SANTA FE INSTITUTE

SPRING-FALL, 1988

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Santa Fe Institute

President's Message

Since the beginning of the New Year, the activities of the Santa Fe Institute have expanded sharply as its programs have been increasingly recognized and supported by funding agencies, foundations, and the private sector. In January the Institute began the first year of a three-year grant from the National Science Foundation totaling $750,000. In April the Department of Energy initiated funding of a three-year grant totaling $930,000. In June we received word of the award of a grant of $250,000 from the John D. and Catherine T. MacArthur Foundation. These grants provide a firm financial footing for a multi-year program at the Institute.

Our current program on the global economy is made possible by grants from Citicorp and the Russell Sage Foundation totaling $200,000 plus matching funds from the DOE and NSF grants and from other donors that bring the total to $447,000. We are pleased to welcome Prof. Brian Arthur, who joined the Institute in June as a Visiting Fellow and who will help focus our research program on the global economy during his fifteen-month stay here.

During the annual meetings of the Board of Trustees and the Science Board in March, several new members were elected. I am very pleased that Charles U. Daly, Carl Djerassi, Brian Goodwin, John Hawkins, M. Peter Heilbrun, Alan S. Perelson, C. S. Holling, Ewart A. C. Thomas, Glenys Thomson, and Christoph von der Malsburg have all accepted our invitation to join the Santa Fe Institute family. We have included brief biographical sketches of each in this issue.

The rapid expansion of our research program on the economy together with the activities of a growing number of visiting scientists for the coming year are described in detail in this issue. These activities support our confidence in the health of the Institute's research programs. They will also fill our convent to capacity and mean that we must now address the problem of constructing a permanent campus.

With our need for a permanent campus in mind, we are beginning an enhanced capital campaign. In this campaign, as well as in other aspects of the management of the financial affairs of the Institute, I am particularly happy to have the energetic assistance of a new Development Committee under Art Spiegel and Larry Huntington and of our new Vice President for Financial Affairs, J. Burchenal Ault.

In view of our newly received, broad, multi-year funding, the enlarged program on the global economy, our enhanced visiting scientists program, the numerous excellent workshop and research programs recommended by the Science Board, and the new strengths brought to the Institute by recent staff and Board appointments, I am sure you will agree we have every reason to be optimistic about the future of the Santa Fe Institute.

George A. Cowan

George A. Cowan

In This Issue:

The cover is a computer-generated fractal generated by Dr. Gottfried Mayer-Kress. See page 9 for his report.

Bulletin of the Santa Fe Institute

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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.

The Developing Academic Program of the Institute

Moving Forward

The new grants announced in the President's Message not only provide a firm financial footing for a vigorous multi-year program at the Institute but, because they are for support of a broad program, they allow us the flexibility to expand the Institute's activities beyond the specifically funded endeavors that we have pursued with restricted funds. This is a step along the way toward achieving our vision of an institution free from the artificial barriers defined by the traditional disciplinary and programmatic limitations. While continuing to support the formal programs of the Institute, such as that on the global economy, we will also be using this flexibility to achieve a necessary balance by supporting at the Institute the presence of excellent scientists with broad interests who are not specifically committed to a single program.

Our increased funding has also provided the means to install advanced scientific workstations. In April we accepted delivery of three model 4/110 computers from Sun Microsystems. While this new computing capability is modest in comparison with that at the supercomputer centers, it exceeds several VAXs and provides high-quality color graphics output. The Suns now form the basis for SFI's local area network, which also includes Apple Macintosh and IBM AT microcomputers, and for our improved communication with the outside world via a new 56kb connection to New Mexico Technet. Stephen Pope has joined the Institute to manage the system and to provide modeling and programming support to SFI researchers. He will be working closely with Doyne Farmer to develop dynamical systems models for prediction of time series.

With the arrival of Brian Arthur, who will spend fifteen months in residence as a Visiting Fellow while on leave from Stanford, June marks the initiation of an enlarged program to understand the economy as a complex system. In September, John Miller, a recent Ph.D. from the University of Michigan, will join the SFI as our first postdoctoral fellow, working on this program. This issue of the Bulletin describes research initiated in the 1987 economics workshop, plans for the 1988 workshop, and for the residential research program to be initiated by Arthur and a long list of distinguished visiting scientists.

Visiting scientists have been coming to the Institute in increasing numbers in recent months. Among these are Stuart Kauffman (University of Pennsylvania), Brian Goodwin (Open University), Ute Dressler (Göttingen), and Gottfried Mayer-Kress (UC San Diego and Los Alamos). An account of Mayer-Kress and Dressler's research is included in this issue. In addition to the very active visitor program associated with the economy research, the Institute will have other visiting scientists in the coming months, including Kauffman, Mayer-Kress, Goodwin, Robert Shaw (Illinois), Lloyd Demetrius (Göttingen), Norman Packard (Illinois), plus regular participation by Los Alamos scientists Doyne Farmer, Alan Perelson, Alan Lapedes, and others. After little more than one year of occupancy of our charming quarters on Canyon Road, we are rapidly approaching the capacity of the building to accommodate our research program.

At its annual meeting in March, the Science Board reviewed a lengthy and ambitious list of innovative proposals. Many of these were directly stimulated by the Science Board under the energetic and imaginative leadership of Murray Gell-Mann and David Pines. The Institute continues to rely on the Board for scientific guidance and leadership in its workshop and research activities. This issue of the Bulletin contains descriptions of the new programs recommended by the Science Board for Institute support.

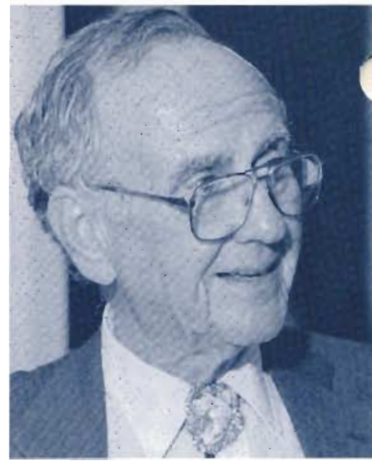
As we move into this expanded phase of the Institute's life, it seems especially appropriate to begin a review of the intellectual roots and vision for the future of this institution. We do this through the voice of one of our most influential founders, President George A. Cowan in an interview conducted by Daniel Tyler. Cowan gives an account of his own view of complexity and the origins of his ideas about the Institute, including the national need for scientists who are both experts in their own fields and generalists capable of dealing with real world policy problems. Many other individuals have played seminal roles in the founding and development of the Santa Fe Institute. In future issues of the Bulletin we will be continuing our series of profiles of influential members of the Institute family.

Among the several new projects recommended by the Science Board for Institute funding is one discussed in some detail by Cowan in the interview that follows and in the article "A World of Possibilities." Throughout human history war has served to resolve the most serious international disputes—but the results have been only the achievement of metastability, with increasingly catastrophic transitions leading to new points of metastability. Cowan is leading a new Institute program, to be initiated with a workshop in the fall of 1988, on the elements of global security. The goal is to understand how to achieve a world that remains intrinsically stable and at peace over long times yet is capable of dynamic evolution toward improved conditions for all humanity, while avoiding catastrophic events such as nuclear war.

With the initiation of this ambitious but essential program, the Santa Fe Institute embarks, at the beginning of its fifth year, on the study of perhaps the ultimate complex system.

— L. M. Simmons, Jr.

Origins and Visions:
George Cowan on the Concept of the Institute



George A. Cowan

George Cowan is retiring from the position of Senior Fellow at Los Alamos National Laboratory to become the full-time President of the Institute. A former member of the White House Science Council and a recipient of the E. O. Lawrence Award, Dr. Cowan is a Fellow of the American Physical Society and the American Association for the Advancement of Science. His special interests include high-technology transfer from government research laboratories to private enterprise; the development of econometrics based on nonlinear dynamic process modeling; research in physics; and new concepts in graduate education. His position as President of the Santa Fe Institute allows him to address all of these concerns.

The Santa Fe Institute became a reality in large part because of your efforts. What led you to envision such a place?

I've been directing research, starting with problems in radio chemistry and nuclear chemistry, since I was about thirty years old. I've dealt with physicists and theorists involved in the interpretation of diagnostic data, and research involving physical, nuclear, and organic chemistry, the life sciences and geosciences. In all of these experiences I was impressed with the fact that usually more than one person or set of people were working with parts of very similar problems. They sometimes spoke different jargons, but they needed to work more with one another. So I've been intrigued most of my life with how to put together a number of these different disciplines in a reasonable way. The only way I was ever able to do it was to get two good people in a room, people representative of different parts of the problem, and let them discuss it. If they agreed that it was a good and necessary interdisciplinary program, and if they more or less liked each other, then you brokered a marriage. And sometimes that was successful and sometimes it wasn't. After dealing with that problem for years I wouldn't know how to write a book about it. It's a black art.

The impression I had that research was too fragmented was reinforced when I went to the White House Science Council. I found even broader subjects, with a great deal of science and technology content, being decided without enough scientific input. Many issues that had decisive scientific considerations were probably being decided largely on the basis of political considerations and pressure—questions like Star Wars, the debate on AIDS, the supercollider, manned space stations, and so forth.

I talked a great deal with other members of the White House Science Council and Senior Fellows at Los Alamos about the need for a department of science and technology, which would draft national strategic science policy. People generally felt that such a department wouldn't be headed by a scientist because they aren't trained broadly enough and don't know their way through the jungle.

So that got me thinking about something like the Santa Fe Institute, how an institute might persuade some people to become generalists, to train people to range more broadly across the disciplines.

A kind of scientific Renaissance man?

Yeah, a twenty-first century Renaissance man, starting in science, but able to deal with the real messy world, which is not elegant, and which science doesn't really deal with. I talked about this man as almost surely able to use very large computers to do numerical simulations. So the Senior Fellows, led by Nick Metropolis, started discussing computational science in the very broadest sense. It's a big umbrella that covers all of these subjects—algorithms that somehow simulate what these systems do.

