Procedural Generation of Geographically Consistent Worlds and Biomes

(Proceduralne Generowanie Geograficznie Poprawnych Światów i Biomów)

Krzysztof Bednarek

Praca licencjacka

Promotor: dr Jakub Kowalski

Uniwersytet Wrocławski
Wydział Matematyki i Informatyki
Instytut Informatyki

Abstract

Most times, when it is needed to create a map consisting of natural terrain and biomes, one uses tools like noise. It can be interpreted as various elements of topography or climate. One can use results to build a desired map. In this paper, I will try to test another approach. Its main idea is to imitate processes which created the surface of Earth: movement of tectonic plates and climate changes over many years of Earth's formation.

Najczęściej, gdy chcemy wygenerować mapę składającą się z naturalnego terenu oraz biomów, używanymy narzędzia typu szum. Możemy go interpretować jako różne elementy składające się na układ terenu lub składniki klimatu. Na ich podstawie możemy zbudować pożądaną mapę. W niniejszej pracy spróbuję użyć w tym celu innego podejścia. Opiera się ono na naśladowaniu procesów które działały na Ziemi: ruchu płyt tektonicznych i zmian klimatu na przestrzeni wielu lat powstawania powierzchni Ziemi.

Contents

Chapter 1

Introduction

Map generation is an important part of creating a game. It is especially important in games, which requires multiple maps or even a generator of maps for the user. For example, in many strategic games, a player expects the ability to generate endless amounts of unique maps, each of which should be fully playable, look unique and – in most cases – have a similar type of terrain one knows from the real world. In other games, a player expects to find a big, open world to explore. Sometimes those maps are just too big to create them manually. In such cases, it is very useful to automate some parts of map creation.

The most popular solution is the noise. It can be easily used to generate the shape of the terrain. Then, using more noise one can create a map of temperature and moisture. Next, using a list of conditions, it can be translated into biomes.

This article will describe another approach. It will base on simulating the movement of tectonic plates and changes of elements affecting which biome is in a specific place, like fertility of ground, humidity, and temperature.

The idea for this article arose from a map generator in game Sid Meier's Civilization VI. It is a strategic game, in which the player manages a civilization and tries to gain an advantage over other players using different means like force or culture. Everything takes place on a procedurally generated maps. Unfortunately, they not always look realistic. Because of the origin of this idea for the paper, the program has been written as a modification to the game. This forced some basic properties of the model.

Chapter 2

Geographic backgorund

2.1 Tectonic plates

The lithosphere is a rigid, outer layer of the Earth. It is around 100 km thick, and consists of the crust and uppermost mantle. It is divided into seven large-sized plates, a few medium-sized, and many small ones. There can be distinguished two classes of plates – continental and oceanic. The first type is in general older and thicker than the second. Each of them moves around 5-10 centimeters per year. Their movement can cause raises of mountains, earthquakes, oceanic trenches, and volcanic activity.

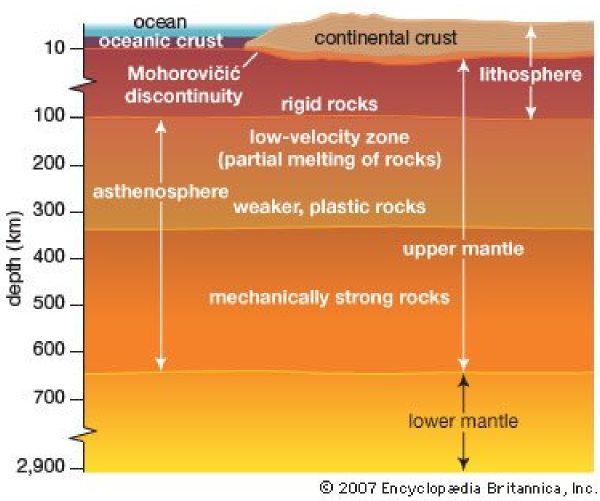

Figure 2.1: Cross section of Earth. Source: [1].

There are three main types of boundaries between them. We will describe them in the next section.

2.1.1 Convergent boundaries

They occur when two plates are colliding. Depending on types of those plates, will give different result:

- If both plates are continental, then both are to light to subduct. This kind of collision creates the largest mountain ranges. The biggest example of this is the Himalayas.
- When plates are of different types, then the oceanic plate is subducted, and the surface of the continental plate is raised. This collision can create mountain ranges. An example is Andes.
- If both plates are oceanic, then one of them subducts under the other. This type of collision creates a tectonic trench and can lead to the creation of undersea volcanoes. An example of a trench formed this way is the Marianas Trench.

In picture 2.2 we can see the visualization of all of the types of convergent boundaries.

