, because long skirts will burn fillrate.

Popping is very noticeable with discrete LOD methods, because a lot of the vertices change abruptly when switching to a different level of detail mesh. This disturbing effect can be eliminated by smooth distance based vertex morphing. To do this, Ulrich assigns a delta value to each vertex that tells its distance from the surface of the parent mesh at that point. Using this delta value it is possible to smoothly interpolate from one mesh to the other. Obviously, runtime morphing of the geometry by the CPU prohibits uploading of the static geometry to video memory. By using vertex programs, however, we can perform interpolating on the GPU, reducing CPU load and enabling uploading static geometry.

Even if the rendering algorithm itself is simple, efficient preprocessing of the mesh is not that easy. The very high triangle count makes multi pass shading computations more expensive. But deferred shading is still possible, given a capable hardware. For games, this method makes it possible to build a huge world using tileable chunks of geometry. Also, this terrain rendering method only supports totally static terrain.

4.3 Progressive meshes

Hugues Hoppe of Microsoft Research has extended his original work on progressive meshes (PM) to be better suited for large scale terrain rendering [5]. The

idea of progressive meshes is to build a special datastructure that allows rapid extraction of different level of detail meshes that represent a good approximation of an arbitratry triangle mesh. Also, this datastructure can handle not only geometry, but possibly other attributes associated with each vertex or corner of the mesh (a corner is a vertex, face pair), like material properties and such.

Building a good PM representation for the mesh is crucial. The process starts with the original high resolution mesh, and then gradually reduces its complexity by collapsing selected edges to a vertex. During this mesh decimation, we save collapse information, making the process reversible. The result is a coarse base mesh, together with a list of vertex split operations. The order of edge collapsing is very important to form a good PM. There are a number of different algorithms for edge selection. For view dependent refinement, the active front of vertices is visited, and a vertex split or an edge collapse operation is performed based on the projected error. This PM representation is very efficient for streaming data. First, only the coarse mesh is loaded, and later, as we need more detail, we can load more vertex split data.

The preparation of the progressive mesh is computationally very expensive, and as such, have to be done as a preprocessing step. Since the simplification procedure should be performed bottom-up, it would prohibit processing of huge datasets that do not fit into main memory at once. Hoppe introduces an alternative block based recursive simplification process that permits simplificaton of large meshes. Hoppe also introduced a couple of other enhancements over the original algorithm. He introduced smooth level of detail control via geomorphing, and also redesigned the runtime datastructures to have output sensitive memory requirements. Of course, these changes can be generalized and used for arbitrary meshes also, not just for terrains.

The main advantage of using a progressive mesh is that it supports arbitrary meshes. This means that PM geometry is not tied to a regular grid, and as a result, usually a fraction of triangles (50-75%) are enough to approximate the original mesh, compared to the other methods.

The downside of this method is that the runtime view dependent refinement procedure is quite expensive. However, there is another method, called VIPM (View Independent Progressive Meshes), that has the benefits of a good progressive mesh representation, without the complicated computations required by the view dependent refinement. For relatively small scale objects, VIPM is definitely a win, but for large terrains it is hard to make it useful.

4.4 The ROAM algorithm

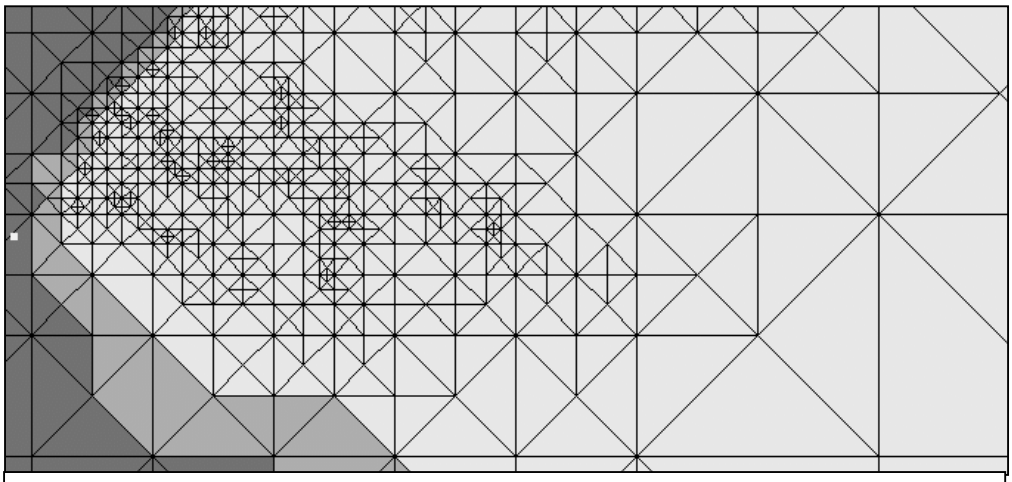


Figure 4-4 ROAM triangulation for an overhead view of the terrain (Illustration by Mark Duchaineau).

Mark Duchaineau et al. developed this remarkable algorithm mainly for simulating low altitude flights. ROAM stands for Real-time Optimally Adapting Meshes. Adapting meshes is a key concept in this algorithm. Since this algorithm has been designed mainly for flight simulation purposes, it was a reasonable assumption to make, that camera movement is continuous. Since there is no sudden change in the viewpoint, it seems to be safe to exploit frame to frame coherence, and assume that the mesh in the next frame will only differ in a few triangles. This means that there is no need to regenerate the whole mesh from scratch every frame. It effectively allows the algorithm to maintain a high resolution mesh (referred to as the active cut), and only change it little by little every frame.

ROAM operates on a triangle bintree (a triangulation can be seen on Figure 4-4). This structure allows for incremental refinement and decimation. To do this on-the-fly mesh refinement, ROAM maintains two priority queues that drive the split and merge operations. The queues are filled with triangles, sorted by their projected screen space error. In every frame some triangles are split, bringing in more detail, and others are merged into coarser triangles. Since the bintree is progressively refined, it is possible to end the refinement at any time, enabling the application to maintain a stable framerate. In order to avoid cracks (T-junctions) in the mesh, one has to recursively visit the neighbours of the triangle and subdivide them if necessary (this is called a forced split, see Figure 4-5). This is a quite expensive operation. Of course the fact that only a few

triangles need updating would still justify this extra overhead, but ROAMs biggest flaw turned out to be in this initial assumption.

For low resolution terrain the chain of dependecy to follow when fixing cracks is not too deep. For higher resolution meshes this operation gets more expensive. Also, the number of triangles that need updating (splitting or merging) depends on the relative speed of the camera. It is important to note the term relative. Camera speed should be measured relative to terrain detail. Given the same camera movement, the number of triangles flown over (and thus, the number of triangles need to be updated) depends on terrain resolution. If the relative speed is high (and it will be, for high resolution terrain, no matter, how slow the camera is moving), the number of triangles that pass by the camera will be high too. Also, since most triangles in the approximating mesh consist of the nearby ones, it means that most of the mesh will need updating.

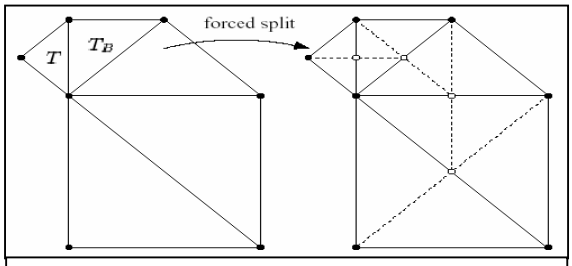


Figure 4-5 Forced split to avoid T-junctions (illustration by M. Duchaineou)

So the bottom line is, that for highly detailed terrain, the approximating triangle mesh will be so different every frame, that there is no point in updating the mesh from last frame. It would mean dropping and then rebuilding most of the mesh every frame, only to save the remaining couple of triangles. Considering how expensive these merge and split operations are, it is clearly a bad idea to do incremental refinement. This is worsened by the feedback loop effect. As one frame takes more time to render, during that time the camera moves farther, requiring the next frame to change even more of the mesh, that takes even more time to render, and so on.

This algorithm is a fine example for demonstrating how the bottleneck moves in the processing pipeline, and how it affects performance. A couple of years ago this algorithms seemed to be unbeatable (well, it is still very good for relatively low detail terrains), but on today's hardware it is very difficult to make it efficient. Lately there has been some work to overcome this fundamental flaw in the algorithm, mainly by working on chunks of triangles instead of individual triangles, but it is still not the right solution.

4.5 The SOAR algorithm

The SOAR (Stateless One-pass Adaptive Refinement) algorithm has been developed by Peter Lindstrom and Valerio Pascucci at the Lawrence Livermore National Laboratory. It combines the best methods published to date, and extends them with some very good ideas. The result is a relatively simple, yet very powerful terrain rendering framework. It has many independent components: an adaptive refinement algorithm with optional frustum culling and on-the-fly triangle stripping, together with smooth geomorphing based on projected error, and a specialized indexing scheme for efficient paging of data required for out-of-core rendering. The heart of the method (as its name, SOAR suggests) is the refinement procedure. Although the original paper recommends some techniques for each component, all the other components can be replaced or even left out alltogether. This makes it easy to compare various techniques in the same framework. This also enables us to focus on one component of the framework at a time. Since this algorithm serves as the basis to my work, I am going to give a more in-depth description.

The refinement algorithm generates a new mesh from scratch every frame, thus avoiding ROAMs biggest problem. The downside is that SOAR can not be interrupted in the middle of the refinement. Once we started a new mesh, it is necessary to finish it in order to get a continuous surface. In reality this is not a serious limitation, because it is possible to adjust the error threshold between frames, so if one frame took too long to build, the implementation could adaptively change refinement parameters.

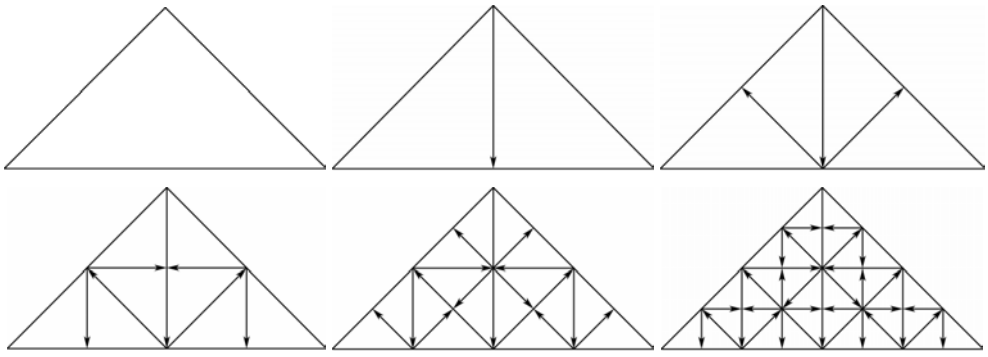


Figure 4-6 Longest edge bisection

SOAR refinement is based on the longest edge bisection of isosceles right triangles (see Figure 4-6). It subdivides each tirangle by its hypotenuse, creating two smaller triangles. This subdivision scheme is quite popular amongst terrain renderers,

because it has two nice properties. First and most important is that it can be refined locally, meaning that a small part of the mesh can be subdivided more than the other parts, without breaking mesh continuity (of course, we have to follow some simple constraints to ensure continuity, see later). This is essential for every CLOD algorithm. Secondly, the new vertices introduced by each subdivision lay on a rectilinear grid, making it easy to map a surface onto it.

The vertices are naturally categorized into levels, by the depth of the recursion. The algorithm starts with the root vertex at level zero. Every vertex has four children and two parents (vertices on the edge of the mesh have two children and one parent only, and obviously, the root vertex has no parents at all). This hierarchy of vertices could be represented as a DAG (Directed Acyclic Graph).

In practice, we almost always want to map our surface onto a square, not a triangle. It is straightforward to build such a square by joining two triangles by their hypotenouse, making a diamond, or joining four triangles by their right apex (illustrated in Figure 4-7). We choose the latter one, for reasons discussed later. Now, the resulting square base mesh can be recursively subdivided to any depth by the longest edge bisection. Note that this kind of mesh has a somewhat constrained resolution. The vertices introduced by this subdivision will always lay on a regular $n \times n$ grid, where $n = 2^k + 1$. The number of levels in such a grid is $l = 2k$ (so the number of levels is always even). This might seem to be a serious limitation, but any surface could be partitioned into such squares, and each partition could be rendered separately. Of course one would have to take special care when joining such meshes to avoid cracks between them.

It is also very important to note that this regular grid does not constrain the layout of the output mesh. It only gives us a way to walk a hierarchy of vertices and defines connectivity between them. So the input data for the refinement is not constrained to heightfields. It can handle general 3D surfaces with overhangs as long as the points of the surface can be indexed with two parameters (as it has been described in Chapter 2.1).

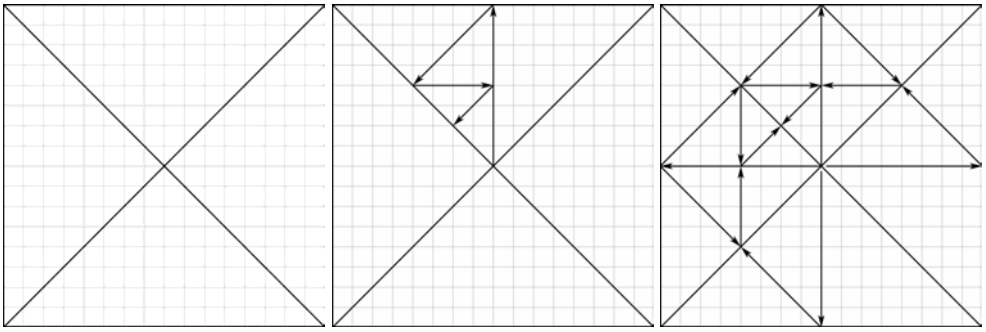


Figure 4-7 Left: Joining four triangles forms a square. Middle: Refining triangles individually results in cracks. Right: Crack prevention

Although the mesh can be refined locally, this subdivision scheme does not automatically guarantee mesh continuity. In order to avoid T-junctions, we have to follow a simple rule. Let us call the vertices that are in the resulting mesh active. For each active vertex, all of its parents (and recursively all of its ancestors) must be active too. This condition guarantees that there are no cracks in the mesh. This could be ensured easily by visiting every vertex in the mesh and activating parents recursively where necessary. As we have seen with previous algorithms, this dependency walk is a very costly operation, and as such, should be avoided, if possible.

