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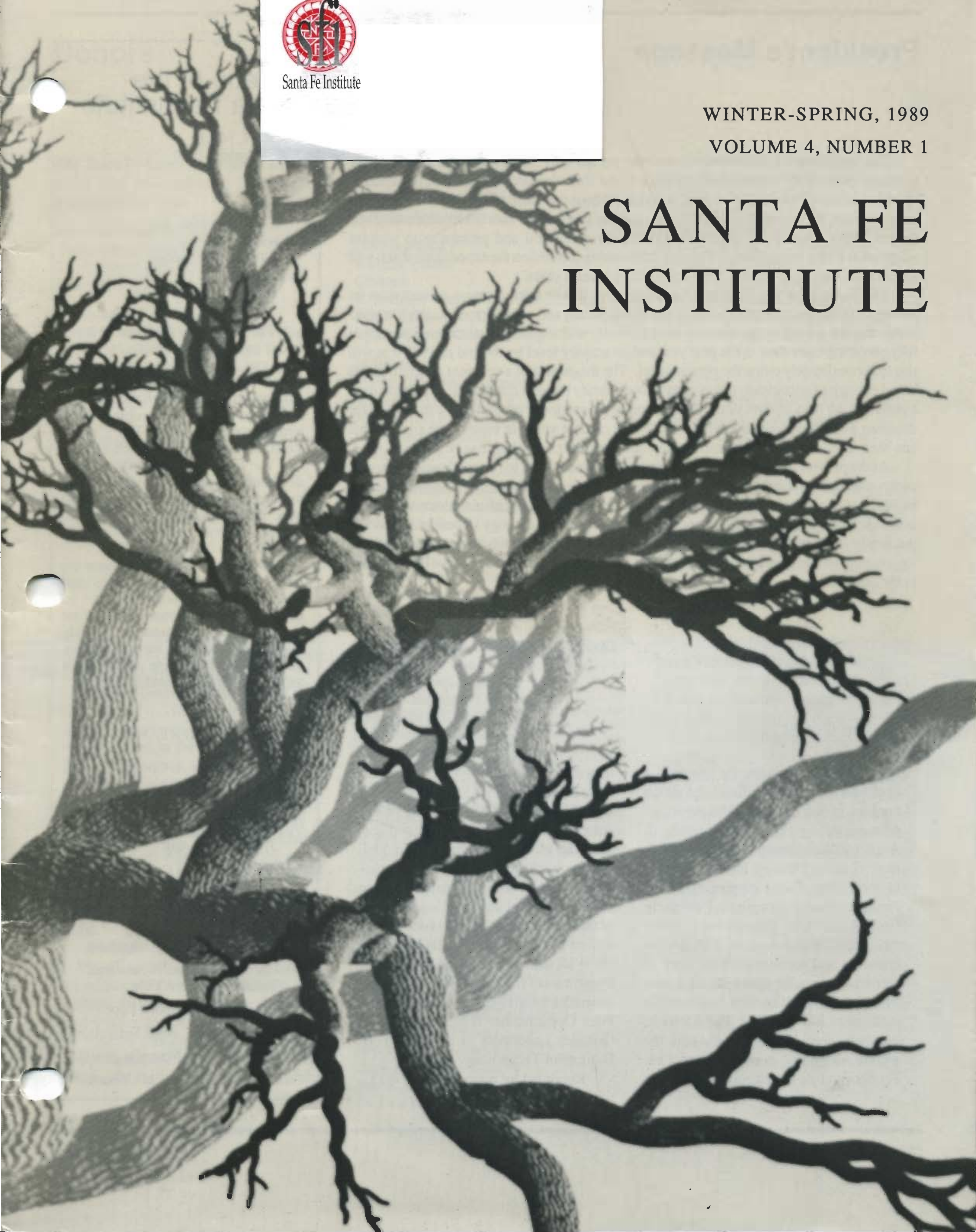

President's Message

The beginning of 1989 reminds me that we are only six months into our first full academic year. I am pleased that this issue of the Bulletin describes a rather remarkable record of accomplishment in so short a period. About one-third of the pages are devoted to economics, reflecting the fact that the ongoing program in economics represents our current major activity. It is already sufficiently successful and promising to warrant adoption as a long-range theme. Our current planning is based on the expectation that it will continue at least at its present level for the next several years.

The Institute ended 1988 at a spending level that is thirty percent greater than its average over the year. Appointment of additional faculty and expansion of research to other major themes related to the sciences of complexity will require a total expenditure about fifty percent greater than in the past year and an activity level by the end of 1989 that will rise to approximately twice the present level. The magnitude of a coherent program that is broad enough to encompass the subject of complexity dictates continuing expansion over a period of the next several years. In addition to the academic programs, we must plan for doubling available physical facilities within the coming year. In view of the support that has been extended to SFI to date, we are confident that these plans can be realized.

At the present time we anticipate strengthening our efforts to further develop adaptive computational algorithms that can numerically simulate the behavior of complex systems, build on our initial exploration last November of the problems of global security and a sustainable world, and initiate a new program in theoretical ecology. These plans will be put firmly in place as new resources are identified, and the list may be expanded. I hope it gives you a sense of our future directions and of the challenges we face as we look forward to the new year.

George A. Cowan

George A. Cowan

On the Cover

The illustration on the cover is a computer-generated artificial tree which appears in the chapter "The Artificial Menagerie," by Peter Oppenheimer in *Artificial Life* edited by C. Langton (Volume VI in the Santa Fe Institute Studies in the Sciences of Complexity series, Addison-Wesley Longman Publishing Group Ltd., 1989). Oppenheimer creates Artificial Life forms on the computer by encoding and manipulating in a set of numerical genes the parameters that control such traits as the angle between the main stem and branches, the size ratio between stem and branches, and the amount of helical twist and curvature. Economy of description is achieved by imposing self-similarity, so that small-scale detail resembles large-scale detail and a simple set of rules relating parent stem to branching offspring can determine the global structure of the model. Making each genetic parameter a random variable with an adjustable variance produces an irregular, gnarled tree such as that on the cover, which is not strictly self-similar but is statistically self-similar. With randomness in the parameters, a single set of tree model parameters can generate a forest of slightly different trees. Peter Oppenheimer is at the Computer Graphics Laboratory at the New York Institute of Technology.

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Bulletin of the Santa Fe Institute

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Editor:
L. M. Simmons, Jr.
Associate Editor:
Ginger Richardson
Publication:
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 multidisciplinary scientific 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.

SFI's Publication Program

Getting the Word Out

Ronda K. Butler-Villa has been director of the Institute's publication program since its inception in 1985. Ms. Butler-Villa produces the camera-ready manuscripts for all of the Institute's publications, including the proceedings volumes published by Addison-Wesley. She is in a unique position to describe the program and to offer her vision of its future directions.

It is easy to say we are excited about the Institute's activities or that a lot is coming out of the workshops, but the publications program provides the only tangible evidence of what is being accomplished. The publications are what get into people's hands.

The Institute's Editorial Board provides direction for the publications program. The board, which is chaired by Mike Simmons and composed of 13 Science Board members, meets biannually, usually in March and September, to decide what should be published and the best publication vehicles, to select editors for the proceedings volumes, and to recommend reviewers. The board also meets once a year with Addison-Wesley to keep the publisher informed.

The Institute's publications include proceedings from the workshops, the Bulletin, which comes out twice a year, and other smaller announcements and updates. The decision to publish a proceedings volume begins with the Science Board. When a program is funded, or even just proposed, the Science Board considers whether a volume is possible or necessary and begins thinking about the publication budget. These early discussions do not result in hard and fast decisions; they are more likely to define probabilities. For example, the Global Security workshop was short and tentative, to get ideas together, and no formal papers were presented. It was clear that no proceedings volume would come out of the workshop. On the other hand, the workshop on theoretical immunology included a lot of valuable but more speculative papers than would be appropriate for publication in journals. So a proceedings volume, *Theoretical Immunology*, was worthwhile.

After a preliminary decision has been made to publish the proceedings, the editor of the proposed volume, who is usually the chairman of the workshop, begins planning the book. The chairman is in an ideal position to assess the workshop participants and the work that is likely to emerge. Thus far, each editor has handled his responsibilities differently. *Theoretical Immunology* included virtually every paper that was submitted on time, but *Artificial Life* includes just eighteen papers. In every case though, the editor reviews each paper to ensure that it is well written, accurate, and worthy of publication.

Thus far, our major publications include five proceedings volumes, which are aimed at scientific audiences, and the Bulletin, which provides information accessible to the general community. The most recent book in our proceedings series is unique. It includes the cream of the crop of papers from our co-sponsored workshop on Artificial Life. They are quite varied—a philosophical paper on the nature of life, teaching children to build robots with building blocks, and the relationship of computerized flocking models to actual flocking patterns. This will be the first book published in the United States on this topic and its scientific and philosophical variety should give it a wide audience. A particularly valuable feature is an extensive annotated bibliography on Artificial Life and on L-Systems containing a total of nearly 500 entries.

This year's publication budget allows the Institute to produce as many as four books, which is all that we can can handle with the present manpower. Early this year we will send two books to press. One is the proceedings from the 1988 summer school, which will include the lectures presented there. The other is *Lattice Gas Methods for Partial Differential Equations*, which is actually volume 4 in our proceedings series. The next planned volume results from the workshop on the "Interface between Computational Science and Nucleic Acid Sequencing," chaired by Science Board member George Bell of Los Alamos. Another planned volume is the proceedings from Wojciech Zurek's workshop on "Complexity, Entropy, and the Physics of Information." This is a very interesting topic and may again open our publications up to a new market and larger audience. And in 1990, we are planning a volume on the workshop on pueblo archeology, co-chaired by Murray Gell-Mann and George Gumerman. That book will mark something new in our publications and, like the book on artificial intelligence, should be something of more general interest. But each of these

In This Issue:

books will have a unique appeal and audience.

Our proceedings volumes have been successful in the academic community. A normal academic printing is around 1500 copies, and generally within six months of publication our books have sold 700 copies, with about the same number in distribution, in bookstores waiting to be sold. Moreover, each of our books has gone into a second printing, so we are doing well in getting the word out. None of our books has been a best seller—to do that we would have to sell about 10,000 copies. While that is unlikely in an academic market, we expect it will happen one day. The new book on artificial life and the summer school volume are likely candidates because they will have broad audiences.

The Institute is developing a reputation for producing its proceedings volumes quickly. Originally, we hoped to produce books within about six months after a workshop concludes, but generally the process takes longer. Researchers usually need at least three months after presenting a paper to fine tune their ideas. They want to include the interactions at the workshop, to give credit for contributed ideas, and to address new questions that come up. A talk can seem very cohesive at the time but can have gaps that need to be filled out in the written version. Then, the production of the camera-ready copy for our publisher, Addison-Wesley, may take three or four months, particularly if it is a three- or four-hundred-page book. The production involves inputting the text, indexing, editor and author proofing, getting copyright approvals for reuse of written material or figures, and so on. Our books are cohesive in their layout, and one of the most time-consuming tasks is altering the illustrations that accompany the written text to achieve a compatible size and style. Finally the publisher needs three to four months to print the book. Generally a book takes 9 to 12 months to appear in print, a remarkably short time for a typeset proceedings volume.

We receive manuscripts in a number of different ways: typewritten pages, stand-alone word-processing diskettes, personal-computer diskettes, Sun tape, and electronic mail. I even received a carbon copy from the Soviet Union. It is often a trick to convert this raw material into our system's formats. We now have high-powered electronic graphics tools and I am investigating new technologies, such as scanners and electronic typesetters, to streamline the production process. We use desktop publishing technologies to produce the camera-ready package that Addison-Wesley prints and distributes. In fact, Addison-Wesley produces only the cover and title and copyright pages. The Institute produces everything else, ready for printing.

In five years, I envision many changes in the Institute's publication program: more books produced every year which are a combination of proceedings, monographs, and reprints; working papers, contributed by Institute academic staff members, distributed on a weekly basis; and an electronic bulletin board or general file that would allow people to read papers that are not yet published. I can also foresee informal newsletters about each of the Institute's core research areas. Eventually, our biannual bulletin could become two publications: a smaller bimonthly newsletter of general information for the community and a separate journal of the Institute.

The Institute has contracted with Addison-Wesley to develop two new series of publications. One involves collections of reprints, possibly of articles directly connected to a research program, or possibly to reflect somebody's idea of what is needed in a particular field. So far, we have done no reprint volumes but I can foresee such books being produced in the future. The other type of publication that needs to be developed is a series of monographs. Monographs could present new material, cover the history and development of a field, or could even present a view of complexity suitable for a general audience similar to James Gleick's *Chaos*. Proposed monographs and reprint volumes will be reviewed and approved by the Editorial Board before being submitted to Addison-Wesley.

As the Institute develops, the publications program will become more complex and important, branching out from just the printed word. Sometimes researchers need face-to-face contact, and it is always helpful to pull somebody into an office and write down ideas on the blackboard, but the nature of the Institute is such that members of its research networks will want to make contact on a daily basis. Although the world may not be ready for electronic books (most people s work with something in hand, something

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The Evolution of the Economics Program

Unorthodox Economics: SFI Research Program Up & Running

The Santa Fe Institute's first major resident research program—on the Economy as a Complex, Evolving System—is in full swing. About twenty-five researchers—economists, physicists, computer scientists, biologists, and mathematicians—have begun to spend periods at Santa Fe ranging from one month to a year. Brian Arthur, on sabbatical from Stanford University, is directing the program this first year.

The economics activities here were initiated a couple of years ago at the suggestion of Citicorp chairman John Reed. Reed felt that an institute devoted to the study of complex systems might have something useful to say about the world economy. In September of 1987 Philip Anderson, Kenneth Arrow, and David Pines assembled a small number of economists and physicists to discuss the economy as a nonlinear, evolving, adapting, complex system. The ten-day workshop that Arrow, Anderson, and Pines organized a year ago in September was an enormous success. It was followed by a similar workshop in September 1988 and has now grown into the Institute's first research program conducted by scholars in residence. "I didn't expect that the physicists and economists would have that much to say to each other," says Buz Brock. "But ideas were put on the table that were truly exciting to both sides. Several of us have developed long-term working relationships. And various cross-disciplinary collaborations are now going strong."

From the rather intensive discussions last September and the year that has followed, two major themes have emerged that the new program has chosen to focus on: learning and *adaptation* in the economy; and *nonlinear (non-convex) mechanisms* in the economy.

Learning and Adaptation

In the last few years, economics has been able to formulate and "solve" more and more difficult strategic, expectational, sequential decision problems, through the use of sophisticated techniques in dynamic programming, game theory, and computable general equilibrium theory. But while theoretical "solutions" can often be derived, they are typically so complicated that there is little hope they match the real decisions of businessmen and other agents in the economy. Not surprisingly, some of the best theoreticians have begun to slacken the assumption of complete rationality and full information, and have started looking at models where agents learn and adapt their way to a solution or equilibrium point. The SFI program is taking up this theme of learning and adaptation by introducing ideas from computer science (the machine learning theory of John Holland and others, for example) and biology (the adaptation and coevolution ideas of biologist Stuart Kauffman, for example).

Nonlinear Mechanisms

The work on the theme of nonlinearity started last year by comparing mechanisms that generate chaotic attractors in the economy with their counterparts in physical and biological systems. Researchers in the program are still interested in this, but over the past year their ideas have begun to crystallize in a slightly different direction. The highly technological parts of the economy appear to operate subject to several important influences: very large design and set-up costs for products, significant learning effects in manufacturing, and possibilities of standardization due to "network externalities." These act to give market advantage to products that have achieved high volume or high visibility. "It appears that the modern, high-technology sectors of the economy operate according to *increasing returns* to quantity produced, rather than diminishing returns," says Arthur. "Therefore, if we want to prescribe sensible policies in international trade, or standardization, or market regulation in high-tech products we need to be able to understand interactions that induce increasing returns or market self-reinforcement."

It turns out that in the last two decades physicists have given deep thought to systems with self-reinforcement, particularly in spin-glass theory and other branches of condensed-matter physics. One of the aims of the program is to see if it can use the ideas and techniques of physics to tackle specific problems in increasing-returns economics. Already the program has achieved a good understanding of pattern formation, the lock-in phenomenon, symmetry breaking, and multiple equilibria from comparing these phenomena in the economy with their counterparts in physical systems. "The Institute is well positioned to exchange theories and techniques among economics, biology, computer science, and physics," says Stuart Kauffman. "My ideas are being absorbed by the economists. But the exchange is going in both directions. I am

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Getting the Word Out *(continued)*

with a spine to crack and to write on), an electronic bulletin board or conferencing system would give us a very fast way to provide information, which is vital for collaborative research networks. The recent news about computer viruses has made people a little wary of public access, but a read-only electronic newsletter, into which researchers can dump new thoughts or information, is certainly feasible. The Editorial Board has discussed this vehicle and a bulletin board is in the works. Finally, I can see a place for other electronic media such as computer disks and tapes, and even video tapes of Institute lectures.

