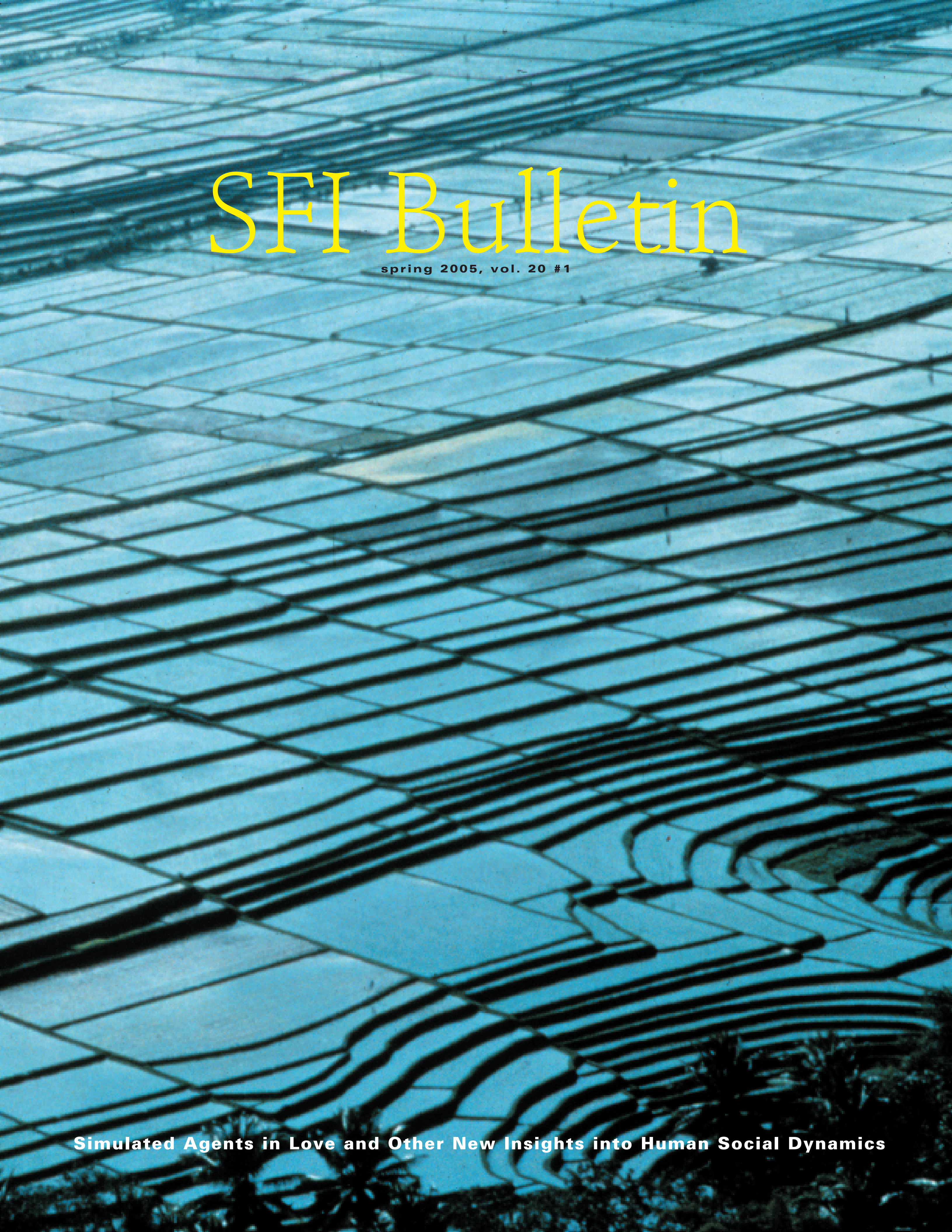

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Simulated Agents in Love and Other New Insights into Human Social Dynamics

Santa Fe Institute Bulletin

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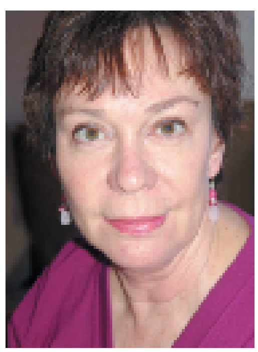
Editor's Note



SFI's founding president, George Cowan, reminded me recently that a goal of the Institute from the very beginning has been to foster better understanding of human behavior. In this spring 2005 issue, we feature two articles about current SFI work to that end. The projects described—far-flung both geographically and topically—have a common element so far as each brings the rigor of a quantitative approach to the social sciences domain.

In Bali, SFI researcher Steve Lansing is looking at how behavioral factors such as language, cultural rules, and ways of economic production affect genetic relatedness within a population. His provocatively named computer mode—Simulated Agents in Love (SAIL)—supplements the fieldwork. External Faculty member Hillard Kaplan and colleagues study the Tsimane, a hunter-gatherer society in Bolivia. Linking medical information with data on cultural norms, diet, housing, and social networks, his team is gaining a cultural/epidemiological understanding of the group's health and aging patterns. This information may shed light on foundational relationships between human life span and culture. In other work, Sam Bowles uses mathematical models and statistics to explore the links between genetics and giving behavior. Marc Feldman's study of the genetic structure of human populations suggests that, particularly for medical purposes, racial categories may not be the best way of grouping people.

Of course even with the use of quantitative tools, linking behavior to genetics remains remarkably complicated and often problematic. That's where SFI's multifaceted approach comes in. Looking at the evolving behavior of individuals in the context of their social, biological, and cognitive underpinnings, as well as their natural and social environments, should help us fathom that most complex of adaptive agents, our fellow human.

GINGER RICHARDSON

SFI Bulletin Spring 2005

New Ways of Viewing the World

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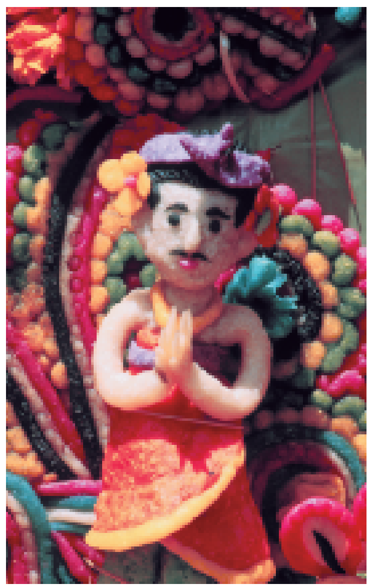
Gregor Mendel, Meet Florence Nightingale, and Other Wonders of the Nature-Nurture Debate

By Lesley S. King

In the terraced rice paddies and the hilly forests of Bali, Indonesia, a history is being unveiled. It's the story of migrations, love and marriage, and of toiling to feed families. In short, it's the history of a people on an island. But this is told not by archaeological artifacts as is often the case. Instead it's written in the DNA of its characters, in the chains of genes that make up their physical bodies.

This is only one of a number of stories being uncovered at SFI as part of its Behavioral Sciences Initiative, an initiative that brings together researchers from many fields to help understand behavior. In this case, scientists are looking at various ways that genetics, the science pioneered by Gregor Mendel, can separate inherited factors from environmental ones, thereby helping to understand behavior's many facets. The studies are, as SFI founder George Cowan notes, "bringing the rigor of more measurable sciences to the study of social sciences," which was one of SFI's initial goals.



Demi Nini, the rice Goddess and Her Consort formed from the first cuttings of rice at the upstream edge of each farmer's field, Bali

PHOTOS: J. STEPHEN LANSING AND UN/DPI PHOTO

SFI Researcher and Professor of Anthropology at the University of Arizona Stephen Lansing is in the forefront of the research. Building on 30 years of study in Indonesia, Lansing and his colleagues are now embarking on a quest to "build a new microscope and aim it at the emergence of patterns of social structure through time." To begin with, they're comparing the genetic relatedness among farmers in rice-growing areas (where cooperation is an engineering necessity) with those who farm the highland forests (who tend to be much more independent). By doing so, they hope to track how "ecological feedback can influence social structure, and note how these processes leave recoverable traces in population genetic structure."

Zero in on a single village in Bali where, uncharacteristically, half the residents live by means of irrigated farming, while the other half live by farming open patches in the surrounding forest highlands. Lansing has already noted different marriage practices in the people within this village. "There are quite different patterns," he says. The relatedness among community members in the irrigated farmers is tighter. That's because they marry each other and stay put. They have to cooperate, whereas those growing rice in the forests are less permanent and less cooperative. Through the passage of time, such differences in behavior may leave traces in the non-coding regions of the farmers' DNA.

But patterns of relatedness within communities can be affected by many factors, including marriage rules, migration, language drift, and historical changes in the modes of production. Is it possible to disentangle these processes? In true SFI form, Lansing is using computer modeling to aid in the research. Utilizing SAIL (Simulated Agents In Love), he can create a population of agents, give them marriage rules and DNA, let them mate, and see how the patterns of relatedness change over time. "We can look at marriage rules, migration patterns, and population size and see what effect those have on relatedness," he says. "We can simulate what might have led up to the patterns we see in the data."

This project brings together specialists in many areas: geneticists Michael Hammer, Tatiana Karafet, and Herawati Sudoyo; linguists Sergei Starostin, Ilia Peiros, and Joel Kuipers, and theoreticians Joseph Watkins and David Krakauer. The team has already obtained samples of dialectical variation from nearly 200 villages in the islands of eastern Indonesia. The next step is to work with a team of Indonesian geneticists and medical doctors to obtain DNA samples from communities in the region. The data will also be used for medical research on diseases such as malaria and thalassemia.

The outcome of such research may have broad implications. Indonesia is an ideal microcosm within which to look at the way behavioral elements such as language, cultural rules, and modes of living affect patterns of relatedness because each island encodes a different history. The archipelago was colonized by Austronesian-speaking farmers and fishermen about 5,000 years ago. Since then, the island cultures have developed in different ways. It may be possible to reconstruct not only the broad outlines of their histories, but also the ways their communities and languages changed over time, and whether these changes had different effects on women and men. If the project turns up clear patterns of association, they can be tested in other regions of the world.

In December, Lansing gave a lecture in Jakarta about the first results from this project, which focused on Bali. The story merited a full page of coverage in Indonesia's leading newspaper, and led to offers of assistance from Indonesian geneticists, archaeologists, and linguists.

THROUGH THE PASSAGE OF TIME, SUCH DIFFERENCES IN BEHAVIOR MAY LEAVE TRACES IN THE NON-CODING REGIONS OF THE FARMERS' DNA.

Gold Mines and Giving

It seems odd that the subject of "giving" would be controversial, but it is. It wreaks havoc in our nation and in our hearts. How much of our tax dollars should go to poor or struggling nations, to support war, to keep peace? How much time or energy should we give to our jobs, our families? How much money to charities? And how much should we get in return? On the dusty rural landscapes of South Africa, a network of giving and receiving has formed among people with difficult lives. The network tells a story of duty, charity, and love, helping explain the nature of "giving."

From an evolutionary perspective, the notion of "fitness" provides insight into understanding this activity. When animals feed their offspring, they perpetuate their genetic makeup, enhancing what biologists call their "inclusive fitness." Does inclusive fitness explain giving among household members? SFI Researcher Samuel Bowles and his colleague, Dorrit Posel, Professor of Economics at the University of KwaZulu-Natal, believe it does, but only in degree. They are studying migrant workers in South Africa, mostly those who spend long periods of time away from their families while toiling in gold mines. The migrants send substantial amounts—called remittances—home to their families, typically amounting to about half of their urban wage.

Bowles and Posel wanted to know: Do they send more if they are more closely related genetically to their household of origin? Their households are large and genetically heterogeneous and thus a good study group. Some of them contain no blood relatives of the migrant (his wife, and her siblings, for example) while others are closely related (his children, his parents, or his siblings).

Through the use of mathematical modeling and statistical testing, the researchers have found that genes do influence the way people give, but they provide only part of the explanation. Referring to the hypothesis that people favor close kin, Bowles and Posel write in a paper appearing in *Nature*, "Data on remittances sent by South African migrant workers to their rural households of origin allow an explicit test, the first of its kind for humans." The researchers employed a number of factors in their model. They used estimates of the fitness benefits and costs associated with the remittance; they took into account the genetic relatedness of the migrant to the beneficiaries of the transfer; and they factored in the beneficiaries likelihood of contributing to future gene pools based on their age and gender. Thus they were able to estimate the level of remittance that maximizes the migrant's inclusive fitness.

They've shown that, "Yes, the migrant worker will give more at a cost to himself if that giving will benefit his own genes," says Bowles. "But the effect is modest," they write. "Less than a third of the observed level of remittances can be explained by our kin-altruism model." In fact, the migrants give much more than they'd give considering only genetic relatedness.

"Nobody thinks that people are trying to spread their genes here," says Bowles. "The motives for giving include love, obligation, and investing in future family ties." But these motives induce people to behave as if they cared about spreading their genes.

Other factors come into play here, such as the presence of a wife. A wife is not genetic kin, but, Bowles and Posel write, the wife's presence in the household may increase remittances both for inclusive-fitness reasons (she cares for the migrant's children and may bear more children) and due to altruistic motives toward non-kin. But Bowles notes that while the wife's contribution to inclusive fitness helps explain remittances, most of the "wife present" effect cannot be explained this way. "Maybe they simply love their wives," says Bowles. Maybe so, but this raises the question: Why are we so nice to people who are not our kin?

The study dovetails nicely with recent experimental work done by Bowles and by SFI Vice President for Academic Affairs John Miller and SFI External Faculty member Ernst Fehr. These experiments—done anonymously and with real money—have been carried out not only on psychology majors and other students, but also (by Bowles and his colleagues) on hunters and gatherers and in other "small scale societies" around the world. The experiments show that people are often generous to total strangers, and are willing to pay to punish those who treat others unfairly.

Cynics like to say that we are born selfish. Recent empirical research – the South African migrants, the experiments on students, hunters and gatherers, and others—suggests a quite different picture. Even though people differ a lot across cultures and situations, and can be influenced by self-interest, they are nonetheless often civic minded even towards non-kin. Says Bowles, "We should think of designing public policies and shaping organizations to bring out the best in people while guarding against the selfish types, rather than just assuming the worst about everyone."

THE RESEARCHERS HAVE FOUND THAT GENES DO INFLUENCE THE WAY PEOPLE GIVE, BUT THEY PROVIDE ONLY PART OF THE EXPLANATION.

Sickle-Cell Disease and Unity

Another exploration of the nature–nurture debate spans across regions as disparate as Africa and the Mediterranean and explores not how behavior affects genes or genes affect behavior, but how best to behave toward genetic patterns. SFI Science Board member and Stanford geneticist Marcus Feldman and colleagues are helping penetrate the mystery of unity in human genetic makeup. They've shown that in terms of racial categories, humans are more similar than was suspected.

