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President's Report

SFI activities are continuing at a constantly increasing tempo in several areas, including planning and research workshops, publications, campus development, public outreach, recruitment of visiting fellows and members of the Board of Trustees and Science Board, and preparation and submission of proposals to support the work of the Institute. What seemed idealistic and visionary just two years ago, now appears to be a reality. SFI has developed a strong institutional foundation, a group of dedicated scientists and scholars investigating important problems, and a new campus. Some of our activities are described at greater length in this issue of the Bulletin.

We are greatly pleased with the present campus of SFI which we occupied last February. It was formerly a convent associated with the Cristo Rey Church and is located at nearly the easternmost part of Canyon Road at the heart of one of the most picturesque parts of old Santa Fe. The staff and visitors particularly appreciate the authentic, cool adobe structure, the compound with flowering fruit trees enclosed by the open, U-shaped building, and the ambience so representative of the most charming features of the Southwest. If our expansion plans proceed on schedule, we expect to outgrow these quarters within the next few years but we are already thinking of ways to make this campus a permanent part of the Institute. We invite all of our Board members, associates, and friends to make a special point of visiting us here.

We have begun our public outreach program with the first of our new series of public lectures on topics related to SFI programs. Dr. Stuart Kauffman spoke to a capacity audience at the campus on the evening of June 11. His topic was "Order from Chaos: Different Ways of Thinking About the Origin of Life."

Your comments and suggestions concerning the plans and activities of the Institute are more than welcome and I shall look forward to hearing from you. Your help in achieving our plans is vital, particularly in making SFI known to people outside the Institute who can add to our intellectual and material resources. As remarkable as our progress has been in the past several months, we are only at the beginning of our task. I am confident that, with the help of our many friends and colleagues, we shall succeed even beyond our great expectations.

Dr. George A. Cowan
President

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The Santa Fe Institute is a growing multidisciplinary research and graduate education center formed to nurture research on complex systems and their simpler elements. A private, independent institution, SFI was founded in 1984. Its primary concern is to focus the tools of traditional disciplines and emerging new computer resources on the problems and opportunities that are involved in the multidisciplinary study of complex systesm - those fundamental processes that shape almost every aspect of human life and experience.

On the Cover

"Dr. and Mrs. Albert Einstein at Hopi House," Grand Canyon, Arizona, 1931. Photo by El Tovar Studio, Courtesy of the Museum of New Mexico, Neg. No. 38193.

REVIEWS AND INITIATIVES

Theoretical Immunology

Theory in immunology spans a wide range of phenomena, beginning at the molecular level with the rearrangements and mutations within the DNA of a single cell that control the diversity of the immune response, and continuing to the surface of a cell where interactions occur which lead to signals that control the immune responsiveness of the cell. Theory is important at the level of populations of cells interacting in complex nonlinear ways in the various immune organs and trafficking throughout the body. Finally, theory can also play a significant role at the level of human populations where the spread of infectious disease and potential vaccination protocols are of importance. The regulation of growth and differentiation of various cell populations either through idiotypic network interactions, control circuits involving helper and suppressor cells, or via soluble mediators all play a role in our theoretical understanding of the immune system. The development of nonlinear mathematical models may help explain the complex phenomena that underlie the operation of the immune system.

The field of immunology itself is one of the most rapidly advancing experimental areas in science. It has been at the forefront of many advances in molecular genetics and has been a driving force for DNA sequencing. There are over forty journals devoted to the publication of experimental results in this field. Yet theories which can organize observations and lead to testable predictions are lagging far behind. Research efforts in theoretical immunology are carried out by individual researchers and small groups of researchers scattered throughout the world. Communication between such workers is rather poor. There is no single journal which one can read to follow current advances, and there is no regularly scheduled conference where workers in this area can meet to discuss current research efforts.

To promote communication in this field, foster new collaborations between established workers and to help young scientists interested in learning about this field, SFI and the Theoretical Biology and Biophysics Division of Los Alamos National Laboratory in June co-sponsored "Theoretical Immunology," a three-day symposium involving more than seventy scientists from the United States, Japan, Germany, France, England and the USSR. The program was supported by funds from the United States Department of Energy.

Assuming that the complex phenomena underlying the operation of the immune system may be better understood through the collaborative efforts of theorists and experimentalists viewing the same phenomena in different ways, the conference focused on themes spanning the field of immunology, with emphasis on areas where theorists have made the most progress. Topics included cell surface phenomena, idiotypic networks, dynamic models of the immune system, and evolution and adaptation in the immune system. In each of these areas there is reason to believe that advances can be made either through interactions among experimentalists and theorists or through the critical look theorists will bring to bear on each other's work.