So how can we avoid these costly operations? Well, vertices are activated (selected into the mesh) based on some kind of projected error metrics. All we have to do is ensure that these projected errors are nested, that is, a vertex's projected error must always be smaller than any of its ancestors'. This way, if a vertex is active then all of its ancestors will be active, resulting in a continuous mesh. Now, the question is, how to ensure these nesting properties? Propagating the object space error terms during preprocessing is not enough. Consider a case when a child vertex is much closer to the camera than its parent. Due to the nature of the perspective projection, the projected error could be much higher for the nearby vertex, even though its object space error is smaller. Since projection depends on the relative position of the camera, it must be recalculated for each vertex, every frame, making preprocessing impossible.

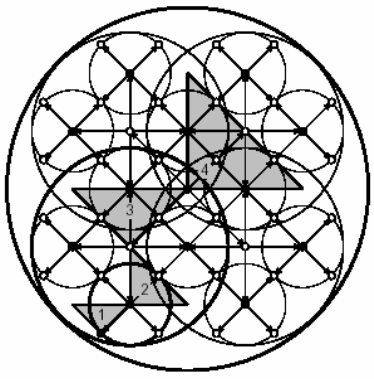


Figure 4-8 Bounding sphere hierarchy (Illustration by P. Lindstrom and V. Pascucci)

SOAR handles this problem in a very elegant and efficient way. It assigns bounding spheres to vertices (Figure 4-8). These spheres must be nested, so that a vertex's bounding sphere contains all of its descendant vertices' bounding spheres. This nested hierarchy of bounding spheres can be built as a preprocessing step. Each sphere can be described by a simple scalar value representing its radius. Now, if we project every vertex's object space error from the point on its bounding sphere's surface that is closest to the camera (Figure 4-9), then the resulting projected error will be nested, thus cracks eliminated.

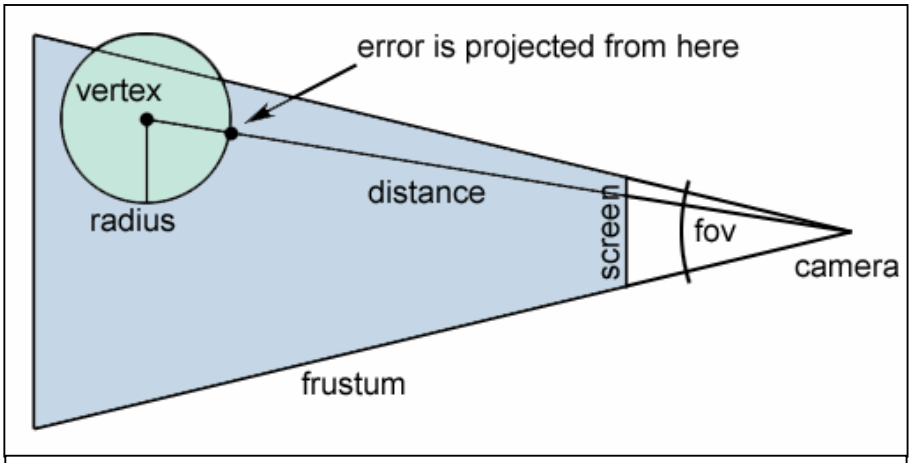


Figure 4-9 Error is projected from the nearest point on the bounding sphere.

Of course this means that the projected error might be much higher than it really is. This way more vertices will be selected into the mesh, than would be necessary for a given error threshold. Considering that most of the extra vertices would be required for crack prevention anyway, the added cost is not significant.

The nested sphere hierarchy also enables very efficient culling to the viewing frustum. If a sphere is totally outside the frustum, then its vertex is culled, with all of its descendants. This way big chunks of unseen geometry can be culled away early in the processing pipeline. Note that this does not break the mesh continuity, since if a vertex's parent is culled then the vertex itself will also be culled. Also, if a sphere is totally inside one plane, than all of its descendants will be inside, thus further checking against that plane is unnecessary. By keeping a flag for the active planes, we can make sure that only spheres intersecting at least one plane will be checked.

Now that we know how it is possible to decide if a given vertex is active, we can continue our discussion about the refinement procedure. The main idea is pretty simple. It recursively subdivides the four base triangles one by one, until the error threshold is

met. The tricky part is building a continuous generalized triangle strip during refinement (see Figure 4-10), that can then be passed to the hardware for rendering. Each triangle is processed left to right. This means that first we subdivide along its left child then subdivide along the right child. In order to make the strip continuous, we have to swap triangle sides each level. So that the meaning of "left" and "right" alternates between consecutive levels of refinement. Since this swapping also affects triangle winding, sometimes degenerate triangles have to be inserted into the strip. Otherwise a lot of the triangles would turn up in the mesh backfacing[1]. The refinement procedure keeps track of swapping by using a parity flag. The new vertex's parity flag is then compared against the last vertex's parity in the strip and a degenerate triangle is inserted if they are equal. For a more detailed explanation refer to the original papers [1][2], or read Chapter 5.1 where a more efficient refinement is discussed.

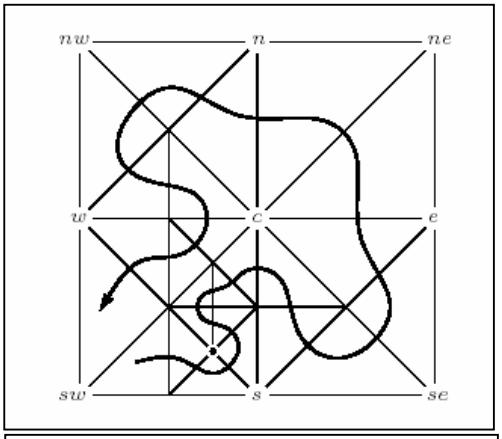


Figure 4-10 Single generalized triangle strip for the whole mesh (Illustration by P. Lindstrom and V. Pascucci).

The framework also supports a nice method for smooth geomorphing of terrain vertices, where the morphing starts from the interpolated vertex position and ends at the real vertex position, and is driven by the vertex's projected error. This is better than time based geomorphing, since its stateless (no need to remember morphing vertices), and vertices only morph when the camera is moving, making it practically undetectable.

Another very important component of the framework is the indexing scheme. When dealing with huge datasets, the bottleneck will almost always be at the I/O device. In these cases cache coherent data access can result in a drastical speedup. All we have to do is store the surface vertices in an order that is close to the refinement order. One such indexing scheme presented by the original paper is hierarchical quadtree indexing. Although it is a little sparse (meaning that it requires more storage space than traditional linear indexing), it does a great job when dealing with huge

[1] Such triangles will be culled away by the graphics subsystem leaving a hole in the mesh. The graphics subsystem could be configured not to clull backfacing triangles, but it is not a good idea to do so, since it saves a lot of fillrate, and also makes z-fighting less likely to happen.

external datasets[1]. The exact details of how to implement this indexing scheme (together with some other alternatives) can be found in the original paper [2].

4.6 Miscellaneous issues

4.6.1 Geomorphing

Every time a new vertex is added to or removed from the mesh, the triangles sharing that vertex will suddenly change (causing the infamous popping effect). Since the human brain is very sensitive to changes, even a small number of popping can be very disturbing. So it is important to totally eliminate these abrupt changes in vertex positions. Although we can tell if a vertex suddenly jumps, we can not tell if a vertex is at the correct position or not. Geomorphing techniques are based on this fact, tricking our brains by slowly moving the new vertex to its real position. There are two main kinds of geomorphing methods: time and error driven. As we have already seen when describing the terrain rendering techniques, error based morphing is preferred, because it morphs only during camera movement and does not need to remember the state (e.g. time) for morphing vertices. Note that for per vertex lighting, not just the position, but the normal vector also requires smooth morphing. The interpolation of the normal vector results in the shifting of the triangle's color, which might be noticeable. When lighting is independent of the actual surface, then vertex morphing works without problems.

Obviously, geomorphing only makes sense when dealing with big error thresholds. If we render a mesh with projected errors below one pixel, than it is unnecessary. Before implementing geomorphing, consider its computing overhead. Sometimes it might be better to skip morphing, and just build a more accurate mesh instead.

4.6.2 Occlusion culling

Another well known acceleration technique is occlusion culling. These algorithms search for occluders in the scene (e.g. a nearby hill) and then cull every detail occluded by it. These methods perform well with scenes having a considerable

[1] Today's CPUs are so much faster than memory modules that quadtree indexing results in a considerable speedup even when the whole dataset fits in the computer's main memory.

depth complexity. Problem is that every chain is as strong as its weakest link. In the worst case we will look at the terrain from birds view, and there will be minimal occlusion (haveing depth complexity of one). Since we require our rendering algorithm to be fast enough in the worst case, there is no win in optimizing the best case. In this case the oclusion culling algorithm will only give unnecessary overhead.

4.6.3 Z fighting

The ultimate goal of terrain rendering is to show the little features on the ground in front of our feet and to show the distant mountains on the horizon. This means that the 24bit Z-buffer found on most of today's graphics cards is not going to suffice. Because the insufficient precision, when rastering triangles in the distance, some pixels will get the same depth value, disabling depth sorting. This phenomenon is known as Z-fighting. Z-fighting can be reduced considerably by enabling backface culling. Backface culling is a very cheap operation and it also reduces fillrate requirements, so it is worth using. Unfortunatelly using this technique still cannot eliminate Z-fighting completely. Also, there is another technique that might be useful, called depth clamping. When depth clamping is enabled, the hardware does not perform clipping to the near and far planes, instead it clamps the fragment's depth value to the depth range. This means that nearby objects will not be clipped, but they will get the same Z value, thus it might result in some rendering artifacts (it is like rendering without a depth-buffer). It is still better than clipping the triangle and usually enables us to push the near plane a little farther without noticeable artifacts.

There are also other, more complicated methods, that increase depth precision, like cutting up the viewing frustum to two or more parts, then rendering the terrain one part a time, clearing the z-buffer between the parts. This method is not really convenient, because it requires some difficult triangle surgery where the frustums connect, to avoid cracks in the mesh.

As we can see, the best solution would be to use a 32bit z-buffer. Combined with depth clamping, it would give all the precision a terrain renderer would probably ever need. There are already some graphics cards supporting 32bit depth, and it is safe to say that it will be a common feature in the near future.

4.6.4 Multi-frame amortized mesh building

When the mesh refinement operation is very expensive compared to the rendering of the mesh (e.g. out-of-core rendering), it is common, to do these tasks in separate threads. So, even if the refinement is only capable of building 10 meshes a second, we could still display it at 60+ FPS, allowing for smooth camera movement. Of course, refinement should work on another mesh. So this doubles the memory requirements. This method assumes that camera movement is slow relative to terrain detail. Otherways, swapping of the meshes will result in severe popping. Unfortunately, this asynchronous refinement makes error based geomorphing practically useless. Even though time based geomorphing might work, it would still be very difficult to make it efficient. If the camera's orientation is not restricted, then view frustum culling should be turned off, so that the camera could turn around freely. Obviously, this means, that we have to build and render a much bigger mesh, to meet the same error threshold.

5 Improving the SOAR algorithm

5.1 More efficient refinement

One of the most performance critical component of SOAR is the refinement procedure that builds a single generalized triangle strip for the whole mesh in one pass. The first paper [1] introduced a very simple, recursive algorithm for generating the mesh. Although it is very short and easy to understand, it is rather inefficient. It suffers from evaluating the same vertices (calculating its projected error, and performing view-frustum culling) multiple times. In their second SOAR paper [2] the authors addressed this issue and proposed a simple improvement over their previous algorithm, that avoids some of these unnecessary calculations, by moving up the recursion by one level. However, it turns out that there is still a lot of room for improvement. In this section I am going to describe an alternative refinement algorithm that produces a more optimal triangle strip and at the same time visits less inactive vertices.

In order to understand the main ideas behind the new mesh generation algorithm, we have to investigate the nature of triangle strips first. A triangle strip is a special format for defining adjoining triangles. Each new vertex is assumed to form a triangle with the previous two vertices. Defining the primitives in such a format is very efficient, because for n triangles, only n+2 vertices are required, compared to 3n for a list of independent triangles. Also, the two vertices borrowed from the previous triangle do not have to be transformed and lit again by the GPU[1]. Winding is automatically swapped after every vertex in order to make all triangles face the same direction. When turning around corners, triangle winding may get out of sync, flipping the faces of triangles. In order to avoid face

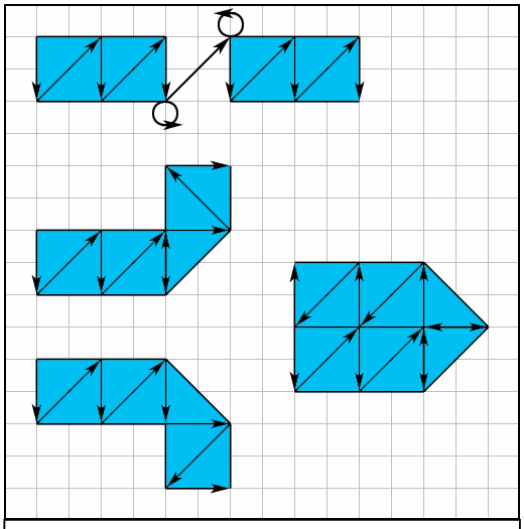


Figure 5-1 Triangle stripping

[1] Note that using indexed primitives also solves most of these problems.

flipping, sometimes a degenerate triangle (a triangle that has all three vertices on the same line) has to be inserted (see Figure 5-1 for examples on how to turn corners). To avoid sending the same vertices over the bus multiple times for a degenerate triangle, it is recommended to use indexed vertices. This way only the index has to be resent which has a negligible cost compared to resending the full vertex data. Indices also make it easy for the GPU to reuse already processed vertices from the post-T&L vertex cache.

