Santa Fe
Institute

1991 Annual Report on Scientific Programs

A Broad Research Program on the Sciences of Complexity

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1. INTRODUCTION

1.1 Current Research

1991 saw continued rapid growth for the Santa Fe Institute (SFI) as it broadened its interdisciplinary research into the organization, evolution and operation of complex systems and sought deeply the principles underlying their dynamic behavior. Much of this work was led by SFI's External Faculty members, eminent scholars from more then twenty institutions. They were joined by more than one hundred short-term visitors—in Santa Fe for periods ranging from a week to several months—attracted by the Institute's meetings, working groups, and research family. To date these 1991 collaborations and workshops have resulted in nearly 50 SFI working papers, 3 volumes in the Institute's series on the sciences of complexity, and nearly 150 other publications in the scientific literature. A dozen conferences during the year fueled the ongoing work of numerous SFI "research networks." The annual Complex Systems Summer School, the only one of its kind in the nation and now in its fourth year, brought nearly sixty graduate students and postdoctoral fellows to Santa Fe for an intensive introduction to the field. On a related front, the Institute sought to strengthen its ties with university communities, forging an innovative research exchange program with the University of Michigan. It intends to extend this effort to other campuses.

Research on complex systems—the focus of work at SFI—involves an extraordinary range of topics normally studied in seemingly disparate fields. Natural systems displaying complex behavior range upwards from proteins and DNA through cells and evolutionary systems to human societies. Research models exhibiting complexity include coupled nonlinear equations, spin glasses, cellular automata, genetic algorithms, classifier systems, and an array of other computational models. Some of the major questions facing complex systems researchers are: (1) explaining how complexity arises from the nonlinear interaction of simple components; (2) describing the mechanisms underlying high-level aggregate behavior of complex systems (such as the overt behavior of an organism, the flow of energy in an ecology, the GNP of an economy), and (3) creating a theoretical framework to enable predictions about the likely behavior of such systems in various conditions. The importance of understanding such systems is enormous: many of the most serious challenges facing humanity—e.g., environmental sustainability, economic stability, the control of disease—as well as many of the hardest scientific questions—e.g., protein folding, the distinction between self and non-self in the immune system, the nature of intelligence, the origin of life—require a deep understanding of complex systems.

The capacity to learn and to adapt is common to many systems on the SFI research agenda. Complex adaptive systems typically are composed of a very large number of interacting "microscopic" components whose dynamic behavior is highly nonlinear and generally displays emergent "macroscopic" features. For an appropriately rich set of interactions, the system may be seen to adapt in response to either a specified set of external conditions or, more interestingly, in response to internally generated forces.

The Institute is founded on the premise that there are common principles that determine this behavior. Among the important characteristics of complex systems is nonlinearity; therefore, they cannot be studied successfully by examining the components separately and combining the results to form a picture of the whole. Instead, it is necessary to examine the whole system, even if the examination is very general or only approximate, and then to search for the emergence of possible simplifications from the larger structure. Consequently, effective research in this field must combine both a broad, general approach and the depth and expertise that is found in individual disciplines. SFI's program thus includes specialized studies of parts of complex systems falling within existing disciplines; overarching studies that attempt to define the connections between the important, interdependent parts of complex systems; and integrative studies that describe the shared features of complex systems. In fact, the Institute relies to a great extent on existing academic research for the disciplinary components. It brings together groups of researchers from the universities and focuses primarily on those interdisciplinary aspects which are most difficult to pursue within a conventional academic enterprise. This approach to complex systems is a prerequisite for understanding both their common features, which can help define the principles of a general science of complexity, and for comprehending the enormous diversity of "adequate" solutions encountered in the real world.

The current program at SFI is devoted to the study of the fundamental concepts and shared features of complexity and adaptation and to exploring their presentation in four, broad, interconnected research areas: adaptive computation, patterns in information, biological systems, and economic and social systems. Within each of these domains common concerns—adaptation, learning, evolution, modelling—emerge again and again; in the descriptions below, these recurring subtopics frequently offer a natural organizational structure for describing the work in each field. One anticipates that as SFI's research effort matures, these common themes may subsume even the very general disciplinary categorization within SFI's programs.

The search for fundamental concepts and common features in complexity and adaptation is a rapidly growing field of theoretical science. Traditionally, theorists have made a virtue of simplicity, choosing simple, exactly soluble models for system behavior. However, the nonlinear interactions characteristic of complex adaptive systems render exact solutions impossible even for low-dimensional systems, as we know from studies of their chaotic behavior. Moreover, ergodic behavior is not found for complex adaptive systems; rather, the norm is non-ergodic behavior of the kind associated with the dynamic exploration of rugged energy landscapes in spin glasses. In addition, complex adaptive systems typically explore new states that cannot be represented by the "fixed" state space typical of both classical and quantum traditional statistical physics. Non-ergodicity and the exploration of open state spaces lead naturally to emergent structures, both static and dynamic. Within this description remain many deep questions about the character and mechanisms of complexity. Is there a defining characteristic of complexity? What are its appropriate measures? What constitutes an adequate model of a complex adaptive system? Examples of other central issues are transitions to complexity and the acquisition of information and modes of transmission within complex systems. SFI addresses these and other topics within its integrative core research effort, its largest single block of programs.

As complex systems research progresses, the need for increasingly powerful and sophisticated computational systems becomes ever more critical. What is required are methods that naturally take advantage of parallel processing, in which appropriate complex behavior emerges from the interaction of simple parts rather than being laboriously preprogrammed, methods that can efficiently search through large amounts of data, that have sophisticated pattern-recognition abilities, and that automatically improve their performance over time, that is, computational processes that adapt or learn from experience. Examples are neural networks, genetic algorithms, immune networks, and simulated annealing. These computational methods have been inspired by, and in turn can be used to model, natural adaptive systems such as the brain, the immune systems, or the processes of biological evolution. The SFI research initiative in adaptive computation thus focuses both on developing techniques to solve difficult practical problems and on using those same techniques as scientific tools to model natural systems. This interaction can also provide insight into general principles of adaptive information processing as it exists in both natural systems and in adaptive computer programs.

Very closely intertwined with its core program and adaptive computation initiative is the Institute's research into patterns in information. Work here spans a broad interdisciplinary group of topics, but they are generally motivated by the limitations imposed by physical laws on computational performance and by the consequences of the laws of computation for natural science. Projects include the development of dynamical-systems-based techniques for time-series forecasting as well as the examination of the role of information in the thermodynamics of complex systems.

The biological world is so complicated that comprehensive, global theories are difficult to validate, but a complex adaptive systems approach clearly captures features that were inaccessible using previous methods and models. Such an approach promises a means of addressing the current lack of theoretical underpinnings for an enormous array of experimental results and discoveries. For example, recent work with adaptive network models for the immune system—much of it done at SFI—is already yielding results that compare well with experimental data. Indeed, these models have become the accepted paradigm in theoretical immunology. Researchers at SFI are hopeful that other critical issues in biology ranging from genetic sequence data analysis to coevolution in adaptive biological systems will yield further theoretical insights as a result of a complex systems approach.

Economics received substantial early attention at SFI, and the program continues as a vital part of the Institute's research agenda. Common to many of the projects within this initiative is a view of the economy as an adaptive, evolving system in which economic agents learn in a highly interactive market. Underlying this approach is the relaxation of three key assumptions of standard economics: that agents are capable of perfect rationality; that expansion of economic activities is subject to constant or diminishing returns; and that trading takes place only in equilibrium. SFI researchers assume instead that rationality is bounded but that agents are capable of improving their decisions and adapting to their environment; that increasing returns or positive feedbacks may be present so that problems become non-convex and their dynamics nonlinear; and that trading outside equilibrium can in many cases be well defined. Many varieties of complex adaptive systems models have been developed at SFI and theoretical progress has been intimately coupled with model simulation. These models often embody a synthesis of economics ideas and computational methods from the theory of learning algorithms. Current work spans such topics as information "contagion" as a factor in consumer choices, the emergence of complex behavior in simple stock markets, self-organized criticality in economic systems, coevolution of strategic behavior in games, and forecasting techniques.

Since SFI's start, there has been a persistent attempt to extend the analytic tools being developed into the broad range of social systems. Among them have been studies of the evolution of human language and models of international security, and a series of programs focused on historical cultural evolution in the Southwest. Currently a joint project with the University of Michigan led by SFI External Professor J. Holland is aimed at developing a policy-makers' tool kit through collaborations involving Michigan faculty, generally from the social sciences, and SFI members, who bring expertise in computational modelling.

1.2 Organizational Structure

The Institute provides an exceptionally effective and flexible option for pursuing studies in the sciences of complexity. Like the topics explored, the research structure at SFI tends to be "self-organizing." Project formats emerge from collaborations among the researchers, and one of the primary attractions of SFI is that these collaborations occur and change easily. This is not a result of any formal requirement, but simply a response to the broad challenges presented by problems in complexity. Although, for the purposes of this document, SFI's work is described within the context of broad categories, most projects are highly interdisciplinary. Throughout this report, researchers' names appear repeatedly; workers are listed more than once in association with a variety of different projects.

SFI has no permanent residential faculty. A small core of local scholars, together with a much larger number of invited visiting scholars, comprise the External Faculty of the Institute. These researchers—about thirty-five people from institutions throughout the U.S. and Europe—agree to spend at least one month per year at SFI where they work on a varied program of mutually supportive research. Visits may be organized around workshops or working groups or, less formally, around time when one or two colleagues will be in residence to work on a problem of mutual interest. In addition there are typically more than one hundred short-term visitors each year, researchers who ultimately become part of the global "research networks" that enable collaborations started at SFI to continue after people leave. SFI also has a small number of postdoctoral fellows in residence at all times. This flow of scholars through SFI enables loosely organized research groups to form and reform as topics evolve, enabling participants to remain active in collaborations after they return to their home institutions and ultimately influencing the course of research and education on academic campuses.

Within the context of its mutable research interests, the Institute does have a typical, if informal, process for engendering and organizing program initiatives. Ideas for full-scale new projects are typically discussed with the President, the Vice President for Academic Affairs, or a member of the Science Board, the SFI body which oversees the overall direction of the research program. After a project has been approved, normally a steering committee of experts from different fields will be appointed to guide the development of the program. One or more workshops composed of experts drawn from relevant fields is held to discuss the appropriate parameters of the program, to stimulate new research collaborations, and to foster networks. SFI supports such networks both directly and indirectly by providing funds and facilities for meetings, acting as a clearinghouse for information, and providing administrative support. Finally, in some cases, research networks will result in the emergence of a residential research program at SFI.

The Institute's broad categories of research described below thus capture work going on simultaneously in a variety of formats: it proceeds both on and off the SFI campus and includes individual projects, collaborations, research networks, and workshops and symposia.

As mentioned, the overall directions of research, and suggestions about who will be invited to participate, are guided by a fifty-person Science Board. The Science Board is responsible for assuring that the appropriate mix of programs is maintained, that the central themes of "complexity" continue to guide the programs, and that the core program remains robust and able to inject new ideas into collaborations and new directions. The Science Board meets once a year to review the current research program, to discuss new programs, and to recommend appointments to the External Faculty. Its Steering Committee meets 2 to 3 times per year to keep the general work of the Board going. A group of local External Faculty and Science Board members meets regularly to advise the Vice President for Academic Affairs on specific research visits and policy questions. Two programs (Economics and Adaptive Computation) have their own oversight boards that serve similar purposes at a more specific level.

2. THE INTEGRATIVE CORE RESEARCH PROGRAM

The Institute's largest single program is designated as "integrative core research." As an incubator for new initiatives and a home for researchers not committed to one of the programs, it captures the work of most of the full-time postdoctoral fellows, who usually collaborate on several different research projects. The program also includes SFI's most broad-ranging research into the principles that characterize the behavior of complex systems. Finally, it encompasses explicitly integrative projects that seek to describe the shared features of complex systems.

2.1 Incubation

The presence of the core initiative assures that SFI maintains a reservoir of first-class researchers broadly interested in complex adaptive systems and that there are always exploratory projects underway. As such the program is a hothouse for new ideas, and the most visible manifestation of that activity can be found in the steady stream of colloquia, seminars, and informal presentations that occur every week. At least three such series take place regularly. The Institute's *Seminars on Complex Adaptive Systems* provide an informal forum in which those associated with the research programs—from senior scientist to undergraduate intern—can discuss in wide-ranging fashion the various manifestations of complexity and adaptation and seek a deeper understanding of these phenomena. The *"Introductory"* series, organized by Postdoctoral Fellow Cris Moore, calls upon a researcher each week to present to his SFI colleagues an overview of his current work—e.g., the mammalian visual system, the theory of money, game theory, the dynamics of HIV infection—at an introductory level. Friday afternoon colloquia usually feature a relatively technical presentation on current research by one of the Institute's many visitors. (A listing of these colloquia is contained in Appendix III). Several informal working groups also meet regularly. The Institute also hosts a variety of workshops. Residential members of the SFI research community have an open invitation to audit meetings and frequently become major contributors.

To the same end of encouraging new ideas, the Institute's administrative policies aim to create an open research environment dominated by a multidisciplinary and multigenerational approach. Planned collaborative meetings aside, research visits are clustered in time to provide optimal windows for interaction and possible collaboration. Prior to their residency, visiting researchers inform SFI as to their anticipated work, and this information is made available to the research community. Office assignments consciously juxtapose research interests and mix disciplines.

2.2 General Concepts of Complexity

2.2.1 Models for Adaptation

Dynamical Systems with Discrete Degrees of Freedom

SFI Postdoctoral Fellow Mats Nordahl's wide-ranging collaborations provide a particularly apt illustration of the "incubative" nature of the research environment at SFI. His work focuses on the relation between computation-theoretical and statistical (physical) properties of systems with discrete degrees of freedom. Such systems provide a well-established laboratory for exploring some fundamental theoretical, computational, and physical properties of complex systems. In 1991 he worked on:

Models of Coevolution: Understanding evolutionary processes requires understanding the dynamics of many simultaneously evolving species. In previous work Nordahl has constructed a class of coevolutionary models with stochastically determined interactions (e.g., random or spin-glass-like) between a variable number of species. The fitness landscape for a species is then a function of all other species present, in contrast to models of evolution in a fixed fitness landscape. Mutations capable of changing the genome length make the space searched in the evolutionary process potentially infinite-dimensional. This model suggests that the interesting dynamic phenomena—e.g., periods of stasis separated by periods of rapid evolutionary change, apparent power law distribution of extinction events—found in a particular model based on the Prisoner's Dilemma (Lindgren, in SISOC PV X) are, in fact, characteristic of a large class of models and, thus, possibly of relevance to biology. In recent work, the evolution of hierarchical food webs and cooperative structures in related models has been studied. Together with K. Lindgren, he has also investigated evolutionary models with spatial degrees of freedom and game theoretic models where the game itself is determined through evolutionary mechanisms. Studies of coevolution may also lead to improved methods for problem solving, an area which is almost completely unexplored (one of very few exceptions is the work by Hillis, in SISOC PV X). They are presently exploring versions of genetic algorithms where the genetic operators coevolve with the problem instances.

Spreading Rates and Lyapunov Exponents for Spatially Extended Systems: The concept of spreading rate of a perturbation has recently been used extensively in numerical investigations of systems such as spin glasses, using Ising models and other spin systems, random Boolean networks, and cellular automata. In recent work (Nordahl, 1991) he has developed an analytic approximation scheme for one-dimensional systems where spreading rates are calculated in mean field theory for symbol blocks of some finite length. These methods are equally applicable to deterministic and stochastic systems. Nordahl has applied them, e.g., to probabilistic cellular automata, in particular to calculate the phase diagram of the Domany-Kinzel cellular automaton, where a new phase characterized by a non-zero spreading rate is observed.

Transient Behavior in Spatially Extended Systems: Together with W. Li (SFI and Rockefeller) (and also J. Theiler [LANL]) he has begun a program to classify spatially extended dynamical systems according to their transient behavior. A first report (Li and Nordahl, 1992) contains a study of a particular cellular automaton rule (rule 110), where non-trivial power law scaling is observed, e.g., for average transient times on finite lattices. More general analytic results have been obtained for simpler regimes where transient times are logarithmic. Recently, they have also investigated the chaotic repellers found in some cellular automata and their relation to the transient behavior.

Geometrical Aspects of Computation Theory: A computation-theoretic classification of patterns in higher dimensions would be useful for describing the dynamics of cellular automata in more than one dimension, and for a possible symbolic dynamics of spatially extended dynamical systems. Some work on such analogies of formal languages has been done in computer science and pattern recognition, but the theory is far less developed than conventional formal language theory. To characterize finite time sets of cellular automata, he has studied generalizations of regular languages to two dimensions (with Cris Moore [Cornell, now SFI postdoctoral fellow], and also Kristian Lindgren [Göteborg]). Some inequivalent generalizations were previously known; however, for finite time sets of cellular automata, it turns out that one needs to introduce a new and more general class of languages—homomorphisms of finite complement languages. Together with previously known generalizations (which form subsets of this language class), a hierarchy of two-dimensional regular languages is obtained.

He has also investigated more complex classes of two-dimensional languages (context-free and higher) and the undecidability issues involved in extensions to infinite configurations. This work has a number of possible physical applications: it applies directly to the ground states of classical spin systems, and one can give various structural criteria for the (non-)validity of the third law of thermodynamics. This work is also relevant to ergodic theory; the language class mentioned above gives rise to two-dimensional subshifts analogous to Sofic systems in one dimension.

Statistical Mechanics of Random Dynamical Systems: Networks of randomly chosen Boolean functions were first studied by Kauffman as models of gene regulation. When the number of function inputs is suitably chosen, there is evidence that biological scaling relations such as the number of cell types (corresponding to attractors of the network) as a function of the number of genes in an organism can be reproduced. With W. Li and C. Langton, an extensive numerical investigation of the properties of this model has been initiated. In the limit when all functions are connected to each other, the Kauffman model corresponds to random maps of a finite set. The statistical properties of random maps (or random permutations) have been extensively studied by mathematicians and, more recently, by physicists. He has introduced a spectrum of new models by defining probability distributions in terms of Hamiltonians on the space of mappings of a finite set. In this way a number of interesting phenomena can be generated, such as phase transitions between various forms of scaling behavior for average transients and periods. These have been investigated by combining techniques from dynamical systems and statistical mechanics.

Reversible Cellular Automata and Physical Modelling: Reversible cellular automata provide simple model systems where the emergence of thermodynamic behavior from microscopic dynamics can be studied. With K.-E. Eriksson and K. Lindgren, Nordahl has shown that for discrete reversible systems, not only is microscopic entropy globally conserved, it can, furthermore, be viewed as the spatial average of a localized quantity obeying a continuity equation. This proves and extends a conjecture due to Toffoli for small perturbations around lattice gas equilibria.

Turbulence: In collaboration with Valerij Zimin (Houston), Peter Frick (Perm), and Erik Aurell (Stockholm), a project to develop a Connection Machine implementation of the hierarchical turbulence model constructed by the Perm group (essentially a wavelet transform approach to the Navier-Stokes equations) has been initiated. This approach might provide new numerical methods for the Navier-Stokes equations more in tune with the hierarchical structure of the turbulent medium. The project includes computer implementations, but also additional theoretical developments, e.g., to handle various boundary conditions.

Neural Networks—evolutionary approaches: In collaboration with K. Lindgren and two students from Göteborg (Ingrid Råde and Anders Nilsson were at SFI as Science Board Fellows during the fall of 1991), evolutionary approaches to neural network design have been studied (Lingren et al., 1992). The work focuses on evolutionary methods where networks are allowed to add and delete nodes in the course of evolution, in contrast to standard genetic algorithms where in most cases representations in terms of fixed-length symbol strings are considered. This allows for successive refinements of a solution to a problem. Evolutionary methods might, in particular, prove important for recurrent networks, where traditional learning algorithms are less useful. These methods have been applied to regular language inference, and they have also studied more complex problem domains provided by various games (in particular Go on a sequence of boards of increasing size). A separate issue raised by these investigations is that of choosing suitable test problems for learning algorithms, genetic algorithms, etc. Here they have started to develop an approach where fundamental information-theoretic quantities (such as observables quantifying the amount of correlations present) are systematically varied.

A principal theme of the research of SFI Postdoctoral Fellow Wentian Li has also been the study of dynamical systems with many degrees of freedom, especially the fully discretized dynamical systems called cellular automata, and the application of the concepts of bifurcation and phase transition to the study of the global structure of the rule space with all possible dynamics. This global study of all possible higher-dimensional systems, or the study of the structure of the rule spaces, turns out to be closely related to the study of phase transitions in statistical physics and bifurcation phenomena in lower-dimensional dynamical systems. SFI External Faculty member Norman Packard (U. Illinois) and Chris Langton (LANL) have studied the same problem.

The main idea behind these studies is that a change in the dynamics rule sometimes changes the actual behavior of the system, and sometimes does not. This is similar to the case when increasing the temperature may or may not melt a piece of ice. When it does, the melting temperature, or critical temperature, has been reached. In the well-known logistic map, a one-dimensional dynamical system, tuning the nonlinear parameter may or may not change the basic feature of the dynamics, but when it does (such as a change from a fixed-point dynamics to a two-cycle one), we say that the map is at a bifurcation point. In these examples, there is a tendency toward a global chaotic state as some parameter is maximized (e.g., ice to water, then to vapor, as the temperature becomes high; fixed-point to two-cycle to four-cycle, and so on; and to chaotic dynamics as the nonlinear parameter in the logistic map is increased). It is in contrast to rule spaces with "rugged landscapes" in which any global tendency, if one exists, is hidden in the constant transitions between one behavior and another. A good example is the space of RNA molecules, where it is difficult to identify the two "extreme" phenotypes analogous to the fixed-point and global chaotic dynamics located at the two ends of the space.

In cellular automata rule space, there are many parameters to tune (not only is the dynamical system high-dimensional, the rule space is also high-dimensional because each rule needs many parameters to characterize it). Langton first used the λ parameter (the proportion of zeros in the rule) to control the transition to chaos. It is not surprising, however, that a single parameter cannot completely characterize the transitions in a space with many dimensions. One of the challenges in the study of cellular automata rule spaces is to find a minimum number of parameters that can accurately locate the transition surface.

Li has also used the Z parameter (due to SFI Member Wuensche) to study cellular automata rule spaces. This parameter roughly measures the stability of a cellular automaton rule table. For two-symbol, nearest-neighbor cellular automata, there are two Z parameters besides one λ parameter. It seems that the incorporation of two more parameters still cannot characterize the dynamical behavior completely, but it at least solves the puzzle of why some fixed-point rules (e.g., the identity rule) have the same λ value as many chaotic rules.

Finally, Li has studied parameterizations of the cellular automata rule space by "mean-field parameters." For two-symbol, nearest-neighbor cellular automata, there are four mean-field parameters. These provide an improvement over the characterization by the single λ parameter. Mean-field parameters provide an almost perfect characterization of the rule space for non-local cellular automata (i.e., cellular automata with non-local connections).

Space Structures in High-Dimensional Systems

External Associate Professor James Crutchfield (UC Berkeley) conducted research on state-space structures in high-dimensional systems during a two-month visit to SFI in the first quarter of 1991. One goal in this general area is the extension of the basic constructs of qualitative dynamics (attractors, basins, and separatrices) to spatial systems. Once identified these can be used to investigate the geometry of high-dimensional systems and also to infer the types of intrinsic computation embedded in their behavior. "The Attractor-Basin Portrait of a Cellular Automaton" (Hanson and Crutchfield, SFI 91-02-012) was completed and submitted to the *Journal of Statistical Physics*. Much time also was spent writing a survey, "Transients in High Dimensions" (Crutchfield and Kaneko, 1991). The premise of this project is that, in spatial systems, transients dominate (i) the short- to intermediate-time behavior, (ii) the underlying state-space geometry, and (iii) the nature of the embedded computation. In this transients are distinguished from the traditional focus on invariant sets and attractors.

In related research, extending classical work on statistical methods for Markov chains to stochastic automata and employing the more modern theory of large deviations, Crutchfield has developed a "thermodynamic" description of finitary stochastic automata. This gives an improved (and implementable) analysis of the structure of invariant sets for such processes and suggests new quantifiers for Bayesian model learning. This work provides a direct connection between his approach to physical complexity, what he calls computational mechanics, and the "thermodynamic formalism" and work on multifractals found in the dynamical systems literature. The results are reviewed in "Machine Spectroscopy" (Crutchfield and Young, 1992).

The winter 1991 stay was Crutchfield's first visit to SFI as an External Associate Professor. The new relationship provided the opportunity to work toward a longer term association to facilitate projects in computational mechanics. The goal over the next year is to obtain a major source of funding for projects at SFI related to the qualitative dynamics of and intrinsic computation in spatial systems. Initially the thrust will be the analysis of cellular automata, both the state space structure of individual rules and the structure of CA rule space. The approach is to integrate computational mechanics with (i) the algebraic methods developed by Erica Jen (SFI and LANL) that give a very detailed picture of CA state space and (ii) the simulation approach of Chris Langton (SFI and LANL) to characterizing the "macroscopic" structure of CA rule space. One focus is to identify and analyze those CA structures supporting useful computation. The project complements SFI's efforts in nonlinear modeling and the physics of information and complexity.

Random Grammars

In the past fifteen months SFI External Professor Stuart Kauffman has begun exploring a new intellectual world characterized by what he calls "Random Grammars, A New Class of Models of Functional Integration and Transformation."

Consider a finite alphabet, say, 0 and 1, and the set of all possible finite-length sequences of these letters. Any such sequence is a symbol string. An "input bundle," a "machine," and an "output bundle" are each defined to be a finite ordered set of symbol strings. Input bundles, machines, and output bundles are drawn from the power set of finite symbol strings acting upon itself into or onto itself. Kauffman uses the term "a Grammar" to refer to one specific mapping of this power set acting on itself into itself. The set of all possible mappings of the power set of strings acting upon itself into itself is non-denumerably infinite. The class of all effectively computable functions over this finite alphabet is a denumerably infinite subset. Any single grammar can be thought of as an example of the "Laws of Chemistry" for the interactions of symbol strings in the computational world created on a computer.

Such symbol string interactions give rise to new classes of objects (Kauffman, in SISOC LV III). Some bear faint echoes in computer science. A "jet" is a set of symbol strings emerging from a sustained founder set of strings, having the property that, as the strings interact, only new types of symbol strings are generated. For example, string interaction may always yield product strings longer than input strings. ("Splinters," a topic in logic and computer science, are subsets of jets.) A "mushroom" is a set of symbol strings springing from a maintained "food set" of symbol strings, where the mushroom has the property of making old strings by new pathways. Kauffman's autocatalytic polymer sets are examples of mushrooms.

Jets or mushrooms may be finite or infinite. Finite systems have the property that, as strings act on strings, only a finite number of kinds of strings can be formed from a given food set. Alternatively, as the "grammar" mapping of the power set of strings acting on itself into itself iterates, the diversity of strings produced may increase without bound. Kauffman calls such systems "supracritical" in his autocatalytic polymer system article and, importantly, was able to characterize a phase transition from subcritical finite behavior to supracritical behavior as the complexity and diversity of the symbol strings in the system increases past a threshold. Supracritical systems may give rise to "filigreed fogs," consisting of infinitely many types of symbol strings but never forming certain specific symbol strings. Alternatively, a system may be a "pea soup," ultimately forming all possible symbol strings of any desired finite lengths. An intriguing object is an "egg," a set of symbol strings which collectively forms only itself. An egg is a collective identity operator. Modified eggs might squirt jets which might be finite or infinite.

Eggs, jets, mushrooms, and so forth appear to be new kinds of mathematical objects. Two forms of stability of such systems warrant study. First, the compositional stability of such sets can be investigated. Injection of a novel string into a finite egg might transform it into an infinite filigreed fog. Exchange of symbol strings between two finite jets might trigger a supracritical explosion in the more complex joint system. In addition, dynamical stability is open to investigation. An egg might regenerate itself in a dynamical steady state, along a limit cycle, or via chaotic dynamics.

Grammar models harbor old and new questions. Among the old questions, many issues of formal undecidability will arise. For example, whether a specific system from a specific food set is finite or infinite may be undecidable.

Development of a new statistical mechanics constitutes perhaps the most important approach to the study of the string world. Kauffman's aim is to explore the statistically robust properties of regions of "grammar space," each of which will constitute a "universality class." Kauffman uses the concept of a Universality class in the physicist's sense of a set of models exhibiting the same properties. Spin glasses are an example, as are his studies of ensembles of random Boolean network models of genomic systems (Kauffman, 1991). One averages over an ensemble of spin glass systems, or model genomes, each drawn at random from a defined ensemble, to find the statistically robust properties of members of this class.

Kauffman is exploring "grammar space" by creating mappings of increasing complexity from the power set of strings acting upon itself into itself. Such complexity can conveniently be quantified in terms of the number of input bundles, machines, and output bundles defined in the grammar, the complexity and diversity of symbol strings in bundles or machines, as well as by the diversity and complexity of symbol strings in sustained founder sets. He is investigating whether phase transitions occur between subcritical and supracritical behavior and among the kinds of compositional objects (jets, eggs, and so forth), as the complexity of the mapping and the complexity of the set of strings in initial or maintained "food founder set" is altered. He already has clear evidence of this: Simple systems are, in fact, subcritical. Beyond a threshold level of complexity of founder strings, the same grammar engenders supracritical explosion. The transition complexity in the founder set is sensitive to the complexity of the input bundles and machines in the grammar in ways requiring exploration.

Coevolution to the Edge of Chaos

For the past several years External Faculty members J. Crutchfield, Stuart Kauffman, C. Langton, J. Miller, N. Packard, and R. Palmer, together with P. Bak (Brookhaven), B. Derrida (Saclay) and SFI Postdoctoral Fellow W. Fontana, have explored the relationship between complex dynamics, computation, and evolution. C. Langton first noted that the space of cellular automaton rules, a particularly rich class of complex dynamical systems, could be classified into different behavior, ordered, complex, and chaotic, and that the three could be reached by parametrized movement in the space of rules, with the complex rules lying exactly in between the ordered ones and the chaotic ones, i.e., on the "edge of chaos." The transition as Langton's parameter is varied strongly resembles a phase transition. Langton hypothesized that the cellular automaton rules capable of computation should belong to the complex class, because only these rules can both store and transmit information for arbitrary times and over arbitrary distances simultaneously.

N. Packard then performed an evolutionary experiment in the space of cellular automata, in which the evolution was directed by a prespecified computational goal. The evolution in the space of rules took a random initial population toward a population that was concentrated on the edge of chaos. This result tended to confirm Langton's original hypothesis on evolution over the space of rules and indicated, moreover, that complex, computationally efficacious dynamics could be reached through an evolutionary process.

S. Kauffman and S. Johnson found similar evolutionary phenomena in a different class of systems, NK Boolean networks. These systems are analogous to cellular automata but with inhomogeneous rules and global couplings (with N total elements, each coupled to K others chosen at random).

In the past year Kauffman has seen hints of what may be a new universal in coevolving systems. Ecological systems of coevolving myopic agents and economic systems of optimally boundedly rational economic agents may coevolve to an analogue of the phase transition region which appears in Boolean networks. Systems at the edge of chaos typically exhibit a power law distribution of the frequency of some characteristic event (in Langton's work, for example, the distribution is in the length of non-periodic transients). Three lines of evidence suggest that ecosystems, like sand piles, may tune themselves through natural selection, as if by an invisible hand, to the edge of chaos. The first evidence derives from models of coevolving systems. If natural selection acting on the inclusive fitness of individual members of coevolving systems can adjust the ruggedness of their "fitness landscapes" and how richly intercoupled such landscapes are, then the set of coevolving entities attains the phase transition region. Here avalanches of coevolutionary change propagate through an ecosystem with a characteristic power law distribution (reminiscent of that encountered by Bak in self-organized criticality): many small avalanches, few large ones (Kauffman, in SISOC PV X). A second line of evidence concerns extinction events in the geological record. In biology, an avalanche of coevolutionary change transiently lowers fitness and would be expected to lead to extinction events. Is there a power law distribution of such events? Remarkably, the actual known distribution of sizes of extinction events in the Phanerozoic fits this same power law pattern. While there is evidence of a giant meteor for one of the large extinction events, the rest may be endogenously generated because ecosystems are, in fact, at the edge of chaos. The third bit of evidence comes from Tom Ray's Tierra synthetic life model. Ray, a Visiting Professor at SFI and an ecologist at the University of Delaware, has created an ecology of computer parasites in a computer core. These coevolve, create an ecology, and undergo speciation and extinction events. The distribution of extinction events in Ray's study exhibits a power law distribution. Ray and Kauffman plan to assess more fully whether these parasites are at the edge of chaos. If coevolution attains the edge of chaos in Ray's case, where selection is acting on individual myopic adaptive agents, then it may be that the same ideas will generalize to economic and other systems with boundedly rational optimizing agents. Coevolution to the edge of chaos, as if by an invisible hand, could emerge as a powerful unifying concept.

2.2.2 Scaling and Self-Organized Criticality

It is accepted in each of a wide variety of fields that phenomena often exhibit scaling behavior and scaling laws. The books of Mandelbrot have called attention to the existence of fractals in many phenomena in nature, especially land forms (such as coastlines), clouds, geological formations, etc., as well as in some human artifacts such as political boundaries. A fractal is a geometric object which exhibits a scaling law for the frequency of a characteristic geometrical scale; other scaling laws for other types of variables appear in diverse phenomena such as earthquakes, for which the scaling law in energy is $p(E) \propto dE/E^{1.2}$, and many types of electronic noise, where one often finds "1/f" noise $\propto 1/f^{1+a}$. Moreover, human activities often scale; there are well-known power laws for the population of cities, $dn(P) \propto dP/P$, and for the distribution of wealth W, $n(W) \propto dW/W^3$. Some rather unexpected phenomena show scaling: for instance, the power spectrum of classical music, noise in some neural circuits, and the height of stages of the Nile, all show "1/f" spectra. There is a suspicion that out to some distance, the distribution of matter in the universe may be fractal.

Scaling laws in physics have a long history but are mostly relatively trivial consequences of conservations; an exception was the ideas on turbulence of Kolmogorov and others, where scaling is seen as a response to the need to degrade energy fed in at large scales to dissipative processes operating at atomic scales. Another important exception came with the 1960–70 decade in which critical phenomena at thermal phase transitions became understood; it became clear that at a "critical point" non-trivial scaling laws operate and that the structure at criticality in, say, the percolation transition was essentially fractal. Bak, Tang, and Wiesenfeld combined these two concepts into the theory of "self-organized criticality," showing that in many types of systems, a disparity of scale between the driving processes and the damping mechanisms would cause systems to automatically remain at critical values of parameters.

