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BULLETIN

ECOLOGICAL COMPLEXITY TAKES ROOT

MESSAGE FROM BRUCE ABELL, VICE PRESIDENT, FINANCE AND OPERATION

HARD CHOICES IN SFI'S SECOND DECADE

The previous SFI Bulletin commemorated the first decade of the Institute's life. This issue inaugurates our second decade. We expect to face some quite different kinds of governance problems than we did in the initial years.

One significant change will come in the collision of our 20+ percent rate of annual growth with a self-imposed limit on eventual size of 50-60 scientists in residence at any one time. A large measure of SFI's intellectual strength derives from its intimacy. Because SFI is small, there is a fair chance that scientists in residence, even those in residence for as little as a week or so, will be able to interact with a significant range of other scientists at SFI. This has been critical to the innovation in our research program and to SFI's appeal to scientists to come for research visits.

So far, we have been relatively free of constraints in pushing into new areas that SFI-affiliated scientists want to explore. We have been able to find room for additional people in our current facility, which can accommodate up to 35 scientists (albeit with almost intolerable crowding). We are now almost full. We plan to expand it soon, and that will buy us some time. But soon enough we will confront hard decisions about how to make room for new science.

We have ample experience with how expansion can be the engine for new initiatives in institutions. We know far less about how to maintain an organization's intellectual momentum without physical growth. That will be the challenge facing SFI. This topic has been addressed by both the Board of Trustees and the Science Board in their recent meetings, and it will become a more central focus of attention over the next few years.

A number of possible mechanisms are being considered:

- First, of course, is to expand our campus. Our goal in doing that will be to reduce crowding, provide badly needed space for informal meetings, enlarge the cramped library, and provide quiet offices for more people.
- We exist, in part, to catalyze how science is done in other places. Scientists who spend time in residence and then return to home institutions are having a significant impact. We will encourage more short-term visitors, using workshops and working groups to allow people to become familiar with SFI research and take ideas away. We are experiencing growing requests for very short-term visits, particularly from people in business and government. They represent a way (if we have some additional space) to expose many more people and institutions to SFI research. They also bring their own unique, and valuable, perspectives on science to people at SFI.
- The hardest part will be to decide to phase out or transfer scientific efforts to other places. Few places deliberately cast off their successes, but we may have to. SFI's efforts should complement those at other institutions, and there is no need to compete once SFI-inspired work gains a foothold in larger institutions. Our major concern will be that SFI-started research not become orphaned.
- We will encourage replication of the SFI approach to science elsewhere and establish more linkages with other institutions. We will also explore establishment of new research partnerships, such as the SFI-inspired Diversity Biotechnology Consortium, to continue and enlarge on our initial efforts.
- We must continue to bring in new people to the SFI community. New people may wind up competing for presence with those who are now active. This will be painful, but necessary.
- As organizations age, they often become less agile, falling into comfortable structures that make it harder for new people and new ideas to impact their cores. SFI must fight that tendency.

Just as we can look with satisfaction at our success in establishing the Institute during its first decade, we should make some efforts to keep it a little unstable to permit intellectual niches to continue to evolve.

Visitors often comment that SFI is a particularly good example, itself, of the kinds of evolving, complex, adaptive system it studies. That seems a little facile, but we hope we can learn a bit from SFI's science how to keep SFI's organization flexible, receptive, and renewable.

Bruce Abell

NEWS AND FEATURES

RESEARCH UPDATES

COVER

Photograph taken across the fence of an experimental plot in the Chihuahuan Desert in March 1995, showing the orders of magnitude higher densities of wild mustard flowers inside (left) where kangaroo rats have been absent for 17 years.

We all know that great imaginative literature can be read on many different levels—Shakespeare could simultaneously produce gripping plots, sensitive character delineations, Tudor propaganda, and philosophical reflections on fate and social responsibility. I am going to advance a similar claim for the scientific models we are producing here at Santa Fe. My basic message is that while each of these models is primarily directed at some particular world of experience—which might be physical, chemical, biological, social or economic—on another level they can lead to new insights about other worlds of experience, including those that we ourselves inhabit in our personal and professional lives. These insights, I believe, can be encapsulated in the form of aphorisms, whose meanings are shaped by an understanding of the modeled worlds, and from there can extend metaphorically, to help us reinterpret our own worlds of experience.

—David Lane, from SFI Working Paper "Models and Aphorisms"

SFI'S NEXT GENERATION OF MODELS TACKLES THE REAL WORLD

Janet Stites

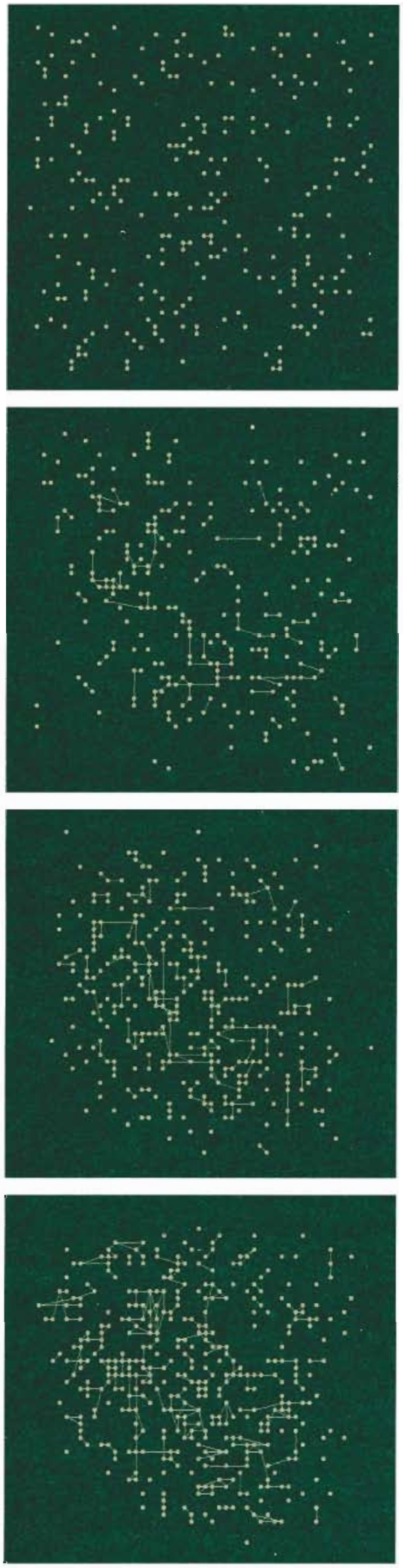
In David Lane's SFI Working Paper "Models and Aphorisms," he articulates what many at the Institute intuit: that insights provided by computer modeling can be compressed into "truths" that in turn may provide great insight into our natural world. Indeed, in the first decade of the Institute, computer modeling has emerged as an integral part of its research, as important to its mission as its interdisciplinary approach. A major theme running through all of this modeling work is that a system of agents following very simple rules can exhibit complex behavior. Some members of SFI's family believe the Institute has now come to a pivotal point in regard to its work with modeling; that the models have matured, and are ready to be tested against reality and ultimately extended metaphorically.

Marcus Feldman, Director of the Morrison Institute for Population and Resource Studies at Stanford University and a member of the Institute's Science Board, finds the modeling going on at SFI valuable because of its unique approach. "The kind of modeling that is being done at the Institute is different from modeling done in standard biology and economics," Feldman says. "It tries to integrate the structure used in one discipline into another. For instance, integrated into Sugarscape are the mathematical theories of epidemiology, economics and demographics. But it is not using the math itself." Sugarscape is a model developed by Joshua Epstein and Robert Axtell, SFI Members and scientists at the Brookings Institution. Feldman goes on to explain that modeling being done at SFI is what's known as "agent-based modeling," the mathematical counterpart of which would be differential equations. He uses an analogy from physics to clarify. "You can write down the differential equations for fusion," he says. "Or you can talk about how the molecules bump into each other." Both are important. The differential equations summarize ways the pieces of the puzzle fit together, while the discussion unveils what actually happens. Feldman believes a similar system of checks and balances operates between mathematical models and agent-based models.

Feldman contends the modeling conducted at the Institute has matured enough to warrant such analysis. "We need to bring in the people who are good at integrating the different parts," he says, "who can develop statistical tools comparing how the agent-based models match the mathematical models." Feldman compares computer modeling to experimental mathematics. "When you have an experiment," he says, "you have to do the data analysis." Feldman's comments stem from a wealth of personal experience. For 25 years, he has looked at applying mathematics to genetics, often using mathematical modeling. At SFI, he's worked with computer scientists John Holland and Melanie Mitchell. "Working with them has given me a new perspective on a number of problems," he says. "It's allowed me to approach them in a fresh way."

Physicist Murray Gell-Mann has long been a proponent of modeling and shares some of Feldman's opinions and concerns. "With very complex systems analytic study of what's going on is often difficult," he says. "Computer modeling or simulation is often the best way to learn something." Gell-Mann describes a spectrum of modeling and simulation activities, ranging from models with extremely simple rules, which usually operate in conjunction with chance, to models with more information in the form of real details corresponding to what has actually happened. "Seeing that real or apparent complexity emerges from very simple rules, usually with the addition of chance, is a very exciting activity," Gell-Mann says, "even addictive."

Most of the modeling being done at the Institute is done at the "simple" end of the spectrum, according to Gell-Mann. He suggests it may be time to move more toward the middle. "The modeling that's been done is very useful," he says, "and some day mathematicians will take a hand in it and there will be a whole mathematical theory of these very simple sets of rules that give rise to



Agents move around a spatial distribution of renewable resources maximizing their utility functions. They make bilateral trades with neighbors at prices determined through barter. These heterogeneous agents are represented as nodes, with connecting lines denoting trades. Over time the trade density increases, as shown above. (Figures courtesy Joshua Epstein and Robert Axtell.)

apparent or real phenomena. But what we need for applications is to move toward the middle of the spectrum, where quite a bit of information about real life and real societies is put in." Gell-Mann acknowledges that to do so presents a challenge, that there is a danger of double-counting. "Typical modeling exercises that are instructive involve the appearance of higher level organization from lower level," he explains. "One puts in organisms, one gets out ecological communities. One puts in households, one gets out villages. One puts in villages, one gets whole tribes or provinces. If you do that, you have the following problem in that if the model or simulation is sufficiently rich, you will see evolution of a higher level of organization. The trouble is actual villages have emerged as well in history and you may want to put in the characteristics of the ones that did evolve. Nevertheless, your model is already generating such things."

The difficulty, according to Gell-Mann, comes in reconciling the actual with what might emerge in the model; to put in some information about the higher level, without taking out the potentiality for generating the higher level. "If you're dealing with complex adaptive systems such as organisms, human beings and so on," he says, "and you're looking at composite complex adaptive systems like villages made of people, markets made of investors, ecological communities made of organisms, then a serious simulation would involve schemata not only at the level of the adaptive agents out of which the composite complex adaptive systems are composed, but also the schemata at the higher level." If you have villages and tribes emerging from households, not only would the individuals or households have their schemata, but the villages or tribes would also have schemata. "Of course," Gell-Mann adds, "the more complex the model gets, the harder it is to analyze."

Much of SFI's first decade of work has focused on the development of models, many of which were described at the March Science Symposium. And, in fact, models such as Chris Langton's Swarm, John Holland's ECHO, Epstein and Axtell's Sugarscape, and biologist Tom Ray's Tierra, have captivated not only some of the world's leading scientists, but also representatives from industry. Yale biologist Leo Buss is working with former SFI Postdoctoral Fellow Walter Fontana (now at the University of Vienna) to answer the deep question: If the clock were set back to the beginning of time, what conditions would have to be present to produce contemporary classes of organisms, such as multicellular organisms? Using a modeling program developed by Fontana called Alchemy, they are trying to model the simplest interactions in a community. By doing so, they hope to understand better, not the survival of the fittest, but the origin of the fittest.

Roger Burkhart, Staff Engineer at Deere & Company, has been working "on location" in Santa Fe with Chris Langton to help develop software for Swarm. Burkhart explains that the same kinds of object-oriented simulation capabilities used in an artificial world are needed in an industrial world. Deere & Company is a member of the Institute's Business Network, a liaison initiated by Staff Analyst Bill Fulkerson. "It became clear that nonlinear system and/or biologically motivated computing would have to be evaluated," Fulkerson says. It is his contention that as we move from an industrial age to an information age, communication outside the factory will be more important than movement through the factory. "What we anticipate is that as manufacturing becomes more built around a "virtual organization" it will exceed the capabilities of discreet event simulation," he says. "We will need more applications to handle information flow *versus* material flow." Which is exactly what they hope to find in Swarm. Fulkerson sees this as a long-term effort. Deere already uses software based on genetic algorithms to deal with problems of assembly line sequencing. To Burkhart, the practical applications of developing software within a framework like Swarm include improved manufacturing operations on the shop floor, better understanding of distribution chains, and a way of forecasting demand.