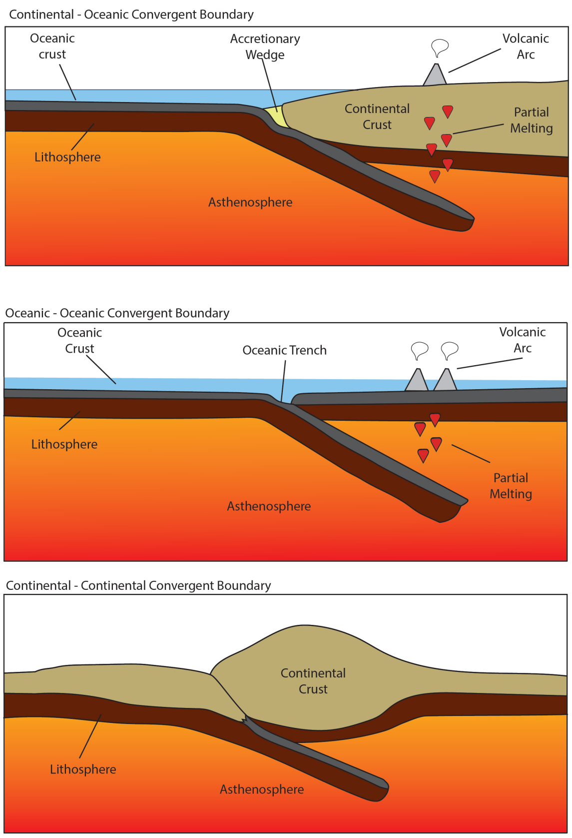

Figure 2.2: Simplified diagram of convergent boundary. Source: [3].

2.1.2 Divergent boundaries

Divergent boundaries appear when two plates are moving apart. Space they leave between them is filled with new, oceanic crust. As plates move farther away, the new ocean gets wider. Visualization of this process in the picture 2.3.

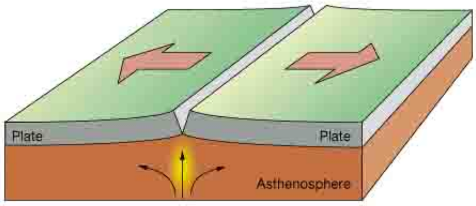

Figure 2.3: Simplified diagram of divergent boundaries. Source: [4].

2.1.3 Transform boundaries

It occurs when two plates slide past each other without colliding. There is no crust created or destroyed, but it can cause earthquakes. This process is visualized in the picture 2.4.

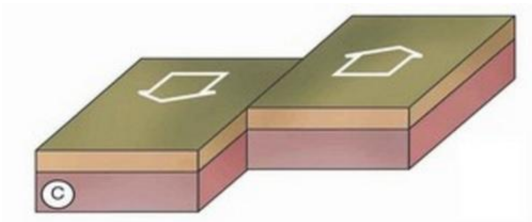

Figure 2.4: Simplified diagram of transform boundary. Source: [5].

2.2 Volcanoes

Volcano is a vent in the crust of Earth, through which molten rock, ashes, and gasses erupt onto the surface. There are three types of volcanoes, depending on how they were formed:

- Subduction volcanoes – occur near the convergent boundary with oceanic plate subducted under continental one. They are on land, in some distance from the boundary. Most times they have shape popularly associated with volcano – cone with summit crater. Around 80% of all Earth volcanoes are subduction volcanoes.

- Rift volcanoes – connected to diverging plates. Occur exactly at the boundary, or near it. Most times they are less explosives and more gentle than subduction volcanoes. Around 15% of all volcanoes are rift volcanoes.

- Intraplate volcanoes – they are not connected to plate, but to hotspot – very hot area inside Earth. From there magma rises through mantle and crust resulting in volcanic activity. When a plate, on which the volcano is located moves away, then it loses its source of magma and becomes extinct. Visualisation in pricture 2.5.

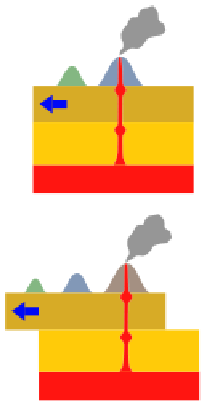

Figure 2.5: Diagram showing movement of plate above the hotspot. Source: [8].

2.3 Global atmospheric circulation and biomes

The equator is hotter than the rest of the Earth. Because of that, the air in this region rises. It can not go up forever, so at some point it turns toward poles. During its way over there, it is cooling down, and it sinks at the pole. When it is climbing, it takes water vapor with it. As it rises, it cools down and water starts to create clouds. Since around the equator is a lot of rising air, then there is also lots of rain. And around poles air is mostly sinking, what causes them to receive very little rain and snowfalls.

Earth is rotating, and this causes a Coriolis effect. As a result, the air in higher levels of atmosphere turns and never reaches the poles. The same happens to air coming back from poles on lower levels. As a consequence of that, each hemisphere has three loops of air. Picture 2.6 illustrate those loops.

2.4 Rivers

Rivers are natural streams of water. They start in the source. It can be glacier, snow, lake or underground spring. It has enough power to change terrain around

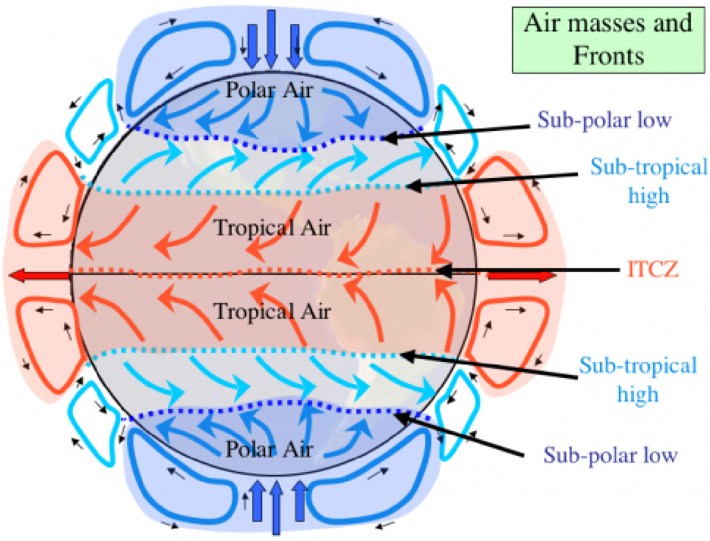

Figure 2.6: Ilustration of global atmospheric circulation. Source: [13].

