Adaptive Terrain Rendering using DirectX 11 Shader Pipeline

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Abstract

This thesis is about the development of a terrain rendering algorithm that uses the DirectX 11 shader pipeline for rendering and the ability of DirectX 11 to render a view-dependent level of detail system. The basics of terrain rendering and level of detail systems are described and previous work that has been done on the subject of adaptive terrain rendering is discussed. In addition, an explanation of the DirectX 11 shader pipeline is provided. This shows how the new shader stages of the pipeline are integrated to support hardware tessellation. Accordingly the developed algorithm will be described and its usefulness for terrain rendering will be explored. Finally the difficulties of the development will be mentioned and the future work will be discussed.

Keywords: thesis, terrain, view-dependent level of detail, tessellation, DirectX 11, refinement, adaptive, hull shader, tessellator, domain shader

Declaration of originality

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication.

I certify that, to the best of my knowledge, my thesis does not infringe upon anyone's Copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices.

Markus Rapp, April 4, 2011

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1. Introduction

Terrain rendering has a wide application area. It has been used for virtual tourism, education in subjects such as geography, for weather visualization, and to calculate the most efficient positioning of radio, TV or cellular transmitter. Large companies such as Google use terrain rendering for products like Google Earth.

Especially in the video games industry terrain rendering plays a big role as main geometry for outdoor scenes. Open world games like Grand Theft Auto 4 or Mafia 2 were not be possible without a good terrain system. Also, for first person shooters terrain is the main geometry for outdoor scenes. Game engines like Unreal Engine 3 and Cry Engine 3 have their own terrain systems. Racing games use terrains for making the tracks. Even dynamic terrain was used in games. One example is Sega Rally Revo which was released in 2007 for PC, Xbox 360 and PS3. It uses a deformable terrain system, which changes the course each lap. [1]

What qualities and capabilities do we look for in a terrain renderer? A perfect terrain would be a single continuous mesh from the foreground to the horizon with no cracks or holes. A perfect terrain renderer would allow us to see a wide area over a large range of detail. We want to walk on the terrain or fly over the terrain in real-time. To achieve these requirements a rendering terrain algorithm has to be developed that has the ability to blend out detail that is not seen or distant. This is done to save computing resources to be able to show as much detail near the viewport as possible.

The first terrain renderer had a static geometry. Because of lack of these algorithms to adapt geometry dependent on changing scene conditions it has always been necessary to find a balance between small terrain with large detail and large terrain with less detail.

Since the 90's a lot of research has been done about terrain rendering that supported a greater level of detail (LOD). The main focus on development of these algorithms has been to render a terrain in real-time that is as large as possible and has as much close up detail as possible. [2]

The first rendering algorithms that tried to achieve this target were CPU bound. The final geometry was calculated on the CPU and send to the GPU for rendering. The GPU only got the final data, which it had to render.

With the rapid development of graphics hardware the algorithms moved increasingly to GPU. Therefore the algorithms had to be adapted to the specialized hardware to be massively parallel.

[1] cf. http://www.gametrailers.com/video/preview-hd-sega-rally/26005 (accessed March 2011)
[2] cf. [Vir10], http://www.vterrain.org/LOD/Papers/ (accessed March 2011)

In 2005 ATI was the first company to integrate a hardware tessellator in their graphics cards. With this tessellator it has been possible to refine the geometry entirely on the GPU. ATI published a Tessellation SDK which made it possible to use the tessellator together with DirectX9. [3]

Two years later Microsoft released DirectX10 with Shader Model 4.0 which included the new geometry shader. This made geometry refinement possible on all GPUs that support DirectX 10.

The big break-through of hardware tessellation came with the introduction of DirectX 11, which Microsoft released together with Windows 7 in 2009. DirectX 11 sets a standard for hardware tessellation with the new hull shader, tessellator and domain shader. With this development, NVIDIA also decided to develop graphics cards that are capable of tessellation.

The goal of this thesis is to develop a view-dependent LOD system. The main focus is to develop a LOD system that is not visible for the user. It should show as much detail as possible. Additionally an adaption of the detail should be possible in order that faster hardware will show more detail than slower hardware. At the same time, the development of the program should allow backward compatibility to older approaches. This backward compatibility allows the use of old data. Terrain can also be rendered on graphics cards that do not have a hardware tessellator integrated. The amount of visual quality would be reduced, but the application could still run on older hardware.

In the end result it should also be possible to use a collision detection system or a physics engine for the terrain. This would make it possible to walk over the terrain. All this should be accomplished in real-time. For a fluid application it is important to have at least 60 frames per second. In most applications terrain is only the base geometry. Thus it would be better when a higher frame rate than 60 frames per seconds would be achieved. Finally it should be developed a terrain editor that gives artists the ability to model a terrain that uses the developed terrain rendering algorithm.

These goals will be attempted using the DirectX 11 shader pipeline with Shader Model 5.0. The hardware that is used for development is an AMD Radeon HD 6870.

The second chapter of the thesis will describe the basics of terrain rendering and level of detail systems. In section 3 previous approaches to the topic will be discussed. The following section is about the DirectX11 shader pipeline. Shader stages will be explained. Section 5 will be shown the new developed tessellation terrain rendering system. The final section will deal with the results of the new rendering system and possible work for the future.

[3] cf. http://developer.amd.com/gpu/radeon/Tessellation/Pages/default.aspx (accessed March 2011)

2. Basics

In this section you'll find some basic terms and definitions about terrain rendering. Additionally you'll read what exactly a LOD system is and which types of LODs exist.

2.1. Coordinate System

First it is important to decide which coordinate system to use. In Direct3D for example it is possible to use a left-handed or right-handed Cartesian coordinates. *Figure 2-1* shows the different coordinates.

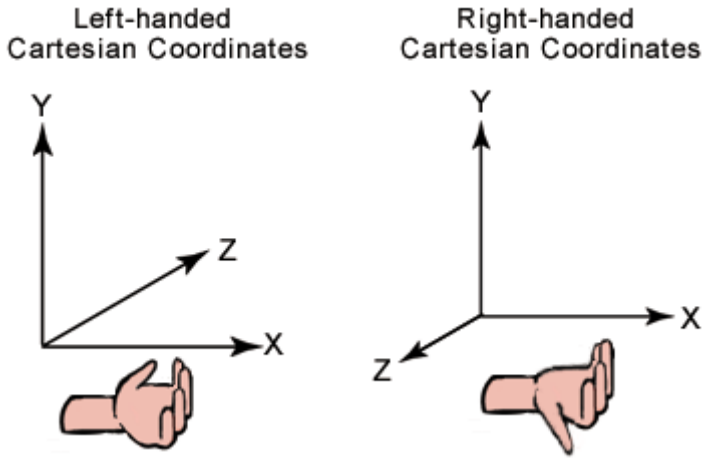


Figure 2-1: Left-handed and right-handed Cartesian coordinate systems [4]

In this thesis the left-handed Cartesian coordinates will be used. All explanations that have to do with coordinates will be explained using left-handed Cartesian coordinates. The x coordinate stands for length, y coordinate stands for height and z coordinate stands for width.

2.2. Terrain Structure

The structure of a terrain can be differentiated in two major approaches, triangulated irregular networks (TINs) and regular gridded height fields. Those two structures will be described in the next two sections. [5]

2.2.1. Triangulated Irregular Networks

A TIN constructs the terrain with a set of triangles dependent on the surface appearance. Each vertex need to be stored. *Figure 2-2* shows a terrain with 512 vertices. On the

[4] cf. [Mic11], http://msdn.microsoft.com/en-us/library/bb204853%28v=vs.85%29.aspx (accessed March 2011)
[5] cf. [Lue03], page 188

lower right you see a part of the height field, which is flat. This part can be represented with a few polygons. On the left side the surface is very bumpy. More polygons are necessary to approximate the surface.

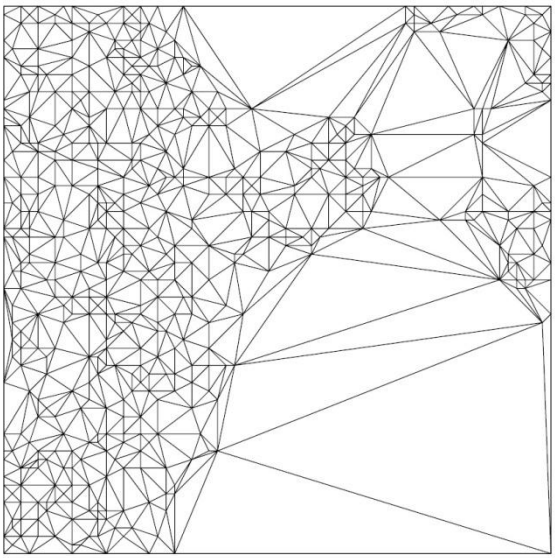


Figure 2-2: TIN representation [Gar95]

Advantages:

- Surfaces can be approximated to the required accuracy. Large flat regions can be represented with few polygons.
- TINs are more flexible. Caves and overhangs can be constructed.

Disadvantages:

- Irregularities of the surface make parallelization, collision detection, view-space culling and dynamic deformations more complex.
- TIN has a poor applicability for run-time view-dependent LOD.

TINs are not suitable for this analysis. The first reason is that parallelization is more complex. This does not work for an approach that is mainly calculated on the GPU because the architecture of a GPU is massively parallel. The second reason that makes TINs impossible to use is that they are not applicable in a run-time view-dependent LOD. Therefore TIN will not be used in this thesis. [6]

2.2.2. Regular Grid

Regular or uniform grids are made out of quads. Each quad has the same size and consists of two triangles. Grids are regularly spaced for length and width of the terrain. The height of the terrain can be stored in an array or a height map.

In *Figure 2-3* a regular gird of 8-to-8 is shown. It consists of 128 triangles.

[6] cf. [Lue03], page 188 to 190

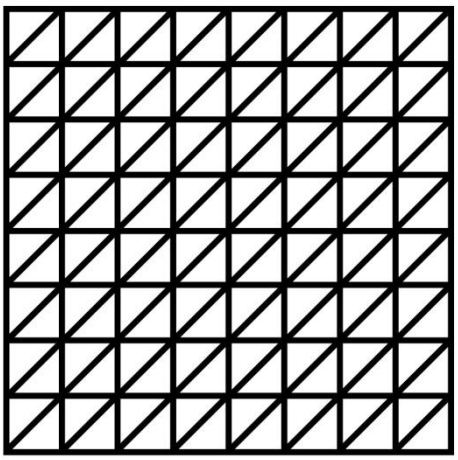


Figure 2-3: Regular grid [Lue03]

Advantages:

- X and z coordinates for width and length can be generated. Only the height needs to be stored. Therefore less storage is needed.
- Data can be stored in a texture. This is better for processing with GPU.
- Regularity of the surface makes parallelization, collision detection, view-space culling and dynamic deformations easier.

Disadvantages:

- A grid has a less optimal representation and is unable to present different complexity because same resolution is used over entire terrain.
- It's not possible to model overhangs or caves with a regular grid.

Grids are the perfect terrain structure for my requirements. All advantages are good for less data storage and for parallel processing. The disadvantage to be not able to present different complexities is not fatal because with tessellation it is possible to have different resolutions. Of course the base grid is the lowest possible resolution. However, over a million triangles will be rendered and the percentage of the possible number to reduce when using another structure is so much less that it doesn't need to be considered. Also the disadvantage of not being able to model overhangs or caves is not serious because there are other techniques like a Voxel Engine[7] that can be used. [8]

For these reasons I will use a regular grid as base structure for my algorithm.

2.2.3. Height Map

A height map is the best way to store height data for a regular grid. A height map is a texture where the height data of a terrain is saved. There are four different approaches to store the height data in a height map. One approach is to use the R-, G- and B-channel

[7] cf. [Cry08], http://doc.crymod.com/SandboxManual/Voxel.html (accessed March 2011)
[8] cf. [Lue03], page 188 to 190

of a texture.[9] In each channel the same data is stored. The result is a picture representation of the heights in a gray scale. *Figure 2-4* shows an example of such a height map. This is nice for generating a height map. You can see on the texture how the terrain will look like. Black stands for minimum height and white stands for maximum height. However, the problem of this height map is its small data range. Only 256 different heights are possible. Therefore this type of height map is only good for terrains that have a smaller difference in height. Another difficulty with this type of height map is that 16 bit per pixel are wasted because the same data is saved in the R, G and B channel of the texture.

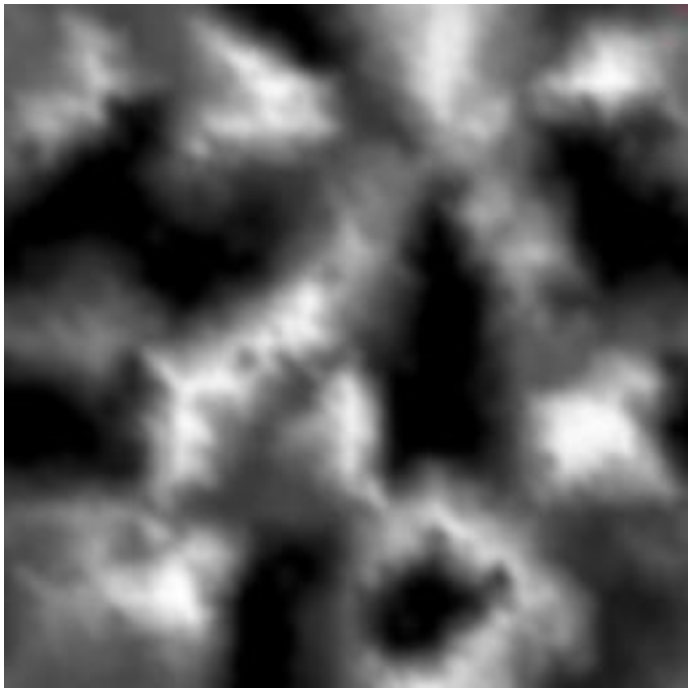


Figure 2-4: Gray scale height map with resolution 256 x 256 [AMD09]

A second approach is to use a color height map. The representation of heights is now displayed in colors. R, G and B channel of the texture are used for the height data. The highest value is still white and the lowest value is black. With this approach 2^{24} (16777216) different height values are possible. The advantage is that you still can represent the different heights with colors in a picture. As well as in a gray scale height map the alpha channel is free to use for additional data.

[9] A texture has four channels: Red, Green, Blue and Alpha.

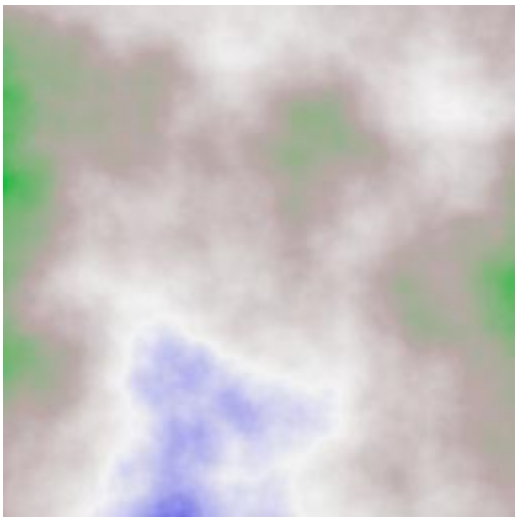


Figure 2-5: Color height map [Wig10]

A third approach is to use the R and G channel for the height data. Now 65536 different heights are possible. This is enough for the most applications. The B and Alpha channel is still available for other data. The problem here is that you don't have a picture presentation of the heights. There have to be other ways to change the height data. One approach could be to use a color height map at first to model a height map in a 2D texture view. After this the height data is converted to the 16 bit to fit in the R and G channel.

It is also possible to use all channels of a texture for height data. With this 2^{32} height values are possible. [10] [11]

The advantages of height maps are that they are easy to implement and require substantially less memory than a polygon mesh representation. Furthermore GPUs are specialized to access textures. So a height map is also a good data representation for a GPU.

2.3. Level of Detail

In computer graphics level of detail is a technique that is concerned with the reduction of complexity of 3D polygon models. This reduction of complexity is done for the purpose of decreasing the workload of graphics hardware to be able to show more detail where it is needed.

The necessary polygon count of an object depends on the shape of an object as much as on the distance and orientation of the object to the camera. The used screen resolution is a dependency for the polygon count, as well. A level of detail system tries to calculate a representation of a polygon object according to these dependencies.

[10] cf. [Sch06], page 756
[11] cf. [Wig10], page 308, 309

There are several different approaches of level of detail systems.

2.3.1. Discrete Level of Detail

Discrete LOD is a scheme where several discrete models with fewer triangles are calculated or modeled for a complex model. The different models are precomputed offline and can then be used inside the application when they are needed. At run-time the application chooses which representation of the model is best suited to the scene conditions and should be rendered.

Discrete LOD is also called view-independent LOD. When the LODs are computed it can't be predicted in which direction the camera shows.

In *Figure 2-6* you see how the different LODs of a model could look like.

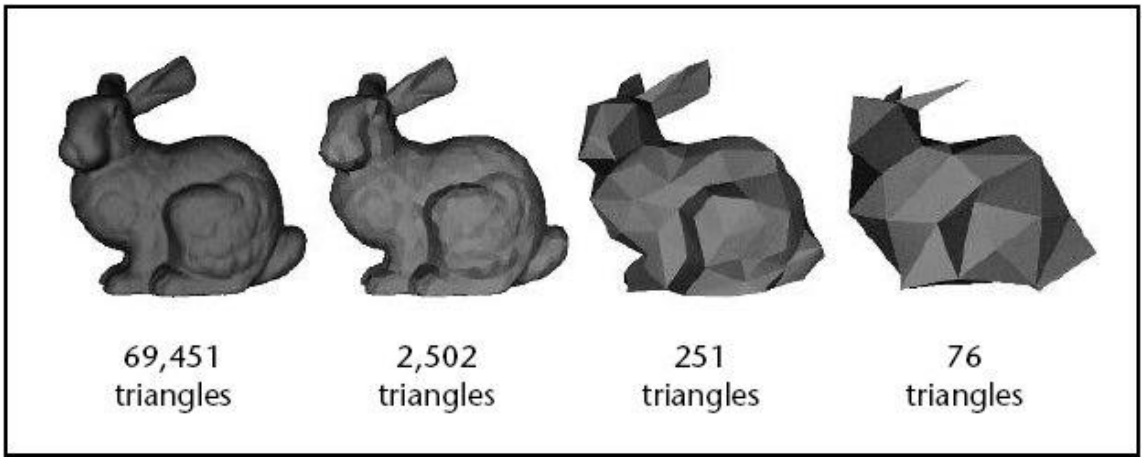


Figure 2-6: Different LODs of Stanford Bunny [Lue03]

Advantages:

- Decoupling simplification and rendering makes it good for real-time applications. Expensive precomputation for precise LODs can be made offline. At real-time not much processing power is needed.
- It is very simple at run-time. Only the model needs to be switched.

Disadvantages:

- Additional memory is needed to store each representation of the model.
- Switching between different LODs is visible for the user because of the little number of LODs.
- Discrete LODs are not dependent on viewing direction.

Discrete LODs are applicable for applications that don't have much compute power. But using a discrete LOD system also means a poorer visual quality.

In a terrain system you would have a grid with different quad sizes. Some quads of the grid would be very small for a high resolution and some quads of the grid would be very large. *Figure 2-7* shows different resolutions of a quad. The sizes of the quads would be

selected according to the scene conditions. Because there are only a discrete number of quad sizes, the user would see a change of shape of the terrain when one quad size changes to a lower or higher quad size. [12]

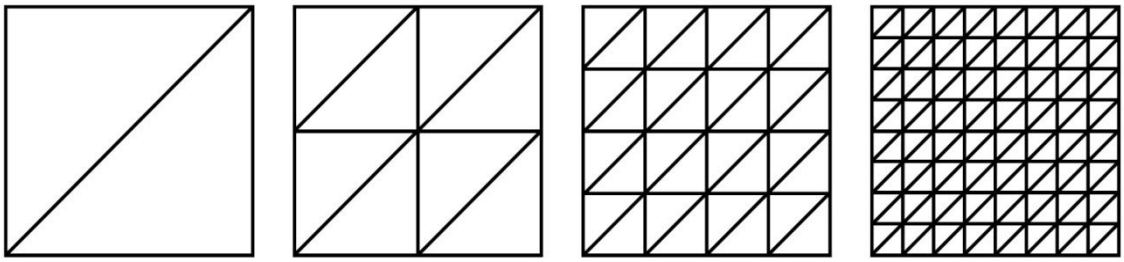


Figure 2-7: Different LODs of a quad [Lue03]

2.3.2. Continuous Level of Detail

Continuous LOD is completely different to discrete LOD. Rather than have some discrete LOD models, continuous LOD defines a continuous spectrum of data detail. This spectrum reaches from a low polygon mesh to a high polygon mesh. All you need for this is a low poly mesh and a data structure that defines how this mesh can be refined. According to this structure a mesh can be created on run-time that fits to the scene conditions.

Advantages:

- Continuous LOD has a better granularity because the number of possible meshes with different LODs is much higher than with discrete LOD.
- The better granularity leads to a better fidelity. An exact model can be created, and only the number of polygons that are essential will be created.
- The better granularity also leads to a smoother transition because the difference between the possible LOD meshes is very small.
- Streaming of the refinement data is possible.

Disadvantages:

- Continuous LOD is much more complex.
- More processing is needed at run-time.

In conclusion, continuous LOD offers a much better visual representation with the cost of additional computation. [13] [14]

An example for a continuous LOD is the progressive mesh representation that was presented from Hugues Hoppe on ACM SIGGRAPH 1996. The progressive mesh representation works with two operations, edge collapse (ecol) and vertex split (vsplit).

[12] cf. [Lue03], page 5, 9, 334
[13] cf. [Lue03], page 10, 332
[14] cf. [Red03], [Lue031]

Figure 2-8 shows how these operations are performed. For edge collapse you have four vertices V_l, V_r, V_t and V_s. V_t and V_s are unified into to one vertex V_s. Vertex split is the reverse of this operation. It splits V_s into two vertices V_t and V_s.

