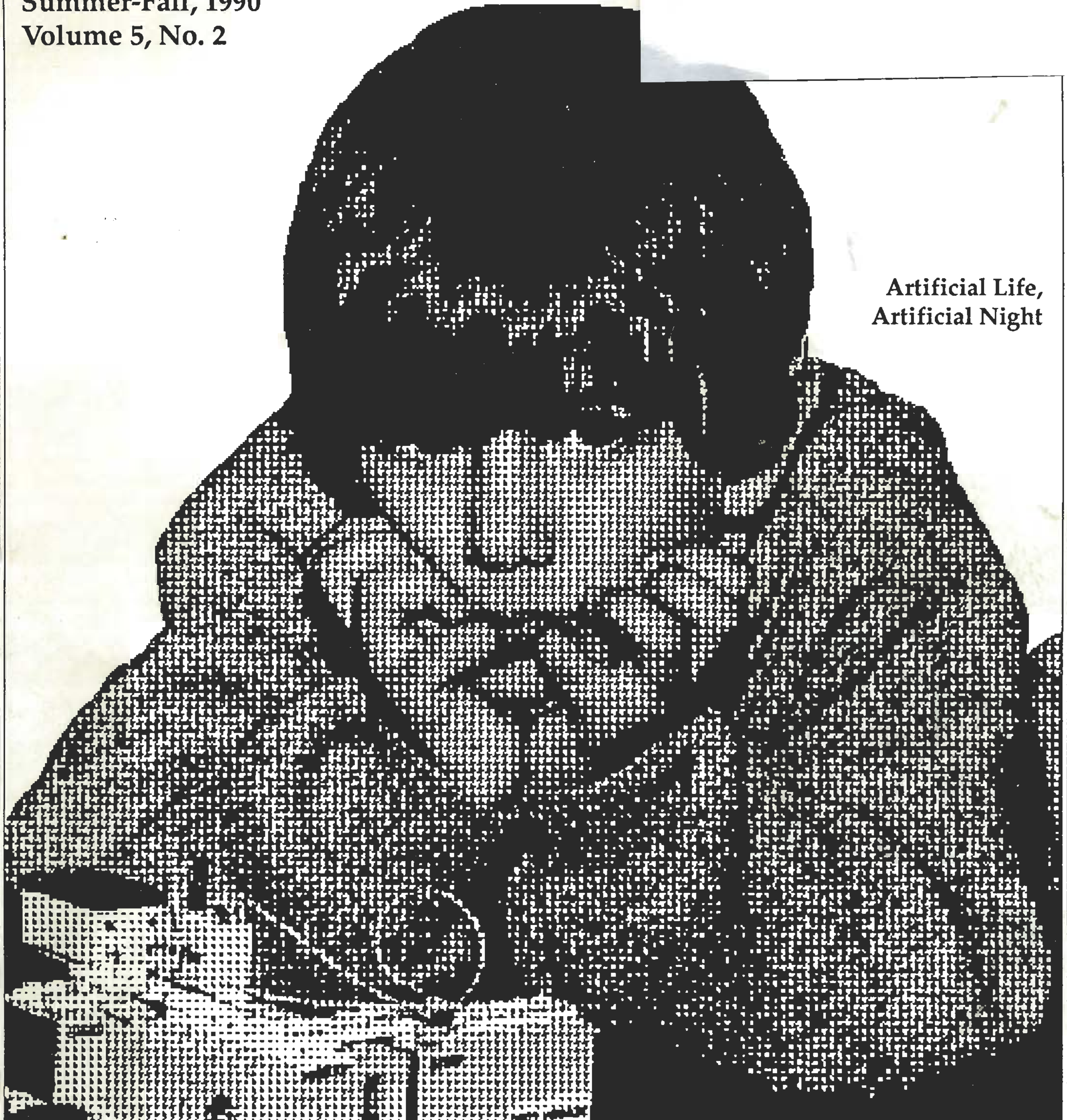
Bulletin of the Santa Fe Institute

Summer-Fall, 1990
Volume 5, No. 2

Santa Fe Institute



Artificial Life,
Artificial Night

In This Issue

Cover

Nicolo Boldrin observes artificial life at the "Artificial Night" public presentation; more on page 17. Original photograph by Cary Herz © 1990, modified in MacPaint.

President's Message

One of the most heartening events in the brief history of the Institute has been the commendation of the John D. and Catherine T. MacArthur Foundation which has not merely renewed its annual grant but increased it and lengthened the term to three years. It is the tangible and encouraging kind of recognition we always hope for but are freshly surprised and delighted to receive. A rosy glow, which has been particularly evident around here since the recent burst of national publicity about the Institute, has now become radiant.

The intellectual agenda has never been more crammed and the interest in participation has never been greater. The fact that our opportunities are growing faster than our resources is challenging but also enormously encouraging. We are very busy trying to measure up to the challenge and thank all of you who are supporting us for your help. We hope you share our cheerfulness about recent events and our determination to do more in the future.

Passing thoughts: There is something in the SFI environment that reshapes our thinking and the things we say. I was reminded of the "SFI effect" recently while reading an interview published in the magazine *Manhattan, Inc.*, in which John Reed, CEO of Citicorp and a sponsor of the SFI economics program, described himself as a complex, adaptive system. That makes sense to me, particularly with respect to John Reed, but I'm curious to know what it might have meant to the million or so New Yorkers who read it. It's tempting to believe that our phrases and metaphors might be migrating from Canyon Road to the outside world, like our current favorite "We're walking the line between order and chaos." Just the other day I said to a nuclear physicist, "I'm caught in a basin of attraction." His response was "You're obviously talking too much to nonlinear dynamicists." I'm afraid that my wife, who has been looking increasingly puzzled by my Newspeak, might agree with him. Is my growing tendency to regard everything as a complex system a passing aberration in a person who has always valued the virtues of simplicity? Maybe so. I'll keep an eye on it and hope that my best friends will tell me when things get out of hand.

George Cowan

Bulletin of the Santa Fe Institute
Volume 5, No. 2
Summer-Fall, 1990
505/984-8800

Editor: L. M. Simmons, Jr.
Associate Editor: Ginger Richardson
Design: Ronda K. Butler-Villa

The Bulletin of the Santa Fe Institute is published biannually by SFI to keep our friends and supporters informed about the scientific and administrative programs. The Bulletin is free of charge and may be obtained by writing to the Editor, 1120 Canyon Road, Santa Fe, New Mexico 87501.

The Santa Fe Institute is a private, independent organization dedicated to multidisciplinary scientific research and graduate education in the natural, computational, and social sciences. The driving force behind its creation in 1984 was the need to understand those complex systems that shape human life and much of our immediate world—evolution, the learning process, the immune system, the world economy.

The intent is to make the new tools now being developed at the frontiers of the computational sciences and in the mathematics of nonlinear dynamics more readily available for research in the applied physical, biological, and social sciences.

Theoretical Immunology

The immune system is our primary defense against pathogenic organisms, harmful environmental chemicals, and cells that have become malignantly transformed. The last decade has seen an explosion in detailed experimental findings about the cells, molecules, and genes that make up the immune system. Despite this, much remains to be learned. For example, Acquired Immune Deficiency Syndrome (AIDS) is far from being understood. The epidemic underlines both the importance of the immune system in protecting us from disease as well as our inability to design vaccines and to usefully manipulate the immune system.

The human immune system is a complex system of cells and molecules distributed throughout our bodies. Because it must protect all of the tissues of the body it is necessarily dispersed. The most important cells of the immune system are a class of white blood cells known as lymphocytes. These cells are transported throughout the body via the blood stream and lymph, the fluid bathing the cells of the body; they look for foreign molecules or cells, objects which immunologists call antigens.

Analogies have been drawn between the immune system and the nervous system. Like the nervous system, the immune system performs pattern-recognition tasks, learns, and retains a memory of the antigens that it has fought. Many of the "players" in the immune system, the specific cells and molecules whose coordinate activity produce the phenomena of immunology, have been identified. The interactions between these cells and molecules are slowly being discovered. However, the mechanisms that regulate the immune system are by and large still unknown. Among the goals of theoretical immunology is to identify and characterize possible regulatory schemes and the mechanisms underlying learning and memory. In this article, I provide a brief introduction to the biology of the immune system and attempt to summarize some of the main theoretical efforts occurring at the Santa Fe Institute.

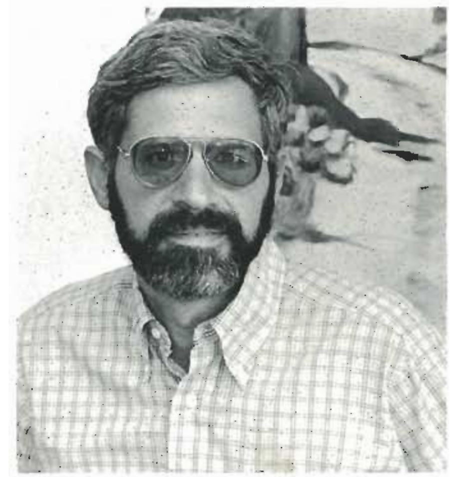
Biology of the Immune System

Lymphocytes have been subdivided into two major classes: B cells and T cells. B lymphocytes secrete antibody, one of the major protective molecules in our bodies. T lymphocytes are involved in cell-cell interactions. Some T cells are responsible for killing tumors or cells infected by a virus, whereas others, helper T cells, secrete factors that promote the growth and differentiation of B cells and other T cells. Both B cells and T cells have receptor molecules on their surface that can recognize antigen. These cells thus provide specificity to the immune system and are responsible for its apparent cognitive properties: pattern recognition, learning, and memory.

Pattern recognition in the immune system is done rather differently than in other systems. Patterns are recognized by a process that is intrinsically random and seemingly wasteful. The problem that the immune system needs to confront is the recognition of all possible foreign organisms and molecules, even ones that have never before been seen in the course of evolution. The strategy that the immune system uses is called *clonal selection.* It is most easily understood in the context of generating B cells that can secrete antibody aimed against any foreign organism. The body creates a very large diverse set of B cells, each B cell carrying a receptor able to recognize some molecular shape or set of related molecular shapes. The receptors are made by a complex genetic process that is highly error prone and thus to a large extent the receptors have binding sites with random shapes. Many, perhaps most, B cells express receptors that are useless and detect nothing. Such cells die within a few days. However, on occasion a randomly made receptor is useful and detects something. The cells carrying this receptor are stimulated to grow into a clone of identical cells, and the receptor molecule, now known to be useful, is secreted as antibody.

Maturation of the Immune Response

During the proliferation of the cells, mutations occur at unusually high frequency within the genes coding for the receptor molecule. Thus further refinements in receptor and antibody specificity occur during the course of an immune response. The details of this refinement process, known as the maturation of the immune response, have been studied by Stuart Kauffman, an External Professor at the Institute; SFI visitor Catherine Macken, currently in the Mathematics Department at Stanford University; SFI visitor Patrick Hagan, an applied mathematician at Los Alamos National Laboratory; and me.



Alan S. Perelson. Photo: Cary Herz © 1990.

