Book Review

Review of *The Computational Beauty of Nature* by Gary William Flake ☆

Melanie Moses [a,*], Stephanie Forrest [b]

[a] *Department of Biology, University of New Mexico, Albuquerque, NM 87131, USA*
[b] *Department of Computer Science, University of New Mexico, Albuquerque, NM 87131-1386, USA*

The field of artificial intelligence promotes a computational view of cognition, and the analogy between thinking and computing has led to important advances in both cognitive science and computer science. Similar attention, however, has not been devoted to computation in other biological, physical, or socio-cultural systems. In *The Computational Beauty of Nature*, Gary William Flake provides convincing evidence that the charter of computer science should be broadened to include the study of computation throughout nature. The benefits are two-fold: by understanding how information is processed in natural systems, we may design better computers and computational techniques; and, using information-processing principles, we may further our scientific understanding of natural processes.

The Computational Beauty of Nature provides an excellent synthesis of a number of topics relating computation and nature. In this introductory text, Flake reviews computation theory, fractals, chaos, agent-based simulation, neural networks, and genetic algorithms in a way that is exciting and easily understood. He connects these apparently disparate topics as phenomena that emerge at the boundary of computability and incomputability, and he argues that these phenomena are fundamental to both computation and nature. This view provides important insights about how to model and understand the natural world.

Flake describes a world in which the growth of trees, ecosystem dynamics, and human social interactions are emergent properties of relatively simple processes. In this world, order emerges from the parallel and repeated interactions of apparently disordered components. The processes of nature are characterized by self-similarity, parallelism, recursion, and feedback. In Flake's words: "At all levels of nature, recursion and multiplicity of agents promote emergence and self-organization to yield an almost

unexplainable form of complexity." This is the central theme of *The Computational Beauty of Nature*.

Flake demonstrates deep and intriguing relationships between computation and the processes of nature on many levels. His intellectual biases and enthusiasms are clearly reflected in his focus on emergent phenomena at computational boundaries. "Nature then appears to be a hierarchy of computational systems that are forever on the edge between computability and incomputability." In Flake's view, interesting properties emerge at the boundaries between ordered patterns and chaos, between stasis and stochasticity, between reductionism and holism.

The book explores the relationship between the complexity of cellular automata, the emergence of chaos, and the structure of search spaces. It describes how fractal patterns in state space can lead to chaos, how chaos emerges in agent-based simulation, and how adaptive agents can simulate natural processes and interactions. Most of the arguments and analogies are clear, convincing and exciting. Flake relates Stephen Wolfram's classifications of the behavior of cellular automata (static, periodic, complex, and chaotic) to continuous dynamical systems and to the connectivity of Stuart Kauffman's Boolean networks. Complex behavior arises with just the right number of rules, sensitivity to perturbation, or connectivity of components. He repeatedly points to the balance between opposing forces in natural systems: gene networks give an organism the right balance of stability and adaptability; social organization is a delicate balance between cooperation and competition; neural networks (natural and artificial) require the right combination of inhibition and excitation.

The book also touches on provocative theories about the nature of knowledge. An example is the proposition that Gödel's Incompleteness Theorem and Turing's Halting Problem suggest that nature cannot be completely understood or predicted by science. Flake equates predicting certain chaotic dynamics with solving the Halting Problem. The infinite sensitivity to initial conditions of chaotic systems implies that we may not be able to predict some natural processes using finite computational resources. Flake's argument that nature is infinitely complex is perhaps a hope that nature holds an inexhaustible supply of problems for science to model and solve. He argues that reductionist approaches cannot predict emergent phenomena and that holistic approaches don't adequately describe the interactions of components; however, computer simulation offers a way to see the whole and the parts simultaneously. This is an example of how Flake relates the many topics in complex adaptive systems to broader issues about the nature of science and knowledge. In some cases he provides convincing evidence, in others only provocative ideas. Regardless, he forms an intriguing framework through which to understand the reciprocal relationship between computation and nature.

