

THE BULLETIN OF THE SANTA FE INSTITUTE

SUMMER 1994 • VOLUME 9 • NUMBER 1

BULLETIN





EDITOR'S MESSAGE

THE SPRING AND EARLY SUMMER OF 1994 have been exceptionally eventful for SFI. In April we were visited by Vice President Al Gore and NM Senator Jeff Bingaman. Sen. Bingaman, who has long been interested in the work of the Institute attended our annual Science Symposium in 1993. While he was still a US Senator, the Vice President learned about

the work of SFI in an afternoon of conversation with SFI's first President, George Cowan, and me. This was followed by similar conversations with W. Brian Arthur and with John Holland. All of us were impressed with the intensity of Sen. Gore's interest and the penetrating questions he asked. The visit this past April was equally intense, and there was, of course, quite a bit of excitement attendant on multiple visits from the Vice President's staff, the Secret Service, and the White House Communications staff. We were also pleased to take this occasion to introduce Gov. Bruce King and Mrs. King and Santa Fe's new mayor, Debbie Jaramillo, to the work of the Institute. In spite of all the excitement, however, the main purpose of the the occasion was to respond to the Vice President's request to learn more about the research of scientists at SFI. Most of his visit was occupied by conversations about their research with Stephanie Forrest, John Holland, and Terry Jones, and with Jim Crutchfield and Melanie Mitchell. The universal description of the encounter was "he asks very good questions."

Our other big event is the move to our new campus at 1399 Hyde Park Road. By the time this reaches most of our readers, SFI will have vacated its rented quarters on Old Pecos Trail and occupied newly renovated buildings at our permanent campus. This spectacular and tranquil 32-acre site overlooks the entire city of Santa Fe with equally impressive views toward the Jemez and Sangre de Cristo mountains. In addition to the largely untouched and beautiful natural setting of the campus, which offers ample opportunity for researchers to experience the out-of-doors, the site has exciting options for the construction of additional research space. The new facility features (finally!) a truly adequate conference room plus smaller meeting space and enough office space to meet our immediate needs. The central jewel of the main building is, however, its spacious atrium, readily accessible from any part of the building. The atrium, the large kitchen, the new patio on the east side of the building, and the portal overlooking the city offer many locations for the serendipitous but intense scientific conversations that are a key feature of research life at SFI.

The renovations were designed by local architect Jeff Harnar with guidance from a program developed by architect Laban Wingert after interviews with many staff and researchers. Overseeing the renovation contract was a committee of Trustees chaired by Darragh Nagle. A mainstay of the entire effort was the continuing support, advice, and interest of architect and Trustee Armand Bartos. Day-to-day oversight was the responsibility of Ronda Butler-Villa, who took part-time leave from her duties as Publications Director to undertake this task, and who did her usual superbly thorough and well-organized job. Special thanks, however, are due to the members of the SFI Board of Trustees, who not only contributed generously to make possible the original purchase of the campus last year but who continued their generous support this year, making possible the essential and beautiful renovations to our new home.

Mike

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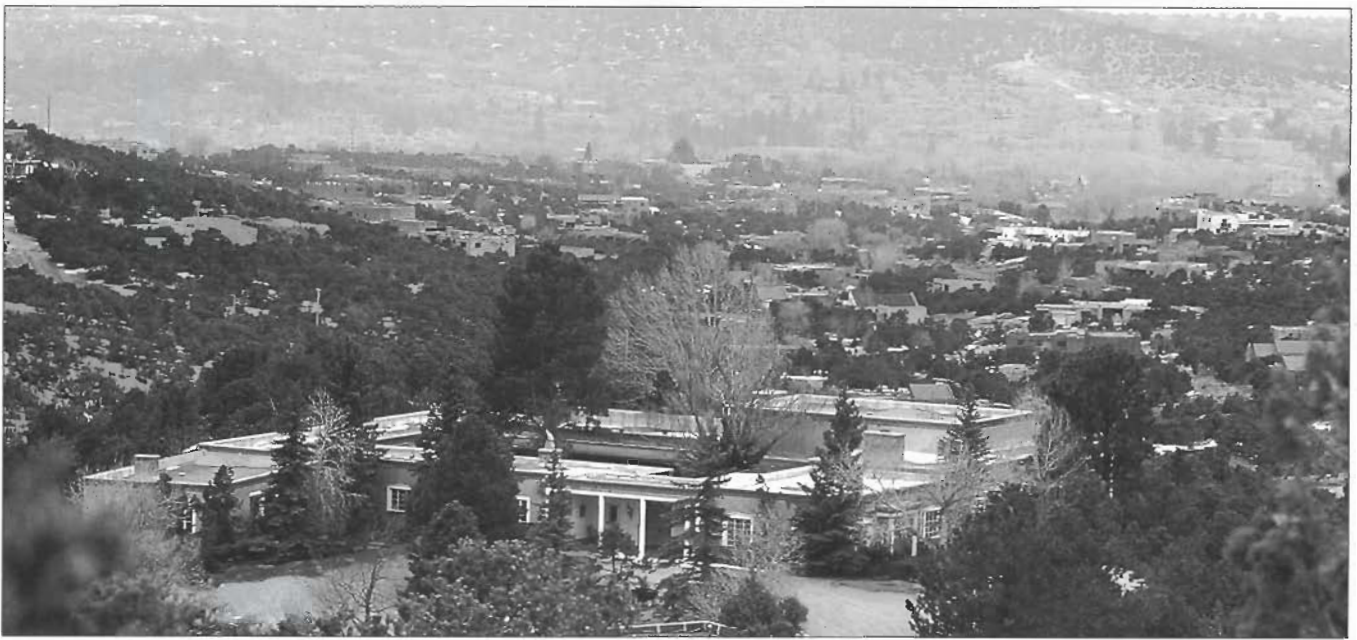
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Graduate Fellow Terry Jones shows the ECHO modeling program to Vice President Al Gore during Gore's visit to SFI.



TEN YEARS AFTER ITS FOUNDING, SFI MOVES TO A PERMANENT HOME

IN 1993, with the enthusiastic support of its Trustees, SFI acquired a 32-acre campus in the hills above Santa Fe. The site has been a landmark in the city since the large house was built in the late 1950s by General Patrick Hurley. In the 35 years since, houses and roads have inundated the surrounding hills, but the 32 acres around the house have remained untouched, a park-like jewel, visible from much of the community. SFI will retain all but a fraction of the site in this natural state, both to preserve a natural vista for the community and as part of its commitment to creating a serene environment for scientific research.

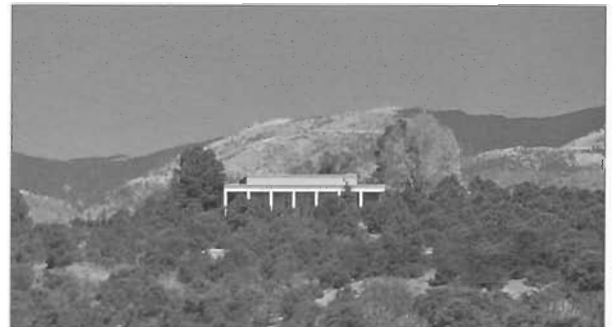
In early 1994 renovations began on the 14,000-square-foot structure that was the main house, and in July SFI moved to its permanent new home. The house, designed to accommodate large numbers of people, is built around a spacious atrium that will be used as an informal gathering place in all but the worst of weather. Wide hallways, a large kitchen, and the addition of a small outdoor courtyard all will encourage the informal exchange of ideas that is an SFI hallmark.

A spacious, comfortable main conference room will flexibly accommodate larger groups of varying sizes, in strong contrast to our current cramped conference room. Immediately adjacent to the main conference room, a wide portal offers meeting participants an inviting opportunity to stretch and pace with a commanding view of the City of Santa Fe and the Rio Grande Valley. Also within the main building, SFI will finally have space to develop a modern library of books, journals, software, on-line resources, and videotapes.

Ronda Butler-Villa, SFI's Director of Publications, has taken time off from some of her publications duties for the daunting task of coordinating all SFI activities related to the new campus renovation and the move. Santa Fe architect Jeff Harnar designed and is supervising current renovations of the existing building. Harnar is also working on a master plan for the campus which will feature the addition of

new office space, allowing some of the large rooms in the main house to be used more appropriately as conference and meeting space. Because of anticipated pressure for more space brought about by the inflow of new research, the Trustees are committed to advancing the expansion phase as soon as possible.

An important feature of the renovation is a modern electrical system and the installation of a state-of-the-art fiber-optic network for high-bandwidth internal communications to better support the Institute's growing computational needs. At the new campus, the SFI computer network will be connected to the world-wide internet by a much higher speed T-1 link.



TWO HIGH-TECHNOLOGY INDUSTRY VETERANS ELECTED AS CHAIR AND VICE-CHAIR OF THE SANTA FE INSTITUTE



David Liddle



Robert Maxfield

AT THEIR ANNUAL MEETING in March, the SFI Trustees elected David Liddle and Robert Maxfield as Chair and Vice-Chair. In addition, the Board elected one new Trustee, Henry Lichstein of Citibank.

Liddle, co-founder, with Paul Allen, of Interval Research Corp. (IRC) in Palo Alto, California, has been an active trustee and advocate of SFI since 1992. Liddle has spent his professional career focusing on client/server architecture and on user interfaces designed for business professionals. IRC performs research and advanced development in the areas of information systems, communications, and computer science. Liddle has a Ph.D. in Computer Science from the University of Toledo.

Maxfield, co-founder of ROLM Corp. and President of the Maxfield Foundation in Saratoga, California, has been a member of the Board of Trustees since 1992. Maxfield is a Consulting Professor of Electrical Engineering and Engineering-Economic Systems at Stanford University and serves on the Board of Directors of Software Publishing Corporation and Echelon Corporation.

He has a Ph.D. in Electrical Engineering from Stanford University.

Liddle and Maxfield replace former SFI Board Chair James L. Pelkey, a private investor in Atherton, California, and former Vice-Chair Robert McCormick Adams, Secretary of the Smithsonian Institution (retired), in Washington, D.C. Both Pelkey and Adams continue to be active Trustees of the Santa Fe Institute.

Henry Lichstein has held a variety of positions at Citibank and has been assistant to Citibank's Chairman, John Reed. Lichstein has been closely associated with SFI since 1989, playing an important role as consultant to the Institute's research program in economics as a complex adaptive system—for which Citibank is a major source of support—and as an advisor on development issues. As a Trustee, Lichstein will assume a leadership role in the Institute's campaign to fund its campus expansion.



Henry Lichstein

POSTDOCTORAL FELLOWSHIP PROGRAM

David Liddle has announced the establishment of the Interval Research Corp. Postdoctoral Fellowship in Adaptive Computation at SFI. The first Interval Fellow is expected at SFI in the fall of 1994. Interval's support reflects interest in the collaborative approach to problem solving at SFI in the sciences of complexity, and in how the SFI approach can provide insights into practical research issues.

ALIFE JOURNAL AND JOURNAL OF COMPLEXITY MAKE DÉBUTS

COMPLEXITY: THE JOURNAL OF COMPLEX ADAPTIVE SYSTEMS

The premiere issue of *Complexity: The Journal of Complex Adaptive Systems* will appear early in 1995. One of the main goals of the new quarterly—to be published by John Wiley and Sons with editorial offices at SFI—is to provide a timely and widespread means of communication for scientists working in different subfields of the sciences of complexity. Harold Morowitz, Clarence Robinson Professor of Biology at George Mason University and a SFI External Faculty member, is Editor-in-Chief of the magazine. John Casti is *Complexity's* Executive Editor. Associate Editors are Michele Boldrin (Northwestern), Peter Carruthers (U. Arizona), Marc Feldman (Stanford), Joseph Traub (Columbia), and Wojciech Zurek (LANL).