At the "Scaling and Self-Organized Criticality" workshop held in October 1991, led by SFI External Faculty member P. W. Anderson (Princeton) and Sid Nagel (U. Chicago), researchers met to review recent research in this field with the aim of better understanding the underlying dynamics which cause the scaling phenomena which are observed both in nature and in society. The discussions covered such questions as: What is self-organized criticality? Is it just critical phenomena and tuning to T_c? Is it a theoretical field, or is it relevant to the real world?

Much of SFI Postdoctoral Fellow Wentian Li's work focussed on studies of 1/f noise in a variety of contexts. He searched for long-range correlations, in many natural and artificial systems, especially those with power law correlation functions of very small scaling exponents and logarithmic correlation functions (these belong to the phenomenon called 1/f noise because the power spectra resulting from these correlation functions are almost inversely proportional to frequency [i.e., f]). He also studied the dynamical models which can generate these long-range correlations.

Earlier work by Li searched for 1/f spectra in spatial sequences generated by cellular automata. The result was negative for all two-symbol, nearest-neighbor cellular automata. The implication of this finding is that it is very difficult for locally interactive systems to generate correlations at ranges much longer than the range of the interaction. Li noticed, however, that it is much easier to generate long-range correlations if the size of a system is allowed to increase, which led to his model of spatial 1/f spectra called "expansion-modification systems," an example of the Lindenmayer system.

With K. Kaneko (Tokyo U.), Li has investigated the possible connection between his model and the elongation of the nucleotide sequences. The early searches for long-range correlations and 1/f spectra were all negative. Most protein-coding sequences are like random sequences with only short-range correlations (within codons or between neighboring codons). Only after they extended the search to non-coding sequences (intron sequences) did they observe a partial 1/f spectrum in the human blood coagulation factor VII gene, which contains mainly intron segments. Although the correlation lengths of other intron sequences are not sufficiently long for the sequences to belong to the same class as 1/f spectra, it is typical for non-coding intron sequences to have longer correlation lengths than protein-coding sequences. This result is not conclusive, but it provides an appealing and simple way to distinguish protein-coding and non-coding sequences. One possible explanation of this observation is that intron sequences tend to contain more repetitive patterns which may not have any meaningful functions. These meaningless segments will not be selected in protein-coding sequences but have a better chance to be preserved in intron sequences.

Li has checked the correctness of some claimed 1/f noise in nature. Typically the exponent α in a $1/f^{\alpha}$ spectrum should be very close to 1 to be of interest. If α is too close to 0, the signal is too similar to a random time series. If α is too close to 2, the correlation function decays as a linear function, which can be an easy consequence of the Taylor expansion of an exponential function. A random walk provides the most famous example of a $1/f^2$ spectrum, where the long recurrent time to the origin (and, as a consequence, the lower-frequency divergence of the spectrum) does not result from true long-range correlations, but from the open-ended boundary of the random walkers.

His spectral analysis on the Dow Jones industrial average shows that it has a $1/f^2$ instead of 1/f spectrum. Other similar analyses on the Standard and Poor 500 index, U.S.-Canada dollar exchange-rate fluctuations, the Milan stock exchange index, bond prices, etc., all show the same $1/f^2$ power spectra. Actually, it is well known that stock prices are difficult to predict; in other words, in the first-order approximation, the price fluctuations can be considered as random walk signals. He has also checked the spectrum for the annual water level of the Nile river (from 622 to 1921). This river-level fluctuation can be fit reasonably well by a 1/f spectrum.

The Complex Systems Winter School, led by SFI Science Board member Peter Carruthers (U. Arizona) centered on the geometrical and dynamical behavior of scaling complex systems. Topics covered included turbulence, percolation, self-organized criticality, 1/f noise, the mathematics of hierarchical systems (emphasizing fractals), fractal graphics, and scaling structures in physiology, in galaxies, and elsewhere. The school is described in further detail later in this report.

2.2.3 Measuring and Predicting Complexity

Characterizing the Complexity of Dynamical Systems

SFI Postdoctoral Fellow Cris Moore's research interests focus on characterizing the complexity of dynamical systems, and on the question of the Church-Turing thesis: namely, how can computation be embedded in physical systems, and can any physical systems perform computations that a digital computer cannot? The following projects and papers are in progress.

Braids in Classical Gravity: Periodic trajectories of the n-body problem in the plane can be topologically classified; this allows us to extend "symbolic dynamics" to high-dimensional systems, which normally don't work beyond one or two dimensions. Moore uses the Lagrangian formulation of mechanics to find solutions of various topologies and prove some preliminary results about their existence and stability.

One-Dimensional Maps Capable of Universal Computation: This rounds out his thesis work (Moore, 1990) on smooth maps of the plane which are computationally universal and, therefore, inherit the formal unpredictability of Turing machines; a much stronger kind of unpredictability than the usual "chaos," since it does not rely on any uncertainty in the initial conditions.

Symbolic Dynamics, Transcendentality, and Complexity at the Transition to Chaos (with Erik Aurell): Moore and Aurell are examining the symbolic dynamics at the period-doubling fixed point of the one-humped map, and look at the transcendental behavior of its growth and generating functions. They also classify it in some more detail than the earlier work of Crutchfield and Young. This falls in the "complexity at the edge of chaos" category.

Counting Elliptic Orbits in Hamiltonian Maps: Moore applies generating-function methods to typical Hamiltonian systems, to calculate the number of elliptic orbits of a given period.

Oracular Dynamical Systems: He is constructing smooth flows in four dimensions which can solve the Halting Problem in a finite time. These are quite pathological, but in an interesting way; they can be made smooth, but clearly there's something nonphysical about them.

Optimal Solution of 3-Satisfiability—Exponentiality in Physical Computation: His work shows that a classic NP-complete problem can be solved in linear time using idealized classical components; however, the energy must grow exponentially, corresponding to the increasing spatial density of information required.

Various Papers on Two-Dimensional Patterns and Languages (with M. Nordahl): They extend the Chomsky hierarchy to two dimensions and find a very rich set of language classes. These can be used to classify the complexity of spin systems, quasi crystals, coupled map lattices, and other two-dimensional systems.

Measures of Complexity

SFI External Assistant Professor Seth Lloyd's work has concentrated on the two complementary questions of: how to identify physical systems that are capable of complex behavior and how to quantify the complexity of that behavior. For both questions, complexity is defined analogously to the ideas of complexity in computer science. Systems are capable of complex behavior if they can perform complicated information-processing tasks; the complexity of these tasks can be measured by putting a number to the amount of information processed the course of those tasks. The tools used in the analysis of these questions are classical and quantum mechanics, information theory, and the theory of computation.

In computer science, the complexity of the computation is measured by the number of elementary logical operations performed in the course of the computation (temporal computational complexity) and by the amount of memory space needed to store information as the computation progresses (spatial computational complexity). As physical processes do not obviously consist of sequences of elementary logical operations, the physical analogue of temporal computational complexity is not obvious. In contrast, the physical analogue of spatial computational complexity can be defined in information theoretic and thermodynamic terms and is measured, roughly, by the number of degrees of freedom that a physical system brings into play in the course of a given process, a quantity known as thermodynamic depth. A physical, statistical-mechanical analogue of the measures of complexity proposed by Shaw, Grassberger, and Crutchfield for dynamical systems, thermodynamic depth allows one to measure the amount of information stored by a physical system as it carries out some process. Lloyd has applied this measure to systems that process information but are not computers, to quantify their information-processing ability. For example, he has measured the information-processing capacity of colonies of bacteria to measure their ability to absorb information from their environment that is relevant to their survival. In related work, he applied the measure to quantum-mechanical systems that are capable of simulating the operation of computers to make the connection with statistical mechanical properties of the systems and their ability to process information.

In other work, Lloyd has been investigating the class of quantum-mechanical systems that are capable in principle of performing arbitrarily complex computations, and he had identified a class of quantum-mechanical "universal simulators," each of whose members is capable of simulating the time evolution of any diagonalizable quantum-mechanical system to an arbitrary degree of accuracy. In particular, each universal simulator can simulate the time evolution of a universal computer. The class is very large, containing such familiar quantum systems as the harmonic oscillator and the particle in a box. The usual simple behavior of such systems is revealed to be a property of the particular states in which they are found in nature, rather than a necessary consequence of their dynamics: if prepared in the proper states, such systems can undergo arbitrarily complicated dynamical evolution.

In a related project, Lloyd investigates the question of nonstandard logic gates. Suppose that one is given a large supply of devices with many inputs and many outputs, whose output signals are some function of their input signals. When can such devices be assembled into a general-purpose computer? He supplies criteria for binary and non-binary devices to suffice as a basis for computation and is working on general criteria for identifying computationally useful devices whose outputs are noisy functions of their inputs.

2.3 Simulations of Nonlinear Dynamical Models

SFI Member Gottfried Mayer-Kress and his collaborators worked on a variety of projects involving simulations of nonlinear dynamical systems with varied applications including international relations and EEG analysis.

2.3.1 Optimal Stimulation of a Conservative Nonlinear Oscillator—Classical and Quantum-Mechanical Calculations (with S. Krempl, T. Eisenhammer, A. Hubler, and P. W. Milonni)

A new method for nonlinear polychromatic resonant stimulation of conservative nonlinear oscillators is introduced. For example, they consider a Morse potential that serves as a model for the HP molecule. Numerical results show that a large energy transfer to such a conservative oscillator is possible under optimal stimulation with small driving fields. This makes selective excitation of certain modes possible. The classically determined optimal force was also applied to the corresponding quantum system, with similar results in energy transfer and dissociation.

2.3.2 Algebraic Calculation of Stroboscopic Maps of Ordinary, Nonlinear Differential Equations (with R. Wackerbauer and A. Hubler)

The relation between the parameters of a differential equation and corresponding discrete maps is becoming increasingly important in the study of nonlinear dynamical systems. Maps are well adapted for numerical computation, and several of their universal properties are known. Therefore, some perturbation methods have been proposed to deduce them for physical systems, which can be modeled by an ordinary differential equation (ODE) with a small nonlinearity. A new, iterative, rigorous algebraic method for the calculation of the coefficients of a Taylor expansion of a stroboscopic map from ODE's with small nonlinearities was presented. It was shown analytically that most of the coefficients are small for a small integration time and grow slowly in the course of time if the flow vector field of the ODE is polynomial and if the ODE has a fixed point in the origin. Approximations of different orders respective to the rest term have been investigated for several nonlinear systems.

2.3.3 Nonlinear Mathematical Models for International Relations (with D. Campbell, R. Abraham, A. Keith, and M. Koebbe)

Chaos provides a new paradigm of a complex temporal evolution with bounded growth and limited resources without the equivalent of stagnation and decay. This is in contrast to a traditional view of historical evolution which is perhaps best expressed by the phrase: "If something stops growing, it starts rotting." The exploration of a large number of states by a single deterministic solution creates the potential for adaptation and evolution. In the context of Artificial Life models, this has led to the notion of life at the edge of chaos—the principle that a delicate balance of chaos and order is optimal for successful evolution. Among existing arms race models, Mayer-Kress and his collaborators consider a special class which is related to population dynamics and which was first introduced by L. F. Richardson after the Second World War. The examples they discuss, however, have discrete-time dependence. For certain ranges of their control parameters, these models exhibit *deterministic chaos*, and they discuss how this behavior limits our ability to anticipate and predict the outcomes of various situations. In the second part of this project, they did a computational study of the non-gradient double cusp, in which the degeneracy of Kadyrov's model of opinion formation is unfolded in co-dimension eight. The nonlinear Kadyrov model can be used to study the transition of political systems due to the influence of its decision-making population groups and their influence on the corresponding groups in a hostile country. The recent development in eastern Europe and the former Soviet Union revitalized the interest in Kadyrov's model. Also, they developed a discrete-time cusp model, studied the corresponding double cusp, established its equivalent to the continuous-time double cusp, and discussed some potential applications. They found bifurcations for multiple critical point attractors, periodic attractors, and (for the discrete case) bifurcations to quasi-periodic and chaotic attractors.

2.3.4 Nonlinear Dynamical Systems Methods for EEG Analysis (with M. Palus and A. Longtin)

They have developed a joint proposal to NIMH to do joint EEG work at SFI. The EEG literature contains increasing evidence that low-dimensional, deterministic, dynamical systems provide useful concepts to describe coherent, global behavior of brain events. This evidence has led to numerous publications in which single-lead EEGs have been used for time-delay reconstructions of chaotic attractors. If a subsequent estimate of the correlation dimension of this vector data set appears to be low, the dynamics of the neural system, as manifested in the EEG data set, have been interpreted to approximate that of a chaotic attractor. This interpretation has a theoretical justification if the EEG is, indeed, deterministic and globally coherent. In that case, the measurement at a single lead would provide complete information about the dynamics of the whole system. However, in typical cases the coherence of the EEG is only partial, as evidenced by the differences among reconstructed attractors obtained from different leads. Several different approaches have been undertaken to improve this situation. One approach, pioneered by the group of Drs. Dvorak and Palus, creates high-dimensional vectors from simultaneous recordings of spatially separated leads. This has led already to very promising new results such as the characterization of the effect of different drugs. In this project, the spatio-temporal signal is decomposed into orthogonal modes. There are several basic ways in which one could construct such optimal modes: one could use analytic basis functions, which are selected according to a theory or based on symmetry conditions, or one could use purely statistical criteria for the construction of orthogonal modes. In a previous paper, they focussed on a hybrid approach involving an orthogonal decomposition—the Karhunen-Loeve decomposition and attractor reconstruction. Here the orthogonal (Karhunen-Loeve) modes are explicitly related to spatial structures and not to the temporal dynamics of the system. In that respect one selectively projects the spatio-temporal dynamics into spatially (global) coherent modes. Incoherent local fluctuations are thereby averaged out and do not contribute to the deterministic dynamics of the reconstructed attractor. Dr. Palus' new approach is the integration of spatial but also temporal transforms of the EEG signals into wavelets. This method has proven to be highly superior to Fourier analysis methods in areas of self-organized coherent structures in fluid turbulence. The geometrical and dynamical properties of EEG or MEG activity is sufficiently similar to those data, so that they expect a large improvement of the accuracy of this analysis method compared to previous spectral approaches. This holds not only for spontaneous electromagnetic brain activity but also, and especially, for evoked responses, where the signal is intrinsically localized in space and time.

2.4 Rendering and Display

Complex systems present many difficulties in data acquisition, display, and rendering. Several innovative projects led by SFI Members G. Mayer-Kress and G. Kramer address some of these problems.

2.4.1 Wavelet Analysis of Complex Spatio-Temporal Data (Mayer-Kress with T. Avila)

Spectral decomposition has been used as a classical tool for a reduced description of structures that evolve in space and time. For structures that consist of an irregular ensemble of localized objects, this method is not very efficient. Several methods have been proposed (e.g., by Heisenberg, Weyl, Wigner, Gabor, and others) in order to overcome the limitations of standard Fourier analysis. Significant progress has been made recently with the introduction of compactly supported ortho-normal wavelet bases with locally quadratic approximation properties of smooth functions. They use those basis sets for the representation of arrays of wind velocity data of the El Niño phenomenon. They reconstruct attractors from vector sequences of the original data and compare them with those obtained from fast Fourier and fast wavelet (spatial) reconstructions.

With A. Pang, Mayer-Kress proposes to explore the effectiveness of using wavelet transforms in direct volume rendering. They want to compare this method with Fourier volume rendering (FVR). However, there are some areas where the use of wavelet transforms with basis functions of compact support can make significant improvements. Notably, the data shift problem encountered in Fourier transforms of multidimensional data is replaced by data representations at different scales. This offers an attractive possibility for generating progressively more detailed volume-rendered projections. Further enhancements will allow viewing volume data at interactive speeds. One of the steps in Fourier volume rendering is to resample the frequency domain at the desire projection angle. With wavelets, this process corresponds to resampling at different scales and combining information from different spatial scales and locations. Thus, the intensity in the wavelet spectrum would automatically indicate if they have large contributions from detailed structures, such as textures in some areas of the object, or larger structures, such as smooth surfaces in other areas of the object. This distribution of scales also can change with lighting and perspective and can be very naturally implemented with compactly supported wavelets. The interpolation order then roughly corresponds to the number of different scales present in the space-scale transform. Another avenue that wavelets offer is their localization property: This can be used for an ordering of voxels along a given projection through a transformation into color and opacity information. Thereby, it becomes possible to generate true volume-rendered images as opposed to x-ray-like images.

2.4.2 Audification

"Audification" refers to the use of changes in sound to "display" the status of a multi-dimensional system. Currently three-dimensional graphics displays are most frequently used in the attempt to comprehend multiple dimensions. Using color and time, such displays may represent as many as eight variables simultaneously. Higher-dimensional systems with 20 or 30 variables may have dynamic relationships between the components that are too complex to understand via relatively limited visual displays. Audification may bring comprehensibility to such higher-dimensional dynamic systems. This technique enables the data analyst to employ the substantial pattern-recognition capabilities of the auditory channel. When combined with visualization, audification can contribute significantly to the understanding of complex data. For example, audification could be helpful in representing complex computer models such as ecosystems, immune systems, and economic or disarmament scenarios. There are also applications to work in adaptive computation (artificial life), virtual reality (verdical systems), and the monitoring of complex laboratory, medical, or industrial processes.

In 1991 SFI Member Gregory Kramer, Clarity, was program director and worked on three projects in this area. Beginning in February 1991 and extending to the present, research awards from Apple Computer have enabled his group to generate a powerful sonification tool kit on the Macintosh computer and related sound synthesis devices. These tools were integrated with a predator/prey model that the Apple Classroom Project had been using in the schools to see how students interact with such a model and form a concept of what the model's dynamics are. The sonification was intended to enrich the comprehension of the data by providing both more information and information over more sensory channels. These concepts are being tested by Apple this year.

This grant also enables Kramer to develop a general sonification tool kit that may be employed to listen to other complex problems. Working with Gottfried Mayer-Kress, Kramer has sonified a variety of nonlinear equations and data sets. The tool kit was designed to allow one to import different data sets for display by an ever-widening variety of synthesis and control techniques. The modular nature of the software has expedited its production but will limit its portability to other platforms. This problem is currently being addressed. Mayer-Kress was commissioned to assemble an installation for the well-known electronic arts festival, Ars Electronica, in Linz, Austria for September 1991. With the task of showing how a global modeling project and access to a wide array of information sources could effect our concepts of the planet and our interaction with the environment, sonification was given the role of pointing the way towards understanding some of the results of complex equations that make up these models.

A nine-dimensional Lorenz equation, as has been used to model the El Niño effect, was implemented on a Silicon Graphics computer. The data streams were both visualized on the SGI and sonified on the Mac by sending data from the serial port of the SGI to the serial port of the Mac. The flexible mappings possible in the auditory display system formed an interactive environment for the public to explore this nine-dimensional space.

Kramer has planned an Audification conference in October 1992. This meeting will provide a forum for presentation of current work in the field. The proceedings of this conference will be the first publication dedicated entirely to audification. Additionally, a compact disk and/or video will be produced from the conference.

2.4.3 Global Information, Visualization, and Simulation Project "EarthStation" (Mayer-Kress with G. May, G. Kramer, R. U. Ayres, and many others)

The amount of information available about the state of our planet with all its subsystems increases dramatically. The data come both from direct observations as well as from computer simulation and more traditional methods. The representation and structuring of this rapidly changing information flood is a challenging and unsolved problem. From the theory of chaotic dynamics and the study of complex adaptive systems, Mayer-Kress and his collaborators have a quite sophisticated mathematical and computational tool box available. These tools have been applied and tested for quite a number of model systems in more or less abstract contexts. From a different angle they have been most successfully applied in "virtual realities" of educational computer games. Both of these examples deal with a closed environment of theoretical and game-pragmatic assumptions and parameters. What is lacking is some efficient interface to the real world of global dynamics. The technology for such an interface is currently developed as global communication and information systems, high-speed computer networks, network-wide information servers, and other areas of global networks. In this project they made a first attempt to utilize some of these modern communication, computer, and multi-media technologies to approach this problem. A pilot project version of this approach has been presented as an interactive computer installation "EarthStation" presented at the 1991 ARS Electronica. Our concept is mainly based on hierarchical network representations of relevant problem areas. Each node of the network corresponds to an object which can be of a very general type: a network on a lower level; images and charts which themselves can act as background for new networks or annotation with sound messages (news clips) or other general programs; simulation tools; programs that connect to other units such as other computers, on which different types of programs can be launched; or general multi-media devices. This framework is a natural background for geographic information systems, both static and dynamic. The links that connect these objects can be adapted very easily in a graphic, object-oriented programming style and, thereby, have a great advantage compared to classical world-model programs: The contents and the structure of the simulation and visualization tools can be easily updated as the state of the real world changes and evolves.

2.4.4 Audification/Sonification of Complex Systems (Mayer-Kress with G. Kramer and G. May)

Representation of complex data through scientific visualization has proven to be very useful in understanding complex dynamics. Typically one is limited, however, to few dimensions. Mayer-Kress, Kramer, and May explored the possibilities of using sound for further characterization of higher-dimensional systems. One example has been investigated in the installation of the EarthStation project described above. The dynamics and sensitivity of specific, multidimensional simulation models (in our case, a nine-dimensional model for the El Niño phenomenon) are represented on two different platforms (SGI Iris and Macintosh with special MIDI hardware and software); the simulation of the model and the graphics rendering the solutions of the model are done on the Iris. The user can select (through radio buttons) the projection and perspective of a laboratory ("tower") perspective or co-moving ("cockpit") perspective. A spaceball interface allows the interactive perturbation of the equations of the model. The model's nine dimensions are represented by a set of maximally orthogonal musical dimensions. This application explores the possibilities of new multi-media approach of complex data analysis and representation.

2.5 Integrative Activities

2.5.1 *Complexity*, a Journal

In 1991 the Santa Fe Institute completed plans to found a new journal, tentatively entitled *Complexity, an International Journal of Complex and Adaptive Systems*. Prof. Harold Morowitz, a distinguished biophysicist, a member of the SFI Science Board, and a Clarence Robinson Professor at George Mason University, has accepted the post of Editor in Chief of *Complexity*.

Among the goals of the new journal is to provide a timely and widespread means of communication for scientists working in different subfields of the sciences of complexity. It is also intended to provide understandable reports of recent research results that may prove of general applicability and to encourage the examination of the extent to which novel computational techniques, theoretical concepts, and models developed in one area of the sciences of complexity may be applicable to other areas.

The journal will consist principally of refereed scholarly papers in the sciences of complexity. The field will be broadly covered with an emphasis on papers that suggest or apply possible integrating concepts or themes of considerable commonality. Scholarly, commissioned review articles will be a regular feature. A part of each issue will be devoted to commentaries, book reviews, and news. The journal will serve an international community of physical, biological, mathematical, behavioral, computer, and social scientists carrying out research on complex systems. Initially *Complexity* will be published in four issues per year, a number that will increase as the demand increases. The first issue is planned for the winter of 1992. The editorial offices of *Complexity* will be in the Publications Department of the Santa Fe Institute, under the direction of an Executive Editor. The Institute and Pergamon are currently in the process of selecting the Executive Editor. The Editor in Chief and the Executive Editor will work closely with a board of Associate Editors who will participate in the process of soliciting and selecting articles for the journal and will assist in choosing appropriate referees. The Associate Editors are M. Boldrin (Northwestern), P. Carruthers (U. Arizona), M. Feldman (Stanford), and W. Zurek (LANL). A distinguished international Advisory Board will advise Morowitz and the board of Associate Editors on the operation of the journal. The Advisory Board is listed in Appendix VIII.

2.5.2 Meetings

The annual gathering of the SFI Science Board provides the opportunity for the key participants in Institute programs and workshops to come together to focus on the emerging common threads and overarching themes of SFI. In 1991 a one-day symposium on adaptive computation and artificial life systems was held in addition to the Science Board meeting (which is devoted to specific program review). Symposium speakers included Stephanie Forrest ("Adaptive Computation"), John Geanakoplos ("The Economy as an Adaptive, Complex System"), Alan Perelson ("Mathematical Models of the Immune System"), Peter Wolynes ("Spin Glass Engineering"), and Marc Feldman ("Sex, Genetics, & Evolution").

In the planning stages for 1992 is a ten-day workshop on "Common Principles of Complex Systems." This meeting will review work done at SFI and elsewhere over the past half-dozen years, compare approaches and results, and, it is hoped, begin to construct an overview of the commonalities in the behavior of complex systems. This program is being directed by a steering committee chaired by G. Cowan.

3. ADAPTIVE COMPUTATION

The study of adaptive computational systems is proving to be a major cornerstone in the effort to understand complex adaptive systems. It promises not only a deeper insight into the nature and consequences of these systems, but also the application of these lessons to the creation of a new generation of computer-based systems endowed with advanced adaptive capabilities. Work in this area has been a long-term effort at SFI, inspired and led by External Professor John Holland, a pioneer in this field. (Holland developed the original genetic algorithm model.) This program is targeted for major expansion in 1992 in light of the fact that efforts to date have already proved very fruitful. Current work within the Adaptive Computation program addresses several broad areas. One issue is identifying scientific and technological problems to which adaptive computational techniques can be successfully applied. Another central issue is finding useful ways to integrate such techniques into models of complex systems. A third issue is developing a theory of the foundations of such techniques that will allow researchers to better understand how they work and in what situations they are likely to perform well. Reports of the applications of adaptive computation are covered in other portions of this document; this section summarizes activities in the latter two areas.

3.1 Computational Models of Complex Adaptive Systems

3.1.1 Artificial Life

SFI External Faculty member C. Langton and his collaborators have originated a new field of scientific research dedicated to making fundamental contributions to theoretical biology through the use of computer—and other "artificial"—models of biological phenomena. This field, called Artificial Life, studies natural life by attempting to capture the behavioral essence of the constituent components of a biological process and endowing a collection of artificial components with similar behavioral repertoires. If implemented and organized correctly, the aggregate of artificial parts should exhibit the same dynamic behavior as the natural system.

Such "bottom up" techniques have been widely used in the study of many physical phenomena (e.g., hard-sphere simulations of fluid dynamics, "lattice gas" models for the study of fluid dynamics). Now that supercomputer technology has provided greatly increased computational power, it is beginning to be feasible to perform such simulations of biological systems, in which the components and their interactions are much more complex than point particles.

The motivating objectives of the Artificial Life project are (1) to understand the role that self-organization and collective dynamics have played in the evolution of life and intelligence and (2) to demonstrate the utility of "bottom up" computer modeling and experimentation for the understanding of complex biological phenomena.

In 1991 Langton and his collaborators in the Computer Science Department at UCLA, David Jefferson and Robert Collins, continued to develop a general-purpose software system for modeling and testing theories about complex biological phenomena on the Connection Machine (CM2), and to apply this general-purpose software to the construction and testing of models for specific problems in gene-regulation, molecular self-assembly, insect-colony behavior, ecosystem dynamics, and evolutionary theory. They have developed and tested an efficient code for running large populations of individual processes in emulation of MIMD (multiple instruction, multiple data) computation on the CM2. They have applied this code to the parallel simulation of ant colonies involving almost a million ants. In these simulations, each "ant" consists of a large neural net, and the SIMD (single instruction, multiple data) code broadcast to all of the processors consists of universal instructions for updating neural nets. The result is a population of "ants" acting as if they were a large collection of MIMD programs running within the CM2 processor space. Because SIMD on the CM2 enforces global instruction synchrony, this "quasi-MIMD" emulation runs *very* efficiently. Currently the group is investigating the emergence of various classes of collective behavior, such as cooperative foraging.

Langton is also working on the Genetic Programming Paradigm (GPP) (evolution over Lisp expressions) with Stephanie Forrest and several of her students at the University of New Mexico. He supervised a student at SFI and Los Alamos, Yann David, who implemented and tested the GPP on both standard workstations and on the CM2. The group will be applying the GPP in the domain of mobile robot control and in the study of coevolutionary dynamics. They are working with researchers from the MIT mobile robot lab for some of the robotic control research. Also, they are redoing some of the original work with the GPP paradigm in an effort to determine its robustness and scalability.

Langton also is collaborating with SFI Member Andrew Wuensche and Mike Lesser on new parameters for characterizing CA rule space. They are in the final stages of producing *The Global Dynamics of Cellular Automata: An Atlas of Basin of Attraction Fields for One-Dimensional Cellular Automata*, which will be published by Addison-Wesley in the SFI series. This is due out in June 1992.

In a related effort, Nils Nilsson (Stanford), during his visit to SFI, began a study of "reinforcement learning," "classifier systems," "genetic algorithms," and other machine-learning methods that might be relevant to the problem of having a mobile robot automatically learn goal-achieving sequences of actions. Particular attention was paid to those methods that could be employed to adjust pre-existing robot control programs rather than to learn ew programs from scratch. An algorithm that combines temporal-difference/delayed-reinforcement methods with input generalization was developed, and preliminary versions of it were programmed and tested. This algorithm is described in draft notes he prepared entitled "An Approach to Learning Sequences of Actions: Combining Delayed Reinforcement and Input Generalization." He also proposed an algorithm for learning control programs written in the teleo-reactive formalism. This algorithm is described in a draft memo entitled "A Proposed Algorithm for Learning: A Teleo-Reactive Plan."

3.1.2 Tierra Synthetic Life Model

During his 1991 visit Thomas Ray (U. Delaware) worked on his Tierra synthetic life project, an effort he continues during a 1992 sabbatical leave he is spending at SFI. Synthetic organisms have been created based on a computer metaphor of organic life in which CPU time is the "energy" resource and memory is the "material" resource. Memory is organized into informational patterns that exploit CPU time for self-replication. Mutation generates new forms, and evolution proceeds by natural selection as different genotypes compete for CPU time and memory space.

Observation of nature shows that evolution by natural selection is capable of both optimization and creativity. Artificial models of evolution have demonstrated the optimizing ability of evolution, as exemplified by the field of genetic algorithms. The creative aspects of evolution have been more elusive to model. The difficulty derives in part from a tendency of models to specify the meaning of the "genome" of the evolving entities, precluding new meanings from emerging. The Tierra model has several innovative features which allow creative open-ended evolution of the genome.

The primary feature is the "fitness function," or what is used to determine the reproductive success of a genome. This function is often explicitly stated a priori, tending to limit the creative potential. Tierra uses a more natural, implicit mechanism of survival of the fittest. The second feature is the use of an objective "machine code" in specifying the genome. There is no explicit ordering or a priori meaning for the informational patterns. Traditionally, behavioral traits (such as "defense" or food preference) are inferred from predefined sections of genome. Careful consideration of Tierra's fundamental "machine codes," allows for a theoretically open-ended range of behaviors, which only evolution shapes.

From a single rudimentary ancestral "creature," very quickly there evolve parasites, which are not able to replicate in isolation because they lack a large portion of the genome. However, these parasites search for the missing information, and if they locate it in a nearby creature, parasitize the information from the neighboring genome, thereby effecting their own replication.

Several recognizable modes of creature interaction evolved in early experiments. The abundance of ancestral creatures created the opportunity for parasites. Theses parasites evolved to take advantage of a part of the ancestors reproductive code. Quite often, due to the pressure of competition, an immune host would evolve.

When immune hosts appear, they often increase in frequency, devastating the parasite populations. In some runs where the community comes to be dominated by immune hosts, parasites evolve that are resistant to immunity. Hosts sometimes evolve a response to parasites that goes beyond immunity, to actual (facultative) hyper-parasitism. The hyper-parasite deceives the parasite, causing the parasite to devote its energetic resources to replication of the hyper-parasite genome. This drives the parasites to extinction. This type of "evolutionary arms race" continues, and behaviors get increasingly complex.

The only genetic change imposed on the simulator is random bit flips in the machine code of the creatures. However, it turns out that parasites are very sloppy replicators. They cause significant recombination and rearrangement of the genomes. This spontaneous sexuality is a powerful force for evolutionary change in the system.

One of the most interesting aspects of this instance of life is that the bulk of the evolution is based on adaptation to the biotic environment rather than the physical environment. It is coevolution that drives the system.

Encouraged by the initial success, several augmentations to the model are planned. The potential for large-scale collective behavior (multi-celled organisms), and the use of the system as a learning tool for real-world complex evolving systems, will be explored. Finally, the use of Tierra to solve or optimize real or "hard" problems will be studied.

3.1.3 The "Echo" Model

John Holland (U. Michigan) is in the early stages of developing the "Echo" model which provides a computational base in which to conduct experiments on a simulated multi-agent "ecology." The model consists of populations of evolving, reproducing agents distributed over a geography with different inputs of renewable resources at various sites. Each agent has simple capabilities—offense, defense, trading, and mate selection—defined by a set of "chromosomes" that evolve via a genetic algorithm. Although these capabilities are simple and simply defined, interacting collections of agents can exhibit analogues of a diverse range of phenomena, including ecological phenomena (e.g., mimicry and biological arms races), immune system responses (e.g., interactions condition on identification), evolution of "metazoans" (e.g., emergent hierarchical organization), and economic phenomena (e.g., trading complexes and the evolution of "money"). Thus, although the system is couched in terms of the language of biological ecologies, it is meant to be general enough to model phenomena in a number of areas. This generality can help shed light on commonalities among phenomena in diverse areas and can get at the essence of some central questions about complex adaptive systems.

3.1.4 An Evolutionary Model of Learning and Memory

Researchers: SFI External Professor Marcus Feldman and Aviv Bergman

The evolution of learning capabilities in organisms is one of the more perplexing issues in evolutionary biology. Several studies on the evolution of learning proposed the idea of learning as a mechanism to adapt to changes in the environment during somatic time. These studies are based on the "absolute fixity argument," that is to say, in the presence of an absolutely fixed environment, an individual should develop a genetically fixed pattern of behavior (assuming some cost associated with learning).

On the other hand, in an absolutely unpredictable environment, where the past and present state of the environment bears no information about the future, then there is nothing to learn, and assuming some cost to learning, there is no driving force for learning capabilities to evolve.

D. W. Stephens (Stephens, 1991) proposed a different strategy. He argues that the pattern of predictability in relation to an individual's life history determines the evolution of learning. His study concludes that the value of learning is for those things that change between generations and are regular within generations. An alternative view is learning as the ability of an individual to construct a correct model of its environment and, by proper use of the model, to be able to predict future states of its environment.

