Advanced Graphics and Real Time Rendering (Semester 2)

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Terrain Rendering, Tessellation, and Skeletal Animation

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# Introduction

This project aims to explore real-time rendering features such as multiple types of terrain mesh generation (with procedural heightmap generation), hardware tessellation, and skeletal humanoid animation.

Various stages of the Graphics Pipeline are utilised for the implementation of these features, such as the Hull and Domain stages which are used for tessellation and modifying applying the heightmap transformations for rendering terrain. Terrain rendering uses multiple algorithms, one for generating a plane mesh where vertex positions are altered in the Domain shader, and another uses the marching cubes algorithm to allow for more versatile and interesting terrain featuring caves and overhangs.

Skeletal animation is implemented using the MD5 file format. Models and animations are split into separate files which contain information regarding the bone structure and positioning data. Vertex positions are then calculated at runtime using the loaded bone/joint data.

# Implementation

## API

The graphics application programming interface (API) chosen for the development of this application is DirectX 11, paired with DirectXTK (DirectX Tool Kit), which provides a collection of helper classes for writing C++ DirectX code (Microsoft, 2022). DirectX 11 allows for applications to utilise graphics hardware via shaders, which are small programs written in a C-style language that are executed on the graphics processing unit (GPU) in parallel.

A common alternative to DirectX 11 would be OpenGL, which is very similar in features and performance, but offers multi-platform support whereas DirectX 11 is limited to the Windows operating system.

Other modern graphics APIs such as DirectX 12, Vulkan, and Metal offer the developer lower-level control of the rendering process. The low-level control can lead to increased performance due to the mitigation of driver overhead, where the driver software can make less assumptions about the desired functionality, thus reducing CPU load (Furmaniak, 2018). However, the amount of control offered by these APIs often leads to more verbose code.

## Graphics Pipeline

This application utilises multiple stages of the DirectX 11 graphics pipeline (appendix 1) for the implementation of various features. The programmable stages DirectX 11 offers are the Vertex Shader, Hull Shader, Domain Shader, Geometry Shader, and Pixel Shader. Non-programmable stages include the Input-Assembler stage, Tessellator stage (between Hull and Domain), Stream Output stage (after Geometry), Rasterizer stage (before Pixel), and finally the Output-Merger stage. This application takes advantage of all stages except the Geometry Shader stage. The programmable sections of the graphics pipeline in this application are as follows:

|  |
| --- |
| Domain Shader  Pixel Shader  Hull Shader  Vertex Shader |

Tessellation can be applied to objects in this application and is used for LOD’s when rendering terrain. Tessellation is configured in the Hull shader, which is executed for each control point, and applied following the Hull stage, the Domain shader is then executed for each vertex (including new vertices) and modifications can be applied.

Tessellation can be applied by increasing the tessellation factor in the Hull shader, then the tessellator stage, following the Hull stage, will subdivide each triangle based on the tessellation factor. The tessellator stage is fixed-function and generates sample points and topology for a given patch based on the tessellation factor (Nießner et al., 2015).

## Features

### Heightmap Generation

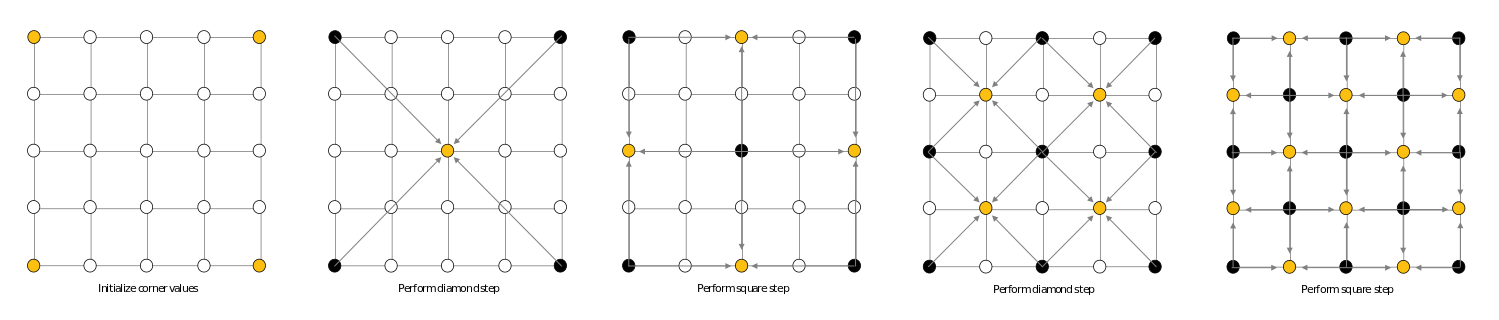
Heightmap textures can be generated or loaded at runtime, which are later sent to the domain shader to be applied to the plane mesh in order to render the terrain. The heightmap values are also used in the player controller to set the player’s height, which allows for the player to walk across the terrain. There are four options to create a heightmap, loading from a .RAW file, generation using the Diamond Square algorithm, generation using the Fault Line algorithm, and generation using multiple players of Perlin noise.