In a study of the genetic structure of human populations, Feldman, working with colleagues Noah Rosenberg and Jonathan Pritchard, both alumni of the SFI Summer School, looked at the genetic makeup of 1,056 individuals from 52 populations and found that people are less different than one would think. Generally, race has been defined by phenotypes such as skin color, facial features, and hair type, but these data show that "the within-population component of

SO FOR THE VAST MAJORITY OF THEIR DNA, AN AFRICAN OR ASIAN PERSON IS AS SIMILAR GENETICALLY TO A CAUCASIAN, AS A CAUCASIAN IS TO HIS CAUCASIAN NEIGHBOR.

genetic variation, estimated in the study as 93 to 95 percent, accounts for most of human genetic diversity. Thus most genetic diversity occurs within groups, and very little is found between them." So for the vast majority of their DNA, an African or Asian person is as similar genetically to a Caucasian, as a Caucasian is to his Caucasian neighbor. Of course, the picture is more complex than saying we're all one, but their point is, that particularly for medical purposes, racial categories are not the best means of grouping people.

Writing about this finding in *Nature*, Feldman and colleagues Richard Lewontin and Mary Claire King state that ancestral genetic data are far more useful. They cite sickle-cell disease as an example. Often thought to be an African disease, tendency toward it is actually tied to ancient ancestry in a geographic region where malaria was endemic. Africa is one region, but so are the Mediterranean and southern India. Thus people whose ancestors come from those areas might be more prone toward the disease. "To use genotype effectively in making diagnostic and therapeutic decisions, it is not race that is relevant, but both intra- and trans-continental contributions to a person's ancestry," they write.

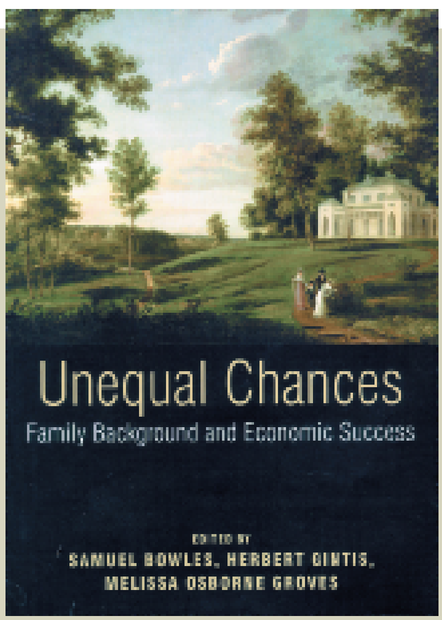
The findings have many ramifications. "The assignment of a racial classification to an individual hides the biological information that is needed for intelligent therapeutic and diagnostic decisions," the group writes. They note that a person classified as "black" or "Hispanic" could have a mixture of ancestors when looking at his or her continent of origin. "Confusing race and ancestry could be potentially devastating for medical practice," they say. They hope that, when treating diseases with genetic influences, their findings will lead to an understanding that all contributions to a patient's ancestry might be relevant.

Feldman also hopes that the findings affect the way disease is studied as well. He explains that today many research dollars are funneled into understanding dis-

Equality and the Lack of It

By Lesley S. King

In recent months, SFI Researcher Samuel Bowles has been causing a stir. He's appeared on National Public Radio and his research has been cited in *The New York Times*. The attention is because of ideas he and colleagues are presenting in a new book titled *Unequal Chances – Family Background and Economic Success* (Princeton University Press, 2005), which presents the results of a workshop held at SFI. The findings ought not to surprise anyone, but somehow they tear into the very heart of America's self-love: Bowles' research is revealing that America



isn't the land of equal opportunity after all.

He delivers this message not in tones of antagonistic fervor, as some politicians and activists tend to do. Instead he uses statistical data drawn from studies, some of them including genetic data. The group found, for example, that a son whose parents are in the top tenth of income earners has more than 20 times the chance of ending up in the top ten percent himself compared to the son born to parents in the poorest tenth. However, it's not a doomsday picture they present, but instead a scientific portrait of equality and the lack of it, with hopes of one day leveling the playing field so that this country can move closer to its ideal.

"Genes are apparently part of the picture," says Bowles about the unlevel playing field, "but not a very large part, and not for the reasons most people would think." Bowles, working with Herbert Gintis, SFI External Faculty member and ease on a molecular level, but that DNA can explain only a tiny percentage of major behavioral differences or chronic diseases. "When the focus has been so much on reducing behavior or chronic disease to a molecular phenomenon, we lose sight of the other factors involved in cultural variation, and the resources do not go to study these," he adds.

Many problems exist in attempting to link behavior and genetics. He cites, for example, studies in the past that have attempted to say the reason fewer women than men pursue science is due to genetic differences. Feldman says we first have to discount the importance of societal issues, such as the fact that women often balance child-raising and careers, and even developmental ones. Girls often lose on the social value scale by being good on the math scale, he notes. "We know those sex differences exist as they do with race, but to claim that a difference in achievement is due to genetic differences between females and males is the same kind of statement that has continually been used about races. And until we know that we have the environmental and opportunistic issues resolved, we cannot rely on statistical correlations to claim causation."

He notes that SFI's Behavioral Sciences Initiative is an important step in looking at such issues. "There have been a lot of conclusions made about the role of genetics, but we really have to look at the whole, be careful not to miss other influences, such as fine-scale geographic and lifestyle differences, for instance. So much of the picture can be there, and can be missed by assuming that it can all be reduced to molecular causes."

Lesley S. King's articles have appeared in The *New York Times*, *Audubon*, and other publications.

Professor Emeritus of Economics at the University of Massachusetts, Amherst, and Melissa Osborne Groves, Assistant Professor of Economics at Towson University, seeks to "uncover the channels through which parental incomes influence offspring incomes." To do this, they study the income of twins. Twins provide insights into the nature-nurture debate because in most cases they have been reared in similar environments, thereby holding "nurture" constant. The researchers found that identical twins' earnings were more similar—one twin to another—than were the incomes of fraternal twins. "The remarkable income similarity of identical twins compared to fraternal twins suggests that genetic effects may be important," they write.

But they caution that heritability can be affected by changing the environment. And, echoing the work of Marcus Feldman and his colleagues, they stress that estimates of this kind are sensitive to plausible alternative assumptions. Surprisingly, they found that the genetic inheritance of IQ plays a negligible role in the process. "Other similarities between parents and children—of race, personality, looks, and health status—are likely to provide a better explanation of the role of genes in keeping wealth in the family," concludes Bowles.

The book tackles subjects far beyond the twin studies and the United States. In *Unequal Chances*, the team looks at influences such as personality, race, wealth inheritance, and even luck as forces affecting the transmission of economic success across generations. The study could impact many areas of public policy, and, judging from the stir it's creating, public opinion as well, especially since it shines an unwelcome light on such factors as race and class, identifying them as helpers or hindrances to success—things that the U.S. "melting pot" has pretended to transcend. "It hits the funny bone of America," says Bowles. "People still like to say that anyone can get to the top. I wish it were true. "

Seeking the Body's Innate Fountain of Youth

By Barbara Ferry

In the Beni region—the lowlands—of Bolivia, the Tsimane people still live by traditional means, employing hunting, fishing, and modest horticultural gardens to obtain their food. A rare example of a traditional subsistence population, they have lean bodies that endure high rates of disease, tough workloads, and little modern medical care. Because of these factors, Hillard Kaplan, SFI External Faculty member and professor of anthropology at the University of New Mexico, believes the Tsimane will provide a window into understanding the process of aging. For three years, Kaplan has been researching this population alongside Michael Gurven of the University of California at Santa Barbara and graduate student Jeff Winking, University of New Mexico.

Most of what we know about the aging process comes from studying modern populations. However such studies provide an incomplete picture because they leave out a vast majority of humans' evolutionary history. By studying a traditional society, a group about which very little is known in regards to aging and the epidemiology of disease, Kaplan hopes to contribute to a debate on the human life span that ultimately seeks to answer the questions: what causes humans to age and die and how long can people live?

It is almost certain that at least some of the processes leading to aging among traditional subsistence peoples differ from those afflicting people in modern developed nations. In developed nations, humans experience very different diets, activity regimes, and physical assaults on their bodies.

Modern hunter-gatherers are not living replicas of our stone age past, having been affected by global socioeconomic and epidemiological forces. Nevertheless, studying them can provide an important, if imperfect, lens on the life histories of our ancestors and the conditions that shaped the biology of human development and aging. Such research is urgent, because global change is proceeding rapidly, and virtually all human populations will soon be incorporated into global economic and health systems.

The next decade will probably be the last during which such research will be possible. Although the Tsimane were exposed to Jesuit missionaries in the late 17th century, they were never successfully settled into missions and remain relatively unacculturated. The Tsimane are thus an ideal population for a study of the aging process among traditional forager-horticulturalists.

By linking medical information with more traditional studies of cultural norms, diet, hygiene, work effort, activity, mobility, housing, and social networks, Kaplan and his research team hope to gain a more complete cultural epidemiological understanding of health and disease among the Tsimane. A long-term goal of the research is to explain the age profile of human mortality and the rate at which humans develop and age in terms of economic productivity, muscular strength, endurance, body composition, disease resistance, and cognitive function.

Caring Parents

Also working with Kaplan on this SFI project are economist Arthur Robson of Simon Fraser University and Ronald Lee, director of the Center on the Economics and Demography of Aging at University of California, Berkeley. Both Robson and Lee have independently proposed new theories of aging with a common point of departure: classical biological theories of aging are inadequate for species such as humans, which engage in extensive and prolonged parental care.

According to the new theories, resource transfers from parent to offspring are critical to understanding the role of natural selection in determining mortality rates. One goal of the project is to further develop these theories and to work through the shared and unshared features of the two approaches.

The starting point for the new theories on the human life course is the observation that successful reproduction is not mainly a matter of producing offspring, but rather is a matter of acquiring food and allocating it to offspring so as to maximize the number of surviving, sexually mature adults. This perspective places the acquisition and distribution of food at the center of reproductive fitness, rather than fertility. Humans have long childhoods, compared to other species, and may be dependent on parents for as long as two decades. From an evolutionary point of view, it makes no sense for people to be able to reproduce up until their mid-40s if they cannot survive long enough for their children to become self-sufficient. Natural selection seems to have favored long childhoods in humans, and previous theories of aging didn't take this into account.

A second component of the Santa Fe Institute project is to organize a theoretical working group of biologists, demographers, economists, and anthropologists to exchange ideas and promote further development in the theory of the life course. The third component is to assemble another working group of empirical scientists interested in aging research in both developed and less developed contexts, with the goal of stimulating more comparative research.

In addition to informal working group meetings, two workshops will be organized, one focusing on theoretical results and the other on empirical applications.

THIS PERSPECTIVE PLACES THE ACQUISITION AND DISTRIBUTION OF FOOD AT THE CENTER OF REPRODUCTIVE FITNESS, RATHER THAN FERTILITY.

PHOTOS: MICHAEL GURVEN

How We Grow Old—Contrasting Views

Life expectancy in developed countries has increased dramatically in the past 100 years. Medical advances have led to a reduction of infant and childhood mortality rates and helped people live longer. These increases have reopened the debate on the potential length of the human life span, but there are differing views on how aging occurs.

According to one view, the human lifespan is like a ticking clock (time bomb?) with an upper limit of about 85 to 86 years. Improved medical care and public health have allowed people to live longer and caused the distribution of deaths to become increasingly compressed in the upper-age range. This ticking clock view, characterized as the gerontological view, treats the various outcomes of aging as resulting from a single, unitary process, resulting in programmed death.

But, according to an alternative view, there is no set upper limit to the human lifespan, and improvements in medical treatment and living conditions will continue to produce increases in longevity. This view, called the epidemiological view, treats aging as resulting from a competing set of risks due to independent or quasi-independent processes. According to this view, there is no ticking time bomb that results in death, and as advances in medical care succeed in preventing or curing diseases, the causes of aging and death can individually be eliminated.

Genetic Factors Matter

Although there have been dramatic gains in the survival rates of older people in the United States over the last several decades, the potential for improvements remains an open question, because our knowledge about the interaction of biology, behavior, and environmental conditions in determining the aging process and age-specific mortality rates is still limited. There is, however, growing evidence that the aging process is strongly influenced by biological control mechanisms, and that genetic variation among humans and nonhumans is associated with differences in rates of aging. This means that between species, and within the human species, there are genetic differences that code for different rates of aging: genes regulate cellular processes that lead to different rates of cellular, and ultimately whole-organism aging. But the interrelation between genes, genetic expression, and the environment is not completely understood. Progress in mapping the human genome is likely to lead to major advances in our understanding of the genetic substrate governing the aging process.

There is also strong evidence, however, that genetic control mechanisms do not necessarily lead to a fixed pattern of aging. For example, environmental factors, such as restriction of dietary intake in many mammals, is associated with a series of physiological adjustments, including lower growth rates, delayed age at first reproduction, and shortened life span. Human life histories show evidence of systematic variation in response to environmental variation. These outcomes appear to be the result of the interaction between changes in environmental conditions and genes affecting human physiology and behavior.

Diet and Inflammation Count Too

Standard epidemiological theory suggests that chronic diseases, such as heart disease and cancer, have increased in relative frequency, due to reductions in mortality resulting from infectious disease. Fewer people die from infectious disease, so the relative rate of chronic disease such as heart disease and cancer has increased. Changes in diet and exercise in developed societies may also play a role. Yet it also has been argued that aging and the onset of chronic disease may be accelerated in response to poorer nutrition and increased disease loads.

ACCORDING TO AN ALTERNATIVE VIEW, THERE IS NO SET UPPER LIMIT TO THE HUMAN LIFESPAN, AND IMPROVEMENTS IN MEDICAL TREATMENT AND LIVING CONDITIONS WILL CONTINUE TO PRODUCE INCREASES IN LONGEVITY.

Two University of Southern California researchers who have been collaborating with the team recently proposed that major decreases in mortality at the older ages are due to a reduction in the level of inflammation experienced over a lifetime. The human body's reaction to bacteria, viruses, and parasites is to engulf the agent, causing inflammation. These researchers believe that chronic exposure to such physical assaults has negative secondary effects and may cause the body to age more rapidly. Defense and repair is costly to the body. With the introduction of antibiotics and public water systems, exposure to foreign agents, and hence, the body's inflammation, has decreased.

Kaplan's research project is collecting data on diet, weight and growth, biomarkers of inflammatory processes, viral, bacterial, and parasitic infection rates, and aging among the Tsimane to help evaluate the different theories of aging that have been proposed. In addi-

Researchers collect data on the Tsimane's diet, weight, growth and other factors

tion to these scientific goals, Kaplan's research is contributing to student training and the participation of traditionally under-represented groups in research. Both Bolivian and U.S. graduate and undergraduate students have participated in data collection and will continue to do so in the future. The research also involves the community members themselves in data collection, and trains Tsimane in primary health care.