In the meantime, the publications program, and I personally, continue to grow by leaps and bounds. Each book is a new adventure having its own problems, a different editor, and a different market, yet it is a piece of the puzzle in the study of complexity. The interrelationships of proceedings topics, the varied and insightful authors, and the evolving terminology of complexity—these are what keep the program exciting.

— Ronda K. Butler-Villa

beginning to apply ideas from economic game theory in my work on coevolution."

Why SFI?

How successful can a small economics research program in Santa Fe expect to be, when universities across the country can field much larger efforts in economics research? "Economics will in due course encompass the themes of learning, adaptation, and increasing returns, whether our program in Santa Fe exists or not," says Arthur. "But it would be hard to bring computer scientists and physicists interested in nonlinear phenomena and complexity issues into a standard economics department. By being able to do this in Santa Fe, we hope to catalyze these new ideas and short-circuit many of the obstacles to realizing them in economics." Participants are not looking for instant success. Most believe it will take three to five years to bring some of the ideas to fruition.

It is not the intention of the program to transfer techniques blindly from physics or computer science into economics. Rather the method of working is to explore specific open problems in economics, carefully examining the opportunities to be gained from understanding similar problems in other disciplines.

Emerging Problems

A number of specific research problems have emerged within the program. Arthur and computer scientist John Holland are using Holland's genetic algorithm and classifier system to simulate the evolution of buying and selling behavior in a stock market. John Rust, William Brock, Ramon Marimon, and Tom Sargent are studying how play evolves in N-person games when players are not well informed about each other's payoffs and must learn as they play. Rust, Miller, and physicist Richard Palmer are organizing a computer tournament to simulate a Double Oral Auction. Arthur and Norman Packard are studying cellular games, an extension of cellular automata that allows cells to choose their next state on the basis of a reward structure that depends also on neighbors' states. Probability theorists Yuri Ermoliev, Yuri Kaniovski, and David Lane are applying techniques from nonlinear stochastic processes to problems in the evolution of market structure. José Scheinkman, Andrei Shleifer, Palmer, Arthur, and others are attempting to use new theories of self-organizing criticality to study the dynamics of industrial modernization in developing countries.

Plans for the program include two short meetings to discuss research problems in the next months and a major effort involving about fifteen participants spread over the summer. It seems that the "word is out" about what the program is attempting to do. As a result, recruiting first-rate people—whether in physics, biology, or economics—is not a problem. The main obstacle to progress at the moment is on the funding side. The program is looking for financing it can apply to the next three to five years.

— Ginger Richardson

Participants in the SFI Economics Program

Philip Anderson, Physicist, Princeton University
Jasmina Arifovic, Economics graduate student, University of Chicago
Kenneth Arrow, Economist, Stanford University
Brian Arthur, Economist, Stanford University
Robert Axelrod, Political Scientist, University of Michigan
Per Bak, Physicist, Brookhaven National Laboratory
Eric Baum, Physicist, California Institute of Technology
Michele Boldrin, Economist, University of California, Los Angeles
William Brock, Economist, University of Wisconsin
C. Y. Chu, Economist, Academia Sinica, Taiwan
Yuri Ermoliev, Probability theorist, Kiev
Doyne Farmer, Dynamical systems theorist, Los Alamos National Laboratory
Stephanie Forrest, Computer scientist, Los Alamos National Laboratory
John Geanakoplos, Economist, Yale University
Geoff Grinstein, Physicist, IBM
Frank Hahn, Economist, Cambridge University
John Holland, Computer scientist, University of Michigan
Bengt Holmström, Economics, Yale University
Yuri Kaniovski, Probability theorist, Kiev
Stuart Kauffman, Biologist, University of Pennsylvania
David Lane, Statistician, University of Minnesota
Blake Le Baron, Economist, University of Wisconsin
Seth Lloyd, Physicist, California Institute of Technology
Ramon Marimon, Economist, University of Minnesota
John Miller, Economics postdoctoral fellow, Santa Fe Insititute
Barry Nalebuff, Economist, Princeton University
Norman Packard, Dynamical systems theorist, University of Illinois
Richard Palmer, Physicist, Duke University
David Pines, Physicist, University of Illinois
Steen Rasmussen, Physicist, Los Alamos National Laboratory
Paul Romer, Economist, University of Chicago
John Rust, Economist, University of Wisconsin
Thomas Sargent, Economist, Stanford University
José Scheinkman, Economist, University of Chicago
Andrei Shleifer, Economist, University of Chicago
Eugenia Singer, Vice President, Citibank, NA
Daniel Stein, Physicist, University of Arizona
Michael Woodford, Economist, University of Chicago

Can Physics Contribute to Economics?

Physicists are not known for their humility. There is often the feeling among them that physics is the hardest subject around, at least among the quantifiable sciences, and that a sound training in physics is a license for tackling well-posed problems in *any* area. Why then is economics still at large, despite the present interactions between the fields? Are the problems actually *hard*, or are they not well posed, or is the arrogance unjustified? The answer should surely be "all three," although it should also be said that physicists do not have a monopoly on arrogance.

The real issue is the degree of similarity between the fields. The underlying supposition of the dialogue between natural scientists and economists arranged by the Santa Fe Institute is that there is enough common ground to make progress possible. Economic systems can be seen as complex, nonlinear, interacting systems of many parts, and this description also fits problems actively studied in the natural sciences. But, on a more detailed level, is there really enough similarity with economics to justify optimism? It is crucial to go beyond generalities and ask just how the fields differ, and how they are alike.

Dynamical Systems vs. Foresight

Most situations in physics involve particles or objects (e.g., wave functions in quantum mechanics) whose future behavior may be predicted from a knowledge of the present. No knowledge of—or expectation about—the future is needed. In contrast, the regnant approach in economics, rational-expectations theory with foresight, relies explicitly on economic agents who can anticipate the future; the "particles" of the theory form strategies on the basis of future expectations. At first sight this difference is central, but on closer examination it may not be so serious.

On the one hand, there *are* situations in physics where the particles effectively explore possible futures to determine their behavior. Quantum mechanics and classical mechanics can both be expressed in terms of minimizing a "path integral" quantity across all possible future histories. In each case, however, the theory can also be formulated in a way that avoids the apparent dependence on the future. Could the same be done in economics? Can the path-integral methods developed in physics be applied to economics?

On the other hand, the foresight approach is in trouble in economics. The simplest way of formulating the theory expects the agents to be infinitely smart and well informed, a condition clearly not fulfilled in the real world. Economists are now trying to construct modified "bounded rationality" theories which require only limited intelligence or computational power in the agents. Though promising, these ideas are seen as less attractive because, while there is often only one way to be perfectly rational, there are many forms of irrationality, and uniqueness becomes a major issue. An approach in which many of the SFI participants are involved is to give agents only very limited ability to anticipate the future, but to let them *learn* as time progresses so as to optimize their predictions.

A more ambitious type of learning, also under study by SFI participants, is the adaptive systems approach. Here the agents again learn with experience (though not necessarily explicitly anticipating the future), in a rule-based framework. Wholly new rules or modes of behavior can evolve, and the system can adapt to a changing environment. New strategies may in fact *co-evolve* while interacting with each other. These ideas are linked more closely to biology than to physics; the laws of physics do not seem to improve with the universe's experience.

Linearity vs. Nonlinearity

Linearity should not be an issue. Economic systems are obviously nonlinear, as are many, if not most, systems of current interest in physics. A more controversial question concerns the direction of feedback. Whereas a strictly linear system can have only negative feedback if divergence is to be avoided, positive feedback can occur in nonlinear systems if a saturation mechanism operates. Such systems tend to have multiple equilibria or resting points and great sensitivity to initial conditions. Traditionalists find it hard to relinquish uniqueness and global sta-

Simple Problems, Complex Solutions

Suppose that there are strong social norms as to what type of vehicle to drive in Santa Fe. There are, in actuality, only two available types of vehicles in town, cars and pickup trucks. The social pressure is such that it overrides any cost differences between them and, if over one half of the population own a certain type of vehicle, you prefer to own that type. Every now and then, vehicles break down and must be replaced. What will be the characteristic Santa Fe vehicle given each of the following initial circumstances: everyone last year drove cars; everyone drove pickup trucks; or half the people drove each type of vehicle?

Even such a simple economic problem may have difficult solutions. There are two likely outcomes: a heavy predominance of cars or a heavy predominance of pickup trucks. The problem is how does the system arrive at one solution rather than the other? What if both possibilities are equally likely? What if pickup trucks are much cheaper than cars, yet everyone last year drove cars? Is it possible for everyone to be "locked" into a technology that is inferior, too expensive, or otherwise undesirable?

To extend this example to other economic events, one might consider Betamax versus VHS standards in the VCR market; has the inferior product captured the predominance of the market? In modeling economic development, the two options could represent primitive and modern factories.

The potential dynamics of the above scenarios provide a clear contrast between the physicists' and economists' solutions. In a physical system, it would be adequate to take the goals of the agents (which option to choose) and the current state of the system (which option is predominant), and allow the agents to act myopically, that is, to follow their goals assuming that everyone else will continue doing what they are doing. However, an economist would suggest that economic agents may be endowed with expectations and strategic motivations. Agents may base their choices not only on what other agents are currently doing, but also on what the agents think the others will be doing, and how their actions will affect the actions of others.

These scenarios also illustrate the notion of linkages in economics. Some goods may depend on other goods for their existence (for example, internal combustion engines depend on the availability of gasoline). Moreover, the development of new goods may create and destroy different industries (for example, cars created the market for service stations but destroyed most of the buggy whip industry). So, how does one choose?

—John Miller

bility, but physicists are easily convinced (especially by Brian Arthur's examples) and find positive feedback natural.

Deterministic vs. Stochastic Dynamics

Realistic economic theories have to admit the existence of external noise or "exogenous shocks" coming from factors not modeled economically. The dynamics is thus stochastic, involving chance. Physicists too are used to including random noise in their equations, usually to represent the effect of thermal fluctuations. In physics a crucial question is the autocorrelation of the noise; uncorrelated or "white" noise is easily dealt with, but correlated noise can be very tricky. The noise sources in economics include psychological, social, and political effects in the population (unless these are modeled explicitly, which is rare) and are surely not uncorrelated. Are the white noise theories therefore invalid?

Even completely deterministic systems can appear to behave rather randomly when the solutions are "chaotic." It has been popular recently to look for such deterministic chaos in economics, but the fad now seems to be dying down, as perhaps it should. It is certainly true that nonlinear economic models can have chaotic solutions, but it is doubtful whether these occur if the models are adjusted to match reality. And the analysis of economic time series to search for chaotic attractors is plagued by woefully insufficient data, and can rarely be taken seriously. Chaos *may* occur microscopically, but it is unlikely to occur collectively or to be visible macroscopically in aggregated time series. Could one see it by examining many time series in parallel?

Spatial Structure

Almost all theories in physics involve the spatial as well as the time domain. Many phenomena with possible parallels in economics require an interpretation for different spatial locations. Certainly one can use geographical location, but it may not make the most productive analogy. Different *economic sectors* seem likely to be a better choice. In physics a crucial determinant of behavior is very often the spatial dimensionality, with values other than three often being considered for theoretical reasons. The effective dimensionality for a network (or "web") of interconnected economic sectors is less easy to determine. It depends in general on the range of the interactions between sectors: does everything interact strongly with everything else, or only with a smaller number of related sectors? If the effective dimension is high enough, then "mean field" methods from statistical mechanics may work well in economics.

Microscopic Details vs. Generic Behavior

It is generally assumed by economic theorists that a model must be fully specified at the microscopic level; the strategies of particular agents must be known in detail. There was almost shock when an "agent-free" theory was suggested at Santa Fe. And yet some very successful theories in physics have thrown away most of the microscopic details in a problem, and kept only a few central features, average properties, or statistical distributions. One important lesson of the last few decades of work in statistical mechanics has been the realization that there are many behavioral properties for which microscopic details do *not* matter. There may be just a few "universality classes" of behavior, in each of which the simplest possible example is adequate for describing the generic behavior. Might not the same be true in economics?

Can we imagine theories that take into account little more than the topological or statistical structure of the web of interactions between economic agents or sectors? A number of SFI participants think this is possible, and are investigating several directions. One intriguing idea is the analog of "self-organized criticality" in physics: certain stochastic dynamical systems evolve naturally towards a "critical" state in which the distribution of both length and time scales has a special "power-law" form. Models in which spatial diffusion only occurs when a threshold is exceeded fall into this class, and it's easy to find these conditions in economics. A transition to a higher technology does not dif-

Learning and Games

The analysis of games is important to a broad spectrum of disciplines including economics, biology, political science, and sociology. This problem is an example of game theory.

You have arranged to meet a friend for lunch, but you forgot to specify at which restaurant. Unfortunately, there is not enough time to contact one another. In the past you have always met at two popular eateries, Restaurant X and Restaurant Y. You both would rather eat together than apart. To which restaurant do you go?

This is a game of coordination. The traditional approach to solving it is to see if there is a way to prescribe choices such that if both players knew the prescription, they both would follow it. For example, suppose that both you and your friend receive a message that says to meet at Restaurant X. Given that your friend is going to be at Restaurant X, then it is in your best interest to go there. Similarly, if you are going to Restaurant X, then it is in your friend's best interest to meet you there. Thus both of you meeting at Restaurant X as a result of the message is a solution to this game. (This remains a solution even if both of you would rather eat at the other restaurant.)

The main problem with the prescriptive approach is that it makes sense only if both parties know the prescription. An alternative approach is to incorporate learning models into each agent's behavior. What if you and your friend often have similar lunch plans? The experience gained over past meetings could have important implications for where you will go this time. What if one restaurant has an outdoor patio, and it is warm outside?

Another important element of games is that one's best move often depends on the strategies that the opponents choose. Thus a very interesting co-evolving system emerges. The best move depends on the opponents' moves which in turn depend on one's own move. Simply performing better than one's opponents may be as important as performing the best one possibly can, in these systems.

—John Miller

fuse from firm to firm, or from sector to sector, until the pressure for change exceeds a threshold dependent on set-up costs and other factors. If the self-organized criticality paradigm applied, one would expect to see scaling behavior in economic time series and in the distribution of inhomogeneity. A detailed analysis will require knowledge of the statistical structure of economic webs, perhaps available partially in the structure of input/output matrices. Of course, the whole web structure may itself evolve in time, as has been emphasized by Stuart Kauffman.

Simple vs. Complex Systems

"Complex system" probably has as many definitions as there are practitioners, but one common theme is the existence of many possible stable or metastable states (or equilibria), as found in glasses, spin glasses, neural networks, and such. A "rugged landscape" picture is often invoked for the energy as a function of the many-dimensional state of the system. The multiple states and ruggedness usually come about through "frustration," the impossibility of satisfying many conflicting constraints simultaneously. Are there parallels in economics, and are economic systems complex in this sense?

Certainly many economic theories have multiple solutions, though this is often regarded more as a defect than as an expected feature. The natural scientists find it more natural. One might also expect to find a degree of frustration in economic systems, where, for example, trading in an optimal fashion between pairs of agents might not satisfy more global constraints. The reverse might also occur, in which larger markets allow better trading for all. In any case, neither frustration nor rugged landscapes have been much investigated in economics.

Conclusion

I have described a number of similarities, and some major differences, between problems in physics and in economics. I have also posed many unanswered questions; there is no lack of open problems! Since no major breakthroughs have yet emerged from the meeting of the fields, it is clearly too soon to call the endeavor a success. But there seem to be plenty of reasons for optimism, plenty of interesting ideas needing further exploration, and plenty of exciting challenges for all involved.

— Richard Palmer

A Conversation with Kenneth Arrow

Bounded Rationality and Other Departures

Last Fall, SFI President George Cowan and Kenneth Arrow, an economist at Stanford University and SFI Science Board member, discussed the background of neoclassical economics and how the SFI program is moving in a new direction. A Nobel Laureate in economics, Dr. Arrow is a co-editor of The Economy as an Evolving Complex System, *the proceedings of the "Evolutionary Paths of the Global Economy" Workshop, held in September 1987. The italicized text represents Dr. Cowan's questions and comments.*

We are eager to know what fresh ideas there are in economics. What particularly intrigues you? What directions are things moving in? What stimulates change? What does the future hold?