Conference proceedings will appear in a forthcoming volume from Addison-Wesley Publishing Company, due at the end of the year. Future workshops in this area are planned, as well as the establishment of a network of researchers with interests in nonlinear, complex systems modeling and in the immune system.

One potential theme for a future workshop that is of great current concern and for which modeling in complex systems may give insight, is the effect of the AIDS virus on the immune system. Because the virus attacks the T helper cells, macrophages, and monocytes, the immune system is debilitated by the virus at key control points. One issue of concern is that if we stimulate the immune system, say by drugs, will this help fight the virus or will this simply provide a larger pool of cells for the virus to attack and hence allow it to spread more rapidly? Effects such as this can be examined by the appropriate nonlinear model.

Matrix of Biological Knowledge

More than fifty scientists will gather in Santa Fe this summer to begin work on developing a biology-wide information system - a computerized "matrix data base" - structured so that it can be accessed from a multitude of dimensions.

Much of the current interest in the concept of a matrix of biological knowledge has been generated by a recent National Academy of Sciences report on Models in Biomedical Research. "We seem to be at a point in the history of biology where new generalizations and higher order biological laws are being approached but may be obscured by the simple mass of data," the report notes. It proposes that more refined organization of the data, in a form which makes recognition of the cross-connections more explicit, will turn up new theories.

Indeed, biologists have become increasingly aware over a long period of time that the model of physics, with its base in a small number of axioms, is inadequate to support a set of phenomena which have been shaped by three-and-a-half million years of development as well as the underlying laws of physics. As a result, the disciplines of biology have dealt with a degree of complexity which made general theoretical approaches very difficult.

The development of computer technology, information science and knowledge-based systems now makes it possible to view biology in a new light. While no one envisions a unified theory in the physicist's sense of the phrase, it does seem possible to construct a much more highly interrelated discipline than now exists and to test the almost universal feeling that lurking within the data of biology are significant generalizations which will provide explanations for broad ranges of phenomena.

The task of developing such a system is enormous. At the moment, the matrix of biological knowledge is an abstraction, a strong intuition on the part of a number of scientists that the time is ripe to face the vastness of biological knowledge and code it in such a way as to be maximally useful in developing theoretical constructs. As the NAS Report Committee notes, a knowledge system that strives to put "all of biological knowledge in relation to the rest of it" remains a "Platonic ideal." Yet there is an urgent need and practical possibility now to begin bydeveloping a "data base of data bases."

The existence of this kind of biological theory would obviously be of great benefit in guiding experiment and providing a more efficient way of gaining information of value in agriculture, medicine and other areas of biotechnology. Research planning will benefit from a framework in which to search and implement decisions.

The Santa Fe Institute workshop this summer will focus on the development of such a data base; biologists, computer scientists and information specialists will discuss the conceptual problems of constructing the matrix and begin construction in selected domains. The program is led by Yale University biophysicist Harold J. Morowitz, chair of the NAS Report Committee, and Temple Smith, director of the Molecular Biology Computer Research Resource Center at the Dana Farber Cancer Institute, Harvard University. Funding for the program is provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy, and the National Institutes of Health.

The formulation and use of large-scale data bases will be studied in detail. Artificial intelligence will be examined with special reference to querying data bases to become interactive. The problem of very large-scale computation applied to the structure and function of macromolecules will be studied as an example of how the conceptual approaches of physical chemistry can be made interactive with biochemical approaches. A series of biological subject areas will be examined with a view of developing ways to interconnect local domain theories into a more global overview.

"This workshop is fundamentally a think tank to build a biological theory that takes full advantage of computer science and information sciences. It is an attempt to integrate the insights of many specialists", says Morowitz. This initial meeting will be followed by the formation of a research network to continue work begun this summer. The network will schedule several workshop meetings throughout the next year, will establish a communication net, and will explore new ways to train biologists and computer scientists within the context of the matrix.•

Evolutionary Paths of the Global Economy

We rely on the science of economics for its ability to guide a variety of short- and long-range planning decisions in the private and public domains. Because of its importance, its shortcomings are widely publicized, reviewed, and increasingly criticized. These defects are fully acknowledged within the economic community, but the problem of remedying them may be fundamentally immune to adequate solution using current predictive models. What appears to be needed is a conceptual framework incorporating a more appropriate mathematics, particularly with a greatly strengthened capability to deal simultaneously with many variables, nonlinearity, and dynamics. It is, of course, more difficult to take into account human and social factors including memory and a variety of values which cannot be equated with money. Dissipative forces must be identified. The overriding need to maintain international political stability and to avoid a catastrophic war clearly affects current economic policy and must eventually be explicitly included in any model.

