

Procedural Plant Generation and Simulated Plant Growth

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Acknowledgements

Abstract

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Chapter 1

Introduction

Here I will introduce the project and the thesis in general.

1.1 Context and Background

One of the most time consuming parts for digital artists and animators is creating differing variations of the same basic piece of artwork. In most games and other graphics applications environment assets such as trees, plants, grass, algae and other types of plant life make up the large majority of the assets within a game. Creating a tree asset can take a skilled digital artist more than an hour of work by hand, The artist will then have to create many variations of the same asset in order to obtain enough variation that a user of that graphics application would not notice that the asset has been duplicated. If you multiply this by the number of assets that a given artist will have to create and then modify, you are looking at an incredible number of hours that could potentially be put to use creating much more intricate and important assets.

The unique thing about plant life when compared with other types of graphics assets is that plant life is very random in the way it grows and it does not take an incredibly realistic model of a plant life to trick the human mind into believing that what it is seeing is some kind of plant. However what stands out like a sore thumb is when plants that are growing next to each other seemingly have no influence on the plant life around them.

1.2 Methodology

1.3 Timeframe and Scale

Chapter 2

Introducing Lindenmayer Systems

Aristid Lindenmayer is a well known biologist who started work on what would become known as the Lindenmayer System or L-system for short. Lindenmayer initially intended the L-systems to be to be used as a way to describe the development of simple organisms such as algae and bacteria. More recently the concept has been adapted to be used to describe larger organisms such as plants and trees. L-systems have also been used to describe non organic structures like music. [Worth and Stepney, 2005]

An L-system at its core is a definition of a starting point called the *Axiom*, the Axiom is a state or number of states which bear some kind or real world meaning. A single state can then have a number of rules describing what the next state will be. In section 2.1 below, I will be speaking about the most simple type of L-system called a Deterministic 0L-system. These types of simple D0L-systems serve as a good way to introduce the concept of an L-system.

2.1 Simple D0L-system

According to Prusinkiewicz and Hanan a simple type of L-systems are those known as deterministic 0L systems, where the string refers to the sequence of cellular states and '0L system' abbreviating 'Lindenmayer system with zero-sided interactions'. With 0L systems there are only three major parts. There is a set of symbols known as the (*alphabet*), the starting string (*Axiom*) and state transition rules (*rules*). The alphabet is a set of states. The starting string is a starting point containing one or more states. The transition rules are rules that dictate whether a state should remain the same or transition into a different state or even disappear. [Prusinkiewicz and Hanan, 2013].

An example of a deterministic 0L system:

We are given the *alphabet*: A, B
and the *axiom*: A
and the *rule* set:
 $A \rightarrow AB$
 $B \rightarrow A$

The symbol \rightarrow can be verbalised as "replaced by". Therefor it can be said that the string 'A' is replaced by string 'AB' and string 'B' is replaced by the string 'A'.

To start we take the *axiom* which in this case is 'A' and we run through all of the states in this

start string 'A' matches the rule: $A \rightarrow AB$ and is therefor replaced by 'AB'. 'AB' then becomes the new start string and we then match the rules once again. Below I have shown the resulting string up to six generations.

If we then apply the rules to the L-system we find it creates the following generation structure.

- 1.) A
- 2.) AB
- 3.) ABA
- 4.) ABAAB
- 5.) ABAABABA
- 6.) ABAABABAABAAB

This rewriting of initial string using a set of rules is ultimately the underlying concept behind L-systems. There are a number of improvements that can be made to this type of L-system in order to accommodate for more complex and intricate structure. One of which is the inclusion of *constants*. Constants can be considered any state that does not have a rule associated with it or remains the same from generation to generation and therefore holds a consistent value or meaning. These constants are used when the L-system is interpreted and thus holds a constant value during string rewriting, I will be covering this in section 2.2.

Prusinkiewicz and Lindenmayer simulated a blue-green bacteria known as *Anabaena catenula* [Prusinkiewicz and Lindenmayer, 2012]

The DOL-system representation is shown below in the grammar:

$w : a_r$
 $p1 : a_r \rightarrow a_l b_r$
 $p2 : a_l \rightarrow b_l a_r$
 $p3 : b_r \rightarrow a_r$
 $p4 : b_l \rightarrow a_l$

The value w is there to specify the axiom which in this case has the value of a_r . $p1$, $p2$, $p3$, $p4$ are the names of the rules that follow after the semi-colon. In order to simulate *Anabaena catenula* we need four rules.