"The computer-based models have been vital for exploration in most of the areas that are central to the Institute's agenda," says John Holland, "such as adaptive computation and computational economics. The Institute would not be in the forefront in these areas if it had foregone computer modeling." As an SFI External Faculty Member, Co-Chair of the Science Board, and professor at University of Michigan, Holland has been integral to the evolution of modeling at SFI. He is the inventor of genetic algorithms, original developer of ECHO, and former professor to a number of SFI researchers — a group SFI vice-president Mike Simmons calls "the Michigan Mafia," including Melanie Mitchell, Chris Langton and Stephanie Forrest.

Holland had no idea how important modeling would become to the program at SFI when he first became involved with the Institute. "I did know that computer-based thought experiments form a critical 'halfway house' between experiment and theory in the study of complex systems, particularly complex adaptive systems," he says. Holland proposes his "halfway house" theory in his book *Hidden Order: How Adaptation Builds Complexity* to be published early this fall by Addison-Wesley. In it he writes, "A computer-based model is a halfway house between experiment and theory: Looking back to data, we can see if the consequences are plausible; looking forward to theory, we can see if the design suggests general principles."

In regard to the work being done at SFI, Holland explains that it is important to separate computer-based Gedanken (thought) experiments from direct data-driven simulations in real systems. "The former is aimed at discovering mechanisms that are good candidates for theory and mathematization," he says, "while the latter is aimed at generating data that matches experiment. The former is productive if it generates theory; the latter is productive when it is tested against known experiments." In both cases, Holland believes the modelers should keep pressing toward the "end-points."

Holland believes that we're on the verge of seeing more of the rigorous analysis Feldman and Gell-Mann advocate. "We should be seeing more 'end-point' results now that we've made such a substantial effort at modeling," he says. "Otherwise, we've not reaped the return on our investment." Here his thoughts echo those of David Lane. In a working paper Holland presented to the Science Board this spring, he wrote, "Most attempts at modeling, whether it be mathematical modeling or computer-based modeling, start with the same general assumption: There is some more or less isolatable, law-governed segment of the world that is the target of the model." That target sits somewhere under the roof of Holland's "halfway house," where theory meets experiment, biologists meet physicists, math meets models, and the artificial and real worlds brush shoulders under the auspices of metaphor. ⊕

Typical Steps in Building an Exploratory Simulation of a Complex System

Simplify the problem as much as possible while keeping what is essential.

Write program which simulates many components following simple rules with specified interactions and randomizing elements.

Run program many times with different random number seeds, collecting data and statistics from the different runs.

Attempt to understand how the simple rules gave rise to the observed behavior.

Perform parameter changes and "lesions" on the program to locate the sources of behavior and the effects of different parameters.

Simplify the simulation even further if possible, or add additional elements that were found to be necessary.

–from Melanie Mitchell's presentation at the 1995 Science Symposium

FURTHER READING

Several SFI Working Papers – especially those by Stephanie Forrest, Terry Jones, John Holland, Melanie Mitchell and David Lane – address issues discussed in this article. To obtain a list of available papers, send your request by fax to 505 983-0751, by email to *wp@santafe.edu*, or access SFI's home page at *http://www.santafe.edu*

Murray Gell-Mann, *The Quark and the Jaguar,* W. H. Freeman & Co.

Joshua M. Epstein and Robert Axtell, *Growing Artificial Societies: Social Science from the Bottom Up,* forthcoming from the Brookings Institution.

Janet Stites is a free-lance writer whose work appears frequently in the Bulletin.

SYMPOSIUM SHOWCASES A DECADE'S WORTH OF COMPUTER MODELING

Janet Stites

This year the Institute dedicated its Annual Science Symposium to the topic of "Adaptive Modeling of Complex Systems," outlining four of the agent-based models that have been developed by researchers affiliated with the Institute. The symposium was held in March on the SFI campus and was attended by many members of the SFI Science Board and invited guests. It offered a summation of nearly a decade's worth of work for a number of researchers at SFI, work that is fast becoming part of the signature of the Institute, simultaneously depicting its roots and defining its future.

SFI Research Professor Melanie Mitchell opened the day by discussing how computer science developments make such modeling possible. As director of the Adaptive Computation Program, and a former student of both computer scientists Douglas Hofstadter and John Holland, Mitchell is an especially appropriate spokesperson for the field of computer modeling. She explained that there are four approaches to science—theory, laboratory experiments, Gedanken experiments (thought experiments), and computer experiments. Computer experiments, she contends, allow the scientist to incorporate theory and thought in a sort of digital laboratory. Mitchell noted that the first computer experiments were numerical simulations, used primarily to trace missile trajectories and weather patterns. Expanding on numerical simulations, scientists use "data prediction simulations," which are meant to actually predict data from real-world experiments, and "exploratory simulations," which probe the plausibility of a scientific idea rather than to precisely model a real-world phenomenon. Most of the modeling at the Institute is done on the "exploratory" side. Mitchell emphasized that one key to successful modeling is simplification.

Pivotal in the modeling work being done in Santa Fe is SFI Research Professor Chris Langton's general purpose simulation program, Swarm. Bees swarming, birds flocking, and traffic jamming are all analogies commonly used to describe Swarm. What do they all have in common? There is no central authority, no central organization. Swarm demonstrates how obvious patterns and collective behavior emerge from individual agents, following a simple set of rules, from the bottom up. Langton is designing Swarm as a general purpose model that will illuminate the point at which intelligent behavior emerges, or falls apart. Political scientists might use it to understand the collapse of a government; or telecommunications engineers to anticipate a glitch in a switching system. At the symposium, Langton, SFI researcher Nelson Minar, and Deere & Company Staff Engineer Roger Burkhart each gave a presentation outlining different aspects of Swarm. The Swarm team will begin to work with a few collaborating groups this spring to evaluate the use of the system for scientific modeling.

University of New Mexico Professor and SFI External Faculty Member Stephanie Forrest and SFI Graduate Fellow Terry Jones demonstrated how they are using ECHO, a modeling program based on genetic algorithms, to model an ongoing experiment by University of New Mexico ecologist Jim Brown. The team, which includes ECHO developer John Holland, is using population data from plots of desert Brown has been monitoring for nearly twenty years. In the mid-seventies, Brown fenced off the plots and systematically removed desert rats and red ants to see what effect the absence of the rat and ant would have on the ecosystem. The value of running Brown's experiment on ECHO is that there is already two decades of data with which to work, allowing the team to compare the results of the ECHO model with that of the actual data. This works to both make predictions about the future of the plots and verify the ECHO model. Holland often compares ECHO to a flight simulator, where scientists can troubleshoot problems or test hypotheses without setting up a physical experiment.

Joshua Epstein and Robert Axtell, both SFI Members and research scientists at the Brookings Institution, demonstrated how fundamental social structures emerge from the interaction of individual agents in a simulation called "Artificial Social Life" or "Sugarscape." ASL simulates the interaction of adaptive agents that search for food, form groups, trade, and transmit cultural attributes, such as taste. The events unfold on an artificial resource topography—a sugarscape, where sugar can be eaten, stored indefinitely, and traded. The sugarscape is made up of sugar mountains and sugar lowlands and surrounded by sugar badlands. In the simplest version, the agents follow one behavioral rule: find the nearest unoccupied site with maximum sugar, go there and eat the sugar. In this model, Epstein and Axtell hope to be able to decode collective structures, such as, economies, ecosystems, epidemics, social revolutions, arms races, and wars, to uncover simple local rules that generate them. ⊕

BEYOND BUSINESS AS USUAL

SFI expanded its presence in the global business community by recently participating in two conferences organized by Business Network member, The Praxis Group, Ltd. The conferences entitled, "Complexity and Strategy – The Intelligent Organization" were international with one venue San Francisco, and the other London. Between the two conferences over 200 professionals representing about 80 companies attended talks given by a variety of people affiliated with SFI or with business. SFI-affiliated speakers included W. Brian Arthur, Santa Fe Institute; Robert Axelrod, University of Michigan; John Seely Brown, XeroxPARC (SFI Business Network); Michael Cohen, University of Michigan; Mary Cirillo and Colin Crook, Citicorp (SFI Business Network); Murray Gell-Mann, Santa Fe Institute; John Holland, University of Michigan; Stuart Kauffman, Santa Fe Institute, David Lane, University of Minnesota; Christopher Langton, Santa Fe Institute; and Monib Khademi, Mike McMaster, and Howard Sherman, The Praxis Group, Ltd.

When a group of mostly theoretical scientists founded an unorthodox research institute—SFI—a decade ago, they were hardly thinking that they might have an impact on the way business was conducted. They were pushing the limits of ambition just to suggest that they might alter the way some science was done. But SFI's large and multidisciplinary view of science began to spread widely, and even in the early years there was interest from a handful of businesses that came into SFI's modest orbit. Over the past few years, as SFI has become better known, the number of companies attracted to SFI research has increased significantly.

In 1992 SFI established its Business Network for Complex Systems Research, a way by which companies could participate more actively in the life at SFI. There were five members in that first year. In 1993 an additional eight members joined, and the BusNet now has 21 members. Each member agrees to provide at least $25,000 annually to support SFI research.

The range of companies is intriguing, and it continues to diversify: finance, computing, manufacturing, consulting, aerospace, and communications. Not surprisingly, given that range, the BusNet is characterized by many different kinds of interactions with SFI.

In 1994 Deere & Company lent Roger Burkhart, a senior scientific programmer, to participate for more than half a year on Chris Langton's Swarm Simulation team. Roger has returned to Deere as an expert in Swarm, which is a general purpose simulation system under development for modeling interactions of adaptive agents. Several other BusNet members are similarly eager to use Swarm for their own simulation problems, and they await the availability of the software later this year.

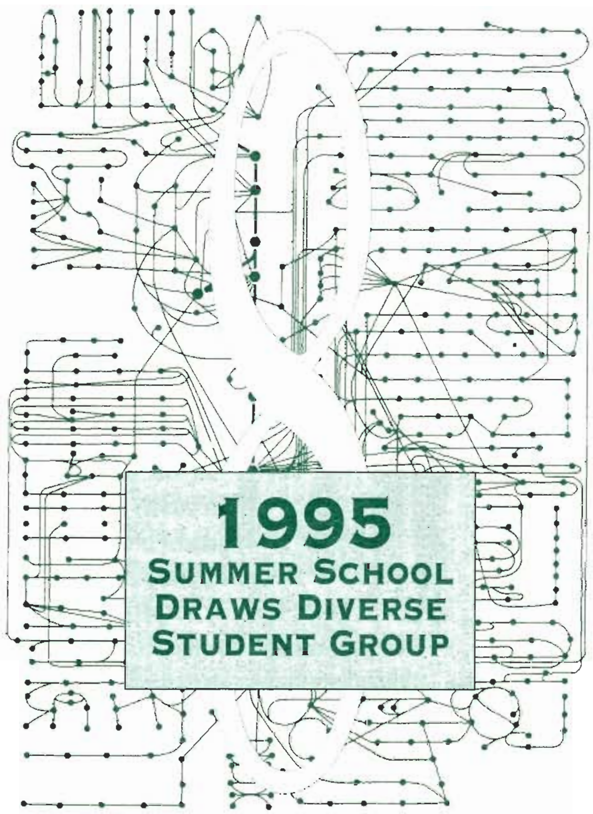
Also in 1994, Coopers & Lybrand produced, and began to use with its clients, a novel business simulation called TeleSim. Modeled roughly after the popular SimCity developed by BusNet member Maxis (the TeleSim work was done in large part by a company spun off from Maxis, Thinking Tools), TeleSim was inspired by work of a number of SFI researchers on adaptive systems. TeleSim's success suggests a way in which these kinds of simulations can be used to give business managers hands-on experience in experimenting (in the computer) with different business strategies.

Following in the tradition started by Business Network TXN who has supported postdoctoral fellow David Wolpert at SFI beginning in 1995, BusNet member Interval Research Corporation began funding a multi-year SFI postdoctoral fellowship in adaptive computation. In January SFI welcomed the first Interval Postdoctoral Fellow, Dan McShea from the University of Michigan. True to its unpredictable nature, SFI chose as a postdoc in adaptive computation McShea, whose specialty is evolution. Evolution, of course, is a dominant mechanism at work in adaptive computation and simulations, and Dan brings a new level of expertise to these collaborations.

To receive a list of current Business Network members, or to receive more information on the SFI Business Network Program contact Bruce Abell, Mike Simmons or Susan Ballati. A current roster of member companies is available via the Internet and is posted on the SFI World Wide Web home page at <www.santafe.edu>. ⊕

PHOTO: KAREN ZURLINDEN

Murray Gell-Mann at Complexity and Strategy conference San Francisco, March 1995



The Complex Systems Summer School, *now in its eighth year, embodies the notion that a new science of Complex Systems has emerged. While many of the topics can be found individually in some university courses or other summer schools, there is no other school which tries to bring together such an outlandishly varied assortment of problems, approaches, and subjects under a unifying idea. Even more ambitiously, the School brings together students from a wide-ranging array of scientific disciplines and attempts to find common grounds and languages. The difficulties and risks are not unlike those facing the builders of the Tower of Babel; the most surprising and unexpected result emerging from the Schools is how well it works. Co-Director Dan Stein notes, "The most gratifying and amazing aspect of each Summer School is how well the students interact, self-organize, exchange ideas, and form their own intact community. How this will occur is always completely unpredictable, but it always does."*

1995 participants Cynthia Ferrell, Christopher Still and Pat Longstaff reflect the student diversity as well as the high caliber of the Summer School applicants. Expect to hear about their experiences and their thoughts about this year's School in a future issue.

