BOOK REVIEW
EMERGENCE: FROM CHAOS TO ORDER
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Understanding Complex Adaptive Systems

As an early member of the Santa Fe Institute, John Holland has played a critical role in the nascent field of Complex Adaptive Systems, beginning with his work with genetic algorithms in computer science. His first, and highly influential book in the area of complex systems, *Hidden Order* (1995), focused on genetic algorithms and built upon this modeling paradigm to explore the properties of adaptation. In his most recent book, *Emergence: From Chaos to Order* (1998) Holland probes further into the idea of emergence, another essential property of complex systems, discussing both examples of emergence, and proposing a methodology for modeling emergence. In the process, he succeeds in establishing a more concrete pathway for moving beyond vague notions of "the whole exceeding the sum of its parts" to achieve a more rigorous analytical treatment of emergence.

Modeling Emergence

Holland outlines a broad class of models used to understand emergence, which he views as one of the core defining features of Complex Adaptive Systems. However, before beginning his exposition of this new class of models, termed *constrained generating procedures* (*cgp's*), he takes the reader through the fundamental motivations and procedures for modeling systems. He lays out the differences between static forms of models, such as maps and other scale models, to dynamic models that have changing configurations. In dynamic models, the goal is to discover the so-called "rules of the game" that determine the laws under which a system can change from one state to another. Although this effort may seem to be intended for the non-technical reader, the explanation of maps and games, as abstracted models of more detailed and dynamic systems, sets the stage for a sophisticated reassessment of the model-building process.

Two ostensibly disparate systems – a game of checkers (Chapter 4) and the central nervous system (Chapter 5) – highlight the principal traits of emergence. In both cases, through modeling these systems via a so-called Checkersplayer computer program[1] and neural networks, one finds that "more comes out than was put in." In the checkers example, a few well-defined rules of interaction can generate complex, unanticipated and perpetually novel strategies.

Similarly, computer simulated neural nets display emergent properties, as the initially supplied random connections between individual neurons begin to acquire persistent patterns and unanticipated behavior over time. Holland notes that among complex systems, "one recurring theme is essential to emergence: in each case there is a *procedure* for freely *generating* possibilities, coupled to a set of *constraints* that limit those possibilities" (p. 122). Additionally, both examples point to the importance of computer-based modeling as a "third way" of science, which incorporates the analytical rigor of mathematical formulations and the flexibility and greater degree of realism associated with experimentation.

The discussion of *constrained generating procedures* (Chapter 7) – in which Holland establishes a set of detailed guidelines for creating *cgp's*, translating those guidelines into mathematical form – forms the intellectual core of the book. Briefly summarizing, these guidelines involve the following steps.

1. Define the *mechanisms* that serve as the rules of the game or laws of the physical system. A mechanism processes inputs, actions and information to produce output.
2. These mechanisms are linked together to form *networks*, which can involve more than one kind of mechanism. These networks are what Holland refers to as *constrained generating procedures.* The complexity is generated when many mechanisms interact to provide organized and unanticipated patterns and behavior. These networks can be fixed, constraining the mechanisms on a fixed landscape. Alternatively, links can be transitional, whereby mobile agents create and dissolve linkages in a changing network.
3. The state of the interlinked mechanisms can then be defined in terms of the component mechanisms. Once the state is defined, one can then describe the *transition function,* which allows for a large set of possible future state changes, constrained by the set of possible interactions of the component mechanisms.
4. Finally, one can begin to describe the *hierarchy* of the system, by using the basic mechanisms as subassemblies to build up to more complex mechanisms. Each *cgp* would then serve as a mechanism to build more complex *cgp's.*

[1] The discussion of the checkersplaying program is based primarily on the work of A.L. Samuel (1959). "Some Studies in Machine Learning Using the Game of Checkers." In E.A. Feigenbaum and J. Feldman, eds., 1963,

This final step in Holland's set of instructions for creating complex systems is critical, since most emergent systems consist of multiple levels of complex systems and subsystems (Chapter 10 outlines the idea of levels in a system in more detail). As stated by Holland, "we can capture the hierarchies that are major features of systems exhibiting emergence, like the molecule, organelle, cell, organ, organism, …hierarchy in biology" (p. 129). This notion of hierarchy – complex systems as layers of networks of interacting mechanisms – reveals how macrolaws and macrodescriptions of a system can be useful in beginning to understand the origins of that system's emergent properties.

Evaluation and Outlook

One of the important contributions of Holland's current work, is his ability to place the ideas and models of complexity in the context of a broader scientific enterprise. A recurrent theme of the book relates to the idea of the *reductionism* that characterizes most of the work in the sciences. Holland begins to reconcile this paradox between complexity and reductionism in the following manner. Rather than holding to the notion "that all phenomena in the universe are reducible to the laws of physics" one should recognize that "all phenomena are *constrained* by the laws of physics" (p. 188). This subtle shift in perspective allows for emergent behavior, while recognizing that these complex emergent characteristics may arise from a small set of building blocks constrained by relatively simple rules.

Furthermore, from the perspective of the systems sciences, emergence breaks from the traditional theories by looking not at the end points where a system reaches an equilibrium or optimum state, but rather the transitional effects of persistent patterns and system improvements. An important lesson to learn from Holland's framework is that "optimization in complex adaptive systems is rarely possible" (p. 244). Under the assumption that socio-technical systems are becoming increasingly complex and interconnected, this change in perspective will be a necessary condition to understanding and controlling these systems at critical stages in the process of emergence. According to Holland, emergence is a "critical feature that does not fit into the formalism of traditional system theory" (p. 240).

Computers and Thought. New York: McGraw-Hill.

In summary, *Emergence* accomplishes two objectives in the knowledge domains of Complexity and Complex Adaptive Systems. First, he brings together several of the exemplary models – Samuel's Checkerplayer, neural networks, Conway's automaton, and Mitchell's Copycat[2] – and methodically compares and contrast each to highlight the underlying similarities and differences, both qualitatively and from a mathematical standpoint. Second, and more importantly, his *constrained generating procedures* framework, which admittedly has not reached the "status of a full-blown theory of emergence," does set the stage for what should be expected in the study of emergence, and more broadly speaking, for the study of Complexity and Complex Adaptive Systems (p. 239).

References

Holland, John H. (1998). *Emergence: From Chaos to Order*. Reading, MA: Perseus.

Holland, John H. (1995). *Hidden Order: How Adaptation Builds Complexity.* Reading, MA: Addison-Wesley.

[2] Note the following references for a more thorough treatment of these emergent systems. For Neural Networks, see Hebb, D.O. 1949. *The Organization of Behavior: A Neuropsychological Theory.* New York: Wiley. For Samuel's Checkersplayer, see the reference cited earlier. For a description of Copycat, see Mitchell, M. 1993. *Analogy-Making as Perception*. Cambridge, MA: MIT Press. For John Conway's simple cellular automata program, called "Life" see Gardner, M. 1983. *Wheels, Life, and Other Mathematical Amusements*. New York: Freeman.