

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 communi-

ties, 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 discon-

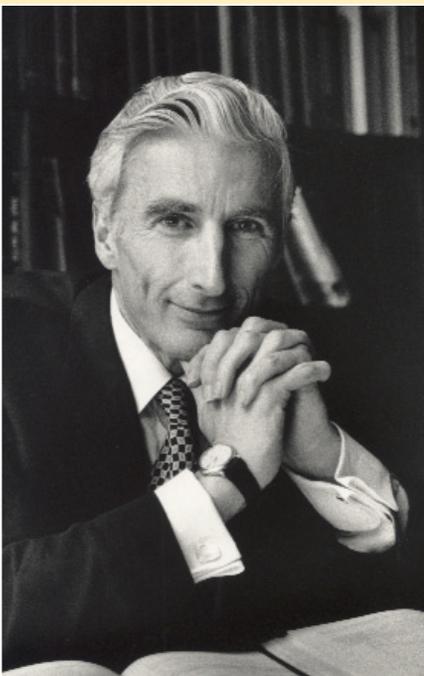
with the most basic ideas in economics: how supply and demand result in prices, a concept casting back to Adam Smith’s “invisible hand.” People submitted computerized trading strategies. Buyers and sellers made bids, and out of that emerged prices.

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 hill-top 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 pub-

lished 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 *Vesmír* (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 gen-

eral, 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-

Ance-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

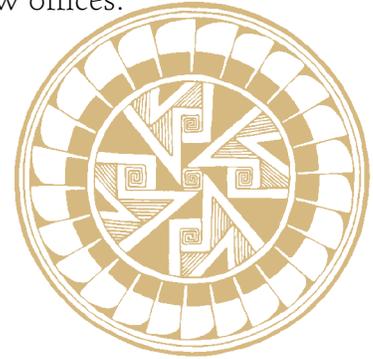
same sociological connections she worked with earlier. The models account for the points of connection between individuals. Each person within a community is represented as a point in the network. The edges that connect a person to other people represent interactions that take place inside or outside 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 com-

fortable 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.