Refereed scholarly papers in the sciences of complexity will be an integral feature of the journal. The field will be broadly covered with emphasis on papers that suggest or imply possible integrating concepts or themes. Additional regular features include scholarly survey articles and shorter tutorials. A part of each issue will be devoted to concise, up-to-date commentaries, book reviews, and news items. Reader letters may open new topics for discussion within the journal's pages.

The journal will serve an international community of physical, biological, mathematical, behavioral, computer, and social scientists carrying out research on complex systems. Casti says, "*Complexity* will be an international journal reaching out to the entire community of scholars studying complex adaptive systems."

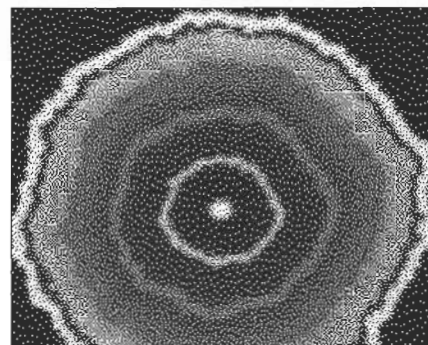
ARTIFICIAL LIFE

Artificial Life, a new quarterly edited by SFI External Faculty member Chris Langton, is the first-ever centralized forum for artificial life research. The journal, which premiered in March with a double Fall/Winter 1993 issue, reports on synthetic biological work being carried out in any medium. This ranges from the familiar "wetware" of organic chemistry, through the inorganic "hardware" of mobile robots, all the way to the virtual "software" residing inside computers. Covering topics from the origin of life through self-reproduction, evolution, growth and development, and animal behavior to the dynamics of whole ecosystems, its articles present novel approaches to the theory and application of biological phenomena.

The initial three issues of Volume 1 consist of a special set of overview articles, written by members of the Editorial Board, giving detailed reviews of distinct sub-disciplines within Artificial Life. Taken together, these articles set out the most thorough and in-depth presentation of the theory and practice of Artificial Life offered to date. They describe promising research directions, review important, open problems, and suggest new methodological approaches.

Artificial Life should prove to be an essential resource for scientists, academics, and students researching artificial life, biology, evolution, robotics, artificial intelligence, neural networks, genetic algorithms, ecosystem dynamics, and the origin of life.

Alife Online service, sponsored by SFI and MIT Press, is also now in operation. This service is intended to be a central information collection and distribution site for any and all aspects of Artificial Life. A special feature is a collection of forty or so local newsgroups dedicated to topics in the field. The service combines the functions of a WWW server, a Gopherserver, an interactive bulletin board system, and Usenet News; for access information telnet to "alife@santafe.edu".



Submission of papers to *Complexity* is invited.

Contact:

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Subscription information and sample copy requests may be obtained by contacting:

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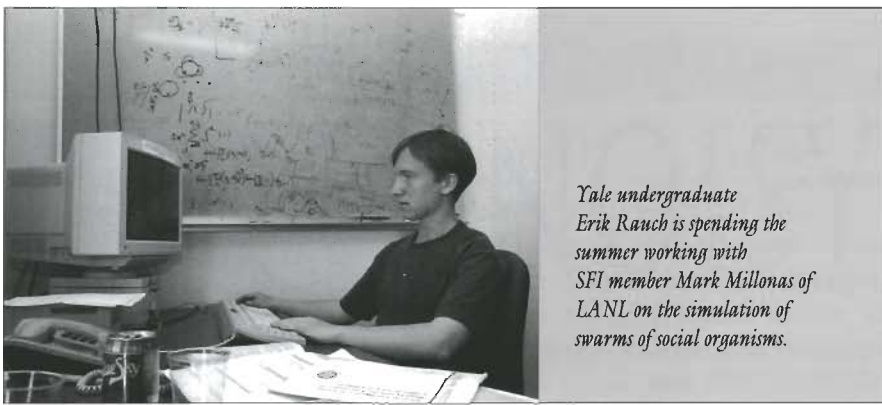
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Yale undergraduate Erik Rauch is spending the summer working with SFI member Mark Millonas of LANL on the simulation of swarms of social organisms.

STUDENT EVENTS HEAT UP FOR THE SUMMER

Summer is high season for the Institute's educational programs. Every June nearly sixty grad students and postdocs arrive for the annual Complex Systems Summer School (CSSS), now in its seventh year. Along with the summer school students, a group of undergraduates takes up residence at SFI as part of the National Science Foundation's Research Experiences for Undergraduates (REU) program. Several graduate students also take advantage of the opportunity to visit SFI for extended periods of concentrated research during the summer.

The month-long Complex Systems Summer Schools have brought more than 400 graduate students and postdocs to Santa Fe over the past six years and introduced them to different aspects of the sciences of complexity. While some of the Schools' topics may be found in some university courses or other summer sessions, there is still no program which brings together such a varied assortment of problems, approaches, and subjects under a unifying idea. 1994 lectures ranged from "Mathematical Models of Hallucination and Migraines" by Jack Cowan (U.Chicago) to Richard Karp's (U.C.Berkeley) "Combinatorial Problems in Molecular Biology" and Jean Carlson's (U.C.Santa Barbara) "Dynamics and Self-Organization: From Sand Piles to Earthquakes."

The School, directed by SFI External Faculty member Daniel Stein and his University of Arizona colleague Lynn Nadel, is a national effort, supported by a number of institutions, national labs, and funding agencies. The University of California

Coordinating Committee on Nonlinear Science (C³NLS) joined the School's list of sponsors this year, combining its 1994 Summer School, organized by Robert Ecke, LANL, with the CSSS.

The Summer School also offers a comprehensive introduction to complexity science for the Institute's undergraduate interns who themselves are working on a wide range of projects. This summer Elizabeth Ayer (Duke) is collaborating with Melanie Mitchell using GAs to evolve cellular automata to perform computations. She is studying whether or not co-evolutionary ideas can improve the performance of the GA, and will analyze the dynamics and emergent strategies of the co-evolutionary system. Greg Stevens (U. Rochester) is also working on GAs with Mitchell, using them to evolve cellular automata to perform computations. Scott Kaplan's (Amherst) project with Stu Kauffman and Bill Macready involves optimization on fitness landscapes. Kauffman and Macready have found that at any fitness there is an optimal distance at which to search. If mating is done according to this preferential distance, an initial random population of searchers speciates into distinct groups of non-interbreeding species. Kaplan is fleshing out this model of speciation.

Mark Millonas and Becca Shapley (Bryn Mawr) are considering biologically meaningful population dynamics models which have a self-

organized critical state. Millonas is also working with Erik Rauch (Yale) on the simulation of swarms of social organisms, drawing inspiration from insects like ants and termites. The simulations will use a connectionist model, and may be written in Swarm.

Caroline Parks (UNM) is working with Stephanie Forrest and Alan Perelson on a model of coevolution in host-parasite systems. Sam Stoller (Colorado State) is studying how scientists use networks in an environment which relies on extensive computer modeling and simulation.

Two graduate students also joined the research staff this summer. Tim Germann (Harvard) is working on an application of dimensional perturbation theory to problems in atomic and molecular physics. Thanos Siapas (AI Lab, MIT) is collaborating with Stuart Kauffman on parameter estimation of chaotic dynamical systems.

This year's undergrad, graduate, and summer school students continue a trend—a trend that is not particularly apparent unless one has watched SFI's student population grow over the past decade. Each year the selection process becomes more challenging as the caliber of students ratchets higher and the number of applicants grows larger. Each year students show themselves to be more aware of SFI's work, better versed in the literature, and often already budding practitioners in the sciences of complexity. In short, this year's Summer School and REU applicants are the most qualified ever, making the 1994 selection process all the more difficult.

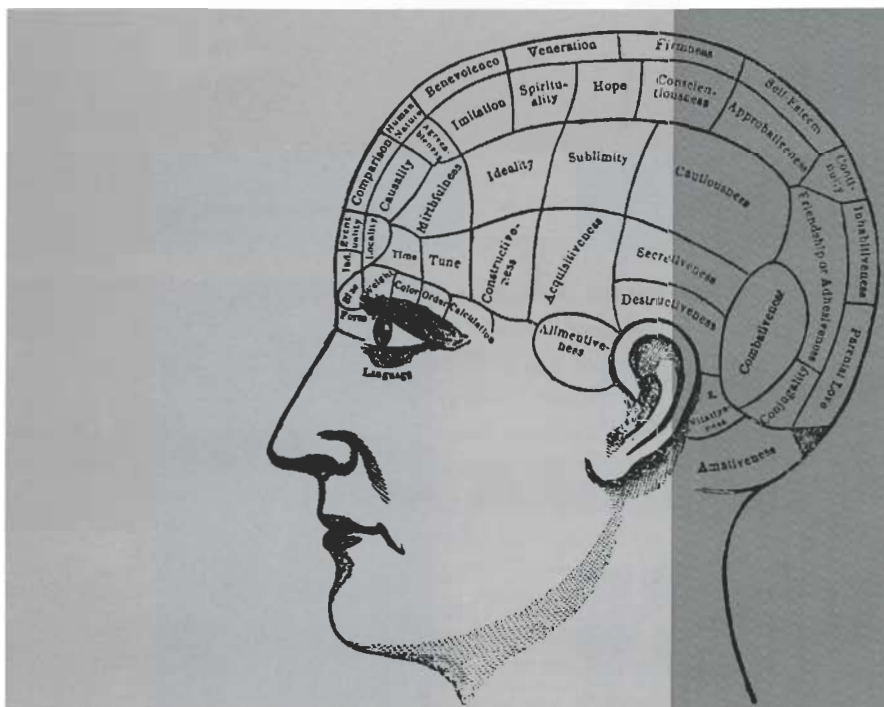
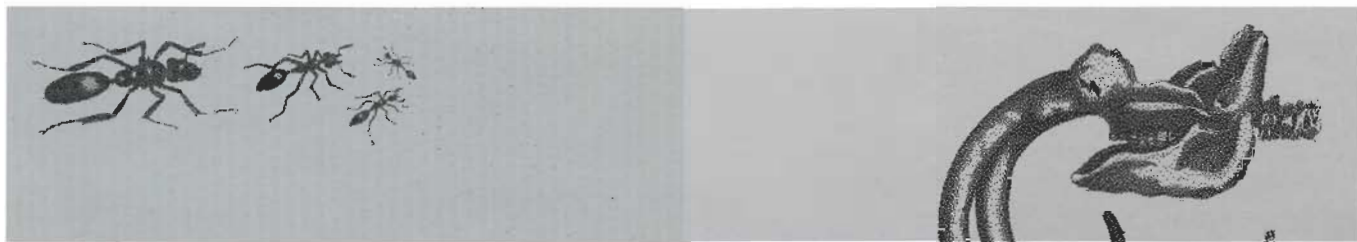
This onslaught of interest suggests that the Institute is succeeding in its role as a catalyst for introducing the next generation to a

different, transdisciplinary approach to science. SFI is actively nurturing this approach elsewhere. There are growing clusters of SFI-influenced research at the Universities of California, Chicago, Illinois, Minnesota,

New Mexico, Pennsylvania, Wisconsin, and Michigan, at the California Institute of Technology, Stanford University, and Yale University. For the time being, the Institute expects student interest in educational opportunities here to continue to grow. As one Summer School applicant put it, "Does an artist want to go to Paris?"



