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Robustness: Key to Survival?

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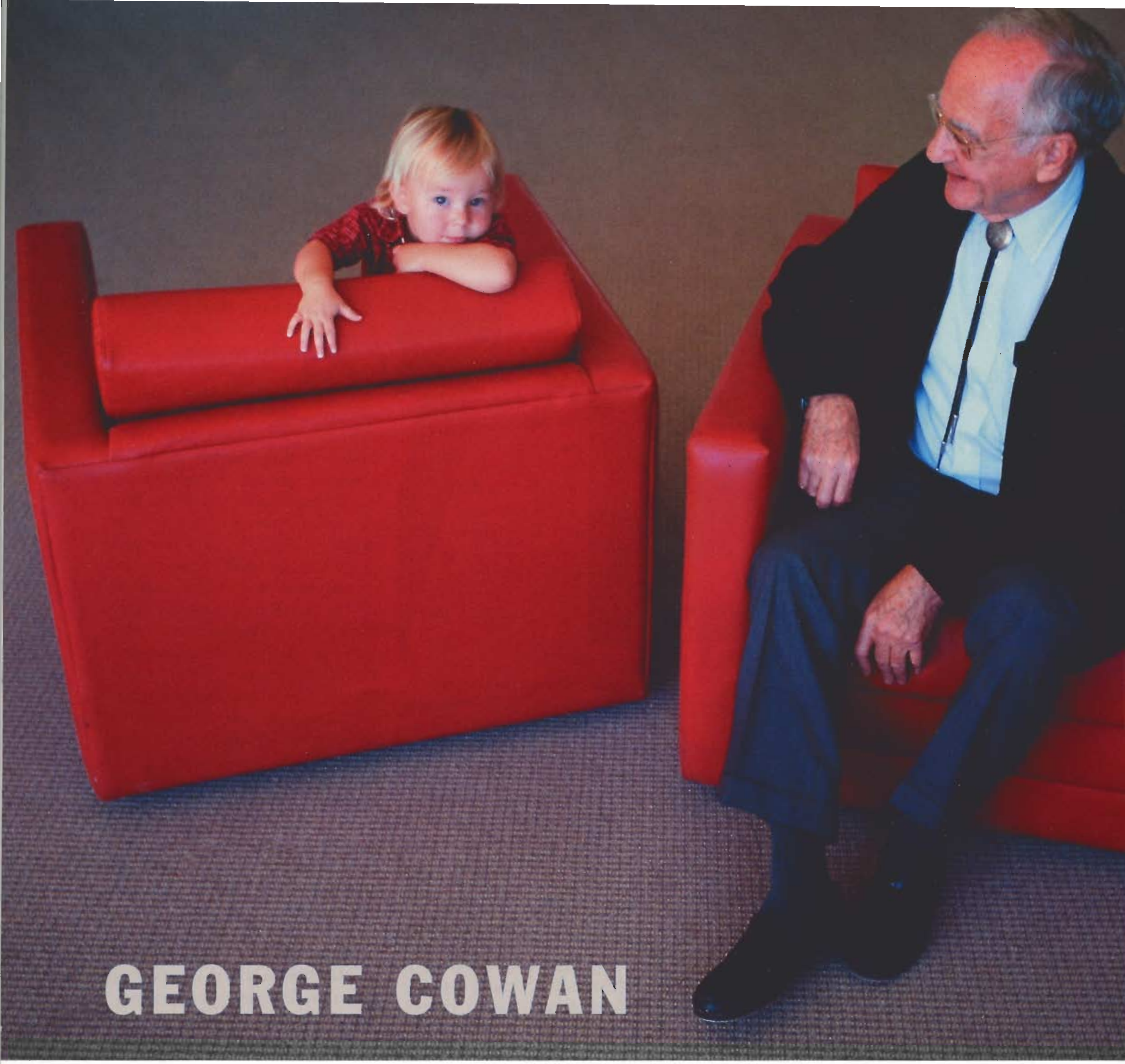


GEORGE COWAN

CHANGING THE WORLD IN MEASURABLE WAYS

by Tamar Stieber

profile

PHOTOGRAPHY: GUY AMBROSINO

Is human behavior more the result of nature or of nurture?
How predictable is the behavior of given individuals or groups?
How malleable are patterns of behavior?

These are the sorts of questions to which Santa Fe Institute founder George Cowan finds himself returning again and again these days. It's not that the 80-year-old nuclear chemist is necessarily growing more philosophical in his old age. Rather, it's all in a day's work for Cowan in his quest to determine not only how the environment shapes the individual, but also whether and how individuals and groups shape the environment. With the advent of complexity science, these sorts of questions that once sat comfortably in the province of philosophy and psychology are beginning to move, somewhat awkwardly, into the domain of neuroscience, a data-rich field that has recently formed connections with the more descriptive field of behavioral science.

"I shouldn't reflect on behavioral science—it's not the kind of science I've done," Cowan remarks bluntly during a recent interview in his unassuming office at the Institute. Further staking out his intellectual territory, he leans back in his chair, crosses his left ankle over his right knee and, folding his hands across the front of his short-sleeved, pale yellow shirt, adds, "And there isn't a lot of my kind of science in psychology."

So what exactly is Cowan's kind of science?

"It involves hard data. Being able to write equations of motion," says Cowan, a soft-spoken man who nonetheless presents his ideas and abundant opinions with the force of knowledge and conviction. "One of my friends says he judges papers by the ratio of narrative to equations. If he doesn't find a single equation, he doesn't read the paper."

The phone chirrups from somewhere on Cowan's mildly cluttered desk. "Cowan speaking," he answers in a manner that reflects his "just-the-facts-ma'am" approach to science. So, for that matter, does his office, a mostly utilitarian affair, which, like the man himself, is compact and relatively unadorned. Computers dominate the room, a bright aqua Mac on the desk; another Mac, this one standard computer color, on the floor; and a Dell on an otherwise underused table. But it's the large whiteboard hanging next to an old poster from the Arts Alliance Center at Clear Lake that grabs your attention. The shiny surface is covered top-to-bottom and side-to-side with a long, complicated equation scribbled in blue marker.

"It describes a neural process," Cowan explains animatedly. "It's a conversation I had about what's going on in a rat's brain, the way a response to a stimulus develops."

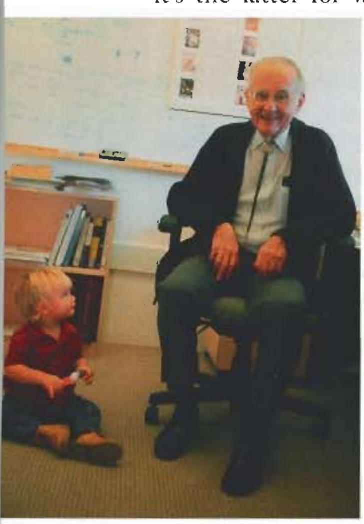
Here was a perfect, if unwitting, illustration of Cowan's Holy Grail: a mathematical equation, in this case to determine how the environment affects the brain and whether changing the stimulus would offer any sort of measurable difference. The operative word is "measurable." It's the difference between description and dynamics, "the latter being what people do around here," states Cowan, the 1990 winner of the Enrico Fermi Award for a lifetime of exceptional achievement in the development and use of energy.

COWAN who spearheaded the founding of SFI in 1984 and served as president until 1991, describes the Institute's mission (what he calls the "central theme") in terms of what it isn't rather than what it is.

"What is done around here is not primarily linear dynamics," he says, emphasizing the "not." In other words, SFI scientists take for granted systems described by mathematical equations that, despite the appearance of an occasional monkey wrench in the works, produce predictable, verifiable results. What captures their interest and their imagination at SFI is nonlinear dynamics, including what is popularly called chaos theory, in which even virtually immeasurable variables can lead to wildly divergent outcomes that appear to be random, but which, in principle, have both structure and predictability. Frequently their job is to seek order in so-called chaos, a word that Cowan says has been "trashed."

"It's a term a lot of people use to mean random. But random is something else," he says with some exasperation. "In nonlinear dynamical terms, chaos means there are so many degrees of freedom that you can't readily perceive the order. If it's a simple system, it only has two or three degrees of freedom. If it has many degrees of freedom, it usually looks disordered. But chaos is really ordered."

Using computer modeling, SFI researchers construct theories of nonlinear dynamics using highly complex and innovative mathematical equations to predict the behavior of complex adaptive systems (CAS), generally living systems. These might include insect colonies, human societies and cultures, or economic scenarios. Arguably, it's the latter for which the Institute is best known, at least among the lay public, thanks to some SFI alumni. W. Brian Arthur has become famous for demonstrating the importance of "path dependence" in predicting the success of technological innovation. J. Doyne Farmer and Norman Packard founded a successful business in Santa Fe by predicting the ups and downs of the stock market using nonlinear dynamics and computer modeling. Cowan describes such modern-day alchemy as "somewhat obvious things" to do with such heady knowledge. But, he hastens to add, "My sense of the interests of SFI people is that economics is not necessarily first and foremost on their minds. If they wanted to make money, they'd probably be doing something else."



He singles out Farmer as a case in point. Having established himself in the business world, Farmer is back at SFI doing what he loves—pure scientific research. It's a passion he shares with colleagues such as Cowan, who himself is no stranger to the business world. A permanent resident since 1949 of Los Alamos (he made his first acquaintance with the Atomic City while working on the Manhattan Project), Cowan was a founding director of Los Alamos National Bank (LANB), now the largest private bank in New Mexico. Its chairman for 30 years, he still sits on LANB's board of directors. He is also a board member of Trinity Capital Corporation, a bank holding company, for which he served as chairman over the same period.

Now, however, Cowan devotes most of his intellectual capital, if not his time ("The bank pays me more," he explains) to studying the physiology of the human brain. He has spent the last decade focusing on early mental development, specifically how physiological changes in the developing human brain relate to a child's behavioral development.

By far the most complex of all adaptive systems, the human brain is also the most mysterious. The brain and the mind mediate human behavior. But some people believe that behavior is ruled by another entity entirely, that the brain is "the seat of the soul." Others believe in a "divine spark" separating humans from the rest of the animal kingdom.

Indeed, Cowan acknowledges that "humans are very special." It's the how and why that's up for argument. The debate, which for centuries focused on whether humans and apes share a common ancestor, has itself evolved into a question of what differentiates the brain and the mind. There's no doubt about where Cowan sits.

"They're one and the same thing," he pronounces. But it remains to be proven—and not by mere narrative description. He leaves that to some of the people in psychology. But he greatly values the work of Jean Piaget, the famous Swiss psychologist who first described early childhood cognitive and intellectual development beginning 70 years ago. While Piaget arrived at his widely embraced theories primarily by watching his own three children and keeping a journal of his observations, Cowan wants to add empirical data from neuroscience. He looks to newly developing techniques that use images of evoked responses, such as those captured by functional magnetic resonance imaging (fMRI).

While fMRI scans provide what Cowan calls "snapshots" of the developing brain, he wants "movies." To that end, he is involved in a number of efforts trying to raise interest in a longitudinal study, one that follows individuals for an extended period of time, to measure the physical changes in developing brains that may correlate with Piaget's behavioral theories. Though it's not likely to settle the nature/nurture argument, such a study could demonstrate that providing pre-school children with more multi-sensory stimuli (nurture), such as an enriched sensory environment, increases their capacity to learn. This has been observed in studies with animals.

Cowan reluctantly allows for the possibility that his study could indicate exactly the opposite, that nature determines a child's learning ability.

"As a scientist, I'm committed to keeping an open mind. I would abide by the result of a carefully designed experiment if it indicated that (environment) makes no difference at all. By the way," he added as an aside, "publishing that will take some thought because it leads nowhere and people will say you're a racist. What you're saying is that it's all nature."

And that, to quote Yogi Berra, would be "déjà vu all over again." (Recall the controversy that still rages over the 1996 best seller, *The Bell Curve: Intelligence and Class Structure in American Life*, whose authors, Richard Hernstein and Charles Murray, were skewered by colleagues and the press for examining the relationship between IQ, social class, and ethnicity.)

Regrettably, it's a worry that for now is purely academic. To date, no one has come forward with a viable study. Such a study, Cowan acknowledges, will be "difficult, expensive, and time-consuming," but not impossible. If the results were to demonstrate the importance of an enriched environment, Cowan thinks the federal government might put up front-end money, say $100 million a year for seven or eight years, to study children of various economic and ethnic backgrounds from comparable communities in all 50 states, each about the size of Santa Fe. He envisions a large-scale three-part experiment looking at the relationships between a baby's neurophysiological development, its cognition and other mental attributes, and its external environment.

"That would be the real brass ring, if you could do that," Cowan says enthusiastically. "You'd get a wonderful movie of the developing brain." That's still a distant goal, Cowan acknowledges. But since meeting in September with colleagues at UCLA who share his vision, the project is one step closer. At the invitation of Ellen Goldberg, president of SFI, John Mazziotta of UCLA, and Cowan, a group of experts will gather in Santa Fe at the end of February to consider an experiment that Cowan considers "very ambitious." He describes it as a modern version of Craig Ramey's "ABCEDERIAN" program, which placed a group of inner-city children in Raleigh, North Carolina, in a highly enriched daycare environment from the age of six or eight months to three years and has followed them into adulthood. The participants excelled throughout school, and now about 28 years old, continue to excel in their professional and personal lives. But critics have poked holes in the study, calling the results too good to be true.

"They said that he must have biased the selection of children when he enrolled them," Cowan recalls. He hopes that by updating Ramey's protocol to include more objective measurable data (that's where neuroscience comes in) and updating the daycare curriculum and assessment protocol, the proposed study will be less exposed to such criticism. Cowan thinks a pilot program could get off the ground within three years. But noting the many fits and starts the experiment has undergone since its conception and its continuation over many years, he says resignedly, "I may not live that long."

Cowan's interest in such studies began in 1992 with an SFI workshop on the plasticity of the brain. It grew the following year when Ramey presented his findings at the Institute. Together with Cornell and Vanderbilt University's Irving Lazar, an SFI alumnus who advises Vice President Al Gore on daycare issues, and early childhood expert Betty M. Caldwell from the University of Arkansas, Cowan approached professionals at the Santa Fe Community College for help in supporting a daycare program whose young enrollees would become long-term test subjects. The idea was so popular that SFI was fielding calls from pregnant women wanting to enroll their as-yet unborn children. But Cowan himself called off the experiment, realizing it would face the same criticisms as Ramey's. "It was embarrassing because we didn't follow through," he remembers. "It was my fault because I said, 'Let's wait until we can flesh it out with a set of neurophysiological measurements to make it more redundant.'"

The agenda goes beyond SFI's apolitical approach to science because a study of this type and magnitude could result in major changes to social and educational policy if it provides empirical proof that enriching any child's environment in a benign, non-invasive way increases her capacity to learn. If the experiment is truly successful, asserts Cowan, "it will be on the front page of every newspaper.

"That payoff could be so big socially that it would be worth attempting," he continues, "even though it will cost a lot of money." As if to remind himself, Cowan stops for a moment to repeat that any reference to sociopolitical action in connection with SFI is "not appropriate.

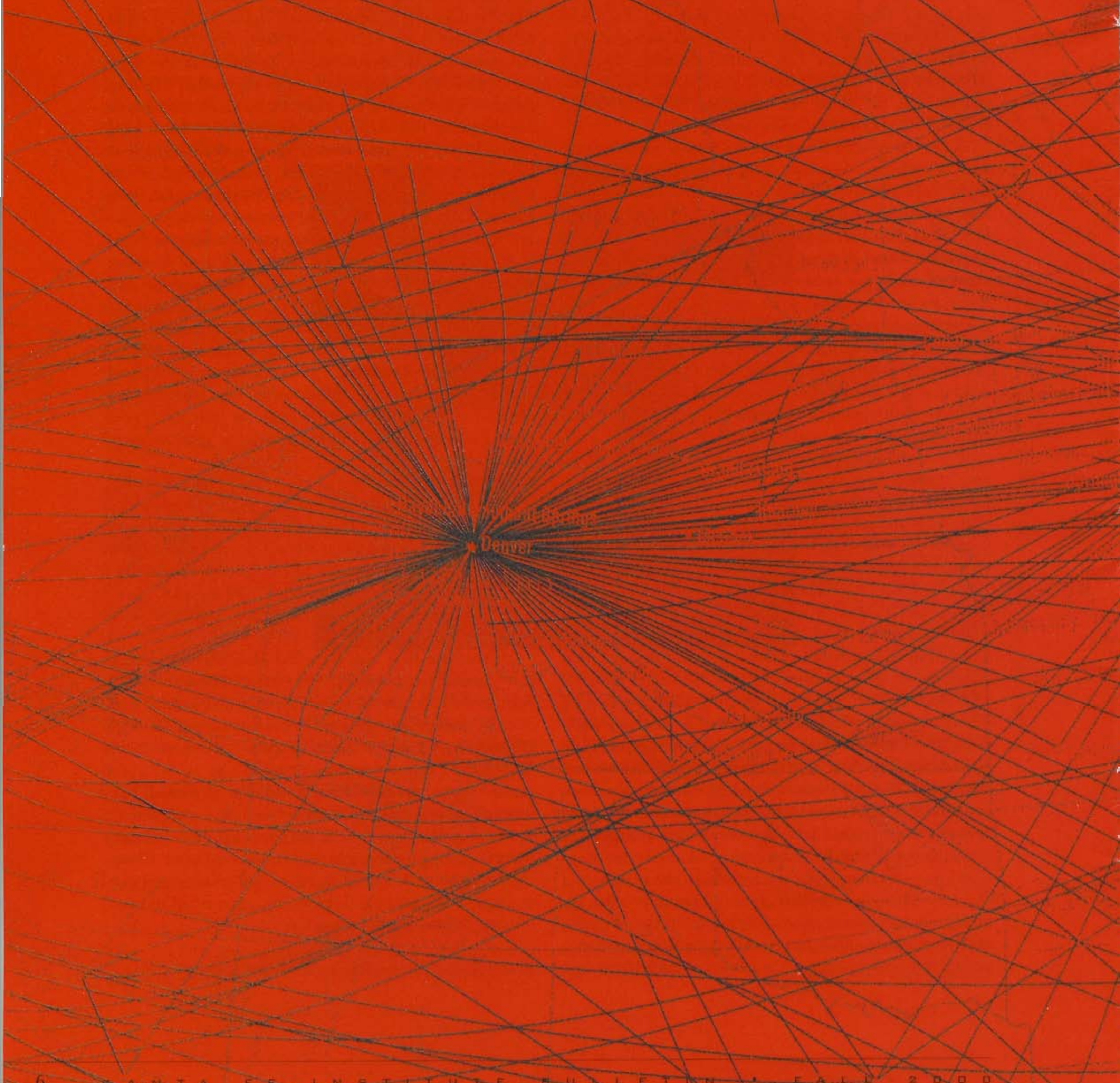
"This is George Cowan talking," he stresses. "It's a possible outcome but political action would have to involve some offshoot of SFI."