#### Loading From .RAW File

Heightmap data is read from a .RAW file by reading a stream each byte of the file into an unsigned char vector, the heightmap size is then determined by calculating the square root of the number of unsigned chars loaded into the heightmap vector, as .RAW files do not provide a header containing this information.

#### Diamond Square

The diamond square algorithm which generates a terrain effect and can be used to procedurally generate a heightmap within this application at runtime. The algorithm iterates over a 2D grid in an alternating diamond / square shape, generating and filling the grid with terrain data until each grid cell is filled. See the diagram (appendix 2) below.



The algorithm requires a 2D array of size (for example, 129x129, 257x257, 1025x1025) and begins with pre-seeded values in the four corners of the array, then iterates over the grid progressively taking smaller step sizes until the grid is filled (Mecom, 2015).

For the diamond stage, the algorithm finds the midpoint and sets the value to the average of the four corner values, plus a random value, the strength of which lessens as the algorithm progresses. The square stage then takes a diamond, finds the midpoints, and averages the values of the four points forming the corners of the diamond, plus another random value of diminishing strength. These two stages are repeated, decreasing the step size upon each iteration, until the grid is entirely populated (Mecom, 2015).

#### Fault Line

Fault line is a terrain generation algorithm which, upon each iteration, divides the terrain into two randomly sized sections, divided by a straight line, and displaces the height upwards of one half while the other half is displaced downwards (Fernandes, n.d.). See the diagram (appendix 3) below, which demonstrates the algorithm over different iterations.

Shape

Description automatically generated

The implementation of this algorithm loops for a pre-determined number of iterations, and for each iteration, selects two random positions on the heightmap grid, of which represent two points of an infinite line intersecting the grid. Then, each pixel is either displaced upwards, if the following equation returns true, or downwards, should the equation return false. In the equation represents the first point in the line, and is the second point in the line (the order is not relevant, though, the positions of each point do determine the orientation of the line, and whether the point is being tested for being, visually, to the left or to the right of the line). is the position of the current pixel being evaluated.

#### Perlin Noise

Perlin noise is a smooth noise where similar inputs result in similar outputs, as opposed to random noise, where similar inputs can result in completely different results. See appendix 4 for an example of 2D Perlin noise.

The Perlin noise algorithm consists of two main stages. The first stage generates a repeatable pseudorandom value for every integer position in 3D space using a hash function. The second stage utilises the pseudorandom integer to access a table of 3D gradient vectors, which is used to calculate a scalar value by calculating the dot product between the gradient value and fractional position within the noise space. The final value is obtained by interpolating between noise values for each surrounding eight points in space (Lefebvre et al., 2005).

Perlin noise can be sampled for terrain generation, from it’s appearance in appendix 4, it is clear that it would produce a somewhat terrain-like result being used simply with 1 sample, but to achieve a more realistic result, multiple Perlin noise samples of increasing frequency and decreasing magnitude are applied. This leads to the initial iterations greatly influencing the terrain, creating the overall shape of hills, with later iterations adding finer detail to the terrain. The following diagram (appendix 5) demonstrates this effect with three iterations of noise.

A picture containing furniture

Description automatically generated

### Terrain Rendering

Once a heightmap has been generated or loaded, a terrain can be rendered using two different techniques which are implemented into this application. The first technique is using the domain shader and a plane mesh. The second does not use the domain shader for rendering terrain, but instead generates a marching cubes mesh which allows for the terrain rendering with caves and overhangs.

Level of detail (LOD) can be applied to the terrain via tessellation (Hull and Domain stages), the amount of LOD applied is determined by the distance from the current triangle being tessellated in the hull shader, to the camera. Values passed from the GUI can determine the LOD spread and maximum intensity.

#### Plane Mesh

For this terrain rendering method, a flat plane is generated at a size determined via the GUI. When the graphics pipeline reaches the Domain shader stage, the heightmap is sampled as a texture (which is bound to the GPU as a shader resource view), and the height of the current vertex is displaced upwards by the terrain height value (determined via the GUI) multiplied by the current heightmap sample. This renders the terrain with the heightmap applied, which can then be textured and shaded in the pixel shader. The benefit of applying the heightmap in the domain shader, rather than baking the height values into the mesh upon the plane being generated, is that when tessellation is applied, the terrain becomes more detailed. Should tessellation be applied to a mesh which has pre-determined vertex positions, the triangle count of the mesh will increase, but the mesh will not gain any more visual detail, which is avoided when using the domain shader.

The plane mesh is generated by performing a nested for loop through the plane size (determined via GUI) and creating a vertex for each iteration position. For every iteration, except for the final iteration on each axis, indices are generated for each quad which makes up the larger plane.

A close-up of a leaf

Description automatically generated with medium confidence

#### Marching Cubes

Rendering terrain using a plane mesh allows for fast mesh generation and rendering but lacks the capability to render overhangs or caves within the terrain. Marching cubes can be slower to generate a mesh but allows for overhangs and caves to be implemented into the terrain.

