SFI Bulletin

SANTA FE INSTITUTE • FALL 1999 • VOLUME 14 • NUMBER 2

HETERARCHY IN THE ALLEY

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Published by the Santa Fe Institute
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Note: The *SFI Bulletin* may be read at the website: www.santafe.edu/sfi/publications/Bulletin/. If you would prefer to read the Bulletin on your computer rather than receive a printed version, contact Patrisia Brunello at 984-8800, Ext. 269 or pdb@santafe.edu

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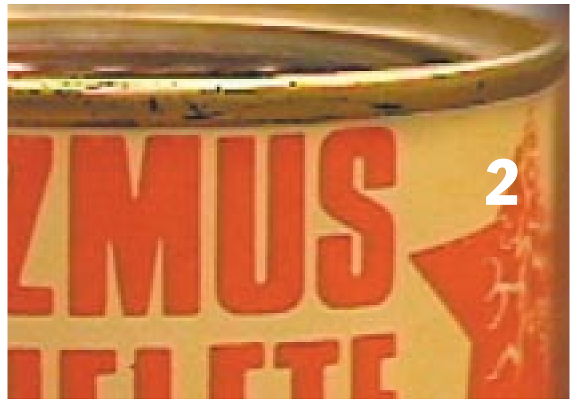

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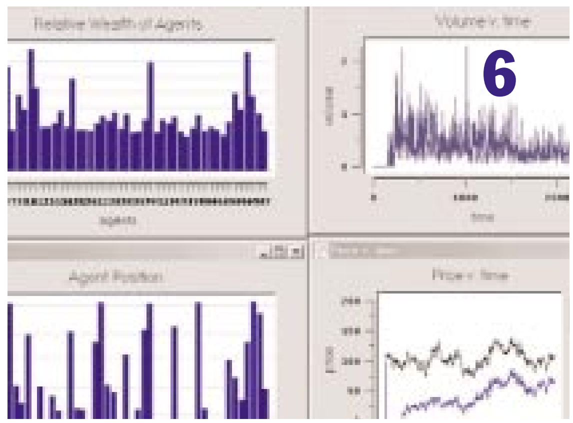

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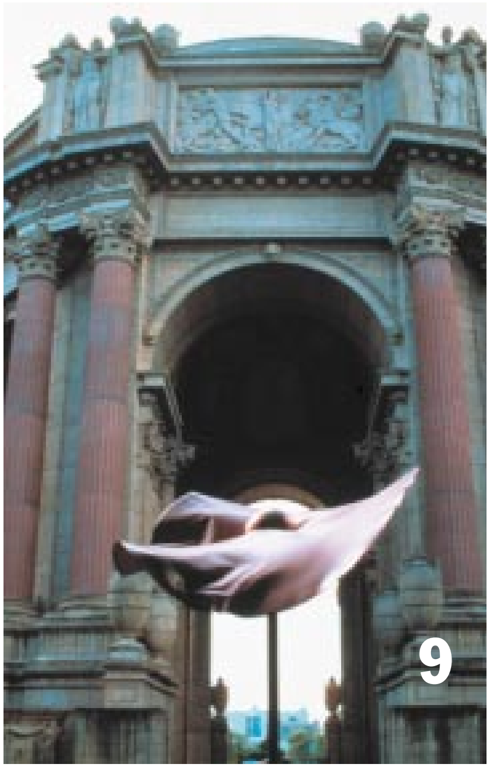

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HETERARCHY

The Organization of Diversity— Travels with Sociologist David Stark through the Uncertain World of Heterarchy

by Janet Stites

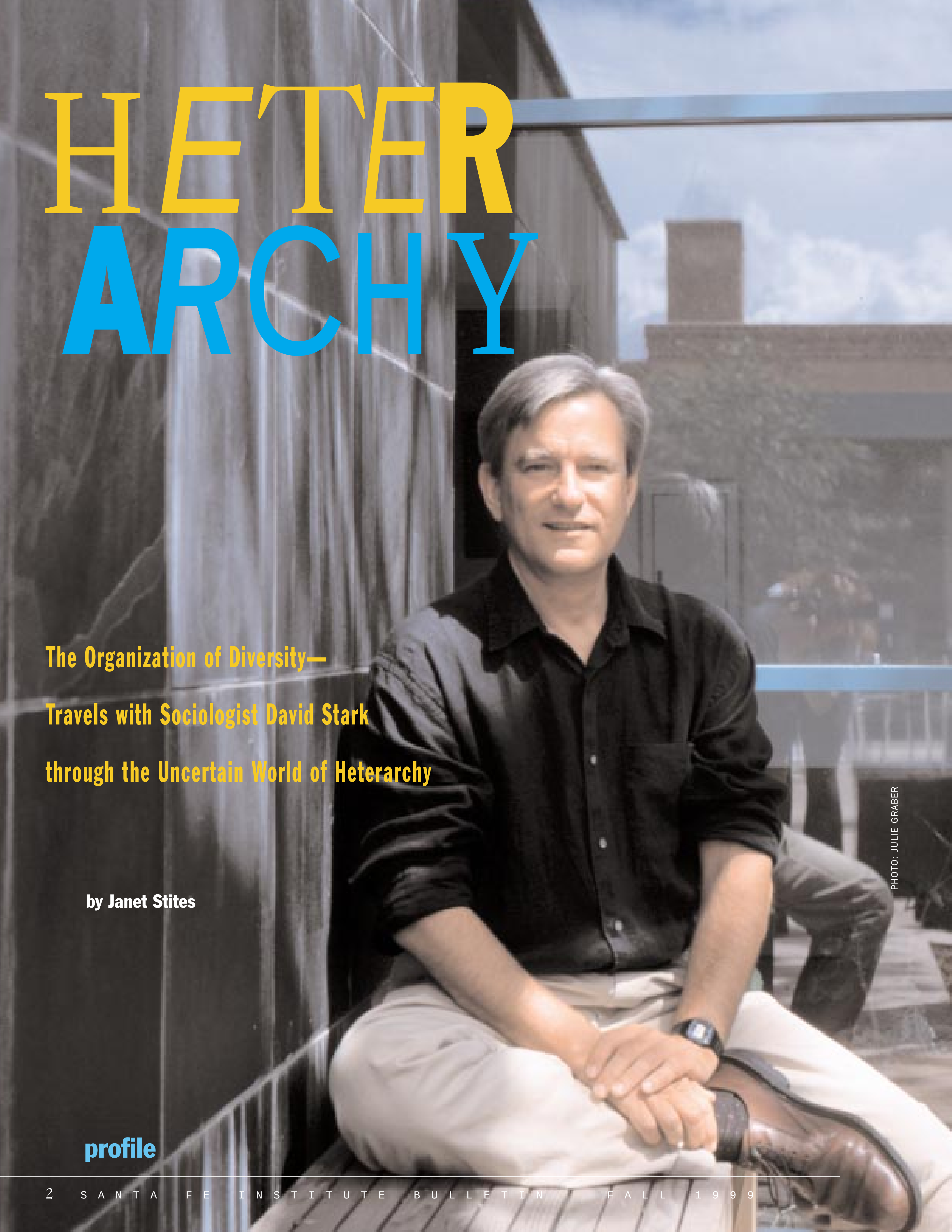
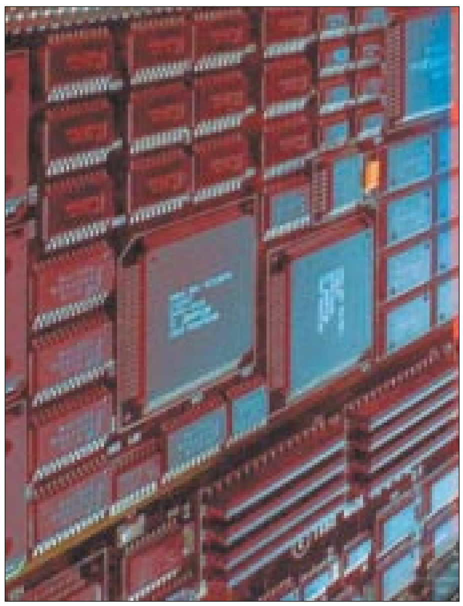


PHOTO: JULIE GRABER

profile

ECONOMIC SOCIOLOGIST DAVID STARK has spent the greater part of his academic career traveling to Eastern Europe, particularly Hungary, to gather data for his research on how post-socialist enterprises reorganize and recombine resources to shape their own distinctive path to capitalism. But it's in his own backyard where the Columbia University professor and Santa Fe Institute external faculty member is now studying the emergence of new organizational forms in the raw lofts and hidden cubbies of downtown Manhattan, where since the advent of the graphical user interface for the World Wide Web, an industry dubbed Silicon Alley has emerged to become one of the most influential centers of the digital economy.

Stark, Arnold A. Saltzman Professor of Sociology and International Affairs and chair of the Department of Sociology at Columbia University, has found many similarities between the organizations of Silicon Alley and those in Hungary. "I ask the question," says the soft-spoken Stark, "are there some forms of organization that are more likely to be able to redefine, redeploy, recombine assets? The answer: Yes, organizations with a capacity for reflexivity. What is the basis of that? Active rivalry of coexisting principles—the organization of diversity."



Central to his work is a phenomenon he calls "heterarchy." He defines organizations operating under the principles of heterarchy as those which operate with minimal hierarchy and which have organizational heterogeneity. There is uncertainty and self-organization. To prosper in such a situation, Stark believes management becomes the art of facilitating organizations that can perpetually reorganize themselves. "The solution is to minimize hierarchy," he says. "Authority is no longer delegated vertically, but emerges laterally."

To be sure, in Silicon Alley, firms are working at lightning speed, and traditional management models with academic flow charts, regular quarterly reviews and the like, are often disregarded if ever implemented at all. In some cases, it's not even clear if successful managers from the traditional corporate world can operate in the start-up world of the digital economy.

"I'm interested in finding out to what extent hierarchy versus heterarchy is there in the new kind of firm which is emerging," Stark says. The benefit of heterarchy, according to Stark, is that firms become capable of learning.

In the case of Hungary and Silicon Alley, both emerging markets find themselves mired in dissonance. Players with varied backgrounds, motives, and even languages, have to learn to work together. There is no established corporate ladder per se, often no company handbook, metaphoric or otherwise. In the case of Silicon Alley, the CEO might want to go public and cash out as soon as possible only to start over with a new idea, the director of business development wants to spend money to acquire competitors, the marketing director wants to produce award-winning design, the programmer wants to write immortal code.

"Dissonance can be positive," Stark says (which is probably easier to swallow in theory than in reality). "These organizations can benefit from the active rivalry of competing belief systems. Rivalry fosters cross-fertilization." The example he uses is the infantry officer who instructs drummers to disrupt the cadence of marching soldiers while they are crossing bridges, "lest the resonance of uniformly marching feet bring calamity," and cause the bridge to collapse. The goal, Stark contends, is to coordinate diverse identities without suppressing differences.

Stark sees both post-socialist Hungary and Silicon Alley as social laboratories that researchers can use to test competing theories, because in both, people are actively experimenting with new organizational forms. Also common to both is the idea that their experimentation is like bricolage—making do with what is available, redeploying assets for new uses, recombining resources within and across organizational boundaries.

In Hungary, that might mean working suddenly without government support, with workers who need retraining, with old equipment, or not enough supplies. In Silicon Alley, it means working without the resources of a corporate structure, in offices where workspace and hierarchy are not well defined, or having to use speculative stock options and new media panache to compete for an otherwise pampered workforce.

But there are differences between post-socialist Hungary and Silicon Alley. "The Hungarian firms knew what they were working toward; there was a model," Stark says. "They knew what capitalism was and how it worked. In Silicon Alley no one knows what the market will be. They are still working in the dark. It's like building a ship while out at sea."

Indeed, Silicon Alley hosts an eclectic group of people scrambling to build businesses, some of which will develop technologies which will be obsolete before they are launched (remember "Push?"), others only to be beaten to market by a competitor or monolith like Microsoft. Some will be acquired and then quietly absorbed or disbanded altogether; others will go public in a flurry of publicity, some successfully, others unsuccessfully to the point of embarrassment.

As an external faculty member of SFI, Stark has found himself most recently discussing the economies of Hungary and Silicon Alley under the sun of Santa Fe. Stark was first invited to SFI in 1997 by SFI external faculty member John Padgett. Having read Stark's work, Padgett, a political scientist at the University of Chicago, recognized Stark's cross-disciplinary approach to studying social transformations. Out of a cast of 20 or so social scientists invited to the Institute in the fall of 1997, Stark now meets and corresponds with a working group of four, including Padgett, Walter "Woody" Powell from the University of Arizona, and Gernot Grabher, an economic geographer from the University of Bonn. (In 1997, Stark and Grabher published *Restructuring Networks in Post-Socialism: Legacies, Linkages, and Localities*, Oxford University Press.)

Each brings to the group similar data sets from vastly dissimilar economies. Padgett's data is gathered from 15th-century Florence (see SFI Bulletin, Summer 1998); Powell's from the bio-tech industry; and Grabher from the advertising industry in London's Soho.

In each, the scientists studied the network of firms and the people operating the firms. They looked to find where the networks crossed, where people crossed, and if the firms were lasting. What is common and of great value among Stark's small group of peers, is that they all have theory supported by a solid data set, and each studied an economy where there was a fast-paced change. "All the economies had a one- to two-year period of vast upheaval, and sometimes external shock," Stark said. "There was a high degree of uncertainty in the organization environment."

Stark says he was thinking in SFI terms long before he got there. "I was looking at changes in economies, not as planned or designed, but as evolving and self-organizing," he says. While browsing the library of the Wissenschaft Zentrum in Berlin, Stark came across an article in *Daedalus* on advances in computer programming written by SFI external faculty member John Holland. "It was a paper on using 'cross fertilization' for computer programs that would be capable of adapting to new problems in the environment. I read it around 1990 at the height of the craze of foreign advisors making recipes, blueprints, and formulas in Eastern Europe—and it meshed with my criticism of 'designer capitalism.'" Since, Stark has been influenced by other SFI scientists, most importantly, economist David Lane for his work on "complex strategy horizons," and theoretical chemist Walter Fontana. Lane, Fontana, Padgett, Powell, and Grabher will be among the participants in an ongoing faculty seminar on "Heterarchy" that Stark is organizing at Columbia in 1999-2000, supported by a major grant from the Andrew W. Mellon Foundation in cooperation with SFI.