Fractals are an excellent example of this relationship. Observation of repeated patterns in nature inspired the modern computational study of fractals. The famous question "How long is the coastline of Great Britain?" is interesting because the answer depends on the measurement scale. The coastline is self-similar (apparently the same when viewed at different scales) and therefore, very complicated to measure. On the other hand, such fractal structures can be approximated by relatively simple grammars known as L-systems. The L-system computer programs accompanying the text give an excellent demonstration of how a few algorithmically simple rules can generate infinitely complex structures, with

great resemblance to natural formations such as rivers, mountains and snowflakes. Flake argues that biological fractals such as the branching patterns of trees are easily formed from simple genetic rules, but the parallel independent growth of the branches allows for complex adaptation to the environment. Fractal patterns appear throughout the text and are useful descriptions of both natural and computational phenomena.

Flake also describes how computation can model social phenomena. The Iterated Prisoner's Dilemma models show how cooperation can emerge from competition in social and political interactions. The Prisoner's Dilemma is a famous game in which an individual player's incentive for immediate reward is at odds with the total collective reward that can be attained by cooperating with the opponent. This game is played repeatedly in the Iterated Prisoner's Dilemma, and under some circumstances players learn to cooperate with one another in order to maximize their long-term payoff. Flake shows how cooperative strategies can be evolved using genetic algorithms, and how cooperation can emerge from selfish players when the game is simulated in a spatially explicit ecological context. "Tit-for-Tat" is generally the most effective strategy, Flake argues, because it balances cooperation with punishment of those who don't cooperate.

The chapters on genetic algorithms and neural networks illustrate mature connections between computation and nature. The principles and mechanisms of neo-Darwinian evolution have been used as models for genetic algorithms (GAs), and these evolutionary concepts can be encoded to solve computational problems. Flake describes artificial neural networks, classifier systems and GAs as different mechanisms for parallel exploration of a search space in order to optimize a fitness function. Several chapters are devoted to a useful description of these computational techniques, followed by a discussion of the nature of adaptation and learning.

Flake provides an intellectually engaging introduction to the theory, philosophy, and history of computation and complex systems. At the same time, he has written a very practical textbook. He presents difficult topics in a way that is accessible to readers with little background in computation or biology. The language is straightforward, and numerous examples illustrate the main points. The reference list at the end of each chapter provides a path to more information. The book provides excellent coverage of a wide range of topics, and in most cases does so in appropriate detail, demonstrating why the topics are fun and interesting, and why they are computationally or biologically significant. However, some topics would profit from a more careful and rigorous exposition. The important topic of self-organized criticality (SOC) is barely mentioned, and it deserves its own chapter. In addition, more rigorous and careful descriptions of fractal dimension, dynamical systems, and chaos would improve the book.

The accompanying computer programs on the web (http://mitpress.mit.edu/flake) are very useful features of the book. Both the C source and compiled programs are available for all of the examples used in the text. In addition, many of the programs have been translated into Java and can be easily run from the web site. Because the source code is available, sophisticated users can explore how easy (or difficult) it is to translate complex concepts into working programs. The compiled code and java translations allow non-programmers to use cellular automata, artificial neural networks, and genetic algorithms to solve problems, and they can play with the Game of Life, generate fractals, and simulate predator–prey interactions.

Flake gives numerous examples of how computation has improved our understanding of nature, and vice versa. He provides a comprehensive review of the emergent phenomena and computational paradigms that collectively form the emerging science of complex adaptive systems. As readers, the book stimulated us to think of other forms of computation in nature, such as homeostatic mechanisms, genetic regulatory networks within cells, and the workings of the immune system. These modes of information processing have evolved over billions of years and form a fascinating reservoir of computational paradigms for computer scientists to explore.

Flake's book illustrates the practical benefits, the intellectual intrigue, and the enormous potential of studying computational processes in nature. Flake has laid a foundation in the form of a coherent introduction to a field that is itself evolving and emerging. He has summarized basic principles from which new and old questions can be asked and answered. Perhaps most importantly, he conveys a contagious enthusiasm for the subject. This seminal work promises to serve as a catalyst for further research into the mysteries and beauty of computation and nature.