SANTA FE COMMUNITY LECTURES PROBE TOPICS FROM ANTS TO DINOSAURS



In October, Walter Alvarez from University of California, Berkeley will discuss "Extinction of the Dinosaurs: Giant Impact and the Mexican Connection." The extinction of dinosaurs 65 million years ago was part of a mass extinction that eliminated perhaps half of all life at that time. That this extinction was correlated with the impact of a giant comet or asteroid is now established, and Alvarez elaborates on the effects of such a devastating event on the complex earth system. He argues the dinosaur extinction is a lesson in the wildly different outcomes that can result from slightly different starting conditions: had the impactor been seconds different in its orbit, the dinosaurs might still be the dominant land animals.

THE SCHEDULE for SFI's popular 1994 public lecture series for the second half of 1994 covers a wide range of topics and draws from a roster of nationally known scholars. These talks in Santa Fe are free to the community.

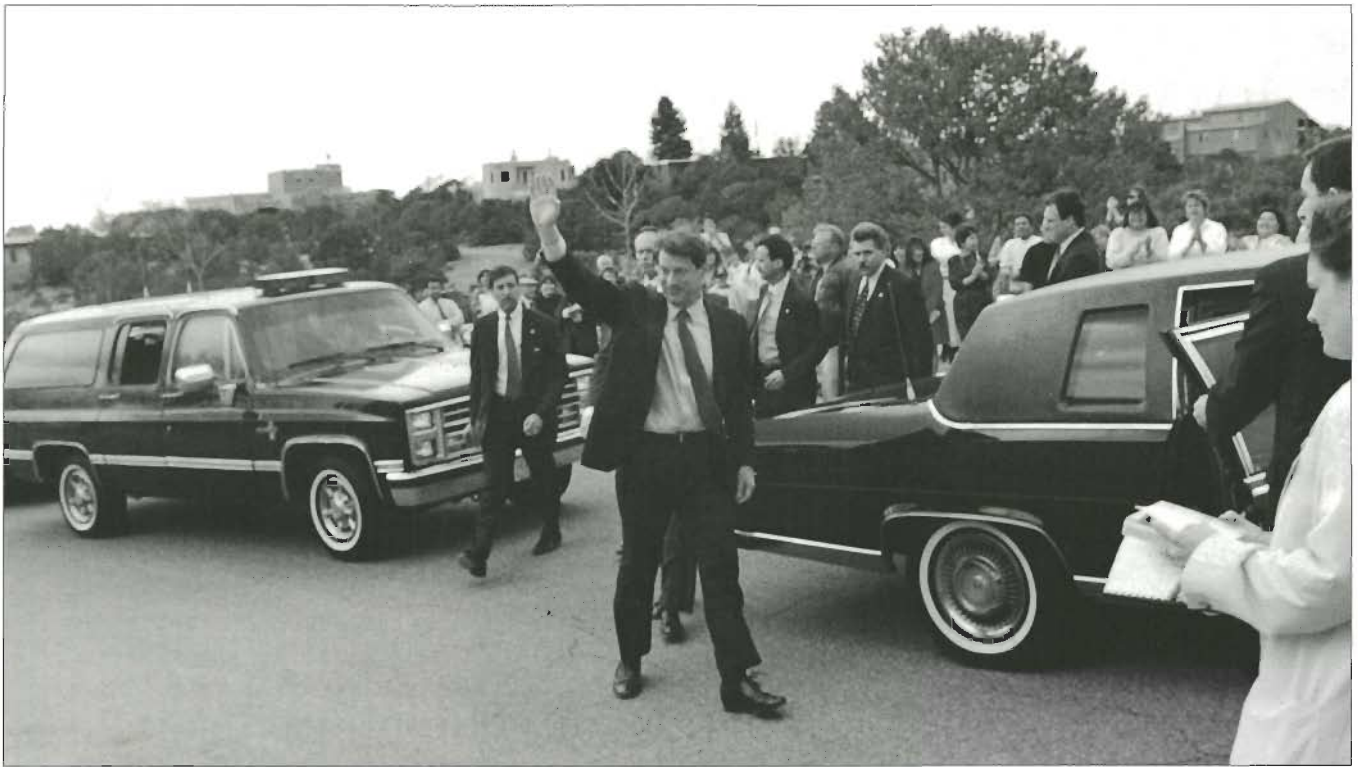
In August Nobel Laureate Francis Crick will explore the question, "How Do We See Things?" "Seeing" requires that we construct in our brains a multilevel symbolic representation of the visual world in front of us. Drawing from his provocative new book *The Astonishing Hypothesis: The Scientific Search for the Soul*, Crick conducts a detailed analysis of how the brain "sees," which leads to an exploration of some of the most fundamental questions of human existence: What exactly is it that makes us sentient beings? Is there such a thing as a soul, or are we nothing more than

an immensely complex collection of neurons? A book-signing is scheduled in conjunction with the talk.

Mitchel Resnick from MIT's Media Laboratory marks the back-to-school season with a September presentation "How Birds Flock and Traffic Jams: Helping Students See the World in New Ways." Resnick examines why people tend to assume centralized control for patterns they see in the world, and why they tend to impose centralized control on the organizations and technologies they create in the world. Resnick will describe new computational tools designed to help people, especially children, move beyond this centralized mindset, helping them to gain a deeper understanding of how decentralized systems work.

Late in the year, biologist Deborah Gordon from Stanford University will discuss "The Dynamics of Ant Colony Behavior". Larger, mature ant colonies are far more stable in the face of environmental changes than younger ones. Since there is high turnover of individual ants through the lifetime of a colony, this behavior cannot be due to the experience of "older, wiser" ants. How does a system with a lot of "simple" individuals and no central authority produce collective behavior that can be intelligent and complex? Models suggest some answers, but for Gordon the challenge is to find out whether real ants behave like the models.

For detailed information about dates, times and locations of these talks, or if you are outside the Santa Fe area and would like to borrow videotapes from this series, call 505-984-8800.



VICE PRESIDENT GORE VISITS SFI FOR ADAPTIVE COMPUTATION BRIEFING

ON APRIL 8, VICE PRESIDENT AL GORE, New Mexico Senator Jeff Bingaman, New Mexico Governor Bruce King, and Santa Fe Mayor Debbie Jaramillo visited SFI for an intense hour and a half of briefings on SFI research. The visit was at the Vice President's request to learn more about SFI activities and marks at least the fourth time (the first time in Santa Fe) he has met with people from SFI to discuss science. Senator Bingaman has also participated in past SFI activities and briefings. At an informal lunch the guests heard a quick overview of the Institute by Ed Knapp and a presentation on simplicity and complexity by Murray Gell-Mann.

Gore told the press that he was at SFI "to learn." The Vice President and Senator Bingaman visited two research offices for informal presentations of SFI research projects. John Holland, Stephanie Forrest, and Terry Jones discussed their work on adaptive modeling of complex adaptive systems with the Echo system. Gore, according to Gell-Mann, suggested that SFI's work might have environmental applications, including management of the Northwest forests and conservation of marine mammals. Melanie Mitchell and Jim Crutchfield discussed their research on evolving cellular automata using genetic algorithms, work they hope will lead to better understanding of how to evolve more sophisticated parallel processing code. As he left, Gore informed reporters he had heard about a lot of "neat stuff." According to SFI researchers, Gore was intensely interested in their presentations, asking numerous, penetrating questions.



Ed Knapp, President of SFI, welcomes Vice President Al Gore to the Institute.



Gore's interest in SFI extends back several years to when former SFI President George Cowan (above) and VP Mike Simmons visited then Senator Gore at his office in Washington.



Governor King and Mayor Jaramillo, who had never visited SFI before, were treated to an overview and history of SFI by former President George Cowan, and a description of complex systems research by SFI External Professor Stuart Kauffman. SFI President Ed Knapp and Vice President for Academic Affairs Mike Simmons also participated in the discussions of current SFI activities.

Gore was in Albuquerque for several appearances, but the visit to the Institute was his only event in Santa Fe. At his request it was a "private" visit—no press, no advance notice to the public (nevertheless, swarms of Secret Service, state and local police, White House communications personnel, and the Vice President's advance team converged on SFI for two days prior to the event, heightening the sense of excitement). Not surprisingly, several hundred people and the local press gathered outside to await his arrival and departure. They were not disappointed; as he left SFI he walked across the street to meet the crowd and shake hands. His motorcade drove up from Albuquerque and returned immediately following the meetings. His visit gave SFI a degree of local attention that even its campaign for a new campus did not achieve.

The occasion of the Vice President's visit also sped the process of completing paperwork on a grant to support SFI's sim-

ulation research from the Defense Department's Advanced Projects Agency (ARPA), which was received on April 7. The award was announced to SFI during the Vice President's visit by ARPA Program Manager Commander Dennis McBride and announced by Senator Bingaman following the Vice President's visit.

Vice President Gore and External Faculty member Jim Crutchfield listen while Melanie Mitchell, Director of SFI's Adaptive Computation Program, explains SFI work on evolving cellular automata using genetic algorithms.

Below, V.P. Gore took time out of his busy schedule to personally meet SFI researchers and staff.



ARPA GRANT FOR SIMULATION RESEARCH

ON APRIL 6 THE INSTITUTE WAS AWARDED A \$323,000 GRANT from the Advanced Research Projects Agency (ARPA) for "Simulation of Adaptive Complex Systems." This grant will support research over a six-month period on Chris Langton's Swarm simulation system, one of several general simulation programs being developed at SFI to study agent-based, evolutionary systems.

Langton began work on Swarm several years ago (he called it the "process gas" then) to meet his own and other researchers' needs for a more efficient way to simulate different kinds of agent-based simulations. His aim has been to provide a simulation system that is user-friendly for scientists who may not have programming expertise.

Swarm is essentially a system for controlling a number of computational agents interacting with each other. Each agent has a few standard attributes managed by the system and application-specific attributes supplied by the modeler. The Swarm system allows one to conduct simulations consisting of large numbers of interacting agents. The user will be able to write modules to describe the types of agents specific to the model, insert them into the general system, and run the model.

Agents' adaptive behavior may be modeled using a variety of techniques, including neural networks, classifier systems, genetic algorithms, and others. Swarm will supply a general user interface that can easily be customized for specific objects; there will be a library of analysis modules available. The approach to developing Swarm is intended to make it readily usable on a variety of computing platforms, including networked computers and parallel computers.

Langton's research team is undertaking intensive programming and testing in the summer of 1994, reuniting many of the people who have worked on Swarm over the past several years. This includes David Hiebeler from Harvard Graduate School, Howard Gutowitz from Ecole Normale Supérieure de Physique et Chimie in Paris, and Nelson Minar, a new graduate of Reed College who participated in the summer of 1993 as part of SFI's Research Experiences for Undergraduates program. Also joining the group is Roger Burkhart from Deere & Company. Burkhart and his colleague William Fulkerson are investigating the application of Swarm techniques to problems in manufacturing systems. Deere is a member company of SFI's Business Network for Complex Systems Research.

The programming team is also consulting with other scientists experienced with related architectures and with those who are knowledgeable about the characteristics of scientific problems to which they want to apply Swarm. This interplay between the use of Swarm on sample problems and the development and study of the Swarm system is essential to the evolution of Swarm as a useful scientific modeling system.

The design architecture of Swarm is innovative, especially in its generality and in its ability to incorporate a variety of adaptive computation features in the evolutionary properties of the agent objects. Swarm does, however, share some features in common with other, more special-purpose software such as the *Logo system. As part of the project, SFI recently convened a workshop on "Multi-Agent Simulation Systems" for developers of other software systems that share substantial common features with Swarm. It is essential to the success of the Swarm project that the best features of related work be evaluated and incorporated into Swarm and that the Swarm design be subjected to the critical appraisal of other experts. More than 40 participants from academia, industry, and government agencies attended the workshop, held from June 16-19. Topics ranged from "Real and Artificial Economies" to "New Directions in Simulating Ecological Processes" and "Modeling Needs of Biosphere II."