In regard to his work on-site in Santa Fe, Stark believes the benefits of being exposed to creative ideas from scientists from different fields will be long-term. "In a certain way, my involvement at SFI mirrors my own view of how organizational innovation comes about," Stark says.

While hesitant to shift the focus of his work in Eastern Europe, Stark believes that what is going on in New York City's Silicon Alley is worth trading in his passport for a Metrocard. So significant is the new industry, he and several colleagues, including his wife anthropologist Monique Girard, are in the process of setting up a center to chart the emergence of collaborative organizational forms in an era of interactive media.

GIORGIO BASARIM (1511-73) "VIEW OF FLORENCE" FRESCO

Already the group is collecting an archive of the websites of 200 of Silicon Alley's most prominent firms to explore connections among the firms through hyperlinks. They are collecting data on the activities of firms in the industry from trade journals and business publications, and developing a database of transactions across firms by using a search engine to look for phrases like "merged," "invested in," "inked a deal." They have spent time closely observing the operations of a number of Alley companies and interviewed numerous Alley entrepreneurs.

But to focus on Silicon Alley is to begin to let go of Eastern Europe, where he had been doing research since 1977. "Staying in familiar territory would have been the easier route," Stark says. "Beginning a completely new project is like launching a start-up company. It's difficult, but exhilarating. The learning curve is steep."

Stark is currently leading a year-long Sawyer Seminar entitled "Distributed Intelligence and the Organization of Diversity" sponsored by the Department of Sociology at Columbia, with support from the Andrew W. Mellon Foundation. The aim of this faculty seminar is to explore the emergence and dynamics of new organizational forms in response to the extraordinary uncertainties of rapid technological, economic, and social change.

On the subject of learning and adapting, Stark likes to tell the story about a souvenir he keeps on his desk: “I have a tin can that I bought in Budapest in the autumn of 1989. It’s considerably smaller than your standard tuna can and extremely light in weight. If you tap your fingernail on it, it gives a hollow ring. But the label, complete with a universal bar code, announces in bold letters that, in fact, it’s not empty: Kommunizmus Utolso Lehelete—The Last Breath of Communism.”

The trinket came not from a clever entrepreneur in post-socialist Eastern Europe, but from a state-owned work team which took advantage of legislation that allowed employees of socialist firms to form “intra-enterprise partnerships.” Such practices were the beginning of organizational hedging, according to Stark—one toe in the water.

PHOTOS: HAWLEY JOHNSON

“The challenge of the modern firm, whether it be a post-socialist firm coping with the uncertainties of system change or a digital technologies firm coping with unpredictable strategy horizons,” Stark writes in his paper, “Heterarchy: Asset Ambiguity and the Organization of Diversity in Post-socialist Firms” (July 1996), “is the challenge of building organizations that are capable of learning. Flexibility requires an ability to redefine and recombine assets: in short, a pragmatic reflexivity.”

Stark believes these attributes are imperative in a volatile, fast-moving market. “It’s the difference,” he says, “between a firm that is adaptable and one that is just ‘adapted.’”

Janet Stites is a free lance writer and publisher of AlleyCat News *(www.alleycatnews.com), a New York-based monthly magazine which covers the business of Silicon Alley. She has written for* OMNI Magazine, Newsweek, *and* The New York Times.

ABOUT SILICON ALLEY

New York's Silicon Alley started with a whimper, not a bang, on the eve of the Internet revolution, when a few individuals—long on foresight—saw infinite possibilities available in consumer and business applications via the World Wide Web. This, thanks to the introduction of a graphical user interface that would become known as a browser.

Initially, the core of the industry was numerous small Web design shops which, because of the agility small businesses afforded them, were able to scoop corporate design shops and traditional advertising agencies to lock in Fortune 1000 design jobs.

It became evident very quickly that there was much to do on the Web beyond design. New York, being the media capital of the world, suddenly found itself rife with companies hoping to develop "content" for the Web. They included iVillage.com, now a Web site for women, initially for parenting; theglobe.com, started by two young Cornell University graduates, who worked tirelessly to corner the market on Generation X; and FEED Magazine, the Internet's answer to *Harper's* or *The Atlantic Monthly*.

Beyond design and content, companies like Internet Advertising Network (now DoubleClick) helped to define the way advertising on the Internet would work. Others specialized in extending the effectiveness of the banner ad or measuring "clicks." With interest in the Internet high, more traditional software companies, previously working in near anonymity, began to surface. Suddenly, if you weren't working in new media, you weren't anybody at all. Otherwise well-paid people traded in their $50-per-square-foot office space, regular salaries and great benefits, to work in dingy makeshift lofts, or in second-rate buildings in the financial district which had stood empty since the late ‘80s bust of the market. From the Flatiron District to Wall Street, a new type of company emerged on the landscape—the “start-up.” A journalist dubbed the area “Silicon Alley” and the moniker, as well as the industry, stuck.

Now the term Silicon Alley is more metaphor than actual place, representing the growth of technology or Internet-based companies throughout the New York City metropolitan area-and beyond. Companies like DoubleClick, iVillage, and theglobe.com have made international headlines with their successful public offerings. The venture capital community and investment banks, once skeptical, are swarming the market. Big city that it is, one can hear people discussing their business plans in parks, on the subways, in coffee shops. Once almost a foreign concept to the New York area (particularly the city), small business and entrepreneurism have surfaced from the shadow of the alleys and skyscrapers to become the darlings of economic development and Wall Street—the core of the big apple.

URLs:
www.iVillage.com
www.theglobe.com
www.feedmag.com
www.doubleclick.net

Janet Stites

SFI ARTIFICIAL STOCK MARKET SOON ONLINE

Recent work on the Santa Fe Institute Artificial Stock Market (ASM) model by SFI graduate student Shareen Joshi, in collaboration with Reed College advisors Jeffrey Parker and Mark Bedau, suggests that this model may be used to understand some interesting features of financial markets, such as the destabilizing effects of technical trading rules, and the profitability of such rules. In short, the research suggests that the frequent revision of forecasts, accompanied by high technical trading, leads to higher volatility and less overall wealth.

With public distribution of the ASM code coming soon to the SFI web site, others will be able to probe these results for themselves. The Artificial Stock Market, one of the first agent-based models of a financial market, was developed in the early 1990s by W. Brian Arthur, John Holland, Blake LeBaron, Richard Palmer, Paul Tayler, and Brandon Weber at the Santa Fe Institute. It contains a population of myopic, imperfectly rational, heterogenous agents who make investment decisions by forecasting the future states of the market, and who also learn from their experience over time. The model illustrates how simple interactions among such agents may lead to the appearance of realistic market behavior.

Results suggest that many features of real-world markets (such as bubbles and crashes in prices) that have in the past been attributed to external influences may actually be internally generated within the market structure itself.

THE MODEL

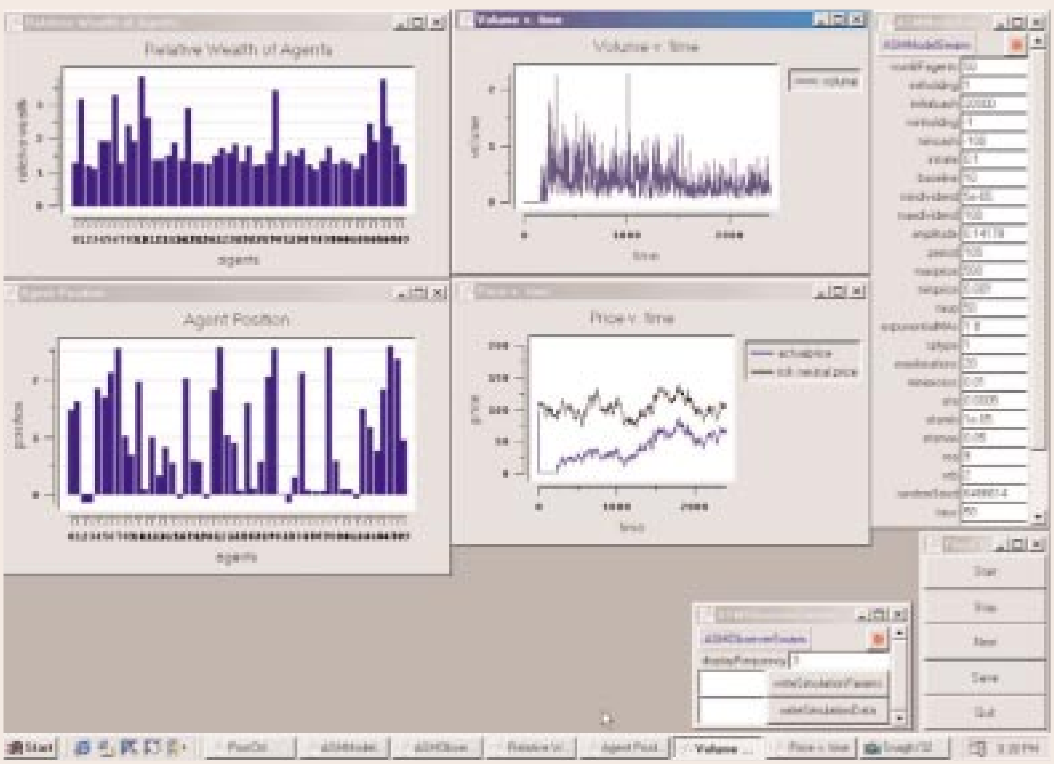
The simulated market contains two assets: a risky stock, in finite supply, and a risk-free bond, available in infinite supply. Agents, initially endowed with a certain sum of money, must decide in each time period of the simulation how to allocate their capital between the two assets. They do this by forecasting the price of the stock, and assessing its riskiness (measured by the variance of the prices). Forecasting rules are IF-THEN statements: IF (a certain market state occurs) THEN (a certain forecast is made).

Agents may recognize two different kinds of market states (possibly simultaneously): technical and fundamental. A market state detected by an agent is "technical" if it identifies a pattern in the past price history, and is fundamental if it identifies an immediate over- or under-valuation of the stock. An example of a technical state would be "the price is greater than the 50 period moving average," and an example of a fundamental state would be "the price is over-valued by 10 percent."

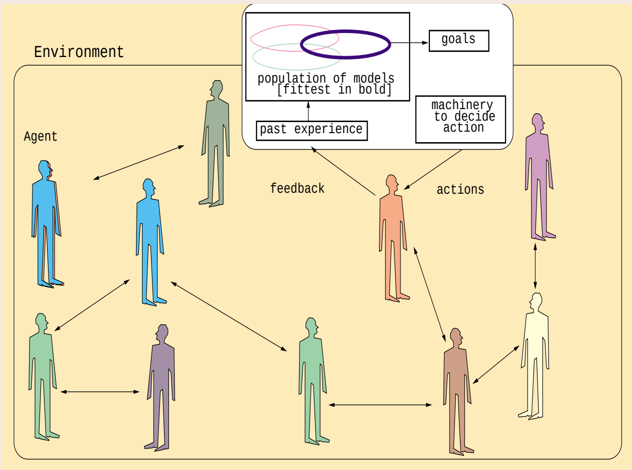
If the market state in a given period matches the descriptor of a forecasting rule, the rule is said to be activated. A number of an agent's forecasting rules may be activated at a given time, thus giving the agent many possible forecasts from which to choose. An agent decides which of the active forecasts to use by choosing at random among the active forecasts with a probability proportional to its accuracy, a measure that indicates how well the rule has performed in the past. Once the agent has chosen a specific rule to use, the rule is employed to make an investment decision.

Agents determine how much stock to buy, sell or hold, using a standard risk-aversion calculation. They submit their decisions to the market specialist, an extra agent in the market who functions as a market-maker. The specialist may use a number of different techniques to declare a market-clearing price (available as parameters).

A genetic algorithm (GA) provides for the evolution of the population of forecasting rules over time. Whenever the GA is invoked, it substitutes new forecasting rules for a fraction of the least-fit forecasting rules in each agent's pool of rules. A rule's success or "fitness" is determined by its accuracy and by how complex it is (the GA has a bias against complex rules). New rules are created by first applying the genetic operators of mutation and crossover to the bit strings of the more successful rules in the agent's rule pool. The GA may be compared to a real-world consultant. It replaces current poorly performing rules with rules that are likely to perform better, much the same way as a consultant urges her client to replace poorly performing trading strategies with those that are likely to be more profitable.



WEB SITE IN PROGRESS—BRANDON WEBER



A Typical Agent-Based Model

It is important to note that agents in this model learn in two ways: First, as each rule's accuracy varies from time period to time period, each agent preferentially uses the more accurate of the rules available to her; and, second, on an evolutionary time scale, the pool of rules as a whole improves through the action of the genetic algorithm.

RESULTS

The most significant early finding was that this market exhibits two quite different kinds of behavior, corresponding to different rates at which market-forecasting rules are being revised by the genetic algorithm. When the GA-invocation interval is large (between 1,000 and 10,000) resulting in forecasting rules evolving relatively slowly, prices are more stable; evolved forecasting rules are simple; levels of technical trading are low; trading volumes are low; and there is little evidence of nonlinearity. Since this kind of behavior resembles the predictions of the theory of efficient markets, this regime has been termed the "Rational Expectations Regime."

On the other hand, when the GA-invocation interval is small (between 10 and 100) it results in forecasting rules evolving relatively quickly, and the variance of the price time series is relatively high; the evolved rules are complex; levels of technical trading are high; trading volumes are higher; and there is strong evidence of nonlinearity. This regime is called the "Complex Regime."

Since 1998 Joshi, Parker, and Bedau have been further studying the dynamics of the ASM. Using a simple game theoretical model together with the Santa Fe Stock Market, they attempted to find the optimal rate at which traders should revise their repertoire of market-forecasting rules using the GA. They showed that the market has only one symmetric Nash equilibrium, and that this equilibrium lay in the "Complex Regime." Most important of all, they concluded that this symmetric Nash equilibrium was "sub-optimal" because in this regime the wealth accumulated by agents was lower than in the Rational Expectations Regime, the asset was riskier (prices were less stable), and the market was noisier.