Most of the theories of aging have been based on analyses of historical populations in societies with a central government, such as historical Europe. By working with the Tsimane, Kaplan and his team will be able to, in a sense, travel back in time and thereby bring new insight to the future.

Barbara Ferry is a staff writer for The Santa Fe New Mexican.

PHOTO COURTESY SFI

First China Summer School Promotes Interdisciplinary and International Collaboration

By James W. Minett

This past year SFI's International Program sponsored a Complex Systems Summer School in China. As a research fellow working in Hong Kong, I learned that William Wang, who supervises the work of our language evolution group at the Chinese University of Hong Kong, would be giving a week-long course in evolutionary linguistics at the Summer School. Then I discovered that John Holland, External Faculty member at SFI and professor in the departments of psychology and computer science at the University of Michigan, was to be his co-lecturer. I knew I would apply. Attending the school would be an opportunity for me to meet a new group of young researchers and to further my current work in modeling processes of language evolution.

The school was held at Qingdao University in Shandong Province, located on the coast of China. Organized jointly by SFI and Qingdao University, with the cooperation of the Key Laboratory of Complex Systems and Intelligence Science of the Chinese Academy of Sciences, the school brought together academics and students from around the world, with about sixty percent of the participants coming from China.

Qingdao University is situated just beyond the city center, whose restaurants, bars and beaches provided ample entertainment throughout our one-month stay. Downtown Qingdao is modern, with newly built office towers and shopping malls. Other parts of the city reflect both the elegant architecture constructed during the European occupation of the city at the beginning of the 20th century and the dilapidated structures of villages that have been engulfed by the expanding city, hinting at an agricultural past. The city even inspired a couple of the projects, with one group modeling the popularity of the city's bars and another studying the self-organization of individuals moving about in bounded spaces, such as the city's buses.

The areas of interest of the students attending the Summer School were broad. Significantly, the research interests of the majority of those from China were on complexity theory and computational modeling techniques, whereas the overseas students tended to focus their research on applications in specific fields such as ecology, economics, and linguistics, although there were exceptions in both cases. This complementary blend of foci was, no doubt, deliberate on the part of the summer school organizers to promote both interdisciplinary and international collaboration.

Like previous schools, the Qingdao Summer School consisted of three weeks of lectures and group project work, followed by one week for the completion and presentation of the group projects. The school focused more on a broad coverage of applications of complexity science than on theory, although the school did begin with a one-week intensive course on fundamental aspects of complex systems research.

After opening preliminaries, Dave Feldman, from the College of the Atlantic, kicked off the main business of the school with a series of lectures on complexity science, summarizing a number of important concepts underlying the analysis of complex systems, such as information theory, entropy, and computation theory. These lectures were helpful in providing a guide to some of the general tools that can be used for complex systems analysis, pointing the way to more detailed presentations in the literature.

Also in week one was a discussion by Thomas Peacock, from the

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Rural/Urban Migration in China Focus of Study

SFI Science Board member Marcus Feldman from Stanford teamed with Li Shouzhou at Xi'an.

In rural China, where a strict patrilineal family system is dominant, preference for sons is ubiquitous. However, in large cities the extent of son preference has been weakened by the process of modernization and improvement in the social security system (families are no longer as reliant on the son to support them in old age). Migration from the country to the city leads to a dramatic change in lifestyle and social networks, which most probably influences the values and concepts of rural-urban migrants. The original, strongly male-biased culture and the corresponding behaviors are likely to be influenced by the host culture, which is more modern. In particular, marriage and childbearing preferences change, as well as other behaviors, which trickle back to the country, influencing those peasants who later marry in the rural areas. The influence may eventually give rise to a cultural transition within the whole population and even a diminution of son preference.

Using social network analysis and models of cultural transmission and evolution, the new research will incorporate personal social networks, characteristics of regions where migrants flow-in and flow-out, living arrangements and duration of stay in urban areas, frequency of returning to the countryside and duration of stay in rural areas, individual socioeconomic characteristics, mass media, as well as local policies and regulations, etc. The models aim to describe interaction among temporary rural-urban migrants and urban residents in terms of culture and behavior and to simulate the dynamics of transmission and diffusion.

Development and testing of models for the cultural transmission and diffusion during the process of rural-urban migration in China as well as the interaction of these migrants and urban residents is important, both academically and practically. The research will help to predict the social and economic consequences of rural-urban migration in China and perhaps produce corresponding policy formulation for community development.

PHOTO COURTESY SFI

Department of Mathematics at MIT, on pattern formation in fluid mechanical systems. Peacock's lectures combined an overview of the mathematics of fluid mechanics, discussing, for example, the Navier-Stokes equations, Rayleigh-Bernard Convection, and Taylor-Couette Flow, with video clips that illustrated vividly the types of patterns that can emerge in such systems. Although his lectures did not provide students with specific tools with which to tackle problems in their own fields, they did serve to highlight the rich behaviors that can emerge from complex systems.

In the second week of the school, the lectures switched to biology and the evolution of agriculture. Eric Smith, a research professor at SFI, and Satoru Miyano, from the Institute of Medical Science at the University of Tokyo, spoke about reaction networks in biology, with Smith providing an overview of the citric-acid cycle and Miyano describing how Petri nets can be used to model interactions among genes. Hao Bailin's (Institute for Theoretical Physics, Chinese Academy of Sciences) discussion of the K-strings method for characterizing and comparing genetic sequences was particularly interesting to me because the technique might find application in the phylogenetic classification of language, one of my own research interests. The opportunity to learn about such a method for potential use in my own field was, for me, one of the most valuable aspects of the Summer School.

The school also included lectures on the evolution of agriculture, specifically rice domestication and cultivation in China, Southwest Asia, and the Americas. It also had lectures on network dynamics, providing a basic introduction to network-based tools for complex systems research.

In the third week, William Wang and John Holland lectured on my own research area of language evolution. The style of presentation here was a little different from the other talks, with Wang and Holland alternating their discussions between the empirical and theoretical. Wang focused on the empirical, sampling a broad range of features that illustrate the structure and complexity of language. From an overview of FOXP2, the so-called "language gene," whose role in the phylogenetic and ontogenetic emergence of language has been much discussed in the recent literature, to the historical development of the Chinese language, his lectures served both to provide a stimulating introduction to the theoretical discussions of Holland and to ground them. Holland concentrated on describing a framework, based on the classifier system, for modeling the emergence and evolution of language.

The Echo system, described in Holland's book *Hidden Order*, was originally derived to study the dynamics of complex adaptive systems. It is an agent-based, rule-based system consisting of heterogeneous, interacting agents that evolve by building up rules to encode beneficial behaviors. This system is a situated model: agents must interact with an environment and survive in it by filling reservoirs, measures of the extent to which they are able to fulfill certain basic requirements, such as acquiring food, finding shelter, and so on. Whenever a reservoir is low, a bridging rule, e.g., a rule stating "I'm hungry!" is activated and stays on until the reservoir is refilled; bridging rules act to keep the agent focused on an important task, such as finding food. New rules are triggered whenever a general set of conditions are met. For example, a child may learn to speak a new word "cookie," if she is hungry, she hears her mother say "cookie," and she happens to be seeing an actual cookie. New bridging rules can be triggered too, when, by chance, an agent undertakes an action that leads to a reservoir being filled when no existing bridging rule is active, allowing agents to learn new ways to focus on important tasks.

Currently, many linguists believe that language is an innately endowed system that evolved through the selection of language-specific cognitive and physiological functions. However, an increasing number of researchers, including both Holland and Wang, now believe that language first emerged through the re-use of existing cognitive, physiological, and social functions. Holland therefore used the lectures to pose the question: can a simple form of shared language emerge among a group of interacting agents based on just domain-general skills, such as shared attention and recognition of recurrent patterns? Although he did not provide an explicit answer to this question, he did describe how a classifier system might be constructed to help answer this question.

Instructive as most of the lectures were, I found the most successful aspect of the Summer School to be the group project work that each of us undertook. The process of forming groups was a complex system in itself: while some people picked a particular topic to work on and stuck with that, others moved from group to group, both to sample the topics being considered and to contribute ideas of their own. Indeed, several students participated in more than one project.

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Shanghai Workshop Explores Organizing Principles of Life

Last May, SFI co-sponsored an International Workshop on Biocomplexity with Fudan University, one of China's leading universities with an international reputation for academic excellence. The workshop also served as the 40th Eastern Forum for Science and Technology sponsored by the Shanghai Municipal People's Government, the Chinese Academy of Sciences, and the Chinese Academy of Engineering. The organizers were SFI International Fellow Hao Bailin, academician of the Chinese Academy of Sciences and professor at the T-Life Research Center at Fudan, and Eric Smith, research professor at SFI.

The meeting was topically broad, including, but also reaching beyond familiar fields in biocomplexity such as genomics and proteomics, bioinformatics, and the genetic reconstruction of phylogenetic (inheritance) trees. Also represented were ecosystem and microbialecology, scaling and invariance principles, and the mathematical structure of evolutionary theory and information transmission across generations. Important new directions that are reshaping classical fields were presented, including quantitative and computational modeling of the emergence of civilizations, and the study of network structure and dynamics. Finally, intrinsic system-level phenomena were discussed, from the structure of inheritance to the emergence of neural maps.

Presenters at the workshop came from China, Taiwan, Korea, India, Germany, and the U.S. Their primary research interests ranged from laboratory synthesis and database creation and mining, to public health and agriculture, to fundamental mathematical and computational representations of living systems.

What held such an eclectic meeting together was a shared sense among the participants that there are organizing principles characteristic of life that transcend these application domains. What we learn about the roles of hierarchy and autocatalysis at the molecular level may also predict constraints on the emergence and succession of forms of civilization. Network dynamical principles discovered to make protein and gene regulation comprehensible continue to be relevant to the structuring of ecologies, epidemics, and immunology. As we understand better the principles that underlie the amazingly diverse yet resilient natural world, we can work to integrate engineering and medical practices within that framework, discovering elegant ways to restore functions that integrate smoothly into the living processes responsible for creating it.

The common interest of our group was extinction, albeit from different perspectives, such as ecology, paleontology, and linguistics. We soon agreed to form a team to model extinction processes, a project that would support my research into the dynamics of language extinction. The range of topics considered in the projects was wide, from the formation of biofilms, the layer of microbial organisms that grows, for example, on one's teeth when left unbrushed; to the modeling of conflict and warfare. Given the short duration of the summer school, the aim of the project work was less about carrying out new research and more about gaining experience with using methodologies that will be useful in future research.

Taking part in the Qingdao Complex Systems Summer School proved to be a rewarding experience, both for the broadened perspective to research in different fields that it offered and for the opportunity to work in mainland China. The different general approaches of the Chinese students —theory-based—and the overseas students—application-based—made for a constructive blend. It is to be hoped that complexity science teaching and research can continue to blossom in the coming years so that the flow of knowledge between nations and across disciplines can grow.

James W. Minett is a research fellow working on evolutionary linguistics in the Digital Signal Processing & Speech Technology Laboratory of the Department of Electronic Engineering at The Chinese University of Hong Kong. For more information on his research, you can visit his homepage at http://www.ee.cuhk.edu.hk/~jminett/

Chinese Dignitary Visits SFI

Geoffrey West and Jiang Mianheng

Jiang Mianheng, son of former Chinese President Jiang Zemin, visited SFI on February 28th and participated in a round table discussion with SFI researchers. Dr. Jiang is a successful entrepreneur instrumental in the development of the information technology industry in Shanghai and also a vice president of the Chinese Academy of Sciences. A guest of the New Mexico Economic Development Board, he requested to visit SFI to learn how the Institute fosters interdisciplinary research and maintains an environment of academic creativity and freedom. This trip followed visits to the MIT Media Labs and Harvard University, where he explored how to ensure standards of academic excellence and how to evaluate the success of a bottom-up organized institution. He explained that the Chinese Academy of Sciences has been undergoing many changes and is committed to building world-class research institutions.

SFI researchers Jessica Flack, John Holland, David Krakauer, John Miller, Eric Smith, Geoffrey West, and Henry Wright participated in the discussion with Jiang, who was especially curious about why the researchers chose to work at SFI over other academic institutions. The group also discussed many SFI/China initiatives, ranging from research collaborations to the upcoming Complex Systems Summer School in Beijing. The discussion also touched on the SFI Business Network, with Ann Stagg, manager of Marketing and Business Relations, explaining how the Network contributes to the environment of scientific entrepreneurialism and innovation, in addition to providing valuable research revenue for SFI. The visit culminated in a tour of the Institute and informal discussions with various researchers.

PHOTO COURTESY SFI

2005 Complex Systems Summer School in Beijing

This summer, the second Complex Systems Summer School to be held in China will be hosted in Beijing by the Institute of Theoretical Physics and the Academy of Mathematics and Systems Sciences of the Chinese Academy of Sciences. The school, which will run from July 11 through August 5, will focus on both theory, with lectures on the fundamental principles and tools of complexity science research; and application, including biological systems, social aspects of language evolution, and population dynamics. The Summer School at Santa Fe, held from June 6 to July 1, will focus more on theory, although it too will deal will such applied topics as the modeling of food webs, the evolution of cancer, and the structure of the World Wide Web.

PHOTO: PATRICK MCFARLIN

Scientists Reunite After Four Decades

"I was browsing through a bookstore in Berkeley and saw a book called *Emergence*," says Bill Wang, research professor of language engineering at the Chinese University of Hong Kong. "I took it off the shelf and was surprised to see it was by John Holland." This serendipitous instance initiated a reuniting of old friends and an important collaboration for scientific research.

Wang e-mailed Holland, who is an SFI External Faculty member and professor of psychology and computer science and engineering at the University of Michigan. "We started by comparing stories about our grandchildren and then the relationship became more and more substantive," says Wang.

"Forty-three years ago," relates Holland, "Bill and I were at the University of Michigan. We had the first appointments in what was then called the Communication Sciences Program." At that time programs such as this existed only at Michigan and MIT. Together Holland and Wang designed and taught the first course in the program. What's now called the Computer Sciences Program, has since become one of the leaders in the study of complex adaptive systems (CAS). Not long after they taught together, Wang got an appointment at Berkeley. "He became well known in linguistics," Holland says. Then time and distance took over, causing them to lose touch with each other for four decades.

After reuniting, they realized they shared many scientific interests. "Ever since that course with John at Michigan, I have been working at adapting ideas from evolution theory to linguistics," says Wang. "Hence my joy at discovering John's book."

Holland went to Hong Kong, where a collaboration began, uniting his research in CAS with Wang's work in language. "Many of the researchers in our program had heard of John and his work, so it was nice to have him in Hong Kong," says Wang. At the time, Wang wasn't new to the work of SFI. In fact he was already on an advisory committee for Murray Gell-Mann's project on language evolution.

