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Santa Fe Institute

1993 Annual Report on Scientific Programs

A Broad Research Program on the Sciences of Complexity

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1. INTRODUCTION

1.1 SFI Origins and Status

The Santa Fe Institute (SFI) is an independent, nonprofit research institute founded in 1984 to pursue multidisciplinary research and for the synthesis of knowledge about systems that span more than one of the traditional disciplines. Science at SFI is broadly collaborative and done by mixtures of resident and visiting scientists from different institutions and disciplines. Most of its research focuses on studies of what has come to be called complexity and complex adaptive systems.

SFI is composed of many dozens of distinguished senior scientists and outstanding younger scientists in this pioneering research. SFI has an active Science Advisory Board of 55 people, as well as an External Faculty of 47 (shown in Appendix X). This group contains four Nobel Laureates (Philip Anderson, Kenneth Arrow, Manfred Eigen, and Murray Gell-Mann), four MacArthur Fellows (David Rumelhart, John Holland, Stuart Kauffman, and Nancy Kopell), and more than a dozen holders of named chairs at major universities, all of whom are engaged in our programs.

In nine years the annual budget of SFI has grown to $3.4 million. Sources of funding reflect long-term commitments from several early funders, with steady diversification of sources as well during that time. The major elements have been, for unrestricted support of research, the John D. and Catherine T. MacArthur Foundation ($500,000/year), the Department of Energy ($268,000 in 1993), National Science Foundation ($341,000 in 1993), businesses and other foundations ($426,000 in 1993), Trustees ($325,000 in 1993), and individual donors ($100,000 in 1993). In addition, SFI received some 70 grants for specific projects ($1,440,000 in 1993). This mixture of funding means that about half of SFI's requirements are assured each year by continuing and predictable sources of funds.

In 1993 SFI took a major step that reflected its commitment as a long-term participant in the nation's scientific research. As a result of a special fund-raising drive by its Trustees, the Institute purchased a permanent campus in Santa Fe. This facility, 15,000 square feet of space on a 32-acre site, will permit stability and long-term expansion of SFI's research program as needed. The Institute will move into the new quarters in 1994.

1.2 Elements that Distinguish SFI from Traditional Research Institutions

Flexibility and Responsiveness to Opportunities

SFI has no permanent faculty. Research at SFI is done by combinations of short-term visiting and long-term resident scientists. Resident scientists include 8–10 postdoctoral fellows with two- or three-year appointments, 2-3 professors on several-month leaves (e.g., sabbaticals) from their universities, a few graduate students conducting research, and 4 scientists (W. Brian Arthur, Stuart Kauffman, Melanie Mitchell, and Murray Gell-Mann) in long-term (one year or more) residencies. They are complemented by the External Faculty, most of whom spend at least one month each year in residence, local External Faculty (primarily from Los Alamos National Laboratory) who are present for perhaps one day a week, and a steady stream of short-term (one week to one month) visiting scientists. The total number of researchers on site at any one time (excepting attendees at periodic workshops) is about 40.

SFI provides modest research facilities for those scientists, consisting of shared office space, a modest library, and networked workstations. The real appeal of residency at SFI is the presence of the other outstanding scientists from a variety of disciplines and the chance to collaborate in free-form ways. The fact that the composition of the resident body changes continuously assures a constant input of fresh ideas, skills, and specialties. It also imparts immense flexibility in choosing the kinds of research topics to pursue. Groups can assemble themselves quickly for workshops or small working groups, and the stature of the core group of scientists makes it possible to attract outstanding scientists to these activities on relatively short notice. Scientists leaving residencies at SFI return to their home institutions with fresh ideas that often have profound impact on their future research and teaching.

In 1993 nearly 100 scientists traveled to Santa Fe for research residencies, and another several hundred traveled to Santa Fe to participate in more than a dozen workshops or working groups. This mixture of people, from leading research universities in the U.S. and Europe, from national laboratories, and from industrial research labs, constitutes the "extended faculty" of SFI. Most of those people, once exposed to the multidisciplinary research environment, maintain a relationship with SFI and with other scientists whom they have met at SFI and begun to work with. Dozens of informal research networks have originated at SFI and continue with great productivity for years afterwards, maintained via Internet communications, visits to one another's institutions, and occasional reconvening at SFI to assess group progress and establish new research agendas.

SFI conducts research of four general types:

1. **Modeling and theory of complex systems, and particularly complex *adaptive* systems, built around investigation of the concept of simple rules leading to complex behavior.** Research in the course of this program will include behaviors of dynamical systems; nonlinear dynamics; low-dimensional chaos; complexity, entropy, and the physics of information; limits to computation; theories of biological organization and origins of life; evolution of systems of adaptive agents on evolving landscapes; self-organized criticality and scaling; and computation-theoretical and statistical properties of complex systems.

2. **Specific applications of that modeling and theory to research in adaptive computation.** SFI will continue to extend the theory of novel computational methods (such as genetic algorithms, machine learning, and most recently, cellular automata) and to develop those combinations of tools into more powerful simulation and problem-solving approaches with broad applicability.

3. **Applications of the modeling and theory, as well as the new tools developed from SFI's research in adaptive computation, to science in general.** This part of the program will focus particularly on complex biological and environmental systems—use of new computational approaches to extract information about folding and functions of proteins based on knowledge of the "strings" of genetic data; to model the mammalian immune systems as a system of distributed adaptive agents; to track mutations in virus in conjunction with epidemiological studies of HIV transmission; to model neurobiological phenomena (sensory and memory); to search for patterns (and the possibility of deterministic mechanisms producing them) in seemingly random data such as brain waves; and to explore dynamics of evolution itself.

4. **Applications of the modeling and theory, as well as emerging scientific insights, to understanding and modeling real world problems.** SFI's approach to simulation and modeling provides a means to develop realistic models of the nonlinear dynamics that dominate real systems. By focusing attention on autonomous and linked agents following relatively few and simple rules in a local environment, it is possible to simulate the behaviors of complex, nonlinear systems. Moreove , because the agents have the capability of adapting (learning), it is possible to study these systems with relatively little programming required to set up the simulation. Several SFI projects are developing generic programming platforms that can be used for a broad range of applications; specialists can tailor the models by marrying the generic simulations with their own data and their own insights about rules and behaviors. Among the areas of application at SFI will be economics (behavior of aggreate ma kets, information contagion effects on business development), origins of life (autocatalytic reactions, protein synthesis and self organization), sustainable development, and adaptation and learning in businesses and other organizations. In addition, business affiliates of SFI will develop simulations using these techniques for utility markets, telecommunication restructuring, manufacturing processes, and others.

As is described in the following sections, the research environment at SFI has enabled a large, diverse group of outstanding scientists to pursue innovative approaches to science and its applications and to create a world center for the study of the sciences of complexity. Over the past half-dozen years this environment has been prolific and productive scientifically and educationally, attracting widespread attention from academic, business, and policy worlds because of the evidence that this approach to science is producing new insights and methods of treating difficult problems.

Santa Fe Institute provides a research environment that complements those of universities, government laboratories, and business. Visitors typically spend a few weeks to a few months in temporary research residencies at SFI, then return to their home institutions. Over the course of SFI's short life small groups of scientists have organized themselves at many of those home institutions to continue research begun or accelerated at SFI, and most of them continue their research collaborations from afar. In addition, both SFI's structure for research and its investigations of nonlinear, complex systems have created a model that is being increasingly emulated in scientific research communities.

Integrative-Synthetic Approach to Science

The two dominant characteristics of research at SFI are *scientific synthesis* and a *multidisciplinary approach.* Obviously, the two go hand-in-hand. SFI's founders saw scientific synthesis as a timely, and missing, complement to the dominant pattern of twentieth-century science. That pattern, enabled by the development of superb experimental tools that revealed detailed knowledge about structures and processes of physical and biological systems, encouraged and rewarded specialization within disciplines. It was far more difficult to apply comparably rigorous analysis to the structure and behavior of most natural *whole* systems, because they were nonlinear, multidimensional, multivariate, and rarely in equilibrium—all of which render them difficult to treat with scientific rigor.

In large measure it was the availability of powerful computing in the 1980s that encouraged some scientists to believe it would be possible to develop new research approaches to understand those nonlinear dynamics. Research in subsequent years validated that belief. In particular, with the use of innovative computer simulations, it has been possible to demonstrate that complex, nonlinear behavior of natural systems could be the consequence of relatively simple although perhaps changing rules governing the action, over time, of a large number of simultaneously interacting agents.

This phenomenon (relatively few simple rules giving rise to complex behavior) has now been seen in simulations of many different systems—biological, ecological, economic, computational, etc. That has encouraged people to think that there may be some common principles, akin to physical laws, that govern the behavior of complex systems in general. This idea has emerged as a powerful integrating focus for much of the research done at SFI in recent years.

Very early in the life of SFI it became apparent that collaborations among scientists from different disciplines could reveal three things: (1) insights coming from commonalities in scientific approach (though arriving at that point usually required time to understand each other's language); (2) cross-fertilization with suggestions for approaches to understanding that which had worked in one discipline and might work in another; and (3) most important, suggestions that common principles might apply across the fields.

There have been repeated instances of the first two mechanisms, and in themselves those two benefits have justified the establishment of SFI as a research environment. But it is this third possibility—common principles—that infuses researchers at SFI with the sense that they may be setting the stage for fundamental new science directions in future years.

Ultimately, as SFI grapples with trying to identify and quantify common principles governing complex systems (both adaptive and nonadaptive), it is also defining the nature of new multidisciplinary sciences. Where this will lead is not clear, but the successful, and provocative, integration of some parts of science so far suggests that it can have profound consequences both on how science is done and how science is taught.

Simulation as a Research Tool

Much of the research at SFI involves model building and attacking scientific questions via computer simulations, rather than by analysis. One of the weaknesses of having to rely on analysis is that it restricts research to those classes of problems amenable to this mathematical treatment, leaving vast, important areas of understanding consequently untouched. Adding computation as a tool removes much of that bias in problem selection. One of the contributions SFI is making to science is the expansion and refinement of the set of computational tools so that they can be applied to a broader class of problems and can eventually offer a level of confidence comparable to that which can be attained using analysis.

Modeling can provide approximations of solutions to problems that are otherwise intractable or can offer insights by simulating the behavior of systems for which a solution is not a well-defined concept. Modeling permits multiple hypotheses to be proposed and tried. Many simulations take advantage of evolutionary mechanisms (mutation, genetic crossovers, selection) to sort and modify the competing hypotheses, and well-made models improve their performance (i.e., their match to reality) over time and between iterations to come closer and closer to reproducing the kind of behavior seen in real-world complex systems. This approach represents a shift from the deductive reasoning of analysis to the inductive reasoning of synthesis.

Inherent in this kind of research is an interplay among the formulation of theory, the implementation of the model by computational experiment (simulation at SFI), and the validation of the theory by comparison to experimental or observational data.

1.3 SFI's Impact on Important Areas of Science

Scientific Computing

SFI's research in adaptive computation underlies, and in turn draws inspiration from, most of the other research that is done at the Institute. The application of new computation techniques to simulations of complex systems (such as the human immune systems, for example) has yielded powerful scientific results, though the main objective of the computation program is to understand better the nature of this kind of computing. Adaptive techniques such as genetic algorithms, neural nets, classifier systems, cellular automata, etc., are inspired by observation of "natural" computing systems (the brain, or the evolutionary process), so it is no surprise that at SFI computer scientists are working intimately with immunologists, neurobiologists, ecologists, economists, etc. in coevolving scientific collaborations. For example, computer scientists observe how the immune system works and incorporate some of those naturally evolved techniques in their programming, and they offer computing algorithms to the immunologists to improve their ability to model the workings of biological systems. (One of the interesting, unexpected outcomes, a collaboration between computer scientist Stephanie Forrest and immunologist Alan Perelson, is a patent disclosure, now under development by a corporation, of a mechanism modeled on the immune system to protect computer systems against viruses and intruders.)

SFI is supporting the development of two adaptive modeling platforms (ECHO and Swarm) that are intended as general tools for use by a wide range of scientists. A preliminary (documented) version of ECHO was recently released.

Most of the modeling of adaptive systems is inherently parallel in structure—many agents, acting and reacting repeatedly within local environments, with their combined actions altering the overall environment at each step in a continuous feedback loop. SFI's research with these parallel systems will inevitably be important in inspiring software to take advantage of massive parallelism in new hardware, and probably in encouraging the development of parallel hardware in response to the availability of programming needs and tools.

In work in part inspired by interactions at SFI and in part done at SFI, Tom Ray (U. Delaware; now at ARL, Japan) is pioneering new techniques to use the power of mutation and selection to evolve optimized code.

SFI's long-term goal in computing is to capitalize on the likelihood that the adaptive techniques already available may represent just a few of the more obvious "natural" computing approaches. There are likely to be other software and hardware analogs discovered, and there should be continuing opportunities to improve computing over the years in ways other than by optimizing technologies already known.

Biological and Environmental Sciences

Part of SFI's work in biology aims at understanding origins of life and the evolution of complex biological systems, and part focuses on dynamics of ecologies (biological and nonbiological). Several software simulation platforms (see above) are being developed that can model ecologies within the computer—a powerful, flexible, and nondestructive approach to understanding dynamics, evolution, and coevolution of biological communities. Work done by Thomas Ray with his Tierra model (see above) suggests that even in very simple evolutionary situations a great variety of familiar biological and ecological features (parasites, hyperparasites, cooperating species, population crashes, and punctuated equilibria) arise with no outside influence, simply from the competition of organisms for resources within a system. John Holland's ECHO model, designed as a general simulation tool that permits agents to compete, cooperate, and reproduce within a confined space, is now being adapted by ecologists to study desert ecologies. This step marries a rich, multidecade base of field data from experimental sites in Arizona with the model. It not only provides a chance to validate the dynamics of the model (and modify it based on the experience of the "users"), but it now provides an experimental ecology, in the computer, to investigate alternative conditions or to go back in time and re-run experiments with altered conditions.

Additional applications of ECHO that are under study include studies of bird populations in Hawaii and studies of human populations in the prehistoric Southwest. This same modeling approach is being developed into a multi-institutional project (Project 2050) partially funded by the MacArthur Foundation, for scenarios that could illuminate conditions for a sustainable world over the next century. Unlike traditional scenario modeling, which is necessarily biased by the model-builders' assumptions, the SFI approach is bottom-up, relying on the computational agents in the nonlinear adaptive model to compete, learn, and coevolve in the changing environment. While such models can only offer gross views of possible outcomes of decisions, they may be able to identify those actions that may have large multipliers downstream.

These same models should be adaptable for looking at more constrained issues such as the impact of energy use on national and natural resources, including the long-term consequences of differing levels of energy consumption and types of energy consumed. Both the ECHO model and its more generic counterpart, Swarm (being developed by Christopher Langton as part of SFI's artificial life research), are progressing toward the point when they can be adapted and used by non-computer scientists for exploring adaptation in systems of their particular interest. Such problems as energy usage and price sensitivity, energy source tradeoffs, even environmental feedback, could be modeled on these platforms. There is good expectation that useful and increasingly accurate models of these inherently nonlinear systems could be developed using SFI approaches.

Computational Biology

A continuing area of research at SFI is the search for patterns in seemingly random time-series data. These series may be from natural sources (e.g., climate, sunspot, or seismic patterns) or from social systems (e.g., financial markets). Tools developed in part at SFI have shown impressive successes in discovering patterns in such data, with the major applications to date being in economic data (SFI researchers J. Doyne Farmer and Norman Packard are founding scientists of The Prediction Company, in Santa Fe, and use these techniques in investment markets.)

Some related techniques have found another application—in extracting meaningful patterns from large biological data bases. This has direct relevance to taking advantage of the rapidly growing Human Genome data base. SFI, in collaboration with several scientists at Los Alamos National Laboratory (Alan Lapedes, Rob Farber), is pursuing several projects to derive meaningful biological knowledge directly from a "reading" of those kinds of data bases. This work, which uses adaptive computation approaches in various combinations, offers the hope of predicting the structure of proteins based on the sequences of amino acids that code for them. Among the results so far are a computational technique utilizing coevolving adaptive networks that are significantly more successful in predicting protein secondary sequence than are other methods; progress in the inverse problem of determining what sequence of amino acids will fold to a desired protein shape; and Bette Korber's work using statistically significant, correlated mutations in the HIV-1 virus to trace routes of infection. In allied work James Theiler is applying other computational techniques to searching for patterns in electroencephalograms. Finding such patterns may then reveal better knowledge of the biological mechanisms giving rise to the medical data.

Fundamental Physics

Within SFI's core research several scientists, led by Murray Gell-Mann, have been exploring the connection between basic laws of physics (the fundamental, quantum mechanical field theory of all the elementary particles of the universe, and the boundary condition on the universe) and what is directly observed in the classical domain where much of SFI's work is concentrated. Among the investigations underway (discussed in more detail in Section 2.2) are information theory and statistical physics, information in the quantum universe, quantum information and communication, quantum computation, and characterization of chaos in classical dynamics.

Economics of Increasing Returns

A general body of research called increasing returns to scale, led at SFI by W. Brian Arthur (Stanford), is developing theory to improve understanding of the nature of technologically dominated businesses and economic consequences of their growth. This research presents a much different picture of how businesses grow, how innovations compete among themselves, and the kinds of investment strategies that are likely to be successful. Much of the existing theory and practice derives from models of resource-based industrial development, as opposed to the kind of knowledge-based development that inceasingly fuels economic growth in leading industrial societies. So a good model for a steel company is unlikely to offer useful guidance for a software or microchip business. In the past few years this work, which is based on assumptions about market behaviors and dynamics that are often at odds with classical economics, has attracted increasing attention and respect from the business sector as well as the economics community. Arthur will be in residence at SFI throughout 1994 to focus on this area of research.

1.4 Impact on Education/Training

Seeding and Supporting Complex Systems Studies in Other Institutions

Because SFI is primarily a visiting institution, hundreds of scientists and students spend time in Santa Fe each year. Over the past nine years the work being done at SFI has begun to find its way into research programs at other institutions, as those visitors return to home campuses and continue complexity studies there. Several new or incipient complexity programs now exist, including these:

- SFI and the University of Michigan have a formal exchange program that brings research visitors to SFI each year and sponsors an annual symposium at Michigan each fall. Recent Michigan participants include John Holland, Robert Axelrod, John Jackson, Rick Riolo, Melanie Mitchell, and Michael Cohen.
- The long-standing cooperation at University of Illinois was expanded in the past year with the appointment of a member of the SFI Science Board, David Campbell, as head of the University of Illinois physics department. Other active participants from Illinois include David Pines, Hans Frauenfelder, Atlee Jackson, Alfred Hubler, Gottfried Mayer-Kress, and Peter Wolynes.
- There is a large contingent of scientists at Stanford who have long been active at SFI, and in the past year they have established a regular complexity seminar in Palo Alto. They include Marcus Feldman, W. Brian Arthur, Kenneth Arrow, David Rumelhart, Aviv Bergman, Robert Maxfield, and John Koza.

- At George Mason University, SFI Science Board member Harold Morowitz will head the new Krasnow Institute there, which will focus on complexity and the brain.
- There is a growing presence of complexity scientists at the University of New Mexico, including Stephanie Forrest, Carlton Caves, Linda Cordell, Bruce Milne, and James Brown.
- At least a dozen scientists and students from Los Alamos National Laboratory participate regularly in SFI research, and several of them (Alan Perelson, Alan Lapedes, Bette Korber, James Theiler, Christopher Langton) lead joint research efforts between SFI and LANL.
- Members of SFI's External Faculty, Science Board, and Board of Trustees (Appendixes X, XII, and XII) represent 39 different universities or research organizations, and all have been facilitating exchange of people and ideas as part of the expansion of influence of research being done at SFI.

Postdoctoral Fellows

SFI also has programs expressly to promote training and education on site. For the past six years it has sponsored or co-sponsored postdoctoral fellows for residencies of one to three years. Including those currently in residence, the number to date totals 13. Additionally, SFI has hosted visits of several postdoctoral fellows with appointments elsewhere, including upwards of a dozen from Los Alamos who have regularly participated in the SFI program. These young scientists have, as a group, produced an impressive body of work, some of which is described later in this proposal. Former postdoctoral fellows now hold academic positions at Carnegie-Mellon, Cold Spring Harbor Laboratory, Chalmers University (Sweden), University of Vienna, North Carolina State University, JPL, National Institutes of Health, and Los Alamos National Laboratory, and one has moved into industry.

The postdoctoral fellows are generally appointed to pursue research within SFI's integrative core, but they often migrate after arrival toward unexpected collaborations. A recent fellow, Thomas Kepler, came with interests in computational neurobiology but was quickly drawn into research on theoretical immunology; within a year, as a result of his success, he was offered a faculty position at North Carolina State University in Biomathematics.

Graduate Students

SFI provides an environment in which a few graduate students come each year to conduct dissertation or other research. Additional students from neighboring institutions, such as the University of New Mexico or Los Alamos National Laboratory, also spend time at SFI conducting research and interacting with SFI scientists. Several of these students have already completed their Ph.D. degrees (in economics and computational biology). Currently graduate students are doing research in computer science, immunology, and neurobiology.

Summer School

The largest educational activity at SFI has been its annual summer schools. Starting in 1988, each year some 60 students (primarily graduate students, but including some postdoctoral fellows and some undergraduates) have come to Santa Fe for one month for lectures, seminars, and projects that introduce them to or strengthen their knowledge of the sciences of complexity. In recent years the students have begun to include scientists from industrial research laboratories as well. A number of the summer school graduates have themselves become "complexity scientists," some through formal affiliation with SFI, some at other institutions. For example, Stephanie Forrest, an early summer school student who is now on the faculty of the University of New Mexico, is a member of the Steering Committee of SFI's Science Board; Bill Bruno is a postdoctoral fellow at Los Alamos National Laboratory; Neil Gershenfeld is a faculty member at the MIT Media Lab; and Andreas Weigend is a faculty member at the University of Colorado.

Undergraduates

SFI has had a modest program to provide research experiences for a few undergraduates since its beginning. The nature of complexity science has made it possible for relatively untrained (but very bright) students to participate in research and make contributions. Most of the undergraduates who took part in this program have gone on to serious careers in science. The success of this early effort was recognized when, in 1993, the National Science Foundation established SFI as a site for its Research Experiences for Undergraduates program. That permitted six additional undergraduates to spend upwards of two months at SFI during the summer working with senior mentors. The research output was impressive, and this program will continue in future years.

1.4 Impact on National Needs

Attacking Whole, "Messy" Systems

The fundamental motivation for the formation of SFI was the limitations of traditional, compartmented science. The founders were well aware of the immense success that this style of science has contributed throughout the twentieth century and will continue to contribute, but they were also frustrated that so much of the world—what we call the complex part of it—was largely ignored by that approach. And yet most of the issues and problems that people, businesses, and governments must grapple with daily are precisely those kinds of messy, integrated systems that do not fit wholly within the confines of a single discipline. The research that SFI has begun may provide a better avenue by which science can contribute to understanding, anticipating, and solving societal problems.

Admittedly, research on nonlinear, complex (and often adaptive) systems is in its infancy. Yet even in these few years it has demonstrated great promise and captured the imagination of many scientists. A review in the February 1993 issue of *Nature* of two of the several new books written about complexity concludes with the statement: "It is time science relearned how to look outwards as well as inwards, to think about meaning as well as counting information, and to appreciate nature's semantics as well as its syntax. This is the core of the complexity manifesto. Read it, think about it, disagree with it, make television programmes about it, write polemics against it—but don't ignore it."

Transfer of Knowledge and Technology

In the past several years the business world has increasingly recognized the potential practical importance of the SFI approach to science by supporting our research. SFI's Business Network for Complex Systems Research, begun in July 1992, currently has 13 members who contributed from $25,000 to $125,000 annually.

One of their areas of interest has been the potential for developing new kinds of software. SFI's research appeals to these companies from two perspectives. One is the use of different suites of techniques for simulations (such as the ECHO model's mixture of genetic algorithms and rule-based systems) or in attacking particular problems (such as the combinations of neural nets for calculating protein structure from amino acid sequences). The other is understanding more about the potential and limitations of the techniques, such as what kinds of problems can be best attacked with which kinds of new computing tools.

Corporations from the manufacturing sector, concerned about the difficulty of managing an increasingly complex product stream and manufacturing process, seek insights and tools from work on complex adaptive systems.

Corporations from the investment and financial sector recognize that SFI, in challenging the conventional rational, decreasing-returns, equilibrium view of economics, is advocating alternatives that offer the promise of understanding the new high-technology world in which U.S. corporations must compete.

Two additional features are worth noting. One is the already-mentioned design of programs and algorithms to reproduce the kind of behavior naturally suited to computation in parallel computing environments. The other feature is the potential for "self-programming," a way not only to speed production of software, but also a way to use evolutionary mechanisms to develop unique and ingenious solutions to problems that are not likely to result from logical programming. The work by Thomas Ray in creating a "digital" soup in which organisms evolve by mutation not only rediscovered some well-known human programmers' algorithms, but also evolved some counterintuitive (but highly efficient) algorithms without human input at all.

Although SFI's focus is on exploration of the sciences of complexity, the tools it develops for simulating complex systems, learning and adaptation, and evolution are readily adaptable to many kinds of application-specific simulations. Two generic modeling platforms for simulating adaptive systems—ECHO and Swarm—have been developed and will soon be made available to users via the Internet. At SFI, those and other programming platforms will be used in new efforts to study adaptation and learning in organizations, to study the evolution of organizations and cultures, to study economic markets (such as how markets evolve prices in trading), to conduct *in silico* ecological experiments in connection with collections of long-term field data, to study long-term issues of human sustainability with particular regard to resource use and renewal, and more.

SFI is improving these models to the point where they can not only be applied to different varieties of problems that people wish to study (taking advantage of the growing evidence that there are common dynamics for all complex adaptive systems), but also to the point where people with limited experience in "running" computer models can readily do so. In particular, the models are being refined so that the experimenters (who may be business people, government officials, or concerned laypeople) can vary the parameters in a visible way and see the impact on how the simulation evolves. John Holland refers to such refined models as "flight simulators for policymakers," in that people can try out policy options in the simulation, get a better understanding for the sensitivities in the nonlinear system (e.g., how sensitive is the system to changes in resource pricing or supply?), and thereby develop a range of real policies that are less likely to fail because of unsuspected feedback.

2. INTEGRATIVE CORE RESEARCH IN COMPLEX SYSTEMS

Science, suggests SFI External Faculty member W. Brian Arthur, "is about the creation of metaphor." Before the 1680s, "people looked at the world and said it was messy, alive, organic. Fifty years after Newton, all people could see was order, stasis, equilibrium, and harmony." The sciences of complexity are an attempt to break away from the Galilean-Newtonian simplicity that has served much of traditional physics so well and to tackle those real-world problems that do not yield to this neo-Platonic view.

The integrative core program is where SFI researchers are most explicitly searching for the components of the new metaphor of complexity, along with the models and mathematics that engender it. Integrative research is the Institute's largest program, at the "core" of its work on complexity, focusing on the most broad-ranging inquiry into the principles that characterize the behavior of complex systems. This core captures the work of most of the full-time postdoctoral fellows who usually collaborate on a broad range of different projects. It also includes much of research done during long-term visits by members of SFI's External Faculty and Visiting Faculty. In fact, since research at SFI is a continuous exercise in self-adaptation, every SFI researcher is in a sense a member of this central core—regardless of nominal program affiliation. Constant interactions encourage SFI researchers' focus to bounce back and forth between the specific topic at hand and broader, fundamental questions like the definitions, measures, and behavior of complexity.

The presence of this core initiative assures that SFI maintains a reservoir of first-class researchers broadly interested in complex systems and that there are always exploratory projects underway. As such, the program is a hothouse for new ideas—one of the most visible signs of that being the steady stream of colloquia, seminars, and informal presentations that occur every week.

The core program is also the source for most of SFI's integrative program activities, those frequent meetings which bring together the Institute's family of researchers to consider broad "system-wide" topics and to continue the ongoing task of constructing an overview of the commonalities in the behavior of complex systems. In 1993, for example, the External Faculty, SFI's "immediate" scholarly family, gathered for an extended meeting at the Institute to explore their common scientific interests. This meeting is likely to be repeated frequently. Next year will also see a broadly multidisciplinary workshop on "What Is Scientifically Knowable," chaired by John Casti (SFI) and Joseph Traub (Columbia U.) Its aim is to provide a first step toward establishing an actual research program to foster some definite conclusions on the matter of scientific, as opposed to mathematical, knowability.

The annual gathering of the Institute's Science Board provides another opportunity to focus on the emerging common threads and overarching themes of complexity research. The overall direction of the Institute's research is guided by this 55-person Board, which is responsible for assuring that SFI research meets high-quality standards, 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.