It seems a long way from the Manhattan Project to early mental development. And indeed, Cowan's work in each arena is separated by six decades and several wars. But the intellectual leap isn't so great once you fill in the ellipses. As Cowan is quick to point out, most of the Manhattan Project scientists opposed use of the bomb against Japan. Even before World War II ended, they were discussing how this new technology could benefit, rather than destroy, civilization. With his focus on early mental development, embraced late in his career, Cowan continues to work toward that goal, influencing new generations of scientists and spreading some small measure of hope for the future of humankind.

Tamar Stieber is a freelance writer in the Santa Fe area.

Growth, Form, Function, and Crashes

by Cosma Rohilla Shalizi



Networks are ubiquitous. They surround us; in our daily lives we participate in dozens of them. Increasingly, the technologies and social institutions on which we depend for our daily life are explicitly engineered as networks. Our understanding of networks, however, has not kept up with our dependence on them. Since networks don't just involve but are also the emergent result of the interaction of lots of adaptive agents, it's natural to hope that the theory of complex systems can shed some light on network dynamics. To survey this new and much-needed field, this August, SFI Research Professor Jim Crutchfield, along with Duncan Watts (Columbia/SFI), convened a conference on "Complex Interactive Networks" at SFI, with the support of the Intel Corporation.

Three themes ran through the conference: the connection between networks' growth and their form; the connection between their form and their function; and the all-but-inevitable catastrophic failures of their function.

What, though, is a network? As used at the conference, a network is essentially anything that can be represented by a graph: a set of points (also generically called nodes or vertices), connected by links (edges, ties) representing some binary relationship. In social networks, the nodes are people, and the ties between them are (variously) acquaintance, friendship, political alliance, or professional collaboration. In metabolic networks, the nodes are metabolites (chemicals) and two nodes are connected if there is a biochemical reaction in which they both participate. In the brain, as Olaf Sporns (Neurosciences Institute, San Diego) explained, there is both an anatomical network, where the nodes are various regions of the brain and the links are actual nerve fibers running from one to another, and a functional network, where the same nodes now are joined to regions that share in the performance of various tasks. In the case of the Internet, the nodes are actual machines, and they are joined by a link when they are physically tied together. In the case of the World Wide Web, the nodes are Web sites, and they are joined when there is a hyperlink from one to the other.

GROWTH AND FORM

How do networks grow, and how does that growth process influence the shape—the pattern of connections—in the network?

There are two "null models" of network form that are typically used for contrast here: regular lattices and random graphs.

In regular lattices, each node has a fixed number of links, and the neighborhood of any node has the same shape as the neighborhood of any other node. Such regular grids are rare in social systems but not unknown. The ancient Romans and Chinese, as well as the modern North Americans, built cities that way, for instance, and the American landscape itself is largely organized by a regular grid of roads, in turn deriving from the grid of survey plots. Socially, hierarchical organizations (as universally found in effective militaries, governments, and corporations) are a kind of regular lattice. As anyone who has tried to navigate a surviving medieval town can attest, the great advantage of regular lattices is clarity: you can figure out how to get from point A to point B easily; in organizations, power and responsibility are clearly delineated, which means (potentially) there will be no confusion about who is to do what and who will be held responsible if it doesn't come out right.

Still, most networks that researchers are interested in are not the product of conscious and, as it were, global design; they grew in a more-or-less (often more) haphazard fashion, and regular lattices are clearly not the right model. This brings us to the other null model, more often invoked at the conference: the random—or Erdos—graph (named in honor of the late Paul Erdos, who first formalized the model). Take a bunch of points, and connect any two with a fixed probability p, independent of everything else. This procedure for forming a network leads to some characteristic features which regular lattices don't share. The number of links varies from node to node, but the variation has a distinct statistical signature, peaking about a mean number of links that gives a "scale" to the connectivity. The mean length of the path between any two nodes, if they're connected at all, goes as the logarithm of the number of nodes. Above a certain critical value for p, the majority, generally the vast majority, of all nodes are part of a single connected component and can be reached by following links from one node to another. This is called, naturally enough, the "giant component." If one adds more nodes, connecting them to the existing ones with the same fixed probability p, then the size of the giant component is proportional to the total size of the graph. (It's easy to see that the giant component will stay the giant component—with very high probability any new node will have a link to some node in the giant component, and so join it—but the scaling relationship isn't trivial.)

Erdos graphs share a number of these properties with real social networks. For example, that mean path length is logarithmic in the size of the graph is the "small world" property made famous as "six degrees of separation." This involves the claim, derived from experiments by the psychologist Stanley Milgram in the 1960s, that almost any two people in the U.S. can be linked by a series of no more than six acquaintances. For various reasons, Milgram probably underestimated the mean path length of the U.S. acquaintance graph—it's probably more than six—but it is much, much less than one would expect from, say, a regular lattice with 260 million nodes and on the order of the logarithm of the population size. Similarly, almost everyone can be connected to almost anyone else by a chain of acquaintances—there is a giant component. A striking illustration of this comes from SFI Research Professor Mark Newman's recent work on scientific collaboration networks, where two scientists have a link between them if they have ever been co-authors of a paper listed in various electronic databases (Medline, the LANL arXiv for physics, etc.). Almost all scientists who publish at all belong to the giant component, and the next largest connected component is tiny in comparison. For the Medline database of biomedical papers, for instance, the largest component contains 1,193,488 authors, or just over 87 percent of the total, and the next largest component consists of just 56 people.

Unfortunately (or perhaps fortunately) for modelers, real-world networks do not have many of the other diagnostic features of Erdos graphs. One of these is statistical independence: in an Erdos graph, when two nodes, A and B, both have links to a third node, C, they are no more likely to be directly linked to each other than if they didn't have a common neighbor. This is not the case with most real networks; the odds that two scientists will collaborate on a paper are much higher if they have a co-author in common than not. This can be measured by the "clustering coefficient" introduced by Watts and Steve Strogatz: take a random node, count how many possible pairs there are among its neighbors, and see what fraction of them are actually linked.

One way of getting, all at once, the "small world" effect, a giant component, and clustering is to build what Watts and Strogatz called, in their original paper, a small world network. Start with a regular lattice, and randomly remove some of the regular links, replacing them with links to randomly chosen nodes anywhere in the graph. Even if the probability of rewiring, of forming a long-range connection, is rather low, this can give rise to all three desirable properties (see *SFI Bulletin*, Fall 1999).

The problem with both Erdos and Watts-Strogatz graphs, as models of real networks, is that they generally get the degree-distribution—the statistical distribution of the number of edges per node—badly wrong. A new model devised by Newman, Watts, and Strogatz, which allows for essentially arbitrary degree distributions, is able to reproduce many of the features of the scientific collaboration network fairly well, and it does an even better job on the "collaboration" network of actors who have appeared in the same movies, and on inter-locking boards of corporate directors.

This model fails, however, to reproduce the patterns of connectivity on the Web, which is where work by Albert-Lazslo Barabasi and Reka Albert (Notre Dame) comes in. Their model of network formation is explicitly dynamical. As new sites are added to the Web, they pick which existing sites they link to. They do not pick uniformly, however; the more links a site already has, the more likely it is that the new site will link there. (Everybody has a link to Yahoo.) By adjusting the extent to which "them that has, gets," Barabasi and Albert are able to reproduce the statistics of the Web, including the power-law distribution of incoming and outgoing links, with considerable accuracy. It is because of this power-law distribution, which unlike that of Erdos graphs doesn't peak around a characteristic scale for the number of links, that they call the networks resulting from this procedure "scale-free."

In a sense, this is simply a version of Herbert Simon's 1955 model for the emergence of power laws in social statistics, which has remained the most convincing explanation for their occurrence. Indeed, sociologists have long been fond of calling this sort of dynamic the "Matthew Effect" (after Matthew 13:12). The extension to network structure is new, however, and it is not just the power law of the Web that gets predicted but other structural features as well. The model also does a decent job, with different parameter values, on the graph of the physical Internet, and even on metabolic networks.

FORM AND FUNCTION

What can we learn from network structure about how the network functions?

In the case of the Web, as Jon Kleinberg (Cornell) explained, one of the things we can learn from the network's structure is how to search better. His group has devised a new search-engine method that finds sites that are "authoritative" on a given topic—ones that contain lots of reliable information, or at least what currently passes for it. They infer authority, not by trying to analyze the content of the sites, but by analyzing the pattern of links that turn up in a simple key-word search for the query terms. Sites that receive many incoming links are initially guessed to be authoritative; sites that point to many authoritative sites are guessed to be good recommenders. Sites' rankings as authorities and recommenders are then updated to take into account the rankings of sites that point to them (or that they point to), and this continues until the rankings settle down.

This is generally a much better way to find useful sites than simple keyword searching—the popular search engine Google uses it (but many types of searches are more useful, since key-word searches are so bad). What's more interesting is that this procedure delivers the graph of a community ("in a slightly perverse sense," as Kleinberg says) of Web pages put up by people who share a common interest. Applied to a hundred-million-odd Web pages indexed by Kleinberg's program, they found they could be parsed into only 50,000-odd communities, naturally with some overlap. Many of these were, to say the least, esoteric. One, for instance, consisted of Web pages devoted to tracking oil spills off the coast of Japan. The specificity of such communities of interest is often very high: the Japanese-oil-spills pages showed much less interest in other sorts of shipping accidents near Japan, or oil spills in other places. Tracking these communities offers a fascinating window into collective cognition—problem-solving and information-processing by a distributed group—as it happens "in the wild."

That the Japanese-oil-spill pages look more tightly bound to each other than to pages belonging to other communities, but are not completely disconnected from them, suggests that it should be possible to quantify the strengths of such connections. Sociologist Doug White (UC Irvine) and his collaborators (working independently from Kleinberg and his group) have done so, calling the resulting measure "cohesion." The cohesion between two parts of a network is the number of nodes that must be removed for them to be completely disconnected. The idea is that, if there are multiple, non-overlapping paths between the groups, then they are more closely tied together—more cohesive. In empirical studies of the evolution of social networks—among high school students, among students at a karate school, among biotech firms and their corporate partners—cohesion, in this sense, contains a great deal of information about how the network will develop. When it splits, for instance, people (or firms) are very likely to go with the part of the network with which they have the most ties—to stay cohesive. Or again, if one examines the political donations of large American corporations (how much to whom and when), they fall into clusters, and the members of each cluster are more cohesive with one another than with outsiders.

Coyote

A Supercomputer for Complex Adaptive Systems

by James P. Crutchfield

Three years ago I ran into a roadblock. After years of focusing on the mathematical foundations of a theory of pattern discovery by intelligent agents, I found myself wondering how to test the theory. The sort of system—a population of adaptive agents—to which the theory applied and the compute-intensive nature of the theory's learning algorithms made it clear that the tests required access to substantial computing resources—resources not available at SFI. Not surprisingly, similar requirements are also characteristic of many other research projects found at SFI. More to the point, SFI has been extolling the virtues of distributed multiagent systems for more than a decade now. These reflections led me to ask, Why not have computing infrastructure at SFI that supports simulations and analysis of this class of system?

At any previous time, satisfying this need would not have been possible at a small research organization, such as SFI, due to the cost of the large supercomputer required. However, the rapid decrease in the cost of desktop computing and networking passed a threshold sometime in the mid-'90s—a threshold that meant it became cost-effective to couple together cheap, off-the-shelf computers and ethernet local area networks into a machine whose aggregate power and architecture matched the requirements of multiagent system simulation.

The hardware revolution would have been useless if there hadn't also been a similar threshold event in software. The most basic piece of software for any computing system is an operating system—the master program that manages a computer's various processing, storage, and communication components and that runs users' programs. Available operating systems either were tied to this or that manufacturer's hardware or simply did not allow programs to run on multiple processors—the actual fact of the matter was that both of these were true of the available alternatives.

In the early '90s, however, a student in Finland, Linus Torvalds, wrote a toy version of the UNIX operating system to run on his desktop computer. Torvalds made the code for his fledgling system publicly available via the Internet for others to copy and improve. This openness and access led the Linux operating system, as it is now called, to rapidly mature into a stable and very popular operating system—one that easily competes with the offerings from major software companies. Linux demonstrated that large, complex, and reliable software could be developed by a loose worldwide network of hundreds of programmers. The key aspect of Linux is that, since the code is freely available for modification, it could be modified to run on multiprocessing machines and also be rapidly tested by dozens of research groups.

The resulting configuration—a collection of high-speed, loosely coupled processors running the Linux operating system—is called a Beowulf, after the mythological character that freed the Danes of Heorot by vanquishing the oppressor Grendel. A Beowulf machine has an almost ideal architecture for distributed multiagent systems: substantial local compute power and storage at each node and a network that supports occasional inter-node communication. At about $1,000 per processor, Beowulfs are quite economical. Equally important, they are scalable, allowing researchers to add additional computing nodes as needed.

Thus, by the time the research roadblock had become apparent, the technology solutions to SFI's computing needs for complex adaptive systems were in place. What SFI needed was support to assemble its Beowulf. This is where SFI's Business Network came into play. It brought together several interests inside and outside SFI. Through the Business Network, researchers at Intel Corporation have been participating in SFI activities for several years, tracking research and looking for topics of common interest. The first proposals were to have SFI host a workshop on the behavior of the Internet—such as traffic and routing dynamics. These initial and tentative joint projects blossomed into Intel's Research Division awarding an unrestricted grant for Duncan Watts's (SFI, Columbia) and my Network Dynamics Program at SFI. Our Beowulf is supported as an essential tool for this program's projects. In a similar convergence of interests facilitated by SFI's Business Network, Cisco Systems recently donated one of their most powerful gigabit (billion bits per second) ethernet switches for the communication network that links the processors.

Given SFI's New Mexico location, Coyote naturally suggested itself as the name for SFI's Beowulf. The "computing center" where Coyote lives is, appropriately enough, made of adobe: one bedroom in the gatehouse—a three-bedroom adobe house at the base of SFI's 32-acre hilltop property. Although Coyote is an economical supercomputer, powering and cooling it are substantial costs. Coyote's bedroom had to be retrofitted to supply hundreds of amps of power and its own air-conditioning system.

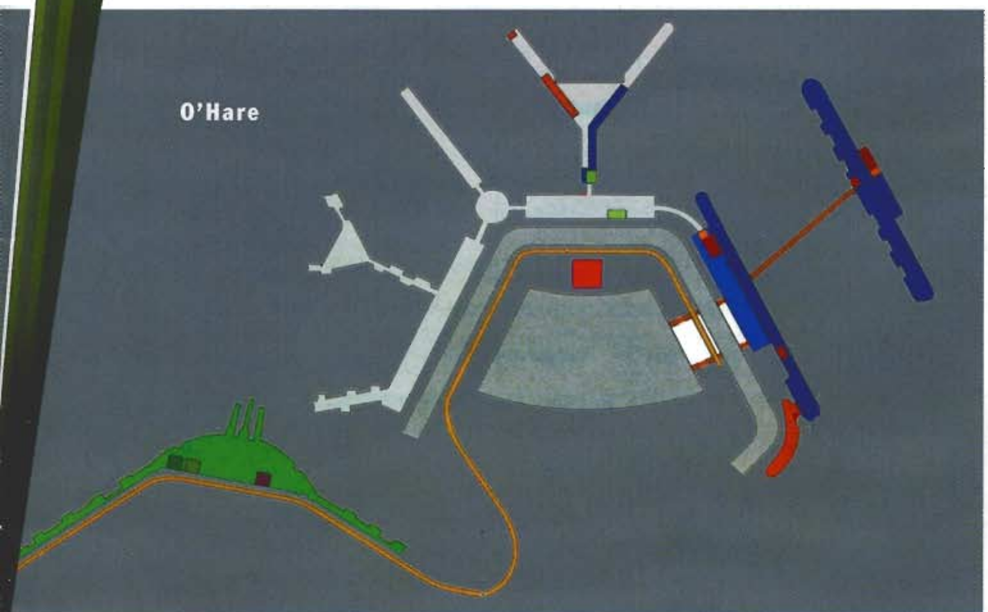
Starting in December 1999 a team at SFI—including system administrators Lolly Brown and Tim Carlson, programmer Alex Lancaster, and myself—designed and began assembling Coyote. It reached half its design capacity, 64 out of an eventual 128 processors, in late summer 2000. This fall we are installing the Cisco gigabit switch. By summer 2001 we plan to have Coyote up to its full capacity and available as a general resource for SFI researchers. Since the smallest cluster was first brought online last winter, Coyote has been in continual use by researchers, despite the team's occasional shutdowns for maintenance and expansion.

Now that it's running, the question arises, is Coyote's multiprocessing architecture actually useful? Nothing succeeds like success, so let me mention just one example—an example from the Network Dynamics Program's founding workshop (described in this issue). Mark Newman (SFI/Cornell), Steve Strogatz (Cornell), and Watts have been analyzing scientific collaboration networks. As Newman recounted in his workshop talk, several of the important statistics they needed to estimate from the collaboration networks required calculations on matrices with millions of entries. From estimates on smaller cases, Newman determined that the calculations would take many months to run on his scientific workstation. Instead, by exploiting an inherent parallelism in the problem, the calculations took only a few days on Coyote. The results were returned fast enough so that Newman presented them in his Network Dynamics Workshop talk, and a paper has already been submitted for publication.

Care to learn more about Beowulfs and stay abreast of Coyote? I recommend starting with the books *How to Build a Beowulf,* by Sterling, Salmon, Becker, and Savarese (MIT Press, 1999) and *Building Linux Clusters,* by David Spector (O'Reilly and Associates, 2000), and the following websites: www.beowulf.org for general information, the Network Dynamics Program site http://discuss.santafe.edu/dynamics, and SFI's computing page http://www.santafe.edu/computing.

THINGS GOING BUST

One implication of the Barabasi-Albert growth process that leads to "scale-free" networks has to do with the vulnerability of such networks to accidents and to deliberate attacks. If nodes are knocked out of the network in a uniform, random fashion—no node is more likely to be removed than any other—then scale-free networks are very robust. You have to knock out a very large fraction of all nodes before the giant component breaks up and the network fragments into separate parts. The reason is that most nodes don't connect to many other nodes, so getting rid of them doesn't do much to the overall connectivity. As Barabasi said, it's like the effect of eliminating the airports in Green Bay or Santa Fe on the national air-traffic network. (That network does not, in fact, appear to be scale-free, however.) On the other hand, it turns out that by selectively eliminating the nodes with the most links, the network can be fragmented with a much, much smaller proportion of its nodes down. A vastly disproportionate amount of the connectivity in the network is provided by the hubs. (Think of shutting down O'Hare or Dallas-Fort Worth.) The hubs, in other words, make the scale-free network both resistant to random failures and vulnerable to targeted assaults.



This theme of a trade-off between resistance to different kinds of insults was further explored by John Doyle (California Institute of Technology). Generally speaking, minor insults are much more common than large ones, which do more harm to the network—the bigger the problem, the more rarely it turns up. (You're bitten by mosquitoes much more often than by tigers.) The large insults may be improbable, but "improbable events permit themselves the luxury of occurring," as Charlie Chan said. In fact, sooner or later they're bound to happen: if you wait long enough, the chances of their not happening get arbitrarily small. Doyle takes the idea further, saying that when systems, including networks, are designed to cope as well as possible with insults below a threshold size, the damage done by insults above that size actually increases. He calls this "highly optimized tolerance," and it seems to offer a choice between constant petty failures, and sporadic but inevitable total breakdowns.