According to Prusinkiewicz and Lindenmayer "Under a microscope, the filaments appear as a sequence of cylinders of various lengths, with a -type cells longer than b -type cells. And the subscript l and r indicate cell polarity, specifying the positions in which daughter cells of type a and b will be produced. [Prusinkiewicz and Lindenmayer, 2012]

This gives us a good real world demonstration of how even a simple DOL-system can represent something in the real world.

2.2 Interpreting L-systems

After we have iterated through each generation, using string rewriting we are left with a string of characters or states which represent a number of different instructions that need to be interpreted.

As with any grammar, there is a number of ways of interpreting the string that is generated by the L-systems rules. One method proposed by Przemyslaw Prusinkiewicz is "to generate a string of symbols using an L-system, and to interpret this string as a sequence of commands which control a 'turtle'" [Prusinkiewicz, 1986].

When talking about a turtle, prusinkiewicz is referring to turtle graphics. Turtle graphics is a type of vector graphics that can be carried out with instructions. It is named a turtle after one of the main features of the Logo programming language. A simple set of turtle instructions can be expressed in the form below and displayed as Figure 2.1.

1. Move forward by 1.
2. Rotate right by 90 degrees.
3. Move forward by 1.
4. Rotate left by 90 degrees
5. Move forward by 1.
6. Rotate left by 90 degrees.
7. Move forward by 1.
8. Rotate right by 90 degrees.
9. Move forward by 1.

In order to quickly and effectively interpret the L-systems resulting string we can define the turtle instructions in the form of the following characters below:

- F: Move forward by a specified distance whilst drawing a line
- f: Move forward by a specified distance without drawing a line
- +: Rotate to the right specified angle.
- -: Rotate to the left by a specified angle.
- [: Save the current position and angle.
-]: Load a saved position and angle.

Similarly a three dimensional L-system string may hold the following commands in the form of symbols.

- F: Move forward by a specified distance whilst drawing a line
- f: Move forward by a specified distance without drawing a line
- +: Yaw to the right specified angle.
- -: Yaw to the left by a specified angle.
- /: Pitch up by specified angle.
- \: Pitch down by a specified angle.
- ^: Roll to the right specified angle.
- &: Roll to the left by a specified angle.
- [: Save the current position and angle.
-]: Load a saved position and angle.

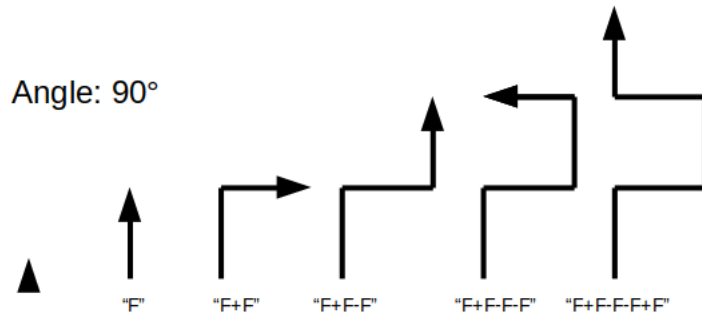


Figure 2.1: Diagram showing a turtle interpreting simple L-system string.

2.3 Branching

In the previous section there are two turtle commands in particular which were not covered. These are the square brackets "[" and "]". The square bracket characters instruct the turtle object to save its position and current angle for use later on. This allows the turtle to jump back to a previous point facing the same direction as it was before. It could then branch in a different direction.

A way to keep track of these saved locations is in the form of a stack structure. Each time the "[" is called the current position and direction of the turtle is saved to the top of the stack. Conversely when the "]" is called we restore the turtles position back to whatever position and direction is stored on the top of the stack structure.

An example of this can be shown below in figure 2.2.