These recent results suggest that financial markets can end up in situations analogous to a multi-person Prisoner's Dilemma game in which frequent revision of forecasting rules can lead to increased price variability and thus reduced overall earnings. When traders do not know a priori what other traders are doing, their optimal strategy is to revise forecasting rules frequently. But when this dominant strategy prevails and market beliefs co-evolve rapidly, the market falls into a symmetric Nash equilibrium with relatively low average earnings for traders. In other words, this work indicates that if every trader used technical analysis the result would be a general loss of profit.

Much research remains to be done in establishing the robustness of these results to variations both in the model's parameters and in the structural design of the model itself. As part of this effort SFI plans to establish a Web site for public distribution of the ASM code. The Web site will be designed to encourage general testing of the code, validation against empirical data, and collection of detailed simulation studies.

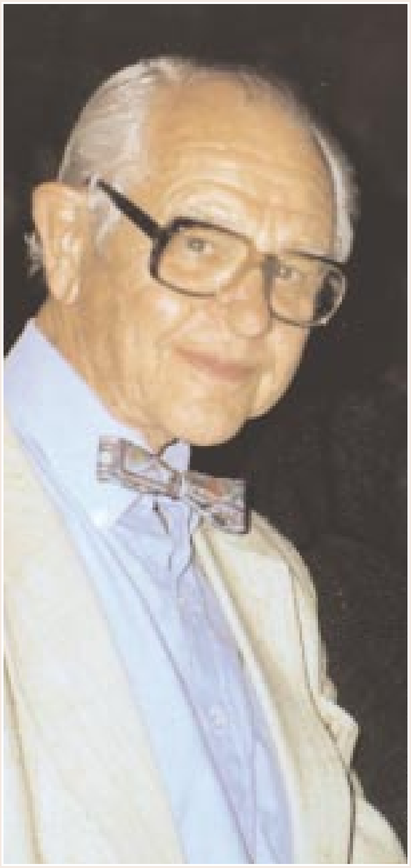


PHOTO: MARY ESHBAUGH HAYES

SFI TRUSTEE JOHN POWERS 1916-1999

SFI Trustee John Powers, a long-time supporter of the Institute's activities and an influential figure in the modern art community, died in September at the age of 83.

Powers and his wife Kimiko moved from New York to live full-time in Aspen in the mid-1970s when Powers retired as president of Prentice Hall Publishing Company. The couple lived first in one of the Aspen Institute trustee houses, and then later moved to Carbondale, Colorado.

Powers donated to the Institute many works of contemporary art—including prints by Cristo, Roy Lichtenstein, and Jasper Johns—which today grace the campus. SFI Founding President George Cowan notes, "John's support of SFI activities never wavered through the years. His own intellectual curiosity, coupled with his creative and artistic sensibilities, found a home here at SFI and at the Aspen Institute where he was also active for many years. We will all miss him."

NEW BOOKS FROM OXFORD

SFI is pleased to announce two new books from Oxford University Press, publisher of the Santa Fe Institute Studies in the Sciences of Complexity (SISOC) book series. Orders can be placed by calling 1-800-451-7556.

Swarm Intelligence: From Natural to Artificial Systems

By Eric Bonabeau, Marco Dorigo, and Guy Theraulaz

Social insects—ants, bees, termites, and wasps—provide us with a powerful metaphor to create decentralized problem-solving systems composed of simple interacting, and often mobile, agents. The emergent collective intelligence of social insects, swarm intelligence, lies not in complex individual capabilities but rather in networks of interactions that exist among individuals and between individuals and their environment.

Swarm intelligence offers another way of designing "intelligent" systems, where autonomy, emergence, and distributed functioning replace control, preprogramming, and centralization. This book surveys several examples of swarm intelligence in social insects and describes how to design distributed algorithms, multi-agent systems, and groups of robots according to the social insect metaphor.

Dynamics of Human and Primate Societies: Agent-Based Modeling of Social and Spatial Processes

Edited by Timothy A. Kohler and George J. Gumerman

This volume presents a series of studies from archaeologists, enthnographers, primatologists, computer scientists, sociologists, and philosophers who use agent-based models to examine social and spatial dynamics. The contributors, convened at an international conference at the Santa Fe Institute in December 1997, consider a variety of societies, from ones as apparently simple as those of primates, to ones as complex as those of contemporary industrial nations. These papers ask and find provisional answers to fundamental questions such as: How do levels of selection and spatial configuration of resources interact in the evolution of cooperation? How can we explain the evolution of inference? And what is the role of warfare in the emergence of state-level societies? Other papers are concerned with understanding how settlement patterns are generated among Mesolithic foragers in the Southern Hebrides or small-scale Neolithic societies in the North American Southwest.

OPREA EARNS PH.D.

In April 1999, Mihaela Oprea was awarded a doctorate in computer science from the University of New Mexico. The main thrust of Oprea's work focuses on the evolutionary aspects of the immune system: how antibody gene libraries encode information about the pathogen environment of the species; how the immune system improves its efficiency of generating high affinity antibodies during on-going immune responses; how mutation rates are estimated; and what mechanism is responsible for somatic hypermutation of antibody genes.

Before coming to the United States, Oprea earned an M.D. from the University of Medicine and Pharmacy at Timisoara, Romania.

Her thesis is entitled "Antibody Repertoires and Pathogen Recognition: The Role of Germline Diversity and Somatic Mutation." Much of her research has been done at the Santa Fe Institute in collaboration with external faculty members Tom Kepler and Alan Perelson under the auspices of the SFI Theoretical Immunology program supported in part by the Joseph P. and Jeanne M. Sullivan Foundation. Currently Oprea is continuing her research with Perelson as a postdoctoral fellow at Los Alamos National Laboratory.

PHOTO OF MIHAELA OPREA: JULIE GRABER

news

DESIGNING THE

PHOTO: DAN BARSOTTI

DISCOVERING PATTERNS—THE INTERFACE BETWEEN ART AND SCIENCE

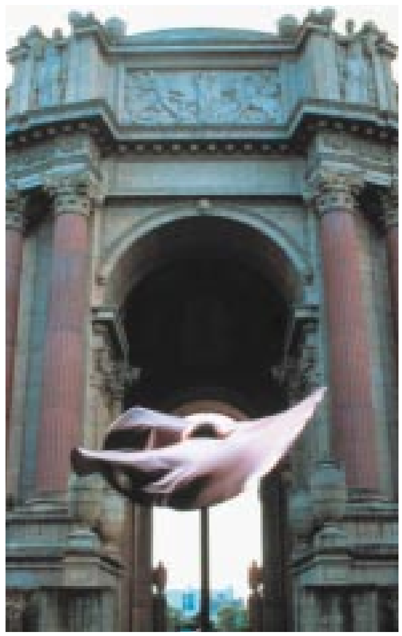
PHOTO: PATRICK MCFARLIN

BY HOLLIS WALKER

These days, Jim Crutchfield is thinking about vocabularies—about how humans continuously extend our vocabularies to describe new realms of experience. His concerns run counter to those espoused by philosopher Ludwig Wittgenstein early in this century, who said that if you don't know about something, you can't talk about it. Crutchfield is more worried about how our perception of the world is limited by our vocabularies and how we transcend those limitations. "How do you extend your vocabulary in a dynamic way? How do you teach yourself to see new patterns you haven't seen before?" he asks.

This fascination with what he calls "pattern discovery" is one of the reasons Crutchfield spends more time hanging out with artists than other scientists. Like mathematics, art can be an iconic substitute for language—and at the same time a vocabulary unto itself. "In a way, art is a theory about the way the world looks to human beings," Mitchell Feigenbaum told James Gleick, author of *Chaos: Making A New Science*. "What artists have accomplished is realizing that there's only a small amount of stuff that's important, and then seeing what it was. So they can do some of my research for me."

Crutchfield says his long-standing friendships with many artists, including Ned Kahn, Sara Roberts, and Gail Wight, have inspired some of his more rigorous scientific inquiries. Kahn, with whom Crutchfield worked on the 1996-97 San Francisco Exploratorium exhibit, Turbulent Landscapes: The Natural Forces That Shape Our World (http://www.exploratorium.edu/complexity), creates art installations inspired by atmospheric physics, geology, astronomy, and fluid motion: flapping flags, dust devils, swirling streams.



top: "Circling Wave" by Ned Kahn, Exploratorium, San Francisco.
bottom: "Encircled Stream" by Ned Kahn, Seattle, Washington

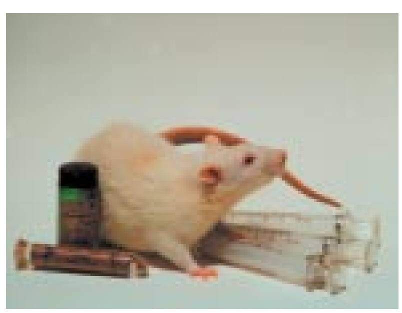
PHOTOS COURTESY OF THE EXPLORATORIUM, SAN FRANCISCO

During the years Crutchfield was at UC Berkeley, Kahn would call him for help on the scientific end of his constructions: "Hey, Jim, I've been squirting water into a satellite dish, and the vortex detaches from the drain. What do you think is happening?" Often Kahn's queries would send Crutchfield into his Berkeley physics lab, his own curiosity piqued. The artist, meanwhile, was looking for a way to put a frame around an active, natural system, then create a way for observers to alter it—in effect, manufacturing curiosity to engage ordinary people with nature, science, and art.

While Kahn formalizes opportunities to perceive and effect natural phenomena, Sara Roberts borrows the mathematics used to describe those phenomena and employs it in the design of her anthropomorphic computer programs. Roberts teaches at the California Institute of the Arts in Valencia, where she also founded and now directs the Integrated Media Program.

"Dynamical systems theory has lots of useful material for me," Roberts explains. "It's not that I'm interested in looking at the world through a dynamical systems filter. It's useful to me as technique." Much of Roberts' work, including her 1994 *Elective Affinities* (based on the Goethe novella), used dynamical systems models to drive the "emotional engines" of multimedia installations. In *Elective Affinities*, the installation became a metaphor for the dynamics of complex human relationships.

A married couple and two close friends are riding in a car together and, as a result of sexual innuendoes bandied about at a picnic from which they're returning, they are thinking about betraying each other. The characters are projected video images in front



PHOTOS COURTESY OF GAIL WIGHT/INSTALLATION PHOTO: BEN BLACKWELL.

and back seats represented by video busts on a pedestal; the scenery outside the car rushes away from them on a screen mounted on the wall behind. Each character runs on its own computer and owns its own emotional program and database of thoughts; all four are networked. Occasionally, one character glances at another. That glance alters the state of the emotional engine in the other character according to a set of rules. "The spectator looking at them doesn't see the system in action, but when you walk close to each character's pedestal, you can hear their thoughts," Roberts says.

Another artist who has worked with Crutchfield is Gail Wight of San Francisco, who is developing a new electronic arts program at Mills College. Wight met Crutchfield while creating a piece for Turbulent Landscapes on biological self-organization in dictostelium slime mold. Biologists are fascinated with this species of slime mold because when a dictostelium cell is in danger of dying of starvation or thirst, it sends out chemical signals to surrounding cells—and they aggregate by moving in synchronized waves into a slug-like creature that forms a budding stalk, which explodes, sending spores flying to distant, and perhaps more hospitable, environments.

Wight was supposed to grow dictostelium as part of her Exploratorium installation, but the spores she was given were a different species (physarum) that only grows in tree-like structures and does not shift from individual cells to a multicellular organism—something she did not discover until after months of waiting for her slime cells to organize into traveling waves. The experience caused her to look at science differently, to question her implicit trust, and led to the way she now uses science in her work—by questioning it. "I started being very suspicious of my own infatuation with science," she said. "I began to wonder, how did we get to this place, this thing we now call science?"

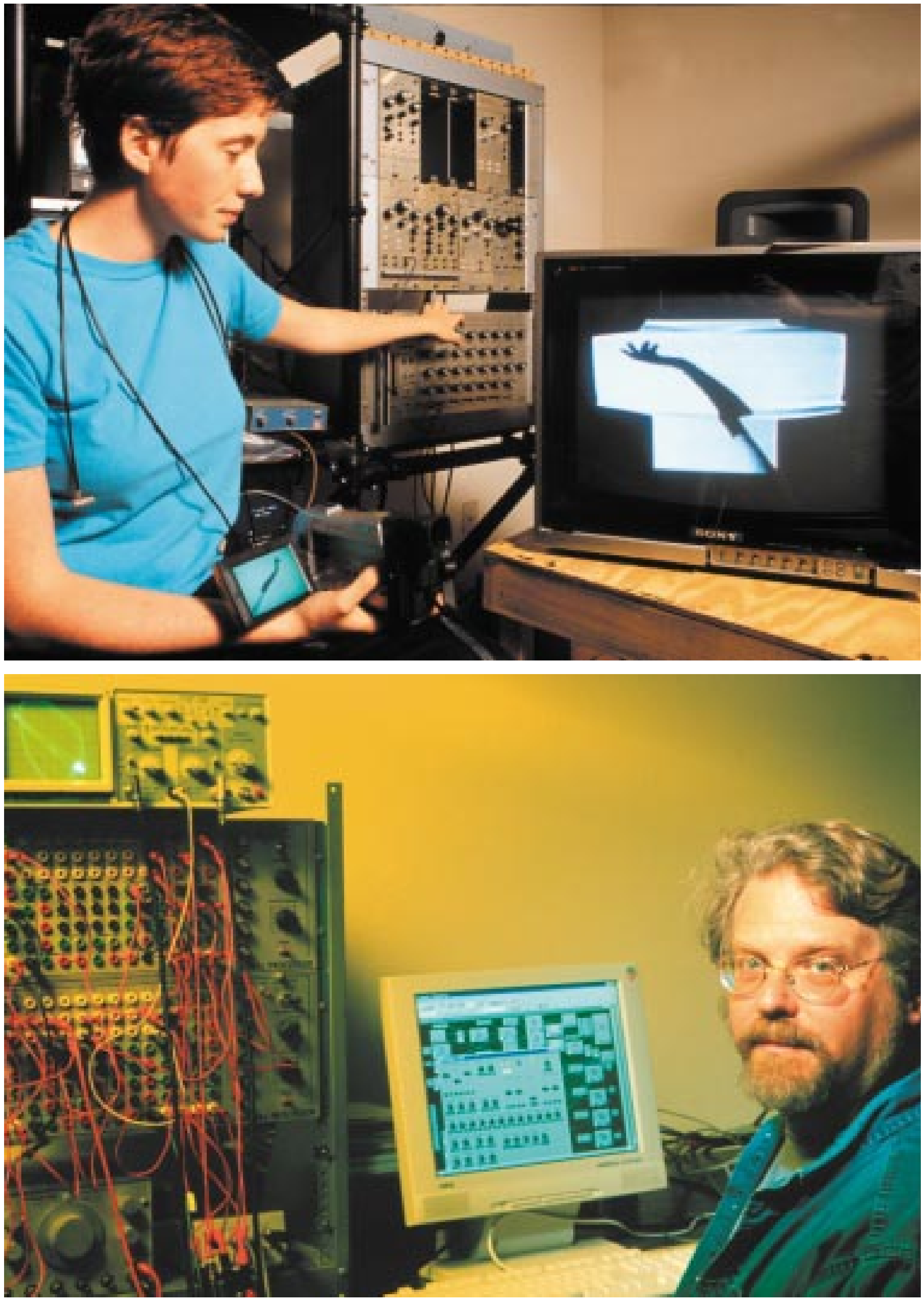
Her question is apparent in a later installation in which she put 50 mice in individual cages; their environments illustrated moments in the history of genetics. One was a portrayal of Mendel's pea garden. Inside the cage was a miniature pea garden, which, eventually, the mouse ate. Another cage illustrated the studies from which scientists concluded twins had little in common genetically—only to later realize that their own biases prevented them from recognizing the twins' shared attributes. One mouse in the twin pair had a tiny baby grand piano in his cage; he decided to sleep inside it. The other had a shabby upright piano; he ate the instrument.