"Evolutionary Paths of the Global Economy," an SFI meeting planned for September 9-18, 1987, will draw together economists, and physical and biological scientists who have developed techniques for nonlinear dynamics and the study of adaptive paths. The aim is to encourage the use of these tools in understanding the clearly complex and arguably chaotic developments of the now worldwide economy. The workshop is supported by funding from Citicorp and the Russell Sage Foundation.

Nothing is more obvious about the economic system than that it is changing over time. The character of the changes depends on the time period considered. Over long periods, the economy is growing and evolving. The advanced countries, at least, have shown movements towards increasingly preferred states, in spite of particular difficulties in the environment and in scarce resources. But this growth is accompanied by qualitative shifts; on the whole, growth does not consist so much of more of the same goods but of different kinds of goods, so that agriculture has declined greatly in relative importance while first industry and then services have increased in volume and variety. Over shorter periods the capitalist world has shown recurrent fluctuations averaging about four years. (Some have also claimed to find fluctuations with periods variously estimated as twenty to fifty years, but there is no consensus on these views.) These are most typically fluctuations in real magnitudes, such as output and employment. There is also considerable volatility in *nominal variables* such as general price levels, individual prices, foreign exchange rates, securities prices, and interest rates. That the *nominal* and *real magnitudes* interact causally is not in doubt, but the nature and extent of the interactions is far from fully agreed on.

The prevailing views in economics all revolve in one way or another around the concept of *equilibrium*. This is a situation in which supply and demand are equal in all markets. Under certain ideal conditions, equilibrium is assured. However, it is less clear that actual markets are in fact in equilibrium, and there are competing views. In any case, the equilibria are changing over time. Theoretically, there are two kinds of dynamics in economics. The dynamics of *adjustment* or *stability* starts with a disequilibrium situation and assumes that prices are adjusting in a manner which reflects the disequilibrium. For example, prices might rise on those markets which show an excess of demand over supply and fall on the others. It can be shown that stability (convergence to an equilibrium) is far from assured under these circumstances. The second kind of dynamics might be termed *equilibrium dynamics*. Here, it is assumed that markets clear at each point of time, but the prices and quantities are changing over time in response to the previous changes. For example, investment at one time changes the possibilities of production in the future. It is frequently assumed in fact that decisions made at one time are made in anticipation of future prices and that these are correctly forecast, at least up to intrinsic uncertainty.

The mathematics of dynamic systems is similar in different contexts, and over the last thirty years there have been repeated applications to economic analysis. Lyapunov functions were applied to stability theory, though in the end it turned out that the domain of their usefulness was very limited. Later stability analysis and optimal control theory were used with considerable success. The tendency had been to find the conditions under which dynamic paths (especially in equilibrium dynamics) converge to steady states (or to exponential functions). With

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Computational Approaches to Evolutionary Biology

In the fall, 1987, the Institute will convene a week-long meeting to begin to explore the qualitative contributions to be gained from applying the latest computational techniques to biological theory. This gathering, an outgrowth of the Institute's 1986 workshop on complex adaptive systems, will have as one of its goals the establishment of an ongoing research network to provide for continuing collaboration on computational approaches to evolutionary biology.

The mathematics of evolutionary theory has addressed issues that range from properties of DNA to properties of human cultures. Although every level of organization demands a different formulation of the transmission mechanism and the action of natural selection, significant collaboration between the evolutionary geneticists and genetic algorithm computer scientists can be achieved at almost every tier.

One issue amenable to such an interdisciplinary approach is the genetics of host-parasite interactions. In the best studied mammals, man and mouse, the genes in the major histocompatibility systems (MHC's) are among the most variable (in populations) of any genes known. The common assumption is that this is an historical result of the continued onslaught of parasites. The host that best combats a parasite has an advantage until the parasite changes and a process of continuing mutation and selection develops. Mathematical modeling of genetic versions of this system is still at a primitive stage, although recent studies have addressed some of the epidemiological issues raised by genetic variability in resistance to parasites. Other studies have suggested that recombination in the genes of the host could be advantageous in promoting the continued ability to combat parasites. There are recent findings of recombinational hotspots in the MHC's of man and mouse that might support this notion. The mathematical models needed to approach these conjectures must include: 1) multiple locus population genetics of the host, with recombination, 2) different generational time scales for host and parasite, and 3) age structure in the host population to allow for the ontogeny of the immune system. The computational approach, informed by the mathematics of the simpler pieces of the models, seems ideal for this class of problems.