This is perhaps not such a worry when it comes to the Internet, since, at least nowadays, it's not actually used for anything particularly critical to society. For the moment, it is a convenience, not a necessity, though this will probably change as more and more services and pieces of infrastructure go online. Matters are very different when it comes to the telephone network, and, even worse, the electrical power network. The problem isn't simply that if Doyle is right, we can be sure these networks will crash, more or less system-wide, at some point. As George Verghese (MIT) explained, failure can actually be contagious in these networks—when one power plant goes down, other stations attempting to take up its load are much more likely to fail themselves. Here the connectivity and clusteredness of the network lead to cascading failure, in a difficult-to-understand and difficult-to-stop way.

Since networks are here to stay, indeed to spread, this may make our technological future sound rather grim. But the study of networks is still, all things considered, in its early days. It may be possible to learn to avoid catastrophic network failures. It may also be possible to design other systems that will mitigate the effects of network failures when they do occur—to have (reliable) insurance against them. Even better would be to both take steps to ward off catastrophes and buffer ourselves against them. Our ability to do either—to even understand the contraptions we've tied ourselves to—will come from more of the kind of research presented at the conference.

Papers and other details from the conference can be found online at http://discuss.santafe.edu/dynamics.

Cosma Rohilla Shalizi is a SFI Graduate Fellow. He writes frequently for the Bulletin.

2000 SUMMER INTERNS: FINDING GLEE IN SCIENCE

by Amanda Silver

left to right top row: Kristina Klinkner, Amanda Silver; middle row: Emily Jin, Matt Landreman; bottom row: Patrick Yannul, Luke Taylor, Jan Szilagyi.

PHOTOGRAPHY: JULIE GRABER

I was sitting in high school calculus when I first got the rush. It was the only time in my memory that the teacher had taken three chalkboards to prove one theorem. I knew we were onto something big. At the very end of chalkboard three, in the bottom right corner, she had done it: she had proven the mean value theorem. It is something that is fairly intuitive—if I explained it to a friend who did not know calculus it would be as obvious as the zit on the tip of my nose that day. But she had proven it mathematically. I felt like I was at the top of the roller coaster about to go down a steep hill. But it was only the beginning.

As we come closer to completing our college careers, we face the same question we had to confront when we began them: What now? Typical answers could include, "I'm going to law school," "I'm going to join the Peace Corps," or, nowadays, "I'm going to work for a dot com." But for the budding scientist, the question is not, what now? Most of us are headed for a higher degree, at least in a few years' time. For us, the more important question is, what drives us? What kind of science is it that makes us want to throw our hands up in the air and yell? Recently, while I participated in Santa Fe Institute's summer internship program, I, along with six other students, found out.

Emily Jin thought that this summer would help her decide what really keeps her interest. "I've found that science is one of the hardest fields to narrow down to one area of study, because of both the amazing scope it covers and the tiny amount that I feel I've been exposed to," she said. Having spent last summer in a chemistry lab, acutely focusing on a project, she was hoping that this summer would expose her to as many realms of science as possible so that she could finally decide what made her hum. "SFI provided me with a unique opportunity to be exposed to new approaches and endless varieties of interdisciplinary research," she said. "It also gave me a chance to interact with scientists from all parts of the world, and it gave me a glimpse into all the different types of research that are going on right now."

Coming from Harvard with a background in applied mathematics and chemistry, she couldn't have predicted that she would end up working on a project in the social sciences. But she was open to experimenting in new disciplines and found that the projects that intrigued her most were those focusing on social networks or models of the stock market. Out of curiosity, she ended up working with Mark Newman on a model for friendship.

In the computerized "community" that Emily created, the probability that a person would develop a friend from a chance meeting was based on the number of friends that person already had and the number of mutual friends between the two. The goal of the experiment was to show community formation within a larger population. The project grappled with questions such as, "What causes one person to become the central connection within a group?" and, "How many friendships are needed to reach an equilibrium state?"

But her experience at the Santa Fe Institute was not limited to the realms of her project. Because she was constantly inundated with new ideas, she still had trouble narrowing down her interests to what she loved most. "So, while I didn't quite solve my problem of finding out exactly what I want to do with my life, SFI taught me that I can use the mathematical tools that I love while studying the social or economic topics that have always fascinated me."

Matt Landreman was hoping this summer would have the opposite effect, delaying the inevitable choice he would have to make regarding his discipline. "Ask any scientist today what he or she does, and the response will be some micro-discipline so precise that it probably didn't exist fifty years ago." By having the chance to spend this summer in an interdisciplinary environment, he didn't have to decide. "I feel a clear pressure to pick exactly what I will be doing for the rest of my life. This summer I was able to put off that decision a bit longer."

At Swarthmore he had a strong interest in physics and cognitive science. While his project with Tim Hely modeling the early visual system allowed him to expand his pursuit to understand human cognition, it wasn't all that he took away from his experience. "I would take a break from my brain-modeling project to talk to a friend about cellular automata, then hear a lecture on the immune system or economics." He says that his experience at SFI brought him back to elementary school when classes were called "science" and he was curious about absolutely everything. He returns to Swarthmore this fall as a junior, and he is more excited than ever to focus on mathematics and physics so that he can tackle as much of "science" as possible.

Matt had the right idea. When we got to SFI, in June, it seemed like we were at a summer camp for smart kids. The first few weeks were spent in the lectures of the Complex Systems Summer School, the days filled with lectures on nonlinear dynamics and scaling laws in biology. Best exemplified by an experimental demo on soap bubbles, the experiments made it clear to graduate students, undergraduates, and lecturers, that the emphasis was on fun. It was undeniably amazing and scientifically intriguing to see the turbulence in the soap film first show an ordered figure eight, then show period doubling (of oscillations), and then decompose into chaos. But it was hard to hide the fact that they were playing with soap bubbles. You could see the excitement in the scientists' eyes.

Patrick Yannul gets the same twinkle when he thinks about how insects are able to live so successfully with such simple world views. Patrick is a kid who comes in every day with a bandanna on his head and pants rolled up above his knees; he always looks like he's ready to have a good time. In fact, he ended up in Santa Fe this summer because he "thought it would be fun" to come and see what the people at the Institute were working on.

Drexel University, where Patrick attends school for six months of the year, has an unusual system where students "co-op" and work in the field for half their college career. Patrick spent his last two "co-op" experiences working for computer companies. Because he was hoping to become a scientist and not a software engineer, by the time he returned to the university for his third year he wanted to continue his inquiry in an academic setting. It was his interest in the physics of computation that brought him to Santa Fe.

For the six months that Patrick spent at the Institute, he was working with Jim Crutchfield on uncovering the mystery behind complexity. Through a computer program, he analyzed rules for one-dimensional cellular automata by using principles of information theory. In this way, he was able to examine how complex behavior emerged from just a few simple rules.

Kristina Klinkner, a senior from University of San Francisco, was also examining the complex from the simple. Her project, supervised by both Jim Crutchfield and Cosma Shalizi (a graduate student at the Institute), focused on pattern recognition. Using concepts from computational mechanics and information theory, the program attempted to recreate the simplest finite state machine that would recognize other strings in the same language as a given binary string. But she had trouble trying to decide what her focus should be. As a result, she also worked with Cris Moore on an independent study of quantum computing.

In fact, the overwhelming commonality among the REUs was that we couldn't decide what we were most interested in.

Luke Taylor, a senior at Princeton, was attracted to complexity because he couldn't narrow down his passion. Searching for a field that intrigued him, and upon the recommendation of an uncle, he tried to find professors at Princeton who were doing research on complexity. As a result he ended up in the ecology department working with Simon Levin. Following his advice, Luke read *Complexity* and *Out of Control,* and tailored his curriculum to spend a summer in Santa Fe.

His project this summer was an attempt to create a small, self-sustaining food web. But, creating a program that simulates life is no small feat; Luke often felt discouraged throughout the summer. "Luckily, Sanjay Jain, my mentor, was there with a steady hand. He said to me, 'Luke, this is a major research project; it is not a quickie.'" Because of the size of the task Luke took on, he will be continuing his research over the coming year, eventually turning it into his senior thesis. "I think complexity is a sexy field, and I love the way the word rolls off my tongue: complexity!"

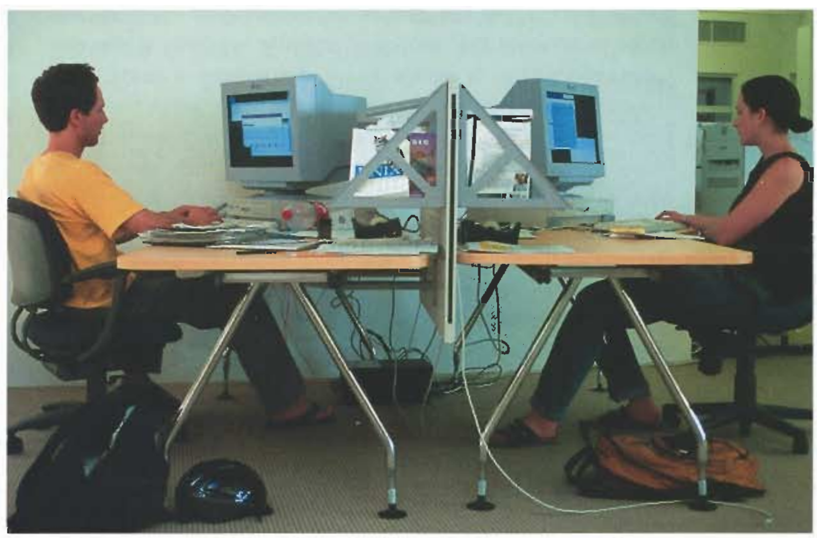
Jan Szilagyi, a senior at Yale this year, came to Santa Fe by working with his mentor John Geanakoplos. This summer, in addition to Geanakoplos, he worked with Doyne Farmer on concepts of market force. As an economics concentrator, he will return to Yale this year and continue his research with his mentor.

My story is a little different. Growing up in Santa Fe, the Institute was as present in my mind as Sun Mountain. I read Kauffman's *At Home in the Universe* during my freshman year at Brown. At that point, I became hooked on the notion of categorizing the difficulty of problems and geared my classes in computer science to understanding the mathematical concepts behind computational complexity and the type of complexity that SFI studies. I knew that I wanted to go to SFI since then, but I did not expect that it would happen during my undergraduate career. Luckily, my high school computer science teacher, James Taylor, who also teaches at the Institute's StarLogo program for secondary school students, recommended that I apply. That's how I ended up there this summer.

While there, the focus, for me, was on expanding my knowledge of science as quickly and broadly as possible. My research was focused in theoretical computer science. I was trying out a new heuristic to find the lower bound of a "very hard" problem. While there, it seemed as though an endless amount of stimuli was available for a person just beginning in the field. I took my research very seriously as did everyone at the Institute. Steen Rasmussen gets to play with mud while studying arroyo formation, Alfred Hubler treats lightening as a toy when explaining his research to colleagues; it seems that everyone that works there is just having a blast all the time. For all of the REUs, the internship was a step on the academic ladder, but the experience was more than just a marker along a ladder to success. It was just plain fun. My hands were up the entire time.

Amanda Silver is majoring in computer science at Brown University.

PHOTOGRAPHY: JANE BERNARD



Teachers describe their model and get feedback from their peers.

Seeding Change:

Bringing Modeling to Science Teachers and their Students

by Vanessa Colella & Eric Klopfer

Computer modeling and simulation are changing the nature of scientific investigation by enabling researchers to pose new kinds of questions and explore phenomena in ways that were not possible just a short time ago. Just as the technological revolution continues to influence the practice of scientific research, it also presents opportunities to change the way that science is taught in the classroom. And just as scientists need to learn about the latest tools in order to use them effectively, teachers need similar preparation to harness the power of technology in their classes. By advancing a new framework for introducing science teachers to investigation through modeling, SFI and the Massachusetts Institute of Technology (MIT) are taking significant steps towards creating lasting change in the way that students and teachers experience science. Through a collaborative effort, the Adventures in Modeling Project is introducing teachers and students to the process of designing, creating, and analyzing their own models of complex, dynamic systems. The goals of this project are to educate and motivate teachers to transform the way that they teach science and to engage students in authentic science practice by giving them the tools and the ability to pose, investigate, and answer their own questions.

For the past three years high school students and teachers have been learning to build and explore computer models in StarLogo during the Adventures in Modeling Workshops. Unlike many other modeling tools, StarLogo does not require advanced mathematical or programming skills, making it possible for model builders to focus on the content of the model rather than simply on the technical aspects of model creation. Using StarLogo and a variety of off-computer activities, teachers and students learn to create and investigate models—and in so doing they develop a deeper understanding of patterns and processes in the world.

Drawing on the talents of a multidisciplinary team including Vanessa Colella (MIT), Eric Klopfer (MIT), Nigel Snoad (NUIX), and Larry Latour (U. Maine), four teacher workshops have been held in Santa Fe and Boston. Since 1998, more than 70 teachers from around the country have participated in the project. Many of those teachers have integrated the tools and techniques of the workshops into their own classes. In 1999, Santa Fe teachers Richard Noll and James Taylor began holding related student workshops of their own.

Workshops

The Adventures in Modeling Workshops are designed to introduce participants to the computational and cognitive aspects of modeling complex, dynamic systems. During the two-week courses, participants work together to design, build, and analyze agent-based computer models. They engage in an iterative process of model creation and scientific investigation as they explore important scientific principles and processes.

Though "on-screen" computer modeling is one focus of the workshops, "off-screen" activities provide another way to connect abstract notions of scientific systems to personal experience. These activities allow participants to consider concepts like exponential growth, local versus global information, and group decision-making from a personal perspective. For instance, in one activity, participants "fly" around the SFI parking lot trying to form cohesive "bird flocks" without the assistance of a leader.

Just like the participants in the workshops, the workshop designers are continually exploring, analyzing, and refining the Adventures in Modeling curriculum. Based on input from researchers at SFI who are actively engaged in modeling and results from the first year, the workshops now have an increased emphasis on building models to answer questions, rather than models that precisely reflect real-world systems. During this summer's workshops, participants were explicitly encouraged to develop deep understandings of their models through experimentation. For instance, workshop participants were asked to alternate between making modifications to their models and assessing the impact of those modifications, and to conceive and run experiments as they explored the behavior of their models. To help participants appreciate the importance—and scientific validity—of this iterative, playful process, researchers were invited to discuss how they generate and explore new ideas through both physical and computer models. This summer, teachers and students achieved a level of fluency that enabled them to explore, analyze, and refine their models, and in turn they developed a greater appreciation for the nature of the modeling process. Perhaps most importantly, participants became convinced that experimentation is an effective means to learn about science.

Looking to the Future

In August, leading researchers from both education and science met at SFI to brainstorm ways to expand the reach of the Adventures in Modeling Project. The group considered a variety of options, from creating partnerships with schools of education to developing a K-12 modeling curriculum. A variety of challenges were discussed, including the general lack of preparation that teachers have for both modeling and scientific investigation and the difficulty of fostering change in classrooms. After much consideration, it was decided that one effective next step would be to offer an Adventures in Modeling Workshop for educators from around the country. Next summer, participants from schools of education, museums, non-profit organizations, and other institutions that engage in teacher professional development will be invited to participate in the Adventures Workshop. After attending the workshop at SFI, they can run similar modeling workshops and courses at their own institutions.

This spring *Adventures in Modeling: Exploring Complex, Dynamic Systems with StarLogo* will be released. This book, by Colella, Klopfer, and Mitchel Resnick, describes the framework that was created to introduce novices to the art and science of modeling. Activities and challenges designed to apply to a wide variety of scientific domains form the core of the book. Together, these materials help people to gain better understandings of modeling and begin to appreciate the dynamic behavior of complex systems.

Harry's Osmosis Model

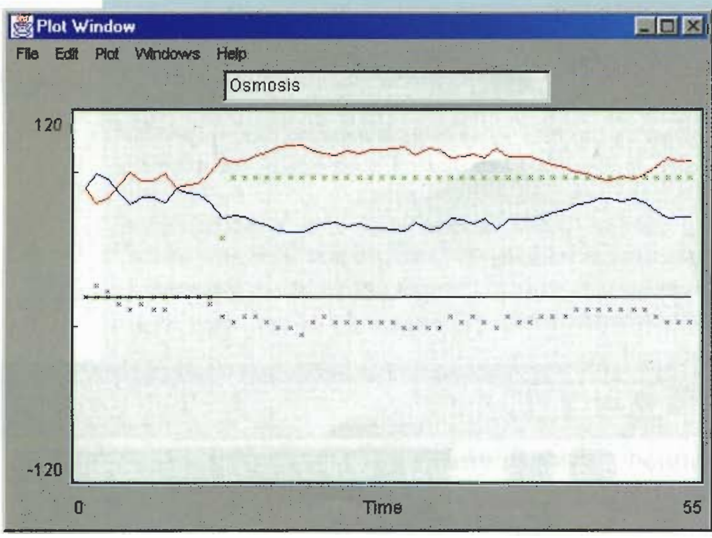
Harry teaches tenth-grade biology. For years he has used a "potato lab" to help his students understand osmosis and diffusion. In the potato lab, students submerge a slice of potato in distilled water and weigh the potato on successive days, noting that the potato absorbs water over time. During an Adventures in Modeling Workshop, he built a model to enable his students to visualize the molecular processes that result in the waterlogged potato (Fig. 2).

Figure 2: Harry's Osmosis and Diffusion Model. Water molecules (yellow) can pass through the semi-permeable membrane while sugar molecules (blue) cannot.

Harry's model has a semi-permeable membrane that splits the StarLogo screen in half. Water molecules start out on the right-hand side of the screen and move randomly, diffusing throughout the environment. His model includes monitors that count the number of water molecules on each side of the screen (representing the amount of water on each side of the membrane at various intervals). Harry also added sugar molecules to the right-hand side of the screen to simulate osmosis. Though the mechanism is not identical to osmosis, the sugar molecules interact with the water, causing water to disproportionately accumulate on the sugar side of the membrane. Harry collected data and built time series plots to show how the addition of sugar molecules caused a corresponding (but not immediate) change in the distribution of water molecules (Fig. 3).

Harry is planning to use this model in his courses this fall, in combination with his "potato model," to introduce students to the macro-results and micro-mechanisms of osmosis and diffusion.

Figure 3: A time series plot showing the concentration of water on the right (red) and left (blue) as sugar (green) is added.



Using Models to Investigate Forest Fires

While studying ecology, students learn about the importance of fire in the life cycle of a forest. They learn that without fire some species of trees, including spruce and sequoia, would be unable to germinate. Yet, the nature of the forest ecology limits students' ability to experiment with its behavior.

For their final project at the SFI workshop this summer, two ninth-grade girls designed a model that allowed them to investigate how various factors affect the dynamics of a forest fire (Fig. 4). They summarized their model as follows:

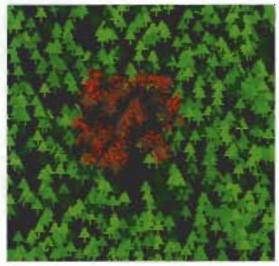


Figure 4: A forest fire burning through a grove of trees.

