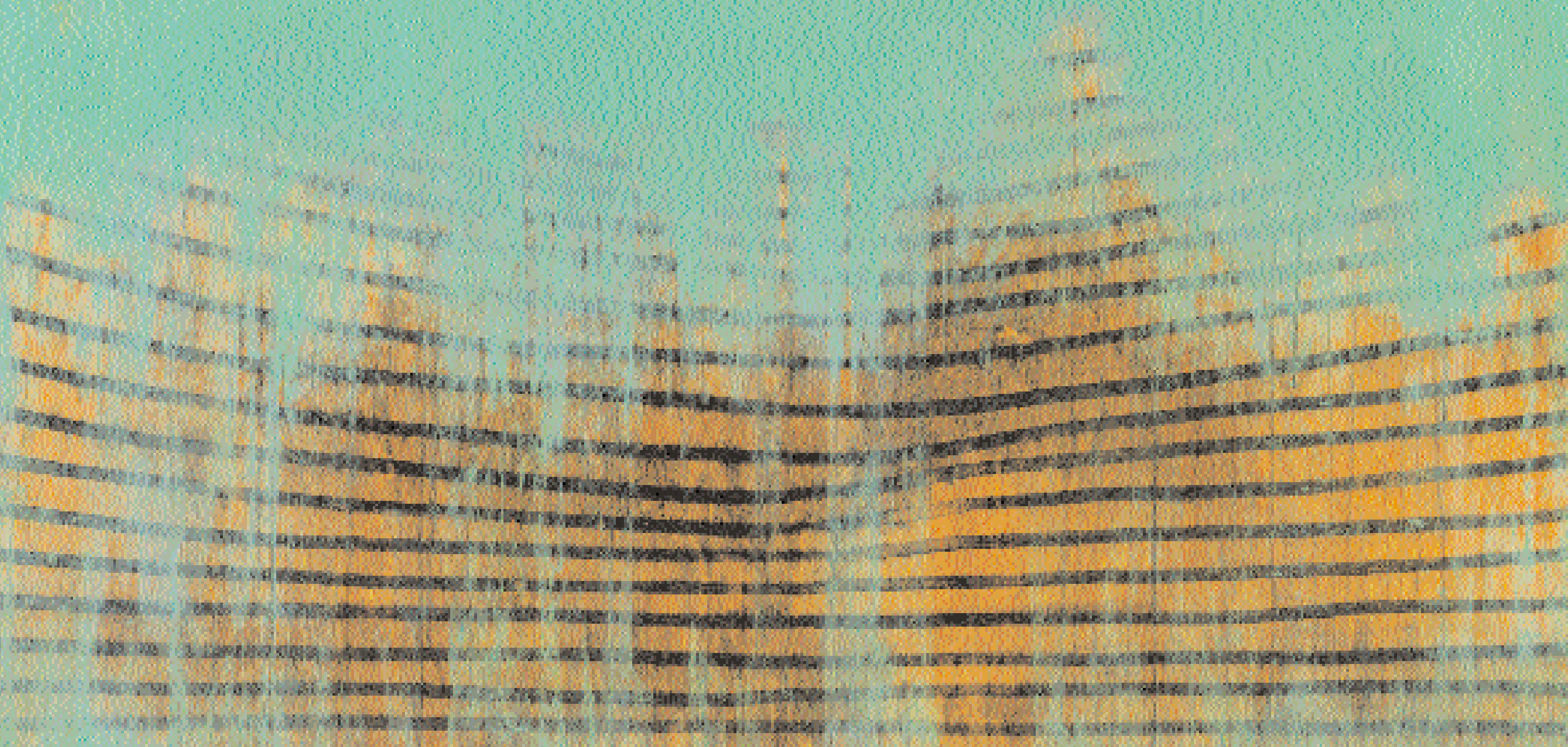
SFI@20

special 20th anniversary edition of the santa fe institute bulletin, fall 2004



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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 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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The cover and interior art works are representations of paintings by Robert Kelly. Kelly works from a studio in his home town Santa Fe, and in New York, and travels the world for inspiration. He was educated at Harvard. His paintings are collected by many museums, including The Brooklyn Museum in New York and the Fogg Museum in Cambridge, MA. His work is also in numerous corporate collections, including AT&T in New York and the Hallmark Collection in Kansas City. Kelly has been represented by Linda Durham Contemporary Art since the mid-1980s. Find out more by logging onto www.lindadurham.com or visiting Linda Durham Contemporary Art at 1101 Paseo de Peralta in Santa Fe 505/466-6600.

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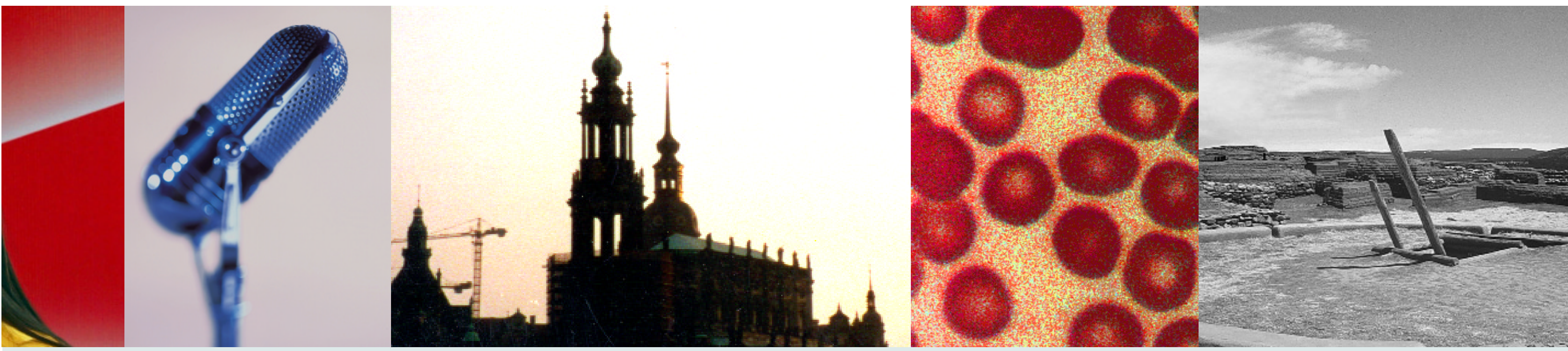
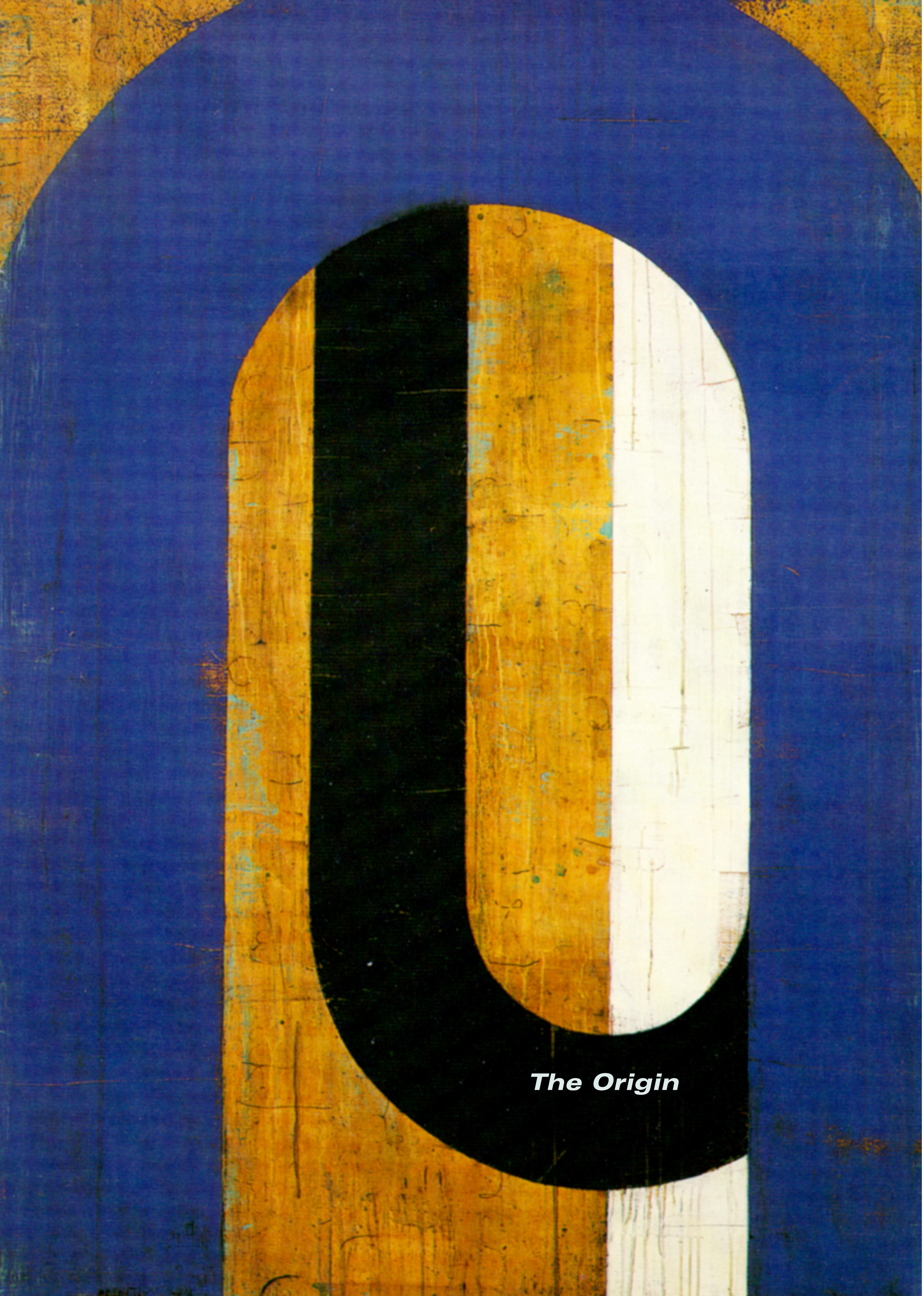




The Origin

The Origins of the Santa Fe Institute

by Lesley S. King

Uniting Disparate Areas of Science

The origin of the Santa Fe Institute is the story of a marriage, an often romantic, often turbulent union between disparate areas of science. "Physical scientists think the social sciences are inelegant," says founder George Cowan, hinting at the root conflict that for years inhibited the union. As a physicist deeply concerned with finding exact solutions, he initiated the whole process with some doubt, but the tenor of the times and the people who joined in the collaboration conspired to create a new synergy.