Equally productive may be the computational approach to the evolution of behavior. With regard to statistics and the nature-nurture issue, for example, recent discoveries of linked markers in certain pedigrees that are informative about Alzheimers disease and manic depressive illness has underlined how little we know about the transmission of these diseases and, indeed, about the genetics of behavior. The major computational tool currently used to evaluate familial aggregation of diseases is path analysis. This method devised by S.Wright in 1921 and applied by him to behavior in 1931 has been applied to everything from disease to attitudes that appear to aggregate within families.

The computational approach to the gene environment question in behavior takes as its point of departure a class of models for the transmission of the trait from parents to child. These models involve both formal genetics and cultural transmission and are completely general. (They do not invoke as a primary parameter the parent-offspring regression.) From these rules of transmission it is possible, although extremely cumbersome and time-consuming, to produce formulae for statistics of the trait frequencies among parents and children. With high-speed numerical computation, it is, in fact, possible to build up expected distributions of these statistics and to assess which model of transmission is most likely to apply to a given set of observations. There is no constraint to use a particular analysis of variance framework such as forms the basis for almost all such studies in behavior genetics.

Similar computational techniques can be applied to questions about evolution of communication. The machinery of communication involves two components, transmission and reception. In many organisms, the anatomical structures involved in these are different although related. In insects, there are pheromone releasing and detecting mechanisms. In man, there is speech and hearing (or writing and reading). Evolutionists agree that this coevolution of these structures must have been a matter of simultaneous biological and cultural evolution, especially as regards communication in man. The central issue is how to model the phase of evolution during which a trait that was initially

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Computational Approaches *(continued)*

the development of newer theories, it has been fully coded in the DNA, i.e., transmitted genetically, becomes one that is learned, i.e., transmitted culturally. For speech in man, the focus of this change probably occurred between 200,000 and 50,000 years ago. Mechanistically, the problem certainly bears on computation aspects of neural networks. But even the simplest dynamical model must invoke both genetic and cultural determination of the transmitted trait.

The idea is to begin with a model of a perfectly innate trait, i.e., one that is evolving under genetic transmission. A class of mutation accumulates that converts this trait to one that is learned. Why should these mutations succeed unless they affect other traits as well? Does the learning have to be within families (as is the case for altruism) to succeed? Is a small population subject to stochastic processes the most favorable for the process to work? From a relatively naive model, this question quickly matures into one that demands very sophisticated interdisciplinary thought.

The Institute will examine these and related problems during its September, 1987, workshop chaired by Marcus W. Feldman, Stanford University, and John H. Holland, University of Michigan.

Evolutionary Paths of the Global Economy *(continued from page 5)*

found that many plausible economic models exhibit cyclical and even chaotic behavior. The range of applications has, however, been very limited, particularly to systems of very low dimensionality, though the economic system is intrinsically one involving many variables.

A better understanding of new developments in dynamic analysis in the physical sciences and of the use of computers to integrate empirical and theoretical analyses will help economists; scientists may benefit by seeing another system which certainly has parallels to ecology and evolution and possibly to some chemical systems. Yet in bringing together these two groups to consider the development of nonlinear adaptive economic models, it is important to keep in touch with real economic problems which present significant, but not necessarily easily quantifiable, aspects of the development and application of economic theory. The workshop focus on the evolution of the present global economy represents such a case study. Along with the expertise of scientists and economists, it will draw upon expert advice as to the role behavioral, sociological and political factors play in the development of today's world economy. Such discussion may encourage participants to begin examining ways in which semi-qualitative scenarios which incorporate such factors could be developed and studied.

Professors Philip W. Anderson, Princeton University, and Kenneth J. Arrow, Stanford University, co-chair this workshop. It will open with eight invited lectures. Four will set forth the basic relevant work in economic analysis, on the following subjects: (1) competitive equilibrium: concepts, limits, and determination through the market and by algorithms; (2) models of capital accumulation; (3) nonlinear mode-locking in economic systems with multiple stationary states; (4) empirical tests of nonlinear deterministic systems in economics. Four lectures will present basic techniques developed in the natural sciences: (1) nonlinear dynamics; (2) complex optimization problems: the statistical mechanics approach; (3) complex adaptive systems and learning algorithms; (4) what can be done with modern computers? Following the initial lectures, there will be about one presentation per day, leaving ample time for individual work, writing and discussion in small groups.

