SFI Profile **John Holland**

John Holland finds causal relationships everywhere, in social as well as scientific settings. Whenever confronted with a new situation, the SFI Science Board member explains, he tries "to make a model of it."

Yet the causes underlying Holland's own career are difficult to formulate. Why, for instance, did the son of a quintessentially mid-Western soybean entrepreneur develop a passion for computers long before they became popular? And how did a scientist with a traditional academic background become involved in creative, interdisciplinary work?

These questions provoke a grin.

As a boy growing up during the Depression years in western Ohio, Holland liked to put together model airplanes and conduct experiments with his chemistry set. He was also an avid reader. "I liked to read almost anything I could get my hands on in science," remembers the still-boyish academic. Atomic reactions and the way they related to other fields, such as astronomy, became a special interest; J. Robert Oppenheimer was an early hero.

Although there were no other academics in the family, Holland's father encouraged his son's enthusiasm for science. An accomplished gymnast, the elder Holland imparted an appreciation for practice and determination. Somehow the combination of an innate scientific imagination and a sense of old-fashioned, mid-Western stick-to-itiveness created a visionary.

Complex Adaptive Systems: A Primer

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This article is adapted from the paper "Nonlinear Systems Far from Equilibrium" presented at the Santa Fe Institute workshop on Complex Adaptive Systems, Summer 1986.

At the core of areas of study as diverse as cognitive psychology, artificial intelligence, economics, immunogenesis, genetics, and ecology, we encounter nonlinear systems that remain far from equilibrium throughout their history. In each case, the system can function (or continue to exist) only if it makes a continued adaptation to an environment that exhibits perpetual novelty. Traditional mathematics with its reliance upon linearity, convergence, fixed points, and the like, seems to offer few tools for building a theory here. Yet, without theory, there is less chance of understanding these systems than there would be of understanding physical phenomena without the guidance of theoretical physics. What's to be done?

Hierarchical organization and building blocks

There are some hints. First, all such systems exhibit an hierarchical organization. In living systems, proteins combine to form organelles, which combine to form cell types, and so on, through organs, organisms, species, and ultimately ecologies. Economies involve individuals, departments, divisions, companies, economic sectors, and so on, until one reaches national, regional, and world economies. A similar story can be told for each of the areas cited. These structural similarities are more than superficial. A closer look shows that the hierarchies are constructed on a "building block" principle: subsystems at each level of the hierarchy are constructed by combination of small numbers of subsystems from the next lower level. Because even a small number of building blocks can be combined in a great variety of ways, there is a great space of subsystems to be tried, but the search is biased by the building blocks selected. At each level, there is a continued search for subsystems that will serve as suitable building blocks at the next level.

A still closer look shows that in all cases the search for building blocks is carried out by competition in a population of candidates. Moreover, there is a strong relation between the level in the hierarchy and the amount of time it takes for competitions to be resolved--ecologies work on a much longer time-scale than proteins, and world economies change much more slowly than the departments in a company. More carefully, if we associate random variables with subsystem ratings (say, fitnesses), then the sampling rate decreases as the level of the subsystem increases. As we will see, this has profound effects upon the way in which the system moves through the space of possibilities.

System-environment interaction

Common features of system-environment interaction in each case provide additional hints about the characteristics of the movement through the space of possibilities:

1) Each of the systems interacts with its environment in a game-like way: Sequences of action ("moves") occasionally produce *payoff*, special inputs that provide the system with the wherewithall for continued existence and adaptation. Usually payoff can be treated as a simple quantity (energy in physics, fitness in genetics, money in economics, winnings in game theory, reward in psychology) sparsely distributed in the environment and that the adaptive system must compete for it with other systems in the environment.