It is possible to define a lot of different triangle strips that all result in the same mesh. Our goal is to find a method that builds a strip that requires the least vertices and the least degenerate triangles for a given mesh.

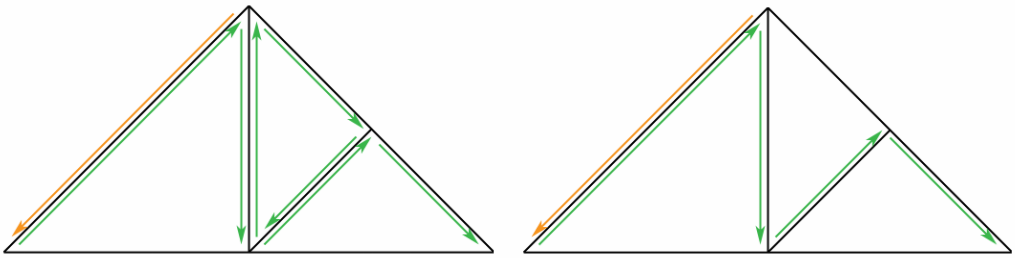


Figure 5-2 Comparing triangle stripping techniques. On the left the original algorithm generates three triangles with 6 vertices and 2 degenerates. On the right side the same setup is drawn by the new algorithm, using only 5 vertices and no degenerates.

Looking at Figure 5-2, it might not be obvious why the original algorithm (on the left) has to send six vertices when there are five vertices at all. Some lines above I have stated that indices can be used to resend vertices virtually for free. While this is true, the algorithm might not know that a vertex has been sent before, therefore it can not send its index. The reason for this lies in the refinement's recursive and stateless nature. The algorithm only has local information about a triangle. It does not know about vertices introduced in other triangles. The trivial case when indices can be sent over instead of vertices, is when turning a corner with a degenerate triangle. Other duplications could be reduced by visiting the vertices in a different order (as can be seen on the right side of Figure 5-2).

Also there is another, more serious problem with the original algorithm. It is worth following the original refinement procedure for a simple mesh on a piece of paper. Although they avoid some repetitive calculations in the new version, they still visit and examine a lot more vertices during refinement, than would be necessary. If a vertex is active, both of its two child vertices will be evaluated. This is not always necessary. We know that we want to build a continuous mesh. This places a lot of

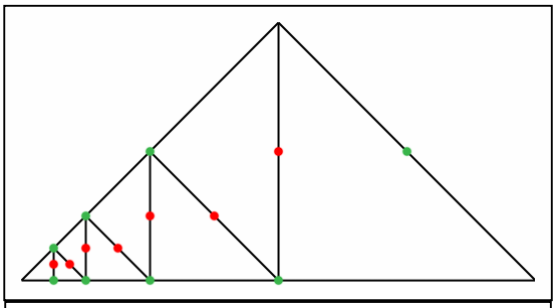


Figure 5-3 Red vertices do not have to be checked. Green vertices have to be checked

restrictions on which vertices can be active. Looking at Figure 5-3 it is clear that if a vertex has no right child node, then refinement can only proceed in a restricted direction on the left branch! Otherwise (if a red vertex is active) there would be a T-junction in the mesh, which is forbidden. By first checking both children and then choosing an appropriate sub-refinement procedure for each child, it is easy to reject a number of vertices without explicitly testing them.

By carefully examining the nature of the refinement, it is possible to develop a more sophisticated algrithm that have more knowledge about triangle connectivity, thus capable of producing a more efficient triangle strip. The basics are the same as in the original algorithm. We process each triangle left to right, swapping sides on each level. The main difference is that we also keep track of the incoming and outgoing edges (sometimes also referred to as enter/leave edges), not just the level parity. We call the hypotenuse the bottom edge and the other two the side edges. Looking at the top triangle in Figure 5-4, a strip always starts from vertex A and always ends at vertex B. The enter/leave edges tell us from what direction the triangle strip arrives at each of these vertices. Using this information we can decide the order in which the triangle vertices should be visited that results in an optimal, continuous strip across the whole mesh. At the figures below we can see how these edges change when subdividing the left or the right child:

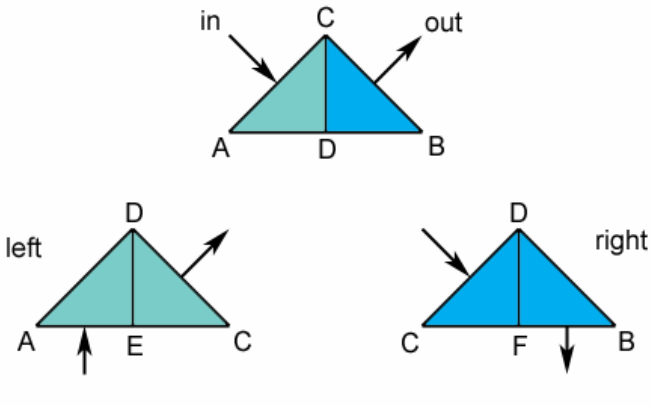


Figure 5-4 Neighborhood connectivity information

By observing this figure, it is possible to draw a simple graph representing the changes of in/out edges, depending on the branch we take on the next subdivision (Figure 5-5). It is easy to convert such a graph into a truth table (or a state machine). Looking at the graph, some simple observations can be made. When subdividing along the left branch, the child's out edge will always be on the triangle's side and the incoming edge will alternate between side and bottom. On the other side, when subdividing along the right branch, the child's in edge will allways be on the side, and this time the out edge alternates. Note that there is never a case when both the incoming and outgoing edges are on the bottom. These flags can be passed along the refinement procedure.

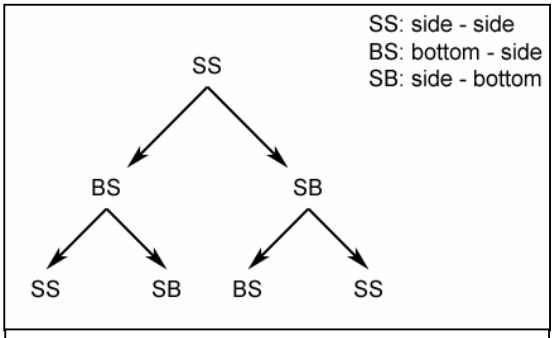


Figure 5-5 Input - output edges follow a simple rule

Knowing the in/out edges for the actual triangle is only part of the required information. We also need knowledge about which children are active. Using all these informations, we can define different procedures for handling each case:

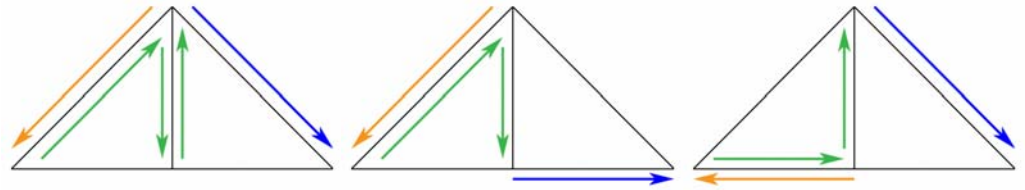


Figure 5-6 Order of vertices when none of the child vertices are active. Orange edge has been defined by the previous triangle and the blue edge will be defined by the next triangle. Only the green edges belong to the current triangle.

Figure 5-6 shows how we should build the triangle strip when there are no active children. The left figure shows the case when both the in and out edges are on the side of the triangle. On the middle figure we can see the a triangle with incoming edge at the side and the outgoing at the bottom. The right figure shows when the incoming edge is on the bottom and the outgoing edge is at the side. Remember that there is no such case when both of the in/out edges are on the bottom.

Now, let us see the triangles with left child only:

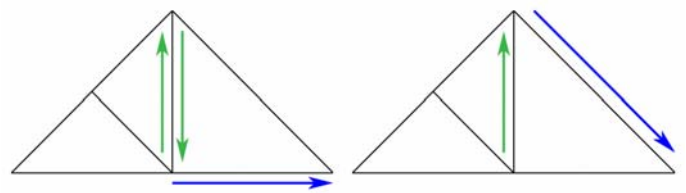


Figure 5-7 Order of visited vertices when only the left child is active.

In this case, we do not care how the left triangle is rendered. We simply recurse down the left branch, and when it returns, we continue the mesh, depending on the leaving edge. In this case, one might wonder about why is the leftmost green edge needed? As I have shown earlier, when only the left child is active, then there is no need to further check right children. So we can use a separate procedure that descends down the left branch, without ever checking the right side. In tis case the leaving edge is not handled (since it is on the right side of the first child triangle), so we have to take care of it explicitly, after the procedure returns.

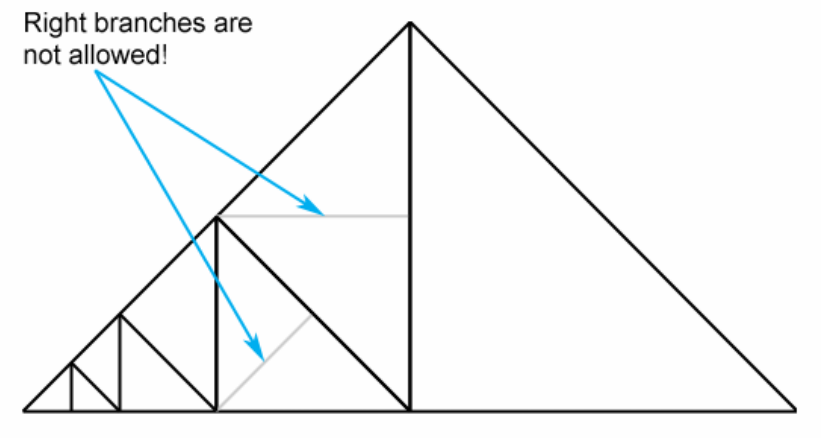


Figure 5-8 Left-only refinement

Processing triangles with right child only is quite similar:

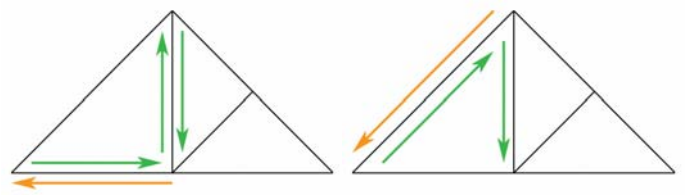


Figure 5-9 Refinement when only the right child is active

First we render the left side as shown in Figure 5-9, and then we recurse down the right branch. This recursion will also be a restricted one, going right only. However, since this is a tail recursion, it can be rewritten into a simple loop, and then inlined, totally eliminating the function call overhead (together with stack maintenance), making the implementation even more efficient.

Now, the only case left out is when both children are active:

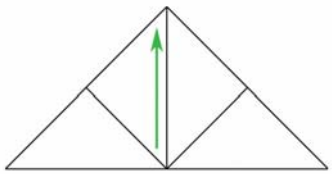


Figure 5-10 The simplest case is when both children are active.

In this case, all we have to do is recurse down the left side, insert the vertex at the apex and the continue down the right side. We do not have to care about which edges are incoming or outgoing, everything will be handled autmatically by the recursion calls.

Now that we have covered all of the possible cases, implementing the set of refine functions (a general, a left only and a right only) should not be hard. Note that in all of the cases above, we now exactly what vertices need to be checked and in what order they have to be appended to the triangle strip. So, although the code is longer, since we have prepared to deal with every possible cases, we do not have to explicitly check against degenerate vertices any more. This makes this algorithm more effective than the original.

Empirical results show that while the original algorithm generates strips that require 1.56 vertices per triangle, my enhanced method generates the same mesh with only about 1.32 vertices required per triangle. In reality the speed improvements are rarely noticeable when using indexed primitives, since these extra vertices are all

degenerates, and thus can be specified with a single index value. An index does not take up considerable space, and it also utilizes the GPU's vertex cache (i.e. no transformation is required). Even if we do not use indexed primitives, the GPU's T&L stage is rarely the bottleneck. The real strength of the algorithm lies in the fact that it checks less inactive vertices during refinement. Since in my work I require some more excessive calculations per vertex (see later in Chapter 6), it is very important that no vertices are processed unnecessarily.

5.2 Lazy view-frustum culling

The hierarchical culling of the bounding spheres against the view-frustum is a very efficient method for rejecting large chunks of vertices, early in the refinement. Spheres outside a plane are rejected, spheres inside all planes are accepted without further testing. This method works very nicely, but there are some subtle problems. First, it is possible to cull away a vertex in the lowest level, that was part of a triangle, thus rendering a coarser triangle. This results in popping (most noticeable at the near clip plane of the view-frustum). Since this popping is the result of vertex culling, using geomorphing does not help. Although this popping is usually not disturbing, there are cases when it results in a serious error (see color plates at page 66). This is not acceptable and should be eliminated. The original paper suggests inflating the bounding spheres until they enclose their parents. However, there is another problem with efficiency. While culling away thousands of vertices with one sphere is very efficient, culling small numbers (or even individual!) vertices at the lower levels is rather inefficient. I propose that at the lower levels, culling should be stopped, and all vertices accepted automatically (as if they were inside the frustum). This eliminates the popping artifacts, and also results in a relative speedup, since the GPU does a far better job of culling individual vertices than the CPU. Note that this does not affect gross culling, since the majority of vertices are culled away high up in the hierarchy. Only vertices on the lower levels and near the clipping planes are affected. This method has its own problems, however, as it does not guarantee mesh continuity outside the viewing frustum (Figure 5-11). This should not be a problem for most applications, since mesh continuity is only required when building the mesh asynchronously in a separate thread. In such cases frustum culling is likely to be skipped alltogether, allowing the camera to turn around freely and still see a detailed mesh, while the other thread is busy building the new mesh.

