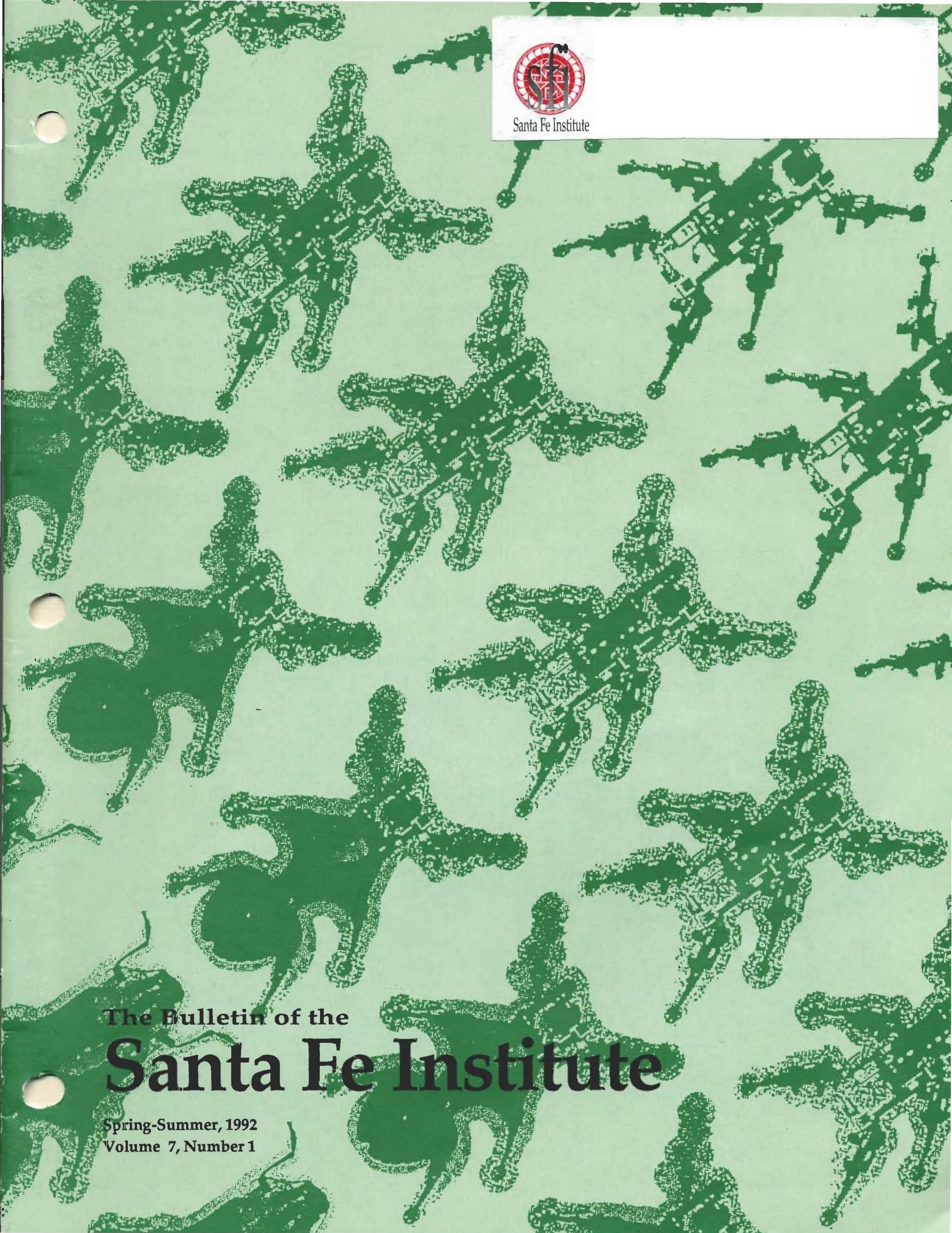

Santa Fe Institute

The Bulletin of the
Santa Fe Institute

Spring-Summer, 1992
Volume 7, Number 1

In This Issue

Special Features

Research Updates

Education

Regular Features

Cover & Credits

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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 at the above address. Letters to the Editor are welcomed.

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

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

First Year in New Facility

After a year with our new president, Ed Knapp, at the helm, the Institute continues to grow and prosper as a unique research and education resource for the academic, government, and corporate research community. The research program can only be described as robust and exciting. This issue includes only a sampling, and only a few are mentioned here.

Our cooperative research program with the University of Michigan, originated under a grant from the Joyce Foundation and led by John Holland, is flowering into new workshops and collaborations, as described in the lead article by Kevin Kelly and in the activity updates. Our cooperation with the University of Arizona in the sponsorship of schools continues apace. This year we host the fifth of our annual Complex Systems Summer Schools, led by Lynn Nadel and Daniel Stein. The first of what may be an annual Winter School was directed by Peter Carruthers. An outstanding group of lecturers and students spent two weeks in intensive discussion of scaling, self-organized criticality, fractals, and related phenomena in a variety of fields from biology to physics.

New programs of particular interest, described in this issue, include adaptive computation and theoretical neurobiology. Melanie Mitchell will be in residence for the next year to lead the multicomponent adaptive computation program, involving seven independent but closely related projects. The SFI is now seeking major new grants of allow this work to proceed. The neurobiology program, originated by Charles Stevens and funded by The Pew Charitable Trusts, seeks to break new ground in developing theoretical neurobiology. If successful, this will be a component of an enlarged research program in theoretical biology, a major recommendation from the annual meeting of the Institute's Science Board.

Not described in this issue, but of key significance to the future, is a new program on a sustainable world. This program, jointly proposed with the Brookings Institution and the World Resources Institute, was recently funded by the MacArthur Foundation. The three institutions are actively planning the early start of research activities and seeking additional funding for what will be a large and important program.

We will soon approach the first anniversary of our move from the fabled Cristo Rey Convent to our new and much larger quarters on Old Pecos Trail. The charm of that original home was real and is already taking on some of the character of myth. The convent nurtured the beginnings of our residential research program, the original economics workshop, which led to our current economics program, and much else. In particular, the sunny courtyard of the convent, the inadequate but cosy kitchen, and the walks down Canyon Road to lunch encouraged informal interactions among the research visitors who passed through the SFI in the first few years and led to much that is unique in our research programs. We miss all of this and are struggling to recreate as much of that interactive atmosphere as possible in our new, more modern surroundings. Most of us don't miss the tiny, overcrowded offices, roasting in the summer sun, or the continual infiltration of dust from the "charming" unpaved roads of the historic east side of Santa Fe.

Mike Simmons (center), SFI Vice President for Academic Affairs and the Bulletin's Editor, with collaborator Fred Cooper, LANL, taking a few moments away from administrative tasks to do a little research.

The robust growth of our research program has already filled the once spacious new quarters to slightly more than capacity for the summer. The president recently appointed a committee of the Board of Trustees to lead the search for the permanent campus that will combine the charm and interactivity of the convent with the good features of our current location and provide the physical basis for continued development of the Institute's research program. We all wish them success.

Mike

A Distributed Santa Fe System

By Kevin Kelly

Be careful. Watch out for that spider!" exclaims the boyish figure fidgeting in front of the computer screen. He turns to his audience. "Spiders are thoroughly bad news in this world." Like Peter Pan leading an expedition to Never-never Land, the grown-up John Holland can hardly contain his enthusiasm as he guides his listeners through a hi-res simulation of an ant colony. "Remember," he cautions, "we're the yellow ant."

The audience nods in appreciation. A simulated ant colony is the latest adaptive system introduced by Holland this week. Twenty scientists of many stripes—biologists, political scientists, mathematicians, and computer specialists—study the demo intently. Then they begin free-associating what they've seen with similar phenomenon in their own specialities. As they talk they struggle to translate the phenomenon of simulation into as many scientific dialects as possible, and then to unify the lingo. After an a hour they'll move on to another deeply complex subject—another complex adaptive system—and repeat the brainstorming, the translations, and the attempt at synthesis. Today, ant colonies; tomorrow, population genetics; the day after, alliances in World War II. During two weeks of freewheeling discussions, someone of the 20 present is sure to flesh out an idea or two later with a mathematical formulation or experiment. Eventually they'll report their findings back to this unique interdisciplinarian group of graduate students and professors dedicated to exploring the vast no-man's land between official branches of science.

Santa Fe–Michigan Collaboration

This could only be a convening of the Santa Fe Institute, if it weren't in Ann Arbor, Michigan. But it is definitely Michigan, during an unseasonably bitter cold two weeks in November 1991, and it is definitely a Santa Fe gathering. John Holland, with the encouragement of the Santa Fe Institute, has incubated a prototype Santa Fe collaboration at the University of Michigan.

Participants in the collaboration investigate a heady mix of interwoven topics. Currently, Arthur Burks explores the tradeoff between short-term and long-term goals in different types of machine learning. Carl Simon investigates the role of interacting populations in epidemics. Michael Cohen probes the structure of human organizations to see how groups routinely learn, especially in surprising environments. Melanie Mitchell evaluates the characteristic components of complex adaptive structures using a simple but versatile learning system she developed called CopyCat. Rick Riolo examines classifier systems—a type of adaptive algorithm—for evidence of internal models which allow the system to anticipate change. Once a week, this group meets to critique their ideas. And for the second year in a row, the University of Michigan and Santa Fe Institute have sponsored a two-week colloquium where collaboration members and other Santa Fe Institute regulars can swap reports of their current work.

Complex Adaptive System Traits

Some common threads crisscross this year's seminars. A few themes keep emerging with enough bite that John Holland takes out a red grease pencil and in the glare of the overhead projector makes a quick catalog of candidates for distinctive characteristics of complex adaptive systems. I've expounded upon his bullets with a synthesis derived from conversations with researchers individually, from debates overheard among them, and from attendance at parts of the two-week colloquia. The short list of traits of complex adaptive systems follows.

Perpetual Novelty

You know you've got a complex adaptive system on your hands when it continues to surprise you no matte[r] how long its been running. The author of the yellow an[t] simulation (sold as a commercial game) reports that he is amazed by the large number of completely unexpected novel tricks other users have found in his world. They write and tell him how clever he is. In reality he is clever by programming a type of connectivity which generates viable surprises. Perpetual novelty is highly desired in a game, but perpetual novelty is sheer disaster in aviation systems or telephone networks. To control perpetual novelty—where and when novelty is wanted—is a fundamental challenge for this new science.

Resilience

The capacity for self-repair is a hallmark of biology, and a goal for synthetic adaptive systems such as networks or computer models. Even if a system cannot mend itself, if it can degrade gracefully—limp along instead of dying—it's got the spunk of a complex adaptive system. Modelers praise a network that can work around troubles and failure, the way a computer hard disk will automatically reformat around its bad sectors. They call it "robust." The more adaptive a system is the more robust and resilient, and presumably vice versa.

Emergence of the Aggregate

The whole is greater than the sum of the parts. It an old idea that is presently gaining experimental proo[f] and precision. When is the whole greater? Under what conditions? Does the sequence in which parts are added make any difference? What causes a complex system to unravel? Bob Axelrod notes that a whole does not break up randomly, but fails by splintering along hierarchical boundaries. Look at the former Soviet Union, he says. It first broke up into republics, then into autonomous regions, and will lastly unhinge into ethnic enclaves. One critical challenge on this frontier, John Holland says, is understanding the way in which the whole begins to influence and modify the parts that sum it. Over time, a cell joining one body will diverge in operation from a cell joining no body. A whole can unravel into a different set of sub-parts than the set that first created it. To use the Soviet example, the former U.S.S.R. may unravel into a different set of ethnic enclaves from those which originally comprised the Union.

Formation of Individuality

Another mark of living things is that each has its own individuality. The components of highly adaptive systems are arranged in nested hierarchies, which breed slightly unique behaviors as the parts are altered or rearranged. In contrast, an unliving electrical appliance or protein molecule can have complication without individuality. Substantial alteration of their complicated parts produces drastically different output of the whole. The deep hierarchy stacked up in a natural organism—molecules, cells, tissues, and organs—compensates for significant variation of parts. Sub-sub-structures can differ slightly while still generating similar top behavior. A complex system such as a peacock may vary in the exact

> A whole can unravel into a different set of sub-parts than the set that first created it. ...the former U.S.S.R. may unravel into a different set of ethnic enclaves from those which originally comprised the Union.

arrangement or numbers of muscle, feather, and brain cells. Every peacock acts both like a standard peacock system and a unique peacock personality. At the same time, the combination of hierarchical dynamics and individual variation permits the system to generate an identity of self—a sense of "me" and "not me"—in the way skin grafts are rejected by nearly identical siblings. Holland says, "Identity of individuality is an emergent property of these systems." He points out that the emergence of individual identity forms a structure upon which new evolutionary pressures can focus. For example, the emergent identity of a colony draws natural selection onto an additional layer, that of the individual colony, and alters the character of the cells constituting the new colony.

Internal Models

There is a suspicion among researchers that the hierarchical architecture of a complex adaptive system permits it to represent a level of abstraction internally. A high-order representation persists longer than the flux of changing influences in lower-level structures. Thus, a dynamic representation serves as a platform for limited anticipation of the future. To anticipate may, in fact, be one of the chief benefits of complex systems. Even the mildest look-ahead ability speeds learning and adaptation. As an example, Stephanie Forrest cites the immune system, which models (almost mirrors) the disease environment in anticipation of an infection. The immune apparatus, she says, "is a very massively parallel, distributed system." It can remember for over 50 years, which is truly astounding since the body is turning over all its molecules weekly. It also means this memory model isn't residing anywhere in particular. Over evolutionary time, the immune system has abstracted the notion of infectious disease and represented it in a very distributed way so that the system itself anticipates diseases it has never seen.

Non-Zero Sum

Game theory was the very first attempt to grasp complex adaptive systems. von Neumann invented game theory at almost the same moment he helped cook up computers. One insight from game theory has penetrated science and contemporary thought: the distinction between zero- and non-zero–sum games. In a zero-sum game, every win is offset by a loss; if there is a winner, there must be a loser. In a non-zero–sum game, both sides can loose, or both sides can win. Complex adaptive systems tend to be non-zero–sum games. The emergence of beneficial properties arising from adversarial parts—take wealth in capitalism as an example—is the first clue that the conservation of gain is broken. Conventional theories of economics and ecology stress the way the game seeks equilibrium, winner balancing loser, as if on a pivoting scale. The new view stresses the non-equilibrium aspects of complex systems. The non-zero–sum, non-equilibrium aspect of life as a system is why more varieties of organisms on a planet increase the opportunity for yet more new species, rather than decrease opportunity for diversity, as in a zero-sum game. In this open-ended kind of a system, non-equilibria moves can have a big impact. Bob Axelrod gave the example of Gorbachov's fundamental insight, "that the Soviets could

Kevin Kelly is a former editor/publisher of the Whole Earth Review, *and* Signal, *a Whole Earth catalog of communication tools. He is now on sabbatical, writing a book for Addison-Wesley on how machines are becoming biological.*

(continued next page)

get more security with fewer tanks rather than with more tanks. They threw away 10,000 tanks unilaterally, and made it harder for U.S. and Europe to have a big military budget."

An Exploration Tradeoff

The price of learning is a sacrifice in efficiency. A complex adaptive system will have one side that seeks new ways to survive (exploration, learning) and one side that seeks to maximize what it knows (exploitation, efficiency). Every act of new learning diverts resources from exploitation of the known. Holland defines the chief task of complex systems as coming up with a mechanism that can optimally balance these diverging poles. Says he, "If I spend all my time looking for the very best rule, I might never get around to using the rules I already have to their best. On the other hand, I'll never discover a better rule while only exploiting the rules I already have." Each type of discovery is rooted in a different mathematical structure, which is also to say that different structures of discovery are best suited for different types of problems. Melanie Mitchell has embarked on a project to characterize the types of problems that genetic algorithms are best for. For instance, one of the drawbacks of genetic algorithms, and even organic genetic crossover in living populations, is that the process tends to converge the population upon a uniform type, so that organisms and solutions begin to look similar to each other. In other words, genetic algorithms emphasize exploitation of the knowledge represented by all the genes inside a population, rather than exploring outside the known gene pool. Mitchell can show on her model how a learning system can get stuck in "brainstorming mode" just as easily as it can get stuck in overspecialization. How might genetic algorithms, or neural nets, and other kinds of structured searches, be combined in appropriate balance to best solve a particular type of problem? A formal answer to this general problem would go a long way not only in artificial intelligence and artificial life fields, but also in practical application to human institutions such as corporations, which must set hard priorities in funding research either for the short term (exploitation) or the long term (exploration).