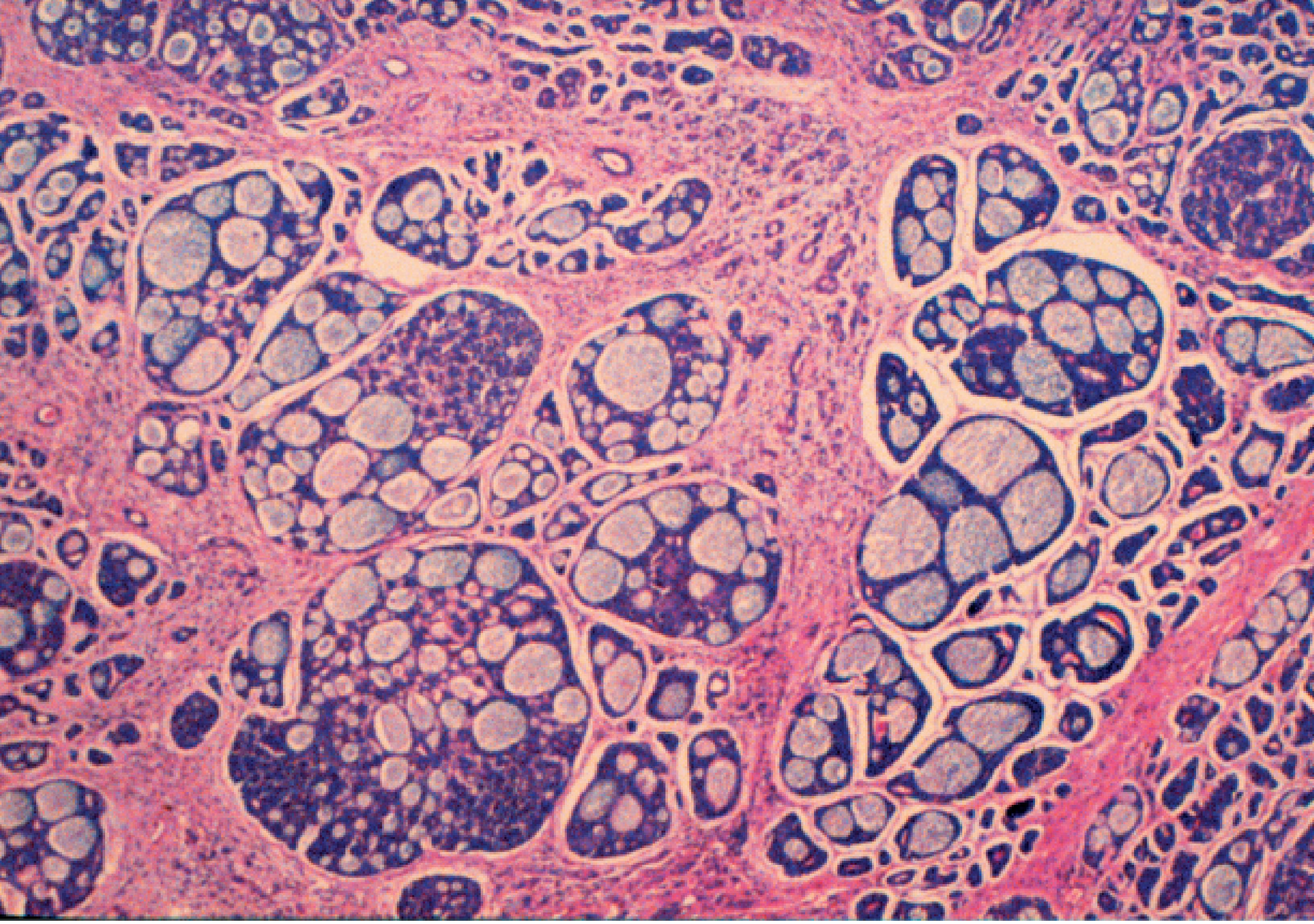
In the research, Holland and Wang are using CAS to redirect the focus of understanding language acquisition, removing emphasis from genetics and placing it on the process of learning. They've created a model in which the agents start with very primitive cognitive abilities. They learn, and adapt through doing so. "If we demonstrate that language can be learned with more primitive abilities, then that would change the way linguistic research is done," says Holland.

This spring the work expanded with the help of a workshop at SFI convened to discuss "Language Evolution and Acquisition: Models, Networks, Robustness, and Diversity." The workshop included Holland, Wang, and six other colleagues from around the world.

"The collaboration became even more interesting since some of SFI's activities were beginning to blossom in Asia," Wang adds. So, 43 years after co-teaching one of the first courses in a field that would one day become complexity science, Holland and Wang co-taught a course in language evolution at the SFI Summer School in Qingdao. They will teach together again at the 2005 school in Beijing.

"What I look for, in life and work, is fun," says Holland. "And this has been really fun."

—Lesley S. King

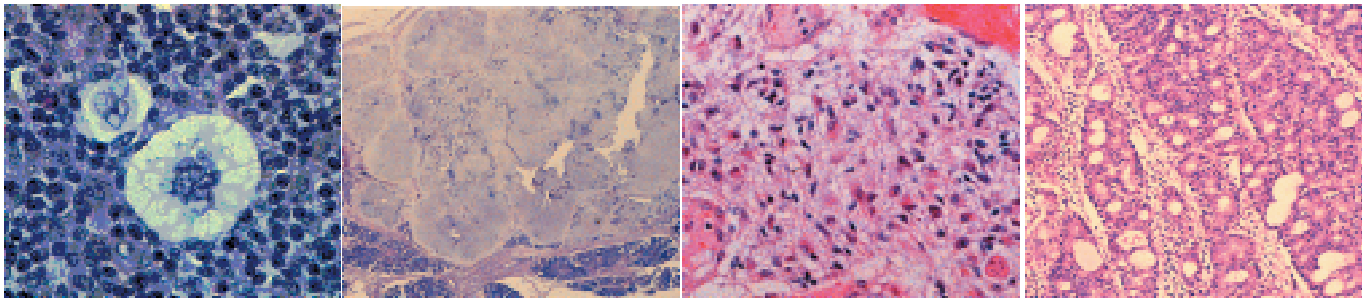


Cancer's Complex Nature

by Daniel Rockmore

Much of what goes on at SFI, indeed even the very creation of SFI, is and was inspired by a desire to study and understand life, from its origins in some primordial molecular soup to the complicated web of interactions into which it has evolved. Nevertheless, many of the tools developed at SFI to plumb the mysteries of the growth and evolution of living systems can also be used to shed light on those darker processes that bring life to an end. These final phenomena range in scale from the grand to the minute: the catastrophic phase transition that could produce a "Day After Tomorrow"-like snowball earth; the cascade of extinctions modeled by the dynamics of a food-web network; the emergent behavior that signals a market crash; or the progress of disease, either across a society or within an individual or even a single cell. It is the last of these, and in particular, toward understanding the etiology of cancer, where SFI scientists are making some significant contributions.

Editor's Note: This is an expanded version of an article that ran in the previous Bulletin.



CELLULAR MANIFESTATIONS OF CANCERS

Cancer as a Complex Adaptive System

At some level of consideration, the healthy human body is a multi-dimensional mosaic of cells, differentiated by their various functions (e.g., skin cells or muscle cells). Cancer develops as an uncontrolled reproduction of abnormal cells, which can then embark on a deadly cycle of invasion and destruction of nearby tissues that spreads throughout the body. Organs become a competitive landscape where abnormal and normal cells are actors fighting it out for resources. Should the abnormal cells gain the upper hand, the function of the organ may be in jeopardy: a liver that suddenly does not have sufficient healthy tissue to maintain the body's chemical balance, or lungs lacking the healthy tissue to absorb the oxygen that sustains life or so heavy with tumor that they collapse under their own weight.

Within this competitive landscape, the etiology of cancer can take on an evolutionary interpretation. Cells reproduce, compete, and evolve with a clear advantage (toward an end goal of population dominance) conferred on that cell type that reproduces the quickest. Evolutionary pressures are also induced by therapies, pushing a "natural selection" of those cells resistant to treatment. The language of evolution, selection, and competition puts cancer research squarely into SFI's purview.

A Universal Law for Tumor Growth

When Distinguished Research Professor (and now Interim President) Geoffrey West came on board at SFI, he was interested in bringing to the investigation of living systems an outlook that was honed over years of study of theoretical physics. In that rarified intellectual world of invisible and indivisible particles, the hallmark of success is the principled derivation of universal laws—simple mathematical formulas like Newton's "F=MA" or Einstein's "$E=MC^2$"—that apply with near, if not exact, agreement across a range of real-world phenomena. West wanted no less from his new work in biology. It is in this spirit that he, SFI External Faculty member James Brown, and Brian Enquist, of the National Center for Ecological Analysis and Synthesis, made their first big hit in the study of allometry. They took the very physics-like approach that fundamental principles for growth in any living form, be it microbe, marmot, or man, can be deduced from considerations of energy and resource transport that are independent of the organism. The crowning achievement of this work has been their discovery of a "universal growth law" for organisms, one that displays a three-fourths power relation between the body mass of an organism and its metabolic rate as well as a principled derivation of the evolved intricate branched systems (for example, the circulatory or pulmonary systems) whose fractal-like structures can be shown to optimize energy delivery and resource access.

West and his group are now using these same tools to try to develop a physics-based model of tumor growth. Herein the idea is to relate tumor growth to the development of the branching system of capillaries, a process called "neovascularization" or "angiogenesis" that is responsible for the delivery of energy to the surface of the tumor. Generally, cell survival is linked to proximity to blood supply, so that a better understanding of the formation and development of these new resource supply chains for tumor growth is a crucial component in understanding cancer. West, former SFI Postdoctoral Fellow Van Savage (now in the Department of Systems Biology at Harvard University), and SFI Graduate Fellow Alex Herman continue to push this work forward and are, according to Herman, "potentially laying the groundwork for theory-based extrapolation of experimental results in animal models of cancer to humans."

This allometric framework is also guiding the work of other cancer research groups. Of particular note is the work of Thomas Deisboeck (Harvard/MIT) who is using these ideas as a foundation for investigating tumor development. The coarse-scale characterization of tumor growth as a rapid (exponential) increase in volume fueled by the concomitant explosion in the number of conduits to sustain efficient blood flow share much with the basic allometric assumptions. By adapting the analysis of West, et al., Diesboeck's group derives an analogous "universal law for tumor growth." It is a first step in a back-and-forth dance between theory and experiment that already seems applicable to the design of therapies. Drug designers can take advantage of the detailed knowledge of the stages of tumor development. For example, just knowing the rate at which tumor cells are both generated and lost at different stages in development will give the clinician a benchmark for the evaluation of therapeutic strategies. Diesboeck, et al., believe that the allometric outlook will have "far-reaching implications" for our understanding of tumor ontogeny.

Cancer Research In Silico

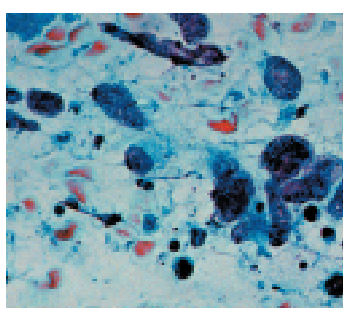
SFI Research Professor and University of New Mexico Professor of Computer Science Stephanie Forrest is involved in a variety of active collaborations in cancer research. Her work in this direction seems a natural outgrowth and synthesis of past and continuing achievements in computational biology, the study of computer viruses and their prevention, as well as computational modeling and simulation.

"We're investigating various simple hypotheses for the dynamics of resource competition among pre-cancerous cells," says Forrest. Initial work with Carlo Maley of the University of Washington's Fred Hutchinson Cancer Research Center uses some of the tools of evolutionary simulation—the same agent-based modeling that came of age in the SFI-led investigations of "artificial life."

Like any good computational simulation, their work creates an in-silico laboratory, not just reproducing known phenomena, but also suggesting and explaining new ideas for therapies. A recent paper with another Hutchinson researcher Brian Reid, investigates the possibility of a new therapy. "Rather than killing off the cancer cells," says Forrest, "it instead seeks to boost the reproductive fitness of relatively benign cells, thereby allowing them to out-compete the cancer cells in the race for dominance."

These in silico ideas are finding an in vitro test site in the investigation of a particular type of esophageal cancer and its precancerous state, "Barrett esophagus," that arises in a significant fraction of those who suffer from gastroesophageal reflux disease. Forrest and Maley have begun the difficult process of tuning their general model to the data of this particular disease. This has already resulted in general insights (in the form of predictions) regarding genetic factors in cancer development.

Lately, Forrest's computational approach to the study of cancer has acquired two new collaborators, Robert Abbott of Sandia National Labs and Kenneth Pienta of the Comprehensive Cancer Center of the University of Michigan. Together they have developed CancerSim, a new and improved artificial life-inspired computer simulation package for investigating tumor growth. CancerSim aims to "characterize the processes of cellular alteration that underlie tumorigenesis." This three-dimensional cellular automata evolves according to a set of rules born of "The Hallmarks of Cancer," a well-known paper written by Douglas Hanahan (UCSF) and Robert Weinberg (MIT) in which they identify six phenotypic cellular characteristics that appear to bear strongly on malignant tissue formation. Forrest and her collaborators translate these hallmarks into parameters for the simulation. Exploration of parameter space in the subsequent simulations allows the scientists to chart the many possible paths in the development of tissue as it grows from single cell to multicelluar entity, cancerous or otherwise. This work has already begun to yield interesting insights into how the hallmarks interact. Among these is a new point of view on the role of angiogenesis, which is the formation and differentiation of blood vessels.



This first version of CancerSim is necessarily a simplified, highly abstracted model of tumor growth. In an effort to make it more realistic, Forrest has begun working with Geoffrey West and Alex Herman, hoping to incorporate aspects of their allometric analysis into a next generation of the computational model.

In order to beat 'em, you've got to change 'em, and keep changing 'em…

Cancer is life run amok—causing the breakdown of a living system via the hatching of a cell that mutates to display a pattern of uncontrolled growth. The population of mutated cancer cells undergoes a "microevolution" in the organ. Therein selection pressure favors those cells that can overcome the "barriers" imposed by immune systems or resource competition. The behavior of the population of cancer cells, in essence, breaks the implicit social (and biological) contract binding together the cellular populations within the multicellular society that is a tissue.

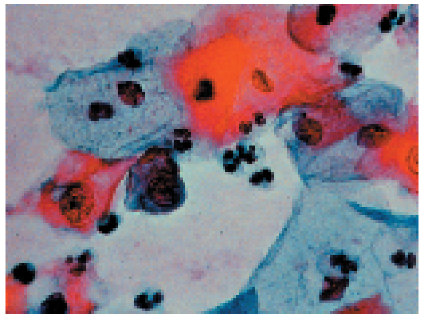
One way in which cancer cells seem to win this microcompetition is through an ability to mutate at a tremendous rate. The sheer numbers of subtle variations achieved through this "genetic instability" effect a shotgun approach to finding routes through and over the life-preserving barriers. The minor genetic variations that occur across the range of cancer cells defines them as a "quasi-species," a notion first developed by SFI Science Board member Manfred Eigen and SFI External Faculty member Peter Schuster.