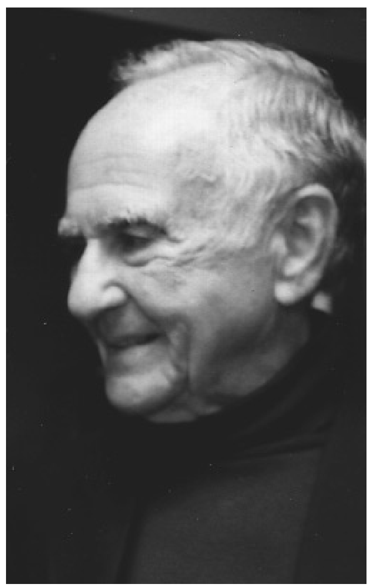


PHOTO: LAURENT GUERIN

George Cowan

Cowan traces the first seed back to an early meeting at the Aspen Institute, an organization fostering new ideas in leadership and humanism, where he, the only scientist in the group, sat at a round table discussion of literature. He appreciated the convening of intelligent minds, but wasn't fully satisfied. "This would be an even greater idea if the discussion were driven by facts rather than essays," he remembers thinking.

This was 1956, when the science world was on the edge of change. Even the social and political climate of the times was stormy. Jackson Pollock was playing with mathematics in his paintings, presenting images that now resonate with chaos theory and its offspring, fractal geometry. Meanwhile, mathematician C.P. Snow, through a series of novels, was urging a mutual understanding between scientists and other humanists. The Civil Rights Movement was gaining momentum, blurring the lines between black and white. Cowan gave a lecture at the Aspen Institute about art and science, in which he talked about society and science in terms of thermodynamics. Specifically, he spoke of entropy—the tendency of things to move toward disorder. "It went over like a lead balloon, but I was asked back," he says humbly.

Those early encounters stayed with Cowan, and their impact compounded when he became head of Basic Research at Los Alamos National Laboratory (LANL). There he oversaw not only work in the exact sciences such as physics and chemistry, but also less structured ones such as biology and new fields such as molecular biology.

It was there he learned the power of what he calls "social engineering." "You don't tell people what to do, you get them involved and interested," he says. "I found myself being a marriage broker," he adds, "getting good people together to do exciting things."

An appointment to the White House Science Council in the early 1980s added a new impetus to Cowan's desire to bring science into more everyday matters. Working on projects such as the space program and, later, AIDS research, he saw decisions made for emotional and political reasons, rather than fact-based ones. He asked council member David Packard, of the Hewlett Packard legacy, "What do you do when you're a science advisor and you encounter a political agenda?" Packard said, "'You learn their agenda.'"

Soon, Cowan had the latitude to take steps in the direction of learning the agenda of the "inelegant camp." When he became a senior fellow at Los Alamos National Laboratory, he had the freedom to range more in his interests, and some of that entailed conversing with other sci-

From Buzz to Action: SFI in the Media

In the upheaval that accompanies the arrival of a grand new idea, there is surely excitement—a buzz surrounding the feeling that with a new way of seeing, anything is possible. It is an excitement that can only surround an idea that is at its start, all light and potential, without any of the weight of counter-example and experimental failure.

This is a partial explanation for the free-thinking, and consequent free-speaking, that permeated a good deal of the media coverage of SFI in its early days. The Institute was a nexus of a diversity of big thinkers—indeed, officially recognized geniuses: Nobel laureates such as Philip Anderson, Kenneth Arrow, and Murray Gell-Mann, and MacArthur Fellow Stuart Kauffman—peopling a place that was to push forward our understanding of a newly recognized uber-view of science: the concept of self-organization. It was a concept far-reaching enough to encompass the origins and evolution of life on all scales, from organism development to the rise of economies and societies. Self-organization would be the lens through which all of life could be seen, quantified, and well, organized—putting the messy sciences that are biology, sociology, and economics (as well as some of the most complicated physical phenomena) into a universal framework where mathematics and computation would guide research and discovery.

So, SFI's birth brought a media splash befitting its noble—and Nobel—origins. Writers keyed on SFI's convent digs, implicitly playing up grand parallels between doing God's work and revealing God's workings. Much was made of, what was then, a new and nonstandard interdisciplinary approach to science. *Omni* magazine described SFI as "an oasis for people interested in the science of complexity," peopled by science "heavyweights," suggesting a picture to be juxtaposed with an arid and ossified landscape of traditional academe. The journal *Nature* touted SFI as a place where "through the interaction of talented people there may well arise new visions of how the world is put together," and *Science* described it as an intellectual playground where scientists knocked around new ideas "like volleyballs." The culmination of this journalistic entists who at the time were formulating similar agendas. They were to become the early founders of the Institute. They met once a week, their goal at the time to get quality physical scientists to talk to people in related, converging fields of research. “Everyone had a different version of what they wanted, but they were all ready to go,” he says.

At the time an interesting change was happening in the science world. LANL was a center for nonlinear dynamics. Cowan defines the science as having problems for which you can’t get an exact solution. While a linear system can be broken into simpler subsystems, studied, and reassembled to understand the full system's behavior, a nonlinear system behaves in a way that is inexplicable in terms of any of its separate subsystems. These more complex systems had become the new focus. And besides great minds at work on them, an element fueling this study was computers that could perform huge numerical calculations.

So the group set to work examining such systems. Cowan gives weather as an example, and explains that when trying to predict weather patterns, meteorologists would make compu-

PHOTO: RON WATTS/CORBIS

praise was Mitch Waldrop's book *Complexity,* which chronicled SFI's birth as the “nerve center” of research in complexity and adaptive systems, inhabited by an eclectic community of horizon-seeking scientists sharing a vision of “an underlying unity” of thought that would “illuminate nature and humankind alike.”

To be fair, the writers were at least, in part, only picking up on and publicizing the optimism voiced by the SFI pioneers; Stuart Kauffman declared that he was “fairly convinced that the things coming out of here will be considered seminal in ten years.” The most famous quote of this genre, attributed to David Pines, was that the goal of SFI is nothing less than to “define the scientific agenda for the twenty-first century,” an agenda that would ultimately influence policy makers on a national and even international scale. The sky was the limit and the articles reflected the promise and hope of a new science and its proponents.

Nevertheless, grand dreams that are publicly pushed to extremes are the primordial material of hype, and as a consequence (or perhaps inevitably) not all the reviews of those early years were good ones. But eventually, promise did turn to action, and the “what-we-might-do’s” become “what-we-have-done’s” as SFI started the hard work of actually building a body of knowledge and results that would help form the foundations of this new science of complex adaptive systems. With real results came a new sort of publicity for SFI, one that derives from the popular media’s scanning of the articles in the top scientific journals such as *Nature, Science,* and the *Proceedings of the National Academy of Sciences* (PNAS).

This is the media climate in which SFI now finds itself. Today the Institute is known mainly and consistently for real scientific achievements. But we can’t rest easy. If after 20 years SFI is on the verge of initiating another paradigm shift, then the hopes and hype are just around the corner.

—Daniel Rockmore

tational calculations but couldn't get the same result twice. "Nor could scientists such as Phil Anderson working with complex metal compounds," he adds. But that very problem opened a door.

"Researching such processes suddenly became okay," he says, brightness coming to his eyes. "Before, it was inelegant and a waste of time. But now it had become a fine way to do science, even though it was approximate."

So, what better time to bring together scientists in disparate fields than in a time when science itself was proving that approximation was not only okay, but would also ignite broad new areas. "It was the right time," says Cowan. "Ten years earlier, the idea would have been dismissed. Ten years later, and it would have been someone else's bandwagon."

Meanwhile, other scientists were having musings similar to Cowan's. Physicist Stirling Colgate was exploring ways to better higher education. With interests ranging from physics to epidemiology, he liked the idea of interdisciplinary research. Murray Gell-Mann, who in 1969 won a Nobel Prize for work in the theory of elementary particles and the discovery of

Artificial Anasazi

George Gumerman's research using agent-based computer modeling began when he, a "dirt archeologist" who had been studying the Anasazi civilization for decades before computers were even invented, bumped into a couple of computer modeling pioneers.

Gumerman had already collected more than 30 years worth of data from Long House Valley, a home of the Anasazi people in northern Arizona who suddenly, and mysteriously, abandoned the area around 1300 A.D.

Today Gumerman, formerly vice president of academic affairs at SFI and newly appointed interim president of the School for American Research, recalls his archeological career B.C. (before computing).

"There were no computers when we started and, of course, there were no modeling efforts," Gumerman says. "I remember being shocked at hearing of one group in the Southwest inputting data from the field into one of those huge, mainframe computers, the ones with punch cards."

Jump ahead a few decades. Increasingly sophisticated programming languages are allowing scientists to create artificial societies. At this point, they are mostly abstract constructs that allow their creators to study provocative scenarios.

"So, for example, you could look at the spread of morals by giving morals to individual agents and seeing what happens under certain conditions," Gumerman says.

In 1994, Joshua Epstein and Robert Axtell from the Brookings Institution showed up at SFI with an artificial society they had invented called Sugarscape, a simulated world where hunter-gatherers keep themselves busy subsisting on a single resource—sugar.

"They gave a lecture here and somebody asked, 'Have you ever tested this model against a real society?' " Gumerman says. "Their answer was no. 'Real societies are far too complex. This is just a cartoon. We couldn't do it with a real society. "

"So," continues Gumerman, " I raised my hand and said, 'Wait a minute. I have a subsistence agricultural society that is simple in many ways. And furthermore it's prehis-

"quarks," the subatomic building blocks that make up protons and neutrons, had his own agenda. He was turning his keen analytical mind to concerns about culture and the origin of language. Edward Knapp, a physicist working at LANL and previously director of the National Science Foundation, was foreseeing major changes taking place in science. He saw an important niche opening up that a team-based approach might fill. Indeed, the newly formed Center for Nonlinear Systems (CNLS) at LANL was taking first steps in this direction. CNLS's scientific emphasis—along with its focus on collaborative, interdisciplinary work, and a strong visitor component—was proving to be an intriguing example of this new approach.

Physicist David Pines was already thinking about ways to improve communications between different disciplines, which led to the founding of the Center for Advanced Study at the University of Illinois. Physicist Darragh Nagle was at the forefront of new computer technology research, already foreseeing how it might help stimulate what he termed a "new science." At LANL, physicist Richard Slansky was seeing the effects of working between

PHOTO: WILLIAM CLARK

toric and we have a lot of data. So maybe we could get together."

They did and the idea for Artificial Anasazi was born.

"This was the first time we were able to bring together the real with the artificial. And it could only have happened at the Santa Fe Institute," Gumerman says with a laugh. "Where else would I go to a lecture on computer-based modeling?"

The agents in this model are Anasazi households living under conditions prescribed by actual archeological, climatic, and other data. By observing what happens to the artificial society, Gumerman and his team are increasing their understanding of the role of environmental versus other factors in driving the real Anasazi out of Long House Valley.

"We know the environment went to hell around 1300 A.D," he says. "But before modeling, the level of the argument was one group of archeologists saying, 'Well we think the environment is very, very important to explain what happened with the Anasazi,' and the next group of archeologists claiming, 'Well, we don't think it was that important.'"

"It was only when we used the agent-based modeling to compare the artificial people with the real people against the same environdisciplines, but he wanted an even broader reach than he was finding at the lab. Also involved with computing was physicist Nicholas Metropolis, who acted as host in his office to some of the early founder discussions.

Free-form meetings started. "The discussions were all over the map," Cowan admits, as though still relishing them. He reflects back, "Herb Anderson said, 'Pick out the best people, bring them in, and ask them to tell us what interests them.'" He pauses and says with emphasis. "We were picking the people, not the topics."

