Animation of Tree Development

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Abstract

The Lindenmayer system (L-system) is a popular technique used in the modeling of plants. Common implementations of L-systems incorporate the definition of tree structure into production rules based on observational biological data. These system produces realistic plants, however a changing environment has no affect on results. This paper proposes animating tree growth using an L-system that incorporates internal plant processes and external factors to alter the form of the tree. This allows the generation of trees that interact with their environment based upon biological and physiological processes.

Keywords: Lindenmayer systems, plant growth, natural phenomena, environment sensitivity

1 Introduction

The Lindenmayer system (L-system) [1] is a well-known technique often used for creating structural models of trees and simulating plant growth. However, most L-system based plant models are defined and generated by production rules derived from observations of plants such as studies in bifurication ratios [2], branching patterns [3], architecture models [4], and growth functions [5]. Though plant models based on these studies create realistic looking static trees and even convincing growth, these models do not take into consideration changing environmental factors which may alter the internal conditions of the plant. It is the internal conditions of the plant that defines how the plant grows. To create a growth model that simulates a living growing plant that interacts appropriately with its ecosystem, the plant's physiological processes and its modification by changing external factors must be taken into account. There has been a move of research towards incorporating physiological related factors in the modelling of plants such as the effects of light [6][7], water flow [8], and soil properties [9]. In this paper, we present an L-system-based model of tree development where growth is defined by internal and external factors. This approach allows the growth of a tree to be affected by its environmental conditions and has applications in several areas such as studies in optimizing tree growth, landscape simulation, and forestry planning.

Although we are interested in the development of trees in this project, the system is not limited to trees. Many trees and plants have similar internal processes and genetic characteristics, and to develop a plant would require only slight alteration to the current system.

We begin with an introduction to L-systems and the extensions we use in our system in Section 2. Section 3 describes how we animate and grow a tree, and the various systems we use to model the tree's various internal and external factors. A discussion on the results is found in Section 4, and we end with some conclusions and future work in Section 5.

2 Lindenmayer system

The Lindenmayer system, which is essentially a string rewriting system, was first introduced as a mathematical theory of plant development [10]. In general, rewriting is a technique for defining complex objects by successively replacing parts of a simple initial string (called an axiom) using a set of rewriting rules called productions. The strength of this system lies in its nature to replace strings in parallel, and is part of the reason why it is a useful tool for modelling plants and their processes. Turtle graphics [11][12] are used to generate the graphical scene by reading and interpretating the resulting string produced by the L-system.

There have been many extensions to the original L-system which add flexibility and power to create more advanced and higher level structures. We utilize the following extensions in our system: the bracketed L-system [11][13], the stochastic L-system [14][15], the context-sensitive L-system [16][17][18], the parametric L-system [19], and the environmentally-sensitive extension [20]. The bracketed L-system extends the original by allowing branching structures to be created. The position and orientation can be saved and restored to generate the rest of the tree without losing the reference point. The stochastic L-system extension allows different productions to replace the same string resulting in varying plant structures. Context-sensitive L-systems allow for rewriting depending on the context of the string of interest, while parametric L-systems allow a richer description of plant parts with states represented as parameters in the module. Environmentally-sensitive L-systems takes into account environmental factors where local properties of the environment affect the plant. A more detailed description of the L-system and its extensions is summarized in [10].

We use L-systems to model the growth of plants for two main reasons. The first is its parallel nature in its re-writing that caters for capturing cell divisions in multicellular organisms such as plants where many divisions may occur simultaneously. The second reason is its ability to capture two fundamental mechanisms that control development, namely the flow of information from the mother module to its offspring and the flow of information between modules.