Recently, Wight designed a similar installation; this one includes five tiny tableaux from history representing "how we came to conceive of ourselves as electrochemical entities." Of this exhibit, Wight said, "These tiny tableaux are sitting inside a square Plexiglas maze, and there's a rat that lives inside of it. The rat will hopefully eat away the tableaux. The rat is sort of the artist."

In the winter of 1998-99, Crutchfield organized a public lecture series in Santa Fe titled "Arts of the Artificial." Motivated by an interest in how art and science will determine the structure of "virtual spaces" created by networked computers, the series included talks by Gail Wight, Roberts, art critic Dave Hickey, and Rodney Brooks, director of MIT's Artificial Intelligence Lab.

The idea of the series was that public exposure to the thinking of those on the forefront of pattern discovery in art and science might inspire others toward similar inquiries. Putting artists and scientists together often causes each to recognize old things in new ways—that mysterious process of pattern discovery at which humans are so good.

Kahn was recently working on a geological installation that represents a slice through a volcanic landscape. Air is pumped up through two sheets of glass, fluidizing a powdery mixture, erupting to the surface and creating a caldera. "When I got this working I called this geophysicist, Raymond Jean-Luz, at (UC) Berkeley," Kahn recalled. "He was so into this thing he spent three hours just staring at it. He came back the next day with a graduate student and they spent all day staring at it. They were looking at something real. It reminded them of why they got interested in geology in the first place."



PHOTOS: DAN BARSOTTI

"Techne and Eros: Human Space and the Machine" drew participants from around the world. Above; student participant. Below David Dunn.

Kahn says looking at real phenomena prompts a different kind of thinking. "Your mind is working on a lot of levels. You're processing this visual information, and you're recognizing patterns, some so subtle you probably can't describe what you're seeing, but on some level aesthetically . . . there's an indication that there is an order in there."

That's similar to what Crutchfield experienced in the laboratory during his experiments on video feedback. These were not focused so much on the rich patterns generated by that system, but on the process of his own perception of those patterns. Eventually, this led him to develop a mathematical framework to describe the process of pattern discovery. He would be looking at the video monitor, thinking, "This pattern looks familiar...similar to something else I saw a few days ago," he recalls. "The empirical facts that I concentrated on were not images that appeared on the screen but the first intuitive impressions of regularity that occurred as I began to see new patterns."

One of the projects Crutchfield began recently involves magnetoencephalography (MEG), a new imaging technique that measures neural activity via magnetic signals generated by the functioning brain—a potentially more sensitive method than the more familiar electroencephalography (EEG). A clinician typically analyzes such data by visual inspection, that is, studying temporal information recorded on strips of paper or on a screen, and recognizing certain patterns within the data.

The problem is that the more sophisticated MEG machines, such as the 122-channel one at the Veterans Administration Hospital in Albuquerque, produce gigabytes of data in just a few minutes of recording from a subject, more data than a clinician could ever analyze by eye. What's needed is the ability to analyze such quantities of data for hundreds of people, over time, to identify norms and anomalies associated with illness. "Can we teach a machine to automatically discover patterns in such huge quantities of data?" Crutchfield asks.

In the past, human beings have been constrained by the limits of our physical world and our evolutionary heritage. Although it may not be possible for the human mind to perceive patterns in more than four or five

SPIRAL DESIGN GENERATED BY JIM CRUTCHFIELD. PHOTOS: PATRICK MCFARLIN, GAIL WIGHT dimensions, once trained, machines may be able to do it for us, Crutchfield says. Such pattern-discovery machines could become our proxies in worlds we cannot visualize. A more intelligent MEG machine would not only produce massive quantities of data, but also be able to recognize patterns in that data—and then point them out to us. Can Crutchfield and his colleagues teach machines to see patterns and regularities in high-dimensional spaces, for example, to analyze those mountains of MEG data? That's their goal.

Some of these ideas will no doubt be on the agenda of a new research facility just formed in Santa Fe. What's tentatively being called The Art and Science Laboratory will involve Crutchfield and pioneer electronic composers and artists including David Dunn and Steina and Woody Vasulka (founders in the 1960s of The Kitchen, an electronic art performance space in New York City). This core group—plus composer/electronic artist Morton Subotnik and composer/vocalist Joan La Barbara—presented a six-week series of workshops, "Techne and Eros: Human Space and the Machine," at the Santa Fe Art Institute this summer that drew students from around the world. A permanent exploratory science-arts facility in Santa Fe will offer them and others working in these loosely defined arenas a way to easily interact with the researchers at SFI and other institutions.

New machines that can think better than we can, communicate in languages we do not speak, in realms of which we cannot perceive—it sounds like science fiction. In fact, these are the characteristics of cyberspace, only the first of the novel non-physical/non-biological realms humans are creating. The inventors of these new, very social spaces should include artists as well as scientists and technologists, Crutchfield says. Why? Consider the innovation in magnetic materials that led to the small, powerful motors which drive Sony Walkmans. Now people the world over are running, riding the subway, racing through their ordinary lives while wearing the ubiquitous headphones attached to miniature music boxes. Science affects technology which drives culture, and culture indirectly determines the directions in which society chooses to invest scientifically.

"Shift that feedback loop into the new virtual spaces," Crutchfield suggests. Imagine that artists, as well as scientists, have primary input into the structure of such new realms. He adds, "It will be an entirely different world, one in which physical and biological constraints are markedly less dominant, and aesthetic choice and design are primary."

Hollis Walker is arts and entertainment editor at The Santa Fe New Mexican. *She was a Pew Charitable Trusts' National Arts Journalism Fellow in 1996-97.*

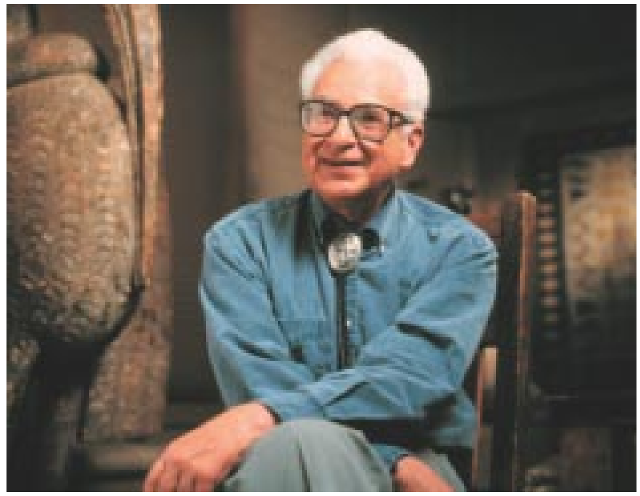


PHOTO:UURRAE HAYNES

MURRAY GELL-MANN AND THE CREATIVE PROCESS

SFI Distinguished Professor Murray Gell-Mann uses neckties as an easy way to talk about simplicity and complexity. "If you're looking at a pattern of a necktie and it's just regimental stripes, it's simple," he said. "But you've seen neckties with much more complex patterns." His point is that those complex patterns have regularities that it would take a long time to describe.

Gell-Mann's interest in questions of simplicity and complexity and their intersections with art led last fall to a forum co-sponsored with SITE Santa Fe called "Simplicity and Complexity in the Arts and the Creative Process." The forum brought together a number of scientists and artists in discussions at the Santa Fe Institute that culminated in a public presentation at SITE Santa Fe. Gell-Mann and his wife poet Marcia Southwick (whose latest book is *A Saturday Night at The Flying Dog and Other Poems,* Oberlin College Press, 1999) together organized the forum. Among the scientists attending were Chuck Stevens and Jim Crutchfield of SFI. Arts panelists included novelist Cormac McCarthy, architect Moshe Safdie, poet David St. John, and visual artist Joseph Kosuth.

Gell-Mann and Southwick also have attended recent meetings (along with others on the faculty at SFI) on connections between complexity and the arts in Abisko, Sweden and Catalina Island, California. Some of the topics explored at the meetings have included: regularities in the visual and musical arts that have counterparts in human brain function; the universal appeal of poetry; and measures of effective complexity in art.

Currently, Gell-Mann, with his assistant Marla Karmesin, is trying to compile a Digital Video Disk of material from the Santa Fe forum, including videotaped lectures, photographs of the art-objects shown, recordings and supplementary materials. The DVD will provide a jumping-off point for future discussions.

Hollis Walker

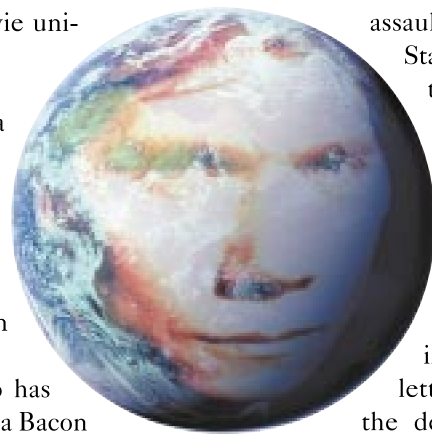
SFI Bulletin

Small-World Networks

DIE-CUT
art, do not print
this white circle

Kevin Bacon, the Small-World, and Why It All Matters

The Kevin Bacon Game is a curious thing to be sure. For those who don't know him, Kevin Bacon is an actor best known for not being the star of many films. But a few years ago, Brett Tjaden—a computer scientist at the University of Virginia—catapulted Bacon to true international recognition with the claim that he was somehow at the center of the movie universe. This is how the game goes:



- Think of an actor or actress.
- If they have ever been in a film with Kevin Bacon, then they have a "Bacon Number" of one.
- If they have never been in a film with Kevin Bacon but have been in a film with somebody else who has, then they have a Bacon Number of two, and so on.

The claim is that no one who has been in an American film, ever has a Bacon Number of greater than four. Elvis Presley, for example, has a Bacon Number of two. For real enthusiasts, Tjaden created a web site that provides the Bacon Number and shortest path to the great man for the most obscure of choices. In fact, Tjaden later fireproofed his claim by conducting an exhaustive survey of the Internet Movie Database, and determined that the highest finite Bacon Number (for any nationality) is eight. This may seem nothing more than a quirky fact about an already bizarre industry, but in fact it is a particularly clear example of a phenomenon that increasingly pervades our day-to-day existence: something known as the "small-world phenomenon."

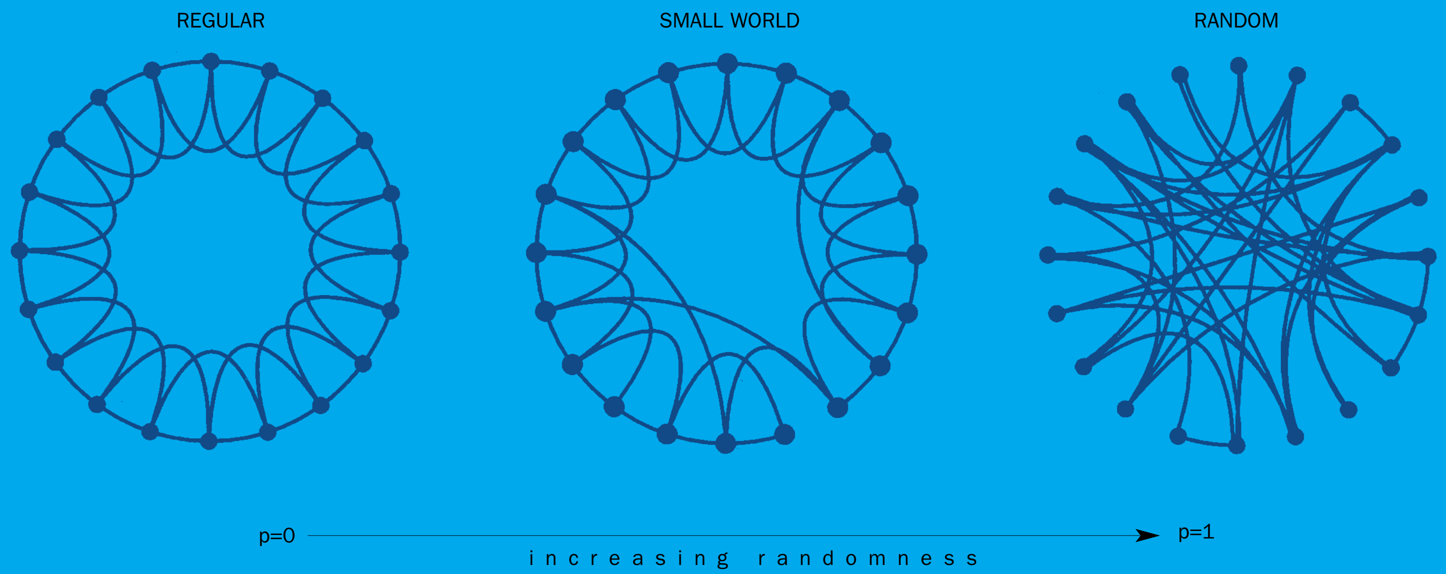
The small-world phenomenon formalizes the anecdotal notion that "you are only ever six 'degrees of separation' away from anybody else on the planet." Almost everyone is familiar with the sensation of running into a complete stranger at a party or in some public arena and, after a short conversation, discovering that they know somebody unexpected in common. "Well, it's a small-world!" they exclaim. The small-world phenomenon is a generalized version of this experience, the claim being that even when two people do not have a friend in common, only a short chain of intermediaries separates them. Stanley Milgram made the first experimental assault on the problem (confined to the United States) by sending a series of traceable letters from originating points in Kansas and Nebraska to one of two destinations in Boston. The letters could be sent only to someone whom the current holder knew by first name and who was presumably more likely than the holder to know the person to whom the letter was ultimately addressed. By requiring each intermediary to report their receipt of the letter, Milgram kept track of the letters and the demographic characteristics of their handlers. His results indicated a median chain length of about six, thus supporting the notion of "six degrees of separation," after which both a play and its movie adaptation have since been named.