Collaboration Foci

By no means are these eight the only features of complex adaptive systems. Nor are these systems the only target of the Michigan group and the Santa Fe Institute. The collaboration focuses on the subject of complex systems that adapt and learn because it is sufficiently broad to interest the needed multidisciplinary crowd, sufficiently specific to hatch tough questions, and because it threads through many of the major problems SFI is addressing, such as: how does the global economy work, what is the nature of evolution, for what good can we use vast computational power? As SFI president Ed Knapp noted in his address to the colloquium, "if we could but know one system well, we'd have a start on the others."

> ...universities are no longer the natural repository for long-range stuff. ...One of the reasons you find such good people clustering around the Santa Fe Institute is it's one of the few places where you can do this kind of long-term, long-horizon research.

In many ways the organization of the Michigan/SFI collaboration reflects the unorthodox organization that has proven to make the Santa Fe Institute so successful. In both locations there are no departments, no positions, no permanent research staff, no day-to-day responsibilities for researchers beyond trying out embryonic interests and following them up. Participants have a home institution, where they are prominent. In Knapp's words, Santa Fe Institute and collaborations are sort of a "homeless idea." A small group of participants hole up together to practice a "collaboration demanded by proximity." In the end the universities affiliated with the participants benefit by these ad hoc convenings.

John Holland agrees. "Because of a desperate chasing of dollars for cash flow, universities are no longer the natural repository for long-range stuff. It's even worse at the top universities because of fights over overhead costs. Almost all the really long-horizon research that I know going on in universities is bootleg, one way or another." Holland isn't exaggerating. One prestigious East Coast school stated in their documents that a three- to five-year horizon is the farthest that they'll look ahead. "This is going to cost this country tremendously. One of the reasons you find such good people clustering around the Santa Fe Institute is it's one of the few places where you can do this kind of long-term, long-horizon research. They really encourage it."

Beginning with the pilot program, the Santa Fe Institute is trying to export this long view back into its "natural repository" of the universities. One who welcomes this approach is Joseph White, Dean of the Business School of University of Michigan, a sponsor of the colloquium. "We are a complex non-adaptive institution," he sighs. "We need groups like this."

Nature Conformable to Herself

What follows is a talk given by Murray Gell-Mann at the 1992 Complex Systems Winter School

More than thirty years ago, I was the first visiting professor at the College de France in Paris, with an office in the laboratory of experimental physics. I noticed that my experimental colleagues were frequently drawing little pictures in their notebooks, which I assumed were diagrams of experimental apparatus. But it turned out that those drawings were mostly of a gallows for hanging the vice-director of the lab, whose rigid ideas drove them crazy.

I got to know the sous-directeur, and talked with him on various subjects, one of which was Project Ozma, the attempt to detect signals from another technical civilization on a planet of a nearby star. SETI, the Search for Extraterrestrial Intelligence, is the present-day successor of that project. "How could you communicate if you found such a civilization?" he asked, assuming both interlocutors would have the patience to wait for the signals to be transmitted back and forth. I suggested that we might try beep, beep-beep, beep-beep-beep, for 1, 2, 3, and so forth, and then perhaps 1, 2, 3,..., 92 for the stable (except 41 and 63) chemical elements, etc., etc. "Wait," said the sous-directeur, "That is absurd. The number 92 would mean nothing to them...why, if they have 92 chemical elements, then they must also have the Eiffel Tower and Brigitte Bardot."

That is how I became acquainted with the fact that French schools taught a kind of neo-Kantian philosophy, in which the laws of nature are nothing but Kantian "categories" used by the *human mind* to grasp reality. [Many also taught, by the way, that artistic criticism is absolute and not a matter of taste, while the opinion that artistic standards are relative was treated as a feature of Anglo-Saxon pragmatism.]

Another notion of a quite different kind, far more Platonic, is rife in mathematical circles in France (and elsewhere). That is the idea that the structures and objects of mathematics, say Lie groups, have a reality, that they exist in a sense, somewhere beyond space and time. [It is easy to see how one can come to think that way. Start with the positive integers—they certainly exist, in the sense of being used to count things. Number theory —OK. Zero and negative numbers—why not? Fractions, square roots? Solutions of algebraic equations in complex numbers? Probably—one is on a slippery slope.]

These two points of view are argued in a book, *Matière à Pensée*, published recently by the biologist Jean-Pierre Changeux and the mathematician Alain Connes. I shall not inflict all their philosophical arguments on this congenial group, and anyway I have never studied them carefully. Let me say merely that the authors do raise the question of what is the role of mathematical theory in our understanding of the world, especially the physical world.

I like to put the relevant questions in the following form: Would advanced complex adaptive systems on another planet come up with anything like our mathematics or anything like our mathematical theories of physical processes, or both? At present, we can only speculate about the answers, but the questions are deep and meaningful.

Eugene Wigner once wrote an article entitled, "The Unreasonable Effectiveness of Mathematics in the Natural Sciences." I don't know what he wrote in the article, but it is certainly a fact that up to now, especially in the domain of fundamental physics, we have had striking success with our use of mathematics.

Sometimes, as with Fourier series, the physicist has to invent the mathematical trick and the mathematicians later formalize and adapt it. Sometimes, as with Heisenberg and matrices, the concept is already known to mathematicians and physicists, but not to the particular theoretician involved, he re-invents it. Often, as with Einstein, the physicist senses what he wants and asks a mathematician to provide it—in the case of the equation describing general relativistic gravitation, Einstein asked his old classmate, Marcel Grossmann, for the tensor he needed, and thus the Ricci tensor became the Ricci-Einstein tensor.

More recently, abstract mathematics reached out in so many directions and became so seemingly abstruse that it appeared to have left physics far behind, so that among all the new structures being explored by mathematicians, the fraction that would even be of any interest to science would be so small as not to make it worth the time of a scientist to study them.

But all that has changed in the last decade or two. It has turned out that the apparent divergence of pure mathematics from science was partly an illusion produced by the obscurantist, ultra-rigorous language used by mathematicians, especially those of a Bourbakian persuasion, and by their reluctance to write up non-trivial examples in explicit detail. When demystified, large chunks of modern mathematics turn out to be connected with physics and other sciences, and these chunks are mostly in or near the most prestigious parts of mathematics, such as differential topology, where geometry, analysis, and algebra come together. Pure mathematics and science are finally being reunited and, mercifully, the Bourbaki plague is dying out. (In the late Soviet Union, they never succumbed to it in the first place.)

An anecdote will illustrate the situation during the '50s. In 1955, at the Institute for Advanced Study in

Nobel Laureate Murray Gell-Mann is s professor at Caltech, an SFI External Professor, co-chairman of the SFI Science Board, and an SFI Trustee.

(continued next page)

Princeton, Frank Yang was discussing with other physicists the recently developed Yang-Mills quantum field theory. At the same time, S. S. Chern was lecturing on pure mathematics. Not only did Frank attend some of the lectures, but he and Chern were old friends, their children played together, and Chern had been one of Frank's teachers in China; neither of them noticed that Chern's lectures on fiber bundles were basically concerned with the same subject as Frank's lectures on Yang-Mills theory! In fact, they didn't learn about this equivalence for many years.

Yang-Mills theory, from the physics point of view, was a generalization of quantum electrodynamics from the gauge group U_1 to the gauge group SU_2 with non-commuting charges. Later, we generalized it to all products of U_1 factors and simple compact Lie groups, including SU_3. Today the "standard model" of elementary particle physics, apart from gravitation, is based on $SU_3 \times SU_2 \times U_1$. Moreover, Einsteinian gravitation has strong parallels with generalized Yang-Mills theory, although the gravitation theory is based on the non-compact Lorentz group and involves a tensor instead of a vector field. What does it mean that this progression from one gauge group to another has worked so well? Are we really dealing with something peculiar to the human mind or with a phenomenon so deeply rooted in the properties of nature that any advanced complex adaptive system would be likely to follow similar paths?

A related set of issues was discussed more than three hundred years ago, especially by Isaac Newton. Children learn that he thought of the theory of universal gravitation when an apple fell on his head. Well, not on his head, but nearby, anyway.

Historians of science are not sure whether to credit the apple at all, but they admit that there could have been an apple. As you know, in 1665 the University of Cambridge closed up on account of the plague and sent everyone home, including Newton, a fresh B.A., who went back to Woolsthorpe, Lincolnshire. There, during 1665 and 1666, he thought a little about integration and differentiation, a little more about the law of gravitation, and a lot about the laws of motion. Moreover, he carried out the experiment showing that white light is made up of the colors of the rainbow. While historians of science now emphasize that he didn't completely clear up all these matters in one "annus mirabilis," or "marvelous year," they admit that he made a good start on all of them around this time. As my friend Marcia Southwick says, he could have written a pretty impressive essay on "What I Did During My Summer Vacation."

As to the apple, there are four independent sources. One of them, Conduitt, writes:

> "In the year 1666 he retired again from Cambridge...to his mother in Lincolnshire & whilst he was musing in a garden it came into his thought that the power of gravity (w^ch^ brought an apple from the tree to the ground) was not limited to a certain distance from the earth but that this power must extend much farther than was usually thought. Why not as high as the moon said he to himself & if so that must influence her motion & perhaps retain her in orbit, whereupon he fell a calculating what would be the effect of that supposition but being absent from books & taking the common estimate in use among Geographers & our seamen before Norwood had measured the earth, that 60 English miles were contained in one degree of latitude on the surface of the Earth his computation did not agree with his theory & inclined him then to entertain a notion that together with the force of gravity there might be a mixture of that force w^ch^ the moon would have if it was carried along in a vortex...."

What interests us here is the extrapolation—if gravitation applies on earth, why not extend it to the heavens and use it to explain the force that keeps the moon in it[s] orbit? Here is how Newton describes the idea muc[h] later:

> "How the great bodies of the earth Sun moon & Planets gravitate towards one another what are the laws & quantities of their gravitating forces at all distances from them & how all the motions of those bodies are regulated by those their gravities I shewed in my Mathematical Principles of Philosophy to the satisfaction of my readers: And if Nature be most simple & fully consonant to her self she observes the same method in regulating the motions of smaller bodies which she doth in regulating those of the greater. This principle of nature being very remote from the conceptions of Philosophers I forbore to describe it in that Book least I should be accounted an extravagant freak & so prejudice my Readers against all those things which were the main designe of the Book."

Today some of us have the same concerns about extrapolation as the ones to which Newton refers—Shelly Glashow inveighs against superstring theory because in embracing Einsteinian gravitation, along with the oth[er] forces, it achieves its synthesis around the Planck mas[s] of 2 x 10^{19} GeV, larger by a gigantic factor than any energy at which particle physics experiments are carried out. But he and others were in the forefront of extrapolating the standard model SU_3 x SU_2 x U_1 to a unified Yang-Mills theory based on SU_5, in which the unification (without gravitation) is achieved around 10^{14} or 10^{15} GeV, which lies most of the way to the Planck mass. Moreover, Shelly and others have alleged that nothing much could happen in between present energies and 10^{14} GeV or so—there would just be a desert.

Well, here in Arizona we know that deserts are not necessarily empty, and that they are often very rich in plant and animal life, so the gap between our experimental energies of a few hundred GeV and 10^{14} GeV may well contain some interesting flora and fauna, especially the supersymmetric partners of the known particles—as suggested by superstring theory.

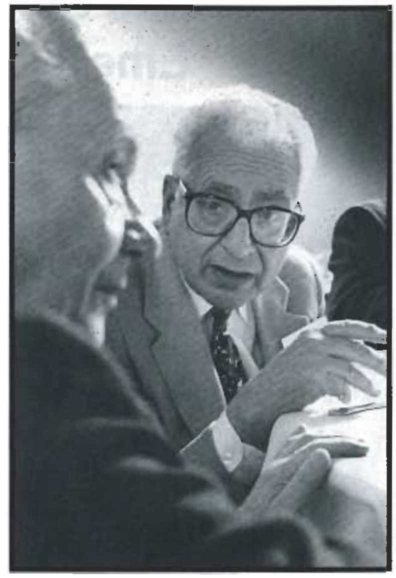
In fact, the unified super-Yang-Mills extrapolation works much better than the straight unified Yang-Mills theory (what some people call, quite inappropriately in my opinion, "grand unified theory").

But, to return to Newton, he was not thinking only of extrapolation. He returns repeatedly in his writings to the idea that Nature is consonant and conformable to herself in more general ways. From the Opticks:

> "For Nature is very consonant and conformable to her self...For we must learn from the Phaenomena of Nature what Bodies attract one another, and what are the Laws and Properties of the Attraction, before we enquire the Cause by which the Attraction is perform'd. The Attractions of Gravity, Magnetism, and Electricity, reach to very sensible distances, and so have been observed by vulgar Eyes, and there may be others which reach to so small distances as hitherto escape Observation; and perhaps electrical Attraction may reach to such small distances, even without being excited by Friction."

Thus he thought of the laws as exhibiting conformability among themselves as well as within each one, just the kind of idea that we have followed in going from electrodynamics to QCD and the electroweak theory and then onward to unified Yang-Mills theory and, with gravitation included, to the superstring theory.

If we modernize Newton's conception a bit, we could say that the laws of Nature exhibit a certain amount of self-similarity and not, of course, perfect scaling, but rather the kind of thing one sees in the Mandelbrot fractal set. So, in peeling the skins off the onion of fundamental physics, we encounter certain similarities between one layer and the next. As a result, the mathematics with which we become familiar on account of its usefulness in describing one layer suggests new mathematics, some of which may apply at the next layer—in fact even the old mathematics may still be useful at the next layer. These generalizations may be performed either by theoretical physicists or by mathematicians. If pure mathematicians are exploring ambitious generalizations of known mathematical structures, they will surely run across some of the new ones that are needed—along with much more besides.



Murray Gell-Mann and SFI Science Board Member Manfred Eigen, Max Planck Institute, at the recent Science Symposium.

Ultimately, then, we can argue that it is the self-similarity of the structure of fundamental physical law that dictates the continuing usefulness of mathematics. Suppose that the fundamental theory of the elementary particles and their interactions is really heterotic superstring theory. It has a huge set of symmetries, including the conformal string symmetries that encompass the bootstrap principle and general relativity, and an internal symmetry group E_8 x E_8 that undergoes spontaneous symmetry breaking. The outer layers of the onion show gravitation and electromagnetism. Penetrating a little further turns up SU_2 x U_1, SU_3 of color, and the bootstrap idea. And so it goes on. The mathematics at each level is not usually identical with that at the next level, but it has a strong family relationship. The successive renormalizable approximate theories, by the way, represent autonomous shells that depend on what is inside only through the renormalized parameters.

At the modest level of earlier science, this sort of self-similarity is strikingly apparent. Electricity, gravitation, and magnetism all have the same $1/r^2$ force, and Newton, as we have seen, suggested that there might be some short-range forces as well. Perhaps in some lost manuscript he proposed the Yukawa potential!

Now that scientists and mathematicians are paying attention to scaling phenomena, we see in the study of complex systems astonishing power laws extending over many orders of magnitude. Often the underlying mechanism is changing while the power law still holds, as for the cosmic ray energy spectrum, the advance of technologies over time, and so forth.

The renormalization group, which we invented for renormalizable quantum field theory, turns out to apply not only to critical phenomena in condensed matter, but to numerous other far-flung subjects as well.

The biological and social sciences are just as much

(continued next page)

The Simply Complex: Trendy Buzzword or Emerging New Science?