During a two-month stay at SFI in 1991, Aviv Bergman (Stanford) developed a population genetics model for the evolution of memory and learning. A mathematical analysis and a computer simulation of this model have been studied, but further analysis was required to complete the model. Bergman worked on developing a model of co-evolution, a system capable of learning to behave adaptively in a changing environment—one able to respond in a distinctive, repeatable way to those environment signals to which it has been exposed; to track changes to its signal environment by recognizing itself; and to do these things spontaneously, with no instruction. The hypothesis is that principles of biological evolution and population genetics provide the basis for such behavior. The process of variation, selection, and differential reproduction are known to produce in natural populations the kind of emergent behavior the model sought to emulate. Yet this very simple model has a problem: eventually such a system can lose most of its viability through inbreeding and genetic drift in finite population size. The species become sets of clones. This is undesirable because variation is essential for rapid reorganization in response to a new environmental source. A future publication from this work will be "The Evolution of Learning" with Marc Feldman.

One way to maintain variability is through mutations, but this is relatively ineffective compared to a less direct, coevolutionary approach.

In addition to the population of individuals, the coevolutionary systems incorporate a population of relatively simple parasites that ignore the environment but attempt to match the genetic code of the individuals. When they succeed, they destroy the individual and spread copies of themselves to neighbors. As a well-adapted, inbred subset of individuals becomes very large, the likelihood of a successful parasite attack grows; after a successful attack the parasitic infection destroys the newly vulnerable inbred subpopulation, but leaves significantly distinct variants of the species uninfected. These eventually repopulate the space left vacant by the "epidemic." Without coevolution the system converges to a rather stereotyped organization which could be thought of as a fixed-point attractor. With coevolution, however, the dynamics appear never to converge and yet are not entirely chaotic. Publication from this work will be "Speciation by Simplicity and Controlled Variability" with Marc Feldman as co-author.

An old question in biology, dating from Fisher (1930) and Muller (1932), concerns the advantage or disadvantage to a genetic system of the presence of recombination. The early speculations were that the presence of recombination was advantageous because it accelerated the reproduction of favorable multiple mutants. Eshel and Feldman (1970) showed that this depended on (1) the initial conditions in the population and (2) the shape of the fitness regime. Another, more mechanistic way of investigating the advantage of recombination involves the use of modifier genes that control the process of recombination itself. A large series of studies (Feldman et al., 1977; Feldman and Brooks, 1980); and Feldman and Liberman, 1986) have suggested that in deterministic systems, near a stationary state, recombination should decrease.

Workers using genetic algorithms GA generally find that search or optimization occurs faster with recombination than with recombination recombination above. Contacts at SFI between GA workers John Holland, Stephanie Forrest, and Melanie Mitchell and modifier workers Marc Feldman, Aviv Bergman, and Freddy Christiansen have led to a series of "hybrid" states that investigate the evolutionary advantage of recombination in complex system. The first results of these meetings concern the role of complexity of the fitness regime for the fate of the modifier of recombination: the more complex the fitness, the less recombination will help. These results are in press in *Physica D* (Bergman and Feldman). Working papers address the time it takes for a desired recombination to appear for the first time and how this is related to the time until the population is taken over by this chromosome. This involves a collaboration among all workers named above.

3.2 Foundations of Genetic Algorithms

A genetic algorithm is an idealized computational model of evolution based on the principles of genetic variation and natural selection. The goal of a genetic algorithm is to find a good solution to a problem by evolving a population of solutions. Individuals in the population are represented as bit strings, collections of ones and zeros, corresponding to the chromosomes of biological organisms. During each generation the fitness of all individuals is evaluated; the best individuals tend to survive and produce new bit strings, while the less-fit individuals tend to be eliminated from the population. Through time the average fitness of the population increases, resulting in better solutions.

At each generation new bit strings may be produced either by mutation (changing a bit value) or through the crossover operator which combines two individuals to produce two new, mix-and-match offspring. Crossover allows two bit strings to combine and, in a single step, occasionally produce a much better offspring with the best features of both parent bit strings. For this ability to leap across to better solutions, the crossover operator is often credited for the genetic algorithm's successful results.

The genetic algorithm, like evolution, exhibits the parallel and distributed behavior of emergent computation systems. The fitness of individuals, for example, can be evaluated in parallel during each generation. Responsibility for crossover and mutation is distributed among all individuals, rather than being given to a central authority. Each individual performs these operations autonomously. The behavior of the genetic algorithm is emergent because, while each bit string may mutate and crossover independently, it is the combined action of the entire population that produces results.

Although it has been successfully applied to many problems since its invention more than fifteen years ago, the genetic algorithm and its behavior remain only partially understood. There is no comprehensive theory that relates characteristics of a problem directly to the performance of the genetic algorithm, or that predicts what the genetic algorithm's performance will be on a given problem. Much of the work in genetic algorithms has been based on what SFI External Faculty member S. Forrest calls "folk theory," ideas and equations that have not been proven in general. Forrest, in collaboration with Melanie Mitchell (U. Michigan), has been working to characterize the genetic algorithm in a formal theory that will explain why it works and for what type of problems it is best suited.

Forrest and Mitchell are developing a set of test functions, called Royal Road functions, with which to probe the workings of the genetic algorithm. These functions allow the experimenter to design problems that exactly emphasize the characteristics needing to be tested. Some problems are difficult for the genetic algorithm because they exhibit multiple local optima, deceptive information, space-sampling errors, or a combination of these and other features. In order to characterize the difficulties associated with each of these features, it is necessary to isolate their effects and analyze them separately. The Royal Road functions provide the experimenter with specific control over which features will be present in a given problem.

As the strengths and the weaknesses of the genetic algorithm become better defined, it should be possible to adjust and improve the effectiveness of the genetic algorithm based upon the characteristics of the problem to be solved. The Royal Road studies will also be used to develop a set of statistical tests for predicting the genetic algorithm's performance on different classes of problems.

While at SFI during the summer of 1991, Robert Lindsay (U. Michigan) collaborated with Forrest and Mitchell on a specific aspect of such fitness problems. Royal Road functions impose a hierarchical organization that presumably should be exploitable by genetic algorithms. Forrest and Mitchell have found, however, that the GA did better when "gaps" were included in the function by removing some of the intermediate layers. This is unfortunate for the GA, although a post hoc analysis makes clear why it should be. After discussion of their results with Mitchell and Forrest, Lindsay has suggested that it would be interesting to see if this gap effect persists when large introns (sequences of non-relevant bit strings) are inserted between the strings that define the hierarchies. The reasoning is that while crossover has the potential of creating new structures, valuable structures are vulnerable because they can be destroyed by crossover, and thus hierarchical structures are unlikely to evolve. One way to prevent this destruction (that is, to lessen its probability) is to isolate the structures so that crossover points are more likely to fall between than within an established structure. It is a surprising and extremely important fact of genetics that large introns have been found in natural genomes. Mitchell is preparing a simulation to see if the use of introns can lessen or overcome the gap effect. It may take some time to adequately test this hypothesis since a proper test will require extremely long sequences and hence a lot of computation time, and because the variances of the performance variables are quite large.

4. PATTERNS IN INFORMATION AND COMPLEXITY

Complex systems present themselves in a variety of modes including many different temporal data series, computational systems such as cellular automata and Boolean nets, stochastic processes, dynamical systems, and so on. Several studies are under way that seek to discover characteristics of the underlying processes and to predict their future behavior by examining the data series, the information content according to various measures, the emergent hierarchies or topologies, and the intrinsic computational limits on complexity.

4.1 Time-Series Forecasting

The Nonlinear Modeling and Time-Series Analysis research network includes SFI External Professor J. Doyne Farmer, SFI Member Andre Longtin, Gottfried Mayer-Kress (U. Illinois), George Mpitsos (Oregon State), Charles Wood (LANL), Michael Mackey (McGill U.), John Milton (U. Chicago), and Ralph Siegel (Rockefeller U.). The group's work is motivated by the observation that apparent randomness in a time series may be due to chaotic behavior of a nonlinear but deterministic system. In such cases, it is possible to exploit the determinism to make short-term forecasts that are much more accurate than one could make from a linear stochastic model. They have been developing nonlinear methods which are valuable not only as short-term forecasters, but also as diagnostic tools for identifying and quantifying low-dimensional chaotic behavior.

With support from a grant from the National Institute of Mental Health, the group has been developing tools for nonlinear modeling of (possibly) chaotic time series and applying these tools to a variety of biological situations, with particular emphasis on the nervous system. Most of the effort to date has been in the theoretical development of methodology, primarily toward a statistical tool for reliably detecting nonlinearity in a time series that they call "the method of surrogate data," but also with some work in developing input-output models. Recently, however, they have begun to more systematically apply this tool to time series which have the potential to exhibit nonlinear structure.

The Method of Surrogate Data

Many of the methods that are currently used to detect chaos in time series—such as estimation of fractal dimension or Lyapunov exponents—are often fooled by non-white random signals. The group has developed and begun to systematically evaluate a more reliable approach to test for nonlinear structure. The method involves the careful statement of a null hypothesis which characterizes the candidate linear process, the generation of an ensemble of "surrogate" data sets which mimic the original data but which are consistent with the null hypothesis, and the computation of a discriminating statistic (such as dimension, Lyapunov exponent, or forecasting error) for the original and for each of the surrogate data sets. The idea is to test the original time series against the null hypothesis by checking whether the discriminating statistic computed for the original time series differs significantly from the statistics computed for each of the surrogate data sets. This provides, on the one hand, a formal test for the adequacy of a linear model to describe the data and, on the other hand, a kind of control experiment to make sure that the evidence for chaos (in the form of a small fractal dimension or a positive Lyapunov exponent) is not merely an artifact of linear correlations in the data.

The method of surrogate data is one of a family of computationally intensive statistical tools, which includes the related technique of "bootstrapping," and which (with the advent of cheap computing) are becoming more widely used. Several algorithms have been developed for generating surrogate data under various null hypotheses. The group is applying this method to a variety of physical situations in which data sets have suggested (but not always convincingly) the presence of chaos or other nonlinear phenomena. These include sunspot cycles, superfluid convection, measles and chicken pox epidemics, and human electroencephalograms.

Bleaching

Most tests for nonlinearity involve first fitting a linear model, then using this model to "filter out" the linear correlations in the data, leaving a new time series of "residuals." Because the residuals have no linear autocorrelation, their power spectrum is flat, or white, and the filtering process is often referred to as pre-whitening or "bleaching." The residuals are tested for against a null hypothesis of temporal independence (that is, that there are no dependencies, linear or nonlinear, between each value and any other value). Since the bleached data, by construction, will have no linear correlations, rejecting this null hypothesis implies nonlinear structure in the original data.

This approach contrasts with the method of surrogate data, which works with the raw data directly, instead of filtering beforehand. The group has shown with a series of numerical experiments that, for chaotic data, the process of bleaching degrades the significance of the evidence for nonlinear structure and provides an argument in favor of using the method of surrogate data on data that have not been extensively filtered (Theiler and Eubank, 1992). Steven Eubank, formally of Los Alamos and now with the Prediction Company (Santa Fe), is a collaborator on this project.

Input-Output Systems

While low-dimensional chaos may be exhibited in free-running oscillations, a more common situation in neuroscience is for a response to depend on a stimulus. Researchers in this group have developed methods for analyzing the possible nonlinear dependence of the response to the stimulus in the context of mechanical vibrations (Hunter and Theiler, 1991). The method distinguishes between chaotic and nonchaotic responses. The group has recently acquired a considerable data base of evoked-response EEG time series (published in Rapp et al., 1989) and intend to apply its methods to determine if there is a nonlinear relationship. Norm Hunter (LANL) is a collaborator on this project.

The EEG (electroencephalogram) has become a widely used tool for the monitoring of electrical brain activity, and its potential for diagnosis is still being explored. A number of researchers have reported low-dimensional chaos in the EEG, based on analysis of the time series. For a recent review, see Rapp et al. (1989). Most of the reports are based on numerical estimation of fractal dimension, yet these estimators are notoriously unreliable (Theiler, 1990).

Researchers have begun to examine these time series using the method of surrogate data (Theiler et al., in SISOC PV XII). While current results are quite preliminary, they find that the evidence for chaos in the time series they have examined is weak, and in some cases, the data are entirely consistent with a very simple null hypothesis of linearly autocorrelated Gaussian noise. Paul Rapp (U. Pennsylvania) has provided his original data and will be a collaborator on this aspect of this project.

Work was also done on the forecastability of EEG time series (Casdagli, 1991). EEG data from a normal subject who is resting with eyes closed and from the same subject under fluroxene-induced anesthesia were investigated. Local linear forecasts were then made on the embedded EEG data, and the resulting forecasting error was computed as a function of the size of the neighborhood used to fit the local linear maps. It was found that the forecast error decreased as the neighborhood size increased, i.e., that global linear models provided better fits to the data than local linear ones (even at high embedding dimensions). This implies that there is little nonlinear forecastability (characteristic of low-dimensional chaos) in these data.

Periodically Forced Neurons

Many neurons in the central nervous system and at the sensory periphery receive some kind of periodic input. Their activity often exhibits a kind of "statistical phase-locking" to the input, in which the neuron fires near a preferred phase of the input, but skips a random number of cycles between successive firings. The origin (and purpose) of this aperiodicity is not known, and one is faced with the problem of identifying, from a time series of neural firing times (i.e., from a point process), the dynamics underlying the behavior of these cells. Simple, model, noisy, bistable systems were shown to exhibit many of the statistical and temporal features of the data (Longtin et al., 1991). However, excitable cell models as well as purely chaotic models also exhibit many features of the data (Longtin, 1992). Further, maximal Lyapunov exponents computed from time series of interspike intervals for all three models are generally found to be positive (one would expect it only for the chaotic one). Researchers have investigated the problem of distinguishing between candidate models by computing the significance with which each can reject a specific null hypothesis (surrogate data technique). This has enabled them to at least separate the chaotic models from the non-chaotic ones. The real data appear to behave as the bistable and excitable models. Dante Chialvo (SUNY Syracuse), William Rhode (U. Wisconsin), and Ralph Siegel (Rutgers) are consultants for this project.

Pupillary Fluctuations

Human pupils exhibit ongoing fluctuations (hippus) in their size, and the perfect synchrony of hippus in both eyes implies this activity is generated somewhere prior to or at the brainstem level. Hippus is normal, but its origin and purpose are not known. Its source may be crosstalk from other neural pathways into that of the pupil light reflex. A research goal is to find out whether there is more to hippus than linearly correlated noise seen through static nonlinearities (such as the iris muscle and the lens through which the pupil area is measured), which is the current interpretation of hippus. Increased determinism in hippus has obvious diagnostic potential. Peter Howarth (Loughborough, U.K.), who provided data, and preliminary results indicate that there is interesting nonlinear structure in hippus. The data consist of 60–90 sec area recordings under constant (mildly bright) lighting conditions. The surrogate data method was applied to the data with the usual discriminating statistics. Researchers were able to reject the null hypothesis of linearly correlated noise filtered by a static nonlinearity with a small yet acceptable level of significance. Another test was then devised to test for the presence of asymmetry in the data, e.g., the fact that increases are often faster than decreases. The statistic in this case was chosen as $(x(t+\tau)-x(t))^3$ where τ is some lag. This gave even larger levels of significance with which to reject the null hypothesis. This same statistic has subsequently been found to outperform most of the usual statistics on many of the data sets analyzed.

SFI Postdoctoral Fellow Martin Casdagli was in residence at the Institute through June 1991. A participant in the projects described above, Casdagli also conducted research into state-space reconstruction and nonlinear modeling methods. Working with Doyne Farmer, Stephen Eubank, and John Gibson, he developed a theoretical approach to state-space reconstruction. This theory sheds light on the following practical questions: To what extent are existing techniques for nonlinear forecasting optimal? How might they be improved? What are the fundamental limitations to such techniques? In order to construct a nonlinear forecasting model from a univariate time series, the first step is to reconstruct a state space from the time series, and the next step is to fit a multivariate nonlinear function to the time-series data in this state space. A theorem of Takens shows that it is always possible to achieve the first step perfectly in the absence of noise. Using geometric insights into Takens' theorem, they have formulated a criterion, called "distortion," for optimal state-space reconstruction in the presence of noise. In the limit of low observational noise levels, they derive a simple expression for the distortion. This expression quantifies the notion of "information flow" between well-observed and unobserved variables and allows for numerically efficient comparison of existing reconstruction techniques. Furthermore, one is able to solve for the optimal reconstruction technique and find a new technique, "local principal components analysis," which minimizes distortion. This new technique is directly applicable to the forecasting of time-series data. Scaling laws which govern the behavior of the distortion in certain limits have also been derived. When applied to high-dimensional "complex" dynamical systems, these scaling laws imply that, in the presence of a small amount of noise, knowledge of a univariate time series is insufficient to make even short-term forecasts. Consequently, such time series behave more like those from random processes than deterministic chaos.

Casdagli also developed an exploratory technique for investigating how much of the irregularity in an aperiodic time series is due to low-dimensional chaotic dynamics, as opposed to stochastic or high-dimensional dynamics. The idea is to construct nonlinear models with a variable smoothing parameter which at one extreme defines a deterministic model and at the other extreme defines a linear stochastic model. Intermediate values of the smoothing parameter define nonlinear stochastic models. The accuracy of the resulting short-term forecasts as a function of the smoothing parameter reveals much about the underlying dynamics generating the time series. He applied the technique to a variety of experimental and naturally occurring time-series data generated from: electronic circuits, fluid turbulence, flame dynamics, speech, electroencephelograms, measles epidemics, and sunspots. In contrast to dimension algorithms, the results show that this algorithm is not the sort of uncritical procedure that identifies low-dimensional chaos everywhere. On the other hand, the algorithm detected strong evidence for nonlinear forecastability in several of the time series.

Postdoctoral Fellow Andre Longtin also was in residence at SFI on a part-time basis as part of this project. Longtin will be returning periodically in 1992 as an SFI Member to continue work on the project. He worked with various collaborators (William Rhode, U. Wisconsin; Dante Chialvo, SUNY Syracuse; Ralph Siegel, Rutgers; Peter Howarth, Loughborough, UK) to specify the desired recording conditions and to obtain their data in a form suitable for analysis. He analyzed human pupillary fluctuation data as described above as well as neural spike trains from periodically forced auditory neurons in cat auditory, visual, and tactile systems.

Analysis of Neural Spike Trains

Much work has gone into qualifying the role of noise in the information-processing task accomplished by sensory neurons (work done jointly with F. Moss, U. Missouri, and A. Bulsara, NOSC). It has been shown that periodically forced sensory neurons behave very much like noisy bistable systems. In fact, experiments done on analog computers mimicking these bistable systems have produced time series of events which follow the same statistics as the neural spiking events. This work implies that the neurons may use the noise to enhance their signal-detection capability, through an effect known as stochastic resonance.

Longtin has expanded this work to answer the following questions: (1) do more realistic neuron models, i.e., ones that entail automatic reset such as the Fitzhugh-Nagumo equations, also exhibit the features of the neural data and stochastic resonance? (2) Is there any predictability in the spike trains of such a periodically forced neuron? And (3) can one reject, by looking solely at the neural firing times, classes of models for the data using the surrogate data method? His numerical simulations indicate that, indeed, excitable cell models (such as FHN) exhibit the features of the data as long as the system is close to a Hopf bifurcation. Further, he has found evidence for a weak form of stochastic resonance in excitable cell models, based on the interspike-interval histogram, which behaves in the same way as residence-time histograms for bistable systems as the noise intensity is varied. Finally, question 3 was addressed by looking at three different models which all reproduce many of the features of the data: a bistable model (in one dimension), an excitable model, and a chaotic model (of Duffing type). By quantifying how each model behaves with respect to the null hypothesis of linearly colored noise, it was possible to distinguish the chaotic model from the other ones and, also, to show that the real data (of Siegel) behaved in the same way as the bistable and excitable models.

Stochastic Delay-Differential Equations

Another aspect of Longtin's work concerns noise-induced transitions in delay-differential equations (DDEs). Systems of stochastic ordinary differential equations (ODEs) are known to exhibit such transitions, such as a postponement of a Hopf bifurcation. The investigation of these transitions had not been undertaken in DDEs because they are infinite-dimensional and non-Markovian, rendering the usual Fokker-Planck-type of analysis inapplicable. Postponements of the Hopf bifurcation in well-known DDEs have been investigated numerically and shown to depend on the ratio of delay to response time of the DDE.

This work shows how the behavior in the limiting cases, i.e., when the DDE behaves as an ODE (zero delay) or as a map (large delay), can be used to understand that of the DDE. This work also provides the first account in any system of ODEs and DDEs of the dependence of this noise-induced transition on the correlation time of the noise.

Along the same line, Longtin has done analytical and numerical work on the dynamics of the delayed Langevin equation. The goal here is to investigate the dependence of the variance of this simple non-Markovian process on the delay.

He also has investigated various schemes with which to approximate DDEs in the chaotic regime. This involves substituting colored noise processes in the place of the delayed variable. These results are intended to simplify the analytical problems arising in the study of recurrent neural systems such as those in the hippocampus.

4.1.1 Time-Series Prediction and Analysis Competition

As noted above, a wide range of new techniques are now being applied to the time-series analysis problems of predicting the future behavior of a system and deducing properties of the system that produced the time series. Tools such as the use of connectionist models for forecasting or the extraction of parameters of nonlinear systems with time-delay embedding promise to provide results that are unobtainable with more traditional time-series techniques. Unfortunately, the realization and evaluation of this promise has been hampered by the difficulty of making rigorous comparisons between competing techniques, particularly ones that come from different disciplines.

In order to facilitate such comparisons and to foster contact among the relevant disciplines, the Santa Fe Institute organized a time-series analysis and prediction competition. The competition was organized and run by Neil Gershenfeld (Harvard), and Andreas Weigend (Stanford and Xerox PARC), and followed a collaboration initiated at the 1990 Complex Systems Summer School. A few carefully chosen experimental time series were made available through a computer at SFI, and quantitative analyses of these data were collected in the areas of forecasting, characterization (evaluating dynamical measures of the system's dynamics such as the number of degrees of freedom and the information production rate), and system identification (inferring a model of the system's governing equations). Currently the performances of the techniques submitted are being compared and published, and the server continues to operate as an archive of data, programs, and comparisons among algorithms. A workshop is planned for May 1992 to further explore the results of the competition.

4.2 Computational Mechanics

External Faculty member James Crutchfield worked on several related projects in computational mechanics:

4.2.1 A Thermodynamic Description of Finitary Stochastic Automata

Extending classical work on statistical methods for Markov chains to stochastic automata and employing the more modern theory of large deviations, he has developed a "thermodynamic" description of finitary stochastic automata. This gives an improved (and implementable) analysis of the structure of invariant sets for such processes and suggests new quantifiers for Bayesian model learning. This work provides a direct connection between his approach to physical complexity, which he calls computational mechanics, and the "thermodynamic formalism" and work on multifractals found in the dynamical systems literature.

4.2.2 Knowledge Convergence

This project of Crutchfield focused on what a model of a nonlinear process tells an observer about the state of a data stream's source. An observer's knowledge of a source is defined in terms of the observer's current model and information about the source's state. Then, using an appropriate variant of Boltzmann's H-function, the convergence to partial and possibly total knowledge of the source's state can be investigated. Depending on the computational properties of the source, there are distinct convergence characteristics. If, for example, the source is a stochastic Sofic system, exact knowledge cannot be obtained; if the source is more restricted, (say) a Markov chain, then exact knowledge is obtained in finite time. SFI working paper 91-09-35 "Knowledge and Meaning... Chaos and Complexity" appears in Lam and Morris (1991).

4.2.3 Semantic Information Processing

This project involved Crutchfield's reinterpretation of a previous paper, "Reconstructing Language Hierarchies" (1990), the burden of which was formalizing hierarchical modeling. It was motivated by the problem that any modeling procedure has an irreducible subjectivity due to the necessary choice of a representation or model class. The answer was the introduction of a learning methodology to infer new model classes from old. The present project emphasizes how in a hierarchical system semantics naturally emerges. Crutchfield gives a quantitative definition of the meaning of a single measurement in terms of the observer's anticipated information gain and the formal language structure of the observer's model of the source. (See SFI working paper 91-09-33 "Semantics and Thermodynamics" which also appears in SISOC PV XII.)

4.2.4 Computational Irreversibility

Crutchfield has also developed a measure of irreversibility that can be estimated directly from a data series. When coupled with the classification of finitary stochastic processes, this work leads to new insights on the types of intrinsic computation in chaotic systems. For example, in contrast to the conventional observer-dependent interpretation of temporal asymmetry due to the second law of thermodynamics, computational irreversibility is an invariant property of a process. In this sense, it is more fundamental than asymmetry due to maximization of entropy.

4.3 Computational Complexity

Joseph Traub (Columbia U.) worked at SFI on computational complexity and the issue of what is scientifically knowable. There are not any known lower bound results on chaotic systems, and it is not even clear what the appropriate questions are to ascertain if there are lower bounds. As a starter, Mats Nordahl has suggested trying to estimate the fractal dimension of certain sets. This should probably be done initially in the worst case deterministic setting. Next, other settings might be considered. The goal of this research would be lower bounds and optimal algorithms for invariants. In addition, Alan Lapedes has suggested the study of optimal estimation and prediction for dynamical systems, and Traub intends to continue along the lines of those suggestions in continuing work after leaving SFI. A promising, but technically very difficult, area is a computational complexity theory for turbulence. This is, of course, an area where one barely knows existence and uniqueness, let alone a theory of optimal sampling and optimal algorithms.

While at SFI, Traub also took up the question of what is scientifically knowable. Theoretical computer scientists have proven many negative results concerning the non-computability and intractability of mathematically posed problems. What does this suggest about limitations on what is scientifically knowable? Can these complexity results provide guidance on what questions scientists might successfully pose? One particular point discussed at SFI is what characteristics an intractable scientific problem might exhibit. For example, if nature can solve a problem swiftly and with limited resources, should we be able to simulate nature easily and cheaply? One example that was the subject of much discussion was protein folding. In collaboration with Stuart Kauffman, Peter Schuster, and Lee Segel, Traub was able to explore various reasons why that might be difficult for computers.

4.4 Topological Computation

Many information-theoretic quantities such as mutual information, metric entropy, complexity, etc., are impossible to quantify without a notion of metric. In other words, it is not possible to discuss information processing and transmission without a notion of distance. In CAs, this is trivial, as the connectedness is regular and every cell that is physically next to another cell is next to the same cell in information space,. In order to quantify information-processing capabilities of more "natural" systems, it is necessary to develop a notion of metric, a concept that mathematically encodes the "informational distance" between elements.

To this end, SFI Member Bruce Sawhill has been investigating "topological computation," searching for methods of relating different computational metaphors to CAs by mapping the information network of the more "natural" system onto a CA. His primary attention has been focused on the relation of Boolean nets to CAs. He has chosen Boolean nets because they are the next less regular system after CAs. Boolean nets consist of a group of N nodes, each of which is characterized by a rule that gives a given output for a set of inputs. In most applications of Boolean nets, the rules are the same everywhere, just as in CAs. In general, each node has k "wires" attached to it, each of which is connected to either an input or an output of another node. "Wiring diagrams" of Boolean nets consist of all possible ways of connecting k wires to N nodes, a topology that is much more analogous to natural systems in which informational proximity is not necessarily correlated with physical proximity.

He has found that a large class of Boolean nets can be mapped onto CAs of dimension equal to $k/2$, where k is the number of wires attached to each node of the Boolean net. In principle, all Boolean nets can be mapped onto CAs of sufficiently high dimension, which brings forth the interesting concept of an effective dimension for information processing. He is currently using graph-theoretic and generating-function methods to enumerate the distribution of CA effective dimensions for all possible Boolean net wiring diagrams and to be able to construct the specific map for a given Boolean net in order to relate it to a CA and, hence, derive information processing measures. It is his intention to work with neural scientists at SFI to explore whether or not effective dimension is a motivating principle in the organization of naturally occurring non-regular information-processing networks.

5. BIOLOGICAL SYSTEMS

Biological systems are among the most complex that we observe. The interplay between biology and complex systems theory and modeling is deep and pervasive. (Within this report, for example, one could argue that some projects appearing under the rubric of core research, adaptive computation, or biological systems are more or less arbitrarily placed.) Because most of the phenomena thought to be characteristic of complex systems are observed in the biological world, biology provides a rich source of ideas to be incorporated in models and a strong challenge to modeling. For example, adaptation and evolution are commonly observed properties of living systems. As noted, much of the work at SFI is concerned with devising computational systems that are capable of adaptation and evolution. Their resemblance to living systems is assumed implicitly or noted explicitly. Adaptive computation techniques are also being applied to develop models that shed light on the operation of biological systems. These applications offer a way to grapple with a growing flood of data emerging about biology at the molecular level; increasingly the critical problems in biology are becoming problems of how to understand the representation and the communication of information in living systems.

5.1 Fitness Landscapes and Evolution Thereon

5.1.1 Mathematical Models for Evolution on Rugged Landscapes

Problems involving multi-peaked fitness or energy landscapes have attracted attention in evolutionary biology, structural biology (protein folding), condensed matter physics (glasses and spin glasses), and computer science (combinatorial optimization). Motivated by an important problem in the biology of the immune system, involving the somatic evolution of antibody molecules, SFI External Professor Alan Perelson and Catherine Macken are developing and analyzing a number of mathematical models for molecular evolution on multi-peaked, or rugged, landscapes. In previous work they have successfully characterized evolution on random landscapes and have used the mathematical results to interpret immunological experiments on affinity maturation by somatic mutation. They are now extending these mathematical results to a family of correlated landscapes. They are also expanding their work to encompass coevolutionary processes such as the simultaneous evolution of antibodies and viruses.

Their random model may be viewed statistically as a sequential sampling scheme. They sample at random from a distribution G. As each sample is drawn, it is compared with the current maximum sample value. If it is larger, then the maximum is updated; if it is smaller, another sample is taken as long as no more than D-1 samples have been taken since the most recent update of the maximum. If D samples have been taken since the most recent update, then the process stops. This sampling scheme has been studied by Jirina and Saunders to estimate tolerance limits. Their results on the fitness attained at the end of a walk, and the number of steps and trials needed to reach a local optimum, parallel those of Jirina and Saunders. In addition, their work provides insight into the progress of the procedure prior to stopping.

The goals in this work are both mathematical and biological. From the mathematical point of view, they hope to advance the understanding of the statistical structure of rugged landscapes, study dynamical processes on them, and exhibit relationships between their work and previous studies in statistics. Perelson and Macken plan to use this knowledge to increase understanding of the basic processes underlying affinity maturation in antibodies. They believe that by elucidating the structure of the fitness landscape underlying evolutionary changes in antibodies, one can gain insights into the manner in which specific mutations affect protein structure and function.

5.1.2 Statistical Characterization of RNA Secondary Structure and Derived Properties

Ribonucleic acids (RNA) are heteropolymers of Adenine (A), Guanine (G), Uracil (U), and Cytosine (C). RNA is unique among biopolymers in that the logic of complementary base pairing (A with U, G with C, as well as non-standard pairing of G with U) provides a replication mechanism by templating and, at the same time, causes single strands to acquire complex spatial structures by folding back onto themselves. The structure is known to affect the overall rate constant of replication as well as the stability against hydrolytic degradation. Because RNA sequences can be replicated (genotype) and because the kinetics of this process are affected by their structure (phenotype), RNAs are and have been ideal objects for molecular evolution experiments in the test tube and within the computer.

The structure of an RNA sequence conveys biological function. This is the case for rRNA, tRNA, RNA involved in splicing, and M1 RNA, the RNA subunit of RNase P from *E. coli*. RNA structure also affects the stability of the molecule, thereby providing an additional mechanism for controlling the lifetime of mRNA. The role of RNA secondary structure is also documented in nature by the conservation of secondary structure elements during evolution.

RNA structure can be broken down conceptually into a secondary structure and a tertiary structure. The secondary structure is a two-dimensional pattern of base pairings. The tertiary structure is the three-dimensional configuration of the molecule. As opposed to the protein case, in RNA the secondary structure is well defined; that is, the secondary structure provides the major set of distance constraints that guide the formation of tertiary structure. The reason is that base-pairing interactions responsible for secondary structure are hydrogen bonds, which are much stronger than the additional interactions responsible for three-dimensional conformation.

The definition of secondary structure used in most present-day computational approaches assumes *planarity*. Planarity essentially means that unpaired nucleotides inside a loop cannot pair with unpaired nucleotides outside a loop. Unfortunately, this is not all there is to secondary structure. Unpaired bases from different loop regions may pair with each other, forming so-called pseudo-knots. While the computational problem for strictly planar secondary structures had been essentially solved in the early 1980s, the problem involving pseudo-knots is still unsolved.

Under thermodynamically reasonable assumptions, the folding problem for planar RNA secondary structure can be attacked by the technique of dynamic programming.

SFI External Faculty members Peter Schuster and Stuart Kauffman, SFI Postdoctoral Fellow Walter Fontana, and their collaborators are working on two major sets of questions pertaining to statistical properties of RNA secondary structures.

The first is a quantification—and eventually a theory—of the variation of properties based on secondary structure as variations are introduced at the sequence level. What measures are appropriate for capturing this kind of "sequence derivative of structure"? How do the variations scale with sequence length? How do they depend on the nature and the size of the nucleotide alphabet over which the sequences are defined? In other words: they want to understand *landscapes* induced by RNA folding. By landscape they denote a map from the space of all sequences of a given length v into the space spanned by some property that depends on the structure into which a sequence folds. Such a property may be a scalar like the change in free energy associated with structure formation, it may be a set of kinetic constants that depend on the structure, or it may be a non-numeric object like the two-dimensional structure itself.

The second is a quantification of the variety of secondary structures that are attained by sequences of a given length, as well as their distribution over the space of sequences. How do the statistical properties of secondary structures vary with the base composition of the sequences? What fraction of those structures realized in the entire sequence space can be accessed within a small neighborhood of any sequence? How does this fraction vary with the base composition of that sequence? This issue is also referred to as "shape-space covering."

Both sets of questions are related with each other. Schuster and Fontana already have achieved progress on a variety of aspects. It is important to underline that they are only interested in a *statistical* quantification. A meta-problem arises when one considers the robustness of an obtained statistical quantification with respect to the details in the methods of folding, for instance. This is of particular importance since a variety of folding methods, emphasizing different aspects of the process, are being used. Results must not be idiosyncrasies of a particular method, but rather reflect inherent properties of sequence-structure mappings in RNA. This is in part already achieved by focusing on statistical features. In fact, their current results show a remarkable stability towards a variety of methodological details.

