In search of the right abstraction: The synergy between art, science, and information technology in the modeling of natural phenomena

Przemyslaw Prusinkiewicz
Department of Computer Science
University of Calgary
Calgary, Alberta, Canada T2N 1N4
e−mail: pwp@cpsc.ucalgary.ca

Abstract

The creation of models of nature is the main objective of natural sciences. Without abstraction, however, models would be as complicated as reality itself; they would mimic nature without helping us to understand it. Identifying the essential features of the phenomena being described is therefore a crucial element of model construction. Unfortunately, an emphasis on objective, measurable characteristics, as promoted by current scientific practices, may lead in the wrong direction. An easily measurable characteristic may turn out to be irrelevant; on the other hand, a feature that eludes precise definition or measurement may be of central importance. The paper illustrates this thesis by referring to the modeling of natural forms and patterns (in particular, plants) using the formalism of Lindenmayer systems combined with computer graphics visualizations. In this domain both precise botanical data and artistic observations play an important role. This synergy gives a new perspective to the centuries−old question of the relationship between science and art in describing the world around us.

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The paper illustrates this thesis by referring to the modeling of natural forms and patterns (in particular, plants) using the formalism of Lindenmayer systems combined with computer graphics visualizations. In this domain both precise botanical data and artistic observations play an important role. This synergy gives a new perspective to the centuries-old question of the relationship between science and art in describing the world around us.

1 Introduction

The tree shown in Figure 1 does not really exist. The image is the result of a computer simulation based on a mathematical model of a horse chestnut tree [15]. The model captures the branching pattern inherent in this tree architecture, and includes a mechanism that modifies branching in response to local light conditions. Branching is most vigorous in abundant light, and decreases if the amount of light reaching a branch is reduced. Branches that are almost entirely in shade become a liability to the tree and are shed.

Is it a good model of reality? What does it mean to say a model is good, and how can we verify it? What is the role of simulation and visualization in model studies of