it, mainly by carving surface it flows on – this process is named erosion. Also, it provides humidity to its surroundings. On the further and flatter part of the river, it can deposit fertile soil on its flood plains.

Chapter 3

Description of the implementation

3.1 General description of the model

The implemented model consists of hexagonal cells laid out on a roughly rectangular grid of 106 by 66 tiles. Each of the cells remembers a description of the place it represents: height, temperature, fertility, etc.

One of the properties required from the model was the ability to move an object through an edge of the map to the other point on some edge. Because of the choice of the rectangular grid, it was very hard to wrap it like a ball – object going out on the top should come in from the top. Instead of this, the model is based on a torus – object going out through the top edge of the map is coming back through its bottom edge.

The main process consists of many iterations. Each of them represents several thousands of years of progress in simulated processes.

Calculations are stoped if in the last few iterations percent of landmass changed only a little.

3.2 Initialization

The map should have a realistically looking variation of terrain before the main calculations happen. To achieve that, the height of all the cells has been initialized using Perlin noise. The smooth wrapping of the map on the torus was one of the challenges with using it. To solve that, four-dimensional noise has been used (based on the idea from [10]). The implementation of this part uses parts of the code from [11].

Another part of initialization was the division of the map into plates. The first approach was to simulate the cracking of the surface of a planet. It would break it into parts. Idea was to generate, in some random way, lines that would serve as borders of the plates. Unfortunately, because of the reasons, which will be discussed in section 4.1, it did not work very well.

The next concept was less based on real processes, but the effect was more accurate to real results. It was using the Voronoi diagram – randomly generate points and each tile is assigned to the nearest plate. It gave a rather good result, but it still had small problems – more in section 4.1.

The solution for the mentioned problem has been found in [12]. The algorithm starts by getting random points. They become staring positions of plates. Next, we choose a random, already assigned cell and register all its unregistered neighbors to its plate. This step is repeated until all tiles get their plates.

We have to generate some hotspots for future uses. It is done randomly — we get some random cells. The only thing we check is not to use a single spot multiple times.

3.3 Tectonic plates

Tectonic plates were an important element in the creation of the Earth's surface. Because of that, they also were a very important part of this article.

In the implementation, each plate is an object containing information about its type – is it a continental or oceanic plate, an array of cells it comprises, and the vector describing its movement. Also, each of them stores data about tiles laying at the boundaries of it. During each iteration, the speed and direction of all plates are changed randomly a little. It simulates additional forces affecting the motion of plates, which has not been included in the model. Then, each plate is moved by its motion vector cell by cell. If the tile tries to move in place already taken by another cell, then the collision happens. If in the last few cycles those two plates already collided, we have saved data about it, and we can check which plate moves under which. Otherwise, we store such information that this cell takes part in collision with that plate. After moving a single plate, we look on all plates with which it started collision and for each of them, we choose which of the two should be on top. Then we add information about the new collision to the list. To avoid two plates endlessly bumping into each other, after each iteration, we change the motion vectors of colliding plates to make them move in a similar direction.

During the collision, the cell which ends on top, gets some of the material from the submerged one. Some of this material spread between the surrounding tiles to make height change a little smoother.

After moving all plates, we need to split objects of plates, which have been divided during collisions. It is done using a simple depth-first search and tracking of visited cells.

Because of colliding, some tiles will disappear. They are replaced by new cells grouped base on the connection between them. Each of those groups is then added to the neighbor oceanic plate with the biggest area of contact with the considered segment. It is calculated by counting tiles lying directly next to it.

3.4 Rivers

The amount of time passing during a single iteration of the algorithm is large enough for the river to completely change its course. Because of that, at the beginning of each iteration, all rivers are removed. To generate new ones, the algorithm searches for cells, which are higher, than anything in the range of two tiles. Each correct one becomes a source of a new river and a place to start generating a river. To do it, we search for the lowest neighbor of it and take it as the next part of the river. The rest of the river is generated in the same way – take the last generated cell and repeat searching of the lowest neighbor. The algorithm stops when we will get to the lowest point in the neighborhood or the ocean.

Because of the erosion, each tile of the river removes a small part of the material from the cell it is going through. Also, it adds some fertility and humidity to the surrounding cells.

3.5 Volcanoes

The algorithm generating a new volcano starts by deciding what type of volcano it will be. If intraplate, then we randomly choose unused hotspot. In the case of a rift or subduction volcano, we choose a plate, and one of its boundary tiles. Then, regardless of type, it creates an object of a new volcano in the chosen place. During each iteration, each volcano has a chance of an eruption.