The next big steps forward involve consideration of nonlinear dynamics and future uncertainties. This is the warp and woof of a lot of economic research.

First, let me review some current ideas. The standard picture of the economy is one which assigns a very great weight to the system of prices for directing the way in which the economy functions.

Firms and households are assumed to be rational in the sense that they are trying to maximize something—in the case of firms, their profits. A firm has various ways of combining inputs to produce possible combinations of outputs. Each technologically feasible combination will produce a certain profit at given prices. The firm, therefore, will choose that set of inputs and outputs which maximizes profit. As prices change they choose different combinations and different scales.

Similarly, the household, which is the consumer, is thought of as choosing some bundle of inputs and outputs, the outputs usually being labor, but possibly other commodities that they own, in order to achieve as high a level of satisfaction or utility as is possible. This procedure defines for each firm or household a certain supply and demand for each commodity. The demand for any commodity or the supply will depend not only on the price of that commodity but on the prices of all other commodities. If nothing else, the rise in the price of some other good will reduce the amount of purchasing power available to the consumer for the purchase of this good. In addition, the price of gasoline, for example, affects the extent to which people use automobiles. The result is that for every set of prices there are a lot of supplies and demands that can be added up over all agents in the economy, giving rise to a net demand. An equilibrium set of prices means those prices at which net demand goes to zero for all commodities and supplies, and remains balanced.

So prices are a result of demands and supplies reacting to create an equilibrium in each situation. Here we are assuming a process by which a set of prices that are not in equilibrium can be altered. We are assembling a great deal of information which is dispersed throughout the econ-

Kenneth J. Arrow

omy in this process. Defects in this information can trigger the statement that the economy is out of equilibrium. It is somewhat more problematic to determine how, with good information, we can guide the economy from an out-of-equilibrium position to equilibrium. This is still an open question.

The present analysis goes further. Obviously, a great many economic decisions are made with a view to the future. For example, when one buys a house, one is expecting to use that house in the future; the ability to use that house will depend upon the ability to pay for the electricity, gas, and so forth. Similarly, in the case of a business firm, expenditures are made, that is, investments in plant and equipment are made. These are inputs to produce future output and are justified only to the extent that output in the future will eventually cover the relevant costs. In an idealized model of an economy, we now have markets for all future goods. Thus, an automobile manufacturer who constructs and equips a plant is, at the same time, selling the product of that plant—automobiles produced five years hence. Therefore, in this ideal model the same structure given to the current-equilibrium case applies.

I shall mention two implications. For one, many markets have to clear. In each the supply has to equal demand. Secondly, this process gives rise to a path in quantities and to a path in prices. It has usually been assumed, without analysis, that these paths tend to converge to a stationary state. Somewhat more exactly, in light of the fact that both technology and population are increasing, they converge to a steadily growing path.

To complete this picture of the ideal model, we have to allow for uncertainty. For example, innovations will take place in agriculture and we don't know what the weather will be. So, the ideal model goes one step further and says there should be a separate market for every future good for each possible history of contingencies. Again, we are multiplying the number of markets. This picture is very complex. We immediately notice that many markets are being assumed that do not, in fact, exist. We do not have many ways of contracting to deliver goods in the future, except in very limited markets, such as agricultural commodities. We certainly have no great number of markets for results contingent on events, although they exist: insurance policies are the most obvious example.

But most of the markets called for by this idealization are nonexistent. Sometimes they can be replaced by a chain of other markets. To some extent this happens, but very clearly the economy, in its intertemporal and risk-bearing aspects, is not fully regulated by markets that exist, even in combination. Therefore, a notion that has played an effective role both in theory and even in practice is that economic agents anticipate correctly what prices would be in markets that don't exist. Notice this doesn't mean, for example, that the price of wheat five years from now is supposed to be anticipated correctly; of course, we know that there are contingencies. But we are saying that for any given set of contingencies, we can predict what the price of wheat will be.

In the end, we still have a lot of problems. We have a problem of how prices even come to work. What is the process by which they make the market? The suggestions I've made turn out mathematically not to imply convergence, in general, except under a very restrictive hypothesis which we do not want to make. We have a problem that the standard model requires incredibly many markets, and the substitute model requires incredible recalculation. The suggestion, therefore, is that we have to emphasize a different kind of world, one in which people, instead of optimizing and rationally forecasting the future, are engaged in much more limited operations more suitable to constraints on human reasoning and calculating abilities and even to those abilities as augmented by computers.

As a new point of view we turn to bounded rationality, a departure from the mainstream tradition. We no longer can assume that every agent is a perfect calculator. This point of view is given a great deal of emphasis by Herbert Simon. Simon argued that people do not maximize. When they're forecasting the future, they do not perform the task of rational analysis. Modern cognitive psychology is almost dominated by emphasis on irrationality in the formation of beliefs and expectations, and experiment after experiment has confirmed this.

In this view does a very large number of participants in a given market expand the space in which the calculation occurs? In other words, is the operation of a million brains additive in some sense and mutually supportive?

My answer to that is unequivocally yes and no. Yes, because it is true that different people can explore different parts of the universe and the competitive struggle would suggest that those who do the best exploration will triumph in the end. If the result of the exploration is to do something more cheaply, then that will drive the others out of business or cause them to imitate it so the idea will spread. On the other hand, many people spend most of their creative power in trying to figure out what other people are doing.

And I suppose they're also influenced by what the other guy is doing, the herd instinct.

One possibility is that people don't innovate enough because if most people aren't innovating, they assume non-innovation must be the right thing. Then you have a second-order effect that says if everybody is doing something, I'm not going to make any money doing it that way. The only hope is to do something different. So it might work in either direction.

We are trying now to use tools which are developed in other disciplines bu which deal with somewhat analogous problems. We do not expect these tools are transplantable without change because they were developed to address a different set of phenomena. The intertemporal equilibrium path, as I have suggested, is supposed to converge toward a steady state or steady growth. However, we can make all the assumptions with perfect foresight, well-behaved production-possibility sets, and so forth, and still it turns out that other behavior, including chaotic behavior, is possible.

Even cyclic behavior, I suppose . . .

Cyclic behavior or chaotic behavior, yes. All these have been exhibited within models that are highly classical. This is more undermining than might appear. It isn't merely that we get a bigger repertory of solutions. The chaotic solutions are disturbing because it's incredible that you can have perfect foresight along a chaotic path. The existence of a chaotic solution, in a sense, undermines the idea of perfect foresight. This points to an interesting way in which economic analysis differs from physics. In economics the particles, i.e., agents, are endowed with some kind of foresight. Their image of the future affects the present. But experienced people are not entirely crazy, and their image of the future and the real future may not be entirely different. People do have some idea of what's going to happen. Their idea of what's going to happen affects what they do today; what they do today affects what's going to happen. So one really unsolved problem has to do with including limited foresight. We have some idea how to model perfect foresight. We have very little way of knowing how to model limited foresight, even to define the term. I think that the dynamic analysis will have to be modified to account for foresight. It is already in our present models but it is treated as perfect, which is not realistic.

I assume that foresight, however limited, will tend to be self-fulfilling.

Not necessarily, but that is frequently the case. The opposite is also sometimes true. Robert K. Merton produced the idea of a self-fulfilling prophecy and a self-denying prophecy. A classic example has to do with elections. Suppose we have polls showing that "A" is going to win. One possible consequence is that the supporters of "A" don't bother going to the polls, while supporters of "B" may double their efforts. Of course, the opposite is also possible. Other examples: Suppose a stock's price has been rising steadily. If tomorrow's price is the same as today's, I might assume the stock price has stopped rising. Then I'll get out of the stock and that, of course, will cause the price to fall. An important reason for holding stocks is that they will continue to provide a good rate of return in capital gains. Any assumption that will make them reach a peak may not cause the peak to be maintained but may cause it to go down.

> "...we have to emphasize a different kind of world, one in which people...are engaged in much more limited operations more suitable to constraints on human reasoning and calculating abilities and even to those abilities as augmented by computers."

People operate in a complex environment. Rationality enters at two levels here, first at the level of forming a model and using it for prediction, and second at the level of behavior. At the first level you just don't have enough experience to really get a whole model; you only have a limited set of observations. You can't even use those efficiently due to limitations beyond your control. So, we find that biologists and computer scientists inspired by biologists have been discussing the idea of getting better and better, not all at once, but step by step. We can discuss several different levels. We can consider a landscape in which we are trying to climb a fitness peak. The problem is that there may be more than one peak. In fact, even if there's only one peak, it would be pretty hard to climb if it is complicated. On top of that, we have the fact that I am gradually adjusting to conditions around me, and so are all the other economic agents in the systems; this may correspond to the idea of co-evolution. Our objective is moving around because other people are involved. And finally, in the economic world and, indeed, in the biological world, the outside environment is changing. We have ice ages and hot periods in economics, new innovations, foreign competitors, and all the rest of the things in the world that change and evolve.

So, we must include the question of learning, of adaptation, and the fact that the agents influence each other, and that the underlying environment can change. We'd like to think that such concepts come back to the very beginning when we spoke of adjusting prices until they come to equilibrium, so that the process becomes a learning process. We are reluctant to entirely abandon the idea of intertemporal equilibrium. So we are trying to borrow and modify these new tools to incorporate a kind of dynamic analysis that goes beyond what is already in economics. The variety of behavior that these processes can exhibit has not been understood until the last few years. Another new factor is further development of the role of learning feedback. How do people behave, what simple response mechanisms are available to them in order to adjust to changing information?

In intertemporal equilibrium there are various factors influencing the particular level of equilibrium. Some kinds of information are available very rapidly and *other kinds more slowly. The various factors may change at very different rates. What are the appropriate time scales?*

If the information disseminates rapidly, prices may change rapidly.

In that case, what would we mean by intertemporal equilibrium?

In the new scheme there will not be intertemporal equilibrium, but there will be some concept that takes the place of that which changes all the time.

Let's go back and review the fresh breezes in economics. You introduced bounded rationality and . . .

Also genetic algorithms, biological analogies, and fitness landscapes.

What we're talking about in all of these cases is a learning and adaptive process.

Well, bounded rationality is kind of a constraint on the learning process. I also want to draw from cognitive psychology because we've developed certain patterns that tell us how people actually behave.

But, in general, what you're saying is that there is a process going on among these agents by which everybody learns, remembers, and adds to the total stock of information which is being applied to a particular situation.

Well, the memory aspect is interesting. The genetic algorithm, if you take it literally, is static. At any moment you've just got a given set of rules. One thing the genetic algorithm doesn't do is remember the path it takes. New observations cause you to modify rules. Those observations are no longer available. They're incorporated in the packaging. If we have settled on a new set of rules in some sense the past is not relevant. If some brand-new rule came into the set, one thing we might do is go back over the past and consider how well it might have worked in the past. It wouldn't be difficult to add except it would impose tremendous memory demands.

But the human memory is capable of that kind of thing. It may operate in precisely that way.

There are some approaches which depend upon using the whole past. There are other approaches in which you start where you are now and never mind how you got there. In the price adjustment, the simplest rule is, if demand exceeds supply, raise the price in that market. You're only looking at the present situation. It's true the prices you're starting with are the result of the whole past but you only use the present. You forget about the rest of your story. Even though theoretically, you could go back and look at the points on that demand function, and ask if it is a plausible demand. So there are, so to speak, two schools of thought,

"So we are trying to borrow and modify these new tools to incorporate a kind of dynamic analysis that goes beyond what is already in economics."

one of which says you start with a certain approximation and then you go on. Another group says you never leave the past out.

In a two-person game, there's an outcome. We both know the pay-offs, so I observe his strategy, and I'll pick a strategy which is optimal against his. Having played many times, I'll note that he's made strategy choices. I now assume he's going to use these strategies with probabilities proportional to their frequencies. So at any moment all the past elements appear in the summary form. But now you're throwing out some information; you're not using the whole past because all you're using is the summary.

You could save something. You could date every input.

You could do that but is there a way you could effectively use those data?

I think the mind does date and otherwise identify data inputs and weights each input by some set of rules that uses this kind of information.

Perhaps so. I would tend to say that the near past is more likely to be relevant than the distant past.

I think we do that. Conversely, we might have reason to discount the near past.

You're moving down the slippery path toward rationality. When you say the mind is that intelligent, you're implying really rational analysis.

But the mind tends to operate that way.

We know it doesn't do it well. The psychologists find there are some circumstances when you are very conservative, and other times when you over-react to current data. People can ignore basic data, past experience, and react too much to the current situation. Sometimes they presume a long history summed up in one fact, but there's a tendency to look only at the latest information and never mind the long term. People also tend to be quite indifferent to the size of the sample. They feel just as strongly about it if it's two to one as if it's twenty to ten. Yet, obviously, any theory you can think of would suggest that you ought to be a lot more sure about a fact when it's twenty to ten than when it's two to one. So there are certain biases; some tend to over-emphasize the present relative to the past, and some tend to develop inflexibility.

We touched on many interesting questions but left some out, ethical standards, for instance. And we barely touched on some of the properties that are apparently common to all complex systems like multiple solutions rather than unique solutions, and rarely, if ever, best solutions. Perhaps we should leave these questions for another time, not too far in the future, I hope. Thank you very much.

The Second Annual SFI Economy Workshop

How to Follow a Great First Act

The September, 1988, workshop on the global economy as a complex adaptive system seemed to those of us participating to be an appropriate sequel to last year's opening workshop. The sense one had was of a consolidation and deepening of a number of lines of thought which originated at the first meeting but had needed a year's time to develop into a programmatic approach to coherent research directions. The meeting was slightly shorter and considerably less formal than last year's and leaned much less on formal presentation than on subgroup meetings; one even sometimes had a feeling that almost the entire workshop would meet as a working group on one subject or another.

I would like, more for the sake of opening a discussion than closing one, to identify three basic themes which seemed to continue through the two meetings, and at least two new ideas—perhaps "tools" in a general sense—which surfaced and which seem to be important to the future developments.

Themes

The three themes were, first, further developments essentially on prediction and analysis of the economy as a dynamic system. While we are still keeping in mind the whole spectrum of learning algorithms, a major effort should be to establish a network sharing data so that different methodology may be used on the same data as well as allowing a maximum input of parallel time series. Doyne Farmer seems to be making progress with the troublesome question of how to introduce exogenous data.

A second theme is a continuation of the "economic web" ideas of the earlier workshop. The grand project which seemed to emerge from this grouping was the possibility of modeling the process of economic and technological growth as a complex web of interdependent agents, each of which can grow in productivity with an "entry cost" which is decreased by the growth of neighboring entities: automobile production encouraging modernization of steel plants as well as the construction of roads and fast-food outlets; this kind of dependency infinitely proliferating was the picture we had in our minds. We felt such a web would exhibit "self-organized criticality" and hence noisy behavior on all scales.

A third theme I would designate as general studies of game playing and markets. Such special topics as Wicksell triangles and the development of money, double oral auctions, and so forth belong in here: my sense is that coherent themes in this area have not yet emerged but that some quite massive and important issues specifically in the global economy—debt problems, trade barriers, exchange markets, industrial strategies—have their appropriate forum in this area. I found fascinating the questions about the origin and meaning of money, which one can only approach this way. Perhaps the most valuable aspect of this kind of activity is that it offers a wide variety of examples of non-classical economic behavior contradicting conventional equilibrium ideas, and as such is a relatively painless way of liberating our minds from the conventional wisdom.

Limits of Rationality

One of the new sets of ideas which impacted in several places was the examination of the limits of rationality which Ken Arrow specifically talked about, as well as Andrei Shleifer, and which was a major area of discussion. To my mind, rational expectations were shown to be an exceptional phenomenon, which I felt was associated more with economists' hopes that a general equilibrium exists in principle, than with observations of actual economic behavior. It may be that poker players act on rational expectations as they play, but if their behavior were really rational would they be playing poker at all?

The world, possibly, and certainly most people's perceptions of it, is much less foreseeable than economists have assumed. One is left wondering whether the common sense which, for instance, ignores prior probabilities, is not rooted in a possibly healthy skepticism about any received wisdom or apparently inevitable outcome.

In any case, the relative weakness of anticipation—or a high discount rate for the future—makes the economy much more similar to ordinary dynamical systems and thus much more likely to have behaviors physicists can understand, as well as to have unstable, chaotic, or noisy behavior. This encourages me to look more seriously at the possibility of low-dimensional chaos or of more complicated behavior such as self-organized criticality.