5.1.3 Immune Networks

External Faculty members A. Perelson and S. Forrest and collaborators are engaged in modeling the mammalian immune system. The immune system is an example of a complex, nonlinear adaptive system that is the focus of much modern biological research. Insights gained into the operation of the immune system will not only benefit the general study of complex systems but also shed light on important biological and medical problems.

Within the Theoretical Immunology Program, a number of different research problems were studied during 1991. These include: (1) the application of genetic algorithms to pattern-recognition problems in the immune system, (2) modeling the dynamics of HIV infection of $CD4^+$ T cells, and the role of HIV in causing the T cell depletion characteristic of AIDS, (3) modeling immune networks using novel computer-simulation techniques, and (4) modeling the control of plasmid copy number in bacteria.

(1) Maintaining diversity of individuals within a population is necessary for the long-term success of any evolutionary system. Genetic diversity helps a population adapt quickly to changes in the environment, and it allows the population to continue searching for productive niches, thus avoiding becoming trapped at local optima. In genetic algorithms (GAs), it is difficult to maintain diversity because the algorithm assigns exponentially increasing numbers of trials to the observed best parts of the search space (cf. Schema Theorem; due to John Holland). As a result, the standard GA has strong convergence properties. For optimization problems, convergence can be an advantage, but for other problems it can be detrimental. Further, even in optimization, strong convergence can be problematic if it prematurely restricts the search space.

    By studying the ability of the immune system to recognize a large diverse set of molecular patterns, Perelson, Forrest. and graduate student Brenda Javornik were able to develop a new version of the genetic algorithm that is able to maintain diversity and solve multi-peak optimization problems. They applied the algorithm to the problem of evolving a set of antibodies that can cover, i.e., simultaneously recognize, a set of antigens.

(2) One of the hallmarks of HIV infection is a gradual decline of the CD4 or helper T-cell population. They developed a dynamic model of the interaction of HIV with helper T cells and were able to show, using realistic parameter estimates, that HIV infection of T cells can cause a gradual decline in the T-cell population over a period of 5 to 10 years, a feature characteristic of AIDS. They were unable to get the T-cell population to fall below $200/mm^3$, and conclude that while direct killing of T cells by virus contributes substantially to T-cell depletion, it cannot be the only factor of importance in the onset of clinical AIDS.

(3) The pattern-recognition capabilities of the immune system are so great that the system can recognize the unique features of its own antibodies, their idiotopes. Because of idiotypic recognition, Jerne suggested that the immune system is organized as a network of interacting cells and molecules. To test these ideas, SFI External Faculty members Rob DeBoer, Gérard Weisbuch, and Perelson, together with Lee Segel, have developed a number of different models of the immune network and studied their properties. In one of their more interesting studies, they built a model containing both B cells and antibodies. The specificity of the antibody and cell surface receptors on B cells were coded for by binary strings. A string-matching algorithm was used to determine when antibodies would bind to other antibodies to form antibody-antibody complexes, or to cell surface receptors, that could lead to the stimulation of B cells. An artificial bone marrow created new B cells every day. If these cells were stimulated by interacting with antibodies in the serum of the animal, they would respond by proliferating and secreting antibody. If they were not stimulated, they died. Over the course of about one month, an idiotypic network developed that had many properties seen in mice. First, the early network was rather large and composed of highly multireactive antibodies. Later in the life of the animal, selection caused the network to grow smaller and to contain more specific antibodies. The model also exhibited oscillations in the antibody of particular idiotypes but maintained a constant total-serum immunoglobulin level. These again are features seen in mice.

(4) Plasmids are independently replicating circles of DNA found in bacteria. They are of great interest to the biotechnology community because extraneous genes can be inserted into a plasmid, the plasmid can be put into a bacterium, and the replication of the plasmid can increase the copy number of the inserted gene. Also, the mechanisms that control plasmid replication are prototypes for general replication control mechanisms. DeBoer, Weisbuch, Segel, and Perelson have been developing a model of replication control of the ColE1 plasmid. The model they have developed incorporates most of the known biochemical facts about the control mechanism. This leads to a model with a great many equations. By using methods of quasi-steady-state analysis they have been able to simplify the model and obtain many analytical results that have helped them understand the principles underlying the mechanism that controls the number of plasmids within *E. coli*.

SFI Postdoctoral Fellow Thomas Kepler joined the Institute's research staff in October 1991. His research involves the mathematical modeling of complex biological systems. In the past I have worked with models of the nervous system, both highly simplified (Hopfield nets) and more realistic. At SFI his attentions have turned toward the immune system, in part because of the challenge of studying a new, relatively unmodeled system, but also to take advantage of the opportunity to study with Alan Perelson, one of the most highly regarded theoretical immunologists working today. Kepler's current work focuses on the immune system, in particular, on the process of hypermutation and selection that plays an integral role in the immune response to foreign proteins. He is studying the ramifications of simplification of dynamical systems on a discrete lattice for computer simulation and trying to determine how much simplification, for a given system (and questions to be answered about that system), can be tolerated before information loss destroys the relevance of the model. He is trying to apply these simplified models to variety of problems arising in the theory of the immune system, including (1) affinity maturation, whereby the response to a given foreign protein involves not only only the "selection" of high affinity clones but the mutation of these clones to higher affinity forms, and (2) self-tolerance—do the peculiar interactions between B cells and T cells act as a safeguard against self-reaction? On a cellular level his research concerns the dynamics underlying calcium release and oscillations in immune-responsive cells. This latter work is being done in collaboration with Janet Oliver and Becky Lee (UNM School of Medicine).

5.2 Models of Genomic Structure and Organization, Gene Interaction, Genome Evolution

5.2.1 Algorithmic Chemistry

"Algorithmic Chemistry" was conceived two years ago with the topic of "molecular evolution" in mind. At that time the goal was to devise a system in which interactions among objects produce specific new objects. By this, SFI Postdoctoral Fellow Walter Fontana, Leo Buss (Yale U.), and their collaborators wanted to go beyond existing conventional models in molecular evolution.

In those models, predetermined features of objects that do not act at all upon each other are optimized by replication, mutation, and selection within a population. See, for example, the quasi-species model of Eigen (1971), or genetic algorithms. Some models, for example Eigen's and Schuster's Hypercycle (1978), include interactions between objects. These interactions, however, are always such that the action of one object upon another results in replication—that is, copying (error-prone or not) of one of the interaction partners. This state of affairs is summarized in the widely used replicator equation, which—as the name suggests—is conceptually based upon the paradigm of the "replicator." The latter is a term introduced by Dawkins and defined as a unit of "which copies are directly made."

It is evident that a variety of objects entertain what they call "constructive" interactions—that is, interactions where specific new objects are built. The obvious example, and main inspiration, was (and still is) chemistry. But one may think as well about cell-cell interactions where a new cell type is induced. The problem, then, was to devise a model where arbitrariness was reduced to a minimum. This effort eventually led to the realization that what one was trying to introduce was precisely the mathematical concept of "function," in particular that of a "computable function." So why not use directly objects that are a suitable representation of discrete symbolic functions? In particular, why not use a representation of "function" with no syntactical distinction between the function, the argument, and the value, so that particles can appear in each of these roles?

The model then became a system in which particles are symbolic expressions built according to simple syntactical rules, and in which a few axioms specify how expressions modify syntactically other expressions. The first implementation of the system was based on a slightly idiosyncratic and down-sized version of toy-LISP, while the current rigorous version is based on the standard λ-calculus.

Pictorially speaking, the system consists of a stochastic "reaction vessel" initially filled with an ensemble of 1000 randomly generated function expressions. Two expressions are picked at random, and the first is applied to the second. The result is a new expression that is released into the system. To keep the system finite—and to apply the simplest selection pressure—one expression is chosen at random from the ensemble and thrown away. The system is back to 1000 particles. The random deletion mimicks an unspecific dilution flow. Hence, expressions that have no production pathways within the system are bound to disappear. In what follows they describe the situation when no individual copy actions are allowed.

Initially almost every "collision" is innovative; that is, the resulting expression has never been in the system before. After a large number of collisions, the system approaches an "attractor," but a new type of attractor: an algebraic (or better, applicative) structure. An abstract applicative structure is a set of objects O, together with a map from O x O into O, that assigns to each pair of objects from the set a third one in the same set. That map is a description of all relationships among the objects. First, their system of function,particles organizes in the sense that this description is always a very concise one compared to a list of all individual pair,interactions in the system. That is, the set of all relationships among objects is itself describable by some rules. And these rules never refer to the syntactical structure of the objects (think of a group, for example). Second, even if the system produces new particles while being on the attractor, these particles do not disturb the applicative structure (that is, the attractor). This simply means that the structure is defined over an infinite set of objects, of which their finite system can "see" only a tiny fraction. The important result, however, is that the attractor is an organization, rather than some ω-limit in concentration space. That is, particles can be created or destroyed, but what remains invariant is an abstract organizational structure—a set of relationships. Furthermore, in compliance with their selection pressure (finite system), all resulting applicative structures are self-maintaining—that is, the set of objects in the reactor, when applied to itself, reproduces itself. This is like an identity function, but at the set level rather than at the individual function level. An important third aspect is that the function particles organize on the syntactical level as well. It turns out that when the system is on the attractor, all expressions share a common syntactic architecture (in addition, obviously, to being "legal" expressions in the first place). That is, they form a language. And, as one may expect at this point, action of any expression upon any other preserves this syntactic architecture. Hence, there is an attractor on the syntactical level as well: a language.

When copy actions were allowed, no complex organizations formed. The system produced an ecology of various individual identity functions.

This line of research entered a new conceptual phase when the collaborators decided not to interpret the function expressions as emulations of some real physical interactors, be they molecules, cells, or whatever, but rather to take them as what they are: abstract functions. That is, they view real objects to be carriers of functions, but they do not take into account the actual physical mechanics by which this is achieved. They solely retain the fact that they are "carriers" (i.e., syntactical level) of "functions" (i.e., maps establishing relationships among objects). In fact, all of the above is purely a logical consequence of the notion of an ensemble of "function carriers."

While it may be meaningless to attempt a one-to-one interpretation of their particular abstract functions in terms of biological objects, it is very meaningful to interpret the generic properties resulting from their model in biological terms. The claim is that irrespective of how "function" is physically instantiated, the generic properties of the model will be always observed, independent of "implementation" details. For example:

- The switching off of copy actions is a necessary and sufficient condition to generate "higher order" entities (sets) that are self-maintaining under their own action.
- Switching on copy actions after higher-order entities have been generated does not destroy their organization.
- The self-maintaining sets show remarkable properties of self-repair, or self-regeneration: deletion of many elements in such a set is tolerated because remaining interactions can re-construct the deleted elements.

In some cases the entire set minus one function can be destroyed, and this one function regenerates the entire organization. There are cases where it didn't even matter which function was left over.

Much more could be added, but this requires a context setting beyond the scope of this report. It suffices to observe that the history of life underwent several crucial transitions in which entire replicator ecologies became new, higher-order, self-reproducing units. Self-replicating molecules aggregated to form primitive cells with metabolisms, primitive cells aggregated to form modern eukaryotic cells, and eukaryotic cells aggregated to form metazoa. During such transitions, life found solutions of how to "switch off" copy actions at the lower level. Such solutions range from the genetic code to developmental cleavage patterns. In this framework this is simply a switch. At this level of generality, nothing can be said about how "the life we know" achieved it. This model can say, however, that—in accordance with the reading of the record—it is a necessary switch in achieving the next level of organization. The model also suggests that the organizational features at level n are set by the no-copy units at level $n-1$ rather than by the replicators of that level.

Buss and Fontana are currently extending the model to level 2 organizations, that is, self-maintaining sets of sets.

Biology lacks a theory of organization. Genes make products, and it is the products that make organizations. Genes—the replicators—change dramatically over geological times; basic organizations do not. The genetic code is practically conserved throughout the living; cell architectures are conserved at the kingdom level; and bauplans of metazoan phyla are conserved since the Cambrian. In the mainstream thinking of theoretical evolutionary biology, however, genes are accorded special status, but organizations are not. The reasons for this are, in part, of historical nature; in part, however, the situation results from the lack of a conceptual framework that is able to address entities that are organizations, that is, sets of functional relationships. Buss and Fontana believe that to make further progress, theoretical evolutionary biology must shift its attention from population genetics to theories of organization. They view their work as a first powerful thrust in the direction of such a paradigm shift.

5.2.2 Computational Approaches to Genetic Data Analysis

Led by SFI External Associate Professor Alan Lapedes, the major focus of this research network has been on the development and application of new learning algorithms to genetic data analysis. The Human Genome Project will be producing billions of bases of sequence information. Analysis of information storage (coding issues) and information usage (e.g., mechanisms of protein folding) will be critical to the success of the Human Genome Project. It is anticipated that an interdisciplinary approach, grounded in the philosophy and techniques of analysis of complex adaptive systems, will not only yield practical advances in understanding biological systems (for which we will soon be inundated by a flood of data), but will also foster the development of new adaptive systems and algorithms useful in data analysis.

In collaboration with Ken Abremski (duPont), they have analyzed the problem of identifying promoter sites in *E. coli*. Here, there is sufficient data to attempt neural net approaches if one employs novel architectures incorporating translation invariance. Future work will compare this approach to the EM method that works well in the data-limited case. Accuracies are the highest reported in the literature. A key aspect to the success of this investigation was an initial, thorough, information-theoretic analysis of the data before using a neural net. By calculating the mutual information of both nucleotides and dinucleotides with the class information (two classes: "True" or "False" promoter), they were able to reduce the number of adjustable parameters and achieve significantly better predictive accuracy than more conventional methods. Very general software for producing a graphical display of various definitions of mutual information was developed and was crucial to visualization of the complex data relationships involved in this problem.

In collaboration with Karl Sirotkin (LANL), they have developed a novel approach to identification of eukaryotic splice sites. Previous work concentrated on the determination of whether isolated acceptor and donor sites are transcribed to RNA. The new approach attempts to determine if the acceptor and donor sites are actually correlated, and then to capitalize on this information for prediction of paired splice sites. Using an information-theoretic analysis and the graphical display of mutual information mentioned above, they conclusively demonstrated that there is significant mutual information between properly paired acceptor and donor sites. Actually using this information to increase predictive accuracy involves a very careful analysis of statistical and neural net procedures which is in progress. Elucidation of the physical mechanism for the shared information is also in progress.

In collaboration with Jim Fickett and David Torney (LANL), an analysis of correlations in DNA over centibase and kilobase scales was performed. A surprising and virtually exact symmetry was discovered between the correlations of the number of base pairs in specified-length "windows" of DNA. The correlations increase with the length of the window, and the following pairs of correlations track each other essentially exactly: correlation of ("a-t" tracks "g-c"), ("a-g" tracks "c-t"), ("g-t" tracks "a-c"). Investigation of possible physical mechanisms for this surprising effect is in progress.

An investigation is in progress on determining the effects of other statistics in addition to codon frequencies in the prediction of whether isolated fragments of DNA come from exons or introns. Use of high-order statistics (beyond the third-order statistics of three adjacent bases) generates an exponentially increasing number of adjustable parameters. They have developed an algorithm that "prunes" away irrelevant parameters and are in the process of using this approach to identify crucial statistics beyond codon frequencies that contribute to the predictive accuracy. They are also developing an information theory package of programs that selects only the relevant statistics and then inputs them into a Bayesian predictive scheme.

Work is in progress on developing a maximum-entropy predictive scheme that uses the maximum entropy probabilities given certain measured marginals in order to improve predictive accuracy. Clearly, these approaches have greater utility than in just DNA analysis and are part of their general program of developing new and novel approaches to the classification of discrete data.

They are continuing their research into the prediction of secondary and tertiary protein structure. Many algorithms, including neural net approaches, have been applied by their group and other groups to the secondary-structure prediction problem with disappointingly low accuracy. This has led to pessimism by researchers in the field that secondary-structure prediction is perhaps intractable given the data available. However, they have observed that the different algorithms use different features in the data and, in fact, make different errors. Thus the fact that no single algorithm succeeds with high accuracy is not indicative that the problem is insoluble given the present data. Indeed, the hope is that by judiciously combining algorithms, one may "tile" the space of accuracy. In other words, what one algorithm misses, another algorithm may predict correctly, and the problem reduces to the proper combination of algorithms.

5.2.3 Morphogenesis and Its Evolution

In May 1991, the international Third Waddington Meeting on Theoretical Biology was held at the Santa Fe Institute. These meetings, founded by the biologist C. H. Waddington in 1966, are devoted to exploring the foundations of theoretical biology, specifically to see if the current theory of evolution provides adequate basis for understanding the living process and, if not, how it needs to be changed. What distinguishes these meetings from most biological inquiry is the recognition that the fundamental entity that needs to be understood is the whole organism with its properties of reproduction, heredity, regeneration, and adaptation; and how these give rise to the order revealed in evolutionary transformations, the hierarchy of organismic forms, and the dynamic balance of ecosystems. The focus is on the science of wholes that complements the analysis of parts, the preoccupation of contemporary biological study.

A topic of discussion at the Santa Fe meeting was the search for a way of describing the properties of self-completion and dynamic stability that characterize the living state and its capacity for reproduction and regeneration. One line of investigation arises from Kauffman's study of the properties of an interacting network of catalytic peptides using analytical procedures similar to those employed in his genetic network model. This scenario for the evolution of self-replicating and adapting networks of interacting components has been developed by Walter Fontana, who participated in this meeting. Fontana reported on the behavior of reactive systems simulating polymer catalysis, synthesis, and degradation, using a basic recursive language that maps character strings into algorithms that symbolically manipulate strings. The result is "algorithmic chemistry," or Alchemy, a powerful tool for the systematic investigation of chemical networks and the search for conditions giving rise to catalytic closure, described in the core research section.

What is absent from Fontana's model, however, is morphology, another distinctive attribute of organisms, along with functional complexity and capacity for reproduction. Some indications of how organismic morphology can be understood in terms of the generic properties of complex dynamic systems, providing a complementary approach to that described by Fontana, come from studies reported by Goodwin and Kauffman on morphogenesis. This work provided the basis for much of the discussion during this meeting.

The substantive point at issue here is identical to that addressed by Fontana but now transposed to the generation of form: is there some simple organizational property of complex molecular systems of the type encountered in organisms that results in robust patterns of morphogenesis? At first sight, one might expect that increasing complexity of dynamic modes available to a system would simply result in a rapidly increasing variety of possible trajectories leading to a combinatorial explosion of potential forms. Such a plenum is actually postulated by neo-Darwinism, which assumes the existence of a dense set of possible morphologies whose differences from one another are small. Natural selection can then proceed by small steps from one adapted form to another, satisfying Darwin's injunction that discontinuities or large jumps are frowned upon by a nature that changes by evolution, not revolution, thus embodying political principles of good taste. The discontinuities that we see between existing species, frogs and horses, poppies and oak trees, arise through natural selection, which stabilizes those forms attaining local maxima of fitness in their habitats. What guides developmental trajectories from simple spherical eggs to complex adult forms is the genetic program of the species, steering the developing organism through dense thickets of possible forms to the structure preferred by natural selection. The stability of the species developmental trajectory, which repeats itself in developing individuals generation after generation, thus arises from the pattern of gene interactions programmed in genomes. Since these interactions arise historically by natural selection, the species is an individual, not a type or a natural kind.

One of the basic difficulties with such a view is closely related to the error catastrophe mentioned in relation to stable DNA replication when the nucleotide sequence exceeds 100 or so. DNA is simply not able to hold the complex developmental process on a low-probability course through a very large set of possible trajectories because mutations and environmental perturbations throw the system off course and result in a broad spread of morphologies distributed over the dense set of possibilities. Therefore, the discontinuous nature of taxa cannot be explained by genetic programs or natural selection. It is necessary to look for other explanations.

What makes the search for alternatives even more urgent is that genetic programs are unable to explain morphogenesis itself. This is because genes make molecules, so the genome can explain the molecular composition of an organism, but molecular composition does not determine form, whether it be in physics, chemistry, or biology (cf. Goodwin, 1990). Other principles of spatial organization need to be introduced to model morphogenesis. It is the study of these that leads to an alternative explanation of morphogenetic stability than that which invokes genetic programs. The key is found in the study of morphogenetic dynamics, which is nonlinear and shows a dramatic reduction in the set of stable states compared with an equivalently complex linear system in which there is a superposition or addition of possible states. Just as interacting nonlinear oscillators tend to synchronize or entrain to stable common frequencies, so nonlinear spatial modes tend to cohere to generate stable spatial patterns. Examples of this type of behavior have been observed by Murray (1989) and deduced by Kauffman for systems with interacting spatial modalities involving processes such as cell sorting due to adhesive gradients and cell state specification by morphogen gradients. Such systems tend to develop along trajectories to stable spatial configurations that are few in number relative to the degrees of freedom of the system; i.e., there are may fewer attractors than one might expect from the complexity of the system. A particularly dramatic example of this is provided by a study carried out by Goodwin and colleagues on morphogenesis in the giant unicellular alga, *Acetabularia*. A three-dimensional model was constructed using basic properties of the cytoplasm interacting with calcium to generate spatial modes of mechanical strain and calcium concentration. This then interacted with the cell wall to produce patterns of growth and morphogenesis. The model was mathematically complex, with twenty-six parameters and a large set of possible behaviors, though it was biologically simple. However, it turned out that the interaction between two dynamic modalities resulted in a great reduction in the set of stable morphogenetic trajectories. These two modalities were the spontaneous symmetry-breaking dynamic of the calcium-cytoplasm system, and the changing shape of the cell due to growth of the wall. Their interaction resulted in the stabilization of particular morphogenetic trajectories which simulated with remarkable precision the patterns of change observed in the actual organism during development or regeneration. The causation here is distributed, and the morphogenetic trajectory appears to be robust, though further studies are required to pursue this systematically. Furthermore, there is virtually no genetic program involved in defining the morphogenetic sequence, which occurs for fixed parameter values. So, just as Fontana's model suggests how reproduction can arise as a robust property of a complex system that is not dependent on a central directing replicator, a DNA, so dynamic models of morphogenesis suggest how this process occurs as a robust dynamic that is minimally dependent on a central controlling genetic program. The genes are, of course, a part of the overall dynamic, just as are environmental factors, but they are not dominant elements. They act within the context of a dynamic system with its own distinctive properties, adding to the stability of morphogenetic trajectories and so increasing the robustness of species morphology rather than being primarily responsible for it; taxa are, from this perspective, stable attractors in morphogenetic space. This stability includes the capacity of the species to persist in particular habitats—i.e., the life-cycle trajectory, not simply the morphogenetic trajectory. The implications of this view regarding the dynamics of evolution are very great, since it is possible that major characteristics of this process such as species' lifetimes, parallelisms, evolutionary stasis, polyphyletic origins of complex structures like eyes, and the hierarchical characteristics of biological taxonomies, are all fairly direct consequences of the robust dynamics of development.

5.3 Neurobiology

5.3.1 Dendritic Neuron Models

"Implications of Dendritic Models for Neural Network Properties," a small, intensive workshop, was held at the Santa Fe Institute in October 1991. Organized by Wilfrid Rall (Mathematical Research Branch, NIDDK, National Institutes of Health), this workshop focussed on the experience and insights gained by participants in their mathematical and computational studies of neuron models which are realistic in the sense that they preserve some of the distributed anatomy and some of the nonuniform, nonlinear, membrane properties of biological neurons.

Most of the participants were experienced both in physics and in experimental neurophysiology; all shared a conviction that dendritic synaptic input patterns and membrane nonlinearity are important in actual biological neural networks. In addition to discussion of recent experiments and computations, attention was given to identifying collaborations that could offer special promise of demonstrating how network properties can be enriched by including realistic neuron properties in network models.

Participants were John Miller (UC Berkeley), Larry Abbott (Brandeis), Idan Segev (Hebrew U., Jerusalem), John Rinzel (NIH), Charles Wilson (U. Tennesee Center for Health Sciences) Julian J. B. Jack (Oxford), William R. Holmes (Ohio U.), Thomas M. McKenna (ONR), Wilfrid Rall (NIH), Bryan Travis (LANL), Valerie Gremillion (LANL and SFI), and Andre Longtin (LANL and SFI).

Likely collaborations to result from this meeting are: Abbott & Rinzel: on nonlinear dynamics of neurons; Abbott & Miller: on an information-theoretic approach to neural coding; Julian Jack & Valerie Gremillion: on some aspects of modeling of synaptic inputs to pyramidal cells of visual cortex; Jack Wilson: on the non-uniqueness in fitting simple neural models to experimental data, especially when anatomical structure is excluded; Wilson, Travis, & Gremillion: computations that incorporate Wilson's experimental data in Travis's comprehensive computer program; Miller, Bialek, & Longtin: on exploration of stochastic resonance; Segev & Rinzel: on axon propagation involving varicosities; Segev & Rall: on reduced neuron models preserving essential nonlinear dendritic processing; Travis & Rall (perhaps with Holmes & Segev): on testing effects of reduced models in the system Travis has programmed; Travis & Longtin: effects of noise introduced into auditory processing .

5.3.2 Theory of Cortical Function

Charles Stevens (Salk Institute) visited at SFI during the summer of 1991 and did exploratory work on a theory for cortical function. The final goal of this work is to describe the mathematical computation carried out by cerebral cortex (!), and the specific goal of his visit was to start developing a theoretical framework appropriate for such a theory.

A lot is known about the structure and function of the cortex. Different cortical areas subserve different functions such a movement, vision, and language, but all cortical regions have a common general structure and develop according to the same rules. A large body of evidence suggests that all cortical areas actually carry out the same computation—the difference between visual and language cortex, then, would lie in the distinct arrangement of cortical inputs and outputs rather than in what computation the cortex does—but this uniformity of cortical function is still not firmly established. Were it true, the existence of such uniformity would make the proposed theory more attractive.

What Stevens did at SFI was: (1) develop a theoretical framework for a description of cortical function that looks much like the usual field theory formalism, and (2) use this formalism for a very simple case. The "field" is the output f(x) of the cortex at location x; one can think of f(x) as the firing rate of neurons at a particular cortical location (but this is a simplification). For simplicity, examples are given only for a one-dimensional cortex where the real thing would have two or more dimensions. Furthermore, the temporal evolution of response has been ignored; this approach considered, for example, the steady response of the visual cortex when the animal views a fixed pattern.

The "works" of the cortex are embodied in a "Lagrangian" L(x) that is a functional of the cortical input s(x), the firing rates of neurons projecting into cortical location x. Stevens plans to try, using information about the cortex (like the fact that cortical function, the number of connections, and size of cortical circuits are unchanged when evolution scales a cortex up hundreds of times), to deduce some general properties of the cortical Lagrangian. The first step, however, was to treat the simplest possible case: to carry through the theory for a model system, a simplified retina, to see what is involved.

Why a field theory? In all types of cortex, the output from a particular location feeds back to modify the output of neighboring locations. Thus, the output at any location depends not only on the entire cortical input, but also on the entire output. Furthermore, the operation of neurons is, in several fundamental ways, probabilistic so that the cortical output to a particular input must be specified as a probability. Thus the cortical state should be described as a probability P[f(x),s(x)] that is a functional of both the output f and the inputs. A good formulation leads naturally to the lowest-order description of cortical function; a theoretical framework should thus should yield a power series (or something similar) in which the first terms give a reasonable approximation.

Stevens postulates that a field theory-like formalism has these desirable characteristics and has begun such a formulation. The formalism provides a natural framework for his simplest example. The question now is if generalizations to more interesting cases will be possible.

5.3.3 Theoretical Neurobiology Initiative

While at the Institute during the summer of 1991, Stevens also worked on a proposal for establishment of a working group on theoretical neurobiology at SFI. This has now been funded by the Pew Charitable Trusts, and it is expected that this field may become the area for a major research initiative at the Institute in 1993 and beyond. Although there is virtual agreement that understanding the complexities of the brain will ultimately require sophisticated theoretical approaches, an effective theoretical neurobiology does not exist. Using the highly successful theoretical immunology program as a model, SFI proposes bringing theorists and "theory aware" experimentalists together in an intensive working group in which theorists and experimentalists can interact for two purposes: to start informing the theorists about what problems would interest the experimentalists, and to establish an appreciation among the experimentalists about theory might offer. The working group will initially be a one-year experiment. If successful, a longer-range plan will be developed.

6. ECONOMICS AND SOCIAL SYSTEMS

6.1 Economics

The Economics Research Program is dedicated to the exploration of the economy as an evolving complex system. In contrast to neoclassical economics—the leading paradigm in economic theory—the program's research is not directed to the search for equilibria, characterized *statically* as systems of production and consumption decisions at given prices under which all markets clear. Rather, its object is to describe the *dynamic* processes operating under conditions of incomplete markets, imperfect competition, and bounded rationality that lead to the creation of markets and prices, and the evolution of economic aggregates and institutions. The program emphasizes the mathematics of stochastic processes and computer simulation, instead of the traditional topological methods of neoclassical economics. In keeping with this interdisciplinary methodology, for the year 1990–91 the economist John Geanakoplos and the probability theorist David Lane acted as program directors. SFI's economics research, including its residential work, research initiatives and workshops, falls into three general categories which capture the program's preoccupation with economic adaptation and its modelling: learning and adaptation in the economy, game theory, and the emergence of market behavior.

6.1.1 Learning and Adaptation in the Economy

Technological Innovation: An Artificial Economy Approach

Researchers: External Faculty members David Lane (U. Minnesota) and John Miller (Carnegie-Mellon); Giovanni Dosi and Marco Lippi (U. Rome, Italy); Franco Malerba and Luigi Orsenigo (Bocconi U., Milan); Paul Tayler (Coopers Lybrand Deloitte, London); and James Pelkey (Santa Fe)

One can assume an economy to be self-organizing, organized into a complex network of different types of agents, interacting with one another through markets and other institutions, generating both positive and negative feedbacks—with an endogenous energy source, technological innovation. To show how such a system can generate its own order—and to determine the nature of that order and the conditions under which it will emerge—this research network focuses on creating a microfounded computer model of an economy. This Artificial Economy is, of course, much simpler than any real economy: it consists merely of five kinds of agents—two types of firms, laborers, research workers, and a central bank; three markets—for labor, machines, and consumer goods—each with its own particular interaction rules; and regulations governing savings, loans, and bankruptcy procedures. Type 1 firms produce machines that Type 2 firms use to make goods that the workers consume. In addition, Type 1 firms may hire researchers to try to design new types of machines, to improve machines they currently can produce, or to imitate machines produced by their competitors.

In this Artificial Economy, Type 1 firms must decide how much to invest in innovative research and development and in imitative search, while Type 2 firms must decide how much to spend on new machines—and which machines to buy. Both types of firms must decide how much to spend in production, how much to borrow from the central bank, how much to pay workers, and how to price the machines and consumer goods that they produce. The firms must *learn* how to make these decisions in the light of the successes or failures they achieve in the market place, based on the decisions they have already made in the past. The aggregate effects of the firms' decisions determine the macroeconomics of this economy: growth, unemployment, labor productivity, capital stock, and all the rest. In addition, as a result of the decisions they make, some firms prosper, some languish, and some die, determining distributions of firm size and life cycles, so that industrial demography will be an emergent property of the model. A demography of *innovation* will also emerge: which firms innovate (as a function of size, market share, age), and which imitate? And more importantly, *why*, in terms of the properties of the industrial environment in which these firms operate?

The model for this Artificial Economy contains a number of system parameters that control such "environmental" features as degree of technological opportunity (how likely it is that an investment of n dollars in R&D will result in a new machine, and, if it does, how efficient and inexpensive will that new machine be?), cumulativeness of innovative search (how past investment and success in innovation by a firm affect the probability of success in future R&D initiatives), and appropriability of innovation (how difficult it is for competitor firms to imitate successful innovations). Thus, the model may be used as an experimental tool to explore how emergent patterns of persistence and stability depend on the level of these environmental features. In addition, it will be possible to analyze the effects of certain public policies: for example, policies like patent laws or government investment in R&D that affect the values of certain system parameters; or policies that change such institutional features as market or banking rules or bankruptcy laws.

At the firm level, the Artificial Economy provides a laboratory for analyzing the effects of learning algorithms and decision rules. For examples, the performance of firms that price only according to fixed mark-up rules can be compared to those which employ adaptive pricing strategies that respond (more or less strongly) to market signals. Again, firms that engage only in "radical" innovative search can be compared to those who seek only incremental improvements in their own existing machines or to those who merely imitate the machines of their competitors. Of course, which decision rule is best can depend on the value of system parameters, as well as attributes of the firm employing the rule (its size, the other rules it employs, the way in which it learns, and so forth).

Random Grammar Models and Technological Evolution

SFI External Faculty member Stuart Kauffman is using grammar models (described in Core Research) to study technological evolution in a new way. There is no theory of which goods are substitutes or complements of one another. But grammar models provide a novel approach. Just as any grammar mapping the power set of strings acting on itself into itself is a mock up of the laws of chemistry, so too any such grammar is an "as if" model of the unknown laws of technological complementarity and substitutability. One has no idea what those laws are. But if researchers can find that large regions of grammar space yield model economies which behave much as do real economies, there will be grounds to map real economic technological growth to the same universality class.

With economist Paul Romer, Kauffman is modeling a good or service as a symbol string. Interactions among symbol strings to produce symbol strings now become the economist's production functions. Strings used in the same "machine" are complements. If one string can replace another in an input bundle or machine and yield the same output bundle, the two strings are substitutes. Each symbol string is accorded a utility via a spin-glass-like model. In the current study, a hypothetical social planner optimizes a finite-time horizon plan for the economy. The economy consists of a set of symbol strings which can be mined from the ground in each period. The planner knows the utility function of all strings and knows the grammar. The planner's task is to optimize the utility of the strings produced and consumed over time subject to a discount for future consumption. Optimization is carried out by linear programming. This model is functioning currently at SFI.

This symbol string model enables the study of three fundamental features of an economy. The first is technological evolution as a function of the complexity of the current economy. The second may be a deep new view of bounded rationality: Optimally rational agents should only plan a finite distance into the future, not due to costs of computation but because plans diverge chaotically. The third, based on the second, is a hint of a new non-equilibrium solution concept in economics. Markets will not clear but nearly clear at the edge of chaos.