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by John Casti

A few years ago, I saw a cartoon showing two scientists arguing over the the meaning of complexity. In suitably dogmatic terms the first scientist asserted, "Complexity is what you don't understand." Responding to this temerarious claim, his colleague replied, "You don't understand complexity." This circular exchange mirrors perfectly to my eye how the informal term "complexity" has been bandied about in recent years—especially within the normally flinty-eyed community of system scientists—as a characterization of just about everything from aardvarkology to zymurgology. Without benefit of anything even beginning to resemble a definition, we find the putative "science" of complexity being described in terms rosy enough to emit heat: *adaptive* behavior, *chaotic* dynamics, *massively parallel* computation, *self-organization,* and even on to the *creation of life* itself within the cozy confines of a machine. And to add a final touch of spice, all of this hoopla often comes wrapped up in language vague enough to warm the heart of any Continental philosopher. But useful as all this fuzziness is for fending off cocktail-party bores and writing research grant proposals, it becomes a major impediment when we start talking seriously about a "science" of complex systems. The problem is that an integral part of transforming complexity (or anything else) into a science involves making that which is fuzzy precise, not the other way around, an exercise we might more compactly express as "formalizing the informal." This short essay represents an exploration into some of the dimensions of this problem, as we try to "scientify" the simply complex.

Still More Complex

The science-fiction writer Poul Anderson once remarked, "I have yet to see any problem, however complicated, which, when you looked at it the right way, did not become still more complicated." Substituting the word "complex" for "complicated," this statement serves admirably to capture the two key points needed to understand what's at issue in turning the casual, everyday notion of a complex system into something resembling an actual science.

> ...complexity is an inherently subjective concept; what's complex depends upon how you look at it...complexity resides as much in the eye of the beholder as it does in the structure and behavior of a system itself.

The first is the realization that complexity is an inherently subjective concept; what's complex depends upon how you look. So when we speak of something being "complex," what we're really doing is making use of everyday language to express a feeling or impression that we characterize by the label "complex." But the meaning of something depends not only upon the language in which it is expressed (i.e., the code), the medium of transmission, and the message, but also upon the context. In short, meaning is bound up in the whole

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Nature (continued)

involved in these discoveries of scaling behavior as the physical sciences. We are always dealing with Nature consonant and conformable to herself, not only within scaling behavior but also in the occurrence of similar phenomenological laws in a plethora of disparate areas. So the approximate self-similarity of the laws of nature runs the gamut from the simple underlying laws of fundamental physics to the phenomenological laws of the most complex phenomena. No wonder our mathematics keeps working so well in the sciences, when self-similarity is so widespread.

Of course there may be something important here about the nature of mathematics itself. In connection with that, let me close by paraphrasing some wonderful remarks made by that brilliant and modest theoretical physicist Feza Gürsey on the occasion of his receiving, at the University of Miami, not the valuable kind of prize he deserves, but half of the $1,000 Oppenheimer Prize.

He said, more or less, that he had achieved some success by pointing, often before other theorists, to mathematical structures that would be useful in the near future in elementary particle physics. But often he hadn't had any clear idea of exactly how or why these mathematical methods would be used. He compared himself with Inspector Clouseau, bumbling along, bumping into walls, but somehow finally pointing to the right suspects. Why, he asked, did the Inspector Clouseau method work? Maybe, he suggested, because such mathematical structures are comparatively rare, so that it is possible to find and identify something like the exceptional group E_8 as an object of interest simply because structures with its remarkable properties are not thick on the ground. Thus it may be that the character of *mathematics* plays a role in our story, along with Nature consonant and conformable to herself.

process of communication and doesn't reside in just one or another aspect of it. As a result, the complexity of a political structure, a national economy, or an immune system cannot be regarded as simply a property of that system taken in isolation. Rather, whatever complexity such systems have is a joint property of the system and its interaction with another system, most often an observer and/or controller. So just like truth, beauty, good, and evil, complexity resides as much in the eye of the beholder as it does in the structure and behavior of a system itself.

The second key point brought out by Anderson's quotation is that common usage of the term "complex" is an *informal* one, the word typically employed as a name for something that seems counterintuitive, unpredictable, or just plain hard to pin down. So if it's a genuine *science* of complex systems we're after, and not just anecdotal accounts based on vague, personal opinions, we're going to have to translate some of these informal notions about the complex and the common into a more formal, stylized language, one in which intuition and meaning can be more-or-less faithfully captured in symbols and syntax.

These points are pretty obvious, I think, and should hardly be matters of debate among the complex systems crowd. Nevertheless, it's from just such obvious points as these that new sciences emerge by looking at the commonplace and the self-evident in new and interesting ways. And bridging the gap between the informal and the formal is a necessary first step in the making of something that passes for a science out of our intuitive, everyday feelings about the complex. But before entering into a discussion of just how this "subjectivistic" formalization might be carried out, let me pause for a moment to consider why we might want such a thing as a science of complexity in the first place.

Why a Science of Complexity

As noted above, the impression of complexity is something like the expression of an experience of meaning, a part of a cultural cognitive map. And the meaning of our lives depends on the particular maps we use to decode our thoughts, choices, and actions. But human societies have evolved to the point where the traditional maps no longer match our collective experience for very long. Thus, by coming up with a workable (i.e., scientific) theory of complexity, we can hope to be able to internalize the experience of change by describing our collective reality as a process. This, in turn, would then be a major step toward the development of a framework within which we can begin to understand how to control

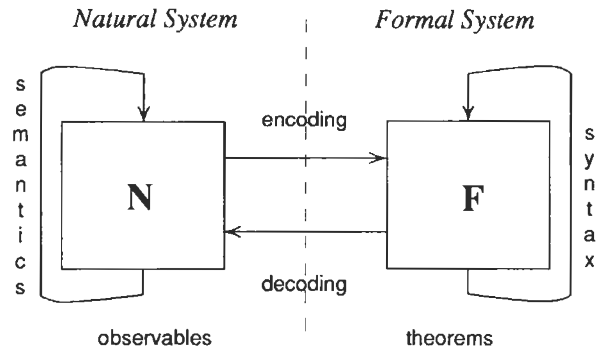

Figure 1: The Modeling Relation.

and manage what our maps tell us are complex processes.

A second, and somewhat more direct, reason for trying to create a science of the complex is to get a handle on the limits of reductionism as a universal problem-solving approach. When faced with a problem we don't understand, the traditional knee-jerk response is to invoke the old adage, "When you don't know what to do, apply what you do know." Most of the time, this translates into an attempt to decompose the "hard" problem into a collection of "simpler" sub-problems that we do understand. We then try to re-assemble the solutions of these bits and pieces into something that looks like an answer to the original question. Unfortunately, this procedure works just often enough to appeal to the prejudice of reductionists seeking rationalization for their particular brand of epistemological medicine. But we're all familiar with examples like the Three-Body Problem, in which any reductionistic approach of this sort irretrievably destroys the very nature of the problem. Such systems are complex. And it would be nice to have a theory tracing out the boundaries of the reductionistic approach, as opposed to blundering about like blind men, crashing up against these barriers before we even know they exist. So much for motivation. Now let me turn to the twin problems of formalization and "objectification" of the informal and subjective. Let's look at formalization first.

Formalization

The heart of the formalization process is shown in Figure 1, which we might term the "modeling relation." Here we see a natural (read: real-world) system N characterized by observations and relations stated in everyday language. The formalization process then involves the encoding of these characterizations of N into the symbols and strings of a formal logical (read: mathematical) system F. The key to understanding this process of formalization is to recognize that all notions of

(continued next page)

meaning (i.e., semantics) reside on the left-hand side of the diagram. So any real-world intuitions we have about *N*—including its complexity—belong to this side of the modeling relation. By way of contrast, there is no meaning at all on the right-hand side; *F* consists of mere abstract symbols, together with rules (a grammar) for how strings of these symbols can be combined to form new strings. Whatever meaning might inhere in these strings is then brought out by the decoding of the strings back into *N*. An example or two will hammer home the point.

The Turing Machine

In 1935, Alan Turing was a student at Cambridge University taking a course in mathematical logic. During the course, Turing was exposed to Hilbert's Decision Problem, and while trying to solve this problem he invented what we now call a Turing machine. For our purposes here, what's important about this "mathematical computer" is that it represents the first successful attempt to formalize the informal notion of what it means to carry out a "computation." So despite the fact that people had been calculating for several thousand years, it was not until Turing's work, less than sixty years ago, that the bridge was crossed from the informal system *N* = computation to its formalization as *F* = Turing machine.

> So it shouldn't come as much of a surprise were we to discover that a successful formalization of complexity will be equally useless from a practical point of view, yet equally profound from the standpoint of setting the foundations for a general theory of models.

While Turing's result showing that all computers are created equal is of enormous conceptual significance, I think it's important to point out that very few computer designers, if any, rely upon this fact as they go about their daily chores. So the formalization of the informal idea of a computation has had very little practical impact on problems of modern computer design and operation, despite the fact that the Turing machine serves as the conceptual foundation for a large part of what we now call "computer science." In passing, let me note another example of the same sort, namely, Gödel's formalization of the informal notion of "truth." Again, not many mathematicians lose any sleep over the implications of Gödel's result for their work. Nevertheless, it's hard to deny the significance of incompleteness as we ponder the soundness of the mathematical enterprise. So it shouldn't come as much of a surprise were we to discover that a successful formalization of complexity will be equally useless from a practical point of view, yet equally profound from the standpoint of setting the foundations for a general theory of models.

Arguing by analogy from the historical genesis of these examples, we see that formalization of the idea of complexity reduces to finding a symbolic structure in *F* that mirrors our informal ideas about what it is that makes a system complex. In Turing's case, everyday ideas about what it means to carry out a computation were mirrored in the operations of the Turing machine, while Gödel mirrored what we think of as real-world truth by the idea of a mathematical proof. Almost all attempts that I've seen to carry out this kind of mirroring for complexity—information content, length of minimal computer programs, entropy, thermodynamic depth, to name a few—come down to the translation of informally felt beliefs about the complex into formal, symbolic operations of one sort or another. But so far none of these formal surrogates has achieved a consensus in the system modeling community as being the "right" formalization. And despite the numerous interesting and technically deep results that have come out of these attempts, I can't think of a single system modeler whose work is influenced in the slightest by any of these characterizations (which, again arguing by analogy with Turing and Gödel, could be taken to suggest that they are on the right track after all, I suppose). This sad fact indicates that there's something missing from these formalizations. Recalling the discussion given earlier, let me now argue that the missing ingredient is the explicit recognition that system complexity is a subjective, not an objective, property of an isolated system. But it can become objective, once our formalism takes into account the system with which our target system interacts.

Objectification

Consider a system *N* and an "observer" who interacts with *N*. (Here and in what follows, I'll use the emotionally laden term "observer" in the weakest possible sense to mean simply some other system that interacts in some way with *N*, and not in the strict sense as a system that measures or observes an attribute of *N*.) The observer creates a linguistic description of the system in the real world. This description is then formalized into a description in the mathematical world *F* by the process just discussed. We now ask: How many *inequivalent* descriptions of *N* can our observer generate? My claim is that the complexity of the system *N as seen by the observer* is directly proportional to the number of such descriptions. Here's why.

Suppose our system N is a stone on the street. To most of us, this is a pretty simple, almost primitive kind of system. And the reason why we see it as a simple system is that we are capable of interacting with the stone in a very circumscribed number of ways. We can break it, throw it, kick it—and that's about it. Each of these modes of interaction represents a different (i.e., inequivalent) way we have of interacting with the stone. But if we were geologists, then the number of different kinds of interactions available to us would greatly increase. In that case, we could perform various sorts of chemical analyses on the stone, use carbon-dating techniques on it, x-ray it, and so on. So for the geologist our stone becomes a much more complex object as a result of these additional—and inequivalent—modes of interaction. We see from this example that the complexity of the stone is a relative matter, dependent on the nature of the system with which the stone is interacting. And this idea is perfectly general. So how do we get a handle on the number of such "inequivalent" descriptions that are available to a given observer?

Recall that the observer begins by stating an informal description of N in the real world. Then s/he must encode this description into the symbols and strings of a formal logical structure in F. Deciding whether or not two informal, real-world linguistic descriptions are equivalent is a pretty fuzzy affair, opening up all sorts of depressing debates and semantic confusions of the kind that permeate the arts and humanities. But not so in the pristine world of F. Every formal mathematical structure in F comes equipped with its own natural notion of equivalence, a notion that can then be used to classify the informal descriptions. The idea underlying virtually all of these equivalence concepts is that two objects are taken to be equivalent if they can be transformed one to the other by a simple re-labeling of the variables used to describe them in F. In short, two objects are equivalent if they differ only in the way we look at them, i.e., by a change of coordinates. So once we have coded our informal description of N into some formal mathematical structure like a set of differential equations, a directed graph, a collection of simplicial complexes, or whatever, the natural equivalence relations for that type of structure can be employed to characterize the level of complexity of the system N. In essence, the complexity level is directly related to the number of equivalence classes that the observer creates by means of the natural equivalence relations defined for the coded version of N in F.

John Casti

The foregoing idea also provides us with a way to identify when the complexity level shifts as we move through the space of descriptions. Additional complexity appears whenever one description *bifurcates* from another. So it's exactly the bifurcation points in F that can be identified with increased complexity and, even more generally, with emergent phenomena. This observation enables us to relate the complexity of a system to things as seemingly diverse as the eigenvalue structure of matrices, the elementary catastrophes of Thom, and the bifurcation points of vector fields.

A Theory of Models

To summarize, in this essay I've argued that for complexity to become a science, it's necessary—but far from sufficient—to formalize our intuitive notions about complexity in symbols and syntax. I've further argued that it's necessary for any such formalization to respect the fact that complexity is a subjective concept. One way to do this is to focus attention on the fact that no system lives in isolation. There are always other systems like observers or controllers that are responsible for deciding upon the particular formalization to be used. And, in fact, it is actually these systems that ultimately render the verdict as to what is and isn't complex. So we come to the perhaps not-so-surprising conclusion that the creation of a science of complex systems is really a sub-task of the more general, and much more ambitious, program of creating a "theory of models." Complexity—as a science—is merely one of the many rungs on this endless ladder.

So we come to the perhaps not-so-surprising conclusion that the creation of a science of complex systems is really a sub-task of the more general, and much more ambitious, program of creating a "theory of models." Complexity—as a science—is merely one of the many rungs on this endless ladder.

Is There Chaos in the Classroom?

Woody Crane is a writer and director with Santa Fe-based Ladder Films. In 1991, he received a grant from the Space Theater Consortium, an organization of museums with IMAX/ OMNIMAX theaters, to develop a film on the subject of chaos.

By Woody Crane

The curious structure of unpredictability, popularly known as chaos, is often described as one of the fundamental sources of beauty and complexity in nature. In the past two decades the initially foreign notions of chaos theory have evolved into a powerful set of analytical techniques with an ever growing number of applications. Chaos has even been called a revolutionary new science. You might expect that chaos would be a significant new element in science education. However, in spite of its ability to capture the imagination of a large audience, chaos has failed to make a substantial impact on college curricula. What makes this generally interesting is that chaos typifies many new ideas coming out of the study of complexity. With its fresh point of view and applications which blur traditional disciplinary boundaries, chaos is pushing a frontier that resists unequivocal categorization. Thus, to some extent, chaos can be considered an arbiter for how other new and relatively broad concepts can be expected to trickle into mainstream science.

The educational system provides a natural place to gauge the importance of any new information. Things like cold fusion are quickly deflected. Better, but rather specialized discoveries like general relativity will end up as electives. But only the most basic and all-encompassing concepts like Newton's Laws will receive the highest honor: inclusion in a required undergraduate course. A quick survey of course catalogs from 25 top rated universities was rather surprising; to date, chaos has made very little apparent impact on undergraduate curricula. There are no required courses which explicitly involve chaos, and relevant electives are scarce, appearing mostly at the graduate level. In addition, many chaos-specific courses, in spite of an unusual popularity, tend to be short-lived, and occur at universities with resident or visiting chaos experts, rather than appearing as a general feature of undergraduate curricula.

