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Modern Game AI Algorithms 2023, Assignment 1

Procedural Content Generation

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1 Introduction

The playable worlds in modern games are becoming very large, requiring lots of manual work by designers to build and place buildings and other elements of the world. Recently, the use of procedural content generation (PCG) in this area stated to increase because it lowers the required amount of work by automatically generating believable content. There are many problems where PCG can be applied, but this report explores the generation of a believable house in Minecraft, including the placement, consistent structure and randomness. For the generation of the house itself, the wave function collapse algorithm will be used.

The wave function collapse (WFC) algorithm [Gum], which was introduced in 2016 by Maxim Gumin, is a new algorithm for PCG inspired by quantum mechanic principles. It uses the concept of superposition and state collapse. A particle can be in a superposition, i.e. in many states at once, until it collapses to a single state. The same concept is used in the WFC algorithm, which first initializes all "particles" in the state space to a superposition and then collapses one of them, propagating the induced changes to neighboring particles that are defined by a set of rules. Take for example a rule that states that next to a particle in state A there must be a particle in state B. If we have a state space of two particles in the initial superposition: $[(A, B), (A, B)]$ and collapse the first to state B: $[(B), (A, B)]$, the rule forces us to choose A for the second $[(B), (A)]$ particle. The algorithm keeps collapsing and propagating until all particles are in a single state.

The WFC algorithm has already been applied to problems in PCG such as building generation [Cha], where the individual particle states need to be thought of as building structure elements like walls, windows and doors, or 2D level generation [Don], where the states are reusable level fragments. It has also been applied to village generation in Minecraft [Mif] using individual buildings and infrastructure components instead of the particle states.

Structure

The report is structured into independent sections, containing the method and results for the respective component. First, a method for the building placement is described, results are shown and limitations are discussed. The next section focuses on the building generation using the WFC algorithm. Third, a method do add interior decoration is shown. Fourth, results for the combination of building placement, building generation and interior decoration are shown. Finally, the report concludes with a discussion of the results, the limitations of this approach and directions for improvement.

2 Building Placement

The terrain in Minecraft can be very different from one location to another. Hence, placing a house in an area can't be don't totally deterministically because it should be adapting to the shape of the terrain to make it believable. For this task, a method for terrain adaptive placement has been developed, which is still very mathematical. First, the terraforming distance [Equation 1](#) is defined as the absolute number of blocks that have to be added and removed to perfectly smooth a fixed size area $l \times w$ at a certain position x, z to a certain height level y . This distance measure can be used to find the smoothest possible surface in a given region. The search

can be implemented as an optimization problem, but it was decided to simply brute force the optimal surface, since the number of possible surfaces is small enough. To do this, an algorithm simply tries all possible sizes at all allowable positions in the building region for different y and calculates the terraform distance for each solution. Unfortunately, the algorithm likely chooses naturally flat areas such as frozen ice or ocean water, which is not desired. Therefore, a constraint to forbid the height $y = 63$, which is just above the sea level, was added. However, this approach has the problem that smaller building areas are preferred, since their terraform distance is always smaller than that of a larger area. To account for this, the terraform distance can be normalized by the size of the surface [Equation 2](#). However, it has been found that it is very difficult to choose the coefficient $c \in \mathbb{R}$ for the normalization in a good way. In order to still choose areas that are not minimally small, the algorithm was modified to randomly choose from the two best solutions per size.

$$\Delta_{TF}(l, w, x, y, z) = \sum_{i=x}^{x+l} \sum_{j=z}^{z+w} |y - \text{heightmap}(i, j)| \quad (1)$$

$$\Delta_{NTF}(l, w, x, y, z) = \frac{\Delta_{TF}(l, w, x, y, z)}{lw^c} \quad (2)$$

3 Building Generation

This section describes the generation of buildings using the wave function collapse (WFC) algorithm.