Self-Organized Criticality

This latter topic was a new "tool" which I brought to the community: an idea pioneered by Per Bak for physical systems, it is an attempt to explain the widespread occurrence of "scale-free" behavior such as fractal shapes of beaches, clouds, landscapes, aggregates, etc.; and relate this to scale-free dynamic behavior such as the ubiquitous "1/f noise" which is exhibited by such different systems as the river Nile and neurons firing.

The idea refers to a situation in which there is a wide difference in scale between the microscopics of the system and the rate at which it is driven. The canonical example is sand flowing through an hourglass and sliding down the pile, where the individual grain motion is much faster than changes in the pile as a whole. It is argued that for many models of such systems the system is driven to a new so-called "critical state" where large areas are nearly unstable, and a single additional "grain of sand" can cause an avalanche of almost any scale.

I am eager to test this idea on models of economic "webs" to see if they can exhibit self-organized critical instability, and I hope that the webs group will eventually get some such system formulated.

In general, I sense a growing willingness among the economists to go a bit beyond the normal boundaries of their subject, and possibly a greater attempt to approach economic professionalism on the part of the physical scientists. I still see the program as an adventure in more or less gently turning aside some channels in economics—hardly the mainstream!—into new and more promising directions. For those new directions nonlinearity, positive-feedback effects, and lack of foresight dominate economic behavior, in contrast to mainstream economics. If we do not attempt this task, we have no reason for being. We can do no less than try to find a set of paradigms for the future, even if their first versions look very primitive, arbitrary and/or artificial.

— Philip Anderson

'88 Reviews, '89 Designs

SFI Hosts Complex Systems Summer Schools

Because of its relative newness and interdisciplinary nature, the subject of complex systems is not easily accessible to researchers as a whole and to students in particular. While several universities are beginning to establish centers for research and teaching in complex systems, strong programs around the country are still several years in the future; the 1988 school was the first of its kind offered in the U.S.

1988 School

Ask a participant in last summer's Complex Systems Summer School what she did during her vacation and, instead of another Winnebago anecdote, you'll hear about neural nets, cellular automata, and adaptive algorithms. For a month last summer seventy-five scientists—graduate students, postdoctoral fellows, and senior researchers—explored the intellectual territory of "complex" behavior in mathematical, physical, and living systems.

Covering such seemingly diverse terrain as pattern formation in physics and chemistry, disordered systems, chaos, biomolecular evolution, statistical mechanics, and economics, the School focused on the connections among these systems. These systems are not linked by virtue of their physical nature, but rather by the emerging tools for studying these phenomena—techniques which combine experimental observation, mathematical analysis, and numerical simulations and which depend in large part on theoretical dynamics and the tremendous increase in available computing power over the last decade.

Professor Daniel Stein of the Physics Department at the University of Arizona directed the School. The program, which was held on the campus of St. John's College in Santa Fe, was supported by the Department of Energy, Research Corporation, the Alfred P. Sloan Foundation, and several sponsoring institutions—the Center for Nonlinear Studies at Los Alamos National Laboratory; the Universities of Arizona, Illinois, New Mexico, and Texas; Sandia National Laboratories; and the Santa Fe Institute, which acted as fiscal and administrative agent.

1989 Summer School

Advisory Committee

Peter Carruthers (Chairman), Physics, University of Arizona
Philip W. Anderson, Physics, Princeton
Kenneth J. Arrow, Economics, Stanford University
Parsi Diaconis, Mathematics, Harvard University
Mitchell Feigenbaum, Physics, Rockefeller University
Marcus Feldman, Institute for Population & Resource Studies, Stanford University
Murray Gell-Mann, Physics and Astronomy, California Institute of Technology
John Hildebrand, Neurobiology, University of Arizona
W. Daniel Hillis, Thinking Machines Corporation
John Holland, Computer Science and Engineering, University of Michigan
Stuart Kauffman, Biochemistry and Biophysics, University of Pennsylvania
Martin Kruskal, Mathematics, Princeton University
David Pines, Physics, University of Illinois
Harry Swinney, Physics, University of Texas
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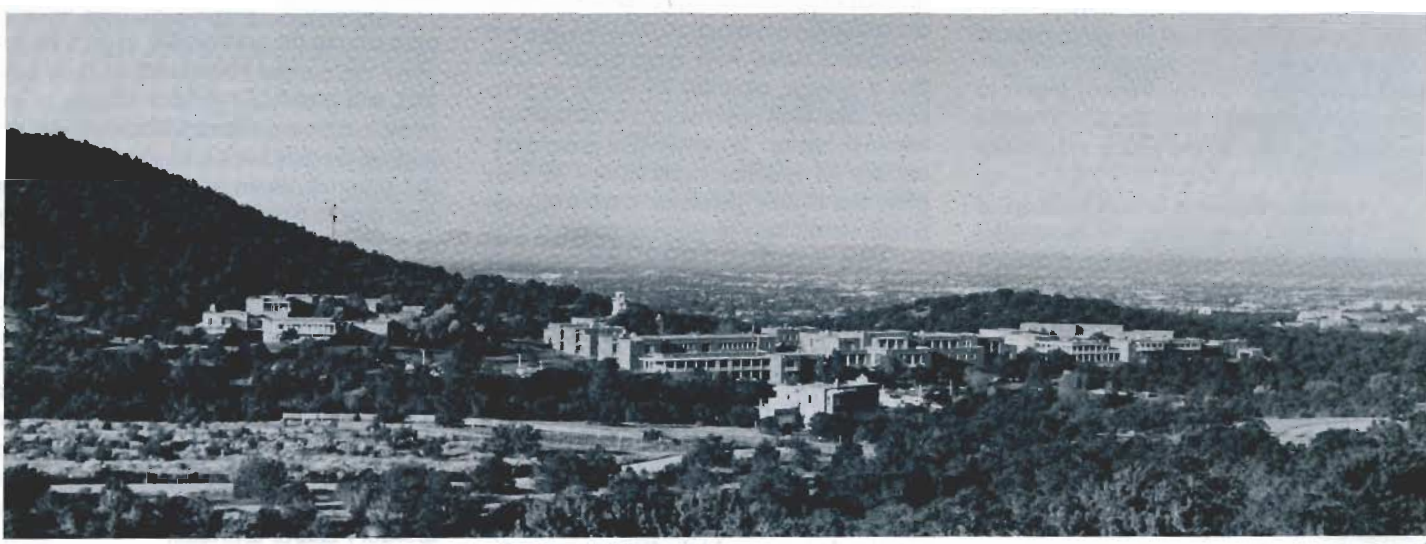
David Campbell, Center for Nonlinear Studies, Los Alamos National Laboratory
Erica Jen, Los Alamos National Laboratory
L. M. Simmons, Jr., Los Alamos National Laboratory and Santa Fe Institute
Daniel Stein, Physics, University of Arizona



St. John's College, Santa Fe, NM; by Lisa Law Productions © 1988; reprinted with permission.

An important part of the School will be the publication of the lecture notes in book form. The aim is to provide students and researchers in the general scientific community with an overview of the emerging concepts of complex behavior and their application to specific systems. The book, *Complex Systems*, edited by Dan Stein, will be available in late Spring, 1989, as part of the series Santa Fe Institute Studies in the Sciences of Complexity.

Less tangible but equally significant are the continuing work, the interactions, and new ideas resulting from last summer. "I have gotten a surprising number of fresh research ideas from the summer school," says one student. "For instance, from Farmer's talk I began thinking about how to formalize his prediction theory by reconstructing the tangent space of a vector field from the dynamical systems orbits generated experimentally. Also, Professor Erica Jen and I have begun thinking about how to apply CA's to the symbolic dynamics arising in physical systems."

The complex systems summer schools originated in conversations among Peter Carruthers, David Pines, L. M. Simmons, and others at the SFI. Carruthers served as chair of the 1988 steering committee and is chairing the 1989 advisory committee. Pines is a member of both the 1988 and 1989 advisory committees, and Simmons is on the steering committees of both schools.

1989 School

A mathematician in the Theoretical Division at Los Alamos National Laboratory and a faculty member of the 1988 Summer School, Erica Jen will direct the second Complex Systems Summer School, June 5 to 30, 1989, again at St. John's College. The overwhelmingly-enthusiastic student response, both critically and in terms of the large number of applications, has borne out the sponsors' original intuition that there is a strong need for an annual program of this sort.

Sponsors of the 1989 School are Brandeis University; Center for Nonlinear Studies, Los Alamos National Laboratory; Institute for Physical Science and Technology, University of Maryland; Santa Fe Institute; University of Arizona; University of California System; University of Illinois; and the University of Texas.

As in 1988, next year's school will include formal lectures comprising a number of "short courses" on selected topics. The subjects provide a representative treatment of the subject of complex systems, with an emphasis consistent with, but different from, last year's program. They too will be collected in a proceedings volume. As last year, the school will feature a state-of-the-art computer lab. Research facilities to be set up at St. John's next summer include computer workstations, experimental equipment, and software and reference material provided by the sponsoring institutions and the individual lecturers.

Following three weeks of short courses, a last "Research Week" will be

1989 Summer School Faculty

Course Lecturers

W. BIALEK, *Berkeley:* pattern recognition and hearing
J. BOWER, *Caltech:* computational and experimental neurobiology
L. BLUM, *ICSI/Mills:* theory of computation over the reals
B. BOGHOSIAN, *Thinking Machines:* modeling physical systems with cellular automata
I. EPSTEIN, *Brandeis:* oscillators and nonlinear chemical dynamics
J. D. FARMER, *Los Alamos:* chaos, prediction, and adaptive networks
C. GREBOGI & J. YORKE, *Maryland:* fractal and chaotic dynamics
C. LEVINTHAL, *Columbia:* 3-D biological structures from 1-D information
G. ODELL, *Washington,* & G. OSTER, *Berkeley:* mechano-chemical models in cell and developmental biology
D. SHERRINGTON, *Imperial College:* complexity due to disorder and frustration

Research Week Advisors/Speakers

J. KELLER, *Stanford:* randomness in mathematical and physical systems
M. KRUSKAL, *Princeton:* nonlinear differential equations
J. LEBOWITZ, *Rutgers:* statistical mechanics of cellular automata
D. VAN ESSEN, *Caltech:* information processing in primate visual systems
S. WOLFRAM, *Illinois:* directions of complex systems research

Seminar Speakers

H. CHEN, *Los Alamos:* lattice gas models
M. FEIGENBAUM, *Rockefeller:* scaling dynamics
B. HASSLACHER, *Los Alamos:* discrete models of field theories
D. HOLM, *Los Alamos:* Hamiltonian chaos in nonlinear optical polarization dynamics
E. JEN, *Los Alamos:* one-dimensional cellular automata
R. KRAICHNAN, *Los Alamos:* Navier-Stokes turbulence
C. LANGTON, *Los Alamos:* artificial life
S. LLOYD, *Caltech:* physical measures of complexity
S. ORSZAG, *Princeton:* fluid dynamics
A. PERELSON, *Los Alamos:* mathematical immunology
W. TAM, *Arizona:* pattern formation in chemical systems
W. ZUREK, *Los Alamos:* algorithmic randomness and physical entropy

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devoted to individual projects, discussion sessions, computer workshops, laboratory demonstrations, and informal interactions. "In the final week," says Director Erica Jen, "students will have the opportunity to do something with the ideas and techniques of complex systems. It will be a time for absorbing, assessing, and applying the material presented in the first three weeks, and should prove to be one of the most interesting components of the Summer School program."

The Human Immune System: AIDS, Abzymes, and Evolution

The human immune system is the common denominator in a disparate array of theoretical and applied fields, from research on AIDS and the development of abzymes (a new class of catalytic molecules based on the synthesis of antibodies) to speculative investigations of evolution. The Institute's work involving the immune system began in June, 1987 with a workshop in theoretical immunology and continued in an October, 1988 workshop, "Modeling the Interaction of HIV with the Immune System." Another meeting, scheduled for the spring of this year, will explore applied molecular evolution and maturation of the immune response.

Modeling the Interaction of HIV with the Immune System

This workshop brought together more than thirty theorists and experimentalists with diverse backgrounds to exchange knowledge and perspectives—experimentalists working on AIDS, mathematical modelers, and epidemiologists. Although the immune system lies at the confluence of these disciplines, AIDS research has not, for the most part, directly combined them. For example, experimentalists have done little mathematical modeling of any kind; epidemiologists have developed statistical models of the incidence and spread of AIDS, but generally do not have extensive knowledge of the immune system or how HIV infection develops within an individual; and immune system modelers have done relatively little work in modeling HIV infection. To date, most of our knowledge about HIV has been gained *in vitro*, but the segregation of disciplines in AIDS research has contributed to questions about the relevance of the circumscribed world of a petri dish to "real-world" phenomena.

Alan Perelson, who works on mathematical models of the immune system at Los Alamos National Laboratory and was the workshop's organizer, explained the workshop's purpose: "AIDS is important enough that we didn't want to go the usual route, to be totally academic, working on a model, publishing it, and then waiting months for somebody to read it and decide whether it's interesting enough to test experimentally: a two-year cycle. By establishing these ties at the workshop we hoped to speed up this process. The experimentalists who attended were anxious to spend time with the theorists and vice versa."

Fifteen papers were delivered in formal sessions, and impromptu *ad hoc* sessions were formed to pursue particular questions. The presentation topics included epidemiology, pathogenesis, and several mathematical models of molecular processes. The presentations helped clarify the areas of knowledge and generated challenging debates about assumptions and results, particularly regarding the mechanisms by which HIV virions kill healthy cells.

Mathematical modeling of HIV and immune system interactions is still a nascent enterprise, one that presents a uniquely complex situation—previous immunological models have not had to consider wholesale molecular processes that destroy the immune system itself. The traditional immunological models may not provide insight into HIV interactions. Theorists and experimentalists benefited from the cross-fertilization, and directions for future research emerged. An experimentalist studying the molecular biology of HIV is planning experiments to refine understanding of the mechanisms that activate the virus, which can remain dormant in infected cells for extended periods of time. Dr. Giorgio Parisi, a theoretical physicist from the University of Rome, presented a speculative paper on ways HIV could infect the immune system. Dr. Mark Greene, from the University of Pennsylvania, will conduct experiments to test these novel ideas. Dr. Carlos Castillo Chavez of Cornell University and Dr. Kenneth Cooke of Pomona College, experts in epidemiological modeling, began a collaboration with Dr. David Pauza of the Salk Institute. They will draw on epidemiological models to design experiments to test the role of macrophages in HIV infection in an individual. Epidemiological models commonly incorporate the idea of reservoirs of infection in animals; macrophages are immune system cells that act as reservoirs for HIV virions.

Because the results presented at the workshop were largely experimental, speculative, or preliminary, a proceedings volume will not be published. However, the resulting collaborations will ensure continued communication among the participants, and another meeting in six months to a year is possible. According to Dr. Perelson, "Unlike some professional meetings, in which people have to be dragged back to the conference rooms, the participants were anxious to return to business. Some sessions actually started ahead of schedule. I'm certain that people will stay in touch as a group, write to each other, and so on. In my own modeling work, which pursues some of the issues raised at the meeting, it will be a lot easier to pick up the phone and throw ideas off experimentalists."

Applied Molecular Evolution and Maturation of the Immune Response

The immune system very rapidly manufactures and adapts a profusion of molecules, particularly the antibodies that recognize disease-causing agents. This rapid evolution, by a process called clonal selection, is very similar to the Darwinian concept of natural selection. In fact, the genes coding for antibodies mutate up to a million times faster than other genes in the human body. During maturation of the immune response, antibodies of progressively higher affinity for the incoming antigen are formed. So, within every individual, an observable microcosm of the evolutionary principles of mutation and selection is continually occurring. These complex processes of molecular evolution are integrally related to both aspects of a dual-themed workshop organized by Science Board members Stuart Kauffman and Alan Perelson. Applied molecular evolution will examine how the emerging synthesis of molecular biology and biotechnology can literally evolve useful new molecules, vaccines, drugs, and enzymes. The second theme will focus on evolutionary processes, both within the immune system and more globally.

