

This work introduces a way to generate "plants", especially tree-esque structures, depending on the simulated light and other environmental influences. The system is designed to model the interactions of a medium to large size of entities, less focused on creating single organisms to export and use in unrelated contexts and more on on the generation of whole "forests", i.e. many interacting individuals, representing a base to simulate full ecosystems with even more complex and entangled behavior in a semi-realistic fashion. Thus, we found a novel way to abstract tree growth in a low-level-randomizing robust fashion, and build a system for plants to interact with each other and with environmental factors.

1 Introduction

Generating content procedurally by algorithms instead of and in addition to manual creation is an important developing area for software design, in the gaming industry and beyond - easily evident by the widespread use of 3D-Art programs like Speedtree and Substance Designer in the gaming industry, and the outstanding commercial success of games like Minecraft, which draws an important part of its appeal from its randomly generated and distinct worldmaps.

Obviously, different use cases require vastly different approaches. The most important distinction one needs to make is probably the one between robust solutions that need to produce decent results every run (most end user gaming applications fall under this category), and solutions that are meant to be heavily edited and parameterized and can have some "bad" (whatever that means in the respective context) outcomes. Usually, diverse possible results are a key incentive to use procedural generation in the first place, and necessarily the degrees of freedom for the generation system become limited with each additional constraint - especially if those are fixed in code, and not subject to manual assessment and editing.

Our method is an approach designed to be fully robust, limiting how much "worst case" results can deviate from desired outputs, while still allowing the system to do as many unexpected things as possible. The system we designed to tackle this problem can be found in chapter 3.3. The goal was to recreate behavior found in real-life biological growth, by modeling rules that govern the development of biological organisms, and less by working with arbitrary constraints that lead to creations that look similar to the originals but because of different reasons than those.

2 Related Work

For this project, there is related work mainly in two categories: On the one hand in the sense of simulated ecosystems, which is obviously a wide subject as many different works could be summarized under this term, and on the other hand in the context of procedural tree generation, which is a lot more of a canonical topic of research.

2.1 Simulated Ecosystems

Many games have smaller or bigger element of life cycle simulation, such as the unsophisticated tree grow features in Minecraft [4], or various features of the first three stages in Spore [5], but they usually have very limited degrees of freedom, or do not use extensive procedural generation at all. Additional, their algorithms usually have easily predictable rules, and they don't form chaotic, i.e. complex, systems as they are mainly meant as an element of game design and not as a point of interest in itself.

Some games even declared their main focus to lie on ecosystems or evolution. Two arbitrary examples to name would be CellLab [6], a mobile game where players have to manipulate time-based cell division rules to create simple multicellular organisms with different properties, and ECO [7], a Minecraft-esque sandbox game which lays it's focus on simulating the ecological impact, e.g. exhaust gas pollution, of the players actions. The concepts in this kind of games are usually very high-level though, and simulate various features of biological organisms by very specific ad hoc features instead of a system that makes this behaviors emerge as special cases of general rules.

2.2 Procedural plant generation

One prominent example for procedural plant generation would be SpeedTree [8], which can generate very realistically looking results, and gets used by 3D Artists for this purpose a lot, but requires extensive manual supervision and is by design focused on the visuals of the results, and not on a simulation of the underlying principles.

The state of the art for generation tool seem to be Lindenmayer-Systems (or L-Systems), which are probably also a part of the SpeedTree-algorithms, and those gave the initial ideas for our plant generation as well. In it's very basic form, L-Systems are string-manipulating formalisms, where letters in a string are substituted by a given rule set in consecutive iterations, and after a certain amount of iterations a 2D or 3D shape is drawn from the resulting string. As L-Systems are very suitable to express self-similarity, very good visual results can be achieved, but those systems do not model ecological influences, and aren't fit for the use of randoming with many degrees of freedom. See for example [11] for in-depth usage examples, and chapter 3.2 for the steps we took away from L-Systems.

3 Implementation

3.1 Engine, Language & Code

The implementation was done in Unreal Engine 4 (UE4 or UE in short)[3], a framework developed by Epic Games. Originally meant to be used as a basis for video games, it soon found applications in many different fields after it became available to the general public in 2014. It offers a strong framework for efficient rendering, collision detection, physics and alike (i.e. it solves many fundamental but hard 3D problems) and is completely free of charge for use cases like ours. Especially the collision detection systems were used

extensively in this project, and UE's ample debugging and performance profiling tools proofed very helpful at various points in development, too.

Most of the code was done in C++, as especially the generation of the organisms is very performance-critical. Blueprints, the visual scripting language of Unreal, was only used occasionally for prototyping and non-heavy-lifting work, e.g. keyboard input handling and variable/property setup.