2.1 Understanding the Behavior of Complex Systems

SFI core program researchers are trying to understand at the most basic level how and why complex systems behave as they do, and in particular how they learn and adapt. Complex behaviors may evolve from a surprisingly few simple rules controlling individual parts of a system, but such behavior is not readily predictable from knowledge of individual elements; instead it reveals itself in the emergent behavior of the system. Questions need to be asked of the system as a whole, often using computer simulation. What, for example, are the stages of operation of complex adaptive systems? Does innovation thrive at the boundary separating order and disorder? What does it mean to have self-organization and the emergence of hierarchy within a system, and what is the relationship between the major steps in biological evolution and the levels of organization in complex adaptive systems? Does evolution, in fact, favor increases in complexity and, if so, why? How does one measure complexity, and is it really necessary to do so? By weaving together insights from a wide range of interrelated core work, SFI researchers hope to address these and other issues to forge a better understanding of the commonalities of complex systems.

2.1.1. Toward a Theory of Biological Organization

SFI Postdoctoral Fellow Walter Fontana and Leo Buss (Yale U.) have taken a different tack on the issue of how new classes of organisms arise (Fontana & Buss, 1993a, 1993b). If the clock were set back to the beginning of time, what conditions would have to be present to produce contemporary classes or organisms, such as multicellular organisms? By trying to model mathematically the simplest interactions in a community, they hope to understand better, not the survival of the fittest, but the origin of the fittest.

The formal structure of evolutionary theory is based upon the dynamics of alleles, individuals, and populations. As such, the theory must assume the prior existence of these entities. At the heart of the existence problem is determining how biological organizations arise in ontogeny and in phylogeny.

Fontana and Buss are developing a minimal theory of biological organization based on two abstractions from chemistry. The theory is formulated using lambda-calculus, which provides a natural framework capturing the constructive feature of chemistry—that the collision of molecules generates new molecules—and chemistry's diversity of equivalence classes—that many different reactants can yield the same stable product. They employ a well-stirred and constrained stochastic flow reactor to explore the generic behavior of large numbers of applicatively interacting lambda-expressions. This constructive dynamical system generates fixed systems of transformation characterized by syntactical and functional invariances.

Organizations are recognized and defined by these syntactical and functional regularities. Objects retained within an organization are characterized by a grammar and interactions among objects by algebraic relationships. The objects that maintain themselves in the system realize an algebraic structure and possess a grammar that is invariant under the interaction between objects. An organization is self-maintaining and is characterized by: (1) boundaries established by the invariances, (2) strong self-repair capabilities responsible for a robustness to perturbation, and (3) a center, defined as the smallest kinetically persistent and self-maintaining generator set of the algebra.

Imposition of different boundary conditions on the stochastic flow reactor generates different levels of organization, and a diversity of organizations within each level. Level 0 is defined by self-copying objects or simple ensembles of copying objects. Level 1 denotes a new object class, whose objects are self-maintaining organizations made of Level 0 objects, and Level 2 is defined by self-maintaining metaorganizations composed of Level 1 organizations.

These results invite analogy to the history of life, that is, to the progression from self-replication to self-maintaining prokaryotic organizations that ultimately yield self-maintaining eucaryotic organizations. In their system, self-maintaining organizations arise as a generic consequence of two features of chemistry, without appeal to natural selection. (Disclosure through Yale, future work).

2.1.2. A Unified Theory of Biochemistry

Science Board member Harold Morowitz (George Mason U.) has been in residence at SFI for a good deal of 1993 developing a unified theory of the biochemical basis of the origin of life, a project at the interface between the vast databases of the biochemical literature and the type of theoretical syntheses central to the SFI approach.

For whatever reason, the universal chart of intermediary metabolism has the structure of shells and gateways (Morowitz, 1992). Shell I consists of the reactions of energy processing and the synthesis of carbon shells leading to membranes; Gateway I is the condensation of ammonia and alpha keto glutaric acid to yield glutamic acid; Shell II is the reactions of amino acid synthesis; and Shell III is the RNA world. Gateway III is the synthesis of deoxyriboses leading to the DNA world.

Morowitz conjectures that the structure determines the sequence of evolutionary development, which opens up several possibilities. He suggests that the structural features of shells and gateways are of more general applicability and extend through all of biology and maybe into the noetic sciences. The second conjecture is that the nature of the first shell is determined by the physical and organic chemistry of small compounds of hydrocarbon and oxygen interacting through phosphate group transfer and redox reactions.

Behind all this biochemical detail are some general principles relating to Dollo's Law, an evolutionary principle of irreversibility relating to complexity. For complex highly interconnected systems with a shell structure, the nesting of shells establishes a depth within the system. In a changing competitive Darwinian world a system must change in order to survive. Deep changes cannot, in general, be tolerated because of the highly interconnected character of complex systems. They change too much. The competitively useful changes will be made at the outer shell or by opening a gateway to a new shell. Thus surviving systems are constantly adding new shells, i.e., becoming more complicated.

This relates to other core program work in several ways. It has the possibility of being a reification of the biological organization theory by Fontana and Buss although it is many hierarchical levels lower on the scheme of things. Nonetheless, it should serve as a check of their hypothesis in considering the causes of metabolic levels.

Morowitz' SFI work in 1993 has concentrated on detailing the shell structure; on developing a detailed theory of how the biochemical subset arises out of the universal set of C1 to C6 compounds; on extending the shells by identifying the gateways into the cellular and developmental stages of biology; and on looking for analogs of this shell theory in other areas of complex systems to generalize the theory of increasing complexity with particular reference to economics and related sciences. All of this is eventually headed toward a book on "A Unified Theory of Biological Organization."

2.1.3. Adaptation and Learning in the Economy

Until quite recently most theoretical reasoning in modern economics has started with the assumption that agents possess "perfect rationality"; that is, they obey certain axioms of reasonable and logical behavior. This works well in simple problems, but it breaks down beyond a "problem complexity boundary" where human computational abilities are exceeded or the assumptions of deductive rationality cannot be relied upon to hold. W. Brian Arthur is re-examining economic decision making in light of the general questions it raises about how we acquire and process knowledge, about how complex systems learn and adapt.

Arthur believes that beyond the "complexity boundary," in decision contexts that are complicated and potentially ill-defined, humans actually use inductive reasoning: they recognize patterns; construct representations and internal models based on these; use these as working hypotheses, possibly carrying out a good deal of deduction based on them; and strengthen or replace them as they receive feedback from their environment. As this learning and mutual adaptation take place, there is a continual formation and reformation of the behaviors, technologies, and institutions that comprise the system. Some part of the economy may be "attracted" to an equilibrium; some parts may continually evolve and never settle.

Arthur, with John Holland, Blake LeBaron, Richard Palmer, and Paul Tayler, has developed a computer simulation of an artificial stock market in hopes of learning more about how agents adapt—in this case how traders learn to make profits—and why markets behave the way the do. While some other models have been based on deductive reasoning, the economic behavior in this market has an inductive pattern approach with competing ideas and hypotheses. The market has a single stock. There are about 100 agents who can buy or sell the stock or place money in the bank; the bank pays a fixed interest rate. The simulation allows researchers to examine the individual traders and what makes them successful. Through genetic algorithms traders replace rules with more inventive ones or they combine and cross over rules to make a new hypothesis. The collaborators plan to continue to refine and run this artificial market, in particular to generate a simulated time series to see what kinds of real-world phenomena are replicated in this computer-generated market.

Arthur's SFI work on learning has led him to also address such questions as these: Does learning and evolution in a system make it more complex? Does evolution, in fact, favor increases in complexity and, if so, why? And can the process go in the other direction too, so that complexity diminishes from time to time? In an attempt to answer Arthur draws cumulative data from a broad range of evolutionary contexts—including not only biology, but from the domains of economics, adaptive computation, artificial life, and game theory.

He suggests there are three ways evolution tends to increase complexity in general systems. First, it may grow by increases in diversity that are self-reinforcing; this Arthur calls *growth in coevolutionary diversity*. This applies in coevolving systems that are open, that is, where the individuals that interact are not fixed in number, so that new ones may enter from time to time. In such systems the individuals coexist together in a diverse interacting population, with some forming substrates or niches that allow the existence of others. When the individuals in such systems create a variety of niches that are not closed off to further newly-generating individuals, diversity tends to grow in a self-reinforcing way. Growth in coevolutionary diversity can be seen in the economy in the way specialized firms within the computer industry have proliferated in the last few decades. (It also shows up in the contexts of Thomas Ray's Tierra system (Ray, 1991), in John Holland's ECHO (Holland, 1993), and in Kauffman's chemical evolution systems (Kauffman, 1991b).)

A second mechanism causing complexity to increase over time Arthur names *structural deepening*. This applies to single entities that evolve against a background that can be regarded as their "environment." Normally competition exerts strong pressure for such systems to operate at their limits of performance. But they can break out of these limits by adding functions or sub-systems that allow them to (a) operate in a wider or more extreme range, (b) sense and react to exceptional circumstances, (c) service other systems so that they operate better, and (d) enhance their reliability. In so doing, they add to their "structural depth" or design sophistication and become increasingly complex. The history of the evolution of technology provides many examples of structural deepening. One laboratory for observing real-time structural deepening is John Holland's genetic algorithm (Holland, 1992).

The third mechanism Arthur calls *captured software.* This is the taking-over and "tasking" of simpler elements by an outside system for its own (usually informational) purposes. Typically the outside system "discovers" the simpler elements and finds it can use them for some elementary purposes. The elements turn out to have a set of rules that govern how they can be combined and used—an "interactive grammar." At full fruition, the outside system learns to use this interactive grammar to "program" the simple elements and use them for its own multipurpose ends. An example of captured software is the way in which sophisticated "derivatives"—Third World debt, Eurodollars, etc.—have arisen and are used in recent years in financial markets. An biological example would be the formation of neural systems, and, of course, biological systems have learned to task DNA and RNA as carrier elements to their own programmable purposes.

Arthur argues that the operations of all three of these complexity mechanisms are intermittent, epochal, and often bidirectional. The first two mechanisms are certainly reversible, so one would expect collapses in complexity to occur from time to time.

Arthur plans to continue this inquiry into the connections between complexity and evolution, drawing from a variety of domains.

2.1.4. Self-Organized Criticality and Scaling

Defining complexity is a problem in its own right. For instance, some systems may be complex, but they do not adapt. Visiting Fellow Per Bak (Brookhaven Natl. Lab) describes the tendency of such large dynamical systems to drive themselves to a critical state with a wide range of length and time scales as "self-organized criticality" (Bak et al., 1988). This idea provides a unifying concept for large-scale behavior in systems with many degrees of freedom; it complements the concept of "chaos" wherein simple systems with a small number of degrees of system display quite complex behavior. Self-organized critical behavior leads to random fractals as descriptions of state and to scaling laws for the distribution of "avalanches." Sometimes this criticality is referred to as "the edge of chaos," the border between order and disorder. In 1994 Bak will continue to conduct theoretical work on models displaying self-organized criticality, and to consider the connection between the concepts of complexity, criticality, and adaptability.

On a related front SFI researchers including Philip Anderson (Princeton), Murray Gell-Mann (Caltech), and Geoffrey West (LANL) are exploring phenomenological scaling laws. Scaling phenomena occur over a wide range of fields from biology and economics to classical nonlinear phenomena (under the guise of fractals, chaos, self-similarity, and the like) and quantum field theory. Scaling up from the small to the large is often accompanied by a progression from simple laws to apparently complex behavior; typically this occurs while certain properties of a system remain invariant or conserved. A possible paradigmatic structure for discussing some of these questions within a general framework is the use of the renormalization group. It has a precise formulation and, consequently, precise quantitative statements concerning scaling in both elementary particle physics and phase transition phenomena in statistical mechanics. It is suggested that anomalous dimensions and the consequent power law behavior that appear in this context are quite analogous to fractal dimensions that occur in classical complex systems. The response of such systems to a probe (which measures and quantifies its size, shape, and tempero-spatial structure) has much in common with self-similarity. This suggests that there may well be an underlying general unified approach to a variety of scaling phenomena occurring in many diverse areas.

2.1.5. Adaptation to the Edge of Chaos

Unlike Bak's complex, nonadaptive systems, other complex systems are composed of agents that are continuously adapting. How do these agents learn and evolve? External Faculty member Stuart Kauffman is probing the relationship between self-organization and selection in biological evolution to answer this question. According to Kauffman, self-organized criticality occurs in models of coevolution (Kauffman, 1991a, 1991b; Kauffman & Johnsen, 1992). For example, communities with a subcritical or low diversity of organisms lack the momentum to develop explosively into a new breed. Supracritical communities expand so rapidly that they consume all of their available food and die off. At the edge of chaos, however, mutation and innovation occur. Kauffman hypothesizes this may be the case regardless of whether the complex system is prebiotic, biological, or even economic or cultural.

The transition regime, whether between subcritical and supracritical metabolic behavior, or between ordered and chaotic dynamical behavior, is both buffered and poised. Small perturbations unleash small or large avalanches of change that propagate through the system. The expected size distribution of avalanches is a power law with many small avalanches and few large ones. At the level of the cell, adaptation to the edge of chaos implies that molecular signals altering the activity of single genes can unleash small and large regulatory cascades altering the activities of other genes and molecular variables in a coordinated way, without triggering chaotic behavior. At the level of coevolving organisms, adaptation to the phase transition implies that the same small-scale perturbations can unleash tiny or vast cascades of metabolic or morphological changes which propagate through the system causing, among other consequences, extinction of old molecular and organismic species and formation of new ones. If ecosystems naturally attain the edge of chaos, current notions of "sustainability" may require rethinking. Ecosystems may be poised, forever changing, in a characteristic stationary state, but not "stable" at molecular or community levels over appropriate long time scales.

Working with programmer Emily Dickinson and Postdoctoral Fellow William Macready at SFI, Kauffman this year continued to explore several related conjectures along these lines. One is that optimal complex computation and adaptation in parallel processing systems occurs at the edge of chaos. Another is that under natural selection, adapting parallel processing systems attain the edge of chaos. Further, Kauffman is looking at the notion that complex adaptive entities modify their internal structure and couplings to other adapting entities such that the entire system coevolves to the edge of chaos.

He is studying the new hypothesis that in coevolving communities, cells or single organisms are metabolically subcritical while the community can be subcritical or supracritical as a function of species diversity and the diversity of novel molecules introduced into the community. In subcritical systems, the generation of molecular novelty in the system following introduction of a novel molecular species is very limited. In supracritical systems the generation of new kinds of molecules is explosive. Increase in species diversity or the diversity of novel molecules introduced into the system may drive ecosystems from subcritical to supracritical behavior. Finally, he is exploring the possibility that natural evolutionary dynamics causes communities locally to coevolve to the phase transition between subcritical and supracritical behavior. Briefly, supracritical communities should rapidly generate many novel molecules, some toxic to some species, causing local extinctions which drive the system toward the subcritical regime. In-migration of metabolically novel species, or evolution of new species, should increase species diversity, hence drive the system towards the supracritical regime. He is assessing whether these processes generically balance at the phase transition itself.

Kauffman's thinking about the edge of chaos has implications for the theory of bounded rationality, work he intends to focus on in the coming year. This is the notion that agents are not all-knowing; instead, they formulate strategies and expectations without full information, often beginning with simple rules of thumb, learning and adapting their way to improved decisions. The concept has proved especially fruitful for the Institute's economics program. Kauffman hypothesizes that coevolving adaptive agents build boundedly complex models of one another's behaviors. Coevolutionary dynamics offers an ordered regime, a chaotic regime, and a phase transition. Within the ordered regime—

corresponding roughly to the idea of perfectly rational expectations in economics—agents have stable models of one another and long series of reliable data; each is driven to build an optimal, more complex model of the others. But such detailed models are more easily disconfirmed, driving the system toward a chaotic regime. In the chaotic regime each agent changes his model rapidly, so there is less reliable data. So to predict optimally, agents should build simpler models, which, while they predict less detail, are also less easily disconfirmed, driving the system toward an ordered regime. Kauffman is exploring whether the phase transition is the natural attractor of this dynamics. If so, this approach offers a theory of optimally bounded rationality in the sense that agents come to use optimally complex models of one another in order to optimally predict one another's behaviors.

2.1.6. A General-Purpose Modeling Platform: The Swarm Simulation System

The Swarm Simulation System is a generalized programming framework, developed by External Faculty member Christopher Langton, for simulating and studying the complex behaviors that arise in systems composed of many components. The project aims to create a fundamental tool for complex systems research.

Most of the complex systems that occur in nature share a common architecture, which Langton labels a "swarm." The term refers to a large collection of simple agents interacting with each other. The classic example is a swarm of bees, whether in flight or inhabiting a nest. The notion of a swarm can be readily extended to other systems with a similar architecture—ant colonies, a flock of birds, traffic considered as a swarm of cars, a crowd seen as a swarm of people. Extending the concept even further, a gas is a swarm of molecules, an immune system a swarm of cells, and an economy is a swarm of economic agents. The operating requirement of a swarm is that it shows collective behavior (of many types, not just motion). The essential structure of a swarm is a collection of relatively autonomous entities with no central organization. In a swarm each of the thousands of individuals makes its own behavioral choices, based upon its own evaluation of the local environment and upon its communication with other nearby individuals. There is no central authority directing behavior. What makes such swarms scientifically important is that, although individuals have limited intelligence and exhibit simple behavior, their collective behavior can appear to be highly intelligent and complex.

The Swarm simulation platform provides a general-purpose simulation environment applicable to many contexts. The system allows one to conduct simulations consisting of large numbers of interacting objects or agents. Each object has a few standard attributes managed by the system, as well as whatever application-specific attributes, supplied by the modeler, are needed. The user will be able to write modules to describe the types of objects specific to the model, insert them into the general system, and run the model. Swarm will supply a general user interface that can easily be customized for specific objects; there will be a library of analysis modules available. The approach to developing Swarm is intended to make it readily usable on a variety of computing platforms, and particularly on massively parallel computers.

2.2 Mathematics/Computation

Two distinct mathematical/computational traditions underlie complexity theory. The first tradition is the child of calculus and traces its origins to the work of Henri Poincaré on nonlinear dynamical systems almost a century ago. With the development of modern bifurcation and chaos theory, it has come to include a range of complex phenomena, from fluid mechanics to brain function. In a related advance the reaction-diffusion approaches pioneered by Turing and others have used the model of morphogenesis and pattern formation in biology. The second tradition is a child of the computer and builds on von Neumann's early investigations of cellular automata. With the refinement of computational methods for the iteration of simple rules to produce complex aggregate patterns of behavior, it has yielded novel insights into self-organization and the emergence of order.

A major part of the SFI's core work continues in these traditions, exploring the computation-theoretical and statistical properties of complex systems. SFI researchers are thinking about *dynamics* (meaning dynamical systems theory) as a source of diversity and different kinds of behavior and as a source of understanding solutions of equations without closed forms. They are also considering geometric methods of analysis and notions of qualitative dynamics separate from quantitative analysis. *Computation theory* is being looked at as a way of articulating what these mechanisms are and their structure. And, finally, connecting things back to the real world, they are working in a third category that can be broadly labeled *statistics*, that is, the mathematical methods that one finds in statistical inference and also statistical mechanics.

The work of SFI postdoctoral fellows Mats Nordahl and Christopher Moore productively ranges over many related projects, all focusing on computation in dynamical systems with emphasis on the connections between physics, dynamical systems theory, and theoretical computer science. For example, discrete methods enter dynamical systems theory through symbolic dynamics, and a more physical view of computation including notions such as continuity, geometry, and probability is leading to new insights in computation theory.

One project Nordahl has worked on is an extensive numerical investigation of the properties of Kaufmann's N-K model. 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. In the limit when all functions are connected to each other, the Kauffman model corresponds to random maps of a finite set. Nordahl's work is on models where probability distributions on the space of mappings of a finite set are defined in terms of various Hamiltonians, and in particular the phase transitions between various forms of scaling behavior for average transients and periods.

In another project Nordahl has constructed various classes of higher-dimensional languages (sets of patterns) and studied their applications to dynamical systems and statistical mechanics. Some work along these lines has been done by computer scientists, but the theory is far less developed than ordinary formal language theory. Even in the case of regular languages, equivalent definitions in one dimension give rise to a hierarchy of language classes in higher dimensions. An example of a dynamical systems application of this hierarchy is that the highest level, which forms the higher dimensional analog of homomorphisms of subshifts of finite type, describes cellular automata finite time sets.

Moore's research focuses in particular on characterizing the complexity of dynamical systems, and on how computation might be embedded in physical systems. Moore, Kristian Lindgren (Chalmers), Nelson Minar (Reed College), and Nordahl are looking at the dynamic aspects of complex classes of two-dimensional languages and the undecidability issues involved in extensions to infinite configurations. Some of these systems seem to be good toy models of glasses. Glasses are known to approach mechanical and thermal equilibrium extremely slowly. Models like spin glasses and disordered Hamiltonians have been proposed to explain this behavior, but the Nordahl/Moore systems are the first in two dimensions, using finite energies, that seem to possess these slow dynamics. In addition to possibly contributing to the theory of glasses, these systems are also admirable examples of "rugged landscapes"—high-dimensional state spaces in which a system can wander for extremely long times before finding a minimum. But they go beyond earlier discussions in showing concrete examples of how defect structures can range from local to global, creating a variety of quantitative behaviors, ranging from power law to exponentially slow relaxation.

Moore, Nordahl, and Lindgren have also worked on a number of different coevolutionary models where the interactions between organisms are either stochastically generated (random or spin-glass-like), or based on game theory (e.g., the iterated Prisoner's Dilemma). Nordahl and Lindgren, for example, have constructed artificial ecologies that derive resources from an external environment. The results of the game determine how resources are distributed. Genomes can encode both strategies and preferences for play. Hierarchical food webs emerge from the dynamics, and they have studied their statistical properties and compared them to those of real ecologies. They have also investigated the evolutionary dynamics of spatial games, where individuals interact only with their neighbors on a regular lattice. A number of phenomena of biological relevance are observed, such as coexistence due to nontrivial spatial dynamics (spatio-temporal chaos or spiral waves), and the possibility of supporting a large diversity of species in complex frozen states. Moore and Nordahl are looking at the evolutionary dynamics of competing growth rules based on L-systems, and also systems where populations of simple computational devices such as finite automata with input and output interact by exchanging symbol strings.

Jim Crutchfield's (U.C. Berkeley) SFI work is on computational mechanics—the intrinsic computation in nonlinear systems. One excellent class of models with which to study the interaction of local computation and information flow is nonlinear, spatially extended systems. Crutchfield's theory and methods allow one to analyze how the latter "implement" complex and potentially useful computation in parallel. Aside from the questions of basic physics this work addresses, the approach promises practical applications in parallel computation such as nonlinear adaptive image processing and improved general theoretical understanding, including tradeoffs between information transmission and local computation.

The Institute's project in Complexity, Entropy, and Physics of Information is led by Murray Gell-Mann with Carlton Caves (U. New Mexico), Seth Lloyd, and Wojciech Zurek (both LANL). Drawing from quantum-mechanical field theory and the semiclassical domain on which much of SFI's work is focused, and using both statistical and information-theoretic methods, this work takes steps toward connecting fundamental laws with what is directly observed.

The work has several threads. One is information theory and statistical physics—the connection between information and entropy has been exploited to formulate a new statistical physics that includes both ordinary entropy and information. The new concepts are being used to explore the dynamical increase in entropy, with the goal of formulating an information-theoretic characterization of chaos that applies equally to classical and quantum dynamics. A second focuses on information in the quantum universe—the need for a consistent quantum-mechanical description of closed systems has led to the decoherent-histories formulation of quantum mechanics, which seeks to explain the quasi-classical domain of everyday experience. Since decoherence alone, however, is not sufficient to pick out the quasi-classical domain, information-theoretic measures to distinguish the quasi-classical domain are being investigated. Quantum information and communication is another focus. An unknown quantum state can be transported to a remote location by transmitting a few bits of classical information and transmitting via EPR correlations the rest of the information necessary to reconstruct the state. The rules for manipulating the intrinsically nonclassical information that is stored in a quantum state are only now beginning to be worked out. A fourth strand is quantum computation—rapid computation performed by densely packed components results in problems of heat dissipation that suggest a switch to reversible quantum-mechanical computers. The formal properties of such computers are being elucidated, and the first investigations of potentially practical quantum computers are under way. Finally, the project is considering algorithmic complexity in classical and quantum dynamics—the essential characterization of chaos in classical dynamics (sensitivity of trajectories to initial conditions) cannot be translated directly to quantum mechanics. Information-theoretic measures may provide tools, applicable both to classical and quantum mechanics, for characterizing certain kinds of complexity. In May, 1994, the CEPI program will host its third major workshop on these topics, co-sponsored by SFI, the Center for Advanced Studies at the University of New Mexico, and Los Alamos National Laboratory.

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3. ADAPTIVE COMPUTATION

SFI's research in adaptive computation underlies, and at the same time benefits from, much of the other work done at the Institute. Research in adaptive computation has several foci. It concentrates on building computational models of adaptive systems. It also focuses on using novel methods inspired by natural adaptive systems for solving practical problems such as large-scale combinatorial optimization, pattern recognition in complex data, and automatic construction of computer programs. Finally, the notion of "computation" provides a conceptual framework for scientists thinking about the behavior of complex systems in nature. One might ask of a complex system, for example, what sort of computation is it performing? How complex is that computation? Such questions are leading to a broadening of traditional notions of how and where information processing can take place.

These three issues for adaptive computation—scientific modeling, technological problem-solving, and theory—are obviously interrelated, and they are pursued in parallel. Ideas developed in the context of technological applications improve existing techniques or lead to the development of new techniques that can then be incorporated into scientific models. Likewise, advances in using adaptive-computation techniques in modeling lead to new ideas for applications. Finally, in order to use any of these techniques successfully, a theoretical understanding of them is of great importance.

3.1 Overview

Neural Networks

Neural networks are pattern-recognition and learning systems. A neural network consists of a number of nodes connected by weighted links. Typically, the nodes in the network are divided up into two or more layers, consisting of an input layer, possibly some internal "hidden" layers, and an output layer. The task of the network is to take an input instance, representing an instance of something the network is supposed to recognize or categorize, such as, say, a set of pixels representing an alphabetic letter in a character recognition task, and to assign a category to that instance (e.g., "the letter A"), or sometimes to determine an action to be performed in response to that instance. The recognition process consists of presenting an activation pattern representing an input instance to the input layer, and allowing this activation to spread throughout the network over the links as a function of the weights of the links. The answer category or action winds up being displayed as an activation pattern on the output nodes. As the network is given more and more input patterns, it gradually improves its performance as a result of a learning algorithm that adjusts the weights on the various links in response to categorization errors the network has made. There are many different learning algorithms used in neural networks. The most common one is known as *back-propagation* (Rumelhart et al., 1986). In a back-propagation network, after each network categorization cycle, the network's output is compared to the correct output value (e.g., what the input letter actually *was*) and an error value is computed. Each weight from the hidden layer to the output layer is corrected according to how much it contributed to the error, and the error is then propagated back to earlier layers, whose weights are similarly corrected. After a number of such cycles, the network is "trained," and can hopefully perform well on the given classification task.

Genetic Algorithms

Genetic algorithms (GAs) are computational search methods inspired by ideas from biological evolution (Holland, 1975; Goldberg, 1989). A GA solves a problem by searching a space for highly fit "chromosomes" representing potential "solutions" to the problem (e.g., numerical values for a numerical optimization problem, potential tours for a Traveling Salesman Problem, or, as will be discussed in the following proposals, mating strategies for ecological agents or bidding strategies for economic agents). Chromosomes are usually represented by bit strings (or strings over some larger alphabet), with individual bits representing genes. In the simplest form of the GA, an initial population of chromosomes (bit strings) is generated randomly, and each chromosome receives a numerical "fitness" value—often via an external "fitness function"—which is then used to make multiple copies of higher-fitness chromosomes and eliminate lower-fitness chromosomes. Genetic operators such as mutation (flipping individual bits in a chromosome) and crossover (exchanging substrings of two parent chromosomes to obtain two offspring) are then applied probabilistically to the population to produce a new population (or generation) of individuals. This process is repeated until some criterion is met (e.g., the optimum solution has been found, or a "good enough" solution has been found, or a maximum number of generations has gone by, etc.). The GA is usually considered to be successful if a population of highly fit chromosomes evolves as a result of iterating this procedure. When the GA is being used in the context of function optimization, success is usually measured by the discovery of chromosomes that represent values yielding an optimum (or near optimum) of the given function. In some other contexts, the GA is viewed as being successful if the entire population evolves a collective solution.