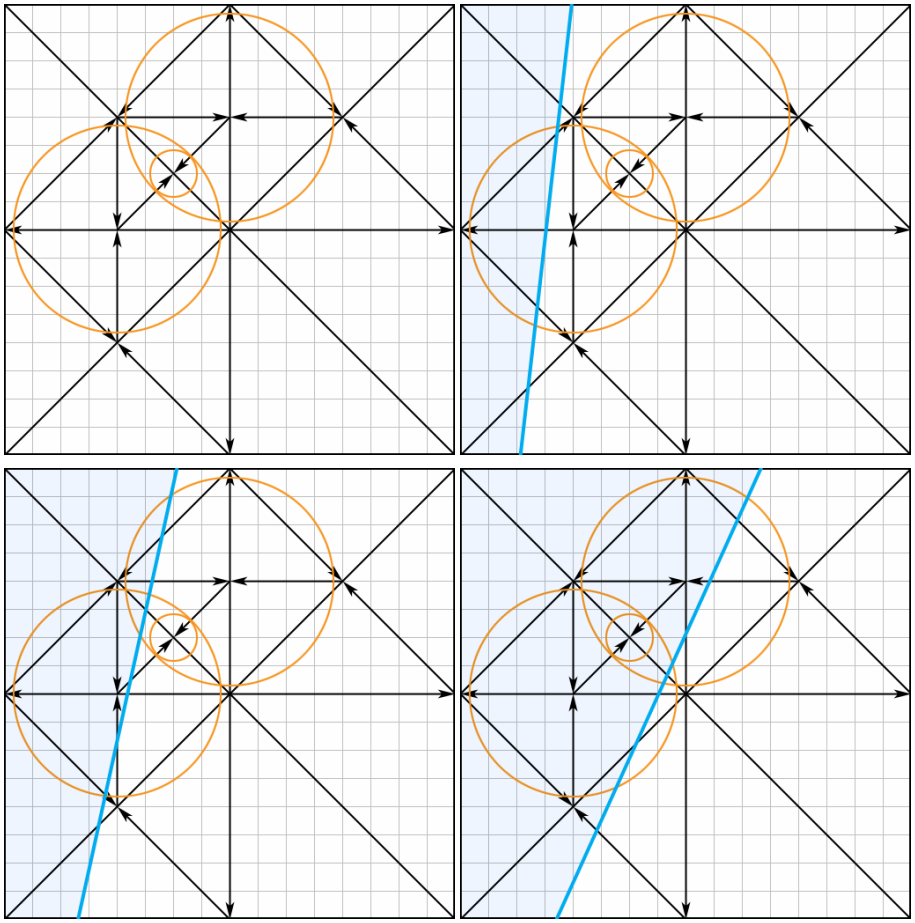


Figure 5-11 Culling the bounding spheres against the view frustum.
The shaded area indicates the inner side of the frustum.

We should investigate the figures above to have a better understanding of what happens when culling the spheres against the viewing volume, and why the new method causes cracks outside the frustum. For the sake of simplicity let us assume that the projected error is bigger than the threshold for every vertex (i.e. all vertices are active, unless culled). Using the original algorithm, only the spheres not intersecting with the viewing volume are culled. This means that the vertex with the smallest bounding sphere on the lower left figure will be culled, coarsening the triangle compared to the lower right figure. This coarsening does not happen on higher levels because the sphere hierarchy is loose enough to enclose the whole triangle. Lazy culling eliminates this popping, since the vertex will be active, even if its sphere is outside the viewing volume (because its parent intersects the volume). However, this will result in a T-vertex on the upper right figure, where the lowest level is activated, but only one of its parents are really active. In the next chapter we will see how the idea of lazy culling fits very nicely with the method for adding detail geometry.

6 Extending SOAR with detail geometry

6.1 Overview

Although SOAR is a very powerful terrain rendering framework, it has some severe limitations. It can only handle a fixed resolution, static terrain. The main reason for these limitations is that the algorithm is heavily dependent on precomputed data (the per vertex bounding sphere radius and the object space error), that can not be computed in real-time.

Fixed resolution means that the amount of detail is limited. Even though the algorithm itself could deal with huge, detailed terrains, storage and preprocessing requirements quickly grow beyond a limit that makes it impractical for most applications. Obviously, if we were about to display only geometry that is based on true measured terrain data, then there is nothing we could do. But in most cases, the extra detail's sole purpose is just adding another level to the illusion of reality. Usually, these tiny details cannot even be measured by conventional methods. So some form of parametric description would be best for such details. The parameters should describe soil properties, like roughness, and such. This would make it possible to define different details for different kinds of terrains.

Static terrain means that it is not possible to change surface geometry on-the-fly, without recalculating a lot of data. For every changed vertex, its radius and error must be recomputed and propagated upwards, through its ancestors, until the nesting requirement is met. Note that this simple propagation only works for incremental object space errors measured between consecutive levels of refinement. With other error metrics, the position change of one vertex could affect the errors of many other vertices (usually the whole terrain), making it impossible to recalculate every frame. If we stick to incremental errors, then this propagation might be acceptable for animating a couple of vertices every frame. However, animation of larger areas are not possible.

In this section I am going to introduce a simple method that enables us to add more detail to the surface and to even have dynamic detail (as it will soon turn out, the requirements for the two are quite similar).

6.2 Basic concepts

There are countless methods to generate procedural detail. Perlin noise is one of the most popular techniques, because it is easy to compute and can give continuous, non-repeating, infinite detail. However, calculating the error term and bounding spheres for such procedural detail is very hard, if at all possible. In a sense, such procedural detail can be thought of as dynamic geometry (they both lack the required information). For the sake of simplicity, I will use a precomputed tileable detail map instead, and apply that onto the base geometry. From now on, I will call the original terrain heightfield the base map and the one containing the detail the detail map.

In order to increase detail, we have to increase the virtual grid resolution of the terrain. This means that we have to add extra levels to the refinement. Figure 6-1 illustrates how this happens: blue vertices represent the base map and orange vertices represent the detail map. Next we have to find a way to embed the actual geometry into these extra levels, so that the new vertices on the grid are assigned proper position information. Besides the position, object space error and bounding sphere radius are also required. Since we are using a precomputed detail map, we have all these information at hand. This may all sound easy, but there are a cuple of caveats. Great care must be taken to insure that these properties will remain valid and nested after the extra detail is mapped onto the original map.

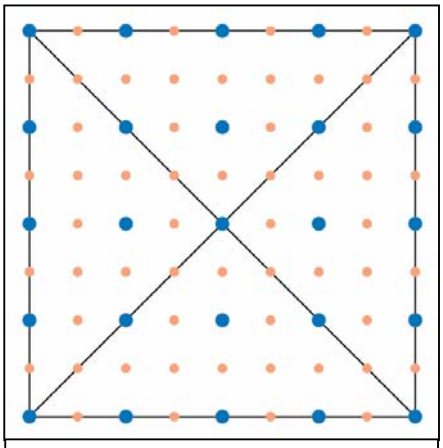


Figure 6-1 Embedding detail map

6.3 Detailed explanation

There are several different ways to combine surfaces together. We could use displacement mapping, or just simply add the two maps (their height values) together. There is a problem, though. Namely that these maps are not continuous (the points are defined at discrete intervals) and they are defined at different resoultions. So, first we would have to interpolate the lower resolution base map, then apply the detail with whaterver method we have choosen. There are many kinds of interpolation methods, each having its own strengths and drawbacks. The cheapest and easiest one is linear

interpolation. In our case, since we are dealing with a surface, we would have to use bilinear interpolation. Using the notations on Figure 6-1, the interpolated value could be calculated like this: $H(x,y) = H_0(1-x)(1-y) + H_1 x(1-y) + H_2(1-x)y + H_3 xy$

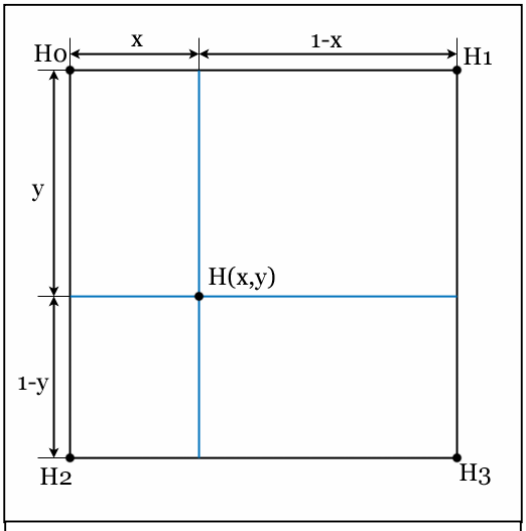


Figure 6-2 Bilinear interpolation

If we introduce the two vectors:

$$h = [H_0 \quad H_1 \quad H_2 \quad H_3]$$
$$c = [(1-x)(1-y) \quad x(1-y) \quad (1-x)y \quad xy]$$

then the result can be written as a simple dot product: $H(x,y) = hc$. This is good, since usually we will have to interpolate many values at a time (position, normal, gradient, color and possibly some other miscellaneous attributes) and can reuse the c vector. Also, these kinds of vector operations can be done quickly using SIMD (Single Instruction Multiple Data) instructions.

Now that we know how to interpolate our surface, we should decide about which combining method to use. Note that a surface usually cannot be mapped onto another surface without distortions. The simplest example is when we try to map an image (defined on a plane) onto an arbitrary surface. Or, thinking the other way around, when we try to map a surface (e.g. a sphere) to a plane. Looking at Figure 6-2 we can compare displacement mapping (on the middle) with simple addition (on the right). Since our detail geometry usually have little or no real physical meaning, distortion is not a problem. In fact, distortion is good, since it makes tiling of the detail map less noticable. Simple addition is also much simpler to compute, which is essential for a real-time algorithm. Combining the height values is the easiest part. Much more problematic is the computing of normal vectors for the resulting surface. It is easy to see that normals cannot be simply added together. Since normal vectors are most important for lighting the terrain, I leave its discussion to the

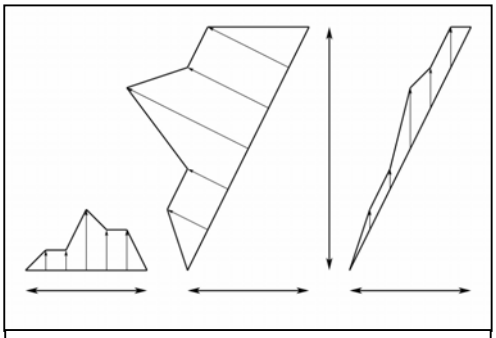


Figure 6-3 Comparing surface combining techniques.

next chapter. For now, let us assume that we can compute the normal somehow and move on to the refinement.

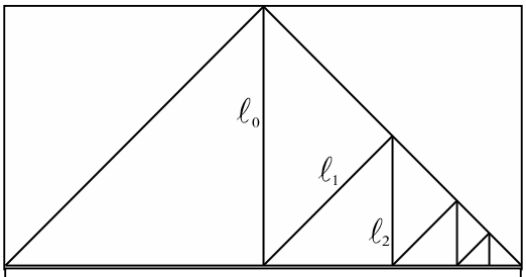


Figure 6-5 Computing bounding circles

Since the detail is distorted, the precomputed errors and radii will no longer be true. In a sense, such detail can be thought of dynamic terrain, since dynamic terrain also lacks proper error and bounding sphere information by definition. Let us first focus on dealing with the bounding spheres. If we discard all height information, and look at the surface in two dimensions, then the bounding spheres will become bounding circles. Without height, vertex positions depend only on their grid locations. This way every vertex on the same level is assigned the same radius. We can precompute radii for every level, since the number of levels is fix and small. Figure 6-4 shows the distance between vertices on successive levels. For each vertex, the radius must be at least this distance plus the radius of the other vertex. This is a recursive definition and could be written with an infinite sum. Since the distance depends only on the level of the vertex, the whole formulae can be written in a closed form (the equations can be seen on the right).

$$r_i = \sum_i^{\infty} l_i$$

$$l_i = \left(\frac{1}{\sqrt{2}}\right)^i l_0$$

$$r_i = l_0 \frac{\left(\frac{1}{\sqrt{2}}\right)^i}{1-\frac{1}{\sqrt{2}}}$$

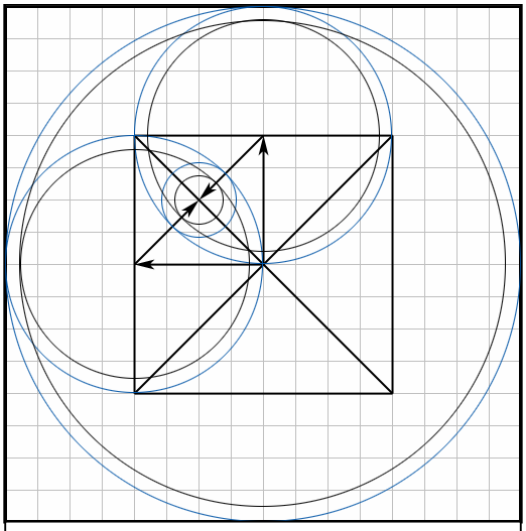


Figure 6-4 Adding a constant value to sphere radius does not break nesting.