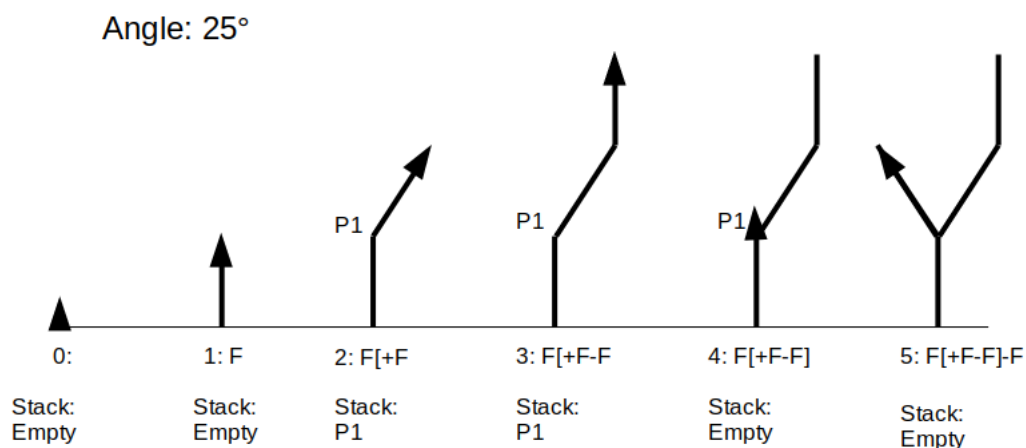


Figure 2.2: Diagram showing a turtle interpreting an L-system incorporating branching.

2.4 Parametric L-system

With simplistic L-systems like the algae representation above, there are a number of details that are skipped over when making this simplistic representation. (talk about the representation for both parameterized and non parameterised Algae systems). When it comes to representing trees as L-systems a simplistic approach would be to just assume that the width and length of each branch section is constant and will not vary depending on where in the tree it is. We can also assume that the angles at which a branch may split is also constant, say 25 degrees. The resulting representation of this L-system is a tree like structure, however it is not a very accurate representation of a real tree in nature.

In order to more accurately model trees we need to take into account the branch width, height, branching angles. There are two different approaches to solving this added complexity. One would be to increase the complexity of the L-system grammar and the other would be to increase the complexity of the interpretation of the L-system.

For instance defining an complex L-system grammar with a less complex interpreting system can give a huge amount of flexibility to define parameters that can accurately define exactly how the L-system should be interpreted, and because the complexity is with the L-system rewriting you also have the control of being able to change the L-system rules.

A parametric l-system be represented as the following:

```
n = 8

R 1.456
r1 85
wr 0.707

w : A(5)

p1 : A(w) : * : F(1)!(w)[/(r1)A(w*wr)][\ (r1)A(w*wr)]
p2 : F(s) : * : F(s*R)
```

The above l-system gives the resulting representation shown below in figure 3.8.

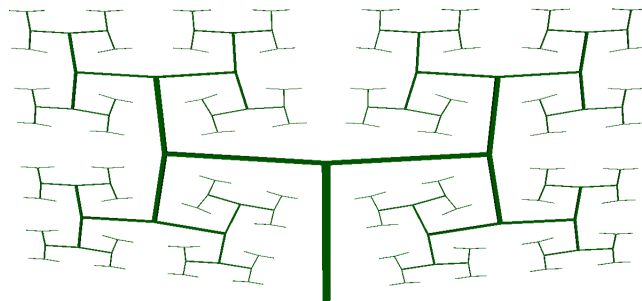


Figure 2.3: 3D Parametric L-system.

Similarly to the 2D L-system in section 2.1, n refers to the number of iterations that we would like to rewrite the L-system. w refers to the Axiom string, the `#define R 1.456` states that there

is a constant number that will be used somewhere in the production rules, with the name R and the value 1.456. P1, P2 refer to the production rules. The 3D L-system introduces the concept of a module.

A module is an instruction or variable which has zero or more parameters. The Axiom A(5) is a module with one parameter which is the number 5. A parameter can either be a number, variable or even an expression of variables and numbers. For instance A(a + 1, a * b) is a valid module A with two parameters a + 1 and a * b, where a and b are variables, however this is only a valid module if the value of a and b can be determined. Each module is treated as a single instruction, it will either be overwritten when matched with a production rule or the expression of each parameter is evaluated and is left unchanged for use when interpreted.

Each production rule is made up of four parts the name, the predecessor module, the condition and the successor modules, each part is separated by a colon. Therefor the predecessor for p1 is A(w), the condition is a '*' which means that in this case there are no conditions, and the successor is F(1)!(w)[/(r1)A(w*wr)][\ (r1)A(w*wr)]

Initially we iterate through the Axiom modules and compare them to the production rule. A match is determined if they meet three criteria.