Cynthia Ferrell

"I want to understand how a complex system—one like the central nervous system or the brain—can be embodied within a robot to produce interesting behavior" says Cynthia Ferrell. Working for Professor Rodney Brooks at the MIT Artificial Intelligence Lab, Ferrell has built sophisticated robots with rich sensing capabilities and animal-like degrees of freedom. She has gone on to program these robots to interact within unstructured environments in biologically motivated ways. Her software, often inspired by the brain and central nervous system, is characterized by complicated dynamic systems of interacting processes. "My bias," she notes, "is that intelligence does not reside only in the brain, but within the entire body and its relationship with the environment. Hence, my approach to studying intelligence is through building artificial creatures."

As a doctoral student she has taken the lead role in building Cog, a serious attempt at developing a humanoid robot with human-like capabilities. The robot resembles an adult human from the waist-up. Recently, the torso, neck, and visual system were brought on-line, and code development for Cog's "brain" and body processes is in progress. Arms, hands, and an auditory system are forthcoming.

Ferrell's dissertation topic is one inspired by the development of cognition and action that occurs in the early years of infants. "I'm interested in the problem of generating novel behavior for an embodied system such as Cog," she says. "Many studies show that the infant's environment and experience play an important role in brain and behavioral development. I'd like to study and emulate similar phenomena on an autonomous robot." Ferrell's hypothesis is that the development of physical and cognitive behavior can be characterized as a complex and nonlinear dynamical system. "Notions of 'emergence,' 'global order from local interactions,' and 'self organization' come to mind when looking at the nature of the developmental process," she points out.

Christopher Still

Christopher Still received his bachelor's degree in biochemistry at Colorado State University in 1993, but his interests have always ranged widely. As an undergrad he probed protein activity while at the same time working on a project on alternative measures of economic well-being across campus in Economics. Undergraduate summers he was involved in ecological field and course work including studies of canopy epiphytes and their importance in forest hydrological regimes in Costa Rica, sapsuckers and their potential role as a keystone species in Colorado, and the effects of an artificial heating of a mountain meadow, also in Colorado, simulating a global warming of several degrees Celsius.

Still's current research interests are focused on global scale changes such as climate change and land use change and their effects on terrestrial ecosystems. One of the key challenges for scientists studying these sorts of problems lies in translating the information gained at one scale of investigation and applying it to questions being asked at other scales. This process is crucial to understanding the underlying physical processes that govern systems across spatial, temporal, and hierarchical scales. From such an understanding one can develop a predictive ability that is essential in global change science. For example, the global climate models that are used to predict future responses to forcing from greenhouse gases operate on scales of tens of kilometers. This level of description is inadequate to accurately predict the effects of future climate changes on terrestrial ecosystems. On the other end of the spectrum, ecological field studies typically cover only some tens of meters. What needs to be included in "scaling up" the results of these ecological studies to the level of description of the global climate models, retaining enough relevant information for predictive capacity? In other words, how much detail needs to be incorporated to represent the physical processes operating at smaller scales that are important for the higher levels of description?

This issue of scaling back and forth between different levels is what interests Stills and it is this that he hopes to address while a student at the Complex Systems Summer School. A number of so-called complex systems exhibit behavior at an aggregate level that is merely the result of simple local interactions between subsystems. These subsystems are scaling up their actions to a higher level. The task of understanding how these aggregate behaviors are produced is analogous to the challenge of scaling from ecological studies to global climate studies.

Pat Hirl Longstaff

Pat Hirl Longstaff has been a communications lawyer for 18 years, but left her law firm last year to attend Harvard's Kennedy School of Government and study the public policy implications of new communications technology. "It felt like time to look at the big picture," says Longstaff. Harvard has since published her paper suggesting information theory as a framework for dealing with the regulation of converging communication technologies. A second paper on the changing role of "universal service" policies is slated for publication by Harvard this summer. She will be an associate professor at the Newhouse School of Communication at Syracuse University in the fall, teaching communications law and policy

Longstaff says she expects to be awed by the credentials of her fellow students. "I'm afraid it won't take long for them to figure out that I wouldn't know a nonlinear equation if one ran out in front of my car." But she hopes her other contributions will make up for her lack of math skills. She will be looking for similarities in how communication works in the wide variety of complex systems discussed at the school. She believes this will be useful to the various industries that make up the communications sector "who are currently in a dynamic adaptation phase themselves and must figure out what communication services will be the most helpful to customers who are also trying to stay adaptive. The work being done at SFI could also have a profound impact on journalism if it helps to redefine the information people need and how they need to get it." She also hopes it can be used by government regulators who must "adapt to the adaptations of the communications sector at an ever-increasing speed."

Longstaff admits to being a closet nerd and "reading science for fun." She hopes she can help build bridges between the worlds of science and public communication on many levels. She is starting by brushing up her math skills before the school starts in June. ⊕

Summer School Fact Sheet

Topics and Speakers

Patrick Culbert,
Anthropology, University of Arizona
Archaeology, Hierarchical Organization and Ancient Maya Culture

Charles Doering, Center for Nonlinear Studies, Los Alamos National Laboratory
Modeling Complex Systems: Stochastic Dynamics in Condensed Matter and Biophysics

Stephanie Forrest,
Computer Science, University of New Mexico
Adaptive Computation

Atlee Jackson,
Physics, University of Illinois, Urbana-Champaign
"Understanding" Our Dynamic World

Stuart Kauffman,
Santa Fe Institute
The Origins of Order: Self-Organization and Selection in Evolution

J. Scott Kelso,
Center for Complex Systems, Florida Atlantic University
Self-Organization of the Brain and Behavior

John Miller,
Social and Decision Sciences, Carnegie Mellon University
Economics and Adaptive Systems

Michael Stryker,
Physiology, University of California at San Francisco
The Development of the Central Visual System: Mechanisms and Models

Support for the 1995 School

General support from the Center for Nonlinear Studies at Los Alamos National Laboratory, Department of Energy, National Institute of Mental Health, National Science Foundation, Santa Fe Institute, and the University of California system.

Student support from Florida Atlantic University, Stanford University, University of Colorado, and the University of Texas at Austin.

The Participants

51 graduate students, 7 post-doctoral fellows, 12 senior researchers representing the fields of Astronomy, Biology, Biomathematics, Chemistry, Computer Science, Decision Sciences, Economics, Engineering, Finance, Genetics, Mathematics, Neuroscience, and Physics.

MENTORING YOUNG MINDS

SFI RESEARCHERS INTRODUCE TEENAGERS TO COMPLEXITY SCIENCE

Marty Peale

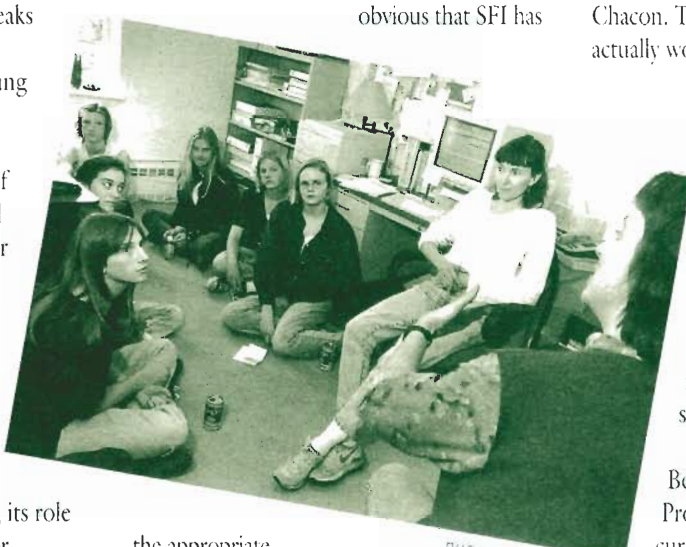
On Bette Korber's computer screen are rows of data from nearly 200 mothers who have given birth in the past year—mothers who are HIV positive. Korber divides her work between SFI and Los Alamos National Laboratory and is currently studying the molecular epidemiology of the HIV virus. For the moment, however, her back is to the screen, as she speaks with eight teenagers seated on the floor of her office. They are all young women interested in, or just plain good at, math and science.

These students are just a few of the high-school and middle-school students who are exposed each year to the Institute's interdisciplinary, computational approach to science. Since 1988, SFI has hosted nearly 500 postdoctoral researchers, graduate students and undergraduates through a combination of its annual Complex Systems Summer School, its role as an NSF Research Experiences for Undergraduates (REU) site, and its residential graduate and postdoctoral fellow programs. Since 1990, the Institute has also been fostering relationships with secondary students.

The work with younger students began nearly five years ago with a pilot program designed to introduce high-school students to topics of research at the Institute, to the men and women who were actually doing the advanced science, and to the reasons why they chose their careers in science. The originator of that program, Suzy Pines recalls, "We aimed at first to build a two-way bridge between the SFI, which was still very young, and the Santa Fe community as a whole, and to provide new exciting scientific experiences for students at the secondary level."

That initial program brought the Institute to the attention not only of students and teachers from the Santa Fe area, but also of specialists in science education from across the country. Pines explains, "There was a great deal of excitement at the national education conferences I attended about what we were doing, because we were trying to work at the cutting edge of science education."

While the Institute has chosen, thus far, not to formalize an outreach program to secondary students, it has continued to respond in specific cases when it is obvious that SFI has the appropriate (and willing) scientific resources, and when it is clear that a short project may have a longer-term effect. SFI Director of Programs, Ginger Richardson, observes that, "The Institute's time, funding, and staff resources are most creatively and efficiently used when we act in a catalytic rather than an extended, programmatic role."



PHOTOS: CARY HERZ

Ed Chacon is a Science teacher at Ortiz Junior High School who is participating in the Program for Math, Engineering and Science Achievement (MESA). The program is funded by the State and local technology-oriented organizations, including LANL, to motivate young students "to aim high." The MESA program targets at-risk students, especially young women and minorities. Chacon's MESA Group is mostly Hispanic girls, and mostly from fatherless homes. "I read about SFI," says Chacon, "and learned that we had Nobel Laureates right here in our community. I thought, 'That's aiming high, and why not.' So I gave them a call."

In September 1994, 22 seventh and eighth-grade girls who are in the MESA program met with women scientists at SFI. "They saw that there are women in the field— really bright women who have Ph.D.s from Yale and Harvard and MIT, that it's an exciting field, and that it's as much for women as for men, or more so," says Chacon. This exposure to women who are actually working at the cutting edge of science, and who are receiving recognition for their achievements, has served as one real-world extension of the support and encouragement Chacon is able to offer his students. He is quick to emphasize the value of such personal contact and the pivotal role it can play in the life of a student.

SFI Postdoctoral Fellow Bennett Levitan and resident Professor Stuart Kauffman are currently mentoring three students from Santa Fe High who approached them for guidance in a year-long project which will culminate in national competitions including the "Super Computer Challenge" and "Adventures in Supercomputing." Jonah Gollub, Rob Franklin, and Richard Rignal explain, "All we knew was that we wanted to do a project that used computers and involved the evolution of simple organisms that mutate and change." Levitan and Kauffman have them off and running on an adaptation of the NK model known as the p-spin model. The students have developed the necessary software and are now analyzing the fitness landscape for the model. Levitan explains that Jonah, Rob, and Richard are giving him an opportunity to explore a research project he wouldn't otherwise have time to pursue. Also, because he plans to teach eventually, he values this chance to practice his mentoring skills. "I'm working all the time," he says, "with questions like 'How much do I do, and how much do I let them puzzle it out for themselves?'" Over the Internet, Jonah writes, "This project with SFI has allowed us to explore many new ideas that we have never thought about before. The help and guidance we've received has allowed us to get a feel for what it is like to be a scientist— the good and the bad. The whole experience has given us a sense of responsibility and perception of reality, a chance to experience the real world!!! We would not hesitate to do it again, given the chance."

Joe Newlander is another teen who frequents the Institute. He is a 14-year-old from Santa Fe Secondary, where students progress at their own pace, and grade levels are not assigned. In school, Joe is finishing Algebra II, but he's also taking statistics, and he's about to begin a trigonometry class at Santa Fe Community College. In science, he and his classmates are participating in a cold fusion experiment under the guidance of a physicist from Los Alamos. He is also sitting in on Cris Moore's weekly course at SFI in computational complexity.