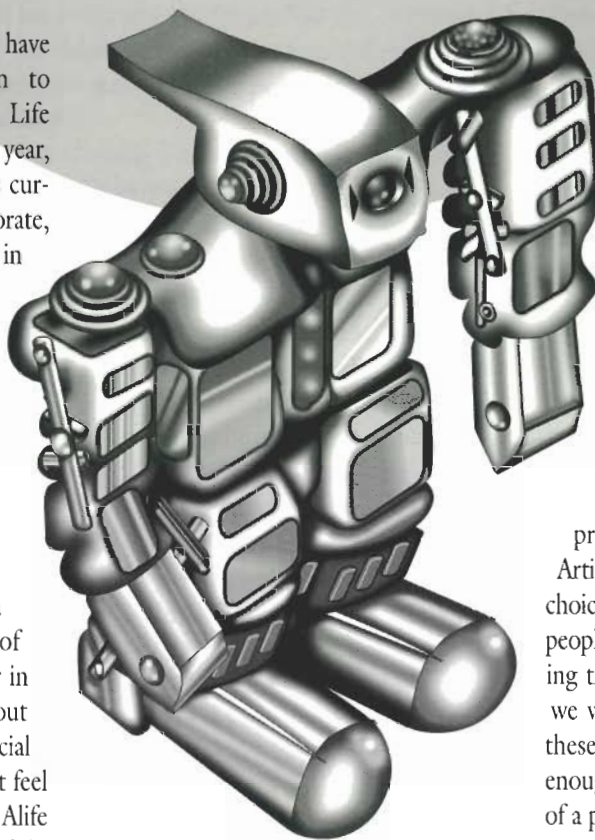


SFI External Faculty member Stephanie Forrest talks with Vice President Gore and Co-Chair of SFI's Science Board John Holland about the ECHO system of computer modeling developed by John Holland.

FROM THE LAND OF ENCHANTMENT TO THE LAND OF THE RISING SUN: ARTIFICIAL LIFE SPREADS EAST

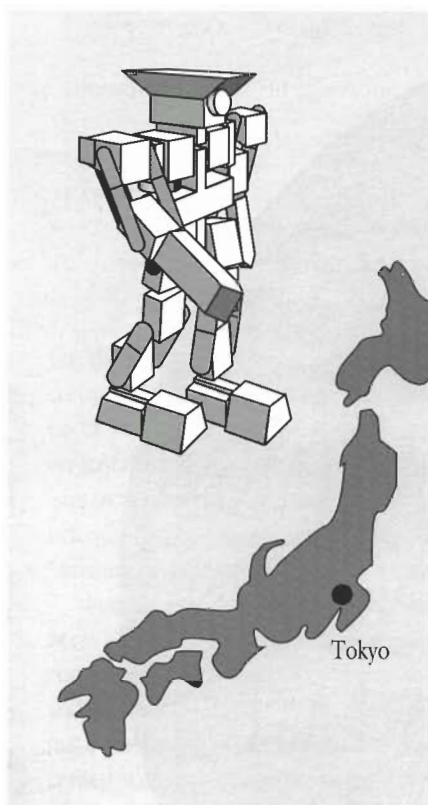
Christopher Langton, Santa Fe Institute

OVER THE PAST FEW YEARS, I have made many visits to Japan to encourage the Artificial Life research effort there. In the last year, Artificial Life has "caught on" and is currently spreading through the corporate, academic, and even popular cultures in almost epidemic fashion. There are now at least four books in Japanese on the topic of Artificial Life, several English language books on Artificial Life are being translated into Japanese (e.g., Steven Levy's book), and there have been numerous Alife conferences. A number of journals have dedicated special issues to the topic, and there is even a Japanese Society for the Study of Artificial Life. When I first went over in 1992, very few people had heard about genetic algorithms, let alone Artificial Life. Now when I'm in Japan I almost feel that I am behind the times, and that Alife research there will quickly outstrip work in the U.S. or Europe.



In fact, traveling to Japan generally seems like going forward in time as well as space: the cars look newer and more advanced, the transportation system is more efficient, the buildings are more modern and high-tech (both inside and outside), the electronic gear available in the Akihabara district of Tokyo today will not show up in the U.S. for a year and a half or so, and everybody is carrying an ultra-thin cellular phone.

Below, I'll describe some of the primary people and places doing Artificial Life research in Japan. I have no choice but to leave out a lot of important people and places, and I'll be brief concerning the material that I do cover. However, we will be hearing a lot more from all of these individuals and institutions soon enough, so take the following in the spirit of a preliminary glance at the future.



THE UNIVERSITY OF TOKYO

The most impressive work in robotics that I have seen in Japan is the remote-brained robotics project being developed by M. Inaba and I. Shimoyama and their students in the Department of Mechano-Informatics at the University of Tokyo. They are engaged in a number of research projects involving collections of mobile robots who all share common "brain" hardware via wireless modems. The shared brain consists of a transputer-based parallel machine which is capable of running the control software of many different robots in parallel. This setup allows research using parallel hardware robot brains, but without having to employ robots massive enough to carry a parallel computer. Hence, the robots can at once be both agile and "smart." Each mobile robot carries a minimal amount of computing equipment on board, and there may even be multiple agents on board a single robot, each running its own

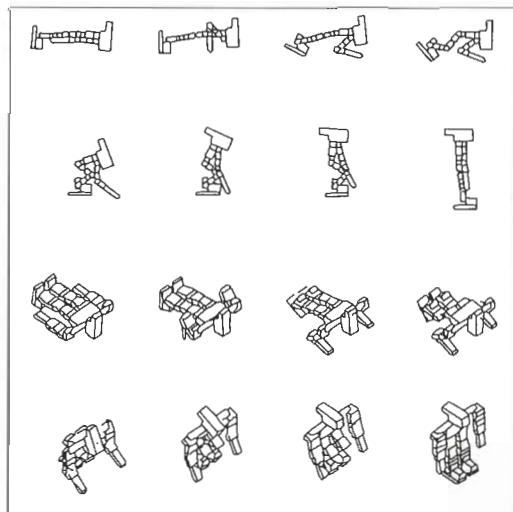
"mind" on the shared-brain hardware, which allows a single robot to be operated by a collection of agents.

Even the notion of a "single robot" gets a bit blurred in their research on reconfigurable robots. This project features a collection of small mobile robots, each of which has a single specialty—e.g., some carry a video camera, some carry a gripper, some carry a flashlight, some even carry mirrors. These autonomous robot specialists are able to assemble in one place and interact with one another to form a more complex robot. For instance, the collective robot might utilize a vision robot and two gripper robots to tie a knot in a string. Each of these robots is running its software in parallel on the shared-brain hardware, and communication between the robots takes place within the shared brain. After a task is complete, the collection of robots will break up and each can go its separate way, perhaps to get caught up in a different collective robot to perform a different task requiring a different collection of skills. This setup allows the researchers to "evolve" the morphology of a collective robot over time, as well as to investigate robot morphologies that change over time.

Another research effort of this group involves humanoid robots. These robots have arms, legs, torsos, and heads in the proportion (and actual size) of a 5-year-old child. The bodies have 16 degrees of freedom, including 2-axis ankles, knees, hips, wrists, elbows, and 2-axis shoulders. These humanoids are capable of quite surprisingly human motion, including standing up very realistically from the position of fully stretched out, face-down on the floor. They also sit down and stand up from a chair, and are just beginning to take their first steps of bipedal walking. Thus, rather than attempt to perfect standing up first, these researchers are concentrating on robots that will initially fall down a lot, but that are capable of getting up again on their own, and of learning over

time (via a neural net brain) how to do a better job of not falling down as they gain more experience in their worlds. In other words, they will have to acquire the skill of bipedal walking much the way real children do. This appears to be a general research principle in the labs of Inaba and Shimoyama, and it is an approach that I find quite exciting.

Also at University of Tokyo is Kunihiro Kaneko, whom I first met ten years ago on a hike up Truchas Peak while Kuni was an Oppenheimer Fellow at the Center for Nonlinear Studies at LANL. Kuni has an international reputation for his work on chaos theory, particularly in spatially-distributed systems, such as coupled-map lattices. In recent years, he has taken up Artificial Life research, and is currently working with his former student, Takashi Ikegami, now an Associate Professor at University of Tokyo. Kuni's most recent research involves the role of chaos in such biological processes as evolutionary and ecological dynamics, and in cell differentiation. His work has provided important insights into the role that chaos can play as a source of complexity, novelty, diversity, and even stability in biological systems. One of his recent projects has provided strong support for the thesis that evolution for complex behavior will drive systems to the point of transition between ordered and disordered behavior—the "edge" of chaos.



Robot standup sequence. Courtesy of Masayuki Inaba.

TSUKUBA: JAPAN'S "SCIENCE CITY"

Tsukuba University, 90 miles north of Tokyo, is one of the centers driving Artificial Life research in Japan. The researchers at Tsukuba are organized primarily around Tsutomu Hoshino, a senior statesman in Japanese research who has always been somewhat of a rebel by Japanese standards. Hoshino designed and built Japan's first functional massively parallel computer, which has been used primarily for QCD calculations and other fundamental physics problems. Recently, he has turned his attention to computational approaches to the study of biological phenomena, and he is currently working on several research projects with Prof. Koichi Fujii and his student Yukihiro Toquenaga of Tsukuba's Institute of Biological Sciences. An example of their research was presented at the Artificial Life III workshop here in Santa Fe in 1992. Computer models of competition among bean weevils were run in parallel with experiments with real bean weevils in an attempt to understand the conditions under which different competitive strategies were more successful. The approach of parallel experiments involving both artificial and real world organisms is a particularly productive one, as questions that arise in one world may only be addressable in the other.

Another active member of the Tsukuba group is Yoichiro Kawaguchi, a computer animation artist at Tsukuba who has used Artificial Life techniques to produce some amazingly complex, organic images in his movies.

Tsukuba is also the locus for the research headquarters of the 6th generation project, called the "Real World Computing" initiative. The term "Real World Computing" is meant to imply computing systems that are capable of dealing with the full complexity of the real world—for example, human or animal

information-processing systems. The research being performed by the RWC project involves the integration of many different computing paradigms including massively parallel computing, logic programming, vision processing, natural language understanding, neural nets, and "flexible computation" (their term for what we would call "adaptive computation"). Thus, they are keenly interested in Artificial Life. When I went to the research headquarters on a spontaneous, unannounced visit last year I found copies of the SFI Artificial Life proceedings volumes all over the building! The RWC initiative is a ten-year effort jointly funded by industry and the Japanese government.

SONY COMPUTER SCIENCE "LABORATORY CITY"

Another locus for Artificial Life research in the Tokyo area is Sony's Computer Science Lab (CSL), run by Mario Tokoro, who also serves as a Professor of Computer Science at Keio University. The work at the CSL includes research on distributed operating systems for managing interactions between hun-

dreds or thousands of autonomous computational objects on computer networks, employing a computational paradigm that Tokoro refers to as "Social Computing," or "Computational

Societies." Also at CSL is Hiroaki Kitano, an AI researcher who has come over to Artificial Life research with a primary focus on evolving control structures for autonomous agents in either hardware or software. Other work going on at CSL involves natural language recognition and generation, including the recognition and generation of facial expressions as a means to enhance the human-computer interface. When you sit down at a computer at the CSL, you are confronted with the "face" of a virtual "person" on the screen, with whom you interact via speech and facial expressions, both yours and "his" (or "hers").

