SFI Bulletin

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EVOLUTIONARY DYNAMICS: What would happen if we reran the tape?

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1399 Hyde Park Road
Santa Fe, New Mexico 87501, USA
Phone (505) 984-8800
fax (505) 982-0565
home page: http://www.santafe.edu

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EDITORIAL STAFF:
Ginger Richardson
Lesley S. King
Andi Sutherland

CONTRIBUTORS:
Rex Graham
Erica Jen
Cosma Rohilla Shalizi
Neal Singer

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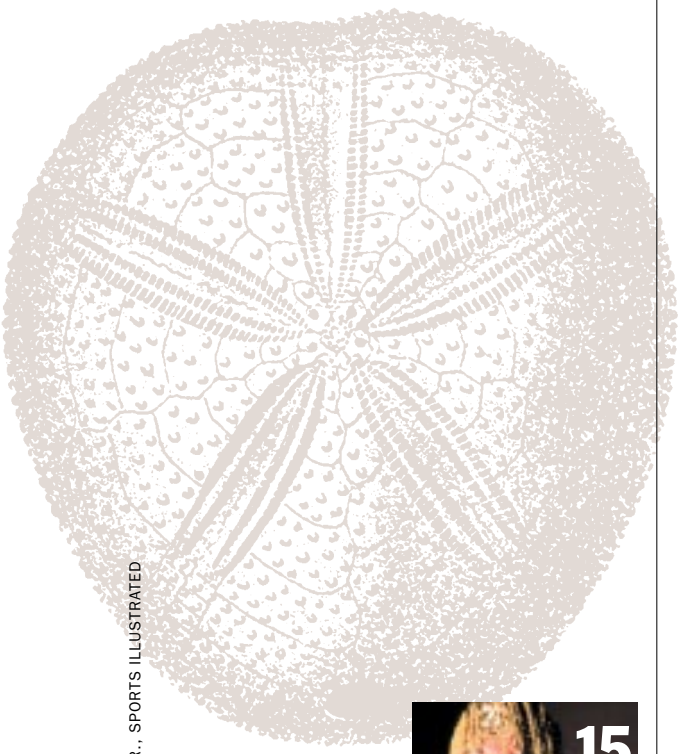

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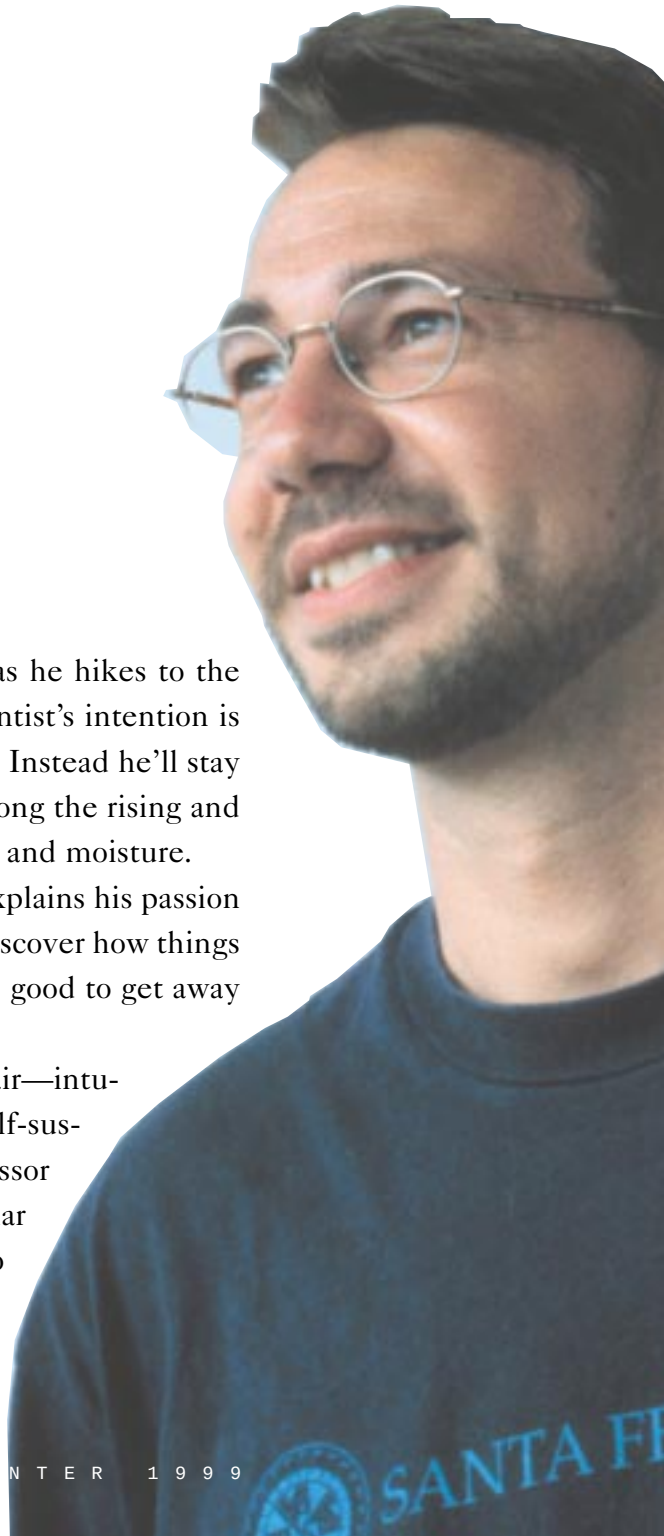
BY NEAL SINGER



PIECES OF SHALE SHIFT UNDER WALTER FONTANA'S BOOTS as he hikes to the top of a ridge south of Belen, New Mexico. The young scientist's intention is to leap off that ridge, but he won't fall straight to the ground. Instead he'll stay suspended by a device called a paraglider while he plays among the rising and failing currents of air generated by interactions of sun, earth, and moisture.

The sport is dangerous, but a quote favored by Fontana explains his passion for it: "Flying gives me a chance to understand systems, to discover how things fit together." On a lighter note, he adds, "Now and then, it's good to get away from it all."

It's fair to say that what Fontana does for relaxation in the air—intuitively trying to understand the emergence of a system of self-sustaining updrafts—he does more formally as a research professor in residence at the Santa Fe Institute, though at the molecular level. Using research from a variety of fields, he strives to achieve new heights of understanding.

profile

PARAGLIDING PHOTOS FROM *ABGEHOBEN* BY ANDREAS BUSSLINGER & ALEXANDRE KOBEL
WALTER FONTANA PHOTO: LAURENT GUERIN

Particularly, he seeks to understand how self-sustaining chemical systems emerge, and to develop a formal method to classify their possible changes. "I want to understand the emergence of molecular organization. Why can't we understand with our present formal tools the products of evolution?" he asks rhetorically in his softly accented voice.

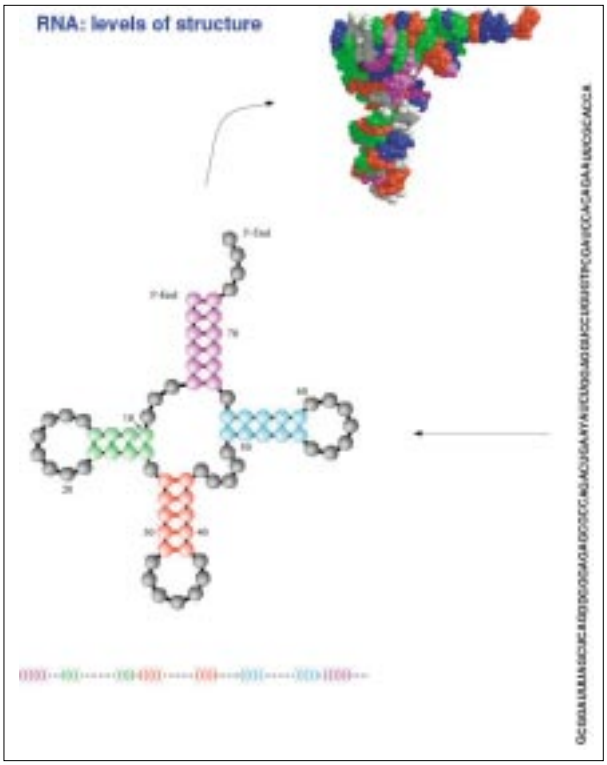
Darwinian selection may explain which of two alternative molecular systems will come to dominate an environment under certain conditions, Fontana says, but it cannot explain how these alternatives originated in the first place, nor offer a complete spectrum of what else could have been possible.

Fontana's interest in the emergence of self-sustaining molecular systems itself emerged from a series of earlier interests, in particular from a much simpler case in which he studied the effect of mutations on the structure of RNA (ribonucleic acid) molecules. This was at the University of Vienna, where he received his doctorate in theoretical chemistry in 1987 and is currently an associate professor.

"RNA is so far the only molecule with which chemists can play Darwinian evolution in the test tube," says Fontana. RNA molecules consist of four building blocks linked like pearls on a string in any order and in multiple appearances. Changing their order means that the molecules may fold into shapes that convey new chemical functions.

It was, in fact, RNA that initially dispelled Fontana's prejudice that chemistry was dull. In high school, he learned from *The Eighth Day of Creation*, (a detailed history of early research in molecular biology by Horace Freeland Judson) that RNA could form a reverse copy, like the negative of a photo, of DNA. When Fontana learned this, he dropped his ideas of majoring in liberal arts.

"When I realized molecules could read, my awe was without bounds," he says of the marvels of molecular translation and regulation.



A string of symbols (denoting molecular building blocks) represents an RNA sequence or primary structure (right). Each symbol likes to pair up with a specific other symbol. The result is a pattern of pairings, a so-called secondary structure (left), that is lowest in energy. The drawing should not be read as a two-dimensional spatial structure, but rather as a representation of which position is connected to which. The actual three-dimensional, or tertiary, structure (top) includes a further layer of interactions beyond pairing.

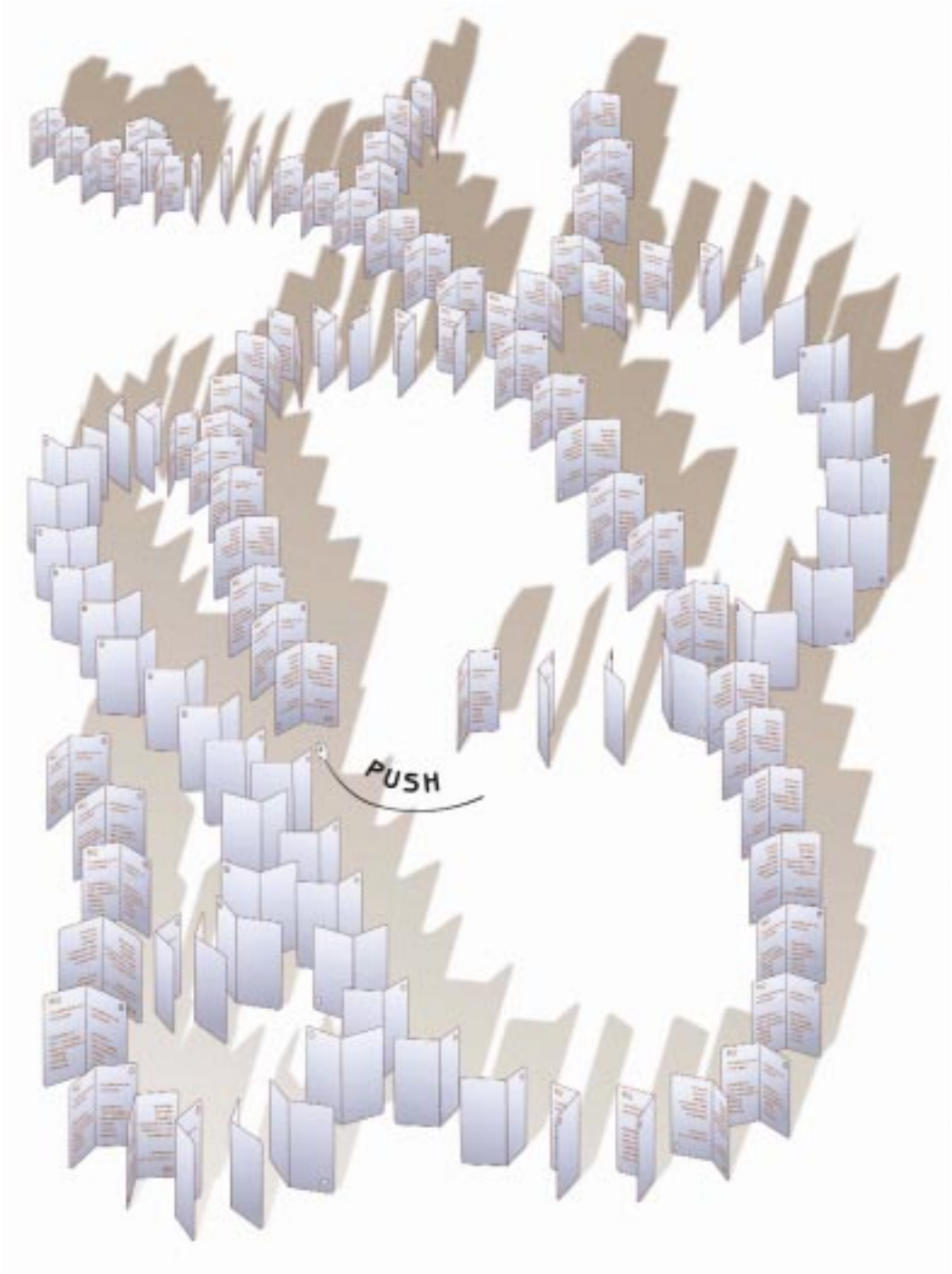


ILLUSTRATION: PATRICK MCKELVEY

But Fontana's initial training in complexity began even earlier, in his childhood home in the South Tyrol, a formerly Austrian region governed by Italy since the end of World War I. There, he spoke only German to his mother and only Italian to his father. He and his father, a court of appeals judge, would lay out networks of cardboard dominoes—some bent along the long axis in the shape of a V—on his father's office floor. A single, falling, V-shaped cardboard could commence the falling of two branching parallel chains of dominoes that would, perhaps, intersect later and, perhaps, partially cancel the "falling domino" effect. Using several V-shaped dominoes, more chains could be set in motion. Networks and parallelism have fascinated Fontana ever since.

As a researcher, he and his colleagues Peter Schuster, Ivo Hofacker, and Peter Stadler—all at the University of Vienna's Institute of Theoretical Chemistry—were able to improve upon an already existing folding algorithm to predict the shapes of RNA sequences. The package Fontana helped develop, commonly called the Vienna RNA Package, is free software and is maintained and updated at the university. It has become a widely used program around the world to predict the folding of RNA molecules.