Swinney's Ambitious Effort

Although chaos has not made the kind of splash one might expect, individual experiences can be illuminating. SFI Science Board member Harry Swinney was involved in a particularly ambitious effort. The experimental University of Texas at Austin course "The Subtlety of Nature: Simplicity, Complexity, and Chaos" was open to undergraduates in a variety of majors. The idea was to bring together a group of 14 lecturers in diverse fields, each of whom would show how ideas related to chaos theory have affected research in their discipline. The highlight of the course consisted of Swinney's nine inspiring lectures on the basic concepts of chaos, including filmed experiments, and classroom demonstrations.

The course was generally well received, but student comments suggested that the "new interdisciplinary science" vision of chaos may be flawed, at least as an organizing principle for education. Complaints centered around the amount of information required to understand diverse applications, and the failure of various applications to really nucleate around central concepts. In a sense, chaos may be like multiplication: just because accountants and astronomers both multiply numbers does not necessarily mean that the two groups will have results whose comparison would be illuminating. As a specific example, the UTA course included a class on chaos in lasers, which involved a big investment in specialized chemistry and physics for a small payoff. In fact, the payoff was actually shrinking as the lecture wore on: as UTA Professor W. C. Schieve pointed out regarding lasers, chaos occurs only in a particularly obscure and uninteresting situation called a "bad cavity condition." Although the balance between theory and applications could be improved if the course were attempted again, the imbalance begins to suggest why chaos tends to appear in mostly graduate-level electives stressing specialized aspects of mechanical engineering, applied physics, fluid dynamics, and chemical engineering.

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Campbell's Promising Course

The most promising current educational effort appears to be in undergraduate electives where the new ideas can be included, not so much as stand-alone courses, but as courses which have a clearer relation to an existing program of study, and a limited number of far flung examples. SFI member David Campbell recently taught a course of this variety at the University of New Mexico in Albuquerque, which was a much expanded version of his chaos course at the 1988 Complex Systems Summer School. In spite of the stuffy title "Advanced Classical Mechanics II," the course was enthusiastically received by students from a variety of disciplines including electrical engineering, physics, chemistry, and math.

Campbell's knack for organizational structure was appreciated by students. His decision to present chaos within the much broader context of nonlinear science as an extension of classical mechanics provided a relatively seamless melding of new and old, at least for physics students. For additional context within nonlinear science, Campbell chose to view chaos as the unpredictable "side of the nonlinear coin," the other being equally surprising emergent structures such as "solitons." Although Campbell was not 100% happy with the course, it appears to have been quite successful. The main gripe from students was the lack of relevant resources at UNM. The course created an enormous appetite for things nonlinear, but the available chaos-oriented books were either too specialized or too general. After the UNM course ended, one student mourned; "Chaos should be offered everywhere, but without Dave, or someone like him, I don't think it's going to happen. There's just no faculty...it's not their area of interest...everyone's optics-happy here." While the UNM course is for the moment gone, Campbell is directly addressing the lack of resources by writing a new text. He believes that chaos is just now "moving into the mainstream of science lore," and a new book aimed at undergraduates may strike the right balance. His recipe includes an introductory but rigorous treatment and, as in his course, a solid context which frames chaos within the broader picture of dynamical systems theory.

An Invisible Revolution

Because chaos enters science at such a fundamental level, it may in the long term express itself as an invisible revolution, supplanting sentences, paragraphs, and chapters in introductory texts across the board, the way the alien pods took over their human counterparts in "Invasion of the Body Snatchers." Superficially, everything looks the same, but underneath, there have been significant changes. Matt Semak, the T.A. for David Campbell's course, who is also involved in redesigning the undergraduate curriculum at Clarkson College agrees that "ideally, chaos should be accommodated through a significant restructuring of undergraduate curricula." But he points out that in spite of substantial interest on the part of undergraduates ("a lot of people show up at talks with chaos in the title"), there is a great deal of inertia to such a change. This sentiment was echoed in a recent series of articles in *The Physics Teacher*. In "Chaos: A New Scientific Paradigm or Science by Public Relations?" Max Dresden argues that when we talk about chaos, "it is better to talk about chaotic behavior rather than chaotic systems"—that "chaos should be included but there should not be too much of it." Dresden also believes that because chaos as a subject remains "sprawling and disjointed," it may be later rather than sooner that it is incorporated into the educational program.

Chaos is clearly not going to go away, but how and where it will appear in education is yet to be determined.

...until there is a formal response, the SFI's activities and educational initiatives will continue to play a major role in getting chaos, and a host of other new ideas in complexity, into the scientific mainstream.

SFI member John Holland suggests that the problem is broader than just chaos, and more substantial than simply finding ways of fitting new ideas into old structures: "If you look at almost any major university, there is a lot more attention to where the dollar goes than there was 30 years ago. Because of a lot of bottom-line issues, courses connected with longer horizons have become progressively more rare." Holland, who has seen many pioneering courses and some entire departments at University of Michigan disappear, says that "at present, the amount of risk-taking is extremely low."

Valuable Ongoing Efforts

One thing is certain: to the extent that chaos and other new ideas in complexity may be something that future scientists should know about, this traditional educational inertia, from wherever it arises, makes ongoing efforts by SFI all the more valuable. This did not escape the attention of the MacArthur Foundation, whose grant award to the SFI specifically cited the significance of the SFI's key educational role as a catalyst, stimulating change in the traditional academic community. Popular demand may ultimately be the force that drives the development of future programs in complexity. Even at present, student interest in complexity appears to be outpacing what universities are providing. However, until there is a formal response, the SFI's activities and educational initiatives will continue to play a major role in getting chaos, and a host of other new ideas in complexity, into the scientific mainstream. Indeed, one of the side effects of David Campbell's recent chaos course was, according to T.A. Semak, "Everyone started to ask about the SFI Summer School."

Book Review

One Long Argument

Thomas Kepler is an SFI postdoctoral fellow.

One Long Argument: Charles Darwin and the Genesis of Modern Evolutionary Thought, by Ernst Mayr (Harvard University Press, 1991); reviewed by Thomas B. Kepler

Our age has not only witnessed an extraordinary number of scientific revolutions, it has embraced them as objects of study in their own right. Several of them have had a significant impact outside of science proper as well as within their own particular sub-disciplines, but none has necessitated so thoroughgoing and irreversible a change in our conception of the world and our place in it as that precipitated by Charles Darwin and his Theory of Evolution. So profound has Darwin's revolution been on contemporary thought, so deeply has it formed our intellectual sensibility, that it is really quite difficult to conceive of the pre-Darwinian world view, and easy, therefore, to underestimate the extent of Darwin's reform. In his latest book, *One Long Argument: Charles Darwin and the Genesis of Modern Evolutionary Thought,* the renowned evolutionist Ernst Mayr sets out to rectify this unfortunate circumstance by laying out exactly what Darwin's theory meant to his contemporaries and examining the vigorous opposition it met on (almost) all sides.

That Darwin's influence transformed biology and went well beyond, into the larger world of ideas, is not novel and does not necessitate the publication of another book. But while reading through the evidence collected and examined by Mayr, the reader with an acquaintance with the physical sciences may be led to consider the influence that Darwin may have indirectly exerted on this area as well. This is not Mayr's intent (and let me quickly add that the responsibility for the wilder historical speculation to follow is mine alone), but it is a conclusion that follows with little effort. It is easy to imagine that Darwin's placing of humanity firmly in the realm of the natural, of nature, was critical for the fostering of an intellectual climate in which Einstein could recognize that the inherent subjectivity of the observation process demands the two great theories of relativity, and ultimately, fittingly, leads to the realization that the universe itself is not static, but evolving. In such an environment, Heisenberg could realize that the act of observation is itself inherently *physical*, inseparably a part of nature with hitherto unimaginable consequences for our view of the physical world and our attitude toward determinism. In fact, quantum mechanics might have eluded invention for some time had Darwin not prepared the ground by creating a clear break with the past and Laplacian determinism by allocating to chance a central position in his thinking. Through the intermediary of chance he essentially reconciled biology and the physical sciences, not by subscribing to the reductionist paradigm, nor by invoking a special place in the physical world for living things, but by invoking the radical and thoroughly modern notion of dynamical hierarchy. While admitting that it is undoubtedly true that processes going on inside living things obey the laws of physics (Mayr counts 106 references to such "laws" in the 490 pages of the *Origin of Species*), Darwin implicitly claimed that this fact is virtually irrelevant to the large-scale unfolding of events in the biological realm. We are just now beginning to investigate seriously the percolation of information from "lower" dynamical levels to "higher," and the relative independence of events appropriately described at these two different levels. Thus, most tantalizing for me is the impression that Darwin might be the first great forefather of the still embryonic sciences of complexity.

Darwin was an exceptionally gifted observer, and in struggling to explain his observations, he saw no alternative to changing the very nature of biological investigation. He argued that its true object must be the individual, rather than the ensemble or its supposed Platonic ideal. He could no longer search for eternal laws when the importance of historical contingency was everywhere in evidence. In short, as Mayr suggests, Darwin ushered in the modern era by rejecting *essentialism.*

Mayr argues that to treat "Darwin's theory" as a single entity is to invite serious misunderstanding from the start. It is, in fact, a complex tapestry of theories, of which he enumerates five distinct strands. He further lists seven ideological beliefs common to Darwin's time that had to be toppled before his vision could be realized. The first four of these beliefs are religious and underlie the notorious (and intellectually irrelevant) rejection of Darwinism by certain curiously influential religious leaders in the U.S. One of the remaining three, the belief in teleology, is primarily of historical interest. In rejecting the efficacy of final causes, Darwin broke with most of the biologists who preceded him. The other two are of considerable import even today. One is the belief in physicalist determinism. In breaking with this tradition, Darwin rejected the ascendent paradigm of his day. The last is essentialism, which Mayr describes as the belief that true nature consists of constant, immutable types, or Platonic ideals, and is arguably a component of both teleology and determinism.

In rejecting essentialism, Mayr argues, Darwin rejected two thousand years of intellectual tradition, from Pythagoras and Plato to Netwon and Descartes, to Darwin's contemporaries. Elementary particle physics remains, perhaps, the most undiluted contemporary expression of essentialism with the belief that its Standard Model (augmented appropriately with some as-yet-unknown theory of quantum gravity) when looked at from the right angle, yields up all the phenomena of the world. The post-modern challenge to that view (and to particle physics traditional claim to the cutting edge) is found in the sciences of complexity. Within this new methodology, the laws of particle physics, while useful in describing the behavior of quarks and leptons, cannot, even in principle, suffice to describe the macroscopic behavior of our world. Euclid's lines and planes must share the stage with Mandelbrot's fractals, no longer dismissed as pathologies. Laplace's omniscient demon has been foiled by the ubiquity of chaos and uncomputability. In many respects, energy and its conservation take a back seat to entropy and its creation. For many researchers, these developments mark the new frontiers of science, and the data presented by Mayr, for altogether different reasons, present Charles Darwin as a founder of this trend.

The book itself, of course, deals with a much larger range of issues than I've presented here, many of them seemingly of only marginal interest to those without a personal stake in evolutionary biology. Arguments over allopatric versus sympatric speciation are not likely to generate much heat among non-specialists. Even here, however, there are lessons to be learned. Darwin came to his revolutionary ideas while considering very specific, concrete problems. One of the critical steps in the development of his thought came after his realization that the mockingbirds found on three different islands in the Galapagos belonged to three different species, not merely different varieties. He did not foment the overthrow of essentialism as an exercise in pure thought. Rather, his revolution *emerged* from his painstaking empirical observations.

Mayr has written this book for a "general" audience, but much of it presupposes some fairly non-trivial knowledge of the issues. It is rather short at 164 pages (plus references and a helpful glossary) and, unfortunately, this brevity comes at the expense of completeness. For example, after saying that "...the objection is sometimes raised that the [neo-Darwinian] evolutionary synthesis can shed light neither on the level of the gene nor on trans-specific levels...," he replies simply that "...this objection is without basis has been shown by Grant...Stebins and Ayala...and other defenders of the synthesis." He does provide complete references, of course, but in a book of this kind, a pointer to the technical literature is a poor replacement for a more thorough discussion of the matter within the pages of the volume in hand.

In spite of this shortcoming, the book is enjoyable and stimulating, and recounts the extraordinary contributions of Charles Darwin in a uniquely transparent way. The book is bound to be of great interest to all for whom the word *"evolution"* denotes not only one of the great triumphs of science, but also a fundamental property of the scientific endeavor itself.

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Lectures Volume IV

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1992 Programs and Activities

Research Networks

The Economy as an Evolving, Complex System
Leader: Martin Shubik, Yale University
Time Series Forecasting
Leader: J. Doyne Farmer, Prediction Company
Complexity, Entropy and the Physics of Information
Leader: Wojciech Zurek, Los Alamos National Laboratory
Adaptive Computation
Leaders: John Holland, University of Michigan, and Melanie Mitchell, University of Michigan
Theoretical Immunology
Leader: Alan Perelson, Los Alamos National Laboratory
Applied Molecular Evolution
Leader: Stuart Kauffman, University of Pennsylvania
Artificial Life
Leader: Christopher Langton, Los Alamos National Laboratory
Macromolecular Sequence Analysis
Leader: Alan Lapedes, Los Alamos National Laboratory

Scientific Meetings

January 12-25
1991 Complex Systems Winter School
(Held in Tucson, Arizona)
Peter Carruthers, University of Arizona
February 18-22
Working Group on Theory of Money and Financial Institutions
Martin Shubik, Yale University
February 20-23
Adaptive Processes and Organization
Michael Cohen, University of Michigan
David Lane, University of Minnesota
February 25-March 1
Resource Stress and Response in the Prehistoric Southwest
Joseph Tainter, U.S. Forest Service
March 10-15
Founding Workshop in Adaptive Computation
John Holland, University of Michigan
John Miller, Carnegie-Mellon University
Adaptive Computation Directorate
March 20-23
Increasing Returns
Martin Shubik, Yale University
April 16-19
Theoretical Computation in the Social Sciences
Michele Boldrin, Northwestern University
John Miller, Carnegie-Mellon University
April 24-26
Biology and Economics: Overlapping Generations
Martin Shubik, Yale University
May 1-4
Working Group on Theory of Money and Financial Institutions
Martin Shubik, Yale University
May 14-17
Comparative Time Series Analysis
Neil Gershenfeld, Harvard University
Andreas Weigend, Xerox Palo Alto Research Center
May 24-26
What OR Models have to Offer CAS, and Vice Versa
John Holland, University of Michigan
Stephen Pollock, University of Michigan
June 1-26
1992 Complex Systems Summer School
Lynn Nadel, University of Arizona
Daniel Stein, University of Arizona
June 15-19
Artificial Life III
Christopher Langton, Los Alamos National Laboratory
July 8-15
Integrative Workshop: Common Principles of Complex Systems
George Cowan, SFI
October 28-30
Audification Workshop
Gregory Kramer, Clarity

Public Lecture Series

March 25
Artificial Life
Christopher Langton, Los Alamos National Laboratory
April 25
The Goddess and the Computer
(Balinese Water Temples)
Steve Lansing, University of Southern California
May 20
Virtual Reality
Thomas Furness, University of Washington
June 24
Megaproblems and Micromodels:
Nonlinear Dynamics and Global Welfare

Activity Updates

These meetings, schools, and initiatives actually represent only the tip of the iceberg in terms of SFI's overall activities. It is, in fact, impossible to capture within the limited confines of the Bulletin summaries of the dozens of residential and off-campus collaborations that are currently in progress. These programs do, however, present a broad sketch of SFI's current work.

Complex Systems Winter School

Peter Carruthers
Physics, University of Arizona

The first Complex Systems Winter School was held in Tucson, Arizona, January 12–24, 1992. Headed by Peter Carruthers of the Physics Department at the University of Arizona, the intensive program attracted nearly thirty participants, some of them alumni from the complex systems summer schools.