This means that, since we are discarding height, and projecting object space errors horizontally, the screen space errors will be higher than they really are. This is not really a problem, we can not live with. The second issue is somewhat more serious: we cannot use these circles for view frustum culling. Considering that a large percent of the nearby vertices are actually detail vertices, we definitely need some kind of culling. Here is our chance to make use of the lazy frustum culling technique described in Chapter 5.2. Note that this technique is totally independent of

vertex positions, making it useful for even culling dynamic geometry. If we do not want to waste many vertices, we could inflate the real bounding spheres (Figure 6-5), so that the lowest level spheres contain all of their vertices' detail descendants.

The next question is how we can assure the nesting of the projected errors. We have two choices. For static detail, we could simply use the precalculated nested object space errors and accept the fact that they will be somewhat inaccurate because of the distorted geometry. Or we could just use a constant error for every detail vertex (this works for both static and dynamic detail), effectively making LOD selection distance based only. This is usually not a serious disadvantage, since detail geometry tends to be featureless, noise like, so the error is likely to be nearly the same for most vertices. Still, we have to make sure that the projected error will be nested with regards to the vertices in the original base mesh. This could be solved by projecting the error from both the real bounding sphere and the bounding circle assigned to the vertex's level, and take the maximum of the two errors and compare that against the threshold. This might seem to be very inefficient, because of the double work, but if the first calculated error is bigger than the threshold, then we do not have to check the other projection. Clearly, for detail level vertices we only have to make the horizontal projection only.

Since we are dealing with multiple separate maps, special care must be taken to insure error nesting between maps (only if the detail geometry has error information of course).

7 Terrain lighting

7.1 Overview

Up until this very moment, we have been dealing exclusively with the geometrical description of the terrain surface. We have shown how to build a near optimal triangle mesh that approximates the surface geometry as seen from a given view. Now it is time to investigate how these triangles actually get turned into colorful pixels on the screen. What follows is a brief description of the OpenGL[1] rendering pipeline, but this basically applies to every other method based on incremental image synthesis. Each of the primitives (in our case triangles) are defined by their vertices in object space. Each vertex can be assigned a number of attributes like position, surface normal, texture coordinates, material properties (like primary and secondary colors) and so on. These vertex attributes are first transformed by the T&L (transform and lighting) stage. This usually includes transforming position and normal vectors to eye space, and calcuating various light contributions that change the vertex's colors. Then the position vector is projected to clip space, and the primitive is clipped in homogeneous coordinates. After clipping, perspective division is applied, resulting in normalized device coordinates, which is further scaled and biased by a viewport transformation to obtain window coordinates (including depth). Using these window coordinates, the primitives are then rasterized. During rasterizing, each pixel inside the primitive is visited, and assigned a fragment. Fragments contain a lot of important information like color, depth, stencil values, texture coordinates and so on. Most of these properties are computed using perspective correct interpolation along the primitive. If all of the per fragment visibility tests (like the ownership, scissor, stencil, depth and alpha tests) are passed, then the pixel is finally assigned a color value that can be stored in the color buffers and displayed on the screen. Which part of the rendering pipeline should be called lighting is not obvious. Formerly all calculations regarding light contributions had been computed per vertex in the (as its name suggests) T&L stage, but today the rendering pipeline is much more flexible. It is possible to define complex per fragment operations to compute each pixel's color individually. I try to be as generic in my

[1] The cross-platform industry standard graphics API, see [14].

definition as possible, so when I say lighting, I am talking about the whole setup of the rendering pipeline.

Lighting can have a great influence on how the final image will look like. For example setting every pixel of the surface to the same color can still be thought of as some kind of (admittedly very trivial) lighting. However, such lighting will not help us (as a viewer) much. We would see a solid color covering most of the screen, no matter how detailed the geometry is. On the other hand, if we could calculate the reflected light based on some physical model, for each pixel, the result could be a much more believable, almost photorealistic image. So our goal is to find an efficient method to perform quality lighting real-time.

Most presented terrain rendering algorithms deal only with the surface's geometric description, they usually do not care much about lighting[1]. The reason for this is that lighting should be independent of how the geometry is built up. While this is true, most lighting computations require a substantial amount of geometrical information. Since we are dealing with CLOD algorithms, we throw away a lot of supposedly unnecessary detail. The truth is that we do throw away important details. In the error metrics, we use vertex positions exclusively, completely ignoring materials and other surface properties. This results in poor approximation of visual appearance. If we did take them into account, however, we would possibly have to tesselate down to pixel sized triangles, to achieve sub-pixel accuracy, which is clearly not possible in real-time. Still, our ultimate goal is precise per pixel shading of the terrain. To achieve this we would need a normal vector for every fragment. Now it can be seen that we have to find a way that is efficient and works with LOD meshes. Using detail geometry makes things even more difficult. Extracting normal vectors from a complex surface, that was combined from several heightmaps is not trivial.

In the following section, I am going to introduce basic and advanced lighting methods. After that I will introduce some techniques that make it possible to light such a detailed terrain.

[1] There are several separate works though, that investigate terrain shadowing and the effect of light scattering in the air.

7.2 Lighting basics

The physics of real-world lighting is quite complex. Radiometry, photometry and colorimetry are not discussed here (refer to [11], [12] for details on these subjects). We use a simplified model instead, to simulate lighting. In this model we can think of lighting as photon particles emitted from lightsources. These particles bounce between objects in the scene, until some of them arrive in the eye. Only those particles that are absorbed by the eye contribute to the final color of a pixel. It is easy to see that the color of one pixel is usually affected by the whole scene. So computing the color of a pixel would require thorough traversing of the full scene (for this reason this is called a global lighting solution), which is usually prohibitively expensive for real-time rendering. For this reason, we have to further simplify our model, by using a local lighting solution instead. This means that each primitive is shaded independently, as if it was alone in the scene. This way, light is coming directly from the lightsources. Indirect lighting reflected off from other surfaces and shadows cast by other objects are ignored in this model. However, it is still possible to approximate environmental reflections and shadows by using some clever techniques.

How a particle bounces off a surface depends on the surface's material. Material can be thought of as a function that gives the spectrum of light that is reflected in a given direction, depending on the incoming light. Finding a compact and accurate representation that describes a surface's material properties at each point is not an easy task. Evaluating such a complex function can also be very expensive. This is the reason why phosphorescence, fluorescence, and light scattering inside an object are discarded even by high quality off-line renderes. A very good material description is offered by BRDFs (Bidirectional Reflectance Distribution Function). However, BRDF is still not a widely used technique. The most common way to describe a material is to give its ambient, diffuse and specular reflection terms. These terms determine how much of a particular type of light is reflected by the surface. Ambient illumination simulates scattered omnidirectional light. It has no source, comes from every direction, and is reflected evenly in all directions. Diffuse light is also reflected equally in every directions, but its intensity depends on the incoming angle. Using the notation on Figure 7-1, it can be calculated by computing a dot product between the normal and light vectors. Specular light simulates highlights on shiny objects. Its intensity also depends on the incoming light angle, just as it is with difffuse lights, but it is reflected back only

in a particular direction. So, how much of it reaches the eye depends also on the viewer's direction. A shininess factor is used to determine how focused the reflection is.

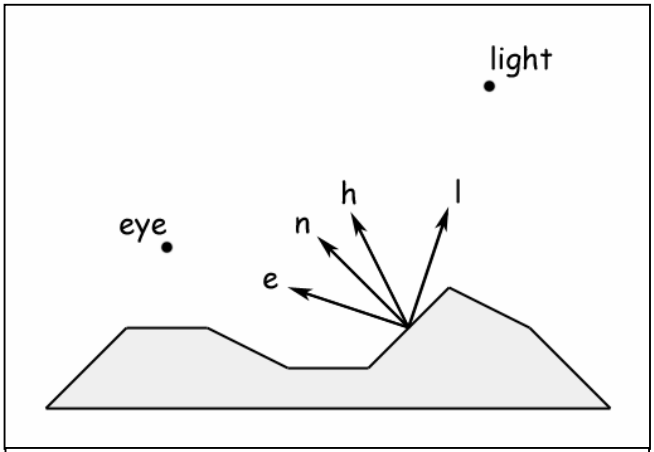


Figure 7-1 Most lighting calculations require these unit length vectors. n: surface normal l: light direction e: eye direction, h: halfway vector (l+e)

There are a couple of ways to calculate a light's specular contribution, a popular one is Blinn-Phong model, which calculates the dot product between the light direction and the halfway vector (see Figure 7-1), and raises it to a power of shininess to make distribution more or less focused. To obtain the final reflected colors, the ambient, diffuse and specular factors must be modulated by the corresponding material and lightsource intensities, and then added together. Sometimes an emissive term is also added to simulate surfaces that emit light themselves. The result is clamped to a dynamic range (usually 0..1). This means that high intensity lights may saturate into white.

These material properties could be defined as simple color values per object or per vertex, or could be stored in a texture map and stretched over an object, effectively resulting in per pixel material resolution. Obviously, the complexity of the per fragment operations that can be effectively calculated depends on the capabilities of the graphics hardware.

Now we have to describe the lightsources. In our simplified model, there are two main types of lights: positional lights and directional lights. The basic positional light (also called a point light) emits light in every direction, its intensity is usually attenuated over distance. There is also a special positional light, the spotlight, which has some additional constraints like a direction vector, cutoff angle and falloff factor that modifies the emitting direction. Directional light, on the other hand is assumed to be infinitely far away (and thus also called infinite light), and for this reason the incoming light can be considered parallel. Since the light direction is constant for the whole screen, direction lights are much cheaper than point lights (for which the direction vector always have to be recalculated). Obviously, attenuation have no meaning for lights that are infinitely far away. A good example of a directional light is the Sun.

There are also some very nice tricks that can simulate much more complex lightsources. The main idea is to use a texture to capture lighting effects (as we have done it with materials). The simplest example is capturing diffuse lighting in lightmaps. These intensity textures hold the amount of light that strikes the surface. Such a map can then be stretched over a surface and modulated with its diffuse color. The lightmap does not have to be statically linked to a surface. Using projective texturing, a lightmap could be projected over any surface to simulate a spotlight for example. Going further, we could render colorful lights into a cube texture map to simulate just about every kind of point lights. Also, we could use the cube map to capture the environment as it is seen from a point (this is called an environment map). This enables rendering of surfaces that reflect their environment. It is also possible to capture the overall ambient and diffuse light contributions for every direction in an irradiance map. The difference between an environment map and an irradiance map is that while the first gives the incoming light intensity from a single direction, the second integrates light contributions coming from every direction. Using these powerful techniques, it is possible to render radiosity quality images. Obviously, there is some cheating in using cube maps for such effects. They contain a snapshot of the surrounding environment as seen from one point in space. Ideally, we would need a different cube map for every point in space. In practice, one cube map is enough, however, if the environment is relatively far. Obviously, for dynamic scenes, we would have to recompute these cube maps.

The possibilities of using texture mapping are endless. For example calculating an attenuation factor for every pixel is very expensive, instead we could use a projected 3D intensity texture as a look-up table for distance based attenuation. Such a texture could also be used the same way to achieve stunning volumetric lighting effects.

As I have stated earlier, shadows are not handled by local lighting models automatically. There are many popular methods that can be used, though, including stenciled shadow volumes and shadow mapping (also called shadow buffers). However, I am not going to describe them in more detail here. Refer to [11][13] for more information on the topic.

7.3 Per pixel dynamic lighting of detailed surfaces

For now, we do not have to care about materials, nor light properties (these are the parts that are independent of the geometry). First, we should only be concerned about having correct surface normals for the detailed terrain at every pixel, even where geometry is not tesselated enough. The trivial solution would be to precompute a texture map that holds normal vectors for the detailed terrain, and stretch this map over the surface. Obviously, this is impractical, considering the resolution of the combined terrain[1]. The other solution would be to combine the base and detail maps at run-time to compute the normal vector at a given fragment. These calculations should be done in a vertex independent manner, to avoid dependency on geometry LOD level.

The original concept of bump mapping is supposed to solve exactly these kinds of problems [15]. A bump map (what is actually a heightmap) is defined to displace the underlying surface, but instead of actually tesselating and displacing the geometry, only the surface normals are perturbed by the bump map in a way, that the resulting vector is the normal for the corresponding displaced surface. So it seems like, as if the surface geometry has been displaced, when in fact it is not. Obviously, this lighting trick does not work for silhouette edges, so it cannot replace geometry totally. Still, it is good enough for simulating relatively small bumps on the surface. Our case is somewhat different, since we do not want to replace all the detail geometry with bump maps. We just want to use the concept to generate normals for per pixel lighting of the surface. Nearby regions will have real geometry, but for far away parts of the terrain, the extra lighting will make up for the lack of detail.

Although the original idea is quite old (it has been invented in 1978 by James Blinn), it is still too expensive to compute the normals for displaced surfaces real-time. Simplified versions of the original approach are widely used, though. By assuming that the bump map is defined in tangent space, the required computations become much more manageable. This assumption means that no combining is required, since the bump map is independent of the base surface. Of course this also means that the lighting calculations must be taken place in tangent space. So, for each triangle in the mesh, we have to calculate its tangent space basis vectors, and transform the lightsources to tangent space. However, that triangle is usually just an approximation of the real

[1] Paging in the huge texture from mass storage devices, using clipmapping might work, but it is not practical in any way.

underlaying surface. This might not be important with well tesselated geometry, but CLOD results in a simplified mesh, meaning that the the tangent space (and thus the normal vectors) will not be valid.

For quality lighting, it is mandatory to have a lighting solution that matches the true underlying geometry at all times, independently of the actual tesselation. Note that instead of true displacement, which is the basis for bump mapping, we used bilinear interpolation and simple addition (which could be thought of as displacement along a constant vector) to generate the combined geometry. As it will soon turn out, computing normal vectors for such combined surfaces is possible in real-time. As it has already been discussed in Chapter 2.3, the surface normal can be calculated by taking the cross product of the partial derivatives of the surface. For discrete heightfields, we can use finite differencing to approximate partial derivatives (Figure 7-2). The question is how can we perturb this normal with the detail map. The answer is that we do not have to perturb it at all. Instead, we just add the height differences together, and calculate the normal vector after the addition by first forming the tangent vectors and then taking their cross product (see equations on the right). While adding normal vectors is not possible, adding height differences is a correct operation (see Figure 7-3). Note that these are very simple operations, even the cross product can be computed by simply rearranging the differences. Unfortunately, we still have to renormalize the resulting vector.