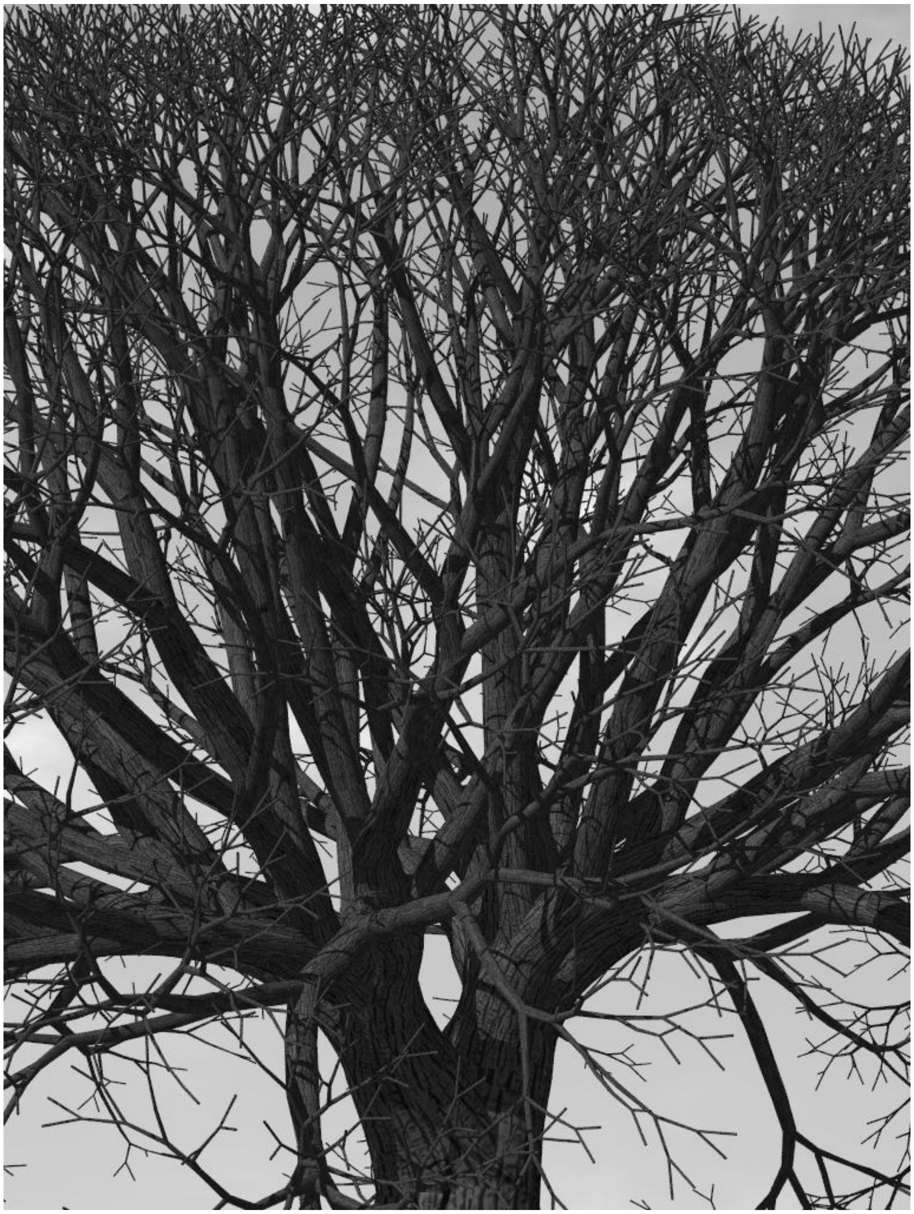

Figure 1: A tree model with branches competing for access to light. From [15].

the natural world? The purpose of this essay is to address these questions using plant modeling as an example.

2 What is a good model?

One intuitive criterion of a model's quality is its faithfulness, or the degree to which it approximates reality. By itself, however, this criterion is insufficient, as illustrated by the following story from Suárez Miranda (1658), presented by Jorge Luis Borges under the title *On rigor in science* [3], and quoted by Umberto Eco in his essay *On the impossibility of creating a map of the empire in the scale of one to one* [7].

> ...in that Empire, the Cartographer's art achieved such a degree of perfection that the Map of a single Province occupied an entire City, and the map of the Empire, an entire Province. In time, these vast Maps were no longer sufficient. The Guild of Cartographers created a Map of the Empire, which perfectly coincided with the Empire itself. But Succeeding Generations, with diminished interest in the Study of Cartography, believed that this immense Map was of no use...

The moral is that simplifications, or abstractions, are a necessary part of the modeling of nature. Without them, the models would mimic reality instead of explaining it.

The question is, what is the right abstraction? In areas of science with a long history of mathematical models — physics in particular — standard abstractions have been developed over the centuries and are widely accepted. For example, in classical mechanics one refers to masses and forces obeying Newton's laws of dynamics. Where the Newtonian approximation fails, different models provided by quantum mechanics and the theory of relativity are used. In life sciences, however, the problem of choosing the right level of abstraction is more difficult. For instance, the same forest will be considered differently by a botanist who studies the development of individual trees, an ecologist interested in the interactions between them, and an artist intent on capturing the beauty of the place. The choice of the right level of abstraction is a highly practical issue, which must be addressed each time a model is built [9, 19]).

The question of choosing a good model when many models exist was considered in detail by Brian Gaines [8]. His point of departure is summarized by the following conversation:

> Imagine that you and I are each given the same sample of behavior and asked to model it from the same class of models. 'My model is a better approximation,' I say. 'Ah,' you reply, 'but mine is a far *simpler* model.'

Using the relationship between complexity and accuracy as the focal notion of his theory, Gaines considers a model admissible, if "any other model that gives a better approximation in accounting for the behavior is also more complex" [8]. Relaxing this definition, we may say that a good model offers a simple (maybe even the simplest possible) explanation of the observed phenomenon at the desired level of abstraction, and thus represents a favorable tradeoff between complexity and accuracy.

Thus, the ultimate goal of modeling nature is to construct simple yet faithful models of reality. This point has been succinctly summarized by Herbert Simon [21]:

> The central task of a natural science is to make the wonderful commonplace: to show that complexity, correctly viewed, is only a mask for simplicity; to find pattern hidden in apparent chaos.

According to this quotation, our perception of the complexity of nature reflects primarily the difficulty in recognizing (learning, inferring) nature's principles and regularities. Once they have been understood, faithful yet simple models can often be found.

