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Winter-Spring 1988

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Just Ahead of the Crash

SFI Examines Economic Ties that Bind

The volatility of the stockmarket was discussed at "Evolutionary Paths of the Global Economy," a September SFI workshop supported by Citicorp and the Russell Sage Foundation. However the workshop members—ten physical, biological and computer scientists, selected by Philip W. Anderson, a Nobel laureate in physics from Princeton University, and ten economists, selected by Kenneth Arrow, a Nobel laureate in economics from Stanford University—were less preoccupied with October predictions than with a more fundamental consideration: can physicists' and biologists' studies of "chaos" lend insights into a system as complex as the global economy?

If so, the results could be improved economic forecasting, with a major impact on economic theory within a decade or two. As Kenneth Arrow noted at the end of the meeting, "It's too early to say exactly what impact these methods will have on economics, but I think they may prove useful."

Network

To further the work begun at this meeting, the SFI Science Board has approved the establishment of a research network, headed by Philip Anderson and Kenneth Arrow, on "The Global Economy as an Evolving Complex System." Plans for the network over the next year and a half include ongoing small-scale research collaborations at SFI and other institutions and another workshop in September, 1988, followed by a full-scale resident research program involving students, postdoctoral researchers and senior faculty from different disciplines and institutions.

Traditional Views

Most economists agree that the economy is far more complex than suspected thirty years ago. This shift of belief is supported by practical experience and theoretical developments.

Economists traditionally have viewed the global economic system as one that tends to stabilize itself, with major changes being

(continued on page 18)

Herbert L. Anderson

Anderson Donates Journal Collection

One measure of any academic institution, however large or small, is its library. For any research organization, the collection of journals plays a vital role. Fully aware of this, Herbert Anderson has recently contributed his personal set of scientific journals to the Santa Fe Institute. Moreover, he has made arrangements for their display. Along with his rare capabilities directed toward the creation of the Santa Fe Institute, this latest thoughtfulness reiterates Herb's long-term dedication to interdisciplinary scientific endeavor.

The expression "Herb Anderson and the Institute" has a familiar ring. After an illustrious career during World War II—most notably with the first nuclear

(continued on page 17)

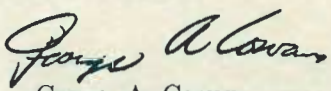
In This Issue

President's Message

The past several months will prove to be a hard act to follow. Each of our workshops seemed to set a new high in intellectual challenge. I have a particularly vivid memory of the C.E.O. at U S WEST, Jack MacAllister, totally immersed in discussions around a Sun workstation at the "Matrix of Biological Knowledge" workshop, having to be pried away so he could leave with his companions, Senator Pete Domenici and Governor Garrey Carruthers, in time for an appointment. The "Theoretical Immunology" workshop was almost captured by the engrossing topic of AIDS. The "Global Economy" meeting, one of the most venturesome, helped elevate dynamics and nonlinearity from somewhat suspect and unrewarding topics in economics to important fields of research. The "Computational Biology" meeting took off from and extended the discussions begun at the 1986 sessions on "Complex Adaptive Systems." And the "Artificial Life" meeting organized by Chris Langton at Los Alamos and co-sponsored by the Institute, will be published in our series on the sciences of complexity. This meeting undoubtedly walked off with first prize for innovative material. If you didn't see the big feature story about it in the New York Times, we'll send you a copy on request.

Clearly, the most rewarding aspect of this office lies in its constant exposure to a barrage of fresh, even outrageous, ideas. There is no safe refuge here for conventional wisdom. These workshops demonstrated that science is broadening and redrafting its agenda and that, willy-nilly, we're all back in school. Although I found a few familiar landmarks during the life science programs, none were in sight as I listened to the discussions among the economists and physicists concerning the relevance or irrelevance of dynamics to economics. I was still considering the comforting notion that the global economy might be finally approaching a state of long-term equilibrium in a better organized and more efficient marketplace when the events of Black Monday changed the scenery. It's not too great an extrapolation to think that, in not so many years, our journals will have to be printed with the morning newspapers and delivered to our doors daily.

The prospects for next year are bright. We constantly see new evidence that the importance of the ideas of complexity and chaos, driven by accelerating advances in computer technology, is being more widely recognized. Our old friends continue to support us and new sponsors are coming forward. But we are still far removed from a time for complacency. Our core activities require considerably more than presently anticipated funding and we are counting on your tangible expressions of support of the Institute's programs as the New Year approaches. Our best wishes for '88.



George A. Cowan
President

Bulletin of the Santa Fe Institute

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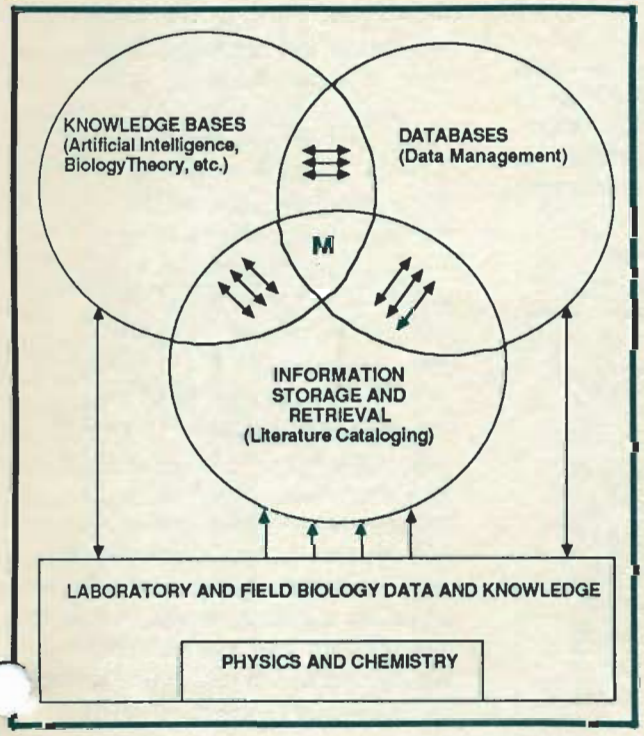
The Santa Fe Institute is a multidisciplinary scientific research and graduate education center formed to nurture deeper examination of complex systems and their simpler elements. A private, independent institution, SFI was founded in 1984.

Its primary concern is to focus the tools of traditional disciplines and emerging new computer resources on the problems and opportunities that are involved in the multidisciplinary study of complex systems—those fundamental processes that shape almost every aspect of human life and experience.

Biology: Getting It All Together

A midnight tour of the Evans Science Building on the St. John's College campus last July or August would have found a suprisingly large number of scientists hard at work in the ambitious, albeit temporary, computer center established by SFI in support of its "Matrix of Biological Knowledge Workshop." Such nightlife suggests the excitement generated during this five-week residential workshop which gathered together biological and computer scientists to address the problems involved in assembling a "matrix of databases," a framework of information encompassing all of biology.

The program, which involved more that fifty participants from universities, industry and government laboratories throughout the United States, Canada and England, was led by Yale University biophysicist Harold orowitz, and Temple Smith, Director of the Molecular Biology Computer Research Resource Center at Harvard University.



It was supported by the Alfred P. Sloan Foundation, the U.S. Department of Energy, and the National Institutes of Health.

Follow-On Activities

An immediate outcome of the Matrix workshop has been a detailed program report which has been distributed within the scientific community. This report may be the basis of a more formal publication, a *Matrix Primer*, as part of SFI "Studies in the Sciences of Complexity" series. The report itself suggests a number of follow-on activities including an international meeting in 1988, another Matrix summer school the following year, the possibility of an electronic journal, and perhaps a national center to establish a knowledge base of databases in biology.

A universal framework for biological information will provide immediately valuable data for medical diagnosis, biomedical research and agriculture.

A biological "database of databases" may also have a significant theoretical impact; this was noted in the 1985 National Academy of Sciences report on Models for Biomedical Research: "[We] seem to be at a point in the history of biology where new generalizations and higher order biological laws are being approached but may be obscured by the simple mass of data." It suggested that a more refined organization of the material, especially in a form that emphasizes cross connections between disciplines, might encourage new theories. Morowitz echoes this intuition saying, "a lot of interesting answers already exist out there that are hidden because we haven't plowed through the data."

Organizing the Data

It's noteworthy that the nerve center, nocturnal and otherwise, of the workshop was the program's computer facility. There, equipment and software donated by vendors from throughout the country enabled workshop members to access nearly every major biological database in the United States. "To plow through the data" the biologist has added computers to his other laboratory tools. "We would be in a bind for what to do with all this information if not for the fact that computer technology is also moving forward at a great speed," Morowitz explained to a workshop visitor. With such technology in place, the opportunity exists to bring

Matrix Tech

Computer support for the Matrix program was provided by:

BBN, Massachusetts
Bionet™ (Intelligenetics), California
Computerland of Santa Fe, New Mexico
DNA Star, Wisconsin
Human Genome Mapping Library, Howard Hughes Medical Institute, Connecticut
National Library of Medicine, Washington, D.C.
Molecular Biology Computer Research Resource Center, Massachusetts
Silicon Graphics, Colorado
Sun Microsystems, Massachusetts
Sybase, Texas
Symbolics, Massachusetts
Tektronics, New Mexico
University of California at San Francisco

the full potential of computer science, database management and artificial intelligence to bear on organizing the vast wealth of biological and clinical data.