By creating receptors at random, throwing out the useless ones and retaining the useful ones, the immune system can recognize essentially any shape. Further, what is perceived as being useful can change during the life of an organism. Thus, if a new virus appears, a cell with a previously useless receptor may now be called into action. This recognition process is called clonal selection because a foreign molecule, antigen, selects which cells of the immune system are to grow into an antibody-secreting clone.

Using data from experimental animals and some simple theory, George Oster (University of California, Berkeley) and I were able to estimate the efficiency of the clonal selection process. We discovered that if the system contains at least 10^5 randomly made receptor types, then any molecular shape could be recognized with enough fidelity to stimulate an immune response. Interestingly, the smallest organism that contains an immune system is the tadpole and it is estimated to have about 10^5 lymphocytes. Human and other higher vertebrates are thought to contain 10^7 different lymphocytes and thus are even more efficient at recognizing antigen.

A consequence of the immune system having essentially complete recognition ability is that the body recognizes its own antibodies as antigens. Antibodies are just protein molecules. A novel protein made by a stimulated B cell and secreted into the blood stream should look to the rest of the immune system just the same as a novel molecule made by a bacterium or some other pathogen. If the antibody concentration gets high enough, the system recognizes the antibody and responds to it by making another antibody that can bind to it. The unique portions of an antibody molecule that the immune system uses for recognition purposes are called *idiotopes*. The antibodies raised against other antibodies are called *anti-idiotypic* antibodies.

The fact that the immune system makes anti-idiotypic antibodies leads to the idea, first presented by the Nobel prize-winning immunologist Niels Jerne, that the interactions between idiotype and anti-idiotype might regulate interactions in the immune system and allow very specific information to be passed between lymphocyte clones. Thus, in contrast to the clonal selection idea in which antigen selects clones that recognize it to respond, with the decay in antigen turning off the response, Jerne suggested that the immune system is organized as an active network of interacting cells and molecules. Thus even in the absence of antigen the immune system would be engaged in internal activities which would then be perturbed by antigen. Although the network idea is appealing and internal activity has been discovered in the immune systems of animals raised in "germ-free" environments, it is nevertheless controversial.

The Network Hypothesis

One area of focus of the Theoretical Immunology program at the Santa Fe Institute and the Theoretical Biology and Biophysics Group at Los Alamos National Laboratory, has been the evaluation of the network hypothesis. For example, one concern raised about the network hypothesis is that if antibodies are made against antibodies, will a cut on your finger lead to a cascade of reactions in which your entire immune system is excited? Such a level of excitation does not fit with observation. Rob De Boer, a postdoctoral fellow at Los Alamos National Laboratory, Gérard Weisbuch, an Institute visitor and statistical physicist from Ecole Normale Supérieure, Paris, and I have shown that this need not be the case and that responses can remain localized within the network.

Immunological Memory

We have also examined the ability of the network to store information and account for "immunological memory." Most immunologists believe that memory is carried by specific cells, memory cells, with one cell population or clone for each memory. This is similar to an idea in human memory which once proposed that we have a specific neuron in our brain that remembers, for example, our grandmother, the grandmother cell. In the theory of neural networks, another area of activity at the Institute, it has been shown that information can be stored in the strengths of connections between neurons. In the immune system we and others have been attempting to show that memory can be stored in the dynamical interactions between cells in a network. Thus, rather than having a static situation where a cell is at rest waiting for antigen to come trigger it, we envision that, due to network interactions, a cell that can recognize antigen is already excited and interacting with another cell or antibody in the network that has a molecular shape similar to that of the antigen. Our analysis to date suggests that memories are stored locally in interactions among a few cell populations. This is quite different than the information storage in a neural network which can be distributed throughout the entire network.

Models

Another area in which the Theoretical Immunology program has been active has been in the development of global models of the immune system. Here the challenge is to discover the means of modeling a system with at least 10^5 different elements, and whose elements change rather rapidly. (Recall that a B cell that is not useful may be replaced in a few days by another B cell with different recognition properties.) This work has much in common with models for autocatalytic networks and the origin of life that are being worked on by Stuart Kauffman, Doyne Farmer, SFI External Professor and Leader of the Complex Systems Group Leader at Los Alamos National Laboratory, and graduate student Richard Bagley, who is visiting Los Alamos and SFI from the University of California at San Diego.

Recently, Rob De Boer and I have implemented a simulation model of the developing immune system in which B cells and antibodies are characterized by binary strings. The system is initiated with a set of maternal antibodies, presumably available to the fetus. If their bitstrings are complementary to any already present in the system, the cells may become stimulated to grow and secrete antibody. The growth of B cells and the changes in antibody concentration are modeled by a set of nonlinear ordinary differential equations. The simulations show that an immune network develops in the course of about one month and then reaches an equilibrium size. Thus, even though the bone marrow continues to make new B-cell clones, the number of clones in the system remains approximately constant at a level determined by the internal activity of the immune system. The model predicts that the average number of connections per clone changes in time, with early networks being highly connected and older networks approaching an equilibrium in which the connectivity is rather limited. Recent experiments are in accord with this prediction—newborn mice appear to have a very highly connected network whereas adult mice appear to have very limited connectivity in their networks. Interestingly, the model also predicts that some clones will not be regulated by the network and will behave as would be predicted by clonal selection theory, whereas others will have their behavior determined by network interactions. Thus, a possible resolution of the clonal selection versus network ideas may be that they are both right but describe different aspects of the immune system!

We have also been involved in the development of models of the interaction of the immune system with the human immunodeficiency virus (HIV), the virus thought to cause AIDS. Here we have been trying to understand how a virus which infects rather few T cells, maybe one in a hundred, can cause the almost total depletion of the T-cell population in an infected individual. The Institute sponsored a workshop in October, 1988, in which AIDS experimentalists and theorists were brought together to help identify fundamental problems in AIDS research and begin communication between these two groups. In the fall the Institute will sponsor a three-month visit by one of the workshop participants, Professor Stephen Merrill, a mathematician from Marquette University in Milwaukee, who has been developing stochastic models for the initial stages of HIV infection. Merrill's work centers on why AIDS has such a long incubation time, close to ten years in adults.

Summary

There are many areas in which theory can contribute to our understanding of the immune system. Space has permitted me to mention only a few. Besides network models and AIDS models, we are very interested in auto-immune disease and the prospect of treating such diseases via network manipulation. Recent modeling work is aimed at elucidating the benefits of having local sites at which immune reactivity is enhanced. Modeling of the complement system, the interaction of the immune system with tumors and virally infected cells, and the basic processes of cellular cytotoxicity have also been some of our activities.

Because the immune system is a complex system it has been difficult to study both experimentally and theoretically. It is our hope that by approaching the immune system from the viewpoint of complex systems theory that we may be able to gain insights and make progress where other approaches have failed. The payoffs for success are great and make this a provocative challenge for the Institute.

–Alan S. Perelson

Dr. Alan S. Perelson is an SFI External Professor and a Member of the Theoretical Division, Los Alamos National Laboratory. He also serves on the SFI Science Board, and has edited three SFI proceedings volumes.

Book Review

Read On

Mathematical Biology
by J. D. Murray
Biomathematics Texts, vol. 19
Springer-Verlag, 1989

The success of the use of mathematical models in the sciences is known to many through a history of striking examples in physics and chemistry. The use of mathematical models to further understand biological processes is a rather newer endeavor, but by no means lacking in success. MacArthur Fellow Charles Peskin, Courant University, has been recognized for his fluid dynamical model of the heart, and its role in the analysis of heart valve designs. Another MacArthur fellow, Art Winfree, University of Arizona, in his work on circadian rhythms, has gained useful insights into possible causes of sudden cardiac death. Theoretical work by Nancy Kopell, Boston University, has led to increased understanding of the central nervous control of the regular muscle activity needed for fish locomotion. A somewhat different investigation is the tracking of the evolution by mutation of the HIV virus, the agent of AIDS, a project managed by Gerald Myers of Los Alamos National Laboratory.

Each of these examples has emerged from a close interaction of biology and mathematics. In recent years, biology, and especially biomedicine, has expanded in scope as a result of breakthroughs like the discovery of the structure of DNA, the design of monoclonal antibodies, and the development of polymerase chain reaction for amplifying minute quantities of DNA, to mention just a few. The biological sciences are becoming increasingly quantitative as the details of immensely complex natural world systems are explored at increasingly finer resolution. No longer is it sufficient for a scientist to simply observe and record. It is becoming imperative to incorporate sound theoretical methods into the range of available experimental and observational techniques. Mathematical models in biology add to the tool kit with which one examines a system or process. The best models do more than mimic observed phenomena: they also predict outcomes, suggesting a direction for future research.

J. D. Murray's *Mathematical Biology* is a superb text. It does not give a description of mathematical techniques with potential biological applications so much as provide sophisticated insight into the subtleties of the mathematical and biological teamwork which leads to relevant and important contributions to biology. As is amply demonstrated in this book, the mathematics is also rich and varied. Professor Murray writes with integrity, true to his stated claim that "Mathematical biology research, to be useful and interesting, must be relevant biologically."

The contents are organized according to classes of biological (and sometimes chemical or biochemical) phenomena.

The first four chapters consider single and two-population models in continuous and discrete time. Although these are described in the context of ecology, they have obvious applications at other levels, for example, cell population studies. Murray develops differential and difference equation models, for which solutions in some cases include chaos. A chapter on reaction kinetics follows with particular attention to Michaelis-Menten enzyme kinetics. With the addition of feedback controls in the form of autocatalysis, activation or inhibition, these models may lead to multiple steady-state solutions.

Biological oscillators are also considered, with an important example of modeling being the FitzHugh-Nagumo model of the Hodgkin-Huxley model of electric potential across a nerve membrane. The subject of oscillators is expanded to consider coupled oscillators (including an introduction to singular perturbation theory), black holes in real biological oscillators, and a chemical oscillator, the Belousov-Zhabotinskii reac-

Book Review *(continued)*

tion. This last is a prototype of an oscillator which is now understood in great detail. Murray gives an in-depth analysis of the Field-Noyes model of this reaction as an illustration of generally useful analytical methods.

Later chapters cover a plethora of examples of wave phenomena. Fish locomotion is considered in detail. A fish propels itself by muscle activity which sets up traveling waves along its longitudinal axis. The central pattern generator is a neural network that generates sequences of signals producing the required patterns of muscle activity. Modeling has been necessary to understand such neural control of locomotion. This work is an important contribution to neurobiology, one of the fields which has particularly benefited from the use of mathematical models.

The chapters that discuss studies of pattern formation are fascinating, and include some figures demonstrating the striking resemblance of mathematically generated patterns to those of, for example, the zebra's coat (no, he doesn't wear pajamas), leopard spots, and butterfly wings.

The last two chapters cover models of epidemics: their magnitude and geographical spread. Murray tells the story of the Black Death in 14th century Europe. The spread of rabies throughout Europe is also modeled, with diffusion effects generating traveling wave fronts, which are used to model the spread of the disease.