Sponsors were the Santa Fe Institute, the Center for Nonlinear Studies at Los Alamos National Laboratory, and the University of Arizona.

The Winter School considered the geometrical and dynamical behavior of scaling complex systems. Topics covered included turbulence, percolation, self-organized criticality, 1/f noise, the mathematics of hierarchical systems (emphasizing fractals), fractal graphics, and scaling structures in physiology, in galaxies, and elsewhere. Faculty included Philip Anderson, Princeton University, on scaling and condensed matter physics; Mitchell Feigenbaum, Rockefeller University, on scaling theory of one-dimensional maps; Michael E. Fisher, University of Maryland, on scaling in statistical mechanics; Murray Gell-Mann, California Institute of Technology, on Zipf's law and related mysteries, and nature conformable onto herself; Larry Gray, University of Minnesota, on time evolution on lattices; Erica Jen, Los Alamos National Laboratory, on cellular automata; C. David Levermore, University of Arizona, on lattice gas fluid mechanics; Paul Meakin, E.I. du Pont Nemours & Co., on applications of fractals and scaling; and Bruce West, University of North Texas, on fractal physiology and chaos in medicine. The aim was to provide graduate students and postdoctoral scientists with an intensive introduction to these closely related and ubiquitous phenomena, leading to a current research-level knowledge of the subjects.

Plans are underway for a second Winter School in January, 1993. Possible topics for the program's focus may be either information, computation, and complexity or the dynamics of conflict.

Resource Stress, Economic Uncertainty, & Human Response in the Prehistoric Southwest

This February meeting was the second SFI workshop to study prehistoric Southwestern societies as complex adaptive systems. The first, held in the fall of 1990, followed a series of advanced seminars at the School of American Research. This most recent meeting, co-sponsored and funded by the U.S. Forest Service as part of its new program in archaeological research in the Rocky Mountain region, was chaired by Joseph Tainter (USDA Forest Service).

What is intriguing about this work on cultural evolution is that it looks at the archaeological record to try to understand if the forces that underlie the rise and fall of societies, in this case a local one, can be correlated with fluctuations in available resources. In a world where predictions are regularly made about the consequences of use patterns of natural resources, it seems instructive to understand better how use patterns related to societies in the past and what forces have led to the collapse of flourishing societies.

This meeting focused on two issues. The first, *Factors of Vulnerability*, included matters such as population trends, climate change, degree of aggregation, availability of naturally occurring foods, agricultural successes and failures, and the costs of supporting political, economic, and ritual systems. The second, *Strategies or Failure of Adaptation*, dealt with subtopics such as increases or decreases in sociocultural complexity, aggregation/dispersion, local/regional abandonments, range expansion/contraction, subsistence shifts and intensification, technological change, economic specialization, and population decline.

Recurrent themes throughout all the talks were risk and variety. Prehistoric Southwesterners were flexible in their adaptations to a risky environment. Their responses included social arrangements for sharing; adjustments to anthropogenic changes; use of famine foods; storage; technological adjustment; environmental manipulation; strategies for obtaining protein; and strategies for settlement relocation.

Plans are being developed for two additional conferences. The first will probably be next year and will deal with the same topic in the North American eastern woodlands. The second will be held in Austria in Fall 1993 and will address the topic internationally. Proceedings from the recent meeting will be published as part of SFI Studies in the Sciences of Complexity book series.

Adaptive Processes and Organization: Models and Data

"There is a widespread conviction that social science studies of or-

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ganization are on the verge of a significant shift in point of view," wrote Michael Cohen (Institute of Public Policy Studies, U. Michigan) in his proposal for the SFI workshop on Adaptive Processes and Organization. "This is motivated by a longstanding dissatisfaction with an account of organization rooted in the economic logic of individual rational maximization and its collective consequences." The new elements in the picture are the revival of interest in the effects of history and institutional structures and the steady emergence of intellectual tools that support theories based on local adaptation and its global consequences. Social scientists are more and more using concepts developed by computer scientists and biologists (e.g., neural networks, John Holland's genetic algorithms and classifier schemes, and Stuart Kauffman's Boolean network models). Further, biologists, computer scientists, and physical scientists increasingly appeal in their own theorizing to analogies to human organizations, and seem interested in moving beyond casual analogy to a more serious encounter with the best research results on the systems that are often inspiring their models.

Experimenting with a novel format at the Adaptive Processes and Organizations workshop, Gérard Weisbuch, CNRS, presented Axelrod's paper on coalition formation and drew out its connection to spin glass and neural net models.

It's too soon to know if the Adaptive Processes and Organization workshop held at SFI in February will contribute to the sea change described by Cohen. However, it was described by several individuals as ranking among the most stimulating meetings they had attended in their entire careers—one workshop member dubbed it "a sabbatical in miniature." The meeting drew 25 participants, social scientists drawn from university departments of economics, political science, and sociology, from schools of business, from the government, and from the private sector. Those from other fields were mathematicians, computer scientists, physicists, and theoretical biologists who have developed tools to model complex adaptive systems.

The group experimented with a novel format. Seven papers were distributed and read in advance. Each provided either a model or data that might stimulate the group. Five papers were by social scientists (John Padgett, Karl Weick, James March, Robert Axelrod, and Michael Cohen). Two were by non-social scientists (John Holland and Stuart Kauffman). The papers were presented to the group not by their authors, but by another participant who hailed from some quite different field. So, for example, Gérard Weisbuch presented Axelrod's paper on coalition formation and drew out its connection to spin glass and neural net models. Dan Levinthal presented Kauffman's paper on biological NK models, and showed its relation to work on business strategy and technological innovation. Les Glasser connected Weick's study of carrier flight-deck crews to issues arising in distributed artificial intelligence. This worked to create a common ground for discussion quickly. The result was a substantial gain for the group, who had a shared awareness of definite and relevant data and models that could be referred to in the discussions that occupied the remainder of the meeting.

Two broad domains of discussion emerged, each with rich potential for further collaboration. The first centered on models that shared a common root metaphor of adaptation as landscape exploration. Several participants interested in these landscape models found it promising to explore their common fascination with technological innovation in economies. Levinthal and Kauffman may work along these lines. Introduction of Hebbian rules into economic and political landscape models, suggested also by Weisbuch, turned out to be quite interesting to both Axelrod and Levinthal. The second, sometimes referred to as the "structuralist" concern, centered on how multiple agents interact to give rise to a superordinate entity with its own coherence, that may in turn constrain the subsequent actions of the lower-level agents. Weick, Padgett, Leo Buss, Holland, and Axelrod are especially interested in pursuing questions about the emergence and persistence of organizational entities. There is also strong interest in convening at SFI a working group to spend an extended period of time on one or two projects/data sets ready to support collaborative, interdisciplinary analysis.

Theory of Money and Financial Institutions

This Spring SFI's working group on the Theory of Money met twice at the Institute to review current work and update collaborations. The purpose of this research initiative is to understand the basic nature and role of various financial instruments and institutions—in particular fiat (or outside) money, inside monies or credit, and bonds. The research is trying to clarify how interest rates are determined (and what leads to the term structure of interest rates) and how markets and financial institutions function. In particular, what is a minimal set of instruments and institutions needed to run an efficient economy—and what costs are incurred by a society for which some of these elements are missing?

The approach adopted to these questions rests on the concept of strategic market games. These are economic process models that are constructed as playable and potentially experimental market games. In these games, price formation mechanisms, markets, and financial instruments are explicitly specified. Thus they can serve as testbeds for behavioral simulations where the performance of human and artificial agents can be compared to the predictions of noncooperative equilibrium and general equilibrium theory. Preliminary work already shows paradoxical results concerning the relationships among monetary wealth, stocks and flows of money, and the needs for and nature of bankruptcy rules to define the treatment of unpaid debts in a dynamic system.

The research draws on the expertise of economists, learning theorists, and computer modelers, as well as the mathematics of stochastic processes, dynamic programming, and game theory. Members of the working group are Robert Anderson (UC Berkeley); Predeep Dubey (SUNY Stoney Brook); John Geanakoplos (Yale); Yannis Karatzas (Columbia); John Miller (Carnegie-Mellon); Lloyd Shapley (UCLA); Martin Shubik (Yale); and William Sudderth (Minnesota).

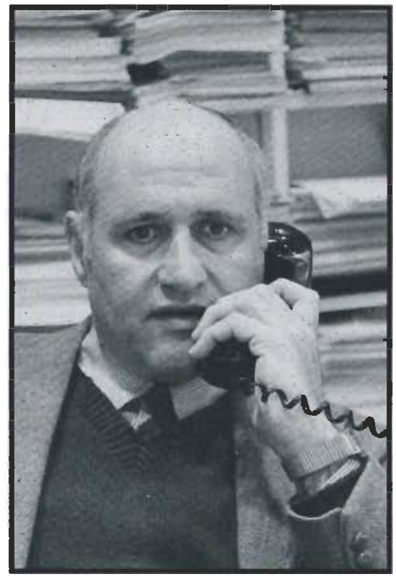
Increasing Returns

The correct characterization and understanding of increasing returns is one of the key problems in economic theory and practice. A variety of analytic, computational, and empirical issues relating to increasing returns was the focus of a recent SFI workshop chaired by Economics Program Director Martin Shubik.

There are many different views of the causes of economies of scale in production. The views include the simple geometric observation that the amount of fencing required to enclose a square field grows as the square root of the size of the field, as does the inventory safety level as a function of the volume of sales in an uncertain environment. A completely different view of increasing returns comes from the presence of indivisibilities in the economy. Still another is provided by those who consider growth based on stochastic processes, where, for example, a new purchase is based on information obtained by random encounters. This type of process is characterized by a process where early chance events lead to increasing advantages to the fortunate firm.

Consider a model developed at SFI by External Professors David Lane and Brian Arthur. Suppose a group of new products are competing for adoption. Each potential adopter decides which of the products to choose on the basis of their prices, which he knows, and performance characteristics, about which he is imperfectly informed. To augment the publicly available information about the products, he samples in addition some of the previous adopters, finding out from each which was adopted and some information about how well the product has performed. Clearly, in this situation, more information is likely to be generated about the products that have been more frequently adopted. Can this informational feedback lead to increasing returns—that is, can a product increase its market share solely on the basis of the information effects of its current market lead? The answer is, "sometimes," and it turns out to depend in subtle (but quantifiable) ways on certain psychological characteristics of the adopting agents. In this model, chance enters the picture through the sampling procedure whereby agents acquire information; thus, who learns what from whom constitute the "small events" that determine whether one or another of the products dominates the market or whether they ultimately share the market with one of the (generally very few) stable frequency allocations that can be computed from the agent and product characteristics that parameterize the model.

Another area which is not quite so easily characterized as increasing returns yet appears to be closely related is evolutionary economics and economic change. It has been proposed that variables as different as technology, law, the structure of firms and industry structure, public programs, and institutions more generally, change as they do as a result of an evolutionary process. If this is accepted, it raises the question of whether the results of evolutionary processes can or should be modeled as the equilibrium of a maximizing process. This question has divided biologists concerned with evolutionary processes and outcomes in their field, and the question is equally divisive in social science and economics. Appreciation of the behavior of variables subject to nonlinear dynamic processes suggest that explicit formal evolutionary modeling is the only appropriate way to analyze evolutionary behavior. Such a research program, however, should not proceed independently of detailed understanding of the actual situations, processes, and histories.



Martin Shubik, Yale University and SFI Economics Program Director

Theoretical Computation in Economics

While the theoretical computation approach has been most widely used in the physical sciences, it is

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likely that these techniques also will have a major and lasting impact on economic theory and the study of financial markets. To accelerate progress in these areas, SFI scheduled a "Theoretical Computation in Economics" workshop held at the Institute in April 1992.


Michele Boldrin


John Miller

The meeting was chaired by Michele Boldrin (Northwestern) and John Miller (Carnegie-Mellon). The Alfred P. Sloan Foundation, National Bureau of Economic Research (General Equilibrium Program), and National Center for Supercomputing Applications (University of Illinois, Urbana-Champaign) joined the Institute in the sponsorship of the conference.

The new computational tools not only complement both existing theoretical and experimental methods, they also hold promise of a number of new opportunities for productive analysis. One obvious application is the analysis of existing theoretic models. Economists have developed a large set of models. Using standard analytic techniques they have been able to derive the basic properties of these models, including: the existence of equilibria, the qualitative properties of such equilibria, some notions of the model's dynamics, the relationship between the model and real-world data, etc. Nevertheless, the preservation of analytic tractability has required a variety of compromises, including excessive aggregation, the simplification of some possibly important features, and often times only the proof of existence but not necessarily the ability to derive the qualitative properties of the equilibrium solution. To go beyond these limitations, it is likely that computation-intensive techniques must be used. Another application of computation is the estimation of appropriate parameter values for the theoretical model.

A complementary field of inquiry is the use of computer-based techniques as the core of the model. These models release researchers from traditional analytic bounds and allow them to explore systems which heretofore have not been easily modeled by existing techniques. Although this area is new, a number of interesting findings have already been made. This modeling approach also offers other opportunities. The methodology creates an easily manipulated model world in which one can generate and test theoretical hypotheses. It also suggests a new direction for economic theory whereby theoretically plausible models of economic behavior are formulated and then placed in an easily implemented empirical framework. Beyond the above, this methodology has a practical application to some important real-world phenomenon. For example, computer techniques provide opportunities to study auction markets. Some questions that can be explored are: what are their stability properties, can strategies be exploited, and what types of strategies will do well in these markets? One can also test new institutional designs with artificial agents before actually implementing the markets.

The meeting will explore these issues with the aim of defining major areas for further inquiry and, if appropriate, establishing a research network.

Biology and Economics: Overlapping Generations

A key problem in biology, economics, and demography is understanding the mechanisms controlling the growth and evolution of population and the intergenerational transfer of resources. The April meeting "Biology and Economics: Overlapping Generations" is aimed at promoting useful interdisciplinary communication among biologists, economists, anthropologists, and others working on these issues. The meeting was chaired by Martin Shubik (Yale), Director of SFI's Economics Research Program, and was made possible by support from the Gordon and Ann Getty Foundation.

Some economists talk of human capital and consider family size selection, marriage, education, health, and old-age care from the viewpoint of consumers optimizing investment in human capital. Other economic theorists considering overlapping generations models of the economy are directly concerned with economic fixes for glueing the generations together and seeing how far market and financial mechanisms can be used to transfer resources from generation to generation by individuals with little or no social concern. In such work, motivation for reproduction and the leaving of inheritances may be covered by assumptions which are not necessarily in accord with the views of other disciplines.

In a different endeavor some biologists joining together with game theorists have evolutionary models of the "selfish gene" where the central actors are the genes, and the *homo oeconomicus* of the economist becomes a mechanism being run by the real players, the optimizing genes. Sociobiologists offer another view of evolution. Yet a different viewpoint is provided by demographers, sociologists, and anthropologists who have a mixed bag of models of human society where births, deaths, and population growth are accounted for by a variety of biological, economic, sociological, and cultural factors.

The givens of one type of analysis are often the variables of another. Furthermore, methods which have apparently worked well in one discipline are often borrowed by other disciplines. Frequently a preliminary mode of borrowing involves the liberal use of analogy and metaphor. This cross-disciplinary activity has both considerable advantages anc dangers. The appropriate skepticism and caution must be manifested when using analogies and borrowing methods from other disciplines. Finally, different social, physical, and biological sciences operate on different time spans. Economics and conscious rational behavior tends to be more successful in the short run. Economic action takes place in the context of the polity which lies within the society, rooted in its culture and bounded by the biological aspects of the human race. All are in a state of change and evolution, and each evolves on its own inherent time scale.

Some of the questions considered during the workshop were: how far can the models based on individual selfish optimization be pushed? What is being optimized by whom? Do the concepts of human capital and wealth have clean analogies in biology? Are culture and even the financial network of an economy exoneural networks which provide control mechanisms on individual selfish humans in a manner which as no close counterparts in the evolution of other species?

It is anticipated that several research collaborations will result from the meeting.

