SFI Bulletin

SANTA FE INSTITUTE • WINTER 1998 • VOLUME 13 • NUMBER 1

EVOLVING BUSINESSES, WITH A SANTA FE INSTITUTE TWIST

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The *Bulletin* of the Santa Fe Institute is published by SFI to keep its friends and supporters informed about its work. The *Bulletin* is free of charge and may be obtained by writing to the managing editor at the address below.

The Santa Fe Institute is a private, independent, multidisciplinary research and education center founded in 1984. Since its founding, SFI has devoted itself to creating a new kind of scientific research community, pursuing emerging synthesis in science. Operating as a visiting institution, SFI seeks to catalyze new collaborative, multidisciplinary research; to break down the barriers between the traditional disciplines; to spread its ideas and methodologies to other institutions; and to encourage the practical application of its results.

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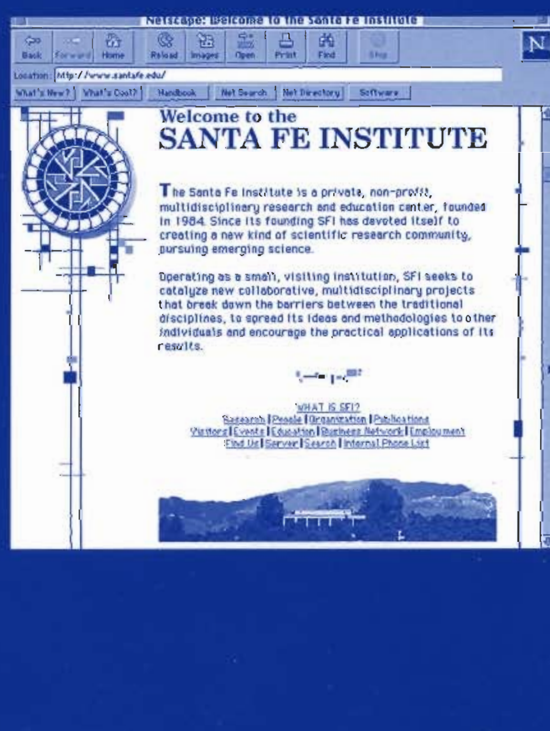
A NEW WEBSITE LOOK FOR SFI PUBLICATIONS. SFI'S REVAMPED PUBLICATIONS WEBSITE HAS LINKS TO BOTH ADDISON WESLEY LONGMAN AND OXFORD UNIVERSITY PRESS, AN ALPHABETICAL LISTING OF TITLES, AND MORE. IF YOU HAVEN'T VISITED US IN A WHILE, GIVE US ANOTHER LOOK: WWW.SANTAFE.EDU/SFI/PUBLICATIONS/.



LIVING PUEBLO AT TAOS, BY WILLIAM CLARK

1998 NSF SUMMER RESEARCH OPPORTUNITIES FOR UNDERGRADUATES

Students work with a faculty mentor on an individual project, focusing on some aspect of the computational properties of complex systems. SFI's broad program of research is aimed at understanding both the common features of complex systems and at comprehending the enormous diversity of specific examples. Projects focus on adaptive computation; on the physics, mathematics, information science, and computational aspects of complexity; on economics as a complex, adaptive system; and on the life sciences including modeling of the immune system, theoretical neurobiology, genetic data analysis, theoretical ecology, and models of protein folding.

This program is highly individualized. Each student works with one or more faculty mentors on a specific project focusing on some aspect of the computational properties of complex systems. The duration of residencies will vary. Participants are expected to be in residence approximately 10 weeks, within the approximate mid-May to mid-August window.

It is expected that during an intern's residency, he/she will make at least one presentation about his/her work to fellow students and their mentors. Students may also want to present a more formal colloquium to the resident researchers at the Institute. If past experience is a guide, there may well be publishable material resulting from your SFI project; in any case, we require a written report at the end of your residency.

Internships may be part- or full-time, although it is likely that most summer students will hold full-time positions.

SUPPORT

Interns receive living stipends (from which housing costs are deducted) during their stay, along with support of round-trip travel expenses (air or car) from their home institution. The Institute will make appropriate, affordable, shared housing arrangements in Santa Fe for REU interns. Since this program is an educational rather than employment experience, stipends are expected to support a "no-gain/no-loss" situation for students (although previous, frugal interns have managed to save modest amounts out of their summer support).

Because Santa Fe lacks a full public transportation system, autos are provided to participants on a shared basis. Those interns who can bring their private transportation are urged to do so.

TO APPLY

Send a current resume, transcript of grades, along with a statement of your current research interests and what you intend to accomplish during your internship. Mathematical or computational skills or experience (particularly knowledge of the rudiments of the Unix operating system and/or a programming language such as C) are favorably considered.

- Please have three scientists who know your abilities write letters recommending you for this program.
- Include your fax number and/or e-mail address.
- Women and minorities are especially encouraged to apply.

Per NSF guidelines, this program is open to U.S. citizens only. Eligible candidates must be enrolled at a degree-granting institution as an undergraduate student. 1998 graduating seniors are not eligible for this program.

Send material to

Christine C. Gonzales
Santa Fe Institute
1399 Hyde Park Road
Santa Fe, NM USA 87501
Phone: (505) 984-8800 ext. 235
Fax: (505) 982-0565
e-mail: cg@santafe.edu

Application deadline for summer 1998 residencies is February 20, 1998.

Support for this program is provided by a grant from the National Science Foundation through the Research Experiences for Undergraduates Program.
Santa Fe Institute is an equal opportunity employer.
Further information at http://www.santafe.edu

SFI 1998 Community Lectures Schedule

The 1998 schedule for the Santa Fe Institute's Community Lecture Series covers a broad range of scientific topics. A number of local businesses and organizations join the Institute in supporting this series, making these talks free to the community.

Wednesday, January 14: "Born to Rebel: Birth Order, Family Dynamics and Creative Lives"

Frank Sulloway, Science, Technology and Society, Massachusetts Institute of Technology

Sponsored by Barraclough & Associates, P.C. Certified Public Accountants and Consultants

Using anecdotal and statistical evidence, Sulloway posits that birth order plays a major role in determining personality and social outlook: firstborns (and to a lesser extent only children) have conformist mind-sets and support the status quo, while the later born, more innovative and creative, most often reject the status quo. By recasting Darwin's theory of natural selection in terms of family dynamics, Sulloway highlights the adaptive tactics that siblings deploy to differentiate themselves from one another.

Wednesday, February 18: "The Beauty and Danger of Comets and Asteroids"

Tom Gehrels, Planetary Sciences, University of Arizona at Tucson

Sponsored by 1001 Nights/Smallwood, Inc.

Comets and asteroids may have contributed water and molecules for life on this planet. They still come into the vicinity of the earth today, and they still present some danger of collision. Dinosaurs were eliminated by such a calamity sixty-five million years ago. It's unlikely that a major comet will crash into the earth—but not so unlikely that scientists haven't begun to plot ways to make sure it doesn't happen. Gehrels talks about his role as head of Spacewatch, a program to study comets and asteroids and the prospect of their hazardous collisions with earth.

Thursday March 5: "Plant Secondary Metabolism: (Plant) Sex, (Human) Drugs, and (Insect) Rock 'n' Roll"

May Berenbaum, Entomology, University of Illinois, Urbana-Champaign

The phytochemical diversity of plants has long been exploited, not only for the treatment of human disease but also for many less noble purposes (including intoxication, seduction, and resolution of intractable political disputes). The function of such chemical diversity in the life of the plants themselves, however, has been a mystery until relatively recently. Today, abundant evidence exists that these biologically active substances provide plants with mechanisms for recruiting allies to promote the business of reproduction and for defending themselves against enemies bent on consuming essential body parts. An understanding of the ecological and evolutionary forces that generate and maintain phytochemical diversity is important not only for designing approaches for conserving biodiversity but also for identifying new sources of drugs, medicines, and other phytochemical products.

Wednesday, April 15: "Fractals and the Tree of Life: A Unifying Theme for Creatures Great and Small"

Geoffrey West, Los Alamos National Laboratory

Sponsored by New Mexico Discount Office Supply

Although life is the most complex physical system in the universe, many of its general physiological features obey remarkably simple scaling laws. Such laws relate how large organisms can be thought of as scaled-up versions of smaller ones. In what sense is an elephant or human being a scaled-up mouse or even a scaled-up cell? West will review the phenomenology of scaling laws and present a quantitative, unified model that can explain the origin of all of these laws. This model can be used as a paradigm for many other complex systems, ranging from those of rivers to corporate organizations and the structure of the elementary particles.

Monday, May 18:
"The Life of the Cosmos"

Lee Smolin, Center for Gravitational Physics and Geometry, Pennsylvania State University

Sponsored by Santa Fe Audio Visual

If the theory of evolution successfully explains the nature of the earth's biosphere, can this theory be applied to the whole of creation? Is the universe perfectly tuned to allow for life because it evolved that way? Smolin discusses his new book, *The Life of the Cosmos,* where he explores the notion of a universe of competing universes, dominated by the ones that are fittest—those best equipped to make the stars and black holes that allow them to reproduce. There are also the universes capable of supporting complex phenomena such as life.

Wednesday, June 17:
"Unnatural Selection—Proteins of the Future"

Frances Arnold, Chemistry, California Institute of Technology

Sponsored by Alphagraphics, Santa Fe and Los Alamos

Arnold will describe how to create novel biological molecules and even whole organisms by mimicking key processes of Darwinian evolution in the test tube. Directed evolution promises to revolutionize the use of biology in industry, environmental protection, and medicine.

Wednesday, July 15:
"Making a State: The Rise of the Medici, 1400-1434"

John Padgett, Political Science, The University of Chicago

To understand state formation, one must penetrate beneath the veneer of formal institutions, groups, and goals down to the relational substrata of people's lives. Ambiguity and heterogeneity, not planning and self-interest, are the raw materials of which powerful states and persons are constructed. In this talk, Padgett analyzes the centralization of political parties and elite networks that underlie the birth of the Renaissance state in Florence.

Tuesday, Wednesday, Thursday, September 15, 16, 17:
Annual Stanislaw Ulam Lectures

W. Brian Arthur, Citibank Professor, Santa Fe Institute

Wednesday, October 14:
"Complexity and the Political Process"

John Miller, Economics and Decision Sciences, Carnegie-Mellon University

Miller explores several applications of complex adaptive-systems theory to the political process, including the phenomena of political parties adaptively modifying their platforms to capture voter support and the issue of how political institutions can be used to sort voters better among localities.

Wednesday, November 18:
"Prospective Lives: Social Consequences of Biotechnology"

Philip Kitcher, Philosophy, University of California at San Diego

Sponsored by Fort Marcy Hotel Suites/Smallwood, Inc.

In 1992, the Library of Congress invited Kitcher to spend a year talking with the scientists associated with the Human Genome Project and evaluating the enterprise. He discusses the results of his research, focusing on the major ethical and social concerns that surround human molecular biology today.

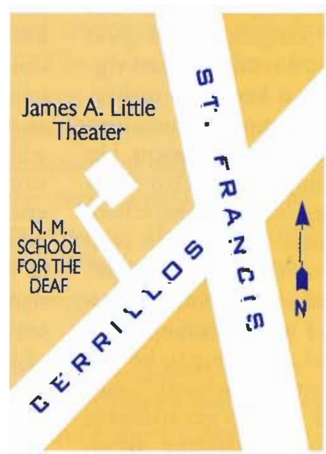
General Information

Talks are held at James A. Little Theater
On the campus of the New Mexico School for the Deaf
1060 Cerrillos Road, Santa Fe.
No admission charge.

All talks begin at 8 p.m. No reservations are necessary, but seating is limited.

All lectures are sign-language interpreted.

Los Alamos National Bank and the McCune Foundation provide general support for this series.



Peter Carruthers, One of SFI's Founders, Dies at 61

Peter Carruthers

Phot courtesy University of Arizona

One of the founders of the Santa Fe Institute, Peter Carruthers, died in August at his home in Tucson, Arizona, after a lengthy illness. He was 61.