Cowan gives credit to the influence of those such as Murray Gell-Mann, David Pines, Nicholas Metropolis, and Herbert Anderson, who, he says, "knew everybody. They could just pick up the phone," he adds.

Meanwhile, the group tackled logistical questions. They got their charter in 1984, then discussed where the Institute should be and how it should be organized. The group knew the importance of place; they surmised that Santa Fe itself would act as a magnet. And thus they set about with the nitty gritty of getting funding.

Again, influential people were key. Arthur

mental factors that we could say 'Wow.' Two-thirds to three-quarters of the population dynamics we see depend on the environment," he says.

Ten years after its conception, Artificial Anasazi continues to evolve, as researchers attempt to model the complex political and religious forces at play in the Anasazi world.

"We know in reality that in about 1300 a religious cult spread over the region," Gumerman says. "So the challenge is, how do we model a cult?" Do we just put it in, or do we grow a religion?"

The challenge, Gumerman says, is to create a model that is sufficiently complex without it becoming, as happened to the obsessive mapmaker in a Jorge Luis Borges' story, a map as big as the kingdom itself.

"If we show this model to a group of archeologists they'll say, 'This is too simple. You've left out this, that, and the other,'" Gumerman says. "If we show it to a group of computer modelers, they'll say, "'My God! This is so complicated.'"

"So we must be doing something right," he says with a chuckle.

An upcoming joint project of SFI and the School for American Research will bring agent-based modeling to another subject of archeological interest, the complex societies of lowland Latin America. Gumerman is assembling a multidisciplinary team of social scientists and computer modelers to study the region during three periods—prehistorically, during the period of contact with Europeans, and in contemporary times. The project will begin with a workshop in Brazil next May.

Social scientists have puzzled over how lowlands people developed complex societies under a challenging environment, Gumerman says. The tools of agent-based modeling may provide some new and surprising answers.

—*Barbara Ferry*

Spiegel of Spiegel Catalog note had become a New Mexican financier and helped raise $50,000; Murray Gell-Mann acquired $25,000 from the Carnegie Foundation, and Cowan was allotted $25,000 from the MacArthur Foundation. "We raised $100,000 or so, including gifts from the founding members, and were able to start paying out some money," says Cowan.

The first meeting at the School of American Research brought together scientists from fields ranging from physics to economics. "The word complexity was used a lot," Cowan says. "Nobody could define it, but it wasn't simple," he adds with a note of humor in this tone. But he elaborates: "Complexity is so different from simplicity. In simplicity you can reason back from the end point. But you can't with complexity. If you try to take a complex system and say where did it come from, you can speculate and say what is plausible, but you can't trace your way back."

It's ironic that with all the physicists in the founding group, the first big money that came in was for economics. The funding came from Citibank: $250,000 to study the global econo-

The Complex Days of Summer

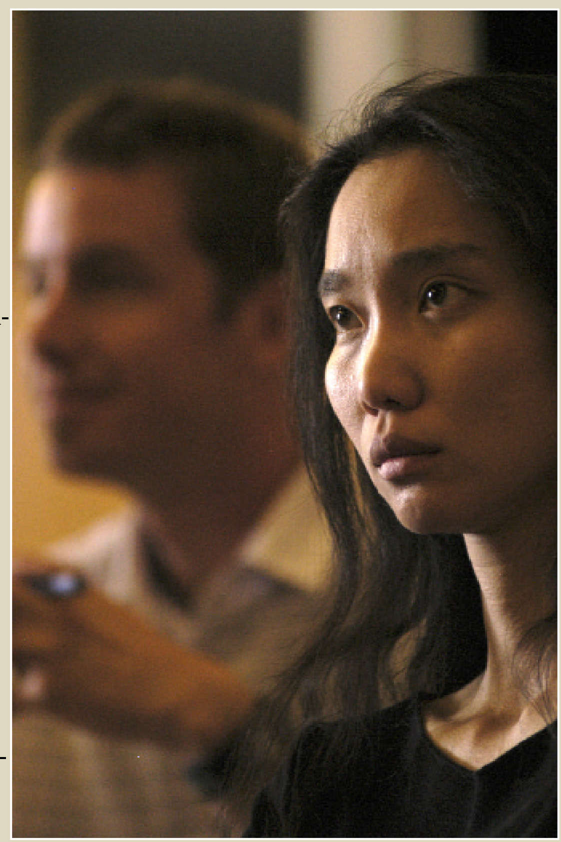


PHOTO:JULIE GRABER

When SFI started its Complex Systems Summer School 15 years ago, complexity science was brand new and the students who made the pilgrimage to Santa Fe didn't quite know what they were about to get into.

All that has changed, says Melanie Mitchell, who has directed the summer school for the past several years. Complex systems research is now more widely accepted in the scientific culture, she says. Students often come to the program with a sophisticated understanding of the research, in some cases having taken courses in complex systems at their own universities.

"Some of our own summer school students have now become professors, and they're starting to offer courses in complex systems," says Mitchell, an External Faculty member at SFI and professor of computer science at the Oregon Graduate Institute in Portland.

"It's funny because originally when we started, people were awed by how incredible this stuff is. Now it doesn't seem as revolutionary as it once did. So we have to constantly figure out how to stay on the cutting edge."

The summer school, a flagship program of the Institute, gives students an intensive four-week introduction to complex behavior in mathematical, physical, and living systems. For this new generation of students, the school is a rare opportunity to think, work, and collaborate on projects outside of their my. Again though, the money was directed more toward people than topics. Nobel laureates Philip Anderson, Kenneth Arrow, and Murray Gell-Mann brought clout to the table. Other funding continued to come. Cowan relates, still with a bit of surprise in his voice, that the National Science Foundation and Department of Energy agreed to give blanket money to SFI, money that could be used as the scientists saw fit. “They’d never done that before,” says Cowan. He’s still impressed by how much influence the people involved had. “If I had gone to the DOE and asked them to pay to study the economy, I would have lasted 20 seconds,” he says chuckling.

“But we had Ken Arrow, a father of neo-classical economics, and Murray Gell-Mann. We were name-dropping, but we weren’t faking it.”

The important names accomplished more than securing funding. “If SFI wanted to brag, it would say it made it respectable for physical scientists to deal with topics where there were no definite conclusions,” he says. “The attitude became ‘It must be okay if Murray Gell-Mann and Phil Anderson are doing it.’ It gave it a certain kind of approval which helped establish

own field, Mitchell says. “In graduate school there’s a feeling that you have to pick a topic of study and dig really deep into it. You’re learning in great depth about a very narrow, specific area.

“In order to study complex systems you need that depth, but you also need some breadth,” Mitchell says. “And you need to learn how to collaborate with people in other fields.”

During the month in Santa Fe, the students do just that. The 70 who assembled at St. John’s College for this year’s summer school were a typically diverse lot, coming from fields ranging from physics to philosophy; from institutions as varied as King’s College in London, the Toyota Motor Corporation, and the South Dakota School of Mines; and from places as far away as Brazil, Estonia, and Finland.

“A big challenge for us is how to pitch lectures to a very diverse group of students,” says Mitchell. The amount of math required to understand the lectures can be daunting, so the school matches up the math-inclined with the math-challenged.

The projects that students team up to work on also reflect a diversity of interests. This year the student projects included models of how a food web could be affected by the removal of a certain species; the elements required for a revitalization of folk music, singing, and dancing; and an agent-based model of civil war.

Further stretching its limits, SFI is taking its Complex Systems Summer School on the road. For two years, the Institute offered a school in Budapest and in July 2004, presented its first school at Qingdao University in Shandong Province, China.

For Jonathan Clemens, a 2004 Santa Fe summer school student, the diversity of the school provided some incredible opportunities. The "visible" diversity—most notably age, gender, national origin—seemed to pale in importance compared with the diversity of backgrounds and disciplines, says Clemens, manager of the technical investigations and emergency response team for Intel in Dupont, Washington.

“I have had opportunities to work with interdisciplinary teams before, but never to the degree of freedom and open-endedness that we experienced,” says Clemens. “ I learned a great deal from the faculty, but I also learned a great deal from the other students.”

—*Barbara Ferry*

complexity as an acceptable field of research."

Though Cowan shies away from the notion of topics as a driving force, he recognizes that "complexity" has been integral to the Institute's success. "I loved it as an umbrella term because people thought it defined what they were interested in. Some people had trouble because it was inexact, but it worked for me because it encompassed what they were doing."

Talking Eyeball to Eyeball

Much of SFI's construct arose through scientists who had experienced many facets of academic life and were ready to create a system that would support those early forms of expression that so crackled with possibility. "We set out to create a new kind of research environment," Edward Knapp wrote when he was president of SFI. "It would be a truly bottom-up culture and an independent haven for multidisciplinary research."

Murray Gell-Mann had been fettered by a system focused on departments, and so insisted there be none. The group discussed becoming a fully accredited graduate school, but realized that without departments it would be hard to

The Holy Grail of Complexity Science

COURTESY M.C. ESCHER FOUNDATION

Where are we on the road to a theory of complex systems?

It might be said that the hallmark of a mature science is the existence of basic laws, fundamental mathematical principles serving as a foundation for empiricism. At this moment, some 20 years after the birth of SFI, and with it, the Big Bang of the study of complex systems, we can take a look back to see where we stand on the journey to maturity: infant, toddler, or adolescent. More particularly, what role has SFI played in this progression?

SFI emerged to address "complex systems": those wonders of self-organization ranging from the microscopic merging of cells responsible for life and thought, to the unconscious large-scale liaisons that make up a language, society, economy, or ecosystem. In order to accomplish this, SFI was to be the "University without Walls," an acknowledgement that progress in understanding complex systems would require an interdisciplinary effort. These initial motivations hint at the diversity of phenomena over which any theory of complex systems must reign.

The interdisciplinary connections sought by SFI are mirrored in the fundamental progress in network theory accomplished by the resident scientists. The Watts/Strogatz theory of "small worlds" initiated a rebirth of the study of real-life networks that has revealed the ubiquity of power laws and reinvigorated the search for a taxonomy of the strucgive Ph.D. degrees. Still, the founders kept their focus on small groups. “We wanted a venue where we could discuss topics eyeball to eyeball,” says Cowan.

“The structure was tailored to the amount of money we had and the flowing nature of our talks,” he says. “We didn’t ever want to be set in concrete.” He admits they had on their side the youth of the organization. “As organizations get older they become less plastic,” he adds, using a term from his most recent work on brain development.