Professor Murray writes in a relaxed style. He has the knack of introducing a new modeling area by capturing the essence of the important questions. His stories have interest and humor. He tells of Bob Dylan and the 13-year cicada connection, as well as the Lake Victoria-Nile perch ecological disaster (which might have been avoided if a mathematical model of the ecological system had been studied).

I particularly appreciate Murray's concern for the usefulness of biological modeling. He issues caveats to the nondiscriminating users of models. Describing a model exhibiting oscillatory behavior, with a spurious interpretation, he says: "The moral of the story is that it is not enough simply to produce a model which exhibits oscillations but rather to provide a proper explanation of the phenomenon which can stand up to ecological and biological scrutiny."

This is not a text for the mathematically faint at heart. It requires competency with differential equations and matrix algebra. Four appendices contain some important details of frequently encountered techniques, such as phase-plane analysis. The bibliography includes 21 pages of references in small type. Substantive problems are given at the end of each chapter. Most problems are framed within the context of a real biological scenario.

There are no stochastic models in this text; they are omitted to keep the book within bounds. However, mention is made of the need for stochastic models to take over from their deterministic analogues as appropriate. Also omitted are some large areas such as population genetics, about which entire books have been written.

Such comments on omissions seem almost irrelevant in light of the impressive compendium here assembled. The book is written with authority and integrity and will, I am sure, be a most useful and entertaining addition to the literature of mathematical biology.

—Catherine Macken

Catherine Macken is currently a Visiting Associate Professor at Stanford University in the Department of Mathematics and Statistics working with Sam Karlin on DNA sequence analysis. Her home instution is University of Auckland, New Zealand. She has a longstanding interest in biological problems.

Board News

At its March, 1990, meeting the Institute added six new members to its Board of Trustees:

Jacqueline B. Cotsen is President of Cotsen Capital, an investment banking firm based in Los Angeles, California. Following a successful career running her own company specializing in business start-ups and turnarounds, in 1976 Ms. Cotsen joined Citicorp, where she was in charge of positioning Citibank within the global economic environment. There she supervised a global study on the convergence of telecommunication and computers. Ms. Cotsen served as an advisor to The Council of Economic Advisors under Presidents Nixon and Ford. She is presently a member of the United States Trade Representatives' Services Policy Advisory Committee.

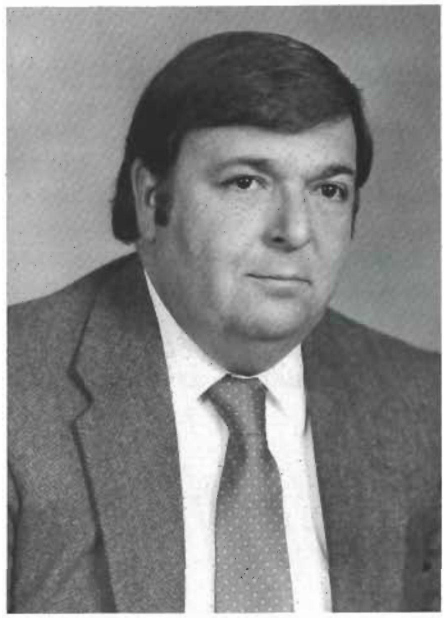
Jacqueline B. Cotsen

Christine Maxwell is Director of Group Business Development for Pergamon Press Publishers. At Pergamon she has worked in a variety of positions including Editor-in-Chief of school educational products and Director of Marketing. Ms. Maxwell is also President of Research On Demand, Inc., a market research firm in Berkeley, California. Before holding these positions, she worked as an elementary school teacher and as a commissioning editor for children's books at A. Wheaton and Company, Ltd. More recently she has served as the general editor of *Nuevas Fronteras/New Frontiers*, a bilingual early learning program in Spanish and English, and for *The CoRT Thinking Program*, both published by Pergamon Press.

Ann Richards Nitze is owner and President of Ann Kendall Richards, Inc., New York, a private international fine art dealership specializing in nineteenth and twentieth century works. She is a Trustee of the Aspen Center for Environmental Studies, and a Member of the National Council of the World Wildlife Fund.

A private investor and consultant in Santa Fe, **James Pelkey** is a former General Partner in Montgomery Securities and former President, Chief Executive Officer and Director of Sorcim Corporation, a Silicon-Valley-based computer company. Mr. Pelkey serves as Chairman of the Board, Digital Sound Corporation; other board memberships include Peregrine Ventures Advisory Board, MCAE Technologies, and the Global Business Network.

Ray Sena is President of Shuttlejack, Inc., a charter bus and route transportation company which operates throughout the West. A native Santa Fean, Mr. Sena is a member of the Harvard Business School Alumni Association, and serves on numerous boards including the Santa Fe Chamber of Commerce and the Santa Fe Symphony.



Ray Sena

Albert D. Wheelon is former Chief Executive Officer of Hughes Aircraft. Dr. Wheelon has a distinguished record of public service, serving on the Defense Science Board and the President's Foreign Intelligence Advisory Board. In 1986 he was named to the Presidential commission on the Space Shuttle Challenger accident. He is a Trustee of the California Institute of Technology, and has published more than thirty scientific papers on applied physics and a book on applied mathematics. Dr. Wheelon is a member of the National Academy of Engineering, and a Fellow of the IEEE and the AIAA.

Albert D. Wheelon

Christine Maxwell

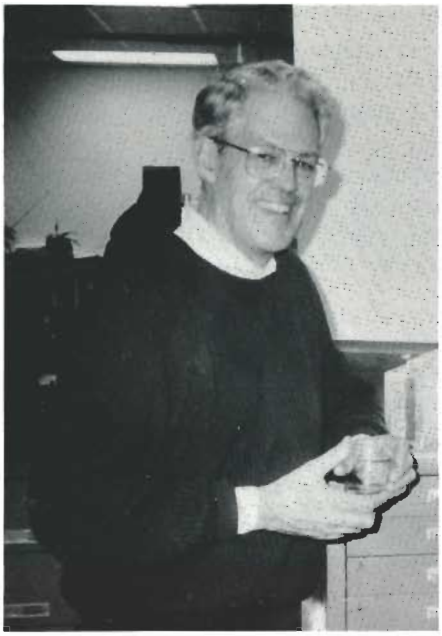
Presidential Search Committee Formed

At their March, 1990, meeting, the Board of Trustees of the Santa Fe Institute approved the establishment of a Presidental Search Committee to accept applications and nominations for the presidency of SFI.

George Cowan, who has held the post since 1984, has asked to be relieved of his duties in order to increase his participation in SFI research activities. "Now is the time for a second generation of leadership at SFI," Cowan commented. "It has been very gratifying to me to have been involved in the launching and early success of the Institute. I am confident our new president will continue to develop this unique endeavor."

Members of the search committee, chaired by Robert McCormick Adams, Secretary of the Smithsonian Institution, include Philip Anderson, Princeton University; Kenneth Arrow, Stanford University; Carl Djerassi, Stanford University; Hans Frauenfelder, University of Illinois; John Holland, University of Michigan; Carl Kaysen, M.I.T.; David Pines, University of Illinois; John Reed, chairman of Citicorp; David Robinson, Carnegie Commission on Science, Technology and Government; and John Schaefer, president of Research Corporation.

SFI Board chairman, Robert O. Anderson has asked the committee for a recommendation by September 30, 1990.



Edward A. Knapp

Interview

Defining the Mission

Edward A. Knapp is Vice Chairman of the Institute's Board of Trustees. He is past President, Universities Research Association in Washington, D.C., and former Director, National Science Foundation. Currently he is a Senior Fellow, Los Alamos National Laboratory, pursuing research in high-energy experimental physics and particle accelerators. He is a Fellow of the American Physical Society and the American Association for the Advancement of Science, and a Senior Member of IEEE. In addition to a B.S. from Pomona College and a Ph.D. from the University of California at Berkeley, Dr. Knapp has been awarded several honorary degrees.

How did the Santa Fe Institute begin?

In 1983 I was still at the National Science Foundation but I came back to Los Alamos from time to time. I was a Senior Fellow at the Laboratory at that point and I talked, particularly at lunch, with a group of Senior Fellows—George Cowan, George Bell, Nick Metropolis, Stirling Colgate, Herb Anderson, David Pines, Murray Gell-Mann, Pete Carruthers, and several others. We became enthusiastic about the possibility of establishing an interdisciplinary institute in Santa Fe. At that point we hadn't homed in on the sciences of complexity and nonlinear systems. We knew that Los Alamos was very good at bringing areas of different disciplines of science to bear on a problem. But we felt that the breadth of problems that could use this interdisciplinary approach was much broader than the Laboratory could attack; the Laboratory didn't have mandates in many of the fields we discussed, such as economics, which we talked about early on.

Although I don't have a strong university background, I did run the NSF for a couple of years and it was clear that within the discipline areas of science in the United States our universities are absolutely the best in the world. But it also was very clear that the boundaries between departments and disciplines at universities are high. In fact, it is very difficult for a young person to go into a university and work in a field of science that spans disciplines. And it is difficult for a person to get tenure without having built a career in a discipline. Our group of Senior Fellows thought it would be very interesting if we could put together an institute where young people were enthusiastically encouraged to do cross-disciplinary research—understanding, of course, that this was going to be outside the typical track of a university profession and that it might be very exciting but also that it might cause career problems at some point in the future.

Somehow this whole business of an institute snowballed and we actually incorporated and became a nonprofit organization in 1984. One of the unique things about the Institute is that, while it started with this relatively small group of people at Los Alamos, it became extremely exciting to everybody around the country—around the world—we explained it to. Soon we had a very strong group of people who decided to join our small group at Los Alamos, to form the Board of Trustees and the Science Board. The time had come for the ideas we talked about during our lunches. The Santa Fe Institute was off and running.

Why did you establish the Santa Fe Institute in Santa Fe instead of at Los Alamos?

One of the ideas was that we were really interested in research areas in which Los Alamos didn't have much funding or much interest. For example, our first major workshop was "Emerging Syntheses in Science." It was held at the School of American Research, which is an archaeological/anthropological organization here in Santa Fe. During this workshop we had a lot of interest from the archaeological community in using the techniques of modern science—physics, chemistry, and so on—to help them address some of their problems. The book that came out of that workshop is a fantastic document in some ways. It points out all sorts of connections that are now being pursued very strongly in university settings. It would have been hard to get money to do such a workshop at Los Alamos or at a university, or to draw the people we ended up attracting to our workshop. Los Alamos has a reputation for working on certain types of problems in a certain way and we didn't want people to dismiss us as just a subset of Los Alamos.

But some of the really exciting things going on in Los Alamos involve the complex systems and interdisciplinary approaches to problems you are pursuing at the Institute.