RNA is of particular interest to the public right now as a means of developing substances that perform new chemical functions. In this process it is possible to let Darwinian evolution in the test-tube do the work of generating molecules that perform certain tasks—a practice called evolutionary biotechnology—rather than attempting to rationally (and often hopelessly) construct "designer molecules" at the drawing board.

"What enables the evolution of RNA strings is [a quality called] neutrality," says Fontana. "Think in terms of an electric circuit metaphor: an RNA sequence is the wiring diagram, and its shape is the diagram's electronic behavior. You never can change the behavior directly; all you can do is change the wiring diagram. Many changes in the wiring diagram do not affect behavior and thus are considered 'neutral.' So," says Fontana, "if you want to change a given behavior into something else not readily accessible from the current wiring diagram, you can; the evolutionary process is not stuck. The current wiring diagram may still be modified 'neutrally' again and again without

destroying its behavior until eventually the next change produces the new, improved behavior."

While Fontana's RNA research continued, he also began to wonder in the early 1990s about how to formalize chemistry so as to capture its generative aspect—the capacity of molecules to construct new molecules upon interaction. Together with Leo Buss, a biologist from Yale, he hopes in this way to understand how entire networks of molecular reactions arise, how they become functionally organized, and how a network defines the ways it can change.

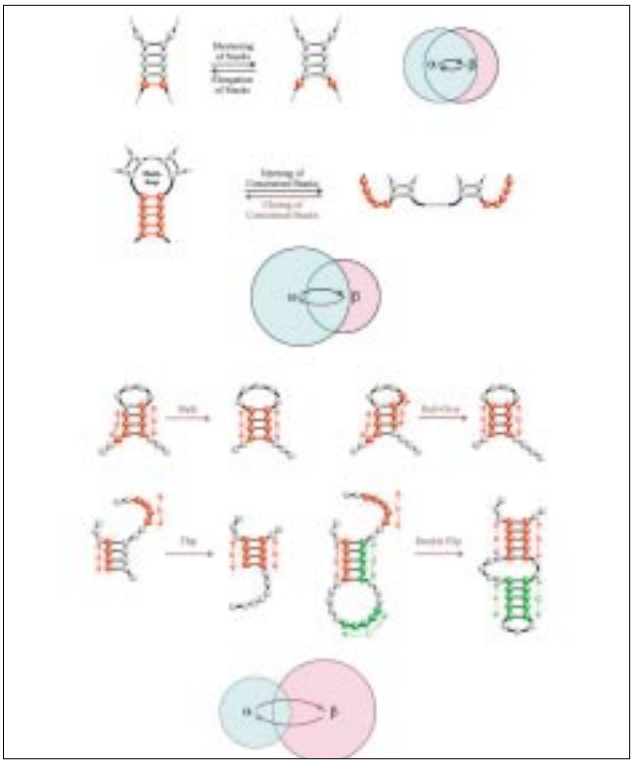
"I wanted to go beyond chemical kinetics, which assumes that a particular reaction network already exists. I wanted to get at the core of chemistry proper: how does a network build itself? What are possible architectures for self-sustaining networks of chemical production and coordination?" he asks.

So he set up what he calls "a toy world," in which mathematical formalisms represent an abstract, very simplified, chemical world. "I try to get rid of everything in the real world that is not the core of the problem." He adds with a helpless smile, "Naturally, this will offend some chemists."

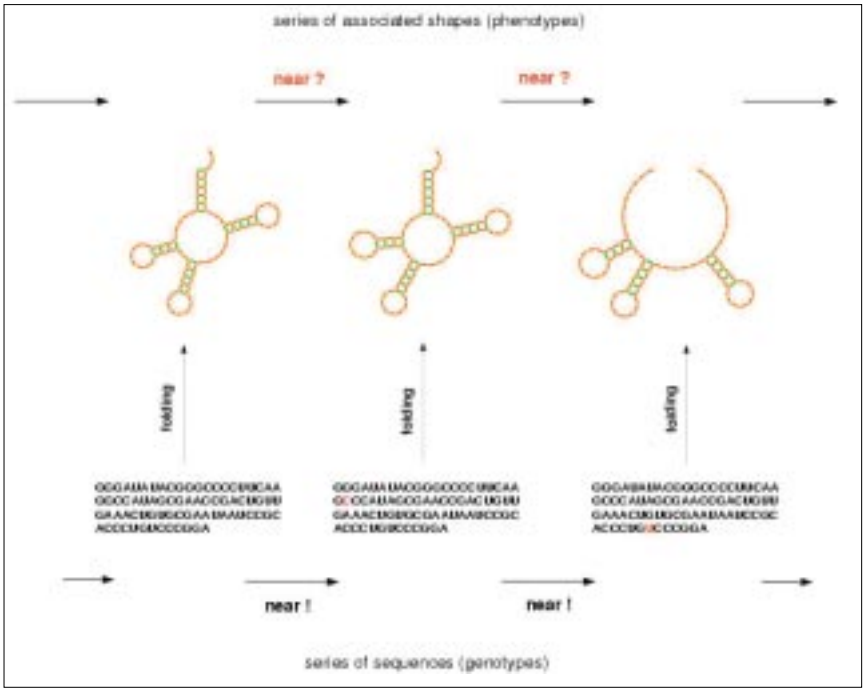
The right simplifications are at the basis of important abstractions. Consider how Newton discarded major topographic features of planets to develop a theory of gravitation that treats physical objects only as mathematical points of mass attracting each other. Sacrificing hills and valleys, and oceans and sands for a useful abstraction, now makes it possible to plot the trajectories of interplanetary voyages.

The physicist George Gamow used the same idea of helpful simplification in 1953 when he attempted to use then-known features of DNA to mathematicize the hereditary properties of living organisms as a long number written in a four-digit system. As physicist and biochemist Francis Crick states in *The Eighth Day of Creation*, the importance of Gamow's idea "was that it was really an abstract theory of coding, and was not cluttered up with a lot of unnecessary chemical details."

But the question arises, how can one achieve a simplified, self-maintaining system that would accurately represent the relevant features of an organization even more primitive than any in reality? The goal, of course, was clear. Fontana wrote in a recent research proposal of his



A series of changing sequences and their structures are shown. The question is: what constitutes "dramatic change"? An evolutionary meaningful definition of "dramatic change" is "a change that is difficult to make on average." Each sequence in the series results from the previous by changing the symbol at one position. Clearly, there is no "dramatic change" at the level of sequences. Contrary to appearance, however, it turns out that the first change in structure is "dramatic" (a shift), while the next (loss of a structural element) is not. The difficulty of a change has nothing to do with similarity.



This is a compilation of difficult changes in RNA secondary structure. Difficult and easy changes are indicated with black and brown arrows, respectively. The point is that difficult change requires the synchronized participation of many positions along the sequence.

intention to develop a mathematical understanding of self-maintaining organizations, that "there exists no readily identifiable scientific tradition that seeks to understand what classes of such systems are possible or to discover conditions necessary to achieve them."

So Fontana was like a person trying to learn to ride a bike when the bike had yet to be invented. Unlike, say, the formal relation developed by Einstein between mass and energy, there existed no formal mathematics to describe how complex systems originate from simpler ones. Without that basic understanding, it was impossible to predict in what ways such networks could change, and how novelty arises in evolution. Why, say, does a cell without a nucleus become a cell with a nucleus, or why do cells band together to form tissues with specialized functions? And what happens when such a molecular system is perturbed by some unexpected element, another molecular organization, or some other intruder?

Fontana offers a simplified handle on his thoughts by discussing evolution. "Have you ever considered what is chance and what is really necessary in the process of evolution?" he asks. "What would happen if we reran the tape, so to speak, and started over again? Would the process end up with the same results—the biological world as it appears to us today—or would things work out differently? Is today's world a completely random event, or would certain aspects have to reoccur once particular building blocks become available? The answer," he says, "is that we don't know. Our science hits a wall. We suddenly realize that our tools—the formal mathematics with which physics is so successful—seem not to have a grip on this kind of question."

The question is fundamental, he says, because traditional dynamical systems approaches are geared to treat change only in some quantitative observable, such as position or density. But in a chemical reaction it is the "things" themselves—the molecules—that change in a chemical transformation, not just some numerical quantities associated with them. "This causes things that haven't been there before to join the stage. These are new variables," says Fontana.

Conventional dynamical systems in use in physics do not have a form that allows treating this situation. Fortunately, he says, he found a tool that enabled him to at least produce a "toy model"—a theory of computation that offered a new perspective, since it is, loosely speaking, based on the transformations that objects can undergo. This tool is the lambda calculus invented by Princeton's Alonzo Church in the 1930s, and introduced to Fontana in a seminar at Los Alamos National Laboratory by MIT mathematician Gian-Carlo Rota in the early 1990s. The salient feature of this calculus is that it treats objects—symbolic expressions—as functions that can act on these very same objects, transforming them into new functions.

"I was amazed by this calculus. It looked chemical to me," says Fontana. "But for my purposes, it was half-baked. It had to be animated with some dynamics." He implemented a computer program based on the calculus. Its purpose was to study the behavior of a soup of such functions viewed as abstract molecules. He left the program working overnight. When he returned the next morning, he found a self-maintaining system.

"This was so interesting in itself that at first I didn't care if it had any application. I took for the first time seriously the idea of molecules as functions. I came to see molecules as themselves rules of interaction, as agents of transformation that act on other molecules to become new agents of transformation," he says.

In Berlin, Fontana had a conversation on the subject with the well-known molecular biologist Gunter Stent. At first, Stent did not grasp Fontana's point, but later he approached Fontana to say, "I see, you are making a distinction between having a function and being a function. Your molecules are functions to begin with."

Fontana was aware, however, that his insight—while a step forward—had still left him far from the solution he sought. Lambda calculus is not real chemistry. "There are many problems. For example, there is no notion of mass, or mass conservation, in this calculus. And in the world of computational logic, there is no sensitivity to resources: everything can be used indefinitely; nothing is ever used up; everything goes on forever. However, in chemistry, if I use a molecule A to prove by synthesis a molecule C, A is gone, and needs to be produced again.

"But we may find a new calculus. I'm dreaming, but this is what drives me."

However, Fontana mentions one source of encouragement: "As we try to modify lambda calculus towards a better chemistry, we end up with problems that have already arisen in computer science for completely different reasons. There is a kind of convergence."

Meanwhile, at SFI, Fontana has used his verbal skills and understanding of the invisible links between complex systems to be helpful to social scientists.

SFI visiting fellow David Stark, chair of the Department of Sociology at Columbia University, was interested in how organizations succeed by "exploitation" (the mining of known resources) and "exploration" (seeking new resources). Describing his discussion with Fontana, he says, "Walter Fontana is one of the most incredible intellectuals I've ever met. That he could talk with people outside his field and explain to them, in terms they can grasp, without condescending

or short-circuiting the idea, the complicated processes he was analyzing in his RNA work, was amazing.

"Walter, says Stark, "shifted the discussion down to the level of genetic mutation and showed [that the notion of exploit versus explore] was a false dichotomy: in order to have direction—a focus to exploit resources, you need drift—apparently aimless exploration." This would be the equivalent of the many seemingly useless, or neutral, changes in RNA structure that, without warning, create the configuration of a valuable new molecule. "Such movement [apparently] isn't leading you anywhere, but without it, you're not going anywhere."

Says John Padgett, a political scientist at the University of Chicago, "Walter is interested in the folding in of chemical networks to get a self-sustaining system called a metabolism. If you look at my networks on marriage and economics in medieval Florence, pictorially there's a great similarity between his pictures and mine, though his are chemical and mine social. Mine fold in to produce political parties.

"So, because I'm looking for self-sustaining mechanisms, I've taken his models and used them for medieval Florence, because complex systems in a formal sense—like Walter does them—can have a number of trajectories. My environmental perturbations are goals and alliances; I know what Florence did, but not the possible histories, or why Florence became different from Venice."

South of Belen, Fontana has made it to the mountain's top. Methodically, he removes his paraglider from his pack. As the breeze catches the unusual device, it folds out into the shape of a cathedral arch.

Fontana takes off with his feet tucked. Then his legs push forward like a child pumping in a swing. Fully launched, he could be riding a flying scooter in an amusement park in which one is whirled round and round a center stanchion, but here, there is no stanchion, only variations in wind and one's skill in riding it. He controls the craft by shifting his weight and manipulating some of the many lines connected in four suites to the trailing edge of the sail.

The average flight time at this site, for fellow excursionists also gliding, seems about 10 minutes. However, 15 minutes later, everyone else is down, but Fontana is still sailing. Turning, dropping, rising, he intuitively rides the complex currents of air. In another 10 minutes, the other paraglide devotees and spectators motor off to lunch.

Fontana is still flying, alone above the ridge.

Twenty minutes later, small against the wide blue sky, Fontana still soars, intuitively riding the thermals that appear and fail in some complex interaction of sun angle and ground and moisture.

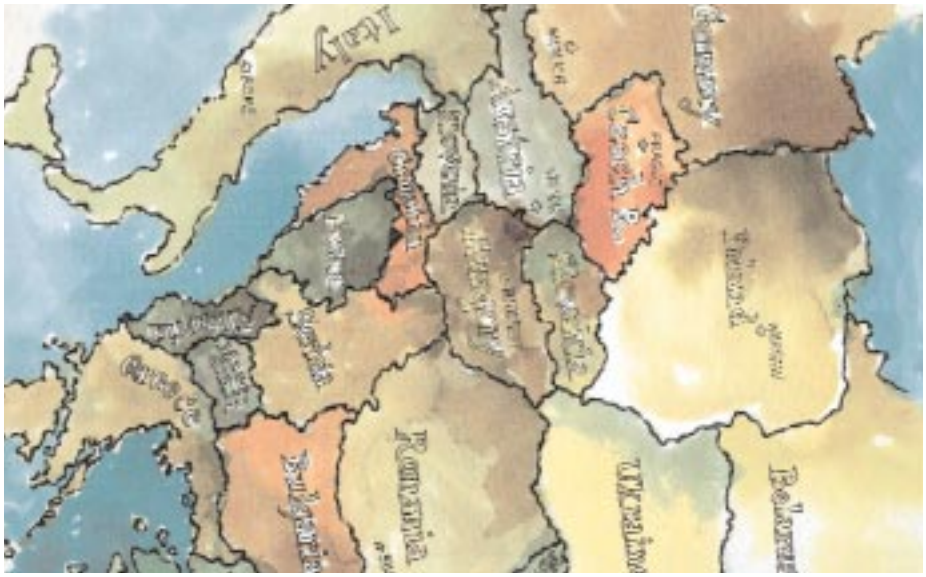
He loses updraft, begins to fall. But hugging the cliff face almost close enough to count pebbles, Fontana locates a thermal and is again aloft above the ridgeline.