The consequence of placing the emphasis on people and their ideas is catalytic. SFI’s External Faculty and visiting researcher components allow the institution to draw the best and most progressive, to enter into the current of ideas already circulating. Today SFI has approximately 100 Resident and External Faculty members and a Science Board that includes five Nobel laureates. Science generated though this free-flowing system is able to reach out to other institutions, other countries and cultures. It changes and strengthens those systems, channeling more open-minded science to their reaches and beyond, through the channels that they touch.

ture of evolved connectivity. Similar form-function concerns have informed the allometry work of SFI Distinguished Research Professor Geoffrey West, SFI External Faculty member James H. Brown (University of New Mexico), and others, whereby they have posited principles that appear capable of a mathematical explanation (dare we say “law”?) of the mysterious “three-fourths” power law relating metabolism and body mass across all organismic scales, as well as the ubiquity of the branched resource delivery systems apparent in so many aspects of life. SFI pioneer Stuart Kauffman’s initial work on Boolean networks—a mathematically informed investigation of inter-gene function—resurrected the general utility of the fitness landscape outlook and echoes in today’s DNA microarray methodology. J. Doyne Farmer and fellow chaoticians married the studies of dollars and sense in order to create "econophysics." Murray Gell-Mann and others bridged life and language as they brought rigorous tools from evolutionary biology and statistics to the search for a Mother Tongue.

These unifications were accomplished through the lingua franca of science that is mathematics, especially the classical tools of dynamical systems, analysis, combinatorics, and graph theory. And, these tried and true techniques were augmented and enhanced through the modern tool of computation. Theorems were proved, but just as importantly, computer simulations were run, and where airtight proof could not be found, theories were supported and suggested by run after run of intricate and inspired computational experiment. Of this was born the SWARM Project, Artificial Life, and agent-based modeling, the latter of which stands today as the primary schema for computer simulation in the life and social sciences.

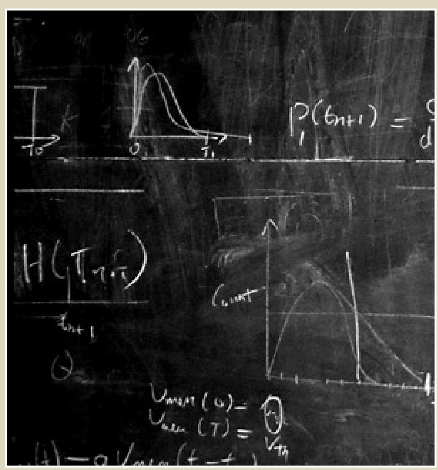
For much of the phenomena of self-organization, theorems are so hard to come by, that increasingly, simulation is an endpoint—an end instead of a means to truth—and some argue that perhaps this is not only all we can hope for, but all we should hope for. Implicitly we are asking if those tools of classic applied math, which served physics so well, are up to the task of quanti-

Thinking back over the history, Cowan grows pensive. “It looks easy now,” he says of the Institute’s creation. “We were touching the right vein at the right time. It worked and it wasn’t because we were brilliant, it just happened at the right time.”

He finishes with an important question for SFI and the future of science: “What questions today are at their right time?”

fying the tangled web of form intermingled with function that is complex systems. SFI researchers such as Walter Fontana and Jim Crutchfield might respond in the negative, as they have been proposing the use of new formal languages that seem better suited to describe the dynamics of a world of complex systems.

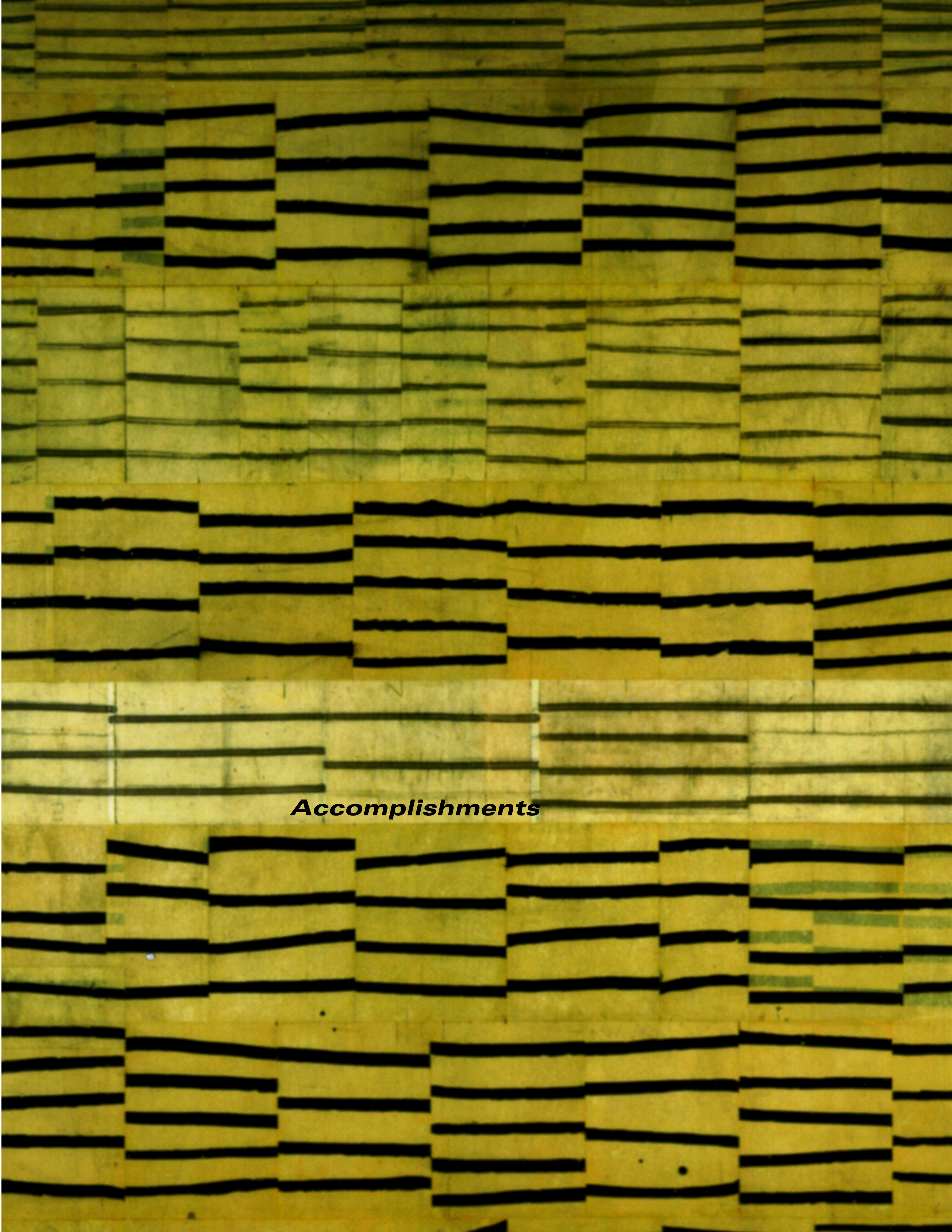
Much of the mathematics responsible for our understanding of the physical world traces its origins to the relatively simple propositional logics born of Aristotelian syllogism. Fontana has for some time been a proponent of the use of the "lambda-calculus"—a logic that may be better suited for expressing the complexities of multiple intermingled processes that seem closer to the interdependencies of biological and social systems.



Crutchfield, on the other hand, is a proponent of the use of "epsilon machines," comprised of a set of causal states as well as transitions between them, as the fundamental objects in a formalism for describing the information-processing architecture of complex systems. Indeed, he has proven that epsilon machines are the optimal and unique predictors of minimal size. “No alternative representation can do better,” he says.

Building on these mathematical foundations, Crutchfield has in mind no less than a goal of a "Grand Unified Theory of Complex Systems” capable of putting all complex phenomena under one mathematical roof. Such a law would be akin to that Holy Grail of physics that aims to explain all the forces of Nature: gravitational, electromagnetic, and nuclear, as particular instances of a single fundamental phenomenon. Today, after centuries of work, physics finds itself short one last mathematical bridge. After 20 years, complex systems is just starting its journey.

—Daniel Rockmore



Accomplishments

What SFI Accomplished

Setting Up House

On Santa Fe's dusty Canyon Road, a route Native Americans and trappers once used to enter town to trade, the early core of SFI set up shop. They moved into an L-shaped convento—or convent, a place with thick muddy-smelling adobe walls and a chapel with stained-glass windows letting in rainbow-colored light. Among the group was an eager young postdoctoral student, the Institute's first, John Miller, who came to Santa Fe in 1988 and is now acting vice president for academic affairs at SFI and professor in the Department of Social and Decision Sciences at Carnegie Mellon University.

"At the time I was working on my thesis," he relates. "It was this Jekyll and Hyde thing that included traditional economic theory and non-traditional study of genetic algorithms (GAs), game theory, and cooperation." He'd come from University of Michigan, where he'd sat in on classes in which John Holland was discussing GAs.

Recalling those days, Miller smiles with the sense of promise that flowed through the convent, a time he described as "a career highlight." Then, George Cowan occupied the Mother Superior's office, he relates with a chuckle. Initially Miller didn't grasp Cowan's full importance, but slowly Cowan's mastery of science and his artful leadership became clear. "The more I learned about him, the more amazed I was," Miller says.

In the initial meetings there was a language barrier, Miller relates, the physicists looking at things in terms of particles and how they behave. "The physicists said, 'Tell us your problem and we'll get it solved.' We said, 'Our particles have expectations and strategies, yours don't, and that makes a difference. When a car is about to crash, the driver behaves differently than the fender.' People started to work things out, to collaborate on key questions.

"It wasn't that a physicist was doing economics, but a physicist, economist, biologist, and chemist all realized that they were working with the same problem. Say you're looking at organization," he explains. "For an economist, that might mean thinking about markets, for a physicist, thinking about magnets, for a biologist, about a cell. We all have our own way of approaching it."

The early participants had many interests: economics, origins of human language, global security, biology and information, learning and cognition, and adaptive agents, topics that vibrated with possibility. Twenty years later these themes still live and thrive in the currents of SFI science.

One focus in those early days was a double-auction tournament put together by Miller, John Rust, Richard Palmer, and others. "We dug into the details of what turned out to be the Internet," says Miller, "and we produced the first Internet auction." The tournament dealt

The Real Who's Who in Science

In an effort to gain a deeper understanding of networks, SFI External Faculty member Mark Newman, a professor at the University of Michigan, chose a subject at his own doorstep: scientific collaboration. Examining who wrote papers with whom took him far beyond there though, through a web of connections spanning the globe.

Newman is one of the leaders in the study of networks. His work explores the "small world concept," the notion that we are all connected to each other by no more than six steps or degrees. He found scientific collaboration to be an obvious choice to provide the data necessary to make conclusions.

"Who has collaborated with whom is well-documented and easy to work with," he says. Because scientific papers are catalogued in online databases and each author is listed by name, there is a well-defined "paper trail." The definition of a relationship between nodes in the network is also clearly defined; each collaborator on a paper can be considered to have a reasonable connection or relationship to the other collaborators.