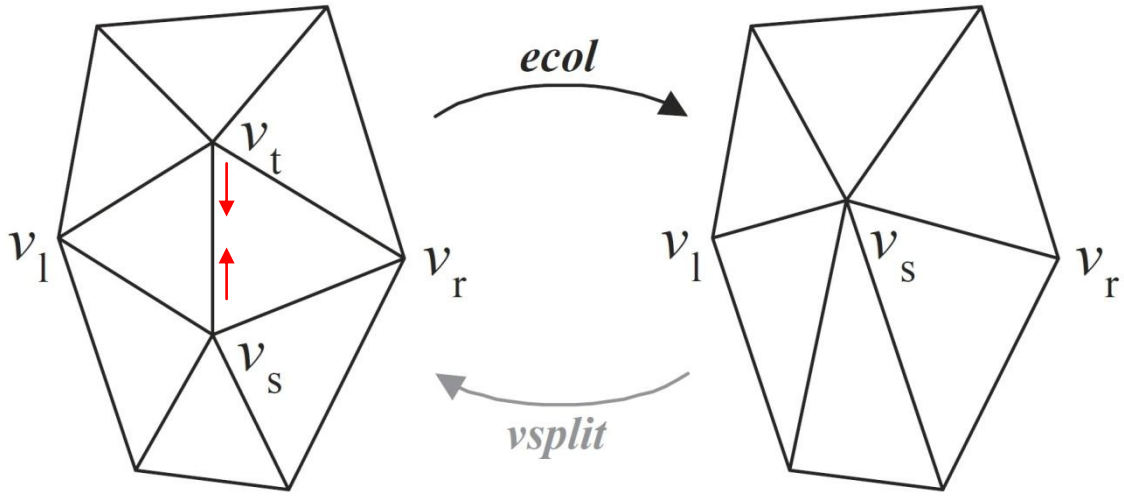


Figure 2-8: Shows edge collapse (ecol) and vertex split (vsplit) [Hop96]

But how are these operations used to make a continuous LOD? First we need to model a high polygon mesh M^n. Next we define a sequence of edge collapses that simplify M^n to a very coarse mesh M^0. After this we have a spectrum that reaches from n to 0 where each step is one edge collapse.

An edge collapse transformation is invertible with a vertex split. When we invert the previous process, we can start with the base mesh M^0 and make vertex split operations until we get to the high poly mesh M^n. Now we have a spectrum from 0 to n where each step is a vertex split.

Figure 2-9 shows four models of a spectrum, which consists of 13369 different models.[15] In an application we use the low polygon mesh M^0 and a sequence vertex splits. According to the distance to the camera we now refine or coarse our model with edge collapse and vertex split operations. [16]

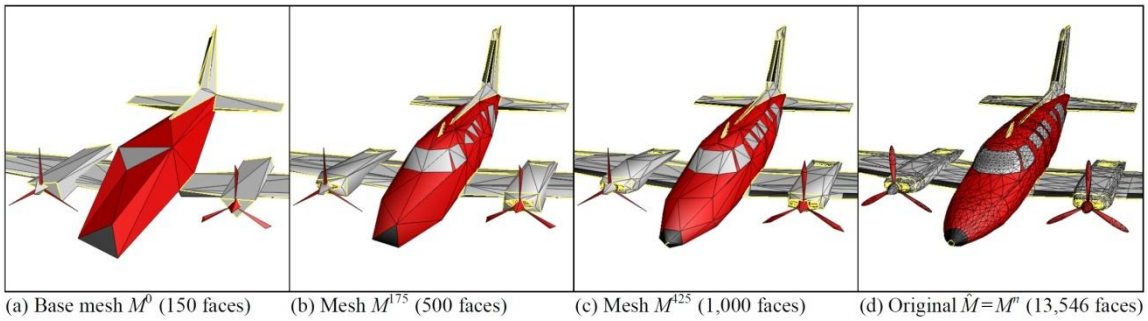


Figure 2-9: Progressive mesh [Hop96]

[15] M^0 = 150 faces, M^N = 13546 faces; number of possible meshes = $(M^N-M^0)/2$ = 13369
[16] cf. [Hop96] [Hop961]

Progressive meshes alone are not applicable for a terrain system. Because we have only one refinement sequence, the terrain only can be refined at one part of its surface. One sequence is enough for a small mesh but for a big terrain it is insufficient.

2.3.3. Distance-Dependent Level of Detail

Distance-dependent is the selection of LODs dependent on the distance between the camera and the rendered object. This selection criterion can be applied to a discrete LOD or a continuous LOD system. In *Figure 2-10* you see an example how the Stanford Bunny LODs are rendered according to the distance of the camera.

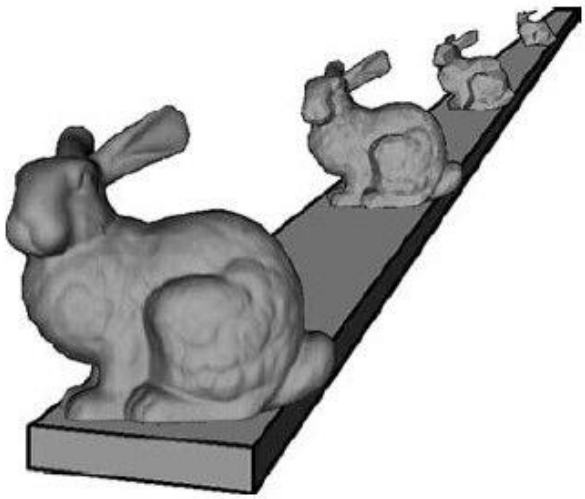


Figure 2-10: Distance selection of Stanford Bunny LODs [Lue03]

When selecting a LOD it is important to use the true 3D distance instead of the distance between camera and object in view-space after projective transformation. It's common in a 3D game or application to rotate the camera rapidly. This rapid rotation of the camera would lead in a screen depth based LOD selection to changes of LOD models, which could lead to visual artifacts.

It is advisable to use tolerance factors like hysteresis to avoid LOD changes resulting from small changes in viewer distance. Hysteresis is a lag between LOD transitions so that objects switch to a lower LOD slightly further away than the defined distance and to a higher LOD at a slightly closer distance. For example if we have a distance of 100 to the camera where we switch from LOD1 to LOD2. Now we define a threshold 10 for the hysteresis. We would switch from LOD1 to LOD2 at 110 and LOD2 to LOD1 at 90. So the range between 90 and 110 is where both LODs could appear. When moving away from the object it is the LOD1 and when moving towards the object it is the LOD2.

Advantage:

- Distance-dependent LOD is simple and efficient to implement. Only the distance in 3D space between two points needs to be calculated.

Disadvantages:

- Only using the distance for LOD selection is inaccurate because shape or orientation of the mesh to the camera are not considered.
- View-distance conditions can change when scaling a mesh or using different display resolutions.

In conclusion, distance-dependent LOD is the best selection for discrete LOD and continuous LOD because the different LODs of the schemes only depend on the distance to the camera. [17]

In section *3.3* a terrain rendering approach is described that uses distance-dependent LOD for its LOD selection.

2.3.4. View-Dependent Level of Detail

View-dependent LOD is an extension of continuous LOD. The selection of LOD is done with view-dependent selection criteria such as screen resolution, orientation of the camera and shape of a polygon mesh. Meshes that are near to the camera have a higher detail than meshes that are far away.

The human visual system is sensitive to edges. Therefore a view-dependent LOD system also provides to have a higher detail on silhouette regions and less detail on the interior regions of a mesh.

One major problem of continuous LOD is that either we have a very detailed mesh or a very coarse mesh. A view-dependent LOD provides the ability to have a mesh that on the one hand has very detailed parts like silhouette of the mesh or parts that are really near to the camera. On the other hand the same mesh could also have some regions of the mesh that are not that detailed. These parts are in the interior region of the mesh or parts that are not that close to the camera. There are also some parts of the mesh that are not seen from the user such as faces oriented to the rear or parts that are outside the view frustum. These parts that are not seen should not be rendered.

Advantages:

- A view-dependent LOD system provides even better granularity than a continuous LOD system. The outcome of the better granularity is a higher fidelity. As a result polygons are allocated exactly where they are needed.
- View-dependent LOD provides smoother transition between LODs. This leads to a reduction of popping effects[18] that plague discrete LOD.
- Drastic simplification of very large objects is possible.

[17] cf. [Lue03], page 88-90, 93-94, 180

[18] Popping effect is the noticeable flicker that can occur when the graphics system switches between different LODS. cf. [Lue03], page 342

Disadvantage:

- Relatively high computational cost at run-time.

View-dependent LOD seems to be the perfect approach to have the best visual quality with fewest polygons. The only problem is the high computational cost at run-time that comes with view-dependent LOD. [19] [20]

An example for a view-dependent LOD is "View-Dependent Refinement of Progressive Meshes". This is a further development of progressive meshes and was developed by Hugues Hoppe. With this approach different LODs can coexist on one mesh. Regions that are outside the view frustum, distant or facing away from the camera are coarsened.

With progressive meshes vertex split and edge collapse operations are only possible in a defined sequence. Therefore it is not possible with this technique to have different LODs on one mesh. To define different LODs on one mesh we need to be able to make vertex split and edge collapse operations on several parts of the mesh. The first thing we need to be aware of is that a vertex split transformation defines a parent-child relationship between the vertex V_s that gets split and the new created vertices V_t and V_u. This parent-child relation can be applied to a binary tree.

Figure 2-11 shows how such a vertex hierarchy of vertex splits is constructed. In this example we got a coarse mesh M_0 that has three vertices V_1, V_2, V_3. Each of these vertices can be split independently of the other vertices. With a vertex split two new child nodes are created. As a result of all vertex splits we got M^, which consists of all child nodes. With this vertex hierarchy we can now make selectively vertex split and edge collapse operations. We don't have a defined sequence anymore. But we still have some restriction. We are not able to split and collapse any part we want.

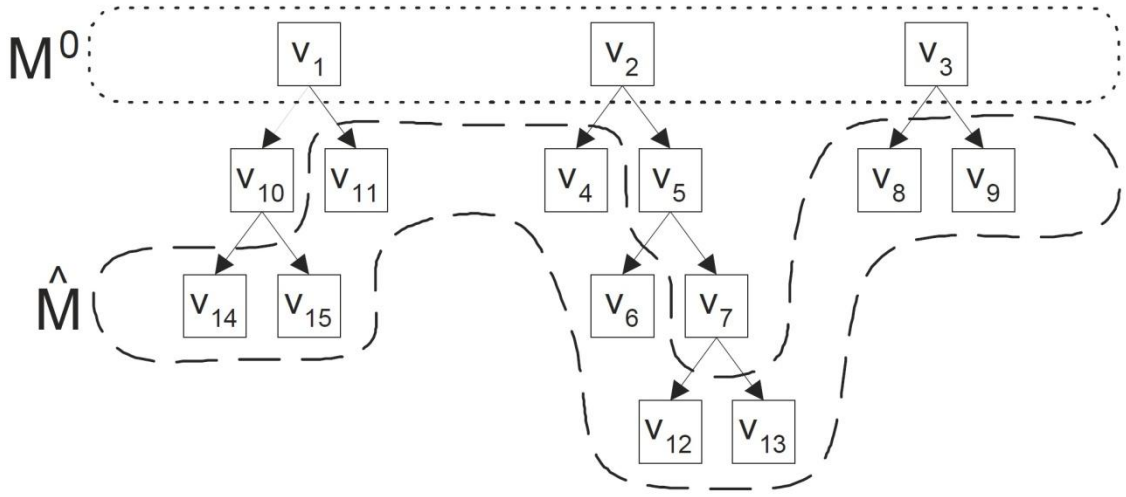


Figure 2-11: Vertex hierarchy [Hop97]

[19] cf. [Lue03], page 10-12, 104
[20] cf. [Lue031]

But what are the restrictions? Before I talk about the restriction for vertex split and edge collapse I need to introduce the modified vertex split and edge collapse operations. The operations where modified because with the old operations it was not possible to define a consistent restriction for edge collapse. *Figure 2-12* shows the new operations. For a vertex split we need to consider the four neighboring faces f_{n0}, f_{n1}, f_{n2} and f_{n3} of vertex V_s. A vertex split now creates two new vertices V_u and V_t. It also creates two new faces f_l and f_r, which are surrounded of the faces f_{n1}, f_{n2}, f_{n3} and f_{n4}. An edges collapse transformation has the same parameters as a vertex split operation and performs the inverse operation.

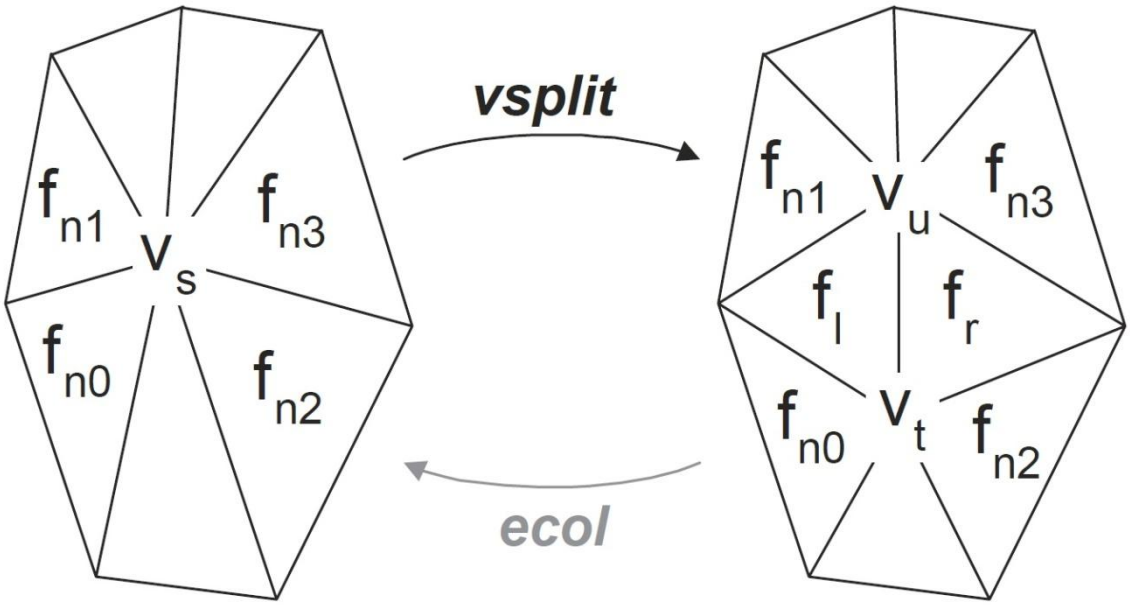


Figure 2-12: Shows modified edge collapse (ecol) and vertex split (vsplit) [Hop97]

There are new restrictions that come with these operations. A vertex split operation is legal if V_s is active and f_{n0}, f_{n1}, f_{n2}, f_{n3} are active. A vertex or a face is active if it exists in the selectively refined mesh M_S. For example in *Figure 2-11* vertices V_1, V_2, V_3 are active in M_0. An edge collapse is legal if V_t, V_u are active and if the faces to f_i and f_r are adjacent to f_{n0}, f_{n1}, f_{n2}, f_{n3}. *Figure 2-13* demonstrates these preconditions.

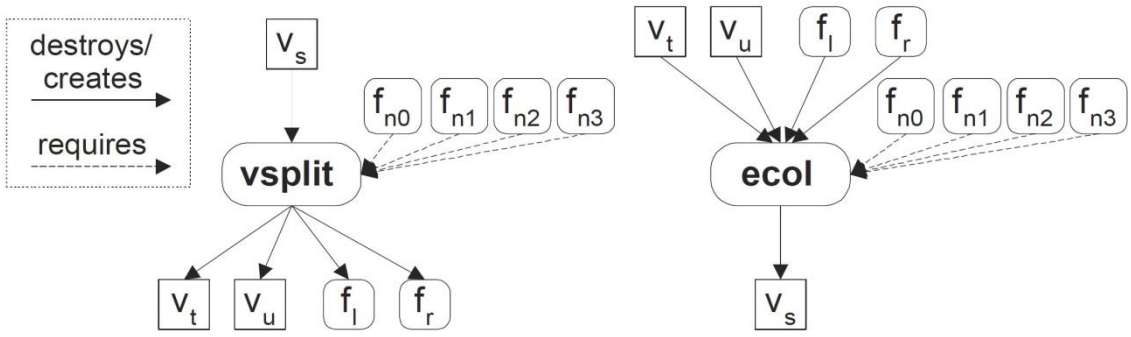


Figure 2-13: Preconditions and effects of vertex split and edge collapse [Hop97]

Now that we have the algorithm to refine the mesh we only need to define the criteria that tell us when to refine the mesh. There are three criteria. The mesh only will be

refined if the surface is inside the view frustum, faces the viewer or if screen-space geometric error exceeds screen-space tolerance τ. The screen-space tolerance can be adapted according to refinement level that wants to be achieved. A byproduct of the screen-space geometric error is that the refinement is denser near the silhouettes and the mesh is coarser the farther it is from the viewpoint.

The selective refinement framework also supports geomorphs. Geomorphs make a smooth transition between two selectively refined meshes possible. M^A and M^B are two selective refined meshes. M^G is a selective refined mesh whose active vertex front is everywhere lower or equal then the active vertex front of M^A or M^B. By interpolating the vertices of M^G, it's possible to make a smoothly transition between M^A and M^B. *Figure 2-14* shows an example of M^A and M^B with the corresponding M^G.

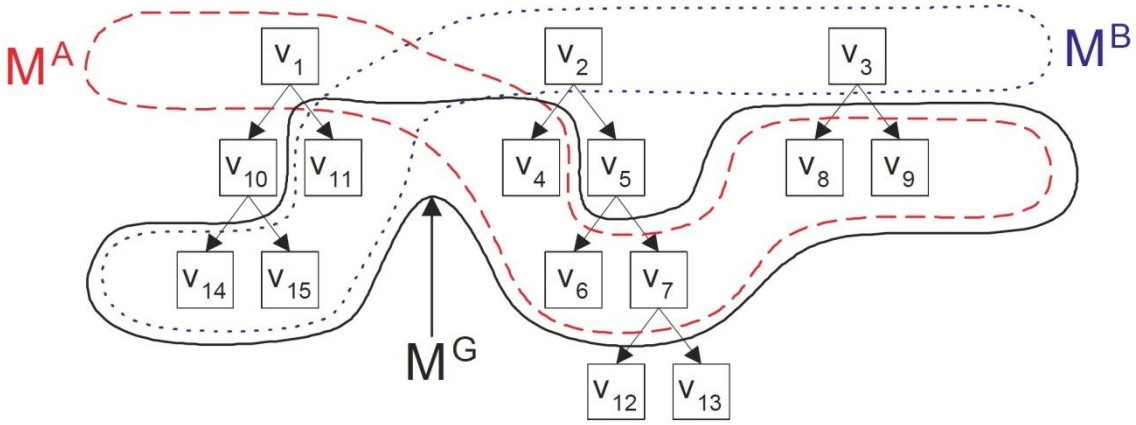


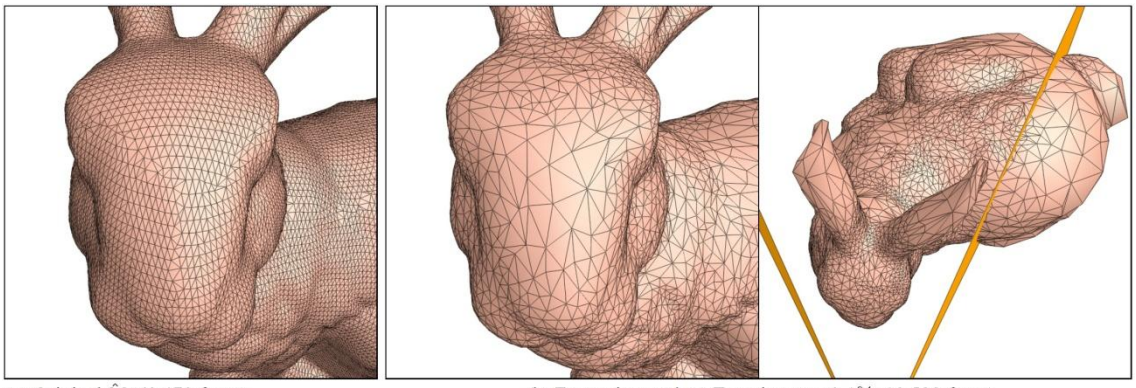
Figure 2-14: Illustration of M^A, M^B and M^G [Hop97]

The presented algorithm exploits frame coherence. The mesh of the last frame is adapted to fit to the next frame. Therefore, small changes in the view are good for this algorithm. Bad for this algorithm are fast camera rotations or rapid movement. The algorithm is efficient. It needs about 15% of frame time. Additionally it is possible to reduce the overhead of this algorithm by considering each frame only a fraction of the active vertex list that leads to a delay of the detail adaption of the mesh.

Figure 2-15 shows how selected refinement is used for a mesh with 69473 faces. In this view it is possible to reduce the face number to 10582 using a screen-space tolerance of 0.1. This is a reduction of about 85% of the faces of the original mesh. [21] [22]

A modified version of this algorithm was used for terrain rendering. This approach will be explained in section *3.2*.

[21] cf. [Hop97]
[22] cf. [Hop971]



(a) Original $\hat{M}$ (69,473 faces) (b) Front view and (c) Top view ($\tau = 0.1\%$; 10,528 faces)

Figure 2-15: View-dependent refinement example of Stanford Bunny [Hop97]

2.4. T-Junctions and Cracks

There is one common problem when using different LODs on one grid. Adjacent triangles with different LODs are not connected properly when the higher LOD has a vertex that does not share a vertex of the lower LOD. This phenomenon is called t-junction. This t-junction could lead to bleeding tears in the terrain.

If additionally the vertex of the higher LOD doesn't lie on the edge of the lower LOD cracks will appear. These cracks lead to holes in the terrain.

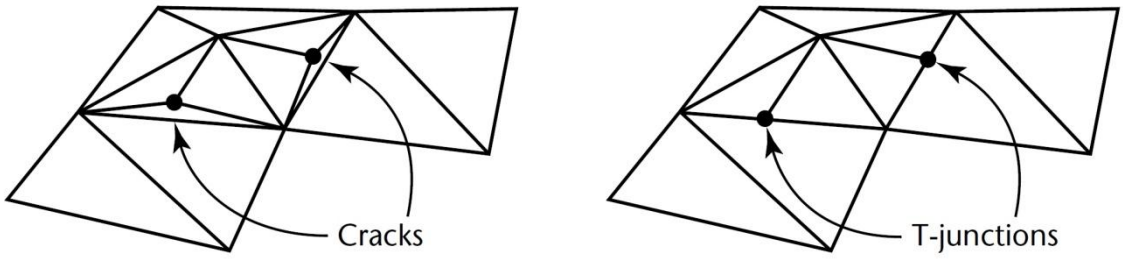


Figure 2-16: Shows cracks and t-junctions [Lue03]

The solution of this problem is to have LODs that share the same vertices on the adjacent edges. How this is implemented is dependent on the LOD system that is used. Therefore I will explain how t-junctions and holes are avoided when I write about the terrain LOD systems. [23] [24]

[23] cf. [Sch06], page 757
[24] cf. [Lue03], page 193

3. Previous Work

In this section three previous terrain rendering algorithms will be explained.

3.1. ROAM

ROAM stands for real-time optimally adapting meshes. In 1997 it was developed in cooperation of Los Alamos National Laboratory and Lawrence Livermore National Laboratory. The algorithm was very popular among game developers and has been implemented for Tread Marks, Genesis3D and Crystal Space engine. ROAM has view-dependent error metrics, is able to achieve specified triangles counts and uses frame-to-frame coherence.