Because plates are moving around, the intraplate volcano can move away from its hotspot. It will make it inactive, so we have to remove it.

3.6 Attributes of cells

Because of rains and wind, after each iteration each tile has some of its material removed and distributed between its neighbors. Another type of erosion is caused by waves. This one was imitated by removing a small amount of material from cells for each lower, submerged neighbor of it.

After each iteration, all attributes of the tiles are recalculated. For example, a river going next to the cell will change its temperature, fertility, and humidity. Similar changes are made based on having an ocean nearby and a fact of eruption of neighboring volcano laying nearby.

Next, there has to be calculated influence of global atmospheric circulation, latitude, and height of the tile. The first one changes mainly humidity, second and third components influence temperature.

Chapter 4

Results

4.1 Division to plates

The first approach tended to create a lot of small and very small plates surrounded by a big one. We can see an example in picture 4.1. This error was a result of the chosen model. Because of hexagonal cells, two lines crossing at a small angle cut out tile laying out between them from its neighbors, turning it into microplate consisting of a single cell. Another problem arises from the fact that the whole map is a torus. Because of that, dividing the main plate to parts is a very hard task – it would have to be split by cracks twice top to bottom and at least once left to right. Each of those cracks would have to wrap around an edge and connect to one of the other two. During tests, it did not happen without dividing the map into a lot of micro-plates.

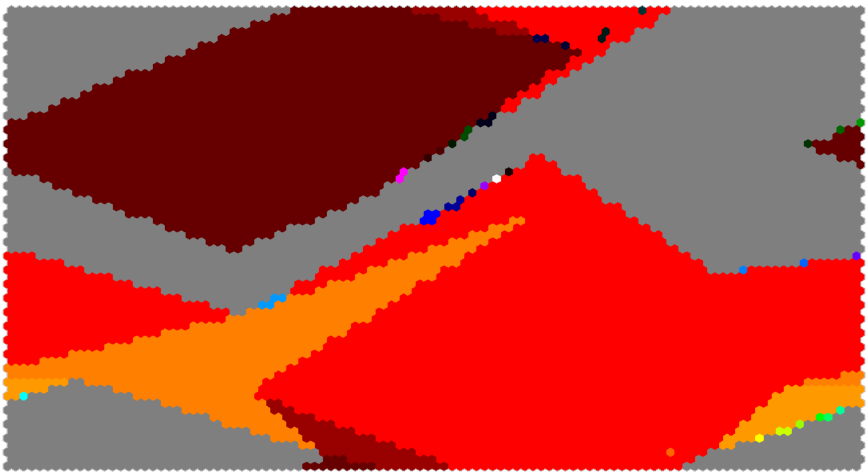

Figure 4.1: Example of initial division of map to plates using cracks. Diffrent colors represents diffrent plates. Generated using Lua framework LÖVE and script utilizing: [16].

The second method worked rather well. As we can see in the picture 4.2, it created eight plates of similar sizes. Unfortunately, they have unnaturally looking, very straight boundaries.

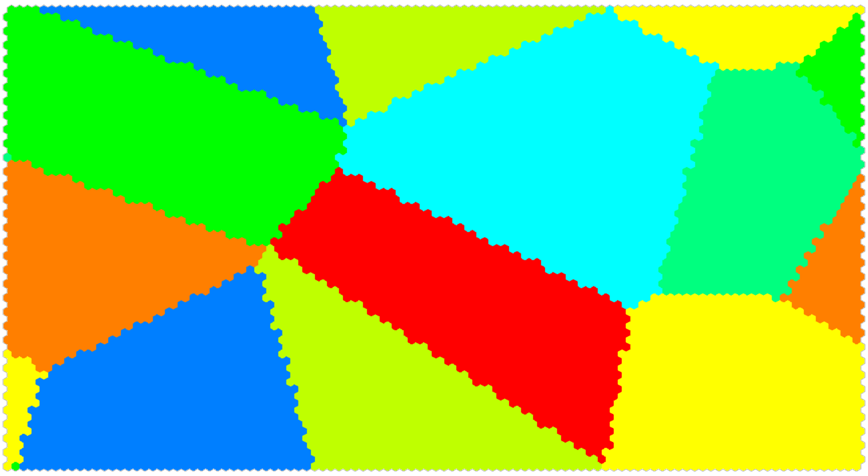

Figure 4.2: Example of an initial division of map to plates using Voronoi diagram. Diffrent colors represents diffrent plates. Generated using Lua framework LÖVE and script utilizing: [16].

The result of the final approach is shown is picture 4.3. As we can see, plates are less balanced in terms of size. Also, their edges are irregular. Together, it gives a natural-looking division of the map into plates.

