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.

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.

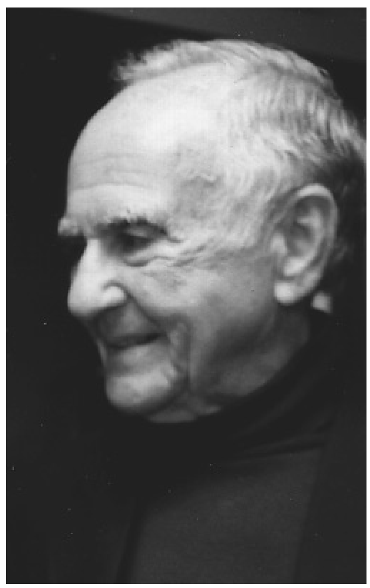


PHOTO: LAURENT GUERIN

George Cowan

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-

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.

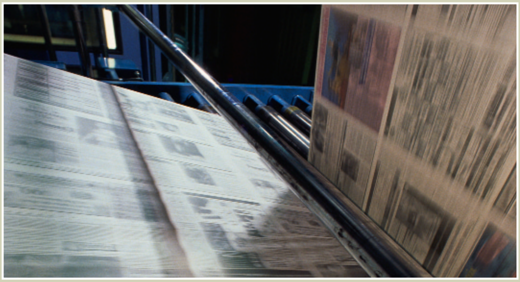


PHOTO: RON WATTS/CORBIS

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

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.

PHOTO: WILLIAM CLARK

"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

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

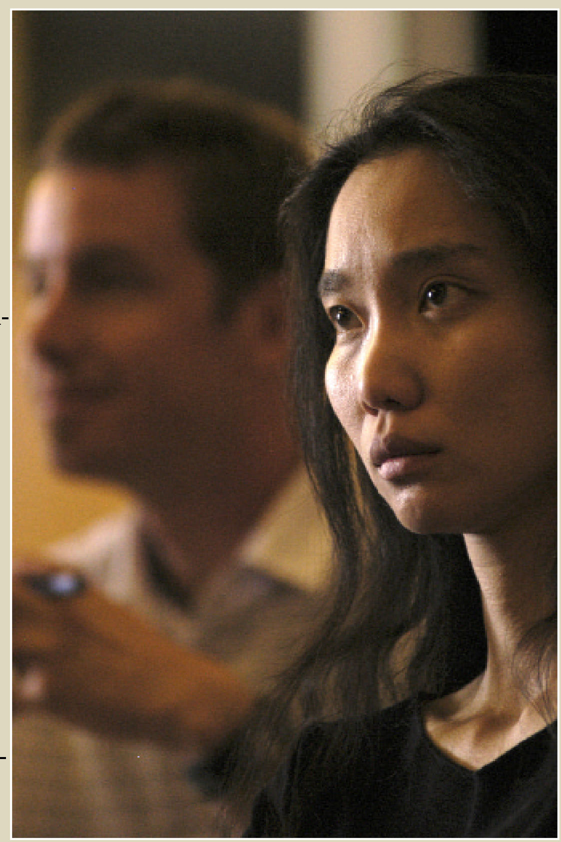


PHOTO:JULIE GRABER

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.

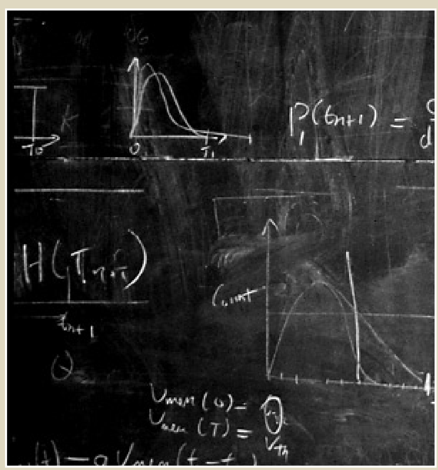
For much of the phenomena of self-organization, theorems are so hard to come by, that increasingly, simulation is an endpoint—an end instead of a means to truth—and some argue that perhaps this is not only all we can hope for, but all we should hope for. Implicitly we are asking if those tools of classic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