3.1 Structure Building Blocks

In order to use the WFC algorithm a set of small structures, sometimes called tiles or prefabs, is required to combine them to a larger structure, i.e. a building. These structures can in general be of any granularity from single blocks to larger groups such as walls, rooms or even whole corridors. However, there is a trade-off between variation and believability. There are more combinations of smaller structures in a fixed area than there are combinations of larger structures but many of these combinations of smaller structure combinations result in unrealistic buildings, e.g. five doors placed next to each other. Therefore, building structures with a size of $11 \times 6 \times 11$ and $11 \times 9 \times 11$ blocks were used, where each represents a single room of a building. This size gives enough possible variations in the typical size of a Minecraft house while believability, accessibility and architectural style. A selection of the designed structures can be seen in [Figure 1](#).

In order to duplicate these structures, and apply translation and rotation onto them, they need to be constructed using a computer program. It was chosen to follow a scanner-builder approach over manually translating these structures into code that constructs them using simple geometry like cuboids because the scanner-builder approach is easier to implement and allows for faster iterations. The scanner¹ works by serializing the user defined build area to a Python pickle file. Afterwards, the builder² can be used to duplicate the scanned structure with arbitrary rotation and translation. Every structure was scanned from the bottom left corner in positive XZ direction, by standing on the golden blocks shown in [Figure 1a](#).

¹`structure_scanner.py`

²`structure_builder.py`



(a) From left to right: building entrance corner, balcony and big window corner.



(b) Doors between each building structure.

Figure 1: Some manually designed building structures which can be combined by placing them next to each other. Doors between them are aligned to ensure accessibility of the whole building.

In total 14 building structures were designed, which are shown in figure [Figure 2](#). They are split between first floor ($11 \times 6 \times 11$) and roof house ($11 \times 9 \times 11$) elements. There are simple corner elements and middle wall elements to allow building $n \times 2$ rectangular shaped buildings. Additionally, center elements like **center** and **courtyard** were added to support $n \times m$ shapes. Later, the concept of an inner corner was added to allow for more complex shapes like L , O and $+$.



(a) From left to right: building entrance corner, middle wall, balcony corner, big window corner, courtyard and inner corner.



(b) From left to right: corner roof house, middle wall roof house, inner corner roof house, courtyard roof house, center, center roof house, corner flat roof and big window flat roof.

Figure 2: All 14 designed building structures in all rotations. Each column represents a single structure and each of the four rows represent a rotation of that structure. The lowermost row is the baseline rotation 0.

With the introduced building structures one can already build whole houses by deterministically placing them next to each other, while making sure that all doors align as they are supposed to. Two examples are shown in [Figure 3](#).

3.2 Wave Function Collapse

With the previously introduced set of structures it was only possible to generate deterministic buildings so far. Using the wave function collapse (WFC) algorithm it



(a) A 3×3 house with courtyard and a second floor (roof house).
(b) A 2×2 house with a flat roof.

Figure 3: Two deterministically built buildings.

will be possible to generate randomized buildings which are still believable because they are only built out of valid combinations of structure building blocks.

3.2.1 Rule Set

To achieve this, it is necessary to define the adjacency rules for each structure. These define how structures can be placed next to each other, whereby rotations of the structures must also be taken into account. For the 14 structures with six sides and four rotations (rotation around the Y-axis only), this would mean that $14 \cdot 6 \cdot 4 = 336$ rotated sides would have to be considered. For each of them one would have to define whether they may be placed next to each other, i.e. $\frac{336(336-1)}{2} = 56280$ rules. Obviously, this is not very practical to define so many rules manually. Therefore, one can make use of the symmetries of the structures and define the adjacency rules only for one rotation of the structure. The others can be derived from this. In addition, one can only define the rules that are allowed, and assume for all rules that are not defined that they are not allowed.

The total of 320 rules³, that were necessary for the 14 structures, were realized directly in Python. A small excerpt from this is shown in Listing 1. Direct relationships between the objects were specified directly, i.e. if A is allowed next to B, there must also be a rule that B is allowed to be next to A. This explicit symmetry makes it easier to create the rules, as errors can be avoided in this way. Additionally, a consistency check `check_symmetry` for the rule set was implemented along with some other unit tests because the process of defining the rule set and the implementation to drive the implicit rules are both nontrivial.