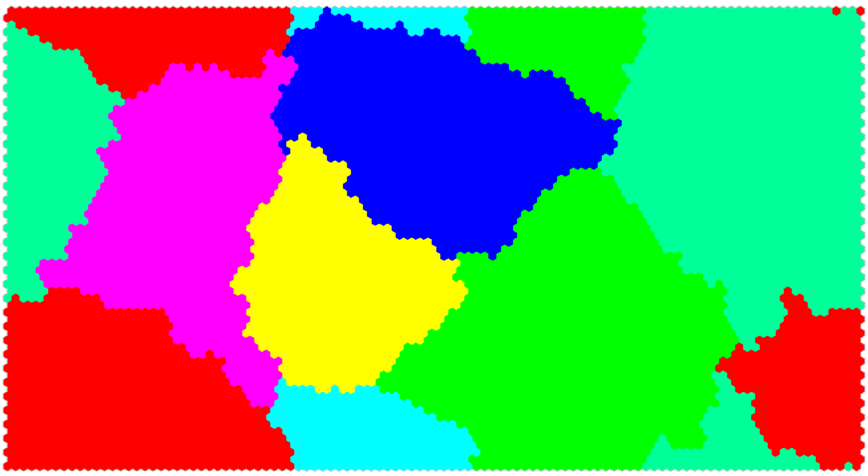

Figure 4.3: Example of an initial division of map to plates using a randomized Voronoi diagram. Diffrent colors represents diffrent plates. Generated using Lua framework LÖVE and script utilizing: [16].

4.2 Terrain

In the picture 4.4, we can see an example of the initialized terrain. Here it may be hard to see, but it is wrapped in both directions. And that is what we wanted from this part of the program.

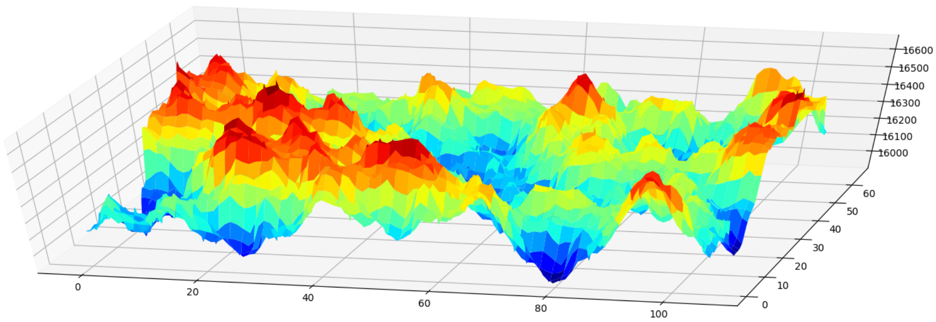

Figure 4.4: Example of initialized surface height. Created using pyplot.

Pictures 4.5 and 4.6 show an example of terrain after a full run of the program. We can see some of the features we would expect from a map. There are a few landmasses and they are around 33% of the surface. This ratio is similar to the one on Earth. Continents have various, irregular shapes. Most of their edges are a little lower than most of their terrain. We can see some coastal mountains and hills on the rest of the border. And on the bottom of the ocean, we can see some ridges. There are several small islands and a few medium ones. In the top right corner, we can see the mountain between two continental plates. Unfortunately, it still lacks some details. Besides the mentioned ridges, the oceanic floor is rather flat. There is the same problem with centers of landmasses – they are mostly flat. Also, all landmasses are much higher than the ocean floor and because of that, there is no real coast.

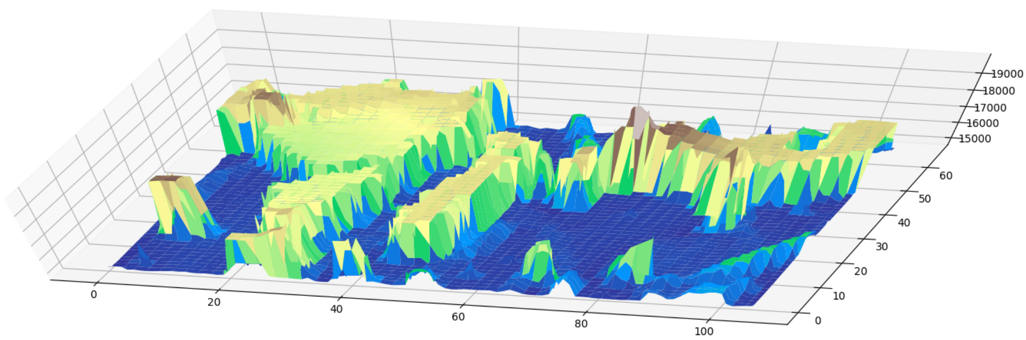

Figure 4.5: Terrain after 400 iterations. Around 33% of cells are above water. Created using pyplot.

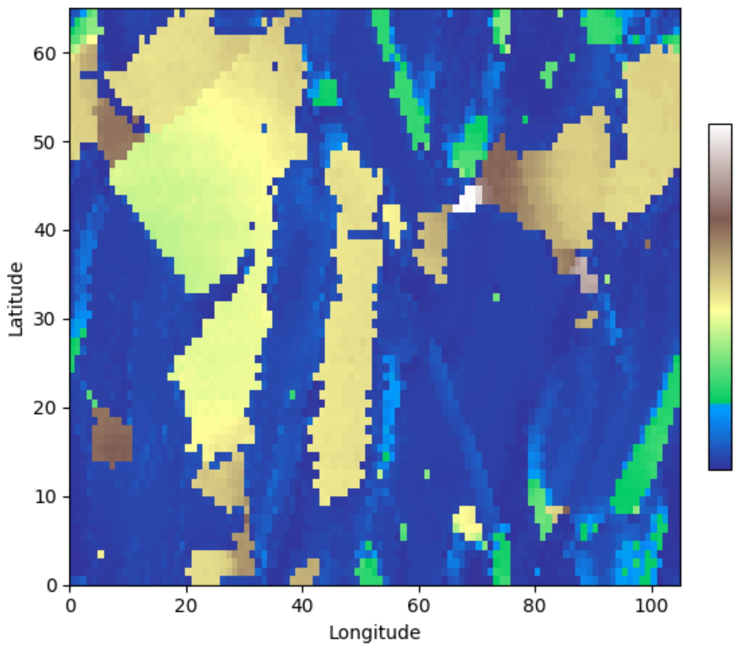

Figure 4.6: Terrain after 400 iterations. Around 33% of cells are above water. Created using pyplot.