These discussions turned to topics like computer science, artificial intelligence, the cognitive sciences, neural networks, and so forth. And as we were joined by Murray Gell-Mann and David Pines and others, we began talking about emerging syntheses, interdisciplinary activities in which chemistry and physics were not enough by themselves.

Of course, the most obvious one of these is molecular biology, which has been a remarkably successful fusion of two conventional disciplines into a new discipline. It has resulted in all of the insights into the genetic code and much of what's happening in the huge ferment in the life sciences, from protein dynamics to more and more understanding of how life processes occur.

Then we proceeded from molecular biology to the resemblance of the social sciences to living systems, which is no accident because social sciences deal with people. And we began to define our theme as complexity. That's where the Santa Fe Institute is now, and it's obvious that this is where much of science is going.

What about those 'real world' problems you mentioned earlier. Can the Santa Fe Institute address them in a practical way?

Perhaps the most complex and important thing we should talk about is global security. By that, I mean a system that is almost failsafe. Military security fails catastrophically in one way or another. Military security based on large nuclear stockpiles fails utterly catastrophically. So when I talk about global security I mean something that eventually—and not too far in the future, in two or three or possibly four generations—is intrinsically stable with respect to going to war.

That's a wonderful and ambitious ideal. Is it possible within a handful of generations?

I think important things can be done in fifty to one hundred years. I don't think much can be done in ten years. But what you can do is to define a grand vision. A grand vision that has a broadly based consensus—within this country and internationally—of major changes in the way goods are distributed and the way social justice is dispensed and a recognition of the aspirations of everybody everywhere to have a significant role.

Specifically, how can the Santa Fe Institute study that problem?

The Institute can help by working closely with other people who look at global security as a large complex system, and who feel the same need to define this grand vision: what kind of a world will exist in peace and meet a large fraction of the needs of its population.

How has the Santa Fe Institute affected the study of complexity?

The issue of complexity has been popping up everywhere. The Santa Fe Institute has given it a little more credibility, I think, because the names attached to it are prestigious. We have a roster of National Academy types and Nobel winners, which suddenly did something very important for the whole notion, that is, to make it look more respectable. So we made waves. Other people are setting up centers to study complexity. We keep getting announcements from such centers—the University of Arizona, Illinois, a town outside of Vienna. And pretty soon there will probably be consortiums, councils, and it will become organized and start to look like one of the sciences. Or really, a science of science.

Do you see that kind of establishment as a potential problem?

Yeah, once it's established, it will start to develop its own specialties and will fragment again. Somehow or other we have to maintain the integrated parts of it. And I hope they're not brought into disrepute by a lack of rules. It's very easy when you generalize to become a scoundrel. Picasso did many great masterpieces but he also dashed things off in thirty seconds that sold for as much as anything else. That's the problem when you start painting in broad strokes. The temptation to be sloppy is always there. So you try to involve people with the specialized expertise that characterizes excellent science, but people who haven't been so brainwashed that they make a special virtue of their expertise and won't talk to people from other fields.

Are you saying that to study complexity legitimately you need a profound understanding of a particular discipline?

Right. You can't arrive at it as a generalist. Science is much too complicated for that. You have to arrive at it through rigor. The generalizations will emerge.You need directed, mutually supported collaborations and programs. And that means a certain amount of organization and willingness to communicate. And a certain security. Most people whose knowledge is limited simply don't do it, they feel vulnerable and they don't reveal their own inadequacies. Secure people do, of course. They revel in their ignorance and try to change it.

" I've been intrigued most of my life with how to put together a number of these different disciplines in a reasonable way. The only way . . . was to get two good people in a room, people representative of different parts of the problem, and let them discuss it."

There has to be wider recognition of the fact that science has reached the point where it can no longer simplify problems so that they don't resemble the real problem. As systems become complex they develop properties of their own. We have yet to successfully apply the reductionist technique in explaining complex systems in terms of their simpler subsystems. That's a profound and ongoing debate in science between the reductionist view, which says you can always find a shorter way to describe properties in the system in terms of its different parts, and the people who say you're going to run out of that capability the moment you challenge it against the real world, against life systems and social systems and so forth.

Nobody has yet been able to do a really good job of taking an even modestly complex system and describing it in terms of its subsystems and showing how all its properties arise from the interaction of all of its parts.

Ultimately, isn't that what the Santa Fe Institute is trying to do?

Well, it would like to define the general elements of the science of complexity, which would permit you to do that, at least to some extent. But it can't assert that one side is correct because the debate is ongoing and evenly matched with people who insist that some part of the properties of a complex system are in effect controlled by something external to the boundaries of the system. It's a religious issue because when you assert that a complex system will fail to be totally autonomous, that there will be some property derived from something external to the system, people will say you're talking about God or some aspect of nature that imposes order on complexity. Or does all the order arise internally? That's a very profound debate, one which I would like to avoid.

"We can talk about global security . . . a system that is almost failsafe. Military security fails catastrophically in one way or another . . . I mean something that eventually . . . is intrinsically stable with respect to going to war."

I was just about to ask you not to avoid it.

Well, as a scientist my only choice is to say that we'll press for reductionism as far as it will go. But I would be agnostic to the extent that I will not be too surprised if I find that I've got to adopt Johnny von Neumann's pragmatic description of complexity. He avoids saying where the properties come from, and says that a truly complex system is best characterized by describing the system's properties. That's a shorter message than describing the subsystems, but you don't find any magic simplicity. Herb Simon calls it pragmatic holism.

Doesn't that undo the supposition that you can find laws that link all complex systems together?

I would like to believe that we'll find a general set of elements that indicate why complex systems behave the way they do, although we may never be able to use them in a predictively useful fashion. In fact, complex systems generally have many possible states, all of which look stable on some time scale. But they're all always metastable, far from equilibrium. If they are in true equilibrium, they're no longer complex, they're stable and probably have elegantly simple properties, and in fact they're dead. Complex systems usually imply a living system, something that's dynamic.

If you treat a complex system as many economists do, as a set of equilibria, it's no longer dynamic and it's of less interest. The Santa Fe Institute is attempting to bring an uncommon paradigm to economics. Economists tend to use the physical science paradigm and look for equilibria on some surface, possibly at some lowest, most stable state. But I think it's obvious that economics operates out of equilibrium. You shouldn't look for stable states, you should look for transitions and for the laws that govern them.

Is this the first time economics has been approached from this direction?

No. Economic texts usually pay attention to nonlinear dynamics, particularly in econometrics. You'll find a chapter somewhere in the book that says that this may be a more realistic way of looking at economics, then it gives up rather quickly because it gets into mathematics that most people don't deal with, except in a rather elementary way. And the consequences of nonlinear dynamics in economics are so awesome that nobody can pursue them very far.

The basic premise in neoclassical economics is that you will achieve an equilibrium. But change the time scale and that's not necessarily the case. You achieve punctuation points, transitions and hesitations. If you want to talk about it from minute to minute—and that's important in the stock market—it may have long plateaus. Of course, by sensing those plateaus you might make a lot of money. But on the other hand, changing the time scale, if you're a long-term trader, it may look totally devoid of any plateaus. So, in fact, the measure of complexity must have an element of time built into it. You always have hierarchy in the reductionist scheme. I suppose in any scheme you have to talk about complexity arising from simple parts that aggregate into more complex parts, which in turn aggregate into even more complex parts, and so forth. The time scale changes at every level.

That tendency to aggregate applies to any complex system, from subatomic phenomena on up?

In physical science, you start with quarks, which may be made up of simpler parts. With quarks you build protons and neutrons and so forth. And when you go from the nuclear interactions we're most familiar with, you go from let's say 10^{-20} seconds to atoms and orbital electrons interacting with each other, to a time scale of maybe 10^{-10} or 10^{-12} seconds. Then when those atoms interact with one another and become complex proteins, you start to talk about biological reactions and change the time scale again, usually by several orders of magnitude. In mental processes, a typical relaxation time is 10^{-3} seconds.

When you aggregate all of these things into cells and organisms the time scale changes again. Now you have circulation and other mechanisms. Even neural impulses from the brain to the toe—these things can change again by orders of magnitude. You have action at a distance, so to speak, both mechanical and electrical, conveyed in ways that take time. And then you have social structures that aggregate living species—for people, the aggregations of course are families that aggregate into communities, communities aggregate into nations, and so forth. In the economic structure you have offices and branches and corporations and working aggregations of corporations and global economies. The whole question of evolution deals with still another time scale.

The relationship of the time scales is fundamental to how a complex system works?

I suppose that one way to talk about complexity is to talk about characteristic relaxation times. At every level of complexity things interact with one another on about the same time scale. But they also see things happening below them, which essentially bias the system. They look like noise; they average out because they're operating so fast that they look like a DC signal. Above them, they see things that are operating so much more slowly than they do that they serve as parameters. So on every level in complexity you're living on a common time scale horizontally, looking at something that operates much faster below you and at something that operates much slower above you. A lot of that has to do with the size of the system and the length of time it takes to convey information, the bit rate, or the entropy if you know how to measure it.

Something important that's happening now is that modern technology is screwing it up by speeding up the bit rate. Information is being transmitted from large units to smaller units, and vice versa, much faster than ever before—TV and 24-hour global satellite communication and visual information. We're saturating social organizations that are geared to processing information at a much slower rate. We haven't invented the structures that can manage that very well.

> "Science has reached the point where it can no longer simplify problems so that they don't resemble the real problem. As systems become complex they develop properties of their own. We have yet to successfully apply the reductionist technique in explaining complex systems in terms of their simpler subsystems."

How has that increased bit rate affected science?

It's permitted us to begin developing the science of complexity. You need large computers to do numerical simulations of high-dimensional problems. They don't have elegant solutions, and the larger the computer, the larger the ability to process information and acquire the data bases you need to do a numerical simulation that resembles reality. We still don't really know how to do it, but it's going to happen. Twenty years from now people will have really sophisticated means for handling large data bases and for letting the parts of highly complex systems interact with one another in ways that may resemble what actually happens. I suspect if we find general elements of a science of complexity, they'll emphasize feedback loops set up among the various parts, both amplifying and damping. Metastability can occur when these tend to balance out.