"Our project is a model of a forest fire. We implemented factors such as wind, rain, and tree density to determine the spread and damage caused by a forest fire...We have run experiments to judge the amount of fire damage under set conditions."

In one experiment they "wanted to find if the time that wind was [introduced] affected the amount of trees the fire burned and how quickly." They ran a series of experiments, using a stopwatch to start the wind at different stages in the forest fire, and summarized their results in a set of annotated data tables.

"There were 750 trees to begin with...We began the wind and fire at the same exact time and the results were fairly constant.

"In the next experiment we had 750 trees...and the variable that was changed was the time we started the wind after we began the fire burn. We waited exactly 30 seconds until we started the wind. The results varied quite a bit from starting the wind and fire at the same time as in the previous experiment.

"By starting the wind later and giving the fire 30 seconds to burn, there were more than double the number of trees burned. And the amount of time for the fire to finally die was double as well."

In their model the girls had different kinds of trees, and, like scientists, they made both quantitative and qualitative observations about the effects of fire on this mixed-species forest. As they ran experiments, they continued to modify their model and assess the results of those modifications. Based in part on their own experiences in previous Adventures in Modeling Workshops, the girls' teachers were able to support them as they engaged in authentic science practice through modeling.

Vanessa Colella is a graduate fellow in the Epistemology and Learning Group at the Media Lab at the Massachusetts Institute of Technology.

Eric Klopfer is director of the Teacher Education Program and assistant professor of Science Education at the Massachusetts Institute of Technology.

SFI Bulletin
WORK IN PROGRESS

A FOUNDING PROGRAM IN THE STUDY OF ROBUSTNESS

SUPPORTED BY THE DAVID AND LUCILE PACKARD FOUNDATION

WORK TO BE SUPPORTED BY THIS NEW EFFORT WILL ADDRESS SEVERAL QUESTIONS:

- What is meant by "robustness" in the various contexts in which the term is used? In what ways does robustness differ from stability, persistence, resilience, and recovery?
- What are the origins of robustness? Do biological organisms evolve robustness? What is the "null hypothesis" regarding robustness; in other words, what does a functionally fit but nonrobust system look like and how does it evolve?
- What are the organizational principles—possibilities include spatial structure, redundancy, modularity, diversification, and hierarchy among others—that characterize highly robust entities? What are the costs of these organizational principles?
- What are the consequences of robustness for evolvability, adaptability, and degree of fitness of an entity to its environment?

The management of the Packard program will be the responsibility of the SFI administration and an Advisory Board of distinguished scientists representing the broadly defined scientific community with interests relevant to the study of robustness. Individuals who have agreed to serve on the Advisory Board include Francis Arnold (chemistry, California Institute of Technology), Steve Carpenter (ecology, Wisconsin), Lee Hartwell (cell biology, Hutchinson Cancer Research Center), John Holland (computer science, Michigan), Leo Kadanoff (physics, Chicago), Mimi Koehl (biology, California, Berkeley), David Krakauer (biology, Institute for Advanced Study, Princeton), and Stan Leibler (molecular biology, Princeton).

A FOUNDING PROGRAM IN THE STUDY OF ROBUSTNESS

SUPPORTED BY THE DAVID AND LUCILE PACKARD FOUNDATION

In uncertain and hazardous times, robustness may be key to survival. The recovery of ecosystems from natural disasters, the ability of cells to tolerate insult, the ability of a computer to compute reliably in the presence of noise or defective components, the viability of an economic organization—in all these processes, it is robustness (rather than, say, optimization) that plays the central role. Yet researchers in the many disciplines for which robustness is a relevant concept are typically hard put even to define the term, much less to contemplate fundamental principles that might apply to general contexts.

We're delighted to announce a new SFI scientific initiative that will explore the origins, mechanisms, and implications of robustness in physical, computational, biological, and ecological systems. This work is supported by a generous three-year award from The David and Lucile Packard Foundation, which was created in 1964 by David Packard (1912-1996) and Lucile Salter Packard (1914-1987). David and Lucile Packard shared a deep and abiding interest in philanthropy. The Foundation provides grants to nonprofit organizations in the following broad program areas: conservation, population, science, children, families, communities, arts, organizational effectiveness, and philanthropy. The Foundation provides national and international grants.

PHOTOGRAPHY: WALTER NELSON

"This research represents a new direction for the Institute," notes Erica Jen, SFI research professor and principal investigator for the Packard program, "although, of course, it will build on previous SFI work in areas such as emergence and evolutionary dynamics. It will be different in that instead of asking a general question such as, What are the collective properties of complex systems? the program will focus on a very specific property—namely, robustness—that we intuitively feel to be a central feature of many of the systems that we find interesting in the natural and social world." In that sense, Jen expects that the Packard program will be "grounded" with respect to reality in a way that may bring a fresh impetus to SFI research. An important consequence is that experimental and empirical studies that provide insight into robust phenomena are expected to play a lead role in the program research.

The Packard Program on Robustness coordinates a range of interdisciplinary, collaborative research projects together with workshop, visitor, postdoctoral fellowship, student, and outreach programs. The emphasis will be on identifying case studies—biological, ecological, computational, and physical—of robust systems, and then constructing from these case studies a general theoretical framework to be validated against empirical data. SFI recognizes that many individuals and research communities—especially from the experimental side of science—that represent important sources of expertise for the study of robustness are not currently affiliated with the Institute. Over the course of the grant, we will be identifying and recruiting these individuals and communities into the research activities.

ROBUSTNESS IN CELLULAR PROCESSES

A major program component will be the study of the robustness of regulatory mechanisms for fundamental cellular processes. It is experimentally and theoretically well established that cellular metabolism and development rely on effective and adaptive coordination within and among intricate networks of inter and intracellular signaling. How do molecular networks perform complex, reliable decision-making in the presence of noise, stochastic fluctuations, and conflicting inputs?

The core of the research will be theoretical and experimental studies on the robustness of regulatory networks at the level of metabolic and genetic circuitry. The primary aim is to explain how the organization of control and regulatory mechanisms enables fast adaptation to changing environmental conditions, while preserving homeostasis. A secondary aim is to explore the range of viable alternative organizations for control mechanisms. What are the implications of major perturbations in the concentrations of molecular populations, or in the sensitivities of pathways to stochastic variation? Answers to these questions will help establish the "null hypothesis" for robustness as well as determine whether control mechanisms have been fine-tuned by evolution to achieve a desired behavior or whether these processes are organized so as to make them robust in the sense of being insensitive to fine-tuning.

A specific research project in this area will build on recent quantitative studies (for an analysis of bacterial chemotaxis) to study the robustness of well-defined metabolic and genetic regulatory pathways with respect to perturbations in their kinetic parameter space and network topologies. Candidate systems include the glycolytic pathway and the citric acid cycle. The approach will use statistical mechanics and stochastic processes to construct the architecture of parameter space under environmental selective pressures and to identify the variants that may be explored by a population evolving under these selective pressures. Once the architecture has been determined, it should be pos-

ROBUSTNESS OF CYTOKINE SIGNALING NETWORKS

Cellular metabolism and development rely on effective and adaptive coordination within and among intricate networks of inter- and intracellular signaling. Lee Segel, a frequent SFI visitor and applied mathematician at the Weizmann Institute, is interested in the architecture and dynamics of the molecular networks that enable cells to perform complex, reliable decision-making under changing environmental conditions. He is exploring the robustness and capacity for specific variation of these networks at the level of metabolic and genetic circuitry. Here the aim is to understand how the organization of control and regulatory mechanisms enables fast adaptation to changing environmental conditions, while preserving homeostasis.

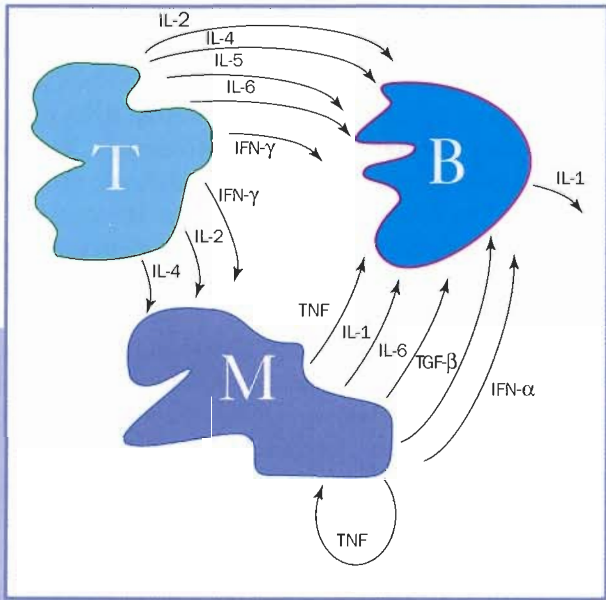
Segel also plans to study the range of viable alternative organizations and principles for control mechanisms. What, for example, would be the implications for cellular processes of major perturbations in the concentrations of molecular populations, or in the sensitivities of intrasignaling pathways to stochastic variation, or in the principles on which the mechanisms are based? Can alternative mechanisms be explored that would be based, for example, on multiple copies of genes, or multiple strands of DNA? Is self-maintenance of simple reaction networks possible in the absence of real-world enzymatic catalysis? What would be the advantages or disadvantages of such mechanisms for amplification, robustness, sensitivity, and the capacity to cope with conditions different from those on Earth?

These questions are important, both for what they say about biological systems and for what they might say about nonbiological systems. To answer them requires an integration of notions of robustness, resilience, and stability in diverse contexts. The question immediately raises the issue of differences between systems on which natural selection has acted and those that either have not been selected for or for which the level at which selection is acting is unclear. In the context of physical or engineering systems, for example, is there a sense in which biological pathways to robustness are similar to the effects of memory?

A specific example of robust cell-signaling networks are the cytokine signaling networks, which Segel and others will study in the context of the immune system (cytokine signaling systems are likely to be crucial in other parts of the body as well). Each immune cell (e.g., a B-cell, T-cell, etc.) in the body (an estimated 10^8 such cells are present at any given time) responds to a host of signaling molecules, called cytokines, which bind on the cell surface, stimulating a cascade of events within the cell. Likewise, every immune cell is capable of secreting a wide variety of cytokines under different conditions. At least 100 different types of cytokines (including the interleukins and interferons) are believed to participate in the immune response, but how they all work together has not yet been explained systematically.

What is known can be summarized (and greatly simplified) as follows. There are a large number of possible immune system (IS) effector mechanisms (e.g., mast cells, macrophages, and killer T-cells), each suited to different host tissue types and different pathogens. Innate (general) IS responses tend to be less specific and less efficient, but more quickly mobilized than adaptive (specific) IS responses. Molecular intercellular signaling via cytokines plays a large role in controlling individual effectors, affecting the differentiation of naive cell types into activated effectors, proliferation of effectors, deletion of ineffective or harmful effectors, recruitment of effectors to infected tissues or lymph organs, and activation of effector functions. Finally, each change in effector populations

Schematic representation of communication between cells of the immune system by the network of hormone-like cytokines such as interleukin-2 (IL-2) and tumor necrosis factor (TNF). T, B, and M respectively represent T cells (that come from the thymus), B cells (that come from the bone marrow) and macrophages. In reality, there are many more cell types and many more cytokines.



also changes the cytokine milieu, creating a complex feedback system. This aspect of the immune system is still poorly understood by immunologists and much of what is known comes from situations in which the system doesn't work properly—for instance, in animals that are susceptible to certain diseases—from knockout studies that remove individual cell types or proteins, or from examining components of the system in isolation.

In spite of these impediments, Segel has constructed a preliminary model of the complex network of signaling molecules and cells. Earlier attempts to model cytokine signaling pathways have concentrated on the effect of cytokines within a single cell. The Segel model concentrates on intercellular signaling pathways, specifically the network of interacting cells. Segel's model aspires to have the following properties: (1) a cell secretes multiple cytokines in response to a single stimulus; (2) each cytokine is secreted by multiple cell types; (3) each cytokine receptor is expressed on multiple cell types; (4) each cell expresses multiple receptors, and there is cross-talk between intracellular signaling pathways, leading to amplification, inhibition, or mixing of signals; (5) the signals can be subverted (for example, viruses can evolve to avoid or interfere with cytokines, such as by blocking receptors), so there is an evolutionary pressure towards robust, secure networks. In collaboration with SFI External Faculty member Stephanie Forrest, a computer scientist at the University of New Mexico, Segel plans to develop a more biologically plausible version of the model, compare it against known immunological data, and test various hypotheses surrounding questions of robustness, including the following: How robust is the model to external perturbations? How big must the model be in order to exhibit robustness? And how difficult is it for such models to evolve?

Initially, they plan to model the population dynamics of cells and cytokines to identify different regimes of system behaviors, such as dominance of cellular or humoral immunity. They will do this using differential equations, ideas from statistical mechanics, genetic algorithms, and simulations of cell populations. Once they have some experience modeling simplified situations, they plan to move to modeling individual immune cells as small finite-state automata (FSAs), which communicate with one another via cytokines (possibly modeled as symbols or words). They can then study the global, or "ensemble," properties of the collection of FSAs using techniques from statistical physics. They chose FSAs because they are readily applicable to many computational domains, so if they can build a reasonable cytokine model based on FSAs, then it would likely be applicable to many computational domains.

Cytokine signaling networks provide interesting clues about how to design a distributed autonomous control network that is dynamic (both the nodes and connections are changing in time) and robust to small perturbations but responsive to large perturbations (important for large fleets of robots working together, for automated response in computer security, for mobile computing networks, or for other distributed intelligent systems).

sible to identify both the typical and the minimal networks that implement the same behavior, and to explore the response of that architecture to fluctuations in the environment.

The research will bring the perspectives of computer science, information theory, nonlinear dynamics, and physics to collaborations among nonbiologists and cell and evolutionary biologists. The coordinator for this research theme will be Walter Fontana (chemistry, SFI). Participants will include, among others: Dennis Bray (biology, Cambridge), Stephanie Forrest (computer science, UNM), Lee Hartwell (biology, Hutchinson), John Holland (computer science, Michigan), Stan Leibler (molecular biology, Princeton), Richard Lewontin (biology, Harvard), and Erik van Nimwegen (physics, Rockefeller).

ROBUSTNESS AND EVOLVABILITY

Understanding the relationship between structure and function is key to identifying mechanisms for robustness. Two central questions in this context involve the effects on function of changes in structure, and the ability of a fixed structure to result in multiple functions. Research will concentrate on systems both biological and computational for which a well-defined genotype and phenotype exist and for which the processes that translate genetic variation into phenotypic variation can be studied.

A core component of the research will focus on mutational robustness, defined as a system's relative insensitivity to mutations. Empirical evidence and theoretical work are accumulating on mechanisms that can promote mutational robustness, including redundancy, DNA repair, RNA interference, selective bottlenecks, and neutral evolution, among others. The goal of future work will be to examine the origins and consequences of mutational robustness in two contexts, one computational and one experimental—namely, the dynamics of RNA sequences undergoing in vitro directed evolution and the dynamics of bacteriophage Ø6, a rapidly evolvable RNA phage.

The research will provide biological case studies relevant to two critical questions. The first question involves distinguishing among the differing organizational principles of redundancy, modularity, and network connectivity in terms of their relation to mutational robustness. The second question involves the tradeoff between mutational robustness, on the one hand, that lessens a system's vulnerability to its environment (and possibly decreases the degree of variability available to selection) and evolvability, on the other hand, that enables a system to adapt to new challenges.

Collaborations on this theme will bring together experimental and theoretical biologists along with physicists and computer scientists and are expected to draw heavily on computational search and optimization as well as on molecular biology. The coordinator will be Andreas Wagner (biology, UNM). Participants currently include Lauren Ancel (biology, Emory/SFI), Lin Chao (biology, UCSD), Jim Crutchfield (physics, SFI), Marc Feldman (biology, Stanford), Walter Fontana (chemistry, SFI), Pauline Hogeweg (biology, Utrecht), Laura Landweber (biology, Princeton), Mihaela Oprea (biology, Rockefeller), Erik van Nimwegen (physics, Rockefeller), and Gunter Wagner (biology, Yale).

ROBUSTNESS IN ECOSYSTEMS

Human activity is altering the Earth in unprecedented ways, inducing completely novel organizations of ecosystems and landscapes as a result. What are the consequences of these transformations for humanity, and for life in general? What are the limits of robustness for the planetary system in which we live, and how does the system react and reorganize when these limits are exceeded?

Research in this theme will concentrate on mechanisms by which evolution at the level of individual organisms results in increased robustness to perturbation at the global level. The key issue here is to identify the appropriate time scales and scales of interaction—among individual organisms, within communities, and with the physical-chemical template of the Earth—and the means by which information is transmitted across scales. A central aspect of the research relates to the fact that ecosystems are not entities upon which natural selection acts directly, but instead represent assemblages of independent agents competing and interacting amongst themselves. How does evolution shape the patterns of structure and dynamics in such systems, and what are the implications for robustness?

The focus will be on studying the relationship between organizational structure and robustness of ecosystems—in particular, how organizational design such as species richness, spatial structure, modularity, and hierarchical interactions determine an ecosystem's response both to small-scale disturbances and to major catastrophes.

A specific component of the work will be a comparison of the resilience of marine and terrestrial systems in terms of their ability to sustain functioning in the face of stress. The basic research paradigm will be to create a standard model for species interactions and then to modify it by varying mixing rates and patterns of environmental variation as well as by introducing novel species through mutation. Patterns of community assembly will be studied in response to varying rates of environmental change and to varying rates of evolutionary innovation. Resultant structures will be characterized in terms of features such as connectedness and their resiliency in the face of novel stresses. The issue of the "identity" of the ecosystem—its persistence ecologically and evolutionarily—will be considered.

The research will emphasize the integration of ideas from evolutionary biology and ecology. The coordinator for this theme will be Simon Levin (ecology, Princeton). Participants will include, among others, Doug Erwin (paleobiology, Smithsonian), C. S. Holling (ecology, Florida), John Holland (computer science, Michigan), Stephanie Forrest (computer science, UNM), Tim Keitt (ecology, UCSB), Mark Newman (physics/paleobiology, SFI), David Raup (paleobiology, Chicago), and Ricard Solé (physics, Barcelona).

"This sea-slug *[Aplysia]* is about five inches long; and is of a dirty-yellowish colour, veined with purple....It feeds on the delicate seaweeds....This slug, when disturbed, emits a very fine purplish-red fluid, which stains the water for the space of a foot around."

CHARLES DARWIN, *Voyage of the Beagle*

PHOTOGRAPHY: ©RALPH A. CLEVENGER/ CORBIS

ROBUSTNESS IN EMERGENT PHYSICAL STRUCTURES

A growing body of experimental evidence suggests that certain physical systems exhibit a kind of robustness analogous to that of biological systems. Specifically, certain systems develop "emergent" structures—examples include lightning bolts, vortices in fluids, and dendritic agglomerates in ballbearing experiments—that are capable of self-assembly and self-repair even when subjected to sudden destructive intervention. What are the mechanisms for this "failure-tolerance"? What is the cost to the system in terms of energy usage and resources? Do some physical systems possess a "memory" that acts like an instruction set in providing a pathway to robustness?