Comparative Time-Series Analysis

Time-series analysis problems are central to a wide range of disciplines, including physics, biology, and economics. New techniques, such as the use of connectionist models for forecasting and time-delay embedding to estimate complexity, promise to provide insights unavailable through more traditional statistical and econometric time-series techniques. Yet the realization of this promise has been hampered by the difficulty of making rigorous comparisons between competing techniques within a discipline and by the difficulty of making comparisons across discipline boundaries.

1992 Visitors

January to April

Kenneth Arrow, *Stanford University*
John Casti, *Technical University of Vienna*
Rob de Boer, *University of Utrecht*
Eric Chopin, *Ecole Normale Supérieure de Lyons*
Guillemette Duchateau, *Ecole Normale Supérieure, Paris*
Ivan Dvorak, *Prague Psychiatric Center*
Wolfgang Fikentscher, *University of Munich*
Jean-Michel Grandmont, *CEPREMAP, Paris*
Greg Kramer, *Clarity*
E. Atlee Jackson, *University of Illinois*
Joel Keizer, *University of California, Davis*
Hidetoshi Konno, *University of Tsukuba*
Kristian Lindgren, *Chalmers Institute of Technology*
André Longtin, *University of Ottawa*
Melanie Mitchell, *University of Michigan*
Milan Palus, *Prague Psychiatric Center*
Ulrich Parlitz, *University of Darmstadt*
Paul Phillipson, *University of Colorado*
Dan Pirone, *University of Delaware*
Stephen Pollock, *University of Michigan*
Tom Ray, *University of Delaware*
Luis Reyna, *IBM T.J. Watson Research Center*
Martin Shubik, *Yale University*
Gérard Weisbuch, *Ecole Normale Supérieure, Paris*
Andy Wuensche, *London*

Expected Visitors (May–December)

Charles Anderson, *J.P.L.*
Joseph Atick, *Institute for Advanced Study*
Denis Baylor, *Stanford University Medical School*
William Bialek, *NEC Research Institute*
Carlton Caves, *University of Southern California*
Francoise Chatelin, *University of Paris*
Daniel Fivel, *University of Maryland*
Scott Fraser, *California Institute of Technology*
Murray Gell-Mann, *California Institute of Technology*
Charles Gilbert, *Rockefeller University*
John Holland, *University of Michigan*
Alfred Hubler, *University of Illinois*
Terry Jones, *University of Indiana*
Christof Koch, *California Institute of Technology*
Tim Kohler, *Washington State University*
Blake LeBaron, *University of Wisconsin*
Zhaoping Li, *Institute for Advanced Study*
André Longtin, *University of Ottawa*
Carlo Lucheroni, *Universita Delgi Studi di Perugia*
David Mackay, *Cambridge University*
Günter Mahler, *University of Stüttgart*
Marcus Meister, *Harvard University*
John Miller, *Carnegie-Mellon University*
Kenneth Miller, *California Institute of Technology*
Melanie Mitchell, *University of Michigan*
Harold Morowitz, *George Mason University*
Richard Palmer, *Duke University*
R. Clay Ried, *Rockefeller University*
Peter Schuster, *Institut für Molekulare Biotechnologie, Jena*
Terrence Sejnowski, *The Salk Institute*
Joshua Smith, *Cambridge University*
Daniel Stein, *University of Arizona*
Charles Stevens, *The Salk Institute*
Michael Stryker, *University of California Medical School*
Guy Theraulaz, *CNRS, Marseille*
David Van Essen, *California Institute of Technology*

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Neil Gershenfeld

Andreas Weigend

Late last year SFI researchers Neil Gershenfeld (Harvard) and Andreas Weigand (Xerox Palo Alto Research Center) ran a time-series prediction and analysis competition through the Santa Fe Institute to help clarify the conflicting claims. A small set of interesting experimental data that spans a wide range of attributes of interest (such as low- versus high-dimensional, deterministic versus stochastic, continuous versus discrete, scalar versus vector, etc) was made publicly available over computer networks, and then quantitative analyses was accepted in the areas of (1) forecasting (using the data to predict a segment of the data set that is not made publicly available), (2) numerical measurement (estimating such quantities as the number of degrees of freedom of the underlying system or the information production rate), and (3) system identification (inferring a model of the governing equations from the time series).

This May 1992 meeting studied the results of the competition. It offered a unique opportunity to advance the understanding of time-series analysis in a wide range of disciplines, because participants had analyzed identical data sets, and quantitative evaluations of the relative performance of their techniques were available. The thrust of the workshop, then, consisted of a common effort to understand the overall results, rather than isolated presentations by investigators claiming research advances. If some techniques prove to perform much better than others, it will clearly be important to understand why this is so; if the performance differences on a class of problems are small, it will be equally important to understand why the theoretical distinctions break down in practice. The workshop participants were drawn from the entrants in the competition. One day of the workshop was spent on each section of the competition, and the competition time-series data was made available on workstations during the workshop so that new ideas can be implemented as they arose. The proceedings of the meeting will be published as part of SFI Studies in the Sciences of Complexity series.

Summer School

More than fifty participants have been selected to attend the fifth annual Summer School on Complex Systems scheduled May 31 to June 26, 1992 at St. John's College in Santa Fe. Co-Directors are Lynn Nadel, Psychology, University of Arizona, and Daniel Stein, Physics, University of Arizona.

The Center for Nonlinear Studies at Los Alamos National Laboratory, the Los Alamos Graduate Center at the University of New Mexico, Sandia National Laboratories, and the Universities of Arizona and California, join SFI in sponsoring this program. Additional support for the school is provided by the National Science Foundation, the National Institute of Mental Health, the U.S. Department of Energy, and the Office of Naval Research.

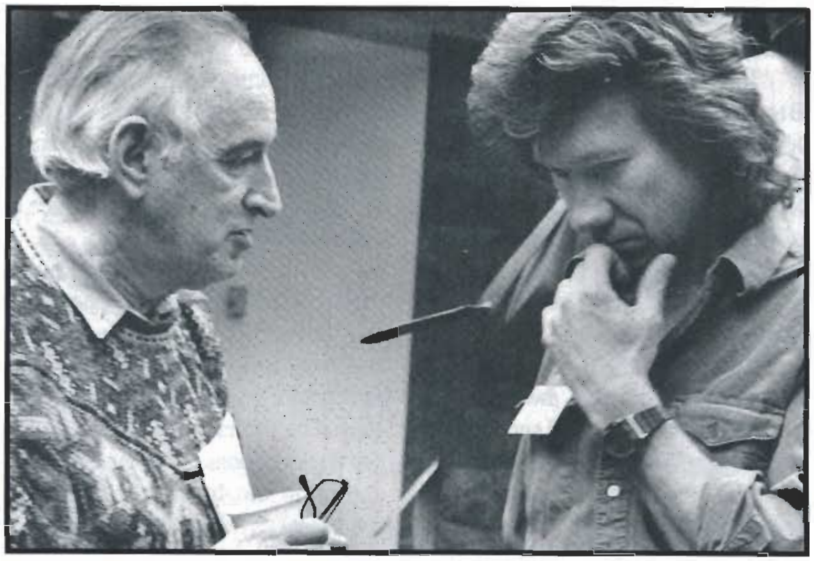
The Complex Systems Summer School provides graduate students and postdoctoral fellows with an introduction to the study of complex behavior in mathematical, physical, and living systems. Emphasis is on combining the understanding of phenomena derived from traditional approaches with that gained from the novel ideas of complex systems. The twelve or so mini-courses within the program focus on developing techniques for measuring and analyzing complex behavior, and applying these techniques to the study of a limited number of specific mathematical, physical, and living systems. This year's topics include genetic algorithms and the ecology of computa-

Daniel Stein (far left), University of Arizona and co-director of the 1992 Complex Systems Summer School is shown with some of the 1991 Summer School faculty: (from left) Alan S. Perelson, Los Alamos National Laboratory; Christopher Lanton, Los Alamos National Laboratory; Richard Palmer, Duke University; Marcus Feldman, Stanford University; and Peter Wolynes, University of Illinois, Urbana-Champaign.

tion; systems with quenched disorder including spin, vortex, and other glasses; the geometry of excitability; nonlinear analysis of brain function; protein biophysics; and nonlinear dynamics and international security issues. In addition to their formal lectures, the faculty are available during the day for informal discussions with the students and frequently schedule supplementary tutorial sessions in the evenings. A computer laboratory containing a range of desktop microcomputers, workstations, and graphics devices is an integral part of the school.

The school has several important outcomes. One product is a yearly lecture-note volume. These texts, which have appeared since 1989, are on their way to becoming standard references in the sciences of complexity. They provide a unique introduction to a broad range of topics within a complex systems context. Equally important from the Institute's perspective is the role the School plays as a resource for SFI's research family. Alumni—including Andreas Weigend and Neil Gershenfeld whose time-series project is described in this issue—have gone on to do extended work at SFI. In addition, several senior members of the Institute's scientific community were introduced to SFI as summer school faculty.

To date, the School provides the only offering of this kind in the nation. While several universities, including some of the sponsoring institutions of the Summer School, are beginning to establish centers for research and teaching in complex systems, strong programs around the country are still several years in the future.



Christopher Langton (right), Los Alamos National Laboratory and coordinator of Artificial Life III, and David Robinson, Carnegie Corp., at the recent Science Symposium

Third Artificial Life Symposium

Mid-June is the date for what promises to be the largest symposium yet sponsored by SFI, the third Artificial Life conference—Alife III. More than 500 hundred participants are expected for the five-day meeting chaired by SFI External Assistant Professor Christopher Langton. The event is co-sponsored with the Center for Nonlinear Studies at Los Alamos National Laboratory. Additional support is provided by the Advanced Technology Group at Apple Computer.

Artificial Life is synthetic biology. It involves attempts to put together life, evolution, and other biological phenomena from first principles for the purpose of scientific experiment and engineering applications. As such, Artificial Life is not restricted to the medium of carbon-chain chemistry in its attempts to synthesize biological phenomena. Rather, it uses whatever medium is most appropriate and convenient for the synthesis of the phenomenon under study. Because of their extreme behavioral plasticity, computers are often the medium of choice.

Furthermore, the lifelike behaviors and structures synthesized by Artificial Life need not be restricted to those found in the products of the evolution of life on earth. Had conditions been slightly different on the early earth, the evolutionary process would have led to entirely different products, with their own distinct biology. It is extremely important for theoretical biology that we explore the ensemble of what could have evolved, not just what did evolve.

The scope of Artificial Life, then, is broader than traditional biology. Artificial life is an attempt to extend the theory and practice of biology beyond life as we know it to the domain of life as it could be, in any of its possible incarnations.

The first four days of the conference will consist of talks on the synthesis of lifelike phenomena in wetware, software, and hardware, in that order. The fifth day will be devoted to an "Artificial 4-H Show" including a Lego-Logo design competition, Robot Olympics, a micromouse contest plus talent shows and other events for hardware and software organisms. Evenings will be given over to poster sessions, special interest group meetings, a video-night, and a night at "The Alife Cafe,"

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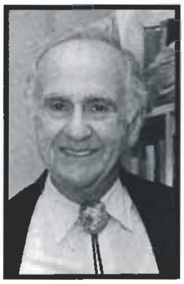


George Cowan, SFI Member and past President, who chairs the Common Principles of Complex Systems workshop steering committee

an evening of general discussion and philosophical debate.

Invited speakers include Rodney Brooks (MIT); Leo Buss (Yale); Jean-Louis Deneubourg (Brussels); Gerald Joyce (Scripps Clinic); John Koza (Stanford); Hans Moravec (Carnegie-Mellon); P. Prusinkiewicz (Regina); Tom Ray (SFI and U. Delaware); Julius Rebek (MIT); and Luc Steels (Brussels).

Artificial Life III, the proceeding volume from this meeting, will become a part of the SFI series in the sciences of complexity. Also anticipated is a video proceedings from the conference, a compilation of computer experiments and simulations.

Common Principles of Complex Systems

One of SFI's most important meetings in 1992 is a workshop in mid-July on common principles of complex systems. This meeting will review work done at SFI and elsewhere over the past half-dozen years, compare approaches and results, and, it is hoped, begin to construct an overview of the commonalities in the behavior of complex systems as well as define the directions for new research. This program is being directed by a steering committee chaired by founding SFI member and past President George Cowan.

The introductory sessions will be devoted to discussion of the fundamental concepts and questions in the sciences of complexity and will be largely theoretical. Six speakers representing a variety of viewpoints will address this same subject, followed by discussion. This part of the conference will be followed by a portion devoted to selected topics representative of the broad spectrum of SFI interests, ranging from non-adaptive systems at the edge of adaptation to complex, adaptive learning systems in biological, neural, social, human behavioral, and learning, and computational sciences. The program will close with a day devoted to revisiting all the major questions with the intention of defining a consensus on integrative themes and some sense of the immediacy and importance of unanswered questions.

"The meeting," Cowan notes, "will provide a historic opportunity to celebrate the fifth anniversary of sustained research at SFI by summarizing and emphasizing a number of shared ideas that have emerged from our deliberations." Proceedings will appear in the Institute's Studies in the Sciences of Complexity series.

Audification Workshop

Auditory Display includes the nascent fields of sonification (the auditory equivalent of data visualization), and audification (making audible such waveform data as radio telescope or seismic information). While sound has been used to comprehend data in isolated experiments for perhaps forty years, only recently has the technology been available to make auditory display techniques truly viable. The driving force behind these techniques, however, is the torrent of information now presented to scientists for comprehension. Auditory display promises a significant development in data comprehension and computer/human interface akin to data visualization. Applications range from geophysical exploration to modeling of complex systems such as ecosystems or turbulent processes. Also included are data base navigation and enhanced education via the use of multi-modelling software.

In October 1992 SFI will sponsor the first International Conference on Auditory Display (ICAD). The meeting is chaired by composer/sound engineer Gregory Kramer who draws on many years' experience working with sound and electronic music techniques. The conference will bring together in a concentrated workshop setting researchers working in areas related to auditory display including workers developing specific techniques for their disciplines such as chemistry and computer diagnosis along with people working on generalized techniques that may readily apply to any discipline. Additionally a small number of statisticians, scientists concerned primarily with visualization, computer/human interface specialists, and others will participate. Participants will present their current research work with the aim of defining future directions of the field.

The proceedings of this conference, part of the SFI series, will be the first publication devoted entirely to auditory display. In addition, a compact disk, audio cassette, and/or a video with quality stereo sound will be produced from the work of the conference.

What OR Models Have to Offer to CAS, and Vice-Versa

Operations Research is a collection of models, methods, and mathematics that allow one to analyze and understand "operational" aspects of the world—that is, those dealing with systems of men, machines, organizations, information, and preferences. During this May workshop, participants compared and contrasted Operations Research (OR) models with SFI's work on complex adaptive systems (CAS). Part of the SFI/University of Michigan Research Collaboration, the meeting was co-chaired by SFI External Professor John Holland (U. Michigan) and Steven Pollack (U. Michigan). It was partly supported by the Joyce Foundation.

In the words of the co-chairs, "The time is ripe for a meeting at which these two styles of using math ematical and computer models to study complex phenomena can be compared, where a common language can be developed and thus information and research results shared with an anticipated outcome of cross-fertilization of ideas." Topics included an exploration of the commonalities and differences between the operations research and complex adaptive systems approach with emphasis on the use of computer models to perform "gedanken" experiments in CAS as compared to the (putative) emphasis on construct validity of OR models; measuring the "goodness" or "quality" of mathematical models of complex phenomena; measuring the performance of optimization heuristics and algorithms for truly large-scale (and possibly non-stationary) situations; and discussing these points with reference to specific research interests such as combinatorial optimization or *n*-armed bandit problems.

Adaptive Computation

The Adaptive Computation residential research initiative geared up in May, 1992 when Melanie Mitchell (U. Michigan) began a one-year residency as program director. Mitchel's visit is just one indicator that this effort is targeted for major expansion in 1992.