One outcome of this meeting will be a volume which contains papers contributed by the participants and a summary of workshop discussion and recommendations, prepared by the workshop rapporteurs and the co-chairmen. This volume will be published by Addison-Wesley Publishing Company as part of a series, *Santa Fe Institute Studies in the Sciences of Complexity*. A second outcome of this workshop will be the formation of a research network, in which participants will begin working together on a program aimed at the development of a conceptual framework for economics which incorporates a number of the basic ideas developed in the study of the dynamic behavior of nonlinear physical systems and of the adaptive, evolutionary, and learning mechanisms in molecular, biological, computer, neural, and social systems.

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.

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Complex Adaptive Systems: A Primer

John H. Holland
The University of Michigan

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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Complex Adaptive Systems: A Primer *(continued)*

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 coadapted 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 variability), 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.

SFI Profile **John Holland**
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By junior high school, Holland had settled on a career in physics. But while attending MIT on scholarship, a close encounter with a primitive computer called "Whirlwind" inspired an interest in mathematics and computer science that has endured.

Between his BS and graduate studies at the University of Michigan, where he is today an engineering and computer science professor, Holland worked at IBM from 1950 to 1952. Using a computer only slightly less primitive than Whirlwind, he became involved in a project to model "nerve nets," or connections between human neurons. The goal was to producea model that could predict the behavior of small networks of neurons.

The work was tedious. The computer was the first IBM commercial electronic model and had to be accessed with punch cards. It had a memory of only 4,000 words and required 30 microseconds to perform a simple addition problem - almost one hundred times slower than today's PC's. Holland's group had use of this marvel between 11:00 p.m. and 6:00 a.m.; they had to reprogram it every night before beginning work and every morning before leaving.

The results of the IBM project were promising, providing a basis for later work in the area. And the experience whetted Holland's curiosity about applying math to biology.

He began graduate studies at Michigan in mathematics, earning an M.A. in 1954. But a friendship with Arthur Burks, whom Holland describes as "one of the real founders of the computer era," resulted in a switch to "communication science," the '50s term for computer science.

At the same time, Holland began reading sorne of the early mathematical geneticists. "I had both nerve nets and biology sitting in the back of my mind," he recalls. "It really excited me...I could see there was a way to take a lot of the information in biology and do things with it mathematically."

After receiving a Ph.D. in 1959, Holland stayed on at Michigan as an assistant professor. Under ordinary circumstance, he would never have received the opportunity to pursue interdisciplinary studies, he feels. But Burks became a shield for him, using "his reputation to get people to let me alone."

"The real rewards in academia are in getting papers out," Holland explains. "And the way to do that is to stick to your field...Universities have a real hard time dealing with the interdisciplinary individual."

Holland's own creativity, born of the futuristic books he read as a teenager under the limitless skies of rural Ohio and nurtured by Burks, led to a new twist in Darwinian evolution. Holland's "recombination theory" disputes a tenet of standard evolutionary theory that mutations are the major source of adaptive changes. Holland realized that the normal process of chromosome crossover, during which a piece from one chromosome becomes attached to another, can also generate unique characteristics. Because chromosome crossover is routine, while the rate of mutation is only one in 10,000,000 per gene, Holland believes it offers a more accurate explanation of evolutionary adaptation.

Holland has applied theories of adaptive systems to economics, artificial intelligence and the immune system as well. In 1985, he and his early mentor Burks applied for a patent for an adaptive computing system that is capable of learning and discovery.

During the past year as Ulam scholar at Los Alamos National Laboratory, Holland was given free rein to pursue a full range of adaptive systems.

"Most complex systems manage to prove themselves if they last over a period of time," he says. "They don't make the same mistakes over and over, they adapt."

In Holland's approach to science, he tries to find "enough of a theory to find the mechanisms by which these things manage this trick."

"We're beginning to see an outline of a general mathematical framework that would encompass the entire range," Holland says of his work at Los Alamos. If a comprehensive theory can be formulated, it will provide a crucial tool for understanding many mysterious features of adaptive systems.