The research will bring together theoretical and experimental physicists in collaboration with applied mathematicians and computer scientists. Preliminary experiments have been designed to study the robustness and self-repair of a number of simple physical systems. Theoretical studies will include the identification of quantitative measures of efficiency for robust emergent structures and the characterization of organizational features such as modularity and redundancy that buffer individual components from changes in the environment. Applications to devices will be explored, such as how this research applies to self-repairing electronics (including wires), atomic neural nets, and self-cleaning batteries with optimal storage capacity.

An important question here is the extent to which the principles underlying robustness in biological systems apply as well to nonbiological systems. In the case of emergent physical structures, the concept of the "function" of the system—the robustness of which is of interest—is not necessarily well defined. The question highlights an essential difference between physical structures versus biological systems that have evolved and developed, and whose fundamental features may well have been selected to be robust. A specific objective of the research will be a comparison between the self-assembling, self-repairing capabilities of emergent physical structures and biological examples such as trail networks and foraging patterns in ant species and building structures in termite nests.

Coordinating this theme, integrating ideas from physics, engineering, and biology will be Alfred Hubler (physics, Illinois). Participants will include Eric Bonabeau (entomology, Bios), Liz Bradley (computer science, Colorado), Jim Crutchfield (physics, SFI), Cris Moore (computer science, UNM), Cosma Shalizi (math, Wisconsin), and Carl Tracy (physics, Illinois).

ROBUSTNESS IN DISTRIBUTED PROBLEM-SOLVING

In recent years a powerful new view of learning and problem-solving systems has emerged: namely, that new paradigms of these processes may be derived by considering not only the mechanisms by which individual agents process information and perform tasks, but also the means by which they may collectively solve the problem by sharing their cognitive systems and resources.

Can groups of individuals carry out learning and problem solving robustly? Impediments to robust problem solving in a distributed context are many—ranging from the imperfect reliability of individual memory, through the presence of noise in information transmission, to destructive nonlinear effects in collective computation. The challenge is to identify population learning algorithms and coordination schemes that overcome these impediments.

The robustness of switching among multiple functional tasks is an example of proposed research that relates both to the theme of distributed problem solving and to the theme described earlier of cellular processes. Numerous examples—such as the conversion of short- to long-term memories in the sea snail *Aplysia* and the molecular processes involved in the yeast cell cycle—demonstrate the robustness of the decision-making processes by which biological networks modulate their circuitries and operating points in order to switch tasks in response to fluctuating environments. Prototypical models of switching involving networks of adaptive agents will be developed to investigate issues including the robustness of centralized versus distributed control and the sensitivity of switching networks to fluctuations in concentrations of molecules in cells.

The research will build on work in dynamical systems, neuroscience, fault-tolerant computing, game theory, cognition, and artificial intelligence. Coordinators will be Jim Crutchfield (physics, SFI) and Michael Kearns (computer science, AT&T). Participants will include, among others, Stephanie Forrest (computer science, UNM), Andy Clark (cognitive science, Washington U.), Lucy Jacobs (animal behavior, Berkeley), Erica Jen (mathematics, SFI), Melanie Mitchell (computer science, SFI), and Charles Stevens (neurobiology, Salk).

SWITCHING JOBS

The ability to carry out multiple functional tasks is one of the hallmarks of complex organisms and organizations. How are the different tasks coordinated, and what is the mechanism for switching among them? Is the same, or different, circuitry used for each functionality? What are the costs and benefits of using a single circuitry that can be reconfigured as needed?

The study of robustness is key to addressing the above questions. Acquiring the flexibility to perform different tasks can be important for improved performance or even survival. Such flexibility brings with it the need for coordination and decision-making—to resolve ambiguous inputs, for example, or to ensure that conflicting behaviors do not take place simultaneously. In other words, the ability to switch among different tasks represents one specific pathway to robustness; in addition, the switching mechanism itself must also be robust so as to give rise to appropriate behavior.

SFI Research Professor Erica Jen is studying a system's ability to perform switching among multiple functional tasks, especially when the switching is characterized by significant overlap in the organizational architecture used for the different tasks. Switching theory has a long history, of course, in the context of electrical engineering, with emphases on questions such as representation, design, and minimization of combinational and sequential switching circuits. While the proposed program would draw on the results of traditional switching theory, the long-term goal is to explore, instead, the nature of switching that takes place in networks of adaptive agents interacting with themselves and with their environments, with the same agents involved in the performance of multiple functional tasks.

PHOTOGRAPHY: ©RALPH A. CLEVENGER/ CORBIS

Examples of key questions to be addressed include:

- What are the mechanisms by which switching is achieved? What are the organizational architectures of systems that are capable of switching?
- What are the implications of centralized control (whether in the form of a single component acting alone or a set of components acting in concert) versus distributed control for switching mechanisms?
- How do the different tasks among which switching takes place overlap or differ in their local properties such as the functional forms of their constituent computations, or in their global properties such as memory usage or computational complexity?
- What are the sensitivity thresholds of the switching mechanisms? How do they function in the presence of noise, stochasticity, and conflicting inputs?
- What is the role of multiple time scales in switching?
- What is the role of oscillatory circuits in switching?
- What are the origins and evolutionary development of switches?
- Are there cost-effectiveness tradeoffs associated with the ability to perform switching?
- Can switches be designed for a given system to endow that system with additional functionality?

The starting point for Jen's work is a survey of a limited number of biological systems that exhibit switching capabilities, together with the models that have been proposed thus far for these systems. The classic example of switching capabilities is that of the sea snail *Aplysia*. In studying how a short-term memory becomes a long-term memory in *Aplysia*, Eric Kandel, of Columbia University, and this year's Nobel laureate in Biology, and his colleagues identified a physiological "switch" that initiates the pathways that govern learning, and that turns new memories into permanent ones. In particular, Kandel's group discovered that the *Aplysia's* short-term memory depends on strengthening the connections between neurons, whereas long-term memory requires the formation of new connections between cells. The role of the switch, then, is to turn on the genes that are involved in the protein synthesis required for the growth of new synaptic connections.

Many other examples of simple but powerful switches are provided by the neural systems of invertebrates, including the swim-withdrawal reflex in the mollusk *Tritonia* and the processing of food in the stomachs of lobsters and crabs. Evidence is also mounting for the existence of similar forms of switching in the neural systems of vertebrates. Striking and elegant examples of molecular switches in simple microbial systems are provided by the circuits that govern phage *lambda* repression, bacterial chemotaxis, sporulation, yeast response to mating pheromones, and the yeast cell cycle.

As the first stage in her research program, Jen is carrying out experimental work in the neurophysiology laboratory of Eve Marder at Brandeis University on the stomatogastric system (STG) of lobsters and crabs. The STG is an ideal system in which to study switching: its neural networks are quite small, and the networks govern well-defined motor patterns. In particular, each of the four parts of the STG—the esophagus, cardiac sac, gastric mill, and pyloric filter—is controlled by a distinct neural network. Coordination among the networks and the associated four motor patterns is required to ensure the smooth movement of food particles through the stomach.

Experimental studies over the past decade suggest that this coordination of motor patterns is achieved through dynamical reconfiguration of the STG neural networks. It has been shown in the STG that both the synaptic connectivities and the intrinsic properties of the neuronal components are dynamic, rather than fixed, variables. Recent evidence, in fact, indicates that synaptic and intrinsic properties at any given time depend on factors including sensory feedback, modulatory inputs, and the patterns of electrical activity over the previous time period. The implications for network dynamics are huge: in the STG, neurons may switch their membership from one network to another, two or more networks may fuse together to form a new combined network, and existing networks may be dismantled with some of their component neurons then reassembled to constitute new networks with new functionality.

Jen hopes to use the STG as a prototypical model for systems that use dynamic reconfiguration to perform switching among multiple functional tasks. The research could be relevant to the study of a broad range of systems in which a specific task is accomplished not by the activation of an appropriate pre-existing subsystem, but through the actions of a network that selects, organizes, and activates itself to perform that task. Examples might include the design of computational architectures, the dynamics of identity and learning in social networks, and task allocation in social insect colonies.

"You need to know China!" With this challenging invitation from Jiang Zhenghua, the SFI/China Working Group began its four-day meeting in Santa Fe. The assemblage met from August 13 through August 17, and included representatives from the National People's Congress of China, the Chinese Academy of Science, Peking University, RenMin University, the SFI Board of Trustees, and researchers from the extended SFI community. Entitled "Modeling of Complex Systems in China," the working group was the first workshop made possible by SFI's newly launched International Program.

Wang Feiyue, University of Arizona

Jiang Zhenghua, vice-chairman of the National People's Congress of China, and a well-known demographer, headed the Chinese delegation. His initial presentation provided an overview of the multiple economic, ecological, and social challenges facing China today. Jiang emphasized the critical nature of the problems currently confronting his country. "China faces two difficult choices that are interrelated and difficult to completely separate: the fast rising economic growth and protection of natural resources against a population with a swiftly falling mortality rate and a tradition of high birth rates which cannot correspondingly immediately change." To emphasize the progress already made between China and SFI, he mentioned the 1998 visit of a Chinese Science and Technology delegation from the National Science Foundation of China (NSFC), and how their visit to SFI had helped to lay the groundwork for this meeting.

Tom Kepler, the Institute's Vice President for Academic Affairs, co-coordinated the meeting with Professor Jiang and acted as moderator. SFI researchers demonstrated their interdisciplinary and model-based approaches to scientific discovery by presenting papers on a variety of topics including population biology, archaeological efforts within central China, new directions for evolutionary computation, and using mathematics to combat Hepatitis C viral infection.

The Chinese delegates' papers also covered a broad range of topics. One presenter discussed the Institute of Automation's efforts to build intelligent software to recognize the more than 3,755 Chinese characters. Another talked about the compositional distance between DNA sequences and the work of assembling compositional vectors to compare genomic data in various organisms.

The working group meeting has already netted some interesting results. When several of the Chinese researchers held their initial planning meeting in Beijing, they realized that they themselves had not previously met each other. They have decided to hold research meetings every month or so in Beijing, and will invite other junior and senior researchers who may be interested in "complex systems."

To provide better access to modeling software for the students in China, the Economic Science Lab at RenMin has undertaken a new project. They will be translating SWARM (an agent-based software toolkit originally developed at SFI) into Chinese; doing so will involve developing a Chinese GUI and writing system information and code notes in their native language.

The meeting ended with an informal planning session in which future collaborations and workshops were discussed. Participants agreed that the next gathering will be held in China. Potential topics are the modeling of water resources in China and a biomedical topic such as stress and the immune system.

As Tom Kepler summarized during the closing discussions, even though this group coalesced at SFI, there is a mutual commitment to continue to grow the network within China, with special emphasis on integrating more junior-level researchers.

left to right: Zheng Wei-Mou, Institute of Theoretical Physics; Yang Zhenzhong, Chemical Research Institute; Jiang Zhenghua, Vice-Chairman, National People's Congress of China

Fang MeiQi, RenMin University of China

Jiang's call to "know China" is a multifaceted challenge. It involves understanding the challenges China faces as a result of the globalization of production, trade, and finance, and the country's efforts to develop Western China. In his talk Jiang discussed the extensive work already begun in the areas of ecological and econometric modeling, and his hope that future coordination with SFI will assist in adopting broader insights into understanding these systems. Now, as a result of the August gathering in Santa Fe, planning is beginning on at least two future workshops in China. Clearly, the process of knowing China has begun.

Suzanne Dulle

Melanie Mitchell addresses the SFI/China working group on "Prospects of Evolutionary Computation."

PHOTOGRAPHY: JULIE GRABER

$S = -k \sum_{i}^{W} p_i \ln p_i$ Boltzmann-Gibbs-Shannon entropy

entropy Boltzmann constant

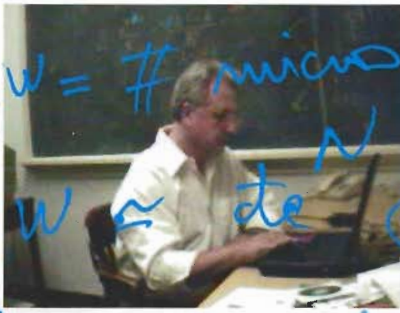
W = # microscopic possibilities

$W \sim e^N$ $N = 10^{23}$

$S \equiv$ lack of information

$\sum_{i=1}^{W} p_i = 1$ $0 \le p_i \le 1$

Constantino Tsallis—Describing a New Entropy



by Rex Graham

Conservation of energy is one of the most helpful and fundamental laws of physics, one used to explain everything from the fusion of hydrogen to the motion of planets orbiting the sun. Another concept is required to understand how the various forms of energy can change form—how the energy in a chunk of coal can move a train, for instance. This is the realm of entropy.

For nearly 120 years, physicists have relied on a particular formula to describe entropy. This formula, often simply called Boltzmann-Gibbs entropy, appears in virtually all modern physics textbooks. But few, if any, textbooks discuss a new expression of entropy that many physicists now describe as a major advance in theoretical physics. Put forth by Constantino Tsallis, a professor at Centro Brasileiro de Pesquisas Fisicas in Rio de Janeiro, Brazil, and a recent visitor at the Santa Fe Institute, the generalization helps explain many physical phenomena, from fractal behavior to time-dependent behavior of DNA and other macromolecules.

First, some background. Rudolf Clausius introduced the concept of entropy in 1865 during the heyday of steam engines; it specified the maximum energy available for useful work. Clausius's entropy also pertains to order and disorder, a feature that Austrian physicist Ludwig Boltzmann presciently included in his famous expression of entropy, S = k log W, where entropy (S) of a system is the product of the Boltzmann constant (k) times the logarithm of the number of microstates or "elementary complexions" (W) of the system. In the United States, J. W. Gibbs, a professor of mathematical physics at Yale College, advanced a branch of physics called statistical mechanics to describe microscopic order and disorder. Statistical mechanics describes the behavior of a substance in terms of the statistical behavior of the atoms and molecules contained in it. For example, in considering the molecules of air in a box, statistical mechanics describes how they bounce, shake, and dart around haphazardly—the most probable state for the system being the one with the most molecular disorder.

In the 1870s, Gibbs introduced another expression to describe entropy, such that if all the microstates in a system have equal probability, his term reduces to k log W. This formula, often simply called Boltzmann-Gibbs entropy, has been a workhorse in physics and thermodynamics for 120 years. Tsallis brought inspiration to the formula and came up with something revolutionary.

"Energy is an extremely rich concept, but it is simpler than entropy," says Tsallis. "Energy has to do with possibilities," he explains. "Entropy has to do with the probabilities of those possibilities happening. It takes energy and performs a further epistemological step."

Tsallis has suspected for years that Boltzmann's and Gibbs' formulas had limitations. They failed, for example, to describe the observed "time evolution" of entropy in critical environments where a system is poised on a razor's edge between order and chaos. So-called Boltzmann-Gibbs entropy also failed to describe self-organized critical systems whose properties evolve in time in a particular way.

p_i^q $< p_i$ if $q > 1$

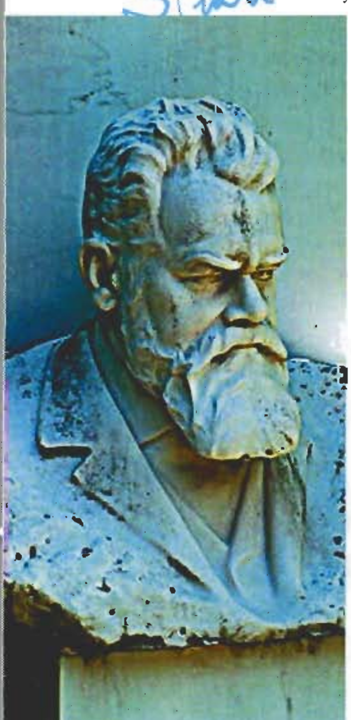
S_q

Physicists around the world are applying Tsallis entropy in many systems—from solid-state physics to information theory. Tsallis entropy can adapt to suit the physical characteristics of many systems while preserving the fundamental property of entropy in the Second Law of Thermodynamics, namely that the entropy of the universe increases with time in all processes. Although Tsallis's definition of entropy includes Boltzmann's expression in one case—when the entropy of a system is merely the sum of the entropies of its subsystems—Tsallis's definition of entropy is much broader. It describes unusual phenomena that, while sometimes rare, are vitally important. "Many physicists will tell you that this is very strange because there is no choice—there is only one entropy," says Tsallis. "I think the concept is larger than that."

TSALLIS was born in 1943 in Athens, Greece. His father, a natural linguist and textile merchant, left Greece with his family in 1947 to escape the country's civil war. The Tsallis family settled in Argentina. Constantino flourished in the Spanish culture, but he has always felt at home with the scientific insights of the ancient Greek philosophers. It was the ancient Greeks, after all, who derived the concept of atoms based on philosophical reasoning rather than evidence. Tsallis argues passionately that truth and beauty are equivalent, a concept that also dates back 2,500 years to the birthplace of theory, democracy, and classical literature.

PHOTOGRAPHY: JULIE FRANTISEK ZBORAY

Even though atoms and molecules had not been unequivocally discovered by the late 1800s, there was enough evidence for their existence for Boltzmann to derive his formula based on the probabilities of what he called "elementary complexions" in the system. Distraught that some of his valued colleagues accepted neither the atomic theory nor his expression for entropy, Boltzmann killed himself in 1906.



In 1994, Tsallis stood at Boltzmann's grave in the Zentralfriedhof, or Central Cemetery, in Vienna, Austria, and gazed at the tragic scientist's mathematical epitaph, S = k log W, carved in granite. Many of the world's most distinguished scientists make the pilgrimage, but even as a young scientist, Tsallis had sensed a weakness in the formula. During the past three decades, Tsallis's theoretical publications have ranged from genetics to galaxies. He was particularly intrigued by fractals, self-similar constructs independent of scale that describe clouds, mountains and coastlines. Earthquakes and the flocking behavior of birds are self-organizing systems that exhibit fractal behavior. Tsallis was intrigued by the ubiquity of fractal behaviors in nature and how Boltzmann-Gibbs entropy essentially doesn't apply to them.

It was during a coffee break at a workshop in Mexico City almost a decade earlier, in 1985, that the idea of the generalization of entropy and Boltzmann-Gibbs statistical mechanics came to Tsallis. It took him three years to decide to publish his idea. "Entropy is a very subtle, controversial topic," says Tsallis. "I was trying to penetrate into the physical meaning and validity of my generalization."

After that fateful coffee break, Tsallis was able to use mathematical analogies he derived from fractals to conceive his expression. Some physicists are calling it a brilliant generalization of the Boltzmann-Gibbs microscopic expressions for Clausius entropy. Over the years, engineers, cybernetics experts, and other theoreticians proposed a variety of new possibilities for entropy, but none were within the scheme set by the great master Gibbs. While those attempts were made with no particular physical goal in mind, Tsallis wanted to generalize both statistical mechanics and thermodynamics. His generalization met all of Gibbs's criteria except one: it did not meet Gibbs's requirement of additivity, which is sometimes referred to as extensivity. In usual thermodynamics, energy and entropy are extensive quantities. That means that the total energy or entropy of two systems that are independent or uncorrelated equals the sum. Tsallis's expression for entropy, published in a 1988 paper in the *Journal of Statistical Physics,* is nonextensive. The paper uses statistical mechanics in the anomalous cases in which a non-Boltzmann entropy seems to reign. It was a crisp break with convention.