Classifier Systems

Classifier systems, like neural networks, are learning systems. A classifier system is composed of a large number of simple agents called *classifiers*. The system has an input interface and an output interface. Into the input interface come "messages" about the current state of the environment and the system's relation to it. The job of the classifiers is to classify messages—that is, to decide what to do in response to them. Classifiers sometimes send messages to other classifiers, and sometimes perform some action on the environment. Environmental actions sometimes result in rewards from the environment. Classifiers that produce beneficial messages for the system (that is, ones that contribute to reward-producing actions) tend to get stronger (via a credit-assignment procedure known as the "bucket brigade" algorithm) and, thus, are more likely to win competitions with other classifiers (such competitions are probabilistically decided on the basis of strength). The genetic algorithm can be applied to classifier systems to effect a kind of natural selection among classifiers in which weak classifiers die out and in which strong classifiers thrive and, via reproduction (involving recombination with other strong classifiers), pass their "genes" on to offspring classifiers. The combination of the credit-assignment mechanism and the genetic algorithm should in principle allow the system to adapt (via reapportionment of strength, deletion of unhelpful classifiers, and creation of new classifiers) to the environment it faces.

3.2 Program Activities

The program, which existed informally at SFI for several years, was officially launched in Spring, 1992 with a Founding Workshop. Under the leadership of resident director Melanie Mitchell, during 1993 the program included long-term projects carried out by resident scientists, short-term visitors, short-term meetings and working groups, and the participation in all these activities by graduate students and undergraduate interns.

Modeling Adaptive Systems

As part of the AC work, researchers are developing a suite of general and specific computational modeling platforms that will allow researchers and applications-oriented developers to accelerate the production of usable simulations and models of a variety of complex systems.

(1) Tierra
K. Thearling (MIT), T. Ray (U. Delaware/ATR Laboratories, Japan)

Begun as an attempt to simulate biological evolution in a simple, machine-code form, this work quickly demonstrated the potential for programming via evolution. Using biological insights to construct instructions, Tierra evolved surprisingly "flexible" machine language code that can evolve to more efficient forms, as well as develop internal "ecologies" of organisms, parasites, hyperparasites, and cooperative species—all using the simplest mechanisms of random mutation and natural selection.

Kurt Thearling and Ray continue to work on a parallel and multicellular version of the Tierra artificial life simulator. This collaboration brings them together in Japan for six months at ATR Laboratories starting in November 1993. The goal of this work is to bring about a type of Cambrian explosion in the simulation allowing multicellular artificial lifeforms to evolve.

Future work in Tierra will introduce additional mechanisms such as genetic crossovers to further investigate the optimization potential for evolving code.

(2) The ECHO Model
J. Holland (U. Michigan), S. Forrest (U. New Mexico), T. Jones (SFI/U. New Mexico) and J. Brown (U. New Mexico)

John Holland's ECHO model is a simulated ecology. It permits the study of populations of evolving, reproducing agents distributed over a geography, with different inputs of renewable resources at various sites and with the capability of resource acquisition and transformation by the agents in the course of their interactions with each other and the environment. These capabilities allow study of a rich set of phenomena including mimicry, interactions conditioned on identification, economic phenomena such as trading, and even emergent hierarchical structures. These systems facilitate explorations of mechanisms that generate phenomena associated with complex adaptive systems. ECHO models can incorporate as special cases a wide range of well-established models—from economics, biology, and political science—that capture relevant abstractions of critical problems in these disciplines.

In 1992 Terry Jones, a Ph.D. student now at the University of New Mexico, began a two-year residency at SFI working closely with Stephanie Forrest and John Holland developing a UNIX version of the ECHO model. Jones' dissertation also concerns ECHO. Jones is working on one of the first real applications of ECHO in conjunction with James Brown (U. New Mexico). Brown has approximately 25 years of data from ecologies that have been perturbed by the selective removal of species. ECHO is particularly well suited for simulations of this kind, and Jones reports ECHO runs that exhibit characteristics of natural ecosystems.

(3) Artificial Economies

Based on the methods described here and other related techniques, a variety of agent-based computational models of economic systems, including specific trading systems, are being developed to explore the evolution and coevolution of economic structures under changing circumstances. These include an artificial stock market composed of many different agents with evolving trading strategies; use of artificial adaptive agents to model the formation of economic markets; and a model of technological innovation. See "Innovative Tools" (Section 5) for detailed information.

(4) Swarm
D. Hiebeler (MIT), H. Gutowitz (Ecole Supérieure de Physique et Chemie, Paris), C. Langton (LANL/SFI)

The development of the general-purpose simulation environment of Swarm is described in the Integrative Core Research section.

Nearly three dozen simulation projects at SFI and elsewhere have been identified as possible beneficiaries of the Swarm programming framework. At the Institute these include work in cultural evolution and algorithmic chemistry, several artificial economy applications, and research in artificial life.

SFI's development of the Swarm system has been fundamentally modular. This entails developing both general-purpose modules that will be called by special-purpose experiments and the development of special experimental subsystems. Effort on the project has so far been divided between developing general-purpose modules and work on simple examples of special-purpose experiments. There is a natural interplay between these efforts. The development of the special experimental modules has greatly illuminated the characteristics needed for the general-purpose modules. To date two working simulations—heat-bugs and traffic—have been implemented into Swarm, largely due to the 1992–1993 work of David Hiebeler, a programmer from Thinking Machines Corporation who was in residence through August, 1993. In July 1993 undergraduate intern Nelson Minar implemented Walter Fontana's lambda-calculus studies using Swarm, and contributed significantly to the Swarm system itself. Additionally, Howard Gutowitz, a collaborator from Paris, spent two months of the summer of 1993 implementing economic models (particularly information contagion) under Swarm.

The Swarm system will be placed in the public domain sometime in 1994, along with full documentation and a library of analysis tools and predefined experimental scenarios for defining and working with models of social insects, economies, ecologies, chemical systems, and evolving populations.

(5) A Population Genetics Model
A. Bergman (Interval Research), M. Feldman (Stanford)

The evolution of learning capabilities in organisms is one of the more perplexing issues in evolutionary biology. While the simplest organisms have information encoded in DNA, for higher organisms extra-genetic means of storing and transmitting information become important. The objective of Feldman and Bergman's work on a population genetics model is to determine what it is about the structure of the environment and the structure of the organism that make it advantageous to expend resources in storage and transfer of information by nongenetic methods. This work pertains to natural as well as artificial organisms and uses analytical and numerical studies of the dynamics of population under different environmental conditions. (For relevant background information, see Ewens, 1979; Gillespie, 1973; Harley, 1981; Harley & Maynard Smith, 1983; Houston & Sumida, 1987; Karlin & Liberman, 1974, 1975; Levins, 1968; Maynard Smith, 1982; and Stephens, 1991.)

For their current work Feldman and Bergman define 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. Individual behavior strategies that use conditional probabilities for future environments and information about past environments are studied. The environments are random and Markovian. The individual uses the information available to it to prepare for the next environmental state in order to increase its fitness. The fitness depends on the discrepancy between the realized environment and that for which the individual is prepared. Additive and multiplicative combinations of the fitnesses accruing to the individual at each environmental epoch are studied. A semi-optimal strategy is found, which maximizes individual fitness given the depth of information about the environment available to the individual. Randomly varying fitnesses and error in individual's perception of environmental parameters may be included in the model.

This work by Bergman—an alumnus of the Complex Systems Summer School, former SFI Graduate Fellow, and frequent Visiting Fellow at SFI—is supported in part by Interval Research Corporation as a member of the Institute's Business Network (see Section 5.7).

(6) Measurements of Computer Models
M. Bedau (Reed), M. Mitchell (SFI), N. Packard (Prediction Company, Santa Fe)

Mark Bedau, a philosopher of science, will visit SFI in 1994 to work on qualitative measures of adaptation in computer models of evolutionary systems. Bedau, with colleague Norman Packard, has been working on developing measures of global, emergent properties such as "rate of adaptation" in a particular model (the "Bugs" model). He will continue working on these measures, and will extend their use to other models, in effect developing dimensions along with different models that can be usefully compared. One possible goal is to organize a workshop on this topic, inviting people working on various models (e.g., Bugs, ECHO, and Tierra).

Next year Mitchell also plans to form a working group to consider the possible measures of complexity in real and artificial systems. There has been much work on different ways to measure complexity, and much question about what the various measures are good for in science. There are additional questions about complexity as its relates to biology or economics, such as whether complexity increases in evolution? If so, what are the mechanisms for the increase? The group will consider these and other issues.

(7) Auditory Display
G. Kramer (Clarity Research and SFI)

Late in 1992 ICAD '92, the First International Conference on Auditory Display, took place at SFI. Plans are currently underway for another ICAD, to be convened in November 1994.

The ability to hear many sounds at once, and to hear one sound change in many ways simultaneously, may help scientists present complex information from high-dimensional systems. To date, computer interfaces have focused almost exclusively on vision as the information conduit. Researchers within the audification project are extending this conduit with new uses of sound.

The major topics of ICAD '92 were sonification, audification, and auditory displays. Simply put, sonification is "data-controlled sound." It is the auditory equivalent of data visualization, the technique of "looking at data" to help analysts comprehend everything from weather information to financial or medical data. Audification is rendering audible such data as seismograms, radio telescope information, mechanical simulations, or equation-generated waveforms. Auditory displays are the sound aspect of general computer user interfaces, such as the icons and menu bars found in most computer software.

Participants described work on using sound to discern seismic events, such as earthquakes; diagnosing supercomputer software; looking for trends in financial data; designing computer interfaces and chemistry lab equipment for vision-impaired persons; monitoring patients under anesthesia; understanding chaotic systems; reviewing census data; and using sound in virtual reality as well as other application areas. There was discussion of the pattern recognition capabilities of the human auditory system, long ignored (with the notable exception of sonar) in information presentation. The proceedings of ICAD '92 will be published by Addison-Wesley in March 1994 as part of SFI's Studies in the Sciences of Complexity Series and will be the first volume dedicated to the field of auditory display.

In the meantime the Audification research network is working on the auditory representation of global dynamics in ECHO. Both the global nature of the variables and the relative frequency of agent interactions in ECHO present formidable problems for graphic display. Auditory display offers a possible solution. Kramer is focusing his initial efforts on developing a display that informs the system user of the status of nine distinct variables, specifically the volume of trading, mating, and combat intractions of three agent species.

Applications of Adaptive Computation Techniques

(1) Evolving Cellular Automata
J. Crutchfield (U.C. Berkeley), R. Das (Colorado State U.), J. Hanson (SFI), M. Mitchell (SFI)

Melanie Mitchell and Jim Crutchfield are heading a project on applying GAs to evolve desired behavior in cellular automata (CA). Cellular automata (CA) are spatially extended parallel computers whose architectures have many desirable features for a large class of parallel computations. In scientific modeling applications, for example, CA have been used to simulate a number of physical processes such as magnetic spin systems (Creutz, 1986; Vichniac, 1984), fluid dynamics (d'Humières et al., 1988; Frisch et al., 1986), chemical oscillations (Madore & Freedman, 1983; Oono & Kohmoto, 1985), crystal growth (Mackay, 1976; Packard, 1986), galaxy formation (Gerola & Seiden, 1978), stellar accretion disks (Scargle et al., 1993), dynamics in cytoskeletal lattices (Smith et al., 1984), and the formation of biological patterns (Campbell et al., 1986; Young, 1984). These simulations have been used as a new way of modeling natural systems. In many cases this computational approach is more appropriate—and has been more successful and efficient—than traditional modeling approaches such as partial differential equations. This wide range of modeling applications reflects the belief that CA can capture essential features of many physical systems in which large-scale behavior arises from the collective effect of large numbers of locally interacting components (Toffoli, 1984; Vichniac, 1988). In the realm of engineering applications, CA have been used to perform a wide range of image processing tasks (Meriaux, 1984; Preston & Duff, 1984; Rosefeld, 1983; Sternberg, 1980; Zamperoni, 1986), including applications in medical image processing (Preston, 1979). CA also could, in principle, be used in a number of other engineering applications in which spatial parallel computation is called for, such as parallel forecasting, spatio-temporal noise reduction, the discovery of coherent structures in data, texture detection, and so on. The massive parallelism and local connection architecture of CA, as well as their potential for resistance to error and noise (Gacs, 1985, 1986), means that hardware implementations have the potential to be extremely fast and reliable even when faced with noisy input data and component failure. CA and other classes of parallel, spatially extended automata with local interactions represent an area of computational science that is rich in potential applications but is as yet largely unexplored and is relatively lacking in theory.

There has been much work on CA in recent years and much new insight into the mechanisms by which complex behavior can arise from simple, locally interacting components (Farmer et al., 1984; Gutowitz, 1990; Toffoli & Margolus, 1987; Wolfram, 1986). However, little is known about how to harness this complex behavior to perform useful computations. This research is aimed at further developing a theory of computation in CA and using it to apply genetic algorithms to the problem of designing CA with desired computational behaviors. This work can be seen as part of a larger and longer-term research effort on understanding and harnessing the computational capability of dynamical systems.

Current work is focusing on providing experimental grounding for this project. It involves extensive simulation of evolutionary mechanisms on relatively simple computational goals with the aim of better understanding what guides and limits the emergence of desired computational ability in CA and related dynamical systems. Future work will focus on theoretical development including the development of a theory of (i) the evolutionary mechanisms studied initially, and (ii) the GA's performance as a function of the complexity of the desired CA behavior. This development will use tools from existing GA theory, statistical mechanics, and mathematical genetics. Ultimately, the project will consider applications to image processing, noise reduction, texture detection, and the automatic discovery of coherent structures in spatial pattern time series.

In September, 1993 James Hanson began a two-year postdoctoral fellowship at SFI. Hanson's expertise lies in the computational structure and qualitative dynamics of cellular automata. He is closely associated with this project.

This project has obvious practical applications, but it has also led to insights into the behavior of GAs—especially the mechanisms by which GAs can create individuals with increasingly complex behaviors. Mitchell and Crutchfield have been using frameworks from both statistical mechanics and from population genetics to understand the behavior of GAs on this task, and this work is very closely related to the "Foundations of GAs" project. Raja Das, a computer science graduate student at Colorado State (working with Darrell Whitley) and a student in the 1993 SFI Summer School, has been working on his own on related projects concerning evolving cellular automata. He also has worked on evolving neural networks with GAs and on the theory of GA deception. In January 1994 he will come to SFI to work with Crutchfield and Mitchell on the "Evolving CA" project (his work at SFI will be included in his dissertation at Colorado State), and also working with SFI's "Foundations of GAs" group.

(2) Protein Folding Prediction and Engineering
J. Bryngelson (NIH), Rob Farber (LANL), Alan Lapedes (LANL) and Evan Steeg (U. Toronto)

Collaborators at SFI are using novel, adaptive computation techniques for data analysis to address one of the most important unsolved problems of molecular biology and biophysics: the prediction of three-dimensional protein structure from amino acid sequences.

A protein is made up of a linear sequence of amino acids, but it is the protein's three-dimensional structure that primarily determines its function. This three-dimensional structure (i.e., how the protein "folds up" in space) is determined by the linear sequence of amino acids, but it is not currently known precisely *how* a given sequence leads to a given structure. A successful prediction method would not only be a tremendous advance in our understanding of the biochemical mechanisms of proteins, but, since such an algorithm could conceivably be used to *design* proteins to carry out specific functions, it would have a profound, far-reaching effect on biotechnology and the treatment of disease.

The existing massive amount of data on amino acid sequences surpasses unaided human capacity for analysis, and it completely overwhelms any current techniques of protein structure determination, such as x-ray crystallography, which is very time consuming and difficult. A main hope for making progress is the development of automatic methods of data analysis and prediction. There have been a number of attempts to address the protein structure problem using standard neural network techniques and other machine learning methods (DeLisi, 1988; Robson et al., 1978; Holley & Kaplus, 1989; Friedricks & Wolynes, 1989), but the results have been disappointing—the best algorithms to date have less than a 65% prediction accuracy rate, whereas much greater accuracy is needed for any real applications (Stolorz et al., 1992).

The Institute's approach is based on the belief that progress will most likely occur when the computational aspects are studied with, and related to, the physical, chemical, and biological aspects of the problem, and, therefore, several related projects, each employing novel adaptive computation methods, are ongoing.

The work by Rob Farber, Alan Lapedes, and Evan Steeg focuses on protein secondary structure classifications that are predictable from sequence. The precise definitions of the protein secondary structure classes alpha helix, beta strand, and a default class of random coil that are in widespread use today are due to Kabsch and Sander. Accurate prediction of these classes from primary sequence has long been an important unsolved problem of computational molecular biology, with ramifications for sequence alignment and calculation of tertiary structure. These collaborators have developed a computational technique utilizing coevolving adaptive networks that define new classes of protein secondary structure that are significantly more predictable from sequence than are the conventional classes. Interestingly, there is a nontrivial relationship between one of the new predictable classes and conventional alpha helixes.

In a related project Mitchell and Lapedes are collaborating with Jeffry Skolnick at Scripps Research Institute, graduate student Jeff Inman (SFI/St. John's College), and Bryngelson (NIH) to apply GAs to the "inverse folding" problem—the search for amino acid sequences that are likely to give rise to a desired protein structure. The usual forward folding problem is, "Given an amino acid sequence, predict the shape." The inverse problem is, "Given a shape, find a sequence that will fold to it." The group has been using recent development in potentials of mean force/contact potentials to attack this problem. The potential is a function of both shape and sequence. Fixing the shape leaves an optimization problem over sequence space. One wishes to optimize the energy gap between a candidate sequence threaded through a shape of interest and the energies of that sequence when threaded through members of a library of protein shapes. This will optimize stability. They are using genetic algorithms to perform the sequence optimization, and are testing results by comparing calculations to published stability results of mutations. The goal is ultimately to engineer complete sequences that will fold to a desired shape. Active collaboration with experimentalists is being sought.

(3) Learning and Adaptation in Robots and Situated Agents
N. Nilsson (Stanford), M. Mitchell (SFI)

In Spring 1993 SFI sponsored two working groups related to learning and adaptation in artificial systems. "Reinforcement Learning in Robotics: The Challenge of Scaling Up" was organized by Nils Nilsson and Melanie Mitchell. Reinforcement learning is an approach to machine learning in which learning agents act in an environment and are intermittently given reinforcements for certain actions. This approach has, in recent years, emerged as a central area in machine learning but it has not yet achieved success on large-scale learning problems, such as learning in real robots in a complex environment. This small working group brought together researchers to discuss what is necessary to "scale-up" reinforcement learning techniques to larger-scale problems. Progress was made on isolating some central issues, especially those related to credit assignment, and on means for addressing these issues. There was also discussion of what are appropriate problems for reinforcement learning.

"Learning and Adaptation in Robots and Situated Agents" brought together people currently working on "bottom up" approaches to learning and adaptation, especially in the context of robots and other artificial agents. These approaches include neural networks, classifier systems, subsumption architectures, behavior networks, "schemechanisms," and certain reinforcement learning techniques. Discussion focused on comparing the strengths and weaknesses of the different approaches and on how to develop new techniques. One workshop participant, graduate student Jonathan Mills (Indiana U.) will likely return to SFI to continue his work on adaptation in robotics. His work at Indiana University focuses on developing solar-powered, programmable, adaptive, autonomous robots, and his demonstration of his "Stiquito" robots at the meeting was impressive.

(4) Application of Lattice Gas Techniques to Biophysical Problems: Lattice Boltzman Simulations of Water and Macromolecules
S. Y. Chen (LANL), M. Dembo (LANL), T. Lookman (U. Western Ontario), and A. Lapedes (LANL)

These collaborators have extended the parallel lattice Boltzmann algorithm for hydrodynamics—this is a massively parallel algorithm related to cellular automata—to include the interaction of rigid bodies and water. They have successfully compared the calculation of spheres in a hydrodynamic flow to exact analytic calculations. In addition they have simulated a simple model of polymer in water consisting of rigid spheres connected by springs in a bath of Lattice Boltzman water. The goal is to extend the simulations to cytoskeleton, as well a lipid bilayers, membranes, and vesicles.

(5) Computer Virus Detection
S. Forrest (U. New Mexico) and A. Perelson (LANL)

Forrest and Perelson have recently developed a computer virus detection system based on immunological principles. The algorithm has several advantages over current detection methods: it is probabilistic and tunable (the probability of dectection can be traded off against CPU time); it can be distributed (providing high system-wide reliability at low individual cost); and it can detect novel viruses that have not previously been identified. In the next year they plan to extend this work to other data and security problems with the eventual goal of building an artificial immune system (say, for a workstation environment) which will learn each user's personal usage patterns and be able to distinguish between "self" and "foreign" activities.

Theoretical Foundations

(1) Foundations of Genetic Algorithms
L. Booker (Mitre Corp.), J. Crutchfield (U.C. Berkeley), M. Feldman (Stanford), S. Forrest (U. New Mexico), T. Jones (U .New Mexico/SFI), J. Holland (U. Michigan), M. Mitchell (SFI), R. Riolo (U. Michigan)

The development and application of adaptive algorithms cannot make true progress without the concurrent development of a theoretical understanding of these algorithms. Essential theoretical questions concerning these algorithms include the following: On what general types of problems is a given algorithm likely to succeed, and why? Can predictions be made about the expected performance of a given algorithm on a given problem? To what degree does the representation of the problem affect the performance of the algorithm?

Genetic algorithms (GAs) are simple but surprisingly effective search and optimization techniques on a variety of problems, and they are also now being used in a number of models of complex systems in various disciplines. Though the algorithm is simple to state and program, its behavior is often complex, and, in spite of its popularity and widespread use, there is still little understanding of precisely how the algorithm works and little knowledge of what characterizes the class of problems on which it is expected to perform well. Making progress on these issues is of central importance to the field of adaptive computation: understanding the GA better is both of intrinsic interest and also necessary in order to give some guide as to when and how it should be used in solving problems and in making models.

Forrest and Mitchell are conducting an in-depth study of GAs with the goal of answering three fundamental questions: (1) What makes a problem easy or hard for a GA—that is, how can one characterize the problems on which the GA works well and those on which it does not? (2) To what extent does the GA scale well—that is, to what extent will the GA continue to perform well as the complexity of the problem increases? And (3) What does it mean for a GA to perform well—that is, what are appropriate ways of measuring the algorithm's performance?

They have addressed these questions by studying in detail the GA's performance on a set of hand-constructed "fitness landscapes" containing various configurations of features that are particularly relevant to the GA. Initial simulation work on this project yielded some unexpected, counterintuitive results about the way the GA processes "building blocks" or schemas. In 1993 Forrest and Mitchell, in collaboration with SFI associates Terry Jones, John Holland, Lashon Booker, and Rick Riolo, continued their work to gain a better understanding of the causes of these results and to apply similar simulations to more complex landscapes. Forrest and Mitchell are also working with University of New Mexico graduate student Tim Preston on using GA's to study simple models of the evolution of recombination. The goal is to learn more about the class of environments in which a capacity for recombination will be selected by an evolutionary process and how the evolutionary viability of recombination in related to its ability to improve fitness in a population.

The existing theory of GAs does, in fact, provide one framework for understanding the process by which GAs search a fitness landscape and by which they achieve "efficient adaptation"—i.e., high fitness in a relatively short time. Yet this framework—given in terms of schemas, implicit parallelism, and recombination of schemas— is by no means a complete theory of GA behavior. There are many versions of the GA, yet a complete theory for the simplest GA is still lacking. A number of outstanding issues remain. These include reaching a better characterization of the effects of crossover on a fixed or changing fitness landscape; identifying what are the appropriate features to use in characterizing fitness landscapes; and exploring in depth the relationships between GA theory and population genetics and statistical mechanics.

Ongoing residential work will address these questions in 1994, and, as mentioned above, graduate student Raja Das will join the on-site work in January. In addition Mitchell plans to schedule at least two working group periods to bring together researchers from the GA, population genetics, and physics/statistical mechanics communities (L. Booker, F. Christiansen, J. Crutchfield, M. Feldman, S. Forrest, T. Jones, R. Palmer, and R. Riolo) to work on selected problems.

(2) Foundations of Supervised Machine Learning
D. Wolpert (SFI)

SFI Postdoctoral Fellow David Wolpert is exploring the general theoretical foundations of supervised learning systems, or systems that learn from examples. Such systems are at present the most widely investigated and used learning methods in the machine-learning community. The class of supervised learning systems can be described as follows: One is given a "training set" of input values along with the corresponding (though perhaps noise-corrupted) output values, and from this finite set must infer the entire input-output mapping. Familiar examples of such problems include visual letter recognition, where the input-output mapping is from a set of visual patterns to the 26 letters of the alphabet; speech recognition, where the mapping is between sonic waveforms and a lexicon of words; and the sequence-to-protein-structure problem described previously. Typically, one wants a supervised learning system not merely to learn a mapping which reproduces the training data, but rather to learn a mapping that permits accurate generalization to new situations. Some of the better known examples of such systems are various neural net systems, classification algorithms such as ID3 (Quinlan, 1986), memory-based reasoners (Stanfill & Waltz, 1986), local linear surface-fitting algorithms, and some forms of Holland's classifier systems (Holland et al., 1986).

Neural networks and other supervised learning systems are now being widely used in a large number of applications. However, there is currently no general theoretical framework for understanding and predicting the behavior of such systems that is both formal and rigorous and is also of real use to practitioners in the field. There are a number of formal approaches to supervised learning, such as Valiant's PAC framework (Valiant, 1984), Bayesian analysis (e.g., Cheeseman, 1986; Smith & Erickson, 1989; Good, 1959), and the "statistical mechanics" school (e.g., Tishby, 1989; Sompolinsky & Tishby, 1990; Schwartz et al., 1990) but, as yet, these formalisms have had quite limited practical value for researchers designing and applying new learning methods. On the other hand, there are many practical heuristics that are well known in the supervised-learning community—for example, very general Occam's-razor heuristics (which state that, given two mappings induced from the same training set, the simpler mapping is likely to generalize more accurately) or more specific heuristics which suggest ways to avoid over-training—but as yet such heuristics have no rigorous theoretical foundation.

Wolpert's work at SFI is directed towards developing a rigorous and useful framework for supervised learning systems. In 1993 he worked on a number of projects, many of which will be carried into 1994. In 1994 his work will be supported by TXN, Inc., a member of the SFI Business Network. TXN is particularly interested in Wolpert's work on the foundations of pattern extraction techniques or "data mining." This past year Wolpert finished a paper with Bruce Maclennan analyzing neural nets consisting of an uncountable number of neurons which evolve continuously in time (rather than via discrete "updates"). In contrast to conventional neural nets, the neurons in the systems they analyzed were purely linear functions of their inputs. The primary result of the paper is demonstrating the computational universality of these systems.

Wolpert also updated previous work with Alan Lapedes on the machine learning theory known as "exhaustive learning" and completed work with Alan Lapedes, Bette Korber, and Rob Farber on estimating and analyzing mutual information between sites in the V3 loop of the HIV virus.

Finally, Wolpert completed a paper reconciling Bayesian and non-Bayesian statistics and presented it at MaxEnt93. He also finished two papers with David Wolf on Bayesian procedures for estimating functionals of probability distributions from a finite set of samples of those distributions. Adopting the Bayesian perspective on neural net training, he has also derived a correction term to conventional back-propagation with weight decay. These results will be presented at NIPS93. In related work, he collaborated with Charles Strauss and David Wolf analyzing the "evidence approximation" in Bayesian analysis, in particular in the context of image reconstruction with an entropic prior and in the context of regression with neural nets. Several papers resulted from this and one more is forthcoming.

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4. ORGANIZATION AND BEHAVIOR IN COMPLEX BIOLOGICAL/ENVIRONMENTAL SYSTEMS

Biological systems are the most challenging examples of complex systems, having been shaped by evolution over long periods of time. Consequently they reflect evolutionary "accidents" frozen in place, redundancies, and both elegant and obsolete structures to carry out their functions. As noted in the previous section, SFI is deeply involved in devising computational systems capable of processes of adaptation and evolution similar to that seen in biology. In an equal effort the tools of adaptive computation are being applied to some fundamental and important problems in biology.

These applications offer a way to grapple with a growing flood of data emerging about biology at the molecular level. The understanding of biology gained from research at the molecular level has revolutionized life sciences over the past 40 years. Yet this wealth of detailed knowledge still does not fully explain how organisms, or major systems, actually function. More and more, the critical problems in biology are becoming problems of how to understand the representation and communication of information in living systems.

Work in this area at SFI follows approaches similar to those taken in modeling and understanding other nonlinear systems. The major difference is that biology requires even more overlapping models because of its convoluted evolutionary path. SFI encourages the use of many different methodologies to look at the same thing in alternate ways, then synthesize results back into models of the whole. In doing so it encourages much-needed intradiscipinary collaboration between theorists and experimentalists.