Many people played an important role in founding and building SFI—there was no single founder. Pete Carruthers was a key member of the small group of senior fellows of Los Alamos National Laboratory whose intensive conversations over a period of many months in 1983 and 1984 led to the founding of the Santa Fe Institute. Subsequently, he served SFI as a trustee from its official incorporation in 1984 until the establishment of the Science Board in 1987. At that time, he joined the Science Board and was a member for ten years. He also served as a vice-president of the Institute in 1986-87.

However, Carruthers played a more significant part at SFI than these official roles indicate. In fact, he was an important source of ideas and a powerful advocate. He made a strong personal commitment to SFI at a point in its history when its future was highly uncertain. Out of that commitment, he gave generously of his time, talent, and money. He believed deeply in the multidisciplinary approach that is the hallmark of SFI research.

Carruthers also conceived of much that is now a continuing part of SFI. The *SFI Bulletin* was Carruthers's idea, and he wrote much of the first issue with David Pines and Mike Simmons. In addition, Carruthers originated the Complex Systems Summer School and vigorously supported it, something that was not always universally recognized as a good idea, but he knew it was and worked vigorously to make sure it became a reality.

It was characteristic of Carruthers that he had an uncanny eye for talent. He recognized, for example, that Dan Stein would be an inspired leader of the school and used his persuasive powers to convince him to take on this daunting task. "[Carruthers] called me in New York a few weeks before I was to come out to Arizona in 1987 and asked me to be the director [of the summer school]," said Stein. "He did a lot to help get speakers for the first school, including Brian Arthur, Stu Kauffman, Marc Feldman, John Holland, and Erica Jen. Unfortunately, he never told me exactly what a Summer School on Complex Systems is: that he left to me, as well as getting funding, preparation, getting more speakers, et cetera. After that, I tried to get out of doing it and succeeded temporarily for one year, but Pete and Mike Simmons jumped me, held me to the ground, and twisted my arm behind my back to get me to run it in a more continuous way." Carruthers chaired the Summer School Advisory Committee for three years and remained on the committee until his death.

The only Winter School on Complex Systems ever held was also Carruthers's brainchild, and he organized it, chose most of the lecturers and students, and participated vigorously. It was, by any measure, a spectacular success.

Born in Lafayette, Indiana, Carruthers received his early training in physics from what is now Carnegie-Mellon University, where he received simultaneous bachelors and masters degrees in 1957. He completed a Ph.D. at Cornell under Nobel-laureate Hans Bethe, joined the Cornell faculty, and quickly rose to the rank of professor.

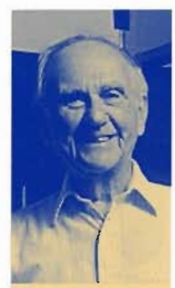
While at Cornell, he was among the first physicists to show a theoretical inkling of the existence of the hypothetical particles called quarks. In 1973, he joined Los Alamos National Laboratory as leader of the Theoretical Division, which he quickly made into one of the world's premier places for theoretical science. In 1986, he became head of the department of physics at the University of Arizona. He remained a professor in that department until his death. For several years, he also served as the director of the Center for the Study of Complex Systems at the University of Arizona.

Described by *The New York Times Magazine* as "a thinker pushing the frontiers of knowledge," Carruthers published more than 130 papers plus four monographs on topics ranging over elementary particle physics, condensed-matter physics, quantum optics, and statistical physics. He was a fellow of the American Physical Society and the American Association for the Advancement of Science and served on many advisory committees worldwide. Among his many editorial activities, he was an associate editor of the journal *Complexity* from its founding.

Although science was the central focus of his career, Carruthers had many other interests. He loved the outdoors and was a devoted and expert birdwatcher and a hiker. But above all other outdoor activities, Carruthers loved trout fishing, which he pursued with a single-minded zeal and a skill of legendary proportion. He taught many at SFI to fly fish in high mountain streams and was proud of his soon-to-be published *Fishing in the Roaring Fork Valley*.

"It was clear he was a twentieth-century Renaissance man, a person who published across disciplines, played the violin at concert-level ability, frequently thought like a trout, and tied customized dry flies which the trout couldn't resist," said George Cowan, an SFI Science Board member. "I greatly valued his friendship. He was intellectually stimulating, a raconteur, a bon vivant, and always great fun. I greatly miss him."

George Cowan Is Elected To Academy



George Cowan

Photo: Dan Barsotti

George Cowan, a past president of the Santa Fe Institute and a Science Board member, was elected a fellow of the American Academy of Arts and Sciences in 1997.

The American Academy is an honorary learned society whose members are elected for distinction and achievement in the entire range of intellectual disciplines and professions. Each year, the fellows of the academy nominate and elect individuals who have made significant contributions to knowledge and culture.

The academy membership consists of approximately 3,300 fellows, arranged in four classes according to their areas of expertise. Each class is further subdivided in sections. Cowan became a member of the Physics Section of the Mathematical and Physical Sciences Class.

Back: Spencer Fornaciari, James Taylor, Melanie Mitchell
Front: Eliot Fisher, Steve Merlan, Naomi Paine

David Sumpter, Leah Henderson, and Carl Anderson relax at the 1997 Complex Systems Summer School

Photos: left, Gene Aker; right, Nigel Snoad

A Case of Sharks and Minnows

SFI Research Professor Melanie Mitchell is a project advisor for the Santa Fe Preparatory School's 1998 supercomputing team. The group—Eliot Fisher, Spencer Fornaciari, Steve Merlan, and Naomi Paine—is developing a computer model of an evolving food chain in which several species of marine life—e.g., sharks, fish, algae—live in a common environment, with fish feeding on algae, sharks feeding on fish, and so on up the chain. The organisms are capable of moving, eating, pursuing other organisms, and fleeing from them. The organisms can learn—via an evolutionary process—to change their behavior in adaptive ways. The students will create the simulation and then investigate what parameters of the simulation lead to stable populations among the co-evolving species. Computer science teacher James C. Taylor is the team's leader.

The New Mexico High School Supercomputing Challenge is an academic program dedicated to increasing interest in science and math among high school students by introducing them to high-performance computing. It is an academic-year-long program that gives students the opportunity to do original computational science projects using high-performance computers. With New Mexico Technet providing the networking and the Los Alamos National Laboratory the supercomputers, a partnership was formed in 1990 with other federal laboratories, state universities, and businesses to sponsor the program.

Suzanne Huebner Named SFI Business Network Director

Suzanne Huebner became the Santa Fe Institute's director of business relations this past summer. She comes to SFI from Molecular Informatics, Inc. in Santa Fe, a bioinformatics software development company, where she was vice-president for operations. Before Molecular Informatics, Huebner was director and vice-president for administrative services at the National Center for Genome Resources in Santa Fe. Notes Huebner, "SFI's research is expanding into the business community in a way similar to genetic research data moving from the National Center into the biotech and pharmaceutical industries, where practical applications are becoming possible. There are some definite parallels."

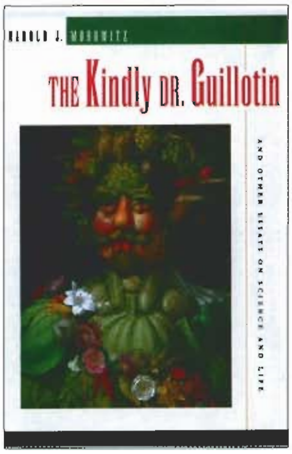
First Philip Steinmetz Fellow Named

Carl Anderson, a Ph.D. candidate at the University of Sheffeld in England, has been awarded the Santa Fe Institute's first annual Steinmetz Fellowship, a prize open to Complex Systems Summer School (CSSS) alumni. The award, which supports a one-month research residency at the Institute, is made to a participant of the school each year to support his/her residency at the Institute the subsequent year. The purpose of the fellowship is to provide the opportunity for CSSS students to pursue research projects in complex systems and to participate in SFI scientific activities.

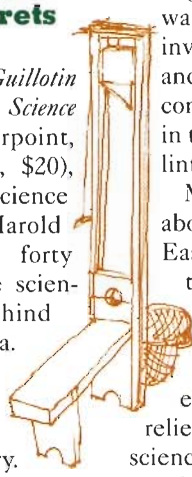
Anderson, a participant in the 1997 school, is investigating ant foraging and self-organized task-allocation mechanisms in social insects. The summer's fellowship will bring Anderson to SFI to implement a generic Swarm model for the division of labor in social insects. The majority of the previous work in social-insect self-organization has tended to concentrate on self-organization within a task, such as how a group of many individuals can collaborate to construct a nest, with decentralized control.

The aim of Anderson's project is to understand self-organization between different groups of individuals performing interdependent tasks. "I intend to explore how individuals making recruitment or task-switching decisions based upon individual experience can give rise to 'optimal' colony allocation of workers," said Anderson. "There are very strong parallels between task partitioning in social insects and social organizations such as large companies, traffic, and factories. I intend to explore the possibility of using this type of model to provide quick, real-time resource-allocation solutions to real-world, unpredictable environments such as machine breakdown or worker absence in factories."

Dr. Philip R. Steinmetz, a professor emeritus at the University School of Medicine in Connecticut and an alumnus of the 1990 Complex Systems Summer School, has generously supported this fellowship. He is particularly interested in complexity in biological systems, including questions of how complex systems develop relatively simple overall behavior and what roles self-organization and entrainment play in complex systems.



Morowitz's New Book Concerns Scientific Secrets



In *The Kindly Dr. Guillotin and Other Essays on Science and Life* (Counterpoint, November 1, 1997, $20), Santa Fe Institute Science Board Member Harold Morowitz gathers forty vignettes about the scientific secrets behind everyday phenomena.

Morowitz's essays range from the historical to the contemporary. The title essay discusses how the name of Joseph Ignace Guillotin become connected to a mechanical contraption he neither invented, built, nor used. A distinguished physician and humanitarian, Guillotin proposed mechanical decapitation in 1789 as a more humane alternative to the ax or noose. But the device that bears the kindly doctor's name—la guillotine—was fabricated by someone in Germany.

In the essay, "Thermal Underthoughts," Morowitz ponders the scientific foundations of laundry day. His analysis describes the way detergent is dissolved in water, the processes involved in removing soil, and the inefficiencies of converting water to vapor in the dryer. Not even the lint trap escapes his eye.

Morowitz also writes about the stone statues of Easter Island; immortality and brine shrimp; how *mouse* became a verb; homeopathic remedies; science literacy and television. He relies on the discipline of science to illuminate these puzzles and celebrates the world's mysteries, large and small.

P U B L I C A T I O N S U P D A T E

SFI has reached two milestones: ten years with Addison Wesley Longman, publisher of the Santa Fe Institute Studies in the Sciences of Complexity (SISOC) book series, and our 40th, and last, book in this series, to be printed in the near future.

Below is a listing of recent and forthcoming SISOC books. Please order directly from the publisher by calling 1-800-822-6339 or from your local bookstore.

Pattern Formation in the Physical and Biological Sciences
Edited by H. F. Nijhout, L. Nadel, and D. L. Stein
Lecture Notes Vol. V, 1997
40844-9 (hardcover)
15691-1 (paper cover)

Nonlinear Dynamics, Mathematical Biology, and Social Science
By Joshua M. Epstein
Lecture Notes Volume IV, 1997
95989-5 (hardcover)
41988-2 (paper cover)

The Economy as an Evolving Complex Systems II
Edited by W. B. Arthur, S. N. Durlauf, and D. Lane
Proceedings Volume XXVII, 1997
95988-7 (hardcover)
32823-2 (paper cover)

Viral Regulatory Structures and Their Degeneracy
Edited by G. Myers
Proceedings Volume XXVIII
Forthcoming, 1998

Ulam Lectures Update

Warriors Within: How Your Immune System Combats Disease
By Alan Perelson
1995 Ulam Lectures
Available early 1998

The Emergence of Diversity: Self-Organization and Ecological Systems
By Simon Levin
1996 Ulam Lectures
Available mid-1998

The Past and Future of the Sciences of Complexity
By Melanie Mitchell
1997 Ulam Lectures
Oxford University Press will publish this book.