Workshop on Learning, Rationality and Games

Researchers: SFI External Professors David Lane (U. Minnesota) and John Geanakoplos (Yale)

Cournot-Nash equilibrium and the learning it allows for is unbelievable for at least three (possibly different) reasons. First, the amount of information that each player must possess is completely unmanageable, as indicated in the speculation example of the beliefs hierarchy implicit in the definition of equilibrium. Second, it is not at all clear how an agent could ever come into possession of knowledge that includes every other agents' plan, even if he could retain it all. Third, the rationality imposed by the equilibrium conditions is so strong that it sometimes rules out plausible behavior. For example, it has been shown (by Milgrom and Stokey, and Geanakoplos and Sebenius, following earlier work by Stiglitz, Kreps, and others) that there can be no pure speculation in Cournot-Nash equilibrium, despite the generally accepted view that there is indeed a great deal of speculation in financial markets. Since Cournot-Nash equilibrium lies at the heart of game theory, which lies at the heart of much of economics, these issues of learning and rationality in games are critical for economics, and they formed the focus of this Santa Fe workshop.

A number of different approaches to bounded rationality in games were proposed at the workshop. The algorithmic approach models each player by a computer program that may evolve through mutation or recombination. Brian Arthur and Peyton Young described that approach, which has been very popular in Santa Fe, and Arthur suggested that by tuning the parameters in the algorithm in his model, he could calibrate human learning.

Economists Kalai, Canning, and Dekel took a probabilistic approach to economic equilibrium. Kalai investigated the conditions under which a touch of the truth could evolve into a full-fledged equilibrium, if the players are Bayesian statisticians. Canning argued that a little bit of external noise helped agents evolve to equilibrium. Dekel studied the interaction of noise and evolutionary stable equilibrium.

Computer scientists Vardi and Moses separately described hierarchical approaches to knowledge and common knowledge and pointed out that similar problems of knowledge arise in economics and computer science. Yaw Nyarko presented an economic model of hierarchical knowledge.

Geanakoplos and Rubenstein each presented models in which agents do not process information optimally. Geanakoplos argued that one could specify precisely what kinds of information-processing errors are necessary to permit speculation, and which are necessary to allow people to agree to disagree.

Gray presented joint work with Geanakoplos on chess. This work has resulted directly from collaborations conducted at SFI. The game is interesting because it is typical of real-life situations in which one cannot quantify one's ignorance. Gray argued that no matter how one quantifies ignorance in chess, as long as it satisfies a few axioms, then a Bayesian approach always yields the same lessons of how to pick the optimal move, and how to search among the nodes of the tree for the right positions to evaluate. He maintains that these lessons could be applied to the design of computer chess algorithms, and he expressed surprise that the Bayesian approach to chess had not been much pursued before.

Blume and Easley cast doubt on the age-old argument that market pressure itself forces agents to act optimally, or else not survive. At the most basic level, an agent can be perfectly rational but prefer consumption today rather than consumption later. Such impatient agents will tend to disappear, despite their rationality. But even assuming all savings rates are the same, it is still not the case that survivability is maximized by betting on the best possible horse, given the odds; i.e., it may not be the case that maximizing solvability is consistent with maximizing any expected utility.

Blume and Easley presented another paper trying to interpret the basic spin glass model in an economic context. This has been tried by several other economists, but it must be admitted that the interpretations have seemed strained, although the prospect that the model could be integrated into economic theory is exciting.

Schmeidler and Machina reexamined one of the foundational issues of decision theory: the derivation of probabilistic beliefs and expected utility maximization. Whereas both of these have been derived simultaneously from the hypothesis of rationality, Schmeidler and Machina show that different kinds of rationality account for each. Schmeidler presented a second paper in which he gave a new axiomatic foundation for MaxMin behavior.

Ashok Maitra presented his remarkable work with Bill Sudderth, proving by transfinite induction that rationality can be defined on infinite-horizon trees, and thus extending and simplifying earlier work by Blackwell and Mertens. David Lane presented joint work with Arthur on information contagion, showing that with a slight bit of non-Bayesian behavior, the way information spreads can dramatically influence outcomes. Stuart Kauffman presented a summary of his work on random grammars and its implications for economic rationality and, in passing, to economic growth.

John Geanakoplos and David Lane have begun an effort to draw together the papers in both workshops on learning into a book on learning and rationality in economics, computer science, and psychology.

Increasing Returns, Information Contagion

Researchers: SFI External Professors W. Brian Arthur and David Lane, and Andrzej Ruszczynski

Increasing returns, in the shape of self-reinforcing or positive-feedback mechanisms present in an economic problem, often cause multiple solutions—multiple equilibria. Arthur's work in this area concerns the question of how one equilibrium, out of the several possible, might be "selected" in the economy. There are several approaches to this "selection problem"; many of these amount to invoking extra conditions to settle the outcome. His approach has been to allow for the presence of small, random events that can cumulate and become magnified by the increasing returns mechanism over time to determine which solution is reached. This captures our intuition that different historical accidents can steer the system into the "gravitational orbit" of different equilibria, over time. Under this approach the selection problem becomes a dynamic one, with well-defined random events. They can then examine equilibrium selection over time by studying the corresponding stochastic process the problem generates.

Different increasing returns problems, it seems, may generate different stochastic processes. Yet many of them turn out to fit a general, nonlinear class of processes—*generalized urn processes*. These were developed separately by Bruce Hill, David Lane, and Bill Sudderth, and, in the early 1980s, by Yuri Ermoliev, Yuri Kaniovski, and Arthur. These assume that one unit (a purchase, say) is added or allocated to one of several categories (different product brands, say) with probabilities that are a given function of the current proportions market share) in each category. Ermoliev, Kaniovski, Lane, and Arthur are currently generalizing earlier work on these processes to allow for random, non-integer allocations, and are studying the speed of convergence to asymptotic states. This will allow them to analyze a wider variety of positive feedback problems in economics.

Arthur is interested in three areas of application where increasing returns are important: industry location; strategic pricing in markets with self-reinforcement; and "information contagion." His interest in industry location came from reading Alfred Weber's ideas a few years ago. Weber showed in 1909 that regional clusters of industry can be self-reinforcing, so that the locational pattern of industry we see in a typical economy can have multiple equilibrium solutions. (Paul Krugman has recently brought Weber's insights up to date, demonstrating multiple equilibria in modern, rigorous, regional economic models.) Weber and the literature that follows him, however, show only that different *static* equilibria might exist. The question of how a locational pattern emerges over time, when there are many possible patterns, interests Arthur. This is, in essence, the equilibrium selection problem applied to regional economics. To explore this, Arthur set up a model in which firms enter an industry one by one; different firm types have different geographical predilections but experience agglomeration benefits when located near other firms; and "historical accidents" dictate which firm type will enter next. He can thus watch the "emergence" of a locational pattern and derive conditions under which one region—a "Silicon Valley"—can come to dominate an industry by historical chance.

Arthur's interest in strategic pricing in the presence of increasing returns is a natural follow-on to his work on competing technologies. Technologies are complicated, almost by definition and, as a result, they are subject to massive up-front R&D costs, to improvement via learning-by-doing, and often to network externalities. These give advantage to increased adoption share and, under certain conditions, can cause a winner-take-all outcome, as long as the technologies are not strategically manipulated. But what if they *are*, by being owned and priced, say? Andrzej Ruszczynski and Arthur have been looking at whether a tendency toward single-product domination holds up when firms strategically price products that are self-reinforcing in the market. The answer, it turns out, depends critically on the rate of discount. If the discount rate is high, firms price only for immediate profit, and pricing mitigates increasing returns effects: the market is shared. If the discount rate is low, a struggle for market share can become the dominating factor in the game, and strategic pricing can amplify any natural positive feedbacks in the market. Ruszczynski and Arthur are currently revising a draft paper on this, entitled "Strategic Pricing in Markets with a Conformity Effect."

David Lane and Arthur are investigating *information contagion*—a phenomenon that can occur when private information is passed among consumers in the economy. Consumers who are in the process of choosing among alternative products they are uncertain about often collect information by randomly sampling other previous purchasers and asking them about their experience with the product they chose. This can put prevalent product brands or technologies at an informational advantage. Prevalent products are more likely to be encountered in this information-gathering process; they are therefore more likely to better understood, less uncertain, than their rivals; and where purchasers are risk-averse, they are more likely to be purchased. Thus, when purchasers collect information from users of competing products to become, in turn, users of these products themselves, future market shares may depend probabilistically on past market shares. The market is path-dependent, and products that by chance early on gain market shares may come to dominate by such information advantage alone. The study of this information contagion phenomenon is in Santa Fe Paper 91-05-026.

Optimal Adaptation in a Randomly Changing Environment

Researchers: External Faculty members Alfred Hubler, J. Miller, and David Pines

Based on real-world data and paradigms in nonlinear dynamics, Alfred Hubler and his collaborators are developing a theoretical framework for management and control in randomly changing environments. They find simple relationships between rationality, complexity, level of adaptation, and level of ignorance of optimal adaptive predictors. This research could make it possible to develop new paradigms for economics as well as guidelines for managing industrial companies and other enterprises.

In recent years adaptive algorithms have found widespread use in computational optimization. Neural nets, genetic algorithms, and evolutionary models including artificial life have been used to solve scientific and technical problems. In addition, adaptive algorithms have been used to mimic the dynamics of certain biological systems, in particular, learning and evolution, as well as the dynamics of economic and social systems. These algorithms usually have many parameters. In most cases the performance of computational adaptation depends sensitively on the adjustment of those parameters. Therefore, a lot of research in this field is focussed on the classification of adaptive systems and the question of which class of algorithms fits best for which set of problems.

Rather than continuing in this vein, Hubler and his collaborators focussed their recent work on detecting and characterizing experimental adaptive systems. They have developed an experimental procedure in order to distinguish between passive and active adaptive systems, and optimal and other adaptive systems, where they assume that the adaptive system is capable of modeling the environmental dynamics and that it adjusts the control parameters of the modeling process through trial and error. As a quality function for the adaptation process, they use the predictive power of the adaptive system. In a real environment other quality functions may be more useful, such as the energy content or the dissipation in a physical system. It seems that their results do not reflect special properties of the system they used, but can easily be adapted to systems which seek to optimize other quality function or use other modeling techniques.

The group plans to investigate adaptive systems which include human behavior. In addition, they intend to study physical adaptive systems, such as networks of dissipative nonlinear oscillators, and compare their dynamical properties with optimal predictors. Further, they will study adaptive systems which can use hierarchical sets of models.

6.1.2 Game Theory

Theory of Money and Financial Institutions

Researchers: Martin Shubik and John Geanakoplos (Yale); John Miller (Carnegie-Mellon); Yannis Karatzos (Columbia); William Sudderth (U. Minnesota); and Ashok Maitra (U. Minnesota)

The purpose of this research initiative is to understand the nature and role of various financial instruments and institutions, in particular, fiat (or outside) money; inside monies or credit; and bonds. The research is trying to clarify how interest rates are determined (and what leads to the term structure of interest rates) and how markets and financial institutions function. In particular, what is a minimal set of instruments and institutions needed to run an efficient economy—and what costs are incurred by a society for which some of these elements are missing?

The approach adopted to these questions rests on the concept of strategic market games. These are economic process models that are constructed as playable and potentially experimental market games. In these games, price formation mechanisms, markets, and financial instruments are explicitly specified. Thus, they can serve as testbeds for behavioral simulations where the performance of human and artificial agents can be compared to the predictions of noncooperative equilibrium and general equilibrium theory. Work is proceeding on several fronts, including infinite-horizon strategic market games. In 1973 Shubik and Whitt formulated and analyzed a two-person infinite-horizon strategic market game with fiat money and no loans. Whitt developed in part the apparatus for extending the analysis to games with a continuum of traders in a stochastic environment. In the last year Karatzas, Sudderth, and Shubik, in consultation with Whitt and several others, have begun to extend the earlier work into several areas:

- Fiat as insurance: The first paper, which is in process, is entitled "Money."

When this paper is completed, it will serve as the basis for several extensions.

- The rate of interest and default: The first extension is a model with one-period lending and a fully specified class of bankruptcy and garnishing rules.
- Term structure, refinancing, and seniority: The second is a model with both one- and two-period borrowing and lending available. As soon as one can borrow both long and short, a new class of problems involving refinancing and the seniority of creditors emerges. Qualitatively, virtually all of the difficulties with the term structure of the rate of interest appear with the one- and two-

period markets. For this reason, at least to start with their investigations, they consider only one- and two-period loans.

- Overlapping generations with stochastic lives: All of the models above are with infinitely lived traders. More reasonable models should have lives with finite expected length. They expect to extend the above models to include this feature. There already exists a substantial allied literature in overlapping generations models. The particular "value added" aspects of the work outlined is in the explicit feasibility or "playability" of the mechanisms which fully define the financial structure.

- A two-person stochastic game: When there are only two individuals in the market, many purely game-theoretic phenomena are encountered. Maitra and Sudderth and, to a somewhat lesser extent, Karatzas, Shubik, and a graduate student, K. Jaywadene, are considering this problem.

Simulation and experimental gaming with strategic market games is another research area. A feature of the strategic market game models which is of value in considering different approaches to investigating economic processes is that the models lend themselves to study via behavioral simulations and experimental games. Thus each model provides for three different approaches. The first, described above, is a mathematical solution. The second is mass stochastic behavioral simulation by a large number of artificial players whose behavior is governed by some form of learning algorithm. The third is by gaming experimentation. Eventually a fourth approach would be the fitting of empirical data from the economy, but this requires models of somewhat greater richness than the current highly stripped down versions being analyzed. John Miller and Martin Shubik have started to simulate several of the models noted above and are simulating and gaming a related model.

- Bidding with fiat money: Karatzas, Shubik, and Sudderth have calculated an explicit optimal policy for a simple example. Miller and Shubik, using a genetic algorithm, are investigating the relationship between the behavior of the simulated players and the predicted analytical solution.

- Money markets and insurance: Miller and Shubik have an overlapping-generations strategic market model which can be solved analytically. Some preliminary simulations using a genetic algorithm have been made, but this work, though partially written up, is in an early stage .

- Multiple equilibria in exchange: In 1977 Shapley and Shubik (1977) provided an example of an exchange economy with three competitive equilibrium points calculated and illustrated in an Edgeworth box. Miller and Shubik have taken this example, modified it to a many-person game with two types of traders, 40 of each type, and have simulated to see which, if any, of the CEs serve as attractors. An experiment has also been designed to be used with live subjects.

6.1.3 Understanding Market Behavior

Double Auction Markets and Trading Strategies

Researchers: John Miller (Carnegie-Mellon), Richard Palmer (Duke), and John Rust (U. Wisconsin)

Understanding the behavior of double auction market institutions has both practical and theoretical importance. Variants of this market institution are used all over the world, including the New York Stock Exchange and the Chicago Board of Trade, and thus a remarkable percentage of the world's commodities and securities are traded using this form of market. Moreover, the rapid flow of information and the ability to instantly undercut existing bids and asks makes the double auction a close approximation to the theoretical economist's notion of a perfect frictionless market. Despite its central role to both actual and theoretical work, there is only a minimal understanding of the behavior of double auction markets.

In 1989, Miller, Palmer, and Rust initiated a Double Auction Tournament (DAT), soliciting computerized strategies for a particular version of the market that closely resembled that used by the Chicago Board of Trade. The use of a computer-based tournament format allowed the researchers to extend current work in a variety of directions, including: (1) the analysis of thousands of tightly controlled experiments, (2) the ability to observe and isolate important strategic components, (3) the development of market software that allowed both human and machine players located anywhere on the worldwide internet network to simultaneously participate in a real-time game, (4) the ability to recreate phenomena such as market crashes, and (5) the direct demonstration that superior strategies exist in such an environment—an important consideration given the current trends towards making major markets electronic, thus allowing the use of computerized strategies. The tournament provided $10,000 in prize money to be divided among the entrants in proportion to their actual earnings in the market. Entries came from computer scientists, economists, mathematicians, and active traders from around the world. The results and design of the tournament are discussed in a number of available papers. The tournament also served as the basis for two workshops held at SFI in 1990 and 1991 (an edited proceedings volume will be released in 1993).

Missing Markets and the Emergence of Market Structure

At the Santa Fe conference on "Emergence of Markets," theoretical economists, anthropologists, political scientists, Wall Street practitioners, and economic leaders in Eastern Europe gathered to consider how markets emerge and what happens when some are missing. Economist John Geanakoplos began the conference describing some of the recent theoretical work on incomplete markets and its potential for reshaping the theories of finance and macroeconomics. Indeed, he argued that it is missing markets that make asset trades and money itself necessary, in effect, creating the theory of money and finance. If markets were complete, consumers would never buy assets; instead, they would purchase directly only those services and goods promised by the assets that they really wanted, thereby avoiding the implicit expense of purchasing services they do not want. Similarly, if all commodities could be traded directly against all other commodities, there would be no need to invent fiat money. Geanakoplos went on to present a single framework for analyzing assets as diverse as durable goods, government bonds, mortgages, credit cards, futures, and options.

Economists Rob Townsend and Chris Udry and anthropologist Keith Hart described the developing economies of rural Africa and India. Despite strict religious prohibitions against lending, these primitive economies apparently have evolved intricate insurance markets against storms and pestilence and the other main risks that affect them, so that they appear closer to the Arrow-Debreu ideal of complete markets than do modern industrial economies. One possible explanation for this paradoxical finding is that in primitive economies the risks are recurrent, making it easy to foresee all the possible contingencies and, therefore, to design instructions that allow the agents to share the risks. Furthermore, everybody knows everyone else, so that cheating can be efficiently recognized and punished.

Turning to financial markets in capitalist societies, Marty Fridson (Merrill Lynch) described the rise and fall of the junk bond market, Darrell Duffie (Stanford U.) traced the history of the futures market, and Martin Shubik gave an overall history of financial markets, re-emphasizing the importance of default, a subject on which he has done pioneering research. Charles Sabel (MIT) and Jim Pelkey described some patterns in markets for new goods: Sabel emphasized the emergence of flexible manufacturing networks, while Pelkey described the ebb and flow of firms and markets in the data communications industry.

During these talks, it became clear that new markets have evolved for a variety of quite different motivations and causes. This is especially true of complex markets for risk, including the asset markets described earlier. The tautological explanation for a market's long-run viability, namely that there is a commodity or instrument that is valued more by some people who do not own it then by some people who do, and that the market facilitates its trade, suggests one scenario for a market's creation: a group of people, recognizing their mutual advantage, meet together and establish a market or exchange. Many different kinds of events can trigger the formation of such new markets: a product that needs to be sold; the sudden accumulation of wealth, such as petrodollars, in the hands of new buyers who are not accommodated by existing markets; the need to finance investment through new financial markets; or an improvement in the transactions technology.

This straightforward mechanism is not the only way new markets come into being. In fact, a great many markets are created by agents who themselves do not wish to trade and who do not directly profit from that trade. Central governments establish markets, standardizing the commodity traded, guaranteeing payments, and even subsidizing trade. The rural credit markets are apparently often established by the village head man. Financial firms create and maintain the information needed to support secondary markets, not for the profits they will earn there, but so that the primary markets in which they do profit will attract buyers who can count on being able to sell the instrument later on the secondary markets.

The initial impetus for the creation of a market may be different from the interests that prevail when the market matures. Sometimes the motivation for a new market is theft. This can take at least two forms. The sellers can be selling something that the buyers, through ignorance or miscalculation, pay too much for or the sellers can sell something they do not really own, by finding loopholes in existing laws. Some economists have attributed the rise of esoteric financial instruments to the first form (e.g., Savings and Loans pay far too much for complicated mortgage derivatives which appear superficially attractive) and the rise of junk bonds to the second form (the original bondholders and share holders can lose part of their wealth when their firm is further leveraged). Markets that, when mature and properly understood, become socially useful can begin for other reasons.

The conference concluded with a timely practical application of the foregoing theorizing about emerging markets to the experiences of Eastern Europe, led by Max Kunyavsky (U. Minsk), the president of the society of Byelorussian entrepreneurs. In a society practically without free markets, in which production has been organized around military needs, what markets should be created first: labor markets, land markets, commodity markets, or financial markets? Consider, for example, the problem of privatizing the great factories of Russia. The obvious way to do so is simply to give them to everyone in equal shares. But then nobody would be in a position to exercise control. Auctioning the shares would be even worse. The total amount of cash the citizens hold is only enough to support the few transactions needed in day-to day transactions in their current limited market economy. The huge transactions would completely destroy the price stability of the monetary system, perhaps leading to a dramatic fall in the prices of marketed goods and ruining any small debtor.

Modelling Stock Market Dynamics

Researchers: SFI External Professor W. A. Brock (U. Wisconsin); Blake LeBaron (U. Wisconsin)

W. A. Brock's work at the SFI and his home institution has centered around the development of statistical inference theory for nonlinear time-series econometrics, which includes testing for the presence of chaotic generators and other complex nonlinear generators.

Present and future work will stress development of economic theory for both macroeconomics and finance which allows for correlated agent characteristics which lead to loss of ergodicity as the economy becomes large. This theory will be constructed at the mean field-theoretic level of accuracy and will be described in more detail below. The intent of the new theory can be explained by using finance as an example.

Finance is dominated by linear methods and continuous-time diffusion processes. When processes which don't have continuous sample paths, such as Poisson processes, are used, there is no theory to explain the emergence of the abrupt changes embodied in the Poisson jumps. The Brownian motion part is usually viewed as the summation of many small, weakly dependent shocks as in the central limit theorem.

Brock's theory proposed attempts to model such abrupt jumps as emergent structures which are parsimoniously parameterized in terms of economic variables.

His recent book, *Nonlinear Dynamics, Chaos and Instability: Statistical Theory and Empirical Evidence* (Brock, Hsieh, and LeBaron, 1992), reports research, done over the last five years, testing economic data for the presence of chaotic generators or other complex data generators which are difficult to detect by conventional statistical methods. The book reports on development of new statistical methods to detect such generators and report on applications of these methods to economics and finance. While the evidence for low-dimensional, deterministically chaotic generators is weak, the evidence for patterns which may be due to nonlinearities appears to be quite strong.

The emphasis of the book is on financial applications. Received-asset pricing models are tested on financial price data by fitting the models and testing the forecast errors for presence of "left-out structure." It is well known that forecast errors from asset pricing models tend to have autocorrelated volatility. The key issue is whether there is any structure in these forecast errors besides this autocorrelated volatility. Brock's testing methods suggest that extra structure exists. More refined testing procedures to be discussed below help determine what that missing structure is.

In Brock, Hsieh, and LeBaron (1992), he not only discusses his own research and that which is closely related, but also attempts to relate it to other work on nonlinear econometrics, time-series analysis, and financial economic theory. Applications stress stock returns and returns on foreign exchange. The statistical methods presented in the book are performance tested by extensive Monte Carlo work of David Hsieh and Blake LeBaron. The Hsieh-LeBaron tables are presented in such a way that they can be used by investigators to do more refined inference for smaller samples. MIT Press will distribute software, written by W. D. Dechert for the IBM PC and LeBaron for the Macintosh PC, which can be used to implement the tests. The software comes with documentation.

Brock and his student Ehung Baek have finished two papers. The first paper shows how to use U-statistics theory to work out the distribution of estimators of correlation dimension and other entities used in nonlinear science. This is done under null hypotheses of weak dependent processes which includes noisy chaos. The paper shows how to work out analytic expressions for the correct standard errors under the simplest stochastic process, which is pure randomness. The paper only briefly indicates how to work out the correct expressions for general, weak, dependent processes. This work can be used to assign more precise standard errors to dimension estimates than were available before. The Brock and Baek work appeared in the SFI working paper series (SFI 91-02-009) and in the *Review of Economic Studies*.

The second paper with Baek extends methodology developed by Brock, W. Dechert, J. Scheinkman, and B. LeBaron to the case of vector-valued stochastic processes. The BDSL work showed how to test a time series that looks random to many conventional statistical tests for randomness. A detailed discussion of the BDSL statistical test for randomness as well as Monte Carlo tables for performance evaluation of the test is provided in Brock, Hsieh, and LeBaron (1992). The BDSL methods, extended to the case of multiple time series by Baek and Brock, are applied by them to specification testing of multivariate econometric models such as VARs, where "VAR" is short for Vector AutoRegressive. "Specification testing" is econometrics jargon for the process of checking whether one's model adequately describes a data set.

They also extend the methods to deal with nonlinear "Granger" causality testing which refers to whether one time series' past helps predict another target time series' future above and beyond the predictive content in the past of the target series. This paper is forthcoming in *Stastica Sinica.*

Brock and Allan Kleidon (Stanford) have finished their project on market microstructure which attempts to model the movement of the bid/ask spread over the day. Movement of the bid/ask spread over the day can lead investigators to falsely conclude they have found useful predictable structure in intradaily stock prices. The "extra structure" may be simple movements in the bid/ask spread. They show that the periodic closure of the stock exchange leads to periodic demand for trading which leads to periodic movements in the bid/ask spread due to peak load pricing of trading services which are not in perfectly elastic short-run supply. Their model predicts that volume will bunch at open and at close and the bid/ask spread will widen at open and at close. This is what is seen in the data.

Rival models are information-based models of volume bunching. But these models apparently require something like periodic forcing to generate the volume bunching which peaks at open and at close. The predictions of many information-based models are for the bid/ask spread to be lower during periods of heavy trading, which is counterfactual at open/close. The idea of the information-theoretic models is this: The low bid/ask spread attracts discretionary traders which, in turn, serve as a mask for information trades which leads to volume bunching. This does not seem to be the right model for explaining the widening bid/ask spread at open/close coupled with the maximal volume bunching observed at open/close. The Brock and Kleidon paper is forthcoming in the *Journal of Economic Dynamics and Control.*

Brock and LeBaron have teamed up with Josef Lakonishok (U. Illinois) to produce a new way of testing econometric models in finance by using Professor Bradley Efron's bootstrap to bootstrap the distribution of conditional moments of returns from following trading strategies. Using almost 100 years of daily returns on the Dow, they found (i) periods of negative excess returns following sell signals of certain trading strategies, (ii) a large class of parameterized versions of the Efficient Markets Hypothesis (EMH) are rejected by a bootstrap-trading, rule-based, dynamic specification test, and (iii) returns following buy signals were too large, and their conditional volatility was too small to be consistent with the null models at the conventional level of confidence.

Recent work by a former student of Brock and LeBaron, Simon Potter (now at UCLA), with Hashem Pesaran (Cambridge) has shown that it is extremely difficult for homogeneous, agent-based, asset pricing models to produce the observed periods of negative predicted excess returns documented by them and related work by Pesaran.

While in residence at SFI from September through December 1991, Brock's colleague, Blake Le Baron, carried out several related projects, completing three papers. "Technical Trading Rules and Regime Shifts in Foreign Exchange" analyzes the use of technical trading rules in foreign exchange markets. These simple rules are often used by traders in lieu of using economic fundamentals. The rules studied in this paper are all of the simple moving average or oscillator type which indicate a buy signal when the current price is above a moving average of past prices and a sell signal when it is below. Economists have generally spent much time and space making fun of these very simple buy and sell rules, but their use persists in many markets. This paper takes on several questions concerning these rules.

First, it asks whether they find statistically significant patterns in foreign exchange series. For this question, trading rule returns are compared to those from simulated stochastic processes that are commonly suggested to represent the dynamics of exchange rates. The results show very strongly that none of the commonly used simulated models are able to replicate the results seen on the actual data.

Second, the trading rule results are actually used in the estimation of linear models to match up with the foreign exchange results. This uses a technique known as simulated method of moments. It simply has the computer search the space of linear models to find parameters that match up with certain characteristics of the data. In this case these include the technical trading rule results and other more standard aspects of the series such as simple autocorrelations. This procedure could be extended to include other interesting statistical measures. This estimation procedure was generally unable to find simple linear models consistent with the data.

Finally, the paper checks to see whether the rules actually make money and, if they do, what kind of risk investors are exposed to. This is done by actually implementing a trading strategy on the foreign exchange series, and accounting for transactions costs and interest rate differentials. The results show returns that are economically significant and comparable to domestic stock-return portfolios. Moreover, the returns on these dynamic strategies are uncorrelated with stock returns suggesting improved risk/return tradeoffs by diversifying. Simulations are performed showing that the performance of the diversified portfolios may dominate the individual stock portfolios. These results are somewhat troubling for market efficiency in foreign exchange, and the paper suggests some possible explanations. Future research hopes to look at the process of central bank intervention and whether it is capable of causing some of the results seen here. This paper implements some of the tests used for foreign exchange on the Dow Jones Industrials.

"Transactions Costs and Correlations in a Large Firm Index" addresses some questions that have been raised by several recent papers on stock returns. In an earlier paper LeBaron showed that autocorrelations in stock-return indices are inversely related to a local measure of volatility. When stock prices are very volatile, the amount of autocorrelation falls.

These early results were obtained using the S&P 500 index. One explanation that has often been given for this result is nonsynchronous trading. In this explanation some stocks do not react to new information immediately because of transactions costs or other market frictions. Therefore, when new information arrives, it affects some firms immediately and others are affected with a delay. This can cause positive autocorrelation in a index of many stocks. Further, this correlation could be inversely related to the current level of trading volume and volatility since trading frictions would be small relative to the amount of new information coming into the system when volatility is high.

This paper explores a smaller, more homogeneous, index constructed from the CRSP data set to closely replicate the Dow Jones Industrials. In this index of large firms, it is hoped that the trading frictions and informational problems that would be present in a larger index will be minimized. However, the same pattern-connecting correlations and volatility is displayed. Also, it is shown that the correlations are connected to trading volume, too, but probably in an independent way.

The paper continues by directly testing whether the changing correlation patterns are coming from autocorrelations across the same firms or across different firms in the index. To test this the time series of firms is studied as a vector time series, and correlations are estimated between different firms and the same firms over time. These results show that most of the correlations are coming across different firms. This suggests a lagged adjustment process where certain firms react more quickly to economic news affecting all firms. The nonlinear aspect of this adjustment implies that these differences in price adjustment speeds are changing over time.

Finally, a simple model of differing transactions costs over firms is simulated to try to replicate some of the earlier results. It is capable of generating similar results but at unreasonably large transactions costs. This model is only a crude first stage in modeling transactions costs, but it suggests that further models incorporating transactions costs and some form of learning and information acquisition are probably necessary to explain these effects.

In looking at conditional index correlations using nonlinear techniques two strong effects have appeared. There is an inverse relation between conditional correlations and both trading volume and volatility. This effect is qualitatively consistent with a broad range of nontrading explanations mentioned previously. While this phenomenon is interesting, it disagrees with some casual evidence that stock prices exhibit some persistence or increased positive correlation when trading volume is high. This belief has generally led to the appearance of technical trading rules that use trading volume as part of their conditions for generating buy signals.

"Persistence of the Dow Jones Index on Rising Volume" finds that there is some evidence for increased positive correlation in the Dow Jones index when trading volume is locally rising. This effect is asymmetric in that it is much stronger in rising markets than in falling ones. This asymmetry is a little difficult to explain. These changing correlations are estimated using multivariate nonlinear threshold-type models. The significance of these results is judged by using a multivariate bootstrap technique that incorporates many of the known features of stock returns and trading volume.

Results such as these suggest that adjustment to new information in financial markets, while pretty fast, is slower than previously thought. This adjustment to new information can be seen in the positive correlation of the index on a sudden burst of new volume. These might be periods which are characterized by a large amount of diversity of opinion and learning, and the market is displaying the properties of processing this new information.

6.2 Social Systems

SFI is deeply interested in the human aspects of complex systems and seeks to apply the analytic tools being developed to understanding the evolution of human culture.

6.2.1 Prehistory of the Southwest

Since 1989, the Institute has sponsored a series of meetings focusing on historical culture evolution in the southwest. Despite local variation, broad regional patterns in the Southwest reveal similarities in the timing of particular economic and social changes as reflected in archaeological sites and artifact assemblages. The trajectories of patterned changes can be viewed as complex adaptive systems showing historical changes over time. This research initiative draws together scientists interested in attempting to explain some of these the patterns within the context of general models of complex adaptive systems. Two major topics are the current focus of work. The first is "Factors of Vulnerability," and includes such matters as population trends, climate change, degree of aggregation, availability of naturally occurring foods, agricultural successes and failures, and the need to support costly political, economic, and ritual systems. The second is "Strategies or Failure of Adaptation" and includes such issues as increases or decreases in sociocultural complexity, aggregation/dispersion, local/regional abandonments, range expansion/contraction, subsistence shifts and intensification, technological change, economic specialization, and population decline. To the extent possible, processes that occurred simultaneously across large areas will be addressed. Some examples, from the puebloan Southwest, are the period of range expansion, ca. 1000-1150, widespread regional abandonments ca. 1300, and significant localized population declines in the fifteenth century. *Understanding Complexity in the Prehistoric Southwest*, edited by George Gumerman (U. Southern Illinois) and Murray Gell-Mann (Caltech) will report on this work in 1992.

6.2.2 Computational Modeling and the Social Sciences

A joint project with the University of Michigan led by SFI External Faculty member J. Holland is aimed at developing a policymakers' tool kit through collaborations involving Michigan faculty, generally from the social sciences, and SFI members, who bring expertise in computational modelling. This program is jointly funded by the University of Michigan and a grant from the Joyce Foundation. During 1991 there were a series of research visits from Michigan faculty.

Richard Nisbeth (Director of the Institute for Social Research). Nisbeth, a psychologist, described to SFI his work on differences in reasoning strategies and training effects on reasoning about statistical and economic matters. He found common interests with, among others, David Lane (economics program) on reasoning and organizational management; Stuart Kauffman (theoretical biology) on heuristics, optimizing, and limits on the value of look ahead in modeling; and John Geanakoplos (economics program) and Lane on "mast binding" procedures in the determination of preferences. It is likely that future collaborations will arise from these interactions. SFI is planning a new program on organization theory, which Nisbeth will join.

Steven Pollock (Professor and former Chairman of Industrial and Operations Engineering). Pollock is currently interested in optimization problems involving stochastic and nonlinear events, problems of the kind being studied by David Lane in the economics program. As a direct result of his visit, Pollock has arranged to spend a portion of his 1991-92 sabbatical at SFI and organized a workshop "Operations Research and Complex Adaptive Systems" to be held in May 1992.

Charles Sing (Professor of Human Genetics). Sing's laboratory has conducted a large population study of coronary heart disease and hypertension, and he is especially interested in insights that complexity research might offer into understanding and modeling these data. Current analytic approaches are inadequate to the complexity of the relationships in the hierarchy between genes and disease end-points. During his visit he explored the overlaps between genetics and economics; the potential of genetic algorithms for modeling complex diseases and for identifying patterns in data sets; and the applicability of rugged-landscape models and models of adaptation at the edge of chaos for describing the evolution of human diseases and the health care delivery system. Sing will return to SFI with the goal of initiating collaborations on some of these questions.