The Institute's interests and work in biology include common features in information-generating systems; learning and memory, especially commonalities among systems (immune, brain, olfactory); computer modeling of protein and RNA folding; interaction of genes and genome evolution, including gene interaction in morphogenesis, and repetitive sequences in genes; evolution of genomes and organisms on fitness landscapes, folding and functions of RNA, maturation of the immune system, population genetics, and the origin of life; and multigenic determination of disease.

4.1 Computational Approaches to Genetic Data

(1) Discovering Structure/Function Attributes from Covarying Mutations
R. Farber (LANL), B. Korber (LANL/SFI), A. Lapedes (LANL), G. Stormo (U. Colorado), D. Wolpert (SFI)

The V3 loop of the Human Immunodeficiency Virus Type-1 (HIV-1) envelope protein is a highly variable region that is both functionally and immunologically important. This group has used an information-theoretic quantity called mutual information, a measure of covariation, to quantify dependence between mutations in the loop using available amino acid sequences from the V3 region. Certain pairs of sites, including noncontiguous sites along the sequence, do not have independent mutations, but display considerable, statistically significant, covarying mutations as measured by mutual information. For the pairs of sites with the highest mutual information, specific amino acids have been identified that are highly predictive of amino acids in the linked site. The observed interdependence between variable sites may have implications for structural or functional relationships; separate experimental evidence indicates functional linkage between some of the pairs of sites with high mutual information.

A natural hypothesis for why certain pairs of positions (that are perhaps distant along the sequence) can display covarying mutations is that they are proximate in three-dimensional space. The group is testing this hypothesis by a careful statistical analysis of variable protein families for which there are many available sequences and for whom the structure is known. Examples are the globins and serine proteases. Interestingly, the analysis is complicated by phylogenetic effects which pose difficult computational problems.

(2) DNA Sequence Data and Pediatric AIDS

A. Amman (Pediatric AIDS Foundation), I. Chen (UCLA), A. Gifford (SFI), D. Ho (Aaron Diamond AIDS Inst.), B. Korber (LANL/SFI), A. Lapedes (LANL), J. Mullins (Stanford), G. Myers (LANL), B. Walker (Massachusetts General Hospital), S. Wolinsky (Northwestern)

The Pediatric AIDS foundation has initiated a multilaboratory project, ARIEL, that brings together the expertise of several of the top AIDS laboratories in the country. The goal is to explore many aspects of mother-infant transmission of HIV-1, the virus that causes AIDS. Bette Korber from the Theoretical Biology and Biophysics Group at Los Alamos National Laboratory is at SFI on a half-time basis to work on this project.

Not all pregnant HIV-1 infected women transmit the virus to their offspring; epidemiological studies indicate that there is a transmission rate of 15–30%. Many elements of this transmission are still a mystery. Why does transmission occur in some, but not all, women? When transmission occurs, is it predominantly happening early during pregnancy, across the placenta, or is it happening during birth? Does the mother's immune system play a role in preventing transmission? Do viruses that are transmitted to babies have common characteristics? Understanding the answers to these questions may give insight into methods that could help reduce the risk of transmission. (For background, see Allain et al., 1991; Fenyo et al., 1992; Fontelos et al., 1991; Hague et al., 1991; Halsey et al., 1992; Johnson et al., 1991; Kreiss et al., 1991; Nei & Gojobori, 1986; Parekh et al., 1991; Rossi et al., 1989, 1990; Wike et al., 1993; and Wolinsky et al., 1992.)

An important aspect of this study is the richness of information available about each of the mother-infant pairs. Complete clinical histories are obtained for every mother entered in the study. The project has a goal of entering 120 mothers, and to date 40 mothers have enrolled in the study, and 16 babies have been born. Surprisingly, all 16 babies are HIV-1 negative; detailed experimental work will begin when there is a set of HIV-1 positive babies to compare with the negative babies. Blood samples are being taken from mother-infant pairs, and virus is currently being isolated from the mothers' samples. The effectiveness of the mother's immune response against the virus obtained from her own blood samples, as well as virus isolated from her baby, will be assessed. The viral load in the mothers is estimated, and the biological properties of the viral isolates will be characterized. Because HIV-1 is highly variable, and varies even within a person, the evolution of the virus in the mothers will be studied throughout gestation, and will also be followed in infected infants after birth, by sequencing viral DNA obtained directly from blood samples.

The studies described above will be conducted in different laboratories, each lab with different expertise (immunology, viral biology, viral sequencing, etc.). All of the laboratories will be working together, using the same samples, and so will be able to interpret their own results in the context of the larger study. All of the data will be brought together at the Santa Fe Institute, along with patient profiles describing the health status of mother-infant pairs. The group will look for meaningful patterns in the DNA sequence data, and correlations between the disparate kinds of data sets. The ultimate aim is to use these results in designing an effective means of intervention.

Work so far has been to create an on-computer database of all clinically related information for the enrolled mother-infant pairs, and initial experimental results are being entered. Korber has designed a system with the capability of linking biological information to genetic sequence data sets. She and collaborators have been developing analysis methodologies for finding patterns in variable sequences that will eventually be applied to the ARIEL HIV-1 data. Also, they have created the first summary report of the data available, and have incorporated the suggestions of colleagues made at a board of scientists meeting in New York in early October 1993, and are automating its production. These reports will be provided to colleagues on a quarterly basis.

A previous study on HIV-1 protein sequence variation (see above) has yielded interesting results concerning covariation of amino acids located in specific sites along HIV-1 envelope protein sequences, the result of an SFI nurtured collaboration between Alan Lapedes (physics), David Wolpert (statistics), Rob Farber (programming), and Korber (biology). As the data sets from the study begin to fill out in 1994, interactions with other members of the SFI community should result in extracting the meaning from the complex data that is becoming available.

(3) Analysis of DNA Sequences Using Machine Reconstruction
J. Crutchfield (U.C. Berkeley), J. Hanson (SFI), C. Macken (LANL)

These collaborators are working on the analysis of DNA sequences. Their approach uses finite machine reconstruction, the theory for which has been developed by Hansen, and Crutchfield et al., and is a use of functions of Markov models to model the structure of sequence data. In particular, they are using machine reconstruction to discern the hierarchical structure that is postulated to exist in DNA sequences. This approach is novel in that it is aimed at describing patterns of unknown function in sequence data. To date, DNA sequence analysis has focused primarily on recognition of known features, such as splice sites, promoters, and genes (Bowie et al., 1991; Goldstein et al., 1992; Levitt, 1976; Levitt & Warshel, 1975; Lüthy et al., 1992; Paine & Scheraga, 1985; Skolnick & Kolinski, 1989). While they, too, are attempting to recognize patterns of known function, they are most interested in developing approaches for analyzing the long stretches of anonymous DNA that experimentalists will be sequencing in the future. They are working closely with experimentalists in the Life Sciences Division of Los Alamos National Laboratory, for help in interpreting patterns found in the DNA sequence.

(4) Protein Structure Prediction from Energy Function
Joseph D. Bryngelson (NIH)

Methods for predicting protein substructure typically seek structures that minimize some approximate energy function, given that this energy is a function of the three-dimensional structure of the protein. Most efforts in tertiary structure prediction have gone into creating approximate energy functions and especially into discovering algorithms for minimizing these functions. Bryngelson has been addressing a complementary issue: when is an energy function sufficiently accurate for protein structure prediction?

The major result of this investigation is that the probability of predicting the correct structure is given by

$$\text{probability} = 1 - k((N^{1/2}\eta)/B)$$

where B is the scale of the monomer-monomer interaction energies, η is the scale of the inaccuracy of the these interaction energies, N is the number of monomers, and k is a constant of order one. This equation implies that, if a potential function is to predict the correct structure, the monomer-monomer interactions energies must have proportional error of less than $1/N^{1/2}$. For a globular protein N will typically be between 50 and 400, so the required accuracy in monomer-monomer interactions is about five to fifteen percent.

It is important to note that this result is the accuracy required for getting all of the monomer-monomer contacts right—that is, predicting the entire contact map with perfect accuracy, a stringent requirement for a potential function. Proteins with 60 or more percent of correct contacts are usually considered to be structurally homologous. Therefore, the protein calculation should be extended to calculate the probability of predicting a structure with a specified fraction of correct contacts, and this will require that the formalism and the model be improved so that it can be used to calculate the probability of predicting one of many, rather than just one, low-energy state.

(5) Computational Approaches to Macromolecular Structure Prediction
P. Stolorz (Caltech)

Biological macromolecules share several distinctive features with heterogeneous physical systems such as spin glasses (e.g., the presence of quenched disorder) that are suspected of contributing very strongly to their structural and folding characteristics. However, little progress has been made at analyzing in a precise way models incorporating these features. In particular, analytical approaches are notoriously difficult. SFI Postdoctoral Fellow Stolorz, now at California Institute of Technology but in residence at SFI through Spring, 1993 instead approached these questions using computational methods.

Stolorz developed a set of novel enumeration procedures based upon a recursive transfer matrix approach, which are able to describe the low-energy states of lattice heteropolymer models. This allows the low-temperature regime of these models to be very carefully explored, resulting in calculations which have not until now been possible. The methods have much in common with the study of self-avoiding walks and related models of homopolymers.

Using essentially the same methods, Stolorz also was able to measure the Parisi order-parameter function for spin glasses in three dimensions, together with the susceptibility, at zero temperature on small lattices, with no equilibration problems at all. The basic method can also be used to investigate the low-energy configurations of RNA secondary structures. This is an advance over previous approaches since it enables one to compute observables of interest at a series of arbitrary temperatures without requiring that the entire calculation be redone each time.

(6) RNA Secondary Structure
W. Fontana (SFI), P. Schuster (U. Vienna, Institute for Molecular Biotechnology, Jena), P. Stadler (U. Vienna)

These collaborators are concerned with the simplest genotype-phenotype relation that is realized in nature: RNA. Complementary base pairing provides a replication mechanism by templating and, at the same time, causes a single-stranded RNA to fold back on itself into a structure. They see the folding of polynucleotide sequences as a map that assigns to each sequence a minimum free-energy pattern of base pairings, known as secondary structure (hereafter referred to as "shape"). Considering only the free energy leads to an energy landscape over the sequence space. Taking into account structure generates a less visualizable nonscalar "landscape," where a sequence space is mapped into a space of discrete shapes. The shape affects replication and degradation rates, recognition processes involving proteins, and catalytic activity. The evolutionary dynamics of viral and structural RNA, therefore, depends highly on the properties of the map that assigns to each sequence a structure (Fontana et al., 1991, 1992a, 1992b, 1992c).

In 1993 Fontana, Schuster, and Stadler continued to work on a statistical characterization of RNA secondary structure, on the correlation properties of the landscapes mentioned above, on the distributions of energy and structure distances with respect to distance in sequence space, and on the reverse folding problem.

For fixed chain length the number of secondary structures is much smaller than the number of sequences. This raises the question about the distribution of structures over the space of sequences. The collaborators have provided an answer with respect to a standard folding algorithm for minimum free energy structures by studying its statistical features. The frequency distribution of structures follows a generalized Zipf law. It is shown, by application of a heuristic inverse folding algorithm, that sequences folding into the same structure are distributed randomly in sequence space. They have defined a distance measure on the set of structures and investigated the distribution of structure distances as a function of sequence distance. Combining both results leads to the conclusion that all common structures can be accessed from any random sequence by a small number of mutations compared to the sequence length. For RNA sequences of length 100 a neighborhood with a diameter of about 18 mutations is sufficient. The sequence space is percolated by extensive neutral networks which connect nearest neighbor sequences folding into identical structures. Implications for evolutionary adaptation and for applied molecular evolution are evident: finding a particular structure by mutation and selection is simpler than expected, and even if catalytic activity should turn out to be sparse in the space of RNA structures, it can hardly be missed by evolutionary processes.

(7) Applications

The goal of the 1994 conference "Designing Active Biological Sequences" to be co-chaired by Alan Lapedes is to stimulate communication between researchers engaged in simultaneous efforts on DNA, RNA, and protein sequences; and to foster further advances by bringing together experimentalists and theorists in an interdisciplinary, interactive conference. There have been significant advances in the past years in experimental approaches for producing active biological sequences. These approaches include: applied molecular evolution experiments; sequence selection according to desired properties from complete, random sequence libraries; genetically engineered modifications of wild-type sequences; and complete, *de novo* design and construction of sequences. The sequences of interest range from DNA to RNA to proteins. There have been concurrent advances in theory, including: theory of evolution on "fitness landscapes"; knowledge-based contact potentials for the "inverse protein folding problem" (designing an amino acid sequence to fold to a desired shape); and recent advances in understanding how the immune system recognizes and reacts to antigens. A number of these ideas and approaches form the basis of nascent biotechnology companies. It appears that a synergistic combination of biotechnology and computational biology has the potential to increase understanding of basic biological processes, and to provide novel approaches to production of active biological sequences including vaccines, therapeutics, and catalysts.

Alan Lapedes (LANL), Gerry Myers (LANL), and Alan Perelson (LANL) have formed an interdisciplinary working group focusing on topics in molecular medicine. The group had an initial meeting in October which covered topics including the biology of the V3 loop and available data sets; work on HIV and immune system modeling and its relation to the development of vaccines; review of common analysis methods like mutual information and neural nets; and a general discussion of potential therapies. The group is generating a major funding proposal to support future work on this project.

4.2 Complexity, Learning, and Memory in the Immune System

The mammalian immune system is a classic example of a complex adaptive system—a distributed collection of specialized cells that self-organizes to perform highly complex, predictable tasks. Its size is comparable to the brain, and it is capable of highly sophisticated pattern recognition. Although the individual components live only for days, the system itself has a "memory" that persists for decades.

The goal of SFI's work in immunology is to use ideas and methods from the newly developing field of complex systems research, including adaptive computation, computer simulation, modeling and nonlinear dynamical analysis, to solve significant problems in immunology. A long-term goal of this program is to develop a better theoretical understanding of the rules or algorithms that govern the operation of the immune system. This year the program has sponsored a number of diverse activities involving two resident postdoctoral fellows, graduate students, an undergraduate student, and numerous visitors.

(1) Somatic Hypermutation and Maturation of the Immune Response
T. Kepler (North Carolina State U.), A. Perelson (LANL)

Postdoctoral fellow Thomas B. Kepler and research program director Alan Perelson developed a new model for affinity maturation. During the course of a humoral immune response the affinity of antibodies for the immunizing antigen increase 10 to 100 fold. At the level of single antibody-secreting clones, this increase has been shown to be due to an extremely rapid process of somatic mutation in which nucleotides in antibody variable region genes are replaced at a frequency of 10^{-3} to 10^{-4} per base pair per generation. Kepler and Perelson showed that in order to optimize the affinity of the antibodies produced by the end of the immune response, the mutation process needs to be controlled, with mutation being turned on in bursts, and then followed by a selection process (Kepler & Perelson, 1993c). They showed how the architecture of a germinal center might implement such a phasic mutation schedule (Kepler & Perelson, 1993a).

Perelson and Kepler are exploring the relationship between stochastic and deterministic models of somatic mutation, with the particular goal of finding approximations that allow one to solve optimization problems. This work may have broad application to problems in biotechnology where one hopes to optimize the design of new molecules through mutation.

(2) Can Immune Networks Generate Immune Responses?
R. DeBoer (U. Utrecht), A. Perelson (LANL), R. Rose (SFI/St. John's College)

Undergraduate Intern Randall Rose and Alan Perelson have been using large-scale simulation models of immune networks to examine the role of immune networks in protective immune responses. By incorporating growing pathogens into a previously developed network model (De Boer & Perelson, 1991), they were able to show that the antibody secreted by network activity (sometimes called natural antibody) was able to protect against slow and intermediately growing pathogens (Rose & Perelson, 1993). However, fast growing pathogens could escape the protection provided by network activity. Thus, networks might be part of a primitive defense mechanism. For organisms to survive rapidly growing pathogens more specific immune responses would be needed.

Rose and Perelson are continuing to study, via simulation models, the ability of immune networks to respond to various challenges. They hope through their modeling to gain further insight into the physiological roles of immune networks.

(3) Modeling B-Cell Proliferation and Differentiation
R. DeBoer (U. Utrecht), A. Neumann (SFI/Weizmann Inst.), A. Perelson (LANL), B. Sulzer (LANL)

Postdoctoral fellow Avidan Neumann and visiting student Bernhard Sulzer have generalized the AB model (antibody B-cell model) by De Boer and Perelson (De Boer & Perelson, 1991; De Boer, Perelson, & Kevrekidis, 1993a,b). This model, which follows the birth, death, and growth of B-cell clones and the concentration of antibody they secrete, has been used as the basis of immune network modeling for the last four years. Neumann and Sulzer showed that including the differentiation of B cells from lymphocyte to plasma cell state increased the realism of the model and provided an explanation for the experimentally observed bell-shaped dose response in many immunological phenomena (Sulzer et al., 1993).

Neumann and Perelson have begun and plan to continue exploring the role of T-cell help in immune network models. Previous models of immune networks have neglected T cells. Preliminary work by Neumann has shown that including T cells can prevent global excitation of networks (percolation). This is a desirable and stabilizing feature.

(4) Evolution of Antibody-Variable Genes
S. Forrest (U. New Mexico), R. Hightower (U. New Mexico), A. Perelson (LANL)

Graduate student Ron Hightower, Stephanie Forrest (U. New Mexico), and Alan Perelson have shown, using genetic algorithms, how information about the pathogenic environment can influence the composition of antibody-variable gene libraries. This has been a perplexing question in immunology, since each individual's genome contains gene fragments that get rearranged to assemble intact antibody molecules. Any particular antibody may or may not be made, and thus even if one's genome contained the information to construct a protective antibody that molecule may not be present at the time it is needed. Further, since each gene segment by itself has no protective value and may be useful only when correctly combined with other segments, it has not been clear how selection could operate. The simulations performed now give the first insights into this evolutionary process (Hightower, Forrest and Perelson, in preparation).

Forrest and Perelson plan to continue exploring the cognitive abilities of the immune system, pattern recognition and learning, so as to elucidate fundamental algorithms. They also plan to continue to explore aspects of the evolution of the immune system.

(5) Memory Capacity of Immune Networks
M. Oprea (LANL), A. Perelson (LANL), G. Weisbuch (Ecole Normale Supérieure, Paris)

It has been suggested that immune networks can carry memory of previous antigen encounters. SFI external faculty member Gérard Weisbuch and graduate student Mihaela Oprea used both analytical estimation procedures and simulation models to determine how many antigens an immune network of size *n* could remember. They showed that "stupid networks" had a memory capacity that scaled as the square root of *n*, but that, if immune responses were correctly controlled, the capacity of a "thrifty network" could approach being proportional to *n* (Weisbuch & Oprea, 1993).

A workshop, Immune Memory: Experiments, Interpretations and Models, held September 19–21, 1993, was organized by Alan Perelson, Avidan Neumann (SFI), and Polly Matzinger (NIH). The workshop brought together experimentalists and theorists interested in immune memory. The most important outcome of the workshop was the decision to form a permanent group, which will work together to design, carry out, and analyze a set of experiments. Furthermore, all six of the laboratories represented at the meeting agreed to collaborate and work on a single immunological system, at least part time. This in itself is somewhat of a breakthrough since up to now immunological laboratories have tended to each specialize on different topics. Further, an attempt is being made for all of the labs to obtain quantitative information (De Boer & Perelson, 1991).

4.3 Evolution of Structures in Neurobiology

This program started at SFI in 1992 with a six-week working group led by Charles Stevens of Salk Institute to create an environment in which theorists and experimentalists could work together. The group was motivated by three things: theory is necessary in neurobiology; theory must relate closely to experiments; and no existing theory has materially changed our understanding of the brain. Yet the fact that theories that make use of general principles are starting to be successful in accounting for common experimental observations indicates a developing maturity in neurobiological theory. A common theme identified by participants as important for theory in the future is the representation of information by the brain, and there was a concentration among the theorists on exploring what is known about visual neurobiology. Many saw techniques for acquiring and handling, in parallel, data from neurons as crucial for the development of neurobiology.

This group reconvened in 1993, led by Michael Stryker (U.C. San Francisco) and Nancy Kopell (Boston University) to continue work on vision and introduce an additional focus on how the central nervous system comes to be organized so that it is both flexible and robust. This theme touches on questions at many different levels of organization and time scale, from rapid signals among neurons to neural development. Questions range from how properties at the cellular level affect emergent network behavior to how learning within a network can be accomplished in a stable manner. One theme of general interest was interactions between neural networks governing motor control and the biomedical environments in which they operate. Another was the role of oscillators in the motor control networks, as well as some sensory processing.

A number of collaborations have resulted from the workshops. For example, L. Abbott (Brandeis) and S. Lockery (U. Oregon) began a collaboration involving the properties of the C. *elegans* neurons. They plan to study how information is encoded in the distributed processing representation found in the leech bending interneurons. They are going to try to reconstruct the location of the sensory input from the pattern of interneuron or motor neuron activations that it produces and their known variances using a method Abbott has developed for looking at cortical representations.

G. Laurent (Caltech) and Kopell have started an ongoing collaboration focused on the insect olfactory networks, which exhibit coherent oscillations; the aim is to understand both the mechanisms of the oscillations and their computational relevance. H. Chiel (Case Western Reserve) has begun a discussion with Kopell and G. B. Enmentrout (U. Pittsburgh) about dynamical systems analysis of small networks to approach questions related to the ability of organisms to respond in a stable, yet flexible manner.

Finally, P. Heilbrun (U. Utah) has found that the concepts used by the other participants related to motor behavior can be applied to analysis of abnormal motor behavior in Parkinson's Disease. There were relevant discussions on transitions from stability to flexibility in motor activity at multiple time scales, stereotypic motor activity at different phases of development, and the role of oscillator coordination in modeling motor behavior. These discussions have led to speculation by Heilbrun on the origin of the deficits seen in Parkinson's and their relation to dynamical mechanisms. A further outcome may be a workshop that brings together medical professionals and dynamical systems experts to discuss this issue.

In addition to the work above, this year saw a new research initiative in which researchers are looking at brain development and memory organization within a complex systems perspective. One aim is to establish whether recent discoveries of cortical malleability warrant a new look at learning and rehabilitation of human infants and adults.

In May George Cowan (SFI) and Bela Julesz (Rutgers) co-chaired a workshop that brought together participants from a variety of fields and research centers to seek new evidence of brain plasticity. Discussions covered the development of the cerebral cortex; cortical topographic organization and reorganization; activity-dependent processes; memory consolidation; behavioral plasticity; development of higher functions; and rehabilitation.

Participants considered new evidence of brain development and sensory processing, among which are evidence of dynamic reshaping of the somatosensory and visual cortex; textual learning and Hebbian chain formation in early vision; the role of sleep in memory consolidation; and constraints on plasticity of higher functions. The emerging new principles should help us better understand the mechanism of learning and memory and the dynamics of nervous system disorders. The general principles of strengthened intracortical interactions via a cascade of local connections and the filling in of weak gaps by strong, surrounding activity unifies the various topics. Equally important, these principles suggest new techniques in rehabilitation, such as enhancing certain circuits and diminishing others.

Proceedings volume from the workshop should be available in 1994. The book promises to be unique because it joins basic research with the work of rehabilitation, presenting experimental work from researchers from sensory, visual, and auditory fields using all accessible techniques in anatomy, physiology, psychophysics, behavioral methods, linguistics, and modeling.

4.4 Underlying Structures in Seemingly Random Data

Time series analysis problems are central to a wide range of disciplines including physics, biology, and economics (Babloyantz et al., 1985; Babloyantz & Destexhe, 1986; Basar, 1990; Dvorak et al., 1986; Glass et al., 1993; Roschke & Basar, 1985). SFI is pioneering the use of novel computational approaches to extract predictable information from what appear to be random sequences.

In the arena of biology, James Theiler (SFI) and collaborators Doyne Farmer (Prediction Company), Dante Chialvo (SFI/U. Arizona), Andre Longtin (U. Ottowa), and graduate fellow Brandt Hinrichs (Beckman Inst., U. Illinois) are currently investigating allegations that the electroencephalogram (EEG) is chaotic and, in general, are exploring the use of nonlinear time series methods in the characterization of the dynamical behavior of the nervous system (Hunter & Theiler, 1992; Longtin, 1992; Theiler et al., 1992a, 1992b). The aim of this work is to discover if there is any underlying deterministic structure that may lie hidden in apparently random neural phenomena. Postdoctoral Fellow Milan Palus is also working on this issue, supported by a separate NIH award. Although the group has seen that unambiguous evidence for nonlinearity has been found in some EEG time series, in no case have they found good evidence for chaos in either normal EEG or in epileptic EEG, despite widespread claims to that effect.

While the evidence for nonlinearity is relatively unambiguous, the issue of chaos is still unresolved. By looking at a spectrum of statistics, including one that compares forward to backward prediction, they are addressing this issue in the context of their EEG time series. The group has recently acquired some EEG data taken not from the scalp, but directly from the brain's surface, and they are now analyzing these sets for evidence of nonlinearity. Because these are also multivariate time series, they will be able to use recently developed tools for generating multivariate surrogate data as part of the tests.

The collaborators are also compiling a software library for nonlinear time series analysis. The package—called **Ts/tools**—will soon be released to the public domain (parts of it are already available). Currently the package includes routines for dimension estimation, nonlinear forecasting, surrogate data generation, recurrence plots, and a host of general-purpose tools such as Fourier transforms and convenient random number generators.

4.5 Artificial Life

C. Langton (LANL/SFI)

The emerging field of Artificial Life, pioneered at SFI, is the most obvious example of the deep connection between the Institute's work in adaptive computation and biological sciences. With the leadership of Christopher Langton over the past several years, research at SFI has virtually single-handedly created this new field, one that promises broad insights for our understanding of traditional biological systems, but also holds tantalizing technological implications.

Artificial Life ("AL" or "Alife") studies "natural" life by attempting to recreate biological phenomena from first principles within computers and other "artificial" media. Alife complements the analytic approach of traditional biology with a synthetic approach in which, rather than studying biological phenomena by taking apart living organisms to see how they work, researchers attempt to put together systems that behave like living organisms. Artificial life amounts to the practice of "synthetic biology," and, by analogy with synthetic chemistry, the attempt to synthesize biological phenomena in alternative media should result not only in a better theoretical understanding of the phenomena under study, but also in practical applications of biological principles that will be of use for industry and technology. By extending the horizons of empirical research in biology beyond the territory currently circumscribed by naturally occurring life—life-as-we-know-it—the study of Artificial Life provides access to the domain of possible life—life-as-it-could-be—and it is only within this vastly larger domain that a firm foundation can be established for a general body of biological theory.

The Santa Fe Institute has been primarily responsible for the birth and development of the field of Artificial Life. An initial workshop in 1987, co-sponsored by the Santa Fe Institute and the Center for Nonlinear Studies at LANL, has been followed up by two successive international conferences run by SFI, one in 1990 and another in 1992. These pioneering efforts of the Institute have given rise to several parallel conference series in Artificial Life worldwide. The next Artificial Life conference in the SFI series—Alife IV—will be held at MIT in July 1994. In Europe, two European Conferences on Artificial Life have been held in the last three years, one in Paris in 1990 and another in Brussels in 1993, with a third planned for 1995 in Granada, Spain. Japan has initiated it own series of Artificial Life conferences this year, and will host and co-sponsor the fifth in the SFI series—Alife V—in Kyoto in 1996. Japan is aggressively pursuing the practical applications of this new field; in late 1993 the ATR Labs in Kansai, Japan, hosted a major conference on this topic. From the large attendance at these conferences, from the enthusiasm of the participants, and from the quality of the research, it is clear that the field of Artificial Life has taken hold in the worldwide scientific community as a legitimate field of scientific and engineering research.

"Integrative Core Research" and "Adaptive Computation" in this report describes SFI's 1993 work on the Swarm system, a general-purpose simulation system being designed to underlie Artificial Life studies (as well as having a number of other potential applications). During the next year, development of Swarm will continue. SFI will hold a workshop in mid-1994 to which it will invite other groups, both academic and industrial, who are working on similar modeling technologies, to explore the establishment of an accepted set of standards for Swarm-like simulation systems. Langton and his colleagues have already identified approximately 40 research efforts involving this class of computational architecture, all in various stages of design or completion, and all apparently being carried out essentially independently from one another with much duplication of effort. The hope is that by working towards a set of standards for distributed simulation systems, a collaborative effort on a common system, with each group contributing its own area of expertise (graphics, networking, parallel processing, etc.) is encouraged.