3 Harnessing model complexity: an example from botany

How can we measure the complexity of a model? One approach, proposed by Kolmogorov (see [12]), is to express it as the length of the shortest description of a model. Strikingly compact, and therefore simple, models of nature can be found in the domain of botany. Below we consider an example to illustrate the point that simple models can indeed capture complex structures.

The key to identifying the regularities that underly plant forms is to look at them as dynamic systems that develop over time. In other words, in order to understand plant structures, we focus on the processes of development from which these structures emerge. This approach has a long tradition in biology, as presented by d'Arcy Thompson [22]:

> ... organic form itself is found, mathematically speaking, to be a function of time... We might call the form of an organism an *event in space-time*, and not merely a *configuration in space*.

The processes of plant development can be conveniently expressed using the formalism of L-systems, introduced in 1968 by Aristid Lindenmayer [13]. An L-system consists of a set of *rewriting rules*, or *productions*, which capture the behavior of individual plant components (modules) over predetermined time intervals. For example, Figure 2 shows a model of a compound leaf expressed using only two rules. The first rule states that an apex (*i.e.* a terminal branch segment) yields a branching structure consisting of two internodes, the apex continuing the main axis, and two lateral apices. The second rule states that, over the same time interval, the internodes will elongate by a factor of two. The bottom part of Figure 2 shows a developmental sequence generated using these two rules. In each step, all apices and internodes are subject to their respective rules, applied in parallel. An intricate branching structure of a compound leaf results.

In the above example, the fate of each plant component was determined at the time of its creation. This corresponds to the biological notion of the control of development by lineage [14]. In nature, plants also employ more complex control mechanisms. These include endogenous interaction, in which control information flows through

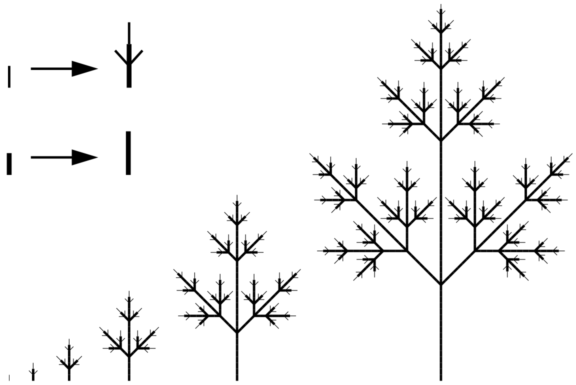

Figure 2: The productions and a developmental sequence illustrating the operation of compound leaf model. The apices are shown as thin lines, the internodes as thick lines. From [17].

the growing structure (for example, in the form of hormones, nutrients, or water), and exogenous interaction, in which information flows through the space in which the plant grows [2, 16]. With proper extensions [15, 18], L-systems can capture both types of information flow, as illustrated by the tree model shown in Figure 1. Although that model is no longer expressed by two simple rules, it is still remarkably compact (of the order of one hundred lines of L-system code).

4 Model validation through simulations and visualizations

Compactness offers a useful measure of model complexity. Let us now return to the other component of model quality, its faithfulness. How can we tell whether a model is a faithful representation of nature? To answer this question, let us consider the traditional process of constructing a scientific theory, which, for the purpose of this discussion, can be equated with the construction of a model (Figure 3). As described by John Kemeny [11], this process begins with the observation of facts. The facts serve as the basis for constructing (inducing) a mathematical model, which is used to deduce predictions concerning the reality. An agreement between these predictions and new observations contributes to our confidence in the model.

In the case of models expressed using L-systems, facts are the forms and developmental sequences of plants observed in nature. The models postulate mechanisms that may control plant development, and the predictions are the developmental sequences and forms resulting from the simulations. Comparison of the simulation results with the observations of reality is based primarily on visual inspection. We claim that Figure 1 represents a faithful approximation or reality, because the generated structures looks similar to a real horse chestnut tree.

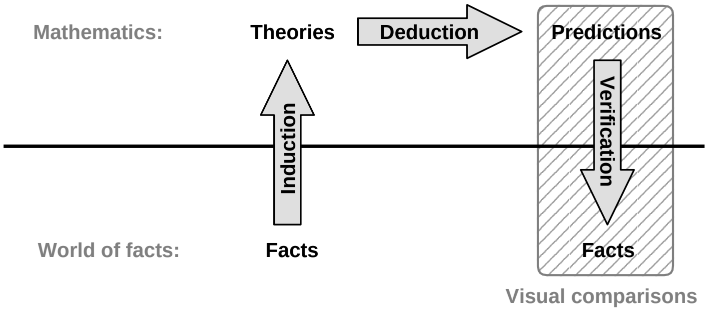

Figure 3: Elements of the process of scientific discovery. Adapted from [11].