Unfortunately, universities still fail to encourage the interaction among disciplines that makes work such as Holland's possible. He hopes SFI will prove to be the missing "mechanism" in the scientific community that will bring researchers from diverse disciplines together.

"What you really need is a group of people who know several disciplines and are good at getting ideas, people who can let their minds roam and are willing to suspend disbelief for awhile."

"Santa Fe Institute will do this - it will get the right pieces together," says the man whose own diverse pieces came together so well.

Board News

THE BOARD OF TRUSTEES

The Institute welcomes four new members to its Board of Trustees:

Jerry D. Geist is Chairman of the Board and President of Public Service Company of New Mexico. He is also Chairman of Edison Electric Institute and of the University of New Mexico Foundation, Inc. A member of the President's Export Council, he is a Director of Lectrosonics, Inc., Southwest Community Services, Resources for the Future, Federal Reserve of Kansas City, Venture Advisors, Inc., AEGIS Insurance Services, Inc., and the National Symphony.

George A. Keyworth, II is Chairman of The Keyworth Company. He is past Director of the Office of Science and Technology Policy and former Science Advisor to the President. A Trustee of the North Carolina School of Science and Mathematics and Director of the Hewlett-Packard Corporation, he is a Fellow of the American Physical Society and Member of the American Association for the Advancement of Science.

George Kozmetsky is Director of IC^2 Institute and an Executive Associate, University of Texas at Austin. He is Chairman of the Board of MCR and Chairman of the Board and President of the Institute of Management Science. A Director of the Amdahl Corporation and Teledyne Corporation, he is a Trustee of Federated Development Corporation.

Robert A. Maynard is President of Sundance, former President of Keystone Resort , and former Assistant Director, National Park Service.

THE SCIENCE BOARD

The Science Board of the Santa Fe Institute, formerly the Board of Advisors, plays a principal role in setting the major directions of the scientific programs of the Institute. Eight new members joined the board at its annual meeting in March:

Kenneth J. Arrow is Joan Kenney Professor of Economics and Professor Operation Research at Stanford University and a Senior Fellow by Courtesy of the Hoover Institution of War, Revolution and Peace. He is a Nobel Laureate, Member and former Chairman, American Academy of Arts and Sciences, a Member of the American Philosophical Society and Fellow of the Institute of Mathematical Statistics, and the American Association for the Advancement of Science. He is a Distinguished Fellow and Past President of the American Economic Association and recipient of the von Neumann Prize.

Albert M. Clogston is a Senior Fellow and former Chairman of the Los Alamos National Laboratory, Center for Materials Science. He is a Fellow of American Physical Society, Fellow of American Association for the Advancement of Science, Member of National Academy of Sciences, former Executive Director of Research of Bell Laboratories and former Vice President of Research, Sandia Laboratories.

Harold J. Morowitz is Professor, Department of Biophysics and Biochemistry, Yale University. He is a Consultant to the Closed Ecosystems Study Group, NASA, and Charter Member of The Biophysical Society and Member, American Institute of Biological Sciences. Dr. Morowitz is a Correspondent to Comment on Molecular and Cellular Biophysics and former Chairman of the National Academy of Sciences Committee of Models for Biomedical Research.

David E. Rumelhart is Professor, Department of Psychology, Stanford University. He was recently named a MacArthur Prize Fellow. Prof. Rumelhard is a Member of the Board of Governors of the Cognitive

Science Society, and a Member of Journal Editorial Boards for *Cognitive Science, Discourse Processes: A Multidisciplinary Journal* and the Harvard University Press Series in Cognitive Science.

J. Robert Schrieffer is Director of the Institute of Theoretical Physics at the University of California, Santa Barbara. He is a Member of the American Physical Society and the National Academy of Science. A Nobel laureate, Dr. Schrieffer is a recipient of the Comstock Prize from the National Academy of Sciences and of the National Medal of Science. He is the author of *Theory of Superconductivity*.

Marlan O. Scully is Head of the Theory Division of the Max Planck Institute fur Quantenoptik and Distinguished Professor of Physics and Director of the Center for Advanced Studies at the University of New Mexico. Dr. Scully is an Adjunct Professor at the University of Colorado and the Italian Institute of Optics. He is a Fellow of the American Association for the Advancement of Science and the American Physical Society and Member of the Max Planck Society.