3.2.2 Wave Function Collapse Algorithm

The wave function collapse algorithm [Gum] is used to generate random valid combinations of the previously introduced building structures. A simplified version of the algorithm⁴ is shown in Listing 2. The algorithm starts with a state space where each cell is in a superposition of all available building structures. If the minimal overall entropy is zero, there is at least one cell for which we can't determine any fitting building structure anymore and the whole WFC process restarts. Otherwise,

³`structure_adjacency.py`

⁴`wave_functionCollapse.py`

```

1  structure_adjecencies = {
2      brickhouse_middle: StructureAdjacency(
3          structure_name=brickhouse_middle,
4          x_plus=[
5              StructureRotation(brickhouse_middle, 0),
6          ],
7          x_minus=[
8              StructureRotation(brickhouse_middle, 0),
9          ],
10         z_plus=[
11             StructureRotation(brickhouse_middle, 2),
12             *all_rotations(brickhouse_center),
13         ],
14     ),
15     brickhouse_center: StructureAdjacency(
16         structure_name=brickhouse_center,
17         x_plus=[
18             *all_rotations(brickhouse_center),
19             StructureRotation(brickhouse_middle, 1),
20         ],
21         x_minus=[
22             *all_rotations(brickhouse_center),
23             StructureRotation(brickhouse_middle, 3),
24         ],
25         z_plus=[
26             *all_rotations(brickhouse_center),
27             StructureRotation(brickhouse_middle, 2),
28         ],
29         z_minus=[
30             *all_rotations(brickhouse_center),
31             StructureRotation(brickhouse_middle, 0),
32         ],
33     ),
34 }

```

Listing 1: A (very) short excerpt from the adjacency rules limited to the middle wall and center structure. All rules are defined from the respective element’s perspective in rotation 0 (lowermost row in Figure 2).

a random cell among all cells with that entropy is selected. Afterwards, that cell is collapsed to a single building structure out of the still possible building structures for that cell (it’s superposition). The cell state collapse is propagated to update all other cell’s superposition using the previously defined set of rules. This is repeated until all cells are collapsed, i.e. exactly one building structure is selected for them.

To ensure that the generated building is closed, in the sense of only outer walls from the outside, it was necessary to introduce the concept of an air building structure. That structure is essentially the same as any other structure, except that it does not contain any blocks and is only composed of air. Using this structure and the appropriate rules that define which sides of an actual building structure need to be placed next to air, one can enforce closed buildings by collapsing the outermost rectangle of cells in the state-space to air. However, this will change the behavior of the WFC algorithm because cells next to the now air cells have lower entropy and will be collapsed before any center cell. This results in structures that can only be placed in the center (e.g. center, courtyard, inner-corner) almost never being selected. To solve this, a few (i.e. 3) randomly selected cells are collapsed before starting with the real WFC algorithm which will use the min entropy heuristic for cell selection. The final result of this step can be seen in Figure 4. Additionally, the

```

1 def wfc(self):
2     self._initialize_state_space_superposition()
3
4     while not self.collapsed():
5         min_entropy = self.min_entropy()
6         if min_entropy == 0:
7             # the current state is unsolvable now. Restart.
8             self._initialize_state_space_superposition()
9             continue
10
11     next_cells_to_collapse =
12         ↳ list(self.cells_with_entropy(min_entropy))
13     x,y,z = random.choice(next_cells_to_collapse)
14
15     state_superposition = list(self.state_space[x][y][z])
16     collapsed_state: StructureRotation =
17         ↳ random.choice(state_superposition)
18
19     self.collapse_cell_to_state(cell_xyz, collapsed_state)

```

Listing 2: A simplified version of the implemented wave function collapse (WFC) algorithm.

creation process can be observed in a video⁵.



Figure 4: Building(s) generated with the WFC algorithm.

4 Interior Design

The buildings that can be constructed using the techniques and assets presented so far are missing interior design like decoration, furniture and lights. To add this to the buildings each building structure can be built with different interior designs, yielding a set of variations of that structure that can be used as a drop-in replacement for each other. After the WFC algorithm finishes, another algorithm may replace any

⁵<https://cloud.fachschaften.org/s/iHzxSNXsZpsr46Z>

number of building structures with such a drop-in replacement to add interior design to the building.

As the focus of this assignment was not on interior design of Minecraft houses, only a few building structures were equipped with these elements. The results can be seen in [Figure 5](#), [Figure 6](#) and [Figure 7](#).



Figure 5: Entrance interior design elements.