That's right. That is certainly the case for the Center for Nonlinear Studies at Los Alamos and the Human Genome Project and a number of applied programs of a more general nature. These programs are interdisciplinary in that they couple engineering sciences and the physical and mathematical sciences. That is one of the things Los Alamos does so well—they have a history and a tradition of doing things this way. But the Santa Fe Institute really wants to push the boundaries of this interdisciplinary study much farther in the sense of not limiting the fields that get involved in a particular problem. In fact, as the Institute has grown and matured, it's homed in on the whole idea of complexity. "Complexity" is kind of a buzz word, perhaps, but we think of a complex system as a system that is probably never in equilibrium, a system with many interacting parts that are not easily described by simple arithmetic. A complex system has lots of inputs and lots of probable outputs; it is nonlinear in that a given input doesn't lead to a proportional output. Our focus on complexity at the Institute during the past seven years means that we think most of the interdisciplinary problems we study have real relevance to the world and also appear to have potential for breakthroughs.

The same interdisciplinary approach might work to study both economic systems and global weather.

There may or may not be similarities between economics and the weather but in any case both systems have complex inputs and a variety of possible paths that can develop in time. It's important in economics and weather prediction and many other fields to be able to track a probable path of evolution, particularly if you want to use your enhanced understanding to make policy decisions—or to decide whether or not to take your airplane off the ground.

Economics and weather aside, there are many other systems that are complex and whose problems may yield to a better understanding by applying new and modern nonlinear mathematical approaches. The immune system, the human body, the evolution of life, the way chromosomes work, the way all living things work, the way an ecology develops—these are all very complex systems that can be understood much more thoroughly by applying sophisticated mathematics. When studying these systems you don't try necessarily to find a solution that yields to some sort of analysis and then try to fit the problem into the solution. Instead, you try to look at the whole problem and see if there is some way you can make your approach to the problem more sophisticated as you go further.

How did you go about putting together the Board of Trustees and the Science Board?

The original people on both of these boards were friends, acquaintances, or scientific colleagues of the founding group of Senior Fellows and visitors to Los Alamos. We knew they would be interested in this sort of science. Both boards were put together ad hoc to begin with and adding people to them became more sophisticated as knowledge of the Institute spread through the scientific communities here and abroad. When the purpose of the Institute was explained to people, they almost universally said they would like to become involved.

But your Boards, especially the Trustees, are not exclusively made up of scientists.

No. In fact, we have a number of people interested in business and people interested in administration of one kind or another. But these people share an interest in the scientific approach to problems and also share an interest in education and understanding—intellectual approaches, if you will.

> "...the Santa Fe Institute really wants to push the boundaries of this interdisciplinary study much farther in the sense of not limiting the fields that get involved in a particular problem."

Was a large part of your time at a certain point spent recruiting people?

I don't recall that being the case. People just sort of gravitated to the Institute from diverse backgrounds. For example, Art Spiegel, a businessman and founding member, was very important in getting the Institute off the ground.

We were worried for a little while that we had too many people from Los Alamos, but we really haven't had any difficulty attracting people from the international scientific community.

You served as Chairman of the Board of Trustees for a couple of years.

Yes. I thought I could help the Institute in that position. I can say I didn't do very much as Chairman of the Board, but during that time we did get a couple of grants from Federal agencies. Perhaps my connections with the Federal government stemming from my days at the NSF and at URA helped us. The bulk of the fundraising work was carried out by George Cowan.

Has the Institute evolved into what you envisioned, or has it changed as it has evolved?

I think it's better now than I thought it would be. I think it's got a lot of focus and a lot of very good people associated with it. Its program has gone from being extremely diffuse at the beginning to being focused on systems of complexity. We work on some of the serious, outstanding problems in science. We have room for addressing other problems, but if we make some major progress in the areas we're presently addressing we will have made a secure and unique place for the Institute.

Where do you see the Institute going in the next couple of years?

At this point the Institute has had several small programs with resident scholars in economics and some of the biological sciences. I think we need a major infusion of funds to have a more active resident program. We have run a number of workshops in which people meet, talk, make networks, go back to their home institutions, and then keep in touch and exchange information. That's worked out very well, but the Institute will not make it on the basis of just being a facilitator of workshops. It has to be a place for scholars to come to work, to discuss, to write papers, and to make solutions to problems. Expanding this role will take quite a bit more money than the institute has right now and I hope that in our drive for funds that we'll get enough support to expand. We need a resident faculty and students—young postdoctoral fellows—so that we can do real forefront interdisciplinary research in the problems of complexity. The Institute now has a large computing capability because of its connections to networks of large computers around the world. I think we're at a point where we could really take off and start making even more major impacts on the scientific community if we could support more people.

> "...we're at a point where we could really take off and start making even more major impacts on the scientific community if we could support more people."

How large do you envision the Institute growing?

In the early days, we didn't discuss that question in detail. We couldn't say we wanted it to be one hundred people in residence or anything like that; we always believed the Institute would evolve into whatever it should become. We're certainly under the critical mass of people in residence and we certainly must become a viable educational institution. On the other hand, we have a good number of people coming to workshops and coming to spend two or three months working here. Even with that relatively small number of people we're making major impacts on science.

What are some of those impacts?

The economics program is by far the biggest program as far as resident scholars are concerned. We have made an impact on the way economists are thinking about how their science is going to evolve and change. There was a recent article in *Scientific American* by Brian Arthur who led the SFI program for a while. This article has received a lot of good attention. It puts forth some of the ideas on economics that have been important at the Santa Fe Institute.

In the area of adaptive systems, John Holland has been influential. Although he's not a full-time resident scientist, he spends a lot of time here and has developed a novel way of looking at approaches to understanding complex adaptive systems.

If you look down the list of programs we have, I think you can see we are making impacts in the areas of immunology, linguistics, archeology and anthropology, computation and neural networks, and artificial life.

Do you see gaps in the kinds of people you are attracting to your visiting scientist program or your resident program?

I see both of those programs growing. It's not a question of who would like to come to the Institute, it's a question of funding to support them. The visiting scientist program is more or less limited to economics and biology because of our funding levels. Once we can get the kind of support we need, we'll be able to support people in many other areas.

Has the Santa Fe Institute changed the way scientists approach problems?

Very definitely. I think we at the Santa Fe Institute were among the first to point out alternative ways to look at problems. But I think that many people are beginning to understand that it will be very productive to approach complex problems with new mathematics in the way we've pioneered.

Even with limited funds you seem to believe the Institute is doing its job well.

The Institute has attracted an extremely able group of people. These people are interested in the work that is going on and are truly dedicated to the Institute. If we did have the money to support more people we'd have a whole other set of problems—organizational problems, facility problems.

We've anticipated some of the problems we'll encounter as we grow. For example, we've worked out a rather complex academic governance for the Institute when we get the support we need to start having a permanent faculty. We don't know if there will be problems with this system until we have a chance to try it. But I'm certain that, as the Institute evolves and becomes larger, there will be all of those problems that are associated with any institution.

Right now, the largest problem we have is general support.

Do you think you're doing a good enough job of getting the Institute's news out?

The publications program that we've put together is outstanding. We've published a large number of books based on the workshops and studies that have been done here. Some of them have become classics already. I think the one on artificial life has become a standard reference for this field. We're talking about the possibility of a journal for the sciences of complexity. I don't know exactly what the name will be, but it would publish works by people who are members of the Institute and also works by people in the general academic fields of interest to the sciences of complexity.

On the scientific side, I think we've done an excellent job of making what we do known and getting our contributions into the literature of the scientific community.

Now the other job we have is to get information to possible supporters of the Institute—donors and foundations. I think we're doing a fairly good job of that. But it's a harder job. There are always a bunch of major foundations and donors one immediately thinks of, and we've approached a good number of them. There are also a good number of people who are wealthy who would like to support this sort of institute, but they're more difficult to get in touch with. We're at the point where we're trying to get information to this group of people.

The problems are somewhat of a chicken-and-egg nature—you have the support and then you have the result and then you can tell potential donors the results. Often, potential donors are impressed only with the results. I think one of my contributions was to help get the federal support that was needed to get the Institute started. But it's time to expand beyond federal support. The Santa Fe Institute should be a privately supported group with an endowment. Such an endowment is always difficult to get and we haven't really cracked that yet. We've begun to work on it hard, but it's still in the early stages.

"...many people are beginning to understand that it will be very productive to approach complex problems with new mathematics in the way we've pioneered."

Besides hard work, raising funds also takes time and patience.

It takes time and patience and also extremely careful planning to make sure that the interests of the institute and the interests of potential donors coincide.

Overall, you seem to think the Institute has grown remarkably well—that the growing pains have been minimal—that exciting things have been happening—that you have a proper relationship between Los Alamos National Laboratory and universities and the Institute—that a lot of excitement is generated during your summer programs.

Yes, I think that's correct. The summer school program on complexity is a very successful thing. It's sponsored by the Universities of Arizona, California, Illinois, New Mexico, and Texas, Los Alamos National Laboratory, Sandia National Laboratories, and the Santa Fe Institute. We've run that now three summers in a row at St. John's College here in Santa Fe. Faculty come from universities and laboratories all over the country. The students tell us that these programs have been some of the most stimulating they've ever experienced. They go away completely enthusiastic. And the books that come out of these summer programs are becoming standard texts for the sciences of complexity. We're very pleased with that. Our summer programs are not the main focus of the Institute, but they are certainly very successful offshoots of it.

—Marc Talbert

Marc Talbert is a freelance writer based in Santa Fe.

SFI to Move in 1991

Although the ambiance of the Cristo Rey Convent has suited the meditative nature of SFI research, the Institute will move to larger quarters when its lease expires at the end of 1990. SFI has signed a lease for two buildings in the Old Pecos Trail Office Compound, near St. Michael's Drive. The new facility will boast a large conference room, adequate parking, and more space for researchers and staff. Ginger Richardson and Ronda Butler-Villa will help coordinate a smooth transition to the new facility. More information should be available in the next Bulletin.

1990 Complex Systems Summer School

For the third time, more than 50 students have gathered during the month of June at St. John's College in Santa Fe for the annual Complex Systems Summer School. The School provides graduate students and postdoctoral scientists from throughout the world with an introduction to the study of "complex" behavior in mathematical, physical, and living systems. The program consists of four intense weeks of course lectures, seminars, computer workshops, experimental labs, and individual research. The school becomes a working community of scholars. Collaborations among participants flourish; also students this year and in the past have begun long-term working relationships with the faculty, and with researchers at the Institute and Los Alamos National Laboratory.

The 1990 school was led by Lynn Nadel and Daniel Stein, both from the University of Arizona. Institutional sponsors were the Center for Nonlinear Studies, Los Alamos National Laboratory; Santa Fe Institute; Sandia National Laboratories; and the Universities of Arizona, California, Illinois, New Mexico, and Texas.

Support

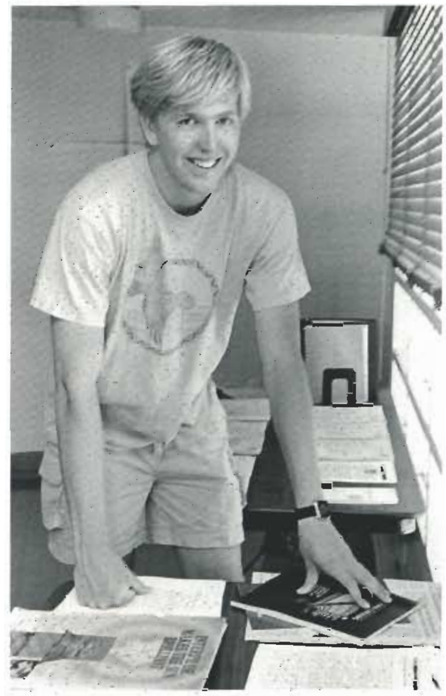
The school was funded by grants from the U.S. Department of Energy, the National Science Foundation, the Office of Naval Research, and Research Corporation. Computer hardware was donated by Apple Computer, Digital Equipment Corporation, International Business Machines, and Sun Microsystems. Computer software was donated by Precision Visuals.