This result was both striking and surprising and continues to be so today, because the conscious construction of such chains of intermediaries is very difficult to do. Ordinarily, our perception of the social world is confined to our group of immediate acquaintances, and within this group there is a great deal of redundancy; that is, within any one circle of acquaintances, most of them know each other. Furthermore, our average number of acquaintances is very much less than the size of the global population (at most thousands, compared with billions). So the claim that some very short chain of acquaintances exists that links us to any other person, anywhere in the world, does seem unlikely.

From *Small-Worlds* by Duncan Watts, Princeton University Press, 1999

Do we live in a small world?

Under what conditions can any network, social or otherwise, be deemed "small"? And if small-world networks can be shown to exist, what does this imply about the behavior of systems that are connected up that way? These questions, among others, have been the research focus of SFI Postdoctoral Fellow Duncan Watts and his collaborators.



This illustrates the random rewiring procedure for interpolating between a regular ring lattice and a random network, without altering the vertices in the graph. Three realizations of this process are shown, for different values of p. For p=0 the original ring is unchanged; as p increases the graph becomes increasingly disordered until for p=1, all edges are rewired randomly. For intermediate values of p, the graph is a small-world network—highly clustered like a regular graph, yet with small characteristic path length, like a random graph.

CLOSE CONNECTIONS

Networks are ubiquitous. The brain is a network of neurons. Organizations are networks of people. The global economy is a network of national economies, which are networks of markets, which in turn are networks of producers and consumers. Diseases and rumors both transmit themselves through social networks, and computer viruses propagate via the Internet.

Any kind of network can be represented abstractly by a graph, composed of nodes (or vertices) and a set of lines, edges, joining the nodes. The nodes represent, say, members of a population, and the edges, their interpersonal ties, business ties, friendships, etc. . . . Traditionally, however, networks have been modeled as either completely ordered or completely random. In an ordered network, like a crystal lattice, each node has the same number of edges that join a small number of neighboring nodes in a tightly clustered pattern. In a random network, each node is arbitrarily connected to nodes that can lie anywhere. Although ordered and random networks are in one sense extreme opposites, they share the common feature of uniformity; that is, locally each network "looks" the same everywhere, and this simplifies their analysis.

However, most real-world networks appear to fall somewhere in between the ordered and random extremes. Friendship networks are a good example of this in-between state. Since people meet most new friends through existing friends, the networks are locally ordered. (Here order means that if A knows B and B knows C, then A is more likely to know C than some other random element.) The outcome of local ordering in such a network is that one individual's friends are more likely than not to know one another: a characteristic that is called "clustering." Many real-world networks, including friendship networks, tend to be highly clustered, but they are not entirely so. If a person joins a club and meets new people or moves to a different city to take a job, new connections can form that are not ordered by the existing network.

In order to simulate this kind of intermediate system one might take an ordered network and deliberately introduce increasing amounts of randomness into it. Watts and Steven Strogatz, Watts' thesis advisor at Cornell University, took this approach, called "random rewiring" in order to explore more deeply what would happen to the properties of initially-ordered networks. For example, beginning with the graph of a 1D lattice (simply a ring of nodes, each connected only to its nearest neighbors within a specified radius) they began replacing near-neighbor edges with edges to randomly selected nodes chosen uniformly throughout the network.

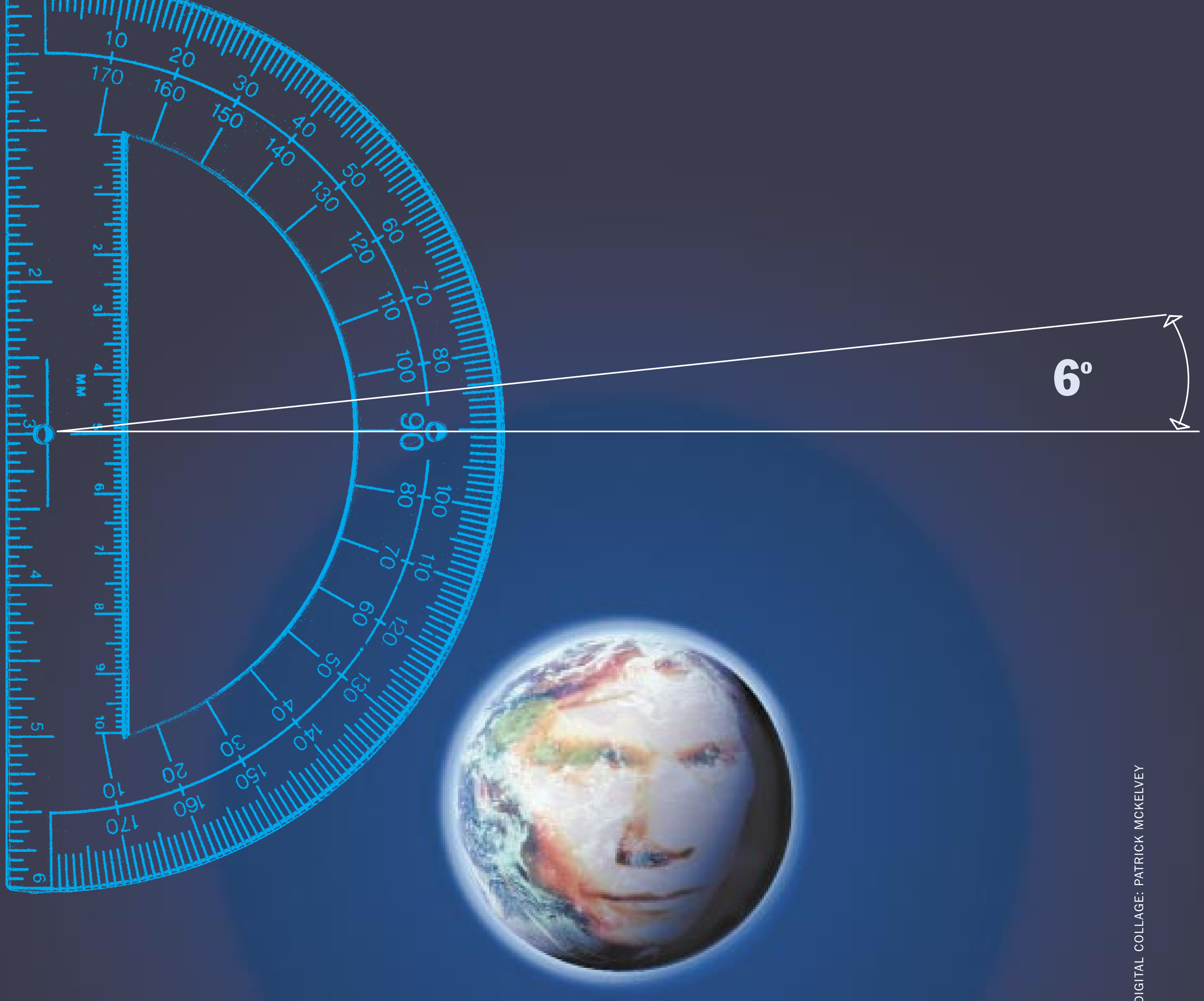
To understand the resulting networks, Watts and Strogatz computed two statistics. The first—the characteristic path length—is defined as the length of the shortest path (i.e., smallest number of edges) required to connect one node to another, averaged over all pairs of nodes. The second parameter—the clustering coefficient—measures the average probability that two nodes with a mutual "friend" will be connected, or in other words, the average cliquishness of local neighborhoods. According to these measures, lattice-like networks have long characteristic path lengths and large clustering coefficients, whereas random networks are "small" and exhibit very little clustering at all.

Studying intermediate kinds of networks led to the discovery that when just a few long-range, random connections replace the local edges of a lattice-like network, the characteristic path length decreases dramatically; a "shortcut" occurs. And while the first random rewiring has a great impact on path length, the clustering changes very little. Even when the separation of elements in a network is very small the clustering can remain almost as high as possible. This result is what Watts and Strogatz call a "small-world network." The name derives from the fact that it exhibits the short global separations that are typified (anecdotally) by social interactions while maintaining the high degree of clustering exhibited in most social networks.

REAL-WORLD NETWORKS, SMALL-WORLD NETWORKS

Idealized models like the one just described suggest that the small-world phenomenon might be common in sparse networks with many vertices, as even a tiny fraction of long-range shortcuts would suffice to make the world "small." But does it arise in the real world? Watts and Strogatz set out to check this, selecting three different real-world networks, for which all the data necessary to compute characteristic path length and clustering coefficient was available. The first system was a database of feature-film actors ordered by their appearance in different films; the second was the electric power grid of the Western United States; and the third was the neural network of the nematode worm *C. elegans*. As Watts and Strogatz wrote in a letter in Nature, "All three graphs are of scientific interest. The graph of film actors is a surrogate for a social network, with the advantage of being much more easily specified. It is also akin to the graph of mathematical collaborations centered, traditionally, on P. Erdos. The graph of the power grid is relevant to the efficiency and robustness of power networks, and C. *elegans* is the sole example of a completely mapped neural network."

Each of the three graphs turned out to be a small-



DIGITAL COLLAGE: PATRICK MCKELVEY

Empirical examples of small-world networks

	L_{actual}	L_{random}	C_{actual}	C_{random}
Film actors	3.65	2.99	0.79	0.00027
Power grid	18.7	12.4	0.080	0.005
C. elegans	2.65	2.25	0.28	0.05

Characteristic path length L and clustering coefficient C for three real networks, compared to random graphs with the same number of vertices (n) and average number of edges per vertex (k). All three networks show the small-world phenomenon $L \geq L_{random}$ but $C \gg C_{random}$.

world network. The scientists were careful to note that these examples were not handpicked. They were chosen for their inherent scientific interest and completeness of available data. What this research suggests is that the small-world phenomenon may be common for many large networks found in nature; it is not merely an artifact of an idealized model.

NETWORK STRUCTURE AND THE BEHAVIOR OF DYNAMICAL SYSTEMS

An obvious question that arises from these conclusions is: What impact might this phenomenon have on the dynamical behavior of a distributed system? Say we're looking at social structure: What is its role in generating globally observable, dynamical features in a social system? In general, if a set of relatively small changes to the edge set of a graph can have a dramatic impact on its global structural properties, might the same changes affect the behavior of dynamical systems that are coupled according to such a graph?

The question is far from straight forward. Even in idealized systems whose behavior offers a relatively clear interpretation, the relationship between structure and dynamics builds on more than one factor. One must consider network structure, as well as a whole literature of distributed dynamical systems, which again traditionally assumes that the relevant coupling topology is either completely ordered or completely random. However, Watts and Strogatz's work suggests that real-world networks may combine significant elements of order and randomness with resultant properties (like small-world connectivity), that cannot be captured by either traditional approach. Thus a realization about network structure suggests a new question for distributed dynamical systems: Do significant new dynamical phenomena emerge when the corresponding network is a small world?

SPREAD OF INFECTIOUS DISEASE

A very simple kind of distributed dynamical system is that of a disease spreading from a small seed of initiators into a much larger population, whose structure is described by some underlying graph. Typically, work on the spread of diseases focuses on populations in which complete mixing is assumed between elements. With this assumption, subsequent analysis of population structure can be ignored and only the relevant sizes of healthy, infected, and immune populations along with the rate of infectiousness need to be known.

Watts and Strogatz took a different approach, simulating the spread of an infectious disease on a simple small-world network model. At time t=0 a single infective is introduced into an otherwise healthy population. After one unit of time, the infective is "removed" (either because it dies or becomes immune) but in that interval it can infect (with some probability) each of its healthy neighbors. The process is then repeated until it reaches a steady state.

Their findings show three distinct regimes of behavior. In the first (for diseases with low infectiousness), the disease infects little of the population before dying out. In the second, a highly infectious disease infects the entire population regardless of its connective topology, but the time taken to reach this steady state varies dramatically as a function of characteristic path length of the network. (Shorter path length implies faster spreading of the disease.) For intermediate levels of infectiousness, there is some complicated relationship between structure and dynamics, which has not yet been completely characterized. Nevertheless, there is a clear correlation between critical infectiousness—the point at which the disease infects a macroscopic fraction of the population—and the amount of randomness in the network. Beyond those conclusions, not much more can be said. However, it is clear that for this dynamical system the attractor for the global dynamics does depend on the coupling topology.

In epidemiological terms, small-world networks imply that the level of infectiousness required for a disease to grow to epidemic proportions can be highly sensitive to the connective topology of the population. This may change our way of looking at social diseases, which are often perceived as confined to isolated subgroups of a population. The highly clustered nature of small-world graphs can lead one to believe that a given disease is "far away" when in fact it is very close. In other words, when looked at on a local level, the change in structure that causes the disease to spread much further and faster may not be observable by an individual who has access only to local information.

GAMES ON GRAPHS

While the spread of disease presents a relatively simple dynamical system, the question of cooperative behavior emerging among competitive agents playing a many-player game is significantly more complicated. Since disease is involuntary and mechanical, it is only on the edge of truly social behavior. However, human behavior as measured through games can bring up more complex behavior.