John Jackson (Professor of Political Science). Jackson's interests are on economic and political institutions, and his group has a large data set on the business firms in Michigan. After extensive interaction with members of the economics program (L. Gray, J. Miller, and J. Pelkey), it appears that there are significant common interests between Jackson's work on political and economic institutions and work currently being done in the economics program, especially in adaptive models. Jackson is accepting some administrative responsibility for coordinating activities of interest to the SFI on the Michigan campus, so his visit was of particular importance to the future of the collaboration.

7. EDUCATIONAL ACTIVITIES/OUTREACH

Since its founding, the Santa Fe Institute has been committed to a program of education in the sciences of complexity. With an innovative undergraduate internship program, co-sponsorship of the graduate-level Complex Systems Summer School and Winter School, and graduate student residencies for thesis research, along with its sponsorship of postdoctoral residential research, SFI pursues a program of complex systems education at all academic levels.

7.1 Complex Systems Summer School

The purpose of the Summer School on Complex Systems, begun in 1988 and held annually each summer in Santa Fe since then, is to provide graduate students and postdoctoral fellows with an introduction to the study of complex behavior in mathematical, physical, and living systems. Because of its relative newness and interdisciplinary nature, the subject of complex systems is not easily accessible to researchers as a whole and to students in particular. The School is intended to address the need for a coherent and substantive presentation of the concepts and techniques emerging in this area. It attracts, stimulates, and educates the best young scientists as they begin to define their own research programs.

To date, the School provides the only offering of this kind in the nation. While several universities, including some of the sponsoring institutions of the Summer School, are beginning to establish centers for research and teaching in complex systems, strong programs around the country are still several years in the future.

The School is co-sponsored by a group of institutes, centers, and universities throughout the country, with the Santa Fe Institute acting as fiscal and administrative agent. Brandeis University, the Center for Nonlinear Studies at Los Alamos, Sandia National Laboratories, and the Universities of Arizona, California, Illinois, Maryland, New Mexico, and Texas have joined SFI as sponsors for this School. In addition, other universities provide financial support for their students in attendance at the school. In this category are Columbia, Princeton, Stanford, the University of Pennsylvania, and Yale.

An Organizing and Steering Committee representing the consortium of sponsors provides general guidance for the effort and oversees the selection of the School's Director(s), who vary from year to year. The 1988 School was led by Prof. Daniel Stein (U. Arizona); Dr. Erica Jen (LANL) directed the 1989 meeting; Co-Directors for the School since 1991 have been Profs. Daniel Stein (U. Arizona) and Lynn Nadel (U. Arizona). They will also co-direct the 1992 school. By virtue of administrative experience with the School and because Santa Fe is a prime site for such a summer activity, it is the consensus of the sponsoring consortium that the likelihood is great that the Complex Systems Summer School will continue to be run in Santa Fe by SFI.

The emphasis in the school is on combining the understanding of phenomena derived from traditional approaches with that gained from the novel ideas of complex systems. To this end, the school focuses on developing techniques for measuring and analyzing complex behavior and applying these techniques to the study of a limited number of specific mathematical, physical, and living systems. The school usually consists of approximately nine to twelve short courses together with a number of seminars on selected topics. Specific foci vary with the director and faculty, but typical topics are nonlinear dynamics, computational and algorithmic complexity, cellular automata, fluid dynamics, disordered systems, neural nets, adaptive learning algorithms, cognition, molecular biology, physiology, neurobiology, evolution, pattern formation in biological systems, and the design of parallel-processing algorithms.

In addition to their formal lectures the faculty are available during the day for informal discussions with the students and frequently schedule supplementary tutorial sessions in the evenings. A computer laboratory containing a range of desktop microcomputers, workstations, and graphics devices is an integral part of the school. Students and faculty bring software to supplement that installed on the network. Students are encouraged to organize their own research groups and student seminars are a common feature of the self-organized part of the program.

Between fifty and sixty students attend the school each year; applications typically are double the number of students accepted.

The schools have several important long-term outcomes. One product of the Schools are lecture note volumes. These texts, which have appeared annually since 1989, are intended to provide an introduction to a broad range of topics and may well become a standard reference in the sciences of complexity. The lectures from the 1991 school currently are being edited by D. Stein and L. Nadel for publication July 1992.

Summer School alumni including Aviv Bergman, Bill Bruno, Stephanie Forrest, Neil Gershenfeld, Wentian Li, John Miller, and Andreas Weigend have gone on to conduct research at SFI, and the schools have also played an important role in introducing more senior scientists to the Santa Fe Institute. Several members of the Institute's research community—including Jay Mittenthal, Joe Traub, Peter Wolynes, and Bernard Huberman—initially came to Santa Fe as Complex Systems Summer School faculty.

7.2 Complex Systems Winter School

An outgrowth of the Complex Systems Summer School, the Complex Systems Winter School took place for the first time January 12–24, 1992 although the balance of its organization obviously took place in 1991. Like the Summer School, this program is intended to provide graduate students and postdoctoral scientists with an intensive introduction to complex systems research, although this effort is much more narrowly focussed than the month-long summer program. This first Winter School, led by Peter Carruthers, head of the Physics Department at the University of Arizona, considered an issue central to complex systems research: the geometrical and dynamical behavior of scaling complex systems. Topics covered included turbulence, percolation, self-organized criticality, 1/f noise, the mathematics of hierarchical systems (emphasizing fractal), fractal graphics, and scaling structures in physiology, in galaxies, and elsewhere.

The school was held in Tucson, Arizona. Sponsors were the Santa Fe Institute, the Center for Nonlinear Studies at Los Alamos National Laboratory, and the Center for Complex Systems Studies at the University of Arizona.

Like its summer counterpart, the school consisted of short courses together with a number of seminars on selected topics. Twenty-five students participated in the program. Faculty and student evaluations of this initial effort were enthusiastic, and plans are being considered to make this program an annual event.

7.3 Residential Programs

The Institute's research is dominated not only by a multidisciplinary, but also a multigenerational approach. Several young scientists, part of the increasing number attracted to complexity science, were in residence during 1991. As these researchers complete their work at SFI and move on in their academic careers, they carry the power of the complex systems approach to other organizations.

7.3.1 Postdoctoral Research

The work of the Institute's postdoctoral fellows comprises an important part of the Institute's research agenda. Occasionally the Institute also hosts shorter research visits from postdoctoral fellows with appointments at other institutions. The 1991 work of these researchers has been described in detail elsewhere in this report.

SFI's Postdoctoral Fellows program has been in place since 1988 and to date has involved nine full-time residential researchers. It is highly competitive, with more than 200 applicants competing annually for one or two positions. Candidates must have or expect to receive soon a Ph.D. and should have backgrounds in theoretical physics or chemistry, computer science, mathematics, economics, game theory, theoretical biology, dynamical systems theory, or related fields. An interest in interdisciplinary research is essential.

Applicants submit a curriculum vitae, list of publications, and statement of research interests, and arrange for three letters of recommendation. Postdoctoral fellows must be sponsored by a member of the Science Board or a member of the External Faculty who agrees to take responsibility for oversight of the research of the fellow. Postdoctoral fellows are, however, free to pursue their own research interests. They are encouraged to attend workshops and to take an active part in any of the research programs of the Institute.

7.3.2 Graduate Students

Another important aspect of SFI educational activities is providing research opportunities in the sciences of complexity for graduate students. Students who have completed course work for their doctoral degree may, with the agreement of their home institutions, conduct thesis research and writing in residence at SFI under the direction of a member of the SFI External Faculty. Their degrees will be granted by their home institutions. Less frequently, students at the pre-thesis graduate level conduct research at SFI. To date the Institute has hosted thirteen such students; in 1991 seven graduate researchers were in residence on either a full- or part-time basis.

The work of Aviv Bergman (Stanford/Stanford Research Institute) has been described in the Adaptive Computation section (section 3) of this report.

Brenda Javornik, a graduate student in the Department of Computer Science at the University of New Mexico, is working with External Faculty members Stephanie Forrest and Alan Perelson on a project formulating abstract patterns that the immune system appears capable of solving. They are then attempting to solve these problems using techniques such as the genetic algorithm and the K-means clustering algorithm. This work is described elsewhere in this report.

Ingrid Råde, a graduate student at Chalmers University of Technology in Göteborg, Sweden, came to SFI in the fall of 1991, to SFI to write her Master's thesis with Anders Nilsson under the direction of Mats Nordahl (and Kristian Lindgren at Chalmers). Her work focuses on evolving neural networks using an evolutionary algorithm based on mutations and selection.

She and her research colleague, Anders Nilsson, are concerned with neural networks. In the field of neural networks there exist several known learning algorithms, where the most applicable is back-propagation. The useful ones have a tendency of working only with a very strict set of preconditions. They have studied various methods to apply evolutionary algorithms in the teaching of neural networks. Earlier work in this area is rather scarce and has mainly concerned networks with fixed architecture or where the architecture has been controlled or restricted in some way. They have designed several techniques where networks can grow freely but under evolutionary pressure.

Francesca Chiaromonte, a graduate student from the University of Rome, joined the Economics program for the spring 1991 semester. As an undergraduate student, collaborating with advisors Giovanni Dosi and Luigi Orsenigo, Chiaromonte developed a model of a two-sector economy which is the basis of the computerized, microfounded model in the artificial economy project. During the spring she worked as the programmer on the learning model for the artificial economy.

Richard Bagley received a Ph.D. in the spring of 1991 from the University of California at San Diego and joined Peter Schuster's group at Vienna as a postdoctoral fellow. External Faculty member Doyne Farmer was Bagley's thesis advisor, and SFI researchers Walter Fontana, Stephanie Forrest, and Stuart Kauffman guided his work while he was in residence at SFI. Bagley's thesis, "The Functional Self-Organization of Autocatalytic Networks in a Model of the Evolution of Biogenesis," focussed on a particular model of self-organization, the transition to biogenesis at the origin of life.

Valerie Gremillion, a graduate student at the Center for Nonlinear Studies at Los Alamos National Laboratory and a Member of SFI, is working on research, conducted with Bryan Travis (LANL), focussing on the building and testing of large-scale neural circuitry models. Utilizing all available anatomical and physiological data, they are exploring models of the visual pathway that conform in great detail to the system as we know it. Using Travis' large-scale simulator code, which enables the three-dimensional construction of neural circuits, they have created models of the cat retina, lateral geniculate nucleus, and parts of visual cortex—the three earliest systems in the visual pathway. The work is unique in its attempt to relate three levels of information within these systems. First, they want to understand the basis of interactions within a single cell—for instance, synaptic conductance and time constant interactions. These understandings can then be applied to reduce the parameter space which must be explored to fit the spatiotemporal behavior of individual neuron types for which they have experimental data. Fitting such data—exploring the genesis of what is termed a cell's "receptive field"—is a difficult process which has not yet been attempted to this degree of precision. This second aspect—to match the models precisely to the available data—is of vast importance because current data do not adequately constrain the hypotheses; because of experimental limitations, only models such as theirs are capable of exploring certain theoretical options. The third aim is to use insights gained in the modeling of explicit cell types and their receptive fields to formulate some general principles of circuitry interactions. These principles can then be applied to other systems, and understanding of their circuitry behavior can then be greatly expanded.

7.3.3 Undergraduates

In 1989 the Institute began a small internship program for students at the undergraduate level. A testament to the Institute's estimate of the importance and commitment to this internship program is the fact that it is supported in part by a fund resulting from personal donations by SFI Science Board members. As part of this effort the Institute has brought a limited number of students to work on SFI programs or to participate in a reading and study program under the guidance of a visiting faculty member, postdoctoral fellow, or external faculty member. Students have pursued several study options: a course of supervised reading and study; investigating one or more carefully chosen research problems; or developing a piece of computer code for a current research program. The only constraint has been that the internship must contribute in a significant and innovative way to the education of the student. In 1991 the Institute incorporated into its residential programs six young interns for periods of one to six months. The outcome of these internships have been impressive both in terms of explicit research projects pursued during and subsequent to the residencies, and in terms of the overall direction of their research.

Julie Pullen, a recent graduate in mathematics and physics major from Macalester College, St. Paul, MN, joined the SFI undergraduate intern program in January 1990, for a month of reading and study under the Macalester Interim program. Her principal mentor was External Professor Stuart Kauffman but she also received significant assistance from Visiting Associate Professor William Wootters and from others. She returned as a student in the 1990 Summer School. Currently she is pursuing graduate study in the Department of Applied Mathematics at the University of Arizona. During the summer of 1991 she worked at SFI with fellow Summer School alumnus Professor Tom Cheetham on the project "Structural Constraints in a Simulated Ecosystem: Network Dynamics and the Conservation of Function."

Julie Rehymeyer, a junior at St. John's College in Santa Fe, worked at SFI from June to September 1991. Under the tutelage of External Professor Doyne Farmer and others, including Richard Bagley, John Gibson, and SFI Member Michael Angerman, she studied dynamical systems theory, learned the Unix system, and learned the C and C++ languages. She also collaborated with External Faculty member Stephanie Forrest on developing genetic algorithms in the C programming language. Her work focused on coding a stochastic iterated hillclimber for use as a contrast experiment for genetic algorithms, as well as designing a program to estimate the total number of hills in a function.

Alan Kaufman, a 1991 Yale graduate, was at the Institute from February through July 1991 as the first Robert Maxwell Undergraduate Intern. Kaufman concentrated on two projects working with External Professor Stuart Kauffman: one focused on strategies to optimize NK landscape functions. These schemes were motivated by economics and attempted to model such issues as firm formation and size, selfish vs. unselfish agents, etc. The other project used a random grammar approach to illuminate nonequilibrium economies. The intent of that model is to explore areas such as bounded rationality, time inconsistencies in roll-ahead planning, and technological innovation, evolution, and growth. Kaufman has gone on to pursue graduate study in Operations Research at MIT.

Erik Schultes, a sophomore at California State University, Humboldt, attended the 1991 Complex Systems Summer School before joining the SFI research staff as an undergraduate intern for the months of July and August 1991. He also worked with External Professor Stuart Kauffman, continuing Alan Kaufman's work on the random grammar project. Schultes is planning to attend graduate school in the fall of 1992.

Alexander Gray, a senior in computer Science at the University of California, Berkeley, was also in residence as an undergraduate intern during the summer of 1991. He worked with External Associate Professor Alan Lapedes and his research group on the analysis of protein structure using information theory. Gray's research focused on a mutual information tool which is used to characterize correlations between codons; further, he applied this analysis to a large body of NIH data.

In July 1991 Marc Lipsitch presented at the Fourth International Conference of Genetic Algorithms at the University of California, San Diego, the results of undergraduate research conducted in 1990 under the supervision of John Miller. This work concerned a class of fitness landscapes that were generated by iterated cellular automata. The paper presented preliminary results on the relationships among cellular automaton type, correlation measures of the derived landscape, and ease of adaptation on the landscape by the genetic algorithm. An abridged version of this paper will be forthcoming in *Review of Economic Studies*. Lipsitch used a brief residence at SFI during the summer of 1991 to continue work along these same lines. He has been awarded a Rhodes Scholarship to study zoology at Oxford University beginning in the fall of 1992.

7.4 Campus Relations

The Institute is synergistic rather than competitive with the great research universities, and it is currently making strenuous efforts to build mutually advantageous programs with them.

SFI continues to work on setting up collaborative programs with faculty and graduate students on other campuses. Implicit within the University of Michigan/SFI research project, for example, is a second aim: to explore the prospects and nature of research exchanges between SFI and university communities. This prototype model has proved quite successful. In addition to the collaborations described above, SFI has under way or in the planning stages several more projects in which University of Michigan faculty are deeply involved. Among these are Adaptive Computation, Theoretical Computation in the Social Sciences, and projects within the Economics program. Visits by advanced graduate students and postdoctoral fellows are also an important part of the program. Four such young scientists from Michigan were supported during the Complex Systems Summer School to educate them in a systematic way about the SFI approach to complex systems. All had completed a winter 1991 course on complex systems taught on the Michigan campus by John Holland. Finally, in November 1991 SFI and the University of Michigan sponsored a second annual joint symposium and faculty workshop on complex systems.

The Matrix of Biological Knowledge (Biomatrix) project, which began with a 1987 workshop, addresses the pressing need to organize, intelligently access, and make available widely the wealth of biomedical information confronting researchers. At a minimum this entails identifying and coordinating access to the proliferating biomedical databases. More prospectively, the Biomatrix project seeks to codify the laws, empirical generalizations, and physical foundations of biomedical knowledge; integrate analytical tools into knowledge-based management systems; and support reasoning mechanisms over the biological domain. The project is loosely knit together by means of the Biomatrix electronic bulletin board, by a Biomatrix newsletter, and by means of a series of annual meetings and workshops. The project has several nodes: George Mason University with Biomatrix founder Harold Morowitz; the University of Houston where Dan Davison runs the Biomatrix archive server; and the Santa Fe Institute, fiscal and administrative home for the project.

SFI Science Board member and Institute co-founder P. Carruthers has established a Center for Complex Systems Studies at the University of Arizona, which has been a co-sponsor since 1988 of the Complex Systems Summer School, and hosted the 1992 Winter School. Discussions continue with Carruthers and SFI External Faculty members D. Stein and L. Nadel (1991 Summer School Co-Director and Deputy Director of the Arizona Center) about collaborative research programs. Discussions aimed at establishing similar programs are underway at the University of Pennsylvania, led by S. Kauffman, and at the University of Illinois, led by D. Pines.

SFI researchers, many of whom move frequently between the Institute and university campuses, are carrying the sciences of complexity to academia, and changes in courses or course offerings are a result. As mentioned above, John Holland offered a complexity seminar on the Michigan campus; SFI External Professor David Campbell taught a similar class on nonlinear dynamics at the University of New Mexico in 1991; Murray Gell-Mann has been offering a seminar on complex systems at the California Institute of Technology; upon returning to his teaching duties at the University of Minnesota, David Lane began to offer a graduate course on "Inference in Artificial Worlds"; and John Miller teaches "Complex Adaptive Systems" at Carnegie-Mellon University.

7.5 Book Series

The purpose of SFI workshops is to stimulate new scholarship in the sciences of complexity. Appendix II lists the papers which have appeared in the scientific literature. For its part, to make these results broadly available, the Institute has a multi-year agreement with Addison-Wesley for the publication of the Santa Fe Institute Studies in the Sciences of Complexity series. To assure that the cost of SFI books is reasonable and that timely material is published quickly, the publication agreement provides for the Institute to produce camera-ready copy and for the publisher to market the volumes rapidly at an affordable price. Typical prices are less than $50 for hardback and less than $30 for paperback books. In addition, most SFI research is available in preprint form before publication in the scientific literature.

The books to date are:

1987:

Emerging Syntheses in Science, edited by David Pines, Proceedings Vol. I [first proceedings volume]

1988:

Theoretical Immunology, Part One, edited by Alan S. Perelson, Proceedings Vol. II

Theoretical Immunology, Part Two, edited by Alan S. Perelson, Proceedings Vol. III

The Economy as an Evolving Complex System, edited by Philip W. Anderson, Kenneth Arrow, and David Pines, Proceedings Vol. V

Artificial Life, edited by Christopher G. Langton, Proceedings Vol. VI [first use of color]

1989:

Lattice Gas Methods for Partial Differential Equations, edited by Gary Doolen et al., Proceedings Vol. IV

Computers and DNA, edited by George I. Bell and Thomas G. Marr, Proceedings Vol. VII

Lectures in the Sciences of Complexity, edited by Daniel L. Stein, Lectures Vol. I [first lectures volume]

1990:

Complexity, Entropy, and the Physics of Information, edited by Wojciech H. Zurek, Proceedings Vol. VIII

Molecular Evolution on Rugged Landscapes: Proteins, RNA and the Immune System, edited by Alan S. Perelson and Stuart A. Kauffman, Proceedings Vol. IX

1989 Lectures in Complex Systems, edited by Erica Jen, Lectures Vol. II

Introduction to the Theory of Neural Computation, by John Hertz, Richard Palmer, and Anders Krogh, Lecture Notes Vol. I [first lecture notes volume]

Complex Systems Dynamics, by Gérard Weisbuch, Lecture Notes Vol. II [first translation]

1991:

Artificial Life II, proceedings and video, edited by Christopher G. Langton et al., Proceedings Vol. X (in print August 1991) [first videotape]

Nonlinear Modeling and Forecasting, edited by Martin Casdagli and Stephen Eubank, Proceedings Vol. XII (submitted in 1991; in print 1992)

1990 Lectures in Complex Systems, edited by Daniel L. Stein and Lynn Nadel, Lectures Vol. III (in print June 1991)

Projected Volumes in Print During 1992 are:

Evolution of Human Languages, edited by Jack Hawkins and Murray Gell-Mann, Proceedings Vol. XI

Principles of Organization in Organisms, edited by Arthur Baskin and Jay Mittenthal, Proceedings Vol. XIII

Understanding Complexity in the Prehistoric Southwest, edited by George Gumerman and Murray Gell-Mann, Proceedings Vol. XIV

The Global Dynamics of Cellular Automata: An Atlas of Basin of Attraction Fields of One-Dimensional Cellular Automata, by Andy Wuensche and Mike Lesser, Reference Vol. I [first reference volume and first volume with software]

1991 Lectures in Complex Systems, edited by Daniel L. Stein and Lynn Nadel, Lectures Vol. IV

The Double Auction Market: Theories, Institutions, and Evidence, edited by John Rust, John Miller, and Richard Palmer, Proceedings Vol. XV

Thinking About Biology, a lecture notes volume based on the Third Waddington Meeting on Theoretical Biology, held at SFI in 1991, edited by Francisco Varela and Wilfred Stein, Lecture Notes Vol. III

7.6 Public Education and Outreach

7.6.1 Public Lectures

The Santa Fe Institute recognizes an obligation to communicate to the general public an understanding of the newly emerging sciences of complexity. As part of this effort it hosts a regular monthly series of popular lectures. The lectures are held on the campus of St. John's College and are widely advertised in the community by posters, mailings, newspaper, and radio. They have been well received in the community and are well attended. A complete list of 1991 lecture titles and speakers appears in Appendix VII.

7.6.2 Secondary School Program

SFI has initiated a lecture/seminar program for Santa Fe's secondary school students designed to introduce them to the sciences of complexity as articulated by some of the leading researchers in the field. This two-part program combines in-school lectures by the Institute's research staff with a seminar program planned for a more limited number of students. Researchers make on-campus presentations in tandem with more in-depth seminar-discussion presentations addressed to gifted secondary school students. Criteria for student selection, program formats, and evaluation processes have been determined in consultation with local secondary school faculty, who also act as program coordinators.

Lecturers are selected from the External Faculty, Visiting Faculty, and other scientists associated with SFI, based on their special research interests and their ability to communicate to the non-scientist. Current lecturers and topics are Christopher Langton (LANL) on Artificial Life; Alan Perelson (LANL) on theoretical immunology; Erica Jen (LANL) on cellular automata; Stuart Kauffman (U. Pennsylvania) on evolutionary biology; and Geoffrey West (LANL) on scaling phenomena.

8. RESEARCH ENVIRONMENT

8.1 Office Facilities

The Santa Fe Institute occupies two buildings at 1660 Old Pecos Trail, Santa Fe, New Mexico. This leased facility provides approximately 11,000 square feet of space, including several small seminar rooms, a conference meeting room seating up to 60, administrative offices for a staff of 15, computer facilities, limited library space, and shared office space for up to 30 scientists.

8.2 Computing Facilities

The computing facilities at the Institute have grown from an initial handful of personal desktop computers to a fully connected network of desktop machines and mini-computer workstations. At present, our machines include a Sun 3 workstation, 20 Sun 4 workstations, 2 DEC workstations, 1 NeXT, 1 Silicon Graphics, 20 Apple Macintoshes, and 5 IBM PCs. The Sun systems provide the backbone of our computational capabilities, as well as our interface, via cisco Systems gateway hardware, to the NSF WestNet and the Internet world outside the Institute (Internet network address 192.12.12 and domain SANTAFE.EDU). The Macs and PCs provide desktop access to electronic mail and word-processing capabilities for all of our staff and resident researchers.

Interconnectivity plays an important role at the Institute. As much of the research supported by the Institute is conducted by teams of researchers spread around the globe and visitors with diverse computation and communications needs, the ability to communicate with distant computational resources is crucial to the success of these endeavors. This is particularly important for those needing access to supercomputing resources, which the Institute could not hope to provide at the present time. Additionally, the ability of the staff to communicate work in progress quickly and efficiently with one another, as well as to share hardware and software resources, has aided greatly with the day-to-day operation of the Institute.

Effort has also been devoted to the development of software resources at the Institute. The availability of programming environments, programming languages, text-processing systems, and advanced graphics-rendering utilities is vital to the computer-bound research programs supported by the Institute. A variety of software is now installed and supported on the Suns including the NeWS window system (OpenWindows), the Kermit communications package, numerous graphics systems, C, C++, Lisp, and Fortran compilers, the Mathematica symbolic mathematical package, name server software, LaserWriter software, Mac-Ethernet connection software, the EMACS editor, the XII window system, NCSA's Imagetool system, and a TEX text-processing system.

8.3 Library Resources

The Institute is slowly building its library resources through purchases and as the recipient of several donated collections. SFI houses approximately 2,000 volumes as part of the Stanislas Ulam Collection, and holds volumes of *The Physical Review*, 1944–1989, as part of the Herbert L. Anderson Collection. In 1990 the Institute received more than 2,000 volumes, principally in mathematics and physics, from the library of the late Paul R. Stein. In 1990 the Addison-Wesley Collection was also established with a initial donation of thirty titles in the Addison-Wesley Advanced Book Program. SFI maintains a growing (p)reprint collection of relevant literature in the sciences of complexity. Current journal subscriptions are *Complex Systems*, *Nature*, *Neural Computation*, and *Science*. Library facilities are supplemented by an interlibrary loan arrangement with nearby Los Alamos National Laboratory.

NOTES

References that appear in the SFI working papers series (Appendix I), the SISOC books series, or in Appendix II, are not repeated here.

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SFI WORKING PAPERS (JANUARY 1991 TO APRIL 1992)

91-01-001 Phenomenology of Non-Local Cellular Automata
Wentian Li

91-01-002 Generating Non-Trivial Long-Range Correlations and 1/f Spectra by Replication and Mutation
Wentian Li

91-01-003 Can Evolutionary Dynamics Explain Free Riding in Experiments?
John H. Miller and James Andreoni

91-01-004 Auctions with Adaptive Artificially Intelligent Agents
James Andreoni and John H. Miller

91-01-005 A Comparison of Some Variational Strategies used in Field Theory, published in *Phys. Rev.* **D43** (1991): 3396
Fred Cooper, H. F. Jones, and L. M. Simmons, Jr.

91-01-006 Simple Technical Trading Rules and the Stochastic Properties of Stock Returns
William Brock, Josef Lakonishok, and Blake LeBaron

91-01-007 Attractor Reconstruction from Event-Related Multi-Electrode EEG-Data
Gottfried Mayer-Kress, Cathleen Barczys, and Walter J. Freeman

91-01-008 Embedology—To appear in *J. Stat. Phys.*
Tim Sauer, James A. Yorke, and Martin Casdagli

91-02-009 Some Theory of Statistical Inference for Nonlinear Science: Expanded Version
William A. Brock and Ehung G. Baek

91-02-010 Dynamic Externalities, Multiple Equilibria and Growth
Michele Boldrin

91-02-011 Adaptation on Rugged Landscapes Generated by Local Interactions of Neighboring Genes—Abridged version will be forthcoming in the *Review of Economic Studies*
Mark Lipsitch

91-02-012 The Attractor-Basin Portrait of a Cellular Automaton
James E. Hanson and James P. Crutchfield

91-02-013 On the Structure and Diversity of Rational Beliefs
Mordecai Kurz

91-02-014 Variational Approximations to the Nonlinear Schrödinger Equation
Fred Cooper, Harvey K. Shepard, and L. M. Simmons, Jr.

91-02-015 Experiments on Stable Suboptimality in Individual Behavior
R. J. Herrnstein

91-03-016 Random Texts Exhibit Zipf's-Law-Like Word Frequency Distribution
Wentian Li

91-03-017 The Santa Fe Institute
Murray Gell-Mann

91-03-018 Approximation Theorems for Gambling Problems and Stochastic Games
A. Maitra, R. Purves, and W. Sudderth

91-03-019 State Space Reconstruction in the Presence of Noise
Martin Casdagli, Stephen Eubank, J. Doyne Farmer, and John Gibson

91-04-020 The Functional Self-Organization of Autocatalytic Networks in a Model of the Evolution of Biogenesis
Richard James Bagley

91-04-021 The Sciences of Complexity and 'Origins of Order'
Stuart A. Kauffman

91-05-022 Nonlinear Forecasting, Chaos and Statistics
Martin Casdagli

91-05-023 A Dynamical Systems Approach to Modeling Input-Output Systems
Martin Casdagli

91-05-024 The Performance of Genetic Algorithms on Walsh Polynomials: Some Anomalous Results and Their Explanation—in the *Proceedings of the Fourth International Conference on Genetic Algorithms*, Morgan Kaufman, 1991
Stephanie Forrest and Melanie Mitchell

91-05-025 Artificial Adaptive Agents in Economic Theory
John Holland and John H. Miller

91-05-026 Information Constriction and Information Contagion
W. Brian Arthur and David A. Lane

91-07-027 Recombination Dynamics and the Fitness Landscape
Aviv Bergman and Marcus W. Feldman

91-07-028 Topological Kinks in ϕ^{2n} Field Theories: A Variational Approach
Fred Cooper, L. M. Simmons, Jr., and Pasquale Sodano

91-07-029 Chaos and Deterministic versus Stochastic Nonlinear Modeling
Martin Casdagli

91-07-030 Long-Range Correlation and Partial $1/f^{\alpha}$ Spectrum in a Non-Coding DNA Sequence
Wentian Li and Kunihiko Kaneko

91-08-031 Endogenous Nonconvex State-Transition Rules and Cyclical Policies
C. Y. Cyrus Chu

91-09-032 Chaos and Politics: Applications of Nonlinear Dynamics to Socio-Political Issues
David K. Campbell and Gottfried Mayer-Kress

91-09-033 Semantics and Thermodynamics
James P. Crutchfield

91-09-034 Discovering Coherent Structures in Nonlinear Spatial Systems
James P. Crutchfield

91-09-035 Knowledge and Meaning...Chaos and Complexity
James P. Crutchfield

91-09-036 Growth in Cities
Edward L. Glaeser, Hedi D. Kallal, José A. Scheinkman, and Andrei Shleifer

91-09-037 Antichaos and Adaptation
Stuart A. Kauffman

91-09-038 Dynamical Signatures
Lyle Noakes and Alistair Mees

91-10-039 A Mechanism of Immune Escape by Slow-Replicating HIV Strains
George W. Nelson and Alan S. Perelson

91-10-040 Recent Approaches to Immune Networks
Rob J. de Boer, Avidan U. Neumann, Alan S. Perelson, Lee A. Segel, and Gérard Weisbuch

91-10-041 What Makes a Problem Hard for a Genetic Algorithm? Some Anomalous Results and Their Explanation
Stephanie Forrest and Melanie Mitchell

91-10-042 Evidence for p55-p75 Heterodimers in the Absence of Interleukin-2 from Scatchard Plot Analysis
Byron Goldstein, David Jones, Ioannis G. Kevrekidis, and Alan S. Perelson

91-10-043 The Evolution of Cenventions
H. Peyton Young

91-10-044 Technical Trading Rules and Regime Shifts in Foreign Exchange
Blake LeBaron

91-10-045 Plasmid Copy Number Control: A Case Study of The Quasi-Steady State Assumption
Lee A. Segel and Alan S. Perelson

91-10-046 The Royal Road for Genetic Algorithms: Fitness Landscapes and GA Performance
Melanie Mitchell, Stephanie Forrest, and John H. Holland

91-11-047 Transactions Costs and Correlations in a Large Firm Index
Blake LeBaron

91-11-048 Random Catalytic Reaction Networks
Peter F. Stadler, Walter Fontana, and John H. Miller

91-12-049 Deterministic Prediction and Chaos in Squid Axon Response
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92-01-001 Persistence of the Dow Jones Index on Rising Volume
Blake LeBaron

92-01-002 Mathematical Approaches in Immunology
Alan S. Perelson

92-01-003 Maxwell's Demon, Rectifiers, and the Second Law: Computer Simulation of Smoluchowski's Trapdoor
P. A. Skordos and W. H. Zurek

92-01-004 Growth and Recruitment in the Immune Network
Rob J. De Boer, Pauline Hogeweg, and Alan S. Perelson

92-01-005 The Dynamics of HIV Infection of $CD4^+$ T Cells
Alan S. Perelson, Denise E. Kirschner, George W. Nelson, and Rob De Boer

92-01-006 On the Connection Between In-Sample Testing and Generalization Error
David H. Wolpert

92-02-007 Statistics of RNA Secondary Structures
Walter Fontana, Danielle A. M. Konings, Peter F. Stadler, and Peter Schuster

92-02-008 Behavior of Trading Automata in a Computerized Double Auction Market
John Rust, Richard Palmer, and John H. Miller

92-02-009 An Evolutionary Model of Bargaining
H. Peyton Young

92-02-010 Three Simple Experimental Games
Martin Shubik

92-03-011 Exact Ground States, Low-Temperature Expansions and the Order-Parameter Distribution of Short-Range Spin Glasses
Paul Stolorz

92-03-012 On The Implementation of Bayes-Optimal Generalizers
David H. Wolpert and Paul Stolorz

92-03-013 A Rigorous Investigation of "Evidence" and "Occam Factors" in Bayesian Reasoning
David H. Wolpert

92-03-014 The Relationship Between The "Statistical Mechanics" Supervised Learning Framework and Pac
David H. Wolpert

92-03-015 Regular Language Inference Using Evolving Neural Networks
Kristian Lindgren, Anders Nilsson, Mats G. Nordahl, and Ingrid Råde

92-03-016 Transient Behavior of Cellular Automaton Rule 110
Wentian Li and Mats G. Nordahl

92-04-017 The Ghost in the Machine: Basin of Attraction Fields of Disordered Cellular Automata Networks
Andrew Wuensche