Living in the Digital Age With Esther Dyson

Santa Fe Institute Trustee Esther Dyson's new book—*Release 2.0: A Design for Living in the Digital Age*, (Broadway Books, October 29, 1997, $25)—offers a detailed view of the rapidly expanding digital environment and provides a framework that encourages people to think intelligently about its effect on their private and public lives. The book outlines the choices and questions active citizens face in defining a new social contract for the digital age. The Internet gives great power to individuals, including the ability to access and distribute information and opinions globally. But greater ability to exercise, or abuse, these rights calls for greater individual responsibility. Dyson explores this tension in her book.

A NEW DIRECTION FOR SFI BOOK SERIES

OXFORD UNIVERSITY PRESS

SFI and its editorial board are excited to announce its new publishing contract with Oxford University Press. This new association began January 1, 1998.

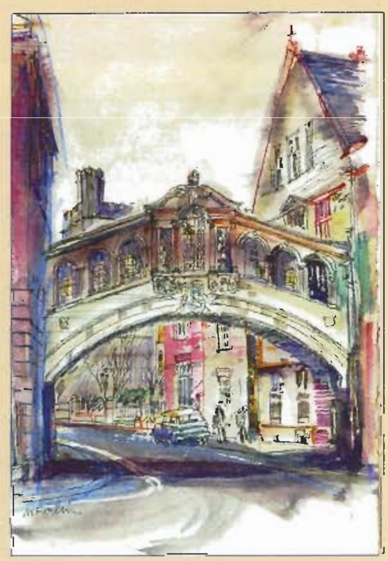
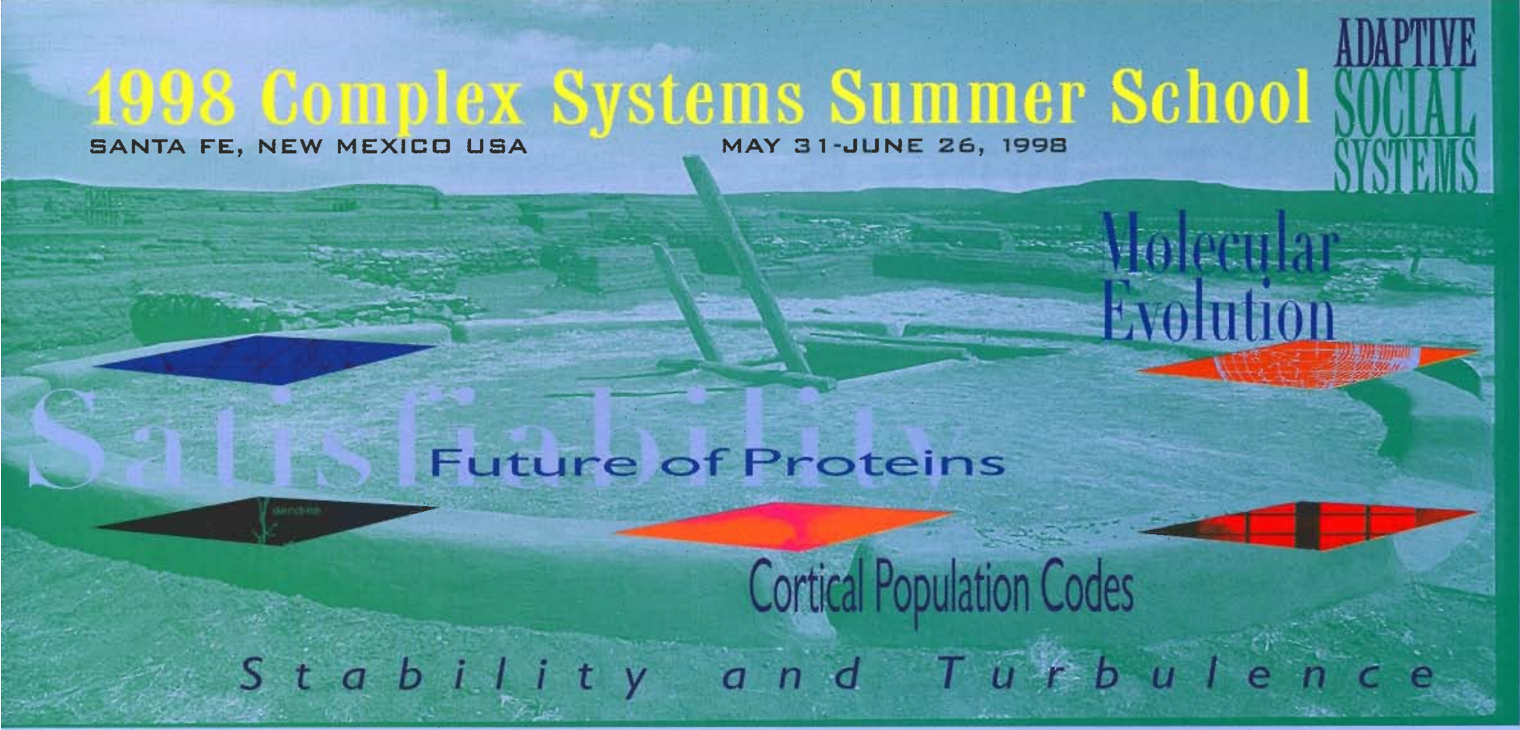


Illustration: Patrick McFarlin



An intensive introduction to complex behavior in specific mathematical, physical and living systems. Group and individual research projects. Computer laboratory.

Planned for graduate students and postdoctoral fellows, the school accepts a limited number of professionals. Tuition is waived for students and postdocs who are expected to attend for the full month; $750/week for professionals.

Lynn Nadel (Psychology) and Daniel Stein (Physics), University of Arizona, Co-Directors.
Administered by the Santa Fe Institute.

Week One

STABILITY AND TURBULENCE

Charles Doering, Mathematics, University of Michigan

ADAPTIVE SOCIAL SYSTEMS

John Miller, Social and Decision Sciences, Carnegie Mellon University

Week Two

THE SATISFIABILITY PROBLEM

Toniann Pitassi, Computer Science, University of Arizona

MODELS OF CORTICAL POPULATION CODES

Richard Zemel, Psychology, University of Arizona

Week Three

MOLECULAR EVOLUTION AND THE PAST, PRESENT, AND FUTURE OF PROTEINS

Frances Arnold, Chemistry and Chemical Engineering, California Institute of Technology
Steven Benner, Chemistry, University of Florida at Gainesville

Week Four

FORM AND MOTION IN PHYSICS AND BIOLOGY

Ray Goldstein, Physics, University of Arizona
Adriana Pesci, Physics, University of Arizona

LEARNING, MEMORY, AND NEURAL PLASTICITY

Robert Sutherland, Psychology and Neuroscience, University of New Mexico

APPLICATION INSTRUCTIONS:

Provide a current resumé with publications list; statement of current research interests; comments about why you want to attend the school; and two letters of recommendation from scientists who know your work. Include your e-mail address and fax number. Send only complete application packages by postal mail to:

Summer School, Santa Fe Institute
1399 Hyde Park Road
Santa Fe, New Mexico 87501 USA
505-984-8800 Ext. 235 (voice)
505-982-0565 (fax)

February 2, 1998 deadline.

Incomplete applications will not be considered.
Women and minorities encouraged to apply.

Further information at
http://www.santafe.edu/sfi/education/summer-school.html
or summerschool@santafe.edu

Evolving Businesses, With a Santa Fe Institute Twist

SFI'S BUSINESS NETWORK MEETING OFFERS PARTICIPANTS A COMPETITIVE EDGE

By Rex Graham

The fifty scientists, engineers, and economists who attended the Santa Fe Institute's recent Business Network for Complex Systems Research meeting were more interested in manufacturing, microprocessors, and novel economic modeling than in the origin of new species. But they all were interested in gaining something Charles Darwin said successful species have in common: an adaptive or competitive edge. Most of the meeting participants were more than willing to entertain the SFI notion that biological systems, built upon a simple nucleic-acid alphabet and layered with features of self-organization and complexity, just might offer practical lessons for business. Why not use the incredible, multilayered sophistication of the mammalian immune system as a model for computer-virus detection and better computer security?

The Business Network meeting was the Institute's sixth. It comes at a time when complexity research has grown in stature to both attract critics as well as proponents armed with ample evidence that conventional economic theory, for example, fails to predict either the direction or magnitude of U.S. interest-rate swings. Institute President Ellen Goldberg opened the meeting by posing this question to speakers who would discuss everything from economic metaphors to "new mental landscapes" to adaptive computation: "How do we apply all of this to business?"

Suzanne Dulle Huebner

Photo: Darryl Black

The mere fact that SFI's leader asks such questions may be one reason the Business Network's membership grew 60 percent in the past year to fifty-three companies. Of course, another explanation for the rise is SFI's growing stature among academicians as the nation's leader in complexity research. A representative of The Boeing Company, a new Business Network member, wrote on a comment card after the October meeting; "This is some of the best work being done on complex adaptive systems."

So what practical lessons can biology offer a company like Boeing, Coopers & Lybrand, or Solectron Corporation? Plenty, it seems. One of the liveliest discussions at the one-day meeting involved the development and use of genetic algorithms, or GAs, as they are more often called. Genetic algorithms introduce a series of "mutations" in software designed to solve a particular problem and then test each mutant's computational performance with a so-called fitness function. Scheduling is one of many applications of GAs.

Deere & Company and Algorithms

One longtime Business Network supporter sitting quietly in the audience—Deere & Company analyst Bill Fulkerson—knows first hand how algorithms can boost factory productivity. After the 1970s and 1980s shakeout in the farm-equipment industry, Deere laid off thousands of workers and razed older plants in the face of a steep downturn in demand caused by declining farm income. The company remodeled its remaining plants and switched to incentives that rewarded the performance of teams of workers.

After Fulkerson learned about SFI's research on

Graphics courtesy Deere & Company

complexity theory and genetic algorithms, he convinced Deere executives to fund development of a prototype system incorporating GAs to schedule the remodeled Moline, Illinois, seed-planter manufacturing plant. The plant relies on a challenging just-in-time-at-point-of-use delivery of parts. The system puts a premium on optimal assembly of parts to assemble eight-, ten-, twelve-, sixteen-, twenty-, twenty-four-, and thirty-one-row planters. Shipping dealer orders directly off the assembly line without large inventories of planters of various sizes can be a day-to-day scheduling conundrum.

At the same time, plant managers are not SFI regulars and no Deere plant manager could be expected to assume the risk of incorporating a GA into his or her facility. To overcome that hurdle, Fulkerson convinced engineering managers at the John Deere Technical Center to assume the risk. They funded the development of the GA for the Moline plant and agreed to assume the liability if it didn't work.

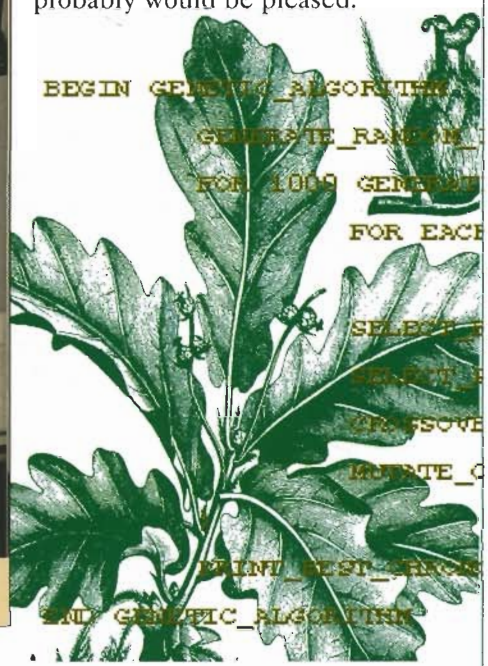
Melanie Mitchell making her presentation at SFI's sixth Business Network meeting

Photo: Darryl Black

Fortunately, a Deere production scheduler at the Moline factory had come up with a few rules of thumb that—when broken—resulted in production delays. For instance, one rule of thumb was: don't build too many identical pieces of equipment in a row. When that happened, key parts were exhausted and that resulted in delays. "These rules of thumb," Fulkerson said, "were incorporated into the fitness function of the GA."