One such game is the Prisoner's Dilemma, which models a situation of two partners in crime who are captured and locked in separate cells between which they are unable to communicate. The dilemma concerns whether each prisoner ought to "cooperate" by remaining silent or "defect" by selling out their partner in order to reap a reward. This game acts as a model for many kinds of interactions (from common pool resource problems to international arms negotiations). The main focus is that essentially competitive agents need to overcome the temptation to exploit each other if they are to reap the rewards of reciprocal cooperation.

Some early and influential research on the subject was done by Robert Axelrod at the University of Michigan, who devised a computer tournament in which players (computer programs) using different strategies competed against each other. Axelrod found that the strategies that performed best did so not by exploiting the weaknesses of others, but by eliciting cooperation, thus allowing both sides to do well. A strategy known as "Tit-for-Tat" devised by Anatol Rapoport (on the basis of his observations of human behavior two decades earlier) emerged as the most effective. Its rules are simple: "Cooperate at first and then, on succeeding turns, do whatever the other player did on the previous turn." The trademarks of TFT—being "nice," "forgiving," "retaliatory" and "transparent"—emerged as generic markers for any strategy to be successful in a sufficiently heterogeneous environment.

	C	D
C	(3,3)	(0,5)
D	(5,0)	(1,1)

PRISONER'S DILEMMA

The conundrum of the Prisoner's Dilemma is captured in the chart above. Defection (D) yields either 5 or 1, and cooperation yields either 3 or 0. The rational decision is to defect. If both prisoners are rational, since they both have the same information, both defect, yielding a payoff of 1 each. If both prisoners cooperate—if both remain silent—both will earn a 3, a considerably better outcome than that generated by the rational action.

In much of the early work on the Prisoner's Dilemma, the population is treated as essentially structureless, a reasonable starting assumption, but not very realistic for large social systems. Lately, interest has emerged into the evolution of cooperation in the presence of population structure, but generally this work has focused on either one- or two-dimensional space. Watts and Strogatz, interested in this question, adopted a generalized version of Tit-for-Tat that could be used by players located on an arbitrary graph. In their version the formulation was entirely local; players could only react to the conditions within their immediate social and temporal neighborhoods.

Similar to the case with the spread of disease, Watts and Strogatz found three regimes of behavior in their simulation. For large h, where now the variable parameter is the average hardness (h) of players—the "harder" a player is, the more reluctant it is to cooperate. Regardless of population structure, cooperation always dies out; for sufficiently low h, cooperation always dominates, but the timescale depends quite sensitively on the fraction of shortcuts; and for intermediate h, how much cooperation succeeds depends on the fraction of shortcuts. What became clear throughout is that as the number of shortcuts increases, cooperation is increasingly difficult to sustain. This is due to the fact that cooperation in the Prisoner's Dilemma context requires that potential cooperators interact with each other preferentially. In this case, in a highly clustered graph, cooperators located in the same cluster can survive, even thrive, even within a noncooperative majority. However, the introduction of even a few shortcuts can weaken the cooperators' position. Those who believe in altruism will be happy to know that if the greater population is sufficiently predisposed to cooperate in the first place, then cooperation will spread much faster in a small world than in a large one.

For those seeking to optimize both the spread and sustenance of cooperation, the primary task is striking a balance between high clustering and speedy transmission. Since small-world topology exhibits both these features it may be truly useful to such an endeavor. However, the matter is not straightforward, even for this model, because for any given constant population structure, any change in the disposition toward cooperation (hardness) can tip the balance from rapid growth to rapid decline. Nevertheless, in the design of organizational structures, the idea of optimizing between clustering and length may be a useful concept.

NEXT STEPS

The work by Watts and Strogatz suggests that distributed systems can exhibit dramatically different behavior within the structural context of small-world networks. In fact, the research has set off a small avalanche among researchers in both the natural and social sciences to explore the implications of the small-world phenomenon. At the Institute, Watts and SFI Research Professor Mark Newman have been examining the scaling properties, phase transitions, and site percolation properties of small-world graphs. Another aspect of the phenomenon will be studied in a working group organized by Charles Sabel on using the intuitions from small-world dynamics to increase the effectiveness of organizations solving complex problems in rapidly changing environments. As Watts notes in one of his early papers on the subject, the notion of small-world connectivity "may have implications in fields as diverse as public health, organizational behavior, and design." The work has just begun.

Homo Reciprocans: Political Economy and Cultural Evolution

By Cosma Rohilla Shalizi

ART: HOLLY ROBERTS, "OLD DOG" OIL ON SILVER PRINT ON PANEL, COURTESY LEWALLEN CONTEMPORARY, SANTA FE

English-speaking social science, especially economics, is dominated by a tradition going back to Adam Smith and the other late 18th- and early 19th-century British political economists and historians of civil society. It focuses on individuals, and sees their acts and choices as primary. Larger entities—markets, states, institutions, cultures, and classes—are shorthand ways of speaking about patterns in the acts of many individuals.

Partly because they lend themselves to precise, mathematical expression, individualist theories have proven theoretically insightful, practically useful, and surprisingly powerful. They are also basically unrealistic. The standard individual economic agent, *Homo economicus*, has been called a "hedonistic sociopath." He also has no culture at all, and is far too smart. Nobody, not even exponents of "rational choice" theories, is much like *Homo economicus*, which is good for humanity, but bad for those theories.

There is another social science tradition, going back to Herder, Hegel, and other German contemporaries of Smith, which evades these problems by focusing on collective entities like cultures and classes: these entities, proponents say, are real, and they do things to people; indeed, they shape the people who belong to them in fundamental ways. This isn't much of an alternative, however, because it amounts to saying that cultural effects are produced by—culture. This is like saying that opium puts people to sleep because it possesses a "dormative virtue." This is a dilemma for social scientists: do they invoke incredible creatures like *Homo economicus*, or vacuous entities that don't really explain anything?

Though most find *Homo economicus* an implausible caricature of human behavior, for want of any replacement, he has had to do. However, one of the most exciting developments in the social sciences in recent years is the emergence of someone to take his place—called *Homo reciprocans* by Samuel Bowles, a professor of economics at the University of Massachusetts at Amherst and a member of SFI's coordinating committee for its Keck Foundation evolutionary dynamics program. Bowles described "reciprocans" during his talk "Social Organization and the Evolution of Norms" at SFI's May 1999 Science Board Symposium which focused on "Humans and Other Social Animals."

Perhaps the most striking way to introduce this character is with some results from experimental economics. Take public goods games: the experimenter gives his subjects some money and explains that they can choose, separately, how much to keep and how much to contribute to a common pool, which will be, say, doubled, to pay for a benefit in which all will share equally. The payoffs are such that contributing nothing maximizes one's individual gains. In such "collective action" situations, *Homo economicus* contributes nothing, and hopes to exploit everyone else. In real-life experiments, however, few, often less than a half of the subjects, start out doing this. When given the opportunity, experimental subjects can be surprisingly determined to punish those who cheated them, even at considerable cost to themselves. More surprisingly, this is true even on the last round of the game, when they couldn't hope that punishing the cheaters now would change their behavior in the future. *Homo economicus*, by contrast, realizes that punishing cheaters under these conditions is, like contributing to the common pool, a pure waste of money, and so refrains from doing so.

H. L. Mencken once defined conscience as "the inner voice that warns us somebody is looking," and social scientists and biologists have often interpreted apparently generous acts as self-interest in disguise. But consider the results of the "ultimatum game," with two players, an experiment that has been carried out in over one hundred studies in twenty countries with highly consistent results. The experimenter picks a player at random, hands him a wad of cash, and tells him to divide it between himself and the other player. The second player can either accept the offer, in which case they split the pot as agreed, or reject, in which case both get nothing. But *Homo economicus*, playing against another *economicus*, offers only one cent, which is accepted. Most people offer between forty and fifty percent, and routinely reject offers of less than a third, even in one-shot games (where there's no chance for retaliation), even when the pot amounts to several months' earnings. That people make large offers is striking enough, but what really rules out *Homo economicus* is that people reject quite substantial offers in order to punish others for not cooperating, even when it costs a lot to do so.

This suggests a very different view of what economic agents are actually like, and thus emerges *Homo reciprocans*. As Bowles puts it in an essay with his long-time collaborator and fellow U-Mass economist Herbert Gintis: "*Homo reciprocans* comes to new social situations with a propensity to cooperate and share, responds to cooperative behavior by maintaining or increasing his level of cooperation, and responds to selfish, free-riding behavior on the part of others by retaliating against the offenders, even at a cost to himself, and even when he could not reasonably expect future personal gains from such retaliation." This is certainly in line with empirical observations: people do produce public goods, they do observe normative restraints on the pursuit of self-interest (even when there is nobody watching), and they will put themselves to a lot of trouble to hurt rule-breakers.

PHOTO: BENN MITCHELL/IMAGE BANK

Besides the fact that typically there have been no other alternatives, another objection to abandoning *Homo economicus* is that he is, in his own way, a reliable standard. There is just one way of being a hyper-intelligent hedonistic sociopath, but there are at least as many ways of being someone mostly inclined to follow norms as there are norms to follow. A single, definite, unambiguous prediction is, for some, superior to an endless series of "maybe" and "it could be this norm…on the other hand it could be that one" predictions. There are two ways out of this, and Bowles, characteristically, takes both.

First, which norms a given group of people follow is a factual question, which can be investigated. For example, to see whether the results of the ultimatum game are uniform across very different types of societies, Bowles, along with anthropologist Robert Boyd, experimentalist Ernst Fehr, and Gintis, have organized field experiments of the ultimatum and public goods games in a dozen simple societies around the world, including some, like the Machiguenga in Amazonian Peru, with very limited exposure to markets and other modern institutions. (No noble savages have turned up so far: the Machiguenga, in fact, are the closest approximations to *Homo economicus* yet discovered.)

Second, norms do not vary in arbitrary and indefinite ways; there are certain patterns which appear to be common across societies. In experimental games, subjects explain their acts by saying that self-seeking behavior would not be "fair." Fairness need not mean equality, but inequality does have to be justified somehow. They must have reasons for it; a person may be rewarded for skill or effort; for virtue; or (a surprisingly common move) because they are more than human, at the very least a different and much better kind of human. (This is borne out by the experimental results: if, for instance, you get to be the proposer in the ultimatum game by passing some test, even a trivial one, you offer less, and the other player accepts less.) Even when norms allow for inequality, they still enjoin some reciprocity; the players accept mutual, if not equal, obligations.

Readers familiar with evolutionary psychology will remember the elegant experiments of Leda Cosmides and John Tooby on "cognitive adaptations for social exchange." They showed that most people can solve certain kinds of logic puzzles when the problem is phrased as one of detecting people breaking rules, even if those same people cannot solve formally identical problems which are presented abstractly or with different subject matter. This suggests that the capability for *reciprocans*-type behavior is something very deeply wired into our brains.

This only makes more pressing the question, which will have already occurred to readers familiar with sociobiology, of how (if at all) *Homo reciprocans* can evolve and sustain itself in a population which contains some exploiters. In the presence of such exploiters, natural selection will tend to eliminate organisms which engage in unprofitable behaviors, such as helping others or engaging in costly punishments. One of the standard theories of the evolution of cooperation between relatives evades this by postulating "assortative" interactions between kin—if organisms tend to interact with their close relatives, which carry many of the same genes, then altruistic behaviors can establish themselves, even in populations which contain many exploiters. Applying such reasoning to non-kin, one of Bowles and Gintis' most recent papers shows that *Homo reciprocans* could have evolved during the Paleolithic era in a similar way: reciprocators could have proliferated in a population, even if their fitness was reduced by upholding norms, so long as reciprocators were more likely to find themselves with other reciprocators in well-ordered groups capable of surviving bouts of material scarcity and attacks that norm-flouting groups could not endure.

Since norms differ from place to place and time to time (sometimes even within a single society at a single time), we would like a theory that explains what determines differences in norms. Such a theory would also help close a significant gap in current individualist models. They regard agents' preferences as "exogenous," as fixed, given—and inexplicable. The question is how to make them "endogenous," to bring them within our models?

The acquisition of norms and preferences (and other bits of culture) is an abiding concern for Bowles; his first book with Gintis, on the role of public education in modern America, was, precisely, a study of how people are acculturated, and a study of the ways in which what is learned is affected by economic circumstances. Acculturation is an individual-level process: we get it not from our culture, but from parents, siblings, other relatives, neighbors, playmates, colleagues, and, of course, teachers. Sometimes, as in formal schooling in developed countries, this is a very deliberate process, and people are taught certain skills, beliefs, norms and preferences, because these are economically useful. In other cases, there is a mutual influence between social and economic organization and culture: people are apt to imitate those who achieve social success.

This kind of "replicator dynamic" is actually easier to model than is deliberate instruction, using extensions of models from population biology originally developed by Marcus Feldman with Luca Cavalli-Sforza, as well as the related evolutionary models of Robert Boyd and Peter

Richerson. Individual rewards in such models are affected both by material circumstances and by economic and social organization—"who meets whom, to undertake which joint activities, with what payoffs and opportunities to acquire new traits," as Bowles puts it. This structure of social interactions, Bowles shows, controls the rate and direction of the differential replication of tastes, habits and norms, whether the replication is genetic, cultural, or some combination of both.

What happens when material circumstances and social structure change? In particular, what happens when those who follow previously accepted norms are liable to fail, whereas those who break them, who adhere to some other set of norms, may be seen to prosper? Such a situation is unsustainable; ultimately, either the norms have to change, or the material situation does. Because most people are merely *Homo reciprocans*, and not "rebels in defense of tradition," it's safe to bet on the norms changing, but this can be a lengthy process. One very common reaction, for instance, to introducing markets, trade, and a money-economy into societies which previously didn't have such institutions is to produce fringe groups of people who are "rootless"—cut off from the older social groups, much more given to the pursuit of individual self-interest. (Bowles' interest in cultural evolution was awakened by witnessing precisely such a sequence of events as a teacher in a remote part of Nigeria in the early 1960s: "What happened in two hundred years of European history unfolded before my eyes in the course of a couple of years.")

In highly marketized societies, careful, intelligent, competitive maximizers of personal gain, unfettered by sentiment or scruple, can do very well for themselves. Certain restrictions on competition are enforced (CEOs of other software companies can't have Bill Gates assassinated), but these have very little culture-specific content, and continual efforts are made to remove any lingering specificity. It's not so much that markets make people into *Homo economicus*, but that they present situations which evoke behavior that resembles his, and reward it. (In experimental Prisoner's Dilemma games, subjects tend to cooperate if the game is called "Community" and defect if it's "Wall Street.")