What Can Emergence Tell Us About Today's Eastern Europe?

COSMA ROHILLA SHALIZI

EASTERN EUROPE IS IN THE MIDST OF A TRANSITION of historic dimension. What is the nature of the political, social, and economic arrangements that are forming from the aftermath of communism? Are activities in the countries of Central and Eastern Europe evidence of the "emergent" behavior studied by SFI Science Board member John Holland and others? These questions were the focus of a panel discussion on "Social, Political, and Economic Changes in Central and Eastern Europe" during SFI's recent Fall Symposium attended by members of SFI's Board of Trustees and Business Network. Loren Jenkins, senior foreign editor at National Public Radio, moderated the event.

John Holland, of the University of Michigan, kicked off the discussion with some general comments about the concept of emergent phenomena, a notion whose definition is still—emerging. Holland probably knows more about emergence than anyone does (that is, as the old joke has it, he's perplexed on a higher and more significant level), but he disclaimed knowing much about Eastern Europe. The other panelists included SFI Trustee Esther Dyson, chairperson of EDventure Holdings, a company focused on new information technology worldwide and particularly the computer markets of Central and Eastern Europe; Harvard University's Anne Goldfeld, a director of the American Refugee Committee; and sociologist David Stark from Columbia University, who has written extensively on emergent economies in the region. Each knew a great deal about Eastern Europe, particularly the final panel member Lorand Ambrus-Lakatos, an assistant professor of economics and political science at the Central European University in Budapest. However, none were conventional researchers into emergence.



There was, nonetheless, an obvious point of intersection between these two sets of interest and expertise. The countries of Eastern Europe and the former Soviet Union had a decidedly non-emergent, non-self-organized dictatorial socialism imposed upon them, first in 1917 and then in 1945. Starting in the early 1990s, they again were forced into a new form of social organization, what David Stark called a

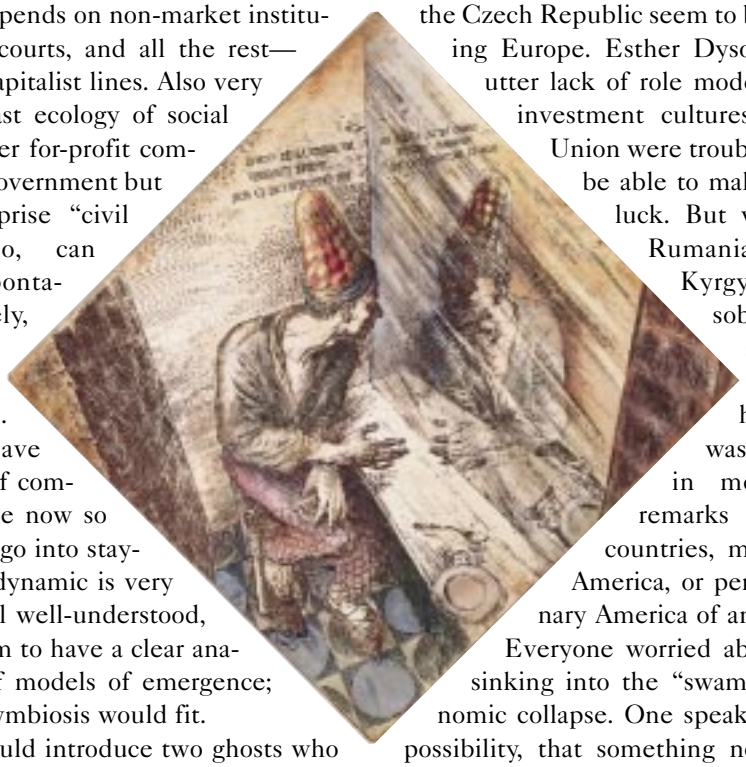
"designer capitalism." Neither form of utopian social engineering met with success. It is scarcely an exaggeration to say that to the extent that any part of these economies works, it was not consciously designed, either by the apparatchiks of Gosplan (the Soviet Planning Commission) or by the professors from Harvard or other western institutions, but grew without anyone really guiding it or realizing what they were doing. In many of these countries, for instance, "inter-enterprise" networks have formed as, essentially, a new kind of property relation. Firms bought into each other, daisy-chain fashion, for want of private individuals with the capital to do so. It is just this kind of self-organization that the theory of emergent phenomena is supposed to help us understand. So what can that theory tell us about things like the emergence of new forms of property?

To begin with, it must be confessed, as John Holland did most forthrightly, that there isn't really a theory of emergence, not in the way that physicists have a theory of fluids, or biologists a theory of natural selection. We don't have the right concepts yet. We're not even agreed, all of us, on what counts as emergence, and we certainly can't predict when it will happen, or why, or what form it will take. With respect to what emergence is, we are in the position of the judge who couldn't define obscenity, but knew it when he saw it. Holland says that it has to do with the way agents interact with each other. Moreover, emergent phenomena only occur when the interactions are such that we can't just average the behavior of all the separate individuals to see what they're doing in aggregate. But, as Holland points out in his book *Emergence,* these are necessary but not sufficient conditions. What must be added for sufficiency, for a proper definition of emergence, is yet to be determined.

On the other hand, we do know quite a bit about specific emergent phenomena. One of the lessons of the theory of natural selection (really, of evolutionary game theory) is that a degree of isolation, or "buffering," can be a great help to a new strategy, a new form of behavior, in gaining a foothold. To use David Stark's phrase, "containment can lead to contagion." Take the Prisoners' Dilemma game, for instance. This is a classic problem of conflict and cooperation in which each of two players has a choice of cooperating with the other or of defecting. If the new behavior is cooperation, it helps greatly if the cooperators can recognize each other, and deal preferentially with each other. Then they can even, sometimes, reach a kind of critical mass, at which point others start cooperating out of sheer self-interest. And it may well be that the same thing is true if the game is not Prisoners' Dilemma but doing business in a newly marketized economy, and the new behavior is not "cooperation" in the senses of the game, but fulfilling your end of a contract. There's even some evidence that those countries which, like Poland, privatized and marketized in stages for internal political reasons, rather than submitting to the "shock therapy" of the Capitalist International, ended up with more vibrant and successful private sectors; they effectively created such buffered situations—without having any inkling that that was what they were doing. In time, the expectation that people will cooperate, or honor contracts, can emerge as a benign self-fulfilling prophecy, an established and reliable fact of social life—in a word, a convention.

Of course, "emergent" does not necessarily mean "good." Corruption can become pervasive and conventional in exactly the same way as cooperation, or honest contracting, to the point where even if most people would prefer not to be corrupt, they have to assume that everyone else is, and will take advantage of them if they

are not. Which brings us to one of the most important points on which the panel was agreed: markets do not make capitalism. Even capital markets don't make successful capitalism. The fantasy of a frictionless, completely market-driven society is just a fantasy, because successful capitalism depends on non-market institutions—schools, police, courts, and all the rest—that are not run along capitalist lines. Also very desirable is a whole vast ecology of social elements that are neither for-profit companies nor parts of the government but that nevertheless comprise "civil society." These, too, can emerge, can form spontaneously. Unfortunately, they haven't in Eastern Europe, at least not as much as they're needed. They may even have shrunk from the days of communism, simply because now so much more effort must go into staying afloat. Clearly this dynamic is very important, but not at all well-understood, and it doesn't even seem to have a clear analog among our stock of models of emergence; perhaps mutualism or symbiosis would fit.



At this point we should introduce two ghosts who haunted the proceedings, the ghosts, aptly enough, of a pair of Central European economists, explorers of emergent and evolutionary phenomena, and of the way market economies fit into the larger society: Joseph Schumpeter and Freidrich Hayek, both originally of Vienna, later of Harvard and Chicago, respectively. They wrote their great works more than half a century ago, and yet echoes of their words could be heard throughout the discussion. Schumpeter's explains how capitalism requires (and supports) a larger society, many of whose institutions are run on quite antithetical lines. Hayek's explains how markets work as distributed computing mechanisms, adaptively optimizing the allocation of scarce resources, and how society itself is held together by conventions, and the shared expectations they produce. (Admittedly, his work speaks of "spontaneous order" rather than the newer term, "self-organization.") Today we have a much better body of abstract theory about emergence, and a wonderful assortment of models, and they make very nice analogies to what Hayek and Schumpeter talked about; Hayek even lived long enough to appreciate some of them. But the question remained, what can they tell us about the real world?

The panel zoomed in from "Eastern Europe" or the "transition economies" to four countries in particular: Hungary, Poland, the Czech Republic, and Russia. A little was said about what used to be Yugoslavia, and about Slovakia; other Eastern European countries weren't discussed. The consensus was that Hungary, Poland, and the Czech Republic seem to be on their way to rejoining Europe. Esther Dyson's warnings about the utter lack of role models for the business and investment cultures in the former Soviet Union were troubling, yet Russia may still be able to make progress, with a little luck. But what was happening in Rumania, or Georgia, or Kyrgyzstan? Beyond the sobering humanitarian perspective offered by Anne Goldfeld, we heard little, and less that was hopeful. It was implicit in most of the speakers' remarks that success, for these countries, means looking more like America, or perhaps the slightly imaginary America of an Economics 1 textbook. Everyone worried about the danger of their sinking into the "swamp" of political and economic collapse. One speaker contemplated a third possibility, that something novel and strange might crawl out of the swamp. It was, David Stark said, possible that some "genuinely new" form of social organization would be produced by the current ferment, something that didn't look much like a liberal capitalist democracy but still, in some fashion, worked. That could be an emergent phenomenon on a very large scale indeed, but it may be a long time before the intellectual descendants of Hayek and Schumpeter and Holland can do anything more to answer such questions than guess, and hope for the best. On a good day, we can cobble a common language for sociologists and scientists out of their analogies live on stage. But the real challenge is to come up with something to say to a legislator in Warsaw or an entrepreneur in Kazan or a homemaker in Bucharest which will help them make more sense of their world.

Cosma Shalizi, University of Wisconsin, is currently a Graduate Fellow at SFI

ILLUSTRATIONS THIS ARTICLE: TRAIAN ALEXANDRU FILIP,
COURTESY TURNER CARROLL GALLERY, SANTA FE.
MAP BY PATRICK MCFARLIN

PHOTO: LUANNE TIMMERMAN

FELDMAN COMPLETES THESIS

David P. Feldman met SFI research professor Jim Crutchfield electronically. "I sent him e-mail asking him what he was up to and if he would be willing to meet," says Feldman. Not long thereafter he asked Crutchfield to help supervise his doctoral research, and the two began collaborating. In September, 1998, Feldman was awarded his doctorate in physics from the University of California at Davis. His thesis is entitled "Computational Mechanics of Classical Spin Systems."

An energetic researcher, Feldman calls his experience working at SFI "awesome," mostly because of the interdisciplinary nature of the place. He says he never had to answer the question "Is what I'm doing physics?"

That non-conformist view is apparent in his research as well. In his summary of his interests, Feldman writes, "I am fascinated by the ways in which nonlinear, interacting systems can produce intricate patterns and organized or collective behavior. But, at present, our notion of pattern and organization is largely subjective. Statistical mechanics has a rather impoverished set of tools for discovering and quantifying structure, pattern, information processing, and memory. My research thus far has shown that computation and information theory significantly enrich our set of tools for analyzing self-organizing and pattern-forming systems. I look forward to continuing to refine these tools and applying them to physical and natural processes."

Feldman is currently assistant professor of mathematics and physics at the College of the Atlantic in Maine. He continues to collaborate with Crutchfield and other SFI researchers in the area of computational mechanics.

TOUCHÉ: YOUNG SCHOLAR WIELDS A SWORD, A RHYME, AN AXIOM

Christopher Douglas, an undergraduate intern at SFI last summer, has been recognized with two distinguished awards—both Rhodes and Marshall scholarships. Rhodes Scholars study at Oxford University. Winners are chosen for their intellectual and academic mastery, integrity, respect for others, and ability to lead and to use talents fully. Marshall Scholars, who can attend various British universities, must demonstrate outstanding academic achievement and a capacity to make a significant contribution to society.

Douglas is a senior mathematics major at the Massachusetts Institute of Technology. As part of last summer's Research Experience for Undergraduates program at SFI sponsored by the National Science Foundation, Douglas worked with research professor Jim Crutchfield to develop an analytical theory of how adaptive learning agents project order and pattern onto otherwise structureless, random processes. Crutchfield has invited Douglas to return to SFI to complete writing up their research for publication.

In addition to extensive work in advanced mathematics, Douglas is a founder of the MIT alternative newspaper *The Observer* and is a prize-winning poet, fencer, and figure skater. He won an award from the International Computer Music Association and is interested in examining the intersections of mathematics, philosophy, and education. Only 19, he will study mathematics and philosophy at Oxford.

LAUREN ANCEL 1999 STEINMETZ FELLOW

Lauren Ancel, a Ph.D. candidate in the Department of Biological Sciences at Stanford University, has been awarded the 1999 Steinmetz Fellowship, a prize open to Complex Systems Summer School (CSSS) alumni. The award, which supports a one-month research residency at the Institute, is made each year to a participant of the school to support extended research at SFI in the subsequent year.

Ancel's research focuses on development of a model of G. G. Simpson's characterization of the Baldwin Effect. The Baldwin Effect is the genetic reinforcement of advantageous but initially non-hereditary traits. She has built a stochastic model for the evolution of phenotype plasticity in a fluctuating environment. The model demonstrates that Baldwin's observations may be explained entirely by mutation and natural selection in a changing environment.

While at SFI, Ancel will work with SFI faculty member Walter Fontana to explore the Baldwin Effect in the evolution of RNA. She will also collaborate with SFI postdoctoral fellow Michael Lachmann to study implications of the error catastrophe on the evolution of sexual reproduction.

Dr. Philip R. Steinmetz, a professor emeritus at the University School of Medicine in Connecticut and an alumnus of the 1990 Complex Systems Summer School, has generously established this fellowship. Steinmetz is especially interested in complexity in biological systems, including questions of how complex systems develop relatively simple overall behavior, and what roles self-organization and entrainment play in these systems.

PHOTO : PATRICK MCFARLIN

YOUNG RESEARCHERS UNSCRAMBLE GENES AND VOTER BEHAVIOR

Beginning this January five scholars from throughout the United States are participating in SFI's new Fellows-at-Large program. This project supports the research efforts of young scholars in the area of complex systems and promotes the establishment of such research agendas in the individuals' home institutions. Among other activities, the program funds SFI-affiliated researchers to visit the Fellows' home institutions for research talks and short-term collaborations.