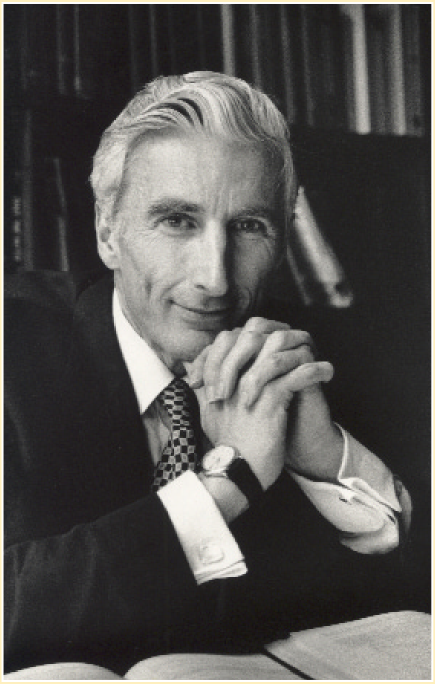
Newman and his colleagues studied databases containing millions of papers written by scientists in biology, physics, math, and computer science and found that although there were significant differences between the fields, there were similarities in the way the researchers tended to collaborate within topical communities, and that most scientists were still only separated by four to seven links. As network mapping goes, these databases are some of the largest networks ever mapped: the biology one alone contained 1.6 million papers.

Newman found that there are notable patterns in the network. Some scientists had many papers and collaborators while others had few, and many manifested clustering patterns, centered around certain influential collaborators. Newman even identified the best-connected scientists in various fields. When astrophysicist Martin Rees, the Astronomer Royal of Great Britain, was crowned the best-connected astrophysicist, he was reported saying, "I'm certainly relieved not to be the most disconwith the most basic ideas in economics: how supply and demand result in prices, a concept casting back to Adam Smith's "invisible hand." People submitted computerized trading strategies. Buyers and sellers made bids, and out of that emerged prices.

This was one of the first explorations of a complex adaptive system, in which individual agents interact to result in a price. "We found that even with very dumb traders, the market would work efficiently. Behavior didn't matter that much," says Miller, sitting forward with excitement of that early discovery. "Very simple rules were all you needed to make a market work."

The double-auction tournament was the first big multidisciplinary project that came out of SFI. It involved physics and economics. "It was wildly innovative," Miller says. But that was the whole tenor of the times at the convent. Every day, conversations ignited new concepts, new directions. "We kept having these ah-ha experiences."

Miller traces the auction project forward in time. It morphed into one of the first agent-based models of a financial market, the Artificial



Martin Rees

nected astrophysicist."

"One's success and centrality depends on one's collaborators," says Newman. However, his network showed that the best-connected scientist did not necessarily have to have the largest number of collaborators. Rather, one could also achieve this honor by having fewer collaborators who happen to be well connected themselves.

SFI Postdoctoral Fellow Michelle Girvan, who worked with Newman and studies many different kinds of networks, notes that studying the scientific collaboration network shows that the driving force in science is not just the subject matter.

"You see these distinct clusters that show the inherently social aspect to science," says Girvan.

—*Rebecca E. McIntosh*

Stock Market, created by W. Brian Arthur, John Holland, Blake LeBaron, Richard Palmer, Paul Taylor, and Brandon Weber. They took those early ideas and put in learning and artificial agents. Today J. Doyne Farmer, heading a team of researchers, has brought the ideas forward to study market forces. "It's a beautiful thread, from the very beginning to now, an example in which research inspires more research."

That early interest in adaptive agents has transformed today into a worldwide use of them in fields ranging from medicine to political science. Information technology has united with biology to solve important problems in the defense against viruses both in computers and in human bodies. Early notions about global security have led to complex understanding of ways in which parties interact in war.

Technology was another defining part of early SFI. There in the century-old Cristo Rey convent, with a hand-carved saint presiding over an inner courtyard, the world's newest computer technology whirred away; this, at a time when the machines were rare. "There were computers everywhere," Miller remembers. "As a tool they helped to bridge the gap between

Expanding the Web—Internationally

Santa Fe Institute's International Program encourages the expansion and enrichment of SFI's research. It does this through funding programs and researchers around the globe. Interested parties find their way into the SFI web in many ways. A prime example is the story of David Storch.

Like many international scholars who come to SFI, Storch was initially inspired by the work of a particular scientist—in this case MacArthur Fellow Stuart Kauffman. Storch first heard Kauffman speak at a conference on evolutionary biology in Debrecen, Hungary, in 1991. The talk piqued Storch's interest sufficiently so that he began to follow the work of SFI scientists closely.

As an associate professor at the Center for Theoretical Physics (CTP) in Prague, Czech Republic, and an ecologist by training, Storch has watched developments in the field of macroecology with interest. In the late 1990s, he was pleased to find that one of the men responsible for seminal works in the field, James H. Brown, was an SFI External Faculty member. At that time, Brown was working with SFI Distinguished Research Professor Geoffrey West and a team of SFI-affiliated researchers developing a theory of allometric scaling.

Storch's trajectory towards the Institute took another step forward in May 2001, when he and several of his Czech colleagues attended an SFI International Workshop in Leipzig, Germany, highlighting complexity science research in Eastern Europe. At the workshop, Storch met West. Since he was just starting to experiment with his own interdisciplinary research team in Prague, Storch was eager to quiz West on the difficulties that inevitably arise when physicists and biologists work together. "Storch was young, intelligent, and inquisitive," says West of this early meeting.

A more substantive relationship with SFI developed with Storch's successful application for an International Fellowship in 2001. Storch visited SFI three times during his two-year appointment as a Fellow and worked with Brown, Murray Gell-Mann, and Researcher Eric Smith on scaling biodiversity.

physicists and social scientists."

Then, he continues, he had to "go and be an adult," so he left for Carnegie Mellon University, but he returned to SFI over the years as an External Faculty member. Around that time SFI began straining against the seams of the convent, so in 1990 they moved to what all refer to dryly as the "law offices." "There's a Zen saying," relates Miller. "After the ecstasy, the laundry." That sums up for him the shift that took place at the time. "The convent had excessive charm and style," he adds. "It was funky, but incredibly small. The law offices provided more space, but weren't designed for interaction." Miller reflects on the change that took place within the new space. "That early energy would have been hard to sustain. We came up with great ideas, but now it was time to turn them into science and publications. We realized we'd made important connections; it was time to figure out what they meant."

The move to SFI's current George Cowan Campus in 1994 brought still another transition. "It was pretty run down," Miller says of the hilltop house. "It had an overgrown courtyard with a crusty old hot tub adorning it." It was a far cry

As well as that research, collaboration with the allometric scaling group also developed, as the group ventured more deeply into the topic of biodiversity. Storch wrote the review "Comment on 'Global Biodiversity, Biochemical Kinetics, and the Energetic-Equivalence Rule,'" which discussed a paper published by Brown and West's group relating temperature to biodiversity. Both appeared in *Science.*

This year, Storch became a pioneer in his own right by publishing in the major scientific journal *Vesmir* (The Universe), the first report on self-organization in biology written in Czech. Most recently, he is acting as co-organizer for the joint SFI/CTP Scaling Biodiversity Workshop in Prague in October 2004. There Storch will likely meet up with other intelligent, inquisitive young scientists, and thus SFI's international web will continue to expand.

—*Shannon Larsen*

from the sleek, inventive structure that steps down the hillside today. "We were still having those same great conversations of the convent days, but in a more mature way."

Expanding the Vision

"Before I came here, I was narrowly focused on my specialty, cellular automata," says Erica Jen, who, in the late 1980s as a focused young scientist, visited SFI from LANL as many did, just to touch into the excitement of the place. Later, in 1996, she became vice president for academic affairs and now is an External Faculty member. "After coming here, all borders were gone in my view," she says. "Everything was thrown open."

Jen's transformation mirrors what's gone on at the Institute itself over the years. After the imaginative convent days and the structuring of the law office ones, in the mid-to late '90s, a new transformation was beginning at the Cowan Campus. "It was a time when we were really developing a more profound and ultimately more powerful understanding of what it means to be interdisciplinary," she says.

Prior to this period, the term interdisciplinary

Predicting the Path of Infectious Diseases

Diseases spread through populations by way of the networks formed by physical contact between individuals. Traditional epidemiological theory, however, ignores the concept of these contact networks in favor of "compartmental" models in which every individual in a population group has an equal chance of spreading the disease to everyone else. Applying such a compartmental model to a phenomenon like the recent Severe Acute Respiratory Syndrome (SARS) results in the prediction that—without public health intervention—all such outbreaks should spark large-scale epidemics. Yet, in fact, this is not the case: during last year's events, some outbreaks did reach epidemic proportions but some did not, and, in general, outbreaks varied greatly in size.

SFI External Faculty member Lauren Ancel-Meyers and her colleagues are looking beyond traditional models and are instead using new quantitative methods of network epidemiology to better predict the fate of such outbreaks. Last year Ancel-Meyers worked with Dr. Babak Pourbohloul, director of mathematical modeling at the University of British Columbia's Center for Disease Control, and members of the Scientific Investigators' Vaccine Initiative (SIVI) to create a mathematical model that describes the spread of SARS through a city. Using demographic and census data from Vancouver—household size, the number of houses, distribution of schools and hospitals, and other data—they built a model of the patterns of interaction in the city.

Using mathematical models to analyze the spread of disease isn't new, but using network theory as an approach to such modeling is. Interestingly, Meyer's approach came about as a result of her own personal network dynamics at work. Network theory is often used by researchers investigating social interactions, and it's become popularized in the past decade through the concept of "six degrees of separation." "Six degrees of separation" asserts that each person on the planet is at the most removed from every other person by six degrees, or six connections with others.

referred to a collaboration between two disciplines, using techniques from one field such as physics, and applying them to another, such as biology. What transpired as SFI scientists from many disciplines worked together transcended that. "We've gotten to a point where two or more people from different backgrounds are changing for each other the questions they're asking. The scientists are informed by the sensibilities of other researchers. It has to do with a real change in perspective," she says.

The collaboration between chemist Walter Fontana and political scientist John Padgett is one example. Through reading a paper Padgett wrote on the flowering of Florentine society, Fontana saw connections with abrupt physical transitions of many chemical reactions. "There was a natural resonance in Padgett's analysis of Florentine society leading up to the Renaissance with the emergence of the first self-maintaining, self-reproducing cell, or how a new paradigm of organization comes into existence," says Fontana. Through sharing their science, both were able to see their own fields through different lenses.

Early in her tenure as vice president for aca-

Ancel-Meyers had worked with epidemiologists and the U.S. Center for Disease Control on developing models to help predict and control the spread of walking pneumonia in closed settings such as hospitals, military barracks, and psychiatric institutions. However, she found herself frustrated with the traditional compartmental approaches to modeling. She went on to become a postdoctoral fellow at SFI, where she and then SFI Research Professor Mark Newman realized that the network theoretic tools he had been developing were perfect for this problem. They adapted them to a healthcare setting in which the nodes in the network were both people (caregivers) and places (wards). They found that modifying the behavior of caregivers

PHOTO: REUTERS/CORBIS

demic affairs, Jen experienced first-hand the convening power of SFI and saw a turning point in the Institute's methods. She was putting together a grant proposal to send to the National Science Foundation. While canvassing among researchers to see what ideas could be brought together, she spoke to statistician and economist David Lane. "He said, 'Instead of building on what you already have at SFI, use the proposal process to reach out to new people and to understand what outstanding challenges exist and how SFI might contribute'"

It's the notion that George Cowan began with, but at this point, the boundaries really split open. "We were poised so we could tap into the intellectual curiosity of first-rate researchers all over the world," she says. "We could just call people up out of the blue, talk to them, and recruit them to become involved. It was a tremendously open-ended view of how an institution could do science."