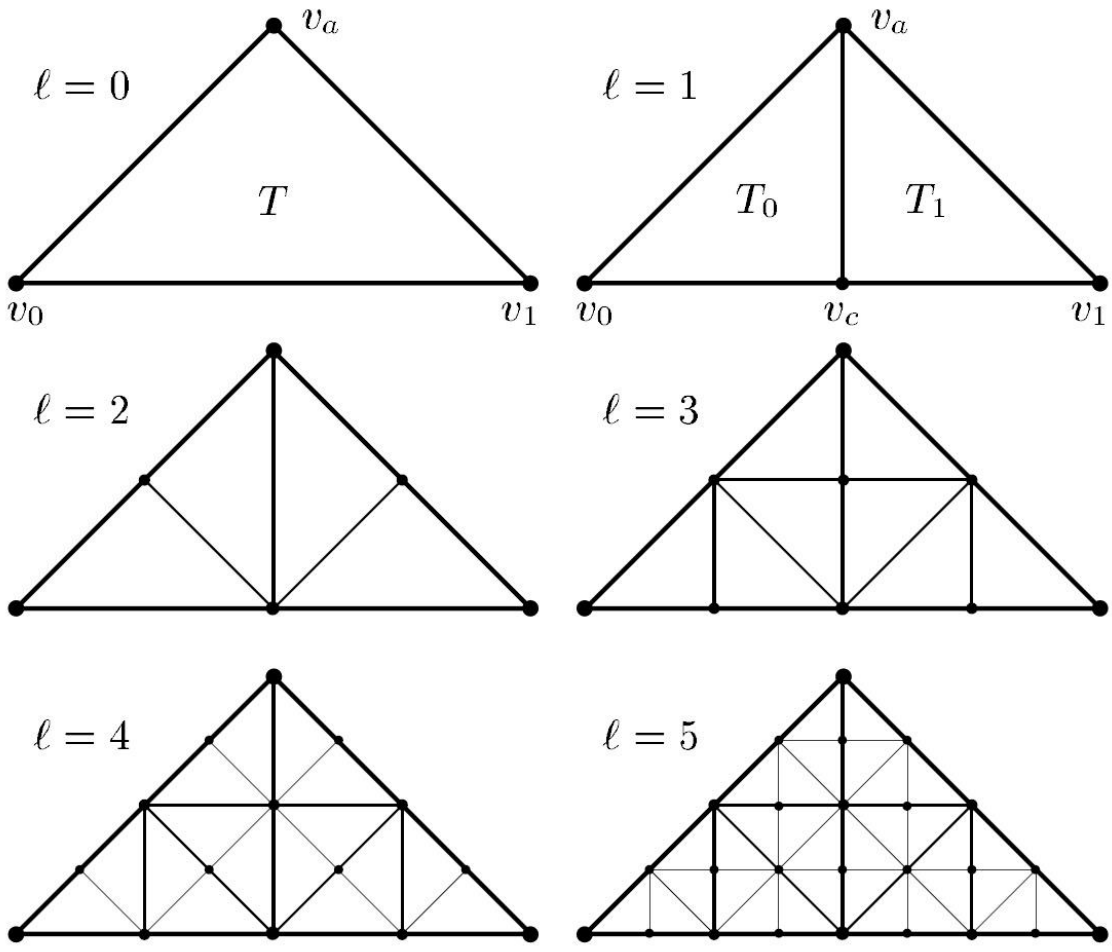


Figure 3-1: Levels 0-5 of triangle binary tree [Duc97]

The base idea of ROAM is to use a right-isosceles triangle T. This triangle has three vertices V_0, V_1 and V_a. The edge between V_0 and V_1 is the hypotenuse of the triangle. V_a is the apex of the triangle. To split T, a new edge is built from V_a to a new vertex V_c, which is in the middle of the hypotenuse of T. The result is two new vertices T_0 and T_1, which have the same size. This split can recursively performed until the necessary

refinement is achieved. This approach works for terrain rendering because a quad of a regular grid consists of two right-isosceles triangles.

Figure 3-1 shows the first six levels of a triangle binary tree. In level 5 the triangle count is 32 triangles. ROAM uses a triangle binary tree structure to keep track of the refinement scale of each triangle. As mentioned in section *2.4* when dealing with different LODs, t-junctions could be a problem. This is a problem of this approach as well. To avoid this t-junctions ROAM stores for each node its left child T_0, right child T_1, left neighbor T_L, right neighbor T_R and its base neighbor T_B. Additionally T_B of T has to have the same LOD level. T_L and T_R of T either have to be from the same LOD level, from the next finer level or from the next coarser level. Taking these restrictions into account we need to split T_B when we want to split T. This split is called diamond split. The reverse of a split operation is called merge. Every split operations are totally reversible. See *Figure 3-2* for a graphical representation of split and merge. On the left side you see a typical neighborhood for T. T_L, T_R and T_B are from the same LOD level and also the neighboring triangles of T_B fulfill the requirements. So a diamond split can be performed, which creates the four new triangles T_0, T_1, T_{B1} and T_{B0}.

To provide a smooth transition splits and merges can be animated by using vertex morphing. Instead of just adding a new vertex V_c as shown in *Figure 3-1*, we could create V_c on the position of V_a and then move V_c over time to its final position.

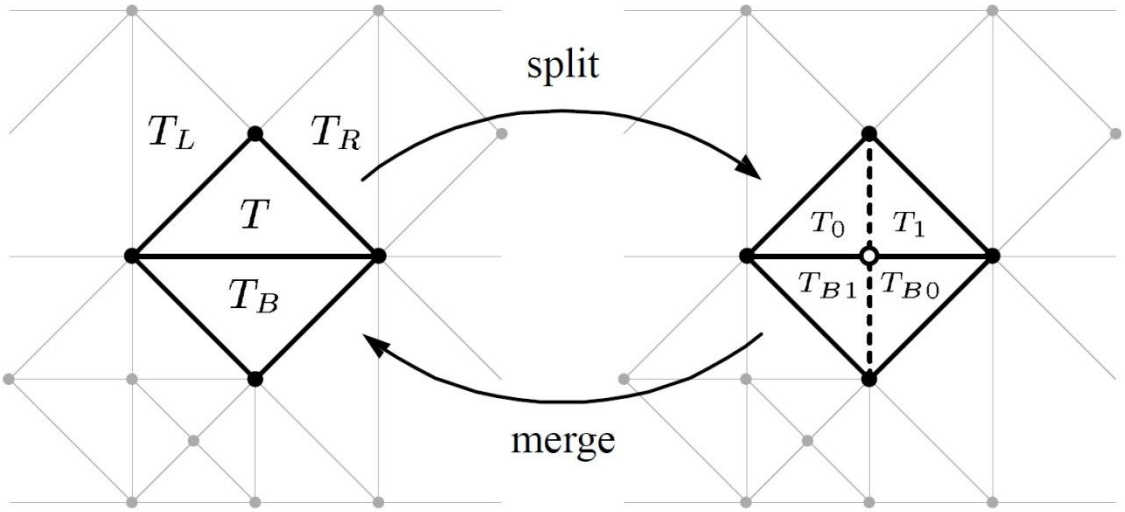


Figure 3-2: Split and merge operation [Duc97]

But what to do when neighboring triangles of T don't fulfill the conditions? If this happens the neighboring triangles need to be forced split or forced merged. *Figure 3-3* shows an example where T_B has one coarser level than T. To be able to split T, T_B needs to be split first. This is not possible because the base neighbor of T_B is from a coarser level as well. So a forced split is performed recursively on the base neighbor until a diamond is found, where a triangle has the same LOD level as its base triangle.

Now diamond splits can be made until T is split. In the case of *Figure 3-3* four diamond splits are required to split T.

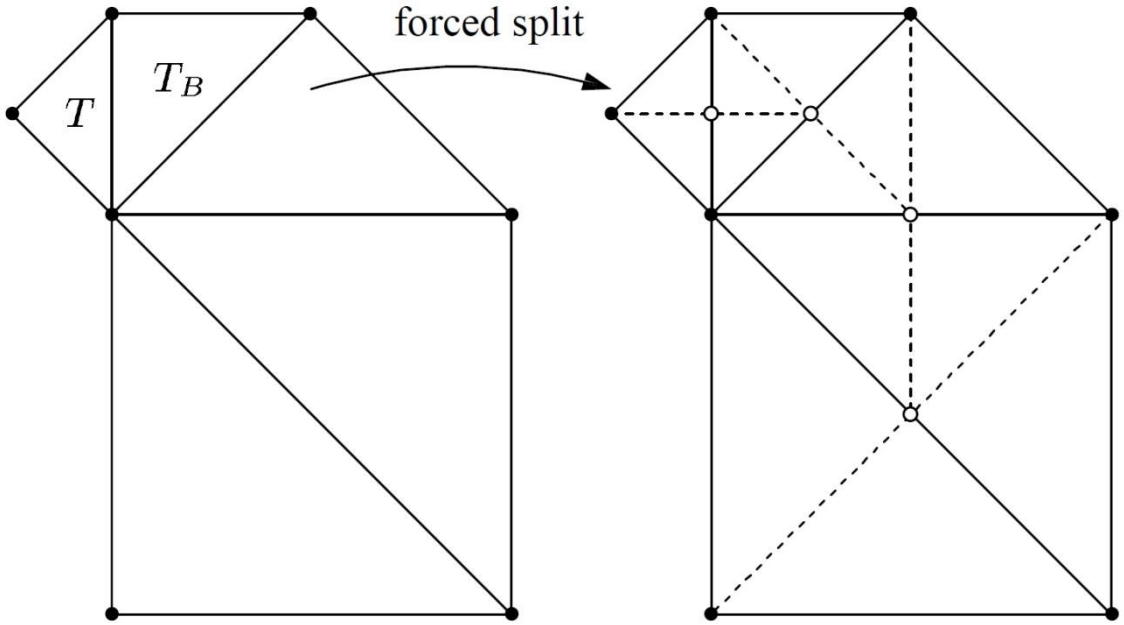


Figure 3-3: Forced split of triangle T [Duc97]

To take advantage of frame coherence, ROAM uses a dual queue approach, the split queue and the merge queue. According to the importance of the split or merge these queues are sorted. The most imported merges and splits are performed first. This gives a good flexibility at run-time. In a frame coherence system the amount of splits and merges are dependent on the change of the viewport. If the change of the viewport is big the system needs to do a lot of merges and splits. This could lead to a drop in the frame rate. With the two priority queues it is now possible to do only the most important calculations in the queue and do the rest in another frame where the change is not that big. So a constant frame-rate can be guaranteed while having only a small error.

The base error metric of ROAM is to calculate the distance between where the surface point should be in screen space and where the triangulation places the point. Therefore nested world-space bounds are needed. These are precalculated bounding volumes around each triangle, which were calculated in world space and are called wedgies. The wedgies allow faster calculation and provide a guaranteed error bound. This error bound is the maximum amount that the plane formed by the triangle varies from the original fine detailed terrain. *Figure 3-4* shows how wedgies are built through the vertices when a merge operation is done. At real-time the precalculated wedgies are transformed into screen space to compute a local upper bound, which represents the base error metric.

Other most important error metrics that can be done with ROAM are back-face detail reduction, view frustum and silhouette edges. For all triangles that are facing away from the camera and outside the view frustum the priority can be set to a minimum. Because the viewer doesn’t see these triangles they can be coarsened in a later frame without the

viewer recognizing it. Silhouette edges are the triangles, where a front-face to back-face transition takes place. To have a good visual representation, it is important to give such triangles a high priority.

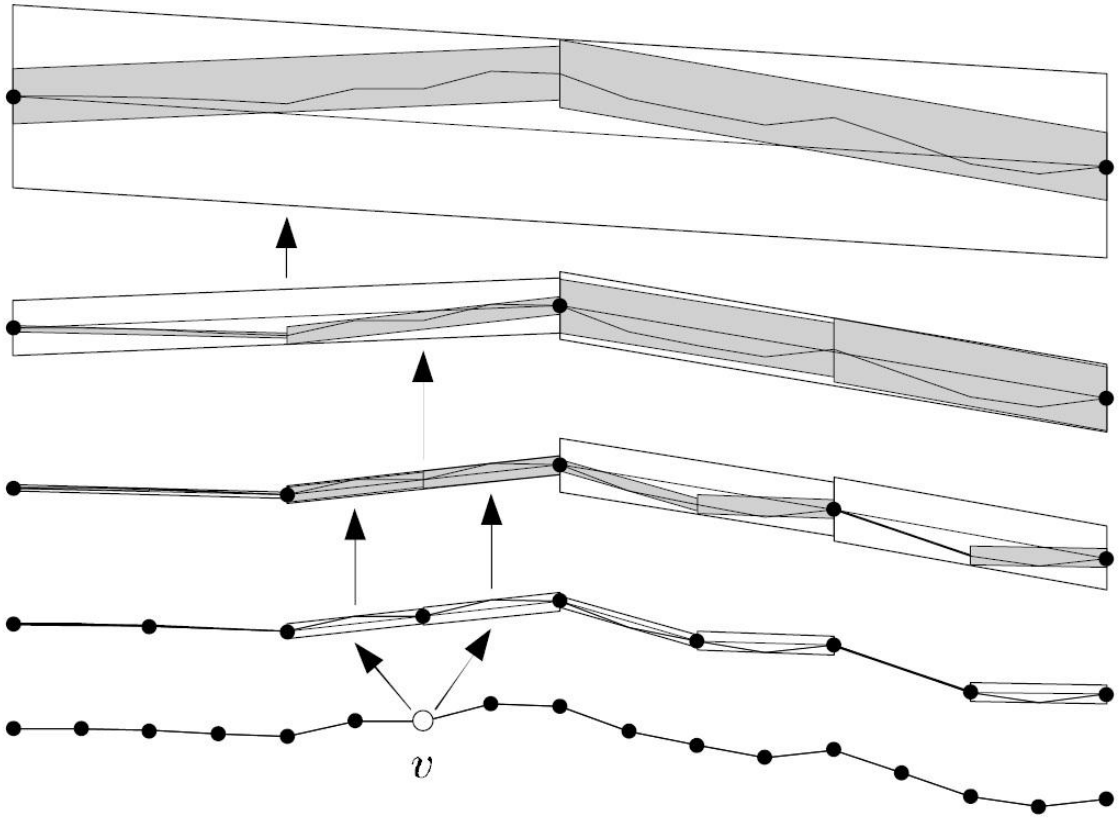


Figure 3-4: Construction of nested wedgies [Duc97]

Now that we have all building blocks of ROAM we can look at the processing phases that are performed each frame.

1. View frustum culling is updated.
2. Do priority update for triangles that can potentially be split or merged in next phase. Split queue and merge queue is updated.
3. Triangulation update driven by split and merge queue.
4. Update all triangles that area dependent on phase 1 and 3.

One limitation for terrain rendering is important to mention. The resolution of the height map is the limitation for the level of refinement of the terrain. So the maximum detail of the terrain is directly dependent of the size of the height map. Therefore the refinement of a triangle stops when either the error is small enough or the maximal triangle count is reached.

In conclusion ROAM is a flexible view-dependent terrain rendering algorithm, which allows a fixed frame rate and can work towards a fixed triangle count. The problem with ROAM is that it makes small sets of triangles for rendering. Modern GPUs are working better with a large number of triangles. Because of that ROAM 2.0 was

developed which mixes the continuous LOD approach of ROAM with a discrete LOD system. [25] [26]

The original ROAM algorithm has been modified and improved by a number of researchers and game developers. One example is the implementation of Bryan Turner. He implemented a simplified version of ROAM. In his approach he uses a split only approach where the terrain is refined from scratch in each frame. Therefore he uses a variance binary tree, which stores geometric error. The variance tree is updated every frame according to the change of the scene. The terrain is then tessellated according to the variance binary tree. [27]

ROAM is also able to deal with dynamic terrain. Yefei He developed a real-time dynamic terrain for an off-road ground vehicle simulation, in which a vehicle can deform the terrain. So it's possible to form skid marks of the car into the terrain. The system is called DEXTER (Dynamic EXTEnsion of Resolution). [28]

3.2. Smooth View-Dependent Level-of-Detail Control and its Application to Terrain Rendering

Hugues Hoppe developed the terrain algorithm in 1998. The representation uses as base view-dependent progressive meshes that were introduced in section *2.3.4*. The target of this terrain rendering systems was to render the Grand Canyon data in real-time, which has about 16.7 million triangles. To be able to render this data the complexity of the terrain needed to be reduced to 20000 triangles. This was the number of polygons, which graphics hardware was able to render in 1997. To achieve this target they would like to adapt the mesh complexity according to the screen-space projected error, which makes a view-dependent LOD system. So the terrain is refined more densely near the viewer, while distance and regions outside the view frustum are kept coarser. It was also the goal to make a terrain rendering system with improved approximation error and that provides scalability. Two important factors for a good terrain system they also tried to achieve were a constant frame rate and the absence of popping artifacts.

To avoid popping artifacts the screen-space error value needs to be near 1 pixel. When the screen-space error is near 1 pixel the change of resolution can't be seen by the viewer. The problem of a constant error tolerance is that the number of faces depends directly on the terrain complexity near the viewpoint. This leads to a non-uniform frame rate because the frame rate is dependent on the number of triangles that need to be

[25] cf. [Duc97]
[26] cf. [Lue03], page 202-206
[27] cf. [Tur00]
[28] cf. [HeY00]

rendered, and these are not constant in this approach. For a constant frame rate, the screen-space error needs to be adjusted. But this leads to popping artifacts. To hide the popping artifacts they use geomorphs. At run-time the triangles of the terrain need to be split or refined to get the needed resolution. Instead of doing the refine and split in one frame they morph it over several frames.

When do we need to use this geomorphing in a terrain rendering system? There are two different situations we need to consider. One is forward moving the other is backward moving.

When we move forward we use geomorph refinement. In *Figure 3-5* we see how the view port changes when we move forward and turn left at the same time. We get three different regions. All parts that are new in the view frustum are instantaneous refined, all parts that are outside the view frustum are instantaneous coarsened and all parts that were visible in the frame before, we need to do geomorph refinement.

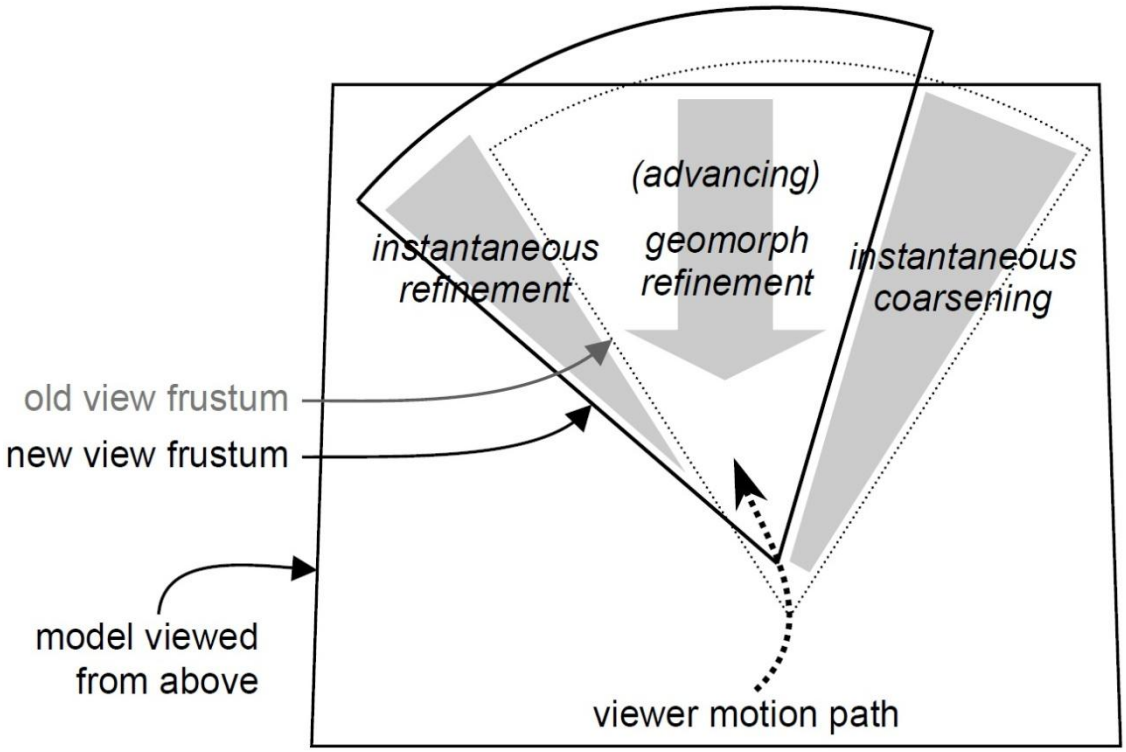


Figure 3-5: Changes to active mesh during forward motion of viewer [Hop98]

Figure 3-6 shows how a geomorph refinement is done. At first we do a split operation. But instead of placing the new created vertex directly on its final position we spawn the vertex on the old vertex. After this we move the new vertex over several frames to his new position. How long this morphing takes, depends on a user specified time, which is called gtime. With a frame rate between 30 to 72 fps the gtime is set to 1 second. A nice thing about geomorph refinement is that while a new vertex is morphing it can be split already. So we're able to do several geomorph refinements at the same time.

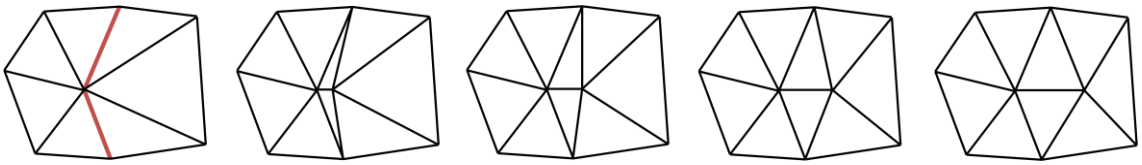


Figure 3-6: Shows geomorph refinement [Hop981]

We use geomorph coarsening for moving backward. When we move backward and turn right at the same time we get three different regions as well. All parts that are new in the view frustum are instantaneous refined, all parts that are outside the view frustum are instantaneous coarsened and all parts that were visible in the frame before, we need to do geomorph coarsening. Geomorph coarsening is more complex than geomorph refinement. It is just the reverse as shown in *Figure 3-6*. We gradually move the vertex to its parent position. Only when the vertex is at its parents position the mesh connectivity can be updated, which means to merge the vertex with its parent vertex. Only one geomorph coarsening is possible at a time. Therefore gtime is reduced to the half. Fortunately geomorph coarsening is only required when the user moves backward, which doesn't happen that often.