2) The environment typically exhibits a range of regularities or *niches* that can be exploited by different action sequences or *strategies*. As a result, the environment supports a variety of processes that interact in complex ways, much as in a multi-person game. Typically there is no super-process that can outcompete all others, hence an ecology results (domains in physics, interacting species in ecological genetics, companies in economics, cell assemblies in neurophysiological psychology, etc.). The very complexity of these interactions assures that even large systems over long time spans can have explored only a miniscule range of possibilities. Even for much-studied board games such as chess and go, this is true; the not-so-simply defined "games" of ecological genetics, economic competition, immunogenesis, central nervous system activity, etc., are orders of magnitude more complex. As a consequence, the systems are always far from any optimum or equilibrium situation.

3) There is a tradeoff between *exploration* and *exploitation*. In order to explore a new niche, a system must use new and untried action sequences that take it into new parts (state sets) of the environment. This can only occur at the cost of departing from action sequences that have well-established payoff rates. The ratio of exploration to exploitation in relation to the opportunities (niches) offered by the environment has much to do with the life history of a system.

4) There is also a tradeoff between "tracking" and "averaging." Some parts of the environment change so rapidly relative to a given subsystem's response rate that the subsystem can only react to the average effect; in other situations the subsystem can actually change fast enough to respond "move by move." Again, the relative proportion of these two possibilities in the niches that the subsystem inhabits has much to do with the subsystem's life history.

Pervasive features of subsystem interactions

Beyond these commonalities there are characteristic interactions between components that can be observed in each kind of system:

1) The value ("fitness") of a given combination of building blocks often cannot be predicted by a summing up of values assigned to the component blocks. This nonlinearity (commonly called *epistasis* in genetics) leads to co-adapted sets of blocks (*alleles*) that serve to bias sampling and add additional layers to the hierarchy.

2) At all levels, the competitive interactions give rise to counterparts of the familiar interactions of population biology--*symbiosis, parasitism, competitive exclusion*, and the like.

3) Subsystems can often be usefully divided into *generalists* (averaging over a wide variety of situations, with a consequent high sampling rate and high statistical confidence at the cost of a relatively high error rate in individual situations) and *specialists* (reacting to a restricted class of situations with a lowered error rate bought at the cost of a low sampling rate).

4) Subsystems often exhibit multifunctionality in the sense that a given combination of building blocks can usefully exploit quite distinct niches (environmental regularities), usually, however, with different efficiencies. Subsequent recombinations can produce specializations that emphasize one function, usually at the cost of the other. Extensive changes in behavior and efficiency, together with extensive adaptation, can result from recombinations involving these multifunctional founders.

Internal models

There is an additional element of importance: these systems usually generate implicit internal models of their environments, models progressively revised and improved as the system accumulates experience. The systems *learn*. Consider the progressive improvements of the immune system when faced with antigens, and the fact that one can infer much about the system's environment and history by looking at the antigen population. This ability to infer something of a system's environment and history from its changing internal organization is the diagnostic feature of an implicit internal model.

The models encountered are usually *prescriptive*--they specify preferred responses to given environmental states--but, for more complex systems (the central nervous system, for example), they may also be more broadly *predictive*, specifying the results of alternative courses of action. We understand little of this process of model building, but it lies at the heart of the problems associated with the emergence of structure in complex systems. For process-like transformations, the relevant mathematical model is a *homomorphism*. Real systems almost never meet the requirements for a homomorphism, but there are weakenings, the so-called *q-morphisms* (*quasi-homomorphisms*). The origin of a hierarchy can be looked upon as a sequence of progressively refined q-morphisms based upon observation.

Mathematical concerns

In looking for a mathematics to deal with these commonalities, one finds relevant pieces in extant studies of particular examples. For instance, in mathematical economics there are pieces of mathematics that deal with (1) hierarchical organization, (2) retained earnings (fitness) as a measure of past performance, (3) competition based on retained earnings, (4) distribution of earnings on the basis

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of local interactions of consumers and suppliers, (5) taxation as a control on efficiency, and (6) division of effort between production and research (exploitation vs. exploration). Many of these fragments, with due alteration of detail, can be used to study the counterparts of these processes in the other areas.