- The name of the axiom module matches the name of the production predecessor.
- The number of parameters for the axiom module is the same as the number of parameters for the production predecessor.
- The condition of the production evaluates to true. If there is no condition then the result is true by default.

Chapter 3

Implementation

Introduction to the implementation section

3.1 Language and environment

To understand what programming language and environment will be best suited for this project, I first provide the technical requirements that will need to be met. The programming language will need to be relatively fast when processing the rules of the L-systems and when rewriting these strings according to those rules.

The program will also need to interpret the strings generated by the L-system rules and be able to generate a three dimensional representation of that L-system. This representation will need to be intuitive and will have to allow me to examine it from different perspectives. In order to make the representation intuitive, the 3D representation should be rendered in real time at multiple frames per second. And the user should be able to use a computer mouse and keyboard to move around the 3D world.

Due to these demands have decided to use the C and C++ programming language. Due to its and thoroughly tested in built standard template library, I can count on it to be reliable and fast enough for the purpose of this project. It will also allow me to use other very useful libraries for 3D graphics such as OpenGL which is also written in C/C++. I will be speaking in more detail about these details of these libraries in later sections.

In order to create a window and provide the environment for writing pixels to the screen I will make use of the Graphics Library Framework (GLFW). Some useful mathematics functions and facilities can be found in the OpenGL Mathematics Library (GLM) and possibly the most important for rendering in 3D is the Open Graphics Library or OpenGL for short. All of these libraries together will provide me with a strong foundation of tools that I can use to approach the practical aspect of this project.

3.1.1 C/C++ Programming Language

The C programming language developed by Dennis Richie and Bell Labs in 1972 has been one of the most popular programming languages for a number of decades now [Ritchie et al., 1975]. The

C language was then extended upon by Bjarne Stroustrup in 1985 to create the C++ programming language [Stroustrup, 2000]. I have included both C and C++ as the programming languages that I will be using, as they are very closely related and C code can be compiled using the C++ compiler. For the most part I will be writing C++ code and making use of its object oriented features. However, there are instances when it will be more convenient to write C code or make use of a C library.

3.1.2 Standard Template Library (STL)

The STL in C/C++ provides a number of useful functions, data structures and algorithms that have been extensively tested for both reliability and efficiency. The most common features I will be using are strings, vectors, stacks and input and output. It is possible that in some cases it may be more efficient to use custom data structures for the most part the STL functions will be more than good enough. [Horton, 2015]

3.1.3 Open Graphics Library (OpenGL)

OpenGL is a 2D and 3D graphics API
talk about GLSL [Movania et al., 2017]

3.1.4 OpenGL Mathematics Library (GLM)

3.1.5 Graphics Library Framework(GLFW)

3.1.6 Git Version Control

3.2 L-system Generator

The purpose of the L-system generator is to read a file containing any information that might be necessary for the string rewriting process. This file must contain the number of times the string will be rewritten (number of generations), a starting point (axiom) and at least one production rule, it may also contain some constant variables.

For simple L-systems, the generator need not be too complicated. The Koch Curve L-system stated below is a good example of this.

Angle: 90

Axiom: F

Rules:

$F \rightarrow F+F-F+F$

Here we have a constant value of 90 degrees, the starting point of 'F' and one rule $F \rightarrow F+F-F+F$. This type of system is very simple to rewrite computationally.

Here we describe some pseudocode

When we move onto some more complicated L-systems, such as those that use parameters which have expressions with both variables and numbers. We end up with an L-system file that is quite

difficult to process and rewrite. In order to compute these complex L-systems we need to first develop a formal grammar that describes how L-system files are defined. Once we have a formalization of how to define an parametric l-system we can create a system to carry out the rewriting.

3.2.1 Building a Generalised L-system Grammar

We are now able to represent complex three dimensional tree structures in the form of a L-system rule set. In a computing sense this rule set can be seen as a type of program. In the program we define the number of generations we would like to generate, the starting point (Axiom) some constant variables (`#define`) and the set of production rules.

Using this information, we iterate through the from generation to generation rewriting the strings and then at the end provide a resulting string which will then be interpreted and displayed on the screen.

We can represent the languages grammar in the form of a Backus-Naur Form, BNF is a notation for Context-Free Grammars used to describe the syntax of different languages. In this case the BNF is used below to describe the syntax of the parametric L-system grammar.