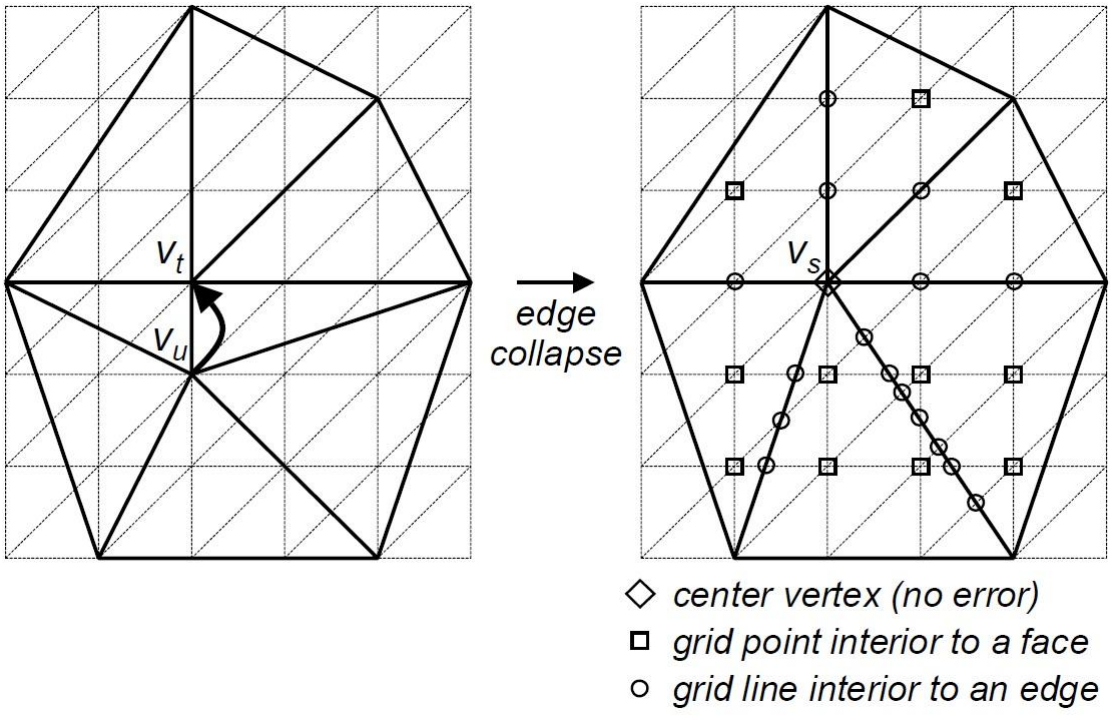


Figure 3-7: Accurate approximation error [Hop98]

For an accurate approximation error they needed a new approach because measuring the error at grid points is not accurate enough. The solution was to take the new added points of the coarsened mesh into account. In *Figure 3-7* all points that need to be taken into account for an accurate approximation error are marked. For definition of the points the detailed terrain mesh as well as the coarsened mesh is needed. The coarsened mesh is set over the detailed mesh. For the calculation of the error we need to select all grid points interior to a face and all grid lines interior to an edge. The computed error is

exact because it is possible to compute it with respect to the original fully detailed mesh. Additionally the error can be precalculated. Therefore this operation is not time critical.

Now let's see how they wanted to achieve scalability. Scalability is very important when you have the target to render a mesh with more than 16.7 million triangles in real-time. To achieve scalability they used a hierarchical approach, which decomposes the mesh into blocks. The difficulty is to preserve spatial continuity. Without spatial continuity cracks or holes could appear which is really bad for a terrain rendering system.

To achieve scalability they developed a hierarchical progressive mesh construction. Their approach is motivated by three considerations. The first is that simplification is memory intensive because it starts from the detailed mesh. The second is that for larger objects even the pre-simplified mesh could be too large to fit into main memory. And the last is that the associated texture image may be too large for memory as well.

In *Figure 3-8* you can see the different steps that are needed for the hierarchical block based simplification. First the detailed mesh is partitioned into blocks of the same size. These blocks are simplified while preserving their boundary vertices. After this step these blocks are merged together to build larger blocks and a bottom-up recursion is applied for further simplification. This is done until we have a very coarse base mesh.

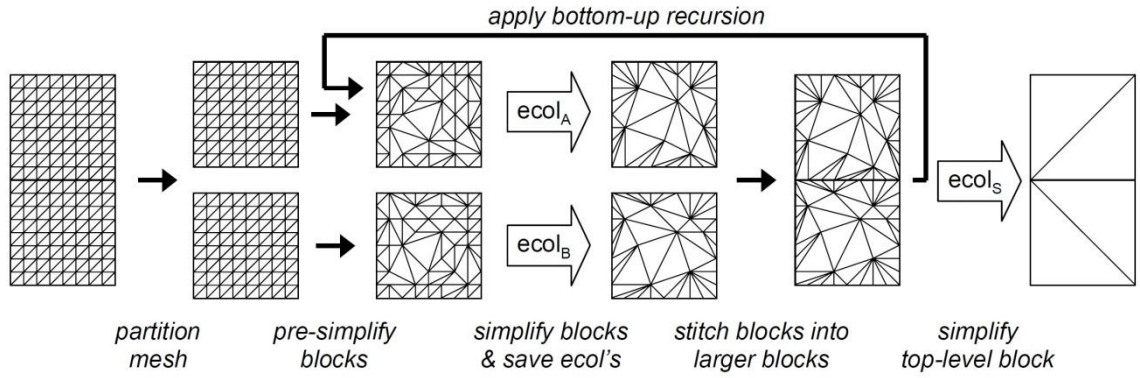


Figure 3-8: Hierarchical block-based simplification [Hop98]

At the end we have a coarse mesh and a sequence of vertex splits, organized into block refinements. But these block refinements permit memory management because the refinement needs to stay in memory even if the mesh is not refined. *Figure 3-9* shows how the coarse base mesh is used with the sequence of vertex splits to create a pre-simplified terrain.

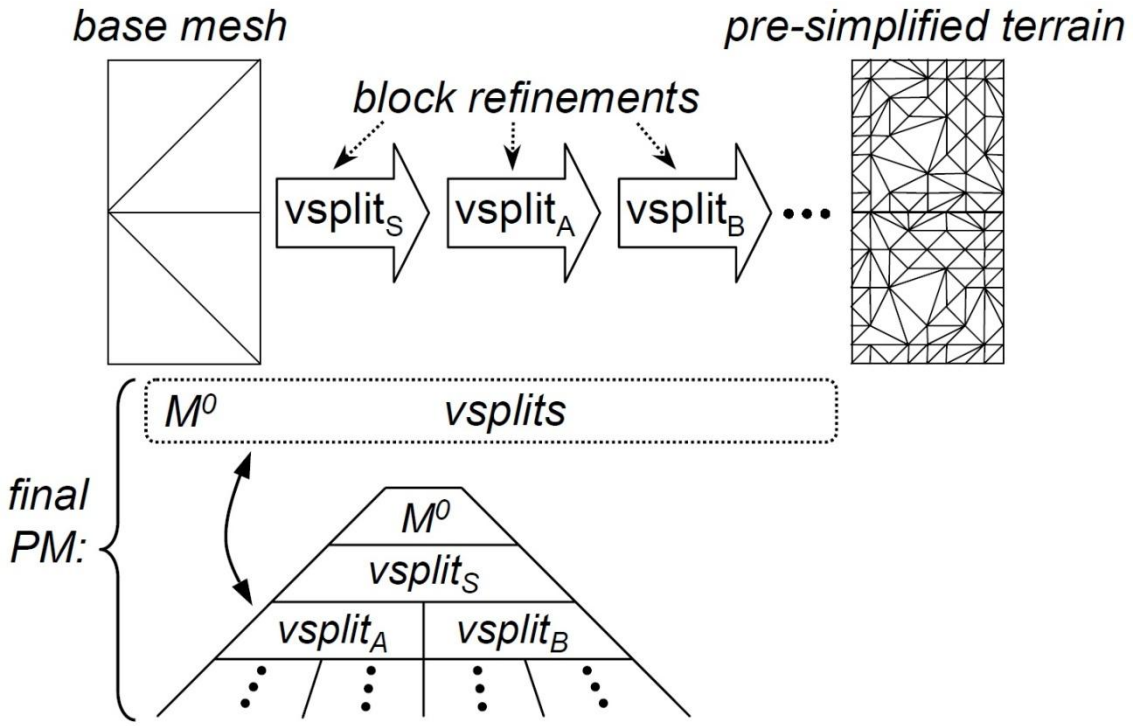


Figure 3-9: Result of the hierarchical construction process [Hop98]

With this rendering algorithm Hoppe was able to scale down the terrain detail from 16.7 million triangles to 12000 triangles with an average error of 1.7 pixels to get 30 fps. With an average pixel error of 3.5 it was even possible to scale down to 5000 triangles to get 60 fps. They tested this algorithm on a 200MHz CPU (SGI Octane, 195MHz R10K, MXI).

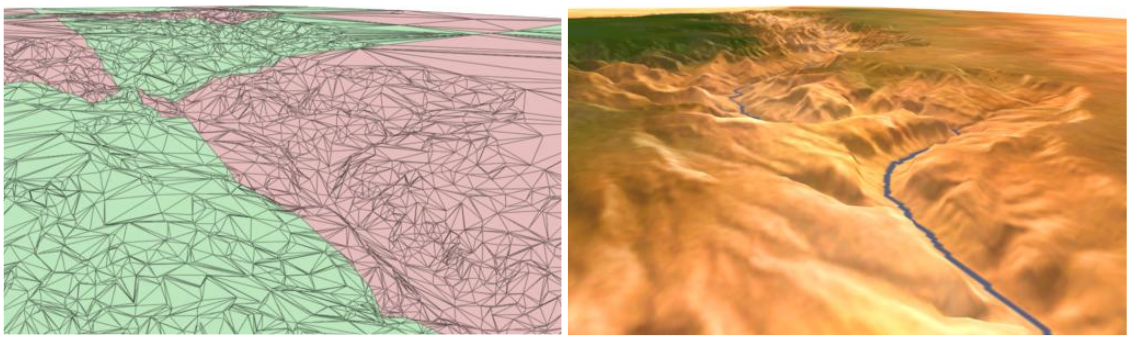


Figure 3-10: Mesh with an average error of 2.1 pixels, which has 6.096 vertices [Hop98]

The advantages of this approach are that it is possible to obtain accurate meshes with few faces and it generalizes easy to arbitrary surfaces. Also the detail of the mesh could be adapted to the Hardware capabilities. Additionally the algorithm is scalable through it block based approach and has accurate approximation error. The algorithm also shows that surface based approximation can be efficiently done with terrain.

The problem of this approach is that the detail is limited by the original terrain resolution. The detail could for example be enhanced through randomly build detail through a noise algorithm. [29]

3.3. Geometry Clipmaps

Geometry clipmaps were developed by Frank Losasso (Stanford University & Microsoft Research) and Hugues Hoppe (Microsoft Research) in 2004. They wanted to master several challenges with their terrain rendering algorithm. One was to be able to store, manipulate and render a large number of samples. So as primary data set they used a 40 GB large height map of the United States. They wanted to render this data set in real-time with a constant frame rate of 60 frames per second. They wanted to have a concise storage and visual continuity. Concise storage means that they didn't want to have loading times during the real-time application or lags because they needed to read data from disk. With visual continuity they wanted to achieve a terrain representation without cracks or popping artifacts. They also wanted to develop a terrain algorithm that is more GPU based and therefore decreases the workload of the CPU.

Former terrain algorithms were view-dependent LOD algorithms. The terrain was adaptively refined and coarsened according to a screen-space geometry error. The screen-space geometric error was dependent on the viewer distance, the surface orientation and the surface geometry. So the geometry was only refined where it was needed to render as less polygons as possible. Geometry clipmaps take quite a different approach. Its LOD system depends only on the viewer distance. Geometry data is stored in a set of uniform 2D grids. The LOD comes from nesting these 2D grids around the player. Each grid differs by a factor of two in resolution at each refinement transition. For example if the coarsest level 0 has a grid resolution of 1-to-1 quads, level 1 has a grid resolution of 2-to-2 quads and level 2 has a grid resolution of 4-to-4 quads.

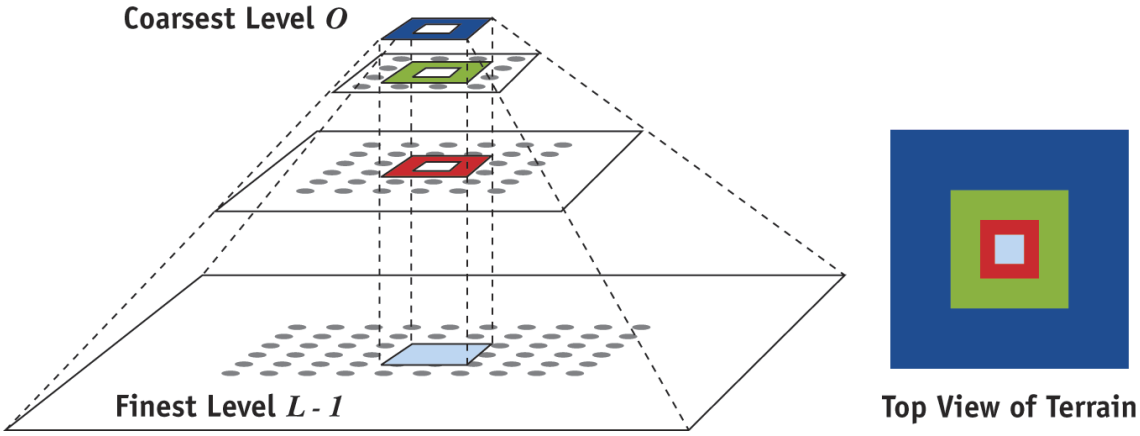


Figure 3-11: How geometry clip maps work [Asi05]

[29] cf. [Hop98], [Hop981]

Figure 3-11 shows how the geometry clip map hierarchy can be illustrated. It can be compared to a mipmap[30] pyramid. The full hierarchy is a prefiltered sequence of all possible grid resolutions, where the finest level contains the whole terrain at the finest resolution. The coarsest level has the size of the active region. The active region is the region that is rendered into screen-space. Its size is calculated according to the windows size W, the field of view φ and the screen-space triangle size s. With W=640 pixels, φ=90° and s=3 pixels we got an active region of 255-to-255.

For creating the terrain we first select the finest level, which is rendered as a grid square. The next coarser level is than selected, where the region of the finest level is cut out. In the same way the other coarser levels are selected until we are at the coarsest level. As a result we get a terrain that is rendered as in *Figure 3-12*. The different regions are shown in different colors.

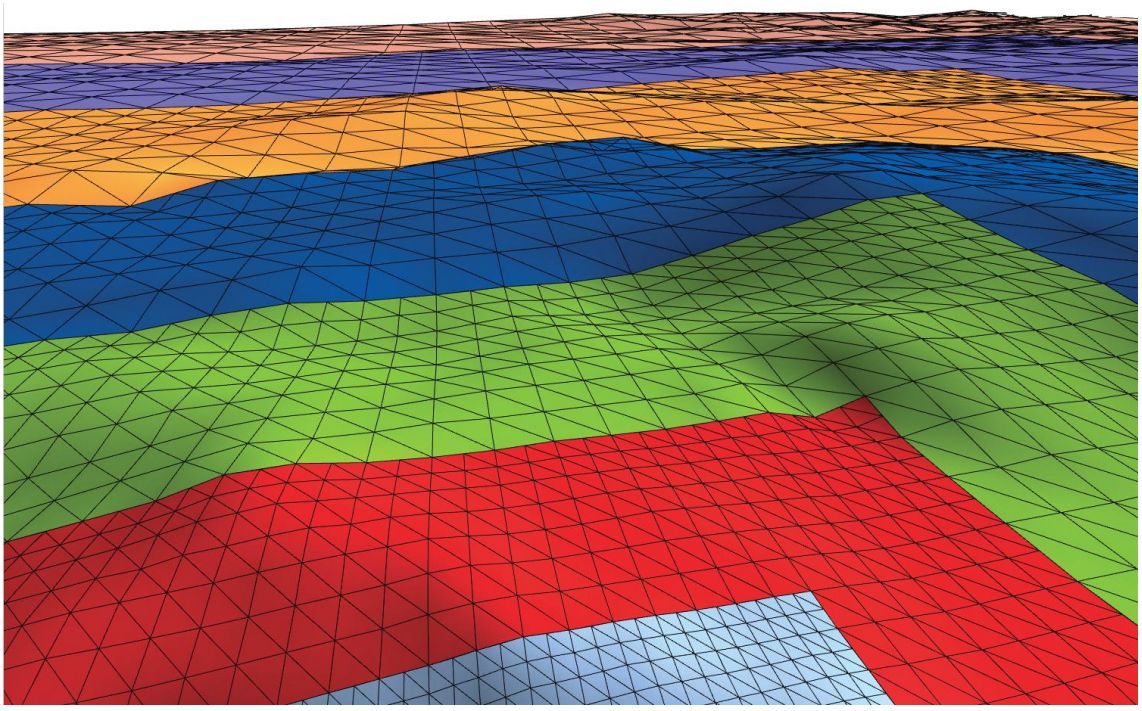


Figure 3-12: Terrain rendering using a coarse geometry clipmap [Asi05]

Lasasso and Hoppe also thought about the texturing of the terrain. They wanted to be able to handle huge texture maps. For texturing they used the same structure as for the geometry clipmaps. Each clipmap level is associated to a texture image. Additionally they store normals in an 8-bit-per-channel normal map. The normal map has twice the resolution of the geometry.

With the current approach of rendering terrain there is the problem that t-junctions and cracks appear on the boarders between the different grid resolutions. Secondly the texture at the border gets blurred because the textures are associated with the clip map

[30] Mip-mapping is a simple texture filtering technique that is intended to increase rendering speed and reduce aliasing artifacts.

levels. To solve these problems Losasso and Hoppe do a transition between the boarders. The transitions for geometry can be performed in the vertex shader and the transition for textures can be performed in the pixel shader. [31] *Figure 3-13* shows the transitions regions.

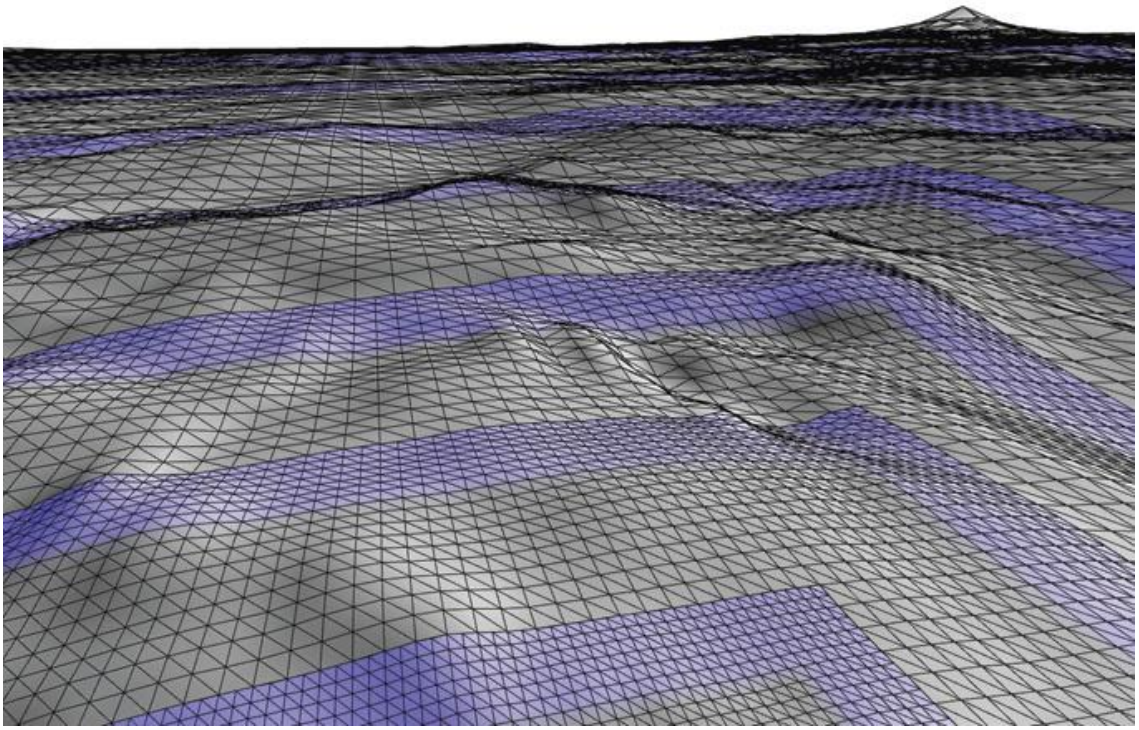


Figure 3-13: Terrain rendering using a geometry clipmap with transition regions [Asi05]

The transition solves the cracks problem for the geometry and the texture problem. But it does not solve the issue with the t-junctions. Before I can explain how the problem with the t-junctions was solved. I first have to explain how the geometry is rendered. To exploit any hardware occlusion culling, the regions around the finest level grid are partitioned in 4 rectangular regions. These rectangular regions are rendered using indexed triangle strips. With this approach it is possible to render about 60 million triangles per second on an ATI R300. *Figure 3-14* illustrates how the regions are created. Concerning the t-junction problem they use a simple solution. They just use zero-area triangles along the render regions boundaries.

Now let's have a look at the steps that need to be performed each frame form the algorithm. First according to the player position the desired active region needs to be determined. With the new active region the geometry clipmaps need to be updated. Therefore we have to update each clipmap level. After the clipmaps are updated the scene can be rendered.

[31] see section Vertex Shader *4.2.* for explanation of vertex shader and section *4.7.* for explanation of pixel shader

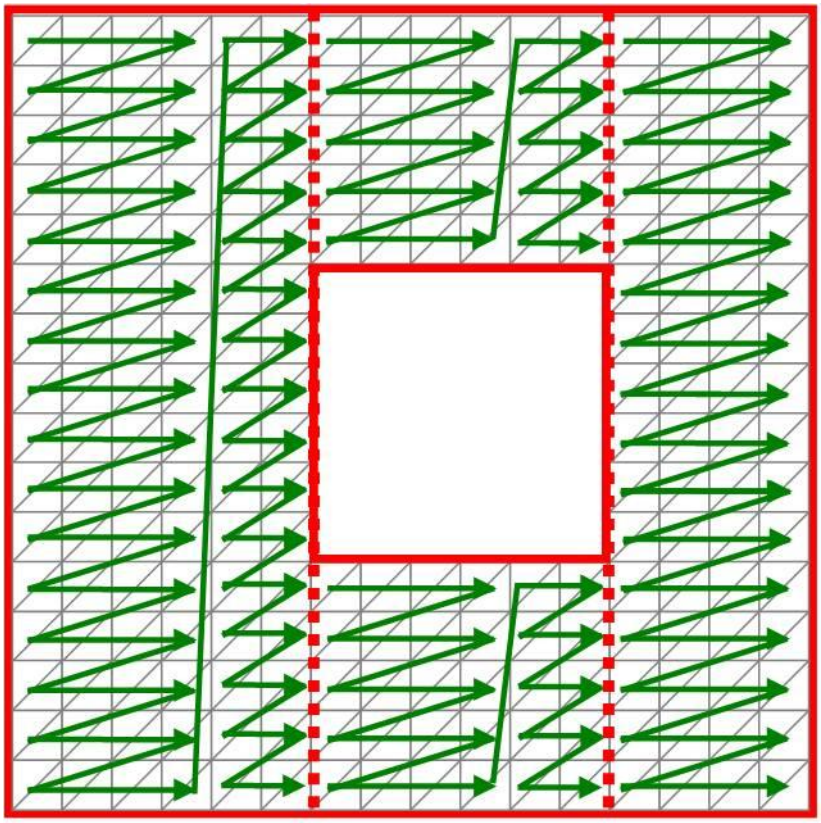


Figure 3-14: Illustration of triangle strip generation within a renderer region. [Los041]

Geometry clipmaps provide a number of advantages. The first is simplicity. There is no complex data structure used and no tracking of refinement dependencies is needed. Geometry clipmaps also provide an optimal rendering throughput. Clipmap vertices can be stored in video memory and indexed triangle-strips can be used for optimal rendering throughput. Visual continuity is provided and can be processed inside the vertex shader and pixel shader. Geometry clipmaps also provides a constant frame rate because the tessellation complexity is independent of local terrain roughness.