3.2 General

The design idea at the very fundamentals was to implement grow logic on the basis of cells, and understand organisms as a collection of connected cells that interact with each other, but are otherwise mostly independent. Cells then can transform or divide into other cell types, a process which forms complex organisms in the end. This is, in a kind, a derivation from Lindenmayer-Systems and it would indeed be possible to encode all cell states in such a way that it would fulfill the respective definition. Yet the resulting strings would be very long and hard to read, and interactions based on positioning in a 3D space are far from the way L-Systems usually work, so it makes a lot of practical sense to drop the formal constraints of thinking in those limiting terms.

Plant cells always have an "attachment parent", not in the sense of being a predecessor in terms of cell division, but in being directly "below". Accordingly, there is a root cell for all plants, and all other cells are "children" or "children of children" and so on of the root cell. Constructed that way, the plant can generate it's visuals recursively, where every cell first draws itself and then it's child or children. This way, position changes (e.g. cell divisions) close to the root can easily impact positioning of cells at the treetop. Different cell types may have different properties (size, whether the cell is influenced by gravity, etc.). This cell type properties are stored on a per-organism basis. i.e. if there is one leaf cell type, all leaf cells will have the same "genetics". On the other hand, interactions and environmental influences (collisions, if the cell gets hit by light) are calculated for each cell separately. Based on this environmental influences, including passing time, is also decided how a cell divides. Each cell type has divide definitions that determine whether the cell divides into horizontally (creating a fork) or vertically (prolonging the branch) arranged children.

Accordingly, each cell needs to be represented by a single mesh - which imposes a problem, as Unreal usually can handle around 1200 draw calls per frame if 60 fps are supposed to be hit. Thus, UE projects can easily be CPU-bottlenecked, even though the amount of rendered polygons isn't exhausting the capabilities of the graphics card. So, geometry instancing was used, in the form of Instanced Static Meshes [9], which is one of the UE variants of this practice. Instanced Static Meshes render the same 3D model multiple times per draw call, improving the rendering speed by several orders of magnitude. On the downside, the difference between instances is limited to scale, size and rotation, and the system is noticeably less flexible than Spline Meshes [10], which would commonly be used to represent linearly arranged meshes.



Abbildung 1: Rosa canina (Dog Rose) [1]

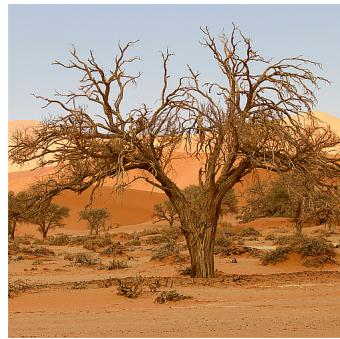


Abbildung 2: Biological tree branching structure [2]

3.3 Plant Grow As Evenly Spread Self-Similarity

If we look at plant structures so different as rose blossoms (figure 1), dandelion seed heads or tree branching (figure fig 2), it turns out that many of those follow a somewhat even spread, and the shapes of the various arrangements are describable by different degrees of freedom. In general, this freedom is radially symmetric in grow direction, so a full description may be given by two angles α_{\min} and α_{\max} , defining the freedom of the distribution to deviate from the grow direction. The objects growing out of the origin then take positions such that the minimal distance between two objects is maximized - an even spread.

For punctiform origins, like those used in this project, the two angles define two circles on a sphere, and the directional possibilities are the set of vectors pointing from the origin to a point on the sphere between the two circles. Thus, a dandelion-like structure corresponds to a minimum deviation of $\alpha_{\min} = 0$ (i.e. directions can be arbitrary close to the grow direction) and a maximum deviation of $\alpha_{\max} \approx 90^\circ$. For "flat" layouts, like those of the petals of the rose in figure 1, is $\alpha_{\max} - \alpha_{\min} \approx 0$ (or small, if there are different layers of petals).

If the number of objects that grow out of a given origin becomes small, such as in the tree in figure 2, this principle is less obvious on first glance, but it remains a special case of $\alpha_{\max} - \alpha_{\min} \approx 0$. In the case of trees, the "objects" that grow out of the origins are actually

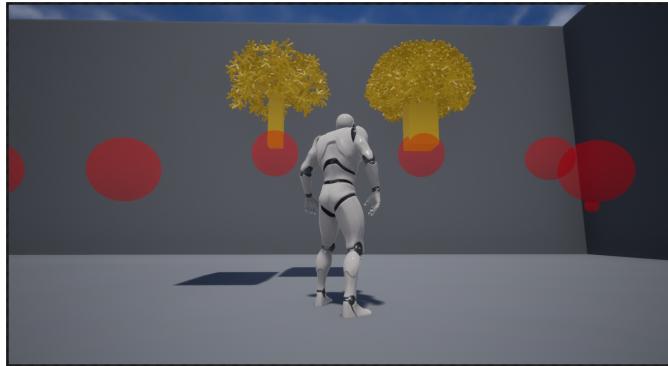


Abbildung 3: Self-collision enabled (left) and disabled

branches, and can branch, i.e. form new origins, in itself. This is the self-similarity in the title of this chapter, and this is also the reason why L-Systems can simulate tree-shapes so well, and why the golden ratio, being an expression of self-similarity, can be found in countless different contexts in biology.