FUJITSU LABORATORY

Speaking of facial expressions and interacting with autonomous virtual agents, Fujitsu Laboratory is conducting a large number of research projects on Virtual Reality, many centered around a sophisticated virtual world "populated" by autonomous virtual creatures. These virtual creatures "live their lives" in their virtual world, interacting with each other and with human "visitors" who drop in from time to time. In the "Charlotte" system, managed by Koichi Murakami, the virtual creatures are autonomous agents with a dynamic "physical" embodiment that incorporates facial expressions, shape and color changes, and vocalizations, all of which can be sensed and reacted to by other virtual creatures and by the human visitors to the world. The Charlotte system is a research vehicle for experimenting with new approaches for the interactions between human and virtual agents, with the long-term goal of providing work environments cohabited by human and virtual agents working "shoulder to shoulder" in a manner of speaking. However, they have also managed to construct a rich virtual world in which a set of autonomous creatures are caught up in a complex web of social interactions "day in and day out." Such virtual worlds could be very useful tools for studying and experimenting with the roots of social interaction and group dynamics, and so the development of sophisticated technology to support such systems is important for the enhancement of Artificial Life research.

ATR

Last but not least, outside of Kyoto is ATR, a highly research-oriented lab spun-off from NTT (Japan's equivalent of AT&T). Much of the research that goes on at ATR is dedicated to telecommunications technology, but there is a good deal of work on parallel computing, optical computing, natural language processing, virtual reality, AI, and, recently, Artificial Life. Katsunori Shimohara heads the Evolutionary Systems Department at



ATR, which employs a substantial number of Artificial Life researchers from the U.S. and Europe, including Tom Ray (the developer of the Tierra system) who has also spent a lot of time at SFI and is now a member of the Institute's External Faculty. ATR is quite well funded and equipped by the Japanese government and NTT. They have a large CM5, and Kurt Thearling (a SFI summer school alumnus and frequent visitor who currently works for Thinking Machines Corp.) recently spent time at ATR helping Tom Ray adapt the Tierra system to a parallel computing environment on the CM5. With this parallel implementation of Tierra, Ray intends to study conditions for the emergence of multicellularity, which, in the context of Tierra, means the co-evolution of parallel programs. This is a significant research effort, but Tom Ray has had success with his Tierra system in the past—including being one of the first people to demonstrate convincingly that one can achieve and experiment with "Natural Selection" within artificial worlds in computers.

RESEARCH CLIMATE AND FUNDING

Let me finish with some observations about the evolving research climate in Japan. In the past, Japan has relied primarily on other countries, especially the U.S., to invest the time, money, and people in fundamental research, being content to invest in the engineering effort required to perfect applications of the fruits of that research. However, as the support for fundamental research in the U.S. has collapsed drastically over the last decade, and as a result of their own significant technological progress, Japan is finding itself in a position where it cannot continue to rely on external research results and must greatly extend its own internal support for fundamental research. This they appear to be doing.

Furthermore, their commitment to research is like nothing seen in the West for a long time. When the Japanese decide

to commit to a research project, it is often for an extended period of time, on the order of 8–10 years. Such a policy has two important benefits. First, the researchers involved do not have to spend 9/10 of their time scrambling for next year's funding for the 1/10 of the time they actually get to spend doing the research, a scenario that is the norm in the West. Second, and perhaps most importantly, every research project has a pre-programmed termination date. If the research during that 8–10 years has proved fruitful, it will need to be incorporated into another 8–10 year project. This philosophy of providing extended but finite support for research projects sets up a climate that allows workers to give their undivided attention to their projects for periods of 6–8 years, before they begin to have to worry about where the next allocation of funds is going to come from. It also sets up a research climate in which the publication of every little incremental result is not so critical as the accumulation over time of a smaller number of more significant results.

Although there are also potential problems with such a funding strategy, I am beginning to see it as very enlightened. I am becoming more and more alarmed at the havoc that has been wrought on fundamental research support in the U.S., which was, for a long time, the best in the world. The current philosophy of "applications-oriented" research, in which an official part of the policy is that research cannot be "merely" curiosity driven, demonstrates a fundamental lack of understanding on the part of the bureaucracy of how science makes progress. In the past, the funding agencies seemed to recognize, if only implicitly, that in order to achieve ten breakthroughs, it was necessary to fund a thousand different research directions, and that it could not be predicted in advance which of those thousand would produce the breakthroughs. In the current funding climate, funding agencies only seem willing to fund a small number of research efforts, and all of these have to guarantee breakthroughs in advance—hence the "Grand Challenges" and the current need to twist

one's research so that it can be painted as part of one of the few approved projects, with the attendant need to point to a specific set of forthcoming engineering applications to boot. God forbid that one's research should be "merely" curiosity driven (unless, of course, one is fortunate enough to work at the Santa Fe Institute(!) or, increasingly, in Japan).

Japanese research efforts in Artificial Life are just getting under way; many of them look quite promising, while for some it is too early to tell. It is clear, however, that the Japanese have assimilated the basic principles of Artificial Life into many of their research efforts, both new and ongoing, and that Artificial Life has now established itself firmly in the East as well as the West.

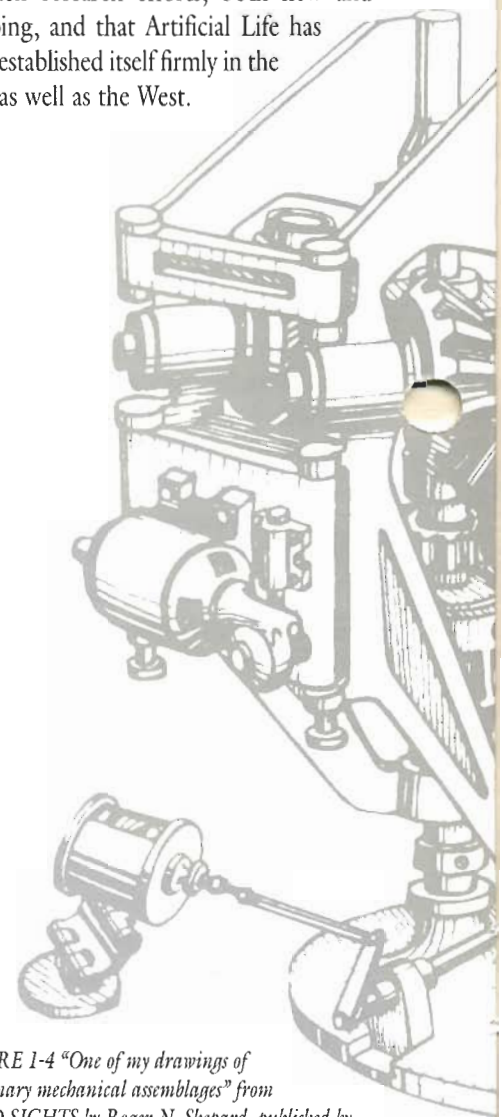
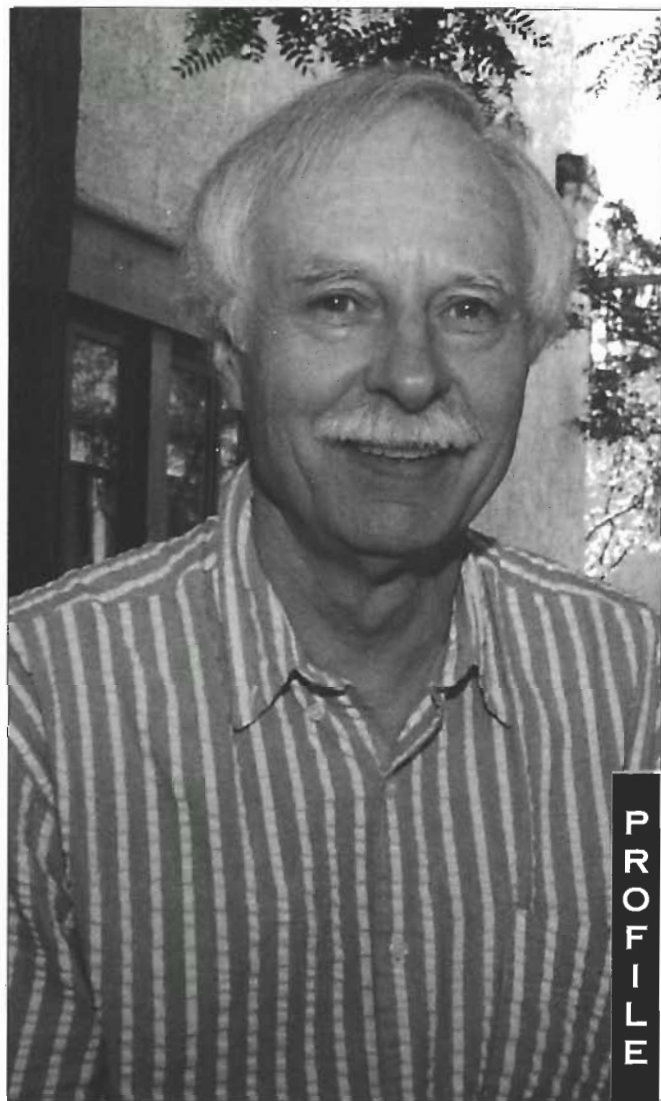
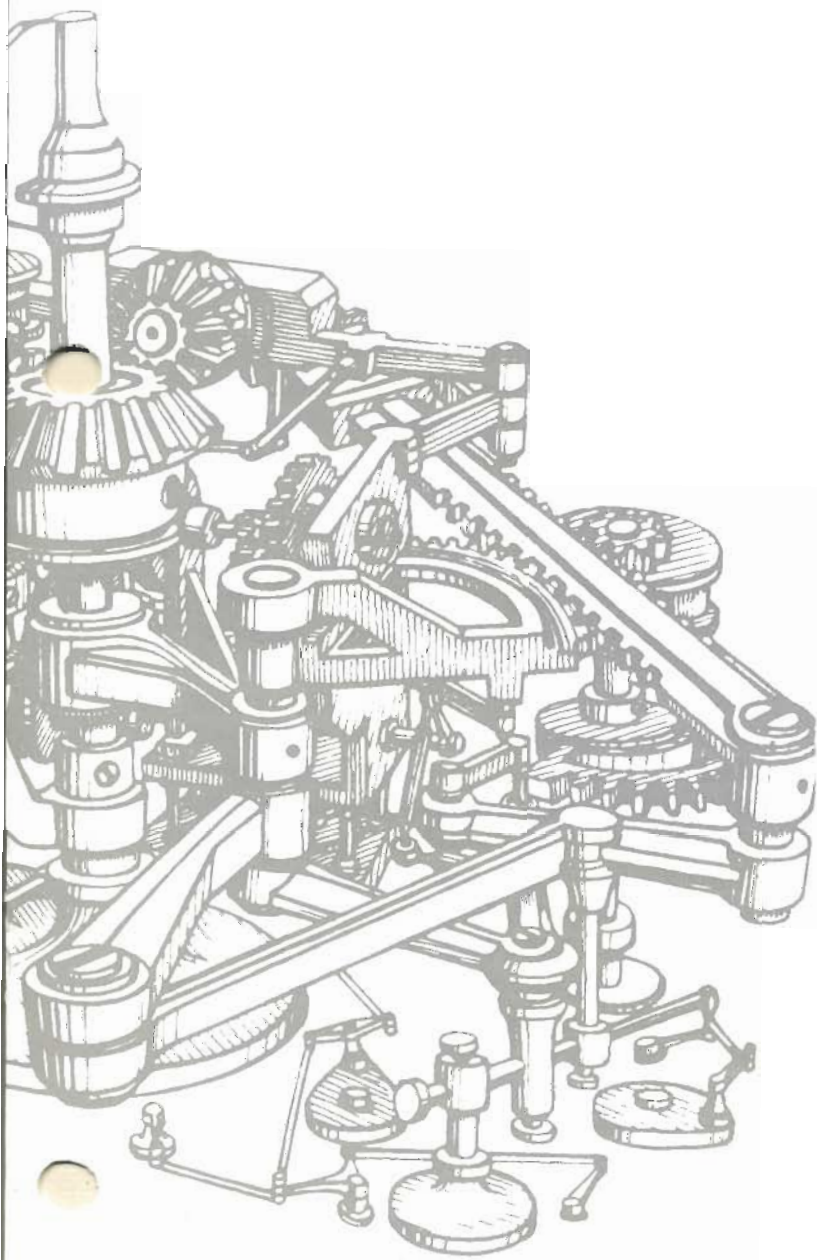


FIGURE 1-4 "One of my drawings of imaginary mechanical assemblages" from *MIND SIGHTS* by Roger N. Shepard, published by W.H. Freeman and Company, New York.