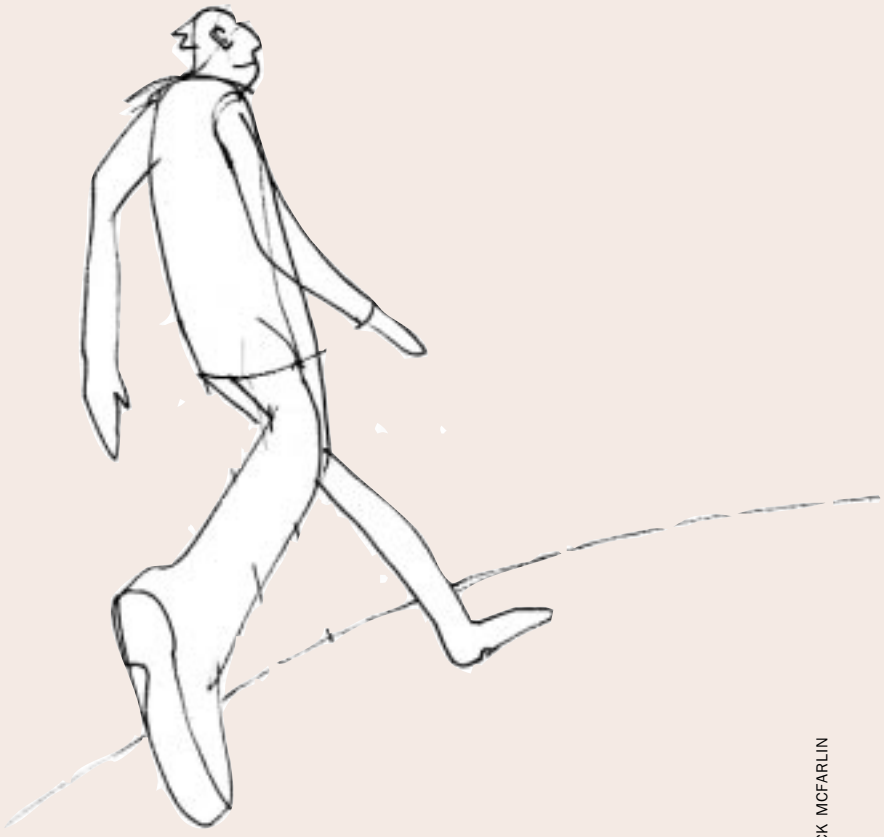
Brian Billman is an assistant professor of anthropology at the University of North Carolina at Chapel Hill and director of Latin American Studies for the Center for Indigenous Studies in the Americas (CISA). His research interests include the prehistory of Andean South America, evolution of complex political organizations (chiefdoms, states, and empires), causes and consequences of warfare, origins of social stratification, cultural ecology, settlement pattern analysis, and the prehistory of southwestern North America.

Scott de Marchi, assistant professor of political science at Washington University, specializes in the fields of computational economics, game theory, the Presidency, and voting behavior. The glue that holds these interests together is a fascination with strategic action under conditions of incomplete information.

Laura Landweber's research interest is the evolution of biological information processing, or complex molecular systems, both in test-tube experiments in the laboratory and in organisms as far ranging as ciliates or trypanosomes. An assistant professor of biology in the Department of Ecology & Evolutionary Biology at Princeton University, Landweber's work on "gene unscrambling" and RNA editing in these organisms offers a fresh way of thinking about the construction of functional genes from encrypted pieces of the genome, as biological computation.

Filippo Menczer teaches courses in management information systems at the University of Iowa where he is an assistant professor of management sciences. Menczer has developed the LEE artificial life simulation tool, which is distributed with Linux and widely used in experimental and instructional settings. His interdisciplinary research interests span from ecological theory to distributed information systems; they include artificial life, evolutionary computation, neural networks, machine learning, information retrieval, and adaptive intelligent agents.

Dagmar Sternad is assistant professor of kinesiology at Pennsylvania State University. Sternad's work focuses on how we coordinate our actions with respect to a perceptually specified goal. Her approach interprets the coupling of actor and environment as a dynamic system, which is highly nonlinear and high-dimensional, and therefore capable of producing orderly and adaptive behavior. Specifically Sternad uses the formal tools of nonlinear dynamics to describe the constraints that cognitive and neural systems exploit in the acquisition and intentional control of behavior.



Fellow @ Large

ILLUSTRATION: PATRICK MCFARLIN

news

http://www.santafe.edu/sfi/research/allpubs

CYBER-LIBRARIAN

Looking for a book or scientific paper authored by a Santa Fe Institute researcher? SFI now has a comprehensive bibliography of nearly 500 entries posted on its web site at http://www.santafe.edu/sfi/research/allpubs. The bibliography is equipped with a search engine to enable searches (e.g., on titles, authors, keywords), and will include links to URLs as appropriate. We expect the bibliography to serve as a resource for the general scientific community interested in research on complex adaptive systems and as a record of SFI's contributions to the scientific literature.

The Institute monitors publications by SFI researchers in the scientific literature in two ways. The first is through self-reports by the authors. SFI also subscribes to the reporting services of the Institute for Scientific Information (ISI) which produces *Science Citation Index* and compiles the contents of about 16,000 journals, all of which are peer-reviewed. Listings from ISI include only those articles for which SFI is listed as a primary or secondary affiliation of one of the authors.

To be included in the SFI bibliography, a publication must meet two criteria: It must have been published, accepted, or submitted for publication since January 1, 1996, in a scientific journal, proceedings volume, or book; and it must also contain results to which SFI has (in the opinion of at least one of its authors) directly contributed in a significant way—for example, through its workshops, visitor program, or other research collaborations.

SFI Working Papers are automatically included in the bibliography (meaning that no special submission is required to list working papers).

Researchers interested in submitting appropriate material to the SFI bibliography should access the submission form on the web site.

CAN COMPLEXITY HALT OUR ECOSYSTEM'S COLLAPSE?

We know that our planet is losing its biological diversity at an alarming rate, with frightening implications for our future. But when does an ecosystem hit the breaking point? In *Fragile Dominion: Complexity and the Commons,* Princeton biologist and SFI external faculty member Simon Levin offers general readers the first look at how complexity science can help to solve our looming ecological crisis.

Levin argues that our biosphere is the classic embodiment of what scientists call complex adaptive systems. By exploring how such systems work, we can determine how they might fail. How much loss can an ecosystem bear before it starts to collapse? How resilient are these systems in general? Do they in fact hover at the edge of disaster? *Fragile Dominion* is a powerful appeal to understand and protect the global "commons."

This book is the outcome of the Institute's 1996 Stanislaw Ulam Lectures. Each year the Ulam Lecture series features one of the founding thinkers in the sciences of complexity who revisits his or her body of work from a broad perspective, and especially considers its long-term implications and future directions.

The book will be available from Perseus Books in May, 1999.

COMPLEXITY AND INFORMATION

Joseph F. Traub is co-author with A.G Weschulz of *Complexity and Information* forthcoming from Cambridge University Press (simultaneous publication in hard and soft cover as part of the series Lezioni Lincee, Accademia Nazionale dei Lincei). The twin themes of computational complexity and information pervade this book. The authors begin with an introduction to the computational complexity of continuous mathematical models, that is, information-based complexity. This is used to illustrate a variety of topics, including breaking the curse of dimensionality, complexity of path integration, solvability of ill-posed problems, the value of information in computation, assigning values to mathematical hypotheses, and new, improved methods for mathematical finance.

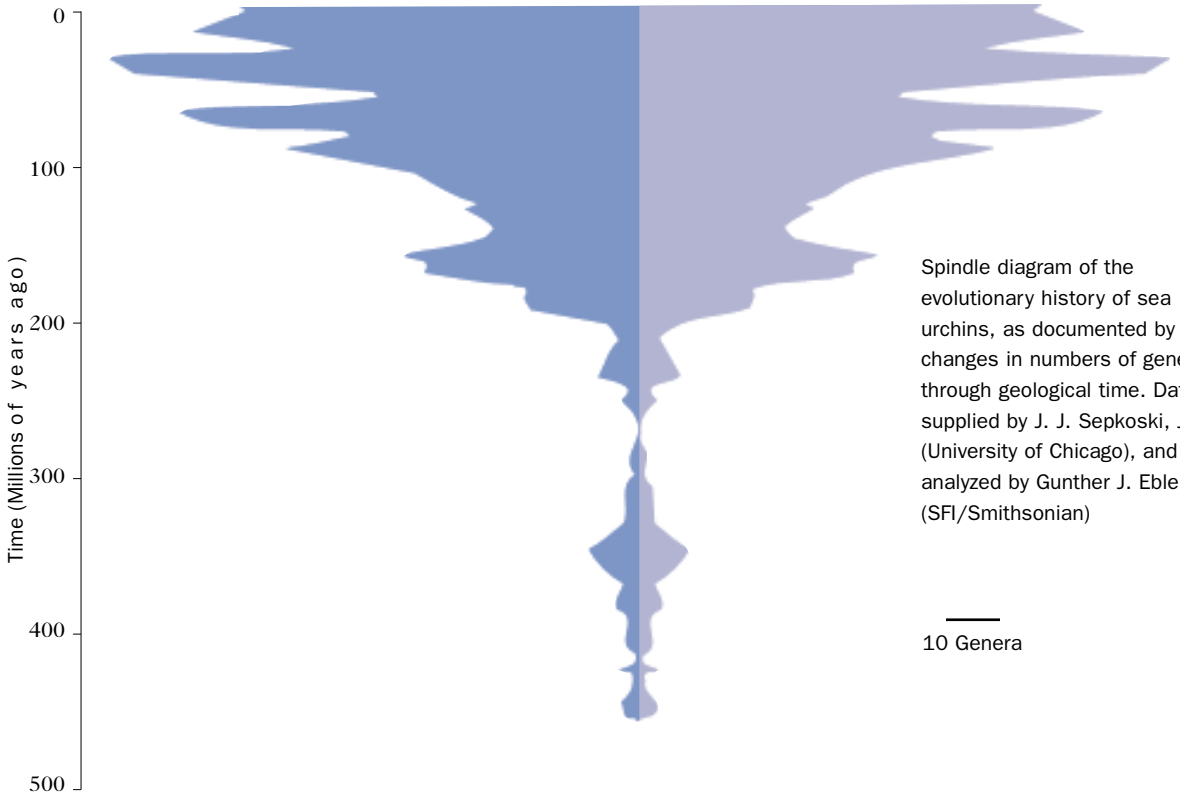
NEW FORMAT

Check out the Bulletin's new format for its *Work in Progress* section, beginning on the next page. Starting with this issue we will devote this feature to detailing the Institute's current work in a particular thematic area. We have positioned it in the central section of the magazine so that it can be easily removed and separately retained.

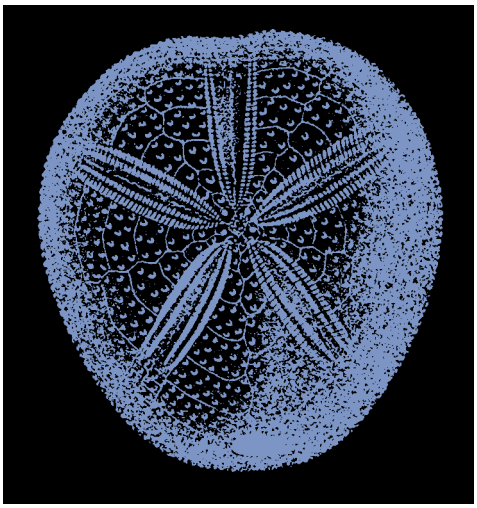
news

SFI Bulletin

Evolutionary Dynamics



Spindle diagram of the evolutionary history of sea urchins, as documented by changes in numbers of genera through geological time. Data supplied by J. J. Sepkoski, Jr. (University of Chicago), and analyzed by Gunther J. Eble (SFI/Smithsonian)



Douvillaster Thomasi, a cretaceous species of sea urchin (after Mortensen 1950)

by erica jen

A CONCEPT WITH BROAD APPLICATIONS

SFI's choice of evolutionary dynamics as the focus of the Keck program reflects the fact that the concept of evolution has become central to our view of a wide range of natural and social phenomena. Biological-like evolution—understood as a process that involves both the origination of novel entities, and the adaptation and modification of those entities through mutation, replication, and selection—is seen as fundamental to the behavior of diverse non-biological systems. Implementations of evolutionary strategies are widely used as the basis of novel computational optimization techniques. Broadly defined, evolutionary strategies are also seen as a central mechanism of social and cultural change.

The multiple interpretations of, and roles attributed to, evolution have expanded our understanding of the term far beyond that envisaged by Darwin and other evolutionary biologists. In order to integrate the piecemeal and often inconsistent notions of evolutionary processes, and to develop a general framework for understanding them, SFI is establishing this new scientific initiative. It is intended to serve as a source of catalysis, synthesis, and innovation for the scientific community interested in evolutionary processes.

An integrated approach will combine general theoretical investigations with detailed case studies of the mechanisms and phenomenology of evolution in both biological and non-biological systems. The approach will emphasize the search for general principles of evolutionary dynamics, general organizational principles, and behavioral commonalities of systems undergoing evolutionary change. Equally important to the approach is a respect for the details and subtleties of specific phenomena, and an emphasis on understanding how and why evolutionary processes differ in diverse contexts. The extent to which biological evolution is valid and useful as a metaphor for other forms of evolution will be an explicit focus.

SYNTHESIZING TWO CENTRAL QUESTIONS

The program's scientific approach will be based on the belief that an understanding of the origins and nature of complexity will bring a novel perspective to the study of evolutionary dynamics. Implicit in the emphasis on complexity is a recognition of its importance in addressing two questions SFI sees as central to evolutionary dynamics:

How do entities with complex organizational structure and function arise and develop, and what organizations are attainable given specific kinds of lower-level constituent entities?

What are the dynamical features characteristic of populations of mutating entities capable of replication and subject to selection?

This initiative is singular in taking the synthesis of the above two questions as its basic perspective. The importance of the first question has been long recognized, but has not been systematically pursued. The second question has been an active subject of research for many decades, especially in the field of population genetics, but has been typically considered in a context decoupled from the first.

By focusing on this synthesis, the program will contribute in a fundamental way to an understanding of the nature of organisms and organizations that arise through the dynamics of the process of evolution; in other words, to contribute to what Leo Buss (evolutionary biology, Yale University, and author of The *Evolution of Individuality)* has called a "theory of the possible." With a synthetic approach, for example, successions of evolutionary innovations will be understood not as isolated events, but in terms of how each innovation affects the potential—in both an organizational and a dynamical sense—for future innovation.