Harry L. Swinney is Trull Centennial Professor and Director, Center for Nonlinear Dynamics at the University of Texas at Austin. Former Editor of *Hydrodynamic Instabilities and the Transition of Turbulence* and Guggenheim Fellow (1983), he is Halliburton Distinguished Lecturer at Texas Technical University, Peyton Nalle Rhodes Lecturer at Rhodes College, Fellow of the American Physical Society, Member of the Advisory Board for the Warwick Nonlinear Systems Laboratory, Member of the External Advisory Board, Center for Interdisciplinary Complex Systems, and Member of the American Association of Physics Teachers.

Stephen Wolfram is Director, Center for Complex Systems Research and Professor of Physics, Mathematics, and Computer Science, University of Illinois at Urbana-Champaign. He is also Consultant to Los Alamos National Laboratory and Thinking Machines Corporation. A MacArthur Prize Fellow, 1981-86, he is former Director and Co-founder of Computer Mathematics Corporation and Founding Editor of the jounral *Complex Systems*. Prof. Wolfram is a Member of the Editorial Boards of the Journal of Statistical Physics, Advances in Applied Mathematics, and Journal of Complexity.

THE REGIONAL COUNCIL

As part of SFI's Science Board, the Institute has formed a Regional Council to help in proposing and implementing joint programs, to recommend adjunct faculty and Visiting Fellows, to coordinate summer/winter school activities and mutually supportive research, and to assist the SFI in operating research networks.

The Regional Council consists initially of representatives from the Los Alamos National Laboratory,

(continued)

SFI Vice President Divides Sabbatical Leave

SFI's Vice President, L. M. Simmons, Jr., an Associate Division Leader for Research, Theoretical Division, Los Alamos National Laboratory, is on sabbatical leave until next June. He will divide his time between administrative functions and initiating research in complex systems at SFI and continuing his research on new methods in field theory at the University of Arizona. Mike also will spend some time this summer in Aspen, where he serves as President of the Aspen Center for Physics.

Visiting Fellows Program

The Institute is pleased to announce the September, 1987, residency of six Visiting Fellows--Prof. Philip W. Anderson, Prof. Kenneth J. Arrow, Prof. W. Brian Arthur, Prof. John H. Holland, Prof. Stuart Kauffman, and Prof. David Pines. The Visiting Fellows Program brings to Santa Fe scientists currently pursuing advanced research in complex systems. Fellowships vary from one to twelve months, and include a living allowance, office space, research support, and stipend.

PHILIP W. ANDERSON is Joseph Henry Professor of Physics at Princeton University. Professor Anderson received the Nobel Prize for Physics in 1977 and the National Medal of Science in 1983. He is a member of the National Academy of Sciences, a Fellow of the American Academy of Arts and Sciences, Vice Chair of the Board of Advisors of the Santa Fe Institute, and past Chairman of the Board of Trustees of the Aspen Center for Physics.

KENNETH J. ARROW is Joan Kenney Professor of Economics and Professor of Operations Research at Stanford University. Winner of the Nobel Prize in Economic Science in 1972, Prof. Arrow is a Member of the National Academy of Sciences and the American Philosophical Society, and a Fellow of the American Academy of Arts and Sciences. He is the author of many articles and books including *The Limits of Organization* (1974) and *Studies in Resource Allocation Processes* (1977).

W. BRIAN ARTHUR is Morrison Professor of Population Studies and Economics at Stanford University. A 1987 Guggenheim Fellow, he is a Member of the International Union for the Scientific Study of Population and the American Economic Association. His research interests include non-linear systems, non-convex economics, economics of technology, and mathematical demography.

JOHN H. HOLLAND is Professor of Computer Science and Engineering at the University of Michigan with special research interests in theory of adaptive systems, advanced computer architectures, and cognitive processes.

STUART KAUFFMAN is Professor of Biochemistry and Biophysics, University of Pennsylvania. In addition to his involvement with the American Cancer Society Study Section, Cell and Developmental Biology, and International Society for the Study of the Origin of Life, he is Co-Chief Editor of *Journal for Theoretical Biology*, aMember of the Editorial Board of Quarterly Review of Biology, Journal of Mathematical Biology, a Member of N.I.H. Ad Hoc Study Section, Systems and Integrative Biology Training Grants, and a Member of Society of Developmental Biology. Prof. Kauffman recently became a MacArthur Prize Fellow.