As Adam Smith knew, the institutions of the market can only work if many people (e.g., police, judges, parents, soldiers) do not, in the line of duty, act like *Homo economicus* at all, but instead act more like *Homo reciprocans*. Balancing two different, incompatible sets of norms—one for the marketplace, the other for the home, and for relations with friends and workmates—is not an easy task, and there is a natural tendency for the balance to tilt in one direction or the other, for the domain governed by one set of conventions to grow at the expense of the other's. Nobody really knows whether this will happen in our case, or whether we'll continue our uneasy impersonation of *Homo economicus*, or even whether we'll hit upon new rules. Bowles quite openly hopes for new rules more conducive to humans flourishing throughout the planet.

Bowles will coordinate a workshop at the Institute next January. "Coevolution of Institutions and Preferences" will bring together economists and other social scientists to discuss the dynamics of institutional and individual behavioral evolution. The goal is to understand how social interactions—defined by markets, intergroup bargaining, firms, and other economic organizations—shape the evolution of individual preferences, and in turn how these preferences shape the evolution, and in particular, the emergence of new economic organization. As part of the Institute's continuing program on evolutionary dynamics, Bowles is planning subsequent workshops including one on the role of group formation, the distinction between insiders and outsiders, and group extinctions in evolutionary processes.

Bowles' papers are available at
http://www-unix.oit.umass.edu/~bowles

PURSUING COMPLEXI-

PHOTOS: JULIE GRABER

PURSUING COMPLEXITY

The undergraduate interns toiling in SFI's offices this summer face an interesting challenge. Most of the institutions from which they come offer only limited course work in the area of complexity studies, and yet the students are hungry for knowledge of this approach. These undergraduates have chosen to explore this new science out of their own initiative and curiosity, rather than as part of an educational track laid before them.

So, what will they gain?

"We'll be prophets," said **Russ Tedrake**, jokingly, when the undergraduates convened for a roundtable discussion on an SFI patio overlooking Santa Fe. Russ is one of seven interns who is spending 10 weeks participating in this National Science Foundation supported annual Research Experience for Undergraduates (REU) program. Each undergraduate is matched with one or more mentors with whom they work on a research project; often these mentorships result in continuing collaborations.

Russ tempered his "prophet" joke by adding, "There are in fact quite a few at Michigan who have a broader perspective. I'll be one of them." Russ's experience in his undergraduate work has been different from many SFI undergrad interns. At the University of Michigan he benefits from the presence of such scholars as John Holland and Rick Riolo. "But all the complexity courses are graduate courses," he said, which means that even at an institution where complexity is a common word, courses are not immediately available to undergraduates. For this reason his experience at SFI has been rich. "It's opening my eyes," he said.

While at the Institute, Russ is working with SFI Postdoctoral Fellow Tim Hely attempting to further the results from a recent paper by Petr Marsalek, Christof Koch, and John Maunsell on the relationship between synaptic input and spike output jitter in individual neurons.

Looking enthusiastically around at the group, **James Brink**, a sophomore majoring in cognitive science, computer science, and mathematics at Indiana University, said his experience at his home institution has involved a considerable amount of complexity science. "A lot of issues we deal with here at SFI are touched on by people at IU. But there's not a complex systems department there. A few of the undergrad cognitive science programs discuss issues being discussed here, so I guess you could say it's not a unified program but is scattered around different departments."

Brink is working with Resident Research Professors James Crutchfield and Cris Moore, using classical inference techniques to attempt to give/reproduce the structure of data produced by a quantum source.

Meanwhile, **Jessica Kleiss** expressed a similar experience at her home institution. "At MIT I would say there are a lot of studies pertaining to complexity, but they're in small, hidden pockets," said this junior majoring in mathematics and atmospheric sciences with a concentration in physics. "You can't minor in complexity studies, but both the Media Lab and the Artificial Intelligence Lab deal a lot with complexity issues, and the math department does a good deal of nonlinear studies."

While at SFI, Jessica's mentor is SFI External Faculty Member Alfred Hubler from the University of Illinois. Their project involves studying the motions of a spring-mass system being fed through a viscous medium, like oil. They have found different states of motion, like waves, loops and kinks in the springs, and they're using the results to gain insight about fluid dynamics.

Next, **Amy Nelson** told the group how exposure to complexity science has unified her interests. She comes from Stanford University, where she's a junior majoring in philosophy with a concentration in metaphysics and epistemology. Since she encounters little exposure to complexity science at Stanford, she's eager to explore the approach during this summer experience. "I'm identifying patterns in areas I'm interested in and finding relationships that I might not have seen otherwise," she said.

Amy is also working with Tim Hely investigating the role of the synchronicity of neuronal firing rates in the perceptual task of feature binding. The project investigates the strategy of temporal binding in the selection and organization of information from highly parallel and distributed functional areas in the cortex.

The group sat silent for a moment as if pondering Amy's notion of unifying interests. Then **Matt Bell**, a sophomore at Stanford who is majoring in computer science and psychology, offered an interesting perspective on why complexity science isn't popular in computer science labs at his home institution. "For better or for worse, the computer science department at Stanford is closely tied to Silicon Valley. So most researchers are very concerned about applications. Consequently, there's little interest in research that does not have financial value. However, there is one course in genetic algorithms taught by John Koza."

While at SFI, Matt is working with SFI Research Professor Walter Fontana examining the evolvability of RNA structures, both in terms of understanding the evolution of RNA itself and as a framework for looking at evolutionary theory in general.

Next, **Hunter Fraser** told the group he'd heard about SFI from his father and then followed up with his own research. "When I told people in the Biology Department at MIT that I was coming to SFI, they thought I was weird. They thought I was going to study math for the summer," said this sophomore, whose interests include biological networks, the origin of life, and immunology.

His mentor is SFI Visitor Charles Sidman from the University of Cincinnati. They are exploring epigenetic interactions and how they may cause the genome to act as a complex nonlinear system in determining an organism's phenotype, instead of the traditional "one gene-one trait" idea of genetics.

clockwise beginning in the upper left: Hunter Fraser, James Brink, Amy Nelson, Jessica Kleiss, Roger Turner, Matt Bell, and Russ Tedrake.

Like Hunter, **Roger Turner**, a sophomore majoring in the history of science at Brown University, found SFI on his own, rather than through his home institution, and he's impressed with what he's experiencing. "It's exciting to see the nature of the place—all these people who majored in one field, got their masters in another, and their Ph.D. in another," he said. "Things have become so splintered in academia. People have one small thing they know about. But here we learn to see patterns. We can study them and apply them to different systems."

His mentor is SFI Visitor Douglas White from the University of California at Irvine. Roger is assisting with the Institute's secondary school computer modeling workshop. This workshop introduced high school students and teachers to the concepts of computer modeling using the Starlogo programming environment. He's also been studying how philosophical and ideological critiques of science, particularly feminist critiques, can suggest improvements in science education.

Roger's comment led the students to talk more about their experience as interns. In some ways they see SFI as a world without boundaries, both in terms of the concrete and the abstract. Many commented on the schedule at the Institute, where work goes on day and night. "You might come in at one a.m. and find all these people here talking," said Amy.

They were somewhat surprised that everyone eats lunch together. This allows the interns to converse with "major scientists." They are encouraged by this kind of freedom at the Institute. "You can even show up at someone's door and ask what they're working on," said Amy. "I'm struck by how people communicate across disciplines here. I've never seen people working and talking together to that extent."

This comment led to discussion about where the SFI experience might lead them. James said his time at the Institute will help him explore new areas when he returns to IU. "From this experience, I'll be inclined to talk to people from different projects."

Meanwhile, Russ introduced the question of getting too broad too fast. "I have a professor who would never have gotten broad until he got a grounding in one field. So while I'm here I try to listen to what people say and take away what relates to me, to what I'm interested in."

Jessica countered, "Some say in grad school you'll learn almost everything about almost nothing or almost nothing about almost everything."

Most of the group chuckled at this, while some nodded their heads.

"But the undergrad years are the best years to explore," said Matt. "It's then that you have a chance to get a general foundation."

Amy, the philosophy major, threw in a joke, "What I've been exposed to here has heightened my prospects beyond bartending when I graduate."

Everyone laughed at that one.

All of the undergraduates agreed their experience at SFI would expand their ways of thinking and help them design their own tracks into the future. Said Roger, "There's a wealth of interesting ideas flowing around here."

Lesley S. King

New Members Named to SFI Boards, External Faculty

PHOTO: DAN BARSOTTI

TRUSTEES

John Koza is a consulting professor in the Medical Informatics Section and the Electrical Engineering Department at Stanford University. He is president of Third Millennium Venture Capital Limited and of Genetic Programming, Inc. Koza is the author of numerous papers and serves on the editorial boards of *Genetic Programming and Evolvable Machines*, *IEEE Transactions on Evolutionary Computation, Evolutionary Computation*, and *Artificial Life*. He is the author of three books on genetic programming including *Genetic Programming III: Darwinian Invention and Problem Solving*, published this year.

Ford Rowan is a former NBC news correspondent and host of *International Edition*, a weekly program on public television. He is the principal author of *Crisis Prevention, Management and Communications* (1991). Rowan has written widely in the media and communications field, including articles on topics such as news ethics and information technology. Rowan has taught at Northwestern University's Medill School of Journalism and at the University of Southern California's Washington Public Affairs Center.

SCIENCE BOARD

Frances Arnold is professor of chemical engineering and biochemistry at the California Institute of Technology. Arnold received her Ph.D. in chemical engineering from the University of California at Berkeley in 1985. At Caltech, Arnold's group is applying state-of-the-art methods to address central issues in protein design and the evolution of enzymes and biosynthetic pathways. This research requires contributions from a variety of disciplines, including biochemistry, molecular biology, chemical engineering, chemistry, and applied physics.

Marjorie Blumenthal is executive director of the Computer Science and Telecommunications Board of the National Research Council, which is part of the National Academy of Sciences. One of the purposes of the Board is to foster interaction among computer science, computing and telecommunications technologies, and other pure and applied science and technology. Last year Blumenthal was a visiting scientist at the MIT Laboratory for Computer Science where she designed and taught a graduate seminar on computing and public policy.

Manfred Eigen, 1967 Nobel Laureate in chemistry, pioneered and remains a leader in the field of molecular evolution. His interests in biochemistry range from hydrogen bridges of nucleic acids, through the dynamics of code transfer, to enzymes and lipid membranes. Biological control and regulation processes, and the problem of the storage of information in the central nervous system also occupy his attention. In 1957 Max Planck Institute in Göttingen appointed Eigen a Scientific Member, where in 1964 he became the head of the Institute. In 1967, he was elected managing director of the Institute for a period of three years. At the same time he was appointed to the Scientific Council of the German Federal Republic. Eigen is recipient of numerous prizes in addition to the Nobel; these include Foreign Honorary Member of the American Academy of Arts and Sciences and the Linus Pauling Medal of the American Chemical Society.

Hans Frauenfelder is director of the Center for Nonlinear Studies at Los Alamos National Laboratory. During his more than 50 years of research in physics, Frauenfelder has moved through a number of different fields. He notes, "I started by studying nuclear energy levels, explored the surface effects with radioactivity, discovered perturbed angular correlation, helped elucidate parity violation in the weak interactions, used the Mossbauer effect, and finally began to investigate the physics of proteins. I find biomolecular physics as fascinating (or more challenging) than any other branch of physics and continue to do work in this field. One of my goals at the Center for Nonlinear Studies is to foster more interaction between theory and experiment, and increase work in biological physics."

Mimi Koehl is a professor in the Integrative Biology Department at the University of California, Berkeley. Her research involves the application of fluid dynamics and solid mechanics to the study of biological structure. The aim is to better understand basic physical rules that apply across taxa and to provide tools for understanding and predicting how organisms interact physically with each other and with their abiotic environments. Koehl's work places a strong emphasis on field work as well as on laboratory experimentation, and investigates structure and function on various levels of organization including tissue, organismal, and environmental.

Laura Landweber received her Ph.D. from Harvard University in 1993. Her area of study was biology in the Department of Cellular and Developmental Biology. She has been an assistant professor of biology in the Department of Ecology & Evolutionary Biology at Princeton since 1994. A recipient of a Burroughs Wellcome Fund New Investigator Award in molecular parasitology, her main 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. Her 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.

Harold Morowitz is Clarence J. Robinson Professor of Biology and Natural Philosophy at George Mason University. Morowitz became a Robinson Professor after teaching at Yale University as professor of molecular biophysics and biochemistry and serving for five years as master of Pierson College. The author of several books, Morowitz has written extensively on the thermodynamics of living systems, as well as on popular topics in science. In his current research, Morowitz is investigating the interface of biology and information sciences and continues his exploration of the origins of life. His books include *The Origin of Cellular Life: Metabolism Recapitulates Biogenesis* and *The Facts of Life* (co-authored with James Trefil). He is director of the Krasnow Institute for Advanced Study and editor-in-chief of the journal *Complexity*.

Mitchel Resnick is currently associate professor at the Media Laboratory at Massachusetts Institute of Technology, where he holds the LEGO Papert Chair. Resnick's research interests include the role of technology in learning and education, design of computational systems for nonexperts and children, decentralized systems and decentralized thinking, informal learning environments, and learning in virtual communities. Resnick co-developed LEGO/Logo, a computer-controlled construction set and PlayWrite, a reading/writing computer program. He also developed Starlogo, a programmable modeling environment designed to help students explore decentralized systems and self-organizing phenomena.

Shripad Tuljapurkar is president and chief scientist at Mountain View Research (MVR) a population-science research firm in California. MVR creates innovative tools for population forecasting. Tuljapurkar has a 1976 Ph.D., and has held faculty positions at Portland State University, the University of California at Berkeley, and Stanford University. His research focuses on uncertainty in human, ecological, and evolutionary processes. Tuljapurkar is author and co-author of numerous scientific papers and two books. In 1990, he was elected Fellow of the American Association of Arts and Sciences, and in 1996 received the Mindel Sheps award from the Population Association of America.