The main task of the 1987 workshop was to convert the "vision" of the matrix into a detailed outline and to mount a sufficient number of test cases to explore the validity of the concept.

Structuring the Matrix

A fundamental consideration is how to structure the matrix so that it can be accessed from a multitude of dimensions. One approach, this from the point of view of the biologist, is to consider a multidimensional relationship of "descriptive domains" suggested by the hierarchies of organization that structure biological theory. The first cut at the dimensions of the Matrix, then, yield the *hierarchy of size*, or the organizational complexity of biological structures ranging from atoms to the global ecosystem; the *evolutionary tree* showing historical relationships; *relational algebra* to describe "functions" and "processes"; and the *trophic energy hierarchy* suggesting a bioenergentic ordering.

"We would be in a bind for what to do with all this information if not for the fact that computer technology is also moving forward at a great speed."

—Harold Morowitz
Workshop Co-Chair

Another path is by way of a *methodological* description, the approach of information scientists. Here, the foundation of the Matrix must consist of the laboratory experiments and field observations of biology. This material, organized by investigators, enters into the domain of *information storage and retrieval* via journal articles and other reports. Selected material is retrieved from the primary information and is classified, modified and entered into *databases*. (Databases, in this sense, have a more theoretical character than the original sources.) Analysis of data with the development of more sophisticated schemes of classification gives rise to *knowledge bases*. The intersection of these three categories is the Matrix, a combination of experimental results organized by theoretical principles, ultimately giving rise to integrative biological theories.

"The workshop clearly showed that scientists widely consider it profitable and worthwhile to extract new information by correlating existing data. To me this indicates a fundamental support for the Matrix concept."

—Richard Campbell,
faculty member

These approaches were considered during the five-week workshop which featured lectures, software and hardware tutorials and group meetings. As the meeting unfolded, certain loosely structured work groups formed, some focusing on specific test cases, some with broader concerns. One topic, for instance, that was considered from several different viewpoints was the metabolic map, the chart of intermediary metabolism which is central to energy processing and is a key to the synthesis of structural components in biology. One group considered the material from the point of view of databases and another in relation to knowledge bases. A third group considered the feasibility of endowing a metabolic database with simulation capabilities. "In essence," Morowitz notes, "for its final three weeks, the workshop functioned as a research institution in theoretical biology." –GR

Computational Biology

Computational biology addresses quantitative issues in areas that range from the properties of DNA to those of human cultures. The discipline consists of the development and analysis of mathematical models of the nonlinear phenomena that emerge in these areas of biology. This requires a high level of interaction between computer-based approaches and formal mathematics as well as a deep understanding of the underlying biological problems. Progress in these areas obviously entails a substantial interaction between specialists in the different components of this interdisciplinary endeavor.

The SFI workshop "Computational Approaches to Evolutionary Biology," chaired by Marc Feldman, Biological Sciences, Stanford University, and John Holland, Computer Sciences, University of Michigan, gathered evolutionary biologists, computer scientists and mathematicans to discuss the most recent advances in mathematical modelling of biological phenomena. Emphasis was on the application of computer-based methods to molecular biology, evolutionary genetics, ecology and epidemiology. The meeting was supported by the Alfred P. Sloan Foundation.

"Although each tier of biological organization requires different formulations of the action of natural selection, it appears significant collaboration between evolutionary geneticists and genetic algorithm computer scientists can be achieved at almost every level," says Marc Feldman. (Genetic algorithms are methods that grew from the idea of studying adaptation in biosystems and using similar strategies to solve problems in complex artificial systems. The approach was pioneered by John Holland.) The results could give a deeper understanding of the nature of genetic development with consequent insights into problems of heredity and disease, as well as a better comprehension of complex dynamical systems. "There are many interesting and difficult problems in dynamical systems coming from questions in computational biology," notes participant Morris Hirsch. "There was an extremely wide range of subject matter at the recent meeting, and I was impressed at how many interesting technical mathematical questions emerged from the discussions."

Although the September meeting dealt with a variety of topics, there was an emphasis on the commonality of research areas, techniques and approaches.

New mathematical and computational theories for the evolution of various forms of chromosomal recombination was the focus of several talks. The discussions ranged from the transformation in bacteria to classical forms of sexual recombination.

Different approaches to the interpretation of epidemiological information about AIDS were considered with attention to modelling the spread of HIV AIDS virus. New strategies for computer-aided synthesis of the huge amount of information related to the mapping of the human genome were also discussed.

"...it appears significant collaboration between evolutionary geneticists and genetic algorithm computer scientists can be achieved at almost every level."

—Marc Feldman
Workshop Co-Chair

Another area of interest was the genetics of host-parasite relationships with specific discussion of the difficulty of finding drug delivery schemes that will slow the development of drug resistance in malarial parasites. The role of modelling techniques for biological pest control was also discussed, focusing on models designed to determine the optimal use of ladybugs to control aphids.

"It's not often that one goes to a meeting and finds that others are doing work as interesting as one's own," noted biologist Bruce Levin. In fact at least one small-group research project has grown out of the meeting, and there may be more joint efforts in light of the group's consensus that there is much common ground for useful collaboration between the diverse parts of theoretical biology.

—GR

Computational Biology Workshop Participants

Roy Anderson
London University
Kenichi Aoki
Stanford University
George Bell
Los Alamos National Laboratory
W. Ford Doolittle
Dalhousie University
Doyne Farmer
Los Alamos National Laboratory
Marcus Feldman
Stanford University
William Hamilton
Oxford University
Morris Hirsch
University of California, Berkeley
John Holland
University of Michigan
Peter Kareiva
University of Washington
Stuart Kauffman
University of Pennsylvania
Mark Kirkpatrick
University of Texas
Eric Lander
Whitehead Institute
Bruce Levin
University of Massachusetts, Amherst
Masatoshi Nei
University of Texas
Rosemary Redfield
Harvard University
Burt Singer
Yale University
Elizabeth Anne Stanley
Los Alamos National Laboratory
Marcy Uyenoyama
Duke University

The Institute's Visiting Fellows Program brings to Santa Fe scientists currently pursuing advanced research in complex systems. During 1987 SFI hosted six fellowships. As project directors, the residencies of three Visiting Fellows—Philip Anderson, Kenneth Arrow and David Pines—centered mainly on activities in connection with the Global Economy workshop. During their stays Brian Arthur, John Holland and Stuart Kauffman participated in SFI's September workshops, collaborated with one another and with other colleagues at the Institute and Los Alamos National Laboratory, and pursued individual research.

Brian Arthur, SFI Visiting Fellow

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

In the last few years I have been looking at what economists call allocation systems with cumulative causation or increasing returns. My stay at Santa Fe gave me a chance to compare positive-feedback theory in economics with its counterparts in nonlinear physics and theoretical biology.

Standard economic theory is built upon the assumption of negative feedbacks—diminishing returns on the margin. If two activities compete—television and movies, for example, in the entertainment market—one activity is consumed until the enjoyment it offers diminishes to the level the other offers. The two are bid into an equilibrium; and given information on people's tastes and possibilities, the equilibrium market shares are determinable and predictable in advance.

Economic theory built upon positive feedbacks or increasing returns on the margin is different. For example, in the video technology field Sony Betamax possesses increasing returns in the sense that increased prevalence on the market encourages more films to be produced in that technology and so returns to purchasing Betamax increase with its market share. If Betamax and its rival, VHS, compete, a small lead in market share gained by one of the two technologies may enhance its competitive position and allow it to further increase its lead. Eventually it may be that one of the two takes 100% of the market. But we cannot say in advance *which* one this will be. There are two possible outcomes or long-run steady-states possible for this market. We cannot guarantee that the better outcome—the more efficient video technology—will dominate. An early run of chance events may give the inferior system sufficient advantage to take the market. And once the market is taken over by one video system, it is difficult to restore a shared market. The system is locked-in.

The are four key properties here: multiple steady-states; possible inefficiency; path-dependence; and lock-in. From what I have seen these recur in other areas of economics whenever self-reinforcement or increasing returns are present. These properties appear to have counterparts in physical and biological systems. Physicists talk about nonlinear mode-locking rather than lock-in, about non-ergodicity rather than path-dependence, and about potential levels rather than efficiency. There are other correspondences. In the video example the market starts out even and symmetric, yet it ends up asymmetric; and so there is "symmetry breaking." An "order" or pattern in market-shares "emerges" through initial market "fluctuations." Biologically we might say that the two video technologies compete to occupy one "niche" and the one that gets ahead exercises "competitive exclusion" on its rival. And if one technology isn't innately superior, it has more chance of taking the market: it possesses "selectional advantage."