Attendants at the workshop will include molecular biologists, immunologists, physicists, and instrument designers developing recombinant DNA techniques to create novel genes and proteins. One class of these synthetic molecules, called abzymes, are antibodies that act as enzymes. Antibodies come in a myriad of shapes, which allows them to complement, or fit, foreign molecules. An enzyme is a protein molecule that simultaneously fits two other molecules into its structure, enhancing their reaction by creating close physical proximity. The artificial design of enzyme-type catalysts has not enjoyed great success. However, it is now clear that antibodies which bind the transition state of a reaction can catalyze the reaction. This fact prompts the general hope that novel proteins able to catalyze virtually any desired reaction can be found by the large-scale exploration of "protein space." Recently pioneered recombinant DNA techniques now allow the development of massive applied molecular evolution procedures to evolve such enzymes *de novo*.

The other part of the workshop will bring together theorists and experimentalists interested in evolutionary processes within the immune system, as well as the relationship of those processes to our understanding of natural selection. The adaptive maturation of the immune system by clonal selection can be thought of as an optimization process in which a huge number of protein molecules have varying degrees of usefulness. The fitness of a molecule to perform a specific job, as a function of its molecular sequence, can be visualized as a landscape with numerous hills and valleys. Physicists have been studying this kind of representation in terms of energy levels in disordered media. Manfred Eigen, of the Max Planck Institute and a member of the Santa Fe Institute Science Board, has done seminal work with these ideas as they relate to evolution.

The workshop will consider the evolution and adaptation of proteins, and their relationship to landscapes. The underlying assumption is that molecular optimization in the adaptation of the immune system is not merely accidental—it results from complex dynamically ordered states associated with natural selection.

The Matrix of Biological Knowledge

The "Matrix of Biological Knowledge" (Bio-Matrix) project, which began with a 1987 Santa Fe Institute workshop, addresses the pressing need to organize, intelligently access, and make widely available the wealth of biomedical information confronting researchers. At a minimum this entails identifying and coordinating access to the proliferating biomedical databases. More prospectively, the Bio-Matrix project will codify the laws, empirical generalizations, and physical foundations of biomedical knowledge; integrate analytical tools into a knowledge-based management system; and support reasoning mechanisms—in particular, reasoning by analogy and homology—over the biological domain.

One of the ultimate goals of the Bio-Matrix project is to provide support for the identification of new generalizations and higher-order biological laws which are being approached but may be obscured by the simple mass of data. More immediately, the concepts and technologies embodied in the Bio-Matrix are essential for the full exploitation of the information generated in the large-scale, complex genome mapping and sequencing projects now being initiated.

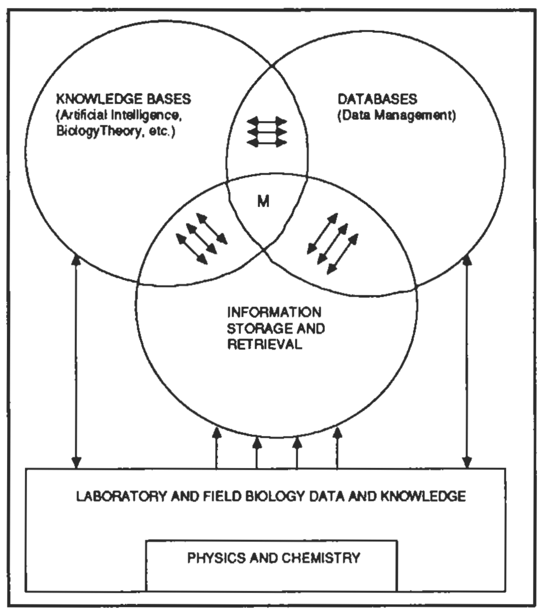
Issues

In October, 1988, nearly fifty scientists representing various database and research projects, along with representatives from the National Institutes of Health and the National Science Foundation, met at a SFI-sponsored meeting to assess current needs and future directions of the Bio-Matrix project. Support for the meeting was provided by the National Institutes of Health; the co-chairmen were Professor Harold Morowitz, George Mason University, and Dr. Christopher Overton, Unisys. Some of the issues discussed were:

System Architecture. The group discussed the architecture of the needed systems and the need to develop an implementation plan which defines areas for development and directed research, as well as areas which require open-ended research.

Standards and Software Distribution. The group discussed the issues of database and interface standards, and the trade-off between standards and open research. They considered how the Bio-Matrix might be distributed, and explored the roles of public domain software (e.g., Gnu-emacs, X-windows, etc.) vs. commercial software.

Education. Participants debated the best ways to educate the biomedical research community at large about the Bio-Matrix project, as well as how to increase



communication and collaboration within the Bio-Matrix community.

Finally, researchers discussed the *Identification and Coordination of Database and Research Projects,* including the identification of database and research projects germane to the Bio-Matrix, and how to coordinate research efforts among projects to minimize duplications and maximize short- and long-term results.

Communication

Communication to date has been helped by the establishment in 1987 of a Bio-Matrix electronic bulletin board. This electronic mailing list allows exchange of information among people interested in the Bio-Matrix concept. At present subscribers on the Internet and BITNET receive notices directly; the list currently contains some 70 names. In addition, arrangements have been made to have the bulletin board read directly by users of BIONET, the molecular biology computing resource, and from there a gateway has been established into SEQNET, the British molecular biology information network. It also reaches Europe and Australia directly. The bulletins are also posted to USENET, a network of some 20,000 Unix machines in North America, Europe, Australia, and Japan. Direct readership is about 100 (some of the "direct" readers are mail gateways in various universities in the U.S.). Potential readership from all nets and subscribers is in the tens of thousands, but a realistic estimate of the total number of people who see the notices is about 1,000-1,500. The direct mailing list has doubled in size since being established, with all of that growth by word of mouth or via the relays.

In April of 1988 an electronic mail archive server was established at the Theoretical Biology and Biophysics Group, Los Alamos National Laboratory. This is an e-mail response program which permits anyone with access to electronic mail to send a request to the server for information. The server at present contains bulletin board notices, the Santa Fe Workshop report, and the Listing of Molecular Biology (LiMB) databases. Soon to be added are a listing of participants and their interests in a database form. To date there have been approximately 250 accesses of the archive server. A British reader of the list has recently established a personnel database in England, independently of the one planned by researchers in the US. These efforts will be joined to minimize duplication.

The Matrix Newlsetter

The first newsletter recently was sent by the SFI to all Matrix Workshop participants, and further newsletters are planned. The newsletter consisted of notices from the electronic bulletin board and announcements about the archive server, as well as biological database issues. Interested readers can obtain a copy of future issues by contacting Della Ulibarri at the SFI.

Meetings Planned

One outcome of the meeting was the plan for a one-day pilot course "Information Technology for Biologists," to be held at George Mason University this spring. Dr. Walter Panko of BBN, Inc., and Professor Harold Morowitz of George Mason University are program organizers. There will also probably be a Matrix workshop at the second "Macromolecules, Genes, and Computers" meeting in August, 1989.

The Paths to Global Security

What will be the prerequisites for global security in a world that no longer relies on nuclear deterrence to discourage resort to war? Two dozen scholars, scientists, and public and corporate leaders considered this and other questions at a November workshop "The Elements of Global Security" co-sponsored by SFI and Los Alamos National Laboratory. As with other studies at SFI, the initial focus was on identifying parts of a very complex system and on the question of whether the essential interactions of the parts can be evaluated in a more broadly scoped study of the entire system. In this instance, the subject was the system that that strengthens or threatens global security. "The consensus of this first meeting," said program chair George Cowan, "was on the need to develop a more comprehensive view of the system, however approximate, that might better inform problem-solving efforts. The collaborative involvement of a wide range of experts should help us to identify most of the factors that may be critical and their relative importance as a function of time. A planning committee has been appointed, and it will meet early in 1989 to consider an agenda for future SFI action."

Emerging Themes

Several major themes emerged from the November discussions:

Although there were some suggestions for strengthened bilateral initiatives between the U.S. and U.S.S.R., more emphasis was placed on the need for broad multilateral "mechanisms" to form and incorporate global policies addressing problems of environment, ecology, and exhaustible resources; of international trade and finance; and of the transnational flows, including the migrations of peoples, that diminish the autonomy of nations in the determination of their own destinies. These mechanisms must be pursued within the framework of the nation states even though they may no longer be the most appropriate unit. The problem of loss of confidence in political leadership was mentioned several times in a number of different contexts. However, policy-making at government levels will remain centrally important in implementing key decisions. Policy-making must be pursued at many other levels also—through international undertakings by scientific and technological organizations, through trade associations and international corporations, and by joint ventures in the arts and humanities.

A root cause of many of the problems that may lead to war or to a drastic decrease in the welfare of people everywhere is the uncontrolled growth of population in many parts of the world. The ability of the globe to support increasing numbers of people is limited by available arable land and water, by the environmental impact of energy use, pollutants, and deforestation, and by the pace of development and deployment of new technologies. Population growth will lead to serious problems within only a few decades. It was suggested that the politica' will to address the problem of population

Global Security Workshop Participants

Robert McCormick Adams, Smithsonian Institution
Ruth Adams, John D. and Catherine T. MacArthur Foundation
Philip W. Anderson, Princeton University
Robert Anderson, Hondo Oil Company
Kenneth J. Arrow, Stanford University
Donald Austin, U.S. Department of Energy
Marcel Bardon, National Science Foundation
David Campbell, Los Alamos National Laboratory
Honorable Jack M. Campbell, Campbell & Black
Nazli Choucri, Massachusetts Institute of Technology
George A. Cowan, Santa Fe Institute
Doyne Farmer, Los Alamos National Laboratory
Marcus Feldman, Stanford University
Murray Gell-Mann, California Institute of Technology
Edward T. Hall, Santa Fe
Sig Hecker, Los Alamos National Laboratory
Edward Knapp, Universitites Research Association
Gottfried Mayer-Kress, University of California-Santa Cruz
Jessica T. Mathews, World Resources Institute
James McNeill, Institute for Research on Public Policy
Frederick A. Morse, Los Alamos National Laboratory
David Pines, University of Illinois
Louis Rosen, Los Alamos National Laboratory
L. M. Simmons, Jr., Santa Fe Institute & Los Alamos National Laboratory
Eugene B. Skolnikoff, Massachusetts Institute of Technology
William L. Ury, Harvard University
Frank Vandiver, Texas A&M
Frederick Wakeman, Social Science Research Council
Paul C. White, Los Alamos National Laboratory

control is so lacking that effective mechanisms will have to rely on new science and technology coupled with non-governmental channels of implementation.

Related to population growth and the increasing demand for energy is the problem of the exhaustion of critical resources and its ecological and environmental effects. Energy use is currently so inefficient that many temporary solutions are still available. The "Greenhouse Effect" may be the most serious of the looming threats. Multilateral action is a prerequisite and, contrary to past practice, major decisions must be made before the threats are definitely described: the need for risk assessment is immediate, and new indices that measure the problems and incorporate the costs into measures of GNP must be developed.

Major Changes

The group noted that the international economy is now so closely knit and interdependent that it is dangerous to ignore the major changes that have occurred in the past couple of decades. The dominant status of Japan in controlling the "blue chips in play" in world trade and finance is new, and failure to accept this fact could have disastrous effects. There are many sources of global insecurity embedded in the economic system, including major decreases in economic growth of both short- and long-term cyclical nature; chronic poverty and exhaustion of resources, not only in the Third World, but also in advanced countries; unmet rising expectations in disadvantaged nations; and the intensive pursuit of economic dominance as a source of national security.

Finally, workshop members observed that the threat of major war continues, but it is probably not as immediate as other looming threats. Careful attention will have to be paid to any instability caused by desirable reduction in levels of nuclear arms, to the continuing problems of nuclear proliferation in volatile areas of the world, and to the management of crises. However, it should be assumed that catastrophic war will be avoided in the next several decades, and that the time must be used to find solutions to non-military threats. "The message that major war is no longer an option is apparently finding increasing acceptance," writes Cowan, "and may eventually be generally acknowledged. As this threat decreases, other threats are growing and will quickly become our major concerns."

Computational Science and Nucleic Acid Sequencing

Nearly one hundred molecular biologists, computer scientists, mathematicians, and diverse other scientists met in Santa Fe, December 12-16, 1988, at a workshop on "The Interface between Computational Science and Nucleic Acid Sequencing."

The workshop was chaired by Science Board member George Bell and Tom Marr, both of Los Alamos National Laboratory. It was co-sponsored by the Los Alamos Center for Human Genome Studies, the National Center for Supercomputer Applications, and the Santa Fe Institute, and was supported by the U.S. Department of Energy, Office of Health and Environmental Research.

Mapping the Human Genome

In large part the meeting was motivated by the Human Genome Program which aims to develop maps of the human genome, including high-resolution genetic linkage maps, physical maps of each chromosome, and, ultimately, the sequence of the three billion nucleotides comprising the human genome. Beyond the problem of dealing with the sheer numbers of nucleotides involved, individual differences (polymorphisms) are essential features of each map and of the sequence itself. To capture, organize, make easily available, and begin to comprehend these data will require the development of many computational tools. The workshop focused on the computational challenges posed by this information onslaught, the current state of relevant databases and analysis methods, and directions for needed research.

Although these topics are given special urgency by the advent of the Human Genome Program, other "megasequencing" projects to sequence bacterial and yeast genomes, together with progress in sequencing technology, made the workshop timely. One important outcome of the gathering will be a proceedings volume which will be issued late this year as part of SFI's Studies in the Sciences of Complexity series.

Participants reviewed anticipated computing needs of the Human Genome and other programs, together with existing capabilities. At present, the human genetic linkage map is assembled by the Howard Hughes Institute at Yale, while the sequence database is assembled as GenBank at Los Alamos, together with complementary efforts at the European Molecular Biology Laboratory and in Japan. A pilot project has been started at Los Alamos to provide a national repository for physical mapping data of various resolutions. It was agreed that there is a need for image processing and data management systems that will enable individual laboratories not only to organize their own map and sequence data but to submit them directly to central databases. GenBank will soon be in the form of a relational database, although some scientists saw the need for object-oriented and hierarchical databases in the future. It was agreed that all databases need to be linked in a transparent manner and must be accessible to individual investigators through their specific workstations. The National Library of Medicine, through its Center for Biotechnology Information, plans to play a major role in coordinating this effort.

Using Supercomputers

How to detect functionally significant patterns in DNA and protein sequences was another major concern of the workshop. A standard procedure is to compare a new sequence with all known ones in a search for significant similarity. Participants discussed the use of the CRAY X-MP supercomputer, as well as massively parallel computers such as the Connection Machine and the DAP-1, for such comparisons. Alan Lapedes, a Los Alamos National Laboratory staff member and a SFI External Associate Professor reported some exciting results on the use of adaptive neural networks to detect protein coding regions, including the intron-exon splice junctions, in human DNA. Sequences potentially regulating gene expressions are more difficult to detect. Many of these are sequences that are recognized by specific proteins. Craig Benham of Mt. Sinai School of Medicine gave an elegant review of how the partial untwisting of the DNA double helix may induce the formation of local structures that can be recognized by proteins.

Finally, the classic problem of predicting protein structure and function from sequence data was discussed. Several approaches to predicting secondary structure from sequences were presented. A major issue concerns the extent to which exons correspond to functional domains of proteins.

In the past few years, many molecular biologists have come to regard computer databases and analysis programs as important components of their research. "In the near future such computer-based tools will be indispensable," said program co-chair Tom Marr. "Participants at this workshop were united in their belief in the importance of this field and in their enthusiasm for a meeting which fostered collaborations in this highly interdisciplinary research. We look forward to another workshop in 1989."