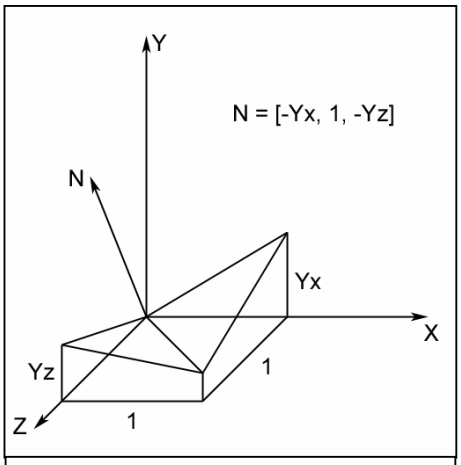


Figure 7-2 Calculating the surface normal from partial derivatives

$$t_x = \begin{bmatrix} 1 & y_x & 0 \end{bmatrix}$$
$$t_z = \begin{bmatrix} 0 & y_z & 1 \end{bmatrix}$$
$$n = t_z \times t_x = \begin{bmatrix} -y_x & 1 & -y_z \end{bmatrix}$$

Now that we know, how to compute the normal vectors, we can turn our attention to computing light direction vectors. Lighting in world space is much easier than in tangent space. We do not have to transform the lights to tangent space at each vertex. Also, with tangent space lighting one has to take care of surface self shadowing manually. When the base surface is facing away the light, but the perturbed normal is towards the light, then the pixel will be lit, when it should be shadowed. World space normals do not have such problems. When using directional lights (which is usually the case with terrains), we can use a single constant direction vector. If we wanted some

positional lights, then we had to calculate the direction vector per vertex, but it is a cheap operation compared to transforming to tangent space. The light vector is interpolated along the triangle, just like other per vertex attributes. This interpolation results in non unit length vectors that would make the shading darker in the center of the triangle. We can normalize the vector by feeding it as texture coordinates for a normalization cube map. The same technique works for other direction vectors, like the local viewer (or halfway vector, depending on the model used for calculating the specular term)

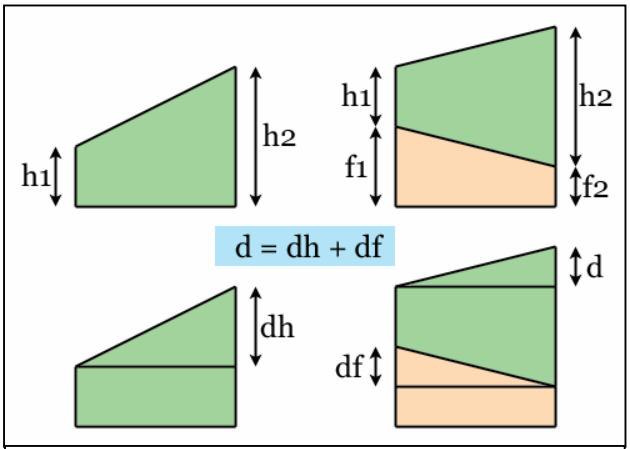


Figure 7-3 Adding differences. Note that these are signed values (ie. df is negative in this case).

Now we have to find a way to do the actual combining with available hardware. We precompute the height differences and store them in separate base and detail texture maps. Using multitexturing, we can stretch these textures over the surface. Note that this mapping requires filtering of the texture map. The simple bilinear interpolation for magnification, and box filtering for mipmapping produces correct difference values, since we used the same method for interpolating the geometry.

If we have a graphics hardware that supports fragment programs (Radeon 9700 or GeForceFX class GPUs), then we can write a simple fragment program that adds the texels, forms the normal vector, and normalizes it using pure arithmetic operations. Since all operations are done using floating point arithmetics, the result is accurate surface normal. Alternatively, normalization could be done using a dependent texture lookup into a normalization cube map, which might be a bit faster in some cases. Computing the dot product between the normal and the light direction vector results in the diffuse term. Modulating it with the diffuse color gains the final color.

Unfortunately GeForce3 class hardware do not support fragment programs, nor dependent texture fetches in the combiner stage. This means that it is not possible to add two textures and do a dependent texture read after that, in the same pass. Still, it is possible to make the necessary computations using a multi-pass technique and a special lookup texture. In the first pass we render the terrain to an off-screen pixel buffer using

additive texture environment mode[1] to add the texels that represent the height differences. In the second pass, we render the terrain again, but this time to the on-screen window. We use the pixel buffer that was created in the previous pass as a texture projected onto the screen to perform dependent texture read using the texture shaders. The two difference values index into a precomputed texture map that contains the unit length normal vectors (encoded as RGB values) for the corresponding differences. We then compute the dot product between the normal vector with the unit length light direction vector (that is provided by a cube map as described earlier), using dot3 texture environment, to get the diffuse contribution for the fragment. Modulating this value with the diffuse color specified by a texture bound to the fourth texturing unit could be used to specify the final color of the fragment.

If the scene contains only static directional lights, than the diffuse contribution could be baked in the lookup texture instead of normal vectors, saving a dot product operation (and also requires less texture space, since it is an internsity value instead of a three component vector).

If the per fragment operations are too expensive then there is an optimization technique that works for both of the methods above. First we render the scene with depth writing and testing enabled to lay out the depth buffer (and, optionally render the diffuse color at the same pass). Then we turn off depth writing and use depth testing only (which is a very cheap operation on decent hardware) to skip invisible fragments in the following passes. This saves a lot of unnecessary per fragment calculations.

The method introduced here is efficient, easy to implement, and results in correct normal vectors at each fragment, representing the true geometry, independently of the actual tesselation.

[1] Every time I write texture environment, it can be done with register combiners instead. I stick to using environment modes when possible, because it is more standard.

8 Implementation

8.1 Overview

Personal computers are so complex and diverse, that it would be impossible to develop software without some powerful tools. Today, there are mature compilers that produce very good, optimized machine code for many different processor architectures. Also, the operating system supports industry standard APIs (Application Programming Interface) that enable easy access to special hardware capabilities from high level languages. It seems that everything is given to produce high performance applications that work on a range of different personal computers.

However, the computing performance of personal computers grow at an astonishing rate. Graphics accelerators are evolving even faster than other components of the PC. The market can hardly keep up with the pace of advancement in technology. We can see graphics cards on the shelves that are three generations away from each other. Even the graphics APIs can barely keep up with the changes. Fortunately, the OpenGL API has an extension mechanism that allows new features to be published quickly by hardware manufacturers, not having to wait for a new version of the API. Of course, this means that to utilize the latest features, sometimes vendor specific extensions have to be used, which makes the software not portable. This is not a serious problem, though, since in the long run, these extensions will likely to be merged into the core API, ensuring that the method is portable across various hardware accelerators.

Today, personal computers are based on the IA-32 family of processors. Although these family of processors have a standard instruction set, we can see similar extensions as with graphics cards. Recent CPUs have special SIMD (Single Instruction Multiple Data) instruction sets that can speed up many computationally intensive applications. Unforunately, since these instructions are not in the core instruction set, not all processors supports them. Different processors have different instruction sets for the same task! Intel has SSE (Streaming SIMD Extensions), while AMD has 3DNOW! giving roughly the same functionality. Fortunately, newer AMD processors (starting from the AthlonXP) support the 3DNOW! Professional extension, which is in fact the original 3DNow! extended with Intel's SSE instruction set. These extensions are not

supported directly by compilers, but they offer so much additional performance, that it would not be wise to discard them.

When researching new, cutting edge technologies, one should not target legacy hardware and legacy functionality. It does not make sense to support them, because most of the time they require a totally different approach to the same problem. So I decided to define a strict minimum hardware requirement for the sample software, and tried to make sure, that this hardware is utilized to its maximum.

8.2 The framework

Although the goal of this work is to develop a high performance terrain rendering application, such software requires a lot of supporting code for window and input management, journaling, scripting, timing, camera handling and so on. These features are required by most similar applications and are thus independent of the actual terrain rendering algorithm. Such features are best implemented in a separate, portable framework.

The framework has a well defined interface, that allows different components to use the services offered by it. A component can even register itself as an additional service, making it easy to further extend the framework. Such component based systems have a lot of advantages. Given a well defined interface, it is possible to develop different parts of the system independently. This makes developing huge, complex software manageable. Components can also be swapped in and out of the framework, or replaced (even runtime) without any modification required to the other components. This independency also helps keeping down build times, which is very important for large projects.

8.3 The preprocessing module

The terrain preprocessing module reads any non-interlaced 16bit per channel grayscale PNG (Portable Network Graphics) file and converts it to a preprocessed terrain data file. Preprocessing is a lengthy operation, it calculates relative object space errors, nested bounding spheres, and gradients for every vertex.

The demonstration program uses the Puget Sound dataset (Washington state, USA) with 160m horizontal and 0.1m vertical resolution. The base grid is made up from 1024x1024 points, meaning that the map size is roughly 160km x 160km. This base map is enhanced with another 1024x1024 detail map (a simple tileable pattern), that is

embedded into 16x16 sized partitions in the base map. This means, that each 1x1 quad in the base map is subdivided to 64x64 vertices. This results in an effective resolution of 65536x65536 height samples, meaning that the horizontal resolution is 2.5m! Note that these numbers are for the actual sample dataset, and that the program itself could handle maps with any other size. Since the rendering algorithm is output sensitive, it scales easily for even more detailed terrains.

I used the built in embedded script language (Lua) of the framework to enable easy configuration of terrain parameters.

8.4 The rendering module

The terrain data is paged in from disk using the file mapping services offered by the operating system (MapViewOfFile in the Windows API). This service maps a file into linear address space. Although this would make it possible, to work with huge maps that do not even fit into the physical memory, the simple linear scheme I used for data access makes it impractical to use very large maps. The reason for this is that such linear data access has very poor spatial locality, and introduces a lot of page faults, making it only useful for in-core rendering. By using the somewhat more complicated hierarchical quadtree method described in [1], it would be possible to use out-of-core rendering for such large maps. Also, it is worth noting that today's computers are usually limited by memory throughput, so this cache friendly memory access pattern should speed up even in-core rendering considerably. There is still a lot of research going on to find even more efficient data layout schemes.

Due to lack of time, I have not implemented per pixel lighting of the detailed surface. The demonstration engine only uses per vertex lighting. However, it uses the same mathematics to compute the normals, what means that I had to interpolate difference values and compute normals using the CPU. The result is that the rendering performance is very much CPU limited. Also, lighting is not nearly as detailed as it should be, because of the CLOD geometry. By implementing per pixel lighting, the performance will likely to go up, besides the increase in image quality.

To perform view-frustum culling during refinement, it is necessary to extract the six clipping planes from the combined model-view-projection matrix. I have used the very elegant method described in [16] to do this.

I used depth clamping (as described in section 4.6.3) to achieve better depth resolution.

In order to minimize memory bus usage, I have used the vertex array range extension that supports writing directly into AGP or local video memory, avoiding unnecessary copying to and from generic system memory. This is most efficient for multipass rendering, since we do not have to resend the vertex arrays every time. I used this technique together with the fence extension that enables asynchronous processing of the vertex arrays.

The sample implementation modulates the vertex lit triangles by a simple 3D noise texture to help perceiving of perspective. I used hardware texture coordinate generation to avoid sending texture coordinates. Normalizing is also done in the hardware T&L stage, to further save CPU cycles.

8.5 Testing environment and performance

The sample implementation have been tested on an average desktop PC. Details:

- Processor: AMD AthlonXP 1800+ (1533Mhz)
- Memory: 512MB PC2700 (333MHz DDR)
- GPU: nVidia GeForce4 Ti4200 128MB
- OS: Microsoft Windows XP Professional

Measuring and comparing the performace of different terrain rendering methods is difficult. It is not possible to give precise and comparable numbers, because of the wealth of parameters that affect visual appearence and thus performance. Since visual quality is subjective, it is not fair to compare the results of different methods. For example pure distance based detail geometry is faster and works well for detail geometry with noise like distribution. On the other hand, error based detail geometry might require less triangles to achieve the same visual quality at the expense of additional computing overhead.

The algorithm is clearly CPU limited, since increasing the window size and doing multiple passes does not affect performance at all[1]. Performance varies heavily depending on the geometry level of detail settings. Also, measuring frames per second is not a good performance indicator, because this number varies based on the viewpoint.

[1] Note that increasing window size should mean that more vertices are required to result in the same screen space error, but I used a projected metric for a fixed resolution window to avoid these differences during testing.

Instead, I measured triangle throughput for the best and worst cases. In the best case I measured pure refinement speed with simple distance based error, without culling. The result is roughly 9 million triangles per second. This is quite good for dynamic mesh generation. However, when doing proper error metrics calculation, together with view frustum culling and detail geometry calculations (terrain interpolation, and normal generation), performance drops to about 2.3 million triangles per second. As stated earlier, using per pixel lighting stresses only fillrate, and would save a lot of calculations that are done by the CPU on this implementation. Also, implementing a datastructure with better cache locality would likely to increase performance even more.

9 Summary

I have successfully developed and implemented an algorithm that supersedes the refinement and frustum culling methods introduced by the original SOAR algorithm. I also showed how this new frustum culling technique, together with static bounding circles, enables adding detail to the original geometry. As a complement for geometry, I also developed an efficient method to perform accurate per pixel lighting of this large and detailed terrain, independently of the geometrical resolution of the output mesh. The result is a robust method that enables rendering and shading of vast surfaces in real time.