DAVID PINES is Professor of Physics and in the Center for Advanced Study at the University of Illinois at Urbana-Champaign. He received the Eugene Feenberg Memorial Medal for Contributions to Many Body Theory in 1985, the P.A.M. Dirac Silver Medal for the Advancement of Theoretical Physics in 1984, and the Fremann Prize in Condensed Matter Physics, 1983. Editor of *Frontiers in Physics* and *Reviews of Modern Physics*, Dr. Pines is a Fellow of the American Association for Advancement of Science, and the American Association for Advancement of Science, and a Member of the National Academy of Sciences.

Board News *(continued)*

Sandia National Laboratories, the University of New Mexico, the University of Arizona, the National Center for Atmospheric Research, and the University of Texas. Additional representatives will be appointed as the need arises. Members include L.M. Simmons, D. Campbell, and A. Clogston, all of LANL, V. Narayanamurti of Sandia, M. Scully of University of New Mexico, P. Carruthers of the U. of Arizona, S. Schneider of NCAR, and H. Swinney of the U. of Texas. It is expected that representatives from the University of Colorado and University of Utah will join the Council soon. The Council will meet regularly to propose and review interactive research programs and people.

At a later time, the Institute will take steps to form an International Council, consisting of individuals at selected foreign research institutions who have demonstrated interest in establishing and implementing interactive programs of research on complex systems at their home institutions and the SFI.

Kauffman and Rumelhart Named MacArthur Prize Fellows

Two members of the SFI Science Board, Stuart A. Kauffman and David E. Rumelhart, have been selected as 1987 MacArthur Prize Fellows. This prestigious, unsolicited award is made by the Catherine R. and John D. MacArthur Foundation to reward highly talented individuals working in a wide variety of fields in the arts, humanities, and sciences. The awards recognize Prof. Kauffmann's work in biology and Prof. Rumelhart's contribution to the field of experimental psychology. SFI joins their colleagues in offering enthusiastic congratulations.

1987 Sources of Support

The Santa Fe Institute is most grateful to the following organizations for their support of our 1987 Summer Workshop Program:

- Citicorp and Russell Sage Foundation for the Global Economy Workshop
- U.S. Department of Energy for the Theoretical Immunology Workshop
- National Institutes of Health, Alfred P. Sloan Foundation, and U.S. Department of Energy for the Matrix of Biological Knowledge Workshop

SFI is pleased to announce the award of two unrestricted grants for a three-year period, one from the Richard Lounsbery Foundation and the other from the H. J. Heinz Company Foundation. These grants will be applied to general operations. SFI is thankful also for the unrestricted support received from Science Applications International Corporation (SAIC) and from Addison-Wesley Publishing Company.

SFI has submitted a major unsolicited proposal to the National Science Foundation (NSF). Initially, SFI is seeking $1 million annually to support SFI's research program on complex systems. Any grant received from NSF will have to be matched on a one-to-one basis from corporate, foundation and individual sources. The SFI proposal is in the process of peer review, and a response from NSF is expected soon.

Thanks to our Donors

The Santa Fe Institute wishes to express its gratitude to all those who have made donations during the first half of 1987:

Philip W. Anderson, Princeton
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Charles Tyng, Denver
D. William Wagner, Los Angeles
Christopher Wright, Washington, D.C.

A very special thanks to Françoise Ulam for her generosity. In addition to donating the library of her late husband to the Institute, she translated a technical paper from French to English for the upcoming reprint of *Emerging Syntheses in Science*.

SFI wants to express its thanks to the many individuals who have made contributions to SFI so far this year. Individual support is critical to the general operation of the Institute, and SFI welcomes charitable donations of all kinds.

Technical Library Established at SFI

The Institute recently added a technical library of over 1,000 volumes. Françoise Ulam has donated the library of her late husband, Stanislaw Ulam, to SFI. This donation begins an aggressive book acquisition program at SFI, and will serve as the core for expansion as program activities require technical information on-site. SFI has begun subscriptions to several scientific journals and has received a donation from Dr. Nicholas Metropolis of issues of *Physics Today* and *Mosaic*, plus volumes of *The Annual Review of Nuclear Science*. SFI encourages donations in the expansion of its library as our need for information resources increases.

SFI ACTIVITIES
Summer-Fall 1987

July 13 to August 14	**"Matrix of Biological Knowledge" Workshop**
July 22	**"Biology in the Computer Age," a public lecture by Harold J. Morowitz, Department of Biochemistry and Biophysics, Yale University**
September 9 to 18	**"Evolutionary Paths of the Global Economy" Workshop**
September 19	**Science Board Meeting**
September 27 to October 2	**"Computational Approaches to Evolutionary Biology" Workshop**

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