For example:

```
<expression> → number
<expression> → (<expression> )
<expression> → <expression> + <expression>
<expression> → <expression> - <expression>
```

The first line states that an `<expression>` can be any number, line two states that an `<expression>` can also be an expression that is inside parenthesis. Line three states that an `<expression>` can be an `<expression>` added to another `<expression>` , furthermore line four states that an `<expression>` can also be an `<expression>` subtracted by another `<expression>` .

The above grammar can be expressed as follows:

```
<expression> → number
               | (<expression> )
               | <expression> + <expression>
               | <expression> - <expression>
```

Here the `|` symbol can be articulated as an OR, therefore it can be said that an `<expression>` can be a number OR an `<expression>` surrounded by parenthesis, OR an `<expression>` added to another `<expression>` OR an `<expression>` subtracted by another `<expression>` .

In addition to this, any statement that is not surrounded by `<>`, states it must match that particular string. The `∈` followed by an `|` states that it can either be nothing or another statement.

3.2.2 Backus-Naur Form of the L-system Grammar

$$\begin{aligned}
\langle \text{prog} \rangle &\rightarrow \in \\
&\quad | \langle \text{stmts} \rangle \text{ EOF} \\
\langle \text{stmts} \rangle &\rightarrow \in \\
&\quad | \langle \text{stmt} \rangle \langle \text{stmts} \rangle \\
\langle \text{stmt} \rangle &\rightarrow \text{EOL} \\
&\quad | \langle \text{generations} \rangle \\
&\quad | \langle \text{definition} \rangle \\
&\quad | \langle \text{axiom} \rangle \\
&\quad | \langle \text{production} \rangle \\
\langle \text{generations} \rangle &\rightarrow \#n = \langle \text{float} \rangle ; \\
\langle \text{definition} \rangle &\rightarrow \#define \langle \text{variable} \rangle \langle \text{float} \rangle ; \\
&\quad | \#define \langle \text{variable} \rangle + \langle \text{float} \rangle ; \\
&\quad | \#define \langle \text{variable} \rangle - \langle \text{float} \rangle ; \\
\langle \text{axiom} \rangle &\rightarrow \#w : \langle \text{axiom statement list} \rangle ; \\
\langle \text{axiom statement list} \rangle &\rightarrow \in \\
&\quad | \langle \text{axiom statement} \rangle \langle \text{axiom statement list} \rangle ; \\
\langle \text{axiom statement} \rangle &\rightarrow \langle \text{moduleAx} \rangle \\
\langle \text{moduleAx} \rangle &\rightarrow \langle \text{variable} \rangle \mid "+" \mid "-" \mid "/" \mid "\" \mid "^" \mid "&" \mid "!" \\
&\quad | \langle \text{variable} \rangle (\langle \text{paramAx} \rangle \langle \text{paramListAx} \rangle) \\
&\quad | + (\langle \text{paramAx} \rangle \langle \text{paramListAx} \rangle) \\
&\quad | - (\langle \text{paramAx} \rangle \langle \text{paramListAx} \rangle) \\
&\quad | / (\langle \text{paramAx} \rangle \langle \text{paramListAx} \rangle) \\
&\quad | \backslash (\langle \text{paramAx} \rangle \langle \text{paramListAx} \rangle) \\
&\quad | ^ (\langle \text{paramAx} \rangle \langle \text{paramListAx} \rangle) \\
&\quad | \& (\langle \text{paramAx} \rangle \langle \text{paramListAx} \rangle) \\
\langle \text{paramAxList} \rangle &\rightarrow \in \\
&\quad | , \langle \text{paramAx} \rangle \langle \text{paramAxList} \rangle \\
\langle \text{paramAx} \rangle &\rightarrow \langle \text{expression} \rangle \\
\langle \text{production} \rangle &\rightarrow \# \langle \text{variable} \rangle : \langle \text{predecessor} \rangle : \langle \text{condition} \rangle : \langle \text{successor} \rangle ; \\
\langle \text{predecessor} \rangle &\rightarrow \langle \text{pred statement list} \rangle \\
\langle \text{pred statement list} \rangle &\rightarrow \in \\
&\quad | \langle \text{pred statement} \rangle \langle \text{pred statement list} \rangle
\end{aligned}$$