With the introduction of the new scheduling system, the atmosphere of the factory improved along with productivity. Shop floor schedulers and supervisors were free to focus on strategic issues. Now, the GA has the final word; it produces daily and weekly schedules. Employees even began checking the GA-generated production schedules to plan their weekly activities—even vacation time. "The GA software became the focal point for improving the processing and performance on the assembly-line floor," Fulkerson said. "Now, production is up 50 percent at that plant, and the scheduling tool is one reason why." Other Deere plants are implementing GAs.

Lawrence "David" Davis, founder of Tica Associates of Newbury, Massachusetts, and a meeting speaker, noted Deere's experience as well as that of U S WEST, which currently is studying the use of GAs to more efficiently route telephone calls through its fiber optic network. Davis also noted that a Pasadena-based investment company manages a $12 billion securities fund with the help of a GA. The software helps its managers decide which securities to buy and which securities to sell. Understandably, Davis said companies and other investment funds that use GAs would rather not talk about their particular applications in great detail. But Davis thinks the potential for GAs is beginning to be realized by other U.S. companies. "There are a lot of GAs out there, and a lot of them are successful—they are exploding right now," he said. "There is a war heating up in the scheduling domain." Charles Darwin probably would be pleased.



How Plants and Animals Evolved

SFI researchers are investigating how GAs might be used to create or modify other computer programs. Their work and that of other researchers also could provide insights into how species of plants and animals evolved. "What I like are these feelings of analogy between GAs and genetics," Davis said, "like how the DNA encodes how to construct more DNA." On the other hand, he said many academics are reluctant to use techniques like GAs for which no theory has yet been developed.

Melanie Mitchell, director of SFI's Adaptive Computation Program, described her research on algorithms. One approach uses a population of virtual chromosomes with "bit strings" of ones and zeros instead of the alphabet of the four nucleotide bases of DNA. "Mutations" are introduced into the virtual chromosomes and the chromosomes are allowed to "crossover," or reciprocally exchange pieces of bit strings among each other. The technique is being used in an attempt to crack one of structural biology's toughest nuts—how to design a protein that, after it crimps, folds, and twists, assumes a desired three-dimensional structure. For a given sequence of amino acids that make up such a hypothetical protein, "fitness" can be defined as a molecule that folds up neatly and, thus, contains low potential energy. "We can't solve it yet," Mitchell said.

However, she said the algorithms have already been used to optimize scheduling, designs of circuits, and drug design, as well as phone-call routing. She said she and her SFI colleagues are trying to understand how to predict which algorithms would work in given situations. "They are not the best algorithms for global optimization, unless they are used in a hybrid way with other search methods," she said. "However, they seem to be good at finding reasonably good solutions fairly quickly."

Roger Ray, program manager of Intel Corporation's External Research Relations, took notes during Mitchell's presentation. Later, during a break, Ray said such novel spin-offs of complexity research are vital to Intel, because they should inevitably create more demand for speedy Intel chips. GAs and other "compelling new software applications" will require the next generation of Intel chips. That, of course, will be good for Intel as well as the users of such algorithms, said Ray. "We need to help the industry discover new applications," he said. "And we continue to look at complex systems, which might create or enable some interesting new applications that involve high performance."

Graphics courtesy Intel Corporation

The Car and How We Live

Intel's strategic corporate approach is itself being viewed as a promising paradigm for building "the new economy." The Intel approach is based on cooperation and interdependence with "complementors," hardware and software companies that might benefit from Intel chips. Intel's interdependent mind-set surfaces on TV advertisements for computer makers that conclude with the microprocessor equivalent of the Nike swoosh, the "Intel Inside" logo and the now-familiar five-tone chime. Harvard Business School Professor Adam Brandenburger, the luncheon speaker at the October meeting and an expert on the science of game theory, said Intel is not alone. "We're constructing new mental landscapes," he said. "We're moving toward greater interdependence."

That interdependence is blossoming on company desktops and the Internet. It is, as Brandenburger said in his luncheon talk, part of "the new infrastructural change" in modern society. The last technologically induced societal shift came with the development of the mass-produced automobile. Of course, the car changed where we live, how we live, and what our society has become. In Brandenburger's new infrastructure, the whole is everything while the parts are nothing: Computer hardware and software, networks and browsers have no value in isolation. The interdependence can be seen each day as millions of computer users boot up and phone lines begin to hum with data. Brandenburger thinks the virtual real estate sitting vacant along the Internet is primed for development. He predicts that things like consumer buying coalitions, custom newspapers, customized compact discs, and search engines that have an individual's interests in mind could soon be a mouse click away. "The only reason we haven't seen consumers doing this," he said, "is they couldn't find each other."

As after-lunch coffee was being imbibed along with Brandenburger's ideas, Rosanne Cahn, chief economist of the equity division of the New York-based Credit Suisse First Boston raised a question. Did his definition of economics include the creation and distribution of scarce resources? Brandenburger responded that his new economics would be one in which entities will be judged in the marketplace by the "value" rather than the "resources" they create.

"There are all kinds of things out there that we would want if we could use our existing resources more efficiently," agreed Cahn. Later, she said she needed to sit down and have a long discussion with Brandenburger about the economic implications of value versus resources.

Such lively interactions were exactly what SFI President Goldberg had hoped for when she opened the meeting. You could call it creating value out of the thin Santa Fe air.

Rex Graham is a senior editor at Astronomy Magazine *in Milwaukee, Wisconsin.*

BASIC FACTS ABOUT SFI'S BUSINESS NETWORK FOR COMPLEX SYSTEMS RESEARCH

How did the Business Network begin?

The Business Network was officially founded in 1992. But from SFI's inception, the business community has shown interest and support in the work SFI did. The initial workshop at Santa Fe Institute's first real home, the Cristo Rey convent on Canyon Road, brought together physicists and economists and was a good precursor of the later linkages between the science of the Institute and some of the applied sciences of the business world. From 1992 to mid 1997 the Business Network was under the capable direction of Bruce Abell, then Vice President for Finance and Operations at SFI.

How much revenue does the program generate?

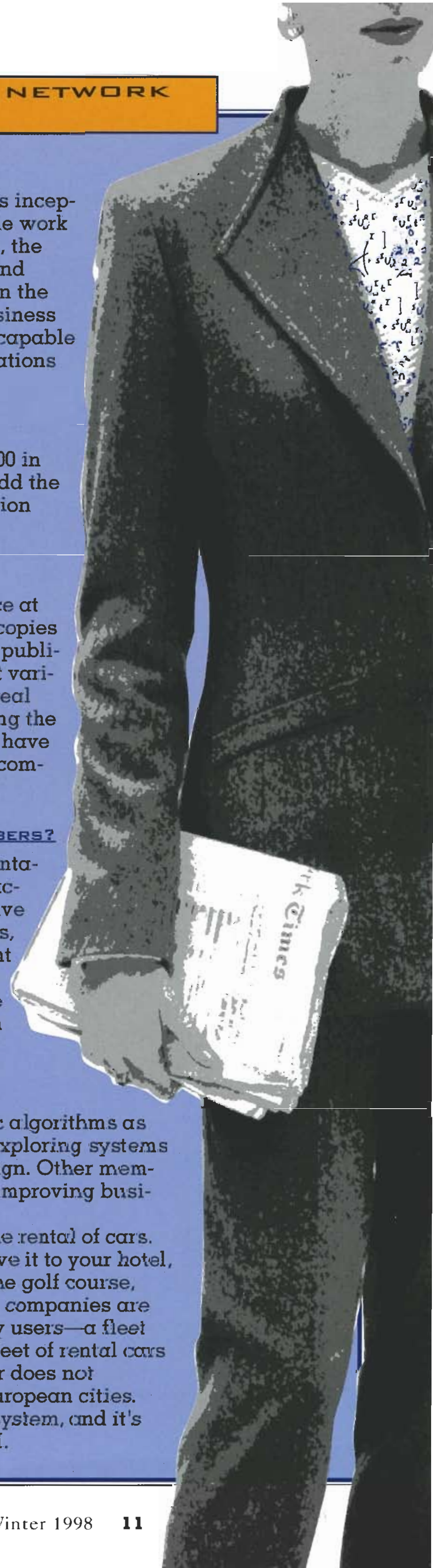
For the fiscal year ending December 1997, SFI received over $800,000 in unrestricted funding from our Business Network members. If you add the approximately $650,000 in restricted funding, SFI received $1.4 million from our Business Network members.

What are the tangible benefits of membership?

Currently they include interactions with our researchers; attendance at an annual meeting; invitations to SFI workshops and conferences; copies of all SFI working papers, books from the Addison Wesley series of publications, and subscriptions to SFI-based journals; and attendance at various topical workshops for our Business Network members. But the real advantage is more intangible: it is the networking that occurs among the businesses themselves. It is important that the member companies have the opportunity to understand how other companies are looking at complexity and attempting to apply it in their own experiences.

What is the current composition of Business Network members?

It's a broad, eclectic group including financial institutions: representatives from high-tech industries such as software, computer manufacturing, and semiconductors; as well as members from the automotive and insurance industry. We have forty-three commercial companies, six governmental agencies, and four nonprofits. From the viewpoint of global representation, we have fourteen international businesses, with the largest concentrations in Europe and Japan. In fact, we are planning a regional meeting for our European members, which will take place next March in London.



How are member firms using SFI's research?

Here are some examples. One of our members is looking at genetic algorithms as they relate to massively parallel computing. Another company is exploring systems that learn and adapt and then applying the results to network design. Other members are focusing on organizational theory, coordinated workflow, improving business "fitness," and electronic commerce.

One firm is working on an idea concerning a fleet approach to the rental of cars. Under the current car-rental model, you rent a car at the airport, drive it to your hotel, and park it. Later, you may drive to your business appointment or the golf course, where you again park it. You're attached to the car. Today, however, companies are thinking about a concept using cars that would be common to many users—a fleet of cars. When you leave your hotel, for example, there would be a fleet of rental cars out front. You simply select one of them. However, one particular car does not "belong" to you. This concept is not unlike bicycle rental in some European cities. The car rental company is approaching the problem as a complex system, and it's working on this problem with some of the ideas it's getting from SFI.

MUTUAL FUND MANAGER BILL MILLER SEES VALUE IN THE BUSINESS NETWORK

His Practical Approach To Picking Stocks Looks to SFI for Useful Insights

By Diane Banegas

Bill Miller is a practical man. He has to be. As director of the $6 billion Legg Mason Value Trust mutual fund, his fitness for picking stocks is tested constantly on the rugged landscape of Wall Street.

Miller's success—the firm's flagship Value Trust fund's performance has beaten Standard and Poor's (S&P) 500 Index for seven straight years—is a rare achievement in the investment world and proof that his brand of pragmatism pays off. In any given year, 85 percent of all managed funds trail S&P 500 earnings.

"We are only interested in what works to help us make money," Miller says. Conventional economic theories and models are woefully inadequate in trying to beat the market, he believes. What he does find "tremendously valuable" is the Santa Fe Institute's Business Network for Complex Systems Research.

Founded in 1992, the Business Network is a loosely knit group of public and private companies and federal agencies that help fund the Institute in exchange for the opportunity to learn more about complex-systems research and how to apply that research to their organizations.

The advantages of BusNet membership are threefold, Miller says. First, the Network is a way to get new channels of information; second, many of the companies interested in BusNet are potential investments for Legg Mason; and third, SFI's multidisciplinary, nontraditional approach to research prompts BusNet members to think in new ways about familiar topics.

People in the investment world tend to move in the same circles and read the same articles, books, and reports, Miller says. After a while, everyone is getting the same information from the same sources. For a guy who is paid to stay ahead of the pack, Miller can't afford to think like the pack.