One of the most obvious loops is in economics—memory. People remember history and anticipate the future. If they feel that the future is going to be like the past, that's a negative feedback loop. They tend to retain the past history. If they feel for any reason the future is going to be different from the past, they behave in such a way as to affect the present. And that's positive feedback. They pop out of whatever basin or plateau they may be on. They may panic, they may become excessively greedy. If they become greedy you may have a boom, if they become panicky you have a crash.

How do you decide which loops to examine when you study a complex system?

When we talk about high levels of complexity we arbitrarily draw the boundaries. There's no natural boundary. Where you draw the boundaries of the system depends on how simple a view you want to take. You can keep enlarging the boundaries all the time. After drawing the boundaries, we usually say, well, we can't handle that, so let's constrain the system some more and see whether we can understand a simpler part of it. But when you reduce the boundaries, at least you know who your neighbors are. And if you start with a simple system you don't even know that. If you examine a larger system than the one you're eventually going to study, at least you know the neighborhood and you can hook up to it in an average way. But you shouldn't remain ignorant of the larger neighborhood, and you particularly shouldn't make a virtue of your ignorance of it, which is what a lot of people do.

Constraining the big picture to look at connections between particular neighbors seems like it would be tricky.

Well, that's why people don't generally do it well. We're talking about a whole new science and you don't achieve it by contemplating your navel overnight. What you try to do is define its general content, and then a lot of good people start to study it. If over the next fifty or hundred years it develops into something useful, it will be because of one hell of a lot of work. If anything I've said implies, "Eureka, we're going to understand complexity," that isn't so. What we're trying to do is establish complexity as a new science worth studying.

You've talked a lot about economics. Is that the most fruitful or promising topic for the study of complexity?

Well, I think it's possibly overly ambitious because if we stuck to the things that we know the most about, like fluid dynamics or cellular automata with fluctuations and errors or interactions with a stochastic external environment that pumps energy into them, they would represent the shortest extrapolations from what we think we know to what we don't know. And we would stop with simple protein dynamics, which is a reasonably well-thought-out, accepted field of research now, but not one people necessarily know much about.

And I suppose we should stop there. But the temptation to see in these life processes analogies with economic and social processes is very great. In fact once you start studying that kind of complexity you begin to see resemblances to larger organizations. And so very good economists are coming here, and we've begun to speculate together about economic processes.

There's a world out there which responds to the notion of new ideas about economics more quickly than to any of the other notions we're kicking around. So there are people who are prepared to support this new effort, and the Institute has moved more rapidly in that direction than caution might have indicated. It's a region in which we're all profoundly ignorant but one in which the payoffs could be big.

Also I have to admit I started out to be an economist so I have certain biases. As an undergraduate I paid more attention to those courses and less attention to physical science. I just found them in some ways more interesting, and I'm still kind of a closet economist.

"People will say you're talking about God or some aspect of nature that imposes order on complexity. Or does all the order arise internally?"

What's the relationship between complexity and the age-old attempts in physics to explain existence simply?

It's very interesting. If quantum fluctuations began the universe, it seems that rather than going to real simplicity, you re-enter a realm of complexity. I don't know whether you read the article by a Russian named Andrei Linde in Phys. Rev. last September called "Inflationary Cosmology." He says that there are many moments of beginning. The process can create a very large number of different universes. If, in fact, the expanding universe in that first moment can bifurcate many times and move into some part of an arbitrary, possibly infinite phase-space, you're back to the same philosophical question—what is the deep truth or is there any? So that's why I say I'm agnostic. It's not clear to me you can ever get back to a deep simplicity.

That reminds me of an ancient Hindu idea that the universe itself pulses, that it awakens and goes to sleep, and with every awakening there are new energies, forces, and natural laws, completely different from those of the previous awake state.

That's a theme that constantly recurs in philosophy. The major rationale of grand unification is that indeed you will grab the brass ring of simplicity. If that escapes people . . . in the end I don't know whether we'll find fundamental truth or have to admit that reality is a series of endless loops, that there's no bottom level in these hierarchal levels of complexity.

Meanwhile the physical scientist holds to the faith that simple components will be found at the bottom. And I don't think that's so bad. I mean everybody needs a working hypothesis.

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

Global Security

A World of Possibilities

SFI has scheduled an informal meeting possibly this fall as the first step in organizing an interdisciplinary research program on global security.

George A. Cowan, SFI President, said approximately 30 scholars, scientists, and public and corporate leaders would be brought together under the auspices of SFI and the Center for National Security Studies at Los Alamos.

"Our primary objective in this initial meeting," Cowan said, "is to create an agenda and to formulate a list of participants for a full-scale meeting on the dynamics of global security to be held next year."

"This is the start of a continuing research program designed to involve a number of different disciplines, at many existing centers, in all of the major elements of global security."

Cowan said that, for purposes of this discussion, the meeting would measure global security in terms of the avoidance of catastrophic war, consistent with preservation of widely held human values, and without primary dependence on deterrence by nuclear weapons or other military means of mass destruction.

The initial elements of such a global security system slated for discussion include: national and supranational governments, including their military components; economic and industrial organization and market and distribution mechanisms; environment, ecology, climate and exhaustible resources; human behavior and society; information and misinformation; and the contributions and problems stemming from science and technology.

Residential Research

Gottfried Mayer-Kress

Gottfried Mayer-Kress of the Center for Nonlinear Studies at Los Alamos National Laboratory and Psychiatry Department, University of California at San Diego, is a visitor at the Institute throughout the spring and summer of 1988. Dr. Mayer-Kress' broad research interests within the area of nonlinear dynamical systems are reflected in the variety of his current scientific collaborations which range from problems in visualization and model simulation, dimensional analysis of human electro encephalograms (EEG's), dimension distributions for different galaxy clusters, to work on speech recognition and nonlinear dynamics.

Here he describes his current work on global stability at SFI, along with some personal background about the pathway to his study of complex systems.

In my former life I worked in the relativistic quantum field theory of elementary particle physics, where all scales are incredibly remote from our own life. However, my Ph.D. work was in the field of synergetics (with H. Haken in Stuttgart) and there the situation was quite the opposite from the ivory tower of DESY (the German electron synchrotron accelerator). Although Haken's institute was an institute for theoretical physics, visitors often wondered why people were working on problems which ranged from galaxy formation, laser theory and fluid convection to problems of brain mappings and the evolution of public opinions. During that time, I gained an appreciation for the nonlinear paradigm and its universal (or at least planetary) manifestations. Today I enjoy working in interdisciplinary collaborations on problems in the natural sciences, medicine, and international security.

Global security is certainly one of the most important, fuzzy, soft, and complex problems we are facing today. It is very tempting to put this global system into a theoretical box and play with it on the computer. Yet there are many problems which have to be addressed if one doesn't want to repeat the mistakes of previous attempts.

Probably the first scientist who thought about deriving mathematical equations for modeling the interactions between nations involved in an arms race was L. F. Richardson, whose main scientific work was in atmospheric turbulence theory. He used ordinary differential equations of motion for describing the interaction between nations. This approach has been challenged. A mathematician would argue that decisions about armaments are not made every picosecond, so they do not constitute a continuous process in the strict mathematical sense. However, we physicists are never really bothered by what mathematicians tell us, especially when it is a proof that something is not allowed or does not exist. The question is, why does one want to make this idealization? Historically the answer is clear: Leibniz and Newton didn't have SUN workstations on their desks and so they had to (a) restrict themselves to simple

Gottfried Mayer-Kress

(mainly linear) systems and (b) invent calculus, in order to find some nice closed-form expressions for processes which would involve infinite iterations.

Today, however, the situation is different. First, the SFI has several SUN workstations, and the problems which want to be solved are intrinsically nonlinear with no hope of any meaningful closed-form expression which would fit on a sheet of paper. Now we are in a situation where the assumption that we are actually performing an infinite number of iteration steps is much more justifiable than some kind of approximate closed-form solution. For example, the SUN workstations can be used to generate fractals (see front cover) which represent a complex system in a visual form.

S. Grossmann and I have generalized Richardson's original model and included nonlinear economical saturation effects together with a discrete-time dynamics. In that paper we also lay out some basic

In a model of a frictionless pendulum driven by an external force, the system diverges along fractal lines to infinity. Basically all complex nonlinear systems under the influence of external stress (like the international arms race models) can show this sensitivity to rapid destabilization and complex divergence to unbounded behavior. The path of the system is three dimensional (above). The front cover shows a computer-generated two-dimensional slice in which each dot represents the intersection of the system path with the plane of the slice. Whereas a three-dimensional picture shows the full continuous flow, the two-dimensional picture plots a cross-section which makes it possible for the same amount of computer time to trade about 50 to several hundred times as many datapoints.

facts of nonlinear dynamical systems and how they might affect our understanding about the interactions among nations. In another more detailed and specific model (again discrete and nonlinear), we simulate in an artificial scenario how the introduction of a new weapons system (SDI) might influence the arms race between superpowers.

Systems dynamics engineers have developed refined methods of analyzing the interactions and influences within large complex systems like international political constellations. But they treat the dynamical system as a black box which automatically takes care of intermediate mathematics. I find it surprising that systems dynamics today uses the same traditional scheme that Richardson used in the twenties, that is ordinary differential equations. This method introduces a new, very nonintuitive and uncontrollable parameter, namely the step size of the integrator. It typically is set to be "small enough" which means that the computation time for simulating the system is very long and the control over the simulation is very low.

I'm working on this problem with R. Abraham at UCSC, G. Tsironis at UCSD, and Andy Ford from USC. We're optimistic that through the introduction of properly designed discrete models, we can increase considerably both the accuracy and speed of a simulation model. We also plan to compare these models with classical models of systems dynamics. In a first step we want to apply this method to a system of three interacting nations and try to verify the (non-mathematical) theory of Ken Waltz of UC Berkeley in which the interaction of more than three nations leads to a rapid increase of crises and complexity of the interactions.