Joe learned about the SFI from the book jacket of *The Quark and Jaguar*. He said "Hey, I live in Santa Fe! I love science, so 'why not here?'" The fact that Joe finds himself in a class surrounded by researchers who've had at least ten years more math than he seems not to phase him in the least. "The greatest thing is to be allowed into such a positive environment where people are thinking and working so hard. The material may seem advanced, but you can pick up the context, and the rest sinks in eventually. Cris teaches how to think, not what to think, and that applies to any field of study."

"More than anything," Joe adds, "I'd like to thank Cris Moore, Michael Angerman, and Nelson Minar for what they've done for me. I feel like the sorcerer's apprentice! If you're willing to learn, they're willing to teach."

Given that the SFI environment allows researchers the freedom to pursue their work without obligations to students, it is perhaps remarkable that so many have proven so willing to make time for these young people. The gesture, in whatever form it takes, is one of personal commitment to mentoring or otherwise cultivating inspiration in the lives of students. "Many very busy researchers and scientists at SFI were very generous," says Pines of the first years. That observation holds true today. Together, Institute researchers have reached a number of students from the public and private high schools in the Santa Fe area.

Most recently, beyond these personal encounters, the Institute has become involved in a couple of system-wide science-education reform efforts. "There is a ground swell of interest in the whole-science, complex-systems approach to science education," Richardson observes, "and we now find ourselves approached to be a partner in such projects. Frankly, we're cautious. We're a small institution with limited resources, and we're experts at science not educational method." Nevertheless, the Institute played the role of scientific advisor in a Santa Fe Community College project which involves a four-week course this summer designed to revive the excitement of discovery in "at-risk" middle-school and high-school students. The focus on water quality in Santa Fe and artificial life (i.e., robots) will integrate physics, biology, task analysis, and hypothesis testing. MIT faculty and possibly some SFI scientists will participate as mentors. These Summer Youth Math Science Exploration (SYMSE) modules are designed to be embedded ultimately in existing curriculum nationwide. Accordingly, the Community College plans to conduct teacher training through workshops and electronic means.

The Institute is also collaborating with Montana State University and the University of Montana in a proposal to NSF's National Infrastructure of Education (NIE) program. One aspect of the project is the development of curricular materials for K-12 math and science education, incorporating high-performance computing and communications technologies. The project includes development and distribution of a CD-ROM introducing the work of SFI researchers and associates around the world. The CD-ROM will include lesson guides, interviews with researchers, reading materials, software, and data sets relevant to fields such as artificial life and societal evolution.

SFI is collaborating with external researchers who are beginning to think about how to apply ideas about complex systems to the ways we learn. In April SFI, along with the Santa Fe Children's Museum and the local public schools, co-sponsored a public lecture and a day-long seminar session with Harvard educator Howard Gardner, an author well-known for his theories of multiple intelligence. "Gardner's work is certainly relevant to new approaches to teaching whole science," says Richardson.

Along the same lines, Richardson emphasizes that she is interested in introducing young women to the professional women at the Institute for more than one reason. "It's not just that I think they can benefit from seeing our scientists as role models. I'm also very intrigued with the possibility— still provocative at this point but there's been some interesting research—that females in general may have the capacity to integrate information in such a way that they can be very, very good at the kind of interdisciplinary science we're doing here."

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Marty Peale is a technical writer and editor living in Santa Fe.

PROFILE OF JIM BROWN

Janet Stites

PHOTO: C. H. BROWN

When Santa Fe Institute External Faculty Member Jim Brown goes out in the field, he has 24 to choose from. Twenty-four half-football field sized plots on a fifty acre patch in the southeastern Arizona desert near the town of Portal. The University of New Mexico ecologist set up the experiments nearly twenty years ago with the primary objective to study how rodents, ants, and birds compete for seeds. He wanted to see how the organisms interacted and how they affected the population dynamics and community composition of plants by selectively consuming particular kinds of seeds. Over the years, responding to the removal of rodents or ants, the plots have changed dramatically, and in a sense, so has Jim Brown.

The 52-year-old Brown earned his A.B. from Cornell University in 1963 and his Ph.D from the University of Michigan in 1967. Prior to coming to New Mexico, he held positions at UCLA, the University of Utah, and the University of Arizona. It was while he was at Arizona that Brown established what has become known as the "Portal" project. To set up the plots, Brown and a number of graduate students had to first fence them. "We then live-trapped the kangaroo rats out of some and poisoned the ants out of others so that we could look at how the community reassembled itself," he says. Early on the group established what Brown had suspected: that some of the organisms compete for seeds and that all three—rodents, ants and birds—have a significant impact on the plants. Moreover, they found smaller kinds of rodents coming in, in the absence of the kangaroo rats, and colonizing the plots.

"The most interesting thing is that we had the good fortune to keep the experiment going long enough that we began to notice a whole lot of other unexpected effects from these initial perturbations," Brown says. "We began to get almost a transformation of the habitat from a desert shrubland into something that more resembled the arid grasslands you find elsewhere in the southwest." This unexpected result provoked Brown to consider the historical condition of the area, to ask the question: Was the original habitat a grassland?

He also gained insights into the role of livestock grazing. "The entire study site has been fenced for 17 years to keep out livestock that continually graze the surrounding area," Brown says. "Yet there haven't been as dramatic changes outside the fence as inside. Still, we know that livestock grazing and other human activities have had a big impact on habitat changes and have contributed to a degradation of grasslands into shrublands throughout the Southwestern U.S."

Brown's plots have become rather infamous in the field of ecology, and more recently, computer modeling, with his work to simulate the evolution of the plots on SFI's own ECHO modeling program. ECHO, which was created by John Holland, SFI External Faculty Member and University of Michigan computer scientist, uses genetic algorithms to create an artificial ecology. It's not clear whether Brown found the Institute or the Institute found Brown. But Brown remembers hearing Holland speak about ECHO during the 1992 workshop on integrative themes, Brown's first trip to the Institute. At the time, he believed ECHO might be modified to simulate particular kinds of ecology systems. "It takes years for things to happen in the field," he says, "which limits the number of experiments one can do." He saw computer modeling as a way to help determine which of his lengthy experiments to implement in the field. Brown also points out that the data he's already collected from the desert plots can be used to validate the ECHO computer model. To do so, he has worked in conjunction with computer scientists Professor Stephanie Forrest and graduate student Terry Jones, both of University of New Mexico and the Institute.

To be successful, the three knew they would have to modify Holland's original model. "Holland had built into ECHO so much ecological realism and complexity that it was difficult to understand the output by looking at the computer code he had written," Brown says. The naive goal, Brown explains, was to tailor ECHO to make it more like a specific ecological system, like his own desert system. "We haven't gotten there yet," he says. Brown, Forrest and Jones believe that it is important to do some computer "experiments" to learn more about how this artificial ecology works before trying to modify ECHO to simulate a real ecological system.

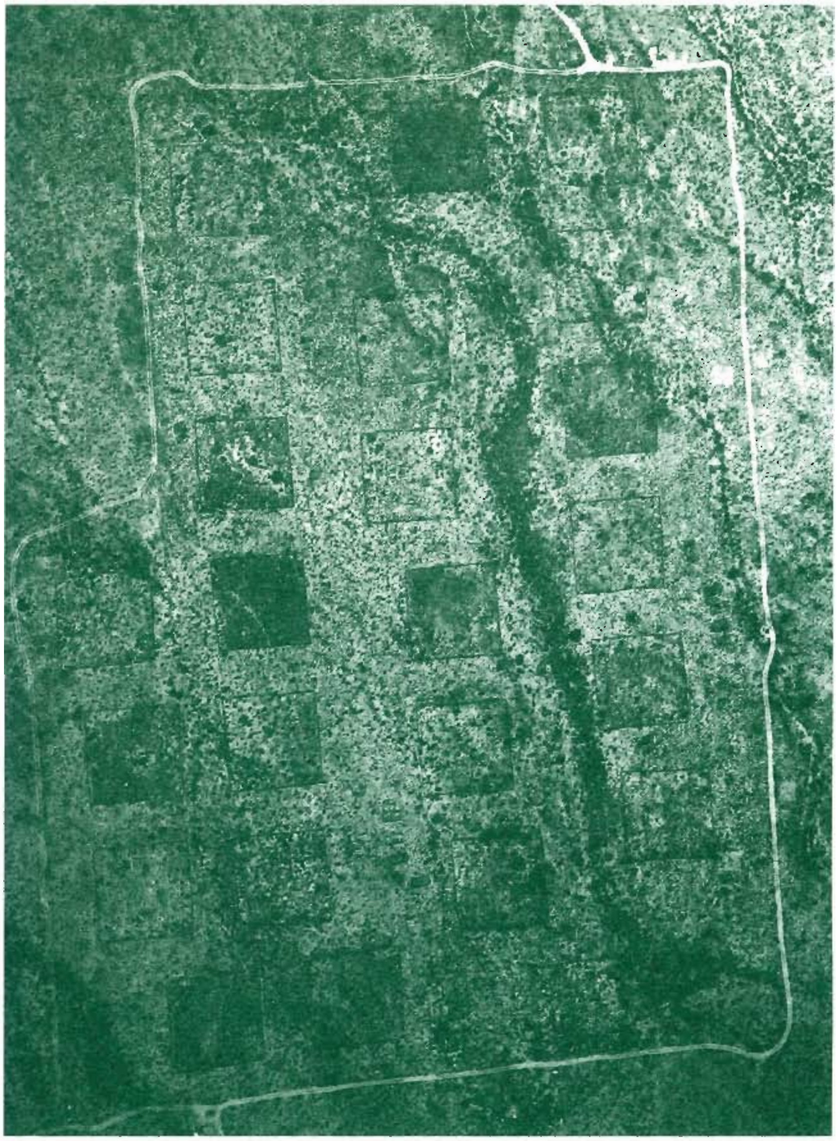
In another SFI collaboration, Brown is working with Chris Langton to model some of the responses of Biosphere II on Langton's computer program, Swarm. The project is somewhat simpler than modeling the desert ecosystem, explains Brown, because the different kinds of organisms and plants found in the Biosphere are relatively small and the changes have been documented by the Biosphere scientists. The Biosphere project has reorganized its scientific research program over the past two years, according to Brown, making it easier for them to obtain the data necessary to guide development of the model.

Most recently Brown played a pivotal role in SFI's bid for the NSF-funded Center for Ecological Analysis and Synthesis, helping bring together a number of ecologists to author a proposal and writing much of it himself. While the Center was ultimately awarded to the University of California at Santa Barbara, the effort has prompted the Institute to organize a number of exploratory workshops in the field of ecology and to establish collaborative research with the new Santa Barbara Center.

Brown has been associated with the Institute for a relatively short time, but his work, both in theme and implementation, echoes what has been going on at the Institute since its inception. "The thing that really interests me is biological diversity," Brown says. "Why there are so many kinds of organisms in the world; why there are so many that live in one place." One aspect of this involves trying to understand how the biota of North America, particularly populations of birds and mammals, are distributed over the continent. To do so he studies patterns of abundance and co-existence over geographic space and changes in the patterns over time. His tools: computerized databases and, again, computer modeling.

But it's the theoretical side of Brown that most resembles the work going on at SFI. Brown believes the field of ecology has been somewhat scientifically conservative, proceeding from a reductionist perspective. "When we've studied complex ecological systems, we always tried to understand those systems by simplifying them," he says. "By using some combination of mathematical models and experimental manipulations we could look at the effect of one or a few components or interactions in isolation. Implicit in this is the hope that we could put these parts back together and understand the properties of the complex whole." But Brown believes this is changing. "I've seen a lot of response from graduate students to thinking about ecological complexity in a new way," he says, adding that the University of New Mexico seems to be a draw for this group.

He acknowledges that his own location, a bit over an hour from the Institute, has been fortuitous to his work and thinking. "The most exciting thing about my association with SFI is that it's stimulating me to think about things that I wouldn't have thought about before" Moreover, ideas about complexity and access to sophisticated computer modeling have given Brown an alternative way to grapple with ecological problems. "I think what



Aerial photograph of Brown's experimental research site in the Chihuahuan Desert. The small squares are the 24 plots, each measuring 50 X 50 meters, from which different combinations of rodents and ants have been removed since 1977. The dark squares in this photo, taken in March 1995, are plots with orders of magnitude higher densities of winter annuals owing to the removal of all rodents or just kangaroo rats.