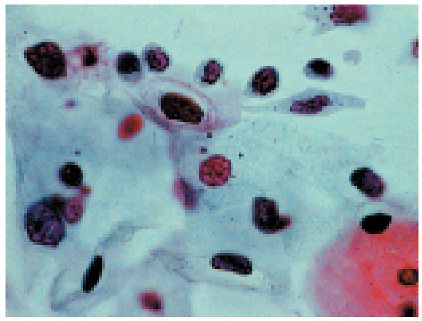
Genetic instability is on the one hand an advantage in the battle to overcome the natural barriers, but can also work against the survival of the "winning" strain which may simply mutate itself out of existence. External Faculty member Ricard Solé has looked into the effects of exploiting the long-term disadvantage of instability. In particular, one

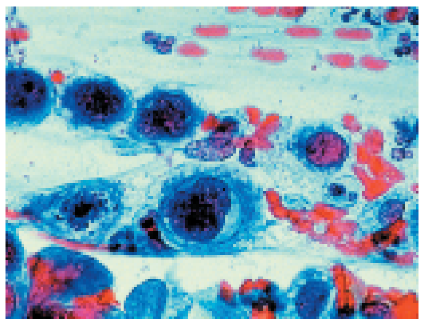
THEY TOOK THE VERY PHYSICS-LIKE APPROACH THAT FUNDAMENTAL PRINCIPLES FOR GROWTH IN ANY LIVING FORM, BE IT MICROBE, MARMOT, OR MAN, CAN BE DEDUCED FROM CONSIDERATIONS OF ENERGY AND RESOURCE TRANSPORT THAT ARE INDEPENDENT OF THE ORGANISM.

idea is to induce increased instability into the tumor cell population. This seems to be an especially promising avenue of therapeutic research for cancers that operate near an "instability threshold," defined as a level of instability close to one in which the tumor cells would begin to fall apart.

In work with Dominik Wodarz, of UC Irvine, SFI Research Professor David Krakauer has studied the implications of genetic instability in the context of cellular evolution, which selects for the ability to promote angiogenesis. Their models suggest that while genetic instability is necessary initially, it becomes a disadvantage in the long run.







From Populations to Particulars

The competitive framework in which cellular phenotypes fight each other for dominance in the tissue casts the cancer problem squarely within the realm of population dynamics. It is an analysis that assumes that the battle within the body has already begun. As such, it begs the question of where and how did the fight begin? What is the set of subcellular conditions that gave rise to that first colony of rogue cancer cells? Our genes contain the basic data that provide each cell with instructions for growth, and Krakauer, as well as many other scientists, have begun to study and model the manner in which various genes work together (or against one another) in order to gain new insights to the origins of cancer.

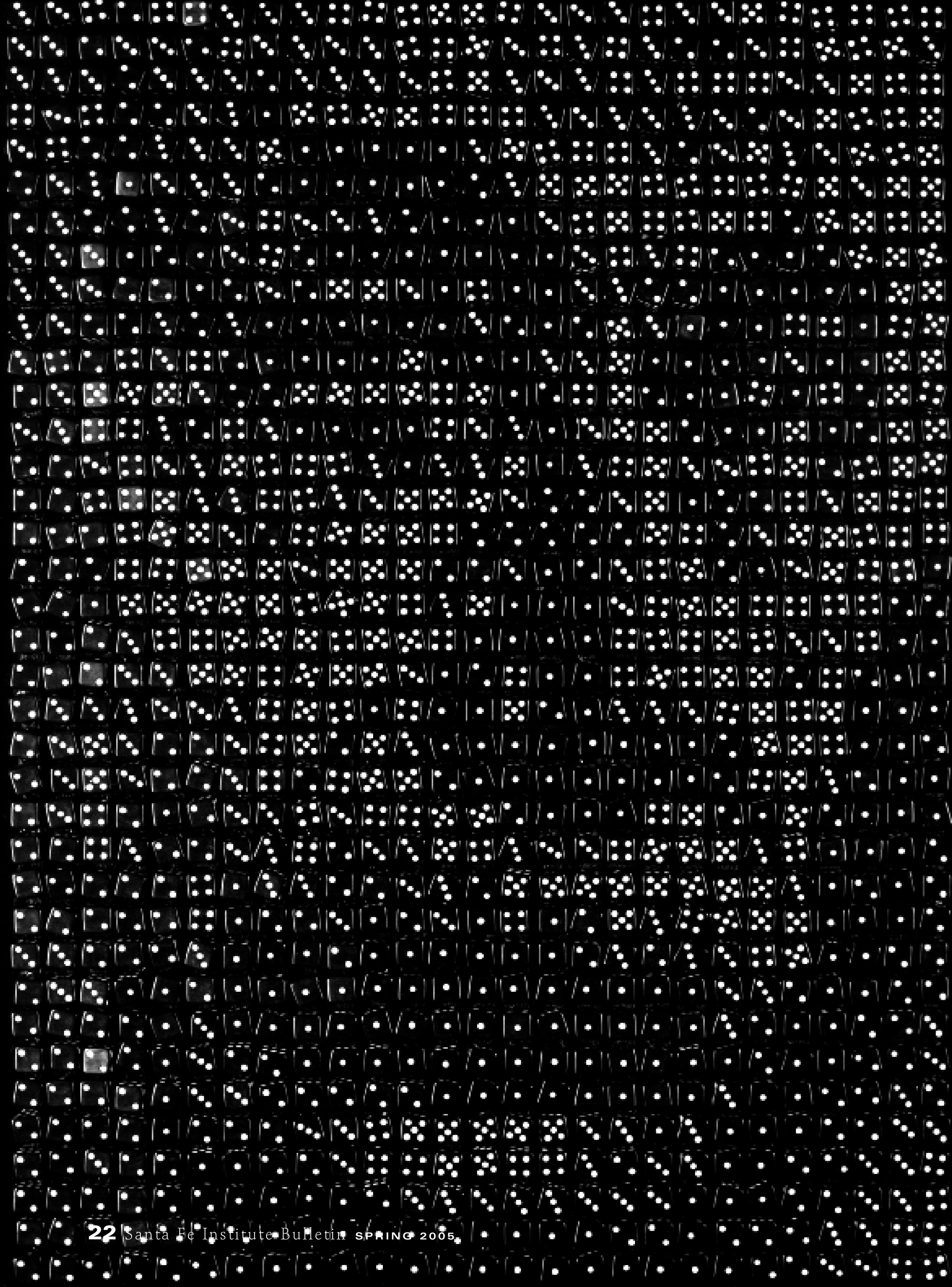
Almost surely, cancer is a multigenic disorder whose understanding will require the unraveling of a complex tangle of genetic influences. Many scientists now see cancer as explained, in part, as a problem of aberrant gene regulation, an instance of confused information flow both into and within the cell. Krakauer is quick to point out that many of the mutations known to occur in cancer development are found in genes involved in signal transduction—meaning those genes that mediate the information flow among genes within the cell, thereby influencing the ways in which proteins are produced. Krakauer and SFI Steinmetz Fellow Sabrina Spencer have begun to study a highly simplified model of the cell, an abstraction that seems to focus on the guts of the problem. In their simplified model, the cell is pictured as housing the interactions of three genes: a proto-oncogene (cancer carrier), a tumor suppressor, and a "housekeeping gene." As Krakauer describes it, the proto-oncogene is the "foot on the gas pedal," and the tumor suppressor is the "brake." Ordinarily, keeping "the pedal to the metal" should put the cell on a road to ruin, signaling the beginning of "programmed cell death" or apoptosis, but what seems to happen in cancer is that the cell acquires the ability to ignore such signals and thereby take a joy ride of never-ending reproduction, whose numbers soon dwarf the population of healthy cells.

Separately, the tools of populations dynamics and genetic networks have each begun to shed light on the complex system that is cancer, but as Krakauer points out, "No one has yet done a great job of integrating the two." In particular, he believes that one huge open question is, "What is the right formalism for studying the logic of the relevant genetic interactions?" In this regard we have begun to see a resurgence of interest in Boolean networks, the forerunner of the modern study of genetic networks. These were first proposed almost 30 years ago by SFI pioneer Stuart Kauffman (who has just been asked to head a new Institute for Biocomplexity and Informatics at the University of Calgary). Krakauer's recent work with former SFI Postdoctoral Fellow Nihat Ay, has begun to develop a formal framework for quantifying the notion of system robustness in order to enable a rigorous analysis of the performance of genetic networks.

With a little luck and much perseverance, perhaps these research collaborations at SFI and elsewhere will in time evolve toward a better understanding of cancer, generating new ideas that will speed us toward a cure, fueling a progress of development at an exponential rate, an ironic intellectual twin of the cancerous phenomena that this research seeks to erase.

"RATHER THAN KILLING OFF THE CANCER CELLS," SAYS FORREST, "IT INSTEAD SEEKS TO BOOST THE REPRODUCTIVE FITNESS OF RELATIVELY BENIGN CELLS, THEREBY ALLOWING THEM TO OUT-COMPETE THE CANCER CELLS IN THE RACE FOR DOMINANCE."

Dan Rockmore is professor of mathematics and computer science at Dartmouth College and a member of the SFI External Faculty



The Character of Biological Law: An SFI Program Searching for Regularities in the Biosciences

By David Krakauer

"How can it be that writing down a few simple and elegant formulae, like short poems governed by strict rules such as those of the sonnet or the waka, can predict universal regularities of Nature?"

Murray Gell-Mann – Nobel Prize Speech, Stockholm, 1969

In the city of Wittenberg, Germany, in the year 1566, the astronomer Tycho Brahe lost the tip of his nose in a duel with a fellow student. In place of a nose, and for the remainder of his life, he wore a sculpted insert made from an alloy of gold and silver. The duel, which was fought with another Danish nobleman, Manderup Parsberg, was ostensibly fought over which of them was the more skilled in mathematics. When Tycho was not distracted by a loose nose (it frequently fell off, requiring that he carry a small snuff box concealing an adhesive), or tending a pet moose celebrated for its beer habit, he was refining the instruments that would permit him to collect the most precise and exhaustive archive of astronomical data in the 16th century.

Tycho's scientific output was considerable: it includes *De Nova et Nullius Aevi Memoria Prius Visa Stella* ("On the New and Never Previously Seen Star," Copenhagen, 1573); *De Mundi Aetherei Recentioribus Phaenomenis* ("Concerning the New Phenomena in the Ethereal World," Uraniburg, 1588); and *Astronomiae Instauratae Mechanica* ("Instruments for the Restored Astronomy," Wandsbeck, 1598). The majority of Tycho's observations were not published during his lifetime. However, the data were made available to his assistant, the young Johaness Kepler, who had been recruited to assist Tycho in the calculation of planetary orbits, and who succeeded Tycho as royal astronomer following Tycho's death from a burst bladder at a royal banquet in 1601.

In a famous argument about the probabilistic nature of quantum mechanics with Dutch physicist Niels Bohr, Albert Einstein remarked, "God does not play dice with the universe."

Ken Knowlton, "God Does Not Play Dice With the Universe," Unretouched Dice, 1999

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Kepler was a champion of the Copernican, heliocentric model of the solar system. He had previously spent 20 years unsuccessfully attempting to map the motion of the planets onto imaginary spheres encasing five perfect geometric figures: the cube, tetrahedron, octahedron, icosahedron, and dodecahedron. However ingenious his geometry, the data refused to fit the theory. Presented with Tycho's high-quality data, Kepler eventually determined that an ellipse with the sun at one focus was a better fit to the trajectory of Mars than a circle with the sun at the center. Building on this breakthrough, Kepler proposed his three laws: (1) The planets move in ellipses with the sun at one focus, (2) planets sweep equal areas in equal times in their motion about the sun, and (3) the average distance to the sun cubed is proportional to the period squared.

The scientific biographies of Tycho Brahe and Johaness Kepler serve to illustrate some very important themes of scientific progress related to the search for scientific laws. To arrive at his laws of celestial motion, Kepler had to first accept in some fashion a general theoretical framework without empirical proof (Copernicanism); second, abandon prevailing scientific dogma (Aristotelianism); third, have access to data with sufficient accuracy to reveal regularities (empiricism); and fourth, adopt mathematics as an elliptical and predictive form of expression for the regularities in the data (mathematical reductionism). This is a canonical example of the inductive-deductive recursion, in which theory and data co-evolve towards improved solutions. In essence, physical theory seeks to explain the regular component in the behavior of objects, through relationships among quantitative variables, and these regularities are called the Laws of Nature. Typically, regularities are expressed using mathematics. A challenge for biology in the 21st century is to bring the sensibility of Kepler to the vast Tycho-like data resources of biological science, and in this way search for the law-like regularities in biology.

The Philosophy of Natural Law

One might ask why laws of nature are of interest at all. They are in part because there seems to be a strong correlation between law-like behavior and our ability to perform inductive inference (Goodman 1947). In other words, laws help us to generalize reliably from instances of an empirical phenomenon. For example, Newton's laws of motion are shorthand for an effectively infinite number of observations on falling apples. Furthermore, laws when expressed mathematically, represent a form of data compression, in which a great deal of phenomenology can be captured in a terse symbolic description (this is what Gell-Mann meant when he spoke of sonnets and wakas). Laws also serve to reveal correlations among different theoretical principles, for example by finding equivalences among equations (Dretske 1977), and thereby pave the way towards superprinciples of nature such as supersymmetry in physics.

The philosophical debate about laws of nature makes a distinction between two broad schools of thought: regularity theories and necessitarian theories.

Both regularity theorists and necessitarians agree on the following conditions for a theory to qualify as a law of nature (see the *Internet Encyclopedia of Philosophy*):

1. The theory relates to a factual truth and not a logical one (SFI is in Santa Fe, N.M., versus every positive integer has a corresponding negative value).

2. The theory is true for every time and place in the universe.

3. The theory contains no proper names (laws relate to general concepts, not people or places).

4. The theory makes universal or statistical claims.

5. The theory makes conditional not categorical claims. (Given a certain mass and acceleration, then the force can be determined, versus the statement "mass exists.")

The necessatarians would append the additional condition:

6. The theory is physically necessary and could be no other way.

This final clause usually implies deriving laws from still more fundamental principles.

While these five conditions might be necessary, they are not sufficient. This is because they cannot distinguish among accidental truths, false existentials, and genuine laws of nature. Accidental truths are statements such as "DNA and RNA are the universal molecules of biological inheritance." Biologists have, after all, never observed an alternative molecule in nature, and all terrestrial species utilize these molecules. Necessary truths are statements such as "no object having mass can be accelerated beyond the speed of light." This statement is not rendered a necessary truth because this prohibition has never been violated, but because it derives from a more fundamental theory of nature, and moreover, is correlated with a larger set of constraints forbidding related behaviors. Philosopher Karl Popper has argued that laws forbid certain actions, whereas accidental truths do not. Another way to think about this is that laws are reinforced by observations, whereas accidental truths are left as unique instances. Philosopher Nelson Goodman (1947) proposes that law-like statements can receive confirmation from events, whereas accidental statements cannot.