What is important here is not just that positive-feedback systems show much the same properties whether they occur in economics or in physics. More interesting are the methods and insights that can be traded from one field to another. In economics we have developed powerful non-linear probabilistic Strong Laws that may become useful in physical chemistry. Talking with people like Philip Anderson and others at the economics workshop I learned that there were nucleation phenomena and renormalization methods in physics that have not yet been explored in economics. The differences in discipline style were revealing too. Physics puts emphasis on spatial dimension (for example lattice structure) which is largely ignored in economics; economics puts emphasis on strategy and formation of beliefs, both of which are not important in physics. Methods in other disciplines are instructive, but not always transferable.

A quite different theme of complex systems—the implications of interlinkage—has also fascinated me for some time. The products, markets, and technologies that make

up an economy form an interlinked web whose complexity appears to increase with time. Why this should be so is the central question of economic development—one that economists are only starting to address. It turned out that Stuart Kauffman had also been thinking about this question. It is a natural analog of the evolution-of-biological-complexity problem that he has investigated for several years. Kauffman and I spent several sessions discussing the evolution of economic structure and the questions this brings up. Under what conditions do economic systems increase in complexity? How do networks of economic activities evolve? How does the stability of an economy or a trading system vary with its complexity? It is probably too early to look for concrete results here, but a program for research has been laid out in Kauffman's paper prepared for the "Global Economy" workshop proceedings.

It is becoming clear to economists that a sizeable proportion of economic decisions involve a degree of calculation that makes optimal or perfectly rational choice highly unlikely. Yet, how to model non-optimal behavior in a way that yields insights remains a problem. I was interested to talk to John Holland at length about this. It appears that Holland's Classifier System and Genetic Algorithm are perfectly suited for the study of how non-optimal, interconnected behaviors evolve, especially where the problem environment is changing rapidly. Holland and I discussed one or two "homework problems" that we could test his methods on. If these were successful they might help clear the "non-optimality" log jam in economics. —WBA

John Holland, SFI Visiting Fellow

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

During the month of September, the Santa Fe Institute sponsored two workshops, *Evolutionary Paths of the Global Economy* and *Computational Approaches to Evolutionary Biology*, as well as co-sponsoring with the Los Alamos National Laboratory a conference on *Artificial Life*. All three meetings had invited me to make presentations, and I served with Marcus Feldman as co-chairman of the *Computational Approaches* workshop. The invitation to serve as a visiting fellow at the Institute during this period was both timely and exciting. I can think of few other periods in my life when I have been exposed to so many new and various ideas in such a short period of time. Moreover, these ideas were presented and explored by some of the very best people in each of the areas involved. It will certainly take several months to digest, and put into perspective, the product of a great variety of discussions, but some new directions for my own research are emerging already, and some active collaborations are shaping up—involving, in separate efforts, (1) Tom Sargent (Stanford) and Tim Kehoe (Wisconsin), (2) Brian Arthur (Stanford), and (3) Marcus Feldman (Stanford). It was also an opportunity to further advance a previous collaboration with Doyne Farmer, Y. C. Lee, and others at the Los Alamos National Laboratory

While most of my time was taken up in one way or another with the three meetings, I did spend a considerable amount of time with Brian Arthur on the problem of limited rationality and multiple equilibria in economic models. Though, prior to now, it has proved difficult to incorporate these notions into formal economic models, we are quite optimistic that substantial progress can be made in this direction. Some of the discussions also involved Burt Singer (Yale) and Eugenia Singer (Citicorp).

Finally, I did find a few hours to further refine some of my recent work on the representation of arbitrary finite nonlinear functions in terms of averages over hyperplanes in the argument space. In fact, there is a unique transform (somewhat like the Fourier transform) that allows conversion between the standard map $\mu : \{0,1\}^1 \rightarrow \text{Reals}^+$ and the map of averages of μ over the hyperplanes. This representation is important to my work because genetic algorithms actually explore and optimize functions by exploiting hyperplane averages.

In sum, it has been an exciting month and one that indicates, to me at least, just how unique are the opportunities offered by the Santa Fe Institute and its way of tackling difficult interdisciplinary problems.

—JH

Board News

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

Mr. Robert O. Anderson is President, Hondo Oil and Gas Company; former Chairman of the Board, Atlantic Richfield Company; and Owner, Diamond A Cattle

Robert O. Anderson

Company. A Past President of Malco Refineries, Inc., he is a Member of the Committee on Economic Development, National Petroleum Council; Chairman of the Aspen Institute for Humanistic Studies; Chairman of the Lovelace Foundation; Chairman of the International Institute for Environment and Development; and a Trustee of the California Institute of Technology.

Mr. Lawrence S. Huntington is Chairman of the Board, Fiduciary Trust International. He is also a Member of the Board of Directors, World Wildlife Fund/Conservation Foundation; a Member of the Board of Directors, INFORM; a Member of the Board of Directors, National Ghost Ranch Foundation; a Trustee of Citizens Budget Committee; Director of Josiah Macy, Jr. Foundation; and a Member of the New York State/City Commission on Integrity in Government.

Three new members have been elected to the Science Board:

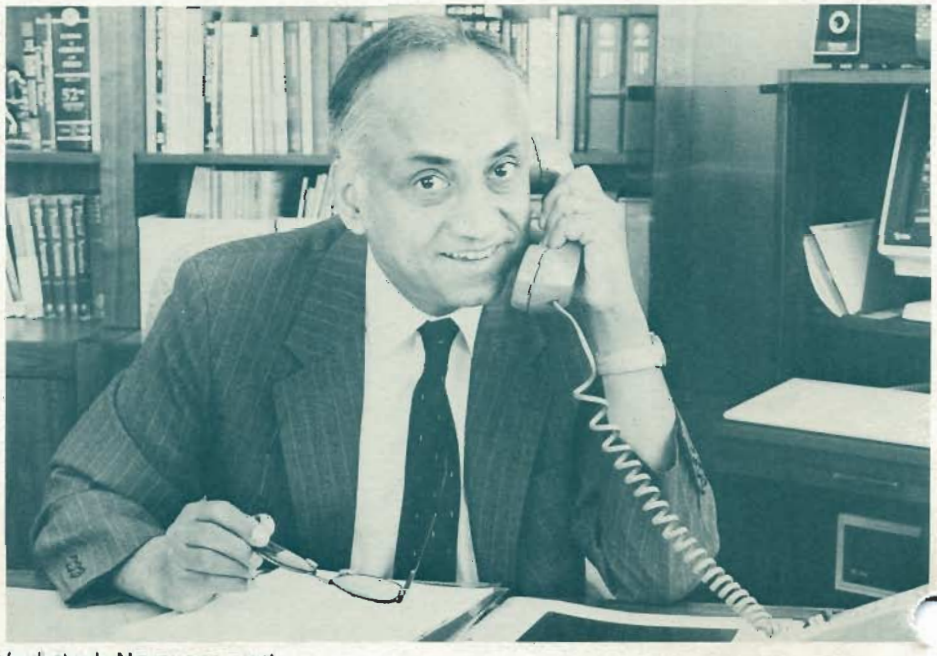
W. Brian Arthur is Morrison Professor of Population Studies and Economics at Stanford University. For more about Prof. Arthur, see his Visiting Fellow report on page 6.

Venkatesh Narayanamurti, Vice President of Research, Sandia National Laboratories, is former Director, Solid State Electronics Research Laboratory, AT&T Bell Laboratories. In addition to serving on the SFI Regional Council, he is a Fellow and Member of the Panel on Public Affairs for the American Physical Society; Fellow of the American Association for the Advancement of Science; Fellow of the Institute of Electrical and Electronics Engineers; foreign Member of the Royal Swedish Academy of Engineering Sciences; Chairman of the Subcommittee on International Scientific Affairs; Vice-Chairman of the NAE/NRC Panel on "Photonics, Science & Technology"; Member of the AIP Committee on International Scientific Affairs; and Member of the Advisory Board, College of Electrical Engineering, Cornell University.

One of the most eminent physicists in France, **Gérard Toulouse** is

Lawrence S. Huntington

Professor of Physics, Ecole Supérieure de Physique et Chemie and a Visiting Fellow at the Institute of Advanced Studies, Hebrew University of Jerusalem. He is also past Maître de Conferences à l'Ecole Polytechnique. He was awarded the Prix Langevin (Société Française de Physique), 1976; the Prix Triossi (Académie des Sciences), 1979; and the Holweck Prize (S.F.P. and British Institute of Physics), 1983.



Venkatesh Narayanamurti

Personal Pathways

One Biologist's Galapagos: Origins of Order in Evolution

Stuart Kauffman

From time to time SFI asks one of its Science Board members to give a personal account of the background of his current work.

Turning points in intellectual life are often less than welcome, brought on by a message one did not seek. One such message was delivered some 10 years ago, as I was walking one spring morning in the Downs of southern England with the evolutionary biologist John Maynard Smith and his biologist wife Sheila. John, remarking on our proximity to Charles Darwin's home, chided me more or less gently: "You really must think about natural selection, Stuart."