A very important aspect of modeling complex systems is sensitivity analysis. In March of this year I collaborated with Ute Dressler, a Ph.D. student from the University of Göttingen, who was also in residence at SFI. We worked on mathematical and numerical methods which allowed us to describe the sensitivity of the state of a model during the time evolution. It appears to be a very typical feature for nonlinear dynamical systems that the time evolution is very nonuniform, that epochs of regular dynamics with very robust responses alternate with turbulent epochs with a high degree of local chaos in which small perturbations can be dramatically amplified, sometimes leading to transitions to qualitatively new states. I think that in any kind of global model it is important to be able to analyze and predict "critical areas" in which little causes might have very large effects. This work is closely related to the work on prediction and forecasting done in Doyne Farmer's group, to projects on multi-photon absorption in Peter Milonni's group and to Yannis Kevrekidis' work on nonlinear control problems in chemical reactors.

— G. Mayer-Kress

ELEMENTS OF FRACTALS

The term was introduced in 1975 by B. Mandelbrot, without precise definition, to describe the very intricate and self-similar nature of the complex patterns he was studying. It has come to refer to an idealized mathematical concept to which snowflakes, clouds, coastlines, etc. provide a physical approximation. Among the shared features are:

Complexity: Fractals possess intricate structure on all scales.

Self-similarity: Small regions, when magnified, are reminiscent of the whole object. In the idealization this self-similarity is recurrent on all scales of magnification.

Fractional dimensionality: Examples can be constructed by a mathematical procedure of removing increasingly larger numbers of increasingly smaller pieces of an object in such a careful way that, as the process increases without limit, something of the object remains, but it is full of holes on an arbitrarily small scale. If the original object was three dimensional, what remains may have a dimensionality, in a technical sense, that is somewhere between an area and a volume.

The Economy as an Evolving Complex System

An Emerging Paradigm

A full-scale research program to consider the economy as an evolving complex system is underway at the Santa Fe Institute. The program has three parts: a research network of scholars working off-campus from SFI on individual or small collaborative projects; a residential research effort involving more than a dozen scholars on hand at the Institute throughout 1988 and 1989; and an annual September workshop in Santa Fe which brings the residential and network researchers together to discuss current work.

The Beginnings

The program is an outgrowth of the highly productive SFI workshop *Evolutionary Paths of the Global Economy* held in 1987. During that program economists and natural scientists began efforts to apply to economics methods of nonlinear dynamics that have proven useful in the study of similar complex problems in physics, computer science and theoretical biology. The 1987 workshop as well as all ongoing activities are funded by the Russell Sage Foundation and Citicorp. Additional support for future activities will be provided by SFI core funding from the Department of Energy and the National Science Foundation.

Collaborations

Several research collaborations have been in place since last September's meeting. John Holland's report in this issue on the current work of the "Webs" research network discusses two approaches that will be major concerns of the SFI research program in the coming year: consideration of the economy as an adaptive evolving system or ANN, and focus on the evolution of economic structure.

Theories that assume full rationality of economic agents and perfect foresight are capable of producing elegant "solutions" to complex economic problems. But these solutions are often far from observed behavior, especially when the problem environment is changing. Holland and others are working on an approach that views agents as operating with less than perfect rationality, acting on the basis of simple rules and with limited look-ahead ability. These rules, and agents' sophistication, evolve as problem-solving experience is gained. From a formal point of view, an economy so-described is an example of an *adaptive nonlinear network* (ANN).

> *"With the researchers the Institute is bringing to Santa Fe, the program ought to be very productive, at least in the long term. SFI is well positioned for an extremely challenging, but rewarding task."*
>
> — W. Brian Arthur

The Evolving Economic Structure

The evolution of economic structure presents interesting questions. While fundamental economic needs may stay much the same, the network of activities that fulfills them changes constantly, and at any time it must be consistent both technologically and economically. How, precisely, do economic networks evolve? Under what conditions do they increase in complexity? How do clusters of economic activities co-evolve? How is the stability of economic networks affected by their complexity? These questions have obvious counterparts in the biological theories developed by Stuart Kauffman to study the evolution of networks in living organisms from simple chemical components. Also related is the work of Paul Romer and others on the increasing specialization of firms within industries as volume grows. This is a form of biological "speciation" in economics and suggests a comparison of the evolution of economic structure with corresponding theories in biology.

Brian Arthur of the Food Research Institute and Economics Department at Stanford University is coordinating SFI's

OVERLAPPING GENERATIONS MODEL

To consider how consumers make investment vs. purchase decisions, economists have developed models which attempt to achieve a well-specified objective based on given or expected prices and resource constraints. Michele Boldrin explains, "The simplest framework is provided by a model of overlapping generations with constant population . . . a representative agent per generation" and an externally determined supply of a consumption good.

Rather than observing the actions of a single group of economic agents over time, this model sets separate consumption rates and goods for each group of agents, such as "youngs" and "olds." Each representative agent has a lifetime utility function or earning power.

In one version of this model, youngs can either save or borrow. They may carry claims or debts into the future, usually through money assets like a checking account. Two scenarios are possible—one where the youngs are impatient and borrow from the olds, and the opposite scenario. Which is more likely to occur is based on the consumption of a representative when he is young compared to when he is old, and the comparison of youngs' consumption to olds' consumption.

For a more complete discussion, see Boldrin's chapter in *The Economy as an Evolving Complex System.*

residential economics research. Beginning June 1988, Arthur will be in residence at SFI for fifteen months. During the next year and a half he will bring senior faculty and postdoctoral researchers to SFI to work with each other and with collaborators linked to the Institute by electronic communication and frequent visits. "With the researchers the Institute is bringing to Santa Fe," says Arthur, "the program ought to be very productive, at least in the long term. SFI is well positioned for an extremely challenging, but rewarding task."

Professor Arthur's current research interests coincide with the third area of emphasis of the SFI economy program, the nonlinear phenomena of cumulative causation or increasing returns. Where learning effects or "increasing returns" occur in the economy, positive feedbacks or nonlinearities are introduced. Products, firms, or regions that have initial success tend to gain further advantage. Multiple market-share outcomes may be possible, but early "random" events decide which outcome will prevail. Which market-share outcomes or long-run economic configurations are possible in a given problem? How is one of these dynamically "selected"? Under what conditions is "competitive exclusion" (one product or firm or region dominates in an industry) inevitable? Answers here are important for understanding how technology patterns, locational patterns, institutional arrangements and market-share patterns are "selected" and lock-in at various levels in the overall economy. To the degree that speculators in securities markets follow other speculators, in that their expectations of profit increase with upward movements in the market, positive feedbacks may be present, creating booms and collapses largely independent of the health of the rest of the economy. Nonlinear dynamics and the theory of punctuated equilibria may be useful in formulating and testing models of the actual, rather than the ideal, behavior of securities markets.

POSITIVE FEEDBACK

Positive feedbacks, or nonlinearities, within the economy mean that products, firms or regions that have initial success tend to gain further advantage. In the video market, for instance, a small lead in the market share gained by one technology may enhance its competitive position and allow it to further increase its lead. Eventually it may be that one of two competing video systems takes 100% of the market, but one cannot say in advance which one this will be. There are two possible outcomes or long-run steady-states possible for this market. There is no guarantee that the better outcome—the more efficient video technology—will dominate. An early run of chance events may give the inferior system sufficient advantage to take the market. And once the market is taken over by one video system, it is difficult to restore a shared market.

Looking Ahead

These issues and others will be the focus of a ten-day meeting in September, 1988. Members of the 1987 workshop, as well as new members of the SFI residential and off-campus research networks, will come together to summarize recent work, exchange ideas, and refine and possibly redirect their research efforts by means of new homework assignments. "We envision the meeting to be a continuation of last year's dialog as well as a kick-off of the residential research program," says David Pines, SFI Science Board Co-Chairman and convenor of the workshop. The workshop is once again co-chaired by Nobel laureate physicist Philip Anderson, Princeton, and Nobel laureate economist, Kenneth Arrow, Stanford University.

It is anticipated that the 1988 workshop will result in a proceedings volume as did the 1987 meeting on the global economy. Last year's work is contained in *The Economy as an Evolving Complex System*, available from SFI and Addison-Wesley this summer. In addition to the proceedings volumes, articles presenting current work should be coming out throughout the year.

— G. Richardson

ECONOMICS VISITORS

Beginning June 1988 scholars will be present at SFI as part of the Institute's resident research effort on the economy as an evolving complex system. Not only will senior scientists be involved, but, as part of SFI's active commitment to graduate education, postdoctoral fellows will be in residence as well. All in all more than a dozen researchers will be on hand for varying times as part of this program. They include:

Kenneth Arrow, Economics, Stanford University

W. Brian Arthur, Food Research Institute, Stanford University

Robert Axelrod, Political Science, University of Michigan

William Brock, Economics, University of Wisconsin

Yuri Ermoliev, Glushkov Institute of Cybernetics, Kiev

Frank Hahn, University of Cambridge

John Holland, Computer Science, University of Michigan

Yuri Kaniovsky, Glushkov Institute of Cybernetics, Kiev

Stuart Kauffman, Biochemistry/Biophysics, University of Pennsylvania

David Lane, Statistics, University of Michigan

V. Mikhalevich, Glushkov Institute of Cybernetics, Kiev

John Miller, Santa Fe Institute

Richard Palmer, Physics, Duke University

John Rust, Economics, University of Wisconsin

Thomas Sargent, Hoover Institution, Stanford University

The Economy as an Adaptive Nonlinear Network

The "webs" group was one of the working subgroups of the 1987 workshop *Evolutionary Paths of the Global Economy*. Our group's members are Brian Arthur, Stanford; John Holland, Michigan; Stuart Kauffman, Pennsylvania; Tim Kehoe, Minnesota; Norman Packard, Illinois; Richard Palmer, Duke; John Rust, Wisconsin; Tom Sargent, Stanford; and Eugenia Singer, Citicorp. This group based its approach on the observation that, at least formally, one can extend many well-known economic models by replacing fixed, perfectly rational agents with agents characterized by limited rationality and the ability to learn, who are engaged in nonlinear interactions. There is reason to hope that some features of real economies, not well predicted by the standard models, will yield to these revised models.