Meanwhile the Swarm system will be applied to several different categories of Artificial Life research. First, SFI will continue study of the structure of the evolutionary record, seeking fundamental understanding of such evolutionary features as intermittent periods of slow and chaotic evolutionary development (sometimes referred to as "punctuated equilibria"), the nature and scaling of extinction events, the onset and maintenance of speciation, the origin and maintenance of sex, stability to external perturbations (à la asteroid impacts), and adaptive radiations and explosions of diversity (à la "Cambrian Explosion"). Second, Swarm will be used to explore the conditions for, and the adaptive advantages of, social organization, via a large-scale simulation of social insects. Understanding the workings of a colony of social insects will significantly advance understanding of social organization in general, as well as provide insights into the basis for higher intelligence. This research will include experiments devoted to studying the origin and maintenance of new hierarchical levels of biological organization—such as the emergence of multicellularity. Third, studies will continue on the conditions for complex behavior in distributed systems and on the relationship between complexity and computational capacity, as observed in cellular automata and other distributed dynamical systems. Swarm will play a significant role in these studies as well.

Several relatively small, highly focused workshops are planned. These will concentrate on the application of Artificial Life techniques to specific open problems in the theory and practice of biology. The first of these workshops, Computational Approaches to Evolution and Population Biology, organized by Christopher Langton and Charles Taylor (UCLA), will be held at the SFI in February 1994. It will bring together a small number (about 20) of the world's experts in this area, both biologists and computational modelers. Participating biologists include John Maynard Smith, Richard Lewontin, Peter Schuster, Marcus Feldman, and others of their stature. Computer modelers include Daniel Hillis, John Holland, Thomas Ray, and Stephanie Forrest. The purpose of this first workshop—and indeed this series of workshops—is to bring together the people having the best theoretical grasp on outstanding problems with the people in possession of the most promising new computational techniques for addressing those problems. The aim is to initiate a number of specific collaborations between the world's leading biologists and computer modelers, each aimed at making significant progress on an outstanding problem in the biological sciences. Topics for future meetings include: Computational Approaches to Growth, Development, and Differentiation; Computational Approaches to the Origin of Life; Computational Approaches to Ecological Dynamics and Community Structure; Advances in Artificially Directed Molecular Evolution; and Computational Approaches to Ethology—the Study of Behavior in Natural and Artificial Organisms.

The Institute will continue to act as repository and dissemination site for Alife information. The first issue of *Artificial Life* , a new quarterly scientific journal edited by Christopher Langton, will appear in early 1994. It will be augmented by an interactive electronic journal—ALIFE—which will serve as an interactive news-server allowing real-time, concurrent discussion, information exchange, and debate on Alife topics; as a pre- and re-print archiver and server; as an on-line bibliographic data base; and as an archive service for uploading and downloading software and data to enhance and encourage collaborative and repeatable research.

A newly created Society for the Study of Artificial Life will take over the direct management of large workshops, in collaboration with the local institutions hosting them. (SFI will continue to co-sponsor and be actively involved in these conferences, and Christopher Langton will serve on their program committees.) The next such workshop—Alife IV—will be held at MIT in early July, 1994—co-sponsored by the SFI, the MIT Artificial Intelligence and Robotics Labs, and the MIT Media Lab. Alife V will be held in Kyoto, Japan, in 1996, co-organized by several Japanese Artificial Life societies, and co-sponsored by the SFI and several Japanese corporations (including ATR near Kyoto, who will host the workshop at their facility).

The proceedings of the Artificial Life workshops are available in the SFI series: *Artificial Life*, edited by Christopher G. Langton, *Artificial Life II*, edited by Christopher G. Langton et al., and *Artificial Life III*, edited by Christopher G. Langton (the latter volume will be available in February 1994).

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5. INNOVATIVE TOOLS AND MODELS FOR THE STUDY OF COMPLEX, REAL-WORLD SYSTEMS

Although the Institute's primary focus is on advancing the sciences of complexity, at the same time the methods developed for simulating complex systems, learning and adaptation, and evolution are relevant to many kinds of application-specific simulations. Particular examples in the computational and biological sciences are described above. Beyond these fields the methods and modeling platforms being developed at SFI promise important applications to the study of other "messy" real-world phenomena; these range from patterns of traffic flow, natural disasters, economic markets, adaptation in organizations, to exploration of long-term issues of human sustainability with regard to resource use and renewal. A number of corporations within the national business community have already recognized the potential of these practical applications. More than a year ago SFI inaugurated its Business Network for Complex Systems Research as an mechanism for companies to affiliate with SFI and to help support its research, and some BusNet efforts are described at the end of this section. The specific applications below grow directly out of SFI's basic research.

5.1 Systems Engineering Based on Self-Organization

Many large, manmade systems have a distributed nature and are thus difficult, or even impossible, to control using centralized controllers. But new concepts and tools drawn from work on artificial life, intelligent agents, and object-oriented software are making possible a new systems engineering. Approaches based on simulation-based representation of many interacting objects, analysis of emergent behavior among the objects, and the exploitation of local and emergent global phenomena to control large systems are becoming possible due to these advances. Moreover, many, if not all, large manmade systems involve human interpretation and cognitive intervention. Representation of these activities pose special challenges to advanced systems engineering.

Steen Rasmussen (LANL) and his colleagues are currently applying simulation tools to two different systems engineering problems, carrying on work done at SFI by Rasmussen as a visiting fellow. The first is a transportation system analysis problem, and the second is a global communication system designed to support a satellite surveillance system composed of hundreds of satellites. The transportation system is an example of a distributed system of locally interacting, intelligent objects with a range of complex emergent dynamics. The satellite system is an example of a distributed system of locally interacting, simple objects where control and part of the intelligence are emergent, global system properties.

(1) TRansportation ANalysis and SIMulation System, TRANSIMS
K. Nagel (U. Cologne) and Steen Rasmussen (LANL/SFI)

This advanced transportation analysis system consists of functional prototypes of inter- and multimodal route planning and high-resolution vehicle representations in simulation that attempt to execute those route plans. At one end is specified the interface of the prototypes to travel demand models and at the other end the interface of the prototypes to high-resolution atmospheric pollution models. Rasmussen and Nagel are currently focusing on: (1) a bottom-up representation of simple and complex vehicles and drivers in the complex end, including the abductive processes undertaken by the drivers; (2) analysis of emergent traffic phenomena such as congestion, atmospheric effects, and accidents; (3) the kind of information that defines the state of a traffic system; and (4) the impact of different implementations of intelligent vehicle highway systems. For example, under which conditions, and in which form, can local and/or global traffic information enhance the trip density, safety, and air quality? Simulation results are continually compared with real-world data.

In the future these collaborators want to simulate whole road networks and they plan to simulate individual routing decisions on these networks. In this context, traffic may be seen as a market: the infrastructure provides capacity supply, the customers have a transportation demand, and the result is a market with noncooperative agents.

(2) Global Satellite Swarm Communication
C. Barret (LANL) and S. Rasmussen (LANL)

The satellite communication and surveillance system is a global system based on a "swarm" of simple, inexpensive, locally communicating satellites (250–500 of them). The global system is able to

(1) propagate a message from anywhere to anywhere else in the constellation or on the globe; and (2) propagate a message from anywhere to survey an area somewhere else on the globe and continuously send information about this area to yet another location (e.g., weather data, tracks). The dynamics of the system are largely governed by the probability of rebroadcasting a message, which depends on the current position together with the origin and the destination of the message. Barret and Rasmussen are currently focusing on (1) the basic communication design of each satellite and (2) how the emergent dynamics (e.g., message path(s), message capacity, message speed) depend on the local communication rules.

5.2 Nonequilibrium Economics and Learning in Knowledge-Based Markets

The economics research program at SFI is building an adaptive, complex, evolutionary viewpoint into the central body of economic theory. This effort, now six years old, was inspired by a challenge by Citicorp Chairman John Reed to consider an alternative approach to economics, one that might provide better understanding of the world financial market. Reed was reflecting the practitioner's view that, while academic economics had made progress in quantifying the science and developing rigorously mathematical theories of economic behavior, it had done so with the requirement for simplifications that seemed to increasingly diverge from the real world. The long-term objective of the Institute's program is to more fully articulate its new viewpoint—and to provide methods, theories, frameworks, and solutions that will help catalyze a change.

In 1993 residential director Blake LeBaron (U. Wisconsin) moved many of the new SFI techniques and strategies out of the testbed and began to apply them to explain real-world economic facts. In tandem with theoretical work, under LeBaron's direction the program this past year has looked at things like technical trading patterns in financial markets and the dynamics of trading volume from the SFI perspective. The economics work has been integrated with other empirical programs at the Institute, especially research in low-dimensional chaos. This encourages information transfer about methods that can be equally useful for a stock-price time series as well as, for example, observations coming from brain wave data. (In 1991, in fact, SFI External Faculty members Doyne Farmer and Norman Packard founded the Santa Fe-based Prediction Company, which makes a business of applying time series analysis tools to financial market prediction.)

As noted previously, LeBaron, along with Brian Arthur (Stanford U.), John Holland (U. Michigan), Richard Palmer (Duke U.), and Paul Tayler (Coopers & Lybrand Deloitte), have developed an artificial stock market model. This simulation provides an environment for studying the behavior of a collection of artificially intelligent agents trying to forecast the future of a traded asset that pays a varying dividend. The agents develop trading rules (based on a variety of market data) by which they determine when to buy, sell, or hold the asset. The aim is to understand what phenomena result from the interactions of different learning algorithms working in a simple stock market trading environment. This model is being used to generate a simulated time series that will be compared to actual time series to see what kinds of real-world phenomena are replicated in this computer-generated market.

The Artificial Economy Project—coordinated by David Lane (U. Minnesota)—takes an engineering approach to the problem of how the economy coordinates itself as a coherent whole, with large-scale structure. The model includes five types of agents within a closed system. One firm manufacturers machinery, which is, in turn, purchased and used by a second firm to produce a consumer product. Both firms employ individuals who use their paychecks to purchase the consumer product. The first firm employs researchers to design new machinery. A bank accepts savings from the workers and the firms and provides loans. The gross domestic product (GDP) can be computed at any time on the basis of all the interactions. The individuals interact within the institutions in the market for machinery, consumer goods, and labor. The simulation looks for global regularities and addresses whether it is possible to describe conditions under which an economy will produce particular manifestations of coordination or stability at the macrolevel that last much longer than the micro agents making decisions. First attempts to implement the model were not successful because the prototype was over-designed and agent behavior was too restricted. The researchers have now switched to an object-oriented version using the Swarm platform.

Some traders of financial assets claim that certain simple rules can be used to help forecast future prices, although this claim has long been disputed. Another current SFI project is shedding light on this debate. Buz Brock (U. Wisconsin), Josef Lakonishok, and Blake LeBaron have used new statistical tests to show that certain simple technical trading rules do find statistically significant patterns in both stock prices and foreign exchange rates. The SFI trio used a simple moving average and trading range types of rules as specification tests for several different stochastic processes of stock returns. But while the trading rules behaved as technical traders would have predicted, none of the tested processes were able to replicate the unusually large returns during buy periods and small returns during sell periods that were found in the original series. Nor did the study adjust for transactions costs and risks. This remains an important empirical component that still needs to be explained.

Human experiments on auctions find that subjects make systematic bidding errors that cannot be explained by standard bidding models. James Andreoni (U. Wisconsin) and John Miller (Carnegie-Mellon) are considering these errors using a model of adaptive learning based on a genetic algorithm. They are finding that artificial adaptive agents exhibit many of the same bidding patterns as those observed in auctions with humans. Andreoni and Miller think that adaptive learning may provide an explanation for the divergence between theoretical and experimental results in auction markets. Their findings suggest that adding adaptive benchmarks to experimental and theoretical results has broad potential for economic analysis in general.

Another puzzle for economic theory is explaining the observed instability of economic aggregates. A number of reasons exist for variation in the pace of production and consumption at the local level, but it is hard to see why there should be large variations in those factors that are synchronized across the entire economy. In an effort to understand this real-world phenomenon Per Bak (Brookhaven National Laboratory), K. Chen, José Scheinkman (U. Chicago), and Michael Woodford (U. Chicago) have constructed a simple model of a multisector, multistage production process. It illustrates that, in fact, small shocks do not "cancel out" in the aggregate. Conventional reasoning fails as a result of significantly nonlinear, strongly localized interactions between different parts of the economy. The type of macroscopic instability that can result has been studied in a variety of other contexts under the name of "self-organized criticality."

5.3 Prediction, Mitigation, and Reduction of Natural Hazards

It has been estimated that within 50 years, more than one-third of the world's population will live in seismically and volcanically active zones (ACIDNHR, 1987, 1989; Bryant, 1991; CEES, 1992) so it is becoming increasingly vital to explore ways to reduce and mitigate the occurrence of devastating natural hazards such as earthquakes, volcanic eruptions, floods, and landslides (Bilham, 1988). The International Council of Scientific Unions, together with UNESCO and the World Bank, have endorsed the 1990s as the Internal Decade of Natural Disaster Reduction and are planning a variety of programs to address problems related to the predictability and mitigation of these disasters, particularly in Third World countries.

New computational capabilities now make it practical to simulate many of these hazardous systems in the computer, thus allowing systematic study of these natural instabilities in a way not possible before. At the same time a variety of new tools of analysis have been developed in statistical mechanics and materials science, raising hopes that the precursors to these instabilities that can be identified.

In early 1994 SFI will host a workshop—chaired by John Rundle (U. Colorado), Don Turcotte (Cornell), and William Klein (Boston U.)—to assess the applicability of these new approaches. As it turns out, this meeting is timely, inasmuch as under the aegis of JUST, the Japanese-US Science and Technology cooperative agreement, a workshop on Applications of Remote Sensing Technology to Natural Disaster Reduction was held in Tsukuba, Japan, in late 1993. An emerging theme at this meeting was the extent to which prediction algorithms can be used together with remote sensing data to anticipate patterns associated with the onset of natural disasters (Hertz et al., 1991; Basdall & Eubank, 1992). The SFI organizers are optimistic that further systematic study of simulations using percolation maps, scaling analyses, and nonlinear prediction algorithms may yield tangible progress in predicting or mitigating real instabilities in nature. If the outcomes of the SFI conference are promising, it may be followed by a more formal, longer term SFI program.

5.4 Modeling Change in Human Organizations

The Institute's work on the evolution of human culture is moving beyond its initial focus on the prehistoric Southwest. Through this more comprehensive approach—which results from several working group meetings in 1993—SFI seeks progress in understanding the evolution of human cultural behavior from its earliest beginnings, some three million years ago, and into the next century. A founding workshop on the broader issues of quantitative approaches to cultural evolution—chaired by Marcus Feldman (Stanford) and Timothy Kohler (Washington State U.)—was held in Fall 1993. It marked the beginning a systematic, long-term program to investigate rule-based (and specifically agent-based) approaches to allow experimentation with relatively simple models of sociocultural change. This is a nearly open niche in terms of current intellectual competition for which the interdisciplinary strengths of SFI are well suited.

Previous approaches to modeling and simulating culture change have had limited success. Genuinely quantitative or formal attempts have been few and have been most frequently expressed as systems of differential equations applied to portions of larger cultural-ecological systems. These quantitative attempts have not generated strong explanations for the emergence of higher levels of political or economic coordination in extant or prehistoric societies; even less progress has been made towards isolating general principles that might be extended to all human cultures. Among the easily identifiable problems that have hindered modeling cultural systems include the representation of schema that could provide mechanisms for "cultural memory" and differential "planning depth"; the identification of the units of cultural inheritance; accounting for social learning and individual, trial-and-error learning; allowing for differential action according to social or kinship distance among agents; and providing a meaningful role for technological change and resource availability and use.

The specific purpose of the workshop was to consider the feasibility of applying agent-based methods to the problems of culture change; to consider how to narrow the research towards feasible goals; and to discuss productive strategies for designing and developing computational platforms for these investigations. A short-term outcome will be a proposal for support of the development of an agent-oriented simulation system useful for studying various problems in cultural transmission, human/environment interactions, and social change in small-scale societies.

Feldman brings particular expertise to this program. He and Stanford colleague L. Cavalli-Sforza, along with L. Zhivotovsky (Russian Academy of Sciences at Gubkin) have developed a "quantitative theory of cultural evolution," an approach to modeling the evolution of learned behaviors in cultures using mathematical applications. To examine the myriad ways nongenetic (i.e., learned) traits are transmitted within a culture, Feldman and his colleagues identify and sort them into behavioral components, or atoms. An atom can refer to a behavioral pattern of a particular group or to a specific trait of an individual's behavior. The pair studies these atoms to devise "sensible" ways of describing their rules of transmission among individuals. In a cultural setting, nongenetic atoms can be transmitted in numerous ways, such as between work associates, via nonparental influencers such as teachers or other appointed mentors, or through such vehicles as books and electronic media. The cultural evolution model can be applied also to quantify changes in learned behaviors and how variation of the changes and other conditions such as genetic predisposition can affect the evolution of a culture. They have applied their cultural evolution theory to an assortment of anthropological groups and situations ranging from a consideration of the "behavioral trait" of dairying to the evolution of sign language within a genetic minority, the deaf. Emphasis has been on using the model to determine how cultural and genetic traits are related and how the interrelationship affects evolution of both the traits as well as of the culture itself. (See Aoki & Feldman, 1991; Aoki & Feldman, 1993; Cavalli-Sforza & Feldman, 1973a, 1973b, 1981.)

Complementing this comprehensive approach is a specific project concerned with evolution and learning in modern organizations. Kenneth Arrow and Murray Gell-Mann co-chaired a founding workshop on this topic late in 1993. This meeting has captured the keen interest of the national business community, and participants will include representatives from Xerox, Perot Systems, TransAmerica, and McKinsey & Co. It has been noted that in the real world, high-technology firms do not operate according to the classical theory of the firm (echoing much of the SFI External Faculty member Brian Arthur's work on why knowledge-based companies respond to markets differently than resource-based companies). SFI will consider these modern innovative enterprises, which are examples of rapidly evolving complex adaptive systems and may be particularly amenable to study. Specific topics may include research into the relation of selection pressures to the evolution of an organization, particularly because selection pressures on individuals within firms can vary significantly from selection pressures on the firm itself; here there are obvious parallels with biological communities and ecologies. This work could shed light on understanding of why modern organizations seem to break so catastrophically. Other possible case studies may be evolution and learning in government bureaucracies; change in military organizations, which tend to be introspective because they conduct formal analyses of failures and successes; and perhaps the study of university organization. A segmented approach might be appropriate, one that will be specific to corporations and other organizations by class but that would then include cross-organizational aspects.

5.5 Climatic Change

On a related topic, SFI will hold a 1994 workshop on the interface between climatic and culture systems. "The Medieval Warm Period of the Ninth to Fifteenth Centuries: Large-Scale Interaction of Climate, Ecosystems, and Human Behavior in North America" will be chaired by Henry Diaz (NOAA), Malcolm Hughes, and Jeffrey Dean (both from U. Arizona). To probe the complex interactions among climate, the geosphere, biosphere, and culture, the meeting will focus in-depth on the climate of the Medieval Warm Period and its effects on the prehistoric environments and populations and North America. This particular case study has been chosen for several reasons: the Medieval Warm Period (MWP) was a time when global climate was markedly different from the present, with temperatures in the Northern Hemisphere averaging perhaps 1°C warmer than during the twentieth century. This period is of particular current interest because it comprises a range of climatic variability that may serve as a useful analog to future climate conditions forced by increases in atmospheric greenhouse gas concentrations. Not only are considerable paleoenvironmental, historical, and archaeological data available for this period, but the relationships between environment and culture are especially distinct in prehistoric Southwest societies.

One aim is to develop a spatial model of climate in North America from A.D. 850 to A.D. 1450 and to relate the results to contemporary climate. A characterization of MWP environmental variability should provide a basis for investigating climate-biosphere-culture interactions and for assessing the potential effects of global warming in North America. A second objective is to investigate the degree to which human cultural changes, as revealed by historical and archaeological evidence, can be linked to changes in the physical environment. In addition to looking at systematic interactions during the MWP, the meeting will also consider the impact of the environmental change immediately following this era that inaugurated the Little Ice Age. Focus on behavioral adaptations to both low-impact, infrequent environmental changes and rapid "regime transitions" should shed light on the interactions among complex adaptive systems deriving from a wide range of time scales. It also promises an empirical basis for evaluating the consequences of changes in our current climate in light of projected greenhouse-gas-induced change. (See Bradley & Jones, 1992; Briffa et al., 1992; Cook et al. 1991; Graumlich, 1993; Graybill & Shiyatov, 1992; Villaba et al., 1990; U.S. Department of Energy, 1989.)

5.6 Transition to Sustainability

Project 2050 is a collaborative effort involving SFI, the World Resources Institute, and the Brookings Institution to use modeling to develop scenarios that could illuminate conditions that could lead to a sustainable world over the next century. Unlike traditional scenario modeling, which is necessarily biased by the model-builders' assumptions, the SFI approach is bottom-up, relying on the computational agents in the nonlinear model to compete, learn, and coevolve in a changing environment.

Graduate Fellow Terry Jones and External Faculty member Stephanie Forrest are preparing to use the artificial world of ECHO as a modeling tool on this project. Among the applications they are considering for this platform are modeling the population levels of introduced species in Hawaii and modeling observed changes in desert ecology under experimental conditions (see Adaptive Computation). Jones is now looking at speciation in this model. Some of the questions he is asking are: When does speciation happen? How long does it take? With what frequency? Is geographical isolation required for speciation? How does the ECHO model relate to the real world in terms of speciation? Once speciation occurs, do the reproductive barriers between species persist—do the new species tend to diverge genetically, or do they hybridize? How does the mate recognition algorithm affect speciation? Do we see something akin to punctuated equilibrium? Is the model close enough to the real world that we should expect to see that sort of thing in the first place? Does phyletic evolution ever get us anywhere? Is there anything analogous to species sorting? Finally, is there a meaningful analogy in ECHO between economic and reproductive adaptations to that in the real world?

In another 2050 modeling project, Robert Axelrod is developing a simulation model to account for the emergence of new political actors. One of the main problems to attaining sustainability is the so-called tragedy of the commons. The tragedy of the commons arises when many independent actors (people, villages, states, or whatever) each "over graze" because there is no mechanism to enforce the collective interests of all against the private interests of each. This leads to resource depletion, elimination of biodiversity, overpopulation, war, and other major social problems. A major route to the prevention of this situation is the emergence of a political actor based upon the organization of previously independent actors. Today there are actors at the national level, but there are no very effective political actors at the transnational level to regulate resource use at the global level. Political scientists have a variety of theories to analyze the emergence of new political actors, but as yet they do not have any formal models that account for this emergence endogenously. Axelrod is developing a simulation model that takes as given the existence of lower-level actors and generates higher level actors from the interactions among them. His criteria for a new political actor are subordination of members of the group; collective action; and recognition by others of the group as an actor. A minimal goal is to provide an existence proof, that is, to show that a set of rules about individual choices, along with set of rules about the physical world, can lead in a natural way to a set of actors forming themselves into a group that meets the criteria for the emergence of a political actor at a higher. A maximal goal is to understand the condition under which new political actors not only emerge, but are able to solve joint problems such as common defense and sustainable growth.

Josh Epstein and Robert Axtell (both at Brookings and SFI) have developed Artificial Social Life (ASL), a simulation that may eventually give insight into a broad range of social issues. ASL simulates the interaction of adaptive agents that search for food and can mate, form groups, fight, trade, and transmit cultural attributes (e.g., tastes). Events unfold on an artificial resource topography—a sugarscape. Sugar can be eaten, stored indefinitely, and traded. Agents come into the world randomly distributed on the sugarscape with randomly distributed traits. Some of these (e.g., vision, metabolism, and sex) are "genetic," fixed for the agent's life. Others (e.g., tastes, or group membership) can change through social interaction and are interpreted as "cultural." In the simplest version there is only the behavioral rule: from all sites within your vision, find the nearest unoccupied site with maximum sugar, and then eat the sugar. The agent's stomach is then incremented by the value of that sugar and de-incremented by its particular metabolic rate. If the result is negative, the agent is dead and removed from play. Otherwise the cycle repeats itself. The asserted tendency of market systems to achieve equilibrium—a state in which supply equals demand—is being challenged by ASL.

In fact, the agents self-organize into a Pareto distribution. If individual preferences evolve endogenously, or if information is imperfect, or if space is explicitly represented, the system can maintain itself far from equilibrium indefinitely. Axtell and Epstein hope to soon provide a version of ASL with easy-to-use interfaces with which to study epidemics, economics, ecosystems, international relations, and civil violence.

5.7 Applications Within the SFI Business Network Community

Over the past year SFI's research has attracted considerable, and diverse, attention from businesses interested in transferring the scientific results into products and services. In June 1992 SFI organized its Business Network for Complex Systems Research. By November 1993 it had 13 member companies, each having contributed at least $25,000 per year in support of SFI research. Their interests are grouped roughly in two areas: computation, and economics/financial markets. Both of those areas make extensive use of novel simulation techniques developed and refined as part of SFI's research.

One of the long-term relationships has been with Maxis Software, which continues to pioneer the development of adaptive simulations with strong educational goals. This was seen early (and with increasing sophistication) in its approach to "Sim" programs (SimCity, SimEarth, SimAnt, SimLife). These Maxis software packages have developed a strong following not only in the consumer marketplace, but also in the schools. As the *New York Times* noted in an article on November 7, 1993, Maxis has provided students with simulations in which they can understand the trade-offs necessary in real decision making and planning. More recently Maxis has begun to develop specialized simulations for business purposes (SimRefinery, developed for Chevron, is a well-known example). In mid-1993 Maxis, in collaboration with the management consulting firm Coopers & Lybrand, began developing a telecommunications industry simulation (TeleSim) that draws directly on research at Santa Fe Institute on adaptation and learning in systems and organizations. At the same time Maxis is developing simulations that are aimed at the policy world, beginning with a simulation of health care policy that is, again, inspired by the simulation approaches at SFI.

In June 1993 the Advanced Research Projects Agency (ARPA) and the Naval Research Laboratory (NRL) joined the BusNet as a way to stay abreast of new simulation and computation research. The primary interest within NRL is in the work in artificial intelligence and machine learning, while ARPA is eager to expose many of its contractors and collaborators to novel approaches to simulation and computation. Similarly, the Electric Power Research Institute plans to take advantage of SFI work in simulation for its needs in understanding the dynamics of power systems and in developing new control systems for energy systems.

A small firm near Santa Fe, TXN Inc., is interested in research done by one of SFI's postdoctoral fellows, David Wolpert, in the area of machine learning. TXN intends to apply that work to extracting patterns from large biological and economic data bases.

One of the first companies to join SFI's Business Network was the newly formed Interval Research, an R&D firm exploring long-term potential applications of new approaches to computing and communications. One of the scientists there, Aviv Bergman, maintains an active role in SFI research as well, having been an SFI Summer School student several years ago. The company will probably increase its support for research in 1994 by funding a postdoctoral fellowship in computation.

Finally, an early Business Network member, John Deere, has been attracted by the virtually untapped potential of the application of complexity sciences to manufacturing. Additionally, SFI has inspired a loosely organized group of manufacturing engineers to pursue these approaches within their own companies, and several dozen of them have become eager audiences for SFI's increasing distribution of research results via the Internet.

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6. EDUCATION AND OUTREACH

Since its founding SFI has been committed to speeding the infusion of complexity science into traditional science practice, and to promoting understanding of the implications of this kind of interdisciplinary research. With a nationally known summer school, innovative undergraduate internships, a popular series of community talks, and a thriving postdoctoral program the Institute pursues this commitment on many fronts.

6.1 Education

Any discussion of SFI educational programs starts with the Complex Systems Summer School which has become a premier training experience for science students considering research careers in complexity science. The six-year-old program has now brought nearly four hundred graduate students and postdocs to Santa Fe and introduced them, in many cases for the first time, to different aspects of the sciences of complexity. Both lecturers and students return to SFI for research and form an international network advancing this new discipline. The School also serves as a comprehensive educational resource for Undergraduate and Graduate Fellows otherwise in residence at SFI. The Proceedings, which are published in book form within a year of each school, have spread the gospel much further, contributing to both the evolving definition and the direction of the field of complexity.

The original, and still primary, idea of the school (held every June) is to provide a concrete manifestation of the notion that a new science of Complex Systems has emerged. While many of the topics can be found individually in some university courses or other summer schools, there is no other school which tries to bring together such a varied assortment of problems, approaches, and subjects under a unifying idea. Each session gathers about 60 outstanding advanced graduate students (along with a few postdoctoral fellows and even some undergraduates) from a broad range of academic disciplines for a month of instruction by leading researchers from fields as diverse as neurobiology, nonlinear dynamics, and computation theory.

The School captures these students at a critical juncture of their careers and, consequently, often has a major impact on their intellectual lives. A zoology postdoctoral fellow from Duke, Lee Altenberg, described his Summer School experience this way: "I came away from it with the sense that I knew some of the basic underpinnings of neural networks, chaos, genetic algorithms, condensed matter...I hope to have two papers directly coming out of having been here, one on genetic algorithms and one on rugged landscape evolution. I may even have a job for this year from a connection I made in part through participation at SFI."