1990 courses

Learning Algorithms
    Andrew Barto, Computer Science, University of Massachusetts

Complexity in Fluid Flow
    Bruce Bayly, Mathematics, University of Arizona

Stochastic Processes in the Physical & Biological Sciences
    Charles Doering, Physics, Clarkson University



Christopher Whitman, the Administrative/ Technical Assistant for the 1990 Complex Systems Summer School. Photo: Cary Herz © 1990.

Visual System Function & Development
    Leif Finkel, Biomedical Engineering, University of Pennsylvania

Movement Complexity
    Ziaul Hasan, Physiology, University of Arizona

Neural Computation & Pattern Formation
    Ralph Linkser, IBM

Evolutionary Biology
    Richard Michod, Ecology and Evolutionary Biology, University of Arizona

Experimental Analysis of Disordered Systems
    Sidney Nagel, James Franck Institute, University of Chicago

Connectionist Models of Cognition
    David Rumelhart, Psychology, Stanford University

1990 Complex Systems Summer School students, from left to right, Julie Pullen, Matthew Semak, and Michael Murillo. Photo: Cary Herz © 1990.

Pattern Formation in Chemical Systems
Wing Tam, Physics, University of Arizona

Computational Complexity
Joseph Traub and Henryk Wozniakowski, Computer Science, Columbia University

Student Comments

The following anonymous quotes are from students of the 1988 and 1989 Complex Systems Summer School.

"At the summer school I made important contacts with other students, with whom I have visited and kept in e-mail contact. Attending the Summer School was critical in helping me find a postdoctoral position (at Los Alamos, working jointly with CNLS and Theoretical Biology).... The Summer School is a uniquely valuable program, especially for students whose research does not fit readily into the more established categories of science."

"While I have been to many other Summer Schools and workshops, this one stands out in many ways: for the first time (after several years of working on the subject) I was presented with a fairly clear and complete picture of the fields and approaches involved, and the unity and diversity of knowledge in this fascinating subject. It also started my interest in spin glasses and neural networks, the area in which I am presently working. Finally, it allowed me to establish valuable contacts with other scientists."

"I am currently serving on an advisory panel guiding the preparation of a conference and videotape on 'Understanding Environmental Rises'.... How does this relate to my experience at the Complex Systems Summer School? ...Learning about theory and experimental research addressing complex systems from a set of excellent lecturers was extremely valuable. The participants formed a truly remarkable, multifaceted group as well. The summer school demonstrates how the intelligence of scientifically and mathematically inclined individuals can be brought to bear on matters of critical importance in our time.... The format of the Summer School also recommends itself to other research and teaching settings. The complex problems before us will require the bringing together of per-

(continued)

Robin Justice, SFI Computer Systems Manager (far right), assists students (from left to right) Paul Laub, Tom Cheetham, and Mark Millonas in the Summer School Computer Lab. Photo: Cary Herz © 1990.

Daniel Stein (far left), one of the 1990 Complex Systems Summer School co-directors, shares a laugh over lunch with (from left to right) Lecturer Andrew Barto and summer school students Daniel Greening, William Welsh, and Sarah Perin Otto. Photo: Cary Herz © 1990.

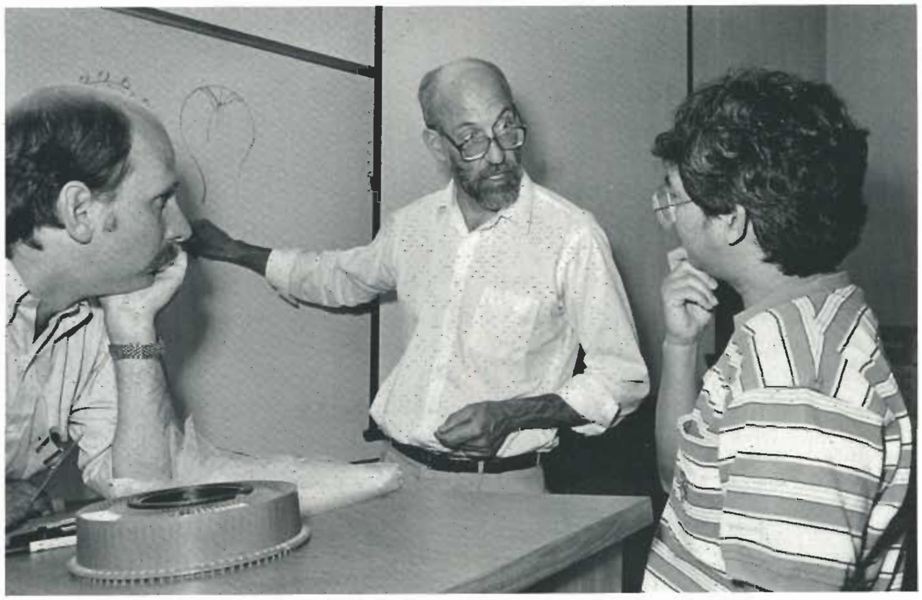
Summer School *(continued)*

sons with diverse backgrounds and expertise."

"The Summer School gave everyone a chance to peek over the interdisciplinary fences and take a look at some of the fascinating problems in other areas of research.... The students benefitted from talking to one another—if one was wondering about immune systems, then one could find and ask a student who knew the field.... The Complex Systems Summer School is the only school of its kind that I know about.... It gave me more depth to my understanding of related fields, and showed me how some things which I thought were unrelated are really in fact similar. In other words, the Summer School showed me many new connections I hadn't seen before, and that's a *very* valuable thing to do."

Valerie Gremillion, a collaborator at the Center for Nonlinear Studies, Los Alamos National Laboratory, helped coordinate the 1990 Complex Systems Summer School. Photo: Cary Herz © 1990.

Organization of Organisms



Jay Mittenthal (center) discusses organization with workshop participants Tim Karr (left) and Gonzalo DeGuzman (right). Photo: Cary Herz © 1990.

A small set of principles may underlie the organization of complex adaptive systems, such as organisms and artificially intelligent systems. Presumably these principles favor the survival of the systems as they meet external and internal constraints. In June a group of junior and senior scientists gathered for the workshop "Organization of Organisms" to survey these axioms and their relationship to constraints to see whether they cohere in a theory for the design and organization of adaptive systems. The meeting was chaired by Jay Mittenthal, Department of Cell and Structural Biology, University of Illinois.

Workshop participants came from diverse fields including theoretical biology, developmental biology, physiology, functional morphology, evolution, and computer science. As is typical with SFI workshops, the degree of interdisciplinary communication was unusual.

A proceedings volume from the workshop will appear in 1991.

Participants' Comments from "Organization" Workshop

- "This workshop will surely affect my research, and several critical problems have been well illuminated. I've interacted with several people with data and theories, gotten references, and have planned two collaborations: one in which I will try to simulate other's data and another where I'll work on theory.

  "I very much hope I can spend some time at SFI again."

- "Overall, I rate it rather high. I was pleased to see a range of interests from reasonably abstract theorists to bona fide wet biologists. In addition, there was a good representation across fields (physiology, development, protein structure, evolution), although there were no practicing ecologists. One new collaboration for me has certainly resulted; perhaps others will, too."

Economics Summer Study Group

About the Program

The Economic Research Program is dedicated to the exploration of the economy as an evolving complex system. In contrast to neoclassical economies—the leading paradigm in economic theory—the Program's research is not directed to the search for equilibria, characterized *statically* as systems of production and consumption decisions at given prices under which all markets clear. Rather, its object is to describe the *dynamic* processes operating under conditions of incomplete markets, imperfect competition, and bounded rationality that lead to the creation of markets and prices, and the evolution of economic aggregates and institutions. The Santa Fe Economics Research program emphasizes the mathematics of stochastic processesd computer simulation, instead of the traditional topological methods of neoclassical economics.

What's New This Summer

This summer's work includes continuing intensive discussion and research on learning in markets and games; nonlinear and nonconvex phenomena in the economy; self-organized criticality; evolution of economic structure; neural networks in economics; and nonlinear stochastic dynamics. The summer study group is led by Brian Arthur.

Participants

W. Brian Arthur, Economist, Stanford University

Per Bak, Physicist, Brookhaven National Laboratory

William Brock, Economist, University of Wisconsin

Vincent Crawford, Economist, University of California, San Diego

Larry Gray, Probability theorist, University of Minnesota

Richard Herrnstein, Psychologist, Harvard University

Stuart Kauffman, Biologist, University of Pennsylvania

Mordecai Kurz, Economist, Stanford University

John Miller, Economist, Carnegie-Mellon University

James Pelkey, Private investor/consultant, Santa Fe

Paul Romer, Economist, Carnegie-Mellon University

Andrzej Ruszczynski, Operations Researcher, Warsaw University of Technology

Paul Tayler, Coopers & Lybrand Deloitte, UK

James Taylor, Psychology graduate student, Harvard University

1990–91

For the 1990–91 academic year, Research Directors for the program will be economist John Geanakoplos, Yale University, and probability theorist David Lane, University of Minnesota.

Economic Working Papers

SFI is pleased to provide to interested researchers copies of working papers, preprints, and reprints from the Economics Research Program, although quantities are limited. The two most recent economic inclusions in the SFI series are:

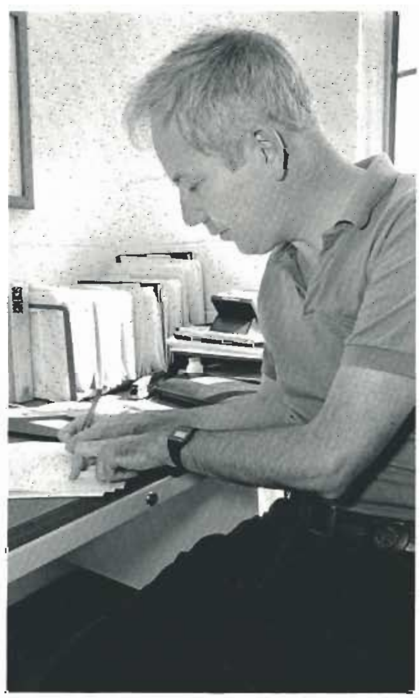
"Learning by Genetic Algorithms in Economic Environments," by Jasmina Arifovic, SFI Working Paper 90-001.

"Economic Life on a Lattice: Some Game Theoretic Results," by R. A. Cowan and J. H. Miller, SFI Working Paper 90-010.

A full listing of SFI working papers is given on page 22; economics papers include 89-001 to 89-007, and the two papers noted above.