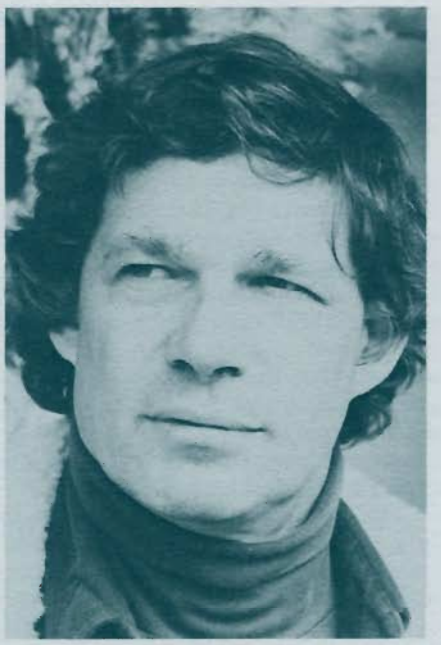
How his comment shocked me! Of course one should think about it! But I had spent more than a decade exploring the idea that much biological order might reflect inherent self-organized properties of complex systems, even in the absence of selection. Since Darwin, of course, we have come to view natural selection, sifting out rare useful mutations from myriads of useless ones, as the sole source of order in biological systems.

But is this view correct? Might not complex systems spontaneously exhibit order? I had begun to ask this question in 1964 shortly after Francois Jacob and Jacques Monod published their famous operon model. Biologists began thinking of the genome as a kind of biochemical computer, in which a gene or its products turn other genes on or off. This view, first worked out in bacteria and viruses and now being extended to higher cells (i.e., nucleated cells or eukaryotes), implies that cell differentiation in development from the fertilized egg is mediated by a complex genetic regulatory network that coordinates synthetic activities of the roughly 100,000 genes in each cell type of a higher eukaryote. By current criteria, a mammal has on the order of 200 to 300 distinct cell types. The regulatory network is thought to control gene expression patterns in these different types. For example, in red blood cells hemoglobin is abundant, while in B lymphocytes of the immune system, antibody molecules are synthesized at a rapid rate. Each cell type is characterized by a particular spectrum of products among the 100,000 genes.

To analyze the problem it's useful to simplify and imagine that each gene can be only active or inactive. Think of a genomic regulatory network as a computer with an on-off switch representing each gene's activity. Since each gene can be on or off, there are $2^{100,000} = 10^{30,000}$ possible patterns of gene activity—a number large enough to catch the attention of even Carl Sagan.

How are we to understand a system with 100,000 genes switching one another on and off? In part, by our natural bent for reductionistic analysis. In fact, contemporary molecular biology and developmental genetics are largely devoted to working out in as much detail as possible, the regulatory architecture and logic in simple and complex organisms. But even should we succeed in analyzing the detailed circuitry, we shall need to reintegrate our knowledge and understand what features of that circuitry mediate the order we see. This necessity is boldly underscored by the fact that, during evolution, chromosomal mutations occur at a rapid pace and literally scramble the genomic regulatory system, altering which gene regulates which gene, and the behavior of the regulated gene as a function of the activities of those genes which regulate it. Viewing the genomic regulatory system as a kind of biochemical computer with 100,000 or more components, we confront the fact that the "wiring diagram" and "logic" of that computer is continuously randomized in evolution, and simultaneously subjected to both natural selection and selectively neutral "drift."

At this point an old interest in self-organization offered a new viewpoint. Jacob and Monod's model of genes turning one another on and off suggested that the idea of "logical switching circuits" was a reasonable way to approach genomic networks. The question I posed early on was whether the richness of connectivity



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

SFI Profile:

Stuart Kauffman

Stuart Kauffman echoes physicist Wolfgang Pauli when he describes inspiration in terms a visual artist might use: "One of the deepest pleasures in science is finding an interpretation for a deeply held image," he says.

As an undergraduate at Dartmouth in the late 1950's, Kauffman, now a member of the SFI Science Board, visualized a diagram that has since pervaded his work. "One day I was walking by a bookstore and thought, 'Someday I'll write a book and on the cover will be

(continued on page 12)

in a genomic network—that is, the number of genes that directly regulate any specific gene—might have an important bearing on the spontaneous emergence of orderly behavior in model genetic networks. To my delight, the answer was yes.

This fact still astonishes me. Consider a model genetic regulatory system with, say, a mere 10,000 on-off genes. Hook the genes together randomly, with each gene directly regulated by only two other genes. Then assign to each gene at random one of 16 possible logical switching rules. Since such a network, which has both a random "wiring diagram" and random "logic," is supposed to model a real genomic system, once it is constructed its structure is fixed. It is therefore a random sample drawn from the pool of all model genetic regulatory systems built with the same constraints on number of genes and numbers of inputs per gene. Do such random systems typically behave in an orderly fashion?

The surprising result I found is that if each gene has only a few direct input genes, which is true in bacteria and viruses and may well be true in eukaryotes, then a system with 10,000 or 100,000 on-off genes settles down to one of only a few recurrent patterns of gene expression. Those patterns are also stable to perturbation: if a gene's activity is transiently reversed, the system typically returns to the same pattern. If we think of such a recurrent pattern of gene activities as a *cell type* in the repertoire of the genomic system, then these "random networks" exhibit an order that is strikingly predictive of features seen in organisms.

(1) Each recurrent pattern of activity into which a network settles cycles among very few combination of activities of the genes. A network with N genes typically settles down to a recurrent cycle of $\sqrt{N}$ states. This result is rather remarkable. The model networks are clearly disordered dynamical systems, constructed at random within the constraint that each gene is regulated by a few other genes. Yet a system with $N = 10,000$ genes and $2^{10,000} \cong 10^{3,000}$ combinations of gene expression will typically settle down and cycle through a mere 100 combinations of gene expression on any model cell type. This implies that such systems spontaneously "box" themselves into tiny volumes of their possible state space, hence exhibit order spontaneously.

(2) The cyclic patterns are stable to perturbation, mimicking the homeostatic stability of cell types.

(3) Any such network typically harbors more than one stable recurrent pattern of gene activities. Each such recurrent pattern is a different model cell type. A central finding is that the typical number of alternative model cell types in such a genomic system is approximately equal to the square root of the number of genes in the network. Thus, a system with 10,000 genes might have on the order of 100 cell types, while a genomic system with 100,000 genes would have about 300 cell types. Not only is this prediction in a numerically plausible range, but more strongly, analysis of organisms from bacteria and yeast to man shows that the number of histologically distinct cell types is, in fact, roughly a square root function of the DNA content of the genome. Thus, the model both draws attention to and appears to predict a scaling relation between genomic complexity and numbers of cell types.

(4) If such a stable recurrent pattern of gene expression models a cell type, then the similarities and differences in gene patterns in different model cell types become predictions about real cell types. Here, too, the parallels are striking. Plant cells typically coordinate the expression of about 20,000 genes. Two cell types typically differ in the expression of a few hundred to perhaps 2000 genes; that is, differences in activities are on the order of less than 10% of the genes. The same occurs in model networks with few inputs per gene.

(5) Further, the models exhibit an unexpected property: a fraction of the genes are "frozen" in either the active or in the inactive state in all model cell types. Typically 70% or more of the model genes are in this "frozen component." Then does such a "frozen component" occur in real cell types? In fact, yes. In higher eukaryotes such as mammals, a common core of genes is expressed continuously in all cell types. This core is about 70% or more of those genes which are ever expressed. Thus, random-model genetic networks in which each gene is regulated by few other genes "spontaneously" exhibit similarities in patterns of activity between model cell types which are close to real higher cells.

(6) If a cyclic pattern is a cell type, then cell differentiation consists in a transition from one such pattern to another such pattern caused by a perturbation which alters the current activity of one or more genes. Such perturbations might be supplied by hormonal or other signals acting on specific genes at specific times in their cell cycle. Then the typical feature of these networks is that any cell type can differentiate directly into only a few neighboring cell types, and from those to a few others. But this implies that ontogeny must be organized around branching lineages of differentiation from the fertilized egg, leading ultimately to the 250 or so cell types of the adult. Is this in fact found? Indeed it is. We know that the ontogeny, or development of an individual organism, in all higher eukaryotes takes place by just such sequences of branching pathways of cell differentiation from the zygote. In short, we confront a novel fact: even randomly constructed model genomic systems with few inputs per gene spontaneously exhibit a wide range of properties which are very strongly similar to those found in real genomic systems. This strongly suggests that the "local features" used in constructing such model genomic networks, namely the constraint that each gene be directly regulated by few other genes, have powerful implications for the large-scale behavior of model genomic systems. Thus, our intuitions about the requirements for orderly dynamics have been mistaken. Global order is implied by mere membership in the ensemble of genomic regulatory systems with few inputs per gene.