The long-range goal of the program is to combine our understanding of evolutionary dynamics and organizational principles so as to understand which features of a phenomenon—in natural, computational, or social systems—are necessary consequences of internal organization, and which are consequences of the particular histories of environment and selection to which those organizations were exposed.

The program will be structured around the following multiple research themes:

- Evolution of complex structure and form
- Dynamics of evolutionary search
- Molecular and genetic insights into evolution
- Evolutionary, developmental, and ecological aspects of biodiversity; and
- Social and cultural evolution.

The first two themes address general theoretical issues relating to the two central questions of organization and dynamics. The next three focus on "case studies" for which the goal is to address organization and dynamics by investigating the details of the specific evolutionary processes, by building theoretical

and computational models that capture their salient features, and by validating these models against experimental and empirical data.

Activities within each research theme will include collaborative research projects, visitor programs, working groups, and educational activities. The program as a whole will also support workshops and group meetings that are expressly designed to address issues that cut across the themes. Suggestions for specific research activities are being considered now. Participation in research themes is expected to evolve over time, and proposals for new themes will be solicited from the general scientific community on an ongoing basis. In particular, the Institute recognizes that many individuals and research communities that are important sources of expertise in evolutionary phenomena are not currently active in SFI research programs, and SFI is committed to identifying and recruiting the best of those individuals and communities into the research activities as they develop.

EVOLUTION OF COMPLEX STRUCTURE AND FORM

Central emphasis will be on theory and model development focusing on major evolutionary transitions involving the evolution of complex structure and form. Such transitions, as identified by John Maynard Smith and Eors Szathmary, for example, involve aggregation of previously separately reproducing units, the emergence of specialization, or the origins of cooperation and collective behavior. Examples include the transitions from unicellularity to multicellularity, and the aggregation of individuals into villages.

Such a theory, if it could be developed, might lead not only to models that exhibit the features of major evolutionary transitions, but also to predictions for (i) the circumstances under which these transitions occur, (ii) measurable characteristics of the state of systems poised to undergo such transitions, (iii) the sensitivity of the transitional process to historical accidents, and (iv) the stability of the new entities that are thereby produced. The goal is to understand not only the dynamics of transitions, but also the organization of the entities that enable these transitions. An essential component of any such theory is an understanding of the kinds of organizations and phenomena to which the theory may not apply.

Work will focus on modeling one aspect of the formation and variation of new entities; namely, the interactions between agents and the aggregates they form. An example of a specific collaboration that may be sponsored by the program is the work by Leo Buss and Walter Fontana (chemistry, SFI) on developing a formalism for describing self-maintaining organized networks of molecular reactions. The formalism that is needed for this problem is one in which the constituent entities have the ability to modify each other and to change from within, and in this sense differs from the formalisms provided by traditional dynamical systems approaches. Research on this effort will focus on developing an appropriate model based on functional calculus, and investigating the functional organizations that emerge in a many-body setting, such as a chemical flow reactor.

Research on the evolution of complex structure and function will be coordinated by Walter Fontana and John Padgett (political science, University of Chicago).

DYNAMICS OF EVOLUTIONARY SEARCH

The dynamics of evolutionary search, in both natural and social systems, represents the second major component of the program. This project will explore the generic features of evolutionary processes in order to develop a theoretical basis for an understanding of adaptive dynamics. It will analyze observable processes and relate them to the repertoire of attainable solutions that are constrained by the particular realization of evolutionary dynamics. Specific research problems include the phenomenon of epochal evolution, the adaptive advantages of recombination, and the dynamics of coevolving systems. Questions to be addressed include conditions for stepwise rather than gradual evolutionary adaptation; the role of selectively neutral variants in adaptation; and trade-offs and scaling relationships among genome complexity, rates of genetic variation, and population size.

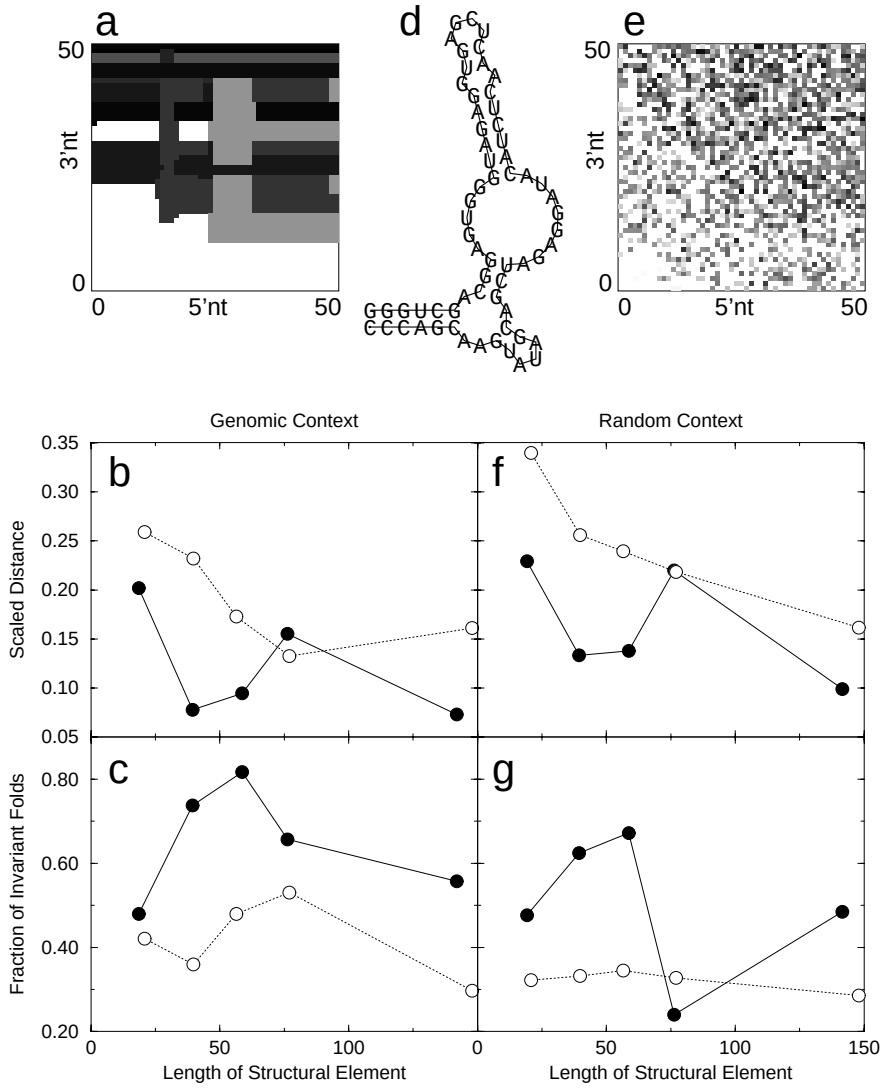
This work will directly draw upon the research in the other topics in the program including the formation of new entities, evolution of RNA secondary structure, originations and extinctions, and evolution in social and cultural contexts. As is true in the first theme, a key question to be addressed will be the interplay of organizational principles, historical accidents, random changes over time, and Darwinian forces such as natural selection.

Work in this area will be coordinated by Jim Crutchfield (physics, SFI), Marc Feldman (population genetics, Stanford University), and Peter Schuster (molecular biology, University of Vienna).

MOLECULAR AND GENETIC INSIGHTS INTO EVOLUTION

The focus of this theme will be on biological systems that provide insight into genotype-phenotype mappings. The work on evolution of RNA molecules, for example, incorporates a study of landscape features, variational constraints, and selective boundary conditions in the development of models for macromolecular genotype-phenotype mappings. By combining theoretical, simulational, and experimental results, a description of the evolutionary process is emerging that explains, for example, the causes of major structural transitions in RNA and consequent evolutionary jumps. This work will build on this new understanding of the evolutionary process to focus on the analysis of predictability in evolution, to address questions of prebiotic evolution, and to make comparisons with artificial systems that perform evolutionary computation.

A second component of the research will focus on evolution of robustness in organismal design. The basic observation motivating this research theme is that organisms appear to be surprisingly robust to genetic and environmental perturbations. The evolutionary origins of robustness, as well as the biological mechanisms that maintain it, remain largely unexplored. This research component of the program will coordinate studies of robustness relating to genetic perturbations and to secondary RNA structure to address questions including: What are the origins of robustness in cellular biology and development? And what are the mechanisms by which robustness is achieved?



Robustness of secondary structure elements to changes of the genomic context. Flanking sequences of different lengths are considered at both ends of a secondary structure element such as (d). The flanking sequences are either part of the genomic consensus sequence (a-c), or generated randomly (e-g). The four panels show that conserved secondary structure elements (full circles) are significantly more robust against changes in their vicinity than non-conserved structures (open circles).

A final component will focus on the evolution of the immune system. The immune system is highly instructive in the ability it has evolved to coordinate adaptive processes at the molecular and cellular levels, including somatic mutation, clonal selection, and affinity maturation, so as to generate useful behavior—such as recognition of a pathogen—at the level of the organism. The immune system research effort will develop models and test hypotheses of how the system as a whole has evolved its sophisticated pattern recognition and information storage capabilities. The fundamental question is to understand the evolutionary mechanisms that enable an immune system with limited genetic resources to attain very broad pathogen set coverage.

The research effort on dynamics of evolutionary search will also be coordinated by Jim Crutchfield, Marc Feldman, and Peter Schuster.

The Santa Fe Institute is delighted to announce that it has received a three-year award from the W. M. Keck Foundation for $1.5 million in support of a new program in evolutionary dynamics.

THE KECK FOUNDATION WAS ESTABLISHED IN 1954 BY W. M. KECK, the founder of The Superior Oil Company. Keck placed a premium on imagination, innovation, and new technology; relying on these principles The Superior Oil Company became one of the largest independent oil-producing companies of its time. Following the example of its founder, the W. M. Keck Foundation is also committed to using imagination and innovation in its grant-giving to support scientific discoveries and new technologies.

According to Erica Jen, SFI vice president for academic affairs and principal investigator for the Keck proposal, "SFI applied to the Keck Foundation for funding for evolutionary dynamics because we regard research in this area as one of the Institute's top priorities over the coming years. We think that the new program could help lay the foundations for a synthetic theory of evolutionary dynamics, and demonstrate its usefulness as a tool for understanding the fundamental processes that lead to change in both natural and social systems."

Jen expects that a number of the scientific projects sponsored by the program will eventually be able to obtain funding support on their own individual merits and within the context of their own disciplinary research. Indeed, one of the most rewarding aspects of the Keck Foundation award thus far has been the new ideas and collaborations—both within and outside the context of evolutionary dynamics—stimulated by the process of submitting the proposal itself. One tangible result of those discussions and collaborations has been the mapping out of several research themes that build on issues in evolutionary dynamics for which the Keck research will provide scientific foundation. A number of new approaches outlined in the current SFI proposal for core support to the National Science Foundation emerged in the process of planning the evolutionary dynamics program. Those included general studies of robustness in natural and social systems and complex network dynamics, as well as specific research projects in social insect behavior and evolution of cooperation in the immune system.

The management of the Keck program will be the responsibility of the SFI administration and an Advisory Board of distinguished scientists representing the broadly defined scientific community with interests related to evolutionary dynamics. Individuals who have agreed to serve on the Advisory Board include Kenneth Arrow (economics, Stanford University), Lee Hartwell (cell biology, Hutchinson Cancer Research Center), John Holland (computer science, University of Michigan), Leo Kadanoff (physics, University of Chicago), Richard Lewontin (evolutionary biology, Harvard University), Jack Sepkoski (paleontology, University of Chicago), and Henry Wright (cultural anthropology, University of Michigan).

EVOLUTIONARY, DEVELOPMENTAL, AND ECOLOGICAL ASPECTS OF BIODIVERSITY

A major focus of this research will be on the interplay between internal evolutionary dynamics of an ecosystem, on the one hand, and external environmental stresses, on the other, in leading to extinctions. A second major thrust will be on understanding the interplay of extinction with macroevolutionary dynamics. A mass extinction event, for instance, may clear the way for the adaptive radiation of a new group of organisms, such as the mammals in the aftermath of the end-Cretaceous extinction, but it may also wipe out many species that were in other respects well-adapted. The objective will be to explore the ways in which extinction can help or hinder the development of successful species, and the type of organization one will expect to see in an ecosystem subject to regular extinction.

The study of extinctions will be closely related to a study of originations and to the diversity of biological forms. Research on origination will focus on the dynamics of novelty generation in evolution, on the nature of major episodes of diversification, and on recoveries from major extinction events. Research on the diversity of biological form will focus on phenotypic variation as an arena in which to explore generic and specific properties of the genotype-phenotype map, and the general issue of the relationship between development and evolution. Current objectives include the identification of developmental constraints on form and structure, as well as of asymmetries in the temporal manifestation of such constraints.

The final component of the biodiversity theme focuses on ecological complexity, and, in particular, the relationship between biodiversity and ecosystem function. The assemblage and self-maintenance of ecosystems represent outstanding problems in understanding the evolution of complex entities. How do the organizational principles of ecosystems differ from those of biological organisms? Unquestionably, ecosystems show regularities in structure and function across regions. An essential first step, therefore, is to catalogue the similarities and differences among and across systems, and then to understand which of the patterns that one finds are uniquely determined by regional climate and soil conditions, for example, and which are the result of internal dynamics including selective processes acting at the level of individual agents. An outstanding challenge will be to compare the organizational and dynamical features of ecosystems with those of biological organisms—the differences in this regard will be as interesting as the commonalities. An engaging question that the program may be positioned in the future to address is the relation between evolutionary processes that take place on long time scales and ecological processes that take place on relatively short time scales, and the possibility of a synthetic approach to these two sets of problems.

Research on evolutionary, developmental, and ecological aspects of biodiversity will be coordinated by Gunther Eble (paleontology, SFI/Smithsonian Institution), Simon Levin (biology, Princeton University), and Mark Newman (physics, SFI).

SOCIAL AND CULTURAL EVOLUTION

The theoretical focus of this research will be on the question of whether the perspective of evolutionary dynamics can assist in explaining social and cultural transformations. To this end, the research will address some detailed mechanisms and large-scale patterns characteristic of social and cultural change. For example, the mechanisms of cultural transmission will be compared to those of genetic transmission with the aim of understanding the implications of the commonalities and differences for the emergence, diffusion, and extinction of population-level change. As a second example, the research will consider the possibility that the human and social context can amplify the consequences of evolutionary factors such as differences between in-group and between-group variances so as to lead to results different than would be expected in biological contexts.

How human behaviors have evolved to support cooperation, generosity, and reciprocity among non-kin is a question to be considered in the future.

This theme will be coordinated by Sam Bowles (economics, University of Massachusetts), Marc Feldman, and Tim Kohler (archaeology, Washington State University).