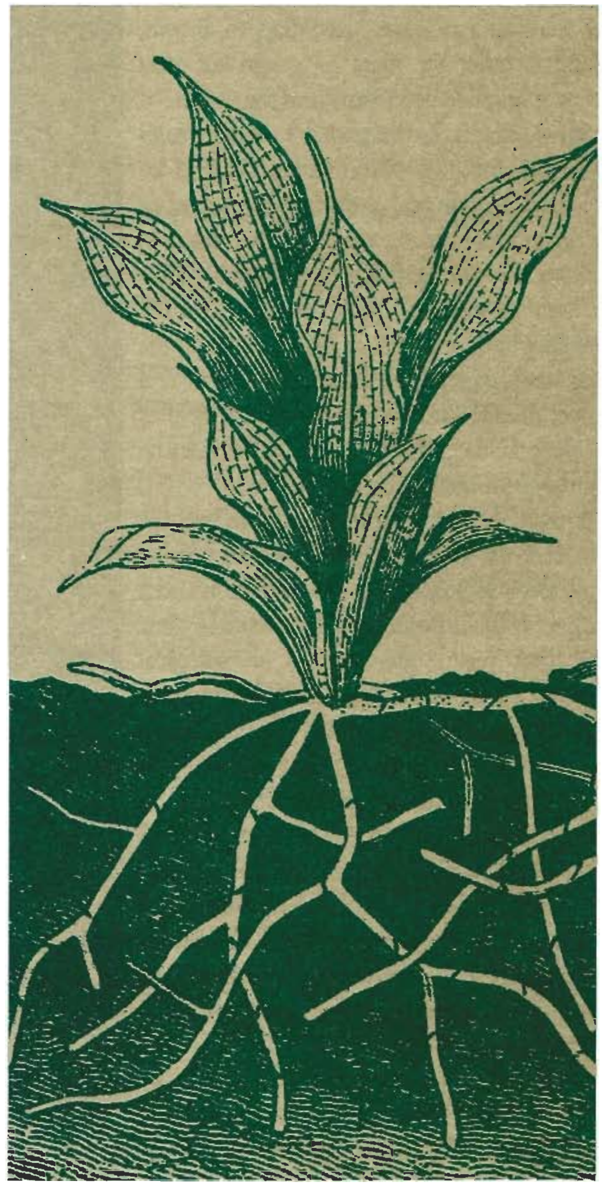
we've seen in ecology is the same thing that a number of people interested in complex systems have seen in their disciplines, whether it be biology, or physics, or economics," Brown says, "and that is that a strictly reductionist approach to science doesn't work. You can take systems apart. You can find out what the components are and you can find how they work in isolation. But this understanding is not sufficient to enable you to put them back together and to re-create the properties of the whole system."

Traces of this sentiment can be found in what Brown refers to as "macroecology." The crux of macroecology is to look at ecological data over both vast geographical areas and long time spans to see how species act on a continental scale. In a well-read paper on the topic Brown published in *Science*, March, 1989, he writes:

> Since the early 1970s, ecology has become increasingly microscopic and experimental in its approach. As answers to the big questions remained elusive, many ecologists focused on problems that could be solved. It is possible to characterize the effects of physical conditions or of other organisms on a certain species in a particular place by means of controlled, replicated manipulations. The problem, however, is not so much in interpreting the outcome of any single experiment as in synthesizing the results of the many different studies to draw useful generalizations about the organization of the natural world. Without a complementary emphasis on large-scale phenomena, there is little basis for determining which results simply reflect the idiosyncrasies of individual species and particular sites and which reflect the operation of more universal processes.

This March The University of Chicago Press published Brown's book on the subject simply titled: *Macroecology.* (For further information on the book, see page 23.)

One way to understand the impact of Brown's work as an ecologist is to talk to his colleagues in the field. University of Wisconsin limnologist Steve Carpenter has worked with Brown on a number of projects and is continually impressed with his seemingly endless energy. "I have a tremendous appreciation for both his enthusiasm and breadth of interest," he says. Carpenter believes Brown has been very instrumental in bringing ecosystem ecology and population ecology together. "These two fields have drifted apart over the past twenty to thirty years," he says. "The ecosystem ecologists have tended to look to elements like climate for changes in a system and have tended to forget the evolutionary context of a ecosystem. The population ecologists have become very reductionistic, looking at isolated populations and forgetting the physical and chemical context in which life occurs." Carpenter believes Brown has brought these two areas together through his work with macroecology and his emphasis on long-term experiments, like that of the "Portal" rat project.



Competition Seeds SFI Ecology Program

Last year the Santa Fe Institute was one of two finalists to be the NSF-funded Center for Ecological Analysis and Synthesis. Although the award ultimately went to the University of California at Santa Barbara, the project brought together a number of the nation's leading ecologists on behalf of the SFI effort. The Institute plans to capitalize on this already assembled group to build up its growing research program in ecology. Chief among the activists are University of New Mexico's Jim Brown and University of Tennessee ecologist Stuart Pimm. Brown has been involved with the Institute for several years (see "Profile") in a number of different capacities. He looks forward to being instrumental in SFI's renewed commitment to ecology. "The next thing I would like to do is organize a workshop that focuses on ecological complexity and bring some really good ecologists together with people from other disciplines who can bring another perspective," Brown says.

Buzz Holling, the Arthur R. Marshall professor at University of Florida concurs. "Brown has a wise, gentleness about his work," Holling says. "He opens up opportunity and encourages innovation." Holling believes Brown's call for macroecology has been instrumental in provoking ecologists to look at the field at a number of different levels. Holling also considers a collection Brown co-edited with Leslie A. Real, mandatory reading for budding ecologists. The book, *Foundations of Ecology: Classic Papers With Commentaries* (University of Chicago Press, 1991) is a compilation of this century's premier essays on ecology with commentary by Brown and Real. "I make every graduate student I have read this book," Holling says.

Brown's contributions to the field have been formally recognized also. He was recently elected to serve as future President of the prestigious Ecological Society of America.

The effects of Brown's work are not limited to the academic field of ecology. Through his work with the desert plots, Brown has become active in a true "grassroots" movement to learn how to manage and restore the range land in the area of his study. What's surprising is the scope of collaborators. "It involves a number of parties who usually view each other with considerable distrust, if not outright hostility," Brown says. "Private cattle ranchers, the Forest Service, the Bureau of Land Management, the Animas Foundation and the scientific research community."

It's clear that, while maintaining his Arizona plots, Jim Brown has had some time to think, that the project has become much more than a collection of data or an observation of an isolated ecosystem, that it has become the seed for his life's work. And it's apparent that there are very low fences between that work and his personal life and interests. His wife, Astrid Kodric-Brown, is a biologist and professor at University of New Mexico, specializing in animal behavior. The two have co-authored papers, raised two children, and share an affection for Southwestern Indian arts and crafts. This year they have a new grandchild. Whenever possible the couple spends time at their cabin in the Chiricahua Mountains, not far from Brown's plots. "There is more wildlife there than anywhere I know of in the U.S.," Brown says enthusiastically, betraying the true kernel of his enthusiasm—spread over a vast geographic space and a long period of time.

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New Directions for ECHO Modeling

James Brown and Stephanie Forrest recently convened modelers and ecologists for an intensive discussion of experiences with ECHO, to map out a set of scientific questions to address with ECHO, and to outline future research directions.The meeting, supported in part by the Santa Fe-based Thaw Charitable Trust and cosponsored by UNM, was held at the UNM Sevilleta Long-Term Ecological Site.

The meeting broke into roughly three topic areas: reports on current activity and results using ECHO; discussions of perceived problems with the current model and questions to address with ECHO-like models; and planning for future work on ECHO.

John Holland led off the meeting with a presentation of his current work and interests in ECHO. He is concerned with mechanisms of adaptation such as exchange of resources, adherence (between agents), and transformation of resources. He also presented several guiding scenarios— behavior he would like to observe in an ECHO model—including evolving Ant-Fly-Caterpillar-like triangles, Prisoner's Dilemma interactions, multi-agents, and seed machines. Julian Adams gave an overview of his *E. coli* experiments in a chemostat with a single limiting resource (glucose). His experiments begin with all identical cells (genetically) and within 800 generations he observes that the population has diversified into three types of cells with quite sophisticated interactions among the cell types. Next, Ginger Booth described what mechanisms she has added to ECHO in order to observe stable trophic cascades. Finally, Peter Hraber reported on his detailed quantitative studies of relative species abundance in ECHO.

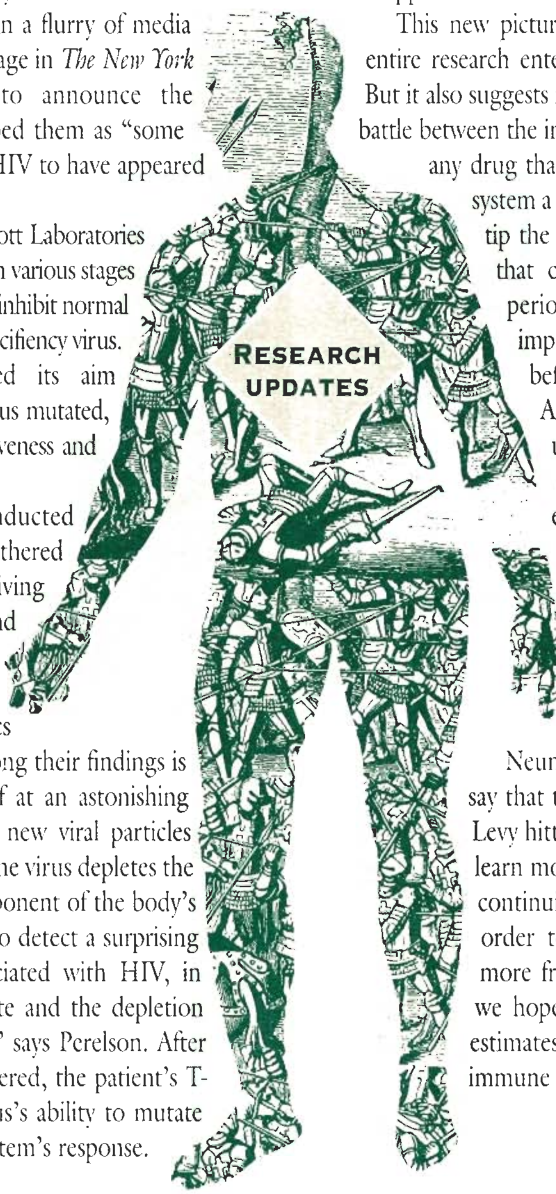
Discussions of what to do with ECHO followed. What are the qualitative phenomena that are of interest? Can we account for diversification and specialization? What is the difference between a good model and a bad model? Much time was given over to discussing the role of mechanistic vs. descriptive models, models as metaphors that change the way we think about a subject. People identified the following topics for further research: evolution of communication and foraging, cohesion between agents, combining classifier systems with ECHO to get some kind of directed behavior, evolution of diversity in specific context of chemostat experiments, studying mimicry and related phenomena, especially as they relate to the use of tags, hierarchical levels of evolution, more ecological questions, such as effects of species diversity on energetics of the system, and how diversity relates to stability to perturbations, porting ECHO to Swarm, using control theory to understand ECHO and food webs, habitat segregation, and keystone species.

Finally there was focused discussion concerning the current status of the ECHO software. Several informal working groups emerged from these discussions, including software tools (including consolidation and redesign), data-free ecology of ECHO, and putting real data into ECHO.

At War in the Body

New Picture of Immune System Battle with HIV May Alter Research

Study of an experimental AIDS drug has revealed surprising facts about the basic biology of the virus that causes the killer disease and helps explain why all drugs tried until now have been ineffective. The theoretical work was done by SFI External Faculty Member Alan Perelson (Los Alamos National Laboratory) and SFI Postdoctoral Fellow Avidan Neumann (now at LANL). The SFI work was partly supported by the Jeanne and Joseph Sullivan Theoretical Immunology Program at SFI. Report of the work, carried out in collaboration with David Ho, Director of the Aaron Diamond AIDS Research Center and George Shaw, University of Birmingham, appeared in January in the British scientific journal *Nature,* resulting in a flurry of media attention including front page coverage in *The New York Times.* At a news conference to announce the discoveries, *Nature's* editors described them as "some of the most significant findings on HIV to have appeared in some time."



The study involved giving an Abbott Laboratories drug, ABT-538, to 20 AIDS patients in various stages of the disease. The drug is intended to inhibit normal reproduction of the human immunodecifiency virus. In the study the drug achieved its aim dramatically—but only briefly. The virus mutated, "learning" to evade the drug's effectiveness and the body's immune response.

Perelson and Neumann conducted mathematical analysis of the data gathered from the patients in the study. By giving these drugs to infected patients and measuring how fast the virus population dies and then recovers, it was possible to calculate the dynamics of the infection more precisely. Among their findings is that the AIDS virus replicates itself at an astonishing rate, creating as many as a billion new viral particles daily. The analysis also showed that the virus depletes the T-helper cell population, a key component of the body's immune system. "We've been able to detect a surprising amount of biological activity associated with HIV, in terms of both the virus' growth rate and the depletion rate of cells in the immune system," says Perelson. After the experimental drug was administered, the patient's T-helper cells rebounded, but the virus's ability to mutate eventually outpaced the immune system's response.

The conventional view of HIV infection was one of a largely quiescent virus hiding in a pool of latently infected cells and remaining dormant until chance activation of the cell. The new results show that rather than a long, quiescent period between HIV infection and the appearance of AIDS, the virus is growing and being destroyed at massive rates. The rapid turnover of the virus now known to take place explains why the resistant forms can so quickly predominate in the body after a drug has been administered. The researchers found that the new drugs could destroy 99 percent of the virus in the body, yet resistant strains of virus appeared within days.