The SFI adaptive computation program serves as a formal structure for integrating research in this field at the Institute. Its purpose is to make fundamental progress on issues in computer science that are related to complex adaptive systems. Many of the complex systems being studied at the Institute exhibit adaptation to some extent. Research efforts on computation concentrate on either building computational models of adaptive systems or on using novel computational methods inspired by natural adaptive systems for solving practical problems. Genetic algorithms, neural networks, classifier systems, and simulated annealing are examples of such methods. These methods have been used both as models of natural phenomena and as novel methods for solving practical problems; as a result of their dissimilarity to traditional methods, they have led to a broadening of notions of how information processing takes place.

In March a Founding Workshop, chaired by SFI External Faculty Members John Holland (U. Michigan) and John Miller (Carnegie-Mellon) reviewed the status of SFI's current work in this area with the aim of defining major projects for further inquiry, expanding the research network, and developing plans to secure major funding.

Fund-raising efforts are now underway. Meanwhile work continues on a number of projects. Mitchell and SFI External Faculty Member Stephanie Forrest (U. New Mexico), in collaboration with John Holland, are working on characterizing the kinds of functions that are amenable to optimization by the Genetic Algorithm (GA), specifically comparing its performance to other hill-climbing optimizers that do not use mutation and recombination (crossover). They have begun with the study of what they have named "Royal Road Functions." These are fitness functions that impose a hierarchical organization that presumably should be exploitable by GA.

Holland is also in the early stages of developing the "Echo" model which provides a computational base in which to conduct experiments on a simulated multi-agent "ecology." The model consists of populations of evolving, reproducing agents distributed over a geography with different inputs of renewable resources at various sites. Each agent has simple capabilities—offense, defense, trading, and mate selection—defined by a set of "chromosomes" that evolve via a genetic algorithm. Although these capabilities are simple and simply defined, interacting collections of agents can exhibit analogues of a diverse range of phenomena, include ecological phenomena (e.g., mimicry and biological arms races), immune system responses (e.g., interactions conditioned on identification), evolution of "metazoans" (e.g., emergent hierarchical organization), and economic phenomena (e.g., trading complexes and the evolution of "money"). Thus, although the system is couched in terms of the language of biological ecologies, it is meant to be general enough to model phenomena in a number of areas. This generality can help shed light on commonalities among phenomena in diverse areas, and can get at the essence of some central questions about complex adaptive systems.

Melanie Mitchell, University of Michigan and Adaptive Computation program director, with SFI Postdoctoral Fellows Paul Storlorz and Walter Fontana at the Science Symposium

Plans for the final half of the year are in progress. One likely activity will be a small SFI workshop on artificial intelligence chaired by External Faculty members Nils Nilsson (Stanford) and David Rumelhart (Stanford).

Selected Updates on Research Visitors

Tom Ray

Kristian Lindgren

SFI's research body is composed almost entirely of visitors. There is no permanent faculty. SFI might best be described as a growing, extended family whose members stay in touch by phone and computer and who return frequently to sit around the table at SFI. The central part of that family is an External Faculty of some 35 people from more than 20 institutions in the U.S. and Europe; each External Faculty member tries to spend some time—a month is typical—at SFI during the year. These visits may be organized around workshops or working groups, or less formally, around a time when one or two colleagues will be in residence to work on a problem of mutual interest.

In addition, there are more than a hundred short-term visitors each year, attracted by the presence of External Faculty or special programs. They, too, become part of worldwide "research networks" that continue collaborations started at SFI after people leave.

This flow of people in and out of SFI is its strength, enabling loosely organized research groups to form and re-form as topics evolve, influencing the course of research at more conventional campuses, and enabling participants to remain active in collaborations after they return to their home institutions. Below is a sampling of the work of a few of the Spring 1992 visitors at the Institute.

John Casti, University of Vienna

My current research activities involve two separate lines of investigation:

• *Theory and Application of Metabolism-Repair Systems*—(M,R) systems represent a kind of mathematical abstraction of the functional activities of a living cell. Presently, I am looking into the ways such units can be combined into multicellular "organisms," with an eye to the construction of an evolutionary framework for populations of such abstract cellular structures.

On the side of application, I am trying to see if these structures can serve as the basis for a biologically motivated metaphor for characterizing the actions of individual traders in financial markets. Of special interest in this regard is the creation of a better way of modeling the diversity of types of investors in such markets, as well as their individual attitudes toward risk.

• *The Structure and Dynamics of Road Traffic Networks*—conventional models of road traffic systems mostly involve translating the traffic problem into an equilibrium-oriented system usually described by a partial differential equation of Navier-Stokes type. I believe that an algebraic framework is more suitable for this class of problems. So at present I'm looking into the use of what's called "q-analysis," which is a kind of generalized graph theory, for describing the algebraic hierarchies of links and routes that will allow road systems of any size to be modeled in a more global manner. This approach focuses more upon the global connectivity of the network, regarding the local dynamics as something that's constrained by this global geometry, rather than the other way around. Currently, the problems I'm studying include how to use this framework to formalize important road traffic observables like flows past given points, vehicle concentration rates, and travel times.

P. S. While probably not relevant to the SFI's research manifesto *per se*, it may be worth mentioning that I'm also engaged at present in writing a general-reader volume on the mysterious ways of complex systems. This book will be published next year by HarperCollins.

Atlee Jackson, University of Illinois

The Metamorphoses of Science

I am trying to pull together my ideas over the past five years that relate to the fundamental changes which I believe have and will occur in science, due to both our knowledge of limitations of mathematical deductions, and to the use of digital computers. While this is obvious at one level, my thesis is that science now has three co-equal operational methods, (1) physical experiments, (2) mathematical models, and (3) computer experiments, each capable of independent discoveries, overlapping each other, and operating in certain number fields and with certain rules (logically, or not). I believe that this will fundamentally change the nature of science, and the philosophical concepts which scientists will use in the future (e.g., laws of nature, goals of descriptions, determinism, etc.). I'm trying to sort some of this out.

Various Controls of Multiple-Attractor Systems

The complexity of many (perhaps most) systems is due to the fact that they have many dynamics attractors. Some of these attractors may be "good" or "bad" for the system, or they may involve various "memory" or "response" features of the system. I am interested in studying reliable methods for transferring such systems from one attractor to another, using a generalization of a control action first proposed by Alfred Hubler.

Semi-Realistic Neural Network Dynamics

I have studied networks with "neurons" which have various dynamic properties, and in many networks that I have tried, the resulting dynamics is temporally very uninteresting. I am trying to figure out why—what is the role of the connection architecture and of inhibitory neurons? There is also a multiple-attractor issue here which I would like to better understand.

Tom Ray, University of Delaware

I am interested in the study of evolution, ecology, and natural history of living organisms. For sixteen years, most of these studies have taken place in the tropical rain forests of Costa Rica. This has included work with beetles, plants, butterflies, and ants. In the past two years I have also begun to study organisms that live in the RAM memory of computers. These are digital organisms, self-replicating machine code programs, of my own creation. The digital organisms live in virtual computers whose operating systems randomly flip bits, thereby causing mutations. As a result of self-replication combined with mutation, the digital organisms evolve by natural selection, rapidly generating complex ecological communities.

Kristian Lindgren, Chalmers University

My primary research plans for this visit are related to the work that remains to be done for the book on "Complexity" that SFI Postdocs Mats Nordahl, Cris Moore, and I are going to write during 1992, for example: (1) the generalization of regular languages to two-dimensional systems: proving properties of an hierarchy of 2-D languages; (2) undecidability in dynamical systems: a formalization of such questions for cellular automata; and (3) application of the continuity equation for entropy in reversible systems to various spin models.

Together with Chris Langton, I am also continuing the work on self-replicating cell-like structures, implemented in cellular automata.

I have had Mats as my guest in Goteborg, and we have (together with Ingrid and Anders) completed the first part of the Evolving Neural Nets Project that we worked on at SFI last fall, by sending a paper to a neural network conference. The second part

(continued next page)

New Theoretical Neurobiology Working Group

Understanding the complexities of the brain will ultimately require sophisticated theoretical approaches. Yet an effective theoretical neurobiology does not now exist. In March 1992 The Pew Charitable Trusts awarded a major grant to the Institute to explore the prospects of developing the field of theoretical neurobiology. Work begins this summer at SFI with the formation of a research group of theorists and experimentalists led by Charles Stevens, Howard Hughes Medical Institutes Director and Professor at The Salk Institute, and Michael Striker, Vice-Chairman of the Physiology Department and Co-Director of the Neuroscience Graduate Program at the University of California at San Francisco.

Theoretical biology, of course, has not been entirely neglected. Limited theories developed to answer specific experimental questions have been widely accepted. However, most neurobiologists regard more general theories as largely irrelevant. One possible explanation for the failure of general theories is that the problems in neurobiology are not yet amenable to theoretical analysis. Or the failure of theory simply may reflect a lack of interaction between theorists and experimentalists: theorists do not know enough biology to have sufficiently good intuitions to solve problems the experimentalists think are important, and the experimentalists have little idea about how theories are developed and what contributions they can make. If this is the reason for theory's failure, it can be addressed.

To do so Stevens and Striker will form the SFI Working Group on Neurobiology. Its aim is to provide an intensive environment where theorists and "theory aware" experimentalists can interact and educate one another. (Here it follows the example of SFI's highly successful program in theoretical immunology which has fostered a number of productive collaborations between these two camps.) About a dozen workers—equal numbers of theorists and experimentalists—will come together for six weeks of collaboration. Because the visual system provides an area in which the understanding of brain structure and function is most complete, they will concentrate, although not exclusively, on this system. The format will stress individual interactions, although each participant will give at least one talk about his work to provide the basis for ensuing discussions.

"We view this as an experiment in starting to develop a theoretical neurobiology," writes Stevens. "If it works, theorists and experimentalists will become acquainted, establish working relationships, and learn how each other thinks about thinking about the brain. At the very least, a number of thoughtful experimentalists will have the chance to talk to each other at length and have time to think about where their work is going and a number of theorists will learn about the brain. At best, this may be the start of an effective theoretical neurobiology."

Computing at SFI

Scott Yelich

Scott Yelich joined the SFI staff as Systems Manager last autumn. He has a strong background in Unix computer system administration having worked as a System Administrator at NASA before coming to Santa Fe. Scott's academic background in computer science, his technical expertise, and his consulting skills are vital to SFI's rapidly growing, heterogeneous computing environment. Below he describes his near-term plans for the system and answers some of the frequently asked questions about the Institute's computing resources.

The Santa Fe Institute has an impressive amount of computing resources. I am delighted that I have the responsibility for maintaining them. I intend to use my experience with much larger networks to bring the system up to its full potential, that is, to become one that will support and enhance all of SFI's computational activities. With the proper configuration and administration, the network has the potential to become top-rate in terms of functionality, power, and performance. Specifically, I plan to work toward these three goals with the system: it should be robust, it should be as transparent as possible, and finally, it should be user-friendly.

Major Components

The system currently consists of 20 Suns, 20 Macs, 3 IBMs, 1 SGI, 1 NEXT, 4 PostScript-capable laser printers, and 2 bridged local networks. The Institute has the class C internet address of 192.12.12 and has the domain name of santafe.edu. The e-mail address of someone at the Institute is <user@santafe.edu>. The full range of 192.12.12.0 to 192.12.12.255 leaves substantial room for additional network nodes and only after SFI requires more than 256 nodes will the class C address have to be changed. The Suns are currently grouped together in the lower addresses, the Macs are using the highest addresses and the rest of the addresses are not yet allocated.

The Institute is connected to the Internet via the local New Mexico wide area network called Technet. The Institute uses a 56 Kbit/second modem that has a maximum throughput of about 6.1 Kbytes/second to communicate with Technet. Within the Institute there are two separate but bridged networks. The UNIX workstations are physically linked with thin ethernet and use TCP/IP to communicate. The Macs are currently linked with Phone-Net and use AppleTalk. A FastPath bridges these networks and allows the Macintosh computers to use TCP/IP to communicate with hosts on the other side of the bridge.

The Institute has two modems connected to a Sun for remote user dial-up access. One is a Telebit T1600 and the other is a Telebit Trailblazer Plus. Both of these modems automatically configure upon answering a call. They both are capable of 19.200 Kbits/second; however, a connection at a rate greater than 2400 baud requires the remote modem and the SFI modem to use the same transmission protocol. The easiest method of testing for compatibility is to call each modem. The Sun communicates with each modem at 19.200 Kbps with 8 data bits no parity, 1 stop bit, and hardware flow control, sometimes abbreviated 8N1, and provides the capability for file transfers with X-, Y-, or Z-modem as well as any 7- or 8-bit protocol. It is possible to connect with 7 data bits, even parity, and 1 stop bit (i.e., 7E1), but certain applications will not work properly with this configuration. The hardware flow control between the SFI modem

Updates (continued)

of the project involves the evolution of game strategies, and we plan to have a paper on that for Alife III. Some generalizations on my evolutionary Prisoner's Dilemma simulations are also tested. I have some undergraduate students who work on an implementation of the lattice game on a Connection Machine that we have in Stockholm. Another generalization involves the introduction of resources as a limiting factor in the population of strategies, which also shall be presented at the Alife III conference.

Martin Shubik, Yale University

Martin Shubik is Seymour Knox Professor of Mathematical Institutional Economics at Yale University. He writes: "My prime area of specialization is Game Theory, with an emphasis on applications in the social sciences. Other topics of particular interest are experimental gaming, the theory of money and financial institutions, and the economics and management of cultural institutions. This somewhat diverse melange of topics nevertheless has a common theme. This is the relationship between statics and dynamics. Much of economic theory and, for that matter, game theory has been developed with an emphasis on statics. It appears that in any attempt to construct a satisfactory dynamic theory, institutions appear as the natural carriers of economic, political, and social purpose. In essence elementary institutions appear manifested in the rules of the game in any attempt to construct playable games or process-oriented models."

and the Sun means that the remote computer does not need to use flow control.

Three of SFI's four laser printers are on the Appletalk network and the last one is connected to a Sun. All of the printers may be accessed from a Sun. The Macs can only print to the ones on the Appletalk network. All of the printers are capable of printing PostScript documents.

That covers the major components of the system.

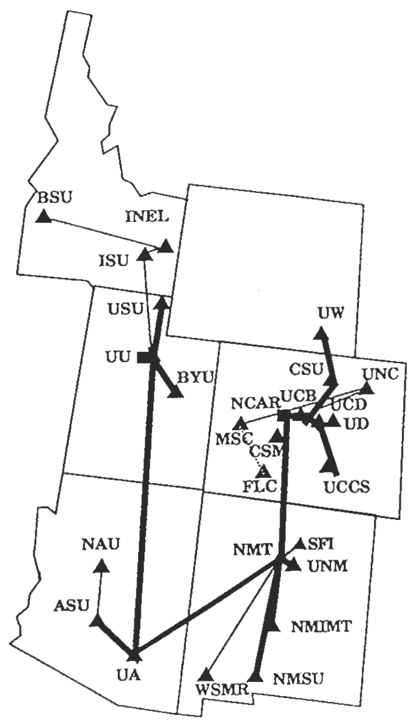
Goals

My first and most important goal is that the overall system be more robust. The basic stability behind the network is the wiring. Each machine connected to the network causes an additional potential fault. The ethernet section of the local area network can be considered a single wire and so a break anywhere will cause this section to fail. One of the printers is separated from the rest in case either side of the network breaks. As an on-going project, I replace faulty cables with new ones that I've assembled. Eventually the entire network will be replaced with new cables. Previously, the ethernet network was failing almost every day. The network has now been stable for several months.

It is not possible to prevent a computer from ever locking up, crashing, or corrupting data. This means that a thorough and verified backup system is necessary to ensure data integrity. The Institute has an 8mm Exabyte tape drive that can store up to 2.4 Gigabytes on a single tape. At this time, all user files can be stored on one tape and so backups are done nightly. Full system backups are also done twice a month.