Miller first learned of the Santa Fe Institute in a newspaper article on chaos theory by James Gleick, a science writer with *The New York Times*. It was after the stock market crash of 1987, and Miller wondered if such work could hold clues for investors. Later in 1991, his work brought him in contact with Citicorp President John Reed, who had provided seed funding for the SFI economics program. Reed introduced him to Henry Lichstein, a vice president at Citicorp and an early member of BusNet.

Photo: Vince Rodriguez

Lichstein encouraged Miller to get involved with the Network.

As a BusNet member, Miller receives SFI's research papers and books, updates about ongoing complex-systems research, and notifications of upcoming visitors, workshops, and colloquia. Most importantly, he has access to SFI's extended scientific staff. "Their research provides insights for practical business people like myself," Miller says. "It's not the job of any researcher to help me beat the market, but they are happy to talk to us about their work. The Business Network provides funding for SFI, and SFI wants to return something of value to Network members."

The economy, Miller says, like other complex systems under investigation at SFI, is a multiagent environment with many local rules and feedback loops. There is no simple cause-and-effect model to predict what next year's market will be, and there is no collection of models and theories that can systematically make accurate long-term predictions about the market. At best, a sophisticated, stock-picking model like the neural network used a few years ago by Fidelity Investments beats the market for two or three years before it degrades and starts lagging market indices. "Today's more advanced computer models still cannot recognize a chair," Miller says. "If a computer cannot recognize a chair, it probably can't recognize a pattern in the stock market."

But Miller does not discount the value of using computer models in his work. He and his staff run multiple models and analyze the data generated as part of their on-going research process. The challenge of their job is sorting through all the data from multiple forecasting agents, including computer algorithms, analysts, traders, and other fund managers. "That's where SFI work really applies to what we do," Miller says. "We see how all these system components and forecasting agents are 'cognized' by the SFI researchers. It's helped us let go of simple models and think more creatively about the market's complexity."

For example, traditional economists tend to think of the marketplace as a dog-eat-dog kind of environment, similar to a jungle habitat, with different species fighting each other for survival. However, biologists today believe there is more peaceful coexistence among species than previously thought. Miller came across a useful example in a book on complex systems that he'd learned of through BusNet. In the example, two species of birds thought to compete for the same food supply, nested peacefully in the same tree, because one species used the tree's upper limbs while the other species contented itself with the lower branches.

Reading about this discovery led Miller to apply similar thinking to the computer industry. "Compaq isn't necessarily in direct competition with Dell Computer. The competition dynamics are much more complicated than many people realize. Actually, both companies have their own niche in the marketplace."

Market analysts also need to update their thinking about today's stock market, Miller says. "Today's S&P 500 Index includes a lot more high-tech companies with very different financial characteristics than those of traditional industrial companies." For example, an acceptable price/earnings ratio for a computer company is higher than an acceptable ratio for an automobile manufacturer or an oil company ought to be.

Miller's success at the helm of the Legg Mason Value Trust is strong evidence that he's "cognizing" better than his competition.

Miller, who earned an economics degree with honors from Washington and Lee University, served overseas as a military intelligence officer, then pursued graduate studies in the Ph.D. program in philosophy at Johns Hopkins University. Prior to joining Legg Mason in 1981, he served as treasurer of the J.E. Baker Company, a major manufacturer of products for the steel and cement industries. In addition to his membership in the Business Network, Miller, a Baltimore resident, serves on the Board of Trustees at SFI.

His own management style is conservative by industry standards. Miller follows the time-honored tradition of looking for companies undervalued by the stock market. His portfolio includes about thirty-five stocks, far less than the typical mutual fund. He holds stocks for an average of five years, an eternity for some investors. And the entire portfolio turns over at a glacial rate of 10 percent per year. Also, any company under consideration by Legg Mason is researched to death.

Miller also admits his work habits are obsessive: He works seven days a week and reads constantly to learn about companies and pick up on social and economic trends that might have a bearing on the stock market.

All fine and good, but how does he come up with such a consistently good record? He could explain his methods, but the information probably wouldn't do another manager a lot of good. The prevailing wisdom on Wall Street these days is that some individuals can consistently beat the market, but you can't identify them in advance and you can't acquire their expertise by simply copying their portfolios. "Their skill," he says, "isn't something that can be taught, since its nonalgorithmic."

Diane Banegas is a writer who lives in Santa Fe.

Biologists and Computer Scientists Establish Dialogue To Study Cell Decision Making

In early October, a group of biologists and a group of computer scientists spent four days at the Santa Fe Institute learning, well, how to talk to each other.

Each group has something the other group wants. But before they can trade solutions, ideas or even words, they must first find some common language to successfully communicate their objectives.

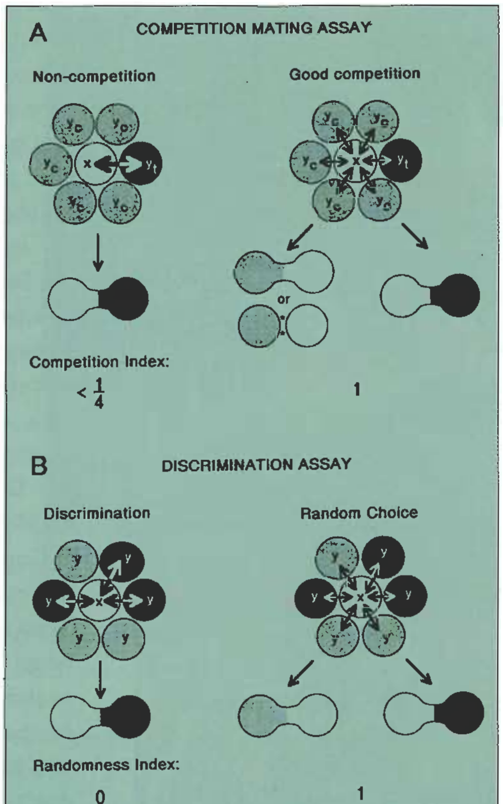
The biologists believe that the information-processing and decision-making ability of a cell surpasses the computational ability of today's most powerful massively parallel supercomputers. They desire to convert their knowledge of molecular networks in microbial systems into theoretical computer models to see if their understanding of these systems is accurate.

"Through modeling, computer scientists can help biologists understand the great body of data we are accumulating," said James Shapiro, a bacterial geneticist from the University of Chicago who is currently working at the the University of Edinburgh in Scotland as a Darwin Prize Visiting Professor. Shapiro led the workshop with John Holland, a professor of psychology, electrical engineering, and computer science at the University of Michigan.

What's in it for the computer scientists? "The cell and the central nervous system are two of the most complex systems we know of," Holland said. "They are orders of magnitude more complex than anything we've built. By working with biologists to study these examples, we can create more sophisticated therefore more useful computer models for a range of purposes."

The Santa Fe Institute, with its multidisciplinary approach to complex adaptive systems was an ideal host for this workshop. Shapiro and Holland believe the workshop was a groundbreaking first attempt to translate some of the fundamental ideas of molecular biology into the context of computational theory and vice-versa.

The first workshop resulted in a consensus of opinion that biological computation is a valid idea—an opinion not held by everyone when the workshop began. Workshop participants also determined that modeling will tell biologists if their understanding of molecular systems is accurate. Lastly, the two groups decided that the most effective way to interact with each other is through an ongoing collaboration dedicated to creating a detailed theoretical model of a particular biological system.



Schematic diagrams of the competition mating and discrimination assays used to assess the ability of cells to choose mating partners during courtship

Graphic: Courtesy of Catherine L. Jackson and Leland Hartwell

Some general principles about biological systems also came out of the meeting. The notion of biochemical robustness — that certain systems work reliably over a range of environments and their performance is predictable even though the biochemistry of their surroundings may change — was accepted. Another principle is that cells have to compute information, because both their internal and external environments are changing constantly and they must continually adapt to the changes to carry out their threefold task of eating, growing, and reproducing. Also, unlike machines, bacteria are dynamic systems whose parts interact and change over time. For example, living systems repair themselves when they are injured. A watch, once broken, cannot repair itself.

"Our challenge now is to develop ways to model these information-processing systems," Shapiro said. "How do they operate, especially at complex levels, and what's possible to make a system work and what isn't?"

The workshop served as an exploratory conference that provided the two groups with enough common language that they can begin their collaboration.

"We need to press forward with all of this information we've acquired, but we must have the help of the computational folks to press on," Shapiro said.

According to Holland, the computational folks are ready. "Molecular biology opened up an unsuspected world of sophisticated information-processing techniques within cells. The lessons learned from studying cells will hold applications for us."

Bad Genes or Bad Luck?

ILLUSTRATION: CATHERINE KIRKWOOD

Why did the dinosaurs die out? Most of us have asked this question at one time or another. As far as we can tell from their fossil remains, the dinosaurs met a sudden fate, completely vanishing from the Earth about sixty-five million years ago.

In fact, the disappearance of the dinosaurs is not the only such mass-extinction event in Earth's history. It is not even the largest. That distinction goes to the late-Permian extinction, about 250 million years ago, which wiped out an extraordinary 95 percent of all the species then alive. In addition, there have been many, perhaps fifty or so, other mass extinctions over prehistoric time, including four that are of a size comparable to the extinction of the dinosaurs.

In recent years, a number of researchers at the Santa Fe Institute have been using computer simulations and techniques drawn from statistics to model the processes by which extinction takes place and to compare their models with fossil data. Current views about the causes of mass extinction fall into two categories.

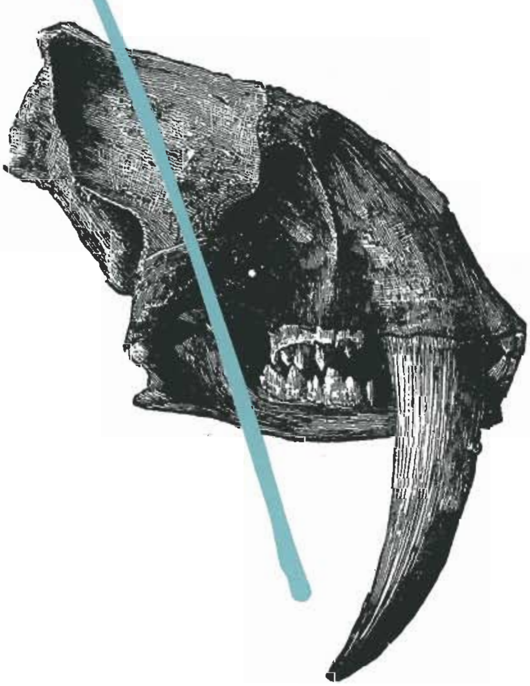
SFI External Faculty member Stuart Kauffman and Per Bak of the Neils Bohr Institute in Copenhagen believe that extinction arises as a natural result of the way in which species evolve. They have suggested that species may die out when other species with which they interact evolve. For example, if you live by eating another species and your prey evolves to run faster, you had better evolve to run faster too. If you don't, you become extinct for lack of food. Kauffman and Bak have worked on "self-organized critical" theories of evolution in which large-scale extinction is caused by "co-evolutionary avalanches"—waves of evolution that cross an ecosystem, leaving many extinct species in their wake.

However, SFI visitor David Raup, a paleontologist from the University of Chicago, gave an alternative theory in a recent lecture in Santa Fe. He said coevolutionary disturbances may not necessarily play a critical role in extinctions.

This idea has been pursued by SFI Postdoctoral Fellows Mark Newman and Gunther Eble, a paleontologist at the Smithsonian Institute. In a recent article in the *Journal of Theoretical Biology,* Newman proposed a simple model of mass extinction in which all extinction is caused by environmental stresses, such as the impact that killed the dinosaurs.

This model makes a number of interesting predictions about how often we can expect mass extinctions to take place and how long species can expect to live on average. It should be possible to test predictions of this kind against the fossil data. Initial comparisons have offered cause for optimism; the agreement between the model and what we know of prehistoric life on the Earth is encouragingly good.