Two former members of the Institute's residential research community have become members of the SFI External Faculty:

W. Brian Arthur is Citibank Professor at the Santa Fe Institute and PricewaterhouseCoopers Fellow. From 1983 to 1996 he was Dean and Virginia Morrison Professor of Economics and Population Studies at Stanford University. He holds a Ph.D. from Berkeley in operations research, and has other degrees in economics, engineering and mathematics. Arthur was the first director of the Economics Program at the Santa Fe Institute in New Mexico; and he currently serves on the Institute's Board of Trustees. Arthur pioneered the study of positive feedbacks or increasing returns in the economy—in particular their role in magnifying small, random events in the economy. His current interests are the economics of high technology, the "new economy" and how business evolves in an era of high technology, cognition in the economy, and financial markets.

Melanie Mitchell received a Ph.D. in computer science from the University of Michigan in 1990. From 1992 to 1999 she was research professor at the Santa Fe Institute, and directed the Institute's program in adaptive computation. She is currently a technical staff member in the Biophysics Group at Los Alamos National Laboratory. Mitchell's research interests include intelligent systems and machine learning; evolutionary computation and artificial life; decentralized parallel computation in spatially extended systems such as cellular automata; and cognitive science, particularly computer modeling of perception and analogy-making, emergent computation and representation, and philosophical foundations of cognitive science.

OTHER EXTERNAL FACULTY MEMBERS BEGINNING TERMS ARE:

Elizabeth Bradley received her Ph.D. in electrical engineering and computer science from MIT in 1992. She is associate professor at the University of Colorado at Boulder, holding a joint appointment in the Computer Science and Electrical and Computer Engineering Departments. Her research interests focus on artificial intelligence, or computer tools that autonomously analyze and/or design things, and on techniques for characterizing and exploiting the unique properties of chaos. Bradley, currently a Packard Fellow, also holds the 1999 John & Mercedes Peebles Innovation in Teaching Award.

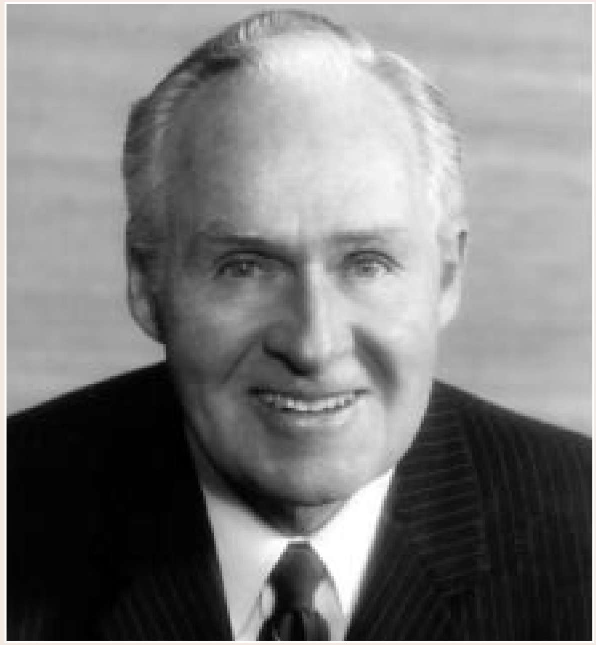
Stephen Lansing is Professor of Anthropology, Natural Resources, and Environment at the University of Michigan. Lansing's research has involved the study of the relationship between Balinese religious systems, farming, and human ecology. He has demonstrated that ideology has strong control over land use and other environmental factors on this island nation. In 1995, he was the recipient of the J.I. Staley Prize from the School of American Research for his book *Priests and Programmers: Technologies of Power in the Engineered Landscape of Bali*. He currently has a book in preparation titled *Ecology, Complexity, and Social Theory* for Princeton University Press.

University of Iowa economist **Scott Page**'s work involves the application of computational and complex systems methods to economics and political economy. Some of his work has focused on how models with interactive agents can illuminate political phenomena such as party platform characteristics and the advantages of incumbency. Page has also done research into diversity and problem-solving and is developing a theory of how different skills produce synergies that result in powerful aggregate problem-solving capacity. With John Miller, Page has been co-director of SFI's Graduate Workshop in Computational Economics since 1995, and he serves on the steering committee of the Institute's Fellows-at-Large initiative.

John Reinitz is associate professor at the Brooksdale Center for Molecular Biology, Mount Sinai Medical School. Reinitz performs both theoretical and experimental studies on mechanisms of segmentation genes expression during early Drosophila embryogenesis. The qualitative characteristics of segmentation genes expression patterns are used as variables in a dynamic model for genes expression pattern formation. The validity and utility of the model has been demonstrated by its successful application to several important problems of embryo development.

David Stark is the Arnold A. Saltzman Professor of Sociology and International Affairs and chair of the Department of Sociology at Columbia University. Stark is currently doing research on new organizational forms among firms in Manhattan's Silicon Alley. In postsocialist Eastern Europe, he studied how interfirm networks facilitated and impeded economic restructuring. His recent publications include *Heterarchy: Distributed Intelligence and the Organization of Diversity*, forthcoming from Princeton University Press. *Postsocialist Pathways: Transforming Politics and Property in Eastern Europe*, with Laszlo Bruszt, Cambridge University Press, is a comparative study of the opportunities and dilemmas posed by the simultaneous extension of property rights and citizenship rights.

Andreas Wagner is assistant professor in biology at the University of New Mexico. Wagner received his Ph.D. from Yale University in 1994. Following fellowships at the Institute for Advanced Study in Berlin and then with Leo Buss at Yale, Wagner was a postdoctoral fellow at the Santa Fe Institute from 1996 to 1998. While at SFI Wagner pursued research projects on the evolution of genetic redundancy and developed mathematical and computational techniques for the analysis of whole genomes. His SFI redundancy work rests on a population genetics model based on the fact that redundancy provides protection against deleterious mutations. Within this framework he was able to show that selection cannot only maintain but increase genetic redundancy in large populations.



MOTOROLA'S GALVIN TAKES SFI POST

Robert W. Galvin was named chairman of the Santa Fe Institute Board of Trustees at its May 1999 meeting. Galvin started his career at Motorola in 1940. He held the senior officership position at the company from 1959 until 1990, when he became chairman of the Executive Committee. Currently, he serves as a full-time officer of the company.

Galvin attended the University of Notre Dame and the University of Chicago, and is now a member and was the recent chairman of the Board of Trustees of the Illinois Institute of Technology.

He has been awarded honorary degrees and other recognitions, including election to the National Business Hall of Fame and receipt of the National Medal of Technology in 1991.

Continuing as vice-chair of the Board is Robert J. Denison, founder and chairman of First Security Management, Inc.

Galvin and Denison replace David Liddle and Robert Maxfield who have served as chair and vice-chair since 1994. Both Liddle and Maxfield remain on the Board of Trustees.

"I shall always be grateful to David Liddle and Bob Maxfield for their help in moving SFI forward," said SFI President Ellen Goldberg at the May meeting. "I look forward to their continued involvement as active members of our Board.

"I am delighted that Bob Denison has agreed to continue on as vice-chairman of the Board. His knowledge of fiduciary issues provides all of us with sound advice, and his breadth of knowledge in a number of fields provides the Institute with a wonderful resource for counsel.

"As to having Bob Galvin agree to become chairman of the Board, I am truly thrilled. He is a visionary who will help move SFI to new heights. I look forward to continuing to work with the entire Board of Trustees, and I thank all of the members for their commitment to SFI. Their guidance has been and continues to be very much appreciated."

Language Issues

BY KEN BAAKE

ILLUSTRATION: G & V CHAPMAN/IMAGE BANK

Issues of language surface frequently at the Santa Fe Institute, where discussions among members often lead to debates about word meaning. One of the biggest challenges in this arena is finding words and metaphors that can stimulate productive scientific thinking without distorting that thinking.

Dynamic new concepts are constantly emerging at the Institute. Just ask librarian Margaret Alexander about her list of scientific "buzz words" that she uses when shopping for books to add to the library. The list is always changing, she says.

The word "complexity," one of the central concepts at the Institute, presents possibly the biggest definition challenge. A number of scientists acknowledge that they do not really know what it means. The apparent vagueness of the term, however, may be what makes it so valuable as a catalyst for thought. A word like complexity is new and unresolved; it is not an inert tool of scientific description, but rather an idea whose meaning evolves as it interacts with researchers.

SFI President Ellen Goldberg says that complexity involves "interacting parts with very simple rules," but she is quick to add that the term does not reduce to a constant definition across disciplines. For that reason Goldberg likes the term; it is flexible and permits multiple definitions. Former SFI president George Cowan also accepts the polysemantic nature of the word. "Its chief value is that it embraces a number of possible systems," Cowan says.

The definition challenges increase when you bring metaphors into the rhetorical equation. Language scholars define metaphor in various ways, but most say that it is a rhetorical device for transporting knowledge by using a word that brings connotations from one field into play in another field. The word has at its roots the Greek word "phora," which means locomotion. SFI theoretical chemist Walter Fontana explains the power of such locomotion in SFI science. "Metaphor makes people realize that certain old questions can be cast as new ones. It triggers new thoughts and speculations."

It can also trigger a lot of discussion. Take for instance the public lecture by Indiana University political scientist Elinor Ostrom at last summer's Integrated Themes Workshop. Ostrom used a game theoretical approach to look at public policy questions. She examined the ways in which a community decides public policy, such as the allocation of irrigation rights among farmers.

Much of the question and answer portion of her talk concerned debate over the word "rules," a term Ostrom used to describe how members of the community would interact with each other and what policy decisions they would make. But one researcher questioned the use of the word "rules" because it implies legal regulations, while much human interaction has nothing to do with laws, he said. Clearly, the semantical debate centered around the specific use of language in different scientific disciplines. As Ostrom explained later, "rules" for biologists might be observed regular behavior or strategies, while "rules" for political scientists might be enforceable laws agreed upon by members of a group.

But terminology can be problematic even when confined to a single scientific discipline. Theoretical biologist Michael Lachmann calls attention to the term "signaling" in biology as an example of a metaphor that is rich, but also defies precise definition. What does it mean when we say a yellow bee is signaling that it is dangerous to eat? "Does that mean that a brown bee is not dangerous to eat?" Lachmann asks. Signaling implies an intentionality on the part of some living agent, but the bee's color is purely the product of evolution. Can we use a metaphor like signaling, with all its connotations of intentionality, to refer to a DNA-coded process? "Who intends the bee to be yellow?" Lachmann asks.

The good news is that such questions lead to further exploration. SFI scientists are constantly stretching terms to help explain new insights. For example, theoret-

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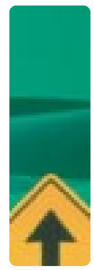
ical chemist Walter Fontana has taken the common word “neutrality” and used it to argue that the genetic code underlying a compound such as RNA (ribonucleic acid) can change frequently without affecting the performance of the compound—until at some point the compound seems to “suddenly” evolve to a higher level of performance. Such “neutral” changes of the underlying genetic sequence make evolution possible, Fontana says.

Still, Fontana acknowledges that the neutrality may only be temporary; eventually the compound evolves. So, it seems appropriate to ask if a change can be called “neutral” when it has no apparent immediate effect on a compound or an organism, yet over time, in combination with other changes, it leads to a profound impact. Again, it is obvious that when scientists struggle with word meaning they often are led to new insights—and new questions.

Fontana’s research has piqued the interest of social scientists affiliated with SFI who are considering whether seemingly unimportant “neutral” events in human history and human economies could have major consequences over time. The neutrality concept also may apply to present-day business. Suppose you are a chief executive officer who wants to reorganize your firm, Fontana says. You know that a successful reorganization would require a lot of small changes affecting the way employees go about their jobs, but you have no way of knowing in advance the best combination of changes to make. Neutrality suggests that you can make small changes gradually—even in an uncertain environment—without risk that you will sink your firm.

Clearly the way scientists stretch metaphors and other terms helps elucidate ideas. But metaphors can lead to distortions as well by spawning unintended connotations that influence society far beyond the intention of those scientists who developed the metaphors as aids to cognition. Einstein’s concept of relativity, for example, has rippled beyond the confines of physics and cosmology into the world at large, where some might argue that it has reinforced a moral relativism in Western society. SFI physicist Cris Moore presents another example—the metaphor of genetic mapping, which implies a certain determinism that could possibly lead to social eugenics.



Metaphors are so powerful that they can paralyze a researcher who becomes so enamored of a term that she or he loses the flexibility to see the world outside of the frame of the metaphor. As Fontana says, “You fall in line with ideas and then you become brittle.” For example, Moore notes that metaphors imported from biology into economics may distort impressions of the economy by making it seem more natural than it really is. “The economy isn’t a jungle,” Moore says. Economic systems have governments, which are not present in the rain forest.

Other times the metaphors are so catchy that they imply quick-fix, real-world applications for a particular theory that cannot be delivered, at least not in the short term. Suzanne Dulle, SFI director of business relations and external affairs, says that the language of complexity has flooded the popular business-book press, leading to an expectation among some business people that they can spend a few days at SFI and come away knowing how to save their company money. Some business managers hearing about self-organization have asked half-seriously if they should step aside and let the company run on its own, Dulle says.

Metaphor is a major rhetorical focus at SFI, but it is not the only one. Other problems involve researchers having to modify their speaking and writing according to the needs of a lay audience. One of the most difficult rhetorical challenges scientists face when explaining their research to the lay public comes in answering the question, “And so what?” Dulle notes. People often wonder what the research means to their lives, to the world at large.

SFI scientists also face a unique challenge when writing to an audience of specialists in another field. At times they’re frustrated when trying to publish their results in scholarly journals that may not be receptive to the unique and almost poetic language of complexity science. For example, economist graduate researcher Shareen Joshi says she often uses concepts like “the edge of chaos” when envisioning the economy in her mind, but she would never use such terms in a journal article.

Joshi’s compromise with eloquent language reveals the true essence of metaphor as a midwife of knowledge. Metaphor can open the researcher’s mind to fresh scientific insights that might remain occluded without the powerful cognitive “locomotion” that metaphor entails. Yet, because metaphor is so powerful and perhaps intrinsic to human cognition, it also carries the dangers inherent in any powerful tool; metaphoric language can distort the truth and imply a greater sense of scientific certainty than the results of rigorous scientific exploration would support. Most at SFI seem willing to accept this paradox; they know that the benefits outweigh the risks.

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