Academic Visitors to SFI, 1988

Ralph Abrahams, University of California, Santa Cruz
W. Brian Arthur, Economics, Stanford University
Kenneth Arrow, Economics, Stanford University
John Dasjvic, Statistics, Central Bureau of Statistics, Oslo, Norway
Richard Day, Economics, University of Southern California
Rob Deboer, Biology, University of Utrecht, The Netherlands
Lloyd Demetrius, Max Planck Institut
Ute Dressler, University of Göttingen
Yuri Ermoliev, Glushkov Institute of Cybernetics, Kiev, USSR
Doyne Farmer, Los Alamos National Laboratory
Andy Ford, University of Southern California
Stefanie Forrest, Los Alamos National Laboratory
Brian Goodwin, Biology, The Open University in the United Kingdom
Frank Hahn, Economics, Cambridge University
Yehuda Hoffman, Los Alamos National Laboratory
John Holland, Computer Science and Engineering, University of Michigan
Yuri Kaniovksy, Glushnov Institute of Cybernetics, Kiev, USSR
Stuart Kauffman, Biochemistry and Biophysics, University of Pennsylvania
Timothy Kehoe, Economics, University of Minnesota
Gottfried Mayer-Kress, University of California, San Diego, and Los Alamos National Laboratory
John Miller, Santa Fe Institute postdoctoral fellow
David Lane, Statistics, University of Minnesota
Alan Lapedes, Los Alamos National Laboratory
Wentian Li, Physics, University of Illinois
Seth Lloyd, Physics, California Institute of Technology
Tom Meyer, University of Illinois
Alexander Mikhailof, Landau Institute, USSR
Norman Packard, Center for Complex Systems Research, University of Illinois
Richard Palmer, Physics, Duke University
Fred Richards, Physics, University of Illinois
John Rust, Economics, University of Wisconsin
Gerald Silverberg, Maastricht Economic Research Institute, The Netherlands
Daniel Stein, Physics, University of Arizona

David Pines

As co-chairman of the Institute's Science Board, David Pines brings a broad background in theoretical physics and considerable experience in institution-building to his consideration of the Institute's intellectual directions. Dr. Pines is a professor of physics in the Center for Advanced Study at the University of Illinois at Urbana-Champaign, and served as the first Director of that Center. Awards he has received reflect his research interests in condensed matter physics: the Eugene Feenberg Memorial Medal for Contributions to Many Body Theory in 1985, the P.A.M. Dirac Silver Medal for the Advancement of Theoretical Physics in 1984, and the Freimann Prize in Condensed Matter Physics in 1983. A member of the National Academy of Sciences and the American Philosophical Society, the Academy of Science of the U.S.S.R., a Fellow of the American Academy of Arts and Sciences and the American Association for the Advancement of Science, Dr. Pines' current research interests range from neutron stars to high-temperature superconductors. He is a past chairman of the Theoretical Division Advisory Committee at Los Alamos and is currently a Fellow in the Advanced Study Program in High Temperature Superconductivity at Los Alamos, where this interview took place.

An Interview with David Pines

Breaking Disciplinary Barriers

What has been your role in the Institute's work?

I'm proud to be counted among the founders. During one of my visits to Los Alamos Nick Metropolis invited me to join the Senior Fellows in a discussion of the design of a research and teaching institution in Santa Fe. It was an interesting concept, and Santa Fe an excellent choice for its location. I suggested that Murray Gell-Mann, who was also visiting the laboratory, be invited as well. There ensued a series of meetings over the next year or two, during which we exchanged ideas on what would be the best scientific focus for the institute, what should be the scale, what was the right mix of students and faculty, how best to broaden the initial group of founders, and the like. Out of each two- to three-hour meeting would come a somewhat different view of the institute. Gradually our views converged, and the present concept of the Institute emerged. This process of defining the Institute was really an evolutionary, adaptive process, of just the kind we encounter in the complex systems which are the focus of much of our work.

The two founding workshops of the Institute, held in October and November, 1984, played a key role in that evolution. The workshops played a multiple role. First, and most important, they let us explore with a significant group of our academic peers the validity of our basic concept of the Institute as an institution without disciplinary barriers which would focus on scientific problems which necessarily involve a number of different disciplines. Second, they enabled us to explore both a broad range of potential topics for our research agenda, and a broad spectrum of scientists who might wish to help us pursue that agenda. I thought the papers given at these workshops were of sufficiently high calibre and lasting interest that it would be good to put out a published proceedings for which, perhaps not surprisingly, I wound up as Editor.

Since those early days I've served the Institute in many different capacities: as Trustee; Vice-President; Chairman of the Board of Trustees; as the convenor of our two workshops on "The Economy as an Evolving, Complex System"; and as Co-Chairman, with Murray Gell-Mann, of the Science Board. I'm particularly happy to be working with the Science Board, which, during these formative years of the Institute, has the responsibility for defining and overseeing the intellectual agenda of the Institute, and to be working closely with Murray. We've known one another well for some thirty-seven years; we have worked together in physics; we share a common vision of the Institute, and a commitment to helping it develop into an absolutely first-rate teaching and research institution.

As co-chair of the Science Board, I have made a special effort to identify the people and research areas we should bring to the Institute, to inquire whether we have put together the right mix of people for a given workshop or research program, as well as whether the topics we examine possess significant commonalities. I have tried to get a hands-on feeling for what we are doing by participating in a number of different workshops, including those, such as the economy or global security, which lie far from my immediate expertise and research experience. I've also tried to make sure that we stick to our core concept of the Institute, that of developing an Institution which will play a major role in defining the scientific and educational agenda of the twenty-first century.

How will you go about defining that agenda?

First of all by focusing on a related group of scientific problems which are likely to shape the directions for science in the next century. These involve, for the most part, the study of complex systems, systems which are inherently nonlinear, dynamical and adaptive, systems which evolve. Some measure of the range and interconnectedness of such problems may be found in the volume, *Emerging Syntheses in Science*, which contains the proceedings of our founding workshops.

There our speakers addressed topics as diverse as molecular and human evolution and the conscious and unconscious stream of thought, and discussed the possibility of building bridges between biology, statistical mechanics, and computer science, of reconstructing the past through chemistry, of viewing war in an evolutionary perspective, and of applying results from the study of dynamical systems to human behavior. One common characteristic of these problems is that their study does not typically lie within the boundaries of a single discipline; rather, these problems are transdisciplinary, requiring for their solution a broad mix of disciplinary skills.

Research universities which tend to be run along departmental, and thus disciplinary, lines find it difficult to develop programs in complex systems research. While an increasing number are establishing centers in which faculty from many different departments come together to work on complex systems, such centers rarely provide tenure appointments, a privilege which is reserved for the departments. This means that young scientists who work in such a center, no matter how gifted, all too often do not receive a tenure appointment, since departments tend to focus on the perpetuation of the sub-fields which currently make up their disciplines. Departments find it difficult to cut back on the number of appointments made within existing sub-fields of the department in favor of emerging sub-fields which do not presently fall within the department's jurisdiction. Moreover, how are they to evaluate young scientists who are working outside the present departmental boundaries? It was difficulties of just this kind which led Sid Drell, a distinguished physicist who has played a major role in arms control research, to resign recently as co-director of Stanford's Center for International Security and Arms Control. Sid resigned because he was unable to secure faculty appointments for the distinguished group of research associates who have been working with him at the Center.

Our solution to this problem is to establish an institution which would be free of the restrictions and bounds imposed by the departmental structure, one which would encourage young scientists to borrow freely from different disciplines and to focus on the problem of a particular complex system, viewed as a whole, rather than a discipline-driven aspect of that problem. In establishing an institution with no disciplinary barriers we hope not only to attract a remarkable group of scientists to work at the Institute, but to provide support for their counterparts in universities, by setting rigorous standards for what constitutes excellence in research on complex systems.

You mentioned Santa Fe as being a significant place for the Institute. Why?

Its historical position as the oldest city in the United States, its geographical location, its climate. For a community of its size it has a fascinating mix of cultures: the Indian culture, which continues to play a real role in the spirit of Santa Fe; the legacy of the Spaniards in the Spanish-American culture; and most recently, the Anglo culture represented by the painters and writers who have been attracted to Santa Fe since the early part of this century. Moreover, there's no real academic center of scientific excellence between, say, Chicago, Urbana, and Madison in the Midwest and the West Coast. With Los Alamos, a major interdisciplinary scientific laboratory, nearby, establishing a major new scientific institution in Santa Fe seems to be both timely and desirable.

"An additional commonality is our effort to look at problems as a whole, rather than chopping them up into little pieces...The problems we address are fundamentally nonlinear, which means you can't really chop them into little pieces. You've got to solve the whole thing."

What are the roles of fundamental, theoretical, and experimental research at the Institute?

I wouldn't make a distinction between fundamental and theoretical research. For the most part, it's fundamental research that people are carrying out here. The dichotomy is really between theoretical and experimental work, or between basic and applied research. We're doing basic research, mostly theoretical, and we'r trying to keep in very close touch with experimentalists, to guarantee that the work carried out here explains or is confirmed by experiment. We also have the idea that some of the things we're working on could lead, perhaps on a very short time scale, to interesting applications.

What to you see as the most significant contributions made by the Institute in its brief history?

I can list at least five: Our workshops on problems as diverse as the economy, global security, and the immune system, which have brought together individuals of markedly different backgrounds who have discovered a common interest and shared goals, and which have led to nascent research networks in these areas; the creation of our Science Board, which contains a marvelous mix of scientists who have made major contributions within a given discipline, but who are now interested in studying complexity in one of its many guises and in advising SFI on programs and people; our co-sponsorship and management of the first summer scho devoted to complex systems, directed most ably by Dan Stein of the University of Arizona; our resident research program on the economy as an evolving complex system which grew out of a workshop, and is bringing together economists, theoretical physicists, computer scientists, and biologists, to work on fundamental questions which may lead to new paradigms for economics; and our publications program, which, beginning with *Emerging Syntheses in Science*, has made available to scientists everywhere the proceedings of our workshops and summer schools.

Another of our accomplishments has been in the field of pure and applied immunology, where we have brought together people doing theoretical work with practitioners and laboratory workers. We've established the ground rules for a successful interaction between the two groups and hope that we can bridge what was a significant gap between theory and application in that area.

There was a wonderful mix of papers in Emerging Synthesis in Science. *It i* *cluded papers by a psychiatrist and a psychologist about the nature of consciousness. Has the Institute pursued that area?*

Yes. At the last meeting of the Institute's Science Board, Jerome Singer, a clinical psychologist from Yale, and David Rumelhart, a Stanford psychologist whose interests include learning algorithms and neural networks, proposed that we hold a workshop which would examine the interplay between the chemistry and neural networks and human behavior. They want to see if they can begin to establish links between the applied side, how the brain functions as described by a clinical psychologist, and the thus far quite theoretical models of neural networks.

In the workshops held so far have commonalities begun to emerge in the quest for underlying principles?

Early on, in the founding workshops, as we explored the areas in which we might most profitably concentrate, and considered the people we'd try to attract, we began to explore the possibility that there may be integrative principles at work in systems as diverse as the economy, the human brain, or the functioning of the immune system.

It is tempting to believe that these exist. For example, is it possible that in a broad class of complex systems one encounters metastable states which may not be the most favorable energetically, but from which it is very difficult to escape. A system moving between such states may not be able to evolve to a more favorable environment unless substantial energy is supplied or, say, a sequence of highly correlated motions takes place. This qualitative paradigm seems equally appropriate for physical systems (spin glasses), individual states of mind (e.g., depression), group behavioral patterns (e.g., the nuclear family), economic systems (third-world debt), or nation states (the Soviet political system). We will be discussing many such possible threads of complexity at an SFI workshop next February on "The Nature of Complex Adaptive Systems" which Murray Gell-Mann and I are chairing.

An additional commonality is our effort to look at problems as a whole, rather than chopping them up into little pieces, and arguing that it is enough to combine solutions for the separate pieces. The problems we address are fundamentally nonlinear, which means you can't really chop them into little pieces. You've got to solve the whole thing. A very approximate, largely descriptive, model solution which reflects attention to all the different relevant components of the problem is better than an exact solution to a tiny piece of the problem. Thus, in examining a complex system, it is essential to bring together experts who are familiar with all the various parts of the system.

The importance of that approach was emphasized at our November exploratory meeting on "The Elements of Global Security." I raised the possibility of viewing global security as an evolving adaptive complex system. It was agreed that were we to do so, it was important at the outset to develop a comprehensive approach to global security. Again, in this meeting we tried to have a real range of participants: from physical scientists who may not have worked on the problem but who are interested in thinking about new applications for their ideas, to practitioners, experts on national security problems and political scientists who have devoted their professional careers to understanding problems of development.

It's a startling idea, to put theoretical physicists in a room with political scientists to talk about global security.

Yes, and what emerged from the meeting is that a role for the Institute to play is to look at the whole system, not simply its military aspects, as is traditionally done in describing security. There was a consensus that as important as, in the long term more important than, military security, is a mixture of economic and ecological security, that is paying attention to the needs of society as a whole in terms of human and natural resources and developing them in such a way that they're renewable. A key aspect is the development of connections between theoretical studies of the ecology and economics.

A developing country, driven by economic concerns, may in the process destroy its ecology and make it all but impossible to continue to develop rapidly. I'm overstating, of course, but things like that have gone on. In the interests of rapid development, for example, agricultural experiments in large parts of the Soviet Union, under circumstances not fully appreciated, have simply destroyed the land for generations to come. There are many such examples; one major concern in this area might be the examination of the likelihood of one worst-case scenario, the displacement of one-third of the world's population in the next thirty years.

What do you mean by displacement?

The land they're on would be underwater. That's the worst-case scenario of the greenhouse effect, and it's pretty startling. How do we plan for it? If it's true, can you change the rate at which it's happening by paying real attention to what you're doing to the environment? How do you make a model for the social consequences? What are the political consequences for countries that have massive borders on the seas? All of that can't be divorced from the military side. What will cause the next set of conflicts? Will these be driven by limited resources, or by the instabilities brought about by limited resources?

It may turn out to be essential to global security for the United States and Europe, the Soviets, and the Japanese, the third-world countries, including China, and the African countries to develop ways of working very closely together, with a degree of cooperation that at the moment looks like a wild dream. So one is led to ask what new kinds of institutional arrangements might be possible, arrangements aimed at solving economic and ecological problems on a scale which cannot be dealt with by any single country.

First you have to decide how to define problems of global security in a way that can be communicated and understood by people working on it. So the feeling was that while many people are working on parts of this problem, one possible role for the Institute would be to design a research year in which we bring together people from many different disciplines, whose knowledge is an essential component of any kind of integrated picture, to explore what kinds of even very crude models might be applicable and useful.

What do you mean when you use the term model?

A comparatively simple mathematical model that incorporates a number of key elements and displays highly nonlinear dynamical behavior. One aspect of such studies would be how the demonstration of the extent to which everything is linked inextricably, by asking what happens if you change one aspect. If the world is at a given level of stability, what happens if one-third of the developed area of the world is underwater? There you're just changing one element, the ecology. That's a gross example, a gross perturbation. But you can ask questions about smaller perturbations. What happens if the temperature increases at a modest one percent a year instead of two percent a year. Can you begin to estimate the consequences?

One of the participants pointed out that the Canadians are proposing to develop a whole new class of nuclear submarines to go under the Arctic ice. If the warming trend continues, the estimate is that the time these submarines would come on line will be just about the time the ice is melted. That's an example of a quite unexpected interplay of the military side and the ecological side.

Has anyone attempted the kind of mathematical model for global security that you're describing?

We were told at the meeting that some thirteen or fourteen global models have been developed, all notably unsuccessful. The natural question is why? Our instinctive feeling is that they've failed because they haven't taken into account all of the relevant factors, and that those which have been included have been treated in too linear a fashion; that the essential nonlinearity of the system has not been recognized. Naturally one of the things we want to do is to have someone tell us in great deal about the failed models.

Of course, our work on the global economy is closely related, and may provide a useful guide on how we should proceed. We had an exploratory meeting about two and a half years ago, in which John Reed and some of his senior executives from Citicorp demonstrated the inability of existing economic models to account for the evolution of the global economy. It was quite clear that there was a problem and that it wasn't being tackled by conventional techniques available to economists.

Follow-on workshops on the economy in September 1987 and this past September have led to the formulation of a number of well-defined problems that physicists and chemists and economists can work on together. If we're successful in solving some of these, we may in time make it possible to develop an understanding of the economy as a highly complex, nonlinear, adaptive system. We all expect something substantive will emerge. Again we've talking about the long term.

> "If we do our job right we should hit some dead ends, but so far we seem to have been singularly successfuly in defining areas of research which are signficant..."

We hope that within a decade we can come up with a set of algorithms and paradigms that apply to the real world. In that process we'll try to make use of all the relevant factors which need to be included in a realistic model of the global economy.

How can a model, mathematical or otherwise, account for essentially unpredictable events, for example charismatic leaders?

Who could have possibly predicted Gorbachev? He's accomplished a remarkable amount. He seems to have an excellent instinct for bringing about change. But he certainly wasn't predictable. And it's hard to decide the extent to which the changes are the result of Gorbachev. Was the system inevitably going it that direction? One never knows. But again, those political changes are going to affect the Soviet economy in a profound way, in a way that's likely not describable in any of the usual economic models.

In a sense then, aren't the kinds of models you're talking about reactive, descriptive after the fact, rather than truly predictive?

One doesn't expect them to be predictive for a very long time. Initially, what you look for are purely phenomenological models with some underlying mathematics, that properly describe effects and reproduce features we can observe. If that's accomplished, we can go on to ask whether such models possess any predictive possibilites. For example, that is what Doyne Farmer is now doing with stock market prices. He is studying the time series of market prices, which may reflect an underlying chaotic behavior, to see whether these series can then be used to predict long-term or short-term market behavior.