Adaptive Nonlinear Networks

We met at the Santa Fe Institute in March, 1988, to pursue this line of inquiry. A model economy, when comprised of adaptive agents of limited rationality, is a particularly rich example of an *adaptive nonlinear network (ANN)*. *ANN*s exhibit behaviors substantially different from those predicted by models based on traditional mathematical tools, such as linearity, fixed points, and convergence. For example, because of the complexity of the interactions and the constantly changing structure produced by adaptation, an *ANN* typically operates far from any attractor. As a consequence of these features improvement is always possible (for example, technical innovation), and the system is faced with perpetual novelty. *ANN*s almost always develop internal structures, sets of *operating procedures*, that enable them to anticipate some changes and avoid large mistakes.

Even the most "centralized" versions of these systems depend upon the anticipations and localized interactions of a variety of agents, each having a limited view of the system as a whole. The resulting behavior is much more subtle, and often more varied, than one would expect using more traditional models. Reactions to major changes may lag substantially behind the changes themselves (for example, over-extension of credit), or anticipations that eventually fail may still divert the system in unexpected directions (for example, speculation "bubbles"). In some situations a local competitive equilibrium may be attained with amazing speed, yielding the self-stabilization expected under traditional models, while in others the system remains "off-balance" over extended periods. At a deeper level, there is a continuing tradeoff between exploitation (using what is known, often with increasing returns rather than returns to scale) and exploration (searching for improvements). With the help of the emphasis on adaptive, nonlinear interactions provided by *ANN*s, we hope to come to a better understanding of the options and forces associated with these economic phenomena .

Science Board members David Campbell and Marc Feldman with Global Economy workshop participants Richard Palmer and Norman Packard.

DOUBLE ORAL AUCTION

A double oral auction is a type of trading institution used by the New York Stock Exchange and by many other securities and commodities exchanges. Buyers and sellers are simultaneously able to call out an offer to buy (a bid), or an offer to sell, or an acceptance of the lowest outstanding bid. The rapid flow of information and the ability of traders to undercut instantly an existing bid or offer makes the double oral auction a close approximation to the economists' notion of a *perfect frictionless market*. It has been extensively studied, both theoretically and in simulations by economists and others.

Application to Economics

To test these ideas, we developed three inter-related approaches during this meeting of the subgroup:

The first approach substitutes limited agents that learn and adapt for the *perfectly rational* agents usually used in economic modeling. Our object is to understand the way in which limited agents modify the solutions for well-known models such as the *double oral auction* and *overlapping generations* models. We start with Axelrod's studies of adaptive agents in the context of the *iterated prisoner's dilemma* game. Actual play of the iterated prisoner's dilemma, as well as play using simulated adaptive agents, provides high-utility cooperative play in contrast to the low-utility minimax solution provided by game theory. Multi-nation versions of the overlapping generations model provide a similar context. Nations can implicitly tax agents in other nations by "printing money," leading to a low-utility solution wherein money is worthless. It is proposed that adaptive agents of limited rationality will avoid such "solutions" in much the same way that the simple limited strategy *tit-for-tat* prevails in the prisoner's dilemma and avoids the low-utility solution. We propose to run a tournament, much like Axelrod's tournament for the prisoner's dilemma, in the uncomplicated context of the *double oral auction*. We hope to find simple, limited strategies that provide the rapid convergence to market equilibrium observed in actual play of the game. If these hopes are borne out, we will then proceed to successively more intricate versions of the *overlapping generations* model.

The second approach builds on a variety of models of physical systems having many stable points sensitive to initial conditions. Cellular automata and spin glasses are such models. Economies contain a variety of positive feedback loops that yield multiple market equilibria, and many theories relevant to economics, such as general equilibrium theory and game theory, exhibit multiple solutions. It is a matter of considerable interest to know how "real" systems select from among the options available. Economic models such as *Wicksell's triangle*, a model for the emergence of commodity money in barter situations, where participants produce one commodity and consume a different one, may provide a useful context in which to test ideas about the way in which limited adaptive agents determine the selected solution.

"With the help of the emphasis on adaptive nonlinear interactions provided by ANNs, we hope to come to a better understanding of the options and forces associated with economic phenomena."

—John Holland

The third approach aims at understanding the evolution of complexity in highly interlinked parts of the economy. The challenge here is to translate ideas that have proven useful in the study of biological interactions, such as the notion of a "rugged adaptive landscape," into a form that has precise economic meaning and is accessible to simulation. This approach is at a much earlier stage in its formulation than the other two approaches, but offers substantial wide-ranging insights if it can be brought into contact with established economic models.

THE PRISONER'S DILEMMA

Two prisoner's are being interrogated in separate rooms concerning a crime they have allegedly committed. Each has a choice between informing on the other prisoner ("defection") or else remaining silent ("cooperation"). If both remain silent, then both go free; if one informs and the other remains silent, then the informer receives an informer's fee and goes free, while the other prisoner is imprisoned and fined (to cover the informer's fee); if both inform, then both are imprisoned (but there are no fines).

In the formal minimax solution, if each prisoner tries to minimize the maximum damage that can be imposed by actions of the other prisoner, then defection is the indicated action. Accordingly the formal solution is that both prisoners defect.

However, the observed (experimental) outcome is, when the game is played repeatedly by the same two players (the *iterated prisoner's dilemma*), players typically learn to cooperate after a time.

The best outcome a player can attain occurs if that prisoner defects while the other prisoner does not. This, together with the fact that defection minimizes damage if the other prisoner does defect, makes it very tempting to defect. How is it, then, that the prisoners learn to cooperate?

One individual strategy in the Prisoner's Dilemma that induces cooperation simply copies on the next move whatever the other player did on the current move, or *tit for tat*. Under this strategy, if the other player begins to cooperate over some extended period, then the *tit-for-tat* player will also cooperate, while a defection by the other player is punished by the *tit-for-tat* player on the next move. If both players adopt a *tit-for-tat* strategy after a mutual cooperation, then cooperation will continue as long as they both hold to this strategy. It has been shown by Axelrod in computer tournaments that *tit for tat* prevails over all strategies submitted; Axelrod also demonstrated that a *genetic algorithm*, when used as a learning technique, can discover strategies that are better than *tit for tat*.

— J. Holland

Reference: Axelrod, R., "The Evolution of Strategies in the Iterated Prisoner's Dilemma," *Genetic Algorithms and Simulated Annealing*, Ed. L. Davis (Los Altos, CA: Kaufman, 1987).

Prognosis

If all goes well, we will be able to weave the individual projects into a broad fabric that suggests an expansion of outlook in economics—one in which theorems based upon the competition of limited agents provide an understanding of some of the departures of real economic activity from the predictions based on perfect rationality. The most important result would be an understanding of the behavior of systems, economic and otherwise, under conditions where improvement is always possible.

In any case, the results of our tournament(s) should move us toward more realistic assessments of the effects of limited rationality, even if the interwoven fabric is a long time coming. There should be immediate benefits, akin to those produced by Axelrod's evolutionary studies of strategies for iterated play of the prisoner's dilemma, wherein the origin and persistence of strategies other than the devastating single-play minimax strategy becomes clear.

— John Holland

1988 Science Board Actions

At its annual meeting in March, the Science Board of the Santa Fe Institute, co-chaired by Murray Gell-Mann and David Pines, had a very full agenda. The Board discussed in detail the reports on the Theoretical Immunology Workshop, the Matrix of Biological Knowledge program, and the program on the Economy as an Evolving Complex System. All three have led to continuing activities which are discussed in separate articles in this issue.

The Board reviewed eighteen proposals for workshops and research programs to be undertaken in 1988 and 1989. Fifteen were approved and the Board made recommendations to the President on the funding of each. In addition, the Board strongly urged that funds be set aside for a vigorous program of visiting scientists as well as for postdoctoral appointments.

The Physics of Information, Entropy, and Complexity

Wojciech Zurek, Los Alamos National Laboratory

Quantum theory of measurement, physics of computation, many of the issues of the theory of dynamical systems, and much of the foundations of statistical mechanics share information as a common theme. This program will consist of a workshop on the interface of physics and information and a network to establish collaborations. Topics to be included are thermodynamic and information-theoretic entropy, quantum measurement theory, algorithmic complexity, and others.

Modeling the Relationship of Human Cognition with Emotion

David Rumelhart, Stanford University
Jerome Singer, Yale University

This workshop will bring together empirical researchers and theorists to address potential approaches to the links between models of human information processing and cognition on the one hand and human emotional/motivational responses on the other. Clinical and experimental studies of thought and memory, theories of artificial intelligence, studies of memory, psychoanalytic theories, studies of neural nets and parallel-distributed processing, neuroscience, and hormonal theories related to the central nervous system will all be components. Ultimately the aim is to tie modeling principles in natural science and biology with such an effort in behavioral sciences.

Proteins, Glasses, and Spin Glasses

Hans Frauenfelder, University of Illinois

Proteins, glasses, and spin glasses all have a highly degenerate groundstate. Crucial aspects of their dynamics are similar: relaxation is nonexponential in time, nonergodicity sets in below a certain temperature, and the energy landscape appears to possess a hierarchical organization. Theory is most advanced in spin glasses, the largest body of experimental data exists for glasses, and the most sophisticated experimental information can be obtained in proteins. This workshop will explore the connections, similarities, and differences in the dynamics of the three systems. Experimentalists and theorists from the three fields will explore the energy landscape of typical systems, discuss the existing experimental data, and propose new experimental and theoretical approaches.

(continued next page)

March Science Board meeting: from left to right, Kenneth J. Arrow, Alan S. Perelson, Theodore Puck, David Campbell, George A. Cowan, Edward Knapp, David Pines, Murray Gell-Mann, Hans Frauenfelder, Darragh Nagle, Stuart A. Kauffman, Marcus W. Feldman, John H. Holland, David E. Rumelhart, and W. Brian Arthur.