SFI has used this approach to initiate several major initiatives. Among them are the Keck Foundation Program on Evolutionary Dynamics; the Founding Program on the Study of Robustness, funded by the David and Lucile

is probably the most important form of intervention—a strategy that had been previously overlooked because of the low numbers of infected caregivers.

Babak Pourbohloul was charged with using mathematical models to help epidemiologists confront SARS when it first appeared in Canada. He ran across the Newman-Ancel-Meyers paper on walking pneumonia (published in *Emerging Infectious Diseases)* and thought that the approach had great promise as a tool for dealing with SARS (and other respiratory-borne pathogens). He called Ancel-Meyers, now an associate professor of integrated biology at University of Texas in Austin, and asked if she would help. Within two weeks they had submitted a grant application to the Canadian Institutes of Health Research along with members of SIVI, and within a few weeks after that, they received an award for their collaborative research. It includes development of vaccines, diagnostic tools, and mathematical models to be used in prediction, intervention, and vaccine deployment.

Pourbohloul and Ancel-Meyers met in person for the first time in May 2003 at the Institute, where they spent a week together laying the groundwork for this project. Mark Newman, now an associate professor at the University of Michigan, was also visiting SFI at the same time, and joined the team.

The mathematical models Ancel-Meyers builds borrow from the same sociological connections she worked with earlier. The models account for the points of connection between individuals. Each person within a community is represented as a point in the network. The edges that connect a person to other people represent interactions that take place inside or outside of the home, including those that take place at school or work, while shopping or dining, while at a hospital, etc. The network thereby captures the diversity of human contacts that underlie the spread of disease.

Some people may come into contact with very few people, but others may have many strands connecting them to other people in the community through their work or social habits. If this highly connected per-

Packard Foundation; the Santa Fe Institute Consortium: Increasing Human Potential; the Robustness in Social Processes initiative supported by the James S. McDonnell Foundation; and the Behavioral Sciences Initiative. "While other institutions were building on existing research, we had the latitude to explore whole new areas," she says.

During this period, the Institute's campus itself changed in a way that reflects the direction of this expansion. The lovely Cowan Campus spread down a hill in tiered levels, with three "pods" of offices connected by comfortable meeting areas, all with easy access to the outdoors. It's an obvious melding of the best of the architectural elements that preceded it. It has the communality of the convent, with the privacy of the law offices.

son becomes sick, he or she has the potential to become what researchers call a "superspreader," someone who spreads disease to a lot of people in the community. Identifying potential superspreaders is one step in curbing an outbreak.

This type of mathematical modeling may have important implications for public health officials. When the SARS outbreak began, officials were in a quandary. They needed to act quickly to control the spread of the disease, yet they lacked the information necessary to determine which interventions would be most effective. Would they be best served by closing schools or by supplying health-care workers with better face masks, by limiting air travel, or by waiting for a vaccine? Such decisions may be easier to make in the future, thanks to advances in mathematical modeling.

Because contact patterns differ from community to community, mathematical modeling requires that a model be built for each individual community. Ancel-Meyers and Pourbohloul are currently working with a large team of Canadian epidemiologists and infectious disease experts to build network models of four Canadian hospitals and two communities—one rural and the other urban. Once good network models of these hospitals and communities are in place, they can be used to predict and control the spread of all kinds of diseases. At the same time, modeling these distinct communities will allow researchers to see if they can draw any generalizations across communities. They hope to be able to say that, in general, one type of intervention works better than another.

Today

SFI Today

Unlimited Intellectual Horizons

Though SFI is now well established, the research continues to reside in a state of creative tension that its past engendered. Led by the faculty, postdoctoral fellows, and students, existing work creates new research directions. These develop substance through "founding workshops," or working groups, which may evolve into more complete research themes. The creativity within the themes spins into new directions, with new researchers joining in to create a steady stream of novel ideas and new scholars, keeping SFI at the forefront of cutting-edge science.

Networks, Robustness and Resiliency

In 1999, when young SFI researchers Mark Newman and Duncan Watts first started sending out papers for publication on network theory, the replies were consistent: no one is interested in networks. Only a few years later those same scientists were appearing on the Discovery Channel (Newman) and in *The New York Times* (Watts). Suddenly, people couldn't get enough of network theory. So what changed?

Newman defines the science as "a bunch of dots joined together by lines." As examples he cites the Internet in which computers are connected in cyberspace, and food webs, in which animals are connected to each other by who eats whom. But his favorite example is a social network in which people are connected through such ties as friendship, family, or business.

He casts his gaze back to the 1960s when a controversial psychologist named Stanley Milgram sent letters to randomly chosen people

The Talk Radio Effect

The mission of the Santa Fe Institute's Business Network is to keep corporations and government entities abreast of SFI's research progress and current thinking, while SFI gains input from those entities. It accomplishes this information exchange through an annual series of conferences and workshops, during which representatives from nearly 60 concerns, such as Ford Motor Company and John Deere & Company convene. Scientists, project managers, and executives attend, often finding new insights into improving their operations or furthering their research. Some even come away with whole new business models. One example is the web site InnoCentive, which offers a quick way to solve daunting dilemmas.

Say the leader of a corporate R&D lab coordinating a big project comes upon a problem that badly needs a solution. Maybe it involves a baffling aspect of cell metabolism, or perhaps necessitates a cheaper way to synthesize an important molecule. Whatever it is, the collective wisdom of the company's team can't find an easy solution, and they say it will require several precious months for them to solve it.

So, the leader posts the question along with a cash award at www.InnoCentive.com. InnoCentive, which was founded by the pharmaceutical firm Eli Lilly and Company, is an online business that offers an unorthodox way for researchers to cut through their Gordian knots quickly. On InnoCentive's web site, the labs in difficulty (Seekers) post their questions (Challenges) for perusal by InnoCentive's community of nearly 70,000 registered scientists (Solvers), who represent over 60 disciplines in biology, chemistry, and biochemistry and hail from countries as diverse as the United States and Russia, Mongolia and Khazakstan. There are about two dozen Challenges posted on the site at any time, and awards range from $10,000 to $100,000. Seekers evaluate the proposed solutions as they trickle in; with a little luck, a good solution comes within a few weeks, a winner is declared, the award is paid, and all parties go home happy.

InnoCentive has been online since 2001. Under the guidance of Lilly's CEO Darren Carroll, it was incubatto see if they would forward them back "home." Though almost all got lost, some found their way back, the letters passing through an average of six pairs of hands en route. Thus arose the theory that playwright John Guare termed "six degrees of separation," and from which arose a cult following for the "Kevin Bacon Game."

When Newman and Watts joined forces at SFI, they, as Newman says, "started working on rather simple mathematical models of networks," exploring the idea behind this "six degrees of separation," namely, how everyone comes to be so close to everyone else.

What they found was that if you take a sampling of people, you'll find that there are connections, but the connections are mostly local. But a small fraction will be random in structure, reaching beyond the local connections. "That was enough to create a 'small world effect,'" he says smiling with excitement at the idea.

With that in mind, Newman wanted to look at what real social networks looked like. But he wanted a large enough sampling to broaden the scope, as did Watts. Newman chose the online bibliography *Medline,* a network which included

ed and launched at e.Lilly, a business division of Eli Lilly and Company that invests in research on alternative business models. More than 30 companies, as well as labs within Lilly itself, routinely use InnoCentive to help accelerate their R&D efforts, according to InnoCentive's Chairman and co-founder, Alph Bingham.

The idea for InnoCentive hit its two founders, Bingham and his partner Aaron Schacht, after they attended an SFI public lecture, and it continued to grow through their exposure to seminars offered by the Business Network. Bingham, who also serves as vice president of e.Lilly and vice president of Lilly Research Laboratories Strategy, says he and Schacht were struck by two things: the Santa Fe Institute-ism "more is different," and the "small world" property of large social networks (this involves the concept of "six degrees of separation," whereby any two people on the planet can be linked to one another through a chain of six or fewer acquaintances). They then set about figuring out how many scientists they would need to achieve what Bingham calls the "talk radio effect": the fact that with a large enough audience, even the most obscure question is likely to be heard by an expert on that topic, or by someone who has the right set of facts to puzzle out the answer.

By analogy, Bingham and Schacht reasoned, an obscure question thrown at a broad and large enough audience of scientists should find its way into at least one "uniquely prepared mind." After growing their network of Solvers past a certain threshold—around 5,000 to 10,000—they got the concept working. The solutions are often novel and surprising, which, of course, is the whole point. For example, Bingham says, one Challenge involving drug metabolism was solved out of left field by an expert in X-ray crystallography, a domain the Seekers never would have thought to look into if left to their own devices.

—Matthew Blakeslee


PHOTO: HENRY BLACKHAM/CORBIS

listings of papers by more than a million scientists. "I wanted a big network to test calculations," he says. Meanwhile Watts did a modern version of Milgram's experiment using the internet, also involving massive numbers of connections, research that led to his popular book titled *Six Degrees: The Science of a Connected Age.*

Of course, one must put at the forefront of network research, the work of one of SFI's original faculty members, MacArthur Fellow Stuart Kauffman. He was one of the first scientists to incorporate the notion of a network in the study of genetics. Many others continue to further the research, delving into areas with applications ranging from virus control in computers to traffic routing in cities. "There are lots of papers on networks coming out today," says Newman. "It was nice that SFI was in there on the ground floor."

Human Social Dynamics

"In traditional economics, actors were thought to be hyper-rational, hyper-informed," says John Miller, of one of the original questions SFI tackled. "SFI was a natural place to speculate on 'What if they're not that way? If

Cancer's Complex Nature

The emergence of complex systems as a discipline came about in large part as a desire to study life, from its origins in some primordial molecular soup to the complicated web of interactions into which it has evolved. Inevitably, as the toolkit of scientific techniques of complex systems has grown, it also has proved to be useful for addressing the darker side of life that is colored by the phenomena of disease and death. SFI scientists have contributed to the treatment of HIV and tuberculosis. Most recently, they've begun to study cancer through the lens of complex systems.

At some level of consideration, the healthy human body is a multidimensional mosaic of cells, differentiated by their various functions (e.g., skin cells, muscle cells, etc.). Cancer develops as an uncontrolled reproduction of abnormal cells, which can then embark on a deadly cycle of invasion and destruction of nearby tissues that spreads throughout the body. Cast in the setting of complex systems, organs become a competitive landscape where abnormal and normal cells are actors fighting it out for resources. Should the abnormal cells gain the upper hand, the function of the organ may be in jeopardy: a liver that suddenly does not have sufficient healthy tissue to maintain the body's chemical balance, or lungs lacking the healthy tissue to absorb the oxygen that sustains life, or so heavy with tumor growth that they collapse under their own weight.

Within this competitive landscape, the etiology of cancer can take on an evolutionary interpretation. Cells reproduce, compete, and evolve with a clear advantage (toward an end goal of population dominance) conferred on that cell type that reproduces the quickest. Evolutionary pressures are also induced by therapies, pushing a "natural selection" of those cells resistant to treatment.