PHOTO COURTESY OF CARNEGIE-MELLON U.

John Miller: a Modeler of Messy Theories

HIS TIRELESS ANTS PROBE FOR WEAKNESSES IN SIMULATION MODELS IN ORDER TO IMPROVE THEM.

By Rex Graham

Much of the work John Miller does is aimed at approximating and predicting the confounding behavior of the real world. As an associate professor of economics at Carnegie Mellon University and an external SFI faculty member, Miller applies computer modeling to such messy human behaviors as politics and voting. Ask not what models can do for social science, Miller's work over the past decade seems to say, ask what social science can do for computer-modeling research.

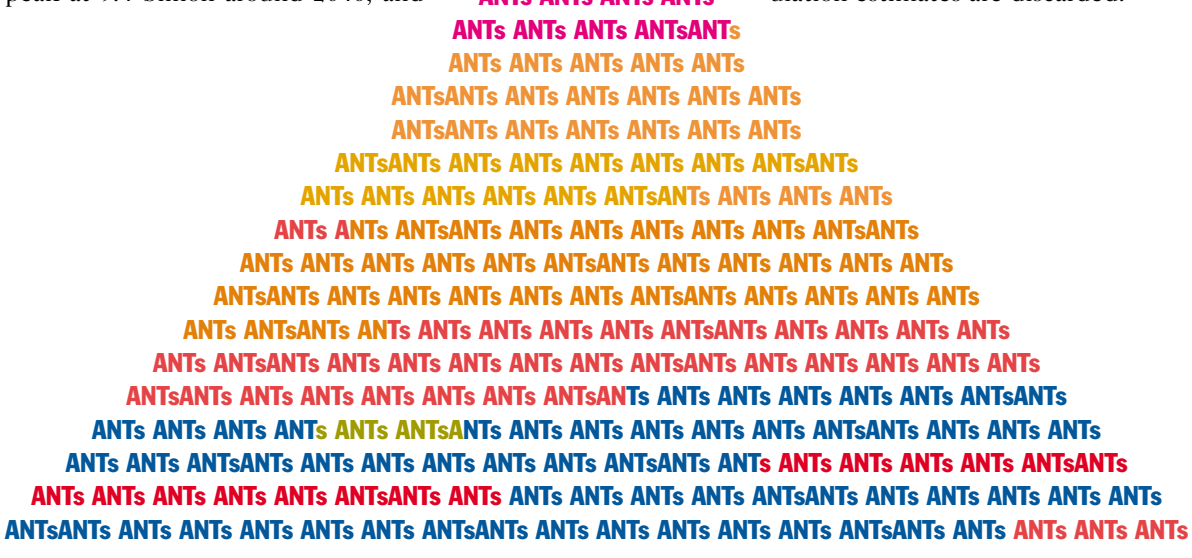
Miller likes to poke fun at orthodox social scientists who "hate to have the real world spoil a good theory." The inevitable guffaws can't conceal a seeming contradiction embodied in Miller's arcane craft: The techniques and approaches he employs to probe for weaknesses in simulation models themselves will be used to help perfect those models. Miller published a paper in the June 1988 issue of *Management Science* in which he demonstrated how only tiny changes in the initial assumptions of a model made it behave strangely.

In this case, his target was World3, a well-known global-population model designed by Georgia Tech economist Peter Brecke. The model, which incorporates approximately 150 formulas, was featured in the 1972 book *The Limits to Growth* and its sequel, *Beyond the Limits*. World3 grimly predicted that the world's population will peak at 9.4 billion around 2040, and then collapse to 3.9 billion by 2100. The model employs 272 variables, 96 of which are set initially for such factors as global food production, and the supply of drinking water.

Miller dissected the population model with computational tools developed at SFI. The dissection itself offers a glimpse of how Miller and his colleagues at SFI can pinpoint weaknesses of any model.

In the case of World3, Miller unleashed ANTs (active nonlinear tests). The ANTs employed two so-called optimization algorithms. One algorithm is a genetic algorithm or GA. It semi-randomly introduces small mutations into the model's 96 "genes" or initial variables—two mutations at a time. The algorithm then computes a new population. The GA also plays the role of virtual matchmaker: It "mates" promising mutant combinations with one another and searches for even bigger population estimates.

The second ANT, called a "hill-climbing" algorithm, is intent solely on finding the biggest global population possible. It seizes local optima as starting points for subsequent iterations of the entire process. Mutations that result in higher global population estimates are saved, while those that generate lower population estimates are discarded.



Miller describes his ANTs as “ready and tireless critics.” They searched across sets of parameters in World3 and detected unexpected relationships that otherwise would have gone unnoticed. His tireless critics discovered a weakness in World3 when they simultaneously mutated two parameters: number 75, the fraction of industrial output allocated to consumption, and number 83, the reproductive lifetime of women. With only those two parameters perturbed, the global-population prediction soared.

The ANTs also found a set of minor perturbations that led to a global-population estimate of 29 billion people by the year 2100 (versus 3.9 billion predicted by the original model). Such a result, so different from the model-maker’s prediction, suggests that World3 may generate big errors in some circumstances and therefore might need refinement. “We need to have ways to break this and other models,” says Miller. “Of course, the fact that you can break a model doesn’t mean that that model is bad. All models have to be responsive to their inputs. Useful models lie in a delicate area between being too responsive to inputs and being too unresponsive.”

Miller says ANTs can’t “guarantee quality modeling.” But, he says, they can help refine a model that is sensitive to initial conditions or one that includes complicated “parameter spaces.” His summary of the ANTs’ success with World3 in Management Science wryly concludes, “Like ants seeking food at a picnic, a variety of avenues are creatively explored, and it is only with extreme care and foresight that the meal remains untouched.”

Miller’s use of biological metaphors is no accident. As an undergraduate at the University of Colorado and a graduate student at the University of Michigan, he was deeply intrigued by the common historical and theoretical roots of economics and biology. English economist and mathematician Thomas Malthus first outlined that connection in 1798 in “An Essay on the Principle of Population As it Affects the Future Improvement of Society.”

Malthus solemnly predicted that the growing human population would inevitably overwhelm the ability of Earth to support it. Malthus said human-population crashes are inevitable. Charles Darwin, a contemporary of Malthus, was inspired by the broad implications of the thesis. Darwin applied the Malthusian theory to all animal species and wrote that every reproducing species sows the seeds for its own difficulties by overproducing offspring.

An additional premise of his theory of evolution by natural selection is that survivors of times of stress would have advantageous traits, and those traits would become amplified over succeeding generations. “Biology and economics started their dance back with Malthus,” says Miller. “During the mid-1900s the two fields separated for a while, but they again have become intertwined.”

After Miller graduated from Michigan, he gravitated to SFI and to John Holland, an SFI Science Board member and the inventor of genetic algorithms. Miller became SFI’s first postdoctoral fellow in 1988, and, one year later, he and Holland co-founded the Institute’s Adaptive Computation Program.

Miller says one aim of his modeling work is to expose the “invisible hand.” The term was coined by Adam Smith, an 18th-century economist and author of *The Wealth of Nations*. Smith’s metaphoric hand is the imperceptible force that sets a price equilibrium when the quantity of a good such as corn or a common stock equals the quantity in demand. “It is remarkable to watch a bunch of sleepy students meander about in an experimental market and act as if there were some centralized force guiding their actions,” says Miller. “But we don’t yet have a coherent explanation for how this happens.”

Miller finds the invisible hand at work in many kinds of social phenomena, even in one of the most baffling human behaviors: politics. Just as Darwin’s finches evolved to prosper and survive on the Galapagos Islands, Miller thinks a form of the invisible hand guides political parties in a democracy to win elections.

Miller and his co-authors have explained, in papers published in the *American Economic Review*, *American Political Science Review*, and other journals and book chapters, how biologically based models can be used to understand political systems. Miller has teamed with colleagues Ken Kollman at the University of Michigan and Scott Page at the University of Iowa.

“What we are trying to illustrate,” says Miller, “is that a very simple system, like voting, can lead to very complicated behavior.” Of course, political complications are grist for public-affairs television programs. The programs’ pundits often predict election results poorly, even though they pore over polling data. Who would predict, for example, that 16 years after segregationist candidate George Wallace won the 1972 Democratic presidential primary in Michigan, civil rights activist Jesse Jackson would win the same voting contest.

In Miller’s model of the political world, an election fulfills the same role as a hostile environment: political parties must adapt to their environment to survive. The traditional model of politics is naive. It assumes that political parties are perfectly rational and perfectly calculating: They know each voter’s position, they accurately know other parties’ platforms, and they simply

select a platform, even one very different from their previous platform, in order to win the most votes. One can almost hear a chortle as Miller critiques that rosy view. "Even if political parties actually knew all that, which they don't, trying to find the best platform is realistically impossible. Our model, instead of being super-calculating about what new platform a party should present to voters, allows the parties to basically grope like a biological system that mutates. The models we are setting up also allow a party to have limited information. It can make a couple of random changes in its platform and then see if voters like that platform better than the previous one. With this model we get much closer to the real world, where parties converge on some issues like welfare and social security reform, and diverge on other issues like abortion."

Miller's political models use artificial adaptive agents, or AAAs, which were first created by Holland, Miller, and others in the early-1990s. With AAAs, "the unfolding behavior of the models can be observed step-by-step," says Miller. One model developed by Kollman, Miller, and Page created virtual parties whose only knowledge about voter preferences was polls. The parties also were not perfect optimizers, and they were either ideologically motivated, or pragmatic in their approach to molding platforms on issues voters care about. "Adaptive parties make good choices in our model, maybe not optimal choices, but very good choices," says Miller. But the voters that political parties try to appeal to have a range of views that sometimes are not reducible to a bell-shaped continuum. "With what we call centrist voters, you get a smooth, Mt. Fuji-looking 'voting landscape' where the elevation at a political latitude and longitude tells you how many people will vote for a platform at that position. And if you are wandering around Mt. Fuji, even in a dense fog, you will end up on the top. But among extremist voters who care deeply about issues like abortion, the landscape is very rugged and parties can get trapped at the top of a local peak: They may end up on an ant pile in the fog, and not know that they are at the base of Mt. Everest."

PHOTO COURTESY OF MINNESOTA GOVERNOR'S OFFICE

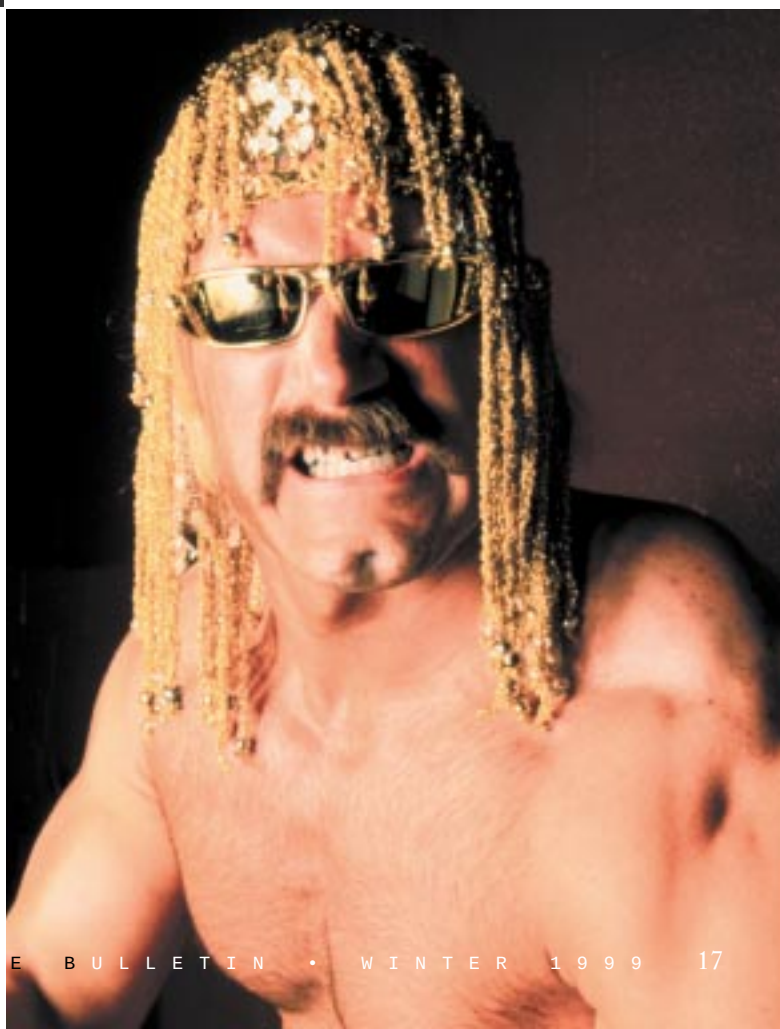
Surprisingly, the most democratic situations sometimes alienate large minorities. In a community in which the majority always sets public policy, large minorities can be unhappy and have no recourse. Miller calls it a stable equilibrium with a less-than-optimal outcome. "Political parties can break the system out of a bad outcome and allow it to go to a better one," he says. With such equilibria, an injection of "noise" is needed to break the less-than-optimal equilibrium.

Minnesota's new governor, Jesse "The Body" Ventura, a former professional wrestler, could be considered such noise. "The overall effect of Jesse's election as governor may be to break Minnesota out of a bad equilibrium," says Miller. "So the key idea here is something called 'simulated annealing.'"

Simulated annealing is a term derived from metal working. In order to make a very strong metal by lining up its atoms, metal workers heat the substance to near its melting point and cool it very slowly, and repeat the process several times. Episodes of political "noise" can accomplish something similar. "You want to put noise into the system when it is in a bad configuration, but you don't want to put noise into it when it is in a good configuration," says Miller. "A clever thing about political institutions is they naturally do that: the more people who are happy, the less likely that change is going to occur."

Few disgruntled voters might use "clever" and "political institutions" in the same sentence. However, voter and consumer preferences and tastes can shift as quickly as the Dow Jones Industrial Average, and Miller's modeling techniques may one day provide a more evolved way to generate the rarest of commodities: foresight.

PHOTO BELOW: WALTER IOOSS JR., SPORTS ILLUSTRATED



CONSIDER A WORLD in which there are two towns, and two kinds of people—red chile lovers and green chile lovers. Suppose the people are distributed in each town as shown below and that each town holds an annual election about what kind of chile to feed everyone in town.

John Miller: moving to a better configuration

With a majority of red chile lovers in each town, the system is stable. Each town votes in red chile for everyone, and no one wants to change towns. Note that although this configuration is stable, all the green chile lovers must eat red chile (a tragedy according to Miller).

Suppose that one day they run out of red chile in town B and must pick and serve green chile. News of this development spreads fast, and we immediately see the townsfolk move to accommodate their culinary desires, the result of which is shown below.