As another example, in mathematical ecology there are pieces of mathematics dealing with (1) niche exploitation (models exploiting environmental opportunities), (2) phylogenetic hierarchies, polymorphism and enforced diversity (competing subsystems), (3) functional convergence (similarities of subsystem organization enforced by environmental requirements on payoff attainment), (4) symbiosis, parasitism, and mimicry (couplings and interactions leading to increased efficiency for extant generalists simply because related specialists exclude them from some regions in which they are inefficient), (5) food chains, predator-prey relations, and other energy transfers (apportionment of energy or payoff amongst component subsystems), (6) recombination of multifunctional co-adapted sets of genes (recombination of building blocks), (7) assortative mating (biased recombination), (8) phenotypic markers affecting interspecies and intraspecies interactions (coupling), (9) "founder" effects (generalists giving rise to specialists), and (10) other detailed commonalities such as tracking versus averaging over environmental changes (compensation for environmental vari-

ability), allelochemicals (cross-inhibition), linkage (association and encoding of features), and still others. Once again, though mathematical ecology is a younger science, there is much in the mathematics that has been developed that is relevant to the study of other nonlinear systems far from equilibrium.

The task of theory is to explain the pervasiveness of these features by elucidating the mechanisms that assure their emergence and evolution. The most hopeful path seems to be a combination of computer modeling and a mathematics that puts much more emphasis upon combinatorics (that branch of mathematics dealing with combinations) and competition in parallel processes.

A prime objective of this theory should be an account of the emergence of q-morphisms in response to complex environments exhibiting sparse payoff. Computer simulations should give a better understanding of the conditions under which the phenomena of interest emerge. The close control of initial conditions, parameters, and environment made possible by simulation should enable the design of critical tests of the unfolding theory. And, as is usual in experiment, the simulations should suggest new directions for theory. The broadest hope is that the theoretician, by testing deductions and inductions against the simulations, can reincarnate the cycle of theory and experiment so fruitful in physics.

Addison-Wesley to Publish SFI Series

The Santa Fe Institute has selected Addison-Wesley Publishing Company's Advanced Book Program to publish its research findings. Entitled SANTA FE INSTITUTE STUDIES IN THE SCIENCES OF COMPLEXITY, the series will include proceedings, monographs, reprint volumes, and other collections.

The first volume to be published as part of this series is *Emerging Syntheses in Science*, a reprint of the proceedings of the Institute's founding workshops. The book will be available through Addison-Wesley in the fall. The second issue of the series will feature proceedings of the SFI symposium *Theoretical Immunology*. Symposium director Dr. Alan Perelson of the Theoretical Biology and Biophysics Division of Los Alamos National Laboratory will edit the volume of some fifty or so papers, which is due to be published in December. The Institute expects that each of its research initiatives will result in at least one volume. Comments SFI President George Cowan, "It is essential to the success of the Institute's program to make its results known to a broad spectrum of workers in science. We believe our agreement with Addison-Wesley will contribute importantly to this essential task."

Lecture Series

"Order from Chaos: Different Ways of Thinking About the Origin of Life," an illustrated lecture for the non-scientist by Prof. Stuart Kauffman, led off a SFI series of public lectures on topics related to its research interests. Talks are scheduled in July and September in conjunction with upcoming workshops. On Wednesday, July 22, Prof. Harold Morowitz, Department of Biochemistry and Biophysics, Yale University, will talk about "Biology in the Computer Age." The aim of this ongoing series is to increase the general public's understanding of the nature of the sciences of complexity and their relevance to today's society. The lectures may be published as part of the Institute's series of scientific books.

Staff Developments

In April, Ronda K. Butler-Villa joined the Institute staff as the Administrative/Technical Secretary. She has extensive word processing background, including networking and phototypesetting, primarily at Chevron Oil Company in San Francisco, California.