A follow-up paper in 1991, co-authored by Tsallis and E. M. F. Curado and published in the *Journal of Physics* titled "Generalized Statistical Mechanics: Connections with Thermodynamics," extended the revolution. "The entropy we have always learned is good for a mass of molecules in a room, for a heat engine, for a million things," Tsallis says, carefully enunciating each word for effect and gazing at a novice with the eyes of an evangelist. "But there are a million other processes in which a different entropy appears to be needed. . . . Many physicists will tell you this is absolute nonsense. But an increasing number will also say it is not nonsense."

The Institute for Science Information cited the 1991 Tsallis and Curado paper as the most-cited Brazilian physics paper worldwide in the 1990s. Three international workshops in 1999 and 2000—two in Japan and one in Texas—were dedicated to exploring the ramifications of Tsallis's ideas. In 2001, a conference on physical applications of Tsallis entropy is scheduled in Italy, and another to be held at the Santa Fe Institute will focus on nonphysics applications. It will be co-chaired by SFI professor Murray Gell-Mann.

Explaining his ideas to a reporter in July 2000, Tsallis, 56, writes equations slowly on a sheet of paper. It's a warm, humid afternoon in Cambridge, MA, and MIT's air conditioning can't quite keep up. Tsallis begins with probability, derives Boltzmann's and Gibbs's formulas, and then draws a solid horizontal line, under which a fractal term with an exponent q appears. He combines q with Boltzmann-Gibbs entropy so that the probability, p, is raised to the power q. Suddenly, the power of this seemingly simple approach is apparent.

"If q equals 1, you get back Boltzmann-Gibbs entropy," he says. "But with some rare event in which the probability is very small, and if you raise it to a power q, which is smaller than 1, its weight grows up." What he means is any small number raised to a power less than 1 becomes larger. (For example, 0.5 to the 0.3 power equals 0.8.) Tsallis's forehead glistens with tiny beads of sweat.

Tsallis uses the example of a tornado to demonstrate how low-probability events "grow up." Normally, the air molecules above a farm or city move about independently and fairly randomly. In such cases, the entropy of two different volumes of air can simply be added. This is his key point: the quantities of two systems that can be summed to yield the total are called extensive quantities. Standard statistical mechanics and thermodynamics are extensive: they assume that the atoms, molecules or particles in a system are independent of each other or that they interact only with nearby particles. A fast-moving air molecule zips past a motionless one with neither greatly affecting the other. However, nature is not always extensive. Tornadoes—systems in which the movements of air molecules are highly correlated—a nonextensive case—happen frequently enough to draw the attention of lots of Midwesterners on stormy summer days.

"A tornado is a very rare event," says Tsallis. "Why? Because trillions and trillions of molecules are turning orderly around. So a vortex is a very low-probability event, but when it is there, it controls everything." Human vision also behaves in very unlikely, nonextensive ways. For example, if a large smooth wall is painted white except for a small red spot, the human eye very quickly finds the dot. "Why?" asks Tsallis. "Because it's not supposed to be there. The phenomenon of visual perception also is controlled by rare events. In fact, we are the offspring of those who quickly saw a tiger nearby, because it should not be there, and ran away."

For most of the systems that people deal with, the assumption of extensivity is very well obeyed. "What Tsallis defined was a simple generalization of Boltzmann entropy that does not add up from system to system and has a parameter q that measures the degree to which the nonextensivity holds," says Seth Lloyd, an External Faculty member at SFI and an associate professor of mechanical engineering at MIT. "Tsallis's is the most simple generalization that you can imagine. And for a variety of systems with long-range interactions—solid-state physics, chaotic dynamics, chemical systems, the list goes on and on—Tsallis entropy is maximized for some value of q. It is mathematically handy."

In nonextensive situations, correlations between individual constituents in the system do not die off exponentially with distance as they do in extensive cases. Instead, the correlations die off as the distance is raised to some empirically derived or theoretically deduced power, which is called a power law.

If a plot of the logarithm of the number of times a certain property value is found against the logarithm of the value itself results in a straight line, the relationship

PHOTOGRAPHY: ©W. PERRY CONWAY/CORBIS

is a power law. The Richter scale is a power law: the logarithm of the strength of earthquakes plotted against the logarithm of the number of quakes yields a straight line. Tsallis entropy is applicable to hundreds of nonextensive systems with such power-law scaling.

Power laws are helpful in describing not only fractal behavior but many other physical phenomena as well. Unfortunately, Tsallis has no proof from first principles that his expression of entropic nonextensivity is the best one possible. Michel Baranger, an emeritus professor of physics at MIT, agrees that the lack of such a proof has led many physicists to be skeptical. "As far as I'm concerned, his formula is excellent," says Baranger. "But I would still like to see justification of this formula from first principles. It will probably come because all indications are that it is good."

"Tsallis did pull this out of thin air," says A. K. Rajagopal, an expert on condensed-matter physics and quantum information theory at the Naval Research Laboratory in Washington, D.C. "What he did, intuitively, was really remarkable. It takes you from ordinary exponential probabilities to power-law probabilities. And it is important because so many physical phenomena—such as fractal behavior, or anomalous diffusion in condensed-matter materials, time-dependent behavior of DNA and other macromolecules, and many, many, many other phenomena—are explained by these power-law probabilities. There is a formula for one class of phenomena, another formula for another class, but there may be basic tenants in common."

"A TORNADO IS A VERY RARE EVENT," SAYS TSALLIS.

PHOTOGRAPHY: ©BETTMANN/CORBIS

Many scientists refer to Tsallis's q parameter as the entropic index or the nonextensive index. He argues that his expression of entropic nonextensivity "appears as a simple and efficient manner to characterize what is currently referred to as complexity—or at least some types of complexity." Not every complexity theorist would go that far, but most of them are willing to entertain the possibility, however unlikely.

Rex Graham is a senior editor at Astronomy *magazine.*

THAW FUNDING SUPPORTS WORK ON BIOLOGICAL RECOVERY AND INNOVATION

Biological recovery and innovation is the focus of a new SFI program headed by Smithsonian Institution paleobiologist Doug Erwin and funded by the Thaw Charitable Trust. The purpose of this new work, a component of the Institute's emerging program on evolutionary dynamics, is to investigate through theory, synthesis, modeling and field investigations the processes involved in the creation and establishment of biological novelty and the links between ecological recovery after biotic crises and evolutionary innovation. The primary focus of this project will be generally to expand our understanding of the evolutionary processes and, in particular, to demonstrate to more traditional evolutionary biologists the requirement for a more expansive view of the processes that have created the diversity of life.

How many species are alive today? Estimates range from 20 million to as many as 100 million species. Other scientists have demonstrated that the diversity of microbial life greatly exceeds what was only suspected a decade ago, and even extends thousands of feet into the crust of the earth. How has this diversity arisen over the past four billion years, and more specifically why are major evolutionary innovations underlying the diversity of life so often clustered into relatively narrow intervals of time? The origin of the major architectures of animals, from sea anemones to fish, the major groups of plants, dinosaurs and modern mammals all occurred in brief bursts. Curiously, many of these creative bursts of evolution followed mass extinctions and other biotic crises, suggesting a link between environmental disturbances and innovation.

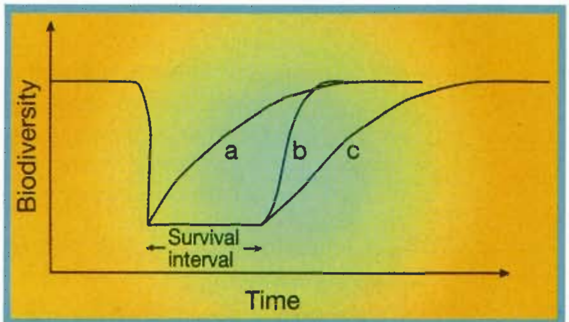
Ecosystems are adapted to disturbances ranging from fire to severe storms and outbreaks of disease. Such minor disturbances generally increase the number of species in an area, and are even required in many habitats for species to thrive. Recovery is generally rapid. More severe biotic disturbances can destroy entire ecosystems, with the rate of recovery dependent upon the extent of the immigration of species into the affected area and upon how quickly the ecological fabric can be rewoven. Modern ecology provides an explanation for disturbances at this level, but ongoing human-induced disturbances are on a far greater scale, more similar to biotic crises that are followed by great mass extinctions documented by the fossil record than they are to relatively minor, short-lived disturbances. Rebuilding ecosystems after crises of such magnitude involves both the origination of new species and the creation of new ecological relationships; the rebuilding process often also produces significant evolutionary innovation. Regrettably, previous attempts to build models of this process have failed to incorporate positive feedback: as species evolve they create opportunities for yet more species. This creative, self-reinforcing aspect of evolutionary recoveries provides much of the impetus for evolutionary radiations and links them to other episodes of biological innovation.

These concerns drive this new project, which will address two fundamental questions:

- Are the rates of evolutionary change during post-extinction biotic recoveries and bursts of evolutionary innovation more rapid than during intervening times?
- How are ecosystems restructured during these events, and, in particular, what feedback processes modulate the size of ecosystems?

Studies of recoveries after the five great mass extinctions, as well as after several small biotic crises documented in the fossil record, have produced a general model of the recovery process. Following the end of the extinction, there is often a burst of highly opportunistic species. Perhaps the best example of this is the burst of ferns in the earliest Cenozoic period immediately after the extinction of the dinosaurs, and many plants, 65 million years ago. A very similar process occurs today in disturbed fields and along the sides of new roads. This survival interval generally lasts only a few hundred thousand years, at most, and is characterized by the occurrence of relatively few species, but with each species occurring in high numbers. Few new species are found in this interval. The onset of the recovery stage is marked by the appearance of new species and the re-emergence of other surviving species in the fossil record. Recent studies have shown that this simplistic model of an initial survival interval of opportunists followed by rapid generation of new species during biotic recoveries is far too simple. Opportunists often are found only in one part of the world, with no apparent opportunists in other regions. More curiously, the re-emergence of new species appears to occur remarkably rapidly. It is clear from empirical studies of these events that the rapid diversification of new species during the recovery interval receives a substantial boost from positive feedback: as new species evolve, and ecosystems are rebuilt, roles are created for yet more new species.

Current modeling and simulation of recoveries has failed to capture this positive feedback process, hampering our understanding and limiting paleontologists' ability to design new investigations of the fossil record. Current models follow one of two approaches: 1) fixed ecospace models



Different models of biological recovery following a mass extinction or other perturbation. Curve A shows immediate logistic growth, as expected by many models, while C shows logistic growth following a "survival interval" during which little diversification occurs. Curve B shows positive feedback in the recovery process where diversification facilitates further expansion of ecological opportunity.

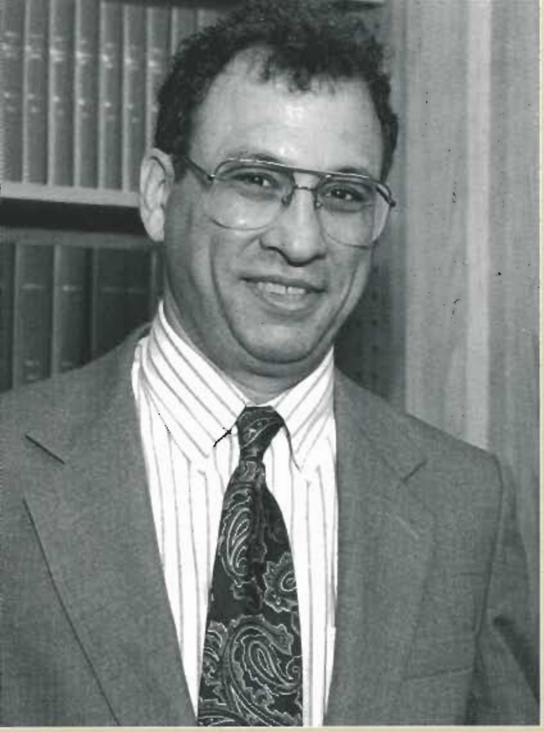
(akin to a chessboard, with the possible ecological spaces specified in advance) in which occupation of model niche space is driven by lineage branching and logistic growth and limited by competition; and 2) simple logistic growth models of interacting lineages. Neither of these approaches is particularly realistic, and they largely fail to reveal anything about the actual processes of recovery or innovation. Additionally, these models assume that a single model applies globally, failing to consider the importance of different patterns in different regions.

Major evolutionary innovations occur in the aftermath of mass extinctions or as the result of major adaptive breakthroughs. The latter case also involves the creation of new ecological space, so biotic recoveries and evolutionary innovations are actually closely related phenomenon, and can best be understood together. Most significant evolutionary innovations occur in discrete bursts that fundamentally reorganize preexisting ecological relationships, essentially creating a new world. Examples of this include the rapid appearance of the major animal groups at the base of the Cambrian (circa 530 million years ago), the diversification of all the major architectures of plants during the Devonian (circa 360 million years ago), the formation of the major dinosaur clades during the late Triassic (circa 210 million years ago), and the extraordinary explosion of new groups of mammals after the extinction of the dinosaurs (65-55 million years ago). These events share a number of similarities, including the diversity of the new groups that appear, rapid evolutionary change, and dramatic shifts in ecological interactions.

Understanding the rapidity of evolutionary change is critically dependent upon having a reliable time scale. A number of new techniques have provided the first real opportunity we have had for understanding how rapidly evolutionary change has occurred in deep time. Until just the past five years or so, evolutionary events older than about 80 million years were difficult to investigate with sufficient temporal resolution: we simply couldn't tell time well enough to distinguish rapid events from slow events. The recent development of new techniques in the very high-precision dating of ancient volcanic ash beds now yields dates with a precision of about 200,000 years for rocks over 500 million years old. Previously, good dates were precise to plus or minus 20 million years. Some events have now been shown to have been misdated by as much as 70 to 80 million years. Coincidentally, paleontologists have developed new analytical techniques for examining rates of change in fossil groups. Thus, we are on the verge of being able to reliably study evolutionary rates in deep time for the first time.

To encourage creative and interdisciplinary research in this area, SFI will host small working group meetings on "Evolutionary Innovation," to include ecologists, evolutionary and developmental biologists, and paleontologists, and meetings on "Rates of Evolution," with evolutionary biologists, geochronologists, and others. One important goal is to develop a new series of models of biotic recovery explicitly relating survival and diversification to the creation of new adaptive space. These models will be tested against data from the fossil record and used to guide exploration of these issues in future empirical work. We expect the model development to be an iterative procedure, with feedback from empirical studies guiding modifications of the model.

The primary output of this project will be a book by Erwin for a general audience tentatively titled *On Evolutionary Innovation*. Erwin also anticipates that the results of this project will appear in more scholarly publications, as well as through the educational and outreach activities of SFI and his work at the Smithsonian Institution's National Museum of Natural History.



PHOTOGRAPHY: ROBERT P. MATTHEWS

LEVIN ELECTED TO NAS

SFI Science Board member Simon A. Levin (Population Biology and Ecology, Princeton) has been elected as a member of the National Academy of Science.

Through brilliant and original theoretical work on the dynamics of ecological communities and landmark collaborations merging theory with experiment, Levin helped create a framework for studying the ecology and evolution of populations in heterogeneous environments. He is a leader in transforming ecology into a quantitative science with rigorous theoretical foundations.

Members and foreign associates are elected to the Academy in recognition of their distinguished and continuing achievements in original research. Election is considered one of the highest honors that can be accorded a scientist or engineer.

SHEPARD RECOGNIZED FOR LIFETIME PROFESSIONAL ACHIEVEMENT

SFI Science Board member Roger Shepard is the 2000 American Psychological Gold Medal Winner for Life Achievement in the Science of Psychology. Shepard, Professor Emeritus in Cognitive Psychology at Stanford, has pursed a variety of research interests including universal psychological laws; similarity, generalization, and classification; perception and representation of spatial transformations and of music; physics and mind; evolutionary psychology; and multidimensional scaling and clustering. This award is bestowed in recognition of a distinguished career and enduring contribution to psychology. It recognizes a notable contribution to advancing the application of psychology through methods, research, and application of psychological techniques to important practical problems.

Shepard has donated a portion of this award to the Santa Fe Institute. The Institute is honored by this gift.

SCIENCE BOARD

The Santa Fe Institute Science Board—the group that advises SFI on broad issues related to its scientific program—welcomes two new members.

Juris Hartmanis is Walter R. Read Professor of Engineering at Cornell University. The strategic goal of his research is to contribute to the development of a comprehensive theory of computational complexity: the study of the quantitative laws that govern computation. Hartmanis's current research interests are focused on understanding the computational complexity of chaotic systems and the study of the computational complexity of scientific theories. A Turing Award Winner, Hartmanis is a member of the National Academy of Engineering and a fellow of the American Academy of Arts and Sciences.

Physicist **Geoffrey West** is a Los Alamos Laboratory (LANL) fellow in the Theoretical Division and has been group leader of the Elementary Particle Physics and Field Theory Group at LANL. He holds the position of adjunct professor at the University of Sussex (England) and the University of New Mexico and is also a research professor of Biology at the University of New Mexico. The author of several books and numerous articles, West's current research interests include the origin of universal scaling laws in biology.

In other Science Board developments, **Sir Robert May**, chief scientific advisor and head of the Office of Science and Technology, United Kingdom, and Royal Society Research Professor at Oxford University and at Imperial College; along with **Harold Morowitz**, Clarence J. Robinson Professor of Biology and Natural Philosophy at George Mason University, have been named co-chairs.

NEW TRUSTEES

William Sick is co-manager and a co-founder of Signature Capital Management, LLC, a venture capital firm in New York, and is chairman and chief executive officer of Business Resources International, Inc., a private investment firm in Illinois. Both firms specialize in early-stage growth companies. He is a member of the boards of MetaSolv Software, Inc., Acoustic Technologies, Inc., and VIRxSYS, Inc. In the 1980s Sick was chief executive officer and a director of American National Can Company, the world's largest packaging company. Prior to that time, he was with Texas Instruments, where he was an executive vice president and a director of the corporation. Sick is a trustee of Rice University, where he received degrees in Electrical Engineering, and of the Shedd Aquarium in Chicago.

Michael Mauboussin is a managing director at Credit Suisse First Boston Corporation in New York City. He is chief U.S. investment strategist and co-chair of the Investment Policy Committee. Mauboussin is an acknowledged leader in the application of value-based tools in security analysis, and has lectured and published widely on the subject. He is an adjunct professor of finance at Columbia Graduate School of Business and is the former president of the Consumer Analyst Group of New York. Mr. Mauboussin has been repeatedly named to *Institutional Investor's* All-America research team and the *Wall Street Journal* All-Star survey in the food-industry category. Mauboussin received a B.A. in government from Georgetown University. He was previously associated with NatWest Securities USA, Nomura Research Institute America, and Drexel Burnham Lambert.