Notice that after these relocations, the towns are again in a stable configuration. When elections are held, everyone in town A votes for red chile and everyone in town B votes for green. Also, note that no one wants to relocate. Finally, and most importantly, notice that everyone is happier in this new arrangement—all the red chile lovers dine on red chile and all the green chile lovers feast on green. The random running out of red chile in town B (a little instability) has allowed the system to move to a better configuration.

POSTDOCS EXPLORE THE GAMUT, FROM COMPUTATIONAL NEUROSCIENCE TO SMALL WORLD PHENOMENON

PHOTO : JULIE GRABER

Each year a handful of young scientists joins the SFI research staff as postdoctoral fellows. They hold these residencies for one to three years, and, when they move on, these scholars become some of the Institute's most effective spokespeople for spreading SFI's multidisciplinary approach to other institutions. Four postdoctoral fellows are recent additions to the Institute's roster of residential scientists.

Tim Hely's main research interests are in the field of computational neuroscience. Since joining the SFI research staff in November, he has begun to investigate the role of the corpus callosum in information flow in the brain. Hely intends to look at interactions between the brain's two hemispheres and the development of functional specialization and lateralization effects. This work is in collaboration with Akaysha Tang at the University of New Mexico.

Prior to coming to Santa Fe, Hely was at the Institute for Adaptive and Neural Systems at the University of Edinburgh where he completed a three-year Wellcome Trust Mathematical Biology Doctorate with the thesis "Computational Models of Developing Neural Systems." As part of this work Hely developed a model of the emergent synchronization of developing neurons. The simulation was based on a general model of synchronization which had been applied to systems ranging from cardiac pacemaker cells, to flashing fireflies and chirping crickets.

The transition from single organisms competing with one another to colonies of organisms which cooperate has occurred many times throughout evolution. **Michael Lachmann** is interested in this evolutionary transition from a unitary organism to multicellularity to eusociality. (Eusocial animals share the reproductive division of labor.) During the transition there is a shift between selection on the individuals at the lower level to individuals at the higher level; this process cannot be accounted for by current population genetic models. Establishing models which can explain such transitions will help enrich understanding of the dynamics of evolution.

Lachmann earned his doctorate in Biological Sciences from Stanford University where he worked with SFI Science Board members Marc Feldman and Deborah Gordon.

While he was a graduate student in ecology at the University of New Mexico's Biology Department, **Brian Enquist** joined SFI collaborators Jim Brown and Geoffrey West to develop a general model of resource distribution networks in biological systems. The model explains from fundamental principles the origin of a number of remarkable universal scaling laws that range from the respiratory complex in mitochondria through unicellular organisms up to whales and giant sequoias. As a postdoctoral fellow jointly supported by SFI and a National Science Foundation Research Training Fellowship in Ecological Complexity, Enquist continues to investigate the role of constraints at the anatomical, physiological, and ecological levels in influencing local and broad-scale biological patterns. Specific work focuses on allometric scaling; ecological ramifications of allometry in plants; long-term population dynamics and community change; and biogeographical patterns.

Duncan Watts describes the overarching theme of his research as "the interrelationship of structure and dynamics in large, distributed systems." His current work focuses on the "Small World Phenomenon." Folklore has it that all of us, regardless of nationality, profession and socio-economic class, are somehow linked to each other via only a few "degrees of separation."

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

Tracking the Chameleon Killer

Tracking the Killer Chameleon

CYBER-SLEUTHS

Imagine how difficult it would be to track down a killer if he or she constantly changed form, if with each person he struck, he took on new characteristics. That's the nature of the deadly HIV virus, and to confront that chameleon-like quality, a handful of elite scientists have been charged with computer mapping HIV DNA in its many disguises. Now, with the mapping process in place, the courts have begun to call on these scientists to help them decipher HIV DNA evidence for actual murder trials.

PHOTOS: JULIE GRABER

SFI visiting faculty member Better Korber is one of those scientists. While she generally spends her days examining the lines of letters which represent HIV DNA, rarely has she met the actual people who carry the virus. Until now.

"I generally get to know the HIV viruses I study quite intimately, but as strings of letters. So initially, DM and JT didn't represent people," she says, speaking straight and easy, her large brown eyes betraying sadness.

"Rather their initials represented viral sequence IDs. It was odd to see the people behind the virus for once, to see Donald (DM) and Janice (JT) in person, and hear their stories."

Donald and Janice were key players in a murder-mystery-like drama that played out recently in Lafayette, Louisiana. The young woman, Janice Trahan Allen, who is infected with HIV and Hepatitis C, accused her former lover, a doctor, of purposefully injecting her with a mixture of blood from two of his patients, one infected with HIV and the other with Hepatitis C. The accused, Dr. Richard Schmidt, denied the allegation. Korber testified as a witness for the defense.

"Janice wept frequently when she was present during the trial and fainted when the verdict was read," says Korber of the victim. "The feelings in the courtroom were powerful and intense, and the situation was tragic."

Korber and her colleagues were charged with exam-

ining the sequences of letters which represent the virus that is in the process of killing Janice Trahan Allen, and determining whether, in its mutable way, it was closely enough related to the doctor's patient's HIV to mean the doctor had actually committed this crime. This was the first time in the U.S. that HIV DNA evidence was used in a criminal case, and Korber is certain that it won't be the last.

WHO-DONE-IT

Korber examines what are called phylogenetic trees, similar conceptually to family trees or genealogies, but these maps are based on genetic sequence relationships of HIV. They can be compared to determine whether or not the virus found in one individual is closely linked to the virus found in another. Viruses from individuals who transmit directly from one to the other will generally have sequences that are more similar to each other than viruses from other unrelated individuals. These sequences are compared though "phylogenetic analysis." Though this seems an obscure form of science, the legal applications are becoming more and more broad.

In one case, the Centers for Disease Control sought the expertise of Korber and her Los Alamos National Laboratory colleague Gerald Myers in a public health study that was the basis for a civil suit in Florida. Five people were thought to be infected with HIV during invasive dental procedures. "The sequences of those patients were extremely close to the sequence of the HIV-infected dentist in that study, and at least two of the five patients had virtually no other risk factor for infection," Korber says. That lawsuit was directed not at the dentist, but at the HMOs that referred the patients to him. After the death of the dentist, the case was settled out of court.

Korber sees the potential for other legal applications of HIV sequence analysis arising. In New York, a man who is HIV positive is suspected of infecting a number of women; he knew his HIV status and failed to inform his lovers. HIV DNA sequence analysis combined with epidemiological data could scientifically pinpoint him as the culprit.

The legal implications of this scenario, if it ultimately reaches the courts, are unclear. "But it would be a precedent-setting case," Korber says. "For a person to be HIV positive and not tell his lovers—if it's that deliberate, could it be considered attempted murder?"

In another recent case, a man was found guilty of injecting his child with HIV in order to avoid child care payments. While this case did not involve HIV sequence analysis, others like it could.

Still another type of case Korber describes seems stranger than fiction: an HIV-infected intravenous drug user robbing people at needle point. Rather than threatening them with a gun, the desperate person holds up a needle filled with his or her own contaminated blood. If the victim were infected in such a case, the sequencing could help prove scientifically that the infection came from the thief. This kind of molecular DNA evidence could also be used in rape cases, to help identify a rapist.

BLURRY CLUES

However, as Korber and the courts found in the Lafayette case, the answers the sequencing analysis provides aren't always clear cut. In that case, the prosecution sequenced the HIV DNA from the victim, Janice Trahan Allen. Scientists compared her viral sequences to those of a man named Donald McClelland, who had been a patient of the accused, Dr. Schmidt. The prosecution held that the doctor had withdrawn blood from McClelland and injected it into Allen. If this were the case, one would think that Allen's and McClelland's HIV sequences would be very similar. Indeed those sequences were more closely related to each other than to any of the control group sequences (viral sequences from HIV positive individuals who live around Lafayette). The prosecution based part of their case on this observation, which Korber confirmed.

"However, the relationships in the HIV envelope gene sequences, one of the two HIV genes that were sequenced from Allen and McClelland, were distant for a recent transmission event," says Korber. She worked on this case with James Mullins and Gerald Learn of the University of Washington, and William Gallaher of the Louisiana State University Medical Center, all experienced HIV researchers. In their collective experience, and in published HIV transmission studies in the scientific literature, they could not find examples of such divergent sequences coming from two people who had recently transmitted virus from one to the other.

Viral envelope sequences are estimated to diverge on average about 1% per year, yet Allen's and McClelland's were on average 6.9% apart only 13 months after the day Allen says she was infected, and none of the envelope sequences obtained from the two individuals were very close. Korber has found studies that include sequences from individuals who are highly unlikely to be directly related, but who carry viruses that are as closely related as Allen's and McClelland's. This raised many questions for Korber and Mullins, including questions about the timing of infection of the individuals used for the Lafayette control group.

Time is critical when working with a virus that is mutating as rapidly as is HIV. "Within each person it's evolving so fast that you can even see variation accumulating during the course of that person's infection," says

Korber. Contrast this to human DNA sequencing—often used in court cases—and you have a whole different character.

When courts use human DNA to prove that someone committed a crime, all they need is, say, a bit of hair. The hair's DNA sequence will be identical to the sequence in the person who lost the hair. In the case of HIV, however, in a short period of time, the virus will have evolved, and as more time passes, it may look very different from the original sequence with which the person was infected.

REMOVING ESCAPE ROUTES

The complexity of working with human DNA led the National Academy of Sciences to publish books in 1992 (*DNA Technology in Forensic Science*) and again in 1996 (*The Evaluation of Forensic DNA Evidence*), which have aided the courts and organizations such as the FBI in their use of such evidence. Both publications were funded by the Department of Justice and the FBI. Korber believes that similar guidelines are needed for viral DNA forensics, and they need to be drafted fast.

First, Korber believes that care must be taken when working with the HIV samples. Above all, the experimental steps should be performed separately for the cases in question, to avoid sample mixup and potential contamination problems. The procedures should be done in duplicate, preferably in two different laboratories. But if that is not possible, they should be performed at least at different times. The person conducting the experiment should be "blinded," which means that when the samples are processed they are coded so it is not obvious during the experiment which are the most interesting samples, and which are the controls.

In the Lafayette case, there was some question about the validity of the sequences which were used during the pre-trial hearing. Both the patient's and the victim's samples were handled in the same laboratory, apparently side-by-side, and some of the local control sequences were found to be contaminations of a common laboratory strain of HIV. Due to this, limited confirmatory sequencing was conducted in a second laboratory prior to the trial, but more testing would have been desirable. "Contamination is very easy with HIV," says Korber. "It happens even in the best labs, and every precaution must be taken."

There should also be guidelines for selecting control samples, Korber believes. In a case like the one in Lafayette, scientists need to be sure that the controls against which they're comparing the litigated cases are from an appropriate risk group and with appropriate timing. If such controls are not available, then they need to be aware of the limitations of their study. The Lafayette local controls were mostly infected in the 1980s. Allen and McClelland were found to be HIV positive after 1990, and so they may have viruses that are part of a pool of virus spreading more recently in the community, and thus they may be closer to each other than to the local controls for reasons other than direct transmission. Comparing the key samples to inappropriate controls might lead to incorrect conclusions, since phylogenetic associations are always relative.

Korber also believes that the courts should request participation by an epidemiologist. The Lafayette case could have benefitted from further investigation of Allen's other risk factors, including a more thorough examination of her previous sexual partners, as well as a detailing of her own history as an ICU nurse, an occupation that exposes her to patients with HIV. Moreover, an epidemiologist could have helped define the appropriate control group.

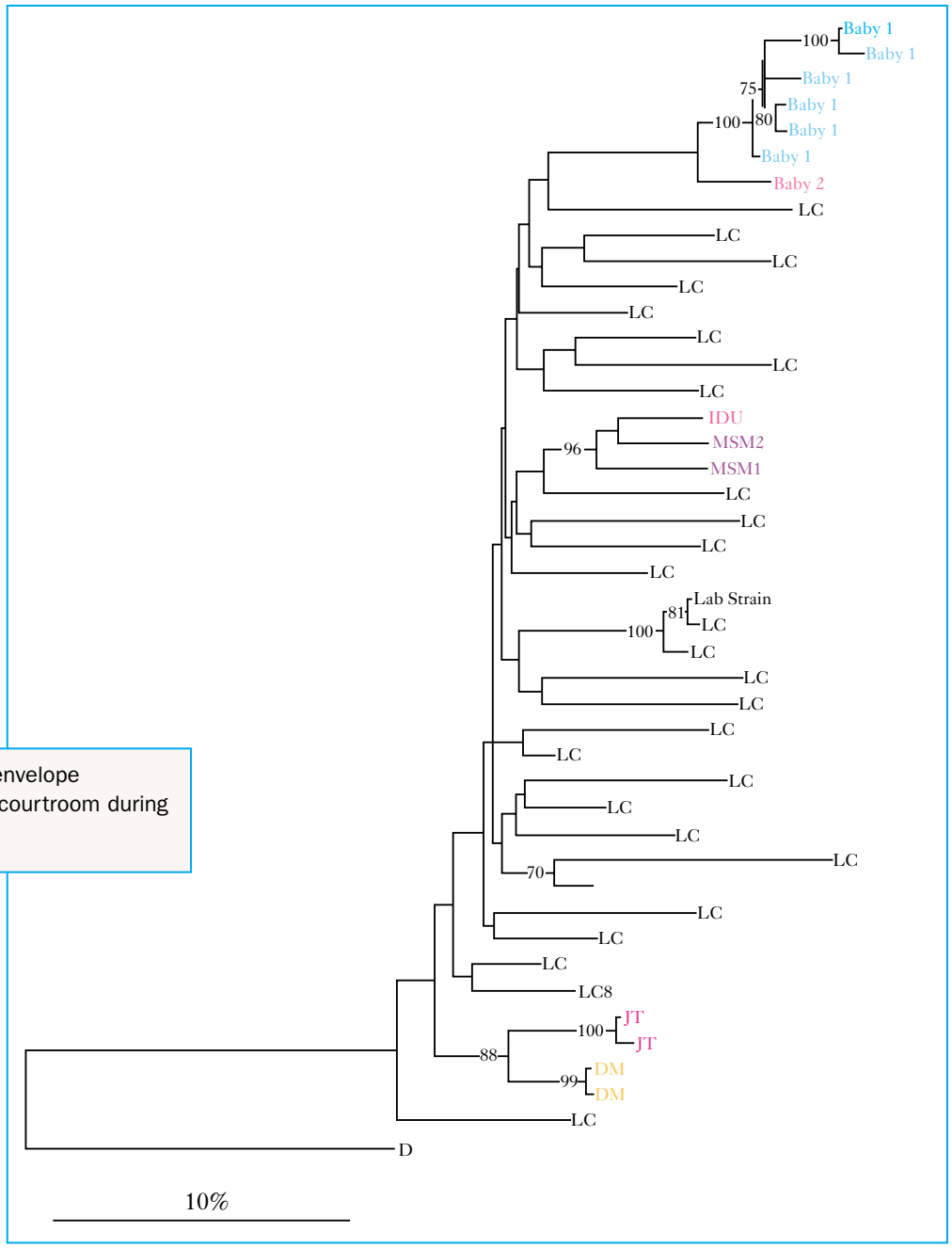
The whole process would be simpler if the courts could define exactly how similar sequences need to be in order for them to be used as evidence. However, Korber believes strict guidelines of this sort would be counterproductive. "The virus is changing too rapidly, and every scenario will be somewhat different," she says.