Pueblo Archeology and the Natural Sciences

Murray Gell-Mann, California Institute of Technology
Douglas Schwartz, School of American Research

What was the nature of the instabilities that led to the successive failures of particular Pueblo cultures in the U.S. Southwest while others survived? An exploratory workshop will bring together archeologists, scientific experts from fields such as holocene geology, radiochemistry, dendroclimatology and paleobotany, and complex systems theorists to consider this question.

Public Policy Studies

Murray Gell-Mann, California Institute of Technology

One or two short exploratory workshops are planned on how policy studies can be improved when they are concerned with values difficult to quantify, such as ecological and social values, and when conditions are changing and uncertain. The workshops will study how to seek better quantitative surrogates for soft but important values, and how to utilize multi-dimensional computer displays to present the consequences of policy options, with their uncertainities, for different sets of values.

The Evolution of Human Language

Murray Gell-Mann, California Institute of Technology
Jack Hawkins, University of Southern California

This workshop will consider issues relating to the origin and evolution of human language. It will include experts from various branches of linguistics, including neurolinguistics and psycholinguistics; they will be joined by specialists in cultural anthropology as well as human evolution and other parts of biology. Possible themes to be addressed include language universals, genetic groupings of languages, aspects of historical linguistics, pidgins and creoles, biology and the evolution of language, neurolinguistics, and human evolution and cultural anthropology.

Global Security

George A. Cowan, Santa Fe Institute

This program is described in a separate article on page 9.

Applications of Chaos to Prediction

Doyne Farmer, Los Alamos National Laboratory

This research will consider an appropriate economic time series—for example, commodities data, the GNP, or interest rates—to determine whether low-dimensional chaos may exist in such a series. A hint that chaos may be relevant exists in work by Scheinkman and Le Baron, Brock and others which suggests that economic time series deviate from the usual "random walk" model. That chaotic models can be useful for predicting the future of time series is given in the work of Farmer and Sidorowich. Stephen Pope will be working with Farmer on this project.

Interaction of the Immune System with Human Immunodeficiency Virus

Alan S. Perelson, Los Alamos National Laboratory

This program is described in a separate article on page 18.

Computer Science and DNA Sequencing

George Bell, Los Alamos National Laboratory

DNA sequences are being determined at an increasing rate and are leading to new insights into biological systems and function. This workshop will bring together experts in the analysis of sequences with innovators in computer science to discuss the requirements for handling this growing body of information.

Adaptive Networks

Alan Lapedes, Los Alamos National Laboratory

Rather than treat one kind of adaptive network, researchers of neural networks and rule-based systems will discover and combine the best features of these and other machine learning/adaptive net approaches in order to develop testbed problems to determine where each method is successful or breaks down.

Applied Molecular Evolution

Stuart Kauffman, University of Pennsylvania

This program and its connection to the following one are described in the article on page 17.

Maturation of the Immune Response

Alan S. Perelson, Los Alamos National Laboratory

This program grows out of the 1987 conference on theoretical immunology and is discussed, together with the related program above, in an article on page 17.

Integrative Workshops

Murray Gell-Mann, California Institute of Technology
David Pines, University of Illinois

This workshop will bring together key participants in other programs and workshops, and will focus on the common threads of complexity running through the various programs and the overarching themes of the Santa Fe Institute.

The Matrix of Biological Knowledge

Focusing on Practice and Problems

The 1987 workshop, "Matrix of Biological Knowledge," has been a catalyst for a least two projects, both focusing on practical implementation of the matrix concept, each at a different lab. The "matrix of databases" seeks to establish a framework of information encompassing all of biology.

Establishing Connections Among Hierarchies

One study, headed by Dr. Temple Smith at the Dana Farber Cancer Institute at Harvard University and Walter Fitch in the Department of Biology at the University of Southern California, seeks to establish connections between diverse biological knowledge through comparison of various developmental, molecular, and phylogenetic hierarchies.

Within biology there are a number of important hierarchies often expressed as dendrograms, or diagrammatic trees. Perhaps the most obvious example is the evolutionary relationships among organisms. Other examples are the cellular lineages of embryos and the biological function of hormones. There is a wide range of "molecular signals" that can probably be hierarchically classified. This project will develop methods for discovering relationships between these different hierarchies by describing each of them as dendrograms and then comparing the numeric and geometric properties of these representations.

Some of the developmental cell lineages that will be entered for comparisons will be the complete embryonic lineage of the nematode *C. elegans*. These developmental dendrograms will be compared with molecular dendrograms of the sequence relationships between families of peptide hormones. There is growing evidence that peptide hormones are major developmental signals which help establish cell fates, so there may be a causal relationship between the evolution of certain peptides and patterns of cell lineage. Finally, these dendrograms will be compared with

Applied Molecular Evolution and Maturation of the Immune Response

Two recent efforts by members of the Santa Fe Institute Science Board are expected to lead to an important conference this fall.

One theme grows out of an application to the National Science Foundation to create a Center for Applied Molecular Evolution focused at the Santa Fe Institute. This effort, led by Board member Stuart Kauffman, has identified twenty molecular biologists, immunologists, physicists, and instrument design experts from major institutions in the United States and abroad who are in the early stages of developing the capacity to use recombinant DNA techniques to create literally billions of novel genes and proteins, then utilize biological screening or selection techniques to identify biomolecules of potential medical or basic scientific interest. Among those interests are the development of new drugs and vaccines.

The second theme grows out of a recent conference on theoretical immunology hosted at the Santa Fe Institute in June of 1987, and organized by Board member Alan S. Perelson. This conference resulted in a two-volume publication, *Theoretical Immunology*, in the Santa Fe Institute series Studies in the Sciences of Complexity.

Common to both themes is the realization that the historical evolution of proteins capable of specific catalytic or binding activities has occurred on a more or less mountainous "fitness landscape" in "protein space." But it is also true that during the immune response a rapid evolution occurs within the body. During this evolution B lymphocytes, which secrete antibodies, undergo a mutational process, called somatic hypermutation, in which the genes coding for antibody mutate at a rate six orders of magnitude faster than other genes. B cells that secrete antibodies of higher affinity for the immunizing antigen are selected for growth by a close cousin of Darwin's natural selection called clonal selection. Such adaptive evolution of the immune response also seems to climb toward the adaptive peaks of rugged "fitness landscapes."

The concept of rugged fitness landscapes, pioneered in part by Santa Fe Institute Board member Manfred Eigen and discussed by him in *Emerging Syntheses*, the first volume of the SFI series, has recently become an area of intense theoretical work. The conference is expected to focus on experimental means to generate, test, and evolve novel proteins on a massive scale; means to understand the structure of the fitness landscapes upon which proteins in general and antibody molecules in particular, evolve and adapt; and finally to understand in detail the somatic evolutionary processes governing the operation of the immune system.

— S. Kauffman & A. Perelson

Focusing *(cont'd.)*

phylogenetic trees to see if there are patterns to the sequence of evolution of certain lineages.

This approach embodies one of the main goals of the Matrix workshop, to find new connections between biological knowledge by examining the structure of that knowledge.

Managing Diverse Data in a Research Environment

A second project, headed by Samuel Ward at the Embryology Department at Carnegie Institution, focuses on the practical problems of managing diverse kinds of data in a working research environment. It addresses a major problem discussed at the 1987 Matrix workshop, namely, how to relate different kinds of data such as pictures and text.

The plan is to use Hypercard, a new programming environment developed for the Apple Macintosh to create a data management program that allows easy entry of and access to textual, numeric, graphic and pictorial data which are linked by many kinds of relationships. Hypercard databases or "stacks" will store information such as descriptions of genetic mutant stocks and individual mutations. Such a stack could be connected to another stack of electron microscope photographs, to one of autoradiograms, and to another of experimental results. The stacks might then be arranged so that with the push of a button, one could move from a description of a particular gene stock to a representative micrograph, an autorad, a complete stock history, a list of literature references or a map of its storage location.

The program will be distributed at nominal cost to any interested user.

— G. Richardson

CNLS & SFI Joint Workshop on HIV

The Santa Fe Institute and the Center for Nonlinear Studies, Los Alamos National Laboratory, plan to jointly sponsor a workshop in late September on the Interaction of the Immune System with HIV. HIV (Human Immunodeficiency Virus) is believed to be the cause of AIDS. Before effective therapies for AIDS can be designed one needs to understand how HIV causes immunodeficiency and if parts of the immune system remain sufficiently intact so that they can be used to combat the virus.

Mechanisms of Pathogenesis

The workshop will focus on discussing the mechanisms of pathogenesis, i.e., the actual means by which the virus causes disease. There are many leads from test-tube experiments. T4 cells (helper T lymphocytes) play a primary regulatory role in the immune response. The loss of these cells in patients with AIDS correlates with the onset of symptoms. Interestingly, however, only one in ten thousand T4 cells seem to be infected with the virus and yet during the course of the disease a majority of the T4 cells within a patient may be destroyed. Quantitative issues thus become important. How fast are T cells regenerated in the bone marrow, how many are killed by virus, how many might be killed by other mechanisms? For example, it has been postulated that the virus may subvert the immune system so as to cause autoimmune disease in which the immune system itself kills uninfected T4 cells. If this is the case, boosting the immune system by vaccination could cause more harm than good.

Experimentalists Quiz Theorists

The workshop will bring together laboratory experimentalists and theorists interested in developing quantitative models of the immune system and HIV infection. Much theoretical effort has been focused on understanding the epidemiology of HIV infection, but until now little theoretical attention has been given to understanding the effects of the virus on the immune system.

Current Knowledge

During the course of the workshop we plan to review the current state of knowledge about HIV, its mechanism of infecting cells, and its mechanism of replicating within cells.

We also will examine other retroviruses to bring to light what is special about HIV in its interaction with the immune system.

Then we will focus on summarizing our current understanding of the effects of HIV on the immune system—its ability to infect T4 cells and macrophages, the role of antibody directed against HIV in eliminating the virus and its potential role in generating autoimmune disease and enhancing the virus' ability to infect cells.