A further conceptual problem with laws is their anachronistic quality. Whereas laws aspire to the very highest levels of generality, they are often subsumed within subsequent theories. Newton's laws of motion are subsumed within Einstein's theory of relativity, and Boyle's law can be derived from the later kinetic theory of gases. There is a historical component of what comes to be called a law based on the perceived generality of the theory to the scientific community of any given time.

(continued)

Wigner on Laws of Nature and Invariance Principles

The physicist Eugene Wigner has suggested that events are organized according to the laws of nature, whereas the laws of nature are themselves organized according to symmetry or invariance principles (Wigner 1963). There is a hierarchy of theory, with laws subsuming observations, and symmetry principles encompassing laws. Symmetry, following the definition of the mathematical physicist Emmy Noether, refers to some quantity expressed in an equation (such as energy) remaining independent of a change in a continuous parameter (such as time).

Scientific explanations provide a few simple principles according to which properties of an object or event can be understood. Our theories serve to eliminate the element of surprise and tend to turn all observations into inevitabilities. Components of behavior not specified by the laws of nature are called the initial conditions. Wigner writes, "The former are precise beyond anything reasonable, the latter virtually nothing is known about."

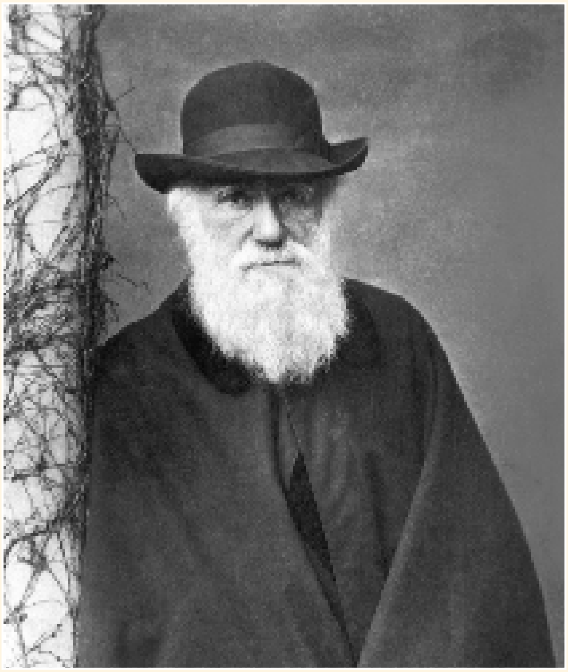
Wigner asks, "How can we be certain that we know all the laws relevant to a set of phenomena?" If we are incorrect in our formulation of these laws, there is a possibility that the number of initial conditions required to specify a behavior would be larger than is strictly necessary (the regulatarian dilemma). One way to determine this would be to show that initial conditions could be chosen arbitrarily. Unfortunately, in most cases, this is not an option. This problem is particularly present in biology, where many phenomena are the outcome of lengthy evolutionary processes, and where changing environments introduce a slew of new initial conditions on which to select.

Laws in Living Systems

If we were to provide a short list of laws of physics we might include Kepler's laws, Newton's laws, Boyle's law, Hooke's law, Coulomb's law, Ohm's law, the laws of thermodynamics, Maxwell's equations, Hubble's law, and elements of the theory of relativity and quantum mechanics. What laws could we write for living systems that are not merely diverse manifestations of the underlying laws of physics (e.g., conservation principles)? We might go with exponential growth without resource limitation, Mendel's laws, the Hardy-Weinberg law, Gauss's law of competitive exclusion, elements of the Darwinian theory of evolution to include genetic drift and kin selection, and signaling with excitable media. Whereas most of the items taken from the physics list conform to the minimal set of criteria required by both the regularity and necessitarian perspectives, most if not all on the biological list violate one or more of these items. For example, exponential growth is the outcome of first-order rate equations; Mendel's laws depend upon a fair segregation, which in turn depends upon meiosis, which depends upon chromosomes in cells, and so on multiplying contingencies.

Darwin's theory of evolution through natural selection has perhaps the best prospect of acceptance as a biological law. A group of physicists at the Institute for Advanced Study in Princeton asked whether evolution should be considered a universal law, such that it too might become a necessary outcome of the minimal theory of "everything" that they were pursuing. At moments such as these it is worth reiterating what Darwin's theory explains. The theory provides—given a set of restricted conditions—a putative algorithm through which living structures with some locally adaptive properties might emerge. The theory does not state that these structures must emerge; neither does the theory provide a sense of the expected distribution of structures from which the observed solution is drawn. The theory provides us with a strong justification for understanding structure by using some evolution-independent variational principles, such as engineering or molecular dynamics. It is not the theory of evolution that tells us how the eye functions as it does; for this we turn to optics and neuroscience.

So while evolution does have law-like properties, in that it applies to all



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organisms with a past—and to a degree allows us to reconstruct the past when coupled with a model of the mechanics of heredity—it lacks the quantitative power that we have come to expect from laws in physics. The question then becomes, is there some fusion of physical theory (or some other approach such as theoretical computer science or non-linear dynamics) with evolutionary theory that would satisfy this requirement? Is there some way of moving beyond what theoretical ecologist and president of the Royal Society, Lord Robert May has elegantly described as "theories of contingent generality," and the philosophers of biology, Kim Sterelny and Paul Griffiths have called "recurrent causal mechanisms"?

Most of the questions that we are asking at the Santa Fe Institute in our pursuit of the Character of Biological Law attempt to fuse data sets derived from modern collection methods in genetics, molecular biology, and behavior, with new organizational theories of biosystems. Now more than ever, biology has the benefit of a profusion of large data sets, and like Kepler with his access to Tycho's orbits, we have no excuse but to search for regularities in our data. Like Kepler, we have to abandon certain cherished ideas and search for an appropriate mathematical language with which to present our new findings.

For example, we might ask which variational principles should we use to understand biological phenomena such as scaling laws, metabolism, or signal transduction? How much generality do conservation principles in physics have in explaining typically biological phenomena? In other words, how much empirical variation can physical principles account for, and at what level of detail? When physical principles fail, can we discover, using new approaches, regularities in information and energy flows in systems with extensive patterns of feedback? There is some evidence from the study of genetic regulation that certain network architectures recur across distantly related lineages for reasons of robustness.

Another set of questions concerns which theories of functional mechanism —such as those developed by engineers—are most appropriate when exploring biological structures? Can we assume that our understanding of the function of a structure is complete enough, and the constraints sufficiently well understood, that we might understand an organism in much the same way that we understand a computer or a clock? Perhaps the optimality perspective fails when the optimality criterion is constantly shifting in time, and is itself the outcome of the behavior of the system? These problems arise frequently in the study of niche construction.

These are the broad questions that fascinate us and call for a data-driven, complex systems science. Below are some summary statements of ongoing research projects being pursued at SFI under this theme of laws in biology. Those interested in further details are urged to explore recent publications and work of the Santa Fe Institute, which can be found through links provided at www.santafe.edu.

A CHALLENGE FOR BIOLOGY IN THE 21ST CENTURY IS TO BRING THE SENSIBILITY OF KEPLER TO THE VAST TYCHO-LIKE DATA RESOURCES OF BIOLOGICAL SCIENCE, AND IN THIS WAY SEARCH FOR THE LAW-LIKE REGULARITIES IN BIOLOGY.

A. Thermodynamics of Metabolism

Biology has become increasingly aware of the role of energetic constraints in the organization of living systems. One practical means of pursuing this issue is through the analysis of the thermodynamical properties of the reductive citric acid cycle. While this is certainly a terrestrial solution to the problem of energy transduction, its largely invariant features shared by all living species are strongly suggestive of fundamental physical limitations. The citric acid cycle is made up of the same 12 chemicals in all terrestrial species, regardless of their environments and their nutrient availabilities. As such, it represents a blueprint common to life and is therefore suggestive of a pathway through which life need evolve, the fundamental engine fueling the acquisition of energy, and the mechanism responsible for the production of essential bio-molecules. This project applies the methods of self-organizing dynamical systems theory to the study of thermodynamics in this pivotal reaction network. The idea of the project is to employ these universals of biochemistry, and ask whether there are elementary physical self-organization mechanisms under which they are favored. The new approach to the analysis of metabolism proposed here emerges from the physics of self-organization in thermodynamically reversible systems. These systems differ from the dissipative reactions traditionally studied in chemical pattern formation, and also from the discrete models associated with self-organized criticality.

B. Energetics and Scaling

In cellular biological systems, diffusion is insufficient to transport energy and nutrients to targets, thus transport systems and pumps are required to move energy efficiently. The structure of these transport systems has a strong influence on the efficiency of energy delivery, and powerful consequences on the macroscopic, morphological variation observed among species, their rates of growth, their ecological distributions, and even patterns of extinction. This project provides a unifying series of models with which to directly address these issues. It is a remarkable fact of biology that the scaling relationships for mass, M, are power laws, yMb, with exponents, b, that closely approximate simple multiples of 1/4 (e.g., 1/4, 3/4, 3/8). For mass dependence, three generic principles, which should be viewed as derivative from natural selection, are postulated: (a) networks must be space-filling in order to service all local biologically active regions in an organism; (b) their terminal units, which interface with the resource environment (e.g., capillaries, petioles, mitochondria, cytochrome oxidase molecules) are invariant in size; and (c) organisms have evolved so that the energy (and possibly other appropriate quantities) required to distribute resources and sustain them is minimized. Building upon these assumptions, we show how 15 orders of magnitude of variation in basal metabolic rate across diverse phylogenetic groups can be reduced to a factor of 20 in M. We plan to extend the theory to cover 27 orders of magnitude from the terminal oxidase molecules of mitochondria to the species areas relationships in ecosystems. We ask whether these scaling principles are likely to be universal by exploring a diversity of temperatures, network topologies, and optimality criteria.

C. Evolutionary Computation & Cellular Signaling

All biological processes make use of catalysts to expedite reactions. Catalysts are operationally defined as participants in reactions which survive reactions unmodified, and without which reactions would proceed at far slower rates. Catalysts in biological reactions range from charged surfaces to protein enzymes and nucleic acid sequences. Simple catalysts lower free energy barriers, whereas complex catalysts are a vital source of information for transforming substrates. The protein kinases are universal transducers of biological information. Prokaryotes and eukaryotes make use of these enzymes—through covalent attachment of phosphates to amino acid residues—to transfer information about the environment into the response mechanisms of the cell. Phosphorylation, in other words, is the particulate current that flows through biological circuits facilitated by kinase catalysts powered by ATP. We examine the way in which catalytic architectures acquire information about the environment, and how kinase networks can act as memory stores. Molecular memory suffers from a constant degradation through proteolysis and decay, which raises the question, How are robust memories constructed? Furthermore, biological information needs to be extracted from storage for development. We explore molecular compression, protein-based data quantization, and concurrent processing with mobile process algebras.

D. Endogenous Versus Exogenous Sources of Innovation

Evolutionary innovations, like other evolutionary changes, reflect the influence of genomic and developmental changes to generate new physiological, developmental, and morphological innovations; the success of such events within the physical and biological environment; and changes in the environment that may either facilitate or retard such success. Here we examine the intersection between organisms and their environment in relation to some significant events in earth history. Of particular interest is the first appearance of multicellular animals at the end of the Proterozoic era closely associated with a series of ice ages commonly called the Snowball Earth. The Snowball Earth events are a special case of a more general problem: What is the interaction between environmental change and environmental response, both internally through changes in genomic and developmental control systems, and externally, through ecological interactions with other species? Most existing models of diversification suffer from a sort of Goldilocks problem: they are either so rococo in their development that they are of little practical use in distinguishing between different potential processes that may be involved in diversification, or they are so simple that they fail to encompass the complexity of interactions between environment, and intrinsic and extrinsic drivers. The challenge is to explore a variety of models that 1) reflect a range of biologically reasonable processes which may be involved in the diversification process; and 2) capture at least the basics of the dynamics between the physical environment and genome/developmental change and ecological interactions.

E. Evolution of Parasitism

The study of the life cycles of simple organisms such as viruses provides a wealth of data on those features of biological organization that remain conserved across groups during evolution, and those features that vary. Virus life cycles are very well documented, with many of the genes contributing to the biological function identified, and their protein products well characterized. Thus viruses provide unique systems for studying what has been called the "logic of life" (Jacob 1974)—meaning that there is a minimal set of basic functions ensuring the persistence of an evolving lineage.

Viruses are obligate parasites. This implies that the hosts with which they interact provide information critical to the completion of the virus life cycle.

LIKE KEPLER, WE HAVE TO ABANDON CERTAIN CHERISHED IDEAS AND SEARCH FOR AN APPROPRIATE MATHEMATICAL LANGUAGE WITH WHICH TO PRESENT OUR NEW FINDINGS.

Different virus groups differ with regard to the amount of information they require from the host for completion of the life cycle. Another way of stating this is to recognize that the host represents a catalyst of varying complexity, facilitating the replication of the virus genome. The viruses therefore provide us with an ideal system with which to study the evolution of autonomy—an increasing independence from environmental variables, and an increasing dependence on factors encoded intrinsically.

In this project, we explore what we might call catalytic grammars of virus life cycles. We denote them as grammars because one of the essential ways in which viruses differ from one another is in the sequencing of their basic replicatory, translational, and regulatory operations. We consider a range of virus life cycles, and their corresponding host contributions, in an attempt to build a kinetic theory of virus diversity based on regulatory variation. This approach differs from standard taxonomies of viruses, which use DNA data, or genomic organization, as a criterion for classification. We use the kinetics of regulation to explore invariant principles found among all translational parasites.

A Concluding Unscientific Postscript

— with Apologies to Kierkegaard

In starting with physics and moving into biology, we have observed that the extent to which science has been successful at discovering mathematical expressions capturing regularities has been graded. This increased difficulty in biology in comparison to physics, reflects several factors, including the contributions of non-linearities, the number and variability of initial conditions, the constancy of the environment, the degeneracy of stable states for a given set of boundary conditions, and the size of the behavioral repertoire of individual units. In biology all of these factors play an important role, and consequently make discovering law-like behavior difficult. These considerations are even more significant when we turn to the social sciences.

Some of the defining, positive features of the 20th century were scientific discoveries (antibiotics, electrical refrigeration, computers, the moon landing, fertility treatment, open-heart surgery). This local progress is often contrasted with the persistence of global social prejudices and economic inequality. Even though natural science has often been misappropriated towards undesirable social purpose, there is little disputing that scientific understanding has made progress.