This new picture of an AIDS virus infection means that entire research enterprises have gone down the wrong path. But it also suggests new strategies for combatting the virus: the battle between the immune system and the virus is so close that any drug that weakens the virus and gives the immune system a slight edge might in principle be enough to tip the balance. Researchers hope to create drugs that can outsmart the AIDS virus for longer periods of time, Perelson notes. "Another implication is it's important to treat early, before the virus population is large," he adds. Although many patients test positive for HIV up to 10 years before showing symptoms of AIDS, treatment might be appropriate even before they begin to suffer from the disease.

The study is continuing with a second set of patients. "The study was more important for understanding the whole system of HIV kinetics than its perturbation by the drug," says Neumann. "Our colleague David Ho likes to say that this study is similar to Comet Shoemaker-Levy hitting Jupiter, which allowed astronomers to learn more about Jupiter than ever before. We are continuing the collaboration with David Ho in order to do the mathematical analysis of even more frequent and more precise measures. This, we hope will enable us to obtain more accurate estimates of the parameters governing the HIV and immune system kinetics." ⊕

Global Politics, Common Culture and Sustainability

Axelrod Builds Two New Models

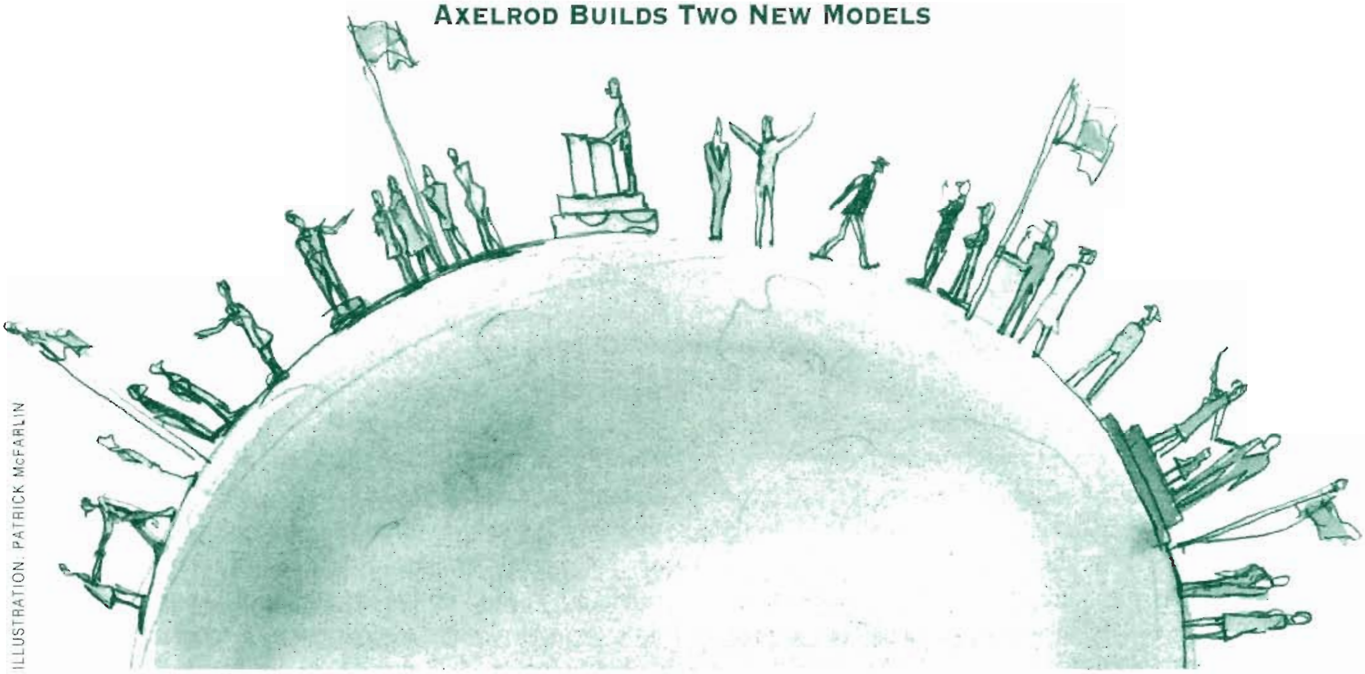


ILLUSTRATION: PATRICK McFARLIN

RESEARCH UPDATES

One of the main obstacles to global sustainability is the "tragedy of the commons." This phenomenon arises when many independent actors (people, villages, states, etc.) each "over-graze" because there is no mechanism to enforce the collective interests of all against the private interests of each. This leads to resource depletion, elimination of bio-diversity, overpopulation, war, and other major social problems. A major route to the prevention of the tragedy of the commons is the emergence of a political actor based upon the organization of previously-independent actors. Today we have political actors at the national level who can regulate resource use within their boundaries, but we do not yet have effective political actors at the trans-national level to regulate resource use at the global level.

As part of SFI's work on sustainability Robert Axelrod at the University of Michigan has developed a model which explores the emergence of "collective" political actors and the consequences for group action.

Political scientists have a variety of concepts and theories to analyze the emergence of new political actors. But, they do not have any formal model that accounts for this emergence from *within* the system. The problem is like biologists' interest in the emergence of multi-cellular organisms: research has tended to take for granted the existence of such complex units and therefore has not developed rigorous theories to explain how they might have come about in the first place. Currently the major research paradigm for formal models of politics is game theory, and game theory takes as given exactly who the actors are in a particular setting.

Axelrod has developed a model based upon tribute to show how new political actors can emerge from an aggregation of smaller political actors. This model offers proof that it is possible to use simple local rules to generate higher levels of organization from elementary actors. In particular it shows that a dynamics of "pay or else" combined with mechanisms to increase and decrease commitments can lead to clusters of actors that behave largely according to the criteria for independent political states. In its broadest perspective, the work can be seen as part of the study of emergent organization through "bottom-up" processes.

For Axelrod a new political actor equals an emergent set of relationships among previously existing units. There are several criteria to be such an actor: the "actor" has effective control over subordinates, is recognized by others as an actor, and there is evidence of collective action — "all for one and one for all."

This tribute model shows that "imperial overstretch" can bring down even the strongest actor. As an actor becomes committed to others due to tribute relationships and fighting together, it becomes exposed to the risks of whatever fights the others get into. Since actors decide on demands and responses based upon their own calculations, even a weak actor can choose to make or resist a demand for its own reasons, and thereby drag into the struggle a strong actor who is committed to it. Civil wars can occur among the smaller members of an alliance cluster. While the strongest member of a cluster can typically prevent a fight among members of the same cluster by taking sides, it would not do so if it had equal commitment to the two sides. Therefore, smaller members in a cluster may fight each other while the strongest member stands aside.

An alliance cluster can have more than one powerful member. It is also possible for the second actor to grow strong in the shadow of the first. Indeed, initial endowment doesn't guarantee or even predict success. Before clusters of commitments are established, wealth can be as much a handicap as an asset. Wealth makes an actor a lucrative target for other strong actors, and can make one over-confident in making demands.

The model demonstrates that a dynamics of "pay or else" combined with mechanisms to increase and decrease commitments can lead to clusters of actors that behave largely according to the criteria for independent political states. A simulation model like the tribute model should lead to insights into where there might be policy leverage in the real world.

Axelrod's second model seeks a deeper understanding of how groups of individuals come to share a common culture, and why the formation of ever-larger cultural units tends to slow or stop. Understanding how a culture becomes established, how it spreads, and how it can be sustained has growing importance in today's world. We applaud the spread of a common culture when it favors efficient communication, prevents unnecessary conflict, and fosters action for global needs such as sustainable growth. Yet we abhor the harm done to peoples whose cultures are destroyed, the loss to the rest of us of the wisdom embodied in those vanishing cultures, and the universal loss of adaptive potential made possible by cultural diversity.

In this model the dynamics are again "bottom-up," and involve social impact. The key premise is that people are more likely to be influenced by others who are already relatively similar to themselves. Emergent properties are stable regions of shared culture.

The likelihood that a given feature will spread from one individual (or group) to another depends on other features they may already have in common. Similarity leads to interaction, and interaction leads to increased similarity. This process need not lead to complete convergence. Indeed, the most interesting thing about the model is the way it can generate few or many distinct cultural regions depending on the scope of cultural possibilities, the range of the interactions, and the size of the geographic territory.

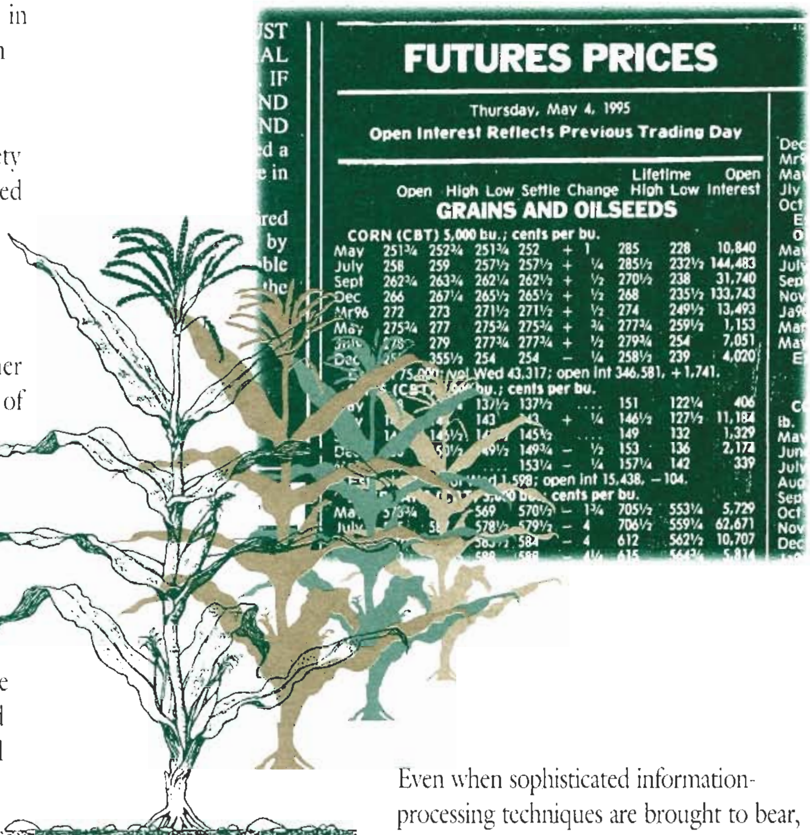
The model shows that the number of distinct cultures that survive increases when there are few features which specify a culture; many values which are possible for each feature; short-range interactions; and a territory that is neither too large nor too small. The first and last of these results are quite counterintuitive. Indeed one of the most valuable lessons of this model is that our intuition about very simple dynamic processes can often be quite poor. For this reason, simple models can be very helpful in discovering the consequences of basic assumptions about interactions among many actors.

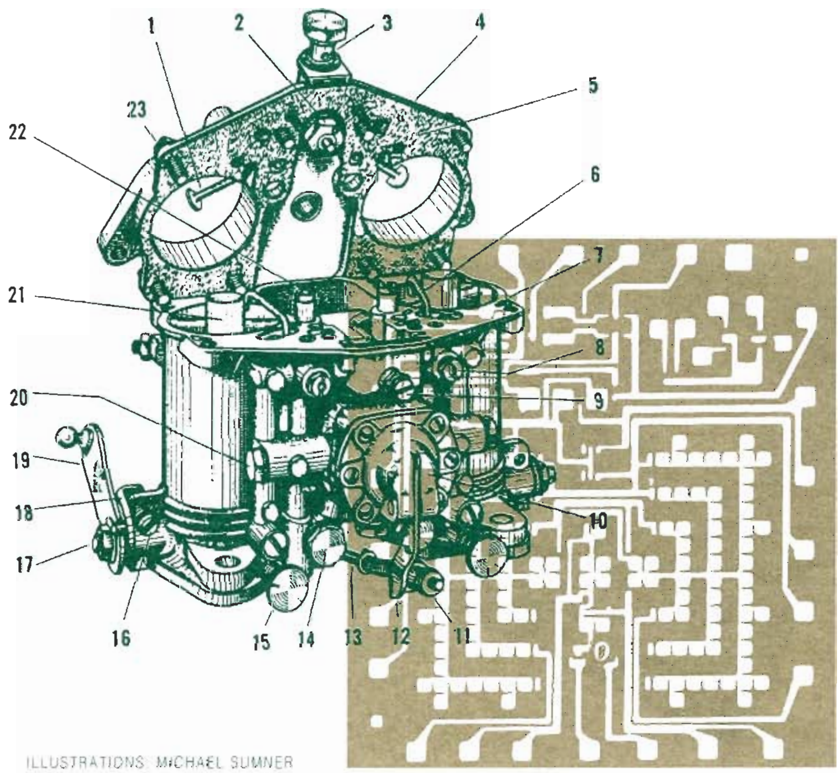
Axelrod's work was one of the research activities partly supported by SFI during its participation in Project 2050, a multi-institution effort funded by the MacArthur Foundation, involving SFI, the Brookings Institution, and the World Resources Institute, is reducing the scope of its efforts due to funding shortfalls. During the past two years there has been a substantial amount of important research done, as well as new collaborations begun. The period of time during which the project has been active coincided with an acceleration of progress at Santa Fe Institute, supported in part by the project and also by other sources of funding, in exploring the variety, utility, and validity of computer simulations to provide insight into exactly the kinds of problems inherent in global sustainability. SFI is committed to continue development and refinement of these models and will be devoting increased resources to them. Understanding and addressing issues of sustainability is an iterative process, and we remain convinced that thoughtful use of carefully developed and validated models will be persuasive tools to help people at all levels better understand the long-term tradeoffs. ⊕

LEARNING HOW TO CONTROL COMPLEX SYSTEMS

Seth Lloyd

Scientists and engineers have been hugely successful in solving problems of design and control. Advances in the physical, chemical, biological, and mathematical sciences have been accompanied and driven by the systematic search for technological benefits for society at large. The successes of this search have transformed the ways in which people live and work. One of the most striking transformations of society is the increasing importance of information in providing solutions for problems that were once completely mechanical. For example, a nineteenth-century farmer who wished to provide a cushion against the failure of his wheat crop would plant some fields of corn: today's farmer sells options—bits of information on pieces of paper—to provide a guaranteed income if the crop fails. Where thirty years ago a hot-rodder seeking extra performance would bore out the cylinders of his car, put on dual exhausts and a four-barrel carburetor, a modern hot-rodder simply removes the microprocessor chip that regulates fuel injection and timing, and replaces it with a chip that sacrifices fuel efficiency, low emissions, and reliability for power.