Lastly, we will develop a flow chart showing the events that occur from the time a virus enters the body until the time that it kills a patient. Various entries in the chart about which we know little will be modeled as "black boxes."

Breaking up into small working groups we will then try to develop quantitative models of various aspects of the disease process, focusing on points in the chart where quantitative issues are important or points at which theory may help open some of the black boxes.

— A. S. Perelson

1988 Complex Systems Summer School

The Santa Fe Complex Systems Summer School, the first intensive graduate summer program in the nation offered on the sciences of complexity, takes place June 13 to July 8, 1988 in Santa Fe. Sponsored by the the Santa Fe Institute, the Center for Nonlinear Studies at Los Alamos National Laboratory, the University of Arizona, University of Illinois, University of New Mexico, and University of Texas, the month-long school will be at St. John's College.

The 1988 Complex Systems Summer School is supported by the Department of Energy, Research Corporation, the Alfred P. Sloan Foundation, and its sponsoring institutions.

Sponsorship and administrative support for the school marks SFI's increasingly active commitment to graduate education in the sciences of complexity. "We anticipate that the summer school will become an annual event, most probably scheduled in connection with shorter winter schools on specialized topics," says L. M. Simmons, Jr., SFI Vice-President for Academic Affairs. "The summer and winter schools, together with postdoctoral residencies and SFI's publications, are evidence of our development toward a full-scale graduate education center."

One result of the school will be a book available late Spring, 1989. The contents will aim at defining the field as it stands, determining future research directions, and aiding active research. Since the school will exist on a continuing basis, such annual proceedings may become a standard reference for the developing sciences of complexity.

A Nation-Wide Effort

"The school is part of a nation-wide effort to promote our understanding of nonlinear complex systems," writes Director Daniel Stein of the Physics Department at the University of Arizona.

> *"The school is part of a nation-wide effort to promote our understanding of non-linear complex systems."*
>
> — Daniel Stein

"It will focus on problems from fields as diverse as chaos, statistical mechanics, biology, chemistry, computer science, psychology, and economics. Many of these problems involve highly nonlinear systems, either deterministic or probabil-

Summer School Staff

GUEST LECTURERS:

Doyne Farmer
Los Alamos National Laboratory
Ziaul Hasan
University of Arizona
Erica Jen
Los Alamos National Laboratory
Y. C. Lee
Los Alamos National Laboratory and University of Maryland
Bruce McNaughton
University of Colorado, Boulder
Richard Palmer
Duke University
George Papcun
Los Alamos National Laboratory
Rick Riolo
University of Michigan
Elizabeth Ann Stanley
Los Alamos National Laboratory

FACULTY:

Experiments on Hydrodynamic Instabilities and the Approach to Chaos
Guenter Ahlers, Physics, University of California, Santa Barbara
The Economy as a Complex Adaptive System
W. Brian Arthur, Food Research Institute, Stanford University
Introduction to Nonlinear Dynamics
David Campbell, Center for Nonlinear Studies, Los Alamos National Laboratory
Mechanisms in Evolutionary Biology
Marcus Feldman, Biological Sciences, Stanford University
Introduction to Classifiers
John Holland, Computer Science and Engineering, University of Michigan
Logic of Life
Stuart Kauffman, Biochemistry and Biophysics, University of Pennsylvania
Spatial and Temporal Organization of Morphogenetic Fields
Jay Mittenthal, Anatomical Science, University of Illinois, Urbana
Neural Networks and Cognition
Lynn Nadel, Psychology, University of Arizona
Dynamics of Patterns: A Survey
Alan Newell, Mathematics, University of Arizona
Adaptation in the Space of Cellular Automata
Norman Packard, Physics, University of Illinois, Urbana
Glasses and Spin Glasses
Dan Stein, Physics, University of Arizona
Chemical Reactions in Complex Systems
Peter Wolynes, Chemistry, University of Illinois, Urbana

istic, that cannot be understood perturbatively; their solutions require more sophisticated techniques. The success of recent approaches involves the ability to apply new mathematical formalisms developed for a particular problem in one field to that in another seemingly unrelated field. The connections between these systems are not in the physical nature of the problems themselves, but instead rest on the possibility of sharing techniques and methods. In part because of the massive increase in computational power, we're now entering a period that presents the possibility of rapid progress in the science of complexity." It is often difficult, however, for graduate students and postdoctoral fellows in any one given department within an institution to be exposed to more than a small part of this interdisciplinary approach.

Preparing Advanced Students

The summer school addresses this need. The program is an introduction to different aspects of active research in the field, preparing advanced students to begin independent work. The subjects are not only topical, but have been chosen to illustrate the various connections among them. They include one-dimensional maps, cellular automata, disordered systems, evolutionary biology, chemical reactions to large molecules, pattern formation in physics and biology, and adaptation in large-scale economic systems. The logic of the field of complex systems is reflected in the organization of the lectures: the program begins with the abstract tools first used to study specific problems in mathematics and physics, and then moves on to show their applications to problems in different fields.

> *"We anticipate that the summer school will become an annual event, most probably scheduled in connection with shorter winter schools on specialized topics."*
>
> — L. M. Simmons, Jr.

IBM ATs, Macintosh SEs, and state-of-the-art workstations manufactured by Sun Microsystems will provide computation support for the school. In addition to units provided by SFI, CNLS and the University of Arizona, Sun will donate several workstations for use during the summer school.

Students Inspired

After more than two hundred requests for information and nearly one hundred applications, the Admissions Committee has chosen approximately fifty students to participate in the school. The scholars, from throughout the United States and Germany, Yugoslavia and Japan, represent a wide range of research areas including chemistry, computer science, biology, materials science, economics, and mathematics. Many participants working in specialized areas anticipate they will benefit from the multidisciplinary perspective. One writes, "At this point in my studies, I feel that I need a broader view of chaos and how it relates to the other sciences of complexity. By understanding parallel developments in other fields and their applications, I will be able to set myself better guidelines for research and to better judge my work."

Another adds this twist, "I find the relinking of formerly disparate disciplines to be one of the most inspiring aspects of the study of nonlinear dynamical systems, although I find an irresistible humor in the thought that the sciences are being reunited by chaos!"

— G. Richardson

Regional Efforts

The Santa Fe Institute's growing volume of activities brings with it increased cooperative research and educational efforts with the region's national laboratories and academic institutions. SFI's Regional Council oversees these joint efforts, meeting as needed to propose and review interactive research programs and people.

One example of these collaborative efforts is the joint sponsorship of the 1988 Complex Systems Summer School. The Institute, along with the Center for Nonlinear Studies at Los Alamos National Laboratory, the University of Arizona, University of Illinois, University of New Mexico and University of Texas, share responsibility for this program. Sponsors provide both faculty and financial support for the School, and representatives of each of the institutions sit on the program's Organizing and Advisory Committees. Sandia National Laboratories recently joined as an institutional sponsor involved in this effort. Sandia will host and provide support for lectures at Sandia by Summer School faculty members Guenter Ahlers, John Holland and Richard Palmer.

Gottfried Mayer-Kress of UC San Diego and Los Alamos National Laboratory has been at SFI as a visiting scientist since April. He has been an important impulse behind the initiation of an informal Friday afternoon discussion series at SFI aimed at increasing dialogue between SFI scientists and their Los Alamos colleagues. Speakers have included Ralph Abraham, University of California Santa Cruz, on "Complex Dynamical Models for International Relations"; Andy Ford, University of Southern California and Los Alamos, on "Systems Dynamics and Large Complex Systems"; and Diane O'Leary on "Objectivity and Complex Systems."

The Institute is discussing with the University of New Mexico the establishment of a similar collaborative discussion group series.

— G. Richardson

Publications

The Santa Fe Institute Studies in the Sciences of Complexity series continues to grow.

Currently Available

Volumes I, II and III are available from Addison-Wesley Longman Publishing Company Ltd. These include *Emerging Syntheses in Science, Theoretical Immunology, Part One*, and *Theoretical Immunology, Part Two. The Economy as an Evolving Complex System*, volume V, has gone to press and will be available by mid-July.

Artificial Life

Our sixth volume, *Artificial Life*, will be our first foray into color printing. Editor Chris Langton, Center for Nonlinear Studies, Los Alamos National Laboratory, has set aside a center section of four to six pages for color slides illustrating various computer-generated life forms. Chapters range from a highly theoretical discussion of whether simulated or computer-generated life can be considered "life," to teaching children about programming robots using LEGO building blocks. The contributors discuss and give examples of various methods for synthesizing the behavior of living systems.

The final chapter of *Artificial Life* will be an annotated bibliography of work in this field. A first in print, this bibliography eventually will be available as a public-access electronic database due to the good work of Christopher Langton and Richard K. Belew, Computer Science Department, UC San Diego. Researchers with access to Internet will be able to browse through the database entitled Biblio. After searching by key words, they may download relevant references using Refer or BibTeX software. This unique database also will allow for user feedback to improve searching capabilities.

This volume will appeal to biologists; computer scientists; graduate students in computer science, computer graphics, artificial intelligence, and biology; non-scientists who are interested in solid science that borders on science fiction; practicing scientists who want to keep abreast of new developments in science; members of the newly emerging "Connectionist," "Parallel-Distributed-Processing" school; and researchers interested in nonlinear dynamics, chaos theory, and self-organizing systems.

This volume should be available by late October.

Lattice Gas

Lattice Gas Methods for Partial Differential Equations has been delayed due to copyright approvals, but impressive new developments in this field will make this a valuable addition to researchers' libraries. Since announcement in the Addison-Wesley Advanced Book Program catalog, additional original, state-of-the-art papers have been added. This volume should be available by year end.

Summer School Volume

The preceding volumes were described in the last Bulletin, but there is one exciting addition. *Complex Systems*, as it is tentatively titled, will include the lectures from the "1988 Complex Systems Summer School." The director of the school and editor for the proceedings volume, Daniel Stein hails from the Physics Department at University of Arizona. Attended by over 50 graduate students and 21 faculty members from around the country, this four-week school is a consortium effort of regional institutions, including the Santa Fe Institute who will administer the program. Generally lecturers will use a series of five talks to bring graduate students from a introductory level to a research level in a topical area (from the physical, biological and computer sciences, mathematics, and economics) while stressing the interconnections among the various disciplines. This volume will be vital to researchers interested in interconnections among the disciplines, and educators and students may find it helpful supplementary reading for their courses. Since annual summer schools are planned, the proceedings may become a standard reference as the science of complexity develops.