$\langle \text{pred statement} \rangle \rightarrow \langle \text{module} \rangle$
 $\langle \text{condition} \rangle \rightarrow *$
 $\quad | \langle \text{left expression} \rangle \langle \text{conditions statement} \rangle \langle \text{right expression} \rangle$
 $\langle \text{left expression} \rangle \rightarrow \langle \text{expression} \rangle$
 $\langle \text{right expression} \rangle \rightarrow \langle \text{expression} \rangle$
 $\langle \text{condition statement} \rangle \rightarrow == | != | < | > | <= | >=$
 $\langle \text{successor} \rangle \rightarrow \langle \text{successor statement list} \rangle$
 $\langle \text{successor statement list} \rangle \rightarrow \in$
 $\quad | \langle \text{successor statement} \rangle \langle \text{successor statement list} \rangle$
 $\langle \text{successor statement} \rangle \rightarrow \langle \text{module} \rangle$
 $\langle \text{module} \rangle \rightarrow \langle \text{variable} \rangle | + | - | / | \backslash | ^ | \& | !$
 $\quad | \langle \text{variable} \rangle (\langle \text{param} \rangle \langle \text{paramList} \rangle)$
 $\quad | +(\langle \text{param} \rangle \langle \text{paramList} \rangle)$
 $\quad | -(\langle \text{param} \rangle \langle \text{paramList} \rangle)$
 $\quad | /(\langle \text{param} \rangle \langle \text{paramList} \rangle)$
 $\quad | \backslash(\langle \text{param} \rangle \langle \text{paramList} \rangle)$
 $\quad | ^ (\langle \text{param} \rangle \langle \text{paramList} \rangle)$
 $\quad | \&(\langle \text{param} \rangle \langle \text{paramList} \rangle)$
 $\langle \text{paramList} \rangle \rightarrow \in | : \langle \text{param} \rangle \langle \text{paramList} \rangle$
 $\langle \text{param} \rangle \rightarrow \langle \text{expression} \rangle$
 $\langle \text{expression} \rangle \rightarrow \langle \text{variable} \rangle$
 $\quad | \langle \text{float} \rangle$
 $\quad | \langle \text{expression} \rangle + \langle \text{expression} \rangle$
 $\quad | \langle \text{expression} \rangle - \langle \text{expression} \rangle$
 $\quad | \langle \text{expression} \rangle * \langle \text{expression} \rangle$
 $\quad | \langle \text{expression} \rangle / \langle \text{expression} \rangle$
 $\quad | \langle \text{expression} \rangle ^ \langle \text{expression} \rangle$
 $\quad | " (" \langle \text{expression} \rangle)$
 $\langle \text{float} \rangle \rightarrow [0-9]+.[0-9]+$
 $\langle \text{variable} \rangle \rightarrow [a-zA-Z][a-zA-Z0-9_]*$

3.2.3 The L-system Compiler

Now that the grammar has been defined we have a very strict syntax in which an L-system can be defined, Although the syntax is quite strict we are actually able to define almost any L-system using this grammar.

3.2.4 Flex - Lexical Analyser

3.2.5 Bison - Parser Generator

3.3 L-system Interpreter

3.3.1 Basic 2D L-systems

There are a number of fractal geometry that have become well known particularly with regards to how they can seemingly imitate nature [Mandelbrot, 1982]. Particularly with the geometry such as the Koch snowflake which can be represented using the following L-system.

Koch Curve:

Alphabet: F

Constants: +, -

Axiom: F

Angle: 90°

Rules:

$F \rightarrow F+F-F+F$

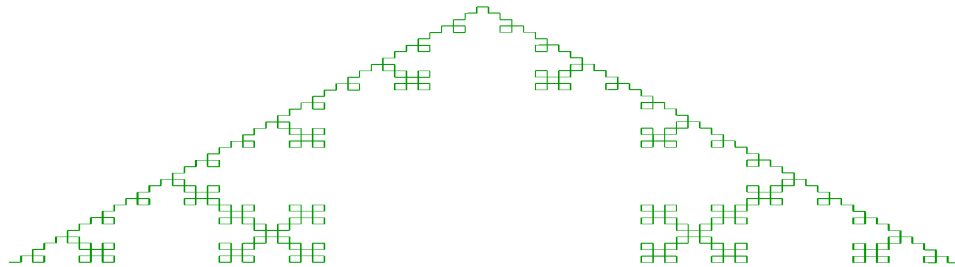


Figure 3.1: Koch Curve.