Newman and Eble are currently working on a more detailed analysis of the fossil record to try and settle the question of whether species die out because they were out-evolved or whether they were just unlucky enough to be around when a particularly large rock landed on the planet. As Raup has put it, is extinction "bad genes or bad luck?" In time, the work of Kauffman, Newman, and others at the Institute may help us answer this question.



A SIMPLE MODEL OF EXTINCTION

The model of extinction proposed by SFI Postdoctoral Fellow Mark Newman is a simple one. He assumes that all extinctions are caused by stress placed on species by their environment. Each species is characterized by a number, x, which measures its ability to survive stress. The higher the value of x, the more likely a species is to survive. Initially, each species is given an x with a random value.

Newman also chooses another random number, η, at regular intervals of time to represent the level of stress. When η is high, there is a great deal of stress coming from the environment (harsh weather, large rocks raining from space, and so forth). When η is small, things are more clement.

The model then works as follows: in each interval of time, we choose a new η at random, and all species for which $x<\eta$ become extinct. The total number becoming extinct is the size s of the extinction event taking place in this interval. Then the ecosystem is repopulated with new species equal in number to the number that just became extinct, so the total number of species stays constant. (This step is justified by the observation that new species appear quickly in the aftermath of an extinction event to take the place of those that have been wiped out.)

The model has a number of interesting consequences. One example is the existence of "aftershock" extinctions. In the normal run of things, the action of average stresses on the system removes all the species with low values of x, leaving only the fittest species, in the language of evolution theory. However, when a large extinction event takes place, wiping out most of the species in the system, we repopulate with a large number of new species. These new species initially get random values of x. This means that many of them will have low x: they are more susceptible to stress than your typical species is.

This means that if a stress of only moderate size, η comes along just after a large extinction event, it will wipe out more species than it would under normal circumstances. We see this as an "aftershock" extinction, a second moderately large extinction event occurring just after a particularly big one. It is not known whether such aftershocks have occurred during terrestrial prehistory, but it would be an interesting question to investigate.

Swarm on the Move

SFI Software Package for Multiagent Simulation Is Helping Shed Light on Questions in Diverse Fields Such as Archaeology and the Semiconductor Industry

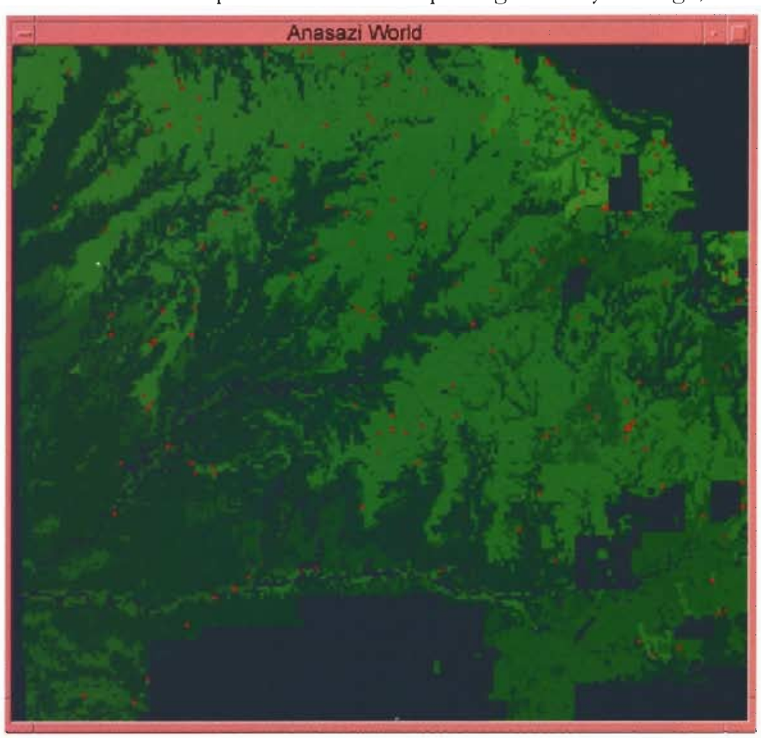
By Ken Baake

Imagine you are an archaeologist at the site in Colorado where Native American people lived some 1,000 years ago. In the dry, high-desert landscape, you find evidence of families growing corn in fields alongside seasonal streams. Data gathered from tree-ring evidence and other sources show that the corn thrived when the rains were plentiful. But in times of scant rainfall, the corn suffered. So you ask yourself, "How could these people have survived the lean years? Did they follow the rainfall? Or did they have other means of feeding themselves when the corn crop was sparse? Why did these people eventually abandon their homelands in the thirteenth century?"

Now imagine you are an economist attempting to understand the complex behavior of today's stock market. You would like to explore what causes investors to pick certain stocks and why those investors often change stock-picking strategies. Sometimes investors seem to pay more attention to the underlying fundamentals of a stock, considering things related to its price-to-earnings ratio and the overall soundness of the company. But at other times, investors seem more interested in trading trends related to the stock. They seem to ignore fundamentals and instead buy or sell the stock because other investors are doing so. What causes traders to shift investment behavior?

These two areas of research questions seem unrelated. The former deals with an early American culture that died out or dispersed sometime around A.D.1300. The latter deals with highly technical traders in today's complex global economy. But these questions share some fundamental conditions. Both involve agents attempting to maximize their well being amid unpredictable environments. And both cultures—early Anasazi and modern stock traders—are more clearly understood today, thanks to the Swarm Simulation System, an artificial life software program first conceived by External Faculty member Chris Langton.

Langton and other Swarm pioneers at SFI developed the software package five years ago,

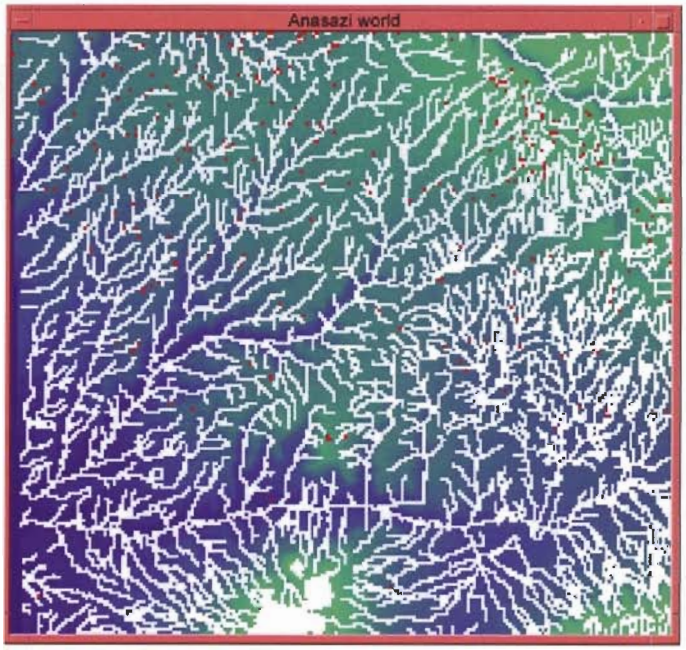


Household location after 5 years. Lighter greens indicate more productive areas; red cells have one or more households; black cells have no paleoproduction estimates because local soil data were lacking when Van West generated these retrodictions. The single white cell is a household that is being "probed" (queried) about its current state.

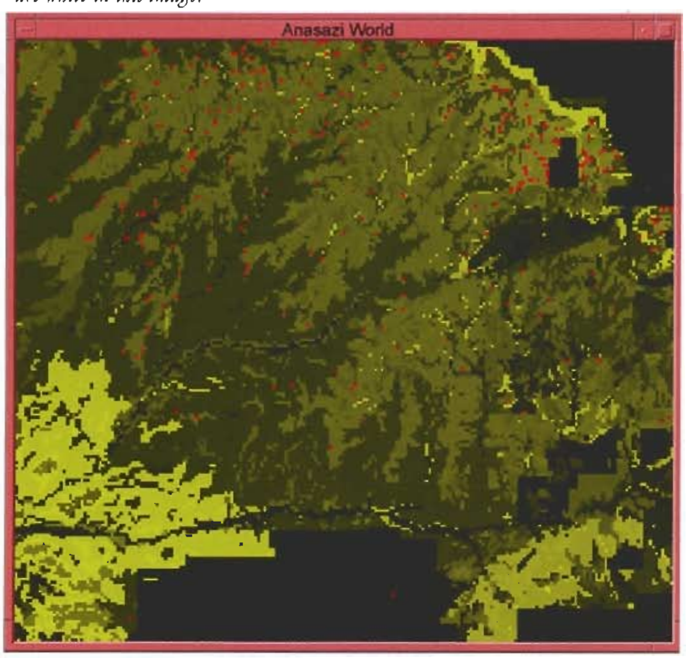
SWARM

basing it on computer simulation programs that had been around for thirty years. Initial funding to develop Swarm came from The Carol O'Donnell Foundation and the Defense Advanced Research Project Agency. Early Swarm simulations focused on natural phenomena such as the behavior of bugs and explored questions such as how individual ants that were foraging for food were able to cooperate to nourish the queen and her offspring. Other early uses of Swarm modeled nuclear-fission chain reactions and similar scientific phenomena that were relatively well understood.

Langton says the impetus for further Swarm software development came from researchers who needed some technique to bridge the gap between theory and observation. The scientific method requires that researchers be able to test their theories to see if they can be proven false. But traditional research often affords scientists only a top-down view of what they are studying. Scientists can examine an ancient human settlement after it has been abandoned or a Black Monday stock-market crash after the traders have gone home, leaving a trail of ticker tape on the market floor. But scientists typically have been unable to look at those events from the bottom up, as they are happening.



Household location after 60 years, this time arrayed against a background of elevation overlaid on water sources. In the elevation layer, darker colors are lower. We distinguish between ephemeral streams, permanent streams, and springs, although all are white in this image.



Household location after 80 years, now shown relative to soil types. Both elevation and soil characteristics affect the computation of potential maize productivity.

It's like a police detective who is called to the scene of a burglary and finds a broken window and disheveled house. The detective has to piece together a series of events. But imagine what it would be like if the detective could turn the clock back to one minute before the crime and watch the events unfold. Solving the crime would be a lot easier. In a way, Swarm allows scientists to turn back the clock to watch events unfold. Scientists using Swarm attempt to recreate initial conditions in the software package and then let the computer simulate what might happen.

So instead of looking at an archaeological site 700 years after it was abandoned or at a stock market after the day's trading is over, Swarm allows researchers to start from the beginning and watch the agents as they interact with their environments. The researchers can plug in variables affecting those environments—such as rainfall patterns or the initial price of a stock—and then let the software run multiple iterations to see what happens.

"If you talk about the Dow Jones average or about biological evolution or an ecosystem in the rain forest, it is difficult to do experiments," Langton says. "You can't go back to Black Monday and change something and run it again. It is difficult or impossible to bring the phenomenon within the scope of experiment."

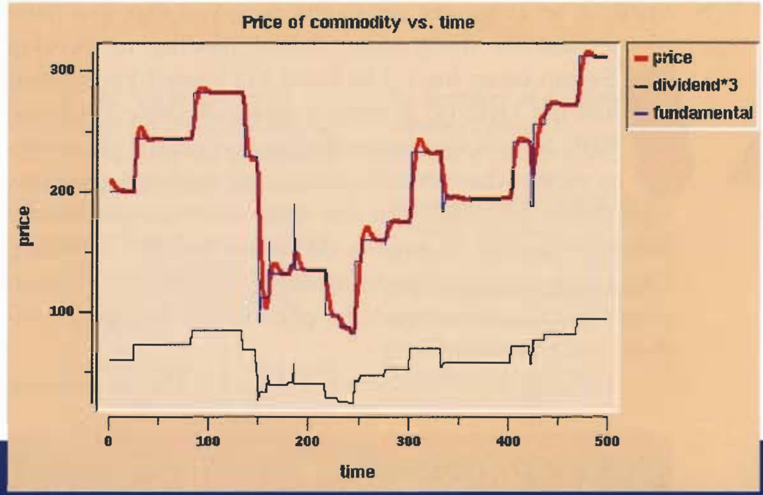
Swarm has shown such promise at shedding light on research questions that it is now being used by some seventy-five academic and nonprofit sites and several score of businesses. Swarm has also attracted recent support from businesses and government for continuing development efforts, and there is substantial interest from companies in using Swarm on domain-specific problems.