I have wanted to believe that such deep properties of ontogeny as the prevalence of branching pathways of differentiation reflect the self-ordered properties of complex genomic systems, not selection. More generally, the fact that randomly assembled model genomic systems exhibit marked order even roughly reminiscent of that found in organisms strikes a blow at our world view, in which selection is the sole source of order in biology. I think that view is wrong. Complex systems exhibit far more spontaneous order than we have supposed, an-

order evolutionary theory has ignored. But that realization only begins to state our problem, for Maynard Smith's admonition is correct. We must think about natural selection. Now the task becomes much more trying, for we must not only envision the self-ordered properties of complex systems but also try to understand how such self-ordering interacts with, enables, guides and constrains natural selection. It's worth noting that this problem has never been addressed. Physics has complex systems and spontaneous order, for example in spin glasses, but need not consider selection. Biologists are fully aware of natural selection, but have never asked how selection interacts with the collective self-ordered properties of complex systems. We are entering virgin conceptual territory.

The challenge has set me thinking about how selection interacts with such self-ordered properties. This job is hardly begun, but several points are clear. First, two kinds of "complexity catastrophes" tend to limit the capacity of selection to attain genomic regulatory systems that are extremely untypical in the ensemble of possible genomic systems. The first complexity catastrophe is due to the balancing effects of mutation and selection. The second is due to the distribution of peaks, ridges, and valleys in the "fitness landscapes" upon which adaptation occurs. Classical population genetic results have long hinted at a limit to selection's power to achieve "maximally fit" genotypes in the face of a constant mutation rate as the number of genetic loci in the genomic system increases. Such work has focused on "additive" fitness models in which each gene makes a contribution to the overall fitness of an organism which is independent of the other genes in the system. The total fitness of the organism is imagined to be given by the sum of the independent fitness contributions of each genetic component. In such additive fitness models, as the number of genes increase, the proportional fitness contribution per gene dwindles, but the rate of mutation altering a good version (allele) of a gene to a less useful version remains constant. Eventually, as the number of genes increases, mutation overwhelms selection and disperses an adapting population away from optimal genotypes. Thus, additive models suggest that selection confronts a limit as the complexity of the genomic system increases.

But a second unsuspected limitation on selection seems to be emerging. Natural selection is a kind of combinatorial optimization process. Typically such processes face a rugged, multi-peaked "fitness landscape" due to conflicting design requirements. Under strong selection, a population will at least climb to a local peak. Simon Levin at Cornell and I found recently that as genetic networks under selection become more complex, attainable fitness peaks often become lower! Worse, this appears to be a general tendency in many combinatorial optimization processes. As the entities under selection become more complex, the optima that can be reached become progressively more mediocre. Thus, even in the limit of strong selection, always able to pull an adapting population "uphill," there is a marked tendency which limits the deviation from the average as the complexity of entities under selection increases. Does this mean that even strong selection cannot achieve highly complex well-adapted systems?

The answer appears to be no, provided certain "design" criteria are met. This summer at the Santa Fe Institute, Edward Weinberger and I began to analyze a class of models which are rather like spin glasses. We suppose that an organism has N genes, each one of which makes a fitness contribution to the entire organism which depends on the allele of that gene itself, and on the alleles, or versions, of K other genes. Such interactions, in which the effects of one gene depend upon other genes, are called epistatic interactions by geneticists. Our question is this: how does K, the number of genes which impinge upon the contribution of each gene, influence the statistical structure of the resulting adaptive landscape? Thus, for $K = 0$, each gene is independent of all other genes, and we recover the additive fitness model above. For $K = N - 1$, each gene's fitness contribution depends upon the alleles present in all genes. Here, alteration of any gene sharply alters the fitness of the resulting "organism." The resulting fitness landscape is nearly random, and Weinberger and I recover the complexity catastrophe noted above in which attainable optima recede toward the average fitness of all genotypes as N (and K) increase. But, strikingly, if K remains small as N becomes large, then such systems exhibit "good" adaptive landscapes in which N can increase but selection continues to be able to attain high optima which do not recede toward the average fitness of all genotypes. This result suggests three conclusions. First, in general, selection cannot do better than attain the optima afforded by the adaptive landscape upon which adaptation is occurring. Second, one design principle which allows complex systems with a multiplicity of conflicting constraints to remain "perfectable" by mutation and selection is that each "part" of the system must interact directly with only a few other parts in the system. Notice immediately that all real organisms, and all real machines are actually constructed this way. Any part interacts directly with a rather small subset of the parts of the whole system. This principle underlies both hierarchical systems, and modular systems. It underlies Simon's near "decomposibility," and Ashby's idea of functionally independent subsystems in a complex system. Presumably it is one very basic way to build complex systems able to adapt. But third, this suggests that selection may itself act in a second-order fashion to achieve the kinds of organisms which adapt on "good landscapes." That is, not only does selection pull forth fitter variants, but it may pull forth variants which are better able to evolve! We confront the question in Kantian form by asking: what must complex systems be such that they can adapt by mutation and selection? And further, can selection itself achieve the kinds of complex systems so able to adapt?

One is led by these considerations to realize that evolutionary theory, indeed our very view of life must be reformulated. Selection is not the sole source of order in organisms. We appear to be at a promising point which is, at best, a beginning.

Parts of this article appeared originally in "Dueling Selectively with Darwin" in The Scientist.

Kauffman *(continued)*

an image of dots connected by a web of lines.'"

"Somehow," he says, playfully, "I've had the notion that if you get enough dots connected by enough arrows, good things will happen."

That concept has echoed throughout Kauffman's 25 years of research in developmental genetics, theoretical biology and evolution. His work is attracting important attention: the MacArthur Foundation awarded him a prize earlier this year, and the Office of Naval Research granted three years of funding beginning in 1985 for his ongoing work in "novel," random, synthetic proteins.

But at 48, Kauffman remains down-to-earth and accessible. He can talk about the way his work "feels," which is "peaceful, like part of the universe is revealing itself to you."

Curiosity regarding the mysteries of life has connected the dots of Kauffman's career, guiding him from aspiring playwrite in Sacramento, California to Professor of Biochemistry and Biophysics at the University of Pennsylvania. Along the way, he learned to look at those mysteries conceptually, studying philosophy at Dartmouth and later as a Marshall scholar at Oxford University.

"There's a lot of diseases now for which people don't make vaccines...What if it turned out they could be made trivially?"

"The path went from being a philosopher,...which actually bears a lot on what I've become," he explains; "It's helped in getting conceptually straight on what the issues are."

In 1963, he decided to head toward "something more practical and tough-minded" than philosophy. This spurred a change of course that led to medical school at the University of California, San Francisco. It was tough starting over as an undergraduate, but it was at San Francisco that he "encountered" the problem of cell differentiation and his work began.

Following up on Nobel laureates Jacob and Monod's discovery that genes turn one another on and off, Kauffman began trying to unravel the kinds of networks by which the human body's 100,000 genes mediate one another's activities.

That led to the conjecture that a lot might be learned about the typical properties of genetic regulatory networks without having to know the precise details.

"For example, lots of the properties might depend on the number of genes which directly regulate any single gene," he speculated. To test this theory, he assigned random switching rules to randomly wired networks in which each gene was directly controlled by only a few other genes. Kauffman found that such networks settle into stable, recurrent patterns of gene expression.

"The typical behavior turned out to be orderly, and the way in which it's orderly, looks a lot like cell-differentiation in organisms," he says.

This discovery seemed to offer a new slant on evolution. Perhaps, Kauffman reasoned, selection is not the only source of order in organisms; perhaps evolution also depends upon "inherent, deep properties" underlying genetic networks.

Fulfilling conceptually his prophecy in front of the bookstore at Dartmouth, Kauffman is now exploring the way selection acts on self-ordered systems in a book with the working title *Origins of Order: Self-Organization and Selection in Evolution*. Harvard University Press has contracted to publish the work, which will also include a discussion of the behavior of genetic networks, the origin of life, and pattern formation in the morphogenesis of organisms.

Kauffman also has set out on a program which might ultimately create self-generating sets of proteins.

"The fundamental problem," Kauffman says, "is to know the probability that an arbitrary protein catalyzes an arbitrary reaction." In order to find out how hard it is to find an arbitrary protein to catalyze an arbitrary reaction, Kauffman has employed genetic engineering techniques to create 10 billion novel, synthetic genes by randomly stringing together DNA.

"...being a philosopher...helped in getting conceptually straight on where the issues are."

The next step is to find or evolve new genes that might be beneficial to medicine. Toward that end, Kauffman is infecting bacterial cells with bacterial viruses containing the novel genes. Eventually, he'll look for novel proteins that can act as drugs or vaccines.

A patent application is currently pending on Kauffman's process for generating novel proteins and peptides and his process for screening for useful ones. "This is industrial strength, applied evolution," Kauffman says. "Industries could come out of it."

Although he currently has "more faith in the questions than in the answers," Kauffman believes strongly the work will yield important results if given the massive effort it requires.

"There's a lot of diseases now for which people don't make vaccines," he points out. "What if it turned out they could be made trivially?"

This is but one of the questions he hopes to answer positively.