Is it acceptable to rely on visual comparisons while constructing and evaluating models of nature for scientific purposes? On the surface, this may seem highly subjective, qualitative, and unscientific. Nevertheless, given the state-of-the-art in characterizing arbitrary forms (for example, developed within the field of computer vision), there is not much more we can do. Satisfactory sets of parameters have been proposed for only relatively simple shapes. For example, we can measure how close an observed rounded shape is to a circle or a sphere [4], but we do not have comparable measures for complex shapes, such as trees. This is why visual comparisons play an important role at present.

This observation raises a question regarding the role of realism in the visual depiction of models. Is it necessary to represent the results of simulations realistically for visual comparison purposes? Maybe more schematic representations would be sufficient? The following example demonstrates that realism is important indeed. Figure 4 looks like an unorganized collection of lines, distributed more densely at the top than at the bottom. Nevertheless, it represents the same tree as shown in Figure 1, except that all the branches have been drawn using lines of constant, equal width. It is difficult to abstract from the arbitrary artifacts in the visual presentation of models, even if they are conceptually small. While carefully chosen simplifications may be useful, realistic representation of the modeled objects is the safest choice for visual comparison purposes.

5 Conclusions

We have sketched the logical path that brings answers to the fundamental questions of the modeling of nature, stated in Section 1. These answers highlight the fact that modeling is an interdisciplinary activity which combines a knowledge of the modeled phenomena, the computer science methodology for creating the simulations, and the craft of visualizing the models for validation purposes. In its highest form, this craft becomes an art, fulfilling the role phrased by Pablo Picasso:

> Art is the lie that helps us see the truth.

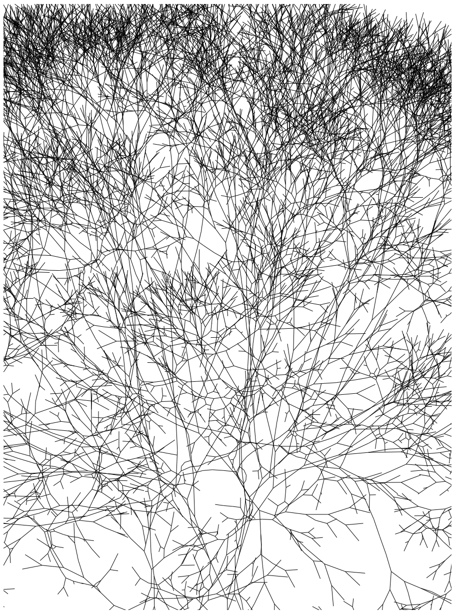

Figure 4: Tree model from Figure 1, rendered using lines of constant width.

The synergy between art and science also has another facet: that of creating images of nature for aesthetic reasons. In this case, an understanding of nature serves as the basis for an artistic process. In the domain of botany, the mutually enriching relationship between art and science has a particularly long and well documented history, which can be traced back to Leonardo da Vinci [6]. An interesting case in point is the comparison of two texts on trees from the beginning of the twentieth century: Rex Vicat Cole's *Artistic Anatomy of Trees* [5] and H. Marshall Ward's botanical treatise: *Trees. Form and habit* [23]. In spite of the differences in objectives and points of view, these books contain many strikingly similar observations and illustrations.

Computer science complements the synergy between art and science in two major ways. First, computer simulations and visualizations are a means for better understanding scientific models. This application of computer science has been emphasized by Alan Kay [20]:

> The strength of our culture over the past hundred years has been our ability to take on multiple points of view. That's what simulations allow you to do.

Second, computer science contributes to the process of scientific discovery by providing a focus on control mechanisms and the flow of control information in nature. This perspective, well manifested in L-system plant models, has its roots in cybernetics [1] and was recently stated by Gruska and Jürgensen [10]:

> ‘Computer science’ should be considered as a science with aims similar to those of physics. The information processing world is as rich and as important as physical world for mankind.

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