Schumpeter Prize Awarded to Arthur

Brian Arthur, SFI Science Board Member and External Professor and Dean and Virginia Morrison Professor of Population Studies and Economics at Stanford University, has been awarded the prestigious Schumpeter Prize. The award is for his pathbreaking work on the dynamics of competition among alternative technologies in which each gains value as its use is augmented. Much of this work was done at SFI, where Arthur spent a year and a half between 1988 and 1990 as Director of the Economics Research Program. He shares this year's prize with Joel Mokyr, Departments of Economics and History at Northwestern University, and with Manual Trajtenberg, Department of Economics at the University of Tel Aviv.



Brian Arthur. Photo: Cary Herz © 1989.

Program in Adaptive Computation Flourishes

Since January, 1990, External Associate Professor John Miller has been in residence at SFI as Director of the Institute's growing research program in adaptive computation. The notion of computational systems actively adapting to an evolving environment is prevalent across a wide range of fields; the program is benefitting from the combined contributions of biologists, chemists, computer scientists, economists, mathematicians, and physicists. Researchers involved include SFI External Faculty members Marcus Feldman, Stephanie Forrest, John Holland, Stuart Kauffman, and Alan Perelson along with SFI Members Gottfried Mayer-Kress and Walter Fontana. Projects focus on models from biology (coevolution of species, development of the immune system, and genetics), chemistry (autocatalytic sets and the origin of life), and economics (auction markets, games, and technological webs). The goals of the adaptive computation program are to gain a deeper understanding of these models, and to apply these insights to the creation of a new generation of computer-based systems endowed with advanced adaptive abilities.

John Miller, coordinator of the SFI program on adaptive computation. Photo: Cary Herz © 1990.

The research emphasizes systems that involve the distributive, adaptive, nonlinear interactions of large numbers of agents. The usual mathematical tools—exploiting linearity, fixed points, and convergence—provide only an entering wedge when it comes to understanding such systems. Instead, Institute researchers are using sophisticated computer models, combined with a mathematics that puts more emphasis on adaptive algorithms and combinatorics.

One project goal is to develop a unified model of adaptive agents. This model will be a general representation of a large variety of adaptive systems and should prove useful in a variety of fields. Researchers are developing both a mathematical and computational framework for this model. To the latter end, the Institute has initiated two software projects. The first is the development and distribution of a complete research/educational software package which will allow scholars to easily develop, modify, and analyze their own adaptive models. Secondly, the Institute is also pursuing the development of software tools for implementation on massively parallel computer hardware. The locally interactive nature of these models makes such hardware a natural choice for studying such systems. The software developed in both of these projects will provide users with a large aggregate of programmable "objects," that can be tuned to mimic the components of a wide array of processes, from molecules to economies.

Designers of artificial systems face a set of common problems regardless of whether the system is an entire computer network or a single computer program. SFI research results will provide some possible solutions to these problems. Ideas from immune systems about pattern recognition and self-repair will be useful. Economic notions about auction markets and individual behavior in games will provide mechanisms which can efficiently allocate the system's resources. Artificial systems may face novel situations that not only require immediate action, but may also present unforeseen opportunities. The study of niche expansion and speciation from biology may be helpful in such situations. Ultimately, it may be desirable to give systems a set of simple parts and allow them to self-organize their own sophisticated structures. Ideas about the origin of life suggest that such structures might emerge from a primitive "computational soup."

Beginning in the fall of this year SFI's research in adaptive computation will be boosted by the establishment of the Robert Maxwell Professorship in the Sciences of Complexity, funded by the Maxwell Foundation. In establishing this pioneering new professional chair, Mr. Maxwell has expressed his desire to support and accelerate the development of advanced mathematical and computational techniques to help policy makers select useful options for dealing with rapidly changing major problems in the world community. The first occupants of this new chair will serve on a rotating basis beginning with Murray Gell-Mann, who will be succeeded by John Holland.

1990 Research

Artificial Night

As part of the second Artificial Life workshop, a public presentation of demostrations and performances featured examples of artificial life such as LEGO-based creatures, a zoology of fractal animals, and a performance by Mark Pauline's Survival Research Laboratory. Entitled "Artificial Night," this presentation appealed to children as well as adults, as shown by our cover photo of Nicolo Boldrin, son of SFI External Assistant Professor Michele Boldrin. Local school teachers have inquired about similar programs that may be suitable for children, and SFI hopes to expand its role with the local public schools in order to excite the scientists of the future.

SFI sponsors free public talks related to the various workshops in progress or other topical issues to inform and involve the community in its research.

New Mathematical Approaches to DNA

More than one hundred scientists attended the January workshop "New Mathematical Approaches to DNA." SFI provided administrative coordination for this meeting, which was chaired by Nicholas Cozzarelli, University of California at Berkeley, and Sylvia Spengler, Lawrence Berkeley Laboratory. The workshop was sponsored by the National Science Foundation Program for Mathematics and Molecular Biology. Two plenary meeting sessions dealt with questions of mapping and matching of DNA sequences—issues that have come up in the sequencing of large pieces of DNA, including genomes. The balance of the sessions in the five-day workshop focussed on the topology and geometry of DNA including energetics and alternative structures.

Artificial Life

In February, an eclectic group of more than 300 scientists and researchers met in Santa Fe at the second Artificial Life conference, co-sponsored by SFI and the Center for Nonlinear Studies, Los Alamos National Laboratory. Artificial life "is an attempt to abstract the principles of life from its material organization, and recreate them in other materials," according to Christopher Langton, Los Alamos National Laboratory, one of the conference organizers. The other program co-chairs were J. Doyne Farmer and Steen Rasmussen, also from Los Alamos National Laboratory, and Chuck Taylor, University of California at Los Angeles.

In the same way that experimenters in artificial intelligence use computers to model thought, "artificial lifers" rely on software and silicon to emulate life and evolution. Artificial life may also take the form of self-replicating robots, genetically engineered organisms, or possibly even new organic life forms grown from scratch. Regardless of the form, artificial life researchers are trying to mimic simple behaviors in hopes of discovering the basic laws that cause living things to emerge and to organize themselves into complex forms.

More than fifty researchers reviewed their current work during the five-day meeting; presentations ranged from lectures and video presentations to an evening public performance called "Artificial Night" (see sidebar).

At least two products have resulted from the program: a refereed proceedings volume that will include about twenty papers from the meeting, and a separately packaged video that will contain dynamic presentations of selected papers along with original stand-alone pieces. Both the book and the video will be available in 1991 as part of SFI's Studies in the Sciences of Complexity published by Addison-Wesley.

Enjoying the presentations from Artificial Night are, from left to right, Steen Rasmussen, workshop co-director; Mike Simmons, SFI Executive Vice President; George Cowan, SFI President; Stephen Wolfram; and Christopher Langton, workshop co-director. Photo: Cary Herz © 1990.

Mutagenesis Measurement

In March, Science Board Member Theodore Puck chaired a meeting at SFI to plan new strategies for the measurement of mutagenesis in mammalian cells. This work resonates with research being done by fellow SFI researchers, particularly Stuart Kauffman and Alan Perelson, on molecular evolution and maturation of the immune response.

An eventual outcome of such measurement may be reduced cancer and human genetic disease through increased knowledge and control of exposures to the physical, chemical, and biological agents that cause mutation. Currently the incidence of cancer and genetic disease in our society cannot be explained in terms of known mutation incidence, although this is the initiating event in both kinds of disease. For example, the current high rates of cancer which occur in dwellings containing extremely low levels of radon gas are not understood theoretically.

Participants discussed the theoretical background and inherent gross errors that affect conventionally accepted methodologies. They considered the possibility of a new theoretical framework, and also discussed an experimental approach that detects significant mutations at doses hundreds of times lower than those detected by current methods. Based on these discussions, members agreed on a set of collaborative experiments to be carried out in the coming year.

Double Auction Tournament

Todd R. Kaplan, an economics graduate student at the University of Minnesota, submitted the top-ranked trading program in the 1990 Double Auction Tournament sponsored by the Santa Fe Institute in March (see past issue Vol. 4, No. 2). The tournament was based on a computerized simulation of a double auction (DA) market, a simplified version of the type of trading institution used by major securities and commodities exchanges such as the Chicago Board of Trade. The major difference was that SFI's double auction market consisted entirely of computerized traders that buy and sell a fictional commodity called "tokens." Thirty computer programs competed for a share of a potential pool of $10,000 prize money in over 13,000 separate double auctions.

Programs were submitted by entrants in the U.S., Canada, and Europe, including faculty and graduate and undergraduate students in economics, mathematics, and computer science, as well as one entry from a professional broker. The programs employed a variety of strategies ranging from simple "rules of thumb" to complex artificial intelligence approaches including a neural-net program submitted by two cognitive scientists in England and a "cellular adaptive curvefitter" submitted by a mathematician at Princeton University's Institute for Advanced Studies. Tournament results seem to indicate that simpler strategies do better than more complex methods. Kaplan's program used a few simple rules that codified his "market intuition."

The tournament was designed and developed by Richard Palmer, Duke University, John Rust, University of Wisconsin, and John Miller, Carnegie-Mellon University. They developed double auction software that allowed entrants to set up their own computerized DA market on a variety of machines ranging from an IBM PC to a Cray supercomputer; they also created the Santa Fe Token Exchange (SFTE). The exchange, which is still in operation, opens at the start of each hour for (non-profit) token trading. Anyone who has access to the worldwide Internet computer network can log onto the SFTE and compete against programs selected from the 30 tournament entries.

The organizers intend to hold future DA tournaments so that entrants' strategies can evolve in light of the results of this first tournament. In particular, the initial 30 entrants have been encouraged to revise their strategies by July 1, 1990, for a non-profit "scientific tournament"

Visitors: January to June, 1990

Tom Ainsworth, Texas A&M
Luca Anderlini, Harvard University/St. John's College, Cambridge, UK
James Andreoni, University of Wisconsin
W. Brian Arthur, Stanford University*
Mark Bedeau, Dartmouth College
Tony Begg, Brunel University, England
Ted Bergstrom, University of Michigan
Michele Boldrin, UCLA/Northwestern*
Peter Carruthers, University of Arizona
Bernard Derrida, S.E.N., Saclay, France
Gary Hansen, UCLA
John Heumann, Hewlett Packard
John Holland, University of Michigan
Felix Izrailev, Institute of Nuclear Physics, Novosibirski, USSR
Erik Reimer Larsen, London School of Business
Marc Lipsitch, Yale University*
Catherine Macken, Stanford University/University of Auckland*
Daniel Martinez, University of Delaware
Gottfried Mayer-Kress, UC Santa Cruz*
John Miller, Carnegie-Mellon*
Lynn Nadel, University of Arizona
Norman Packard, CCSR/University of Illinois*
Richard Palmer, Duke University
Asher Peres, Technion, Israel
David Pines, University of Illinois*
Edward Prescott, University of Minnesota
Julie Pullen, Macalester College
John Rust, University of Wisconsin
Petar Simic, Caltech
Carl Simon, University of Michigan
Pete Skordos, MIT*
Daniel Stein, University of Arizona*
Gary Stormo, University of Colorado
Paul Tayler, Coopers & Lybrand Deloitte, London
Gérard Toulouse, Ecole Normale Supérieure, Paris
Edward Trifonov, Weizmann Institute, Israel
Jochen Wambach, University of Illinois
Gérard Weisbuch, Ecole Normale Supérieure, Paris
Peter Wolynes, University of Illinois
William Wootters, Williams College*

*more than one month

also to be held at SFI.