The practical implementation of these principles obviously imposes difficulties, which were only solved by approximation in this project. For example, the distance of objects growing out of origins was approximated by the "distance" of grow directions only, and the algorithm used to generate these directions only yields semi-satisfactory results for $\alpha_{\min} \neq \alpha_{\max}$. More variety in basic forms was cut in scope in favor of factors of interacting grow - see chapter 3.4.

3.4 Influencing Thingies

The following behaviors are simulated:

- Plants in water are allowed to have more cells than those without access to it
- Wind/storm blows over a part of the stage, destroying parts of plants that get hit by too much wind
- There is a cone-shaped light source, leading plants to grow in the direction of the light as they divide faster on the light-faced site, have smaller leaves and to have a higher total cell count
- The diameter of cells grows when a higher "weight" rests on them, i.e. when they have many "attachment-descendants"
- The grow direction can have a positive or negative correlation with gravity, leading to trees that always grow upward, and trees that "bend over", even off the stage
- Cells divisions cannot result in children that collide with external objects or other cells of the plant. Figure 3 shows an example



Abbildung 4: Roots growing on the floor and up a wall



Abbildung 5: Influence of different light conditions on plants with identical genetics

- Certain cells - in this case the roots - can grow attached to the ground and up to walls when they hit them (figure 4)

As hinted above, the numerous collision features of Unreal were used extensively. On the one hand directly to check for overlapping collision shapes (e.g. for the water mechanics) or in the form of "Raycasts/Line Traces" that determine where a point that travels on a given line segment hits something. This was, for example, used for the light and wind mechanics, which are modeled by around 10.000 Raycasts each grow iteration. One possible influence of light is shown in figure 5. The light comes from the left, and the source is very close to the tree on the left. This tree has noticeably more leafs and children than the one further in the background, even though the "genetics" / properties of the plants are the same. Additionally, it can be clearly seen how the tree divided more on the site facing the light source. The image also shows nicely the vastly different possible diameters of cells depending on the number of "attachment descendants" they have, and the effect of the trees bending upwards as they have a positive correlation with gravity, too.

3.5 Paramteter / gewähltes teilungsverfahren

In it's very fundamentals, the used division schemes are based on three states, K , F and H ($A \rightarrow B$ means that A divides into B):

$$K \xrightarrow{\text{time}} F, H \quad (\text{vertical}) \quad (1)$$

$$F \xrightarrow{\text{time}} F, F \quad (\text{vertical}) \quad (2)$$

$$H \xrightarrow{\text{light}} \overbrace{K, \dots, K}^k \quad (\text{horizontal}) \quad (3)$$

$$H \xrightarrow{\text{time}} \overbrace{K, \dots, K}^{k'} \quad (\text{horizontal}) \quad (4)$$

"Vertical" division means that resulting cells are aligned such that every cell has one attachment child, and one attachment parent (i.e. the grow is "straight"). "Horizontal" division means that all new cells have the same parent as the initial cell, and are spread evenly.

For the branches, the cells with state H are the leafs, and in these sense scheme (3) defines the way a leaf divides if a certain amount of light hits it in a given iteration. (4) defines leaf division independent of light. In general is $k > k'$, to establish the behavior of trees growing towards light, in the sense that they divide more into this direction. Roots follow the same scheme, with different settings though, and their even spread is only in a plane and not full 3D space.

Regarding (2), there are actually multiple F states, to allow a slowing down of branch grow (i.e cells that divided out of a H in very recent iterations have a faster division rate than "older" ones). In scheme (1), the time is 1 iteration, while it is a plant property in scheme (2) and (4).

4 Observations

4.1 Distribution And Controls

The distributed compile of the project is constituted of two parts: One map where it is possible to set values (e.g. leaf size) for a given tree at runtime and see the distinct possible results, and one map

Switching from one map to the other is done by pressing M on the Keyboard. The control of the character ("Mannequin") is the same for both maps: jumping and flying is done by pressing *Space*, and the movement itself is done via industry-standard *WASD*/mouse controls. P toggles the rendering of leafs. I updates the tree from the input values on the Value-Manipulation-Map and adds 10 rendering iterations on the forest map. O re-randomizes the values of the single tree, and resets the whole forest on the respective maps.