The two most important features of geometry clipmaps are compression and synthesis. Geometry clipmaps can compress a terrain data of 20GB to 375 MB. So the data fits into the main memory. The algorithm can decompress this data and render it at 60 fps. With synthesis of procedural terrain it is even possible to generate finer geometry detail through a noise function than the height map provides.

But there are also some limitations of this approach. The geometry is sometimes more complex than is optimal. The worst case is always expected that the terrain has a uniform detail. Sometimes too many vertices are rendered. With geometry clipmaps only fine-grained detail is possible near the viewport. So silhouettes of mountains that are distant to the viewport could sometimes not be rendered with the needed detail. But on the other hand this is also the reason the mesh is regular and can reside in video memory, which gives an optimal rendering performance and a constant frame rate.

Hugues Hoppe and Arul Sirvatham (Microsoft Research) improved geometry clipmaps to make it more GPU-based. They achieved that everything except of the decompression could be done on the GPU. With the GPU based approach they are able to render the terrain at around 90 fps what gives a performance gain of about 50%. [32]

[32] cf. [Los04], [Los041], [Asi05]

4. DirectX 11 Shader Pipeline

In the past rendering of highly detailed models were not possible in real-time. The main limitation for the number of polygons to render was the bus bandwidth between CPU and GPU. Every highly detailed polygon mesh needed to be transferred over that bus. An additional limitation was the main memory of the graphics hardware. Even when it was managed to transfer the data, it couldn't be stored on the memory of the graphics card. To be able to render a high number of polygons on the graphics hardware, the way of how to render high polygon meshes needed to be rethought.

Figure 4-1 shows how meshes were modeled in the past. First the artist modeled a low poly mesh, which is called control cage or subd mesh, in Autodesk Maya[33] or Autodesk 3ds Max.[34] After that the mesh was imported to Pixologic ZBrush.[35] In ZBrush the low poly mesh was refined to a smooth surface. With the help of a displacement map it was now possible for the artist to model a heigh detailed displaced surface. The final displaced surface was converted in a high polygon mesh. For the polygon mesh several discrete LODs were created. This discrete LODs had much less polygons. For rendering on the GPU the low poly mesh and the different generated LODs were used.

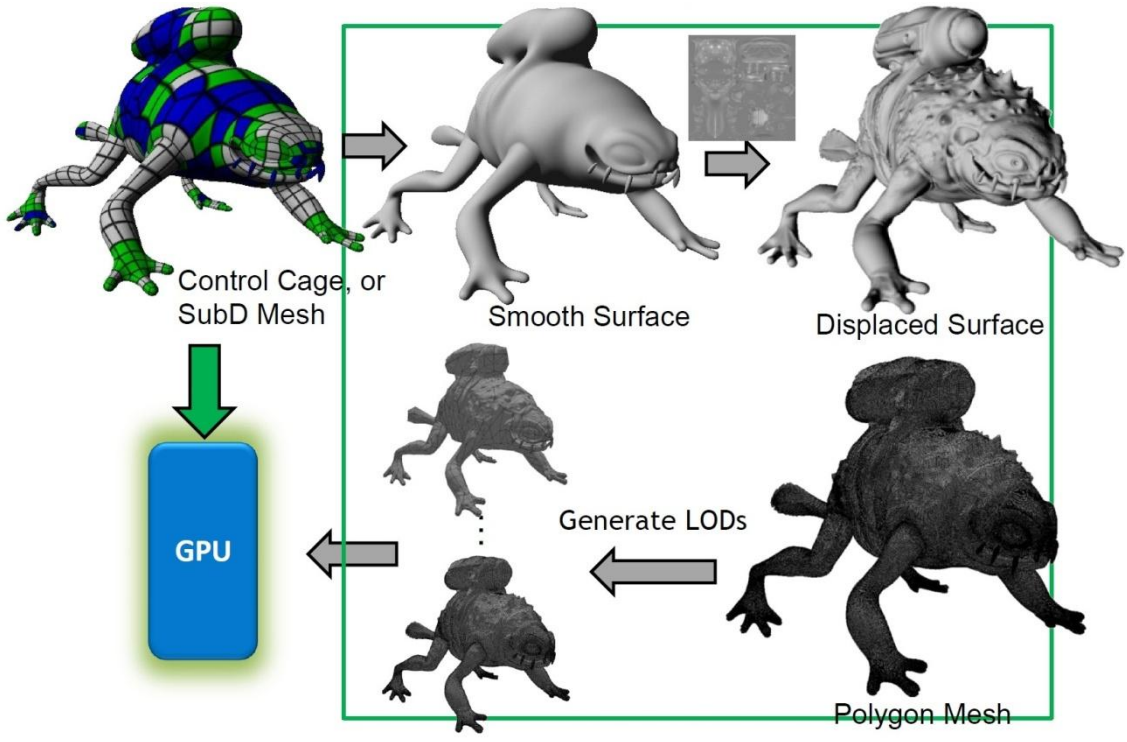


Figure 4-1: Authoring pipeline of the past [NiT09]

[33] see http://usa.autodesk.com/maya/ (accessed March 2011) for product description
[34] see http://usa.autodesk.com/3ds-max/ (accessed March 2011) for product description
[35] see http://www.pixologic.com/zbrush/ (accessed March 2011) for product description

With real-time tessellation a totally different approach is now possible. Instead of generating a high polygon mesh it is possible to use a control cage and a displacement map to generate an optimally tessellated mesh in the GPU. Therefore the displacement map is used, which was also used from the artist to model the displaced surface. *Figure 4-2* shows an illustration of the new approach. It allows rendering smooth and continuous surfaces. Additionally the new approach is also a type of data compression. It is only needed to save the low polygon mesh and a displacement map. The rest is calculated in the GPU on the fly for every frame. The optimal tessellated mesh does not need to be stored. It is only generated for one frame. This gives the possibility of creating a view-dependent LOD system.

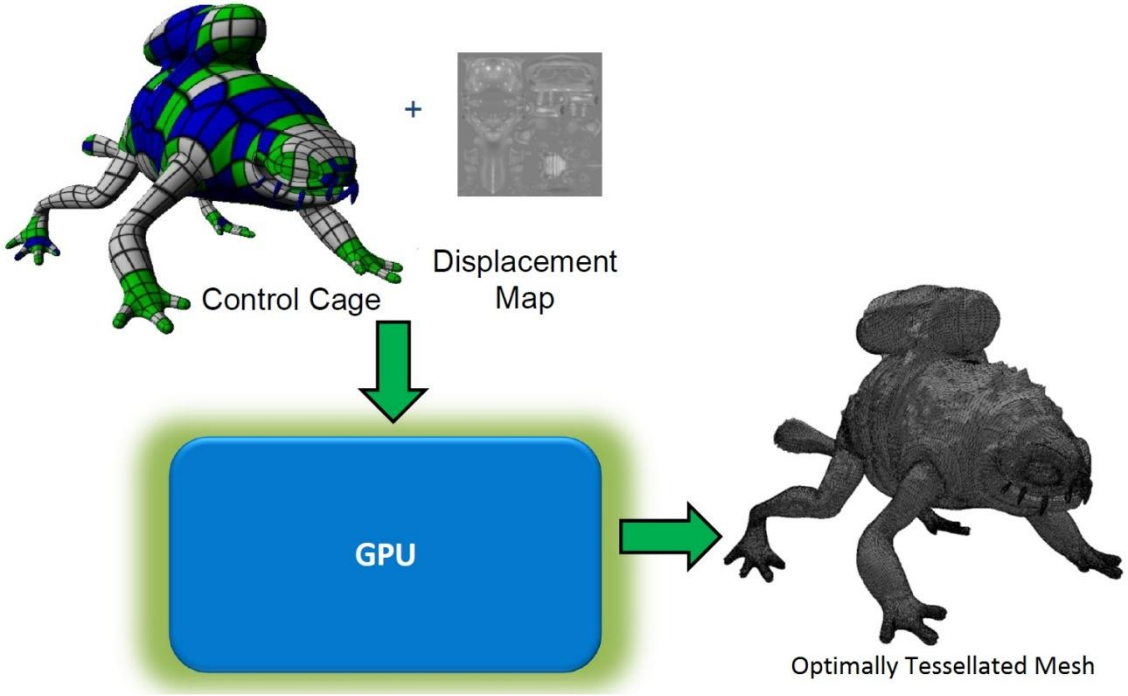


Figure 4-2: Real-time tessellation rendering [NiT09]

Another big advantage of tessellation is that faster dynamic computations can be performed. Things like skinning animation, collision detection or any per-vertex transforms on a mesh can now be done faster because the low poly mesh is used for these operations.

Real-time tessellation rendering solves the problem of rendering highly detailed models in real-time. But what do we need to be able to use this approach on a GPU? First we need to be able to program the GPU. Therefore we need shaders. A shader is a script that tells a state of the graphics hardware what calculations to do. It gives a developer the freedom to decide what and how something is processed on the graphics hardware. A shader is executed repeatedly for different inputs according to the configuration of the developer. The first graphics card that supported shaders was the GeForce 3, which was

created by NVIDIA.[36] It was released in 2001 and supported shader model 1.1. The first version of the shader model gave the developers only a little possibility to program the GPU. Over the years, shader model was more and more extended.

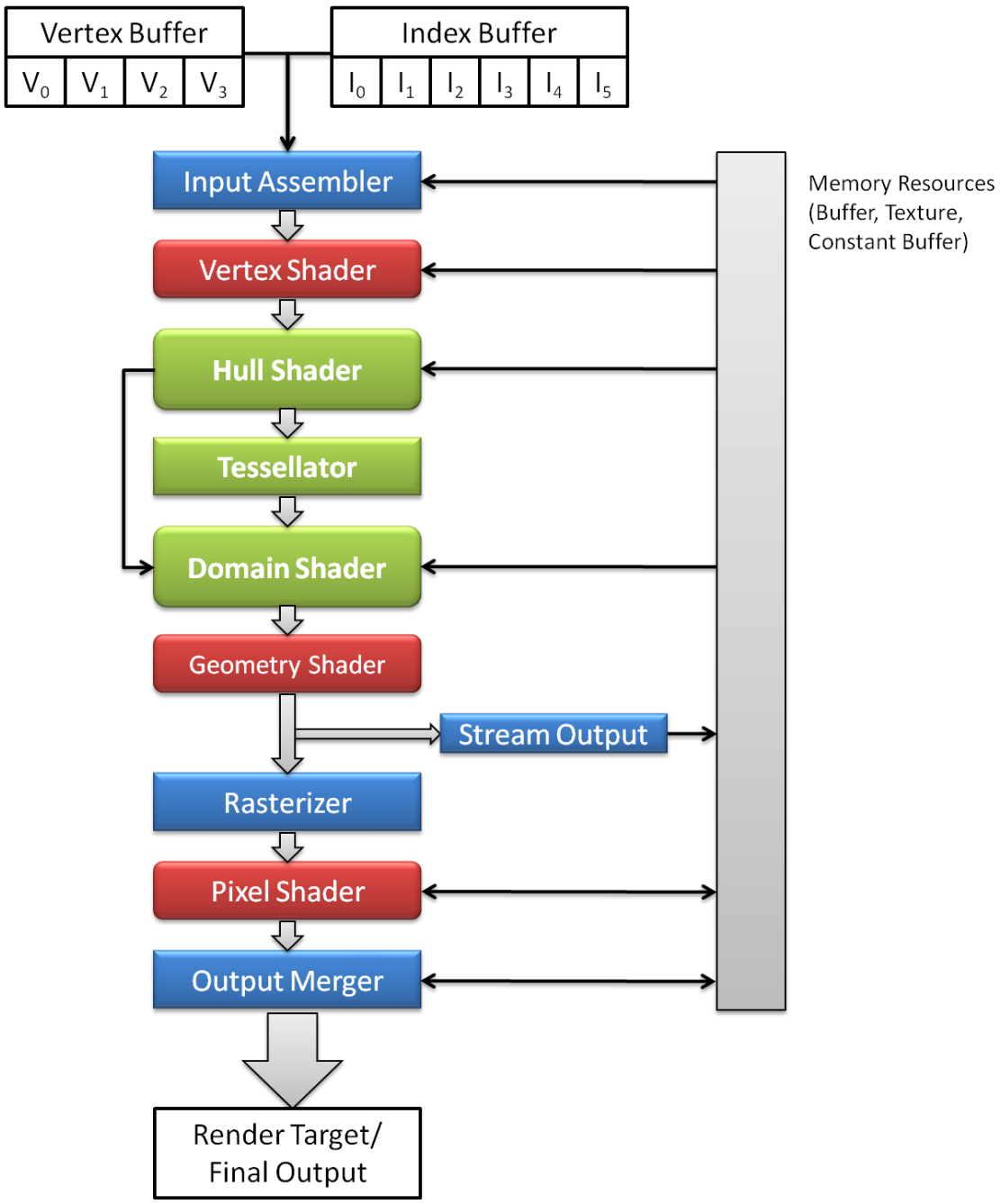


Figure 4-3: Shader pipeline DirectX 11 [37] [38]

Today the newest shader model is shader model 5.0, which is part of DirectX 11. DirectX 11 extends the DirectX 10 shader pipeline with three new stages, the hull

[36] GeForce 3 Announcement. February 20, 2001 http://www.youtube.com/watch?v=vXklWt0SD9I (accessed March, 2011)
[37] cf. [Mic11], http://msdn.microsoft.com/de-de/library/ff476882%28v=VS.85%29.aspx (accessed March 2011)
[38] cf. [Jef09], [Lee09]

shader, the tessellator and the domain shader. These stages offer a flexible and programmable hardware support for tessellation. Domain shader and hull shader are fully programmable. The second thing that is needed is the ability to tessellate a low polygon mesh directly on the GPU. The tessellator is a fixed function that supports some basic settings. The number of rendered polygons is no longer limited by the bus bandwidth between CPU and GPU. It's now limited by the processing power of the GPU. *Figure 4-3* shows the different stages of the pipeline. The green boxes are new in shader model 5.0. The rest was part of the previous shader model 4.0. The functions of the different shader stages will be explained in the next sections. [39] [40] [41]

4.1. Input Assembler

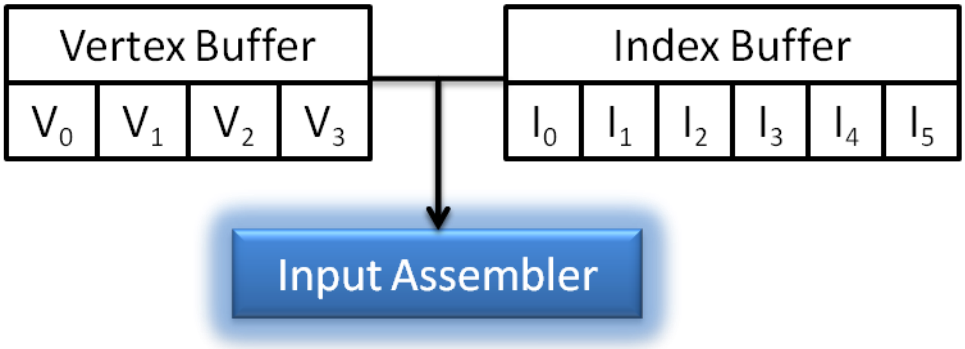


Figure 4-4: Input assembler

The input assembler gets the data of the vertex buffer. The data that is stored in the vertex buffer can be defined by the programmer. Normally data in the vertex buffer is the position, texture coordinates, normal or tangent of the vertex. Optionally an index buffer can be used from the developer. An index buffer points to a vertex of the vertex buffer. A vertex of a mesh is often used several times. So it is possible to save data when using an index buffer. The method `ID3D11Device::CreateBuffer`[42] is used to create a vertex buffer or an index buffer.

The input assembler can output primitives with up to 32 vertices. The primitives that are used need to be defined with the enumeration `D3D11_PRIMITIVE_TOPOLOGY`[43] using

[39] cf. [Mic11], http://msdn.microsoft.com/de-de/library/ff476340%28v=VS.85%29.aspx (accessed March 2011)
[40] cf. [Val10], page 1-3
[41] cf. [Jef09], [Hex10]
[42] cf. [Mic11], http://msdn.microsoft.com/en-us/library/ff476501%28v=VS.85%29.aspx?appId=Dev10IDEF1&l=EN-US&k=k%28ID3D11DEVICE%29;k%28DevLang-%22C++%22%29&rd=true (accessed March 2011)
[43] cf. [Mic11] http://msdn.microsoft.com/query/dev10.query?appId=Dev10IDEF1&l=EN-US&k=k%28D3D11_PRIMITIVE_TOPOLOGY_3_CONTROL_POINT_PATCHLIST%29;k%28DevLang-%22C%2B%2B%22%29&rd=true (accessed March 2011)

the method `ID3D11DeviceContext::IASetPrimitiveTopology`.[44] These topologies determine how the vertices will be rendered on the screen. For tessellation 32 new primitives topologies were added. The topology that's need to be set is `D3D11_PRIMITIVE_TOPOLOGY_n_CONTROL_POINT_PATCHLIST`, where n stands for the number of vertices per primitive. If we use a quad we would use for example `D3D11_PRIMITIVE_TOPOLOGY_4_CONTROL_POINT_PATCHLIST`. So the input assembler would read the vertex buffer in chunks of four vertices. These chunks will then be put to the next stage, which is the vertex buffer. [45]

4.2. Vertex Shader

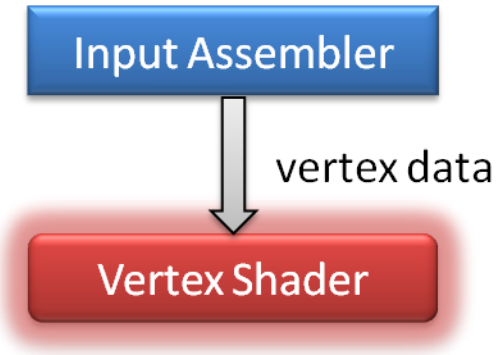


Figure 4-5: Vertex shader

The vertex shader gets the vertex data from the input assembler. It is executed once per control point and can only see one control point at a time. The vertex shader is capable of manipulate a vertex. Skinning animation, collision detection, morphing and any per vertex transforms can be done with the vertex shader. It also provides the possibility that no calculations are performed by the vertex shader. In this case a pass-through vertex shader must be created. It is not possible to deactivate the vertex shader stage. Vertex data cannot be seen by later stages. Everything that later stages need from the vertex data, have to be passed through the pipeline. The vertex shader doesn't need to calculate a projection-space vertex as in shader model 4.0. It passes data down to the hull shader. [46] [47]

[44] cf. [Mic11] http://msdn.microsoft.com/en-us/library/ff476455%28v=VS.85%29.aspx (accessed March 2011)
[45] cf. [Jef09]
[46] cf. [Jef09]
[47] cf. [Mic11], http://msdn.microsoft.com/de-de/library/bb205146%28v=VS.85%29.aspx (accessed March 2011)

4.3. Hull Shader

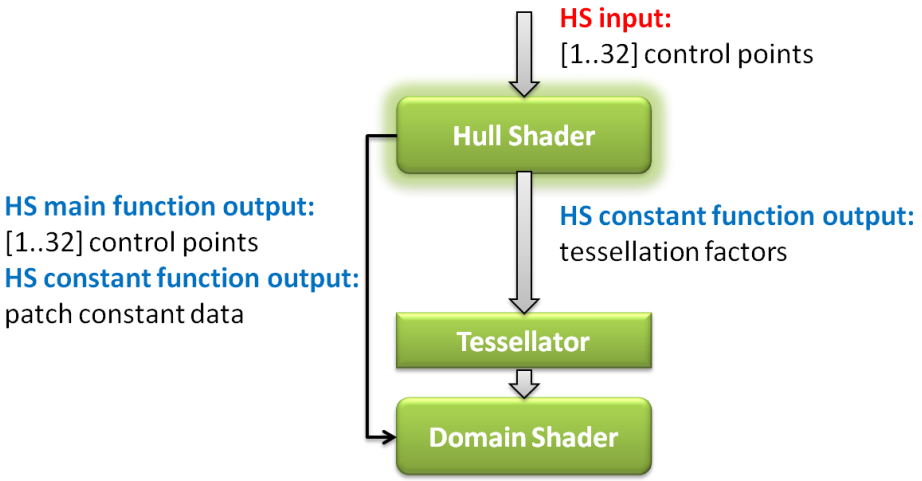


Figure 4-6: Hull shader

The hull shader is fully programmable. It receives patch control points from the vertex shader. The number of the control points of a patch is between 1 and 32. The number depends on the primitive topology. The hull shader is divided in two parts. The hull shader constant function and the hull shader main function. They have both fully visibility of the vertex shader output and run in parallel.

The hull shader constant function is executed once per-patch. Primary it is for the calculation of the tessellation factors that determine how much the tessellator has to subdivide the mesh. Is any tessellation factor set to less or equal 0, the patch will be culled. As a result the tessellator will not run and the domain shader will not run for this patch. So it is very important to calculate all patches that are not visible. With this calculation a lot of unnecessary processing can be saved. Which tessellation factors have to be calculated is dependent on the domain type that is used. Triangle, quad and isoline are the three different domain types that are possible. For a triangle four factors have to be calculated, three tessellation factors for the sides and one for the inner part of the triangle. A quad needs four tessellation factors for the sides and two for the inner part. An isoline has two tessellation factors. One is for the line-detail tessellation factor and the other is for line-density tessellation factor. Line-density tessellates the line and line-detail describes how many times to instance the tessellated line. The hull shader constant function is also for the calculation of patch constant data. This data is passed to the domain shader. Patch constant data is data that is calculated for one patch and could be useful for further calculations in the domain shader. The calculation of a patch constant data is optional. The output is limited to 128 scalars, which are the same as 32 float4's.