4.3 Biomes

Most of the considered biomes are where we would expect them to be. Grasslands are mostly near water sources, and most of the land is taken by plains. Deserts occur mainly around areas of the Tropics of Capricorn and Cancer. Jungles are mainly on the equator and nearby.

Unfortunately, not everything is perfect. In reality, deserts occur also in rain shadows of mountains and on western edges of continents. Jungles are spread a little more than they should – some of them are little too much to the south. Also, there are grasslands inside the terrain with permafrost, where it should be too cold for them to live. Rivers are very short, or they are going through the middle of the land and not to any bigger reservoir. Another problem is a very straight line, where tundra begins. Additionally, shallow water should be mostly near the land, very rarely in the middle of the ocean. Pictures 4.7, 4.8 and 4.9 show examples of generated maps of biomes. The first of them comes from the same run as 4.5 and 4.6.

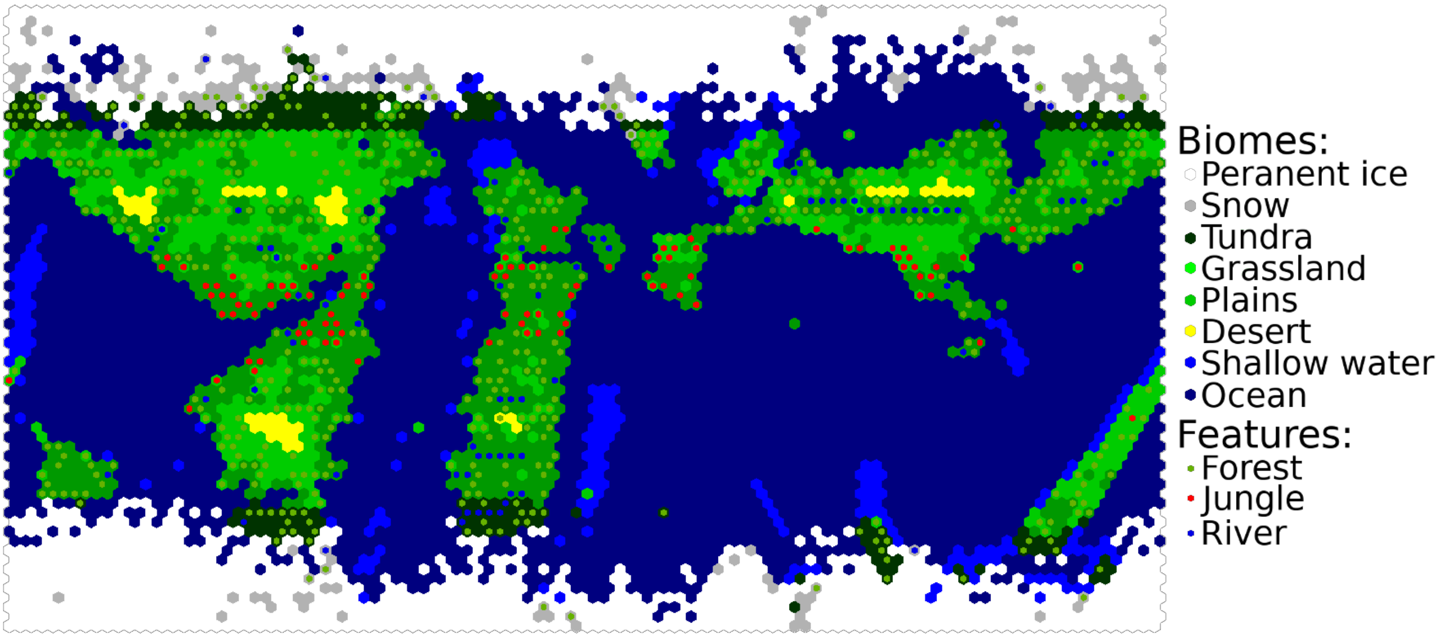

Figure 4.7: Biomes generated after 400 iterations. Visualization generated using Lua framework LÖVE and script utilizing: [16].