3 Animation of Growth

Animation of tree growth is performed in discrete time steps. There are three main modules involved in each growth iteration of the animation. The first step of the iteration involves the L-system-based *tree generation* system. This system defines the morphological structure of the tree based on genetic factors and is modified by information retrieved from the environmental system. After each growth by the tree generation system, the *update* system updates internal factors and conditions of the tree. Lastly, the *environmental* system calculates the changes in external factors and conditions at each time step of the animation. Tree-related metrics such as space competition and light availability is calculated in this system, and passed on to the tree generation system where the next iteration takes place. We discuss each of these systems in order of the plant's development stage.

3.1 Tree Generation System

The tree model used in this system is not based on any specific species of trees but on a plausible tree representation. The main structures that make up a tree are branches, leaves, the trunk, and roots. Important growing organs are the apical (tip) and lateral (side) buds. We use these structures in our tree model. The symbols representing these structures are shown in table 1.

3.1.1 Branches and buds

The tree branches are modelled by connected internode segments, ending with an apical bud. Each internode has the following parameters: *localHeight*, *heightAccum*, *width*, and *currentPos*. The *localHeight* and *heightAccum* parameters hold information on the height of the internode with respect to individual internodes, and the height of the internode in relation to its connected branch respectively. Each apical bud has the following parameters: *position*, *orientation*, *phyllotaxisAngle* and *branchOrder*. The apical bud contains the additional *orientation* parameter allowing the branch to bend and to determine the direction future buds may grow. The *phyllotaxisAngle* parameter holds the angle at which buds and leaves grow on sides of branches. Trunks and branches differ only in their branch order value, *branchOrder*. The branch ordering system used sets the trunk's branchOrder = 0, while new branches are of an order one larger than their parent branch.

Table 1: Tree symbols and their definitions.

Symbol	**Meaning**
A	Apical Bud
I	Internode
S	Seed
R	Root
N	Node
B	Lateral Bud
L	Leaf

The apical bud uses environmental information to determine its growth. Its environmental parameters are: *energy*, *exposureLight*, and *newPosition*. The new position (*newPosition*) of where the apical bud will grow to is determined by the amount of light it receives (*exposureLight*) and the amount of energy allocated to the apical bud (*energy*).

The growth of the apical bud is expressed in the following L-system production rule:

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A = I A if (height(A) < height(N))
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The rule states that for every apical bud in the plant, it will be replaced by an internode followed by an apical bud, given that the height does not reach a level where a node should be inserted. If the height is sufficient for a node to be inserted, the apical bud is replaced by a node with its leaves, lateral bud, and apical bud(s), as stated in the following L-system production rule:

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A = N [ L(s) B(s) ] [ A(s) ]
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The generation of lateral buds and associated leaves is dependent on the species of the tree. The number of lateral buds produced at each node is determined by the constant *LATERAL_BUDS_NO*. The default angle at which it branches from the parent stem is defined by the constant *BRANCHING_ANGLE*. Each lateral bud produced has the following parameters: *position*, *orientation*, *branchOrder*, *dormancyPeriod*, and *state*. Lateral buds may be dormant for a temporary period until adequate resource requirements are met, and this is used in the *dormancyPeriod*. The parameter *state* defines the state of the lateral bud: dormant, growing, or dead. Lateral buds die because they become a liability to the tree and are pruned to release energy to other tree organs. Lateral buds have the same environmental parameters as apical buds but instead are used to determine the length of the dormancy period. In growing environmental conditions, lateral buds grow into branch structures according to the following production rule:

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B = B A if (dormancyPeriod equals 0)
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3.1.2 Leaves and root

The leaf has the following parameters: *position*, *orientation*, *size*, and *state*. Leaves have a maximum size which they grow to and is defined by the constant *MAX_LEAF_SIZE*. The *size* parameter indicates the proportional size of the leaf. The leaf has two states: terminated or growing. Similar to lateral buds, leaves may become a liability to the tree and may need to be pruned. Leaves have the same environmental parameters as lateral buds, and are used to determine the growth of the leaves. Roots are not modelled in depth in the tree system, and only have a single parameter, *energyStored*, which defines the excess energy stored at each growth stage.