The hull shader main function is executed per output control point and it can see all input control points of the patch. In this stage any change on the primitive can be

calculated. Developers can declare how many output control points will be generated. The number of the generated output points is independent on the number of the input control points from the vertex shader. The output is limited to 128 scalars or 32 float4's. The maximum output for all hull shader invocations is 3968 scalars. In practice this means when outputting 32 control points only 31 float4's can be used. The control points are output to the hull shader. [48] [49]

4.4. Tessellator

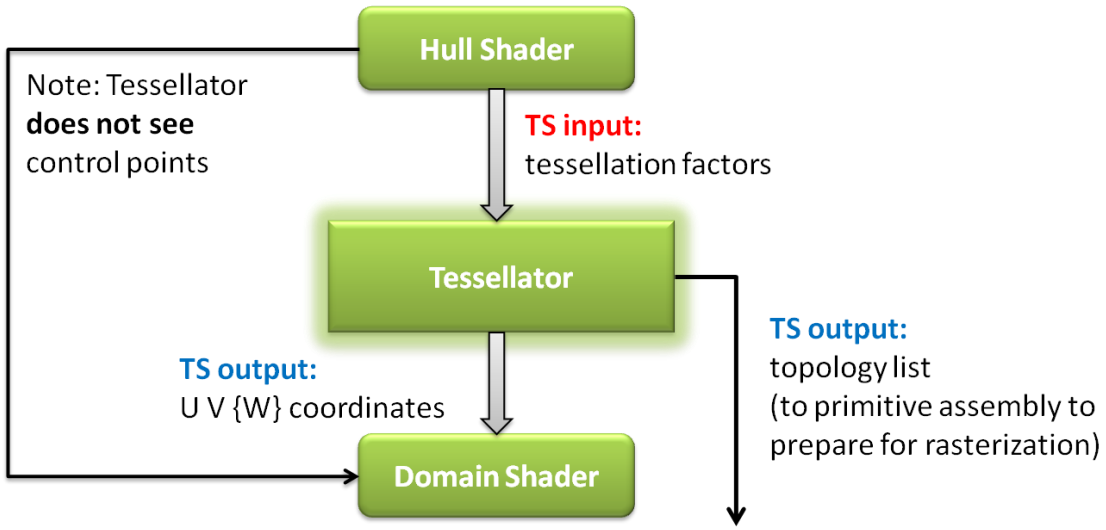


Figure 4-7: Tessellator

The tessellator is a fixed function stage. It has the purpose to subdivide a domain into many smaller objects. The tessellator operates as a black-box. The only inputs it gets are the tessellation factors of the hull shader. It is important to understand that the tessellator doesn't see any control points. All the tessellation work depends only on the tessellation factors and some predefined compile-time settings. These settings are specified with the hull shader. Following settings are possible to set up.

- domain(x)
  It is possible to choose between `triangle`, `quad` or `isoline` for the domain.
- partitioning(x)
  Here the type of partitioning can be set up. It determines in which way the tessellation factors are interpreted. The different values that can be set for x are `integer`, `pow2`, `fractional_even` or `fractional_odd`. Integer and power 2 have the same behavior. They have a range from 1 to 64. Each value defines a discrete refinement level. The tessellation factors are interpreted in whole

[48] cf. [Jef09], [Lee09], [Hex10]
[49] cf. [Mic11] http://msdn.microsoft.com/de-de/library/ff476340%28v=VS.85%29.aspx (accessed March 2011)

numbers. Value 2 for example means that the patch is refined one time. Fractional even and fractional odd interpret the tessellation factors as floats. They provide morphing to avoid popping effects. So in-between numbers such as 2.5 lead to a position of a new refined vertex, which is between the position of refinement level 2 and 3. Fractional even and fractional odd differ in the type of morphing. Fractional even morphs from the inside to the outside. Fractional odd morphs from the outside to the inside. They also differ in range. Fractional odd has a range of 1 to 63 and fractional even of 2 to 64. *Figure 4-8* shows three patches that were refined at tessellation factor 2.5 using the different partitioning types.

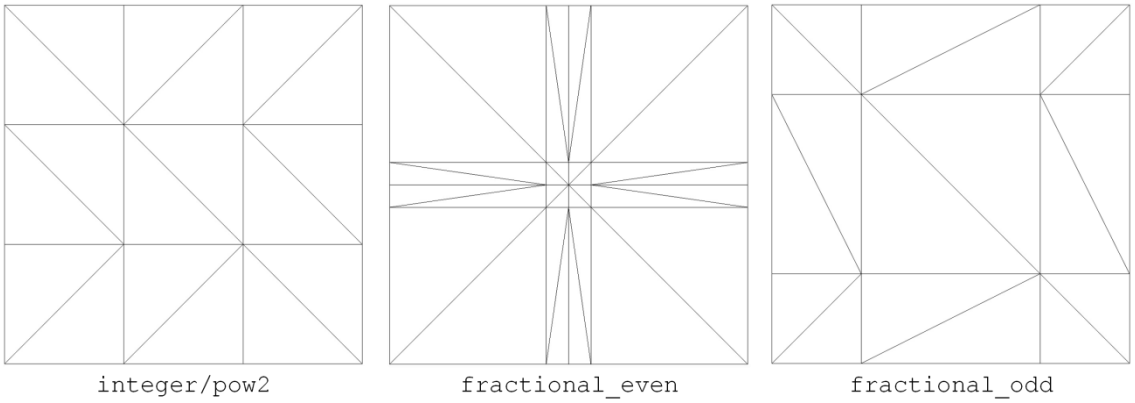


Figure 4-8: Tessellation of a quad with tessellation factor 2.5 [50]

- outputtopology(x)
  The output topology defines the kind of primitives after tessellation. It can be decided between `triangle_cw`, which stands for clockwise triangulation and `triagle_ccw`, which stands for counter clockwise triangulation.
- outputcontrolpoints(x)
  This configuration defines the number of output control points. Between 0 and 32 control points are possible.
- maxtessfactor(x)
  The maximal tessellation factor can be set with this configuration.
- patchconstantfunc("function_name")
  The last configuration sets the hull shader patch constant function. Here the developer has to type in the function name of the patch constant function.

It is possible for the tessellator to create up to 8192 triangles for every primitive. Is for example a quad tessellated 64 times. So we get a grid of 64-to-64 that has 4096 quads. One quad consists of two triangles. So the final result is 8192 triangles. Now when we use a regular grid of 256-to-256 quads (131072 triangles) we can get a maximum triangles number of 1.07 billion triangles. Of course there is no graphics card at the

[50] figure was created with a modified version of [Val101]

moment which can handle billion polygons per frame but we're theoretically able to render this high amount of detail. The generation of the triangles is not free, we need processing power of the GPU to create these triangles. Therefore we need to decide where exactly to place the largest number of triangles. That's where we need a LOD system that can refine the mesh where it is needed. Therefore the tessellator gets different tessellation factors so that it can be decided at which part of the primitive the refinement is important. *Figure 4-9* shows three different patches that were constructed with different tessellation factors.

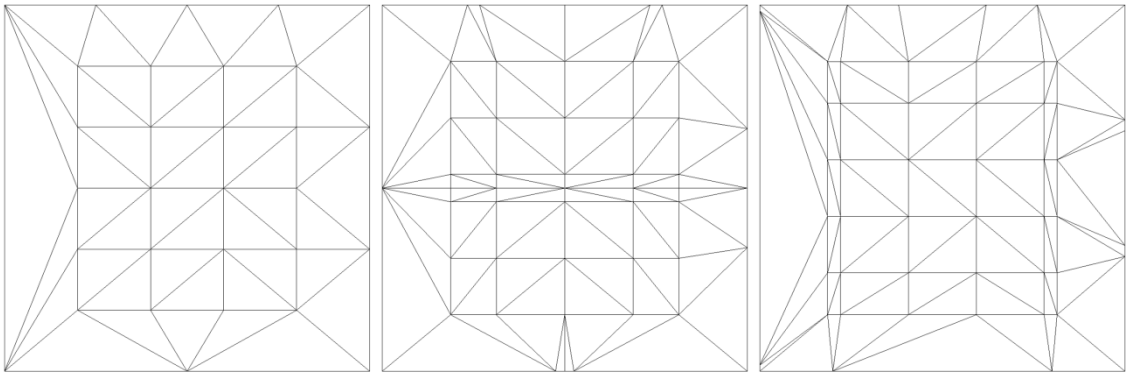


Figure 4-9: Quads with different tessellation factors [51]

The tessellator tiles the domain in a normalized zero-to-one coordinate system. The output of the tessellator is a set of weights corresponding to the primitive topology. For a triangle it outputs barycentric coordinates (U, V, W), for a quad and isoline it outputs texture coordinates (U, V). These coordinates describe the relative position on the primitive and are sent to the domain shader. The tessellator also handles the necessary relations between domain samples. It creates a topology list that it outputs to the primitive assembly. So it is later possible to rasterize the created primitives. [52] [53] [54]

[51] figure was created with a modified version of [Val101]
[52] cf. [Jef09], [Lee09], [Hex10]
[53] cf. [Mic11] http://msdn.microsoft.com/de-de/library/ff476340%28v=VS.85%29.aspx (accessed March 2011)
[54] cf. [Mic11] http://msdn.microsoft.com/de-de/library/ff476339%28v=VS.85%29.aspx (accessed March 2011)

4.5. Domain Shader

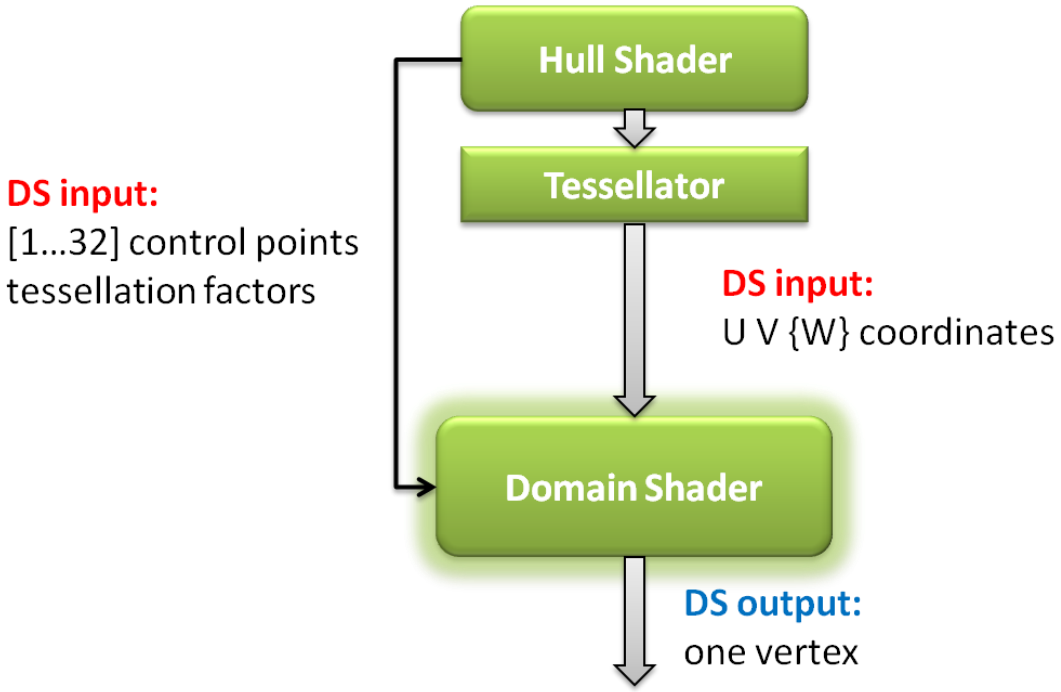


Figure 4-10: Domain shader

The domain shader is a kind of post vertex shader. It has the same ability as the vertex shader. But it uses the output vertices of the tessellator. The domain shader runs once per tessellated vertex. As input it gets the control points and tessellation factors from the hull shader and the UV{W} coordinates from the tessellator. With this input the final position of the vertex is calculated. The new position of the vertex needs to be converted to projection-space before it is output to `SV_Position`.[55] This conversion can also be done by the geometry shader, but it would not be efficient. [56] [57]

[55] cf. [Mic11] http://msdn.microsoft.com/en-us/library/bb509647%28v=VS.85%29.aspx#VPOS (accessed March 2011)
[56] cf. [Jef09], [Lee09], [Hex10]
[57] cf. [Mic11] http://msdn.microsoft.com/de-de/library/ff476340%28v=VS.85%29.aspx (accessed March 2011)

4.6. Geometry Shader

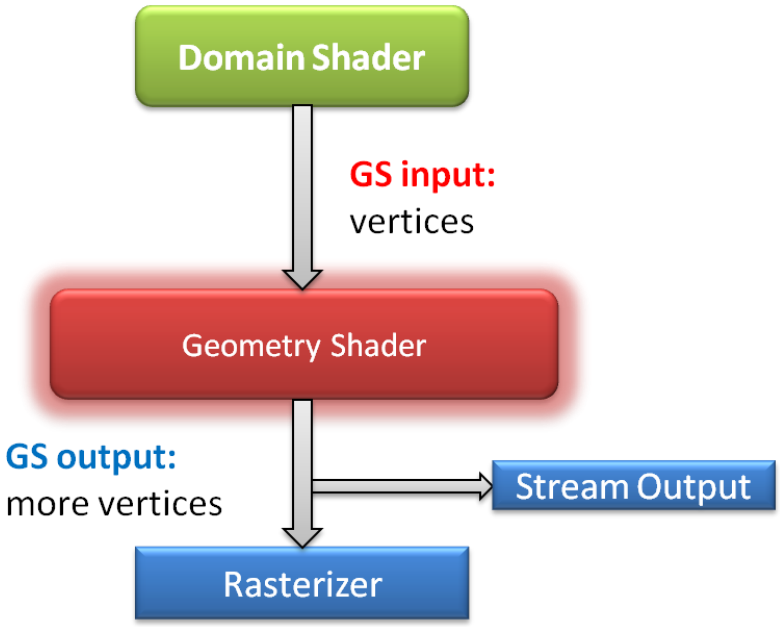


Figure 4-11: Geometry shader

The geometry shader works the same as in DirectX 10. The only difference is that it is executed after the domain shader instead of the vertex shader. The use of the geometry shader is optional. The geometry shader can only see the output of the domain shader. The number of executions is dependent on the number of vertices that were output by the domain shader. The geometry shader has the ability to create new vertices. It works on the vertices of a primitive and has also access to three adjacent triangles. Algorithms that can be written for the geometry shader are point sprit expansion, dynamic particle systems or shadow volume generation. [58]

[58] cf. [Mic11] http://msdn.microsoft.com/de-de/library/bb205146%28v=VS.85%29.aspx (accessed March 2011)

4.7. Pixel Shader

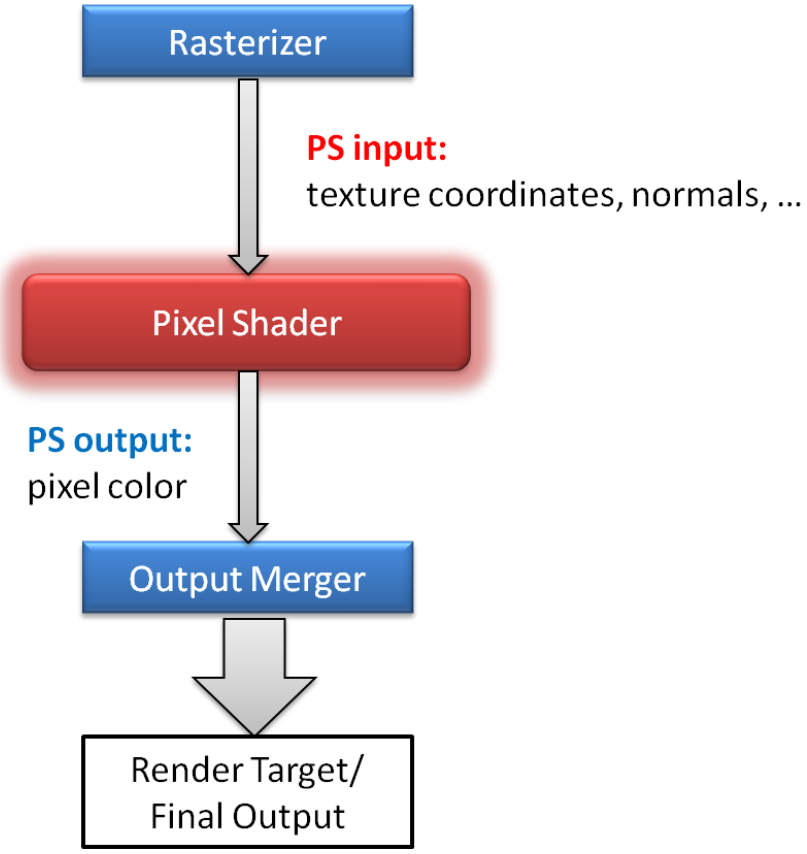


Figure 4-12: Pixel shader

The pixel shader is executed after rasterization and operates on pixels. Texturing, per-pixel lighting and post-processing operations like blurring can be done with the pixel shader. The pixel shader is independent of the geometry. It is invoked once per covered pixel. So the number of invocations of the pixel shader is dependent on the screen resolution of the user. The output of the pixel shader is a color of a pixel. [59]

[59] cf. [Mic11] http://msdn.microsoft.com/de-de/library/bb205146%28v=VS.85%29.aspx (accessed March 2011)

5. Terrain Rendering with DirectX 11

This section is about the implementation of a terrain rendering algorithm that uses DirectX 11 shader pipeline. First the architecture of the terrain system will be explained. After this the shader operations that were performed for terrain rendering are described in depth. At the end of the section the result of this rendering approach will be discussed.

5.1. Architecture of Terrain Engine

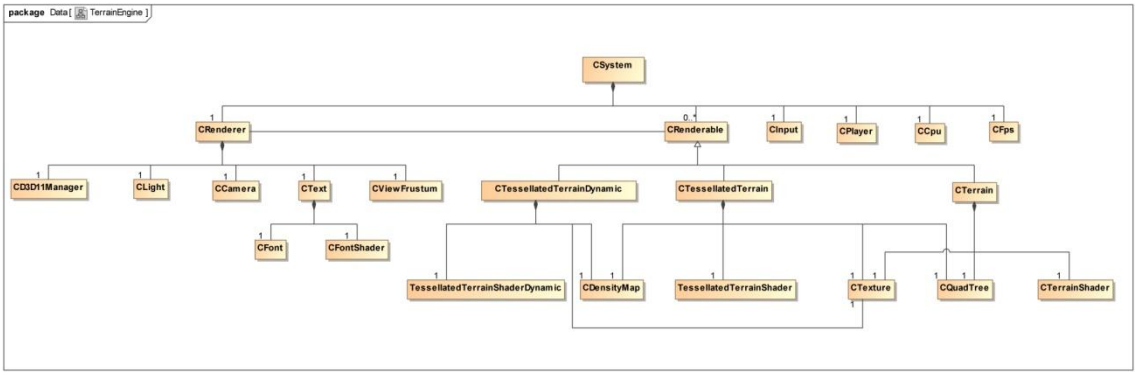


Figure 5-1: Class diagram of terrain engine [60]

As a demo application I programmed a terrain renderer. The base for this terrain renderer was the tutorials of Raster Tek.[61] I used these tutorials to program the base of my terrain renderer. After that I improved and expanded it to fit to the purposes of my terrain rendering system. I modified the input system. The terrain renderer provides a fly over control for the user. The user is able to look around with the mouse, move forward and backward, strafe left and right, and move upward and downward.

This section will give an overview over the terrain engine. It will be explained which classes are used and what function they have.

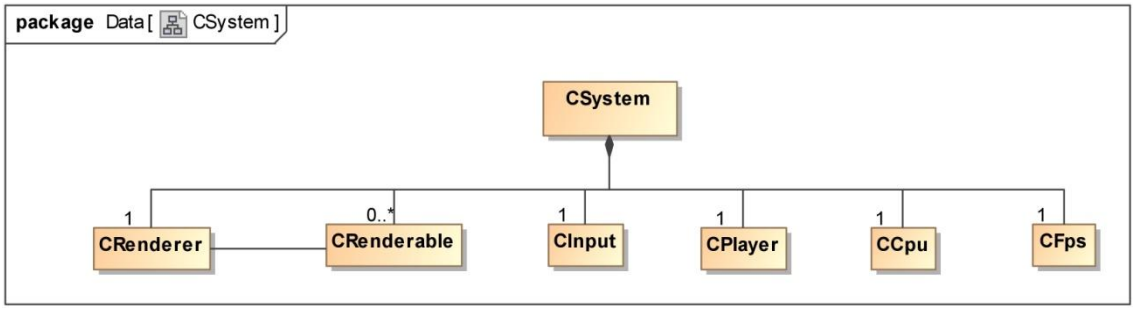


Figure 5-2: Class diagram of CSystem [62]

[60] built with Magic Draw 15.5
[61] cf. [Ras11]
[62] built with Magic Draw 15.5

The main class is the class `CSystem`. It starts the application in window mode or in full screen. In window mode the resolution is set to 1280x720. In full screen mode the resolution is set to the current display resolution. `CSystem` has a composition with the classes `CInput`, `CPlayer`, `CTimer`, `CCpu`, `CFps`, `CRenderer` and `CRenderable`. `CSystem` creates and initializes these classes. The only exception is `CRenderable`. All objects of the class `CRenderable` are stored in a `std::vector` container. There is no maximum number of render able objects defined. `CRenderer` gets the pointer to the render able objects container. All render able objects are initialized from `CRenderer`. `CSystem` also sets the start position of the viewport. After execution all objects are destroyed from `CSystem`.

To start an application `CSystem` needs to be constructed, renderable objects need to be added to the container and `CSystem::Run()` needs to be started. The main loop is executed in the run method. First Windows messages are handled. If Windows gives a signal to end the application, execution of the application will be stopped. Otherwise a frame will be processed. In the frame method the system stats for timer, frames per second and CPU usage are updated. Timer is especially important for the movement of the camera. The timer calculates the time that was needed since the last frame. This time is needed to calculate the distance the camera has to move. The next thing that is done in the main loop is to read and interpret the input of the user. First the Esc key is checked to determine if it was pressed. If yes the application will be shut down. Otherwise F1 key and F2 key are checked. If F1 was pressed the scene will be rendered in solid mode. If F2 was pressed the scene will be rendered in wireframe mode. Then F3 key is checked. Pressing the F3 key toggles debug view on or off. After this the inputs for movement will be handled. According to these inputs the position of the camera will be updated. After all inputs were handled `CRenderer` will do the frame rendering. Therefore frames per second, CPU usage and frame time are sent to the renderer.