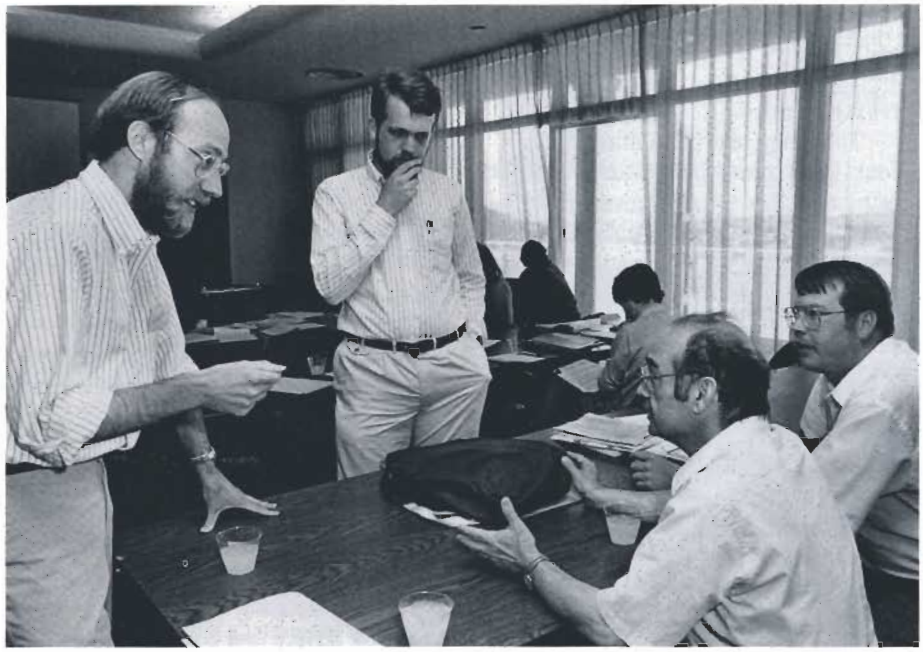
In May a small SFI workshop "Price Dynamics and Trading Strategies in Double Auction Markets with Human and Computer Traders" reviewed progress to date, and set strategies for future research.

In June the project received funding from the National Science Foundation for a series of human double-auction experiments to generate a matching data set for comparison to computerized "robot traders." These experiments will take place throughout the next year at the University of Arizona under the guidance of Vernon Smith.

Complexity, Entropy, and the Physics of Information

One of the objects of the April, 1990, CEPI workshop—the third such gathering in twelve months—was to continue to bring people together who are working on various aspects of this topic, but who might not otherwise interact with each other. This recent meeting was again chaired by Wojciech Zurek, Los Alamos National Laboratory, who guided inquiries into problems such as understanding the emergence of the classical world out of a quantum universe, using algorithmic information theory to see why Maxwell's demon has had a hard time making entropy decrease, estimating the weight of a bit of information, and expressing geometry in information-theoretic terms. Some of the calculations whose results were presented at the conference were performed during the week of the meeting in response to presentations and collaborations.

During the Spring several researchers visited SFI as part of the CEPI program. Visiting Professor Bill Wootters completed a year's residency at the Institute in June. While in Santa Fe his work focussed on algorithmic information and the second law; information, quantum chaos, and restricted randomness; and quantum communication theory. During the month of April, Asher Peres, Technion Institute, collaborated with Wootters on a number of topics including work on a simple algebraic proof of Neumark's theorem; the result will eventually appear as part of an article honoring the 60th birthday of John Bell (to appear in *Foundations of Physics*). In June graduate student Pete A. Skordos, MIT, arrived at SFI to work with Zurek on the relation between information and thermodynamic entropy and heat in a context inspired by Maxwell's demon. They are building computer programs to simulate the motion of gas molecules in a box of two chambers connected via an "intelligent" trap door; computer graphics will allow them to develop an intuition about the demon that would not otherwise be possible. They hope to have a video of the experiment by summer's end.



An informal discussion at the 1989 Complexity, Entropy, and the Physics of Information workshop: (left to right) William Wootters, Williams College, Benjamin Schumacher, Kenyon College, Asher Peres, Technion (Israel), and Warner Miller, Air Force Weapons Laboratory, Kirtland Air Force Base. Wootters and Peres have visited SFI this year as part of the new research network. Photo: Cary Herz © 1989.

Glasses

In May, a "Glasses, Biomolecules, and Evolution" workshop, co-chaired by Hans Frauenfelder and Robert Young, University of Illinois, examined mounting theoretical and experimental evidence that many, maybe all, complex systems exist in a very large number of conformational substates, valleys in the conformational landscape corresponding to slightly different structures. Glasses, spin glasses, proteins, nucleic acids, evolutionary systems, and neural nets all exhibit conformational substates. The unifying concept of a rugged landscape suggests deep connections among complex systems.

Scientists from various fields explored the energy or fitness landscape of typical systems. Most of the week-long workshop was spent on in-depth discussions of novel approaches and techniques in the various fields.

Sustainable Human Society

In May, SFI held the second planning workshop for what will probably be its most broadly cast topical program to date, "Multiple Paths toward a Sustainable Human Society," a research program chaired by SFI President George Cowan. The aims of the recent meeting were to name and estimate the relative importance of the factors that are essential to a sustainable society, and to suggest the next steps in organizing among cooperating institutions a broadly representative and coherent study of the complex systems that will define the nature of our society in the

(continued)

1990 Research *(continued)*

coming decades.

The group sees population as the most important factor to global sustainability. As population grows it becomes increasingly difficult to support conditions of social equity and security. If the problem is not solved within the next generation, major reliance for achieving sustainability must be placed on unforeseen scientific and technological fixes and, even so, will probably involve a sharp decrease in the average standard of living. Second, in addition to the impact of attitudes and beliefs on the population problem, it is critically important to prepare and distribute information that will modify current attitudes in a way that will nurture fundamental changes in the consumption of goods and the economic structure that prices goods, particularly in the use of exhaustible resources; in the redistribution of goods and acceptance of greater social equality; and in the development and legitimization of the kind of governance that will be needed. Third, economic stratagems must be devised that more fully incorporate the capital value of exhaustible resources into the price structure, and take into account their value to future generations. Fourth, a food crisis is possible in a relatively short time. It could have grave consequences for global stability. Quasi-governmental organization can play a key role. Finally, the work requires a global coalition with real responsibility for regulating military power. The problem of mobilizing political legitimacy for such a coalition will require redirecting major resources.

The group agreed that the time is ripe to convene a small group representative of key institutions and areas of individual expertise to put a master plan together for a consortium that can mount a coordinated study on the components of the stability problem, including their interactive properties. SFI will act as a coordinating center.

Development Activities

Development Committee Appointed

The Santa Fe Institute's Board of Trustees has appointed a new development committee. The seven-member group will assist George Cowan and Director of Development Susan Wider in carrying out the annual and capital fundraising programs. Appointed to the committee were nine Trustees: Marcus Feldman, Lawrence Huntington, George Keyworth, Edward Knapp, Ann Nitze, James Pelkey, and Ray Sena, with Robert O. Anderson and George Cowan serving ex-officio. Cowan characterized the group as "a welcome addition to SFI's fundraising activities. We will seek their advice and help in broadening the base of support for the Institute. Our goal will be to raise ten million dollars within the next two years to establish a permanent campus, a small resident academic core, an expanded academic program, and a funded Office of the President."

James Pelkey, a high-technology venture capitalist and private investor, chairs the committee. Pelkey, who recently relocated to Santa Fe from San Francisco, is an enthusiastic advocate of SFI. "Many of the problems society faces today have defied simple solutions," he notes. "The need to change our approach to these problems demands an interdisciplinary effort such as the one employed at the Santa Fe Institute." He hopes to see the committee "mount an expanded campaign for funds beginning immediately."

A stronger fundraising program and increased revenues will make it possible for SFI's leaders to pursue these priorities:

- Recruit an internationally known scholar and administrator to assume the office of the President in 1991. George Cowan does not intend to stop working on behalf of the Institute but, having reached the age of seventy, he believes that "bringing a younger, outstandingly qualified person to this office will strengthen the Institute's management and longevity."
- Add two major, multi-year programs including one to help develop the most promising new ideas in adaptive computational methods. Such methods provide an essential base for modeling and presenting in a more readily understandable and accessible form the dynamic behavior of all of the complex systems of interest to the Institute. Discussions are underway about the nature of a third program in the field of theoretical ecology or in human sustainability.
- Strengthen SFI's relationships with leading campuses and research centers by fostering collaborative programs. Examples of efforts currently underway are the establishment of "SFI outposts" at the Universities of Michigan, Pennsylvania, and Illinois.
- Supplement the number of outstanding junior people in residence at SFI with additional faculty and with postdoctoral or graduate students who will be granted degrees by collaborating universities.
- Provide a suitable permanent home for the Institute.

Susan Wider describes the new committee as "essential to SFI's future. We need to call on the broadest range of experience and sophistication to help us build upon our early success." The development committee will help identify prospective donors, assist in their cultivation, and, when appropriate, ask for gifts on behalf of SFI. Committee members will organize meetings in their regions of the country to promote the Institute.

Correction

The name of Darragh E. Nagle was inadvertently omitted from the list of contributors to the Santa Fe Institute which appeared in SFI's 1989 Annual Report and in the Bulletin of the Santa Fe Institute, Vol. 5, No. 1 (Winter-Spring, 1990).

Funding Support

The Santa Fe Institute received these funding awards and equipment grants during January-June, 1990:

For the 1990 Complex Systems Summer School, support from the National Science Foundation, the Department of Energy, the Office of Naval Research, Research Corporation, as well as support from the School's co-sponsoring institutions;

For computational support for the 1990 Complex Systems Summer School, equipment from Apple Computer, Digital Equipment Corporation, Innovative Computing, NeXT, and Sun Microsystems and software from Silicon Graphics;

For research on the "Comparison of the Behavior of Human and Robot Traders in a Computerized Double Auction Market," support from the National Science Foundation;

From the Alfred P. Sloan Foundation, support for a workshop on "Glasses, Macromolecules, and Evolution";

From the University of California, support for a workshop on "Organization of Organisms";

Support for the Artificial Life conference and joint theoretical research from Los Alamos National Laboratory;

From Sun Microsystems, equipment support for "Analysis of Strategic Behavior" research and for joint Santa Fe Institute/Los Alamos National Laboratory research on theoretical immunology, HIV, and DNA sequencing; and

For general support of the Santa Fe Institute's research and administration, funding from the John D. and Catherine T. MacArthur Foundation, the Ann and Gordon Getty Foundation, the Richard Lounsbury Foundation, and Volvo Corporation.