–Louis Weisberg

Louis Weisberg is a freelance writer in Santa Fe. He is a frequent contributor to The Scientist, *and his feature articles appear in the* Philadelphia Inquirer, The Denver Post, Houston Chronicle *and* The Albuquerque Journal.

SFI Update

Philip Anderson, Princeton University, is steadily working on the theory of the new superconductors, with Princeton students and visitors. He notes, "We are well in the lead in that our theory seems to be the only one with any predictive power at all."

Kenneth J. Arrow recently participated in the International Economic Association Conference "Survival and Growth in a Policentric World" in Basel, Switzerland. His current research, conducted with Frank H. Hahn at the University of Cambridge is on the stability of competitive economic equilibrium.

Earlier this year **Bill Brinkman** was named Executive Director of Research for the Physics Division at AT&T Bell Labs, Murray Hill, New Jersey. Bill returns to Murray Hill from Sandia National Laboratories.

Peter Carruthers is Chairman of the Technical Committee for the Arizona Superconductivity Super Collider project. He is currently Acting Director for the University of Arizona Center for the Study of Complex Systems, presently in formation.

Al Clogston, Los Alamos National Laboratory joins the NAS/NAE Committee on Science, Engineering and Public Policy. His current research interests focus on the nonlinear localization of vibrational energy in solids.

Marcus Feldman has been elected to the American Academy of Arts and Sciences. His new book *Mathematical Evolutionary Theory* is forthcoming from Princeton University Press.

John Holland is the most recent recipient of the University of Michigan's Distinguished Faculty Achievement Award.

George Kozmetsky, IC^2 Institute at the University of Texas at Austin, will be teaching a graduate course this Spring on creative and innovative management. His current research interests include international

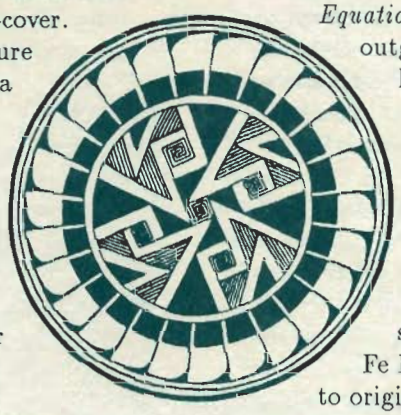
(continued on page 15)

Science Board

Publications

The first volume of the Santa Fe Institute Studies in the Sciences of Complexity series is now available. *Emerging Syntheses in Science*, edited by David Pines, is $43.25 in hard cover or $21.50 in soft-cover.

To order this or future volumes, contact Celina Gonzales, Advanced Book Program, Addison-Wesley Publishing Company, 390 Bridge Parkway, Suite 202, Redwood City, California 94065, or use the order form included in this issue.



The logo for SFI volumes is a Mimbres pottery design, circa A.D. 950-1150, drawn by Betsy Jones for this first volume.

Theoretical Immunology, proceedings from the June, 1987 SFI workshop, is due out next Spring. Edited by conference organizer Alan Perelson and containing contributions from more than forty program participants, this issue will be two books—Part I and Part II. Unlike most other publications on the subject, which generally consider only experimental information, these books will give readers a comprehensive view of current developments in this relatively new field which pairs theorists with experimentalists in an effort to unlock the mysteries of the human immune system.

Kenneth Arrow, Philip Anderson and David Pines will edit another proceedings volume, this from the global economy workshop, entitled *The Economy as an Evolving Complex System*. Does this complex system have a pattern, which in part may be revealed by the laws of biology, physics and mathematics which describe other seemingly chaotic systems? Papers from presenters and participants—physical, biological and computer scientists as well as economists—will cover dynamical models, the stock market, and tendencies of economic systems. This will be available next summer.

Our fourth volume, also available in 1988, is a volume on lattice gas automata, *Lattice Gas Methods for Partial Differential Equations*. This project is the outgrowth of a workshop held at the Center for Nonlinear Studies, Los Alamos National Laboratory, and will be edited by Gary Doolen. This workshop was co-sponsored by the Santa Fe Institute. In addition to original papers, the volume will include reprints and translations of foreign articles.

Artifical Life, edited by Christopher Langton, will be the fifth volume in the series. It comes out of a September workshop organized by the Center for Nonlinear Studies, Los Alamos National Laboratory, and co-sponsored by the Santa Fe Institute. This volume, one of the first dedicated solely to artificial life, will include an extended bibliography of work in this field—a valuable reference and research tool. See our next Bulletin for information about a public-access electronic database of this bibliography.

Our publisher, Addison-Wesley Publishing Company, is a full-range global publisher of advanced level textbooks, monographs, reference works, reprint volumes, and software in the sciences and mathematics. Headquartered in Redwood City, California, Addison-Wesley's *Advanced Book Program* handles the SFI series. They also publish the prestigious "Frontiers in Physics" and "Lecture Notes and Supplements in Physics" series.

To work with Addison-Wesley, George Cowan has appointed a Publications Committee, chaired by L. M. Simmons, Jr. who handles the day-to-day concerns of the publications program, and comprised of Robert McC. Adams, Philip W. Anderson, George I. Bell, David K. Campbell, George A. Cowan, Marcus W. Feldman, Murray Gell-Mann, John H. Holland, Bela Julesz, Stuart Kauffman, and David Pines. Members will review publication ideas, suggest possible topics and editors, and approve prepared manuscripts in addition to making recommendations on the development of the SFI publication program.

–RKBV

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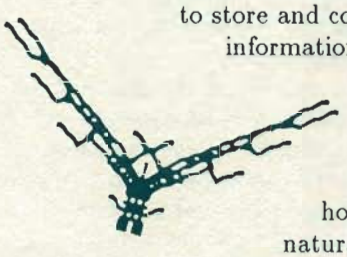
Artificial Life: Computation and Biology Mixed

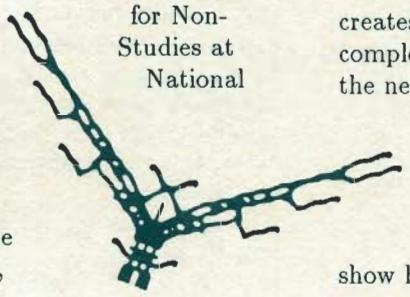
Scientists in the new field of Artificial Life use computer and other modeling techniques to provide ways of thinking about the universal principles of life. Although some experiments imitate real organisms, others use sets of rules to create possible new life forms. The underlying belief is that a pattern or logic of life can be abstracted within the computer.

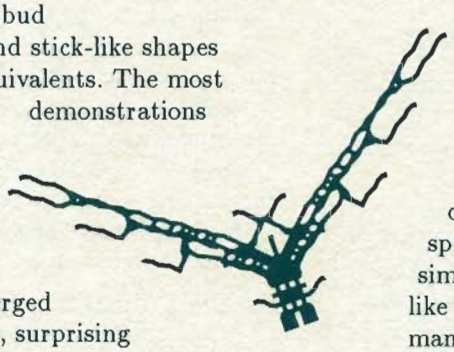
Some of the computer-automated life forms shown at the recent conference sponsored by the Center for Nonlinear Studies at Los Alamos National Laboratory (and cosponsored by the Santa Fe Institute) were flocking birds, schooling fish, flowers which bud and unfold, and stick-like shapes given gene equivalents. The most intriguing demonstrations have been those in which lifelike qualities have emerged spontaneously, surprising even the programmers. One programmer included rules for flocking imaginary birds to avoid hitting their neighbors; unexpectedly, one bird crashed into an obstacle, fluttered for a moment, and then flew on!

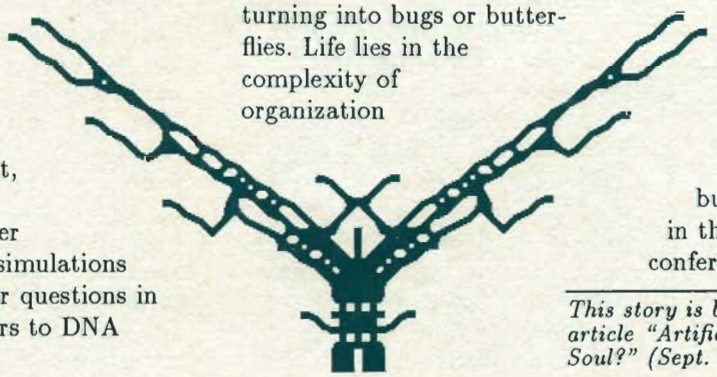
More than computer graphic games, these simulations are dealing with major questions in biology: how precursors to DNA acquired the ability to store and copy information; how natural selection creates structures of extraordinary complexity and beauty and how the needs of individual animals are offset by the laws ecosystems.

Computer models may not solve the mysteries of life, but can show how things plausibly occur and give scientists clues to general principles. Through computer abstraction, for instance, scientists realize that complexity can arise spontaneously from simple systems. Stick-like figures evolved over many generations, show increasing complexity through mutation and directed selection, sometimes turning into bugs or butterflies. Life lies in the complexity of organization









—an essence arising out of matter but independent of it, or "the ghost in the machine," as Chris Langton, the conference organizer puts it. —RKBV

This story is based in part on The New York Times *article "Artificial Life: Can Computers Discern the Soul?" (Sept. 29, 1987).*

SFI Update *(continued)*

competitiveness analyses, space ports and innovative manufacturing systems.