The School is a national effort, supported by a number of institutions, national labs, and funding agencies. Since the beginning the program has had strong support not only from SFI but also from CNLS at Los Alamos; the Universities of Arizona, Michigan, Illinois, Texas, and New Mexico; and Sandia National Laboratories. It has also had financial support from the University of California system, Brandeis, Stanford, Columbia, Yale, Princeton, and the Universities of Pennsylvania and Florida. NSF, DOE, NIMH, and ONR provide core funding.

An Organizing and Steering Committee representing the consortium of sponsors provides general guidance. Co-Directors for the School since 1991 have been Daniel Stein (U. Arizona) and Lynn Nadel (U. Arizona). By virtue of administrative experience with the School and because Santa Fe is a prime site for such a summer activity, the likelihood is great that the Complex Systems Summer School will continue to be run in Santa Fe by SFI. While at the School students are particularly encouraged to attend SFI seminars, workshops, and public lectures, and many do; every year some Summer School faculty are chosen from the SFI postdocs, External Faculty, or Science Board members; and certain sessions are set aside for the students to learn more about research activities at the SFI.

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 the Institute, 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.

If they are in residence at the right time, the Institute's various Graduate Fellows often attend parts of the Summer School. Along with SFI's weekly colloquia and seminars, it gives them insight into the broad basis of complexity research. In 1993 the Institute hosted the residencies of twelve graduate students. Their work is described elsewhere in this report. (All in all the Institute has hosted nearly three dozen such residencies in the past five years.) In most cases—like that of Terry Jones' work on

ECHO—Graduate Fellows are in residence on a long-term basis, often for at least a full academic year They divide their time between thesis preparation and related work on SFI projects, both conducted under the close direction of a senior mentor at the Institute. Although SFI is not a degree-granting institution, it can already point to three Ph.D. degrees for which the thesis research was done at SFI, and several more are in the works now.

The Summer School also provides a comprehensive introduction to complexity science for the Institute's undergraduate interns, most of whom are in residence at SFI during the summer months. This year SFI had six students on hand, supported in part by a grant from the National Science Foundation through its Research Experiences for Undergraduates Program. The Institute has a particularly strong investment in the success of this project which captures students at a very early point in their careers and is aimed especially at minorities and women—particularly from smaller colleges. As part of the program each student works with a faculty mentor on an individual project focusing on some aspect of the computational properties of complex systems. (The mentor also often incorporates Summer School attendance into the project.) This summer the research projects were varied and sophisticated: they ranged from an exploration of the effectiveness of spatial differentiation in the Fontana/Buss ALchemy model to the design of a method for comparing the technique of DNA signature analysis with more traditional phylogenetic tools in studies of the epidemiological linkage of HIV sequences. It is expected that several articles in the literature will result. SFI looks forward to hosting the same number of undergraduates in 1994.

SFI Postdoctoral Fellows Bette Korber, Mats Nordahl, Walter Fontana, and Cris Moore were among the mentors for this year's Undergraduate Intern program, just one reflection of the key role these young scientists play at the Institute. The Institute's Postdoctoral Program has been in place since 1988 and to date has involved 15 full-time appointments. In 1993 SFI was the home institution to 11 postdoctoral researchers. In addition to the individuals named above James Hanson, Bill Macready, Avidan Neumann, Milan Palus, James Theiler, Paul Stolorz, and David Wolpert worked at SFI. Six of these appointments are supported directly by Institute funds; five are supported by restricted monies.

The work of each of these fellows is describ ed in detail elsewhere in this document.

SFI's ability to train these young scientists extends its work as the fellows move into positions at other universities and research organizations. The Institute keeps in close touch with its six postdoctoral alumni, whose ongoing collaborations intermittently bring them back from Europe and throughout the United States to Santa Fe. Tom Kepler, now in the Biomathematics Department at North Carolina State University, continues to work with Alan Perelson on maturation of the immune response. Among other projects at SFI Wentian Li worked on long-range correlations of DNA sequences; now at Cold Spring Harbor Laboratory Li is spending time on computer simulation projects in Tom Marr's laboratory. Paul Stolorz moved on from SFI in April 1993 to a position at the Jet Propulsion Laboratory at the California Institute of Technology. John Miller, an Assistant Professor of Social and Decision Sciences at Carnegie-University, is an External Faculty member who is deeply involved in the Institute's adaptive computation and economics programs. The Institute's first Postdoctoral Fellow, Martin Casdagli, now conducts research in financial time series data at C. S. First Boston in New York. After three years in Santa Fe Mats Nordahl in September accepted a prestigious appointment in Theoretical Physics at Chalmers Technical Institute, Sweden. (But he was back at SFI within a month attending the Fontana/Lane workshop on artificial worlds.) Finally, in January, 1994, Walter Fontana will move from SFI to the University of Vienna. Fontana's work on RNA secondary structure and the structure of biological organization is deeply embedded in the Institute's current research agenda; it is likely he will return to SFI on a frequent basis.

In 1994 SFI anticipates eight postdoctoral fellows in residence at SFI.

6.2 Institutional Relations

Part of SFI's support for its growing postdoctoral program requires forging a strong web of institutional connections. In this way it begins to build a professional career network for the young scientists who have assumed the risks of working in a relatively new field. SFI sees itself as synergistic rather than competitive with the great research universities, and it strives to build strong connections with them, and with the national research laboratories, through its External Faculty connections, visiting fellows program, Complex Systems Summer School participation, and student residencies.

The relationship between SFI and the University of Michigan has established a highly successful precedent. Since 1991 nearly two dozen University of Michigan faculty have spent time in residence at SFI, joining collaborations with new colleagues from other institutions. There is an annual joint complex systems seminar at the University of Michigan campus at Ann Arbor every November.

While no other SFI university relationships approach Michigan in size, there are growing clusters of SFI-influenced research at the Universities of California (Berkeley), Chicago, Illinois, Minnesota, New Mexico, Pennsylvania, and Wisconsin; and at the California Institute of Technology, Stanford University, and Yale University. Internationally there are groups at the Weizmann Institute in Israel, at the University of Vienna, the Max Planck Institutes, and Chalmers University in Sweden. SFI can claim some parentage for the Complex Systems Centers at the University of Arizona and Duke University, and in May, 1993, the newly founded Krasnow Institute of Advanced Study held its founding workshop "The Mind, the Brain, and Complex Adaptive Systems" which featured presentations by several SFI associates.

Several of SFI's visiting scientists have introduced formal courses on complexity and complex adaptive systems at their home universities. These include Seth Lloyd and Murray Gell-Mann at the California Institute of Technology, Harry Swinney at University of Texas at Austin, John Miller at Carnegie-Mellon University, Peter Carruthers at the University of Arizona, David Lane at the University of Minnesota, and John Holland at the University of Michigan.

Two SFI-sponsored competitions—a computerized market and a time-series analysis problem—also have encouraged link-ups with academic and research communities at large. The Arizona Token Exchange—a computerized market in which a fictional commodity is traded—has been created by SFI and the University of Arizona's Economic Science Laboratory to compare the performance of human and program traders. Human players play against computer programs, and dollar earnings accumulate in individual accounts until time of cash out. In 1991 SFI researchers Neil Gershenfeld (Harvard) and Andreas Weigend (Xerox PARC) ran a time-series prediction and analysis competition to help compare various techniques in this field. A workshop last year studied the results of the competition. Although this competition is now formally over—in fact, a proceedings volume summarizing the results appeared this year—the experimental data remains available and is still frequently accessed.

As mentioned, SFI researchers are developing novel simulations and modeling applications in conjunction with several of the Institute's Business Network members. The Network was established in 1992 in response to the growing interest in SFI research by companies. BusNet members have the opportunity to meet with and explore problems of mutual interest with SFI associates. On the one hand, the Network gives corporations a chance to become part of the many ongoing research networks that are centered at SFI; on the other, researchers get a "reality check" on the technological concerns of cutting-edge ventures. To date the SFI Business Network has 13 members.

6.3 Publications

SFI makes a large investment each year (on the order of $200,000) to its publications program. To speed the impact of the Institute's work in complexity science, it has a strong investment in making sure the results are well known and easily available. At the end of the 1993 there are nearly 25 books in print as part of SFI's ongoing series published by Addison-Wesley. This year more than 10,000 volumes were sold, bringing the total sales figures for the series to more than 46,000 books. At least four more volumes are slated to appear in 1994.

This year SFI published more than 70 research papers as part of its Working Paper series, an annual number that has increased since the series began in 1991. More than 10,000 copies of various papers were distributed in 1993. This year the Institute also inaugurated publication of the *Research Update,* a newsletter distributed to SFI's research family on a monthly basis. It joins the more in-depth *SFI Bulletin* which comes out twice a year. The *Update* and *Bulletin* along with a growing number of working papers, are now available through the Santa Fe Institute Bulletin Board System (SFIBBS) which came on-line in March of this year. Finally, the premier issue of *Complexity: An International Journal of Complex Adaptive Systems* is slated to appear in September, 1994, published by John Wiley and Sons. The magazine's home offices will be at SFI. The journal will cover all aspects of the sciences of complexity from a readable, topical slant. Half of each issue will be devoted to tutorial papers, commentary pieces, news items, letters-to-the-editor, and book reviews, with the remainder of the issue consisting of relatively short technical communications. The target audience for *Complexity* consists of professional scientists and engineers, teachers and students in all branches of science, engineering, social science, and the humanities who are involved with complex systems. Although independent of SFI, the venture involves several members of the Institute's intellectual family. Harold Morowitz (George Mason) is Editor; John Casti (SFI) is Executive Editor. Associate Editors are Michele Boldrin (Northwestern), Peter Carruthers (U. Arizona), Marcus Feldman (Stanford), and Wojceich Zurek (LANL).

6.4 Community Outreach

Some of the Institute's programs provide a chance for nontechnical audiences to consider the implications and uses of these new approaches to understanding the behavior of complex systems.

Since 1990 the Institute has hosted monthly talks for the community on a wide range of topics within the sciences of complexity. Speakers have included John Archibald Wheeler, John Maynard Smith, Murray Gell-Mann, Oliver Sacks, and James Gleick. The talks are free, and draw audiences of anywhere from 200 to 700 people. In 1993 three local banks and a Santa Fe-based foundation joined the Institute in supporting this program, testament to the value of the series to the community. Speakers confirmed for 1994 are Leon Lederman, Walter Alvarez, John Holland, Brian Arthur, and Murray Gell-Mann. The SFI librarian catalogs and circulates videos of colloquia and public lectures to a nationwide network of SFI friends. This service is free of charge.

SFI has also extended the concepts of complex systems to local secondary schools in a 1992–93 pilot project to see how those ideas could stimulate interest at earlier stages of education. The program combined in-school lectures by the Institute's research staff with a seminar program for a more limited number of students. Fifty students from five public and private high schools took part. Topics covered artificial life, immunology, cellular automata, and scaling phenomena. The program has been popular with participants—students and teachers alike. Based on this initial project, SFI is considering next steps which may include local teacher training and networking and possible software development.

1993 SFI WORKING PAPERS

93-01-001	Smooth Maps of the Interval and the Real Line Capable of Universal Computation Cristopher Moore
93-01-002	The Evolution of Secondary Organization in Immune System Gene Libraries Ron Hightower, Stephanie Forrest, and Alan S. Perelson
93-01-003	Political Parties and Electoral Landscapes Ken Kollman, John H. Miller, and Scott E. Page
93-01-004	Aggregate Fluctuations from Independent Sectoral Shocks: Self-Organized Criticality in a Model of Production and Inventory Dynamics Per Bak, Kan Chen, José Scheinkman, and Michael Woodford
93-02-005	The Quasi-Periodic Oscillations and Low-Frequency Noise of Scorpius X-1 as Transient Chaos: A Dripping Handrail? Jeffrey D. Scargle, David L. Donoho, James P. Crutchfield, Thomas Steiman-Cameron, James Imamura, and Karl Young
93-02-006	Pathways to Randomness in the Economy: Emergent Nonlinearity and Chaos in Economics and Finance W. A. Brock
93-02-007	On the Use of Evidence in Neural Networks David H. Wolpert
93-02-008	The Santa Fe Art Market Martin Shubik
93-02-009	Combining Generalizers Using Partitions of the Learning Set David H. Wolpert
93-03-010	Turbulent Pattern Bases for Cellular Automata James P. Crutchfield and James E. Hanson
93-03-011	The Evolution of Interface: Reduction of Recombination Among Three Loci David B. Goldstein, Aviv Bergman, and Marcus W. Feldman
93-03-012	Some Advantages and Disadvantages of Recombination Sarah P. Otto, Marcus W. Feldman, and Freddy B. Christiansen
93-03-013	Generic Excitable Dynamics on a Two-Dimensional Map Dante R. Chialvo
93-03-014	Revisiting the Edge of Chaos: Evolving Cellular Automata to Perform Computations Melanie Mitchell, Peter T. Hraber, and James P. Crutchfield
93-03-015	Memory in Idiotypic Networks due to Computation Between Proliferation and Differentiation Bernhard Sulzer, Avidan U. Neumann, J. Leo van Hemmen, and Ulrich Behn
93-03-016	On Overfitting Avoidance as Bias David H. Wolpert
93-03-017	Chaotic Time Series Analysis: Identification and Quantification Using Information-Theoretic Functionals Milan Palus
93-04-018	Real-Valued, Continuous-Time Computers: A Model of Analog Computations, Part I Cristopher Moore

93-04-019	Predicting the Size of the T-Cell Receptor and Antibody Combining Region from Consideration of Efficient Self-Nonself Discrimination Jerome K. Percus, Ora E. Percus, and Alan S. Perelson
93-04-020	How Diverse Should the Immune System Be? Rob J. De Boer and Alan S. Perelson
93-04-021	News from the Northern American Southwest: Prehistory on the Edge of Chaos Timothy A. Kohler
93-04-022	A Model for the Immune System Response to HIV: AZT Treatment Studies Denise E. Kirschner and Alan S. Perelson
93-04-023	Echoing Emergence John H. Holland
93-04-024	Reverse Hillclimbing, Genetic Algorithms and the Busy Beaver Problem Terry Jones and Gregory J. E. Rawlins
93-05-025	Implications of Creation David E. Hiebeler
93-05-026	Don't Bleach Chaotic Data James Theiler and Stephen Eubank
93-05-027	Evolution of Recombination Among Multiple Selected Loci: A Generalized Reduction Principle Lev A. Zhivotovsky, Marcus W. Feldman, and Freddy B. Christiansen
93-05-028	Fluctuation Spectroscopy K. Young and J. P. Crutchfield
93-05-029	The Escape Problem for Irreversible Systems R. S. Maier and D. L. Stein
93-05-030	The Cognitive Revolution? John L. Casti
93-06-031	Random Walks and Orthogonal Functions Associated with Highly Symmetric Graphs Peter F. Stadler
93-05-032	The Theoretical Grapples with Complex Systems Lee A. Segel
93-06-033	The Calculus of Self-Interest in the Development of Cooperation: Sociopolitical Development and Risk Among the Northern Anasazi Timothy A. Kohler and Carla R. Van West
93-06-034	Mogollon Manos, Metates and Agricultural Dependence: Pithouse Villages, A.D. 200-1000 Michael W. Diehl
93-06-035	"Observing Complexity" and "The Complexity of Observation" James P. Crutchfield
93-06-036	The Effect of Focusing and Caustics on Exit Phenomena in Systems Lacking Detailed Balance Robert S. Maier and D. L. Stein
93-06-037	When Will a Genetic Algorithm Outperform Hill-Climbing? Melanie Mitchell and John Holland

93-09-057 Memorandum to: Murray Gell-Mann
Concerning: The Complications of Complexity in the Prehistoric Southwest
Norman Yoffee

93-09-058 Reverse Engineering a Model for T-Cell Vaccination
Lee A. Segel and Eva Jäger

93-09-059 Common Knowledge
John Geanakoplos

93-10-060 Capacity of a Model Immune Network
Gérard Weisbuch and Mihaela Oprea

93-10-061 Critical Computation, Phase Transitions, and Hierarchical Learning
James P. Crutchfield

93-10-062 Innovation in Complex Adaptive Systems: Some Mathematical Sketches
John H. Holland

93-10-063 The Rationality of Adaptive Agents
John H. Holland

93-10-064 The Effect of Labels (Tags) on Social Interactions
John H. Holland

93-10-065 On the Bayesian "Occam Factors" Argument For Occam's Razor
David H. Wolpert

93-10-066 Beyond Digital Naturalism
Walter Fontana, Günter Wagner and Leo W. Buss

93-10-067 What Would Be Conserved If "The Tape Were Played Twice"?
Walter Fontana and Leo W. Buss

93-11-068 A Model of the Emergence of New Political Actors
Robert Axelrod

93-11-069 Landscapes: Complex Optimization Problems and Biopolymer Structures
P. Schuster and P. Stadler

93-11-070 On the Evolution of Complexity
W. Brian Arthur

93-11-071 Evolving Cellular Automata to Perform Computations: Mechism and Impediments
M. Mitchell

93-11-072 Genetic Algorithms and Artificial Life
Melanie Mitchell

93-11-073 Perceptual Cognitive Universals as Reflections of the World
Roger D. Shepard

93-12-074 An Introduction to SFI ECHO
T. Jones and S. Forrest

93-13-075 The Influence of Mutation on Autocatalytic Reaction Networks
P. Stadler and J. C. Nuño

93-12-076 Testing for Nonlinearity Using Redundancies: Quantitative and Qualitative Aspects
Milan Palus

93-12-077 Cooperation: The Ghost in the Machinery of Evolution
John L. Casti

APPENDIX II

1993 SFI VOLUMES: STUDIES IN THE SCIENCES OF COMPLEXITY

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Tim Kohler	Washington State University
Angela Linse	University of Washington
David Pieczkiewicz	Case Western Reserve, Undergraduate Intern
Matt Root	Washington State University

The Economy as a Complex, Adaptive System

James Andreoni	University of Wisconsin
W. Brian Arthur	Stanford University, External Faculty
Larry Blume	Cornell University
David Easley	Cornell University
Dan Friedman	University of California, Santa Cruz
David Lane	University of Minnesota
Blake LeBaron, program head	University of Wisconsin
Martin Lettau	Princeton University, Graduate Fellow
Franco Malerba	Bocconi University
Robert Marks	Stanford University
John Miller	Carnegie-Mellon University, External Faculty
John Moody	Oregon Graduate Institute
Luigi Orsenigo	Bocconi University
Richard Palmer	Duke University, External Faculty
Robert Savit	University of Michigan
Martin Shubik	Yale University
William Sudderth	University of Minnesota
Miguel Virasoro	University of Rome
Nick Vriend	University of Bonn

Patterns in Chaotic Data

Michael Angerman	Los Alamos National Laboratory
Dante Chialvo	State University of New York, Syracuse
Peter Chu	Santa Fe Institute
Doyne Farmer	The Prediction Company, External Faculty
Brant Hinrichs	Beckman Institute, University of Illinois, Graduate Fellow
James Theiler, program head	Los Alamos National Laboratory/SFI Postdoctoral Fellow

Computational Approaches to Genetic Data

Bill Bruno	Los Alamos National Laboratory
Joe Bryngelson	Los Alamos National Laboratory

Rob Farber	Los Alamos National Laboratory, External Faculty
Walter Fontana	SFI Postdoctoral Fellow
Jeff Inman	St. John's College, Member
Bette Korber	Los Alamos National Laboratory/SFI Postdoctoral Fellow
Alan Lapedes	Los Alamos National Laboratory, External Faculty
Michael Lowenstein	Undergraduate Intern
Paul Stolorz	SFI Postdoctoral Fellow

Complexity, Entropy and the Physics of Information

Murray Gell-Mann	California Institute of Technology, External Faculty
Tino Gramss	California Institute of Technology
James Hartle	University of California, Santa Barbara
Seth Lloyd	Los Alamos National Laboratory, External Faculty
Wojciech Zurek	Los Alamos National Laboratory, External Faculty

Artificial Life/Swarm Project

Christian Van Den Broeck	Limburgs University
Stefan Helmreich	Stanford University, Visiting Graduate Fellow
David Hiebeler	Thinking Machines Corporation
Chris Langton, program head	Los Alamos National Laboratory, External Faculty
Bill Macready	University of Toronto, SFI Postdoctoral Fellow
Mark Millonas	Los Alamos National Laboratory
Steen Rasmussen	Los Alamos National Laboratory
Tom Ray	University of Delaware
Bruce Sawhill	St. John's College
Josh Smith	Massachusetts Institute of Technology/Media Lab

Evolution of Structures in Neurobiology

Valerie Gremillion	Los Alamos National Laboratory
Julian Jack	Oxford University
Nancy Kopell	Boston University
Charles Stevens	Salk Institute

Integrative Core Research

Philip Anderson	Princeton University theory of disorder; computers and complexity; scaling phenomena; origin of life and other biophysical topics; neural nets

Michel Baranger	Massachusetts Institute of Technology/Los Alamos National Laboratory
	periodic trajectories as a tools for understanding chaos; the quantization of nonlinear systems with many degrees of freedom with emphasis on low-lying excitations; the philosophical and ethical implications of the chaos revolution—working on a popular book on this topic
Aviv Bergman	Stanford University/Interval Research
	evolutionary biology, population genetics
Leo Buss, Biology	Yale University
	theoretical biology, RNA secondary structure
David Campbell	University of Illinois, Urbana-Champaign
	nonlinear dynamics
John Casti	Santa Fe Institute
	theory and application of metabolism-repair systems; the structure and dynamics of road traffic networks; writing a general-reader volume on complex systems to be published by Harper Collins
George Cowan	Santa Fe Institute
	maturational phenomena and development of mental abilities/ competence in the very young; integrated themes in complex adaptive systems
Jim Crutchfield	University of California, Berkeley, External Faculty
	computational mechanics, state space structures in high-dimensional systems. Joined by his U.C. students Dan Upper , Jim Hanson , and Karl Young.
Jean Czerlinski	New College of University of Southern Florida, Undergraduate Intern
	dynamics of evolutionary systems
Emily Dickenson	Santa Fe Institute
	works with Stuart Kauffman on the implementation and testing of a model of technological evolution based on Kauffman's autocatalytic polymer set model for the origin of life
Kari Eloranta	Helsinki University of Technology
	cellular automata
Walter Fontana	SFI Postdoctoral Fellow
	theoretical biology, RNA secondary structure
Leon Glass	McGill University
	high-dimensional models of gene and neural networks
Jim Hanson	SFI Postdoctoral Fellow
	computation in spatially extended systems

Brosl Hasslacher	Los Alamos National Laboratory nanotechnology
Alfred Hubler	University of Illinois, External Faculty control of chaotic systems, pattern formation and principle of minimum resistance, nonlinear chemistry, algebraic integration of nonlinear oscillators
Atlee Jackson	University of Illinois, Urbana-Champaign foundations of science
Erica Jen	Los Alamos National Laboratory, External Faculty cellular automata
Stuart Kauffman	Santa Fe Institute and University of Pennsylvania, External Faculty behavior of parallel processing, disordered networks of binary elements governed by Boolean functions; the "origin of life" problem; structure of rugged fitness landscapes in biology and some solid state physics problems; adaptation in complex systems; coevolution and game theory
Danielle A. M. Konings	University of Colorado working with Peter Stadler on investigating the relation of genotype and phenotype using the folding of RNA sequences as a computational model
Greg Kramer	Santa Fe Institute and Clarity, SFI Member audification, the use of changes in sound to display the status of a multidimensional system
Gottfried Mayer-Kress	CCSR, University of Illinois at Urbana-Champaign nonlinear dynamics, chaos, and synergetics; applications to medical and security problems; computational mathematics; scientific visualization
Pamela McCorduck	complex adaptive systems in the arts, hypertext, artificial life, knowledge-based systems
Bill Macready	University of Toronto, Postdoctoral Fellow working with Stuart Kauffman
Nelson Minar	Reed College, Undergraduate Intern What distinguished spatial functional organizations from the mean field counterpart? Minar is exploring this question within the lambda-calculus modeling framework of Buss/Fontana.
Cris Moore	SFI Postdoctoral Fellow the complexity of physics, exploring the limits of the physical Church-Turing thesis that the behavior of physical objects is computable

Vamsi Mootha	**Stanford University, Undergraduate Intern**
	secondary structure robustness of introns; the calculation of the density of states of an RNA
Randall Morck	**University of Alberta**
	economics and thermodynamics
Harold Morowitz	**George Mason University, SFI Science Board Member**
	currently, a unified theory of biological organization
Mats Nordahl	**SFI Postdoctoral Fellow**
	models of coevolution, spreading rates and Lyapunov exponents for spatially extended systems, statistical mechanics of random dynamical systems, reversible cellular automata and physical modelling; evolutionary approaches to neural networks
Milan Palus	Prague Psychiatric Center
	applied nonlinear dynamics including information and entropy properties of chaotic systems and spatio-temporal chaos
Luca Peliti	University of Naples
Darren Pierre	Case Western Reserve, Undergraduate Intern
	working with Alfred Hubler
David Pines	University of Illinois, Urbana-Champagne, External Faculty
	condensed matter theory; theoretical astrophysics, integrative aspects of complex, adaptive systems
Alexia Manaster Ramer	Wayne State University
	mathematically bridging the descriptive evolutionary approach to language and the Chomskian approach
Peter Schuster	Institute for Molecular Biology
	statistical characterization of RNA secondary structure and derived properties
Andreas Schwienhorst	Max Planck Institute
	working with Peter Stadler on investigating the relation of genotype and phenotype using the folding of RNA sequences as a computational model
Roger Shepard	Stanford University
	biological evolution; learning and categorization; Bayesian and maximum entropy influence; science of mind
Mike Simmons, program head	Santa Fe Institute
	novel artifical perturbation and variational techniques for treating nonlinear problems
Peter Stadler	University of Vienna
	in collaboration with Walter Fontana and Peter Schuster, investigating the relation of genotype and phenotype using the folding of RNA sequences as a computational model

David Stork	Stanford/Ricoh Research
	machine learning and Bayesian analysis
Ed Thorpe	Thorpe & Associates, San Diego
	guest of John Casti; research interests in games in the stock market
Bill Tozier	University of Pennsylvania
	working with Stuart Kauffman and Bill Macready on subcritical and supercritical reactions in complex chemical systems
Joe Traub	Columbia University
	computational complexity; issues relating to what is scientifically knowable
David Wolpert	SFI Postdoctoral Fellow
	supervised machine learning relating to the fields of neural nets, AI and statistics; time asymmetry, the foundations of statistical mechanics, and the thermodynamics of computation
Larry Wood	GTE
	visting Stuart Kauffman to discuss bounded rationality in economics

LIST OF 1993 COLLOQUIA

Topology from a Time Series
Mark Muldoon, University of Warwick

The Calculus of Self-Interest in the Development of Cooperation: Sociopolitical Development and Risk Among the Northern Anasazi
Tim Kohler, Washington State University/SFI

Autocatalytic Group II Intron Splicing
Kevin Jarrell, Harvard University

A Technologically Feasible Quantum Computer
Seth Lloyd, Los Alamos National Laboratory

Continuous Computers—A Theory of Analog Computation
Cris Moore

Searching for Patterns in Highly Variable HIV Proteins
Bette Korber, Los Alamos National Laboratory/SFI

Oscillation and Chaos in High-Dimensional Neural and Gene Networks
Leon Glass, McGill University

The Cerebellum as a Neural-Net Associative Memory: An Inspiration for Robot Design
Pentti Kanerva, NASA Ames Research Center, Tampere University of Technology

Reverse Hillclimbing, Genetic Algorithms and the Busy Beaver Problem
Terry Jones, University of New Mexico/SFI

Emergence of Mutualism
Gérard Weisbuch, Ecole Normale Supérieure

Chemical Reaction Automata; Some Design Considerations
Per Bro, Southwest Electrochemical Company

Coffee Price Wars and the Genetic Algorithm: Estimating Strategies in a Real-World Oligopolgy
Robert Marks, Stanford University/University of New South Wales

Complexity Increases in Evolution. NOT!
Dan McShea, University of Michigan

Making Genetic Algorithms Fly: A Lesson from the Wright Brothers
David Goldberg, University of Illinois

Are Morphological Characters Recursively Defined by the Genome?
Günter Wagner, Yale University

Incomplete Observation → Infinite States
Dan Upper, University of California, Berkeley

Natural Selection and the Evolution of Evolvability
Günter Wagner, Yale University

Evolutionary Dynamics of Spatial Games
Mats Nordahl, SFI

Dimensional Scaling of Dynamical Correlations
Dudley Herschbach, Harvard University

Economic Theory Past and Future: Economics, Physics, and Biology
Martin Shubik, Yale University

Classification of Patterns Using MLP-Networks Trained by a "Direct" Iterative Procedure
Stefano Fanelli, University of Rome

Coherent Structures in Cellular Automata
Jim Hanson, University of California, Berkeley

Complexity and Chaos on the Modern Battlefield
Dudley Miller and Mark Sulcoski, University of Virginia

Migraine Aura: Self Organization and the Visual Cortex
Oliver Sacks, Albert Einstein University and New York University

An Application of Genetic Function Approximation to Quantitative Structure- Activity Relationship (QSAR) Analysis
David Rogers, Molecular Simulations, Inc.