Michael Grantham is president and director of the Rose-Legett Foundation in New Mexico. He also serves as a director of The National Center for Genome Resources, BIOREASON, Inc., and PhDx Systems, Inc. Grantham is chairman of the Venture Capital Investment Advisory Committee for the New Mexico State Investment Council, and he is a member of the Governor's Business Advisory Council and the Governor's Science and Technology Council. He holds degrees in pure mathematics and petroleum geology from the University of Mississippi.

ARTHUR H. SPIEGEL, 1908-2000

Arthur H. Spiegel, a founding board member and treasurer of SFI and Emeritus Trustee, died in June 2000.

Spiegel was born in 1908. After graduation from Dartmouth College he joined the family mail order business in Chicago. In 1948, Spiegel and his wife and children moved to Albuquerque, where from 1949 to 1960 he was president of the Arthur Stuart Company. In 1963, he established Arthur H. Spiegel Investments, an investment advisory and counseling business that he later sold to Fiduciary Trust International in 1977. From 1977 until his retirement in 1995, Spiegel was a consultant with Fiduciary Trust International.

Spiegel gave generously of his time, energy, and finances to a wide variety of causes and interests, including SFI. One of the founding trustees of the Institute, he was a significant supporter of SFI from its beginning onward. It was Spiegel's office, for instance, that donated clerical and accounting support for the fledgling organization in the months before the Institute established its first small office in 1986.

Arthur Spiegel was inducted into the Albuquerque Senior Citizens Hall of Fame in 1984, received the Outstanding Philanthropist Award for the State of New Mexico in 1992, was given a Special Grant Award from the Albuquerque Community Foundation in celebration of his 90th birthday and in appreciation for community contributions in 1998, and was honored by the New Mexico Council on Crime and Delinquency for leadership in 1999.

GEORGE BELL, 1926-2000

George Bell, one of the founders of the Santa Fe Institute and a Science Board member, died in May 2000 in New Mexico. He was 74.

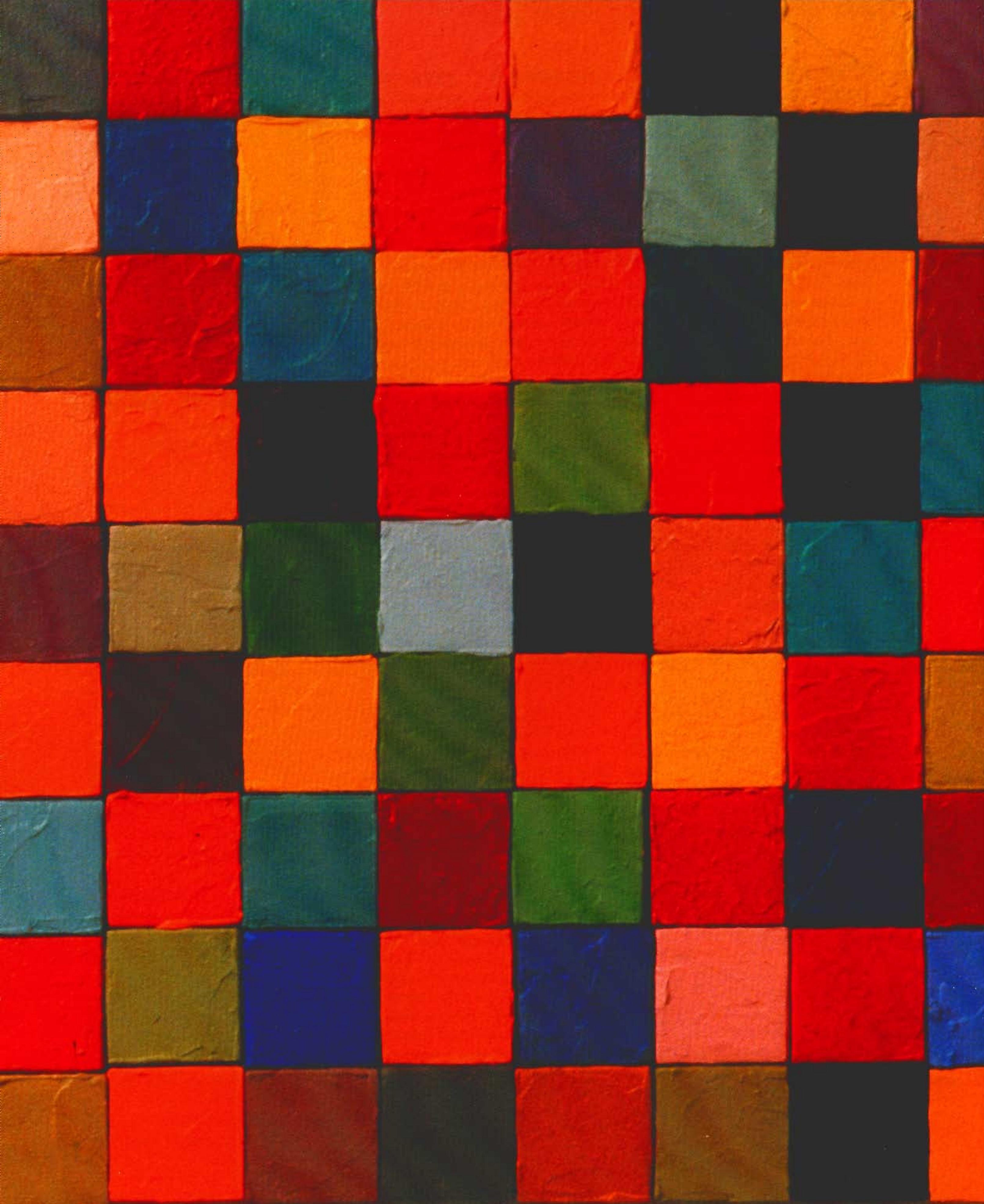
Bell moved to New Mexico in 1951, where he was a driving force in the Theoretical Physics Division at Los Alamos National Laboratory (LANL) until his death. In the early part of his LANL career, he worked on reactor physics and safety. By the 1960s, his interests shifted toward biology and immunology. In 1970, Bell published a seminal paper formulating a quantitative immunological model that could be computationally explored.

He founded the Theoretical Biology and Biophysics group at Los Alamos and deeply influenced the Institute's initiative in theoretical immunology. In the late 1970s, Bell and a prominent Russian academician, G. Marshuk, thought that their respective research groups should meet. Los Alamos was a difficult place to which to invite Russians at that time, and Bell eventually convinced SFI to host the meeting. As planning proceeded, the meeting grew into the first international meeting in theoretical immunology, with about 80 participants from countries throughout the world. Alan Perelson, from Bell's group at Los Alamos, became involved in the meeting organization and thus began his long association with SFI and its Joseph P. and Jeanne Sullivan Theoretical Immunology Program.

Bell served as a group leader for the Theoretical Biology and Biophysics Division from 1974 to 1990 and as Theoretical Physics Division leader from 1980 to 1989. He was one of the founding scientists of the Santa Fe Institute in 1984, a founder of the Center for Human Genome Studies in 1988, and author of three books and hundreds of scientific articles. He was elected a fellow of the American Physical Society and the American Association for the Advancement of Science (AAAS).

Bell was an internationally recognized mountaineer, best known for his participation in the American expedition to the Himalayan peak K2 in 1953. He made several first ascents in South America and returned to the Himalayas many times.

PHOTO COURTESY GINNY BELL



JOHN HOLLAND

CALLS FOR A RADICAL REASSESSMENT

By Thomas Patrick O'Connor

John Holland is a scientist who thinks outside the box—and he hopes others will also. In a challenging talk on complex adaptive systems (CAS) at the Santa Fe Institute, Holland called for a radical reassessment of the tools for understanding complex systems, urging scientists to use renewed mathematical rigor and metaphorical thinking. The key to this radical reassessment, he said, is transdisciplinary thinking. "Scientists must have a broad background and education. They should not be too narrowly focused on science. Everything a person knows contributes to constructing rich metaphors, making mental leaps, discovering links between unlikely things, and finding new and creative ways to combine familiar ingredients."

A scientist calling for the use of metaphor? According to Holland, development of theory involves such "nonscientific" things as metaphor, models, and cartoons. The scientist deliberately exaggerates what he or she wants to study and deletes other details in order to get to the essence of the question. Questions lead the way; then the scientist moves into metaphor. In his talk, Holland referred to the renowned scientist James Clark Maxwell who started with a loose set of metaphors and ended with abstract equations. "How did he do it?" Holland asks with a wry smile. "Metaphor goes from the source to the target. The source is known; the target is not. For Maxwell, the source was gears and fluids. Then he built a model of floating gears and wheels. It is the counterpart of what we now call electromagnetic fields. If you learn science from the deductive method," Holland concludes, "you will miss the part that lets you be a scientist."

Holland earned his undergraduate degree in computer science at MIT and was the first student to earn a Ph.D. in computer science at the University of Michigan, where he is currently a professor of computer science and electrical engineering. Holland originated the field of genetic algorithms, a science that may one day allow computers to evolve flexible intelligence. He is the recipient of the prestigious MacArthur Fellow award and was co-chairman of the Santa Fe Institute Science Board. For a number of years, Holland has been studying complex adaptive systems.

Holland began his talk with a question: What are complex adaptive systems? They surround us, he said, but most of us take their efficient functioning for granted. One example he cited was the central nervous system (CNS). As he noted, "It is one thing to understand how a single neuron works in the mammalian CNS. It is another to understand the interaction of the hundreds of millions of neurons, of hundreds of types, in the CNS." Holland then explained that the operation of an individual neuron is unquestionably complex, but the CNS aggregate identity is much more complex than the sum of its individual neurons. After a century of intensive effort, scientists still cannot model many of the basic capabilities of the CNS.

Other complex systems are equally as mysterious and challenging for scientists who study them: the human immune system, which is such a coherent system that it can distinguish you from the rest of the world and reject cells from any other human; ecosystems with their overwhelming diversity and complex cycles of matter, energy, and information; or cities, such as New

PHOTOGRAPHY: MURRAE HAYNES

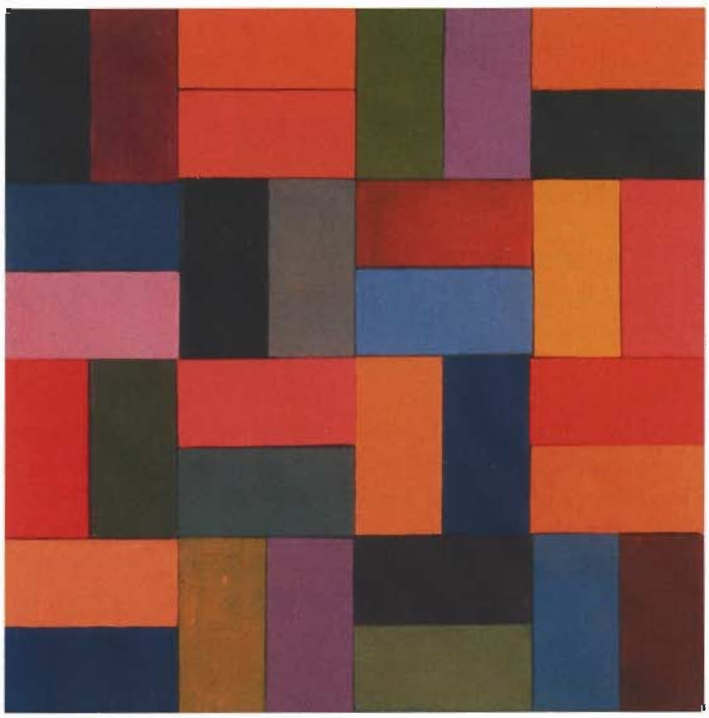
PAINTING BY CARLOS ESTRADA-VEGA, COURTESY HUNSAKER/SCHLESINGER GALLERY, SANTA MONICA, CALIFORNIA

York or Tokyo, that manage to deliver food, medicine, clothing, and other essentials to millions of inhabitants day after day without breaking down.

Although these systems differ in details, according to Holland, the common factor among them is their coherence in the face of change. Elements change, but the system continues to operate. Collecting these systems under the CAS heading signals scientists' belief that the behavior of these systems is ruled by general principles. The challenge is extracting those general principles. The benefits are obvious: these principles can provide useful guidelines for dealing with CAS problems that stretch our resources and defy easy solutions.

In order to study CAS, scientists break them down into components, or building blocks. "Almost all we know or do as individuals at almost every level consists in manipulating building blocks," Holland says. Building blocks play an essential part in physical science, and in recent years we have come a tremendous way in understanding the building blocks of biology: DNA, the amino acids that make proteins, helices (spiral shapes), and so on.

An individual's perception of the world can also be explained in terms of building blocks, says Holland. **"Building blocks are like trees:** If you see something you call 'tree,' it has certain standard parts, and one of the reasons you can recognize that objects that differ in appearance are trees is because all trees have the same basic components—trunks, branches, and leaves. Almost every object is made up of fairly standard elements, and that plays a key role in how we recognize them."



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The properties of particular building blocks determine what we are going to see or think about, Holland explains. He demonstrates this by comparing and contrasting human vision with computer science. "Like human vision, computer science is the routing of messages. In a computer, messages are routed through an artificial neural network, and an output is produced. The central nervous system works in a very different way. The system is largely autonomous and thinking all the time. Input simply changes the direction of a person's thoughts, so in effect the input is modulating an ongoing process. It is not a matter of the switching through of messages."

Holland likes to talk about components of systems in terms of building blocks because they have certain characteristics in common with children's building blocks: first, once you're told what they are, they're fairly easy to recognize, and, second, they can be combined in a great variety of ways even though there are a limited number of them.

Although the building block model is helpful in understanding the world, it has its limitations, Holland says. Before we can recognize the building blocks of a particular complex system, we must first be able to recognize or envision that system. One of the major inventions of the 20th century was the internal combustion engine. The building blocks of the engine were almost all known a century before: Volta's sparking device, the spark plugs; Venturi's perfume sprayer, the carburetor; and gear wheels, which have been known for centuries. Each part was familiar, but to make the internal combustion engine, it wasn't enough to know about the individual parts. The invention came in putting them together. The computer is another example. The Geiger counter, cathode ray tubes, and wires were all familiar components. Even the architecture of the computer was known by the end of the 19th century. The trick was putting them together in the right way. Brute force was not enough to come up with the answer. Vision was needed, as well as direction.

In studying complex adaptive systems, scientists also must have vision. They must look beyond individual building blocks, because the working of these systems cannot be adequately explained by describing the individual parts. Holland contends that scientists must begin to think of building blocks as generators. Seven children's building blocks are the generators of all the different forms a child can build from them. Mathematical theory describes this as a finitely generated group.

Probability theory calls these "generating procedures."

These theories tell us something about dynamic processes, and in fact mathematical theory is where researchers will probably look to formulate the general principles of all complex adaptive systems. In his book *Hidden Order,* Holland describes mathematics as "our sine qua non on this part of the journey. Fortunately, we need not delve into the details to describe the form of the mathematics and what it can contribute; the details will probably change anyhow, as we close in on the destination. Mathematics has a critical role because it alone enables us to formulate rigorous generalizations, or principles. Neither physical experiments nor computer-based experiments, on their own, can provide such generalizations."

Theories tell scientists where to look for answers, but how do scientists come up with theories? This is a question that appears to interest Holland almost as much as the theories themselves. "Theory," he says, "is crucial. Serendipity may occasionally yield insight, but is unlikely to be a frequent visitor. Without theory, we make endless forays into uncharted badlands. With theory, we can separate fundamental characteristics from fascinating idiosyncrasies and incidental features. Theory supplies landmarks and guideposts, and we begin to know what to observe and where to act.

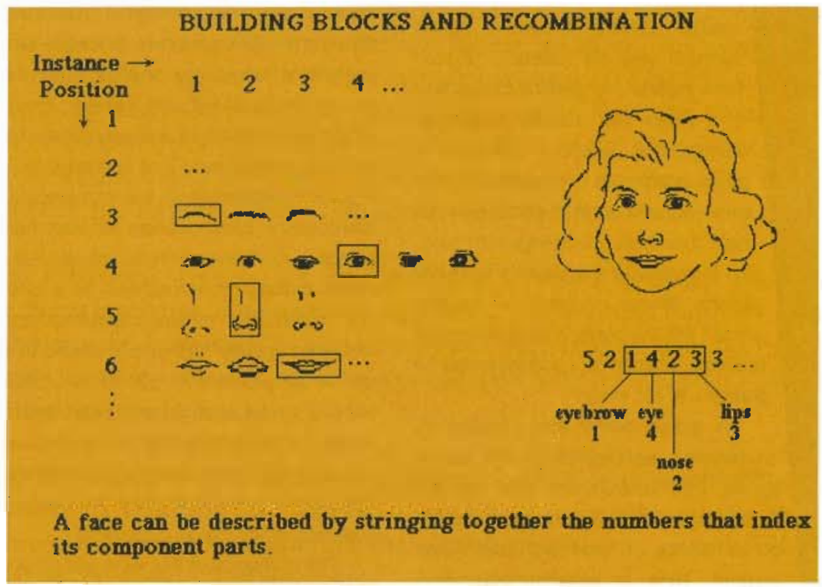
With the conviction of a preacher, Holland concluded his talk with three principles for scientists of the future. Science, he said, involves discipline, metaphor, and reduction. Discipline means that just as a tennis player must internalize the elements of the game in order to play without stopping to think about how to hold the racquet, students must internalize scientific knowledge in order to use that knowledge easily.

These internalized elements are the source for metaphor. Along with discipline, scientists must break out of the narrow confines of their box and think broadly through transdisciplinary experience and education. The broader their background, the more they are able to use such tools as metaphor in constructing theories.

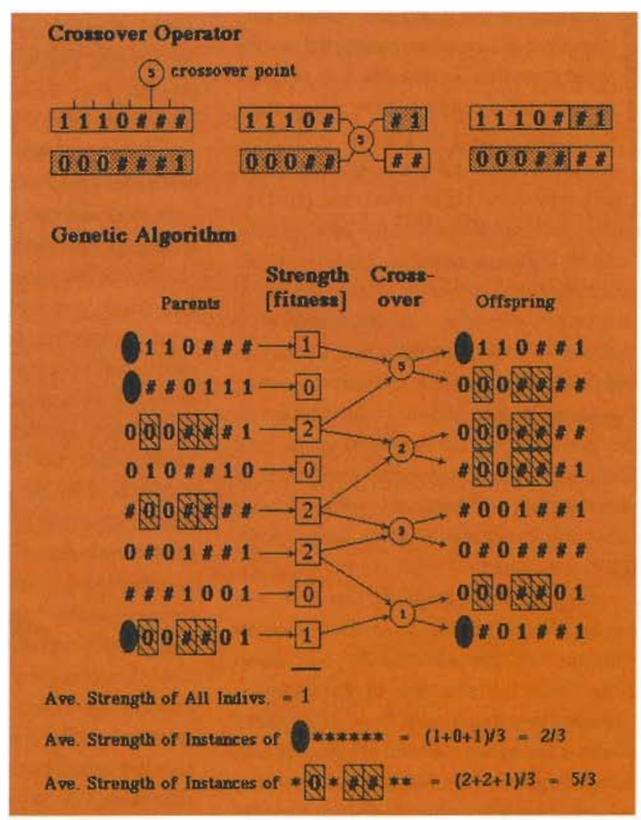
His third principle, reduction, has to do with drawing information together. The work of science is the work of manipulating building blocks, such as creating protein from amino acids. There are levels upon levels of building blocks, but researchers always have to be aware that if they are working on one level, they still have to satisfy the rules of the other levels.