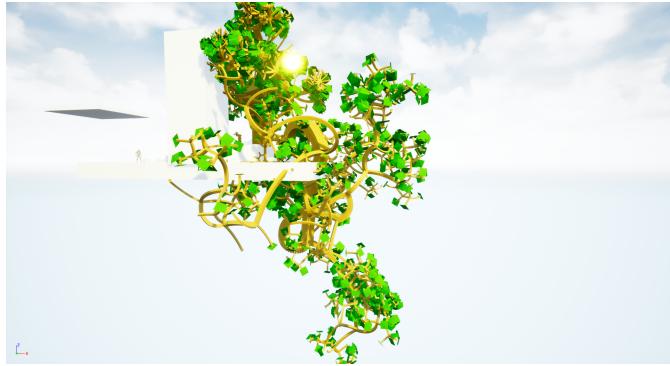


Abbildung 6: Massive tree taken out of an earlier version

4.2 Interactions

For closeness to reality and performance reasons, the number of cells per organism needs to be limited. When simulating multiple or many trees at once, we used this constraint as an additional basis for interaction between organisms and their environment: If tree leafs get hit by light, or tree cells overlap with water, the total amount of cells allowed in the corresponding organism is increased. The influence of light on allowed cell count can be clearly seen in the already mentioned figure 5, and without the influence of water on the tree in the back, the differences would be even more notable.

On the forest map, new trees appear where light hits the ground with randomized properties. Before, trees were spawned on random locations on the ground. As the light source is very close to the stage, this leads to the algorithm terminating after a few hundred iterations. This change also had one complex interaction we didn't see coming beforehand: Very big trees, like the one seen in figure 6, seem to be impossible or at least very improbable now. As far as we can see, these trees occurred if a plant got spawned in the water with a negative correlation with gravity such that the tree bended towards the light, getting both bonuses at once. This isn't possible to this extent otherwise, as the water on the stage is a small distance away from the light source. Now, the spawn positions in the water closest to the light are no longer possible, as the rim of the water basin blocks the light Raycast to these spawn locations. Even though this connection wasn't examined super thoroughly, it definitely resembles an intriguing interaction.

Figure 6 also shows the limits of the collision detection system: As it is only activated on leafs and trunks without attachment children, division of cells closer to the root might brake the system. Especially plants bending with gravity show this behavior and grow through the stage's floor. Figure 7 and figure 8 show two possible states after the algorithm terminated. Right in the center of figure 7 one is also able to see cut off trunks and branches: those are in the corridor of the wind and didn't have the stability to resist it. Figure 8 on the other hand shows another interesting result: the different grow patterns of trees in the water and trees near the light source. The latter do not divide their leaves as often, thus the relevance of their trunks growth is more dominant, leading



Abbildung 7: Terminated algorithm with visible influences of wind



Abbildung 8: Difference of tree shape in water and near to light (reduced wind)

to trees growing into the sky rather than increasing width. There are way more extreme examples, but those are obviously even more cumbersome to depict.

All in all, the shown results are definitely a positive indication that the desired complex and surprising behavior is possible on the basis of the developed system.

5 Conclusion

In this paper, we presented an approach to abstract plant growth in a non-standard way, based on even spreads, self-similarity, and influencing ecological factors. From our perspective, there seem to be two possible directions that seem interesting to improve on: On the one hand, the built system resembles a basis to simulate whole ecosystems in an interactable manner, and could be extended to include some form of nutrient circulation. For example, organisms could take some sort of resource from the ground for growth, which then cannot be used by others plants. The resource would be returned to the ground by tree dead (by age, illness or similar simulated causes) and decomposers that feed on the leftovers of other organisms and recycle the nutrients for the ecosystem. Later, even completely differently constructed organisms could be added to the system, i.e. "animals" that move around the stage and consume parts of plants.

On the other hand, the range of possibilities describable in the terms of chapter 3.3 could really only be scratched at the surface. So, another natural way to expand the project / research would be to try to recreate other plantal features with the developed algorithms by different divide properties, or to improve on those algorithms to yield more satisfying results (especially for $\alpha_{\max} - \alpha_{\min}$ big). The same holds for taking actual shapes into account when calculating even splits, and extensions to allow non-punctiform origins (e.g. for pine cone shaped grow behavior).

In these two directions, countless different features might be added. Maybe it even seems as this work is merely a starting point, and the extended applications definitely seem very interesting - be it in a more close to reality simulation-oriented context, or as an element of an actual game.

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