Let's have a look at the classes that were stored in `CSystem`. The first one is `CInput`. It interprets user input of keyboard and mouse with DirectInput 8. DirectInput 8 is an API from Microsoft for collecting input data from mouse, keyboard and gamepads. `CInput` interprets the mouse movement and calculates with this data the rotation velocity of the camera. `CInput` also provides public functions to check if a button of the keyboard is pressed. This is done to encapsulate the DirectInput 8 syntax from the other classes. So it is possible to integrate another system to handle the input.

`CPlayer` handles the player movement and rotation. It interprets the data of `CInput` to update the position and rotation of the user. Because the user sees the scene through the viewport of the camera the position and rotation of the user is also the position and rotation of the camera.

A class that is important for the calculation of `CPlayer` is the class `CTimer`. It calculates each frame how long the last frame time was. According to this time the player movement is updated to support a continuous movement that doesn't depend on the frame rate.

The classes `CCpu` and `CFps` are for the debug view. The CPU usage and the frames per second are updated every second. Frames per second can be taken for a measurement to show how fast rendering is taking place.

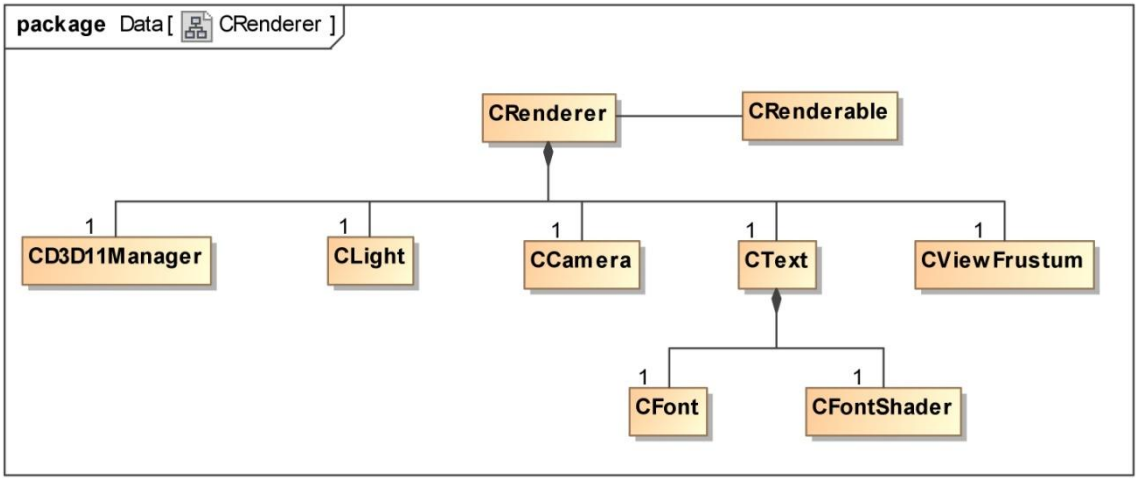


Figure 5-3: Class diagram of CRenderer [63]

The next class is `CRenderer`. Its job is everything that is needed for rendering. Each frame `CRenderer::Render()` is executed. First the world-view projection matrix is calculated. This matrix is needed in the shader to transform a vertex position into projection-space. After this the view frustum is constructed, render able objects are rendered and the debug text is rendered. At the end of the frame method the generated scene is presented on the screen. Therefore it stores the classes `CD3D11Manager`, `CLight`, `CCamera`, `CText` and `CViewFrustum`. `CRenderer` creates, initializes and destroys these objects.

`CD3D11Manager` is responsible for initialization of DirectX 11. During initialization `CD3D11Manager` creates the projection matrix, initializes the world matrix and creates the orthographic projection matrix. The orthographic projection matrix is needed for 2D rendering. The other two matrices are needed to calculate the world-view projection matrix. Each frame `CD3D11Manager` begins the scene. Therefore it clears the depth and stencil buffer. It is also responsible for any stage changes of DirectX that need to be performed. One example is to turn alpha blending and z-buffer off for rendering the debug text on screen. At the end of each frame when rendering is complete, `CD3D11Manager` presents the back buffer to the screen.

[63] built with Magic Draw 15.5

`CLight` is a directional light which implements the phong lighting model. `CLight` stores ambient color, specular color, specular power and the light direction. These data is needed for the pixel shader to calculate per pixel lighting.

`CCamera` stores the position and rotation of the camera. It uses the current position and rotation of `CPlayer`. Every frame it calculates according to this data the current view matrix and the current look at vector.

The class `CText` is used to render debug text. Therefore it stores and updates the text that is rendered to the screen. It creates vertex and index buffer for the text. It uses the classes `CFont` and `CFontShader` for rendering. `CFont` builds the vertex array, loads the font data and font texture. `CFontShader` compiles the shader file "font.fx", set shader variables and renders the text on screen. Data that is rendered on the screen in this application are the current video card, the available video memory, the position and rotation of the camera, the render count, which is sent to graphics card, the render count after tessellation, CPU usage and the frames per second. [64]

`CViewFrustum` is a class that is needed for view frustum culling. It calculates and stores the view frustum for every frame. It provides methods to check if a point, a cube, a sphere or a rectangle is inside the view frustum.

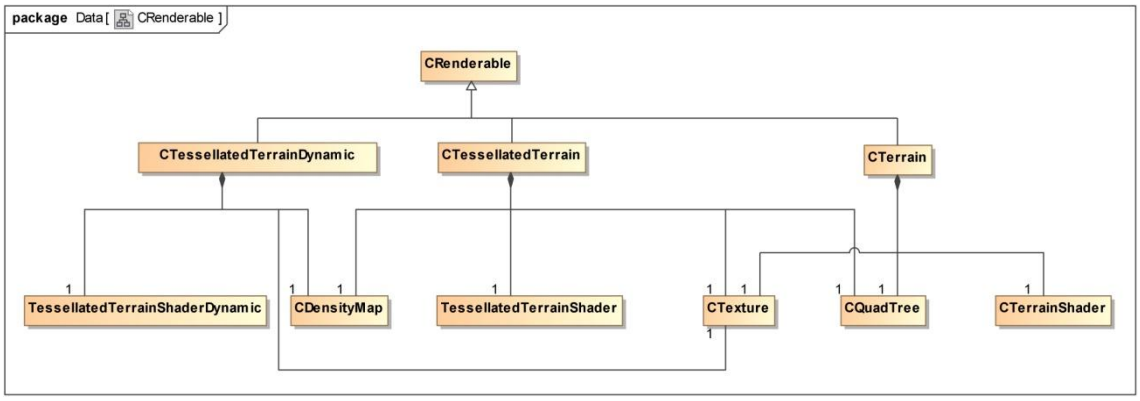


Figure 5-4: Class diagram of CRenderable [65]

The classes that inherit from `CRenderable` are rendered in 3D. `CRenderable` is a abstract class which has three methods that need to be overwritten, `CRenderable::Initialize(…)`, `CRenderable::Shutdown()` and `CRenderable::Render(..)`.

In the current implementation of the Terrain Engine are three classes implemented, `CTerrain`, `CTessellatedTerrain` and `CTessellatedTerrainDynamic`.

`CTerrain` is a simple terrain constructed with a regular grid and a height map. It has a regular grid with a constant quad size. At initialization it first opens the height map and

[64] cf. [Ras11] http://rastertek.com/dx11tut12.html (accessed March 2011)
[65] built with Magic Draw 15.5

reads in the data. According to the height map data a grid is constructed and corresponding normals and texture coordinates are calculated. It also loads the texture for terrain. The used primitive is `D3D11_PRIMITIVE_TOPOLOGY_TRIANGLELIST`. `CTerrain` uses three classes `CTexture`, `CQuadTree` and `CTerrainShader`. `CTexture` is used to load the texture and create a shader resource view. `CQuadTree` uses a quad tree to separate the grid in parts according to a predefined vertex count. For each child the quad tree creates a vertex buffer and index buffer. Which node of the quad tree will be rendered is decided on run-time dependent on the view frustum position. `CTerrainShader` compiles the corresponding shader file "terrain.fx". It also defines the used polygon layout, sets the shader variables and renders the terrain. Data that is used for each vertex is the position, a texture coordinate and a normal. The shader variables are the world matrix, the view matrix, the projection matrix, the world-view projection matrix, the terrain texture, ambient color, diffuse color and light direction. [66]

`CTessellatedTerrain` and `CTessellatedTerrainDynamic` use a view-dependent LOD for tessellation. The refinement of the terrain depends on the screen resolution, the position of the camera, the shape of the terrain and the desired triangle size that wants to be achieved. The used domain for tessellation is a triangle.

`CTessellatedTerrain` creates the grid and calculates the normals on the same way as `CTerrain`. `CTessellatedTerrain` also uses a `CQuadTree` to separate the grid. The first thing that is different from `CTerrain` is that it uses the primitive topology `D3D11_PRIMITIVE_TOPOLOGY_3_CONTROL_POINT_PATCHLIST`. This topology is needed to be able to tessellate the terrain. It uses a triangle as input. `CTessellatedTerrain` uses the class `CDensityMap` to define the tessellation factors of a triangle. This class calculates a density map according to the height map data. The density map describes at which places the terrain needs to be refined and at which places refinement is not needed. Where the height doesn't change there is a flat surface. So there is no refinement needed. From the density map a density buffer is created. In the density buffer for each patch are the tessellation factors stored. This buffer can be read from the shader to set the tessellation factors. How the density map works in detail will be explained in section *5.2.3*. It is important for the use of the quad tree with this approach that for each node of the quad tree a density buffer is created. `CTessellatedTerrain` uses its own shader class `CTessellatedTerrainShader`. This class compiles the shader file "tessellatedterrain.fx". It sets the same shader variables as `CTerrianShader`. Additionally it sets the shader variables which are needed for tessellation.

[66] cf. [Ras11], http://rastertek.com/tutindex.html DirectX 10 Terrain Tutorials (accessed March 2011)

`CTessellatedTerrainDynamic` uses no quad tree and the normals are calculated in the shader "tessellatedterraindynamic.fx". It uses its own shader class `CTessellatedTerrainShaderDynamic`. `CTessellatedTerrainDynamic` uses the height map data in the vertex shader to calculate the final height position of the regular grid. So it is possible to change the height data while run-time without the need to reconstruct the vertex buffer. The rest works the same as in `CTessellatedTerrain`. [67]

5.2. Implementation of View-Dependent Tessellation

In this section it will be explained how a view-dependent LOD system is built with tessellation. Included will be an explanation of how a grid is constructed. Then the implementation of a density map will be explained. After this we will go through the different shaders that are needed. While going through the shader stages some optimizations and techniques are explained that were used for this approach. This will all be explained with the implementation of `CTessellatedTerrainDynamic`.

5.2.1. Grid Construction

The first thing we need to do is to construct a regular grid. We will construct a grid that fits to the resolution of the height map. When we use a height map with 256-to-256 pixels, we will use a regular gird with 256-to-256 quads. For tessellation we use `D3D11_PRIMITIVE_TOPOLOGY_3_CONTROL_POINT_PATCHLIST`[68] as primitive topology and we need to generate triangles. A quad consists of two triangles. *Figure 5-5* shows a simple quad. To define this quad we need to set four vertices V_0, V_1, V_2 and V_3. We then need to define the indices for each triangle. The first triangle has the indices I_0, I_1, I_2 that will point on V_0, V_1, V_2. The second triangle has the indices I_3, I_4, I_5 that will point on V_2, V_1, V_3. The rest of the regular grid can be constructed the same way. [69]

[67] cf. DVD attached "SourceCode\TerrainEngine\TerrainEngine\"
[68] cf. DVD attached "SourceCode\TerrainEngine\TerrainEngine\tessellatedterraindynamic.cpp" line 565
[69] cf. DVD attached "SourceCode\TerrainEngine\TerrainEngine\tessellatedterraindynamic.cpp" line 415-490

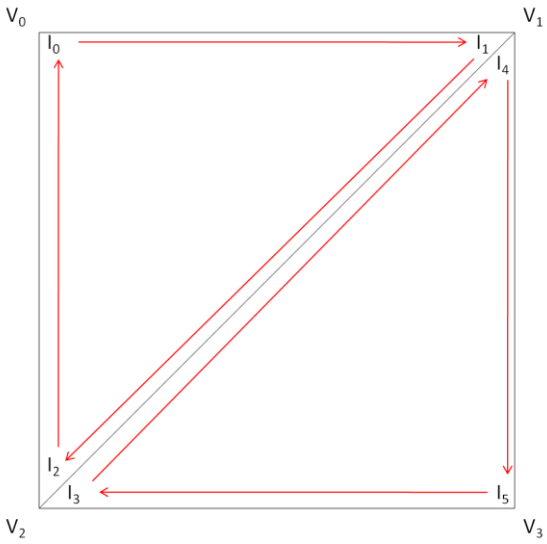


Figure 5-5: How to create two triangles out of one quad

5.2.2. Normal calculation

Another important thing is to calculate normals. We need the normals for lighting, culling and to make the tessellated terrain smooth. There are two different ways to calculate normals. We could calculate the normals at the initialization of the application on the CPU and store the normals in the vertex buffer or we could calculate the normals on the fly in the shader. The static approach calculates a normal for each vertex of the terrain. It takes an average of the normals of each adjacent face of the vertex to calculate the normal for the vertex. [70] [71]

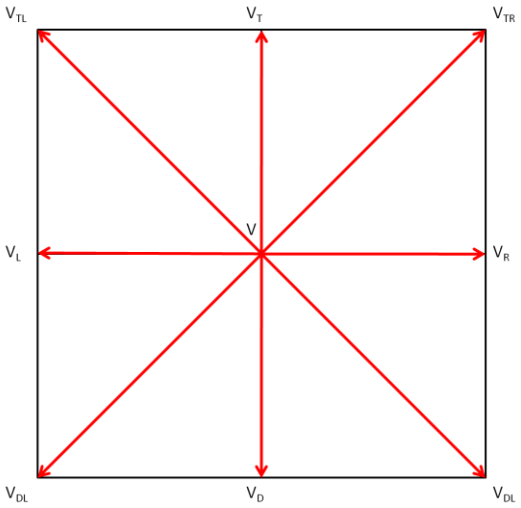


Figure 5-6: Normal calculation

The dynamic approach is a bit different. First the height value of the current vertex V and all surrounding vertices is read from the height map. The positions of the surrounding vertices are calculated in relation to V. The vectors from V to the

[70] cf. DVD attached "SourceCode\TerrainEngine\TerrainEngine\terrain.cpp" line 271-405
[71] cf. [Ras11] http://rastertek.com/tertut03.html (accessed March 2011)

surrounding vertices are calculated as shown in *Figure 5-6*. The cross product of these vectors is calculated to get the vector of the adjacent faces. The average of these vectors is taken to calculate the final normal. [72]

The dynamic calculation of the normals has the advantage that dynamic terrain can be used. This means that the terrain can change its shape at run-time and we are still able to do correct lighting because the normals are correctly calculated. This is also usefull for a terrain editor. So it's possible to see the visual result of the lighting while editing the terrain.

5.2.3. Density Map Creation

For realizing a view-dependent LOD with tessellation we need to create a density map. The class `CDensityMap` was built after the DetailTessellation11 sample of DirectX 11 SDK (June 2010).[73] The density map provides for each vertex a density value. It is created on startup. Its creation is dependent on the height information of the height map. After creation it is saved to disk. This means that when the height map doesn't change, the density map doesn't need to be created. It can be loaded from disk. The density map needs to be recalculated, when the height map has changed. This function is not implemented yet. The only way to force the program to create a new density map is to delete the density map from disk.

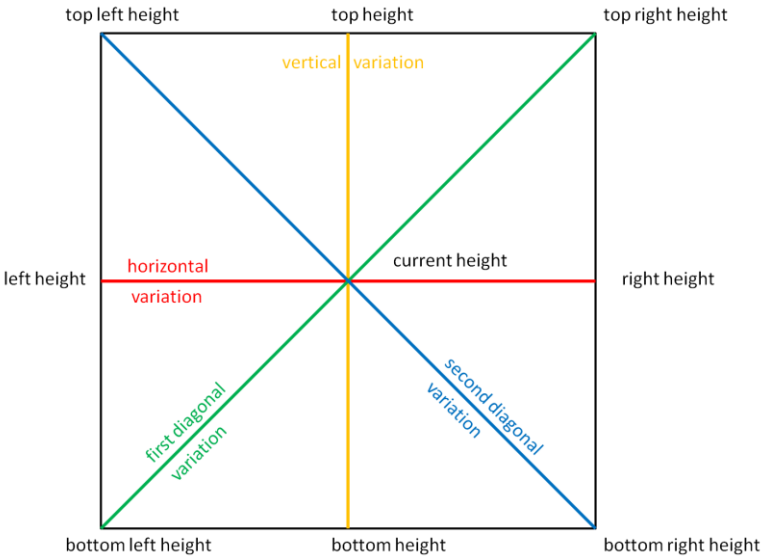


Figure 5-7: Pixel selection and variation calculation for density map creation

How is the density map created? First the height map needs to be loaded. The description of the height map is used to create the description of the density map. The density map is calculated in a loop. For each pixel a density value is calculated.

[72] cf. DVD attached "SourceCode\TerrainEngine\TerrainEngine\tessellatedterraindynamic.fx" line 162-239

[73] cf. [Mic10], „Microsoft DirectX SDK (June 2010)\Samples\C++\Direct3D11\DetailTessellation11\" (accessed March 2011)

Therefore the height of the current pixel and the height of all adjacent pixels are read in. With this height values four variables are calculated, the horizontal variation, the vertical variation, first diagonal variation and second diagonal variation. *Figure 5-7* shows which variation is calculated with which points. For the horizontal variation we need the left height, the current height and the right height. How these values are calculated is shown in *Figure 5-8*. The result is an absolute value of three subtractions. If the right height has a value of 10, the current pixel has a value of 9 and the left height has a value of 8, the result would be 0. This means that the surface is flat for this situation although we have different heights. We do not need to refine the grid at this vertex.

```
float fHorizontalVariation =
              fabs(  (fCurrentPixelRightHeight - fCurrentPixelHeight) –
                     (fCurrentPixelHeight - fCurrentPixelLeftHeight));
float fVerticalVariation =
              fabs(  (fCurrentPixelBottomHeight - fCurrentPixelHeight) -
                     (fCurrentPixelHeight - fCurrentPixelTopHeight ) );
float fFirstDiagonalVariation =
              fabs(  (fCurrentPixelTopRightHeight-CurrentPixelHeight)-
                     (fCurrentPixelHeight - fCurrentPixelBottomLeftHeight));
float fSecondDiagonalVariation =
              fabs(  (fCurrentPixelBottomRightHeight - fCurrentPixelHeight)–
                     ( fCurrentPixelHeight - fCurrentPixelTopLeftHeight ) );
```

Figure 5-8: Calculation of variation [74]

The calculated variations are now added to the density value if the variation is high enough. It is a value defined at which size the variation is big enough. Before the variations are added to the density value, the horizontal and vertical variation is multiplied with 0.293 and the two diagonal variations are multiplied with 0.207. After this the density scale is multiplied with a predefined density scale factor. Then the density value is clamped between 1/255 and 1. Before density value is saved in the height map it is multiplied with 255. [75]

After we have the density map created. We need to create a density buffer, which can be used in the shader to set the tessellation factors. Therefore we loop through all triangles of the vertex buffer. For each edge of the triangle we search the maximum density along the edge. First the correct texel coordinates for the given texture coordinates of the vertex are calculated. How many texels fall on that edge is established. After that the maximum density along the edge is chosen. After we have all edge density values we use the highest values for the inside density. This data is stored with a `D3DXVECTOR4` in a density buffer. This density buffer can be used inside the shader. [76]

[74] cf. DVD attached “SourceCode\TerrainEngine\TerrainEngine\densitymap.cpp” line 248-255
[75] cf. DVD attached “SourceCode\TerrainEngine\TerrainEngine\densitymap.cpp” line 157-297
[76] cf. DVD attached “SourceCode\TerrainEngine\TerrainEngine\densitymap.cpp” line 322-440

5.2.4. Shader Pipeline

I have made two implementations for terrain rendering with tessellation, `CTessellatedTerrain` and `CTessellatedTerrainDynamic`. The two shaders of these implementations are nearly the same. Only the vertex input data and the vertex shader is different. The shader of `CTessellatedTerrain` gets as vertex input the position, the texture coordinates and the normal of the vertex. The vertex shader does no calculation. It only puts through the data to the domain shader. `CTessellatedTerrainShader` gets only the position and the texture coordinates. The normal is calculated in the vertex shader. *Figure 5-9* shows the input and output structure of the vertex shader. The input structure is exactly the data that is stored in the vertex buffer. The output structure of the vertex is also the input structure of the hull shader.

```
struct VS_CONTROL_POINT_INPUT
{
	float3 Position		: POSITION;
	float2 TexCoord		: TEXCOORD;
};

struct VS_CONTROL_POINT_OUTPUT
{
	float3 Position		: POSITION;
	float2 TexCoord		: TEXCOORD;
	float3 Normal		: NORMAL;
};
```

Figure 5-9: Input and output of vertex shader [77]

Figure 5-10 shows the vertex shader of "tessellatedterraindynamic.fx". Here the height data and the normal for the vertex are calculated. The texture coordinates are put through to the hull shader.

```
VS_CONTROL_POINT_OUTPUT VSTerrain(VS_CONTROL_POINT_INPUT Input)
{
	VS_CONTROL_POINT_OUTPUT Output;
	Output.Position = Input.Position;
	Output.Position.y += g_fHeightScale *
			(g_tHeightMap.SampleLevel(SampleType,
			Input.TexCoord, 0).r - 0.5f);
	Output.Normal = FindHeightTexNormal(Input.TexCoord);
	Output.TexCoord = Input.TexCoord;

	return Output;
}
```

Figure 5-10: Vertex shader [78]

[77] cf. DVD attached "SourceCode\TerrainEngine\TerrainEngine\tessellatedterraindynamic.fx" line 246-259
[78] cf. DVD attached "SourceCode\TerrainEngine\TerrainEngine\tessellatedterraindynamic.fx" line 284-299

The next shader is the hull shader. *Figure 5-11* shows the output structures that are defined for the hull shader constant function and the hull shader main function. The output for the hull shader main function is the same data as the input. The hull shader constant function structure consists of three edge tessellation factors and one inside tessellation factor. These are the tessellation factors that need to be defined for a triangle so that the tessellator can do its work.

```
// Ouput Hull Shader Constant Data
struct HS_CONSTANT_DATA_OUTPUT
{
	float Edges[3]		: SV_TessFactor;
	float Inside		: SV_InsideTessFactor;
};

// Output Hull Shader
struct Terrain_CONTROL_POINT
{
	float3 Position		: POSITION;
	float2 TexCoord		: TEXCOORD;
	float3 Normal		: NORMAL;
};

[domain("tri")]
[partitioning("fractional_odd")]
[outputtopology("triangle_cw")]
[outputcontrolpoints(3)]
[patchconstantfunc("ConstantsHSTerrain")]
[maxtessfactor(64.0f)]
Terrain_CONTROL_POINT HSTerrain(  InputPatch<VS_CONTROL_POINT_OUTPUT,3> ip,
                                  uint i        : SV_OutputControlPointID,
                                  uint PatchID  : SV_PrimitiveID )
{
	Terrain_CONTROL_POINT Output = (Terrain_CONTROL_POINT)0;
	Output.Position = ip[i].Position;
	Output.Normal   = ip[i].Normal;
	Output.TexCoord = ip[i].TexCoord;
	return Output;
}
```

Figure 5-11: Hull shader constant data, hull shader main function output and hull shader main function [79]

Figure 5-11 also shows how the configurations for the tessellator are set up. A triangle is used as domain. The portioning is defined as fractional odd. With that smoothing is added to the tessellation. Thus no popping artifacts could appear. The output control point is set to 3. Also, no new vertices are added to the patch. The maximum tessellation factor is set to 64. This is the maximum tessellation factor that is supported from the tessellator. For performance optimization this factor can be set to a smaller number. It is important for the settings to define is the patch constant function. Here it is called

[79] cf. DVD attached "SourceCode\TerrainEngine\TerrainEngine\tessellatedterraindynamic.fx" line 261-274, 368-385

`ConstantHSTerrain`.[80] In this function the tessellation factors are calculated. First a check is performed to see if the triangle is outside the view frustum. For this we need the three vertex positions of the triangle and the view frustum. The view frustum is defined as a shader variable that is updated every frame. To calculate the frustum culling we first need to define a variable of the space outside the view frustum that is still considered as inside. This is important because when we do view frustum culling without this outside space the culled vertices can be seen on screen. Each vertex of the triangle is tested with the left, right, top and bottom clip plane of the view frustum. When the triangle passes all tests the triangle is inside the view frustum. If that's the case the next step is to check if the triangle is back facing. To check this, the edge dot product of each edge normal and the view vector needs to be calculated. We need also to define a variable for which triangles are still considered inside. The three edge dot products are compared with the variable. If all edge dot products are less than or equal to the negative of the defined variable the triangle will be culled. When the triangle is culled it will not be rendered. Otherwise the tessellation factors will be calculated.