3.2 Updating System

Energy levels throughout the tree are re-calculated and modified at each iteration of the updating system. A tree allocates energy to survive and thrive in an environment that never has optimal resources. Trees react to environmental changes with internal modifications and selected competition for the most efficient use of the tree's food. For the energy model, we focus on light as the only contributing factor that affects the tree's energy.

Photosynthesis is the tree's internal physiological energy-storing process in which light energy is converted into chemical energy. Photosynthesis occurs in many areas of the plant, but mainly in the leaves. We assume that leaves are the sole organs in plants to carry out photosynthesis. Photosynthesis takes place in open stomates of the leaves where the leaf layer's moist walls are exposed to the outside carbon-dioxide which sifts in to make food. Photosynthesis stops when the leaf stomates are closed. The amount of energy generated depends on the period the open stomates are exposed to light (assuming there is sufficient water in the leaves).

Trees change form due to variations in their energy supply. When this supply is in shortage, areas of growth and youth compete to retain the energy needed to continue growth and development. Older and less energy efficient plant organs slow or halt their growth and they may be discarded altogether if they become a liability to the tree. To simulate this behavior, we calculate the energy generated by the photosynthesis and the energy used to maintain the tree's organs. We assume in our energy model that leaves and apical buds is the primary users of energy. When the energy usage of a tree exceeds the energy it generates, the tree will need to prune any inefficient organs to free up any energy. Left-over energy is used in the growth of organs, and we allocate the excess energy to leaves in the order of those with highest exposure to light. Energy allocated to apical buds are calculated in a similar manner.

The water model is considered important in the growth of a tree for several reasons. It aids in the food making process, transports vital nutrients around the tree, cools down overheated organs, and provides structural support. The model has not yet been implemented in the system, but will be included in future versions.

3.3 Environmental System

The environmental system provides light and space information taking into account the tree structure and environmental objects in the scene at each growth iteration. It calculates the best growth state of the tree's organs based on its energy levels, exposure to light, and the position and orientation of the organ of interest. Environmental metrics are then updated and returned to the tree system to be updated.

Observation of trees shows growth patterns in the acquisition of maximum resources including the growth of branches to areas of light and space [21][22]. For each position p of interest in the scene, we approximate the amount of light received at p by rendering the scene in six different directions at origin p. The proportion of light pixels visible in each of the renderings is calculated and averaged. The number of renderings taken at each point may be increased to improve accuracy but at a computational cost. To approximate the availiability of space at a particular point, we use a similar method by taking six renderings of the scene, and average the depth value of the pixels. Use of this metric provides simplistic collision avoidance detection.

To simulate the tree's growth behaviour of a branch towards area of light and space, we calculate uniformly distributed sample points in the range of possible growth positions of a branch given its orientation and maximum branching angle. Its energy level depicts the maximum length the branch can grow in a time step. Each sample point is assigned a fitness value based on its light and space availability. The sample point with the highest fitness value is selected as the best growth position and this is passed to the tree generation system.

Air temperature indirectly affects the production of energy through transpiration. Loss of water due to dryness of the air cause the tree to close the stomates of the leaves halting the production of food. We determine air temperature directly from the position of a light source. Air temperature is at its maximum when the sun is directly overhead and has the property that it rises quickly, and falls slowly. At this stage, the air temperature model is not implemented in the system, but will be included in future versions.

4 Results

Our L-system based tree generation system is built with stochastic, parametric, bracketed, context-sensitive and environmentally-sensitive extensions. The production rules and definitions are programmed directly into the L-system instead of reading and parsing them from a file. As the focus of this system is on the correctness of the growing structure in relation to its environmental conditions, less attention is spent on how closely the plant's organ resembles its natural counterpart. As a result, branches and trunks are represented as cylinders and leaves as flat-shaped polygons.