Have there been any notable dead ends in any of the Institute's endeavors, any cases in which different disciplines did not mix productively?

Well, I would say not yet. In a way, almost everything we've tried has worked. That's marvelous, but it has consequences. When you start something and it seems to be working, you have a responsibility to carry on. That is a great drain on the human and financial resources of the Institute. If we do our job right we should hit some dead ends, but so far we seem to have been singularly successful in defining areas of research which are significant and identifying a core group of scientists from a broad mix of disciplines to work on these problems.

We have made some mistakes. We held early on a workshop on complex adaptive systems, in which we tried to search for integrating principles. It was a very interesting workshop, but we made a mistake in that we didn't work hard enough to ensure that participants were around for a long enough period to work together, and we did not ensure that there was a proceedings. It was a meeting in which people would come and go; participants would describe their work; everyone there would listen, and then a new set of people would appear with a new audience. It didn't have the kind of continuity that we've come to realize is necessary to make workshops genuinely effective. I think having a written record is a very good idea, good for those who participate, as well as those who can't. It is always good to be forced to write down your ideas and organize them so that there is a clear record.

There is one other notable exception to our record of success, our inability as yet to identify a donor who has the means and interest to give us somewhere between fifteen and five hundred million dollars, the sort of endowment we need to move most effectively to the next stage. We very much need an appreciable endow ment in order to realize our promise, but haven't found that person or persons yet. Apart from that I think we've been fabulously successful in the rate at which we've grown. Just eighteen months ago we moved into a building that initially was pretty much deserted and now the place is jam packed with researchers and activities.

Has the significant flow of knowledge in the Institute's workshops been from the hard sciences to the softer ones? After all, the physicists and mathematicians seem to be the common denominator at just about every workshop.

We are far more than a collection of natural scientists handing out wisdom and social scientists receiving it. For example, in our program on the economy, the physicists are learning as much from the economists about constructing a model that's relevant to the economy as the economists are learning about the physicists' techniques. Genuine collaborations are evolving. Behavioral scientists have made impressive contributions to our program. At the recent meeting on global security, for example, we had two anthropologists and an archaeologist. Our archaeologist was Robert McCormick Adams, who is the Secretary of the Smithsonian Institution. We are pleased to count him as one of the founders of the Institute, and one of his many contributions was the idea that we get together with John Reed and others at Citicorp to explore the evolutionary aspects of the economy.

That leads to my last question. Where is the Institute heading?

In brief, toward a continued period of rapid growth, constrained only by our financial resources. Thanks to major support from the National Science Foundation, the Department of Energy, and the John and Catherine D. MacArthur Foundation as well as contributions from a number of individuals and other foundations, we have been able to demonstrate the validity of the basic concept of the Institute—that this is the right time to bring together scientists from a broad spectrum of fields and disciplines to work together on a broad spectrum of complex adaptive systems, from the immune system to the economy. We have moreover demonstrated our ability to move from an exploratory workshop to a full-fledged workshop to a resident research program and research network.

All of the pieces are in place for further continued rapid growth. The Institute has a very strong experienced president in George Cowan, who is now able to spend full time in that position. George has assembled an unusually able administrative team, whose abilities have been demonstrated repeatedly during the past year. The Science Board is at its full complement, and has identified a core group of scientists who have initiated an intellectual agenda which is filled with both promise and accomplishment. In some areas, such as the economy as a complex, evolving system, the transition from workshop to a full-fledged research network of scientists at many different institutions is well underway. The Institute is in the process of appointing its first group of External Professors, who hold academic positions elsewhere but who are deeply involved in research programs of keen interest to SFI. External Professors will spend part of each year at the Institute, and are expected to be active participants in SFI resident research programs and SFI research networks. Thus the Science Board and the External Professors will both oversee existing research programs and take responsibility for initiating new ones.

The next significant step will likely be the selection of an initial group of tenure faculty. The timing of this step will depend upon the ability of the Institute to secure the endowment and added annual support needed to attract a tenured staff member. Based on the experience which Murray and I have had with prospective Science Board members (the response to an invitation to join is typically greeted with a resounding "Yes, it's a marvelous idea, when can I start to work?"), SFI has every reason to be optimistic that as its financial condition permits, it will be able to assemble an absolutely first-rate group here in Santa Fe, and I wish them every success.

—Dan Tyler

Dan Tyler is a writer in the International Technology Division at Los Alamos National Laboratory.

Science Board Chairs Gell-Mann and Pines to Head Integrative Workshop

In mid-February, 1989, Science Board Co-chairs Murray Gell-Mann and David Pines will bring together key participants in SFI programs and workshops to focus on the common threads of complexity running through the various endeavors and the overarching themes of the Institute. These are some of the questions that the workshop will address: What is meant by the term "complex adaptive system"? What are the common characteristics that relate biological evolution, pre-biotic chemical evolution, the operation of a mammalian immune system, the generation of new strategies by computers using genetic algorithms, human learning and thinking, and the behavior of the global economy? Are there fundamental distinctions between these subjects on the one hand and, for example, hydrodynamic turbulence or the evolution of the physical cosmos on the other? If so, what are they?

David Pines writes "the tool kit of the complete complex-systems theorist now includes analytic studies and computer simulations of the consequences of a number of well-defined models used by physicists in the last decade to describe the behavior of complex *physical* systems: chaos in nonlinear dynamic systems; spin glasses; self-organized criticality leading to 1/f noise; cellular automata obeying simple rules; Hopfield and Holland learning algorithms; etc. Is this kit sufficient for work on biological systems, the evolution of the global economy, or a description of global security as an evolving complex system? Can we devise "homework problems" analogous to the double oral auction problems under study by John Rusk, Norman Packard, and Richard Palmer in the research program on the economy, which will, to mix metaphors freely, test the "fitness" of these various tools to maneuver in the rugged landscape of complexity?"

Gell-Mann and Pines anticipate that this inaugural integrative workshop will become an annual SFI event.

Complexity, Entropy, and the Physics of Information: A "Manifesto"

Editor's Note: In May, 1989, Wojciech Zurek, a staff member in the Theoretical Division at Los Alamos National Laboratory and an External Associate Professor at SFI will chair a Santa Fe Institute workshop on complexity, entropy, and the physics of information. It is anticipated that the workshop will be the first step in establishing SFI as the hub of a network facilitating collaborations between researchers working on different aspects of the "physics of information." Below, Zurek outlines several long-standing problems in physics along with the relatively new points of view which suggest deep connections between information and the natural sciences.

The specter of information is haunting sciences. Thermodynamics, much of the foundation of statistical mechanics, the quantum theory of measurement, the physics of computation, and many of the issues of the theory of dynamical systems with applications to biology and computer science share information as a common theme. Among the better established, but still mysterious, hints about the role of information are:

• *A deep analogy between thermodynamic entropy and Shannon's entropy.* Since the introduction of Maxwell's Demon[1] and, particularly, since the celebrated paper of Szilard[2] and even earlier discussions of Smoluchowski,[3] the operational equivalence of the gain of information and the decrease of entropy has been widely appreciated. Yet, the notion that a subjective quantity such as information could influence "objective" thermodynamic properties of the system remains highly controversial.[4]

It is, however, difficult to deny that the process of information gain can be directly tied to the ability to extract useful work. Thus, questions concerning thermodynamics, the second law, and the arrow of time have become intertwined with a half-century-old puzzle, that of the problem of measurements in quantum physics.

• *Quantum measurements* are usually analyzed in abstract terms of wave functions and hamiltonians. Only very few discussions of the measurement problem in quantum theory make an explicit effort to consider the crucial issue—the transfer of information. Yet the act of obtaining knowledge is the very reason for making a measurement. Formulating quantum measurements and, more generally, quantum phenomena in terms of information should throw a new light on the problem of measurement, which has become difficult to ignore in light of new experiments on quantum behavior in macroscopic systems.[5]

The central—and still unsettled—issue of the quantum theory of measurement is the clash of the predictions of the Schrödinger equation with our human perceptions. For if quantum theory applies to arbitrarily large objects—including us, "the observers"—*all* the possible outcomes of the measurement should occur with a finite probability each time the measurement is carried out. That is, if quantum uncertainty is responsible for the coin landing "heads" or "tails," both of these options should happen each time the coin is flipped! The same should apply to roulette wheels in Las Vegas. Moreover, if the decisions made by us are at some level influenced by quantum phenomena in our brain—as is likely to be the case—then a similar statement applies to these decisions and their consequences. The world around us should contain all of the "branches" corresponding to all of the possible outcomes, and it should continue branching each time a quantum phenomenon with several possible outcomes takes place. However, our everyday experience tells us that measurements have definite outcomes. Only a single branch appears to survive. The remainder of the tree is somehow "pruned."[6]

The difficulty of finding out what causes "pruning" was apparent to the founders of quantum theory (see articles collected in Ref. 7) The problem is, however, even more pressing today than it was a half-century ago: Immediately after its inception quantum mechanics could have been considered only "provisional" and its domain of applicability limited to the microscopic. However, experiments performed more recently make it abundantly clear that quantum theory is almost cer-

Information Theory

Information theory is concerned with communication (sending information from "here" to "there"—or in the case of storage from "now" to "then"). A seminal paper, providing a quantitative measure of information, was written in 1948 by an employee of Bell Telephone Laboratories, Claude E. Shannon. One of the key questions addressed by Shannon concerns the measure of the amount of information.

The act of communication of a "symbol," (e.g., of a letter), can be viewed as a "choice" of the desired symbol from the "catalog" of all possible symbols (e.g., the alphabet). Different symbols can occur with different probabilities (for instance, in the English language the letter "e" is most probable). Shannon demonstrated that—given certain natural requirements—information content can be measured by a unique function of these probabilities p_i

$$H = -\sum_i p_i \log p_i$$

This function is a weighted sum of the logarithms of probabilities of different symbols. It (1) leads one to a measure of the *capacity* of communication channels; (2) allows one to assess efficiency of the *coding process* (for example, the act of transforming messages into signals suitable for transmission); and (3) is useful when discussing the effect of noise in the communication channel on the reliability of the received messages.

tainly valid for arbitrarily large objects.[5] Moreover, even if it were to be supplanted by some more fundamental theory, its "paradoxical" features are here to stay.

The distinction between *what is* and *what is known to be*, so clear in classical physics, is blurred, and perhaps does not exist at all on a quantum level. For instance, energetically insignificant interactions of an object with its quantum environment suffice to destroy its quantum nature. It is as if the "watchful eye" of the environment "monitoring" the state of the quantum system forced it to behave in an effectively classical manner. Yet, even phenomena involving gravity, which happen on the most macroscopic of all the scales, bear the imprint of quantum mechanics.

• *Black hole thermodynamics* has, for instance, established a deep and still largely mysterious connection between general relativity, quantum, and statistical mechanics. Related questions about the information capacity of physical systems, fundamental limits on the capacity of channels, the origin of entropy in the Universe, etc., are a subject of much recent research.

In fact it was recently suggested that the whole Universe—including configurations of its gravitational field—may and should be described by means of quantum theory.[8] Interpreting results of the calculations performed on such a "Wavefunction of the Universe" is difficult, as the rules of thumb usually involved in discussions of experiments on atoms, photons, and electrons assume that the "measuring apparatus" as well as "the observer" are much larger than the quantum system. This is clearly not the case when the quantum system is the whole Universe. Moreover, the transition from quantum to classical in the early epochs of the existence of the Universe is likely to have influenced its present appearance.

The three puzzles above lie largely in the domain of physics. The following issues forge connections between the natural sciences and the science of computation, or, rather, the subject of information processing regarded in the broadest sense of the word.

• *Physics of computation* explores limitations imposed by the laws of physics on the processing of information. It is now established that both classical and quantum systems can be used to perform computations *reversibly*.[9] That is, computation can be "undone" by running the computer backwards. It appears also conceivable that approximately reversible computer "chips" can be realized in practice. These results are of fundamental importance, as they demonstrate that, at least in principle, processing of information can be accomplished at no thermodynamic cost. Moreover, such considerations lead one to recognize that it is actually the erasure of the information which results in the increase of entropy.

The information which is being processed by the computer is a concrete "record," a definite sequence of symbols. Its information content cannot be measured adequately in terms of Shannon's probabilistic definition of information. One must instead quantify the information content of the specific, well-known "record" in the memory of the computer—and not its probability or frequency of occurrence, as Shannon's formalism would demand. Fortunately, a relatively new development—a novel formulation of the information theory—has been already put forward.

• *Algorithmic randomness*—an alternative definition of the information content of an object based on the theory of computation rather than on probabilities—was introduced two decades ago by Solomonoff, Kolmogoroff, and Chaitin.[10] It is equal to the size of the shortest message which describes this object. For instance, a string of 10^5 0's and 1's:

01010101010101...

can be concisely described as "$5 \cdot 10^4$ 01 pairs." By contrast, no concise descrip-

The Second Law of Thermodynamics, Entropy, and the Arrow of Time

The first law of thermodynamics says that energy is conserved. It is neither created nor destroyed. The second law of thermodynamics states, in effect, that, although energy does not alter its total quantity, it may lose quality. The name Rudolf Clausius gave to the measure of this loss of quality was entropy, from a Greek word meaning "transformation." When a quantity of heat flows out of a hot body, its entropy decreases by the amount of heat divided by the original temperature of the hot body. When that same quantity of heat flows into a cool body, its entropy increases by the amount of heat divided by the original temperature of the cool body. Since the temperature is larger in the first case and smaller in the second, the fraction of entropy decrease is smaller than the fraction of entropy increase; thus a net increase of entropy occurs in the transfer. This increase occurs every time heat flows from a higher to a lower temperature, the basic process by which work is extracted from a heat source. This process is accompanied by an irreversible increase in entropy. Clausius summed it up this way:

The energy of the universe is a constant.
The entropy of the universe increases.

Entropy measures a physical property, the accessibility of the energy of a given system state. Ludwig Boltzmann and J. Willard Gibbs forged the crucial connection between thermodynamics and microphysics: that entropy is proportional to the logarithm of the total number W of microphysical configurations of the system which are consistent with its macroscopic properties such as pressure, density, and temperature. The probability of a configuration is equal to the inverse of this number, 1/W. Hence Shannon's information-theoretic entropy H is expressed by an essentially identical mathematical formula. Entropy measures the degree of disorder in the system.

Entropy increase in a closed system is an irreversible process: It does not decrease unless some extra source of energy intervenes to push it back "uphill." It is thus a physical index of the one-way irreversible flow of time. One can distinguish earlier from later by measuring the increase of entropy.

tion can be found for a typical, equally long string of 0's and 1's generated by flipping a coin. To make this definition more rigorous, the universal Turing Machine—a generic universal computer—is usually considered to be the "addressee" of the message. The size of the message is then equal to the length—in the number of "bits"—of the shortest program which can generate a sufficiently detailed description (for example, a "plot") of the object in question.

It is tempting to suggest that physical entropy—the quantity which determines how much work can be extracted from a physical system—should take into account its algorithmic randomness. This suggestion can be substantiated by detailed discussions of examples of computer-operated engines as well as by results concerning the evolution of entropy and algorithmic randomness in the course of measurements. It provides a direct link between thermodynamics, measurements, and the theory of computation. Moreover, it is relevant to the definition of complexity.

The meaning of complexity, its measures, its relation to entropy and information, and its role in physical, biological, computational, and other contexts has become an object of active research in the past few years. These issues are central to the formulation of the new sciences of complexity and it is appropriate that SFI should begin research in these areas.

Maxwell's Demon

In the nineteenth century a Scottish scientist, James Clerk Maxwell, conceived an imaginary creature now called Maxwell's Demon.[1] He imagined a small intelligent being residing in the microworld of a vessel of gas which is in a state of maximum entropy, that is, in a state of uniform temperature and pressure throughout the vessel. The vessel is separated into two compartments by a partition. Even though the macroscopic temperature of the gas is uniform throughout, individual molecules will move at widely varying speeds. The Demon's task was to sort the fast and slow molecules into two separate compartments by opening and shutting a perfectly frictionless door. For the sake of argument, the Demon was supposed not to expend any energy when opening or shutting the sliding door.