Figure 6: Middle and center interior design elements.

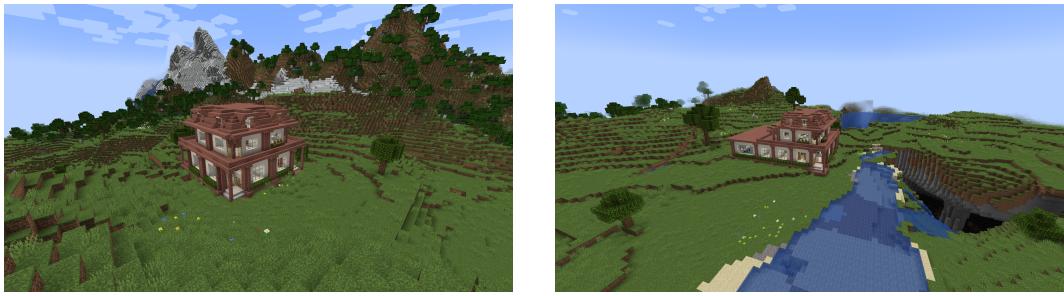
5 Overall Results

This section shows some results from the end to end building generation involving the search for a build area and the generation of the building. The results can be seen in [Figure 8](#). There is also a video⁶ of the generation process. The algorithm is also capable to build buildings on more challenging environments as shown in [Figure 9](#). The algorithm also handles already existing structures, e.g. villages, very well and does not deconstruct them (see [Figure 10](#)). However, the algorithm also sometimes generates unwanted results such as multiple unconnected houses. This can happen if the build area is "too" large. Additionally, the algorithm places buildings on a surface which is assumed to be flat, resulting in overhangs (see [Figure 10](#)).

⁶<https://cloud.fachschaften.org/s/c5NKyaDjYeLwEer>



Figure 7: Center and bedroom interior design elements.



(a) Small-sized building.

(b) Medium-sized building.

Figure 8: Buildings generated with the WFC algorithm and placed in a realistic Minecraft world (easy).

6 Discussion

Within the scope of this assignment a working solution to generate believable buildings in Minecraft was implemented. It consists of a build area selection and building generation step, which is based on the WFC algorithm and a handcrafted set of structures and rules.

The current implementation suffers from some issues which can be improved on. The structure scanner and builder introduced in [subsection 3.1](#) struggle to handle stateful blocks like a burning campfire or blocks that require other blocks to stick to like lamps or banners. The next step, placement, currently struggles to find "the largest reasonable" area and sometimes generates way to large houses (because of the random selection). If one could find good coefficients for the normalized terraform distance, it would work better. Another point is the limited expressiveness of the rule set, with which it is not possible to define global rules. For example, it would be advisable to define that there must be at least one element with a staircase when a second floor is built. This is currently not possible as only direct adjacency relationships can be expressed. In addition, the manual maintenance of the rule set, as described in [subsubsection 3.2.1](#), is very laborious, and another abstraction level would be useful to reduce the manual work. Last, it was unfortunately not possible in the time frame to build more structures with interiors. Here, however, it would also be conceivable to place the individual interior elements such as cabinets, lamps, stairs, etc. by a WFC algorithm in the building and leave the original structures themselves blank.



(a) Medium-sized building on a small island.



(b) Medium-sized building next to a forest.

Figure 9: Buildings generated with the WFC algorithm and placed in a realistic Minecraft world (medium).



(a) Large-sized building next to a Village.
The building does not intersect with the existing buildings.



(b) Two small-sized building in forest. Note the overhang of one building.

Figure 10: Buildings generated with the WFC algorithm and placed in a realistic Minecraft world (hard).

References

- [Cha] Eleni Chasioti. Gameplay with encoded architectural tilesets: A computational framework for building massing design using the wave function collapse algorithm.
- [Don] Martin Donald. Superpositions, sudoku, the wave function collapse algorithm. <https://www.youtube.com/watch?v=2Suv04Gi7uY>.
- [Gum] Maxim Gumin. Wave function collapse algorithm. <https://github.com/mxgmn/WaveFunctionCollapse>.
- [Mif] Jakub Mifek. Procedural generation of minecraft villages utilizing the wave function collapse algorithm.