The tree model has many variables; only the main ones are listed here. The seed initally has sufficent energy to grow a trunk and its first leaves whereafter energy from the leaves alone is used to grow the rest of the tree. The branching angle is set to 50 degrees while its maximum bending angle is set to 40 degrees. We do not define any lateral buds but we create three apical buds and leaves at each node to emphasize how the environment shapes the tree. There is no special dormancy period condition defined for the apical buds; as long as there is sufficient energy in the buds, growth will occur.

Figure 1 shows the resulting images of a tree growing using our system after several iterations in various growing conditions. Image **a** shows the growth of a tree after several time steps with no light or space information taken into account. The energy model is not used, and each bud is set to maximum energy. From the image, it shows many branches colliding.

Image **b** shows the growth of a tree with light and space information taken into account. The energy model is still set to maximum at each bud. We see from the figure that the branches do not collide due to the affect of the light and space model, and branching seems more organized.

In image **c**, we grow a tree using light, space and energy models. It is clear from the image that the system favours higher level buds over lower level buds where there is minimum occlusion by neigbouring branches. There are no collision between branches as they grow into maximum space determined by the system. This point is emphasized particularly in image **d** where a wall is placed beside the seed of the tree. Its growth after several iterations shows branches growing away from the wall and towards the open space.

Figure 2 shows the growth steps of a tree using light, space and energy models. It is clear from this figure that the branches grow at varying amounts throughout the animation. In limited energy conditions, the system grows leaves until sufficient energy is reached and energy is distributed to branches with higher fitness levels.

5 Conclusion

In this paper, we have created an L-system-based system to simulate and animate a tree's development taking into account its genetic factors, physiological processes and external environmental factors. The growth model defines the general structure of the tree, and is modified by the tree's internal and external factors. We use an energy model for the tree's organs based on photosynthesis to determine the amount of growth, while our light model determines the position of growth. We also discuss how water levels and air temperature may affect the tree's physiological levels and in turn affect its final form. Applications of this system include optimizing plant growth studies, long-term evolution of trees, and landscape and forest planning.

Future work will include the design of different plausible tree models, and incorporating the growth of various trees in the same environmental conditions. The environment may be extended to include varying terrain conditions and the addition of man-made objects.

The rendering of the tree can be improved by using more complex geometry for the structural parts of the tree. Textures can be used to simulate surfaces such as bark and leaves, and a better illumination model could be used.

There is also future work in the re-design of the L-system to read in grammar and production rules for plants. For such a data file to be read, the parser needs to be sufficiently flexible to read the complex rules governing the nature of plant processes. The set of operators needed by the production rules needs to be sufficiently general to handle multiple species of plants, and is yet to be determined.