The software package is helping private companies like Texas Instruments plan for competition in semiconductor sales. It is helping California researchers understand how forests reemerge after intense logging activity. A recent conference of Swarm users drew people from Johns Hopkins University, Coopers & Lybrand, Yellowstone National Park, the Naval Air Warfare Center, the Danish Hydraulic Institute, Sandia National Labs, and TRW Inc., among other businesses and institutions. "Business needs something like this," Langton says. "This is the way business sees the world. They see the world as particles, as players. You can't just talk about the paper industry for example, because individual players make a huge difference."

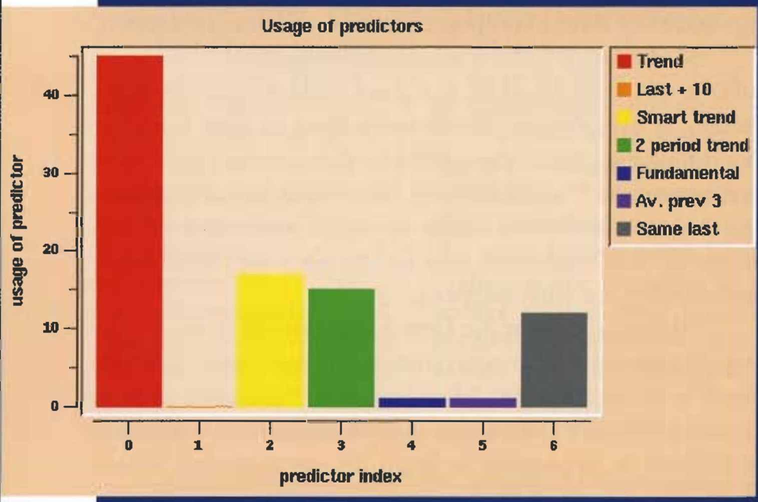
Explosive Next Phase

These are exciting times for Swarm. After the Santa Fe Institute's initial three-year research charter for Swarm ran out in September, SFI's directors agreed to fund the program for another year. Swarm 1.0 is available for download off the Internet, and a new version that is compatible with Windows operating systems is now available. SFI has made the Swarm software available at no cost to the public, expecting the community of users to grow, assist each other in the process of using Swarm and expand its uses, and produce additional software to improve its functionality and applicability.

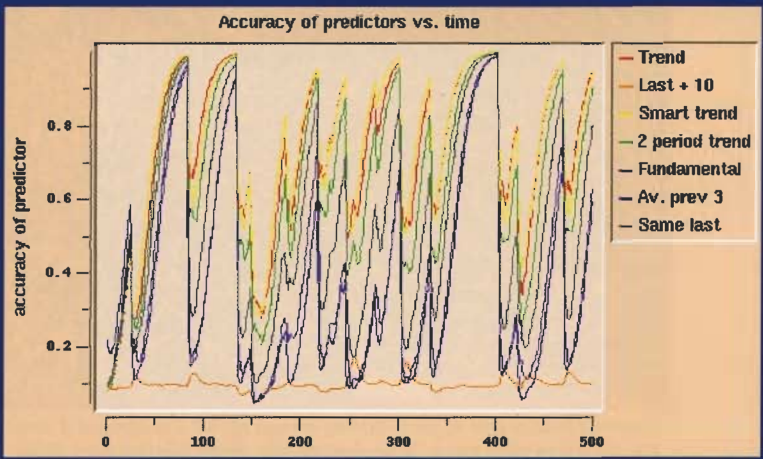
A simple model of a market in a single commodity has been ported to Swarm. This is a simplification of the Santa Fe Stockmarket model developed by W. Brian Arthur, John Holland, Blake LeBaron, Richard Palmer, and Paul Tayler.



The market consists of 100 agents buying and selling a commodity on the basis of their current predictions of what direction the stock's value will go in. The value of the dividend (the black line at the bottom) is changing randomly over time—this in turn causes the price of the stock (in red) to fluctuate as agents revalue the stock. The blue line plots the fundamental value of the stock.



Agents buy or sell stock on the basis of which of their predictors look best at the moment. The price of the stock in turn depends on the buy and sell orders. This histogram is a plot of how frequently the important predictors are being used.



At the end of the simulation (time 500) the trend predictors are most accurate, as reflected in the usage histogram above. Notice that at the beginning of time the fundamental value is the most accurate: early in trading most agents are following fundamental value. As the dividend jumps become larger, trend predictors take over.

"With the completion of the initial phase of software development," says Erica Jen, SFI's vice-president for academic affairs, "the critical question is how to create a structure with the flexibility and fiscal solidity to support what we expect to be an explosive next phase of Swarm development." The new structure, proposed by Swarm researchers and approved by the SFI Science Steering Committee, consists of three components: Swarm.edu will include the network of researchers throughout the general scientific community developing Swarm-based simulations. Swarm.org will organize around a highly distributed and loosely coordinated network for core software development as well as domain-specific efforts. And Swarm.com will be a for-profit company spun off from SFI for private contract work using the Swarm platform.

Institute officials envision swarm.org as the hub for future general-purpose software development. Future Swarm-based scientific research will involve both swarm.org and swarm.edu. The core software-development component of swarm.org will be maintained at SFI, with the domain-specific components (extensions to other platforms, templates for specific research domains, Geographical Information Systems capabilities, et cetera) to involve the participation of multiple-research groups including, for example, those at the University of Michigan and New Mexico State University (NMSU). "We believe it will prove to be of mutual benefit to Swarm and SFI for the Institute to serve as the physical home for the platform's core software development," Jen says. "Swarm has demonstrated the potential to be an important tool for a wide range of research in agent-based systems and applications, and SFI has a vested interest in stimulating this research widely. Swarm has also proven to be a significant attractor for members of the SFI Business Network. Continued proximity of Swarm to SFI will help maintain and grow those relationships."

Seeing the Effects of Individual Players

Swarm is gaining new converts in the business and academic communities among researchers who have recognized its potential to help shed light on complex interdisciplinary problems. For example, Langton and his team are entering into a partnership with the Physical Science Laboratory at NMSU. Mike Coombs, who directs network mathematical modeling for the Las Cruces-based laboratory, sees Swarm as a potential catalyst for linking researchers in various institutions along the Rio Grande corridor of New Mexico. Because Swarm is such a flexible research tool, Coombs says, it can be shared among various disciplines that otherwise would lack a common language for communicating. "One of Chris Langton's strengths is the ability to bring people together, and he is kind of inside Swarm," says Coombs. "He's one of the most unjudgmental people I've ever come across."

Among other things, the NMSU laboratory conducts mathematical research for the U.S. Department of Defense related to the way troops adapt to changing circumstances on the battlefield. The army wants to know how much local decision-making power troops on the ground should be given and how much of that decision-making power should remain in the hands of commanding officers. Coombs says researchers at his laboratory would like to use Swarm for the next phase of this study—where mathematical metrics are applied to computer simulations of the battle field. Swarm also would be useful in helping laboratory researchers model the way governing bodies along the Rio Grande corridor make crucial decisions regarding the allocation of water and other scarce resources, Coombs says.

The power of Swarm is that it allows researchers to see the effects of individual players. Traditional techniques of scientific study tend to sum over the effects of individuals and deal solely with course-grained approximations of the big picture. But for Langton, the most profound events affecting a world like the stock market or a population of early American people are often individual agent-based events that would be missed by ordinary big-picture research.

Langton admits his computer simulation software is not particularly unique. "People have been doing this stuff since the 1960s," he says. But what appears so special about Swarm is some of the assumptions underlying the software program. Those assumptions about the value of individual actions have driven Langton and co-researchers such as Glen Ropella, David Hiebeler, and Roger Burkhart to spend years painstakingly developing a software system that provides a more realistic simulation of local events than what had been available. The Swarm simulation allows agents to interact with their environments in subtle ways that can bring about enormous changes.

One fundamental assumption behind Swarm is that most real-life systems behave in a nonlinear fashion and hence cannot be modeled using traditional techniques. For example, in traditional Newtonian physics, an object will always behave the same. The rules governing the behavior of that object will not change. Objects in traditional physics cannot adapt their behavior according to changes around them. But adaptive behavior is essential to the well being of most complex real-world agents. Darwin's model of evolution, for example, is predicated on the simple notion that organisms change to maximize their well being in a changing environment. The Swarm software allows for complex adaptive behavior among evolving agents and environments, whether they are Anasazi families, troops on the battlefield, or traders on Wall Street.

Langton ascribes to a basic paradigm of complexity science—major events occur when a system is driven to the cusp between relatively stable conditions and chaotic ones. For example, subtle changes in initial conditions can cause carbon molecules to fall to one side of the cusp to form graphite or to another side to form a diamond. Likewise, one or two traders can become nervous about a stock. This can cause virtually no change in its final price or, at the other extreme, a sell-off that leads to a market crash. In most cases, individual actions will cancel each other, hence heading off a crash. But in some instances, small agent-based events ripple through the system causing a profound change in outcome. Swarm allows programmers to run repeated tests, each time varying slightly the initial parameters, to see what can cause these profound changes.

Prior to the era of fast computing, it would have been impossible to model each agent in a population of millions. It also would have been impossible to run billions of iterations to find that unique set of circumstances that would set off a profound change. But as Langton says, there are no shortcuts toward understanding complex systems such as the economy. "The more complex the system it is," he adds, "the more you have to let it run to see what it will do."

But Langton also points out that most of the code governing the interactions of different agents in different environments is the same regardless of the agent or environment. Whether you have 10,000 ants or 10,000 traders in an economy, you still have 10,000 things whose interactive behavior is 99 percent similar. It's only in that one percent region where the computer code must be modified to differentiate between ants, Anasazi people, and stock traders.

Thus, Swarm provides a basic library of algorithms that can be modified to fit specific test situations. For example, a neural-network type of architecture may best describe one stage of an environment while another may be more suitably described by a genetic algorithm. Swarm is robust enough to allow these multiple descriptors to mix in the

same model. Swarm also allows multiple tiers of interaction within a world being studied. For example, interactions can occur among various factories in an industry and, at the same time, among various workstations within each factory.

Langton's goal for Swarm is to provide a generic software that can be applicable to various agents and environments with just minor programming variations. But, he acknowledges, "We have a ways to go with it."

Swarm derives computational power from its bold postmodern philosophical assumptions about the relationship between an agent and his environment. Both are treated equally, in contrast to the traditional human-centered worldview in which an environment is a passive, undefined space and an agent is an active and discrete entity. The old spatial metaphor that has a smart agent engulfed in a dumb environment does not apply. The lattice of agents and environments in a Swarm program allocates equal powers to the ant and the earth, the Anasazi family members and the climate in which they live, the stock trader and the market. Animated life is not privileged over inanimate dimensionality. Each acts upon the other, and the boundaries between where an agent stops and its environment begins are blurred.

Challenges and Enthusiasm

Despite its successes, Swarm faces challenges. Langton says current versions of Swarm rely on a simulated parallel-processing system. SFI researchers now are working on a system that would more closely resemble the real world by using multiple computers operating in parallel. A parallel kernel also will allow faster computation as Swarm models become more sophisticated.

While Swarm offers insights into research questions by permitting a bottom-up approach, the Swarm architecture is still subject to the same limitations that govern statistical econometric curve fitting—the traditional type of top-down research. To build an informative Swarm simulation, a researcher must carefully select the important variables governing the system to avoid specification errors. This challenge is not trivial. The Anasazi model, for example, would not be meaningful if programmers did not realize that the caloric requirement of residents in the community was the fundamental systemic variable.