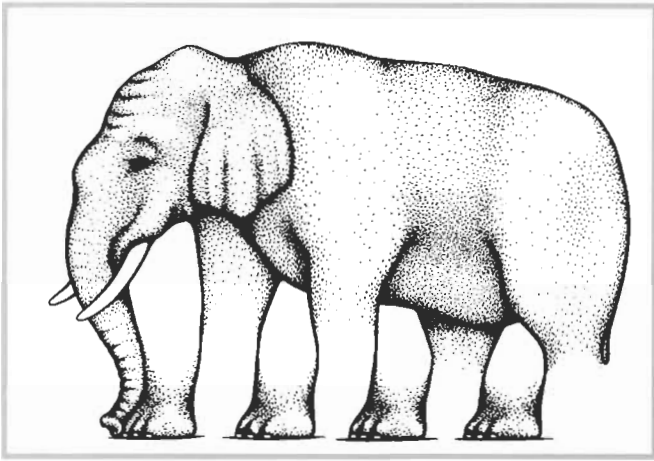


PROFILE

ROGER SHEPARD

Janet Stites

As an undergraduate at Stanford University, cognitive psychologist Roger Shepard had a hard time settling on a course of study. His interests ranged from theoretical physics, to music and art, to the mind. He dismissed physics because he felt the field had a long line of brilliant contributors and that he would be unlikely to go significantly beyond them. An introductory philosophy course turned his world upside down, but he was warned away from this field by a professor disillusioned by the discipline. Scrambling for a major his senior year, he took an introductory course in psychology but was uninspired. Finally, a graduate level course in the study of sensation and perception led to an insight on Shepard's part that would change his major, change his life, and change some ideas central to psychology. He took a risk.



What at first appears as a real object upon closer scrutiny reveals itself to be an — “impossible object” — an example of figure ground impossibilities.

“I felt there were some fundamental aspects of the physical world that could be applied to psychology as well,” he says. “And that maybe there was an opportunity in psychology to apply mathematical theories in a field that hadn’t been much developed.” This thought became an axiom in his work—as a graduate student at Yale, as a researcher for the Bell Telephone Labs, as a professor at Harvard, as a professor at Stanford, and, most recently, as a visiting researcher at the Santa Fe Institute. The insight has served him well.

Essentially, Shepard has pursued the question: could there be some general principles of the mind that are not unlike the universal laws of physics? “I’ve come to the view that psychologists haven’t been thinking big enough,” he says. “Psychologists have been taking it for granted that their subject matter is this particular collection of organisms that they happen to find on this particular planet. But, like the laws of physics, there could be laws that are true throughout the universe, wherever advanced forms of life have evolved.”

An example of such a law may be the idea of internalization, in which the brain assumes order in situations where perceptual information about the outside world is ambiguous. Shepard believes internalization could be either learned, as in the case when a bird learns which caterpillars are poisonous or, surprisingly, genetically encoded as a result of evolution. Shepard posits that the brain has had millions of years to find ways to solve problems, or to interpret a situation when the information provided is incomplete or ambiguous.

“Long ago it was assumed that nocturnal animals know when to leave or return to their burrows by the obvious fact of when it gets dark or light outside,” Shepard says. “Yet in laboratory studies it was found that when put into constant light and a constant temperature chamber, the animals would continue to maintain a 24-hour circadian cycle. The evidence suggests the animals have internalized this.”

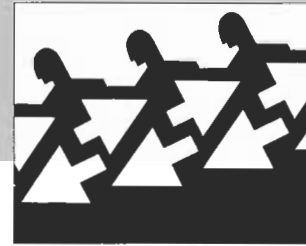
One thing Shepard believes has been internalized is a principle of “generalization.” Pavlov was the first to study generalization, finding that when he rang a bell before feeding his dogs they would salivate; if he rang a bell of a different pitch they would also salivate, but less so. The more the pitch differed from the original, the less they would salivate. “Generalization is a fundamental ability we and all animals have,” Shepard says. “It’s absolutely essential in this world because you never confront the same situation twice. Even if you see the same object again it’s from a slightly different distance, from a little different angle. So, every response you make is, in a sense, a leap in the dark.”

Recognizing a color and identifying an object are cases of generalization. But so is knowing that a Labrador, a collie, and a cocker spaniel are all dogs. Shepard proposed his own theory of generalization in a paper called “Toward a Universal Law of Generalization for Psychological Science.” In a rare moment of presumption from an otherwise modest man, Shepard arranged for the paper to be published in 1987, exactly 300 years after Newton published *Principia*, introducing the universal law of gravitation. In his paper Shepard proposes that the brain represents objects as points in a psychological space. Similar objects, like dogs, fall into the same region. Food will fall into its own region, with foods that taste bad, or are poisonous, nearby.

At the Santa Fe Institute the Law of Generalization states that all visiting researchers must share an office, which Shepard has happily done while on sabbatical from Stanford. “Working at the Institute has been exciting to me because of its interdisciplinary nature,” he says. “I’ve been very interdisciplinary in my interests and it’s always been a frustration that universities are so departmentalized. The faculty are so pressed with their duties of teaching and committees and grading student papers that they don’t have a lot of time. The last thing they are looking for is developing some interchange with somebody in a different field.”

The word around the Institute is that Roger Shepard walked in off the street and simply stayed. Romantic image as it might be, Shepard had been following the work of the Institute through Stanford colleague David Rumelhart, who serves on SFI’s Science Board, and a number of his students who have attended the summer school or worked as interns. Shepard did, however, stop by unannounced while visiting Santa Fe in September of 1992 and spoke briefly with SFI V.P. Mike Simmons. That contact eventually led to a sabbatical visit, and renewed faith on Simmons’ part in serendipity. “When we first brought up Roger’s name to our selection committee there was an electric response,” Simmons says. “Roger has an immense reputation in his field.” At the time the Institute was making a concerted effort to incorporate the social sciences into the scope of research, and there wasn’t a psychologist in residence.

Where does Shepard see his work in relation to the science of complexity and the work of the Santa Fe Institute? “The human



mind is one of the most complex things we know," he says. "But we are only beginning to understand how it works. I have started with very complex phenomena, namely human perception and cognition, and looked for very simple and general principles that may explain how they work."

Shepard feels that most of the researchers at SFI are a step ahead of him because they already know that some of the systems they are working with are mathematically intractable. They have already tried, and failed, to explain some of the phenomena with simple laws like the Newtonian Laws of Motion. "In psychology we don't know which things can be dealt with mathematically and which things are going to require simulation," he says. Taking a cue from his Stanford colleague Rumelhart, Shepard has been using connectionist modeling to study generalization.

While at the Institute, Shepard has devoted much of his time to writing. His first project was to outline a book based on a series of ten talks he gave last year as part of the Paul Fitts Memorial Lectures at University of Michigan, a book that in many ways reflects the work of the Institute. He characterizes the theme as "the search for the elementary principles underlying the complexity manifested by the capabilities of humans and other intelligent beings." His second project was to prepare for the seven William James Lectures he will give at Harvard this fall. Being asked to be a William James lecturer particularly pleased Shepard as it puts him in the company of such luminaries as John Dewey, Robert Oppenheimer, and Bertrand Russell.

Because of his overwhelming writing schedule, Shepard did not have as much time for collaboration as he would have liked. He has, however, made a point of going to most of the seminars and workshops and found that the material was often relevant to his own writing. "I'm not sure I've had too much impact on the Institute," Shepard says. "But I expect my own work will go more in the SFI direction."

Shepard's enthusiasm did not go unnoticed. "It's impossible to imagine Roger not having an impact," Simmons says. "He attended so many workshops and interacted with so many people while he was here. A highlight of his visit was the series of lectures on the emergence of mind that he gave during the fall and winter." Following a phenomenon that seems to be emerging into a pattern, Shepard and his wife, Barbaranne, are considering retiring to Santa Fe. "The Santa Fe Institute is unique," Shepard says, sounding every bit the philosopher. "It's inherent in the nature of the place to take risks."

The underlying information-processing machinery of our brains reveals something of its constructive operations only when challenged with visual displays specially contrived to deviate from the regularities that prevailed in the world of our ancestors. Natural selection has not had time to adapt our biological makeup to the demands increasingly placed on it by technological innovations. For example, because our visual system has evolved to compensate for variations in natural illumination, we readily recognize a familiar object whether it is seen in the (yellowish) direct sunlight of midday, the (redder) direct sunlight toward sunset, or the (bluer) indirect sunlight scattered to an object in shade. But we may walk right past our own car when, in a parking lot at night, it is illuminated only by quite different, artificial light emitted by sodium or mercury vapor lamps.

For every situation, our perceptual system automatically applies its previously successful and now thoroughly entrenched methods of processing. If the situation is quite different from those encountered by our ancestors, however, this system may deliver up incorrect or conflicting interpretations. From an analysis of the conditions giving rise to such perceptual errors and confusions in the psychological laboratory, researchers seek an understanding of the information-processing methods that have until now remained deeply hidden in the biology of the visual system. Part of such an understanding may come from a consideration of how the regularities of the natural world, in which we have evolved, may have shaped our methods of processing the visual information that comes to us from that world.

Janet Stites is a free-lance writer whose work appears in Omni and other national magazines.



SOCIAL SCIENTISTS ADDRESS SOME OF THE MISSING PIECES

EVOLUTIONARY MODELING

For the first time, social scientists outnumbered biologists, computer modelers, and representatives of the “hard” sciences at the Crude Look at the Whole (CLAW) meeting on sustainability held at SFI in April. The resulting chemistry was catalytic with the candid mixture of viewpoints offering participants a chance to address some of the “missing pieces” in SFI’s work on evolutionary modeling.

For the past few years SFI researchers and others have been brainstorming about how to construct scenario and computer models that can capture the full range of issues and data necessary to address the hard questions of achieving a sustainable world. The CLAW working group is concerned with describing our future(s) from the perspective of a “crude look at the whole.” The concern of the CLAW effort is that all the subsystems relevant to sustainability problems are nonlinearly coupled so that is not realistic to consider parts of the problem in isolation from others.

Thus the goal is to retain as many components of the problem as possible, even if only in crude approximation. Among the essential components are some that are difficult to quantify and, hence, frequently neglected in the construction of models and scenarios: political, cultural, and ideological systems. Social scientists must therefore play a key role in CLAW. SFI’s CLAW effort is coordinated by Marc Feldman and Murray Gell-Mann, and is part of the larger “2050 Project” involving SFI, the Brookings Institution, and the World Resources Institute. The project is supported by funds from the John D. and

Catherine T. MacArthur Foundation.