Quantum Teleportation and Other Recent Results in Quantum Information
Charles Bennett, IBM T. J. Watson Research Center

Catching Slippery Quanta: Following Changes in Quantal Size with Changes in Synaptic Efficacy
Julian Jack, Oxford University

Social Relations and Economic Changes Among Prehistoric Mogollon Pithouse Dwellers
Michael Diehl, University at Buffalo/SFI

High-Performance Analysis and Control of Complex Systems Using Dynamically Reconfigurable Silicon and Optical Fiber Memory
Laurence Wood, GTE

Large Ising and Immunology Lattices as Testing Ground for Modern Super-Computers
Martin Shubik, Yale University

What ABOUT Language?
Alexis Manaster Ramer, Wayne State University

Hurricane Andrew and the Ideal Cat
Eric B. Kraus, Director Emeritus, NOAA/University of Miami

What's Missing from the "Standard Model" of Complex Systems, Part One and Two
Mark Millonas, Los Alamos National Laboratory

Complexity and the Study of Privacy in the Digital Age
Tom Johnson, Columbia University and San Francisco State University

Poincaré vs. Einstein
Nandor Balazs, State University of New York at Stony Brook

A Simple Theory of Learning from Examples
Christian Van Den Broeck, Limburgs University

Decision Trees: Constructing and Deconstructing
Cullen Schaffer, CUNY/Hunter

Lattice Polymer Automata and the Emergence of Elasticity
Josh Smith, Cambridge University

What is Going to Replace "Microreductionism" and "Universal Laws"?
E. Atlee Jackson, University of Illinois, Urbana-Champaign

An Evolutionary Iterated Prisoner's Dilemma Game with Choice and Refusal of Partners
Dan Ashlock, Ann Stanley, and Leigh Tesfatsion, Iowa State University

Think You Understand Chaos? Think Again!
E. Atlee Jackson, University of Illinois, Urbana-Champaign

Towards a Theoretical Foundation of Simulation
Steen Rasmussen, Los Alamos National Laboratory/SFI

Direct Gas Dynamics in Cellular Automata
Kari Eloranta, Helsinki University of Technology

Introductory Biology from an Advanced Point of View
Harold Morowitz, George Mason University

Value and Information (A Profit Maximizing Strategy for Maxwell's Demon)
Randall Morck, University of Alberta

Traffic Jams, Cellular Automata, and Self-Organization
Kai Nagel, Los Alamos National Laboratory/University of Cologne/SFI

A Visit to Hungarian Mathematics
Reuben Hersh and Vera John-Steiner, University of New Mexico

Methods and Considerations Concerning the Use of Molecular Epidemiology to Trace HIV Transmission: The Case of the Florida Dentist in Retrospect
Bette Korber, Los Alamos National Laboratory/SFI

Extinction of the Dinosaurs: The Mexican Impact and Its Effect on the Earth System
Walter Alvarez, University of California, Berkeley

World Population Growth (An Essay on Dynamics of the Global Population System)
S. P. Kapitza, Institute for Physical Problems, Moscow

An Introduction to the Theory of Quantum Computation
Tino Gramss, California Institute of Technology

Ca-Waves and the Contractility in Glial Cell Networks: Creative Tension in the Nervous System
Mark Cooper, University of Washington

The Emergence of Complex Society in Ancient Hawaii
Robert Hommon, Naval Facilities Engineering Command

The Collaboratory
David Padwa

Evolution of Universal Principles of Mind: The Emergence of Representation in Complex Systems (6 lectures)
Roger Shepard, Stanford University/SFI

Experimental Approaches to "Real" Fitness Landscapes
Andreas Schwienhorst, Max-Planck-Institute, Göttingen/Institut für Molekulare Biotechnologie, Jena

Optimal Brain Surgeon and Connectionist Network Pruning
David Stork, Ricoh California Research Center

A Sensitivity Parameter for Cellular Automata
Philippe Binder, Wolfson College, Oxford

Sensory Integration for an Artificial Lip-Reading System
David Stork, Ricoh California Research Center

Percolation Phenomena and Critical Environmental Conditions Associated with Woodland Ecotones
Bruce Milne, University of New Mexico

Cooperative Magnetic Interactions in Organic Molecules
Scott Silverman, California Institute of Technology

Algorithmic Information Theory
Greg Chaitin, IBM Yorktown Heights

Mathematical Aspects of Emergence
Nils Baas, University of Tronheim

Evolving Cellular Automata to Perform Computations: Mechanisms and Impediments
Melanie Mitchell, Santa Fe Institute

Earth's Evolution as Autopoietic Complexity
Elizabet Sahtouris

APPENDIX VI

LIST OF 1993 WORKSHOPS

March 7–11	**Reinforcement Learning in Robots: The Challenge of Scaling Up** Nils Nilsson, Stanford University Melanie Mitchell, Santa Fe Institute
May 9–13	**On Learning and Adaptation in Robots and Situated Agents** Melanie Mitchell, Santa Fe Institute
May 22–24	**On Maturational Windows and Cortical Plasticity in Human Development: Is There Reason for an Optimistic View** Bela Julesz, Rutgers University/California Institute of Technology George Cowan, Santa Fe Institute
May 30–June 25	**6th Annual Complex Systems Summer School** Lynn Nadel, University of Arizona Daniel Stein, University of Arizona
June 11–13	**Project 2050: Crude Look at the Whole** Murray Gell-Mann, California Institute of Technology
June 28–July 10	**Scientific Meeting of the SFI External Faculty**
July 11–15	**Plastic Individuals in Evolving Populations: Models and Algorithms** Rik Belew, University of California, San Diego Melanie Mitchell, University of Michigan
July 21–30 and August 9–19	**Theoretical Neurobiology Working Groups** Nancy Kopell, Boston University Michael Stryker, University of California Medical School, San Francisco
September 7–15	**The Economy as a Complex Adaptive System II** Kenneth Arrow, Stanford University Philip Anderson, Princeton University
September 9–12	**Fluctuations and Order: The New Synthesis** Mark Millonas, Los Alamos National Laboratory
September 19–21	**Immune Memory in Theory and Experiment** Polly Matzinger, National Institute of Health Avidan Neumann, Santa Fe Institute Alan Perelson, Los Alamos National Laboratory/Santa Fe Institute
October 30–November 3	**Founding Workshop on Cultural Evolution** Marc Feldman, Stanford University Tim Kohler, Washington State University
November 7, 10–11	**University of Michigan/Santa Fe Institute Annual Seminar** John Holland, University of Michigan
November 11–14	**Artificial World Models** David Lane, University of Minnesota Walter Fontana, Santa Fe Institute
December 3–5	**Workshop on Adaptation and Learning in Organizations** Kenneth Arrow, Stanford University Michael Cohen, University of Michigan Murray Gell-Mann, California Institute of Technology/Santa Fe Institute

December 6–7 **SFI Business Network Workshop**
Ed Knapp, Santa Fe Institute

ROSTERS & SCHEDULES OF 1993 WORKSHOPS

Roster for Workshop on Reinforcement Learning in Robots: The Challenge of Scaling Up, March 7–11, 1993

Prof. Christopher G. Atkeson	Massachusetts Institute of Technology
Prof. Andrew Barto	University of Massachusetts
Dr. Jonathan Connell	IBM
Mr. George John	Massachusetts Institute of Technology
Dr. Sridhar Mahadevan	IBM
Dr. Melanie Mitchell	Santa Fe Institute
Dr. Andrew Moore	Massachusetts Institute of Technology
Prof. Nils Nilsson	Stanford University
Mr. Pete Sandon	Dartmouth College
Mr. Anton Schwartz	Stanford University
Mr. Satinder Pal Singh	University of Mass
Dr. Steven Whitehead	GTE Labs

Program for Workshop on Reinforcement Learning in Robots: The Challenge of Scaling Up, March 7–11, 1993

All formal talks and discussions will be in the mornings, 9:30–12:00, followed by lunch for the working group participants. All morning sessions are open to anyone at SFI.

The schedule for each morning is the following:

9:30	Talk
11:00	Break
11:15–12:00	Discussion

SUNDAY, MARCH 7

Steven Whitehead, GTE Labs
"Reinforcement Learning: Where We Are, What To Do, and There We Fit In"

MONDAY ,MARCH 8

Nils Nilsson, Robotics Lab, Department of Computer Science, Stanford
"On the Problem of Reinforcement Learning of Teleo-Reactive Trees"

TUESDAY, MARCH 9

Andrew W. Moore, MIT Artificial Intelligence Laboratory
"Two Skirmishes .vith the Curse of Dimensionality "

WEDNESDAY, MARCH 10

Sridhar Mahadevan, IBM T. J. Watson Research Center
"Rapid Task Learning for Real Robots"

THURSDAY, MARCH 11

Andrew G. Barto and Satinder P. Singh, Department of Computer Science, University of Massachusetts at Amherst
"Behavior-Based Reinforcement?"

Roster for Working Group On Learning and Adaptation in Robots and Situated Agents, May 9–13, 1993

Prof. Randy Beer	Case Western Reserve University
Prof. Scott Benson	Stanford University
Dr. Bruce Blumberg	Massachusetts Institute of Technology/Media Lab
r. Lashon Booker	The MITRE Corporation
Prof. Lisa Desjarlais	University of New Mexico
Prof. Marco Dorigo	Politecnico Di Milano
Dr. Gary Drescher	Thinking Machines Corporation
Prof. Stephanie Forrest	University of New Mexico
Dr. David Hiebeler	Santa Fe Institute
Prof. Ron Hightower	University of New Mexico
Prof. John Holland	University of Michigan
Dr. Terry Jones	Santa Fe Institute
Prof. Leslie Kaelbling	Brown University
Dr. Krasimir Kolarov	Interval Research
Dr. Christopher Langton	Los Alamos National Laboratory and Santa Fe Institute
Dr. Pattie Maes	Massachusetts Institute of Technology/Media Lab
Prof. Lisa Meeden	Indiana University
Prof. Jonathan Mills	Indiana University
Dr. Henry Minsky	Massachusetts Institute of Technology
Dr. Melanie Mitchell	Santa Fe Institute
Prof. Nils Nilsson	Stanford University
Dr. Steen Rasmussen	Los Alamos National Laboratory and Santa Fe Institute
Dr. Mitchel Resnick	Massachusetts Institute of Technology/Media Lab
Prof. Rick Riolo	University of Michigan
Dr. Stewart Wilson	*Science*
Prof. Brian Yamauchi	Case Western Reserve University

Program for Working Group On Learning and Adaptation in Robots and Situated Agents, May 9–13, 1993

SUNDAY, MAY 9

9:30–10:00 A.M. Continental Breakfast

10:00–10:15	MIKE SIMMONS, Vice President for Academic Affairs, SFI *Welcome and Introduction to SFI*
10:15–10:30	MELANIE MITCHELL, Resident Director, Adaptive Computation Program, SFI *Overview of SFI's Adaptive Computation Program*
10:30–12:00	JOHN HOLLAND, University of Michigan *Building Blocks, Parallelism, and Learning in Adaptive Agents*
12:00 noon	Lunch
2:00–3:30 P.M.	STEWART WILSON, Rowland Institute for Science *Landscapes and Canals along the Animat Path to AI*
3:30–4:00	Break
4:00–4:30	LISA DESJARLAIS, University of New Mexico and Sandia National Laboratory *Linked Learning Classifier Systems for Adaptive Robot Control Title*
4:30–5:30	Discussion

MONDAY, MAY 10

8:30–9:00 A.M.	Continental Breakfast
9:00–10:30	RANDY BEER, Case Western Reserve University *A Dynamical Systems Perspective on Agent-Environment Interaction*
10:30–11:00	Break
11:00–12:30	JONATHAN MILLS, Indiana University *"Let A Thousand Insects Loose": Toward an Adaptive Colony of Adaptive Robots*
12:30 P.M.	Lunch
2:00–4:00	Individual work, smaller groups, SFI activities, etc.
4:00–4:30	BRIAN YAMAUCHI, Case Western Reserve University *Sequential Behavior and Learning in Dynamical Neural Networks*
4:30–5:00	LISA MEEDEN, Indiana University *Emergent Control and Planning in an Autonomous Vehicle*
5:00–6:00	Discussion

TUESDAY, MAY 11

8:30–9:00 A.M.	Continental Breakfast
9:00–10:30	PATTIE MAES, MIT *Issues in modeling Adaptive Autonomous Agents*
10:30–11:00	Break
11:00–12:30	GARY DRESCHER, Thinking Machines *The Schema Mechanism: Steps Toward Artificial Infancy*
12:30 P.M.	Lunch
2:00–4:00	Individual work, smaller groups, SFI activities, etc.

4:00–4:30	BRUCE BLUMBERG, MIT *Brio: An Ethologically-Inspired Toolkit for Modelling Animal Behavior*
4:30–5:00	HENRY MINSKY, MIT *Building A Visual System With Active Perception, Using the Schema Mechanism*
5:00–6:00	Discussion

WEDNESDAY, MAY 12

8:30–9:00 A.M.	Continental Breakfast
9:00–10:30	MARCO DORIGO, Politecnico di Milano *Robot Shaping: Learning to Control a Real Robot By Distributed Learning Classifier Systems*
10:30–11:00	Break
11:00–12:30	LESLIE KAELBLING, Brown University *Hierarchical Reinforcement Learning*
12:30 P.M.	Lunch
2:00–5:00	Individual work, smaller groups, SFI activities, etc.
5:30	Picnic dinner, Patrick Smith Park, East Alameda

THURSDAY, MAY 13

8:30–9:00 A.M.	Continental Breakfast
9:00–9:30	SCOTT BENSON, Stanford University *Agent Architectures Integrating Teleo-Reactive Trees and Planning*
9:30–10:30	Discussion
10:30–11:00	Break
11:00–12:00	Wrap-up discussion

Roster for Workshop On Maturational Windows and Cortical Plasticity in Human Development: Is There Reason for an Optimistic View, May 22–24, 1993

Dr. John Allman	California Institute of Technology
Dr. Antonella Antonini	University of California, San Francisco
Dr. Elizabeth Bates	University of California, San Diego
Dr. George Cowan	Los Alamos National Laboratory/SFI
Prof. Bela Julesz	Rutgers University
Dr. Avi Karni	National Institutes of Health
Dr. Mark Konishi	California Institute of Technology
Dr. Ilona Kovacs	Rutgers University
Dr. Michael Merzenich	University of California, San Francisco
Dr. Tim Pons	National Institutes of Health—NIMH
Dr. Vilayanur S. Ramachandran	University of California, San Diego

Prof. Jeff Shrager	Carnegie-Mellon University
Dr. Joan Stiles	University of California, San Diego
Dr. Paula Tallal	Rutgers University
Prof. Edward Taub	University of Alabama
Dr. Leslie Ungerleider	National Institutes of Health

Program for Workshop On Maturational Windows and Cortical Plasticity in Human Development: Is There Reason for an Optimistic View, May 22–24, 1993

SATURDAY, MAY 22

8:30–9:00 A.M.	Continental Breakfast
9:00–9:15	GEORGE COWAN, SFI President (Retired) *Welcome and Introduction to SFI*
9:15–10:00	BELA JULESZ, Rutgers Uuniversity *Introductory Talk. Learning in Early Vision*
10:00–11:00	MICHAEL MERZENICH, UCSF *Cortical Plasticity: Shaped, Distributed Representations of Learned Behaviors*
11:00–12:00 P.M.	JOHN ALLMAN, Caltech *Learning to See Embedded Visual Figures: A Fast, Robust and Lasting Form of Memory*
12:00–2:00	Lunch
2:00–3:00	ANTONELLA ANTONINI, UCSF Medical School *Development of Cortical Columns and Their Thalamic Inputs*
3:30–4:00	MARK KONISHI, Caltech *A "Critical Period" in Birdsong Learning*
4:00–5:00	EDWARD TAUB, U. of Alabama, Birmingham *Behavioral Plasticity Following Central Nervous System Damage in Monkeys and Man*

SUNDAY, MAY 23

8:30–9:00 A.M.	Continental Breakfast
9:00–10:00	GYORGI BUZSAKI, Rutgers University *Memory Consolidation and Sleep: Physiological Perspective*
10:00–11:00	AVI KARNI, NIH *Where Visual Experience Makes Visual Skills: The Functional Localization and Temporal Course of Learning a Basic Perceptual Task*
11:00–12:00 P.M.	TIM PONS, NIH *The Plastic Brain of Adult Primates*
12:00–2:00	Lunch
2:00–3:00	V.S. RAMACHANDRAN, UCSD *Plasticity in the Adult Human Brain: Phantom Limbs and Scotomas*

3:00–4:00	LESLIE UNGERLEIDER, NIH *Development and Plasticity of Cortico-Limbic Circuits in Monkeys*
4:00–5:00	PAULA TALLAL, Rutgers U. *In the Analysis of Speech, Time is of the Essence*

MONDAY, MAY 24

8:30–9:00 A.M.	Continental Breakfast
9:00–10:00	JOAN STILES, UCSD *Constraints on Plasticity in the Development of Language and Spatial Cognition I.*
10:00–11:00	ELIZABETH BATES, UCSD *Constraints on Plasticity in the Development of Language and Spatial Cognition II.*
11:00–12:00 P.M.	JEFF SHRAGER, Carnegie-Mellon *Modeling the Development of Cortical Representations*
12:00–2:00	Working Lunch

Roster for Sixth Annual Complex Systems Summer School, May 30–June 25, 1993

Faculty

Dr. David K. Campbell	University of Illinois at Urbana
Dr. Susan N. Coppersmith	AT&T Bell Laboratories
Prof. Brian L. Keeley	University of California, San Diego
Dr. Catherine Macken	Los Alamos National Laboratory
Dr. Jay McClelland	Carnegie-Mellon University
Dr. Bartlett Mel	California Institute of Technology
Dr. Cris Moore	Santa Fe Institute
Pro. Lynn Nadel	University of Arizona
Dr. John Pearson	Los Alamos National Laboratory
Dr. Bruce Sawhill	St. John's College
Dr. Olaf Sporns	Neuroscience Institute
Prof. Daniel Stein	University of Arizona
Dr. Randall Tagg	University of Colorado
Dr. Kurt Thearling	Thinking Machines Corporation
Dr. Matthew A. Wilson	University of Arizona

Students

Eric Anderson	Duke University
Philip Auerswald	University of Washington
Wendy N. Baldwin	University of New Mexico

Ann M. Bell	University of Wisconsin
Gregery Buzzard	University of Michigan
Ajay Chitnis	The Salk Institute
Vincent Darley	University of Cambridge
Rajarshi Das	Colorado State University
Mark William Davis	New Mexico State University
Benoit Desjardins	University of Pittsburgh
Karl Diller	University of New Hampshire
Irina Eckardt	Harvard School of Public Health
Arne Elofsson	201 Molecular Biology Institute, Los Angeles
William J. Fortin	Florida Atlantic University
Christopher Fuchs	University of New Mexico
Gyöngyi Gaál	Brown University
Liane Gabora	University of California, Los Angeles
Afshin Goodarzi	NYNEX Science and Technology
Ari Hershowitz	Yale University
Allen Hjelmfelt	Standord University
Maureane Hoffman	Duke University Medical Center
Takashi Iwamoto	Mitsubishi Electrical Corporation
Tom Johnson	*Popular Science*
Calvin Johnson	Los Alamos National Laboratory
Risto Karjalainen	University of Pennsylvania
Timothy Keitt	University of New Mexico
Jan T. Kim	Max-Planck Institut
James Kittock	Stanford Unversity
Jochen Kumm	Stanford University
Ladislav Lhotka	Laboratory of Biomathematics, Institute of Entomology CAS, Czech Republic
Pietro Lio	University of Firenze
Jose Lobo	Cornell University
Michael Lowenstein	Stanford University
Xiaowu Lu	Emory University
Michael Lyons	California Institute of Technology
Armando Machado	Duke University
L. Mahadevan	Stanford University
Kenji Matsuoka	State University of New York at Stony Brook

David McCormack	Bullard Laboratories
Brett McDonnell	Stanford University
Carrie Merkle	University of Arizona
William Farrington Miller	Armstrong Laboratory
Jim Oliver	University of Pennsylvania
Arjendu Pattanayak	University of Texas
Penio Penev	Rockefeller University
Shirley Pepke	University of California
Marcelo S. T. Piza	New York University
Kenneth S. Ray	aexpert
Marshall Rockwell	Pacific Palisades, CA
David Rosen	University of Nevada
Klaus Schmoltzi	Institut für Theoretische Physik
Andrew Sonnenschein	University of California
Zvezdelina Stankova	Harvard University
Janet Stites	*Omni Magazine*
William Sulis	McMaster University
Manfred Tacker	Institut für Theoretische Chemie
Xianzhu Tang	College of William and Mary
Patrick L. Tufts	Brandeis University
Ken Umeno	University of Tokyo
Andreas Wagner	Yale University
Clay Williams	Texas A&M
Dongjun Wu	University of Pennsylvania

Program for Sixth Annual Complex Systems Summer School, May 30–June 25, 1993

Each week includes two full series of course lectures. In addition there are daily seminars (one–two per day), and research collaborations with fellow students. A computer laboratory is available on a 24-hour day basis.

MONDAY, MAY 31 TO FRIDAY, JUNE 4

"Introduction to Nonlinear Phenomena" (series of five lectures)
David K. Campbell, Physics, University of Illinois, Urbana

"Neural Models of the Visual Cortex" (series of five lectures)
Olaf Sporns, The Neuroscience Institute, New York

MONDAY, JUNE 7 TO FRIDAY, JUNE 11

"Single Neuron Computation" (series of five lectures)
Bartlett Mel, Biology, California Institute of Technology

"Instability and the Origin of Complexity in Fluid Flow" (series of five lectures)
Randall Tagg, Physics, University of Colorado, Denver

MONDAY, JUNE 14 TO FRIDAY, JUNE 18

"Complex Structures and Dynamics in Condensed Matter Systems" (series of five lectures)
Sue Coppersmith, AT&T Bell Laboratories

"Adaptive Evolution on a Rugged Landscape" (series of three lectures)
Catherine Macken, Theoretical Biology, Los Alamos National Laboratory

"Connectionist Models of Cognition and Learning" (two lectures)
Jay McClelland, Psychology, Carnegie-Mellon University

MONDAY, JUNE 21 TO FRIDAY, JUNE 25

"From Network Models to Network Recordings" (series of five lectures)
Matthew Wilson, Arizona Research Laboratories, Neural Systems, Memory and Aging Division

"The Computation Paradigm of Complexity" (series of five lectures)
Cris Moore, Santa Fe Institute

ADDITIONAL SEMINARS

"Self-Organized Criticality" (two seminars)
Bruce Sawhill, Human Interface Technology Laboratory and Santa Fe Institute

"The Genome: A Helical Tale" (two seminars)
Catherine Macken, Theoretical Biology, Los Alamos National Laboratory

"Massively Parallel Computing and Complex Systems" (two seminars)
Kurt Thearling, Thinking Machines Corporation

Roster for Workshop on Project 2050: Crude Look at the Whole, June 11–13, 1993

Prof. Brian Arthur	Stanford University
Dr. Rob Axtell	Brookings Institution
Prof. Nazli Choucri	Massachusetts Institute of Technology
Dr. Rob Coppock	World Resources Institute
Prof. Marc Feldman	Stanford University
Prof. Murray Gell-Mann	California Institute of Technology/Santa Fe Institute
Dr. Valerie Gremillion	Los Alamos National Laboratory/Santa Fe Institute
Mr. Joseph Jaworski	Shell International Petroleum Co., Ltd.
Prof. Geoff McNicoll	Australian National University
Prof. John Miller	Carnegie-Mellon University
Dr. Avidan Neumann	Santa Fe Institute
Mr. Roger Rainbow	Shell International Petroleum Co., Ltd.
Dr. Bruce Sawhill	St. John's College/SFI
Dr. Gérard Weisbuch	Ecole Normale Supérieure

Program for Workshop on Project 2050: Crude Look at the Whole, June 11–13, 1993

No program available.

Roster for Scientific Meeting of the SFI External Faculty, June 28–July 10, 1993

Prof. Philip Anderson	Princeton University
Prof. W. Brian Arthur	Food Research Institute, Stanford University
Prof. Aviv Bergman	Stanford University/Interval Research
Prof. William Brock	University of Wisconsin
Prof. James Crutchfield	University of California, Berkeley
Dr. Robert Farber	Theoretical Division, Los Alamos National Laboratory
Dr. J. Doyne Farmer	The Prediction Company
Prof. Marcus Feldman	Stanford University
Prof. Stephanie Forrest	University of New Mexico
Dr. Murray Gell-Mann	California Institute of Technology
Dr. Jonathan Haas	The Field Museum of Natural History, Chicago
Prof. Alfred Hubler	University of Illinois, Urbana-Champaign
Dr. Erica Jen	Theoretical Division, Los Alamos National Laboratory
Prof. Stuart Kauffman	University of Pennsylvania
Prof. David Lane	University of Minnesota
Dr. Christopher Langton	Theoretical Division, Los Alamos National Laboratory
Dr. Alan Lapedes	Theoretical Division, Los Alamos National Laboratory
Dr. Seth Lloyd	Theoretical Division, Los Alamos National Laboratory
Prof. John Miller	Carnegie-Mellon University
Prof. Richard Palmer	Duke University
Dr. Alan Perelson	Theoretical Division, Los Alamos National Laboratory
Prof. David Pines	University of Illinois, Urbana-Champaign
Prof. Peter Schuster	Institut für Molekulare Biotechnologie
Prof. Gérard Weisbuch	Laboratoire de Physique statistique, Ecole Normale Supérieure
Dr. Wojciech Zurek	Theoretical Division, Los Alamos National Laboratory

Program for Scientific Meeting of the SFI External Faculty, June 28–July 10, 1993

No program available

Roster for Workshop on Plastic Individuals in Evolving Populations: Models and Algorithms, July 11–15, 1993

Dr. David Ackley	Bellcore
Prof. Richard K. Belew	University of California, San Diego

Dr. Aviv Bergman	Interval Research Corp.
Ms. Esther Dyson	EDventure Holdings, Inc.
Ms. Liane Gabora	University of California, Los Angeles
Mr. William Hart	University of California, San Diego
Dr. Nick Littlestone	NEC Research Institute
Mr. Michael Littman	Brown University
Mr. Fillippo Menczer	University of California, San Diego
Mr. Orazio Miglino	University of California, San Diego
Prof. Melanie Mitchell	Santa Fe Institute
Prof. Stefano Nolfi	National Research Council
Prof. Domenico Parisi	Institute of Psychology
Prof. Jonathan Roughgarden	Stanford University
Prof. Johnathan Schull	Haverford College
Dr. Sharoni H. Shafir	Stanford University
Prof. Charles Taylor	University of California
Dr. Peter Todd	The Rowland Institute for Science
Dr. Stewart Wilson	The Rowland Institute for Science

Program for Workshop on Plastic Individuals in Evolving Populations: Models and Algorithms, July 11–15, 1993

SUNDAY, JULY 11

8:30 A.M.	Breakfast
9:00	Plenary: Overview
12:30 P.M.	Lunch
2:00	Working Groups

MONDAY, JULY 12

8:30 A.M.	Breakfast
9:00	Plenary: Biological Issues
12:30 P.M.	Lunch
2:00	Plenary Behavior Issues

TUESDAY, JULY 13

8:30 A.M.	Breakfast
9:00	Plenary: Computational Issues
12:30 P.M.	Lunch
1:30	Sol Y Sombra Tour

2:00	Off (individual writing)
5:00	Picnic

WEDNESDAY, JULY 14

8:30 A.M.	Breakfast
9:00	Working Groups: Reports
12:30 P.M.	Lunch
2:00	Working Groups: Reports

THURSDAY, JULY 15

8:30 A.M.	Breakfast
9:00	Plenary: Recap
12:30 P.M.	Lunch
2:00	Meeting Adjourned

Roster for Working Groups on Theoretical Neurobiology: Dynamic Control of Stability and Flexibility, July 21–30, 1993

Dr. Larry Abbott	Brandeis University
Prof. Anne Bekoff	University of Colorado
Prof. Hillel J. Chiel	Case Western Reserve University
Prof. G. Bard Ermentrout	University of Pittsburg
Prof. Mimi Koehl	University of California, Berkeley
Prof. Nancy Kopell	Boston University
Prof. Gilles Laurent	California Institute of Technology
Prof. Shawn Lockery	University of Oregon
Prof. Thelma Williams	University of London

Program for Working Groups on Theoretical Neurobiology: Dynamic Control of Stability and Flexibility, July 21–30, 1993

TUESDAY, JULY 20

6:00 P.M.	Get together at NK's place

WEDNESDAY, JULY 21

10:00 A.M.	Hillel Chiel will talk on the "Dynamics of Adaptive Behavior," including bistabilty in cultured neurons, neural basis for switching some behaviors, and the role of the periphery vs. central networks in enforcing stable gaits.