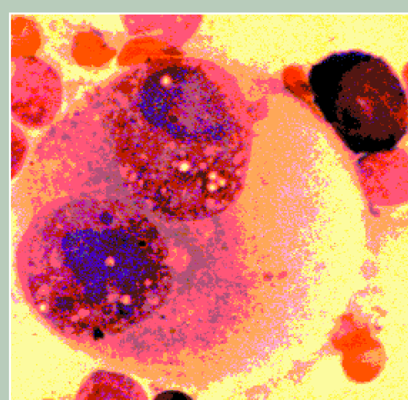
The language of evolution, selection, and competition, puts cancer research squarely into SFI's purview. In particular, SFI Science Board member (and University of New Mexico professor of computer science) Stephanie Forrest is involved in an active collaboration with Carlo Maley of University of Washington's we have adaptive agents, how will they behave differently?'" Answers have come, exposing the weaknesses of the traditional model and opening up whole new ways of thinking. "We've seen that humans, for instance, are not as selfish as we thought," says Miller. "People actually like to give to other people. Prior to this, economists didn't believe this." Such is the root of the Human Social Dynamics initiative, which explores why actors, whether people, viruses, or countries, act as they do, what such actions mean, and how they affect the larger context of action.

Facilitating the project is the variety of fields convening to look at behavioral questions, ranging from biology to economics, physics to archeology. Miller continues, "For the longest time, economists ignored psychologists and neuroscientists, but now we're recognizing the connection between the fields. To have good economic theory you have to understand psychology, to understand psychology, you need to understand how the brain works. They are groups that really should be talking to one another but for whatever reason hadn't."

Until now.

Fred Hutchinson Cancer Research Center. Forrest and Maley use some of the tools of evolutionary simulation—the same agent-based modeling that came of age in the SFI-led investigations of "artificial life."

"We're investigating various simple hypotheses for the dynamics of resource competition among pre-cancerous cells," says Forrest. Like any good computational simulation, their work creates an in-silica laboratory, not just reproducing known phenomena, but also investigating new ideas for therapies. A recent paper with another Hutchinson researcher, Brian Reid, investigates the possibility of a new therapy. "Rather than killing off the cancer cells," says Forrest, "it instead seeks to boost the reproductive fitness of relatively benign cells, thereby allowing them to out-compete the cancer cells in the race to dominance."



Hodgkin's Disease/Reed-Sternberg cells

In another direction, SFI Distinguished Research Professor Geoffrey West is studying tumor growth. He and his group take the approach that fundamental principles for growth in any living form, be it microbe, marmot, man, or malignant tumor, can be deduced from considerations of energy and resource transport that are independent of organism. This is the study of allometry. West and his group are using these tools to try to develop a physics-based model of tumor growth that explores energy delivery via capillaries at the tumor surface, as well as applying their understanding to healthy ontogenies.

Cancer is essentially life run amok. SFI scientists are part of the effort looking for ways in which this complex system can be explained and contained.

—*Daniel Rockmore*

Today, as well as more open conversation, tools—methods, data, and technologies—exist to delve deeper than ever before into understanding subjects as complex as disease spread, learning, ageing, and language.

Working individually and in teams, the scientists involved in the Human Social Dynamics theme are performing research that spans across the globe. The projects range from exploring cooperation among groups in Bali to examining the brain in order to better understand how humans learn and how they make decisions.

Living Systems

"A small, swift organism like SFI could have an advantage here," says Walter Fontana reflecting on SFI's future in science. He's pondering how the Institute came to be what it is. "How did it happen? How can we write a recipe? What are the design principles of the SFI system? How can we create and maintain a space where the unexpected can happen?"

His questions resonate with those being explored in SFI's Living Systems initiative. They also resonate with work he's been doing over the near decade since he came to the Institute,

It's Alive!

Currently, teams around the world are competing to be the first to create artificial life. They're doing so by either minimizing the contents of existing cells, or building new cells from scratch. Steen Rasmussen, a Santa Fe Institute (SFI) External Faculty member and theorist at the Los Alamos National Laboratory (LANL), has one such team.

He believes they've found the winning approach when it comes to creating artificial cells, or protocells as they are often called. Rasmussen's team, which includes Liaohai Chen of Argonne National Laboratory (ANL), has examined the minimal requirements for a cell to be considered alive, and how best to meet those requirements in a laboratory setting. The definition of life, although constantly debated, includes the ability to utilize and transform resources, to self-assemble, to grow, to replicate, and to evolve. Therefore, each cell must have metabolic elements, a container, and a way to store and pass along genetic information.

Modern cells have a membrane composed of lipids and proteins that work together to selectively allow things in and out. In order to keep it simple, Rasmussen's innovative approach to making a cell container is to use similar lipid-like molecules in a micelle or sphere, but to have many of the protocell's components stick to the outside, thereby eliminating the need for a selective barrier. He describes it as looking like a bunch of cell components stuck to a glob of chewing gum. Some components do end up being inside the cell, but overall, the nutrients and waste are able to attach and detach without the need for a complex membrane.

"People have to forget everything they know about modern cells," Rasmussen says. In fact, the novel approach his team envisions for a living protocell resembles a normal cell turned inside out.

The team proposes to use PNA, a nucleic acid with a protein backbone instead of a phosphate-sugar one (so that it will stick to the lipid aggregate), and a polycyclic hydrocarbon that uses light to create energy. The protocell is actually designed to use the gene sequence as part of the metabolic pathway. Parts of the protocells have been well tested, such as where he has served as a research professor for the past six years. During that time he's helped science itself wed areas as disparate as physics and chemistry with biology and computation.

He's had a long and exciting journey into the very heart of how novelty arises in evolution. "In biology, genes instruct the production of molecules whose interactions generate the organism," he says. He explains further that during evolution, genes are changed randomly, but through a series of complex processes, selection informs the organism that is constructed from genes.

"When we think about the innovation of biological organizations, we must bear in mind that these processes are responsible for the consequences of genetic mutations," he says. As an analogy he presents the 1914 assassination of the heir to the Austro-Hungarian empire in Sarajevo. "We cannot say that genetic mutations cause organizational change in biology any more than that assassination caused World War I. Whether and how a mutation alters an organism is a matter of the molecular processes that interpret the genetic information, and these processes are themselves subject to evolution."

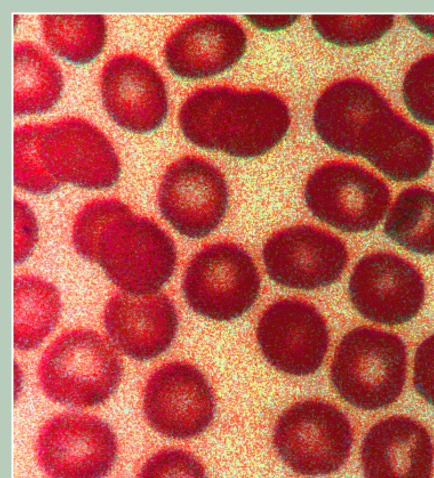
the self-assembly of the micelle, the nature of PNA and hydrocarbons, and the likelihood they will behave as planned. However, an actual protocell has yet to be made.

"The big challenge is to put all the pieces together and have them work in concert," says Rasmussen.

He and his colleagues think they have the right angle on how to create artificial life, but they are not alone; groups around the globe are working on similar endeavors. In September 2003, Rasmussen and Chen, along with David Deamer (UC Santa Cruz), David Krakauer (SFI), Peter Stadler (U. of Leipzig/SFI) and Norman Packard (ProtoLife/SFI), co-organized a workshop on bridging nonliving and living matter held at Los Alamos National Laboratory and the Santa Fe Institute.

If Rasmussen's team or his competition is successful, and humans can generate something that qualifies as life, many exciting things are possible. By capturing the mechanisms of self-assembly, self-repair, and evolution that living cells use so wisely, machines and other inanimate objects might infinitely benefit. Such programmable nanomachines may have applications in tasks like environmental remediation, energy production, and enhancing human health. And as with all new scientific discoveries, there are uses we can't even imagine.

"This is kind of a new approach for us," says SFI Research Professor David Krakauer, referring to the experimental nature of the project.



Normal peripheral blood smear

Krakauer explained that protocells could reveal many basic principles of biology, in turn enabling new research and modeling of how biological systems acquire and transmit information.

—*Rebecca E. McIntosh*

He adds: “Mind-bending, isn’t it?”

Indeed, it is. Fontana’s methods are equally so. Rather than modeling a whole organism, his tact is to take a single type of molecule—RNA—and think of its sequence as analogous to the genome, its shape as analogous to the biological organization, and the process of folding, which determines how a change in that sequence results in a new shape, as analogous to development.

“Behavior is not something that can be altered directly,” he says. As an example he gives a change in the behavior of a society at large. “All you can change is a rule of interaction, like a law or an institution, and watch how the resulting dynamics unfold in the given context, leading to some new behavior at the system level.

“So you want to change something at one level, but you can’t do so directly at that level. You have to change something at the lower level.” He’s interested in how the processes that mediate change from the lower to the higher level organize the landscape of the possible at the higher level. “There’s always a certain element of surprise, but science is about getting

The Beauty of Collective Wisdom

Though the term diversity is used often today, economist and political scientist Scott E. Page says that, until recently, the theoretical implications of diversity have not been well understood.

“There’s a sort of loose idea that different types of people bring different and fresh perspectives to a problem, but there’s been little formal theory on diversity,” says Page, a Santa Fe Institute External Faculty member and professor of complex systems, political science, and economics at the University of Michigan.

“I’ve been trying to play mathematically with this idea to find out whether diversity is a good thing when it comes to decision making and problem solving.”

Here’s one of the problems that Page has been playing with: Take a group of agents that have differing levels of skills and put them to work solving a complex problem. Now group them together into different teams. One team consists of the agents that individually are the best at solving the problem. The other team is selected randomly.

Which team wins? The answer is surprising.

“The random group will do better,” says Page. And the reason for this is diversity.

Page’s research has been championed by James Surowiecki, in his recent bestseller, *The Wisdom of Crowds: Why the Many Are Smarter than the Few and How Collective Wisdom Shapes Business, Economies, Societies and Nations.* Surowiecki, *The New Yorker’s* business columnist, uses Page’s modeling with agents to argue that diversity is one of the core conditions for good group performance. Without diversity of opinion and information, “wise crowds” tend to become mindless mobs.

“On the group level, intelligence alone is not enough, because intelligence alone cannot guarantee you different perspectives on a problem,” Surowiecki writes.

For Page, who, after all, teaches complex systems, diversity isn’t a simple panacea. It may frustrate decision making and make simple problems unnecessarily burdensome. But when it comes to solving sophisticated problems (how to design a car, how to design a welfare policy), rid of surprises. There's more awe in understanding than in being surprised."

He's found statistical regularities that may hold for other, more complicated, mappings, not just RNA. Through exploring those patterns, he's elucidated one aspect of how biological systems are capable of evolving. Thus arises the term evolvability—the capacity of a system to innovate—to change phenotype. "Many exciting research developments in systems biology are unraveling the mechanisms that help us understand what the design features of biological systems are that enable them to evolve," he says.