CONFUSED CONVICTION

The nature of testifying presents another obstacle to the accurate use of phylogenetic analysis in court. "It is difficult to qualify your comments in a courtroom," Korber says, "because the jury needs clarity, and it is hard to explain scientific subtleties to non-scientists in a short time." That means that in situations like the Lafayette case, in which there are gray areas, scientists are encouraged to make simple strong statements. This can result in leaving out important distinctions and not fully describing ambiguities, in situations where the evidence is neither simple nor strong. This could make or break a case. In the Lafayette case, the prosecution opted to summarize their conclusions and did not show or explain the phylogenetic trees to the jury. The defense, however, explained the basic concepts and science to the jury and showed them phylogenetic trees.

Ultimately, in that case, the doctor was found guilty of attempted murder. He faces 15 to 50 years in prison. "I suspect the DNA figured very little into the jury's decision, in the end," says Korber, "because it was hardly mentioned in the prosecution's closing arguments. I think this, in an odd way, was a minor victory. The prosecution had been arguing that the DNA data was conclusive, but let it go in the end. Since I was trying to argue that the DNA evidence was inconclusive in this particular case, I was pleased with this result."

It seems strange that this modern detective would be pleased that the outcome disregarded the science with which she works daily. In a way the changing HIV thwarted the efforts of science. But Korber notes that the data was ambiguous in this case, and it might not be in others. This points to the complexity of using this kind of cyber-evidence. Until it can be well utilized, its power may need to be tempered.



Phylogenetic tree of the envelope sequences shown in the courtroom during the trial of Dr. Schmidt.

This tree can be roughly considered an HIV family tree, but rather than knowing the exact relationships, you infer them from DNA sequences. The branching pattern indicates the relationships of sequences in the tree; these patterns are always relative to the sequences included in the tree. The horizontal branch lengths represent the genetic distance between sequences (or how much the DNA has mutated between the sequences). The small numbers written on some of the branch forks are bootstrap values, a statistic often employed in phylogenetic studies, and indicate the reliability of a particular branch. The end points of the branches represent individual HIV sequences.

The sequences labeled LC were the local control sequences used in the study, sequences obtained from the Lafayette region. The two LCs that branch close to the sequence labeled "lab strain" were laboratory contaminations. JT and DM are the labels of the sequences in question; it is clear that they are closer to each other than to the other local controls. However, the branch lengths, or total genetic distance, between the two was unexpectedly large for a very recent transmission event.

Baby 1 and Baby 2 are two infants from New Orleans, who were infected by their mothers. Their mothers were almost certainly infected heterosexually, so between the two infant's infections are, at minimum, their two mothers and one man. Yet the infant HIV sequences are as closely related as JT and DM. Similarly, the MSM and IDU sequences are from men from New Orleans whose risk factors for infection are homosexual behavior and IV drug use. Again, they are as closely related as JT and DM. While it is not easy to find transmission cases with branch lengths as long as JT's and DM's in the literature, there are many examples of unrelated cases that are as close or closer to each other than JT and DM. These observations resulted in questions regarding the appropriateness of the local control population.

This tree was provided by Dr. Gerald Learn.

1999 Community Lectures in Santa Fe
AT THE JAMES A. LITTLE THEATER

FEBRUARY 17: THE LAWS OF THE WORLD WIDE WEB

Bernardo Huberman, Research Fellow, Systems and Practices Laboratory, Xerox PARC; Consulting Professor, Physics, Stanford University

Sponsored by Barraclough & Associates, P.C.
Certified Public Accountants and Consultants

Surfing on the Web can be described by a universal law. Because of the Web's sheer size and complexity, users often resort to recommendations from others to decide which sites to visit. Huberman and his colleagues have developed a theory of influence—verified by empirical evidence—which predicts site visits by users of the Web and predicts bounds on the rate of novelty encountered by users.

MARCH 10: SOCIAL SECURITY: GAMBLING WITH YOUR FUTURE

Shripad Tuljapurkar, President and Chief Scientist, Mountain View Research (MVR), a population science research firm

Sponsored by Smith Barney Inc., Santa Fe

Social Security provides pensions and disability payments to millions of Americans. However, declining birth rates means that fewer people are now contributing to the system; meanwhile, more people are living longer, putting more demand on the system. Proposals to cope with the resulting growth in Social Security costs include benefit reductions, tax increases, private retirement accounts, and investments in the equity market. Because the future is unknown, any policy choice is really a gamble. Because policy is a matter of politics, any decision must contend with strong, conflicting interests. Tuljapurkar shows that an analysis of history yields effective knowledge of the odds that any chosen gamble will pay off. Using probabilities generated by a new method of forecasting, he identifies efficient policies that serve a number of conflicting interests.

APRIL 14: WHICH WORLD? SCENARIOS FOR THE 21ST CENTURY

Allen Hammond, Senior Scientist and Director of Strategic Analysis, World Resources Institute (WRI)
Sponsored by McElvain Oil and Gas Properties, Inc.

Hammond draws from the work of the 2050 Project, a program on long-term sustainability conducted jointly by WRI, Brookings Institution, the Santa Fe Institute, and a global network of scholars. Using scenarios, he explores the complex possibilities for how the future might unfold—scenarios that reflect very different mindsets or world views as well as different trajectories into the future.

MAY 19: SCIENCE, MEDIA AND PUBLIC: A COMPLEX MALADAPTIVE SYSTEM

Tom Siegfried, Science Writer,
The Dallas Morning News
Sponsored by Alphagraphics, Santa Fe

Generating greater funding for science requires media attention to catalyze governmental action. Yet errors and misunderstandings plague the communication channel between science and the media; scientists and journalists are "worlds apart," a recent analysis has concluded. As a result, science suffers from lack of public support and society suffers from a lack of sound scientific information. Improving this situation demands not only better journalism, but also a concerted effort by the scientific community, in league with other elements of society, to inject science more fully into the mainstream of modern culture.

JUNE 17: THE EVOLUTION OF ALTRUISM

Elliott Sober, Vilas Research Professor and
Hans Reichenbach Professor of Philosophy,
University of Wisconsin at Madison
Sponsored by Dr. Penelope Penland, Licensed Psychologist

Sober discusses altruism throughout the animal kingdom—from self-sacrificing parasites to insects that subsume themselves in the super-organism of a colony to the human capacity for selflessness. Co-author with David Sloan Wilson of *Unto Others: The Evolution and Psychology of Unselfish Behavior*, Sober's research offers a case-study of scientific change as well as an argument for group selection as a legitimate theory in evolutionary biology.

SEPTEMBER 21, 22 AND 23: ANNUAL STANISLAW ULAM LECTURES THE REGULAR AND THE RANDOM

Murray Gell-Mann, Distinguished Fellow,
Santa Fe Institute

OCTOBER 13: UNINFECTABLE: THE QUESTION OF CELLULAR IMMUNITY TO HIV

Janis Giorgi, Professor of Hematology/Oncology,
School of Medicine, UCLA
Sponsored by Santa Fe Audio Visual

Giorgi discusses her laboratory research on the role of cellular immunity as a defense against HIV infection. Evidence suggests that, along with antibodies, living cells—called killer T cells—also have the potential to identify and obliterate cells that have been HIV-infected. In long-term survivors of HIV infection, these cells also produce chemicals that suppress HIV replication.

NOVEMBER 17: LEAKY SYSTEMS

Andy Clark, Professor of Philosophy and Director,
Philosophy/Neuroscience/Psychology Program,
Washington University
Sponsored by Sierra del Norte Subdivision, Ltd.

In studying cognition we may often abstract too far from the very body and world in which our brains evolved to guide us. Mind, Clark argues, is a "leaky" system, forever escaping the barriers of skin and skull to exploit features of the physical and artifact-rich environment in which the biologic brain finds itself. Clark will sketch a broad framework for thinking about the leaky mind, and draw out some key ideas, puzzles, and implications.

Talks are held at James A. Little Theater on the campus of the New Mexico School for the Deaf, 1060 Cerrillos Road, Santa Fe. No admission charge.

Most talks take place on Wednesday evenings, beginning at 8 p.m. No reservations are necessary, but seating is limited.

Please contact the Santa Fe Institute to arrange for sign-language interpretation if necessary.

General support for this community lecture series is provided by Los Alamos National Bank.

PHOTO: PATRICK MCFARLIN

SFI Founders Took a Gamble

GINGER RICHARDSON

In the Institute's beginning days back in the early 1980s, the Science Board members were fond of describing SFI as "a floating crap game." It was a clever and apt description then, and it still applies today.

SFI's research body is composed mostly of visitors. There is no permanent faculty. The players come and go, the rules change, and the research foci evolve. We see this flow of people in and out of the Institute as one of its major strengths. It enables loosely organized research groups to form and reform as topics mature, and it encourages participants to remain active in collaborations after they return to their home institutions. This, in turn, influences the course of research and teaching at more conventional campuses around the country.

Such an administrative structure necessarily puts a great deal of emphasis on constant outreach to the scientific community at large. In fact, at SFI the notion of outreach is no mere altruistic afterthought; it is an intrinsic part of the Institute's mission to support fresh, catalytic research.

There is no denying that the SFI campus plays a central role in the metabolism of its far-flung community. Much of our work takes place on-site in Santa Fe. Every year, for example, more than one-third of our 55 external faculty members spend an average of one month on campus. These visits are often organized around working groups, or the visits may coincide with the visits of other colleagues to work on problems of mutual interest. Our external faculty join a core group of scientists including postdoctoral fellows and resident researchers who are on hand for longer periods of time and who provide necessary continuity to our programs.

Beyond the external faculty, more than one hundred additional researchers come to SFI each year. Most of our visitors come in response to invitations from our residential and external faculty. But they also find their way to the Institute on their own initiative using an open application process available on our web site. Approximately one-third of our visitors are first-timers at SFI. Over the past year, visitors in residence clocked more than ten "person years" of effort—that is, work equivalent to that of ten full-time researchers.

In a new effort to attract first-time visitors, this summer we have scheduled a July integrative themes workshop which will bring our scientific community together to address fundamental issues of simplicity and complexity in natural and social phenomena. Participants in the workshop will include members of the SFI external faculty as well as a small number of SFI Science Board members. But there is an additional twist to the meeting, a BYOB—Bring Your Own Buddy—component. Each SFI participant has been asked to invite a non-SFI "buddy," an individual who hasn't before been involved with the Institute but who is pursuing research which may complement SFI's emerging research foci.

Workshops are another powerful engine for bringing new members into the SFI community; we rely heavily on our meetings as a mechanism to catalyze new interdisciplinary networks of collaborative research. Typically 15-20 workshops are sponsored each year. Topics for workshops are proposed by researchers throughout the general scientific community (often with no official affiliation or previous contact with SFI) and are accepted (or declined) for sponsorship through discussion by SFI's Science Steering Committee. Some of the Institute's most successful meetings have been conceived as "founding workshops" for topics for which the central scientific questions are yet to be identified. Participants in these workshops have often had no previous contact with SFI, and are deliberately chosen from widely disparate disciplines. Nearly one thousand scientists participated in SFI workshops last year. About one-half of these visitors were new to our community.

Last October we officially dedicated the Institute's new 9,000-square-foot wing of researcher offices and common space. This expansion allows us to increase the number of researchers at SFI at any one time from 35 to 50. It also adds several conference rooms and generally provides a better environment for our researchers to think, work, and interact.

Implicit in the Science Board's original description of SFI was the notion that the scientific action might move from place to place, or take place simultaneously at many sites. Indeed, alongside its residential researchers, an equal force in SFI's intellectual life is its network of external researchers. Scientists who visit SFI become involved in collaborations and generally continue these interactions subsequent to leaving SFI. In this way, SFI's work "floats" to sites at other universities and research institutions. With encouragement from SFI, an extended community of scientists and educators remains in electronic (and sometimes physical) contact despite being highly distributed geographically, and many of them receive travel support from us to enable them to update research collaborations, either at the Institute or elsewhere.

To encourage networking and collaborative research for its postdoctoral fellows, the Institute provides funding to support extended research visits to off-site affiliates. The Institute has also recently strengthened the empirical component of postdoctoral research by providing support for fellows to participate in off-site experimental and data-collection projects. Eric Bonabeau, for example, is devoting a significant portion of his tenure at SFI to participating in experimental design, specimen collection, and investigation of foraging and task allocation in ant colonies and sociogenesis in social wasps.

PHOTO: LAURENT GUERIN

In this issue you can read about SFI's new Fellows-at-Large initiative, a program which provides funds for its participants to invite SFI-affiliated researchers to visit the fellows' home institutions for research talks and short-term collaborations. In another new venture, SFI and the Hutchinson Cancer Research Center have developed an exchange program to encourage the integration of theoretical and experimental approaches in the study of biological phenomena. The aim is to provide opportunities for postdoctoral-level researchers with interests in theoretical biology and biophysics to collaborate with experimentalists at Hutchinson, as well as with researchers at SFI.

These new initiatives build on a firm foundation of established, ongoing institutional collaborations. One of the most active sites is the University of Michigan where Robert Savit heads a graduate program for the study of complex systems. SFI's proximity to the University of New Mexico has stimulated collaborations between scientists associated with SFI and UNM. The large number of SFI-affiliated people at Stanford, including SFI external professors Kenneth Arrow (economics) and Marcus Feldman (population genetics), have formed an independent group that meets regularly to discuss research in complexity and explore potential new collaborations there. Duke University, inspired by SFI's experience, has also established a new center for complex systems.

By their own admission, SFI's founders knew that the stakes would be high as they attempted to forge a new approach to scientific research. Fortunately, however, they seemed to have had the organizational vision to support their venture. Within the SFI extended community, the game—relatively formless, highly mutable, intentionally risky, subject to changing players—is still going down.

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1399 HYDE PARK ROAD
SANTA FE, NEW MEXICO 87501
U.S.A.

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