Marching cubes renders the terrain using a terrain sampling function, which returns whether a given 3D position is solid, or not. The function utilises the heightmap to determine whether the given position’s height is above or below the terrain, or whether it is inside of a cave/overhang. Perlin noise is used for creating caves. The advantage to using a single function to determine whether a point is inside the terrain or not, is that it allows for as much, or as little, detail as the user would like. Generating a marching cubes mesh from voxel data would limit the ‘resolution’ of the mesh to what is stored within the data and would use much more memory.

The marching cubes algorithm has five key stages (Preim & Botha, 2007):

1. Determine the case index of each cell
2. Determine the intersected edges
3. Compute intersections using linear interpolation
4. Triangulate intersections
5. Calculate surface normals

The algorithm iterates over a uniform grid of cubes, if all 8 points/vertices of the cube are either solid or empty, no triangles are created for that cell. Otherwise, the cube uses a look-up table (as there are possible combinations) to determine which triangles should be constructed based on which vertices of the cell are solid. Another table of indices can then be referenced to triangulate the intersections (Fisher, 2014).

Once the mesh has been triangulated, surface normals are calculated using the cross product of the tangent and bitangent of a triangle. The following equation represents the calculations needed for calculating the surface normal. and are the directional vectors of two edges of a triangle, , , and are each vertex position of a triangle, and N is the final normal value.

Marching cubes pic

### Skeletal Animation

#### Mesh Loading

#### Mesh Animating

# Critical Evaluation

# Bibliography

Fernandes, A. (n.d.). *The Fault Algorithm*. Retrieved May 1, 2022, from http://www.lighthouse3d.com/opengl/terrain/index.php?fault

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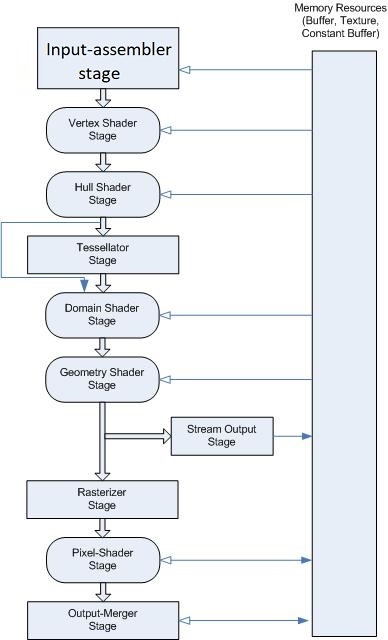
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Preim, B., & Botha, C. P. (2007). *Visual Computing for Medicine: Theory, Algorithms, and Applications*.

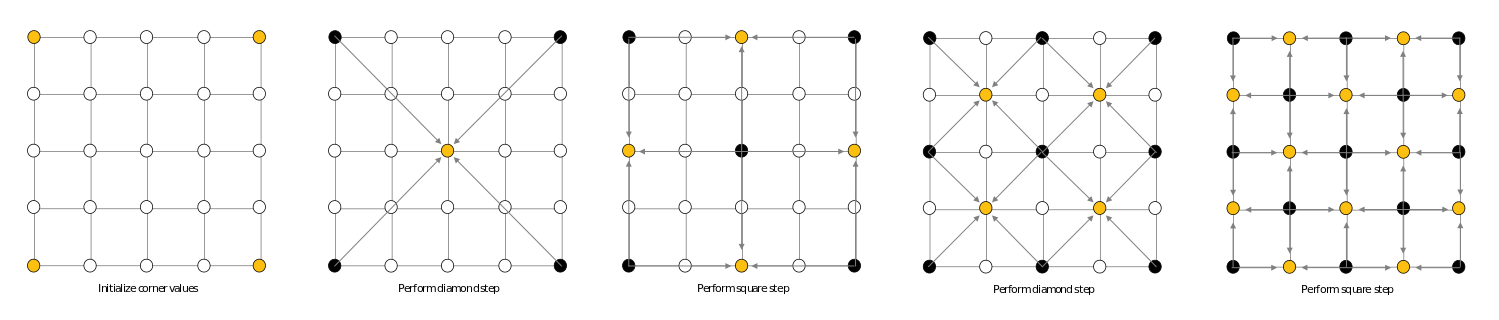
# Appendices

## Appendix 1:



Microsoft (2022). Available at: <https://docs.microsoft.com/en-us/windows/win32/direct3d11/overviews-direct3d-11-graphics-pipeline>

## Appendix 2:



Mecom (2015). Available at: <http://jmecom.github.io/blog/2015/diamond-square/>

## Appendix 3:

Shape

Description automatically generated

(Fernandes, n.d.). Available at: <http://www.lighthouse3d.com/opengl/terrain/index.php?fault>

## Appendix 4:

A close up of a person's face

Description automatically generated with medium confidence

(Biagioli, 2014). Available at: <http://adrianb.io/2014/08/09/perlinnoise.html>

## Appendix 5:

A picture containing furniture

Description automatically generated

(Red Blob Games, 2015). Available at: <https://www.redblobgames.com/maps/terrain-from-noise/>