ILLUSTRATIONS: MICHAEL SUMNER

Even when sophisticated information-processing techniques are brought to bear, however, many problems stubbornly resist solution. The initial promises of cybernetics, and more recently, of artificial intelligence, have proved harder than expected to attain. Some problems in pattern recognition and robotics appear to be simply difficult, in spite of the fact that humans solve such problems every day. These seem to exhibit an intrinsic complexity, a complexity that the process of finding their solutions must share. In addition, though information processing has become so ubiquitous a part of design and control that the humblest of kitchen appliances seems to contain a microchip, success inevitably gives rise to new possibilities for failure. Highly-leveraged option traders, when their hedged bets go bad, fail spectacularly. Engines regulated by microprocessors may be efficient and reliable, but they are hard to fix when they break down.

Information is Physical

From one perspective, dynamical systems can be viewed as simply behaving—obeying the laws of physics. From another perspective, they can be viewed as processing information: how systems get and use information determines how they behave. This article describes research at the Santa Fe Institute and the Massachusetts Institute of Technology that combines these two complementary perspectives to provide a stereo view of dynamics and control. A mathematical framework that treats dynamics and information on an equal footing is used to provide a systematic treatment of how complex adaptive systems face and solve problems of control. This framework, developed by the author with Murray Gell-Mann at the Santa Fe Institute, describes how systems get information, how they incorporate that information in models of their surroundings, and how they make decisions on the basis of those models. This framework is designed to support both what Herbert Simon calls blueprints—descriptions of state—and recipes—prescriptions for action—and to provide for their interaction: in our models, adaptation is the co-adaptation of blueprints and recipes. Systems learn about their environment by attempting to control it, and modify their representation of the environment as a function of the results of those attempts at control. The research taking place at MIT in collaboration with Jean-Jacques Slotine emphasizes specific problems in robotics: how can a robot that has been assigned a particular task, such as catching an irregular, bouncing ball, decide what information is important to gather, how can it best incorporate that information in a model of its task, and how can it learn to perform that task in real time. The answers are relevant to biological systems undergoing natural selection, or to any system that processes information in order to adapt.

History

Historically, though they developed in parallel, dynamical systems theory and the mathematical treatment of information are distinct subjects. After its beginnings in the work of Lyapunov and Poincaré a century ago, dynamical systems theory went through a fifty-year lull before exploding in the last half century to provide a mathematical understanding first of linear systems, and more recently, of nonlinear systems. The methods of dynamical systems theory derive largely from deterministic, classical mechanics.

In contrast, the methods of information theory derive from statistical mechanics, which is probabilistic, and at its base, quantum-mechanical. Information theory originated a century ago when Maxwell, Boltzmann, and Gibbs developed successful statistical treatments of thermodynamic problems. Fifty years later, their work formed the mathematical basis for Shannon's development of a formal theory of information for the purposes of communication, a theory that has expanded to encompass a variety of subjects in computation, control, artificial intelligence, robotics, and a host of other fields.

Although the backgrounds and methods of dynamical systems theory and information theory are historically distinct, in practice, the two fields overlap. This arises from the concurrent development of nonlinear systems theory and of ever-more powerful digital computers. Computers play a complementary role to analysis in the study of nonlinear systems because the only practical way to follow the individual trajectories of a non-integrable system is to simulate its dynamics on a computer. That is, in practice, our descriptions of the dynamics of nonlinear systems are at least in part algorithmic—a computational procedure. The method of this research program is to make algorithmic descriptions of dynamical systems a virtue as well as a necessity.

Control and NP-Completeness

An algorithm that allows one to simulate the dynamics of a nonlinear system starting from a

specific state does not necessarily allow one to control that system. In contrast to the problem of controllability for linear systems, even though following an individual trajectory of a nonlinear system may allow one to verify that a properly chosen sequence of inputs controls the system according to a suitable criterion, it may not necessarily allow one to find such a sequence of controlling inputs or to predict the effect of perturbations on the system and its controls.

Consider the problem of landing an airplane. Suppose that one has programmed a computer to simulate the effect of applying a particular sequence of controls to an airplane in flight. Suppose further that this simulation is both accurate, in the sense that how the airplane actually responds to a particular sequence of controls corresponds closely to the computer's predictions, and efficient, in the sense that the computer can make its predictions of how the airplane responds in "real time," that is, sufficiently rapidly for those predictions to be used to fly the airplane. One can ask, given the assumptions of accuracy and efficiency on the part of the computer, how hard is it to find a set of controls that lands the aircraft safely?

The answer is that, even given the "ideal" qualities of the simulation, the problem of landing the aircraft is still hard to solve. The reason is simple: even though the computer's predictions are accurate, and the effect of a possible sequence of controls can be determined in a short time, there are an exponentially large number of sequences of possible controls, and to verify the consequences of each one of these sequences in a search for the optimum sequence takes exponential time. That is, if the computer has to answer n Yes/No questions properly in order to land the plane, then there are $2n$ different possible sequences of answers, only one of which may actually be the right sequence. Even if it is simple to decide whether or not a given sequence is correct, as n gets large, searching through all possible sequences of Yes/No answers to find the right sequence becomes difficult.

A mathematician would say that the problem of trying to find the proper controls to land the plane falls in the computational complexity class NP.

This class consists of problems for which any one potential solution can be easily shown to be correct or incorrect, but for which the space of potential solutions is exponentially large, so that the ability to verify potential solutions easily does not obviously translate into the ability to find a solution. NP problems are in general difficult to solve. If what is meant by an "efficient" simulation of a given system is that the consequences of applying a particular sequence of controls can be evaluated easily, then the problem of finding a sequence of controls that suffices to drive the system to some desired state falls in the computational complexity class NP. That is, even if one assumes that the response of the system that one desires to control can be accurately and efficiently simulated, the problem of finding an adequate set of controls is hard.

In the above treatment, it was assumed that it was possible to predict precisely the result of the application of a particular sequence of controls to the airplane. In real life, of course, whether the plane responds in a desired way to the application of controls is not necessarily fully predictable: for example, the plane may be subject to unpredictable variations on wind speed and shear. Or the plane may respond differently depending on the temperature and density of the air. All such unknown factors can be lumped into a single category called "noise." Noise represents all that is unpredictable about a problem. A particular set of values of the noise factors is called a perturbation, since the noise 'perturbs' the system in some random fashion. The presence of noise and perturbations makes the control problem harder.

In the absence of noise, the control problem can be stated, "Does there exist a sequence of controls that drives the system to the desired state?" In the presence of noise, the control problem becomes, "Does there exist a set of controls that, for all possible unpredictable perturbations, drives the system to the desired state?" Adepts in the field of computational complexity will note that where the first problem lies in the computational complexity class NP, the second lies one step further up the so-called "polynomial hierarchy" of problems: if one is given a sequence of controls, and a sequence of perturbations, then as long as one's simulation is accurate, one can verify easily whether the sequence of controls is adequate to drive the system to the desired state in the presence of those perturbations. But now, even to verify that a given sequence of controls produces the desired state in the presence of all perturbations is itself a difficult problem, in this case in the class Co-NP. Finding an adequate sequence of controls in the presence of noise requires the solution of a potentially infinite number of nested NP problems.

On first sight, these results relating control theory to the theory of computational complexity might seem only to verify in a fancy fashion what engineers have known all along: control of nonlinear systems is difficult. In fact, making explicit the relation of problems of control to NP problems not only shows that these problems are difficult, it shows how one might attempt to solve them. Though seemingly hard in the worst case, many NP problems prove relatively straightforward to solve on average. Over the years, computer scientists and mathematicians have accumulated a library of techniques suitable for attacking various sorts of NP problems. For example, at Caltech, John Doyle has taken a "branch and bound" analysis that has proved successful on a variety of NP problems and applied it to the automatic pilot for the Space Shuttle to show the existence of previously unsuspected unstable regimes during re-entry to the atmosphere.

Adaptive Control

Of course, the general control problem is even harder. Usually one does not even know the dynamics of the system that one wants to control well enough to program a computer to simulate them, let alone how to control the system in the presence of perturbations.

To solve problems of control and stability, one needs a picture of the qualitative behavior of the system. That is, for nonlinear systems, control requires insight into the nature of the system's dynamics. Nonlinear control scientists and engineers have developed a number of powerful techniques for characterizing the controllability and stability of nonlinear systems. Some of the most useful of such techniques are Lyapunov's direct method and its extensions, in which the problem of stable control is reduced to finding sequences of inputs that guarantee the uniform convergence of suitably chosen scalar functional to a fixed point. To find a proper such functional in general requires a qualitative understanding of the dynamics of the system in different regimes. For nonlinear systems, control requires intuition.

Traditionally, although techniques such as feedback linearization, optimal control, dynamic programming, etc., have provided a measure of generality in suggesting approaches to control problems, the practical estimation and control of nonlinear systems has proceeded on a system-by-system basis. The necessity for such a case by case treatment of nonlinear control problems arises from the lack of robustness for such "universal" techniques when faced with incomplete system identification and perturbations to system dynamics. The goal of this research is to provide a general framework for the systematic construction of algorithms for the control of complex, nonlinear systems in the presence of incomplete system identification and dynamic noise. But as just noted, control of complex, nonlinear systems requires insight and intuition. How does one provide a framework for the construction of "intuitive" algorithms? An algorithm is a procedure for processing information. To control a nonlinear dynamical system, an algorithm must embody a model for the system: that is, the way in which the algorithm processes information must mirror the way that the system processes information. For the algorithm to model the system successfully, it must be an adaptive algorithm: to acquire intuition, one must learn.

An adaptive algorithm for control alters itself in response to information that it gets about the system that it tries to control. In order to treat the process of adaptation systematically, we introduce a mathematical framework that unifies the description of regular and random features. When represented algorithmically, information about dynamics can be combined with other forms of information to encompass both deterministic and apparently random behavior within the same mathematical framework. The logic behind this unifying framework is simple. The behavior of any system, whether a turbulent fluid, a robot, or the Dow Jones index, exhibits "regular" features that are predictable and deterministic according to some set of rules, and features that the rules fail to predict, and that are apparently random. Both predictable, regular features and unpredictable, apparently random features can be described using information theory. On the one hand, the amount of information required to specify the regular features can be identified with the length of a suitable computer program that details the set of rules from which the predictable features can be derived, and then derives them. If such a program is of minimal length (i.e., no other program for deriving the predictable features is shorter), then the length of this shortest program is called the algorithmic information of the predictable features. On the other hand, the amount of information required to describe unpredictable, apparently random behavior can be identified with the Shannon information of the ensemble of residual random behaviors of the system after its predictable, rule-based behavior has been specified. These two types of information—algorithmic information to describe rule-based behavior, and Shannon information to describe apparently random behavior—can be added together to give the total information required to describe both predictable and unpredictable behavior.