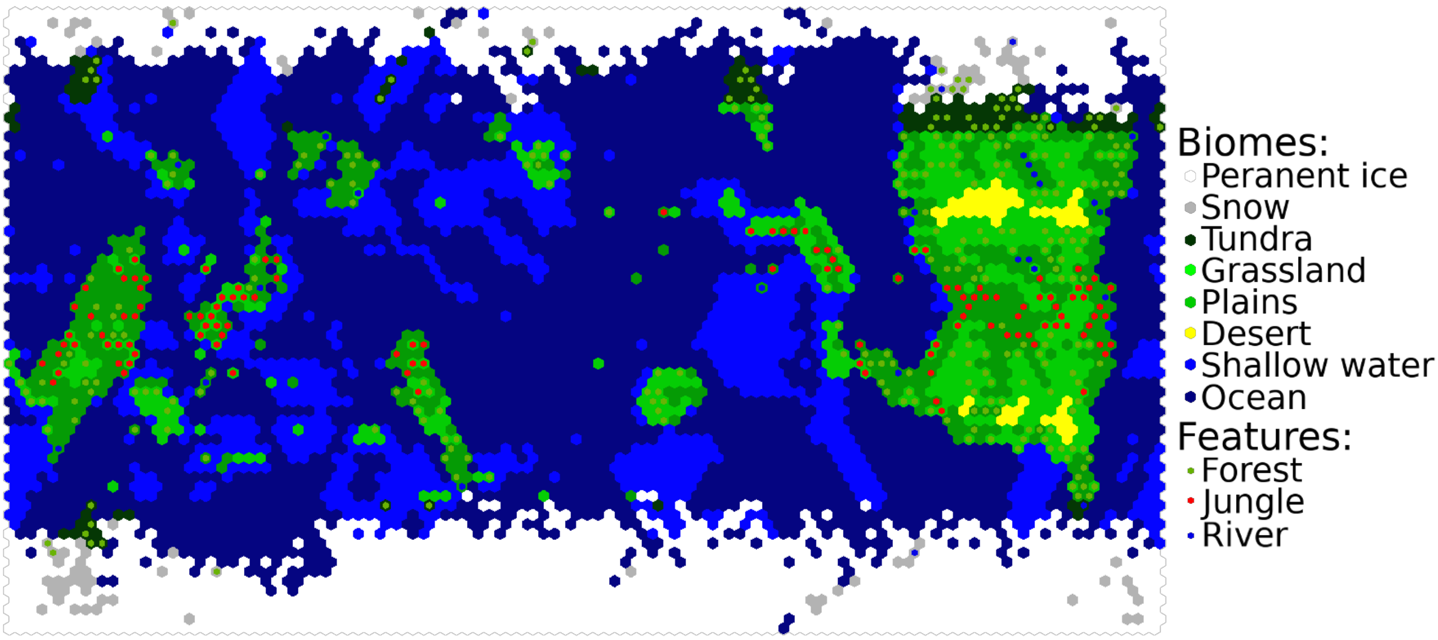

Figure 4.8: Biomes generated after 600 iterations. Visualization generated using Lua framework LÖVE and script utilizing: [16].

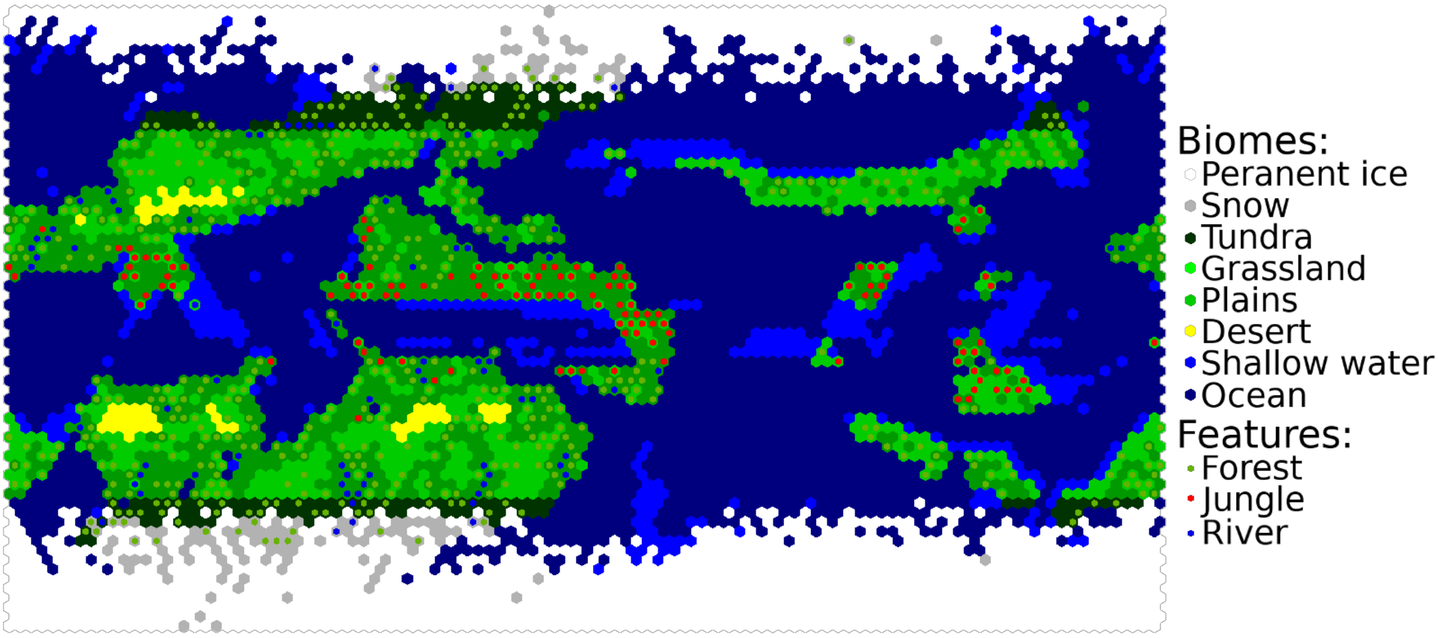

Figure 4.9: Biomes generated after 600 iterations. Visualization generated using Lua framework LÖVE and script utilizing: [16].