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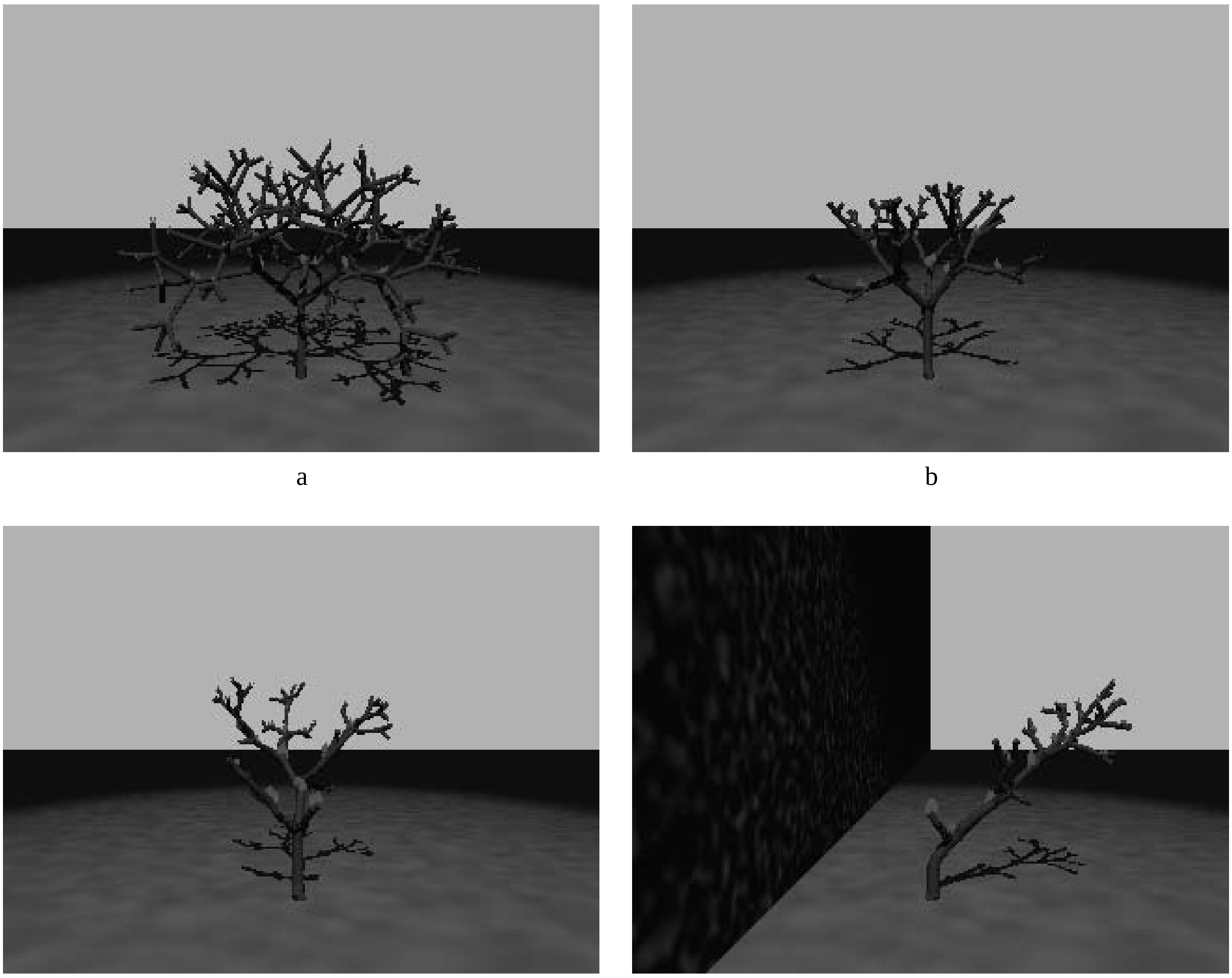

a b

c d

Figure 1: The result of a tree growing using our system after several iterations using: a) no environmental factors, b) light and space models, c) light, space and energy model, d) light, space and energy model with a wall.

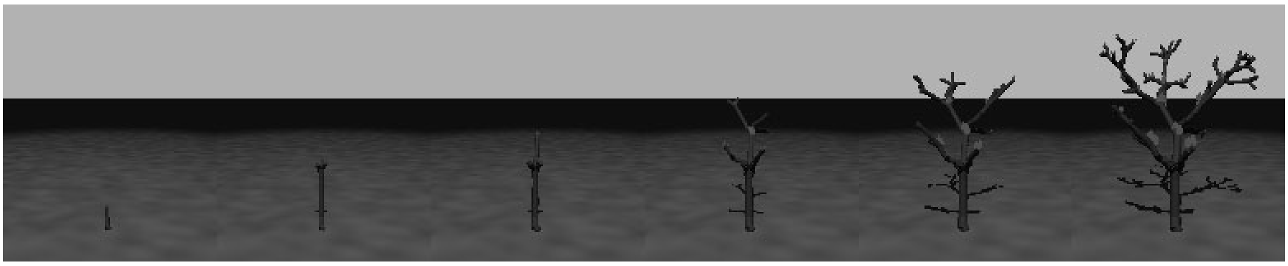

Figure 2: Frames from an animation of a tree growing using light, space and energy models.