Regardless of whether or not this feat was practically possible, it was conceivable in principle, and suggested a way of violating the law of entropy increase. If the Demon could unmix the molecules of gas, so that the fast ones were in one compartment and the slow ones in the other, the system would have a hot compartment and a cold compartment. The entropy of the system would have been decreased without expending any energy, it would be possible to extract additional work from the gas, and the second law of thermodynamics would have been violated. The Demon would have reversed an irreversible process and achieved a result ruled impossible by thermodynamics. Careful analysis[3] resolves the paradox by showing that a mechanical Demon will heat up.

However, even if the Demon uses no physical energy when sorting, he does need information about each molecule in order to decide where to put it. Is information itself enough to reduce the entropy of a system? Leo Szilard[2] in 1929 argued that the Demon, simply by acquiring the information necessary to sort the molecules, creates as much entropy as he eliminates. Therefore, according to Szilard, not only work must be paid for by the irreversible degradation of energy measured by the increase in entropy, but an increase in entropy is also the price of information.

References

1. J. C. Maxwell, *Theory of Heat* (Longmans, Green & Co., London, 1908), p. 338
2. L. Szilard, *Zeits. Physik* **53** (1929), p. 840-856. English translation, "On the decrease of entropy in a thermodynamic system by the intervention of intelligent beings," can be found in *Behavioral Science* **9** (1964), p. 301-310, reprinted in Ref. 7.
3. M. Smolouchowski, in *Vorträge über die kinetische Theorie der Materie und Elektrizität* (Leipzig, 1914), established that—because of thermal fluctuations—devices which do not involve explicit measurements (such as ratchet and pawl) cannot work as "demons." He writes, "As far as we know today, there is no automatic, permanently effective, perpetual motion machine, in spite of the molecular fluctuations, but such a device might, perhaps, function regularly if it were appropriately operated by intelligent beings."
4. K. G. Denbigh and J. S. Denbigh, *Entropy in Relation to Incomplete Knowledge* (Cambridge University Press, Cambridge, 1985).
5. See, e.g., "Chapter II: Macroscopic Effects in Quantum Theory," in *Ann. New York Acad. Sci.* **480** (D. M. Greenberger, ed., 1985).
6. E. Schrödinger, in *Naturwissenschaften* **23** (1935), p. 807-812, 823-828, 844-849, introduced his famous cat with these words:

"One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following diabolical device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny bit of radioactive substance, so small, that perhaps in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The first atomic decay would have poisoned it. The wave function of the entire system would express this by having in it the living and dead cat (pardon the expression) mixed or smeared out in equal parts.

It is typical of these cases that an indeterminacy originally restricted to the atomic domain becomes transformed into macroscopic interdeterminacy, which can then be resolved by direct observation."

The English translation, entitled "The present situation in quantum mechanics," by John D. Trimmer was originally pub

Book Reviews

Read On

This is the first of what will be a regular Bulletin feature highlighting new and recent publications of interest to students of the sciences of complexity.

An Introduction to Chaotic Dynamical Systems
By Robert L. Devaney (Addison-Wesley, 1987)

Nonlinear dynamical systems theory has come to play an increasingly important role in a number of fields of modern science. Its ideas are ubiquitous in the study of complex systems. This book offers a useful and quite accessible introduction to many of the most important ideas.

Devaney is a mathematician and this is an introductory mathematics text. It is devoted to the fundamental ideas and treats them carefully, proving many theorems and foregoing much of the expected discussion of applications. Nevertheless, the treatment is useful and accessible to non-mathematicians because the text assumes little more than an education in advanced calculus and linear algebra and presents a largely self-contained treatment. Moreover, the discussion is illuminated by many illustrations, numerous examples, and supplementary exercises. Even those readers who do not want to follow the mathematical details of all the proofs should find this a valuable introduction. The main ideas are clearly presented and well illustrated.

The book considers only discrete, dynamical systems (iterated maps). The longest chapter, half the book, is devoted to one-dimensional dynamics and offers extensive discussion of the logistic map $F_\mu(x) = \mu x(1-x)$. Among the important topics covered are chaos, bifurcation theory, and the period-doubling route to chaos. The second third of the book covers dynamical systems in two and three dimensions beginning with linear maps and proceeding through such subjects as Smale's horseshoe map, attractors, the Hopf bifurcation, and ending with a short section on the Henon map. A relatively short final chapter on complex analytical dynamics begins with a summary of the elements of complex analysis, but readers not already familiar with that subject may find the subsequent discussion of quadratic maps, periodic points, and Julia sets tough going. Each chapter ends with a useful set of suggestions for further, more advanced reading.

It is commonplace in the community of dynamical systems practitioners that experimental mathematics is, if not a prerequisite for progress, at least a very valuable source of insight. Moreover, the beautiful computer graphics displays that result from these experiments are a source of fascination and inspiration for most who see them. Apart from the cover display of the Julia set of the complex exponential function, there is no hint of this in Devaney's book and this is a loss. Even the lengthy and lucid discussions of the logistic map are not illustrated by the usual computer-generated display of the period-doubling route to chaos.

Unfortunately the index is minimal. Ubiquitous terms like fixed point and critical point receive a single entry—to the page on which they are defined. The student seeking a list of examples and exercises is which the term appears will look in vain.

These are minor shortcomings. I found this book to be generally well written. It will reward the reader with a solid understanding of the topics it covers and it provides good preparation for more advanced topics.

— L. M. Simmons, Jr.

Signal: a whole earth catalog; Communication Tools for the Information Age
Edited by Kevin Kelly (Harmony Books, 1988).

Anyone familiar with the other Whole Earth Catalogs will feel at home puttering around in this one. The names have changed but the style, the generally informative reviews, the eclectic breadth of coverage, the slightly counter-culture flavor, and the occasionally wacky entries are just what you remember. So is the general impression that this is a useful tool for access to and information on lots of hard-to-find or even hard-to-find-out-about items. The subject is information and communications, broadly interpreted. The book is organized under somewhat arbitrary main topical headings with numerous subheadings. Some of the main headings are listed below, together with a list of subtopics that I found noteworthy.

Prime information: Books (on subjects such as fractals, chaos, cellular automata, and cybernetics), journals (including Wolfram's *Complex Systems*, cellular automata boards, a brief catalog of computer viruses, and even a review of the Artificial Life Workshop sponsored by SFI and Los Alamos National Laboratory.

The order of languages: mostly books and a little software covering programming languages and techniques, hackers, writing, wordprocessing, mathematics, and foreign languages.

Publishing frontiers: online databases, desktop publishing, independent publishing, reference and news sources, and a section on "small magazines of the fanatic."

Network societies: electronic networks, bulletin boards, and conferencing systems with some software and books.

Visual knowledge: maps, computer graphics (books, journals, software).

Digital thinking: personal computer purchasing, care, software, books, shareware; robotics.

Information civics: copyright, intellectual property, freedom of information.

Most readers will find at least a few items in *Signal* that they want to explore further.

— L. M. Simmons, Jr.

Complexity *(continued)*

lished in *Proc. Am. Phil. Soc.* **124** (1980), p. 323-338, and is reprinted in Ref. 7.

7. J. A. Wheeler and W. H. Zurek, eds., *Quantum Theory and Measurement* (Princeton University Press, Princeton, 1983).
8. An accessible discussion of this idea by one of its originators can be found in S. W. Hawking, *The Brief History of Time: From the Big Bang to Black Holes* (Bantam, 1988).
9. C. H. Bennett and R. Landawer, "The fundamental physical limits of computation," *Sci. Am.* **253(7)** (1985), p. 48-56.
10. See G. J. Chaitin, "Randomness and mathematical proof," *Sci. Am.* **232(5)** (1975), p. 47-52, for an accessible and fascinating introduction to this subject.

— Wojciech Zurek

1989 Calendar

January 25	Public Lecture: "Chaos: Making a New Science" James Gleick, author, *Chaos: Making a New Science*
February 10-13	"Integrative Workshop on the Nature of Adaptive Complex Systems" Co-chaired by Murray Gell-Mann, California Institute of Technology, and David Pines, University of Illinois
March 11	Annual Meeting of the Science Board of the Santa Fe Institute
March 12	Annual Meeting of the Board of Trustees of the Santa Fe Institute
March 13-15	Research Network Meeting, Economics Program Chaired by John Holland, University of Michigan
March 27-31	"Applied Molecular Evolution and Maturation of the Immune Response" Co-chaired by Stuart Kauffman, University of Pennsylvania, and Alan Perelson, Los Alamos National Laboratory
May 28-June 10	"Complexity, Entropy, and the Physics of Information" Chaired by Wojciech Zurek, Los Alamos National Laboratory
Late May	"Proteins, Glasses and Spin Glasses" Co-chaired by Hans Frauenfelder and Robert D. Young, University of Illinois
June 4-June 30	"Complex Systems Summer School" Erica Jen, Los Alamos National Laboratory, Director
August 21-27	"Evolution of Human Language" Co-chaired by Murray Gell-Mann, California Institute of Technology, and Jack Hawkins, University of Southern California
Late August	"Theoretical Ecology" Co-chaired by Marcus Feldman, Stanford University, and John Roughgarden, Stanford University
Mid-September	Annual workshop of the Economics Research Program
Sept. 25-30	"The Organization and Evolution of Prehistoric Southwestern Society" Chaired by George Gumerman, University of Southern Illinois
October 13-15	"Modeling the Relationship of Human Cognition with Emotion" Co-chaired by David Rumelhart, Stanford University, and Jerome Singer, Yale University

Other workshops to be scheduled:

"Public Policy Studies," Chaired by Murray Gell-Mann
"Global Security," Chaired by George Cowan

Board News

Philip Anderson was elected to the Japanese Academy of Science in September, 1988.

Los Alamos National Laboratory Director **Sig Hecker** was recently induced into the National Academy of Engineering. The Academy cited him for his research in plutonium and his leadership in developing energy and weapons systems.

Bela Julesz has retired from AT&T Bell Laboratories to become a State of New Jersey Professor of Psychology and Director of the newly established Laboratory of Vision Research at Rutgers University. He will retain his part-time appointment as "Continuing Visiting Professor" in the Biology Department, California Institute of Technology.

George Kozmetsky received several awards in 1988. An inductee into the Texas Hall of Fame, he also was honored with the Thomas Jefferson Award conferred by the Transfer of Technology Society, and was named Doctor of Humane Letters by St. Edward's University.

In addition to the SFI double-volume *Theoretical Immunology*, **Alan Perelson** had two other volumes appear in 1988. Perelson is editor (along with Byron Goldstein, Micah Dembo, and J. Jacquez) of *Nonlinearity in Biology and Medicine*, the proceedings volume of the seventh annual conference of the Center for Nonlinear Studies. *Stem Cell Proliferation and Differentiation: A Multiple Branching* is a research monograph co-authored with C. Macken.

David Pines was recently elected to the Academy of Sciences of the U.S.S.R.

Louis Rosen was instrumental in initiating an international conference on Technology-based Confidence Building which will be hosted by Los Alamos National Laboratory and will take place in Santa Fe this summer. The Laboratory recently awarded Rosen for outstanding service, citing his role as originator and first Director of the the Clinton P. Anderson Meson Physics Facility.

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Philip F. Voegelin, Santa Fe
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Herman Wisenteiner, Santa Fe
Ranier Wollman, Santa Fe

Board News *(continued)*

Gian-Carlo Rota was recently awarded the Steele Prize by the American Mathematical Society. He will spend the month of March, 1989, in Sardinia.

Isadore Singer received the Wigner Medal in July, 1988. Between professional achievements, he reached the Quarter-Final round in the Acton/Boxborough Tennis Tournament.

Jerome Singer's report "Family Mediation and Children's Cognition, Aggression and Comprehension of Television: A Longitudinal Study," recently appeared in the Journal of Applied Developmental Psychology. In Sydney, Australia, he addressed the International Congress of Psychology on "Imagery, Cognition and Health."

Anthony Turkevich, who received the Pregel Award of the New York Academy of Sciences, is working with the West Germans on an experiment on the Soviet space mission to Phobos, a moon of Mars. The mission will get to Phobos early this year. The experiment is designed to determine the chemical composition of this moon.

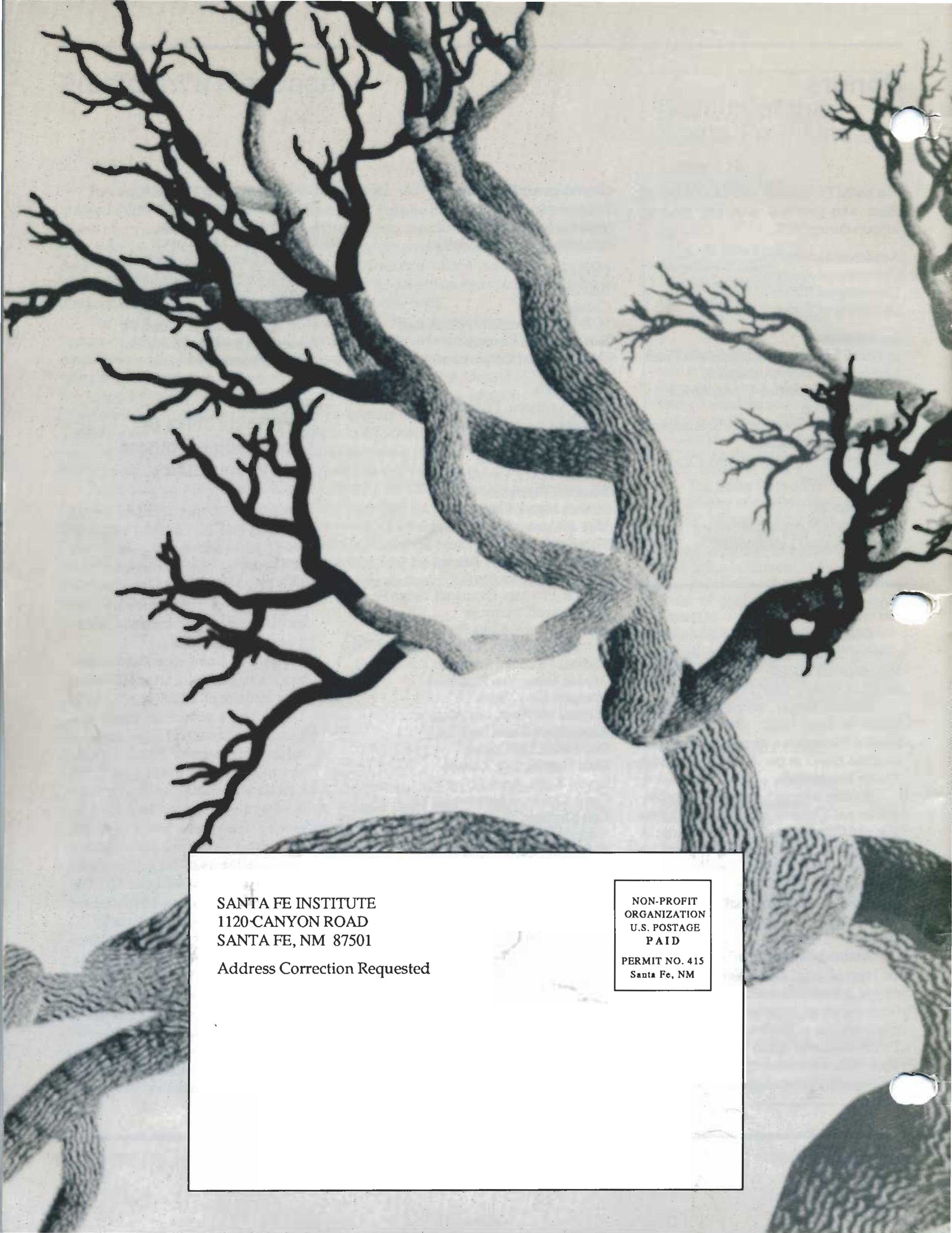
SFI Hosts Talks by Best-Selling Authors Brand and Gleick

More than two hundred people crowded into the St. John's College Great Hall one evening early last November to hear author/editor Stewart Brand talk about the fundamental redefinition of communications and media technologies currently taking place on a global scale.

In 1986 Brand spent three months as a Visiting Scientist at the Massachusetts Institute of Technology's Media Laboratory, a new center established to explore current and future transformations of electronic communication technologies. As Brand puts it, the Media Lab's underlying focus is "how humans connect, how they are connecting faster, and how they might connect better." Brand's time there resulted in his 1988 book *The Media Lab: Inventing the Future at MIT*. He drew upon his book and other related experiences for his Santa Fe talk.

On January 25, writer James Gleick, author of the best seller *Chaos: Making a New Science* will discuss the birth and development of the science of complexity. Again, the talk will be at St. John's College.

Admission to the program is free. For further information call Andi Sutherland at 984-8800.



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