92-04-018 Self Organized Criticality and Fluctuations in Economics
Per Bak, Kan Chen, José A. Scheinkman, and M. Woodford

92-04-019 Recasting Deterministic Annealing as Constrained Optimisation
Paul Stolorz

92-04-020 A Rigorous Investigation of Exhaustive Learning
David H. Wolpert and Alan Lapedes

92-04-021 An Analytic Approach to Practical State Space Reconstruction
John F. Gibson, J. Doyne Farmer, Martin Casdagli, and Stephen Eubank

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LIST OF 1991 COLLOQUIA

The Evolution of Complexity: Some Empirical Results from a Simple Microbiological System
Julian Adams, University of Michigan

Social Impact of Human Genome Science
Jonathan Beckwith, Harvard Medical School

Proto-Oncogene Activation vs. Anti-Oncogene Inactivation in an Experimental Tumor Model
Thomas Benjamin, Harvard Medical School

Virtual Reality
William Bricken, University of Washington

The High-Performance Computing and Communications Initiative
Charles Brownstein, National Science Foundation

"Rebinding" Kinetics and a Double-Edged Approximation of a PDE with an ODE
Bill Bruno, Los Alamos National Laboratory

How to Analyze the Fractal Texture of Matter Distributions
Peter Carruthers, University of Arizona

Managing Complexity vs. Modelling Complexity—the Basic Research Gap
Roger Cox, Sandia National Laboratories

The Attractor-Basin Portrait of a Cellular Automaton
Jim Crutchfield, University of California, Berkeley

Thermodynamics of Evolution
Lloyd Demetrius, Harvard University

The Physics of Roulette
J. Doyne Farmer, The Prediction Company

Computing with Structured Connectionist Networks
Jerome Feldman, International Computer Science Institute

Complexity and Bounded Rationality in Economics and Chess
John Geanakoplos, Yale University

How to Extract Rules from Neural Networks
C. Lee Giles, NEC Research/University of Maryland

Sets of Similar Polygons are Hard to Learn
Paul Goldberg, University of Edinburgh

Adaptive Behavior—a Partial Description of Robust Dynamics?
Brian Goodwin, Open University, UK

Fault-Tolerant Universal Cellular Automata (CA)
Larry Gray, University of Minnesota

Coding Structure of RNA Sequences & Self-Structuring as Substrate of Evolution
Pauline Hogeweg, University of Utrecht

Optimal Prediction in a High-Dimensional, Evolving Environment
Alfred Hubler, University of Illinois

Building the Open Road: Policies for a National Public Network
Mitch Kapor, Electronic Frontier Foundation

Biosim—Game-Oriented User Interface for A-Life Simulation
Ken Karakotsios, Algorithmic Arts/Maxis

Waiting for Carnot: The Search for Laws Governing Complex Adaptive Systems
Stuart Kauffman, University of Pennsylvania

Fun with Attractors and Chaos in Neural Network Autoassociative Memories
Tom Kepler, Santa Fe Institute

Charles Peirce: Complex Systems and Systems of Signs
Roberta Kevelson, Pennsylvania State University

Networks in Neurophysiology: Mathware for Wetware
Nancy Kopell, Boston University

Artificial Life on the Edge of the Charles
Chris Langton, Los Alamos National Laboratory

Volatility, Volume, and the Changing Cross-Sectional Correlations in the Dow Industrials
Blake Le Baron, University of Wisconsin

Technical Trading Rules: The Scientific Evidence
Blake Le Baron, University of Wisconsin

Fractal Analysis for the Studies in Complex Systems
Alain Le Méhauté, Alcatel Alsthom Recherche, France

From Data to Schemata
Seth Lloyd, Los Alamos National Laboratory

Mapping Psychoanalysis to Cognitive Science
John Lundgren, Los Angeles Psychoanalytic Institute

Optically Driven Quantum Networks: An Approach to Programmable Matter
Günter Mahler, University of Stuttgart

Ecological Dynamics of Game World
Kazuhiro Matsuo, Fujitsu Labs, Japan

A Multi-Media Approach to Global Visualization and Simulation Environment—Some Excerpts from the "Earthstation" Installation
Gottfried Mayer-Kress, University of Illinois

Qualitative Information from a Time Series
Alistair Mees, University of Western Australia

Lags and Chaos in Economic Dynamic Models
Alfredo Medio, University of Venice

What are Genetic Algorithms and What can They Do for You?
Melanie Mitchell, University of Michigan

Unpredictability and Undecidability in Dynamical Systems
Cris Moore, Cornell University

Modelling Dynamical Phenomena in Motile Systems
Masatoshi Murase, University of California, Davis

The Versatility of RNA: Lessons from the Ciliate Tetrahymena
Henrik Nielsen, University of Copenhagen

Toward Agent Programs with Circuit Semantics
Nils Nilsson, Stanford University

Antigenic Diversity in HIV Infections: A Mechanism for AIDS Pathogenesis
Martin Nowak, Oxford University

Khoros: An Open Environment for Information Processing, Data Visualization, and Software Development
John Rasure, University of New Mexico

Optimization and Creativity in Evolution
Tom Ray, University of Delaware

Beyond the Centralized Mindset: Learning to Think About Self-Organization
Mitchel Resnick, Massachusetts Institute of Technology

Statistics of RNA Secondary Structures—an Example of a Realistic Shape Space
Peter Schuster, University of Vienna, Austria

Complex Combinatory Landscapes
Peter Stadler, University of Vienna, Austria

Replicator Dynamics and Beyond: Differential Equation Models of Complex Systems
Peter Stadler, University of Vienna, Austria

How the Complexity of Neuronal Circuits Varies with Brain Size
Charles Stevens, The Salk Institute

Analog Entropy as a Tool for Combinatorial Optimization, Adaptive Learning, and Clustering
Paul Stolorz, Santa Fe Institute/Los Alamos National Laboratory

Mean Field Analysis of Systems that Exhibit Self-Organized Criticality
James Theiler, Los Alamos National Laboratory

Dynamical Analysis of Biological Regulatory Networks: A Logical Method and Its Automatization
Denis Thieffry, Université Libre de Bruxelles

Information Based Complexity: Recent Results and New Research Directions
Joseph Traub, Columbia University

The Economics of User Interfaces
Hal Varian, University of Michigan

The Immune System as a Dynamical Network
Gérard Weisbuch, Ecole Normale Supérieure, Paris

On the Connection Between In-Sample Testing and Generalization of Error
David Wolpert, Santa Fe Institute

Stacked Generalization
David Wolpert, Santa Fe Institute

The Global Dynamics of Cellular Automata: An Atlas of Basin of Attraction Fields of One-Dimensional Cellular Automata
Andy Wuensche, Santa Fe Institute

Listening to the Ear
George Zweig, Los Alamos National Laboratory

LIST OF 1991 WORKSHOPS

January 11–17	Learning in Economics, Psychology and Computer Science: An Exchange of Ideas *Brian Arthur, Stanford University* *Richard Hennstein, Harvard University* *John Holland, University of Michigan*
February 13–17	New Technology for Prediction and Pattern Recognition: Applications to Financial Markets *John Geanakoplos, Yale University* *David Lane, University of Minnesota*
April 3–8	Learning, Rationality, and Games *John Geanakoplos, Yale University* *David Lane, University of Minnesota*
May 13–17	Third Waddington Meeting on Theoretical Biology *Brian Goodwin, The Open University, England* *Stuart Kauffman, University of Pennsylvania* *Francisco Varela, CREA, Ecole Polytechnics, France* *Lewis Wolpert, The Middlesex Hospital Medical School, England*
May 19–23	Missing Markets and the Emergence of Market Structure *John Geanakoplos, Yale University* *David Lane, University of Minnesota* *Martin Shubik, Yale University*
June 2–29	1991 Complex Systems Summer School *Daniel Stein, University of Arizona* *Lynn Nadel, University of Arizona*
June 9–10	Price Dynamics and Trading Strategies in Double Auction Markets II *Dan Friedman, University of California, Santa Cruz* *John Geanakoplos, Yale University* *John Rust, University of Wisconsin*
August 9–11	Planning Workshop on Adaptive Computation *John Holland, University of Michigan*
August 12–14	Simulation Authoring Tools and SimToolkit Project Symposium *James Klein, Simulation Laboratories*
September 12–16	Self-Organized Criticality *Philip Anderson, Princeton University* *Sidney Nagel, University of Chicago*
September 27–29	Growth and Cities *José Scheinkman, University of Chicago*
October 10–14	Implications of Dendritic Models for Neural Network Properties *Wilfrid Rall, National Institutes of Health*
November 4–18	SFI/University of Michigan Adaptive Computation Meeting (Held in Ann Arbor, Michigan) *John Holland, University of Michigan*

LIST OF 1991 VISITORS

Julian Adams	University of Michigan
Philip Anderson	Princeton University
Robert Artigiani	U.S. Naval Academy
Tony Begg	Brunel University, UK
Tom Benjamin	Harvard Medical School
Aviv Bergman	Stanford University
Hugues Bersini	University of Belgium
William Bricken	University of Washington
Tony Burgess	University of Arizona
David Campbell	Los Alamos National Laboratory
John Casti	Technical University of Vienna
Francesca Chiaromonte	University of Rome
Jim Crutchfield	University of California, Berkeley
Rob de Boer	University of Utrecht
Lloyd Demetrius	Harvard University
Giovanni Dosi	University of Rome
Pradeep Dubey	State University of New York at Stony Brook
Michael Ekhaus	University of Minnesota
Marc Feldman	Stanford University
Wolfgang Fikentscher	University of Munich
Michael Fishman	Weizmann Institute
John Geanakoplos	Yale University
Murray Gell-Mann	California Institute of Technology
Neil Gershenfeld	Harvard University
Eddy Glaeser	University of Chicago
Donald Glaser	University of California, Berkeley
Alex Gray	University of California, Berkeley
Larry Gray	University of Minnesota
Paulien Hogeweg	University of Utrecht
John Holland	University of Michigan
Alfred Hubler	University of Illinois
Setsuo Ichimaru	University of Tokyo
John Jackson	University of Michigan
Eva Jaeger	Weizmann Institute
James Kalin	Simulation Laboratories
Hedi Kallal	University of Chicago
Ioannis Karatzas	Columbia University
Alan Kaufman	Massachusetts Institute of Technology
Stuart Kauffman	University of Pennsylvania
Tom Kepler	Brandeis University
Roberta Kevelson	Pennsylvania State University
Nancy Kopell	Boston University
Vladimir Kuznetsov	Academy of Sciences, Moscow
Brenda Javornik	University of New Mexico
David Lane	University of Minnesota
Erik Reimer Larsen	Copenhagen Business School
Blake LeBaron	University of Wisconsin
Gene Levy	University of Arizona
Kristian Lindgren	Chalmers Institute of Technology
Robert Lindsay	University of Michigan

Marji Lines	University of Venice
Marco Lippi	Modena University
Marc Lipsitch	Yale University
Seth Lloyd	California Institute of Technology
Jon Lunine	University of Arizona
Catherine Macken	Stanford University/University of New Zealand
Günter Mahler	University of Stüttgart
Ashok Maitra	University of Minnesota
Franco Malerba	Bocconi University
Gottfried Mayer-Kress	University of California, Santa Cruz
Alfredo Medio	University of Venice
Alistair Mees	University of Western Australia
Tom Meyer	University of Illinois
John Miller	Carnegie-Mellon University
Melanie Mitchell	University of Michigan
Cris Moore	Cornell University
Harold Morowitz	George Mason University
Masatoshi Murase	University of California, Davis
Richard Nelson	Columbia University
Anders Nilsson	Chalmers Institute of Technology
Nils Nilsson	Stanford University
Richard Nisbett	University of Michigan
Luigi Orsenigo	Bocconi University
Richard Palmer	Duke University
David Pines	University of Illinois
Dan Pirone	University of Delaware
Steve Pollock	University of Michigan
Andrew Postlewaite	University of Pennsylvania
Ingrid Råde	Chalmers Institute of Technology
Tom Ray	University of Delaware
Mitchel Resnick	Massachusetts Institute of Technology
John Rust	University of Wisconsin
José Scheinkman	University of Chicago
David Schmeidler	Ohio State University/University of Tel Aviv
Erik Schultes	Humboldt State University
Peter Schuster	University of Vienna
Lee Segel	Weizmann Institute
Alex Shevroniski	University of Michigan
Martin Shubik	Yale University
Charles Sing	University of Michigan
Pete Skordos	Massachusetts Institute of Technology
Peter Stadler	University of Vienna
Ann Stanley	Iowa State University
Dan Stein	University of Arizona
Charles Stevens	Salk Institute
William Sudderth	University of Minnesota
Joseph Traub	Columbia University
Ted Uede	Northwestern University
Hal Varian	University of Michigan
Massimo Warglien	University of Venice
Andreas Weigend	Stanford University
Gérard Weisbuch	Ecole Normale Supérieure, Paris
Peyton Young	University of Maryland
Michael Zeilik	University of New Mexico

ROSTERS & SCHEDULES OF WORKSHOPS

Roster for the Workshop on Learning in Economics, Psychology, and Computer Science: An Exchange of Ideas

Prof. Kenneth J. Arrow	Stanford University
Prof. W. Brian Arthur	Stanford University
Prof. Margaret Bray	The London School of Economics, U.K.
Prof. William Este	Harvard University
Prof. Drew Fudenberg	Massachusetts Institute of Technology
Prof. John Geanakoplos	Yale University
Prof. Itzhak Gilboa	Northwestern University
Prof. Larry Gray	Santa Fe Institute
Prof. Richard Herrnstein	Harvard University
Prof. John Holland	University of Michigan
Prof. Keith Holyoak	University of California, Los Angeles
Prof. David Lane	University of Minnesota
Prof. Ashok Maitra	University of Minnesota
Prof. Nils Nilsson	Stanford University
Mr. James Pelkey	Private Investor/Consultant, Santa Fe
Prof. Charles Plott	California Institute of Technology
Prof. Dragen Prelec	Harvard University
Prof. David Rumelhart	Stanford University

Program for the Workshop on Learning in Economics, Psychology, and Computer Science: An Exchange of Ideas, January 11–17

Formal program not available.

Roster for the Workshop on New Technologies for Prediction and Pattern Recognition: Applications to Financial Markets

Dr. Thomas Anantharaman	Tudor Investment Corp.
Prof. Philip Anderson	Princeton University
Prof. Brian Arthur	Stanford University
Mr. Bob Battenfelder	Citibank
Dr. Tony Begg	Brunel University, UK
Mr Terry Benzschawel	Citibank
Dr. W. E. Bosarge, Jr.	Frontier Financial Corp.
Prof. William Brock	University of Wisconsin
Mr. Michael Browne	Tudor Investment Corp.
Dr. Martin Casdagli	Santa Fe Institute
Dr. Gregory Chenizer	Wall Street Consultant
Ms. Elizabeth Corcoran	*Scientific American*
Mr. John Davies	Citicorp/Citibank
Mr. William Dunn	Dow Jones & Company
Ms. June Durnall	Citibank GSO
Mr. Andrew Dyson	Citicorp Scrimgeour Vickers Int'l. Ltd., UK
Mr. Chris Ekins	Midland Montagu, UK
Ms. Marjorie Engber	Citicorp
Stephen Eubank	Los Alamos National Laboratory
Dr. Doyne Farmer	Los Alamos National Laboratory
Mr. Kent Frazier	Citicorp TTI
Prof. John Geanakoplos	Santa Fe Institute
Mr. Bill Hendrick	Atlanta Constitution
Mr. David Hirschfeld	Tudor Investment Corp.
Prof. John Holland	University of Michigan
Mr. Nick Idelson	Midland Montagu, UK
Prof. Edwin T. Jaynes	Washington University
Dr. Roger Jones	Los Alamos National Laboratory
Mr. Alan Kaplan	Citicorp Retail Services
Mr. Don Kumka	Citibank
Prof. David Lane	University of Minnesota
Dr. Steffen Lauritzen	Aalborg University, Denmark
Prof. Blake LeBaron	University of Wisconsin
Mr. Henry Lichstein	Citicorp
Mr. Greg Lieb	Bear Stearns
Ms. Sue Malley	Citicorp Select Investments
Mr. Peter McAllister	Citicorp Retail Services
Mr. Ed Meihaus	Hanseatic Group, Inc.
Dr. Joseph Mezrich	Salomon Brothers Inc.
Mr. Andre Mirabelli	Kidder Peabody
Mr. Richard Musci	Citibank
Prof. Norman Packard	University of Illinois
Prof. Richard Palmer	Duke University
Mr. Sunil Panchal	Midland Bank, UK
Mr. Edgar Peters	Concord, MA
Mr. Terry Vance Pukula	Pukula and Co.
Dr. Rick Riolo	University of Michigan
Mr. Bradley Rotter	Echelon Group
Mr. Sylvain Roy	Citibank Bank Cards
Dr. Juana Sanchez	University of Missouri

Prof. Tim Sauer	George Mason University
Prof. Jose Scheinkman	University of Chicago
Mr. Daniel Schutzer	Citicorp Technology Office
Dr. Stephen Schwanauer	Darien, CT
Dr. George Sugihara	Scripps Institute of Oceanography
Prof. James Stock	University of California, Berkeley
Ms. Peg Trench	Citibank
Mr. Alfred Weinberger	Salomon Brothers
Mr. Larry Weiss	Goldman Sachs
Prof. Hal White	University of California, San Diego
Dr. Michael Zaretsky	Kidder Peabody

Program for the Workshop on New Technologies for Prediction and Pattern Recognition: Applications to Financial Markets, February 13–15, 1991

All sessions will be held at the Santa Fe Institute, 1120 Canyon Road.

WEDNESDAY, FEBRUARY 13, 1991

DAY 1: PROBLEMS

8:30 A.M.	*Continental Breakfast*
	The following groups of financial experts will describe problems that may be susceptible to analysis by the techniques to be presented on Thursday. The talks range in depth from 1/2 to 1 hour.
9:00 A.M.	W.E. Bosarge, Jr. J. Mezrich and A. Weinberger, L. Weiss J. Davies E. Peters G. Chenizer D. Hirschfeld
6:00 P.M.	Dinner at Rancho de Chimayo

THURSDAY, FEBRUARY 14, 1991

DAY 2: TECHNIQUES

8:30 A.M.	*Continental Breakfast*
9:00 A.M.	"Nonlinear Dynamics in Financial Time Series" W. Brock, B. LeBaron
10:00 A.M.	"Nonlinear Time Series Prediction" D. Farmer
11:00 A.M.	"Maximum Entropy Methods for Econometric Time Series" E. Jaynes and J. Sanchez
12:00 P.M.	*Lunch*
1:30 P.M.	"Bayesian Expert Systems" S. Lauritzen
2:30 P.M.	"Neural Nets" R. Jones, R. Palmer, and H. White
4:30 P.M.	"Genetic Algorithms and Pattern Recognition" N. Packard

FRIDAY, FEBRUARY 15, 1991

DAY 3: DISCUSSION

8:30 A.M.	*Continental Breakfast*
9:00 A.M.	"Classifier Schemes" J. Holland, R. Riolo
10:00 A.M.	Discussion Group
12:00 P.M.	*Lunch*
1:30 P.M.	Discussion Group

Roster for the Workshop on Learning, Rationality, and Games

Prof. Kenneth J. Arrow	Stanford University
Prof. W. Brian Arthur	Stanford University
Prof. Margaret Bray	The London School of Economics
Prof. William Estes	Harvard University
Prof. Drew Fudenberg	Massachusetts Institute of Technology
Prof. John Geanakoplos	Yale University
Prof. Itzhak Gilboa	Northwestern University
Prof. Larry Gray	University of Minnesota
Prof. Richard Herrnstein	Harvard University
Prof. John Holland	University of Michigan
Prof. Keith Holyoak	University of California, Los Angeles
Prof. David Lane	University of Minnesota
Prof. Ashok Maitra	University of Minnesota
Prof. Nils Nilsson	Stanford University
Mr. Jim Pelkey	Private Investor/Consultant, Santa Fe
Prof. Charles Plott	California Institute of Technology
Prof. Dragen Prelec	Harvard University
Prof. David Rumelhart	Stanford University

Program for the Workshop on Learning, Rationality, and Games, April 3–8,1991

All sessions will be held at the Santa Fe Institute, 1120 Canyon Road.

WEDNESDAY, APRIL 3, 1991

8:30 A.M.	*Continental Breakfast*
9:00–10:25 A.M.	Larry Blume "Statistical Mechanics of Strategic Interaction"
10:25–10:40 A.M.	*Break*
10:40–12:05 P.M.	David Canning "Average Behavior in Learning Markets"
12:05-1:15 P.M.	*Lunch*
1:15-2:40 P.M.	David Schmeidler "A Neo-Bayesian Foundation of the MaxMin Value for Two-Person Zero-Sum Games"
2:40–2:55 P.M.	*Break*
2:55–4:20 P.M.	Ashok Maitra "Repeated Games with Imperfect Information"
4:20–4:35 P.M.	*Break*
4:35–6:00 P.M.	Karl Shell "Symmetry Breaking in Economics: Stochastic Allocation of Indivisible Goods"

THURSDAY, APRIL 4, 1991

(Please note earlier starting time)

8:15 A.M.	*Continental Breakfast*
8:45–10:10 A.M.	Mark Machina "A More Robust Definition of Subjective Probability"
10:10–10:25 A.M.	*Break*

10:25–11:50 A.M.	Nils Nilsson "Learning Sequences of Actions"
11:50 A.M.–1:00 P.M.	*Lunch*
1:00–2:25 P.M.	Ariel Rubenstein "On the Strategic Manipulation of Consumers' Computational Complexity"
2:25–2:40 P.M.	*Break*
2:40–4:05 P.M.	George Mailath "An Evolutionary Model of Naive Learning"
4:05–5:30 P.M.	Yaw Nyarko "Bayesian Rationality and Learning Without Common Priors"
6:00 P.M.	Dalai Lama Public Talk at Santa Fe High School (Optional)

FRIDAY, APRIL 5, 1991

8:30 A.M.	*Continental Breakfast*
9:00–10:25 A.M.	Ehud Kalai "Rational Learning Leads to Nash Equilibrium or Merging Economic Forecasts"
10:25–10:40 A.M.	*Break*
10:40 A.M.–12:05 P.M.	Moshe Vardi "Knowledge Without Probability"
12:05–1:15 P.M.	*Lunch*
1:15–2:40 P.M.	John Geanakoplos "Game Theory and Decision Theory with Information Processing Errors"
2:40–2:55 P.M.	*Break*
2:55–4:20 P.M.	Yoram Moses "Murder Stories and Agreeing to Disagree or Basing Decisions on Relevant Information"
4:20–4:35 P.M.	*Break*
4:35–6:00 P.M.	Brian Arthur "A Behavioral Approach to Bounded Rationality"

SATURDAY, APRIL 6, 1991

8:30 A.M.	*Continental Breakfast*
9:00–10:25 A.M.	Stuart Kauffman "Towards a Theory of Bounded Rationality and Non-Equilibrium Price Formation in a Model of Technological Coevolution"
10:25–10:40 A.M.	*Break*
10:40 A.M.–12:05 P.M.	David Easley "Economic Natural Selection and Adaptive Behavior"
12:05–1:15 P.M.	*Lunch*
1:15–2:40 P.M.	Eddie Dekel "On the Evolution of Optimizing Behavior"
2:40–2:55 P.M.	*Break*
2:55–4:20 P.M.	Larry Gray "Foresight and Bounded Rationality"
4:20–4:35 P.M.	*Break*
4:35–6:00 P.M.	Giorgio Rampa "Finite-Degree Rationalization and Conjectural Equilibria"

SUNDAY, APRIL 7, 1991

8:30 A.M.	*Continental Breakfast*
9:00–10:25 A.M.	John Miller "A Strategic Taxonomy of Repeated 2 X 2 Games Played by Adaptive Agents"
10:25–10:40 A.M.	*Break*
10:40 A.M.–12:05 P.M.	Peyton Young "Cooperation in the Short Run and in the Long Run"
12:05–1:15 P.M.	*Lunch*

MONDAY, APRIL 8, 1991

8:30 A.M.	*Continental Breakfast*
9:00–10:25 A.M.	David Lane "Information Constriction and Information Contagion"
10:25–10:40 A.M.	*Break*
10:40 A.M.–12:05 P.M.	Discussion

Roster for the Third Waddington Meeting on Theoretical Biology

Dr. Per Bak	Brookhaven National Laboratory
Prof. Germinal Cocho	Universidad Nacional Autónoma de México
Dr. Rob De Boer	Bioinformatica, The Netherlands
Dr. Bruno D'Udine	Gorizia, Italy
Prof. Brian Goodwin	The Open University, UK
Prof. Deborah Gordon	Stanford University
Dr. Wilhelm Hansberg	Universität Düsseldorf, Germany
Prof. Mae-Wan Ho	The Open University, UK
Prof. Stuart Kauffman	University of Pennsylvania
Dr. Chris Langton	Los Alamos National Laboratory
Dr. Francisco Lara-Ochoa	Centro de Investigacion Sobre Fijacion de Nitrogeno, México
Prof. Jay Mittenthal	University of Illinois
Dr. Fritz Popp	International Institute of Biophysics, Germany
Prof. Rudy Raff	Indiana University
Prof.. José Rius	Universidad Nacional Autónoma de México
Prof. Peter Saunders	Kings College, UK
Prof. Wilfred Stein	State University of New York at Syracuse
Prof. Lynn Trainor	University of Toronto, Canada
Prof. Francisco Varela	CREA, France
Prof. Elizabeth Vrba	Kline Geology Laboratory

Program for Waddington Meeting

Formal program not available.

Roster for the Workshop on Missing Markets and the Emergence of Market Structure

Prof. George Akerlof	University of California, Berkeley
Prof. Beth Allen	University of Pennsylvania
Prof. Bob Anderson	University of California, Berkeley
Prof. Kenneth J. Arrow	Stanford University
Dr. J. D. Benassy	Centre d'Etudes Prospectives d'Economie Mathematique Appliquées à la Planification, France
Prof. Frances Berdan	California State University at San Bernardino
Prof. Don Brown	Stanford University
Prof. David Cass	University of Pennsylvania
Prof. Graciela Chichilnisky	Columbia University
Mr. John Davies	Citicorp
Prof. Gerard Debreu	University of California, Berkeley
Prof. Rudiger Dornbusch	Massachusetts Institute of Technology
Prof. Pradeep Dubey	State University of New York at Stony Brook
Prof. Darrell Duffie	Stanford Business School
Mr. Marty Fridson	Merrill Lynch
Prof. Roman Friedman	New York University
Prof. Larry Gray	University of Minnesota
Prof. John Geanakoplos	Yale University
Prof. Keith Hart	Cambridge University, England
Mr. Stephen Judelson	Morgan Stanley & Co.
Prof. Aron Katsenelinboigen	University of Pennsylvania
Prof. Stuart Kauffman	University of Pennsylvania
Prof. Tim Kehoe	University of Minnesota
Dr. Charles Kindleberger	Lexington, MA
Prof. Max Kunyavsky	Belorussian Institute of National Economy
Prof. David Lane	University of Minnesota
Mr. Henry Lichstein	Citicorp
Prof. Robert Lucas	University of Chicago
Prof. Michael Magill	University of Southern California
Prof. Andreu Mas-Collel	Harvard University
Prof. Richard Nelson	Columbia University
Mr. James Pelkey	Private Investor/Consultant, Santa Fe
Mr. Alan Petersen	Signa Corporation
Dr. Stuart Plattner	National Science Foundation
Prof. Heraklis Polemarchakis	Columbia University
Prof. Martine Quizzi	University of Southern California
Dr. Roy Radner	AT&T Bell Laboratories
Prof. Mark Rosenzweig	University of Pennsylvania
Prof. Charles Sabel	Massachusetts Institute of Technology
Mr. Jeffrey Sachs	Eco Link
Prof. Wayne Shafer	University of Illinois
Prof. Robert Shiller	Yale University
Prof. Martin Shubik	Cowles Foundation
Prof. Robert Solow	Massachusetts Institute of Technology
Prof. Hugo Sonnenschein	University of Pennsylvania
Prof. Joseph Stiglitz	Stanford University
Dr. Lawrence H. Summers	The World Bank
Prof. R. Townsend	University of Chicago
Prof. Chris Udry	Northwestern University
Mr. Ken Urbaszewski	Kemper Financial Services

Dr. Eric Wanner	Russell Sage Foundation
Prof. William Zame	John Hopkins University
Dr. Michael Zaretsky	Kidder Peabody

Program for the Workshop on Missing Markets and the Emergence of Market Structure, May 19–23, 1991

The main aim of the workshop is to discuss what ought to be the elements of a general theory of emergence of markets structure. The format of the workshop will be group discussions prompted by informal presentations The tentative schedule is as follows:

SUNDAY, MAY 19, 1991

11:00 A.M.–12:00 P.M.	*Brunch*
12:00–4:00 P.M.	"Missing Markets: Current Theory" Presenters: John Geanakoplos, Yale U./SFI, and David Cass, U. Pennsylvania
4:00–5:30 P.M.	"The Creation of Markets for New Financial Instruments I" Presenter: Marty Fridson, Merrill Lynch

MONDAY, MAY 20, 1991

9:00–9:30 A.M.	*Continental Breakfast*
9:30 A.M.–12:00 P.M.	"The Emergence of Markets: An Anthropological Perspective" Presenter: Keith Hart, Cambridge U.
12:00–1:30 P.M.	*Lunch*
1:30–5:00 P.M.	"Markets in Developing Countries" Presenters: Robert Townsend, U. Chicago, and Chris Udry, Northwestern U.

TUESDAY, MAY 21, 1991

9:00–9:30 A.M.	*Continental Breakfast*
9:30 A.M.–12:00 P.M.	"The Creation of Markets for New Financial Instruments II" Presenters: Martin Shubik, Yale U., and Darrell Duffie, Stanford U.
12:00–1:30 P.M.	*Lunch*
1:30–5:00 P.M.	"Markets and Organizations" Presenters: Charles Sabel, MIT, and James Pelkey, SFI

WEDNESDAY, MAY 22, 1991

9:00–9:30 A.M.	*Continental Breakfast*
9:30 A.M.–12:00 P.M.	"The Creation of Markets: The Experience in Eastern Europe" Presenters: Max Kunyavsky, Belorussian Institute of National Economy; Aron Katsenelinboigen, U. Pennsylvania; and Jeffrey Sachs, Eco Link
12:00–1:30 P.M.	*Lunch*
1:30–5:00 P.M.	"The Emergence of Markets: Self-Organization vs. Centralized Construction"

THURSDAY, MAY 23, 1991

9:00–9:30 A.M.	*Continental Breakfast*
9:30 A.M.–12:00 P.M.	Discussion: "A Research Agenda in Emergence of Market Structures"
12:00–1:30 P.M.	*Lunch*

Roster for the 1991 Complex Systems Summer School

Faculty

Prof. Gail Carpenter	Boston University
Dr. Predrag Cvitanovic	NORDITA, Denmark
Dr. John Denker	AT&T Bell Laboratories
Dr. Bernardo Huberman	Xerox Palo Alto Research Center
Prof. John Lowenstein	New York University
Dr. George Mpitsos	Mark O. Hatfield Marine Science Center
Prof. Lynn Nadel	University of Arizona
Prof. Fred Nijhout	Duke University
Prof. James Sethna	Cornell University
Prof. Carla Shatz	Stanford University
Dr. Michael Shlesinger	Office of Naval Research
Dr. Sara Solla	AT&T Bell Laboratories
Prof. Nicholas Strausfeld	University of Arizona
Prof. Daniel Stein	University of Arizona
Prof. Peter Wolynes	University of Illinois

Participants

Tom Abeles	I. E. Associates, Inc.
John Jeremy Ahouse	Brandeis University
Lee Altenberg	Duke University
P. R. Andrews	Cambridge University, U.K.
George Atkinson	University of New Mexico
John M. Barrie	University of California
Richard Bleakman	University of New Mexico
Erhard Bruderer	University of Michigan
Nicolas Brunel	Laboratoire de Physique Statistique, France
David Cai	Los Alamos National Laboratory
David W. Chappell	University of Texas
Leonard K. Cheng	University of Florida
Clare Bates Congdon	University of Michigan
Jeff Davitz	Los Alamos National Laboratory
Rudi Edward De Koker	Stanford University
Deirdre Des Jardins	Los Alamos National Laboratory
Rogene M. Eichler	University of Minnesota
Dr. Lawrence Eisenberg	Southern Methodist University
Svetlozar Enev	Brandeis University
Jutta Elvira Escher	Louisiana State University
Bryan Galdrikian	Los Alamos National Laboratory
Srinivas Gazula	Washington University in St. Louis
Angelica Gelover-Santiago	Universidad Nacional Autónoma de México
Jack Gorski	The Blood Center of SE Wisconsin
Xiangdong He	Los Alamos National Laboratory
David Heatley	University of Arizona
Kevin Higgins	University of California, Davis
Shane L. Hubler	University of Wisconsin at Madison
Sandor Kadar	Brandeis University
Kevin Kerle	University of California, Davis
Norio Konno	Muroran Institute of Technology, Japan

Paul M. Kulesa	University of Southern California
David Lazar	University of Michigan
Sidney Lehky	National Institute of Mental Health
Zhaoping Li	Princeton University
Mitchell Maltenfort	Northwestern University
Armando Manduca	Mayo Foundation
Omar Manuar	University of Pennsylvania
Susan Elizabeth Minkoff	Rice University
Pedro Miramontes	Universidad Nacional Autónoma de México
Magnus Nordborg	Stanford University
Nancy Norris	Princeton University
Pedro de Oliveira	University of Sussex, UK
Scott Page	Northwestern University
J. Antonio Palacios	Arizona State University
Donna O. Perdue	Oregon State University
Franck Plouraboué	Ecole Normale Supérieure, France
Sharon Reilly	University of Michigan Medical School
Paul Renteln	Claremont Colleges
Jeffrey Reznic	University of Illinois Medical Center
Ken Rice	Harvard University
Mrs. Ute Riemann-Kurtz	University of Bremen, Germany
Andrew Risdale	Cornell University
John A. Salon	Oregon Health Science University
Erik Schultes	Humboldt State University
Antonio da Silva Filho	University of Sussex, UK
Sanjeev Sridharan	University of California, Irvine
K. Srinivas	Yale University
Dr. James Sterling	California Institute of Technology
Brian M. Sutin	University of California, Santa Cruz
William Tozier	University of Pennsylvania
Todd Troyer	University of California, Berkeley
J. D. van der Laan	University of Utrecht, The Netherlands
Stella Veretnik	University of Minnesota
Jin Wang	University of Illinois
Paul B. Watta	Wayne State University
Matthew Wiener	University of Chicago
David Wolf	Los Alamos National Laboratory
Xia Yuan	Los Alamos National Laboratory

Program for the 1991 Complex Systems Summer School, June 2–28, 1991

WEEK ONE, JUNE 2-8

Sunday, June 2

12:00 noon–7:00 P.M. Registration—Second Floor, Peterson Student Center

5:00–7:00 P.M. Welcoming Reception—Senior Commons Room, Second Floor, Peterson Student Center

Monday, June 3

(All meetings take place in the Great Hall, Peterson Student Center, unless otherwise noted)

8:30 A.M. Welcoming Remarks
Mike Simmons, Executive Vice President, Santa Fe Institute

8:45 A.M. Introduction to the 1991 Complex Systems Summer School
Dan Stein, Co-Director

9:00 A.M.	"Neural Network Algorithms and Architectures" John Denker
10:30 A.M.	*Break*
11:00 A.M.	"Waiting for Carnot: The Search for Laws Governing Complex Adaptive Systems" Stuart Kauffman
12:30 P.M.	*Lunch* - Dining Room, First Floor, Peterson Student Center
1:30 P.M.	"Global Climate Change, 3-D Lagrangian" Harold Trease
3:30 P.M.	Tour of Summer School Computer Lab
Tuesday, June 4	
9:00 A.M.	"Neural Network Algorithms and Architectures" John Denker
12:00 noon	Optional talk at the Santa Fe Institute "Waiting for Carnot: The Search for Laws Governing Complex Adaptive Systems" Stuart Kauffman
1:30 P.M.	"Bayes Theorem and Neural Net Predictions Protein Structure" Paul Stolorz
Wednesday, June 5	
9:00 A.M.	"Neural Network Algorithms and Architectures" John Denker
10:30 A.M.	*Break* University of New Mexico Graduate Center Registration
10:45 A.M.	"Waiting for Carnot: The Search for Laws Governing Complex Adaptive Systems" Stuart Kauffman
12:30 P.M.	*Lunch*
1:30 P.M.	"Pattern Formation in Convection" Tim Sullivan
Thursday, June 6	
9:00 A.M.	"Neural Networks for Adaptive Pattern Recognition" Gail Carpenter
10:30 A.M.	*Break*
10:45 A.M.	"Neural Network Algorithms and Architectures" John Denker
12:30 P.M.	*Lunch*
	Afternoon free for individual projects.
Friday, June 7	
9:00 A.M	"Neural Networks for Adaptive Pattern Recognition" Gail Carpenter
10:30 A.M.	*Break*
10:45 A.M.	"Neural Network Algorithms and Architectures" John Denker
12:30 P.M.	*Lunch*
	Afternoon free for individual projects.