Sierpinski Triangle:

Alphabet: A, B

Constants: +, -

Axiom: A

Angle: 60°

Rules:

$A \rightarrow B-A-B$

$B \rightarrow A+B+A$

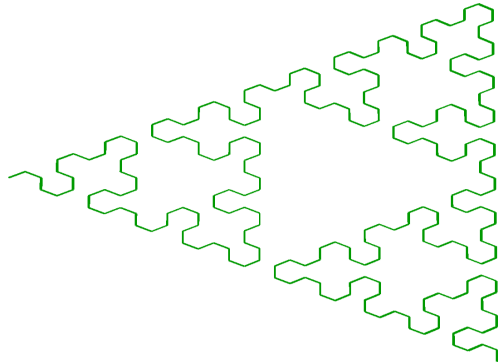


Figure 3.2: Sierpinski Triangle.

Dragon Curve:

Alphabet: F, X, Y

Constants: +, -

Axiom: FX

Angle: 90°

Rules:

$X \rightarrow X+YF+$

$Y \rightarrow -FX-Y$

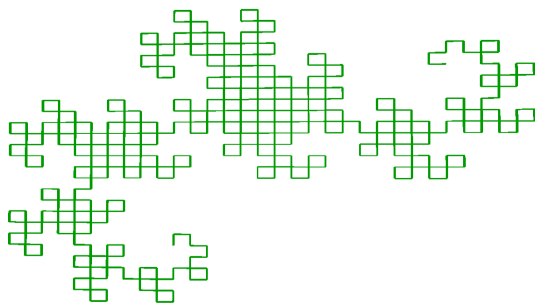


Figure 3.3: Dragon Curve.

Fractal Plant:

Alphabet: X, F

Constants: +, -, [,]

Axiom: X

Angle: 25°

Rules:

$X \rightarrow F-[[X]+X]+F[+FX]-X$

$F \rightarrow FF$

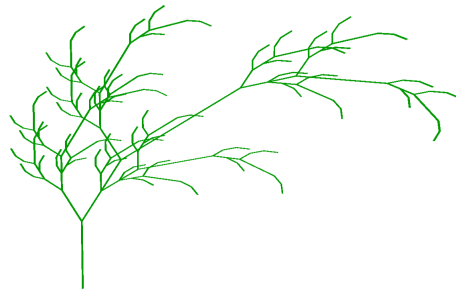


Figure 3.4: Fractal Plant.

Fractal Bush:

Alphabet: F

Constants: +, -, [,]

Axiom: F

Angle: 25°

Rules:

$F \rightarrow FF+[+F-F-F]-[-F+F+F]$

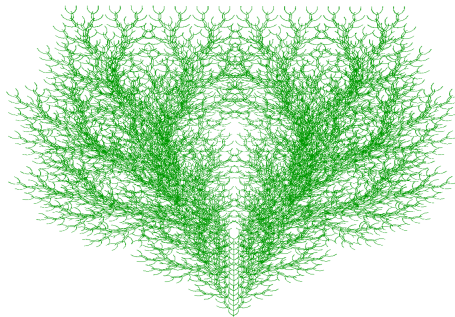


Figure 3.5: Fractal Bush.

3.3.2 The Use of L-systems in 3D applications

L-systems have been talked about and researched since its inception in 1968 by Aristid Lindenmayer. Over the years it's usefulness in modelling different types of plant life has been very clear, however its presence has been quite absent from any mainstream game engines for the most part, these engines relying either on digital artists skill to develop individual plants or on 3rd party software such as SpeedTree. These types of software use a multitude of different techniques however their methods are heavily rooted in Lindenmayer Systems.

Chapter 4

Findings and Data Analysis

Chapter 5

Discussion

Chapter 6

Conclusions

Acronyms

API Application Programming Interface. 13

BNF Backus-Naur Form. 14, 15

CFG Context-Free Grammar. 14

GLFW Graphics Library Framework. 3, 12, 13

GLM OpenGL Mathematics Library. 3, 12, 13

GLSL OpenGL Shading Language. 13

STL Standard Template Library. 3, 13

Glossary

C/C++ Refers to the C and C++ programming languages. 12

OpenGL The Open Graphics Library is a cross-platform, cross-language application programming interface used in creating graphics applications. 12, 13

Appendix A

Appendix

A.1 Appendix 1

A.2 Bibliography

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