Chris Langton’s and John Holland’s simulations of artificial worlds, Swarm, and ECHO, are relevant to CLAW’s aims, because they are inherently nonlinear models that capture some aspects of the emergent behavior of large numbers of agents. Likewise, Brookings researchers Joshua Epstein and Robert Axtell, influenced by interactions with SFI, have developed Artificial Social Life (ASL), a computer simulation that explores how collective behaviors can emerge from the interactions of individual agents obeying simple local rules. However, within this work on evolutionary simulation and modeling driven by “simple rules,” there are some significant gaps. For example, these models

are generic; as yet there are no detailed properties of specific real-world behavior incorporated into them. Also, these models currently lack multiple levels of organization: no provision for level is made explicit either within the model itself or as stipulated from external causes.

This raises a related question about what level within the hierarchy of social organization (ranging from the individual to the global) is the appropriate place for a model. Further, how can schema for higher levels of organization emerge within the model if, as is now the case, agents have no individual “memory”? Finally, current models lack interfaces or levels that reflect cultural factors including interactions of populations, resources, and technology; information and communication; policy perspectives and social priorities; and modeling styles and contrasts in perspectives.

Herein lies CLAW’s central challenge: how to model “wholes” and “parts” in internally consistent and robust ways.

Data-based modeling is theory-driven and empirically derived.

By contrast, agent-based modeling (e.g. artificial social life) “grows” social processes with little attention to reality.

Participants agreed that in order to be policy relevant, there must be a convergence between data-based modeling and agent-based modeling. As both modeling approaches lack the specification of levels and the articulation of social relations, scenario writing may be helpful in tying the literary to the computational approach. Once a scenario is laid out, modeling might be used to examine its premises or to attempt, by evolutionary exploration central to adaptive modeling, to discuss flaws in the scenarios.

Many issues remain to be debated as part of CLAW’s agenda and many intellectual and scientific gaps in its approach still need to be addressed. In the meantime, however, the interdisciplinary temper of the recent meeting was “a remarkable experience in effective communication across disciplines, theoretical and modeling traditions, policy perspectives, and international divides” according to MIT political scientist Nazli Choucri.

The next step may be to explore these convergences in approach within the context of a sample scenario. On a more general basis, the group will also continue to discuss how to interface SFI research priorities with the emergent research agendas in the social sciences.

RESEARCH UPDATES

MODELS HOLD PROMISE FOR PREDICTING EARTHQUAKES

HAZARD REDUCTION



Effects of the San Francisco earthquake of April 18, 1906. Offset fence on the ranch of Mr. E.R. Strain located north of San Francisco. The fence was offset 8.5 feet as a direct result of a sudden horizontal slip on the fault trace at the time of the earthquake. This figure is contained in the report of the State Investigating Commission for the San Francisco earthquake of 1906, chaired by Professor Andrew C. Lawson, University of California, Berkeley.

RESEARCH UPDATES

By 2050 more than a third of the world's population will live in areas that are volcanically or seismically active. Will there be better ways to predict when and where catastrophes like earthquakes, volcanic eruptions, floods, and landslides will occur? Earlier this year two dozen geologists, geophysicists, hydrologists, physicists, and mathematicians gathered at SFI to discuss new tools—particularly computer modeling—that may help predict and possibly reduce the losses from these natural disasters. The workshop, unique for the diversity of its participants, is proving productive on several timescales. A meeting report has been accepted for publication in the *Transactions of the American Geophysical Union*. A book is planned to appear in Spring 1995. More prospective but equally important, the program has generated interest within the insurance community, which sees a need for ongoing research bringing fresh approaches to the field of hazard reduction.

The working group was headed by Bill Klein (Boston University), John Rundle (U. Colorado), and Don Turcotte (Cornell) with funding from DOE, NASA, and NSF.

The focus of the meeting was the possible applicability of dynamical systems concepts—including fractals, chaos, nucleation, self-organizing systems, and critical phenomena—to seismic events, other natural hazards, and geomorphic processes. Discussions covered the application of current techniques from one field to another using examples like the spatial and temporal clustering of earthquakes and the appropriate definition of a flood. Participants also debated the relative merits of the variety of slider-block (quasi-static vs. elastodynamic) and drainage-network (Gibbs vs. diffusive) models. The slider-block models clearly provide a basis for testing various earthquake prediction algorithms, and the drainage-network models offer a means of evaluating the effects of dams and other drainage-altering events. It was concluded that computer simulations and analysis of these dynamical systems offer an attractive method for predicting the future evolution of systems and for testing a variety of hypotheses.

Klein and Rundle returned to SFI this summer to discuss the structure and aims of an ongoing research program in this field. In related work, Cheryl Stewart from UCLA is in residence at SFI this summer developing a cellular automaton model of plate tectonics.



BRINGING ALIFE AND BIOLOGY TOGETHER TO SOLVE REAL-LIFE PROBLEMS

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Developments in computer technology tend to progress through a standard cycle: the technology improves, which in turn creates new tools and services, and finally a fundamental transformation in the nature of our activities occurs, often resulting in the performance of tasks previously inconceivable.

For example we see computers driving the transition from traditional to numerical taxonomy; the change in statistics to analysis of variance and multivariate statistics and more recently to tools like jackknifing and bootstrapping; and in population genetics, a move from analytically tractable equations to diffusion equations and coalescents. Current tools of DNA sequence analysis would be impossible without the ability to rapidly make and evaluate large numbers of comparisons computationally.

The study of evolution and ecology has moved through the first two stages of technological improvement and innovation. With the creation and study of artificial life, these fields are now at the threshold of transformation. Alife computational tools are now sufficiently developed to allow the creation of simulations that capture much of the complexity of natural biological systems. Among other things, these offer the prospect of creating and manipulating emergent properties in synthetic systems.

Earlier this year two dozen experts from the fields of evolutionary biology and artificial life met at SFI to begin to flesh out how artificial life systems can most effectively be directed to solving real-life problems in evolution and population biology. The strategy was to get the people with the best understanding of the outstanding biological problems together with the people with the most promising and powerful new computational tools for an intense, free-ranging exchange of ideas and specific proposals for research. The meeting was hosted by SFI External Faculty member Chris Langton and evolutionary biologist Charles Taylor, UCLA. It was supported by funding from the National Science Foundation.

The meeting began with a discussion of some current applications of artificial life to biology—the work of Kristian Lindgren and Tom Ray on open-ended evolution, Peter Schuster's research on adaptive surfaces, and that of David Jefferson and Charles Taylor on mosquito control. Attention then turned to how to apply these techniques further to solving real problems

in ecology and evolution. Participants broke up into working groups to frame specific problems and get a start on collaborations. The idea was to pair those who have developed the computational tools and best recognize their potential (largely physicists and computer scientists) with biologists who are likely to know how these techniques could be used.

One project built on biologist John Maynard Smith's questions about the role of biotic vs. abiotic factors in driving evolutionary change and community stability. There are fairly good historical records of temperature throughout the past million years.

RESEARCH UPDATES

These have regular fluctuations and it is thought that many species are so carefully attuned to their environments that they could not live through such cycles unless they evolved exceedingly quickly. Not surprisingly, speciation events seem to be especially common at those points in the cycles where temperature changes are greatest. How much this reflects adaptation to temperature and how much to changes in the remaining community is difficult to determine in nature, but these events might be examined in the controlled environments of simulated populations.





Another project is directed at exploiting the emergent properties exhibited by Ray's Tierra ecosystem. While parasitism and cooperation among programs did evolve, the system was apparently not such that it would lead to the evolution of sex, genetic recombination, or multicellularity. What is necessary for these to emerge? An Alife system might offer an unusual opportunity to study these widespread and puzzling phenomena.

At a higher level of organization, the role of instinct vs. learning in language development and use has been an enduring problem in linguistics and cultural evolution. It seems plausible that language is programmed into the human genome, though it is far from clear that this is necessary. What about bees' dances and the alarm calls of monkeys? There does, however, seem to be a conjoint role of environment and genotype in the acquisition of language, and this takes on a special significance for humans because the use of language plays such an important part in providing the collective power to control the environment and perhaps even the ability for consciousness. Several groups of researchers have constructed systems that permit the evolution of language to be observed. Michael Dyer at UCLA has focused on the grounding problem linking signifier with signified and David Ackley at Bellcore has explored the power that language can give for deception and manipulation of others. With either of these artificial life systems it should be possible to examine how group selection, kin selection, and population structure contribute to the linkage of signifier to signified and the coevolution of senders with receivers.

Another collaboration builds on Joe Felsenstein's suggestion that a core problem in theoretical biology is to learn how the mass of molecular data now being accumulated is best interpreted. Among the most urgent of these problems is how to construct phylogenies from amino acid or nucleotide sequences. With only a few taxonomic units, the number of possible phylogenies can be enormous. The search is easier if there are known biological or molecular constraints. Yet a way needs to be found to limit the phylogenetic search to only those evolutionary hypotheses that fit the known constraints. One way to unravel this link may be to study the evolution of a reasonably well-understood system—for example, transfer RNA molecules with well-characterized constraints on their stability and adaptive landscape—as it develops within a computer simulation.

"If we want to discover generalizations about evolving systems," says biologist John Maynard-Smith, "we will have to look at artificial ones." How this transformative approach will finally unfold is still unclear, but with these research collaborations at SFI and elsewhere it seems certain that it is underway.





SEQUENCE DESIGN MEETING WEDS DIFFERENT APPROACHES FOR NEW BIOTECH RESEARCH

SEQUENCE DESIGN

Today biology is poised on the brink of a revolution. A combination of biotechnology and computational biology promises not only to increase our understanding of basic processes; it is also driving the discovery of drugs, enzymes, and biosensors. The new techniques rest on the capacity to generate and search enormously diverse libraries of novel RNA, DNA, and protein sequences for molecules of interest. Libraries with a diversity of 10^{14} sequences are being explored. Intriguingly, these new methods suggest that rational design (i.e. protein engineering) and irrational design (i.e. molecular evolution) might be united in a common theoretical approach based on rugged fitness landscapes.

In April SFI hosted the conference "Searching Sequence Space: Rational and Random Approaches to Sequence Design" to begin to flesh out this framework. Nearly 100 people at the leading edge of molecular diversity research, protein folding, and rational drug design working in academia, private industry, and federal agencies traded information on common aims and theories.

The meeting was organized by an international group representing a broad range of interests and institutions: Alan Lapedes (LANL), David Eisenberg (UCLA), Stuart Kauffman (SFI), Walter Fontana (U. Vienna), Alan Perelson (LANL), Peter Schuster (Inst. for Molecular Biology, Jena), and Peter Stadler (U. Vienna). It was supported by the Department of Energy, with additional financial and logistical support from the Theoretical Division at Los Alamos National Laboratory, the Center for Nonlinear Studies (LANL), the UCLA-DOE Laboratory of Structural Biology and Molecular Medicine, and the Santa Fe Institute.

Experimental techniques for producing biologically active sequences—sequences of amino acids or nucleotides—are making stunning advances. Applied molecular evolution; sequence selection for desired properties from random sequence libraries; genetically engineered modifications of wild-type sequences; and *de novo* design and construction of protein sequences are examples of these new tools. They allow construction of sequences never before seen in nature, as well as construction of libraries of new sequences that can be culled for desired properties.

The ability to produce sequence libraries with desired properties extends to RNA, DNA, and peptides. The different sequences in a selected library presumably have similar structures, and therefore similar functions. These libraries contain a wealth of information linking sequence to structure, and structure to function.

