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.

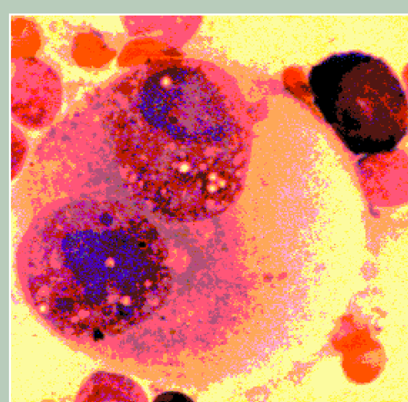
The language of evolution, selection, and competition, puts cancer research squarely into SFI's purview. In particular, SFI Science Board member (and University of New Mexico professor of computer science) Stephanie Forrest is involved in an active collaboration with Carlo Maley of University of Washington's 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."

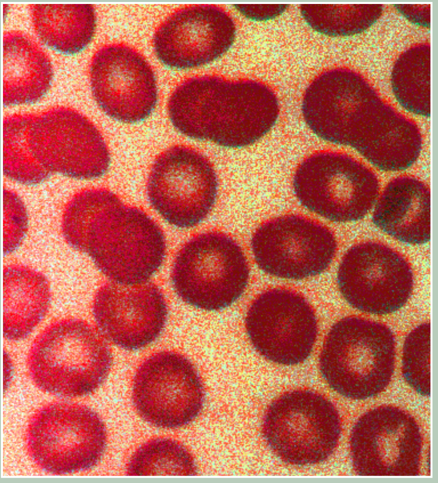
the self-assembly of the micelle, the nature of PNA and hydrocarbons, and the likelihood they will behave as planned. However, an actual protocell has yet to be made.

"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."

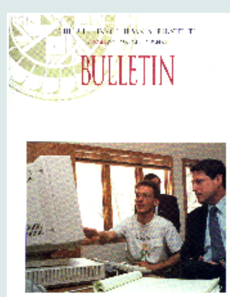
In work with colleague William Wang, professor emeritus at UC Berkeley and professor of language engineering at the Chinese University of Hong Kong, Holland is using CAS to redirect the focus of understanding language acquisition, removing emphasis from genetics and placing it on the process of learning. 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.