Kerry Hanson, manager of mixed-signal application for specific products at Texas Instruments in Dallas, says his company has used Swarm to look for competitive advantages in the semiconductor industry. He is also considering a Swarm study of new product applications in digital-signal processing. But Hanson says Swarm will have to become easier to use before it catches on widely in the business community. Texas Instruments is in the early adopter stage of Swarm, he says, in part because it still requires good software engineering expertise. Hence, "People outside the computer science labs tend not to be interested."

But those researchers who have become comfortable with Swarm have found it invaluable. Tim Kohler, chairman of the department of anthropology at Washington State University, says Swarm has fully lived up to his expectations. The simulation software has led to intriguing insights into the ways in which early Native American peoples coped with changes in their environments. Swarm has corroborated theories suggesting that Anasazi cultures developed maize trading among households to contend with variable patterns of rainfall.

In the Swarm Artificial Anasazi model, the terrain of Southern Colorado 1,000 years ago shows up on the computer as a green topographical map, crisscrossed with streambeds. Families show up as pixels of light. The model simulates life among the people using some thirty variables—birth rates, death rates, local topography, corn-storage potential, rainfall, and the like. The computer races through each year in a matter of about ten seconds, allowing researchers to tweak one or two variables and rerun the model to see what changes occur. Researchers then study the survival rates among the pixels representing families.

Kohler and co-researcher Carla Van West have found that families tended to be risk averse. They would share maize with other families in exchange for a promise to return the favor. But sharing was more prevalent in times of high overall productivity across the entire region when productivity also varied from year to year and local area to local area. But when the entire region suffered from low maize productivity, families tended to hoard.

Research on the Artificial Anasazi project suggests that environmental degradation forced the people to abandon their homes in the thirteenth century. But the Swarm model also suggests that one-third of the population could have survived if they had redistributed themselves on the land.

Kohler is excited to be going on sabbatical next year, when he hopes to use Swarm to research other questions about the Anasazi people. He wants to find out how variations among local conditions rather than among regional ones affect sharing behavior among the virtual Anasazi population and how sharing rules change over time. He says Swarm overall has been widely accepted among the archaeological community. "There is a great deal of enthusiasm for it," Kohler says, "and a number of people have told me that they are very interested in this project."

Ken Baake is working on a Ph.D. in rhetoric and professional communication at New Mexico State University. He is also an El Paso writer.

Photo: William Clark

Interdisciplinary Approaches

Postdoctoral Fellowships in Complex Systems Studies

NONLINEAR DYNAMICS
PATTERN FORMATION
MEASURES OF COMPLEXITY
AGENT-BASED MODELING AND SIMULATION TOOLS
MODELS OF THE IMMUNE SYSTEM
CELLULAR REGULATION
LEARNING ALGORITHMS
EVOLUTIONARY BIOLOGY
MODELS OF ECONOMIC, POLITICAL, AND SOCIAL INTERACTIONS

The Santa Fe Institute expects to have an opening for one or more Postdoctoral Fellows beginning in September 1998.

The Institute's multidisciplinary research program is devoted to the study of complex systems, especially complex adaptive systems. Topics currently under study include nonlinear dynamics and pattern formation; measures of complexity; learning algorithms; agent-based modeling and simulation tools; evolutionary biology; scaling in biology and ecology; models of the immune system, cellular regulation, and other biological systems; models of economic, political and social interactions, and others. Postdoctoral Fellows work either on existing research projects or on projects of their own choosing. Travel funds are also available to support research visits by Postdoctoral Fellows to collaborate with offsite members of the SFI Science Board and External Faculty.

Candidates should have a Ph.D. (or expect to receive one before September 1998) in the mathematical, computational, physical, biological, or social sciences, with an academic record of scientific excellence, a demonstrated ability for independent research, and a strong interest in interdisciplinary approaches.

Special consideration will be given to those applicants who propose, as an integral part of their research at SFI, a specific project involving experimental work or data collection at locations other than SFI. Candidates with such interests are requested to submit an outline of the proposed offsite project, along with a supporting letter from the organization through which the experiments or data collection is to be coordinated. Although their primary research site will be SFI, successful candidates in this category will receive salary and travel expenses from SFI in support of offsite research.

Applicants should submit a curriculum vitae, list of publications, statement of research interests, and three letters of recommendation. Incomplete applications will not be considered.

Non-U.S. applicants are eligible to apply. Successful foreign applicants would enter the U.S. on either a J or, less likely, an H visa.

All application materials must be received by February 20, 1998. Decisions will be made by April 1998. Send application materials to: Postdoctoral Committee, Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, NM 87501, USA. Send complete application packages only, preferably by postal mail, to the above address. Include your e-mail address and/or fax number.

independent research

SFI is an equal opportunity employer. Women and minorities are encouraged to apply.

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INSIDE SFI

BY ERICA JEN
VICE PRESIDENT FOR ACADEMIC AFFAIRS

The last issue of the *Bulletin* described the beginnings of an internal review process at the Santa Fe Institute—an opportunity for us to structure our internal debate and ask hard questions on issues relating to the scientific excellence and vitality of SFI. The internal review panel's report, released in September, has been reviewed by our Science Steering and Executive committees, the external faculty, and the Science Board. The report recommended that:

- New, dynamic research themes and individuals be given a more salient place in SFI's future
- Close attention be paid to the continuation of support for individual researchers, development of nascent research efforts into formal programs, and reduction of support for research endeavors when appropriate
- Identification of crosscutting intellectual themes—supported by liberal visitor policies, special workshops, and reworking of physical space to encourage general discussion—be undertaken
- In view of the critical importance of the SFI site, close attention be paid to the allocation of the physical resources here and to the question of the optimal size of the on-site community
- An atmosphere that facilitates free exchange of ideas be encouraged
- The SFI postdoctoral program be continued with appropriate integration and constructive mentoring
- Research professor positions—with terms of one to two years and renewable for an additional two to four years—be retained
- Senior resident professor positions be phased out
- Program responsibility be distributed to more than one individual, and off-site as well as on-site individuals be involved in SFI programs
- A diversified funding profile that combines an endowment with research grants (excluding proprietary research and reliance on single-funding sources) be developed.

On the basis of the recommendations of the internal review—and the discussions it sparked among the external faculty, Science Board, and Science Steering Committee—the SFI administration is beginning to implement changes in several aspects of the SFI research program.

CHANGES IN THE POSTDOCTORAL FELLOWSHIP PROGRAM

The internal review reaffirmed the importance of the postdoc program while pointing out the challenges SFI's research environment poses for postdoctoral fellows. The primary one is the difficulty of carrying out a focused research program in an environment that is enthusiastically interdisciplinary and centered around visiting rather than resident senior researchers.

SFI postdocs are deliberately chosen in part for their ability to conduct independent research. As a group, they have been remarkably successful not only in their tenures at the Institute but also in their careers after leaving SFI. Nevertheless, it is inarguable that being a postdoc at SFI is not easy. An SFI postdoc may be the only researcher in residence in his area of interest. This situation, not always enviable, necessitates that he/she be willing and able to formulate and lead Institute research in that area with less than the usual amount of day-to-day interaction with other colleagues in the field.

We will be taking steps to facilitate networking among postdoctoral fellows with other members of the Institute community. SFI Science Board and external faculty members will be encouraged to take a more active role in sponsoring and initiating research collaborations with our postdocs. Travel money will be provided so postdocs can arrange extended research visits to the home institutions of Science Board and external faculty mentors. Additionally, we recognize that a critical mass of postdocs at SFI is essential. In the coming years, all attempts will be made to maintain the program at its current size of eight to nine individuals in residence at SFI.

MODIFICATIONS IN THE PROGRAM STRUCTURE

The current administrative structure at SFI centers on programs that differ greatly in their scope, maturity, and levels of activity. Associated with each program is a program director and budget. There is not, as of now, any mechanism for review or turnover of programs.

The program structure has been successful in encouraging the coordination of broadly defined research projects that have grown from relatively small efforts into major scientific thrusts. On the other hand, the structure has, perhaps by virtue of its success, contributed to an environment in which the programs have acquired a life of their own. In other words, researchers both within and outside the SFI community increasingly look to the program structure to define SFI research and the people associated with that research, rather than the other way around.

Based on discussions with SFI's external faculty and Science Steering Committee, we are modifying the program structure to put the focus on people and projects. In particular, we are working with SFI-affiliated researchers to identify programs that will function not so much as disciplinary or topical umbrellas, but as conceptual hubs with spokes reaching throughout the Institute to other conceptual hubs. The programs will emphasize crosscutting intellectual themes, and each program will have a timeframe for future review, determined on a case-by-case basis. Also as recommended in the report, off-site researchers will be invited to take the initiative in proposing and pursuing these efforts, and responsibility for the programs will be shared by groups that include members of the external faculty and Science Board.

IDENTIFICATION OF CROSSCUTTING INTELLECTUAL THEMES

One of SFI's less modest but nonetheless oft-stated goals is to use crosscutting themes to achieve an intellectual integration between specificity and generality, in other words, to develop an understanding of specific natural and social phenomena and to abstract from these phenomena fundamental principles of general complex adaptive systems.

So what are the themes of SFI research? E-mail correspondence stimulated by the internal review report among resident and external faculty (with Jim Crutchfield, Walter Fontana, Melanie Mitchell, and Richard Palmer being especially vocal) could be compressed to state that the current themes at SFI involve the study of dynamics, interactions, emergence, learning, evolution, ecologies, and economies as applied to the understanding of structure, function, and history of complex adaptive systems.

Meta-speak aside, the use of crosscutting themes to achieve integration is of course nontrivial. One attempt is the "Integrative Themes" workshop being planned for summer 1998. This two-week event will include presentations and discussions centered around specific crosscutting topics including open-endedness in evolutionary systems, learning in distributed systems, and decision making in complex environments. Participants in the workshop will include members of the external faculty and a limited number of Science Board members.

PHASING OUT OF THE SENIOR PROFESSOR POSITIONS

While recognizing the enormous debt SFI owes its senior resident scholars and the critical role their research programs play in the Institute's agenda, the internal review panel stressed the importance of continuing to develop new themes and new directions. From discussions with SFI's research community, the internal review panel concluded that such development of new themes and directions was more likely to succeed in an environment that builds on the essentially visiting rather than residential nature of the Institute. As the report states, the panel has "learned that the limiting and phasing out of the category of senior resident scholar on active (as distinguished from some form of inactive or emeritus) status is broadly supported within the larger SFI community, and on balance this recommendation has our support as well."

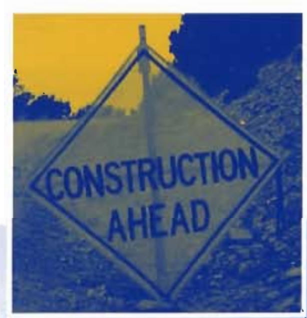
While phasing out professor positions, it is critical that contributions—past, present, and future—of the individuals currently in those positions be recognized and that a framework be devised for ensuring a smooth transition and their continued, active scientific involvement with SFI.

The internal review panel did recommend that the category of research professor be retained. This category is intended to be appropriate for researchers at all career stages, including senior researchers on sabbatical leave from their home institutions. Despite the availability of research-professor appointments, however, the elimination of the five-year professor category raises an important question: how do we ensure long-term scientific continuity at the Institute? The discussions relating to this issue gave a sense that while the five-year professor category is thought to be inappropriate for SFI, other options should be considered. One possibility, for example, is to encourage individuals to be in residence half time at the Institute on a long-term basis, without relinquishing their affiliations with their home universities.

OPTIMAL SIZE CONSIDERATIONS

The internal review report recommended that attention be paid to questions of the Institute's optimal size and allocations of its physical resources. Both questions are clearly critical. They call for a better understanding of the type of commitments the Institute can make to its research affiliates, as well as the expectations the Institute should have of those affiliates.

Questions of optimal size and allocation of resources will not go away with the planned campus expansion; they'll just acquire new dimensions.



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