Alongside these new tools, new theories provide general formalisms for analyzing the map between sequence, structure, and function. They also suggest new design methodologies, as well as a general framework for thinking about natural and laboratory molecular evolution. These new ideas include the theory of evolution on fitness landscapes. The "ruggedness of a landscape" is a measure of the difficulty of solving a problem. For example it might represent the success, or "fitness," of a complete set of biological sequences at solving the problem of binding to a particular molecular site. Another new concept is a burgeoning theoretical formalism for the "inverse folding problem" in proteins (designing a sequence that folds to a desired structure). In addition, new data analysis techniques are being developed to mine the wealth in experimentally selected sequence data.

RESEARCH UPDATES

The SFI meeting offered a rare forum for discussing emerging theoretical formalisms and new experimental capabilities. This joint approach should greatly expand our ability to survey molecular space to better understand the links between biological sequence, structure, and function. "I am very excited about this," said attendee John Wooley from the U.S. Department of Energy. "I think the sorts of ideas that were discussed at the meeting will be useful . . . in contributing not only to abstract theory, but also [to] theory that can be applied to contemporary problems."

Already these developments are driving a wave of new biotechnology companies producing novel medicines, enhanced foods, and other products. These fast-breaking industrial developments suggest the need for another kind of cross-cutting cooperation, that is, collaboration among academia, industry, and federal laboratories. The April meeting, which involved experimentalists and theorists from a wide variety of companies, agencies, and institutions, embodied such an approach. It continued at a follow-up meeting which took place in June at North Carolina's Research Triangle. Researchers from Glaxo, Smith Kline Beecham, Ixsys, Duke University, SFI, and North Carolina State met to discuss further collaborations.

WHAT IS SCIENTIFICALLY KNOWABLE?

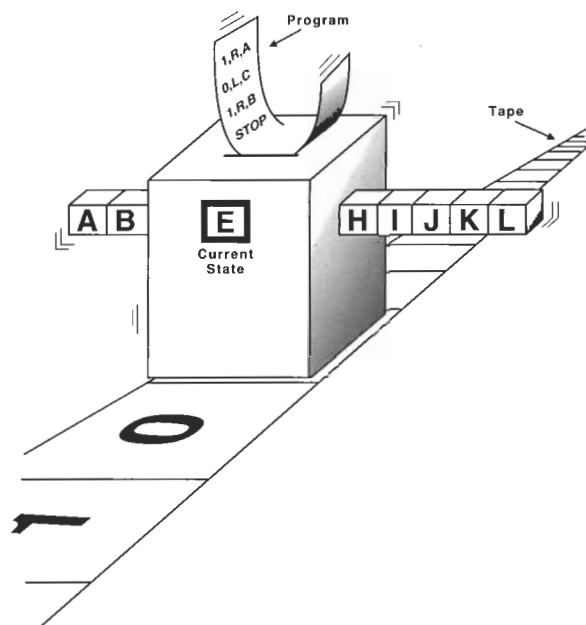
The story of mathematics in the latter half of this century has to a great extent been the story of “nonexistence” theorems. Gödel’s observations on the existence of undecidable propositions in number theory and Turing’s proof of the undecidability of the halting problem in computer science are probably the best-known examples of this. They demonstrate the existence of mathematical questions that are forever beyond the powers of the human mind to answer by carrying out a computation.

Do the same kind of nonexistence results apply to the seemingly more complex world of natural phenomena? In particular, are there important and interesting scientific questions that defy rational analysis? Given that interactions in areas such as physics, biology, and economics are vastly more complicated than those found in the simpler domain of arithmetic, it is not unreasonable to suspect that such unanswerable questions do indeed exist. If so, what are they like?

In science a common method by which questions are answered is to carry out a computation—either explicitly by means of a computer program or implicitly by constructing a mathematical model embodying an algorithmic relationship between the components of a given system. So when it comes to unanswerable scientific questions, we can sharpen the issue considerably by asking whether there are questions that cannot be answered by performing a calculation.

Since complexity is a key issue in determining what we can and cannot know and since the question is inherently multidisciplinary, SFI offers an appropriate venue for exploring these matters. During the period May 24–26, a workshop organized by John Casti from SFI and Joseph Traub, Columbia U., was held at SFI as a first step toward establishing a long-term program by which we could come to some definite conclusions on the matter of scientific, as opposed to mathematical, knowability. The meeting, which drew about thirty participants from a variety of disciplines, was supported by the Alfred P. Sloan Foundation.

The opening day focused on brief reports by a few participants on general aspects of impossibility problems, as well as disciplinary perspectives from biology, physics, economics, and computation. In addition, there were two discussion periods during which matters raised in these short presentations were examined and various notions of scientific unknowability were refined.



RESEARCH UPDATES

The morning of the second day was devoted to general discussion of what it means for a question to be unanswerable, and whether there exist natural questions outside of mathematics and theoretical computer science that fall into this category. That afternoon, the participants split up into groups—biological, mathematical, physical, and social sciences—to consider the issue of unanswerable questions from the disciplinary point of view. The day’s discussions suggested that the likelihood of establishing such impossibility results was high enough to warrant a focused research effort.

On the final morning, the participants considered the shape and content of a research program on the “limits to scientific knowledge.” Due to the generally positive response from the participants, the workshop organizers plan to pursue a longer-term, more structured research effort on these issues. In this same regard, the Sloan Foundation may initiate a program on the limits to knowledge.

A set of videotapes is available for those who wish to view the workshop discussions. They may be obtained on loan by contacting Margaret Alexander, the SFI Librarian.

THE IMPORTANCE OF BEING NOISY

Mark Millonas

Santa Fe Institute and Los Alamos National Laboratory

IN MY VIEW

TWENTY YEARS AGO scientists found it hard to believe that deterministic systems could exhibit low-dimensional chaotic behavior that was indistinguishable from random motion. Today it seems that many complex systems researchers have a hard time believing that there is any other type of randomness. It is currently quite popular when faced with a system that exhibits unpredictable behavior, such as the stock market, to apply tools more appropriate to the analysis of chaotic deterministic systems, in spite of the fact that such systems may be random at a much more fundamental level.

This approach is even less valid now that it is beginning to be understood that the addition of even an infinitesimally small amount of noise to a nonlinear dynamical system can alter its behavior in a fundamental way. Just as it is not possible to separate nonlinear dynamical systems into simple parts which can be understood separately, it is not always possible to separate the deterministic element from the stochastic element in systems subject to fluctuations. Since randomness enters into the fundamental processes that make up complex systems in nature, it is probably impossible to understand the vast majority of them, even qualitatively, without explicitly incorporating this randomness into our models.

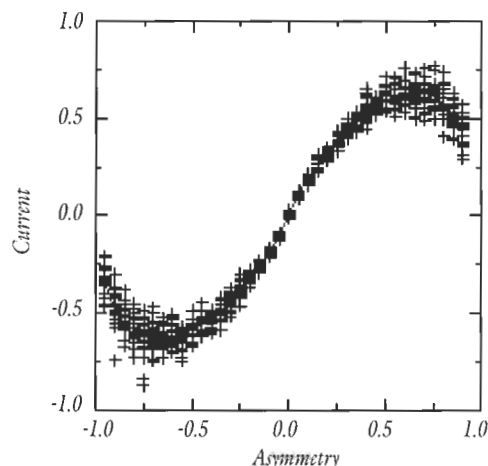
There are many reasons why people have trouble with noise. While I do not believe that we are born with an inherent belief in regular deterministic behavior, I do believe that this belief incubates in the

educational system. Just as chaos was not intuitive to the generation of scientists trained on linear systems, the true significance of fluctuation is not readily apparent to those whose only contact with randomness is equilibrium statistical mechanics, and this is commonly all that even the vast majority of Ph.D.s in physics have been exposed to. Researchers with other backgrounds commonly have even less.

At the lowest level of sophistication there is often an implicit assumption that noise is negligible. This is the assumption that is always made whenever one studies deterministic models of natural processes. On the next higher level, noise is often regarded as a source of pure disorder. This is the misleading lesson of equilibrium statistical mechanics. Many researchers organize their understanding of a particular complex system around such pictures without any clear understanding of their validity, and sometimes even without conscious awareness.

On a still more sophisticated level is the paradigm of "order through fluctuation," put forward by Prigogine and others in which, near an instability, fluctuations can be amplified, causing an onset of a more ordered macroscopic state. This idea I call the passive noise paradigm, in that only the transitions to certain ordered macroscopic states, and not the states themselves, are influenced by the fluctuations. Along with this idea there is often the assumption that the probability that a system will be found in one of a number of

possible ordered states after the transition can be determined from macroscopic criteria, without reference to the detailed kinetics. The former idea is often true in systems composed of a great number of parts, but the latter is in general not true. In systems where the internal fluctuations are large, or where there are external fluctuations, neither of these is generally true. This is the category into which most complex systems in nature fall.



Plot of the current versus asymmetry parameter for a correlation ratchet driven by temporally asymmetric fluctuations. This system was invented by Dante Chialvo and Mark Millonas and illustrates the effects of temporally asymmetric fluctuations. Although this type of temporal asymmetry is quite common, particularly in biological systems, it has not previously been investigated in detail.

More generally it can be shown that even when the fluctuations are small, the probability of a macroscopic state depends on the explicit details of the global kinetics, and cannot be determined from the macroscopic state alone. In addition, if the fluctuations are macroscopically large, which is the case in very many complex systems, the qualitative structure of the macroscopic states, as well as their relative probabilities, will also depend on the global kinetics. The noise may then be said to play an active role in the formation of order. These types of phenomena are to be strongly contrasted with the passive noise-type paradigm, and in fact represent an ever-growing, and at this point definitive body of evidence against the general applicability of the ideas of the Prigogine school. Complex is complex, and there are no magic prescriptions. If it is true that many of our present "intuitive" notions are not valid ways of understanding most complex adaptive systems, then we may need to radically reappraise the role that noise plays in the behavior of such systems.

Many new and exciting active noise type phenomena have recently been discovered, many that may have important implications for biology. Biological systems are fertile ground for the application of this new understanding since, on the biomolecular level, the fluctuations are large and important. Somehow these systems maintain their order and complexity in this violent environment and even use the noise to their advantage. Stochastic resonance and correlation ratchets are two such recent inventions. Stochastic reso-

nance is a phenomenon in which a signal in a fluctuating environment can, under the right circumstances, actually be made clearer if the noise is increased. Stochastic resonance has been studied with respect to the transmission of information in sensory neurons which have their own internal noise sources which may exist precisely to aid in the transmission of information. Correlation ratchets are thus "information engines" analogous to Maxwell's Demon Engines, which extract work out of a thermal bath by rectifying the thermal fluctuations of the system. Systems such as this have been proposed as models for how muscles and other cellular motile processes work on the molecular scale.

A group is forming at SFI which we hope will catalyze discussion of these new phenomena, particularly with respect to real biological systems.

"What are the fundamental elements underlying most complex systems in nature?" We need to look deeply at this question, and the example of noise shows that the neglect of any one of these elements can lead to completely misleading results. While the simplifications which are always made in the modeling process may produce approximate descriptions of nature, the neglect of a fundamental element is likely to produce nonsense. Just as atomic theory is not possible without the principles of quantum mechanics, it may be that a complete theoretical framework for the understanding of complex systems is not really possible without an adequate treatment of fluctuations.

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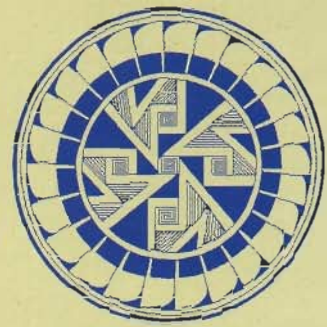
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