Chapter 5

Future work

There are a few things that could be upgraded or added to increase the accuracy of the model.

The first one is the handling of rivers. Now they just go straight to the lowest point and stop there. This part lacks splitting rivers in a more flat part of terrain. There should be lakes collecting water and, after reaching a certain point, releasing it into a future journey.

In reality, a big part of the climate is controlled by ocean currents and inland winds. They could bring even more details into the model.

The created model lacked precision — every created thing was calculated in terms of cells. If we assume, that we work with a world similar in size to Earth, then each tile has a diameter of over 377 kilometers. It means that during each collision there is destroyed at least 142000 square kilometers of plate. And the influence of rivers, volcano eruptions and all the other parts of the model is calculated in hundreds of kilometers. Because of that, it would be good to increase the size of the grid. It has not been done for this article, because a single run of the current version of the program takes more than 10 minutes.

Events like ice ages had a significant effect on the shape of the surface of the Earth. Also, some natural resources, for example coal and oil, are created during the formation of a planet. Considering that, this project could be extended to simulate geological periods and generate natural resources.

Chapter 6

Summary

The goal of this article was to test the possibility of generating terrain and biomes using simulation of natural processes and possible use of the result as a map in Sid Meier's Civilization VI.

The outline of acquired land looks pretty good. The terrain is a little worse – it has most of the expected features, but it still lacks some of them and there is no smooth transition between ocean floor and land. Acquired biomes are rather good. Rivers are the biggest problem, but some of the concerns with them arise from troubles with the terrain.

A question is, would this program work as a map generator for Civilization? Because of the mentioned problems with the result, it would be harder to play on it than on a map created using the standard generator. Lack of coasts would make impossible to build some of the wonders and use ships in the early game. Another problem comes from flatness of the middle of landmasses. In Civilisation, tiles are distinguished by height into three categories – plains, hills, and mountains. The last two give some important bonuses. Unfortunately, it would be hard to translate the result map into something with diversified terrain. In terms of biomes, the outcome ispretty good. Biomes are spread and varied, but they have a small problem – rivers. As was mentioned, they do not look very realistic and there should be more of them.

All things considered, the presented program is not the best possible option for generating maps yet, but with more features and some adjustments, it could generate really good maps.

Bibliography

[1] Britanica, Plate tectonics [online via https://www.britannica.com/science/plate-tectonics]

[2] GNS Science, Tectonic Plates and Plate Boundaries [online via https://www.gns.cri.nz/Home/Learning/Science-Topics/Earthquakes/Earthquakes-at-a-Plate-Boundary/Tectonic-Plates-and-Plate-Boundaries]

[3] Wikimedia Commons, Simplified diagram of convergent boundaries. [online via https://upload.wikimedia.org/wikipedia/commons/5/52/Simplified_convergent_boundaries.jpg]

[4] Geology page, What are the different types of plate tectonic boundaries? Chapter: Divergent boundary. 30-03-2019. [online via http://www.geologypage.com/2019/03/what-are-the-different-types-of-plate-tectonic-boundaries.html]

[5] Freie Universität Berlin: Department of Earth Science, Plate Boundaries: transform. [online via https://www.geo.fu-berlin.de/en/v/geolearning/mountain_building/plate_tectonics/plate7/index.html]

[6] Britannica, Volcanoes related to plate boundaries. [online via https://www.britannica.com/science/volcano]

[7] Explore volcanoes, Types of Volcano. [online via http://www.explorevolcanoes.com/types-of-volcano.html]

[8] New world encyclopedia, Hotspot (geology). [online via https://www.newworldencyclopedia.org/entry/Hotspot_(geology)]

[9] National Geographic, River. [online via https://www.nationalgeographic.org/encyclopedia/river/]

[10] Ron Valstar, Creating tileable noise maps. Chapter: A 2D tileable image. 26-9-2012. [online via http://ronvalstar.nl/creating-tileable-noise-maps/]

[11] Adrian Biagioli, Understanding Perlin Noise. 09-08-2014. [online via http://flafla2.github.io/2014/08/09/perlinnoise.html]

[12] Red Blob Games, Procedural map generation on a sphere. Chapter 3: Tectonic plates. 22-10-2018. [online via https://www.redblobgames.com/x/1843-planet-generation/#tectonic-plates]

[13] Montessori Muddle, Global Atmospheric Circulation and Biomes. 21-04-2011. [online via http://montessorimuddle.org/2011/04/21/global-atmospheric-circulation-and-biomes/]

[14] BiteSize, Desert biomes. [online via https://www.bbc.co.uk/bitesize/guides/znxsgk7/revision/1]

[15] Britannica, Origin Of Coal [online via https://www.britannica.com/science/coal-fossil-fuel/Origin-of-coal]

[16] Github – Phoenix Enero, Hexagonal Grid Library for Lua. [online via https://github.com/icrawler/HexaMoon]