— R. Butler-Villa

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The Economy as an Evolving Complex System
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Artificial Life: Proceedings of an Interdisciplinary Workshop on the Synthesis and Simulation of Living Systems
Edited by Christopher Langton
Volume VI

Complex Systems [tentative title]
Edited by Daniel Stein
Volume VII

To order any or all volumes, fill out and mail in the tear-out card, or dial (800)447-2226. All volumes are available in hardback or quality paperback versions.

Board News

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

CHARLES U. DALY is Director of the John F. Kennedy Library. Mr. Daly is past President of The Joyce Foundation, former Vice President for Government and Community Affairs, Harvard University and former Vice President for Development and Public Affairs, The University of Chicago.

CARL DJERASSI is a Professor of Chemistry at Stanford University. He is former Chairman of the Board, Zoecon Corporation, former Chairman of the Board of Governors, Synvar Associates, and former President and Director, Syntex Research. Professor Djerassi serves on the Editorial Board of *Tetrahedron, Steroids, Organic Mass Spectrometry.* He holds numerous honorary degrees and was awarded the National Medal of Science in 1973.

STUART KAUFFMAN will serve as SFI Trustee as well as Science Board member. He is Professor of Biochemistry and Biophysics, University of Pennsylvania. In addition to his involvement with the American Cancer Society Study Section, Cell and Developmental Biology, and International Society for the Study of the Origin of Life, he is co-Chief Editor of *Journal of Theoretical Biology*, a Member of the Editorial Board of *Quarterly Review of Biology, Journal of Mathematical Biology*, a Member of N.I.H. Ad Hoc Study Section, Systems and Integrative Biology Training Grants, and a Member of Society of Developmental Biology. Prof. Kauffman became a MacArthur Prize Fellow in 1987.

J. ROBERT SCHRIEFFER moves to the SFI Board of Trustees from the Science Board. He is Director of the Institute of Theoretical Physics at the University of California, Santa Barbara. A Nobel laureate and recipient of the National Medal of Science in 1985, Professor Schrieffer is author of *Theory of Superconductivity.* He heads the PNM Advanced Study Program on the Theory of High Temperature Superconductivity at Los Alamos National Laboratory.

Nine new members have been elected to the Science Board:

BRIAN C. GOODWIN is Professor of Biology at The Open University in the United Kingdom. He serves on the Editorial Boards of *Journal of Embryology and Experimental Morphology*,

Charles U. Daly

Rivista Biologia, Journal of Theoretical Biology, and *Bulletin of Mathematical Biology.* Professor Goodwin is a Member of the Cell Biology Society, British Society for Developmental Biology, Society for the Study of Time, and the Committee on Mathematical Biology.

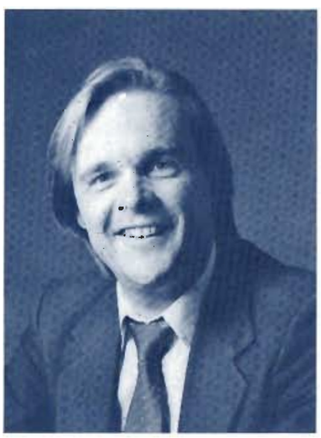
JOHN A. HAWKINS is Professor of Linguistics and Chairman of the Department of Linguistics, University of Southern California. A former Senior Scientific Staff member at the Max Planck Institute, his major research

Board of Trustees Meeting—front row, from left to right: Lawrence Huntington, Narragh Nagle, David Pines, Michael Claffey (consultant), Edwar Knapp, George A. Cowan, L. M. Simmons, Jr., Murray Gell-Mann, Nicholas Metropolis, Stirling Colgate; back row: Jack Cowan, Ron Zee (staff), Ginger Richardson (staff), Marc Feldman, J. I. Staley, Robert Craig, Carl Kaysen, Bob Maynard, George Stranahan, and Anthony Turkevich..

interests are universal grammar, psycholinguistics, syntax and semantics.

M. PETER HEILBRUN is Professor of Neurosurgery and Head of the Division of Neurosurgery at the School of Medicine, University of Utah. He is President-Elect of the Medical Board at the University of Utah Medical Center and a Member of the American Medical Association, American Association of Neurological Surgeons, Congress of Neurological Surgeons, and the Neurological Research Society.

Ewart A. C. Thomas



John A. Hawkins

C. S. HOLLING is a Professor at the Department of Zoology and Institute of Animal Resource Ecology, University of British Columbia, and an Honorary Professor, Community and Regional Planning at the University of British Columbia. A former Director of the International Institute for Applied Systems Analysis (IIASA), he is a Fellow of the Royal Society of Canada, a Member of Ecological Society of America, a Member of the British Ecological Society, a Member of Canadian Society of Zoologists, a Member of Research Council of the Canadian Institute for Advanced Research, a Member of Canadian Editorial Board for *General Systems Journal*, and a Member of the Editorial Advisory Committee for *Natural Resource Modelling*. He received the Austrian Cross of Honour for Arts and Sciences in 1985.

Glenys Thomson

NICHOLAS C. METROPOLIS is a Senior Fellow at Los Alamos National Laboratory and a founding member of SFI. He moves to the Science Board after distinguished service as a SFI Trustee. Former Professor of Physics and former Director of the Institute for Computer Research, University of Chicago, Dr. Metropolis was developer of the MANIAC I and MANIAC II computers. He is a consultant to Argonne National Laboratory, Brookhaven National Laboratory, Lawrence Radiation Laboratory, and the University of Illinois.

ALAN S. PERELSON is a Staff Member of the Theoretical Biology and Biophysics Group and the Center for Nonlinear Studies at Los Alamos National Laboratory. He is a Member of the American Association of Immunologists, Society of Industrial and Applied Mathematics, Institute of Electrical and Electronics Engineers, and the Society for Mathematical Biology. Editor of the SFI volumes *Theoretical Immunology, Part One* and *Part Two*, Dr. Perelson serves on the Editorial Board of *Mathematical Biosciences*, Springer-Verlag, *Textbooks in Biomathematics, Journal of Mathematical Biology* and *Journal of Theoretical Biology* and is Associate Editor of the *Bulletin of Mathematical Biology*.

EWART ARTHUR CORT THOMAS is Professor of Psychology and Dean of Humanities and Sciences at Stanford University. He is a member of various Fellowship and Review Committees at the National Institute of Mental Health, National Science Foundation, and National Institute of Education and a Consulting Editor of *Psychological Review*. His major research interests are development and application of mathematical and statistical models in many areas of psychology, signal detection, information processing, attribution, motivation, game theory, dynamics of language variation, economic planning, and biomathematics.

GLENYS THOMSON is a Professor in the Department of Genetics, University of California at Berkeley. Her major research interest is the development and application of multi-locus theory and disease modeling to the human histocompatibility (HLA) system.

CHRISTOPH von der MALSBURG is a Senior Scientific Staff Member in the Department of Neurobiology at the Max Planck Institute. His major research interests are the theory of organization and function of the brain, applications to the visual system, and artificial intelligence in neural architecture on massively parallel computers.

New Staff

J. BURCHENAL AULT has assumed the position of SFI Vice-President for Financial Affairs. Mr. Ault's responsibilities at the Institute include development as well as financial administration. From 1970 through 1985 he was associated with St. John's College, serving as Vice-President at the Santa Fe campus, and from 1980 to 1985 as Provost of the College. He brings to SFI extensive experience in the area of institutional development, noting "I am both at heart and in action most effective in the advocacy of interestingly different, important institutions, causes, and ideas." Mr. Ault will focus on building SFI's endowment and its capital building fund, and increasing program support.

MARCELLA AUSTIN has joined the SFI staff as Financial Assistant with responsibility for SFI's accounting operations. Ms. Austin has run her own accounting firm, Austin Accounting Services and was a staff member in the office of William Takala, CPA, in Santa Fe.

STEPHEN POPE joined the Institute staff in June as our Computer Expert. Stephen is responsible for working with researchers on programming, hardware and software needs, and managing our heterogeneous in-house network of Sun, IBM and Apple workstations. A physics graduate of the University of California at Santa Cruz, Stephen has collaborated with Rob Shaw, Peter Scott and Doyne Farmer, utilizing his excellent physics, computer programming, and database management skills.

CRAIG PREVOST has joined the staff to provide clerical assistance during the peak summer months, in particular, working at 1988 Summer School in Complexity. A well-traveled local high school student, Craig is interested in science, music, and computers.

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SFI Circle Slates Community Talks

The Santa Fe Institute Circle has been formed to serve as a liaison between the Institute and the community. A primary goal of the group is to raise SFI's profile within northern New Mexico through the sponsorship of public lectures and other events which illuminate the sciences of complexity; another aim is to act as a local host to SFI visiting scholars. The Circle is headed by Laughlin Barker of Santa Fe and incorporates the membership of the SFI Associates.

The Circle sponsored a talk for non-scientists entitled "Maps and the Brain," June 15 at St. John's College in Santa Fe. The speaker was Lynn Nadel, Professor of Psychology and Cognitive Science at the University of Arizona and a member of the 1988 Complex Systems Summer School faculty. Professor Nadel is editor of the journal *Psychobiology* and an expert on learning, memory, and brain function.

In August, Nobel laureate J. Robert Schrieffer, Director of the Institute for Theoretical Physics at the University of California at Santa Barbara, will discuss recent work in high-temperature superconductivity. Professor Schrieffer is Head of the PNM Advanced Study Program on the Theory of High Temperature Superconductivity at Los Alamos National Laboratory.

Circle talks are free and open to the public. For more information about the SFI Circle and public lectures, call Andi Sutherland at 984-8800.

— G. Richardson