WEEK TWO, JUNE 9–15

Sunday, June 9

6:00 P.M.	Beer and Chips, Senior Commons Room

Monday, June 10

9:00 A.M.	"Artificial Life" Christopher Langton
10:30 A.M.	*Break*
11:00 A.M.	"Artificial Life" Christopher Langton
12:30 P.M.	*Lunch*
1:00 P.M.	Speaker to be announced

Tuesday, June 11

9:00 A.M.	"Complex Liquids and Solids" James Sethna
10:30 A.M.	*Break*
11:00 A.M.	"Artificial Life" Christopher Langton
12:30 P.M.	*Lunch*

Wednesday, June 12

9:00 A.M.	"Noise, Fractals and Scaling" Michael Shlesinger
10:30 A.M.	*Break*
11:00 A.M.	"Noise, Fractals and Scaling" Michael Shlesinger
12:30 P.M.	*Lunch*
1:30 P.M.	"Complex Liquids and Solids" James Sethna

Thursday, June 13

9:00 A.M.	"Complex Liquids and Solids" James Sethna
10:30 A.M.	*Break*
11:00 A.M.	"Noise, Fractals and Scaling" Michael Shlesinger
12:30 P.M.	*Lunch*
1:30 P.M.	"Artificial Life" Christopher Langton

Friday, June 14

9:00 A.M.	"Complex Liquids and Solids" James Sethna
10:30 A.M.	*Break*
11:00 A.M.	"Artificial Life" Christopher Langton
12:30 P.M.	*Lunch*
1:30 P.M.	"A Hénon Map Picture Gallery" Michael Gehmeyer

WEEK THREE, JUNE 16–22

Sunday, June 16	
6:00 P.M.	Beer and Chips, Senior Commons Room
Monday, June 17	
9:00 A.M.	"Chaos and Other Forms of Variability in Self-Organizing Adaptive Systems" George Mpitsos
10:30 A.M.	*Break*
11:00 A.M.	"Neural Activity and Pattern Formation During Visual System Development" Carla Shatz
12:30 P.M.	*Lunch*
1:30 P.M.	"Modeling Migration of Contaminants in the Subsurface Environments" Bryan Travis
Tuesday, June 18	
9:00 A.M.	"Chaos and Other Forms of Variability in Self-Organizing Adaptive Systems" George Mpitsos
10:30 A.M.	*Break*
11:00 A.M.	"Neural Activity and Pattern Formation During Visual System Development" Carla Shatz
12:30 P.M.	*Lunch*
1:30 P.M.	"Dynamics of Stochastic Webs" John Lowenstein
Wednesday, June 19	
9:00 A.M.	"Chaos and Other Forms of Variability in Self-Organizing Adaptive Systems" George Mpitsos
10:30 A.M.	*Break*
11:00 A.M.	"Pattern Formation in Animals" Fred Nijhout
12:30 P.M.	*Lunch*
1:30 P.M.	"Neural Basis of Vision in Insects" Nicholas Strausfeld
Thursday, June 20	
9:00 A.M.	"Pattern Formation in Animals" Fred Nijhout
10:30 A.M.	*Break*
11:00 A.M.	"Neural Basis of Vision in Insects" Nicholas Strausfeld
12:30 P.M.	*Lunch*
Friday, June 21	
9:00 A.M.	"Pattern Formation in Animals" Fred Nijhout
10:30 A.M.	*Break*

11:00 A.M.	"Neural Basis of Vision in Insects" Nicholas Strausfeld
12:30 A.M.	*Lunch*

WEEK FOUR, JUNE 23–28

Sunday, June 23

6:00 P.M.	Beer and Chips, Junior Commons Room

Monday, June 24

9:00 A.M.	"Statistical Mechanics of Neural Networks" Sara Solla
10:30 A.M.	*Break*
11:00 A.M.	"Chaos" Predrag Cvitanovic
12:30 P.M.	*Lunch*
1:30 P.M.	"Spin Glass Engineering as an Approach to Protein Structure Prediction" Peter Wolynes

Tuesday, June 25

9:00 A.M.	"Statistical Mechanics of Neural Networks" Sara Solla
10:30 A.M.	*Break*
11:00 A.M.	"Chaos" Predrag Cvitanovic
12:30 P.M.	*Lunch*
1:30 P.M.	"Spin Glass Engineering as an Approach to Protein Structure Prediction" Peter Wolynes

Wednesday, June 26

9:00 A.M.	"Statistical Mechanics of Neural Networks" Sara Solla
10:30 A.M.	*Break*
11:00 A.M.	"Chaos" Predrag Cvitanovic
12:30 P.M.	*Lunch*
1:30 P.M.	"Inferring the Movements of the Tongue" Tim Thomas

Thursday, June 27

9:00 A.M.	"Statistical Mechanics of Neural Networks" Sara Solla
10:30 A.M.	*Break*
11:00 A.M.	"Chaos" Predrag Cvitanovic
12:30 P.M.	*Lunch*
1:30 P.M.	"State-Space Reconstruction" John Gibson

Friday, June 28

9:00 A.M.	"Statistical Mechanics of Neural Networks" Sara Solla
10:30 A.M.	*Break*
11:00 A.M.	"Chaos" Predrag Cvitanovic
12:30 P.M.	*Final Lunch* (location to be announced)

Roster for the Workshop on Price Dynamics and Trading Strategies in Double Auction Markets II

Prof. Colin Camerer	University of Pennsylvania
Prof. Timothy N. Cason	University of Southern California
Prof. Ian Domowitz	Northwestern University
Dr. Marek Fludzinski	D. E. Shaw & Co.
Prof. Dan Friedman	University of California, Santa Cruz
Prof. John Geanakoplos	Yale University
Prof. Larry Gray	University of Minnesota
Prof. John Kagel	University of Pittsburgh
Prof. Stuart Kauffman	University of Pennsylvania
Mr. Warren Langley	Hull Trading Company
Prof. John Ledyard	California Institute of Technology
Dr. Jean Lequarré	Union Bank of Switzerland
Prof. Ashok Maitra	University of Minnesota
Prof. Kevin McCabe	University of Minnesota
Prof. John Miller	Carnegie-Mellon University
Prof. Mark Olson	California Institute of Technology
Prof. Richard Palmer	Duke University
Prof. Charles Plott	California Institute of Technology
Prof. Stephen Rassenti	University of Arizona
Prof. John Rust	University of Wisconsin
Prof. Mark Satterthwaite	Northwestern University
Prof. Sanjay Srivastava	Carnegie-Mellon University
Prof. Shyam Sunder	Carnegie-Mellon University
Prof. Steven Williams	Northwestern University
Prof. Robert Wilson	Stanford University

Program for the Workshop on Price Dynamics and Trading Strategies in Double Auction Markets II, June 9–10, 1991

All events will take place in the Nambe Room, Hotel Plaza Real, 125 Washington Avenue, unless otherwise noted.

SUNDAY JUNE 9, 1991

11:30 A.M.–12:30 P.M.	*Brunch (Santa Clara Room)*
12:30–1:30 P.M.	Dan Friedman "The Continuous Double Auction Market Institution: A Survey" Discussion Leader: Shyam Sunder
1:30 –2:30 P.M.	Ian Domowitz "The Electronic Book and Automated Trade Execution" Discussion Leader: Warren Langley
2:30–3:00 P.M.	*Break*
3:00–4:00 P.M.	Mark Satterthwaite and Steven Williams "Theoretical Results on the BBDA Institution" Discussion Leader: Robert Wilson
4:00–5:00 P.M.	John Kagel "Buyers' Bid Double Auctions: Some Initial Experimental Results" Discussion Leader: Mark Satterthwaite
5:00–5:15 P.M.	*Break (Library - 2nd Floor)*

5:15–6:15 P.M.	Steven Rassenti "A Uniform Price Double Auction: Experimental and Field Evaluation" Discussion Leader: John Kagel
6:30 P.M.	Dinner (The Pink Adobe, 406 Old Santa Fe Trail)

MONDAY, JUNE 10, 1991

8:00–8:30 A.M.	*Breakfast (Santa Clara Room)*
8:30–9:30 A.M.	Sanjay Srivastava "Cross Market Liquidity and Efficiency in Double Auction Asset Markets" Discussion Leader: Marek Fludzinski
9:30–10:30 A.M.	Shyam Sunder "Dynamics of Surplus Exploitation in Sequential and Stepwise Double Auction" Discussion Leader: Colin Camerer
10:30–10:45 A.M.	*Break*
10:45–11:45 A.M.	John Miller, Richard Palmer, and John Rust "Behavior of Trading Automata in a Computerized Double Auction Market" Discussion Leader: Shyam Sunder
11:45 A.M.–1:00 P.M.	*Lunch (Santa Clara Room)*
1:00–2:00 P.M.	David Easley and John Ledyard "Theories of Price Formation and Exchange in Double Oral Auctions" Discussion Leader: John Geanakoplos
2:00 –3:00 P.M.	Tim Cason and Dan Friedman "An Empirical Analysis of Price Formation in Double Auction Markets" Discussion Leader: Kevin McCabe
3:00–3:15 P.M.	*Break (Library, 2nd Floor)*
3:15–4:15 P.M.	Colin Camerer "Convergence and Bubbles in Experimental Double Auctions for Probabilistically Lived Agents" Discussion Leader: Sanjay Srivastava
4:15–5:15 P.M.	Laura Clauser and Charles Plott "The Conspiracy-Breaking Feature of the Double Auction" Discussion Leader: Dan Friedman
5:15–6:00 P.M.	Roundtable Discussion

Roster of Summer Study on Visions of a Sustainable World

Participants

Dr. Harold Agnew	GA Technologies
Dr. W. Brian Arthur	Stanford University
Dr. Robert U. Ayres	International Institute for Applied Systems Analysis, Austria
Dr. Steven Bankes	Rand Corporation
Dr. Al Binger	Rockefeller Foundation
Dr. Nancy Birdsall	The World Bank
Dr. Peter Brecke	BDM International
Dr. George Cowan	Santa Fe Institute
Dr. Herman Daly	The World Bank
Dr. Josh Epstein	Brookings Institution
Ms. Dorothy Etoori	Ministry of Environment Protection, Uganda
Mr. Paul Faeth	World Resources Institute
Dr. J. Doyne Farmer	The Prediction Company
Dr. Marcus Feldman	Stanford University
Dr. Harold Feveison	Princeton University
Ms. Ann Florini	University of California, Los Angeles
Dr. Stephanie Forrest	University of New Mexico
Dr. Gilberto Gallopin	International Institute for Applied Systems Analysis, Austria
Dr. Murray Gell-Mann	California Institute of Technology
Dr. Raj Gupta	Goldman Sachs and Company, UK
Dr. Allen L. Hammond	World Resources Institute
Dr. Peter Hardi	The Regional Environmental Center, Hungary
Dr. John Holland	University of Michigan
Dr. Thomas F. Horner-Dixon	University of Toronto, Canada
Dr. Robert Kates	Brown University
Dr. Edward Knapp	Santa Fe Institute
Dr. Christopher Langton	Los Alamos National Laboratory
Dr. Rob Lempert	Rand Corporation
Dr. Jim MacNeill	Institute for Research on Public Policy, Canada
Dr. Jessica Tuchman Mathews	World Resources Institute
Mr. P. J. Mkanga	Ministry of Tourism, Natural Resources & Environment, Tanzania
Dr. Bruce Murray	California Institute of Technology
Prof. S. S. Mushi	University of Dar-es-Salaam, Tanzania
Dr. Brian M. Pollins	Ohio State University
Dr. Robert N. Schock	Lawrence Livermore National Laboratory
Mr. James Gustave Speth	World Resources Institute
Dr. John Steinbruner	Brookings Institution
Ms. Nina Tannenwald	Center for Science and International Affairs
Dr. Alvaro Umana	Ministerio de Recursos Natur, Costa Rica
Ms. Edith Weiss	Environmental Protection Agency
Dr. Robert Williams	Princeton University

Observers

Mr. James Furman	Santa Fe
Dr. Robert Glasser	Los Alamos National Laboratory
Mr. Charles Halpeern	Nathan Cummins Foundation
Mr. James Kalin	Simulation Laboratories

Mr. Dan Martin	John D. & Catherine T. MacArthur Foundation
Mrs. William Nitze	Ann Kendall Richards, Inc.

Program for the Workshop on Visions of a Sustainable World, July 16–24, 1991

Co-sponsored by the Brookings Institution, the Santa Fe Institute, and the World Resources Institute and held at St. John's College, Santa Fe, New Mexico

TUESDAY, JULY 16

2:00–5:00 P.M.	Formal Registration—Marriott Residence Inn Lobby
Opening Reception/Dinner	
6:00 P.M.	Buses depart Marriott Residence Inn for Janus Gallery
6:30–7:30 P.M.	Reception—Janus Gallery, 225 Canyon Road
7:30–9:30 P.M.	Dinner and Keynote address Presenter: Murray Gell-Mann, California Institute of Technology

WEDNESDAY JULY 17

9:00–9:30 A.M.	Introduction of project and participants
9:30–10:30 A.M.	"The Unsustainability of Current Patterns" Presenters: Gus Speth, World Resources Institute, and John Steinbruner, Brookings Institution
10:30–10:45 A.M.	*Break*
10:45 A.M.–12:15 P.M.	"What is Sustainability?" Brainstorming.
12:15–1:15 P.M.	*Lunch at St. John's cafeteria*
1:15–3:00 P.M.	"The Demographic Transition"
7:30 P.M.	Optional, "Footsteps Across New Mexico" (Historical and cultural slide-show presentation)

THURSDAY JULY 18

9:00–10:30 A.M.	"Economic Transition"
10:30–10:45 A.M.	*Break*
10:45 A.M.–12:15 P.M.	"Knowledge Transition"
12:15–1:15 P.M.	*Lunch at St. John's cafeteria*
1:15–2:45 P.M.	"Military/Security Transition"
2:45–3:00 P.M.	*Break*
3:00–4:00 P.M.	"Social Equity Transition"

FRIDAY JULY 19

9:00 A.M.–12:00 noon	"State of the Art of Modeling"
12:00–2:00 P.M.	*Lunch* and demonstration of computer models
2:00–4:00 P.M.	"More on Modeling"
7:00 P.M.	Optional, free performance of Twelfth Night at St. John's College

SATURDAY JULY 20

9:00–10:30 A.M.	"Technology Transition: The Case of Energy"
10:30–10:45 A.M.	*Break*

10:45 A.M.–12:15 P.M.	"More on Technology"
12:15–1:15 P.M.	*Lunch at St. John's cafeteria*
1:15–3:00 P.M.	"Governance/Institutional/Ideological Transition"

SUNDAY JULY 21 (FREE DAY)

1:00 P.M.	Optional, bus departs for Puye cliff dwellings, dinner at 5:00 P.M. at Chimayo, bus returns to hotel at 7:30 P.M.

MONDAY JULY 22

9:00–10:30 A.M.	"Relationships among the Transitions, Part I"
10:30–10:45 A.M.	*Break*
10:45 A.M.–12:15 P.M.	"Relationships among the Transitions, Part II"
12:15–1:15 P.M.	*Lunch at St. John's cafeteria*
1:15–4:00 P.M.	Divide into small groups for discussion of: 1) How do the variables discussed all week relate to one another? 2) What kind of research/project is needed to understand these relationships?

TUESDAY JULY 23

Lessons from the Week

9:00–10:30 A.M.	Reports from small groups and discussion
10:30–10:45 A.M.	*Break*
10:45 A.M.–12:15 P.M.	Continuation of reports from small groups and discussion
	Free afternoon or continuation of discussion
7:00 P.M.	Final reception/dinner, location to be announced

WEDNESDAY JULY 24

Concluding Sessions

9:00–10:30 A.M.	"Identification of Relevant Work"
10:30–10:45 A.M.	*Break*
10:45 A.M.–12:15 P.M.	Continuation of discussion
12:15–1:15 P.M.	*Lunch at St. John's cafeteria*
1:15–3:00 P.M.	Final Session: "Design Future Agenda"

Roster for the Workshop on Simulation Authoring Tools and the SimToolkit Project Symposium

Mr. Michael Angerman	
Dr. Steve Bankes	Rand Corp.
Prof. Rob Collins	University of California, Los Angeles
Dr. George Cowan	Santa Fe Institute
Dr. Walter Fontana	Los Alamos National Laboratory
Prof. Stephanie Forrest	University of New Mexico
Mr. Jim Gasperini	
Mr. Daniel Goldman	
Mr. Don Goldman	
Prof. Alex Gray	University of California, Berkeley
Dr. David Hiebeler	Thinking Machines Corp.
Prof. John Holland	University of Michigan
Dr. Bob Jacobson	University of Washington
Prof. David Jefferson	University of California, Los Angeles
Dr. Dave Johnson	
Prof. Steve Johnson	
Mr. James Kalin	Simulation Laboratories
Prof. Stuart Kauffman	University of Pennsylvania
Dr. Ed Knapp	Santa Fe Institute
Dr. John Koza	Third Millenium Venture Capital Ltd.
Dr. Chris Langton	Los Alamos National Laboratory
Prof. Steve Lansing	University of Southern California
Prof. Gottfried Mayer-Kress	University of Illinois at Champaign-Urbana
Prof. John Miller	Carnegie-Mellon University
Prof. Melanie Mitchell	University of Michigan
Dr. Alan Perelson	Los Alamos National Laboratory
Dr. Steen Rasmussen	Los Alamos National Laboratory
Dr. Everett Rogers	University of Southern California
Dr. L. M. Simmons, Jr.	Santa Fe Institute
Mr. John Stadler	Paradigm Investments
Dr. Ann Stanley	Santa Fe Institute
Prof. Chuck Taylor	University of California, Los Angeles
Dr. Mark Wieder	Mark Wieder Hardware/Software Engineering

Roster for the Workshop on Simulation Authoring Tools and the SimToolkit Project Symposium, August 12–14, 1991

Formal program not available.

Roster for the Workshop on Self-Organized Criticality

Prof. Philip W. Anderson	Princeton University
Dr. Per Bak	Brookhaven National Laboratory
Prof. Jayanth Banavar	Pennsylvania State University
Dr. Shobo Bhattacharya	NEC Research Institute Inc.
Qi-Zhong Cao	Hasbrouck Lab, University of Massachusetts
Prof. Jean Carlson	University of California, Santa Barbara
Dr. Susan N. Coppersmith	AT&T Bell Laboratories
Prof. Maria De Sousa Vieira	University of California, Berkeley
Prof. Steve Durlauf	Stanford University
Prof. Jerry P. Gollub	Haverford College
Dr. Geoffrey Grinstein	IBM T. J. Watson Research Center
Prof. Thomas C. Halsey	The University of Chicago
Dr. Pierre C. Hohenberg	AT&T Bell Laboratories
Prof. Leo P. Kadanoff	The University of Chicago
Prof. Mehran Kardar	Massachusetts Institute of Technology
Prof. Stuart Kauffman	University of Pennsylvania
Prof. James Langer	University of California, Santa Barbara
Prof. Jorge Lomnitz-Adler	Universidad Nacional Autónoma de México
Prof. John Machta	University of Massachusetts at Amherst
Prof. Sidney Nagel	The University of Chicago
Prof. Anatol Roshko	California Institute of Technology
Dr. John Rundle	Lawrence Livermore National Lab
Prof. Christopher H. Scholz	Columbia University
Prof. Eric D. Siggia	Cornell University
Prof. Harry Suhl	University of California, San Diego
Prof. Glenn H. Swindle	University of California, Santa Barbara
Prof. Chao Tang	University of California, Santa Barbara
Dr. John Toner	IBM T. J. Watson Research Center
Prof. Donald Turcotte	Cornell University
Prof. Michael B. Weissman	University of Illinois at Urbana
Prof. Robert Westervelt	Harvard University
Prof. Po-Zen Wong	University of Massachusetts
Prof. Michael Woodford	University of Chicago

Program for the Workshop on Self-Organized Criticality, September 12–16, 1991

THURSDAY, SEPTEMBER 12

8:30 A.M.	*Continental Breakfast* (Sidney Nagel)
9:00 A.M.	Per Bak "Introduction to Self-Organized Criticality"
10:15 A.M.	Leo P. Kadanoff "Scaling and Universality in Avalanche Models"
11:30 A.M.	*Break*
11:45 A.M.	Geoffrey Grinstein "Generic Scale Invariance in Noisy, Chaotic, or Turbulent Systems"
1:00 P.M.	*Lunch* (Philip W. Anderson)

2:00 P.M.	Robert M. Westervelt "Avalanches in Cellular Magnetic Domain Patterns"
3:15 P.M.	Harry Suhl, "Magnetization Fields as a Test Case of Self-Organized Criticality"
4:30 P.M.	*Break*
4:45 P.M.	Donald L. Turcotte "Evolution of Landscapes as Self-Organized Criticality"

FRIDAY, SEPTEMBER 13

8:30 A.M.	*Continental Breakfast* (James Langer)
9:00 A.M.	Michael B. Weissman "1/f Noise in Ohmic Resistors"
10:15 A.M.	Shobo Bhattacharya "1/f Noise in Charge Density Wave Systems: Experimental"
11:30 A.M.	*Break*
11:45 A.M.	Susan Coppersmith "1/f Noise in Charge Density Wave Systems: Theoretical"
1:00 P.M.	*Lunch* (Glen Swindle)
2:00 P.M.	Po-zen Wong, University of Massachusetts, Amherst "Experiments on Moving Interfaces"
3:15 P.M.	Michael Woodford "Avalanche Models in Economics"
4:30 P.M.	*Break*
4:45 P.M.	Christopher H Scholz, "Earthquakes and Faulting: Examples of Self-Organized Critical Phenomena with a Characteristic Dimension"

SATURDAY, SEPTEMBER 14

8:30 A.M.	*Continental Breakfast* (Thomas Halsey)
9:00 A.M.	John Toner "Dirt, Sand and Self-Organized Criticality"
10:15 A.M.	Jean Carlson "Self-Organized Criticality and Singular Diffusions"
11:30 A.M.	*Break*
11:45 A.M.	Mehran Kardar "Symmetries and Conservation Laws in Dynamical Systems"
1:00 P.M.	*Lunch* (Jayanth Banavar)
2:00 P.M.	Anatol Roshko "Coherent Vortical Structure in Turbulent Shear Flows"
3:15 P.M.	Eric D. Siggia, "Organized Structures in Fully Turbulent Flows"
4:30 P.M.	*Break*

4:45 P.M.	Jerry Gollub "Temperature Fluctuations of a Stirred Fluid in a Steady Temperature Gradient: Experiments"

SUNDAY, SEPTEMBER 15

8:30 A.M.	*Continental Breakfast*
	(John Machta, University of Massachusetts, Amherst)
9:00 A.M.	Chao Tang "Earthquake Dynamics"
10:15 A.M.	Maria De Sousa Vieira "Simulations of Buridge-Knopoff Models in a Variety of Parameter Regimes"
11:30 A.M.	*Break*
11:45 A.M.	Jorge Lomnitz-Adler [title not available]
1:00 P.M.	*Lunch*

MONDAY, SEPTEMBER 16

8:30 A.M.	*Continental Breakfast*
9:00 A.M.	John B. Rundle "Relevance of Self-Organized Criticality to the Dynamics of Earthquakes"
10:15 A.M.	Stuart Kauffman "Evolution to the Edge of Chaos: Selection and Self-Organized Criticality"
11:30 A.M.	*Break*
11:45 A.M.	Pierre C. Hohenberg "Conference Summary"
1:00 P.M.	*Lunch*

Roster for the Workshop on Growth and Cities

Prof. Kenneth Arrow	Stanford University
Prof. Brian Arthur	Stanford University
Prof. Paul Bairoch	Université de Genève
Prof. Eric Baum	NEC Research Institute, Inc.
Prof. Rolland Benabou	Massachusetts Institute of Technology
Mr. Edward Glaeser	University of Chicago
Prof. J. Vernon Henderson	Brown University
Mr. Hedi Kallal	University of Chicago
Prof. Larry Katz	Harvard University
Prof. Stuart Kauffman	University of Pennsylvania
Prof. Paul Krugman	Massachusetts Institute of Technology
Prof. David Lane	University of Minnesota
Mr. Henry Lichstein	Citicorp
Dr. Ashoka Mody	The World Bank
Prof. James Rauch	University of California, San Diego
Prof. Paul Romer	National Bureau for Economic Research
Prof. José Scheinkman	University of Chicago
Prof. Allen Scott	University of California, Los Angeles
Prof. Andrei Shleifer	Harvard University
Mr. David Warsh	*The Boston Globe*

Program for the Workshop on Growth and Cities, September 27–29, 1991

FRIDAY, SEPTEMBER 27

9:00 A.M.	*Continental Breakfast*
9:30 A.M.	Paul Bairoch "Growth and Cities: A Nonlinear Historical Relationship"
11:00 A.M.	Ashoka Mody "Growth in an Inefficient Economy"
12:30 P.M.	*Lunch*
2:00 P.M.	Allen Scott "Some Recent Developments in Urban Geography—with Particular Reference to the City as a Production System"
3:00 P.M.	Discussion. Chair: Andrei Shleifer

SATURDAY, SEPTEMBER 28

9:00 A.M.	*Continental Breakfast*
9:30 A.M.	Larry Katz "Regional Cycles"
11:00 A.M.	Paul Krugman "Increasing Returns and Economic Geography"
12:30 P.M.	*Lunch*
1:30 P.M.	Informal Discussions
3:30 P.M.	Discussion. Chair: Paul Romer

SUNDAY, SEPTEMBER 29

9:30 A.M.	*Continental Breakfast*
10:00 A.M.	Informal Discussions and Summary
12:00 noon	*Lunch*

Roster for the Workshop on the Implications of Dendritic Models for Neural Network Properties

Dr. Larry Abbott	Brandeis University
Ms. Valerie Gremillion	Los Alamos National Laboratory
Dr. William R. Holmes	Ohio University
Dr. Julian J.B. Jack	Oxford University Laboratory of Physiology
Dr. Thomas M. McKenna	Office of Naval Research
Dr. John P. Miller	University of California, Berkeley
Dr. Wilfrid Rall	NIDDK, National Institutes of Health
Dr. John Rinzel	NIDDK, National Institutes of Health
Dr. Idan Segev	The Hebrew University, Israel
Dr. Bryan Travis	Los Alamos National Laboratory
Dr. Charles J. Wilson	University of Tennesee
Dr. Charles C. Wood	Los Alamos National Laboratory

Program for the Workshop on the Implications of Dendritic Models for Neural Network Properties, October 10–14, 1991

OCTOBER 10, 1991

8:45 A.M.	*Continental Breakfast*
9:15 A.M.	Welcome and Introduction to the Santa Fe Institute
9:25 A.M.	Participant Two-Minute Introductions
9:50 A.M.	*Break*
10:00 A.M.	John Miller
10:30 A.M.	Discussion
11:00 A.M.	*Break*
11:15 A.M.	Larry Abbott
11:45 A.M.	Discussion
12:15 P.M.	*Lunch*
2:00 P.M.	Idan Segev
2:30 P.M.	Discussion
3:00 P.M.	*Break*
3:15 P.M.	John Rinzel
3:45 P.M.	Discussion
4:15 P.M.	*Break*
4:30 P.M.	Announcements and discussion of Friday's agenda
5:00 P.M.	Break for dinner

Formal programs for October 11–14 are not available.

Roster for the Workshop on Adaptive Computation

Dr. Felix E. Browder	Rutgers University
Prof. Arthur Burks	University of Michigan
Dr. George Cowan	Santa Fe Institute
Mr. Robert A. Dolan	Private Investor
Mr. John Downing	Private Investor
Ms. Esther Dyson	ED Venture Holdings
Ms. Carole Ely	Consultant, Santa Fe
Dr. Walter Fontana	Santa Fe Institute
Prof. Stephanie Forrest	University of New Mexico
Prof. John Holland	University of Michigan
Mr. James Kalin	Simulation Laboratories
Prof. Stuart Kauffman	University of Pennsylvania
Dr. Ed Knapp	Santa Fe Institute
Dr. John Koza	Third Millenium Venture Capital Ltd.
Dr. Chris Langton	Los Alamos National Laboratory
Dr. Alan Lapedes	Los Alamos National Laboratory
Dr. Nicholas C. Metropolis	Los Alamos National Laboratory
Mr. Morton Meyerson	2M Companies
Prof. John Miller	Carnegie-Mellon University
Prof. Melanie Mitchell	University of Michigan
Prof. Nils Nilsson	Stanford University
Mr. James Pelkey	Private Investor/Consultant, Santa Fe
Dr. L. M. Simmons, Jr.	Santa Fe Institute
Mr. Bob Wickham	Consultant, Santa Fe
Dr. Will Wright	Maxis

Program for the Workshop on Adaptive Computation, August 9–11, 1991

FRIDAY, AUGUST 9

8:30 A.M.	*Continental Breakfast*
9:00 A.M.	Welcome (Ed Knapp)
9:15 A.M.	Introduction to Adaptive Computation (John Holland)
10:15 A.M.	*Break*
10:30 A.M.	Discussion of Program Plan (John Holland & Directorate)
11:45 A.M.	*Lunch*
	Sampling of Adaptive Computation Projects
1:00 P.M.	Walter Fontana
1:45 P.M.	John Miller
2:30 P.M.	*Break*
2:45 P.M.	Melanie Mitchell
3:30 P.M.	Stephanie Forrest
4:30 P.M.	*Adjourn*

SATURDAY, AUGUST 10

8:30 A.M.	*Continental Breakfast*
	Sampling of Adaptive Computation Projects (Continued)

9:00 A.M.	Chris Langton
9:45 A.M.	Stuart Kauffman
10:30 A.M.	*Break*
10:45 A.M.	Alan Lapedes
11:30 A.M.	Review of draft program plan and discussion (Directorate & Advisory Committee)
12:30 P.M.	*Lunch*
1:30 P.M.	Review of draft program plan and discussion (continued) (Directorate & Advisory Committee)
4:30 P.M.	*Adjourn*

SUNDAY, AUGUST 11

8:30 A.M.	*Continental Breakfast*
9:00 A.M.	Review of draft program plan and discussion (continued) Directorate & Advisory Committee
12:00 noon	*Lunch*
1:00 P.M.	*Adjourn*

1991 PUBLIC LECTURES

March 27	"Nature, Nurture, and Numbers: How to Interpret 'Heritability'" Marcus Feldman, Director, Morrison Institute for Population & Resource Studies and Morrison Professor of Biological Sciences, Stanford University
April 24	"Understanding Media: Spatial Editing or How to Lie with Computers" Dr. Alvy Ray Smith, Co-founder and Executive Vice President of Pixar, San Rafael, California
May 29	"Chaos, Order, and Patterns: Paradigms for Our Nonlinear Universe" David Campbell, Director, Center for Nonlinear Studies, Los Alamos National Laboratory
June 19	"Human Vision: How Our Brains Reinvent the World" Donald A. Glaser, Nobel laureate and Professor of Molecular Biology, University of California, Berkeley
July 24	"The Santa Fe Institute: Catalyzing New Directions in Scientific Research" Dr. Edward A. Knapp, President, Santa Fe Institute
September 24	"Growth in Cities: The Role of Diversity in the U.S. Urban Experience" José Scheinkman, Alvin H. Baum Professor of Economics, University of Chicago
October 9	"Justice and the Human Genome: Social and Ethical Issues of the New Biology" Marc Lappé, Professor of Health Policy and Ethics, University of Illinois College of Medicine
November 13	"Thermodynamics of the Artificial" James Crutchfield, Assistant Research Physicist, University of California, Berkeley
December 4	"Fun with Size & Scale: Elephants, Quarks, and the Early Universe" Geoffrey West, High Energy Physics, Theoretical Division, Los Alamos National Laboratory

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