SFI Sustains Media Attention

A recent *Wall Street Journal* article on the Institute served to increase national awareness of SFI and led to a flood of inquiries. The article entitled "Big Thinking: Santa Fe Institute Engages in Research with Profit Potential" by Bernard Wysocki, Jr. appeared on the front page of the May 8, 1990, *Journal*.

Mr. Wysocki spent the better part of two weeks interviewing SFI scholars including Brian Arthur, Michele Boldrin, George Cowan, Doyne Farmer, Stuart Kauffman, John Miller, Alan Perelson, David Pines, and Mike Simmons. His article stressed SFI's entrepreneurial spirit: "Ideas bandied about here have aroused the interest of the commercial world, from Wall Streeters, to California venture capitalists, to Citicorp's chairman, John Reed."

The *Wall Street Journal* piece was one of several recent articles featuring or discussing SFI that have appeared in such publications as *The Atlanta Journal and Constitution, The Washington Post, Science, Science News*, and *Manhattan, Inc.*

The Atlanta Journal and Constitution focused on the economics research program. Writer Bill Hendrick said, "Institute scientists claim that making long-term economic forecasts is as futile as trying to predict today how fast the wind will blow at next year's Macy's Thanksgiving parade. But, with modern computers that can process 'experimental' mathematical techniques, they claim they can improve short-term forecasting—perhaps dramatically." Mr. Hendrick's article also ran in *The New Mexican, The Albuquerque Tribune*, and *The Cleveland Plain Dealer*.

SFI president George Cowan described the recent press attention as gratifying. Cowan said, "The media have taken an interest because our program has been successful, thus far. This attention is helpful because what we are trying to do is stage a revolution in the way science is taught and carried out in the United States. There is a broad need for public understanding of our goals."

Publications Update

The SFI Studies in the Sciences of Complexity series through Addison-Wesley and SFI's working papers series continue to grow and expand. Here is a summary of their progress.

New Books in Print

Two new volumes have just been released.

Complexity, Entropy, and the Physics of Information, Proceedings Volume VIII, edited by W. H. Zurek; proceedings from the 1989 workshop of the same title. Published May, 1990. ISBN numbers: hardback 15687-3; paperback 15688-1.

1989 Lectures in Complex Systems, Lectures Volume II, edited by Erica Jen; lectures from the 1989 Complex Systems Summer School. Published June, 1990. ISBN number: hardback only 50936-9.

To order these volumes, call the Addison-Wesley order desk at 800/447-2226 or fax your request to 617/942-1117. Include the ISBN number for the book, the author's or editor's last name, the title of the book, your shipping address, your credit card type and number, and, if a fax order, your signature for credit card authorization.

Volumes in Progress

These volumes are currently in production.

Molecular Evolution on Rugged Landscapes: Proteins, RNA, and the Immune System, Proceedings Volume IX, edited by A. S. Perelson and S. A. Kauffman; proceedings of the 1989 workshop "Applied Molecular Evolution and the Maturation of the Immune Response." Available October, 1990.

The Evolution of Human Languages, Proceedings Volume X, edited by J. Hawkins and M. Gell-Mann; the proceedings of the 1989 workshop of the same title. Available December, 1990.

Artificial Life II, Proceedings Volume XII, edited by J. D. Farmer, S. Rasmussen, and C. Langton; the proceedings of the second co-sponsored work-

Publications *(continued)*

shop on artificial life. Available February, 1991.

Introduction to the Theory of Neural Computation, by John Hertz, Richard Palmer, and Anders Krogh; based on a course on Advanced Topics in Statistical Mechanics given at Duke University. Lecture Notes Volume I. Available October, 1990.

Complex Systems Dynamics, by Gérard Weisbuch, translated from the French (*Dynamique des systèmes complexes*, InterEditions, 1989). Lecture Notes Volume II. Available October 1990.

Working Papers

This category includes scientific papers intended for publication in the scientific literature; some have already appeared. Generally they are distributed to the SFI family of researchers as requested. A limited number of copies of the following papers are available to interested researchers on a first-come/first-served basis.

"A Double Auction Market for Computerized Traders," by John Rust, Richard Palmer, and John H. Miller, SFI Working Paper 89-001.

"Communication, Computability and Common Interest Games," by Luca Anderlini, SFI Working Paper 89-002.

"The Coevolution of Automata in the Repeated Prisoner's Dilemma," by John H. Miller, SFI Working Paper 89-003.

"Money as a Medium of Exchange in an Economy with Artificially Intelligent Agents," by Ramon Marimon, Ellen McGrattan, and Thomas J. Sargent, SFI Working Paper 89-004.

"The Dynamical Behavior of Classifier Systems," by John H. Miller and Stephanie Forrest, SFI Working Paper 89-005.

"Nonlinearities in Economic Dynamics," by José A. Scheinkman, SFI Working Paper 89-006.

"'Silicon Valley' Locational Clusters: When Do Increasing Returns Imply Monopoly?," by W. Brian Arthur, SFI Working Paper 89-007.

"Mutual Information Functions of Natural Language Texts," by Wentian Li, SFI Working Paper 89-008.

"Learning by Genetic Algorithms in Economic Environments," by Jasmina Arifovic, SFI Working Paper 90-001.

"Optimal Detection of Nonlocal Quantum Information," by Asher Peres and William K. Wootters, SFI Working Paper 90-002.

"Artificial Life: The Coming Evolution," by J. Doyne Farmer and Alletta d'A. Belin, SFI Working Paper 90-003.

"A Rosetta Stone for Connectionism," by J. Doyne Farmer, SFI Working Paper 90-004.

"Immune Network Theory," by Alan S. Perelson, SFI Working Paper 90-005.

"Protein Evolution of Rugged Landscapes," by Catherine A. Macken and Alan S. Perelson, SFI Working Paper 90-006.

"Evolutionary Walks on Rugged Landscapes," by Catherine A. Macken, Patrick S. Hagan, and Alan S. Perelson, SFI Working Paper 90-007.

"Transition Phenomena in Cellular Automata Rule Space," by Wentian Li, Norman H. Packard, and Chris Langton, SFI Working Paper 90-008.

"Absence of 1/f Spectra in Dow Jones Daily Price," by Wentian Li, SFI Working Paper 90-009.

"Economic Life on a Lattice: Some Game Theoretic Results," by R. A. Cowan and J. H. Miller, SFI Working Paper 90-010.

"Algorithmic Chemistry: A Model for Functional Self-Organization," by Walter Fontana, SFI Working Paper 90-011.

"Expansion-Modification Systems: A Model for Spatial 1/f Spectra," by Wentian Li, SFI Working Paper 90-012.

"Coevolution to the Edge of Chaos: Coupled Fitness Landscapes, Poised States, and Coevolutionary Avalanches," by Stuart A. Kauffman and Sonke Johnsen, SFI Working Paper 90-013.

Staff News

Diane Banegas has joined the Institute staff as our Executive Assistant. Diane moved to Santa Fe one year ago, from Reno, Nevada, where she worked as a news writer for the University of Nevada at Reno. She holds a bachelor's degree in animal science from UC Davis and a master's degree in journalism from the University of Nevada at Reno. She has several years' experience in both journalism and office adminstration.

Patrisia Brunello joined the Institute staff on August 1 as our Receptionist/Clerk, replacing Shona Holmes and taking over receptionist responsibilities from Diane Banegas. A native New Mexican, Patrisia most recently worked at a local law firm as a receptionist and assistant office manager.

Shona Holmes will be leaving the Institute to attend Fort Lewis College in Durango, Colorado. There she plans to pursue studies in environmental conservation and wildlife biology. Shona has worked part-time as a Clerk for SFI since 1989.

During June **Christopher Whitman** worked as the Administrative/Technical Assistant for the 1990 Complex Systems Summer School. A 1990 graduate from Santa Fe High School, Chris will be attending Carnegie-Mellon University where he will major in Computer Engineering and Industrial Management.

Diane Banegas. Photo: Cary Herz © 1990.

The "Pit"


Margaret Alexander in the "Pit" at SFI. Photo: Cary Herz © 1990.

There is a dim and grubby side to the Santa Fe Institute. It is the "pit," a small room without windows, whose entrance is a closet and exit is the mechanical room of the quirky adobe convent, home of the Santa Fe Institute. The pit and I were introduced last summer when I volunteered to put the past records (files, correspondence, memos) of the SFI into order. Even after almost nine months of my Wednesday mornings, it is still stuffed with the back files of the Boards, scholars and staff, but also with boxes of current in-house publications awaiting the mails.

The archives of the SFI are its past records deemed worthy of being saved. The archives also preserve material which sheds light on administrative and legal issues.

Since SFI is young, only six years old, the back files are in relatively good shape, being managed, more or less, by the various staff members who kept files.

But over the years the files lost their continuity, stopping and starting depending upon the tenures of staff. Adding to the tendency toward chaos in the filing cabinets was the evolving structure of SFI. In the early days board members performed administrative tasks. Expert and scholarly volunteers carried the responsibility for getting the Institute off the ground. Their correspondence criss-crosses between grand policies and day-to-day operations, making it difficult to figure out where their letters belong in the hierarchy. After a small permanent staff was hired in 1986, and the Science Board and the Board of Trustees became separate entities in 1987, the dilemma of where to put things becomes more clear-cut.

Now in the archives the files form a cohesive series, rolling along with the years. In the future the archives will continue to acquire relevant papers from the men and women who are currently active in the growth of the Institute.

Perhaps surprisingly, the papers in the archives display a remarkable degree of harmony. They suggest that SFI generally operates on a consensus basis. Names and faces may fade away, but there seems to be no acrimony among the people represented in the papers.

Less well expressed in the documents is the strong sense of place which both newspaper and magazine journalists have found in their visits and interviews. Nearly every article calls upon the picturesque charm of New Mexico and Santa Fe. SFI strives to create an atmosphere conducive for the exchange of ideas, and Santa Fe itself is seen as a component in that atmosphere. As an archivist I hope that future memories and oral histories will fill this gap.

One final observation on the archives: from the beginning through the present, the staff has been careful to save the history of SFI. Many institutions do not have a sense of their own significance. SFI does. The "pit" may be dim and grubby, but it holds the collective memory of the Santa Fe Institute.

—Margaret Alexander

Margaret Alexander, Archivist

Since last fall, the Santa Fe Institute has been fortunate to have the volunteer services of archivist Margaret Alexander. Margaret has worked extensively organizing SFI's files and establishing the Institute's collection of scientific articles.

Margaret holds an M.L.S. from the University of Oregon; she was formerly a Museum Curator at the Arvada Center for the Arts and Humanities in Colorado. A number of her articles have appeared in publications of the Kansas City Museum and the Arvada Center for the Arts and Humanities.

Volunteers

In addition to Margaret Alexander, Nick Secor, an astrophysicist and professional photographer, has been providing invaluable assistance with the SFI library. If you would like to volunteer your expertise a few hours per week, please contact Ginger Richardson at 984-8800.