Most of the machines are set up as individual workstations and are not fully integrated into the network. This makes it difficult for a user to move from one machine to another. A program may compile or an application may run on one machine but not on another or all hosts. For instance, the Suns currently have different versions of the SunOS operating system and varying amounts of memory. Over the next few moneths, all Suns will be upgraded to SunOS 4.1.2, OpenWindows 3.0, and X11 Release 5, and each will be expanded up to at least 24 megabytes of memory.

Considerably additional central disk storage space will be added within a year and older versions of currently installed packages will be upgraded. These packages include Open Windows, X11, TeX, LaTeX, gnuplot, and khoros. I will also be re-installing no longer functional software, such as Island Write/Paint/Draw, Mathematica, and Wingz and installing new packages such as Usenet News, as available disk space allows. Whenever possible, the same or similar package will be installed on all platforms.



WESTNET MAP
Summer 1991

Legend

Circuits
- ---------- 9.6 kbps
- ——— 56 kbps
- ━━━ T-1 (1.544 Mbps)

Routers
- ▲ cisco Gateway
- ■ IBM NSS

The Internet is a world-wide web of inter-connected networks. Local Area Networks (LANs) connect into regional networks which then connect to other regional networks. The larger, more distributed networks, are called Wide Area Networks (WANs) with no clear distinction between where a LAN becomes a WAN.

The Institute has two LANs which merge at the gateway to the New Mexico Technet WAN. Technet then connects to other WANs. For example, the NSFnet backbone is four hops, or gateways, and approximately 50ms away.

The specific hardware components of each network dictate the theoretical and actual maximum data transfer rates. SFI has a 56Kbps link to Technet which averages around 6.1K/second in actual transfers. Technet has a T1 (1.544Mbps) link to NCAR which is on a 44.736Mbps NSFnet network.

One of the most significant facts about using the Internet for communications is that, provided the links are operational, transfers are primarily immediate instead of queued and batched. For instance, during non-peak usage times with no strange astronomical interference, Taiwan is only seventeen hops and only a half-second away from SFI.

System administration is both system support and user support. SFI's system needs to be more user-friendly. Now that the system is generally stable and more computers and packages available, a further goal is to facilitate automatic first-time use or easy access to applications.

A first step toward this goal is currently underway, the preparation of one-page documents that describe and explain how to set-up and use the various applications. Eventually, the single-page documents will be put together into a user's guide to the computing facilities.

The computing environment at the Institute has been changing rapidly over the past few months. I look forward to continual improvements in the system to meet the needs of our user community.

Board & Faculty News

S. Forrest

G. Gumerman

S. Levin

R. Palmer

N. Kopell

The Institute welcomes the following new members to its Science Board:

Partha Dasgupta is Professor of Economics, Professor of Philosophy, and Director of the Program on Ethics and Society at Stanford University and Professor of Economics at the University of Cambridge. He received a B.Sc. in Physics from the University of Delhi in 1962, a B.A. in Mathematics from the University of Cambridge in 1965, and a Ph.D. in Economics in 1968, also from the University of Cambridge. Dasgupta is a Research Fellow at the Center for Public Policy Research in London; a Research Advisor to the Program on Environment and Economic Development at the World Institute for Development Economics Research; and a Visiting Fellow, Santory-Toyota International Center for Economics, at the London School of Economics. He is the author of ten books and more than one hundred articles in the fields of capital and optimum growth theory, taxation and trade, industrial structure and technological change, and game theory among others.

Stephanie Forrest is Assistant Professor, Department of Computer Science, University of New Mexico. Before joining the UNM faculty in 1990 she was a Director's Postdoctoral Research Fellow at the Center for Nonlinear Studies, Los Alamos National Laboratory. Forrest earned her Ph.D. in computer and communications sciences from the University of Michigan in 1985, where she also received her masters in the same department in 1982. Recently Forrest received a prestigious Presidential Young Investigator Award by the National Science Foundation, selected for her work on emergent computation and computational models of the immune system. Forrest is on the editorial board of the *Journal of Experimental and Theoretical Artificial Intelligence* and, in addition to publications in several technical journals, she is the author of *Parallelism in Classifier Systems*. Forrest, a SFI External Assistant Professor, is working on several projects as part of SFI's adaptive computation and immunology research programs.

George Gumerman recently retired as Professor of Anthropology and is past Director of the Center for Archaeological Investigations at Southern Illinois University at Carbondale. He also serves as an Archaeological Associate, Office of Archaeological Studies, Museum of New Mexico. Gumerman's research interests are in the archaeology of the American Southwest, archaeological theory, and cultural ecology, and he is deeply involved with the Institute's research program on cultural evolution in the prehistoric southwest. Author of numerous articles and chapters in professional books, Gumerman is co-editor with Murray Gell-Mann of the forthcoming *Organization and Evolution in the Prehistoric Southwest* (School of American Research), a proceedings volume from the SFI workshop of the same name.

Nancy Kopell is Professor of Mathematics at Boston University. Prior to joining the Boston University faculty she was Professor of Mathematics at Northeastern University. Kopell received her A.B. from Cornell University and a M.A. and Ph.D. with a speciality in dynamical systems at the University of California at Berkeley. A MacArthur Fellow (1990–1995) she serves on the Boards of the Mathematical Sciences Research Institute and Society for Mathematical Biology, the Advisory Board of the *Journal for Mathematical Biology*, and the Editorial Board of the *SIAM Journal of Applied Mathematics*. She is the author of more than fifty articles.

Simon Levin received his B.A. in Mathematics from the Johns Hopkins University in 1961 and earned a Ph.D. in Mathematics from the University of Maryland in 1964. In 1965 he was appointed Assistant Professor at Cornell University, where he is currently the Charles A. Alexander Professor of Biological Sciences. Levin will move to Princeton University in July 1992 where he has been named the Moffett Professor of Biology. Levin's current research interests are at the interface between population biology and ecosystems science, especially regarding the importance of scale in the analysis of community and ecosystem pattern. Other major interests are in the evolution of life history traits in complex environments, and in the dynamics of host-parasite interactions.

Richard Palmer is Professor of Physics, Duke University, with research interests in neural networks, the dynamics of glasses and the glass transition, and complex systems in economics. Palmer attended the University of Cambridge where he received a B.A. in Theoretical Physics in 1970 and a Ph.D. in Condensed Matter Theory in 1973. A co-organizer of many conferences and currently a referee for ten journals, Palmer has published contributions in the areas of spin glasses, combinatorial optimization, renormalization group theory, broken ergodicity, neural networks, glassy dynamics, the dynamics of complex systems, and complex systems in economics. An SFI External Faculty Member since 1989, Palmer is in residence at the Institute late this Spring working with Melanie Mitchell and John Miller on theory of Royal Road problems, with Stuart Kauffman and Daniel Stein on landscape structure and history dependence, and with John Miller on planning and designing a second double auction tournament.

Peter Wolynes received an A.B. from Indiana University in 1971 and a Ph.D. from Harvard University in 1976. He was a member of the faculty at Harvard from 1976 to 1980 at which time he joined the faculty at the University of Illinois, Urbana-Champaign, where he is Professor of Chemistry, Biophysics, and Physics. Wolyne research is broadly concerned with the dynamic theory of processes of chemical interest in condensed matter. His research ranges over all states of matter including liquids, amorphous solids, and biological macromolecules. Specific issues include the search problem in protein folding, quantum processes in many-body systems, and quantum theory in disordered systems.

Daniel Stein is Associate Professor, Physics, University of Arizona. Before joining the Arizona faculty, he was Assistant Professor at Princeton University from 1980 to 1987. Stein received a Sc.B in Physics from Brown University and a M.S. and Ph.D. in Condensed Matter Theory from Princeton University. An SFI External Associate Professor, Stein's research interests include the dynamics of glasses; protein dynamics and folding; and transport through biological membranes. Stein has played a key role in the Complex Systems Summer School since its founding in 1988 serving as Director and Co-Director. In June, he and Lynn Nadel (University of Arizona) will direct the 1992 School.

Four individuals have recently been appointed as SFI External Faculty members. SFI's External Faculty consists of some 35 people from more than 20 institutions in the U.S. and Europe; each External Faculty member tries to spend some time—a month is typical—at SFI during the year. These visits may be organized around workshops or working groups, or less formally, around a time when one or two colleagues will be in residence to work on a problem of mutual interest.

Rob De Boer is currently a Postdoctoral Fellow with the Bioinformatics Group at the University of Utrecht. Prior to his appointment at Utrecht, De Boer was a Postdoctoral Fellow at Los Alamos National Laboratory. He received his undergraduate education in biology at the University of Utrecht and completed his graduate studies there in theoretical immunology. De Boer's recent work is devoted to models of the B-cell immune network, focussing on memory phenomena and the development of the network. This involves the analysis of chaotic attractors, shape-space models, and bit-string topologies.

Alfred Hubler is Assistant Professsor, Department of Physics and Beckman Institute, University of Illinois at Champaign-Urbana. He serves as Associate Director for the Center for Complex Systems Research at UIUC and heads the Turbulence Laboratory at the Beckman Institute. Additionally, he is currently a Fellow of the Center for Advanced Studies at UIUC. Hubler received his Ph.D. in Nonlinear Dynamics from Technical University of Munich in 1987, held a postdoctoral fellowship at the Institute for Theoretical Physics and Synergetics at the University of Stuttgart in 1988, and came to the University of Illinois in 1989. He is the author of numerous articles in the fields of control of chaotic systems, pattern formation and the principle of minimum resistance, nonlinear chemistry, and algebraic integration of nonlinear oscillators.

Late in 1991 **Peter Schuster** was named Founding Director of the Institute for Molecular Biotechnology in Jena, Germany. Prior to this prestigious appointment Schuster was Professor of Theoretical Chemistry and Head of the Institute of Theoretical Chemistry at the University of Vienna, positions which he retains. Schuster is the author of more than 200 papers and reviews in scientific journals and five books. A frequent visitor to SFI, Schuster's work in adaptive molecular evolution involves active collaborations with a number of Institute researchers including Stuart Kauffman and Walter Fontana.

Gérard Weisbuch is Senior Research Associate in Physics at CNRS (National Council for Scientific Research, France) and works in the Physics Department of Ecole Normale Supérieure, Paris. Weisbuch received his Ph.D. in Physics from the University of Paris. After working in solid-state physics research, he became involved in modeling biological systems with networks of automata. His contributions, based on numerical simulations, concern the theory of the dynamical properties of networks of automata, and the modelization of the functional organization of the brain, of evolution of species, and most recently, of the immune system. Weisbuch is the author of *Complex Systems Dynamics*, a lecture notes volume in SFI's Studies in the Sciences of Complexity series.

Board Members Honored

SFI Science Board and Editorial Board member Harry L. Swinney, Director of the Center for Nonlinear Dynamics and Trull Centennial Professor, both at the University of Texas at Austin, was recently elected to the National Academy of Sciences. Elected by the members, he joins a select group of about 2000 scientists, less than 200 in the area of physics.

SFI Science Board member and External Professor John H. Holland, University of Michigan, has been named one of 33 MacArthur Foundation Fellows for 1992. The citation for Holland's five-year award of $369,000 said that he "has pioneered new forms of computation in computer science, including adaptation, machine learning, optimization, and artificial intelligence.

D. Stein

P. Wolynes

A. Hubler

P. Schuster

G. Weisbuch

1991 Contributors

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Academic Institutions

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Apple Computer
Batterymarch Financial Management
Campbell & Black, P.A.
Citibank, N.A.
Pittsburgh National Bank (Alex C. Walker Foundation)
Santa Fe Audio Visual
David E. Shaw & Company
Shuttlejack

Foundations

J. C. Downing Foundation
Ann & Gordon Getty Foundation
Richard Lounsbery Foundation
John D. & Catherine T. MacArthur Foundation
Maxfield Foundation
Maxwell Foundation
Pinewood Foundation
Alfred P. Sloan Foundation

Government Agencies

Los Alamos National Laboratory
The NATO International Science Exchange Programs
National Science Foundation
U. S. Department of Energy
U. S. Office of Naval Research

Individuals

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Ruth & Robert McCormick Adams, Washington, DC
Harold Agnew, Solana Beach, CA
Margaret & Lewis Agnew, Jr., Los Alamos
Margaret Alexander, Santa Fe
Jean Anderson, Los Alamos
Philip Anderson, Princeton, NJ
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Private Money: SFI and the Entrepreneurial Investor

By Susan Wider

Susan Wider is SFI's Director of Development

The success of any fund-raising program is measured first in terms of the bottom line numbers. How much are we raising? Are we meeting our goals? How many donors are making repeat gifts? How many new donors are we bringing into the family?

But once the numbers are tallied, we have to look behind them and ask the "people questions." Who are these donors? Why do they support us? And most important, how can we keep them enthusiastic and involved?

In the last two years, SFI has had a significant increase in contributions from individual entrepreneurs. In 1989 Intel founder Robert Noyce made a major gift to SFI which sent a message of credibility and intellectual curiosity to other philanthropists. Perhaps it is because they sense an affinity between what they do in the corporate world and what SFI does in the scientific world—discover and organize new knowledge for the benefit of society.

By 1991, a half-dozen additional entrepreneurs and venture capitalists were making major gifts of $10,000 or more to SFI. Among them were Robert Dolan, founder of ComDesign, manufacturer of data communications products; John Downing, founder of Pacific Data Products, a peripheral laser products manufacturer; John Koza, developer of the instant rub-off lottery ticket; Dan Lynch, founder of Interop, specialists in computer networking education; and Robert Maxfield, a co-founder of ROLM Corporation.

What brings these supporters to SFI? And why do they stay? Why do they go beyond simply writing a check and having their name associated with scientific innovation?

Robert Dolan: "SFI is quite a stimulating environment. If anyone can help us understand the next generation of intractable problems, the people at SFI can do it. I am particularly intrigued by the SFI approach to economics and I also think their Adaptive Computation program, once it is fully funded, holds great promise."

John Downing: "I established the J.C. Downing Foundation as a way to invest money that lets me make a definable, measurable difference in the world. Very few organizations have been able to do cross-disciplinary work in the way SFI has. They have created an atmosphere that encourages true cross-fertilization among scientists and businessmen."

John Koza: "I hold John Holland's work in high esteem. When I learned that John was devoting significant time and energy to SFI, I began to pay attention. This is an organization that lets people do science in a unique new way and I want to be part of the exchange."

Dan Lynch: "My excitement for the Santa Fe Institute comes from my belief that complexity science has a range of real-world applications. SFI is demonstrating new capabilities of incorporating learning and evolution in simulations and modeling. My financial support for SFI to fund their promotional efforts is intended to help spread the word about SFI wider and faster."

Robert Maxfield: "I am very impressed by the quality of the people involved with SFI. I believe that the theories they are developing for Complex Systems, coupled with advances in computing technology, will yield valuable insights for some of the most important problems of our time."

SFI's entrepreneurial investors not only provide funding for our work and *participate in SFI activities*, they also serve as advocates in the broadest sense. They are active in our fund-raising and promotional activities. They introduce us to other prospects and help us with prospect cultivation. A number of them even make gift solicitations on our behalf.

James Pelkey, SFI board member, drew many of these people to SFI. "For individuals and businesses interested in preparing for the future, and not just being a victim of it, SFI will be of interest. Given the rapid rate of global change, SFI represents an opportunity to anticipate, to prepare, to be more effective in an increasingly complex world."

SFI's search for private support has seen continued success with foundation funding, which accounted for 33% of total income in 1991, and we have improved our success in securing corporate funding, which represented 19% of total income in 1991. But we place major attention on individual donors because, to use fundraising's favorite Willie Sutton paraphrase, that's where the money is. The American Association of Fund-Raising Counsel in their annual publication *Giving USA* has again reported that 83% of all charitable giving comes from individuals, with an additional 8% from bequests.

We expect to invite a growing number of entrepreneurial philanthropists into the SFI family in the years ahead.

Dan Lynch (far right), founder of Interop; Peter Heilbrun (center), University of Utah; and John Casti (behind Dr. Heilbrun), Technical University of Vienna, listen to Bela Julesz, Rutgers University, at the recent Science Symposium.

SFI Officers & Staff

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