A number of SFI researchers are contributing to furthering the understanding of living systems in a variety of ways, ranging from a model capable of explaining why factors such as metabolism and lifespan vary with body mass, to building a structural analysis of life.

Theory of Complexity

"The whole thing started with a problem that crossed a lot of boundaries," says John Holland, SFI External Faculty member and professor of psychology and engineering and computer science at University of Michigan. He's referring to

PHOTO: HUREWITZ CREATIVE/CORBIS

he notes, "Similarly skilled people tend to get stuck at the same places."

"At that point you have two options: you dig your heels in or you try something new," Page says.

His interest in new approaches keeps Page connected to SFI, where he teaches computational economics each summer. The contacts he makes have been intellectually vital for him. "The Institute has a lot of people trained in completely different ways. At afternoon tea, you might have a physicist or someone studying ecosystems ask why you aren't modeling a problem the way they would do it.

"In fact," says Page, "You might say SFI defines diverse robustness."

—*Barbara Ferry*

the history of what one might call SFI's original initiative, complexity. Over 20 years ago, he and others recognized that there must be some way to approach problems that are so complex that traditional scientific methods cannot fully explain them.

They came upon the notion of complex adaptive systems (CAS). He defines the term: "There are systems where there are a lot of individual agents that interact and also learn and adapt." An example he gives is the stock market, in which agents—traders—learn day-by-day and change their actions as they go. Another good example is the immune system. "It starts off naïve but learns how to prevent you from getting measles and other illnesses," he says.

"The nature of CAS is that it not only involves a lot of interaction, but agents learn as they interact, so they change." Through the years Holland and many others have taken the theory of CAS and used it to help understand a range of phenomenon from the workings of the global economy to the spread of the flu. Holland's newest application is toward language.

For the last 30 or so years, most linguists held to the Universal Grammar Theory, a theory that linguists see as having a genetic basis. "This grammar is wired in," Holland explains.

Time-traveling with the SFI Bulletin

The SFI Bulletin began as a photocopied flier circulated in order to inform interested parties about the burgeoning Institute's development. It transformed into a black and white newsletter, and today has become a colorful magazine. Clips from it tell a story of the exciting process of discovery.

1986

TWO-YEAR DEVELOPMENT PLAN

1. Appoint a President
2. Launch a full-scale development campaign
3. Make initial (visiting) faculty appointments
4. Expand to a year-round Visiting Fellow program
5. Select the first group of Postdoctoral Fellows
6. Complete construction of the first building on the permanent site, with occupancy by January, 1988
7. Conduct five or more workshops in Santa Fe
8. Expand the contract-funded research program
9. Acquire a major minicomputer and upgrade microcomputers
10. Establish three or more active research networks

■ Twenty-five scientists, from fields as diverse as population biology, theoretical physics, psychology, computer science, mathematics and political science will discuss interdisciplinary aspects of complex adaptive systems in a two-week

Santa Fe Institute workshop organized by Santa Fe Institute Trustees Jack Cowan (Chicago) and Marcus Feldman (Stanford). The workshop will be at the School for American Research from July 28 to August 9. It has been made possible by a substantial grant from the Alfred P. Sloan Foundation.

1989

■ The September 1988 workshop on the global economy as a complex adaptive system seemed to those of us participating to be an appropriate addition to last year's opening workshop. The sense one had was of a consolidation and deepening of a number of lines of thought which originated at the first meeting but had needed a year's time to develop into a

"Just twist a few knobs to set it to Chinese or Canadian." He pauses for emphasis. "It puts a lot of pressure on genetics."

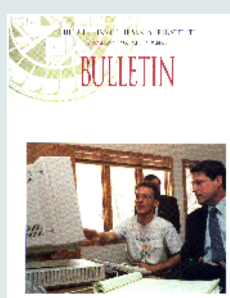
In work with colleague William Wang, professor emeritus at UC Berkeley and professor of language engineering at the Chinese University of Hong Kong, Holland is using CAS to redirect the focus of understanding language acquisition, removing emphasis from genetics and placing it on the process of learning. They've created a model in which the agents start with very primitive cognitive abilities wired in, not more complex than those of, say, a dog. The agents learn and adapt and through doing so, show that "a grammar" or language can be acquired.

The outcome of exploring this complex system is two fold, says Holland. "If we demonstrate that language can be learned with more primitive abilities, then that would change the way linguistic research is done." Secondly, he notes that the same kind of model can be used to study the evolution of language, tying it in with work already underway by Murray Gell-Mann and colleagues. "This has a lot to do with networks," Holland says. "Social interaction becomes possible because of language, so the model should generate networks of interaction. Through this we can look at how language differences originate."

programmatic approach to coherent research directions. The topic of self-organized criticality was a new tool which I brought to the community: an idea pioneered by Per Bak for physical systems, it is an attempt to explain the widespread occurrence of "scale-free" behavior such as fractal shapes of beaches, clouds, landscapes, etc.—*Philip Anderson*

■ "Complexity is almost a theological concept," observes Daniel Stein, editor of SFI's newest book *Lectures in the Sciences of Complexity* (SFI Studies in the Sciences of Complexity, Lectures Volume 1, Addison-Wesley, 1989). "But nobody knows what 'it' really is." Stein, director of the 1988 Complex Systems Summer School, has pulled together lecture and seminar notes from the school, and while they don't presume to definitively identify the elusive "it," the contents shed new light on the definition of the emergent discipline.

■ If things go right, both the organizers and the players of the SFI-sponsored Double Auction Tournament should be happy. The organizers will gain new insights into the workings of markets such as the New York Stock Exchange and the Chicago Board of Trade, and the tournament players have the opportunity to compete for reward money totaling $10,000.



1994

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

■ The Santa Fe concepts of complexity and chaos have upset the thinking of many economists, including myself. The mysterious dynamics of the economy at least resonate with the many parallels with physics, biology, and chemistry.
—*Kenneth Arrow*

■ The fact that New York City works

Currently at SFI, CAS is being used on a range of research topics. Scientists are using robots to help understand individual and collective behavior. They're also studying the workings of microscopic parts that make up solids, helping to measure such forces as entropy, structural complexity, and memory, work that has applications in nanotechnology. Such research combines to further SFI's larger goal of developing a theory of complexity, common principles and mechanisms that apply over a range of complex systems. Says Holland, "I think we've barely begun to scratch the surface with CAS. There are still major areas to explore."

Gazing Forward

George Cowan's and the early founders' vision truly has developed into a system that embodies its fields of study. From networks to complexity, robustness to evolvability, SFI is a thriving agent. Researchers get excited when they look at the new possibilities this type of science poses. "We've amassed a bunch of information about networks," says Mark Newman about where he plans to go with his research. "Now we can make predictions." In discussing the future of complexity, John Holland cites exciting work being done in cancer research. "We think we can really get some

"just in time" without central authority is an example of a complex adaptive system. And with this illustration, Holland launched into a detailed description of his research using a delightful array of analogies, metaphors, and common-sense thinking. "Complex systems come in many shapes and forms," Holland began. "Examples include economies, ecosystems, immune systems, and nervous systems. Each has the ability to anticipate the future, learn, and change in ways that are not well understood. They are diverse and highly innovative."

1999

■ In *Fragile Dominion: Complexity and the Commons,* Princeton biologist and SFI External Faculty member Simon Levin offers general readers the first look at how complexity science can help solve our looming ecological crisis. Levin argues that our biosphere is the classic embodiment of what scientists call a complex adaptive system. By exploring how such systems work, we can determine how they might fail. The book is the outcome of the Institute's 1996 Stanislaw Ulam Lectures.

■ In a letter to the journal *Nature,* Duncan Watts (SFI) and Steven Strogatz (Cornell) showed that the "Small World Phenomenon" is actually an extremely general property of large, sparse networks that are neither completely ordered, nor completely random. This result, which applies as much to networks of computers or neurons in the brain as it does to social networks, has implications for problems as diverse as the diffusion of innovation in an organization, the computational capabilities of cellular automata, or the synchronization of coupled oscillators.

■ Swarm intelligence offers another way of designing "intelligent" systems, where autonomy, emergence, and distributed functioning replace control, preprogramming, and centralization. *Swarm Intelligence: From Natural to Artificial Systems* by Eric Bonabeau, Marco Dorigo, and Guy Theraulaz surveys several examples of swarm intelligence in social insects and describes how to design distributed algorithms, multi-agent systems, and groups of robots according to the social insect metaphor.

■ While browsing the library of the Wissenschaft Zentrum in Berlin, David Stark (Sociology, Columbia) came across an article in Daedalus on advances in insights into how cancer cells change," he says. Fontana notes the loop that has formed between computer science and other disciplines: "Computer science was originally an engineering discipline, but more and more it has become a basic science on a par with physics and chemistry. It is providing novel concepts and mathematical techniques that other disciplines are increasingly using to justify their own ontology."

Applications of such research range broadly and impact all the initiatives at SFI. On first glance the work may seem distant from George Cowan's early concerns about uniting the exact sciences with the less-measurable ones, but on deeper reflection the same elements are at play here. The elegant precision he so loves is present within each initiative, while being informed, and possibly expanded by the "inelegant." The synergy is still scientists sitting across from each other igniting each others' ideas.

computer programming written by SFI External Faculty member John Holland. "It was a paper on using 'cross-fertilization' for computer programs that would be capable of adapting to new problems in the environment," said Stark. "I read it around 1990 at the height of the craze of foreign advisors making recipes, blueprints, and formulas in Eastern Europe—and it meshed with my criticism of 'designer capitalism.'" Since then Stark has been influenced by other SFI scientists, most importantly, economist David Lane for his work on "complex strategy horizons," and theoretical chemist Walter Fontana.

2004

■ Nearly two dozen middle and secondary school teachers from Northern New Mexico came to SFI for two weeks this summer to form what will be an ongoing community of practice. The focus is on how to integrate cutting-edge computer modeling, information technology (IT) tools, and complexity science into local classrooms. With support from the National Science Foundation, the project will for the next three years train New Mexico science, mathematics, and technology teachers to integrate IT concepts and computer modeling—especially of complex adaptive systems—into their courses. They will use StarLogo simulation software, participatory simulations with handheld computers, and related computer technologies.

■ For five weeks in June and July, a diverse group led by Harold Morowitz, Jennifer Dunne, and Eric Smith met to examine some of the universal structures and patterns in living systems, from biochemistry to ecology, and to ask which might have arisen from the action of underlying "laws of life." The goal was a set of rules or principles that select living forms from chemistry and geophysics, the way simple rules like the Pauli exclusion principle generate the periodic table of the elements, and all of chemistry, from a few properties of the proton, neutron, and electron. The discussion ranged from narrow technical details of core biochemistry, to broad philosophical questions of what should be meant by "laws" in biology. While the deeper questions about the ontological role of laws were largely left unresolved, a serious attempt was made to account for the specific universal features of life that are simplest and most primitive, for which the predictive power of biological laws should most resemble those in physics and chemistry.

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