As John Holland works on finding the principles behind complex adaptive systems, he practices what he preaches—vision, breadth, and interdisciplinary work. And if he has anything to say about it, so will the next generation of scientists.

Thomas Patrick O'Connor is an Associate Professor of Media Arts at James Madison University and a freelance writer.



A face can be described by stringing together the numbers that index its component parts.



Building Blocks for Faces and Crossover and Genetic Algorithms (both diagrams from Holland's *Hidden Order* published by Addison Wesley)

POST DOCTORAL FELLOWS

New SFI Postdoctoral Fellow Eizo Akiyama (KEIO University) is interested in the dynamics of games in which the payoff structure is influenced by the players.

Akiyama is considering the connection between a player's payoff function and his "state." "State" here means any general properties of a player that may be subject to change. For example, consider a player continuing a contest with the same opponents in a game environment that does not change with time. Will the utility of the player's possible actions always continue to be the same? Will the player's assessment of possible actions vary accompanied by changes in his state?

In game theory this situation is sometimes represented by one (large) game. That is, from the past into the future, all possible actions of all players at all points of time are taken into account. Thus all possible bifurcation patterns of the game are derived, with this situation as a whole depicted as one huge gametree. In this way, it is possible to project the course of time into a static game and analyze its solution in the form of a gametree or a game matrix. "Strategy" here means the action plan for all points in time, and the analysis of the rational solution for a game is possible only when all the possible actions from the past to the future are known. In reality, however, human decisions are not made on this basis. In order to deal with these types of problems in which the game itself is affected and changed by the players' behaviors over time, Akiyama has built a model where the game itself is described as a "dynamical system," aptly called the Dynamical Systems Game model (DS Game model).

There are many game-like situations that are appropriate for this dynamical model. For example, in a "game of chicken," such as an arms race, the dilemma of both players becomes heightened with time. Other social issues such as the problem of resource consumption gain a different perspective if they are considered from the viewpoint of the DS Game.

This fall **Lauren Ancel** (Stanford University) takes up a joint postdoctoral fellowship at Emory University and SFI.

In collaboration with Walter Fontana, Ancel studies how the mapping from genes to phenotypes influences (and is influenced by) evolution. Ancel uses the folding of RNA sequences into shapes as a simple model for a relationship between genotype (sequence) and phenotype (shape). The model implements phenotypic "plasticity" by allowing an RNA molecule to wiggle among alternative low-energy shapes. The model reveals an intriguing link between the thermodynamic stability of a shape (against temperature fluctuations) and its robustness to mutation (alterations in the sequence). The evolutionary consequence is that natural selection for thermodynamic robustness produces mutational robustness as a by-product. In the RNA model, mutational robustness can impede further phenotypic innovation to an extent that populations become trapped in an evolutionary dead end. The model further shows that the simultaneous evolution of thermodynamic and mutational robustness is facilitated by the concurrent evolution of structural modularity.

The relevance of this work with RNA consists in unveiling connections between concepts—such as environmental and genetic robustness, plasticity and modularity—that originated in evolutionary biology at the organismal level. It is difficult to make these connections precise and to understand them unless they crystallize in a simple model that captures essential features of complex genotype-phenotype relations.

During her tenure as a postdoctoral fellow, Ancel and Fontana will continue their work on plasticity in RNA molecules. Ancel also plans to develop theoretical models to study the evolutionary origins of genetic networks. She conjectures that modularity in development, like modularity in RNA structure, may arise as a side effect of environmental canalization, independent of the ultimate contribution of modularity to evolvability.

Homayoun Bagheri-Chaichian (Yale University) joins the SFI research staff as a Postdoctoral Fellow. He is studying how complex physiological adaptations evolve. Evolutionary theory offers one of the main explanations for justifying the existence of complex adaptations in organisms. The intricate design of any physiological adaptation is attributed to the action of some form of an optimizing search through an adaptive landscape. However, the most developed mathematical models deal with either the evolution of quantitative characters or the evolution of properties attributed to a single macromolecule. The mathematical treatments that do attempt to address system properties have no explicit propositions on the mechanistic underpinnings of the physiology.

Further, at the heart of most physiological adaptations is a system of regulation and feedback that helps maintain a stable state. This "self-maintaining" aspect of physiology is considered to be a unifying principle, the same way that evolution serves as a unifying principle in biology. However, these two concepts have never met on common ground, each one being treated as a separate question. Bagheri-Chaichian thinks that biochemical physiology is a good starting point for addressing the unification of these two ideas: How is the network of biochemical pathways in the cell coordinated as an integrated system? How does this coordination come to exist? The insight from molecular biology is that genes code for enzymes; the enzymes, in turn, control biochemical physiology. Yet most of our mechanistic understanding of biochemistry and biochemical kinetics revolves around single-enzyme kinetics; the behavior of multi-enzyme systems is not well understood.

Bagheri-Chaichian's work centers on developing a mathematical model of multi-enzyme systems in which the possibility of regulatory feedback is included. Using this model, he hopes to determine the structure of the evolutionary search space for transcriptional regulation of the pathway. Finally, he will look at the properties of the evolutionary search space in order to determine the dynamics that could lead to the evolution of self-maintenance in biochemical physiology.

P. Jeffrey Brantingham (University of Arizona) begins residency this fall as a SFI Postdoctoral Fellow. His research has centered on Paleolithic archaeology. The period between 35,000 and 45,000 years ago witnessed several critical events in human evolutionary history. The appearance and elaboration of novel Upper Paleolithic technologies and modern human behavior, the disappearance of archaic hominid species (e.g., Neanderthals and their kin), and the apparent ascendance of anatomically modern humans all took place within this relatively brief time. These events are often billed as a "revolution" in biology and behavior. Yet, the ecological and evolutionary processes underlying these events, as well as the nature of

Upper Paleolithic stone blade recovered from the Chang Tang Region, Northern Tibet at 4500m elevation. This type of stone tool is characteristic of late Pleistocene hunter-gatherer adaptations to the extreme environments of Northeast Asia.

any causal connections between them, remain poorly understood. For instance, what were the underlying biological, behavioral, and environmental factors structuring and/or driving the emergence of Upper Paleolithic technological adaptations and modern human behavior? And what organizing principles, both inherent in these complex systems and emergent through their interactions, allowed modern humans to colonize extreme environments such as the High Arctic, the arid core of the Mongolian Gobi, or the hostile, high-elevation environments of the Tibet Plateau?

Brantingham's research has centered on the areas of north China, Mongolia, and southern Siberia. Current evidence suggests that behavioral, ecological, demographic, biogeographic, and climatic processes played significant roles in structuring human evolutionary history in the region. However, present anthropological models for these processes are primarily anecdotal.

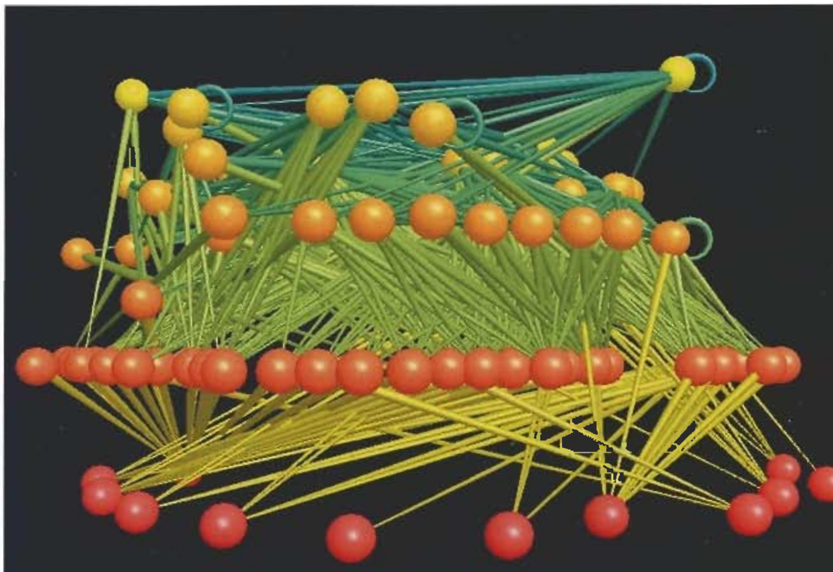
Many of the variables at play remain to be rigorously modeled, both individually and collectively, including the complex decision-making processes of individuals and small-scale foraging groups confronted with variable ecological situations, the influence of climatic and environmental fluctuations on human cultural systems, the demography of foraging groups, and human bio-behavioral tolerances under variable ecological conditions.

Brantingham will approach these issues from a computational standpoint. He remains involved in active archaeological field projects in China, Mongolia, and the Tibetan Plateau. Modeling efforts at SFI will feed directly into these field projects, helping to structure ongoing approaches to archaeological data recovery and interpretation. In turn, fieldwork will provide empirical feedback for improved modeling.

Due to habitat destruction, climate change, alien species introduction, and pollution, most of the Earth's ecosystems are experiencing losses of biodiversity. SFI 2000 Postdoctoral Fellow **Jennifer Dunne's** (University of California at Berkeley) research aims to shed light on why. Effects of these losses depend on the number and function of species lost. However, a long history of research has yet to effectively address large biodiversity losses or to clearly distinguish between effects of such losses due to species richness and those due to species functions.

Early food web theory and recent biodiversity experimental efforts suggest that altering species richness has many effects. Other theory and experimentation focus on the functional roles of species and suggest that one or a few keystone species or dominant functional groups and interactions drive effects on many ecosystems. Such theoretical and field-based studies have limited application to determining the impacts of reducing biodiversity in complex communities. Theory tends to focus on simple analytical models that describe general relationships of species richness to properties such as stability, and generally ignores variation in species function. Experiments on effects of species richness and function are necessarily limited to focusing on small assemblages of species and very few trophic levels, as well as on a few of many possible levels of diversity and combinations of interacting species. In addition, the question of whether the effects of species richness can be separated from function in field experiments remains unresolved.

Dunne's research aims to step beyond these limitations by using advanced computational techniques and food web data. Food webs, long a central theme in ecology, provide complex and comprehensive depictions of species diversity and species interactions. High-quality food webs summarize decades of intensive field research and represent an important source of standardized, detailed ecological data for modeling and simulations. She will work to develop new applications of global optimization techniques to simulate the effects of deleting groups of species on the structure and function of communities. This research, supported in part by a fellowship from the National Science Foundation, will allow her to quantify and assess the effects of species richness reductions and to examine whether, which, and why particular groups of species appear to have particularly strong or weak effects when removed from a community.



Little Rock Lake food web consists of 92 benthic and pelagic species spanning 4 trophic levels from phytoplankton at the base, through zooplankton and insects at intermediate levels, to fishes with cannibalistic loops at the top.

New SFI Postdoctoral Fellow **D. Eric Smith** is studying self-starting "engines" as a class of dynamical pattern-forming systems. Examples where patterns of events are spontaneously "formed" are thermoacoustic engines, weather "objects" like tornadoes and hurricanes, biotic and pre-biotic autocatalytic chemical networks, and replicating systems such as DNA and its associated network of catalysts. The defining (and curious) feature of engines is that they place energy in ordered forms by first taking in disordered forms and then discarding all of the extra disorder while siphoning off some of the acquired energy to do ordered work. Those that can self-start the sequence of events to perform this cycle also thus create dynamical patterns.

The reason patterns formed by engines are especially interesting is that the flux of disorder through an engine can enable it to pass entirely through a sequence of states (like sound waves or large molecules) that are not thermodynamically the most stable, in preference to others that are. Smith's interest is in the curious conservation laws that enable such a "current of disorder" to stabilize (and even create) the highly ordered and complex forms we see everywhere in nature.

In addition to applications to physical thermodynamics, he suggests that there are applications to coding theory, and perhaps the spontaneous selection of coding methods in languages or biological systems, studying thermoacoustic engines as examples of dynamical critical (phase transition) systems.

Karina Yusim holds a dual appointment with Los Alamos National Laboratory (LANL). Her research at LANL and SFI with Bette Korber focuses on the evolutionary history of HIV. Recently, HIV-1 sequences were analyzed by Korber and others to estimate the timing of the ancestral sequence of HIV-1, yielding a best estimate of 1931 (1915-1941). If, according to this study, the initial transfer of HIV-1 did occur in the first half of this century, then one is still left with the puzzle of why AIDS went undetected until 1981. One answer is that AIDS is a complicated disease, leading to a suppressed immune condition that invites other diseases, and therefore difficult to recognize; whether or not this explanation is adequate is arguable.

Korber and Yusim have recently undertaken new phylogenetic analysis of an extremely diverse set of HIV sequences from the former Zaire, now the Democratic Republic of the Congo (DRC). DRC has some of the earliest AIDS cases, and virtually all subtypes of HIV-1 co-circulate there, suggestive that the region may have been a focus of the expansion of the epidemic. An analysis of the DRC data results in a model of epidemic growth suggesting that the first twenty years of the epidemic were characterized by an extended period of slow spread. Essentially, HIV-1 exhibited a low profile early on, followed by an increase in the exponential growth rate of the infected population through time. This analysis suggests that the hypothesis that HIV was present but undetected for an extended period is plausible.

MANIFESTING COMPLEX ADAPTIVE SYSTEMS IN THE WORLD

by Tom Kepler

PHOTOGRAPHY: GUY AMBROSINO

Simona is a shark immunologist. She and I huddled in a dark barroom corner, between sessions of the Asilomar Midwinter Immunology Conference, pecking at the laptop keypad, poring over dozens of DNA sequences. The TV behind the bar flickered and murmured as we hunted for clues to the extraordinary event that caused the vertebrate immune system to appear, fully developed, in sharks (and subsequently all later vertebrates) when not a trace of such a thing can be found in their closest, earlier relatives, the hagfishes and lampreys. In spite of my sparkling articulation of a keen insight into the nature of immunity, a rapt blankness washed over Simona's face. She turned slowly toward the jabbering television. I ceased my own soliloquy to listen to the televangelist ranting against Evolution in particular and Science in general. Anger replaced blankness as Simona turned back toward me and declared that people who reject science shouldn't be allowed on television: "How the hell do they think TV works? Where do they suppose it came from?" She shook her head and returned her gaze to the smaller screen filled with As, Gs, Cs, and Ts.

This scene came back to me early this July, while driving from Raleigh to Santa Fe to start my new job as academic vice president at the Santa Fe Institute. On day three of the trek, I crossed the border westward from Texas directly into a monstrous thunderstorm. Rain fell so thickly that I couldn't see the other side of the median; I pulled over to wait it out as the wind threatened to blow my Honda across the prairie like a tumbleweed. Once I became habituated to the hailstorm tattoo on the roof and the cardiac crescendo in my chest, I had a few quiet moments to contemplate Simona's reaction. My first thought was to wonder why the Asilomar scene, rather than, say, my life, was playing before my eyes, but I quickly realized that her reaction vividly embodied some ideas that had been on my mind since I first contemplated coming to SFI.

How extraordinary that she should seize upon television while such beautiful evidence for evolution sat blinking at us from the LCD! Why?

Well, the gorgeous intellectual labors of, say, Maxwell and Heisenberg are such rarefied works of the mind that it takes considerable preparation to appreciate their elegance and genius. But television is their word made flesh. We can debate over caffe lattes and Gauloises the reality of electromagnetic fields and puzzle over just what, if anything, the Schrödinger equation refers to, but press that button on the remote, and David Letterman appears, undeniably, pop-eyed and mugging: I confirm science, thus!

So how does work on complex adaptive systems become manifest in the world? Agents make regular appearances within our models; but what informs our own agency? What plays *sarx* to our *logos*? While the SFI product is still largely theoretical, as well it should be, two recent public lectures point out promising directions for putting theory into practice.

Michael Cohen, long-time SFI friend and co-founder of the Center for the Study of Complex Systems at University of Michigan, described work he has done with Bob Axelrod in a lecture entitled "Harnessing Complexity." Their work develops out of evolutionary theory, computer science, and social design, and provides a framework for human organizational structure and decision making appropriate for a world in which information is costly and small interventions can have very large—often unanticipated—consequences. Most of us spend the bulk of our lives in formal organizations of one type or another; by far the most important and numerous of our acts in the world are social. Serious efforts aimed at making organizations more responsive and robust are likely to have profound impact.

The challenge is huge, though. While it is clear that formal organizations are "complex adaptive systems" (CAS), and the lessons learned from CAS have a distinct cogency, the means by which these lessons most effectively become manifest in practice will require great effort to elucidate.

Avidan Neumann, External Faculty member and former SFI post-doc, described his work on modeling the viral dynamics of Hepatitis C under drug therapy. What made this lecture particularly exciting was his description of an upcoming new clinical trial for anti-hepatitis therapy that will use mathematical models of within-host viral dynamics, frequent data collection from study subjects, and statistical analysis to tailor the therapy to individual subject needs. It has become clear that individual-to-individual variation is a complication for drug development; a compound's effectiveness, on the one hand, and the seriousness of its "side-effects," on the other, are dependent on individual genetic makeup.

The underlying principle of this approach is similar to that advocated in Michael Cohen's lecture. Long-term prediction in specific cases is rendered impotent in the face of system sensitivities and the unavoidable lack of necessary information. Thus, a flexible strategy that demands monitoring and mid-course correction is preferable to a "ballistic" strategy, which is set into motion with fingers crossed. The former approach requires constant data collection and processing to determine what the relevant information is and extract it dynamically into a system representation. These are real and immediate challenges for researchers in CAS, but ones that can have huge repercussions. Such prospects are exciting and intellectually invigorating.

To be sure, the purely theoretical work is the heart of the SFI enterprise. None of what I described above would be conceivable without the freedom to pursue "decontextualized ideas" (to use Randall Collins's evocative phrase). I am still deeply curious about whether adaptive immunity would arise in parallel with predation if the tape were to be run again. I wonder whether horizontal transfer of a transposon from a bacterium into an early vertebrate sparked off the "immune big bang," as some (Simona among them) have so intriguingly speculated. But I also have to ask how our knowledge of immunity—amplified, honed, and integrated—using tools and techniques derived from the study of a variety of CAS, can be utilized to increase the sum of human happiness.

And I have great confidence that it can. Furthermore, immunity is certainly not the only, nor probably even the best, field in which fertile theoretical ideas from CAS can take root to yield real fruit for real people. That is one of the reasons I am so delighted to have been asked to come to SFI and so excited to be here now. I look forward to doing all I can do to help develop and nurture breathtaking new ideas born into the mysterious realm of words and ideas, through to their incarnation in the world of actions and consequences, of blood, sweat and tears, of infectious disease, business plans, and hailstorms.

Tom Kepler is Vice President for Academic Affairs at SFI.