Venkatesh Narayanamurti, Sandia National Laboratories, has been elected a member of the Royal Swedish Academy of Engineering Sciences. He was nominated by the Academy's division for basic and interdisciplinary sciences, "for his eminent achievements in solid state physics and electronics, with special regard to his pioneering effort in developing the field of phonon optics."

As part of his activities in arms control as a member of the LANL Center for National Security Studies, **Louis Rosen** took part in this summer's Trinity Forum for International Security and Conflict Resolution. In November he attended the US-USSR Joint Coordinating Committee meeting on the Fundamental Properties of Matter.

Stephen Schneider is principal Co-Convener of a Chapman Conference on the Gaia Hypotheses for the American Geophysics Union in March, 1988.

Earlier this year **Marlon Scully** was honored as an annual research lecturer by the University of New Mexico. His presentation was entitled "From Laser Physics to the Life Sciences: Ramblings of a Quantum Cowboy." His current fields of interest are quantum optics, general relativity, and bioengineering.

1988 SFI Activities Include Summer School, Study of World Problems

SFI will co-sponsor a graduate summer school on complex systems in 1988 in addition to program activities which address some of the world's most pressing problems. "SFI has a stimulating program developing for 1988," notes L. M. Simmons, Jr., SFI's Vice President for Academic Affairs, "activities that will move the Institute more deeply into complex systems research and graduate education and maintain SFI's position in the forefront of this exciting new field of complexity."

Research Networks

The Institute expects to see the establishment of three research networks, each an outgrowth of a 1987 meeting. The "global economy as an evolving complex system" network is headed by workshop co-chairs Philip W. Anderson and Kenneth J. Arrow. Some possible topics for small-scale collaborations may be the study of trading and development patterns between countries with unequal market power; the connections between growth and long-run financial cycles; and the evolution of economic structure.

A research network in theoretical immunology has also been established. Its steering committee involves three theorists—George Bell (Los Alamos National Laboratory), Charles DeLisi (Mt. Sinai), and Alan Perelson (Los Alamos National Laboratory)—and four prominent experimentalists—Herman Eisen (Massachusetts Institute of Technology), William Paul (National Institutes of Health), Ronald Schwartz (National Institutes of Health) and Irving Weissman (Stanford University). The group anticipates ongoing collaboration in 1988 and at least one or two working group meetings; one may focus on the interaction of the AIDS virus and the immune system.

Matrix workshop members also foresee ongoing work together with emphasis on several issues, for instance, the building of a knowledge and data base for peptides. A small group meeting is planned for June, 1988.

Research collaborations will be augmented by the presence of several long-term Visiting Fellows at SFI. It's anticipated that 1988 residencies will involve extended return visits by some of this year's Visiting Fellows including W. Brian Arthur from Stanford University, John H. Holland of the University of Michigan, and Stuart Kauffman from the University of Pennsylvania.

Exploratory Meetings

In tandem with its follow-on activities, SFI will initiate several exploratory workshops. It will sponsor a meeting of invited consultants to consider the agenda and participants for a workshop on "Elements of International Stability." Members will be asked to identify the prerequisite components of a comprehensive plan designed to minimize the probablilty of a nuclear confrontation and to discuss how these components might interact and behave as a complex system. In addition to arms control options, economic, political and other sociological elements will be considered. The possibility of numerical simulation of appropriate parts of such a complex system would also be addressed.

Program coordinator George A. Cowan writes, "In undertaking this initial discussion, we are fully aware of the vast number of efforts which focus on the same problem area and the odds against making a significant contribution. However, we feel quite sure that the paths which can eventually lead to a more stable peace will move across the rugged landscape of a highly complex system. The Institute will attempt to describe some of the hills and valleys on that landscape."

One or two short exploratory workshops are planned on how policy studies can be improved when they are concerned with values difficult to quantify, such as ecological and social values involved in loans for rural projects in tropical countries, and when the conditions are changing and uncertain. Traditional cost-benefit analysis, which attempts to reduce all values to a single dimension (basically money) and then to optimize in that variable, may be appropriate under simple static conditions, and when the main issues are narrow economic ones, but it has severe limitations otherwise, especially when the conditions are so complex that optimization is practically out of the question.

The workshops will study how to make better use of the inventiveness of experts to enlarge the sphere of policy options, how to seek better quantitative surrogates for soft but important values, and how to utilize multi-dimensional displays (made possible by modern computer methods) to present the consequences of policy options, with their uncertainties, for different sets of values.

Graduate Summer School

More generally, SFI will co-sponsor and administer "The Santa Fe Complex Systems Summer School," a consortium effort of regional institutions including the Center for Nonlinear Studies at Los Alamos National Laboratory, the University of Arizona, and the University of New Mexico. Under the direction of Professor Daniel Stein of the Physics Department at the University of Arizona, the four-week school will take place at St. John's College next June and July. Stein notes, "The school is part of a nation-wide effort to promote our understanding of nonlinear

Anderson *(continued)*

eactor on the squash court of Stagg Field and later at Alamogordo—he returned to The University of Chicago to participate in the creation of the Institute for Nuclear Studies. It was one of three new institutes at the University, a bold innovation in academic circles to introduce an interdisciplinary concept in the physical sciences. Years later he would return to the same approach, this time at the Santa Fe Institute.

Herb studied at Columbia University, receiving a bachelor's degree and then a doctorate in physics. As an undergraduate he played water polo on the varsity team, and later the open skies of New Mexico inspired skiing in the mountains near Los Alamos. Like Oppenheimer he loved to ride, and after the war took his horse in a trailer to Chicago. Herb has a keen sense of balance and knows how to relax so that he can return to his ntense research with even greater vigor.

Shortly after Fermi's premature death in late 1954, the Institute for Nuclear Studies became the Enrico Fermi Institute, to honor its most distinguished adherent and to be mindful of the last of the universal physicists. Anderson became its director in 1958 when Samuel Allison retired. During this administrative phase, Herb maintained a very active scientific career and continued a series of fundamental physics experiments.

Upon formal retirement from the University, he pursued his studies at the Los Alamos National Laboratory. His recollection of the intense activity during wartime Los Alamos and the spirit of camaraderie that prevailed had not diminished. He was not ready for the leisure life; there was too much science still to be done. His scientific horizons broadened with the initiation of his ongoing collaboration with Theodore Puck on problems of molecular biology. Simultaneously he has carried on important experiments in muon decay. As if this menu were not sufficient, he has kept in touch with the developments of computer science, something he has done ever since the birth of electronic computing in the 1940's. Herb has always availed himself of the latest techniques to maximize their impact on his own experiments.

All these activities prepared him well for the challenges that were yet to come. During the past few years, Herb has been very active in a small group of Senior Fellows of the laboratory, including some Visiting Fellows. Among others, George Cowan and Stirling Colgate are members. These "elder statesmen" have focused on new scientific directions and principles, that is to say, on questions rather than problems.

One question of persistent interest has been the emerging syntheses of various disciplines. By its very nature Los Alamos has shown, almost by inadvertence, the efficacy of cross-fertilization in the sciences. Academia often has been slow to move in this compelling direction, but it cannot be denied that a certain inevitability of mutual stimulation in the sciences persists. This then was the situation several years ago: could the Senior Fellows implement this concept of cross-fertilization?

Led by George Cowan, the Santa Fe Institute was born in 1984. Among the founding members of the Board of Trustees was Herb Anderson. More recently, he has been serving on the Science Board, a notable collection of scientists drawn from a wide variety of disciplines. Herb brings impressive credentials to the group, having been awarded the Enrico Fermi Prize in 1982 by President Reagan. He is of course a member of the National Academy of Sciences and the prestigious American Academy of Arts and Sciences.

Herb Anderson has always given SFI wise counsel. His arguments have been well-reasoned, simple, straightforward and completely objective. How could it have been any different for one who had been the principal collaborator of Enrico Fermi? Herb's wisdom and guidance is embodied in his most recent gift, just a part of his intellectual legacy to the Santa Fe Institute. –Nicholas Metropolis

Nicholas Metropolis is a Senior Fellow at Los Alamos National Laboratory. His friendship with Herb Anderson began in 1942 at the University of Chicago.

1988 *(continued)*

complex systems. As such, we're delighted to be gathering many of the leading scientists in this field."

More than fifty doctoral and post graduate students are expected from throughout the United States. Lectures and seminars will focus on material drawn from the physical, biological and computer sciences, mathematics and economics, chosen not only for its topical interest, but to illustrate connections among various disciplines. Course work will be supplemented by a lab featuring state-of-the-art equipment and software. Program proceedings will be published, and since the school is intended to exist on a continuing basis, such annual proceedings may become a standard reference as the science of complexity develops.