However, this is just the first step in creating truly realistic visualization of a detail rich terrain. There is still a lot of challenge ahead. Ultimately, what we would like to see, is not just a bare surface, but a scenery full of nature's wonders. There are a lot of other aspects of realistic terrain visualization that we have not talked about in this paper. Terrain self shadowing makes the scene much more convincing, and can be accomplished by horizon mapping [8]. More realistic lighting (that depends on the time of day and the weather) could be achieved by taking into account the light scattering in the air [9]. Volumetric fogging, clouds and other environmental and weather effects would increase reality even further. Particle systems could be used to simulate fire, dust, wind, snow and rain. Modelling of ecosystems is also very important for a natural appearance [10]. Flora (trees, bushes, grass) could be selected based on some kind of quadtree structure and rendered using impostors. Integrating portal based visibility culling into the terrain rendering algorithm would enable combining of large outdoor areas with indoor areas (like a house). Hardware displacement mapping coul be used to add even more dynamic detail, like sand, or snow.

The list of possible enhancements is practically endless. Now we can see that there is a long way ahead for someone aiming at real-time visualization of natural looking terrains. I can only hope that the methods and ideas introduced in this paper will serve as a basis to some techniques that will present an even richer visual experience.

10 References

[1] *P. Lindstrom, V. Pascucci*: Visualization of Large Terrains Made Easy [2001]

[2] *P. Lindstrom, V. Pascucci*: A General Framework for View-Dependent Out-of-Core Visualization [2002]

[3] *P. Lindstrom et al.*: Real-Time, Continuous Level of Detail Rendering of Height Fields [1996]

[4] *M. Duchaineau et al.*: Real-Time Optimally Adapting Meshes [1997]

[5] *H. Hoppe*: Smooth View-Dependent Level-of-Detail Control and its Application to Terrain Rendering [1998]

[6] *R. Pajarola*: Large Scale Terrain Visualization Using The Restricted Quadtree Triangulation [1998]

[7] *T. Ulrich*: Rendering Massive Terrains Using Chunked Level of Detail Control [2002]

[8] *P.P.J. Sloan, M.F. Cohen*: Interactive Horizon Mapping

[9] *N. Hoffman, A. J. Preetham*: Rendering Outdoor Light Scattering in Real Time

[10] *J. Hammes*: Modeling of ecosystems as a datasource for real-time terrain rendering

[11] *T. A-Möller, E. Haines*: Real-Time Rendering, 2nd edition [2002]

[12] *L. Szirmay-Kalos*: Számítógépes Grafika [1999]

[13] *E. Lengyel*: Mathematics for 3D Game Programming & Computer Graphics

[14] *M. Woo, J. Neider, T. Davis, D. Shreiner*: OpenGL Programming Guide [2000]

[15] *M. J. Kilgard*: A Practical and Robust Bump-mapping technique for Today's GPUs [2000]

[16] *G. Gribb, K. Hartmann*: Fast Extraction of Viewing Frustum Planes from the World-View-Projection Matrix

[17] www.vterrain.org

[18] www.opengl.org

Appendix A: Glossary

BRDF: Bidirectional Reflectance Distribution Function

CLOD: Continuous LOD

Fragment: During rasterizing, each pixel is assigned a fragment, that contains its color, depth and possibly some other data.

Generalized triangle strip: A triangle strip that has degenerate vertices to support turning around corners.

GPU: Graphics Processing Unit

HDR: High Dynamic Range

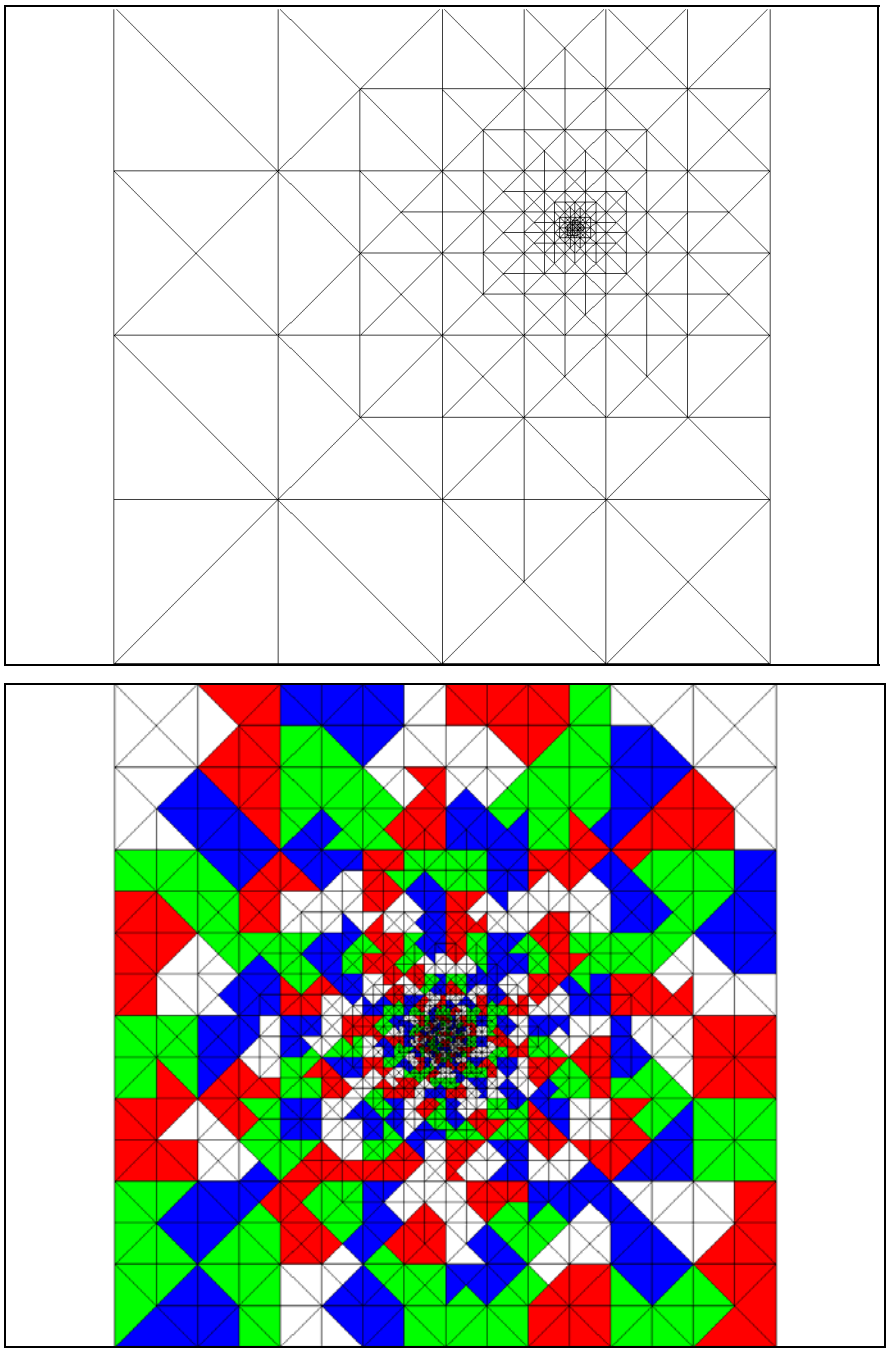
LOD: Level of Detail

T-junction: A place in the mesh where a vertex is not connected to one of its neighbouring edge's endpoints. Even if the vertex lies on the edge, floating point inaccuracies may cause cracks to appear in the mesh (causing the infamous missing pixels effect).

T-vertex: see T-junction

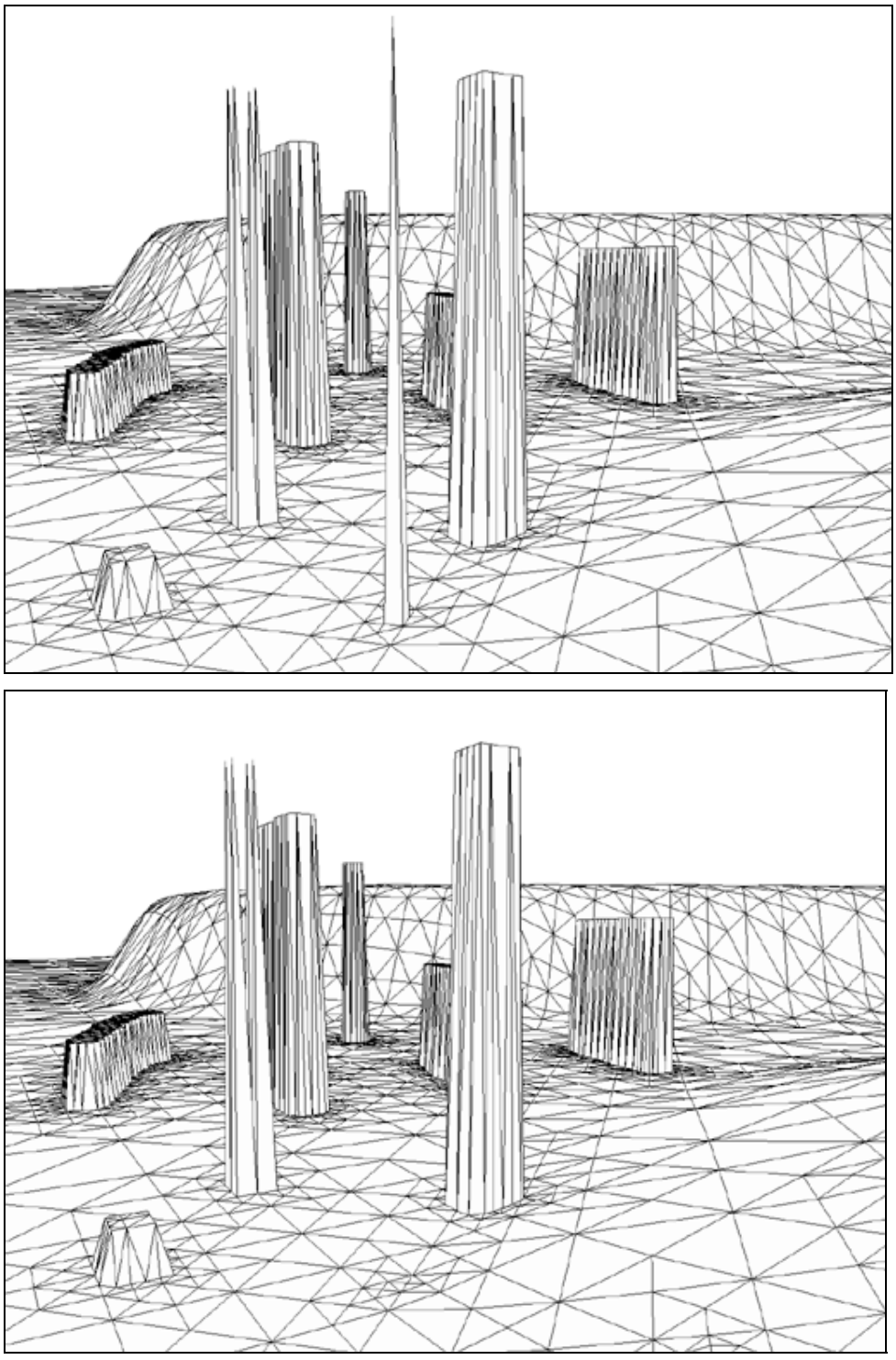
Triangle strip: An efficient format for defining adjoining triangles, where each new vertex defines a triangle together with the previous two vertices.

Appendix B: Color plates



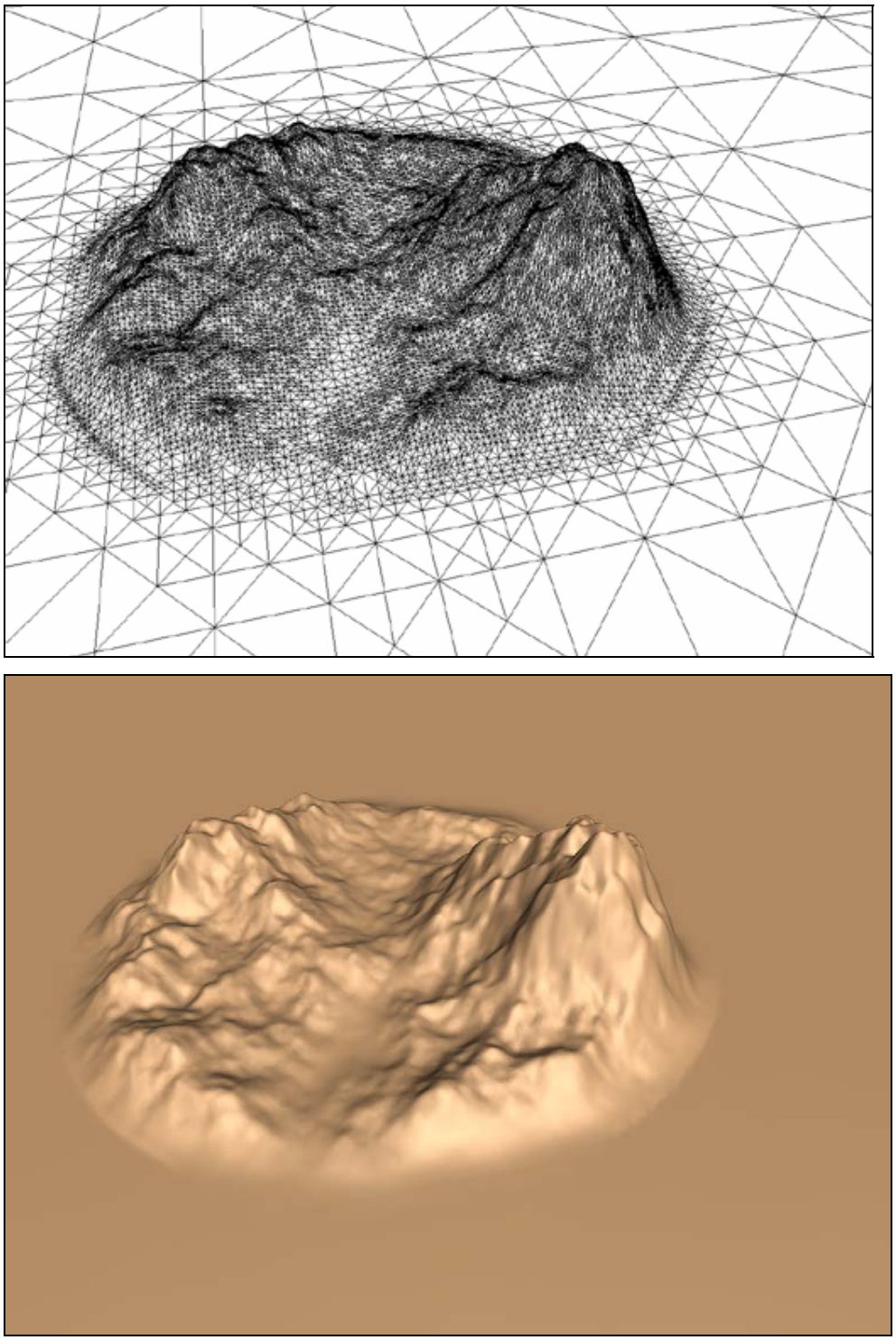
Top: Testing the refinement algorithm on a flat plane.