The idea of combining algorithmic and probabilistic information was recently suggested by Gell-Mann and Hartle as a way of making sense of the transition from quantum behavior to classical behavior. They noted that one criterion for identifying the quantum mechanical operators that correspond to classical systems is to select those that had concise descriptions and whose time evolution was predictable and decoherent. The motivation for introducing total information as a tool for characterizing problems in nonlinear dynamics and control is twofold. First, as noted above, to describe dynamics algorithmically is simply a way of acknowledging and making mathematically precise the importance of computation for characterizing the behavior of nonlinear dynamical systems. Second, and more important, the combining of algorithmic and probabilistic information suggests new methods for addressing problems of measurement, adaptation and stability that are relevant to the control of complex, nonlinear systems. Information theoretic techniques allow new characterizations of observability and controllability suitable for complex nonlinear systems. In particular, the trade-off between algorithmic and probabilistic information in the formula for total information allows the identification of sampling rates and scales at which such systems are controllable or observable. Of particular interest are what we call "natural" scales and sampling rates: as one goes to finer and finer scales, and to more and more frequent sampling, a scale may arise at which an uncontrollable system suddenly becomes controllable.

According to the particular model that an adaptive controller possesses for the system that it is to control, some of the system's behavior is rule-based, or regular, and some is not rule-based, but irregular and apparently random. When the controller adapts, it changes the algorithm that it uses to model the system, and thereby changes what it regards as regular, and what it regards as irregular. What the controller treats as order and what it treats as disorder is therefore to some extent arbitrary, and as the controller adapts, there is a trade-off between apparent order and apparent disorder. This trade-off is not a zero-sum game.

Since total information represents the trade-off between rule-based and random behavior, it decreases monotonically as long as addition of extra rules to describe regularities of a system is more than compensated for by a decrease in the system's apparent randomness. This property of total information means that a learning process that minimizes total information is in a sense optimal: arrival at a minimum of total information implies that one has obtained a complete description of the predictable features of a system, and expressed this description in the most compact form. In fact, the model for a system's behavior that minimizes total information is optimal in a strict mathematical sense as well: in a maximum likelihood theory of inductive inference, the model that minimizes total information can be shown to be the maximum likelihood model—it is the most concise model that makes the best possible predictions given data. In effect, total information makes mathematically precise the intuition that the world contains both order and disorder, which interact in complicated ways. To characterize and control our surroundings, we must identify the parts of the world where order can be increased at the expense of disorder.

Conclusion

It is no secret that the world is glutted with information. The volume of junk mail, advertising, newsprint, cable channels, Ph.D. theses, and scientific papers is growing exponentially. No matter how quickly they are constructed, the lanes of the information highway soon slow to their customary speed-of-light crawl. In such a world, the capacity to ignore selectively becomes ever more valuable. A system that is to control its environment successfully, be it a consumer, a scientist, or a robot, must adapt by constructing models that allow it to decide what information to get, and how to act on it. ⊕

Further Reading

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For further reading on ideas of algorithms and information, the reader can turn to T. M. Cover and J. A. Thomas, *Elements of Information Theory*, Wiley, New York, 1991. For a general introduction to the theory of NP-completeness, I recommend M. R. Garey and D. S. Johnson, *Computers and Intractability*, Freeman, New York, 1979. A review of nonlinear theory can be found in J.-J. E. Slotine and W. Li, *Applied Nonlinear Control*, Prentice Hall, Englewood Cliffs, 1991.

SFI External Faculty Member Seth Lloyd is at the Massachusetts Institute of Technology

New Books, from the SFI Family

FIVE NEW BOOKS ARE SLATED TO APPEAR AS PART OF THE INSTITUTE'S SERIES "STUDIES IN THE SCIENCES OF COMPLEXITY" PUBLISHED BY ADDISON-WESLEY.

Reduction and Predictability of Natural Disasters, edited by John Rundle, Don Turcotte, and William Klein should be a significant milestone in the newly emerging discipline of "disaster science." It contains possible answers to the question of how natural disasters—like earthquakes, floods, and volcanic eruptions—might be predicted using complex systems theory. It has recently been estimated that within 50 years, more than a third of the world's population will live in seismically and volcanically-active zones. The book is particularly timely because the 1990s have been endorsed by a consortium of global agencies as the International Decade of Natural Disaster Reduction (IDNDR), and programs are being developed to address problems related to the predictability and mitigation of these disasters, particularly in third world countries. Developing the capability to forecast these disasters is also of interest to the U.S. property insurance industry, which is currently at significant risk of complete bankruptcy if an insured loss comparable to that of the Kobe earthquake were to occur in this country. Such a loss is only a matter of time for cities like Los Angeles and San Francisco.

Resource Stress, Economic Uncertainty, and Human Response to the Prehistoric Southwest edited by Joseph and Bonnie Tainter is a follow-on to *Understanding Complexity in the Prehistoric Southwest*, SFI's first book in the field of Southwest archaeology. What is intriguing about this new 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 and societies can be correlated with fluctuations in available resources. Prehistoric Southwesterners were flexible in their adaptations to a risky environment. Their responses included social arrangements for sharing, use of famine foods, storage, environmental manipulation, and strategies for settlement relocation. In a world where predictions are regularly made about the consequences of use patterns of natural resources, it is important to understand better how these patterns related to societies in the past and what forces have led to the collapse of flourishing societies.

Increasingly brain development and memory organization are the focus of considerable research. Yet to date there has been no book that has brought together material from experimental researchers – those from somatosensory, visual, and auditory fields – using different tools drawn from anatomy, physiology, psychophysics, behavioral methods, linguistics and modeling. Nor has there been any joining of basic research and rehabilitation methods. *On Maturational Windows and Cortical Plasticity in Human Development: Is There Reason for Optimism?* edited by Bela Julesz and Ilona Kovacs fills this gap. The book, which results from a 1993 SFI meeting, presents new evidence of dynamic reshaping of the somatosensory and visual cortex, the important role of sleep in memory consolidation, and constraints on plasticity of higher functions. The general principles of strengthened interactions *via* a cascade of local connections and of filling in weak gaps by strong connections unifies the different topics and suggests new methods for rehabilitation, such as enhancing certain circuits and playing down others.

For seven years the Complex Systems Summer School has contributed to education and research in complex systems. *1993 Lectures in Complex Systems* edited by Lynn Nadel and Daniel Stein presents a wide array of topics in the field, including condensed matter dynamics, self-organized criticality, complex fluids, evolution, time series analysis, and neural models of perception. This book is a compilation of many of the lectures and contributions of the 1993 School. The collective volumes in the series—with this new book there are now six—comprise a growing, broad, interdisciplinary review of complexity science, one unavailable elsewhere.

Adaptive Individuals in Evolving Populations: Models and Algorithms, edited by Rik Belew and Melanie Mitchell, is based on a 1993 workshop which brought together scientists from the disciplines of biology, psychology, and computer science, all of whom were doing computational modeling research on interactions between the evolution of populations and individual adaptation in those populations. This volume is a collection of papers based on the presentations and discussions at the workshop. The book also includes reprinted "classics" on this topic by Lamarck, Baldwin, Waddington, James, Hinton, Nowlan, and others, with prefaces putting these classic works in a modern perspective. A central theme of this book is that the possibility of computer simulation, where models of adaptive individuals can be combined with models of population evolution, will be essential for a truly interdisciplinary understanding of these phenomena.

Other New Books

In *Macroecology*, published this March by The University of Chicago Press, SFI External Faculty Member Jim Brown proposes a radical new research agenda designed to broaden the scope of ecology so that it can address questions on much larger spatial and temporal scales. Much ecological research has been narrowly focused and experimental, providing detailed information that cannot be used to generalize from one ecological community or time period to another. Macroecology advocates the creation of a less detailed but much larger picture, one with a greater potential for generalization. It suggests new ways to investigate problems that can only be addressed on a much smaller scale by traditional approaches and offers a richer understanding of how patterns of life have moved across the earth over time. Brown also discusses the advantages of macroecology for conservation, demonstrating how it allows researchers to look beyond endangered species and ecological communities to consider the long history and large geographic scale of human impacts.

Stuart Kauffman's *At Home in the Universe: The Search for Laws of Self-Organization and Complexity* is due out from Oxford University Press this summer. Drawing from his *Origins of Order* —which was written for specialists—this new book for general readers focuses on the paradigm of self-organization. "What we are only now discovering," Kauffman says, "is that the range of spontaneous order in nature is enormously greater than supposed." How does this spontaneous order arise? Kauffman contends that complexity itself triggers self-organization, or what he calls "order for free." If enough different molecules, for example, pass a certain threshold of complexity, they begin to self-organize into a new entity, in this case a living cell. Kauffman proposes that all complex systems—from the origin of life to ecosystems, economics, and cultural systems—evolve in similar ways. If, as he argues, life were bound to arise not as an incalculably improbable accident, but as an expected fulfillment of the natural order, then we truly are at home in the universe.

The GREAT COMPLEXITY

AT THE LINNEAN SOCIETY ROOMS, BURLINGTON HOUSE, LONDON

We were extremely privileged to witness what must be the lecture of the year so far, a debate at the Linnean society in London between Stuart Kauffman and John Maynard Smith. Both spoke for an hour, Kauffman first, followed by a joint, half-hour question time. You could tell from the audience that this was one to file under "not to be missed," with the room crammed with the great and good of UK science. These included Lewis Wolpert, Brian Goodwin, and *Nature's* John Maddox.

The evening started with all the pomp that only England can (or want to) muster. The Chair of the Linnean Society, with no trace of amusement, announced new members whilst sat on a throne (which appeared to be covered with crocodile skin) wearing a large, three-cornered hat which would have not looked out of place in a low-budget television costume drama. (New members notably included the Earl of Selbourne and a descendant of Joseph Banks, the famous naturalist and proposer of the Linnean Society.) The Chair finished by announcing that the Linnean Society was awarding its highest honour, the Gold Medal, to Maynard Smith, for his life long contribution to science (1-nil to Maynard Smith).

Is life on the edge of chaos?

With the pre-match entertainment drawn to a close, an expectant hush fell over the crowd. Kauffman strode majestically to the rostrum and proceeded to deliver his speech to a appreciative, but mostly skeptical home crowd. His opening gambit was to try and indicate the possible limitations of natural selection for the production of complex biological entities, with references to algorithmic incompressibility. From the start, Kauffman stuck to the same game plan found in his monograph, but his delivery was such that, despite the non-mathematical background of his audience (biologists you understand), the concepts of the book were clearly explained. These concepts included an introduction to NK models. Kauffman used the NK model to illustrate the requirement for a smooth fitness landscape for sex to be of evolutionary benefit. He linked NK models to self-organization and to the sand-pile model of Bak. Kauffman then drove home the importance of complexity theory as the means of explaining a number of observable complex behaviors, such as the weather. (In his words, "Be they meat or metal.") Kauffman's was a consummate performance which included the joke: "What do you get when a deconstructionist joins the Mafia? An offer you can't understand."

Which was unlike the Kauffman lecture, where you got biological theory for the new millennium, in a form you could understand. The crowd went wild (as wild as Brits can).

Do we need complexity theory?

In spite of his initial pre-match lead, it was obvious that Maynard Smith was now coming from behind. As he removed his jacket and started to deliver a freeform speech, it became obvious that we were in the presence of a colossus in the world of evolutionary biology. Maynard Smith began by outlining, what he regarded as, essential mathematical knowledge for biologists. He suggested that limit cycles, bifurcation, and chaos theory were required "mental furniture" for the debate on evolution. On this basis, most biologists I know rent their flats unfurnished.

The great man's talk was impassioned and delivered with an energy beyond his years. Although Maynard Smith agreed with the central tenets of Kauffman's talk (the requirement for an over-arching theory of complex behavior across disciplines and the necessity for evolution to occur on a relatively smooth fitness landscape), his long experience told him to be wary. He explained that having produced a vast number of unpublished models, his experience told him they would produce very similar complex results, when flexed in the correct manner. It is possible that NK/Bak/Complexity models were the same and therefore should not be presented as the answer to everything. Raking back his golden hair with both hands, the great man sat down to rapturous, and well-deserved applause. The empire had struck back.

DEBATE

Cross Examination

At this point Kauffman joined Maynard Smith at the rostrum and cross examination began. As the first hand went up you could sense that this was a question time for the big hitters, and that the ruffled skepticism of the British scientific establishment had not been calmed by Kauffman's smooth delivery. The questions, all directed to Kauffman, were mostly on points of definition but were delivered with plenty of spin (I believe you in the USA call this English!). Kauffman played all with straight bat.

They both spoke with an honest fondness for each other, and an admiration of each other's work. Towards the end of question time, Maynard Smith suggested that his real problem with a lot of complexity theory is that it fails to ground itself in reality.

Maynard Smith: "My problem with Santa Fe, is that I can spend a whole week there... and not hear a single fact." Kauffman: "Now that's a fact!" [loud laughter from everyone]

So who won? For my money, Kauffman because NK and self organization is just so god-damn beautiful (and in reality Maynard Smith does not disagree with complexity theory). But I suppose the real winner was science, and those in the audience who were privileged to be present. The moment that will stick in my mind is Kauffman helping Maynard Smith put on his jacket (and taking care to turn down the wrinkled collar); there was real affection there. And, thinking of it, real affection for them both here too.

You should have been there.

Ricardo Colasanti and Tash Loder, University of Sheffield

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