THURSDAY, JULY 22

10:00 A.M.	Mimi Koehl will discuss interactions between the nervous system and its mechanical/peripheral context, from the point of view of biomechanics.

3:00 P.M.	Shawn Lockery will discuss self-organization in the leech (bending) and nematode (chemotaxis).

FRIDAY, JULY 23

10:00 A.M.	Larry Abbott will discuss activity-dependent regulation of channels and non-Hodgkin-Huxley behavior of ionic channels.

SATURDAY, JULY 24

Free

SUNDAY, JULY 25

11:00 A.M.	Gilles Laurent will discuss oscillations in the olfactory nervous sytem of an insect and dendritic mechanisms for gain control

MONDAY, JULY 26

10:00 A.M.	Thelma Williams will talk about work on the lamprey central pattern generator, including connections to muscle mechanics and fluid dynamics of swimming
3:00 P.M.	Nancy Kopell will discuss mathematical mechanisms associated with self-organization in the nervous system, illustrated by case histories relating both ionic channel level and small circuit level to larger network behavior.

TUESDAY, JULY 27

2:00 P.M.	Bard Ermentrout will discuss various topics concerning oscillatory and excitable systems related to the CNS.

WEDNESDAY, JULY 28

10:00 A.M.	Anne Bekoff will talk about "Development of Motor Patterns in Chick Embryos and Newly Hatched Chicks: Continuities and Transitions"

THURSDAY, JULY 29

10:00 A.M.	J. Bower will have the last (official) word.

Roster for Working Groups on Theoretical Neurobiology: Visual Object Recognition, August 9–19 , 1993

Dr. Shimon Edelman	Weizmann Institute
Dr. Terrence Sejnowski	Salk Institute
Dr. Michael Shadlen	Stanford University
Prof. Michael Stryker	University of California
Dr. Hiroshige Takeichi	RIKEN
Dr. Keiji Tanaka	RIKEN
Prof. Shimon Ullman	Weizmann Institute of Science

Prof. Malcolm D. Young	University Laboratory of Physiology
Prof. Steven Zucker	McGill University

Program for Working Groups on Theoretical Neurobiology: Visual Object Recognition, August 9–19, 1993

The topics in which the workshop participants work include, in addition to the stated workshop topic, aspects of lower-level vision, visual development, adult plasticity, shape and stereo vision, and issues in perception and perceptual learning.

Talks will be scheduled for 10 A.M. and 1:00 P.M., with some days having only the A.M. talks.

MONDAY, AUGUST 9

P.M.	Orientation (SFI staff)
	Zucker: Overview of competing computational approaches to object recognition

TUESDAY, AUGUST 10

10 A.M.	Michael Stryker: Biological constraints on how the brain does object recognition: the organization of cortex and how this organization might develop
1 P.M.	Michael Shadlen: Object lessons in MT (medial temporal) cortex

WEDNESDAY, AUGUST 11

10 A.M.	John Assad: (adult plasticity) How the brain might represent that something is moving in space

THURSDAY, AUGUST 12

10 A.M.	Steve Zucker: Shapes, shocks, and deformations
1 P.M.	Shimon Edelman: Representation, similarity, and the chorus of prototypes (Tech Report avalable by anonymous ftp from 132.76.80.53)

FRIDAY, AUGUST 13

10 A.M.	Keiji Tanaka: Object recognition and neuronal responses in inferotemporal cortex

MONDAY, AUGUST 16

10 A.M.	Shimon Ullman
1 P.M.	Hiroshige Takeichi

TUESDAY, AUGUST 17

10 A.M.	Terry Sejnowski (& Zucker on curvature detection)

WEDNESDAY, AUGUST 18

10 A.M.	Malcolm Young

THURSDAY, AUGUST 19

10 A.M. Summary and Conclusions

Roster for Workshop on The Economy as a Complex Adaptive System, II, September 7–15, 1993

Prof. Philip W. Anderson	Princeton University
Prof. Kenneth J. Arrow	Stanford University
Prof. W. Brian Arthur	Stanford University
Dr. Per Bak	Brookhaven National Laboratory
Prof. Michele Boldrin	Northwestern University
Prof. William A. Brock	University of Wisconsin
Dr. George Cowan	Los Alamos National Laboratory/Santa Fe Institute
Prof. Giovanni Dosi	fondazione assi
Dr. Walter Fontana	Santa Fe Institute
Prof. John Geanakoplos	Yale University
Dr. Valerie Gremillion	Los Alamos National Laboratory
Mr. William H. Janeway	Warburg, Pincus Ventures, Inc.
Dr. Stuart Kauffman	Santa Fe Institute
Mr. Henry Lichstein	Citicorp
Seth Lloyd	Los Alamos National Laboratory
Dr. Ben Martin	Harvard University
Mr. Robert Maxfield	Saratoga, CA
Prof. John H. Miller	Carnegie-Mellon University
Prof. Melanie Mitchell	Santa Fe Institute
Prof. Richard G. Palmer	Duke University
Mr. James Pelkey	Atherton, CA
Prof. Roberto Perazzo	Universidad de Buenos Aires
Prof. David Pines	University of Illinois
Prof. José A. Scheinkman	The University of Chicago
Prof. Martin Shubik	Cowles Foundation
Prof. Glen H. Swindle	University of California, Santa Barbara
Prof. Miguel Virasoro	Universita di Rome I, La Sapienza
Mr. Barrett Walker	Walker Foundation
Mr. Thomas U. Walker	Walker Foundation
Mr. Martin Wildberger	Electric Power Research Institute

2 of 2

Program for Workshop on The Economy as a Complex Adaptive System, II, September 7–15, 1993

TUESDAY, SEPTEMBER 7

8:30–9:00 A.M.	Continental Breakfast
9:00–9:15	ED KNAPP, SFI President *Welcome and Introduction to SFI*
9:15–9:30	Introductions
10:00–11:00	Phil Anderson
11:00–12:00 P.M.	Ken Arrow
12:00–12:30	Brian Arthur
12:30–1:30	Lunch
1:30–5:00	Talks to be announced
5:00	Welcoming mini-reception

WEDNESDAY, SEPTEMBER 8

8:30–9:00 A.M.	Continental Breakfast
Morning Session	
9:00 A.M.	Glen Swindle José Scheinkman
12:15 P.M.	Lunch
Afternoon Session	
1:00 P.M.	Giovanni Dosi Ben Martin

THURSDAY, SEPTEMBER 9

8:30–9:00 A.M.	Continental Breakfast
Morning Session	
9:00 A.M.	Stu Kauffman Buz Brock
12:15 P.M.	Lunch
Afternoon Session	
1:00 P.M.	John Miller
	Short Presentations: Phil Anderson George Cowan Others to be announced
3:30	Tea
3:45	Discussion and planning session

FRIDAY, SEPTEMBER 10

8:30–9:00 A.M.	Continental Breakfast

Morning Session

9:00 A.M.	Miguel Virasoro Martin Shubik
12:15 P.M.	Lunch

Afternoon Session

1:00 P.M.	Brian Arthur/Richard Palmer Michele Boldrin
3:30	Tea

SATURDAY, SEPTEMBER 11

8:30–9:00 A.M.	Continental Breakfast

Morning Session

9:00 A.M.	Michele Boldrin Per Bak
12:15 P.M.	Lunch

Afternoon Session

1:00 P.M.	Discussion of the "Great Questions" A. Facts

SUNDAY, SEPTEMBER 12

8:30–9:00 A.M.	Continental Breakfast

Morning Session

9:00 A.M.	Continued Discussion of the "Great Questions" B. Concepts

Roster for Workshop on Fluctuations and Order: The New Synthesis, September 9–12, 1993

No roster available; workshop coordinated by CNLS, Los Alamos National Laboratory.

Program for Workshop on Fluctuations and Order: The New Synthesis, September 9–12, 1993

No program available.

Roster for Workshop on Immune Memory in Theory and Experiment, September 19–21, 1993

Dr. Russell W. Anderson	Los Alamos National Laboratory
Dr. Franco Celada	Hospital for Joint Diseases
Dr. Gundi Ertl	Wistar Institute
Mr. Michael A. Fishman	Los Alamos National Laboratory
Prof. Stephanie Forrest	University of New Mexico
Dr. Byron Goldstein	Los Alamos National Laboratory
Dr. Garnett Kelsoe	University of Maryland School of Medicine
Dr. Thomas Kepler	North Carolina State University

Dr. Polly Matzinger	National Institutes of Health
Dr. Ramit Mehr-Grossman	Weizmann Institute
Dr. George Nelson	Los Alamos National Laboratory
Dr. Avidan Neumann	Santa Fe Institute
Dr. Mihaela Oprea	Los Alamos National Laboratory
Dr. Alan Perelson	Los Alamos National Laboratory
Mr. Randall Rose	Santa Fe Institute
Dr. Lee Segel	Weizmann Institute
Dr. Philip Seiden	IBM Research Center
Prof. Eli Sercarz	University of California
Mr. Derek J. Smith	University of New Mexico
Dr. Paul Stolorz	Jet Propulsion Lab
Dr. Bernhard Sulzer	Los Alamos National Laboratory
Dr. John Tew	Medical College of Virginia/VCU

Program for Workshop on Immune Memory in Theory and Experiment, September 19–21, 1993

SATURDAY, SEPTEMBER 18

6:00–8:00 P.M.	Get-together reception at the Neumanns' house

SUNDAY, SEPTEMBER 19

8:30 A.M.	Continental Breakfast
9:00	Welcoming Remarks
9:15–12:30 P.M.	•Phenomenological Definition of Memory •Memory Cells
12:30	Lunch
2:00–5:30	•Mathematical Models in Immunology •Network Memory
7:30	Dinner at the Perelsons' house

MONDAY, SEPTEMBER 20

8:30 A.M.	Continental Breakfast
9:00–12:15 P.M.	•Retained Antigen •Memory Transfer
12:30–4:30	Picnic and Hiking Session at Pecos
5:00–8:00	•Vaccines •Memory in More Specific Cases

TUESDAY, SEPTEMBER 21

8:30 A.M.	Continental Breakfast
9:00–12:30 P.M.	•Germinal Centers •Affinity Maturation
12:30	Lunch
2:00–6:00	Concluding Sessions

Roster for Workshop on Cultural Evolution, October 30–November 3, 1993

Prof. Robert Boyd	University of California, Los Angeles
Dr. Linda Cordell	University of Colorado
Mr. Michael W. Diehl	University at Buffalo
Prof. Joshua Epstein	Brookings Institution
Prof. Stephanie Forrest	University of New Mexico
Dr. Murray Gell-Mann	Santa Fe Institute
Dr. George Gumerman	Santa Fe Institute
Dr. Jonathan Haas	Field Museum of Natural History
Dr. Barry Hewlett	Washington State University
Dr. Robert Hommon	National Park Service
Mr. Terry Jones	Santa Fe Institute
Dr. Stuart Kauffman	Santa Fe Institute
Prof. Timothy Kohler	Washington State University
Prof. Joseph Lambke	Illinois Institute of Technology
Dr. Stephen H. Lekson	Crow Canyon Archaeological Center
Dr. Mats Nordahl	Chalmers Tekniska Högskola
Prof. Ann Stanley	Iowa State University
Dr. Gérard Weisbuch	Ecole Normale Supérieure

Program for Workshop on Cultural Evolution, October 30–November 3, 1993

SUNDAY, OCTOBER 31

8:30 A.M.	Continental Breakfast
9:00	*Introductions and welcoming remarks* Murray Gell-Mann: Welcome and background of SFI George Gumerman: Archaeology program to date at SFI Andi Sutherland: Administrative details
10:00	*Analytical models for culture change, and their limits.* Informal presentations and moderation by Marc Feldman and Rob Boyd
12:00 P.M.	Lunch
1:00	*Complete discussion of analytical models for culture change*

2:00	*Case studies of culture change in the prehistoric Southwest* (possible foci for building simulation models). Informal presentations by Tim Kohler and Jonathan Haas; moderation by George Gumerman
5:00	Adjourn

MONDAY, NOVEMBER 1

8:30 A.M.	Continental Breakfast
9:00	*Spatial games and evolutionary dynamics* Mats Nordahl
10:30	*Presentation/demonstration of Epstein-Axtell Sugarscapes* Discussion
12:00 P.M.	Lunch
1:00	*Presentation/demonstration of SWARM* Discussion
3:00	*Presentation/Demonstration: ECHO* Terry Jones; discussion
5:00	Adjourn
6:30	Group Dinner

TUESDAY, NOVEMBER 2

8:30 A.M.	Continental Breakfast
9:00	*Discussion on representations of culture and possible operationalizations, including neural nets* Moderation by Gérard Weisbuch
10:30	*Concluding discussion of knowledge/culture representation issues*
12:00 P.M.	Lunch
1:00	*Towards a coherent plan for simulating social change/cultural evolution on landscapes in small-scale societies*
4:00	Adjourn

Roster for University of Michigan/Santa Fe Institute Annual Seminar, November 7, 10–11, 1993

No roster available.

Program for University of Michigan/Santa Fe Institute Annual Seminar, November 7, 10–11, 1993

No program available.

Roster for Workshop on Artificial World Models, November 11–14, 1993

Prof. W. Brian Arthur	Stanford University
Prof. Leo Buss	Yale University
Prof. Giovanni Dosi	fondazione assi

Prof. Stuart Dreyus	**University of California**
Dr. Walter Fontana	**Santa Fe Institute**
Prof. George Lakoff	**University of California**
Prof. David Lane	**Universite di Modena**
Prof. Blake LeBaron	**University of Wisconsin**
Prof. Daniel Levinthal	**University of Pennsylvania**
Prof. Franco Malerba	Bocconi University
Mr. Robert Maxfield	Saratoga, CA
Dr. Ashoka Mody	The World Bank
Prof. Richard Nelson	Columbia University
Prof. Luigi Orsenigo	Bocconi University
Prof. John Padgett	University of Chicago
Mr. James Pelkey	Atherton, CA
Mr. Leland S. Prussia	Bank of America
Prof. Charles Sabel	Massachusetts Institute of Technology
Prof. Sidney Winter	University of Pennsylvania
Prof. Jonathan Zeitlin	University of Wisconsin

Program for Workshop on Artificial World Models, November 11–14, 1993

THURSDAY, NOVEMBER 11

8:30 A.M.	Continental Breakfast
9:00–12:00	Introduction: David Lane and Walter Fontana
12:00 P.M.	Lunch
2:00–5:00	John Padgett Leo Buss Jim Pelkey
5:00	Welcoming Reception

FRIDAY, NOVEMBER 12

8:30 A.M.	Continental Breakfast
9:00–12:00	Brian Arthur Blake LeBaron Stuart Dreyfus
12:00 P.M.	Lunch
2:00–5:00	Giovanni Dosi Dan Levinthal Sid Winter
5:00	SWARM presentation

SATURDAY, NOVEMBER 13

8:30 A.M.	Continental Breakfast
9:00	Richard Nelson Ashoka Mody Franco Malerba
12:00 P.M.	Lunch
2:00–5:00	Discussion: George Lakoff and Bob Maxfield

SUNDAY, NOVEMBER 14

8:30 A.M.	Continental Breakfast
9:00	Discussion: "Where do we go from here?"
12:00 P.M.	Adjourn

Roster for Workshop on Adaptation and Learning in Organizations, December 3–5, 1993

Prof. Kenneth J. Arrow	Stanford University
Prof. W. Brian Arthur	Stanford University
Dr. John Seely Brown	Xerox PARC
Prof. Michael Cohen	University of Michigan
Dr. Fernando Flores	Business Design Associates
Mr. Richard N. Foster	McKinsey & Co., Inc.
Dr. Murray Gell-Mann	Santa Fe Institute
Dr. Mark Gerstein	Perot Systems Corporation
Mr. Joel Getzendanner	Joyce Foundation
Ms. Tracy Goss	Goss-Reid Associates
Prof. Michael Hannan	Stanford University
Ms. Susan Haviland	Palo Alto, CA
Prof. John Holland	University of Michigan
Prof. David Lane	Universite di Modena
Prof. Daniel Levinthal	University of Pennsylvania
Prof. Thomas Malone	MIT Sloan School
Mr. Morton H. Meyerson	Perot Systems
Mr. Charles Miller	Transamerica Criterion Group
Prof. John Padgett	University of Chicago
Dr. Richard Pascal	Perot Systems
Mr. James Pelkey	Atherton, CA
Mr. Jacques Raiman	General de Service Informatique

Prof. Massimo Warglien	University of Venice Ca'Bembo
Prof. Sidney Winter	University of Pennsylvania

Program for Workshop on Adaptation and Learning in Organizations, December 3–5, 1993

FRIDAY, DECEMBER 3

8:30 A.M.	Continental Breakfast
9:00	Ed Knapp, SFI President *Welcome*
	Andi Sutherland, SFI *Administrative Details*
	Brief Self-Introductions by Participants
	Ken Arrow, Stanford, and Murray Gell-Mann, SFI *What the Workshop Can Achieve*
	Mort Meyerson, Perot Systems Corporation *What the Workshop Can Achieve*
11:00	Break
11:15	Sidney Winter, Wharton School *Total Quality Management as an Organizational Learning Strategy*
12:30 P.M.	Lunch
1:30–5:00	John Seely Brown, Xerox Corporation *Organizational Learning as Leveraging the Social*
	Brian Arthur, Stanford University *Bounded Rationality, Adaptation and Organizations*
5:00	Welcoming Reception

SATURDAY, DECEMBER 4

8:30 A.M.	Continental Breakfast
9:00	Michael Hannan, Stanford University *Adaptation and Its Limits in Populations of Organizations*
	David Lane, University of Modena *Connections to Other SFI Projects on Complex Adaptive Systems*
12:30 P.M.	Lunch
1:30–5:00	Tom Malone, MIT *Tools for Inventing Organizations: Toward a Handbook of Organizational Learning*
	Dan Levinthal, Wharton School *Adaptive and Non-Adaptive Properties of Organizational Learning*

SUNDAY, DECEMBER 5

8:30 A.M.	Continental Breakfast

9:00	John Padgett, University of Chicago and Michael Cohen, University of Michigan A panel organizing a closing discussion: *Themes from the Workshop; Ideas for the Future*
12:00 P.M.	Adjourn

Roster for SFI Business Network Workshop, December 6–7, 1993

Mr. Bruce Abell	Santa Fe Institute
Ms. Catherine Allen	Citicorp Technology Office
Prof. W. Brian Arthur	Stanford University
Ms. Susan Ballati	Santa Fe Institute
Prof. Michael Cohen	University of Michigan
Mr. Colin Crook	Citibank, N.A.
Ms. Esther Dyson	EDventure Holdings, Inc.
Dr. Doyne Farmer	The Prediction Company
Mr. K. Winslow Farrell, Jr.	Coopers & Lybrand
Mr. William F. Fulkerson	Deere & Company
Dr. Edward A. Knapp	Santa Fe Institute
Dr. Christopher G. Langton	Los Alamos National Laboratory and Santa Fe Institute
Mr. Dean LeBaron	Batterymarch Financial Management
Dr. David Liddle	Interval Research Corporation
Mr. Thomas Linkas	Batterymarch Financial Management
Mr. Mike McMaster	Center for Organisational Learning (UK)
Mr. William H. Miller, III	Legg Mason Mutual Fund
Dr. Melanie Mitchell	Santa Fe Institute
Mr. James Pelkey	Atherton, CA
Ms. Janet Ruggles	SENCORP
Dr. Daniel Schutzer	Citibank
Mr. Howard Sherman	Center for Organizational Learning (USA)
Dr. L. M. Simmons, Jr.	Santa Fe Institute
Mr. Kenneth Slocum	SENCORP
Mr. Henry S. Vaccaro	TXN, Inc.
Dr. David B. Weinberger	The O'Connor Partnerships
Mr. Martin Wildberger	Electric Power Research Institute
Mr. Andy Zimmerman	Coopers & Lybrand

Program for SFI Business Network Workshop, December 6–7, 1993

SUNDAY, DECEMBER 5

7:00 P.M.	Dinner Keynote by Colin Crook, Sr., Technology Officer, Citicorp

MONDAY, DECEMBER 6

	Morning Moderator: David Liddle, Co-founder, Interval Systems
8:30 A.M.	Continental Breakfast
9:00	General Introductions
10:00	Break
10:30	Michael Cohen, University of Michigan Institute for Public Policy Studies *Learning in Organizations* (talk and general discussion)
12:00 P.M.	Lunch
	Afternoon Moderator: David Weinberger, General Partner, The O'Connor Partnerships, and Managing Director, Swiss Bank Corporation
1:30	Brian Arthur, Food Research Institute, Stanford University *Adaptation and Complexity in the Economy* (talk and general discussion)
3:30	Break
4:00–5:00	Business Network members talk in detail about their key interests
7:00–9:00	Dinner Keynote by Doyne Farmer, Founding Scientist, The Prediction Company

TUESDDAY, DECEMBER 7

	Morning Moderator: L. M. Simmons, Jr., Vice President for Academic Affairs, Santa Fe Institute
8:30 A.M.	Continental Breakfast
9:00	Melanie Mitchell, Resident Director, Adaptive Computation Program, Santa Fe Institute *Adaptive Computation* (talk and general discussion)
10:15	Break
10:45	Business Network members talk in detail about their key interests
12:00 P.M.	Lunch
	Afternoon Moderator: Esther Dyson, Editor & Publisher, Release 1.0
1:30	Chris Langton, Theoretical Division, Los Alamos National Laboratory *Artificial Life* (talk and general discussion)
3:30	Break
4:00–5:00	Follow-up planning for next Business Network meeting

RESEARCH ENVIRONMENT

Facilities

The Institute currently occupies office space in three 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 17, computer facilities, library space, and shared office space for up to 30 scientists.

In September 1993 the Institute purchased a 32 acre site with a 12,000-square-foot facility which will become SFI's permanent campus. The current facility is was originally a private home, constructed in the late 1950s, built in a rectangle around an atrium. The vast open middle of the house may be one of its best features since it is very conducive to informal interactions. There is adequate space to accommodate meetings of up to 50 people, a well as several seminar rooms. The move to the new campus will take place in Spring, 1994. Initially researchers and staff will find the new space both inspiring and confining. The inspiration comes from the 32 acres of hillside which surround the new campus; the confinement comes from trying to fit into a house with fewer, but larger rooms than SFI currently occupies in its office suites. The Institute expects to build additional space as soon as finances permit.

Computational Environment

The computing system at the Santa Fe Institute was greatly expanded during 1993. The primary area of expansion was in the area of desktop UNIX workstations which provided additional CPUs, faster CPUs, and minimal additional storage space. The total expansion amounted to nearly doubling the total processing power and file storage space available at the Institute.

Interconnectivity plays an important role at the Institute. As much of the research supported by SFI is conducted by teams of researchers spread around the globe and visitors with diverse computation and communication needs, the ability to communicate with distance computational resources is crucial to the success of these endeavors. This is particularly important for those needing access to supercomputing resources, which the Institute cannot currently provide. A 56-kb link to New Mexico TechNet provides SFI's connection to NSFNet and, thereby, to worldwide Internet. Local connectivity is provided by Ethernet and Appletalk local area networks.

Current intermediate-range plans for the computing system entail establishing a minimum performance threshold in terms of computing power while maintaining compatibility and available resources. This requires making the administration and research networks more homogeneous. With a more homogeneous computing base, concern can be turned towards software and other computing concerns. Currently the Institute has only about six gigabytes of storage space available for user data files. Within two years there will be a need to have over 30 gigabytes of space available. The Institute also needs to acquire a fully integrated programming environment. Internet access connectivity is always increasing so a faster Internet connection is needed. The Institute will have a need for a full T1 within two years. The minimum performance level will be used when evaluating or purchasing any new software or hardware items. This minimum performance level will then be increased as technology progresses and items become available and will be used to direct future purchases.

Library

The Institute has been building its library resources since 1988 through purchases and as the recipient of several donated collections. The current collection includes about 4000 volumes. New acquisitions have increased by 50% each year, and in 1993 approximately 200 volumes were added to the collection.

SFI maintains a growing preprint collection of relevant literature in the sciences of complexity. Among the 29 current journal subscriptions are *Nature*, *Neural Computation*, and *Science*. Library facilities are supplemented by interlibrary loan arrangements with Los Alamos National Laboratory and the University of New Mexico.

SFI library resources are managed by a part-time librarian.

Collaborative Environment

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. Prior to their residencies, visiting researchers inform SFI as to their anticipated work, and this information is made available to the residential research community in order to speed the collaborative process. Office assignments consciously juxtapose research interests and mix disciplines.

APPENDIX IX

1993 PUBLIC LECTURES

George Gumerman, Southern Illinois University at Carbondale/SFI
Anasazi Prehistory Reconsidered

Blake LeBaron, University of Wisconsin
What Does the Stock Market Tell Us About Real-World Behavior

Oliver Sacks, Albert Einstein University and New York University
Neurology and the Soul

Will Wright, MAXIS
Software Toys: Computer Modelling for Everyone

David Campbell, University of Illinois, Urbana-Champaign
Chaos, Order and Patterns: Paradigms for Our Nonlinear Universe

Charles Stevens, Howard Hughes Medical Institutes and The Salk Institute
The Brain as a Computer

Robert McCormick Adams, Smithsonian Institution
Reflections on Ancient and Modern Iraq

Dee Hock, Founder, VISA
On the Nature of Beasts: Adaptation and Learning in Institutions

John Horner, Museum of the Rockies at Montana State University
The New Age of Dinosaurs

Roger Shepard, Stanford University
Perception, Pictures and Paradoxes: What Illusions Reveal About the Mind

APPENDIX X

SFI EXTERNAL FACULTY

Prof. Philip Anderson	Princeton University
Prof. Kenneth Arrow	Stanford University
Prof. W. Brian Arthur	Food Research Institute, Stanford University
Dr. Per Bak	Brookhaven National Laboratory
Prof. Michele Boldrin	Northwestern University
Prof. William Brock	University of Wisconsin
Prof. David Campbell	University of Illinois, Urbana-Champaign
Prof. Jack Cowan	University of Chicago
Prof. James Crutchfield	University of California, Berkeley
Prof. Rob De Boer	University of Utrecht
Dr. Robert Farber	Theoretical Division, Los Alamos National Laboratory
Dr. J. Doyne Farmer	The Prediction Company
Prof. Marcus Feldman	Stanford University
Dr. Walter Fontana	Interval Research Corporation
Prof. Stephanie Forrest	University of New Mexico
Prof. John Geanakoplos	Yale University
Dr. Murray Gell-Mann	California Institute of Technology
Dr. Jonathan Haas	The Field Museum of Natural History, Chicago
Prof. John Holland	University of Michigan
Prof. Alfred Hubler	University of Illinois, Urbana-Champaign
Dr. Erica Jen	Theoretical Division, Los Alamos National Laboratory
Prof. Stuart Kauffman	University of Pennsylvania
Prof. Thomas Kepler	North Carolina State University
Prof. Timothy Kohler	Washington State University
Prof. David Lane	University of Minnesota
Dr. Christopher Langton	Theoretical Division, Los Alamos National Laboratory
Dr. Alan Lapedes	Theoretical Division, Los Alamos National Laboratory
Prof. Blake LeBaron	University of Wisconsin
Prof. Kristian Lindgren	Chalmers University
Dr. Seth Lloyd	Theoretical Division, Los Alamos National Laboratory
Dr. Melanie Mitchell	Santa Fe Institute
Prof. John Miller	Carnegie-Mellon University
Prof. Nils Nilsson	Stanford University
Prof. Mats Nordahl	Chalmers University

Prof. Norman Packard	University of Illinois, Urbana-Champaign
Prof. Richard Palmer	Duke University
Dr. Alan Perelson	Theoretical Division, Los Alamos National Laboratory
Prof. David Pines	University of Illinois, Urbana-Champaign
Prof. Thomas Ray	University of Delaware
Prof. José Scheinkman	University of Chicago
Prof. Peter Schuster	Institut für Molekulare Biotechnologie
Prof. Martin Shubik	Yale University
Prof. Peter Stadler	University of Vienna
Prof. Daniel Stein	University of Arizona
Prof. Charles Stevens	Salk Institute
Prof. Gérard Weisbuch	Laboratoire de Physique statistique, Ecole Normale Supérieure
Dr. Wojciech Zurek	Theoretical Division, Los Alamos National Laboratory

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