Bottom: Splitting the mesh to several short strips.



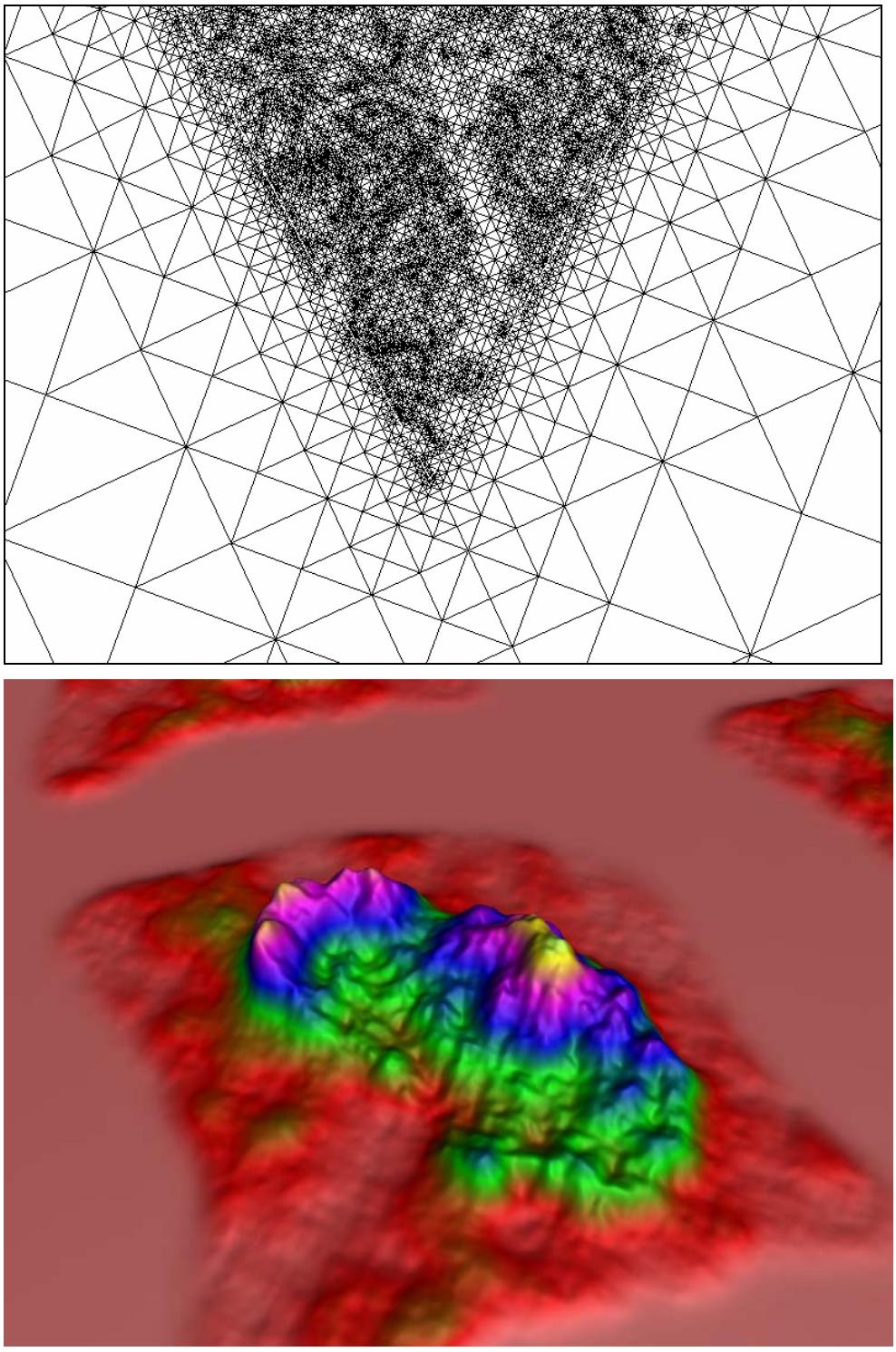
Top: The column in the front is inside the viewing frustum.

Bottom: Tilting the camera a bit results in the top vertex of the colum being culled away by the original algorithm, making the whole column disappear.



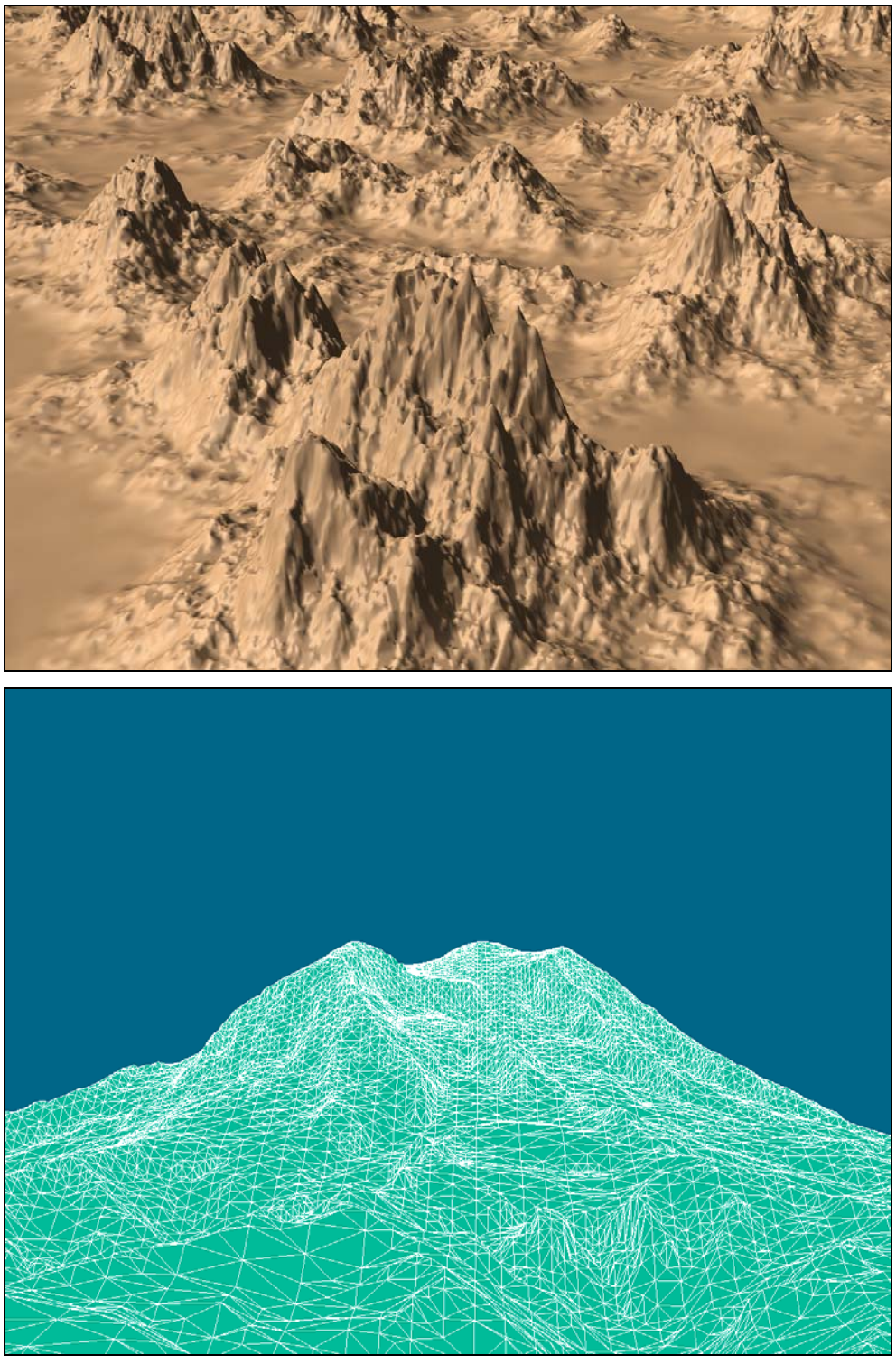
Top: Illustrating local refinement.

Bottom: The same mesh rendered with smooth shaded per vertex lighting.



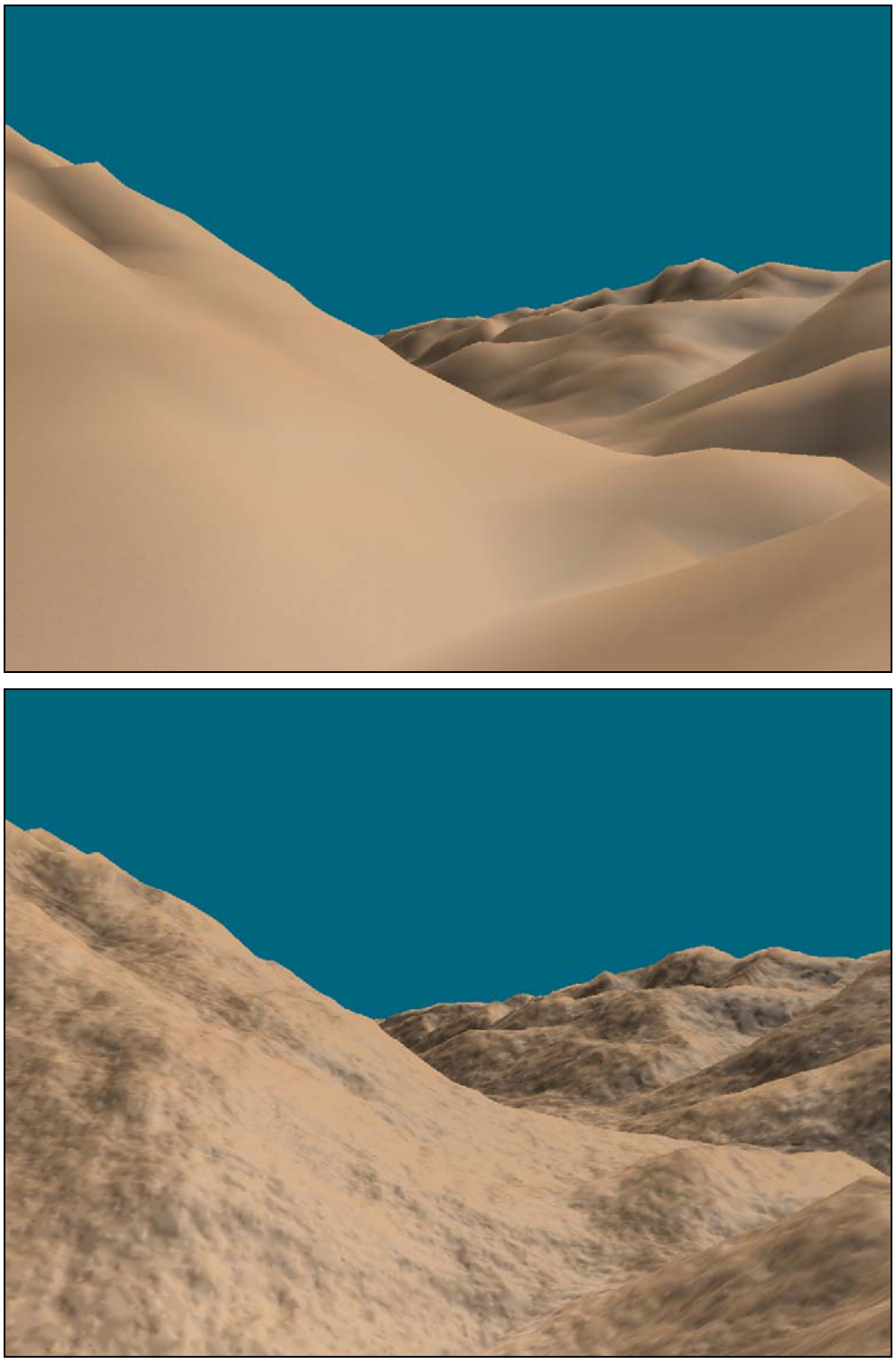
Top: View frustum culling in action.

Bottom: False coloring using a one dimensional texture.



Top: Smooth shaded rendering of a high resolution fractal terrain.

Bottom: Wireframe rendering of Mount Rainier (4391m), Washington, USA.



Top: Rendering of the original terrain dataset, without extra details.
Bottom: Rendering of the same view of the same dataset, but with added detail geometry, to improve visual quality.