Economic Ties *(continued)*

offset by the very reactions they generate. For example, high oil prices resulting from the shortages in the 1970's caused energy conservation and increased oil exploration, precipitating a price drop. But the history of capitalism also has included stabilities and fluctuations—such as business cycles, recessions and depressions—that seem to defy economists' assumptions regarding equilibrium.

Economic forecasts have had limited success. As Kenneth Arrow noted during the workshop, "Economists have a reasonable view of how the world works, but their record is very poor in quantative predictions of, say, changes in foreign exchange rates."

In economic theory, recent research shows that the phenomenon of "increasing returns" is more common than previously thought. It helps explain how a large market share captured by a product may lead to an even larger one. Such "positive feedback loops" may encourage multiple market equilibria, along with a tendency for the economy to settle into patterns that are both difficult to predict and to escape.

Similarly, both general equilibrium theory and modern game theory—mathematically the most sophisticated parts of economics—find that problems of allocation normally have multiple solutions.

"I look back on the ten days with undiluted pride in our accomplishments. New methods for understanding in homogeneity and complexity in economic systems will undoubtedly emerge from our work.

—P. W. Anderson
Workshop Co-Chair

Need for New Tools

In light of these findings, economists are eager for new analytical tools, according to workshop member Mario Simonsen, former minister of Finance and Planning to Brazil. His sentiment was echoed by Kenneth Arrow who said, "What we want to look at is whether methods used by the natural sciences can be applied to economics, to help us find order underlying the movements of everything from trade prices to interest rates."

The workshop focused on the possible application of techniques that have proven useful in similar complex problems in physics, computer science, and theoretical biology—mathematical methods of nonlinear dynamics that have helped to reveal hidden patterns of order in what had appeared to be random behavior of molecules and particles.

"The workshop participants were...willing to work in another science and take the obvious risks by so doing. You don't get this kind of opportunity in the departmentalized American university system."

—Buz Brock,
workshop participant

Recognizing that such techniques may lend new insights, economists also realize that methods will also have to be tailor made. One reason is that the interacting "particles" in economics—consumers, firms and government agencies—act strategically and with expectations. They condition their behavior not so much on the current configuration of other "particles," but on their assessment of the reactions of other "particles" to their behavior as well as on their beliefs as to how these reactions and the overall system will evolve in the future. In other words, in economics, unlike physics, future expectations affect the present.

The ten-day workshop began with seminars on both economic and complex adaptive system theory; these provided economists with the opportunity of learning at first hand about recent developments (especially in the use of statistical physics methods and genetic and learning algorithms) in the understanding of complex systems, and gave the other scientists insights into the present theoretical understanding

Global Economy Workshop Participants

Philip W. Anderson
Yale University
Kenneth J. Arrow
Stanford University
W. Brian Arthur
Stanford University
Eric Baum
California Institute of Technology
Michele Boldrin
University of California, Los Angeles
William Brock
University of Wisconsin
Hollis B. Chenery
Harvard University
Doyne Farmer
Los Alamos National Laboratory
Jack Guenther
Citicorp
John Holland
University of Michigan
Stuart Kauffman
University of Pennsylvania
Timothy Kehoe
University of Minnesota
Norman Packard
University of Illinois, Urbana
Richard Palmer
Duke University
David Pines
University of Illinois, Urbana
David Ruelle
Ecole Normale Supérieure
Thomas Sargent
Stanford University
Jose Scheinkman
University of Chicago
Mario Simonsen
Brazil Institute of Economics
Eugenia Singer
Citicorp
Lawrence Summers
Harvard University
Eric Wanner
Russell Sage Foundation
Karl-Heinz Winkler
Los Alamos National Laboratory

of the economy. The gathering was then given over to working group meetings which enabled the workshop members to discuss general questions in greater depth and to formulate, and in some cases begin work on, homework problems that focused on specific aspects of the economy as a complex evolving system.

Some issues discussed during the group sessions included:

Dynamical Models of the Economy The economy seems to have remarkable stability properties: external accidents either have very little effect, or the effects (such as wars) are important but wiped out rather rapidly. This would suggest that there are robust laws for economic evolution, and that it should be possible to find and state these laws. Looking at things more carefully, however, one finds that successive adaptations of the economy to successive crises do not correspond to the same phenomenon: the crises are different and the resolutions are different. This suggests more difficulty in finding simple laws for economic evolution.

"It's quite possible that the discussions and collaborations initated here will lead to a radically new formulation of fundamental economic theory."

—*David Pines*
Science Board Co-Chair

The Stock Market Can a computer model be developed to explain the current stock market situation? It was proposed that there are both "sophisticated" and "noisy" traders sharing the market. "Noise" is anything that makes data difficult to interpret. These traders have different strategies, and one can formulate in this way a model based upon "chaotic time evolution." It must be admitted, however, that there is yet no convincing model. Another question related to the market is the connection between speculation and volume, and the problem of excess volatility. One explanation proposed that the influx of information is a driving market force. Again, information is interpreted differently by noisy and prudent speculators, leading frequently to an increased trading of shares and an increased volatility. The market is itself a source of information; thus the process is self-sustaining.

These and other issues will be more fully presented in the proceedings of the workshop, to be published by Addison-Wesley in early 1988, as *The Economy as an Evolving Complex System*, a part of the series "Santa Fe Institute Studies in Sciences of Complexity."

"What we want to look at is whether methods used by the natural sciences can be applied to economics, to help us find order underlying the movements of everything from trade prices to interest rates."

—*Kenneth Arrow,*
Co-Chairman

Collaborative Research

An important immediate outcome of the meeting were three specific research projects, at least two of which will be followed up by collaborative work at people's home institutions. Eric Baum, Buz Brock and Larry Summers will attempt to use neural net learning algorithms on sets of economic data, especially macroeconomic data. Michele Boldrin, Jose Scheinkman and Norman Packard have evolved a two-country model with an internal structure and an increasing return feature that may serve as a model for testing certain effects; a variable embodying the various effects of "learning by doing" infrastructure and education is considered in a way which is suggestive for many other problems. Brian Arthur and Philip Anderson are discussing a cooperative "nucleation-like" economic model which may be applicable to known features of the pattern of fertility change.

That these three projects distilled so quickly from the relatively short meeting suggests the unusual level of serious dialog between the two groups. As Eric Baum noted, "The atmosphere at this meeting was extraordinary. Everybody had something to contribute all the time. Everybody worked extremely hard. In my opinion, the level of interdisciplinary understanding and communication was greater than would reasonably have been predicted." Buz Brock writes, "The workshop particpants were an extraordinarily eclectic group of people distinguished not only by high-powered credentials, but also by a willingness to learn the methodology of other sciences. Not only that, they are willing to work in another science and take the obvious risks by so doing. You don't get this kind of opportunity in the departmentalized American university system."

What final results may be forthcoming from these projects and SFI's continuing research network and when they may develop are open questions. Market watchers will have to be patient. "However," David Pines notes, "it's quite possible that the discussion and collaborations initiated here will lead to a radically new formulation of fundamental economic theory."

–GR

Compiled from articles by W.B. Arthur, Willian Hart in Dallas Morning News, *David Pines, and Byron Spice in* The Albuquerque Journal.

"Evolutionary Paths of the Global Economy" was convened by David Pines, SFI Science Board Co-Chair. The 1987 meeting is an outgrowth of "International Finance as a Complex System," a 1986 SFI workshop convened by Robert McCormick Adams and George A. Cowan.

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Staff News

In September, **Andrea Sutherland** joined the SFI staff as Office Manager. Andi provides administrative support to the staff and visiting faculty and handles the myriad details of workshop coordination. A native New Yorker, Andi resided in the San Francisco Bay Area for a decade before coming to New Mexico four years ago. She lives in Santa Fe with her husband, Alan, and their eighteen-month-old son.

Ronda K. Butler-Villa, who joined the staff last April, has been named Director of Publications. Ronda is in charge of day-to-day administration of the SFI publications program and serves as the principal point of contact with our publisher, Addison-Wesley Publishing Company. Ronda draws on an extensive technical publications background, much of it garnered at Chevron Oil Company in San Francisco, California.

Ginger Richardson has assumed the position of Director of Workshops and Public Relations. Ginger oversees the administration of SFI's workshops, Summer and Winter Schools and other public educational activities and acts as general community and media liaison for the Institute. Ginger gained her background in academic administration during more than ten years' work at the University of California at Berkeley.

SFI's Corporate Vice President **L. M. Simmons, Jr.** has assumed the staff position of Vice President, Academic Affairs. Mike, who is an Associate Division Leader for Research in the Theoretical Division at Los Alamos National Laboratory, is on sabbatical leave from LANL until June 1988. He will divide his time between administrative functions and initiating research in complex systems at SFI and continuing his research on new methods in field theory at the University of Arizona.

Ronald A. Zee, initally SFI's Executive Director, has taken on increased reponsibilities in his new position as Vice President, Development and Operations. Ron came to SFI from The Keystone Center, a national environmental policy think tank based in Colorado, where he served as Vice President. Ron's prior management experience was in government and with other non-profit organizations.