The obvious answer to these questions is that human society is far more complex than the non-human, natural world, and human planning and understanding makes for individual variation that disrupts our best attempts at discovering cross-cultural statistical regularities. The factors listed at the start of this section are impediments to progress. Human culture is so combinatorially rich and self-referential that prediction becomes ineffectual.

While the complexity defense certainly is part of the story, it does not imply that we shall never discover regularities in behavior and culture. Indeed, structural anthropology, comparative linguistics, and developmental psychology pursued exactly this objective before falling foul of relativism. The Santa Fe Institute is, in parallel and in conjunction with the natural sciences, actively pursuing regularities in the social sciences through the use of quantitative models and theories. These include programs looking at very particular regularities in financial markets, to more general regularities found in all human societies, such as cooperation among unrelated individuals, the emergence of institutions, the multiple network structure of social systems, the course of cultural and linguistic history, and the neural basis of learning and socialization.

The sciences of humanity are the most recent to adopt the quantitative and compression-based approach of mathematical and computational theory. Arguably those of us working in the natural sciences have a vested interest in their success. It is, after all, social institutions and their occupational networks that fostered and now perpetuate the scientific revolution.

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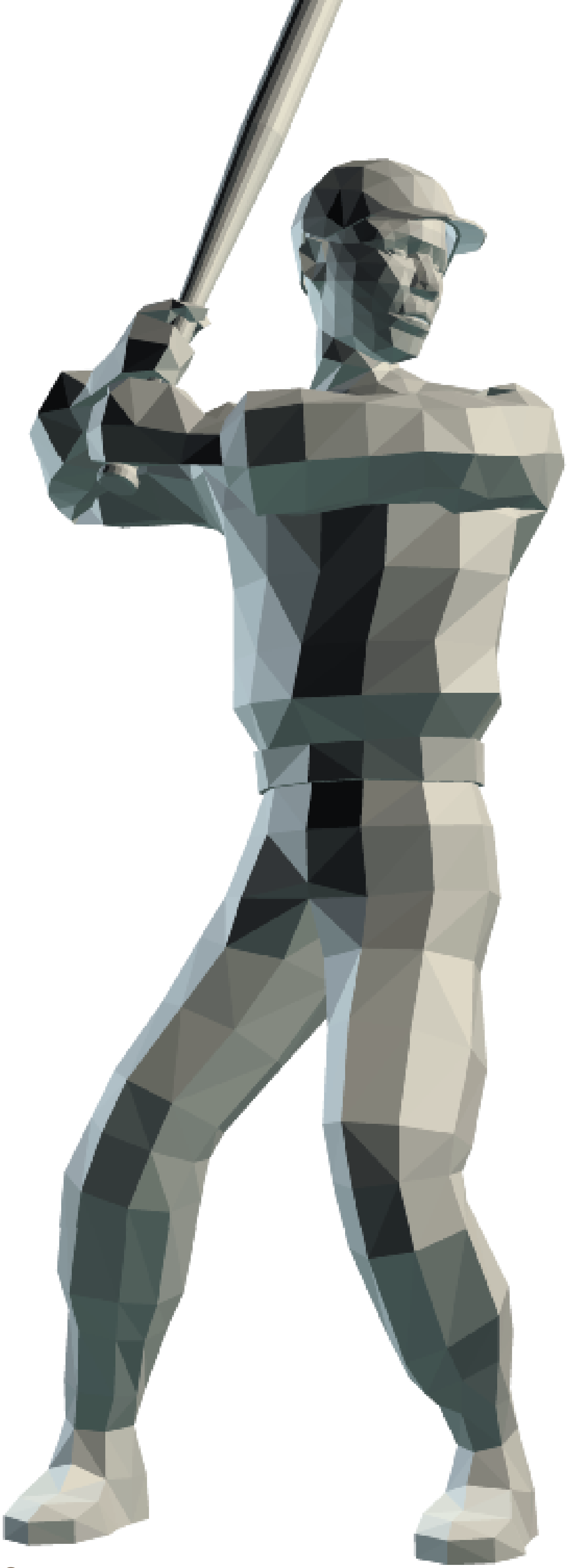


A Complex Look at Sports

By Matthew Blakeslee

Thirty years ago if you'd wanted to invest your money, you would have probably entrusted it to a cigar-smoking, gray-haired sage who'd been a Wall Street player for decades. He would have been a big node in the old boys' network, steeped in the traditions and lore of stock trading that dated back, with only minor mutations, to the days of the robber barons. True, he would base his decisions in part on "the numbers," but he would base them equally as much on his personal relationships, the rules of thumb inherited from his mentors, and on gut instinct.

ILLUSTRATIONS: SPENCER LEVY

But in the 1990s things started to change. Enter stage left the physicists, the modelers, the geeks bearing silicon, offering complex analytic methods for dicing up market dynamics in powerful new ways. These innovations paved the way for the revved-up financial world of today, with its new money-making schemes, such as currency speculation and time-series forecasting, which were inconceivable back in the days of the three-martini lunch.

In June 2004, a genial assortment of business people, sports luminaries, and academics convened in Los Angeles to discuss whether the same sort of revolution might be brewing in the world of sports. The meeting was underwritten by SFI Business Network members Legg Mason Funds Management Inc. and Credit Suisse First Boston, and hosted by the Trust Company of the West. The question on the table: Can game theory, complexity science, or even neuropsychology lend useful insights into how to build better teams, rank teams and value players, and predict tournament outcomes better than the simple methods that are still the industry mainstay?

Many of the participants were optimistic that the answer is yes, and glimmers of this new method do indeed seem to be appearing. For instance, much on everyone's lips was Michael Lewis's 2003 bestseller, *Moneyball*. The book follows the story of the Oakland Athletics as they came up with a new and unconventional set of yardsticks for valuing players, and, in the process revolutionized the way baseball is managed. With only a shoestring budget, the A's, as they are known, put together a first-rate team using players who had been passed over by all the big shots of the Major Leagues.

Ranking Teams—The Worst Way is to Have a Tournament"

Ranking teams is a messy exercise, said Ken Massey, a visiting professor of mathematics at Hollins University. He is in a position to know. Massey publishes the well-known Massey Ratings on his web site, primarily as a hobby. These ratings are used as part of the formula for the BCS (Bowl Championship Series) Rankings each year to determine which college football teams should face each other in the NCAA championship bowls. Massey outlined several kinds of mathematical models that people have used to try to capture the dynamics of teams or other institutions competing for the same prize. These included classical linear statistical methods, Markov Chains (which are the crux of the Google search engine), maximum likelihood models (on which the Massey Ratings are based), and neural networks.

"People are often confused with the BCS Rankings," Massey said, "because they think that when the championship game is played, that's the definitive answer as to which is the best team."

But team sports are so high-dimensional, he said, the very idea of creating a one-dimensional list of teams in order of merit, not to mention the notion of singling out the team that is "best," is inherently artificial. To make matters more difficult, the data sets in sports tend to be very small and very noisy. Luck, weather, and injuries play big roles in game outcomes. So do hard-to-quantify psychological factors such as slumps and home-field advantage. Even the random ordering of team face-offs in a tournament can introduce statistical artifacts into the rankings, Massey said. In addition, he discussed some of the ways even the good models can go wrong: sometimes they lead to strange rankings that put bad teams over good, or even more absurdly, rank teams in circular relation to one another, the same way paper beats rock beats scissors beats paper.

"The worst way to figure out the best team is to have a tournament," he said.

And yet, that is what's called for. Massey said that at best his maximum likelihood model is able to predict roughly 75 percent of games in baseball and about 66 percent in the NFL. The rest, he said, is where all the fun of watching and arguing about sports is found.

Scott E. Page, SFI External Faculty member and a complex systems professor at the University of Michigan, agreed that linear models can never capture the complexity of interactions inherent to team sports, and spoke of a better way to search for useful patterns that human intuition can't spot. He calls it the General Manager's Backpack Problem: given a finite budget, your job is to look at players on a few key dimensions (pitch speed, batting average, forty-yard dash time, or similar criteria) and put together the best team you can through an auction competing against other teams.

"It's a nightmare problem," Page said. "It's beyond NP hard!"—which is an engineer's way of saying that in practice you can never solve it no matter how big a computer you sic on it.

This brought Page to the centerpiece of his talk, the simple strategy game called Colonel Blotto. In Colonel Blotto, each of two opposing sides is given an army of equal size and must compete for control over a set number of territories. Each side assigns any

IF AN NFL COACH WERE TO GO BY ROMER'S CHART AND RUN ON THE FOURTH DOWN AND FAILED, IT WOULD PROBABLY BE HIS LAST SEASON COACHING, NEVER MIND THAT IT MAY BE A SUPERIOR STRATEGY OVER THE LONG RUN.

number of available troops to each territory. After all the troops have been placed, the total number of troops in each territory is revealed to both sides. The side with the greatest number of troops in a territory wins it.

In its basic form, there is no best strategy for winning Colonel Blotto; it is overwhelmingly a game of luck.

"ONE WORD HAS BEEN LEFT OUT IN ALL OF THIS SO FAR," HE SAID: "EMOTION. FOOTBALL IS A GAME OF EMOTIONS, NO QUESTION."

However, Page showed how through introducing externalities (such as interactions or nonlinearities) into the game, thereby rendering it more complex, meaningful strategy options emerge.

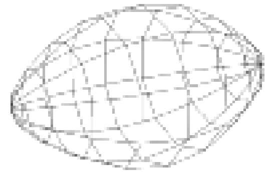
As he put it, "Complexification (of the strategic environment) leads to simplification (of the strategies)."

For example, if it turns out that controlling France and Germany also gives you extra "bonus" influence on Luxembourg and Belgium, you have a strong strategic incentive to invest troops in those two countries. Negative externalities are also possible: for instance, placing more troops in a particular region might paradoxically destabilize it by stoking native resentment. Discerning and exploiting such nonlinearities is key to forming useful strategies.

By analogy, Page said, the General Manager's Backpack Problem becomes more tractable with a more complex model of players.

"Instead of simply summing up a player's vector of attributes," he said, "look for interactions between them."

He argued that this should make the problem of picking players and building an effective team around a well-thought-out strategy easier, not harder as one might expect. He also said it could lead to a more interesting "meta-game," in which different managers pursue a range of finely minced strategies and counterstrategies.



To Punt or Not to Punt

David Romer, a professor of political economy at U.C. Berkeley, then turned to the subject of punting. Specifically, he's analyzed the common decision faced by NFL coaches of whether to punt or go for the first down. Romer has programmed a complex model that analyzes the vast, chess-like tree of contingencies sprawling before the future of any decision of whether or not to punt. Romer used the model to derive a graph prescribing when a team should kick and when it should "go for it."

Romer argued that his model shows that NFL football teams are punting much too often; they are following imitative rules of thumb that coaches have always used that are strategically poor. This pack mentality also exists in markets, causing financial bubbles. For instance, his graph shows that if a team has fourth down and one yard to go on their own 10-yard line—90 yards from the end zone—they should nevertheless go for the first down. This runs counter to the conventional wisdom, which holds that the ball should be sent as far away from the goal line as possible, even if it means giving the ball to the opposing team. Romer estimates that by following his model (and assuming that the opposing team doesn't follow this strategy), the average NFL team would win one more game per season than it does now—a considerable gain.

The next two speakers were stars of the sporting world: Norman Chow, offensive coordinator for University of Southern California, and Paul DePodesta, general manager for the Los Angeles Dodgers, and before that, one of the stars of *Moneyball*. Both men affirmed that many of sports' standard procedures and strategies exist mainly through momentum and tradition. They also agreed that even if some of these traditions are exposed as non-optimal, supplanting them will be difficult.

"In college football, people are reluctant to try new things because you never want to lose," said Chow. "We have to treat every game as if it were the Rose Bowl," he added, echoing Romer, meaning that they are so busy exploiting a good rule that they are not exploring anything better.

DePodesta echoed this in his discussion of the "management turnstile" so notorious in professional sports. If an NFL coach were to go by Romer's chart and run on the fourth down and failed, it would probably be his last season coaching, never mind that it may be a superior strategy over the long run.

According to DePodesta, almost everyone in sports, from the fans to the general managers to the investors, has an extremely short focus: this year's championship.

"There is no excuse accepted for not winning," he said. "The ends justify the means, as far as most sports people are concerned."

DePodesta, who had been hired to improve what had been a lackluster Dodger club, said he has found little enthusiasm for a team development process that takes the long view—say, sacrificing the likelihood of grand victories for several years in order to cultivate some well-chosen talent.

"Our obsessive focus on outcomes at the expense of process is counterproductive," he continued. "Teams that have good process, and patience, often do better. But few teams are willing to do it because of the mindset that you have to win a World Series or you're nothing."

Basketball or Moneyball

Dean Oliver, author of the book *Basketball on Paper*, is the creator of RoboScout, a software program that watches basketball games and analyzes them with a keen statistical eye. In much the same way the Oakland A's crunched the numbers to find new, better criteria for valuing baseball players, RoboScout looks for—and apparently finds—factors that can better predict the outcome of basketball match-ups.

Oliver used the specific example of the Los Angeles Lakers versus the Detroit Pistons NBA finals in 2004. First he listed the most common rationales people had given before the finals for favoring the Lakers at eight-to-one. These included statements such as, "The Lakers can turn up the heat any time they want to," "They have the two best players," and so on. Next he ran through the rationalizations people had offered after the Detroit Pistons won, such as, "The Lakers didn't want it badly enough," and "Detroit controlled the tempo."

Oliver quipped at this point, "Everybody has to be right both before and after."

He then went on to deflate all of those arguments, calling them superficial.

"Both of these sets of reasons are immeasurable," he said, "and therefore unmanageable. If you can measure it, you can manage it; if not, not."

In analyzing the same games, Roboscout came up with several nonstandard observations that would have predicted the Pistons' victory. For example, RoboScout observed that the Lakers couldn't get easy buckets, the Pistons forced the Lakers inside, and the Pistons controlled the offensive glass. (You can read more about RoboScout at www.82games.com.) Oliver said that tools such as RoboScout aren't used much yet, although they are starting to catch on with management. He predicted coaches would soon follow suit.

Emotions in the Game

Colin Camerer, a Caltech economist who studies the cognitive basis of economic decision making, strategic thinking, and risk taking—in a word, "neuroeconomics"—spoke of the need to inject psychology into game theory. Game theory involves the formal analysis of situations where completely rational individuals strive to maximize their own gains by competing or cooperating with others according to an established set of rules. The theory captures certain aspects of economics and strategy extremely well, Camerer said, but is deafeningly silent on all sorts of other factors—things like pride, herd mentality, and emotional attachment—that influence economic and strategic decisions in real life.