To calculate the tessellation factors we first need to calculate the screen position of each vertex of the triangle. For this calculation we need the view-projection matrix and the screen resolution. With the results of these calculations we can calculate the tessellation factor for each edge based on the desired screen space tessellation value. The screen space tessellation value is calculated with 1/desired triangle size. The inside tessellation factor is the average of the edge tessellation factors. After that the tessellation factors are multiplied with the data of the density buffer. Finally the tessellation factors can be set.

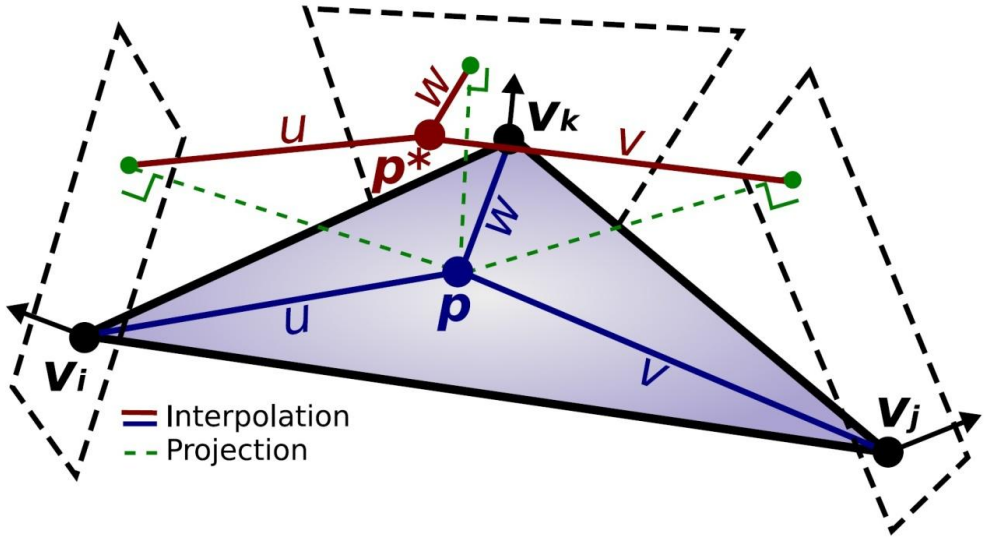


Figure 5-12: Phong tessellation principle [Bou08]

[80] cf. DVD attached "SourceCode\TerrainEngine\TerrainEngine\tessellatedterraindynamic.fx" line 301-365

```
[domain("tri")]
DS_OUTPUT DSTerrain( HS_CONSTANT_DATA_OUTPUT input,
                     float3 UVW : SV_DomainLocation,
                     const OutputPatch<Terrain_CONTROL_POINT, 3> op)
{
       DS_OUTPUT Output = (DS_OUTPUT) 0;

       float3 position, projection0, projection1, projection2,
              projectedPosition, finalPosition, normal;

       //Phong Tessellation
       //1. barycentric interpolation of positions
       position =    UVW.x * op[0].Position +
                     UVW.y * op[1].Position +
                     UVW.z * op[2].Position;

       //2. caluculate projections
       projection0 = position -
              dot(position-op[0].Position, op[0].Normal) * op[0].Normal;
       projection1 = position -
              dot(position-op[1].Position, op[1].Normal) * op[1].Normal;
       projection2 = position -
              dot(position-op[2].Position, op[2].Normal) * op[2].Normal;

       //3. barycentric interpolation of projections
       projectedPosition =  UVW.x * projection0 +
                            UVW.y * projection1 +
                            UVW.z * projection2;

       //Interpolation between linear(flat) and Phong Tessellation
       finalPosition = lerp(position, projectedPosition,
                            g_fPhongTessellationShapeFactor);

       Output.Position = mul(float4 (finalPosition,1.0f),
                                  g_mWorldViewProjection);

       //barycentric interpolation of texture coordinates
       Output.TextureUV =   UVW.x * op[0].TexCoord +
                            UVW.y * op[1].TexCoord +
                            UVW.z * op[2].TexCoord;

       // barycentric interpolation of normals
       normal =normalize(   UVW.x * op[0].Normal +
                            UVW.y * op[1].Normal +
                            UVW.z * op[2].Normal);

       //multiply with world matrix
       Output.Normal = normalize(mul(normal, (float3x3)g_mWorld));

       return Output;
}
```

Figure 5-13: Domain shader [81]

Now that we have set the tessellation factors in hull shader constant function and we have put through all data from hull shader main function to the domain shader, we can examine the domain shader. In the domain shader the final position of each vertex that

[81] cf. DVD attached “SourceCode\TerrainEngine\TerrainEngine\tessellatedterraindynamic.fx” line 388-433

was created by the tessellator is calculated. For this approach the tessellation technique called phong tessellation[82] is used. This technique has proven to be very fast to calculate and gives a terrain with a smooth surface without the need of additional data. First we do a barycentric calculation to calculate the position of the vertex on the triangle. We get the blue point p that is shown on *Figure 5-12*. The second thing we need to do is to calculate for each vertex a projection. The projection is calculated with the position and normal of each vertex of the input triangle. This is done by multiplying the normal with the dot product of normal and p minus the position of the vertex. This result is subtracted from p. With these projections we can calculate the position p*. With the linear interpolation between p and p* we can now decide how smooth the surface should be. The big advantage of this position calculation is that we can define for each triangle a tessellation shape factor that describes the smoothness of the surface. This can later be used in an editor to give an artist the opportunity to define how smooth the surface should be. The range of the phong tessellation shape factor is between 0 and 1.[83]

After we have calculated the final position we need to multiply the final position with the world view projection matrix. At the end of the domain shader we need to calculate the texture coordinates and the normal. This is done with barycentric interpolation. At this point we have to multiply the normal with the world matrix.

Finally we are arrived at the pixel shader. Here the texture of the terrain is set and the per-pixel lighting is calculated. This lighting model uses the light direction of a directional light and the normal to calculate the light intensity. We need to calculate the final color of each pixel. First we add the ambient light to the final color. Then light intensity is multiplied with the diffuse color and added to color. At the end we multiply the color with the texture color. Now we have calculated the final color for the pixel. [84]

The result we get with this approach is shown in *Figure 5-15*. We get a smooth terrain that is refined on the silhouettes according to the screen resolution. We also can see that the terrain is not refined on flat surfaces.

[82] see http://perso.telecom-paristech.fr/~boubek/papers/PhongTessellation/ for more information
[83] cf. [Bou08]
[84] cf. DVD attached “SourceCode\TerrainEngine\TerrainEngine\tessellatedterraindynamic.fx” line 435-473

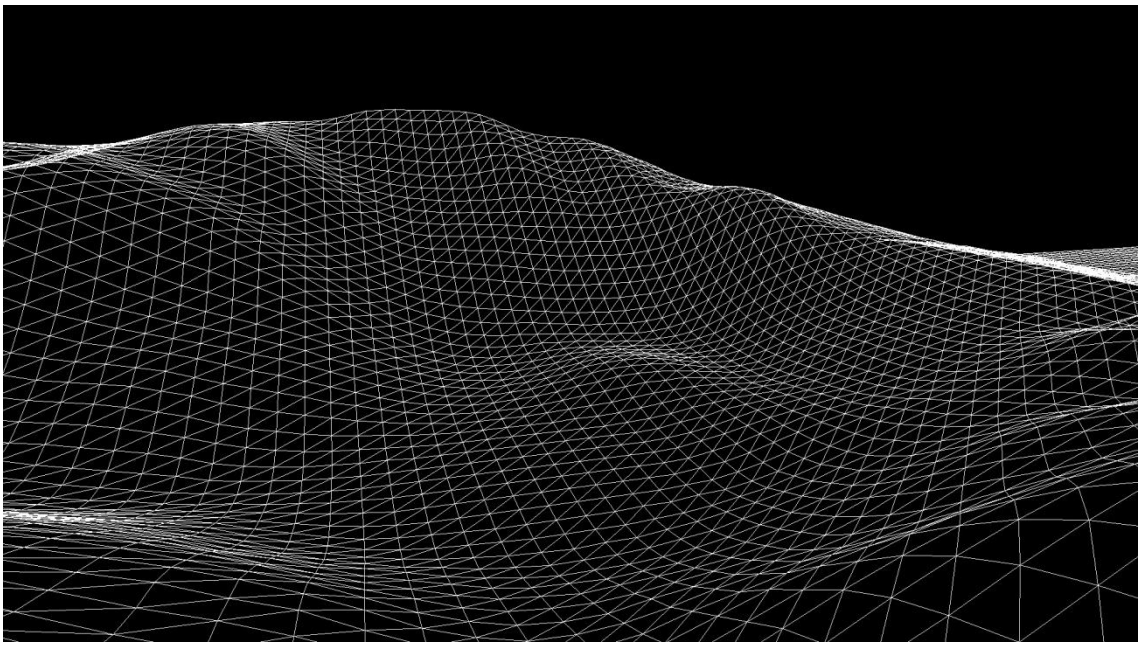


Figure 5-14: Terrain without tessellation

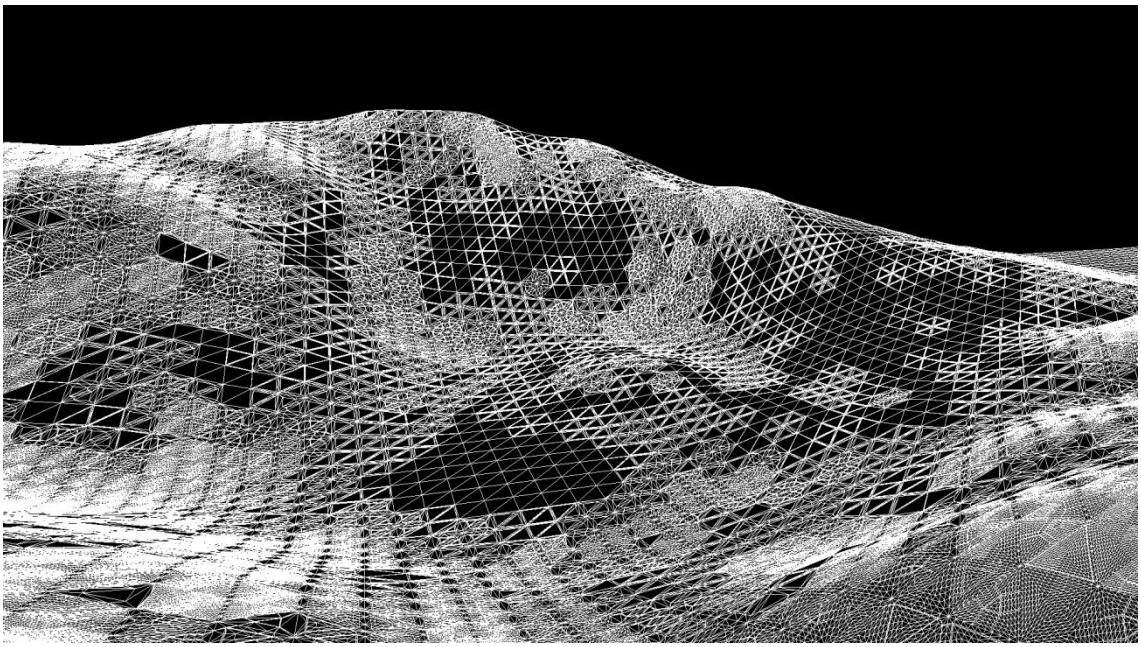


Figure 5-15: Terrain with tessellation

6. Conclusion

Within the bachelor thesis a terrain renderer was developed that refines the geometry dependent on the screen resolution, height data and predefined screen space triangle size. It had been shown that DirectX 11 shader pipeline is able to generate a large number of triangles. It is very important to use a view-dependent system to reduce the number of triangles to a minimum.

The development of the terrain renderer for this thesis has made it apparent to me that a great deal of time and effort is required. A main factor of the work involved was to acquire the necessary knowledge about DirectX 11 and about level of detail systems. The acquired skills were described in the first sections of the thesis. This skill set made the development of a terrain rendering system possible by adapting the terrain tutorials from DirectX 10 to DirectX 11. [85]

My original plan was to develop a terrain editor, but I discovered this was not possible with time available to me. However it was possible to implement two different versions of the algorithm which I found to be a very good learning experience. One implementation uses a quad tree and has static normals. The other implementation has dynamic normals. As *Figure 6-1* shows the calculation of the normals doesn't make the algorithm slower. The three versions were tested for performance with a 256-to-256 height map. The hardware that was used for development is an AMD Radeon HD 6870. It was used a desired triangle size of 4 pixels. The test shows that it is possible to render a high amount of detail. However it also shows that tessellation is not free. The additional processing power that is needed to calculate tessellation can be seen in the lower frame rate. As shown in *Figure 6-1* the frame rate of the tessellated terrains are not very high when the minimum of triangles are rendered. `CTerrain` has over 1200 frames per seconds while the other two implementations have only around 300 frames per second. It is better to turn tessellation off if nothing is tessellated. The frame rate depends on the number of rendered triangles. Overall tessellation brings the opportunity to show more detail. But it is important to show the detail only where it is needed.

CTerrain	CTessellatedTerrain	CTessellatedTerrainDynamic
1281 [131072]	309[131072]	295 [131072]
131072	107 [2434538]	96 [2539877]

Figure 6-1: Frame rate comparison with 256-to-256 height map (frame rate [rendered triangles])

One problem that appears with phong tessellation is cracks in the terrain. These cracks appear when the phong tessellation shape factor is too high or the refinement of the

[85] cf. [Ras11], http://rastertek.com/tutindex.html DirectX 10 Terrain Tutorials (accessed March 2011)

terrain is too low. *Figure 6-2* shows a screen shot of the crack in the terrain. It appears with a tessellation shape factor of 0.75 and a desired triangle size of 4.0 pixels. This only happens at the horizon of the terrain.

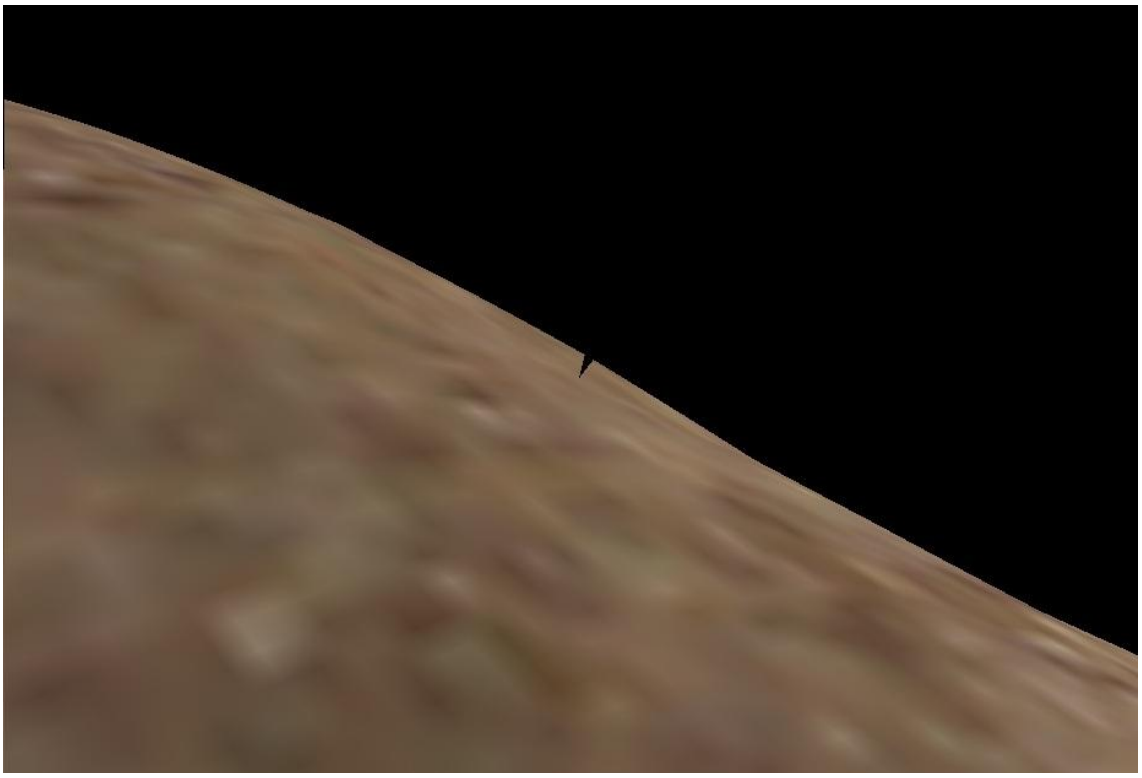


Figure 6-2: Crack in terrain

6.1. Future Work

What else can be done in the future to improve this terrain rendering system? The first thing that needs to be implemented is occlusion culling. The current implementation doesn't use occlusion culling. A lot of detail is generated that cannot be seen in the view port. That is a waste of performance. Therefore, it is a very important next step. It would be ideal to develop an occlusion culling algorithm that is done entirely on the GPU.

The next thing that should be implemented is the ability of mapping several textures to the terrain. Blending between the textures should be possible and would provide more variety on the surface of the terrain. Another thing that needs to be implemented is the use of a 16 bit height map. In the demo only a gray scale height map was used. This is fine for a small terrain of 256-to-256. However, for larger resolutions 8 bit for height data are too small. For example, the R and G channel could be used for the height data. The B channel could be used for the phong tessellation shape factor. With this factor it is possible to decide per vertex how smooth the surface should be. The alpha channel could be used for multi-texturing to decide which texture should be mapped on the surface.

To provide a fine-grained detail displacement maps should be supported. Displacement maps could provide the textures of the terrain with geometry detail. In this way, it would be possible to adapt the geometry to the texture. In a displacement map a normal and height is stored for each texel. The problem of supporting displacement maps is the change of density of the surface. It needs to be explored how the density data of the height map and the density data of the displacement map can be combined to calculate the correct density map. An additional problem is that the transition between different displacement maps needs to be handled to avoid cracks and holes in the terrain.

Another way to add detail to the terrain is to make use of generation of detail with a noise function. The detail is generated on the fly and needs no additional data. This approach works well in a distance-dependent LOD system that has constant vertex count. In a view-dependent approach this is more difficult because the density map needs to be adapted according to the generated noise.

To support a good visual quality it is also important to provide a good lighting. The lighting of the demo is not sufficiently detailed. It only simulates indirect lighting with a constant ambient light factor. A better lighting model would significantly improve the visual quality.

To provide the ability to walk over the terrain it is important to have a collision detection system or a physics engine. One example for an integration of a physics engine would be to integrate the Havok Physics.[86] The engine can be integrated at no charge for non-commercial use. The base regular grid could be taken as collision volume. This provides a fast calculation. Of course it could lead to overlapping geometry when the refined terrain differs too much from the base grid. If the error is too large it could also be used a regular grid as collision volume with a higher resolution than the base grid.

For the implementation of an editor it would be helpful to first create a height map with a graphic editor. In the graphic editor an artist can paint a height map. At the same time the artist should be able to see the result of the painted height map in a 3D view. Additionally different noise functions should be supported to be able to model detail quickly. The height should also be changeable in the 3D view. It should be possible to point at the position where the height of the terrain needs to be changed. By clicking Ctrl and left mouse button it should be possible to raise the terrain. By clicking Ctrl and right mouse button it should be possible to lower the terrain. Flat surfaces should be easy to model. Therefore the artist should be able to define a constant height. This height should be set on all places of the terrain that the artist has defined. A function to

[86] see http://www.havok.com/index.php?page=havok-physics for product information (accessed March 2011)

smooth the terrain heights is needed as well. This function could be combined with the phong tessellation shape factor. It should also be possible for the artist to manipulate the density map. The artist can decide which parts of the terrain need a higher density. Finally it should also be provided a button to generate a new density map for the current height map.

In conclusion there is still much to be done to improve this terrain rendering system. However, it does show that today it is possible to render fine-grained detail on current hardware and support at the same time a view-dependent LOD system. The biggest challenge for the future will be to support a view-dependent LOD system and still provide a constant frame rate. Distance-dependent LODs can easily provide a constant frame rate. But these LODs lack of the ability to show detailed silhouettes of the terrain that are distant. So for a finer detail that is also depended on the screen resolution it will be no alternative for view-dependent LOD.

While working on the thesis I learned a lot about terrain rendering. I also discovered I would benefit from a better understanding of terrain editors and how they work. Definitely the skills I acquired in the process of researching and writing this thesis will be important for my future work or for continuing my studies. I did not achieve my original target because I underestimated the amount of time and work involved to learn DirectX 11 fully, and to develop both a terrain rendering system and an editor.

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