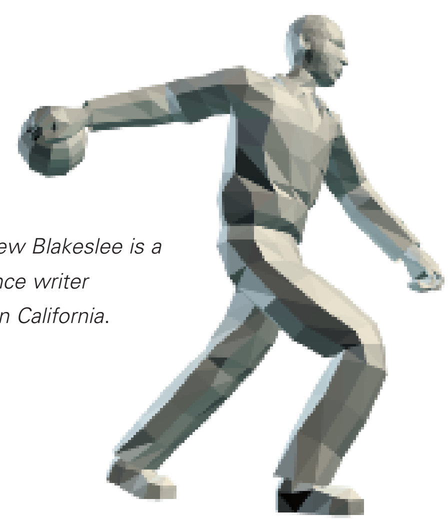
USC's Chow touched on this issue earlier in the day. "One word has been left out in all of this so far," he said: "Emotion. Football is a game of emotions, no question. The human element is so important…These are twenty-year-old kids playing in front of a crowd of fifty thousand people. Some of them are afraid, some of them are nervous, some of them are giddy. Some players choke under pressure while some really thrive." Managing all that is at least as important in his job as coordinating plays, he said.

Camerer agreed, commenting, "A five hundred-page book on game theory won't even have 'emotion' in the index. And here's the coach telling us it's the most important thing."

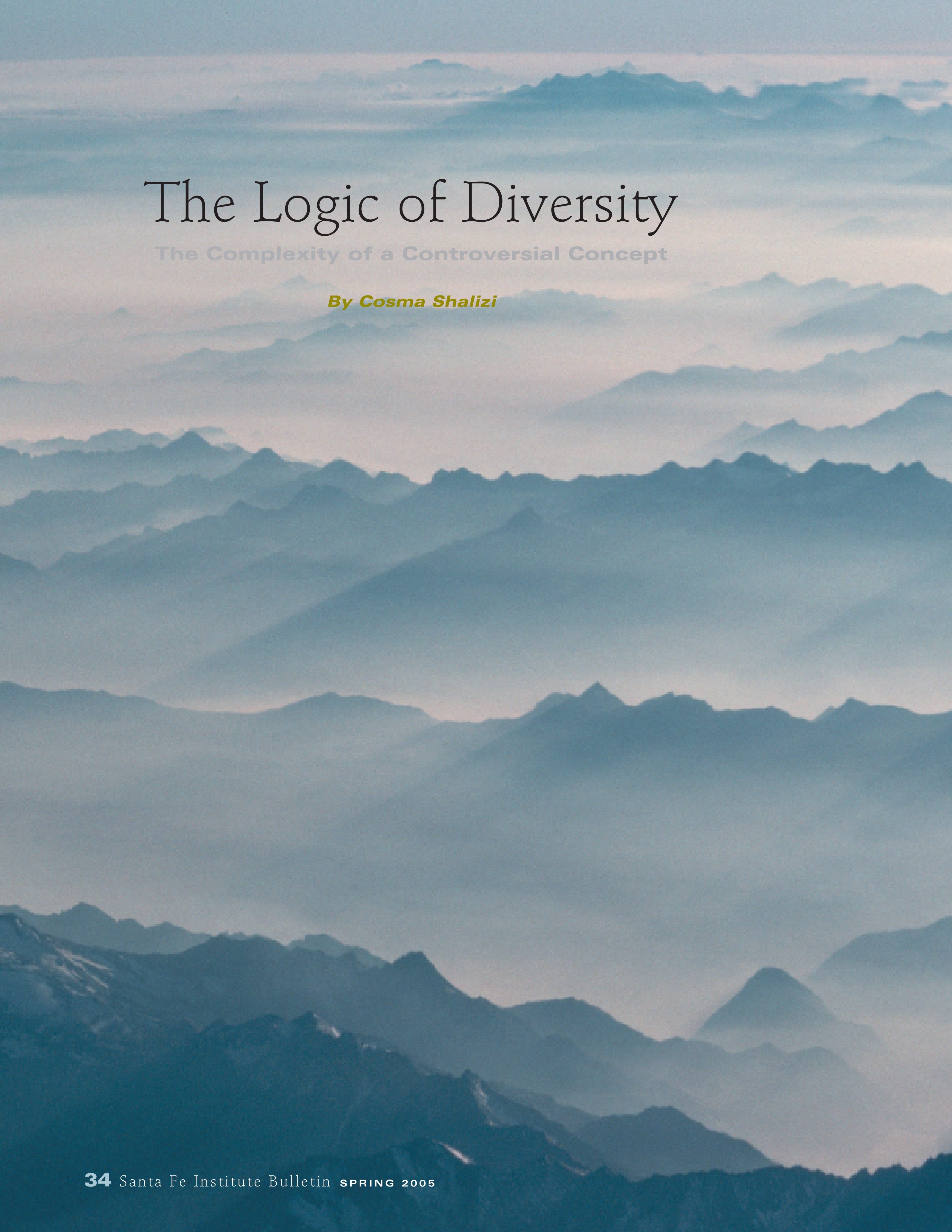
According to Camerer, game theory not only leaves out emotion, it also assumes things about people that aren't true. For example, game theory assumes we all chase the logical conclusions of our strategies to infinity, while in reality most people can only think a handful of steps into the future, if that. He also documented the fact that people often misapply or underuse the information they possess in predictable ways.

Essentially Camerer was proposing that a better understanding of people in neuropsychological terms might be able to supply analysts with new variables and insights for structuring their models. For example, DePodesta suggested that someday it may become possible to "brain type" players in order to better predict what kind of training is best for them and how they will react to pressure or deal with success.

People like DePodesta, Oliver, and most of the other speakers believe it should be possible to develop a more rigorous science of what leads to success in sports. This generated discussion regarding the emerging synthesis between pro sports and science, and the role that SFI might play in advancing that research agenda. Sports may seem an odd research subject—many think it's not serious—but it is awash in data, and the rules are well defined. It is a good environment for researchers to cut their teeth, providing insights into complex systems with human actors. Sports metaphors are often invoked by politicians and business people, and there's a reason. Features of the sporting world: heterogeneity, strategy, adaptation, creation and implementation of rules of thumb, the rise and fall of dynasties (think Rome, think Enron, think Cowboys), also apply to the business and policy worlds.



Matthew Blakeslee is a freelance writer living in California.



The Logic of Diversity

The Complexity of a Controversial Concept

By Cosma Shalizi

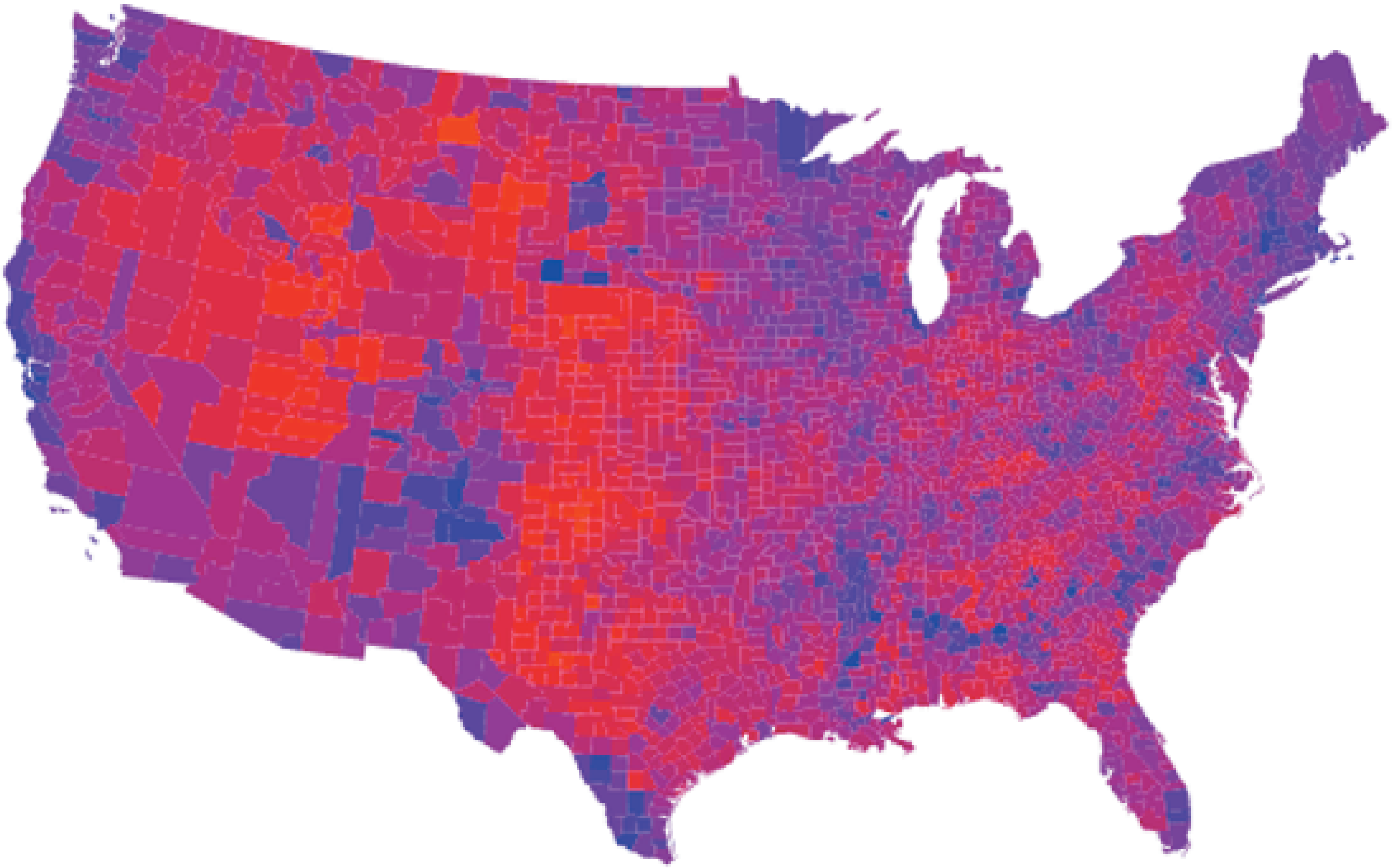
PHOTO: COURTESY CORBIS

Over the last fifty years or so, diversity has joined motherhood and apple pie as something everyone embraces, at least in public. But many who would never say publicly that there is only one correct way to do things and one admirable type of person, express such feelings in private, at least about what's important to them. For them, diversity may be okay, even good, for the recreational, shopping-mall side of life—food, clothes, music. But when it comes to the serious work of the world, there's One Right Answer, and what counts is getting as close to it as possible. Diversity seems beside the point, if not a liability. To such people, the usual platitudes about diversity sound like obvious, if perhaps well-intentioned, nonsense. Such attitudes do sometimes surface in public. In the recent Supreme Court case about affirmative action at the University of Michigan's law school, Justice Antonin Scalia opined, during the oral arguments, that the only reason there was an issue was that Michigan insisted on having a "super-duper law school" (as he put it) that was also diverse, assuming that these were incompatible goals. If Michigan wanted a diverse student body, Scalia said, it simply had to "lower the standards" and admit a certain number of incompetents.

Such views understandably infuriate many people, who nonetheless can't say just what's wrong with them. This is where the work of SFI External Faculty member Scott Page and his collaborators comes in, by showing that diversity can actually help find the One Right Answer. Page, a political scientist and economist at (coincidentally) the University of Michigan, has drawn on ideas from the study of complexity to outline what he calls "the logic of diversity." Just as classic work in political economy established the "logic of collective action" (Mancur Olson) and the logic of social choice (SFI External Faculty member and Nobel laureate Kenneth Arrow), Page thinks he has found the basic rules explaining how diversity works in society, and complexity science plays an essential part in his explanation. He shows that not only can diversity be helpful in finding good solutions, but it can even be more beneficial than individual competence.

Start with the idea of a complex problem—one that has many aspects that are strongly interdependent. Because of that interdependence, it's hard to modify just one aspect of a solution at a time—if you try to improve one thing, you'll often end up breaking several others. The idea of a "search landscape" is a convenient way of visualizing this. Picture potential solutions as points on a relief map; the height of the map at each point indicates the quality of the solution. The fact that the problem is complex, with many interdependent aspects, corresponds to the landscape having many local peaks. (Search landscapes come from evolutionary biology, where ones like this are called "rugged.") Even if there's a unique highest point on the landscape—a single optimal solution or right answer—it can be hard to find. For large, industrial-strength problems, the only way to find the optimum may be to enumerate all the possible solutions, which is prohibitively time-consuming. So, in practice, any agent trying to solve such a problem will have to employ heuristics, tricks or short-cuts that may work on particular problems, but can't be guaranteed to always find the right answer.

Closely associated with this, agents



Cartogram of the results in the 2004 U.S. presidential election. Each county is shown with an area proportional to the number of major-party voters, and with a color that reflects the proportion of those voters going to the two parties—bluer counties voted more Democratic, redder counties more Republican. Figure by Michael Gastner, Cosma Shalizi, and Mark Newman, using a cartogram algorithm developed by Gastner and Newman, and a color scheme proposed by Robert Vanderbei.

will have particular "perspectives" on the problem, paying attention to some aspects of it and filtering out all the others. If an agent faces two problems that, from its perspective, look the same, it will attempt the same solution to both, even if it notices differences between them. From its perspective, everything important is identical. If the problem is to estimate the value of a building, one agent might look at just its location and size. It will then guess similar values for similarly situated buildings, regardless of, say, age—it doesn't "see" age. Because perspectives filter out some aspects of the problem, they limit the kinds of heuristics agents can use. For example, if an agent doesn't "see" a building's age, it can't use a valuation heuristic that combines age and size in guessing maintenance costs. Conversely, every heuristic has an implicit perspective, because it responds to some aspects of the problem but not to others.

A weak heuristic is one which comes up with solutions to the problem which are, on average, only a little better than one would expect from chance. These tend to be heuristics which get stuck near local peaks in the search landscape, and can't get out of those traps, never reaching the optimum. A strong heuristic, on the other hand, is one that gives a solution that is generally nearly as good as the actual optimum. Counterintuitively, Page, with long-time collaborator Lu Hong, professor of finance at Loyola University, has shown that, under very general conditions, a diverse population of agents, each with a different weak heuristic, will outperform a single agent with a very strong heuristic—as Page and Hong say, "Diversity trumps ability." One way to grasp Page and Hong's result is to imagine the diverse but inept agents taking turns at the problem, each one starting from where the last one got stuck. Each of them tends to get trapped at local peaks, but, because they're diverse agents, they get trapped at different peaks. By using each other's work, the group avoids these local traps, and gets arbitrarily close to the optimal solution—closer than any given individual agent with a strong heuristic.

Remarkably enough, one doesn't get the same improvement from using

IN THE END THE LOGIC OF DIVERSITY EXPLAINS WHY DEMOCRACY IS SO HARD, AND SO NECESSARY.

a diverse population of agents with strong heuristics. The reason is that the strong heuristics all tend to be similar to one another—they know the same tricks, as it were—and so tend to get stuck on the same local peaks. Because they're all good in the same way, they have no ability to compensate for each others' weaknesses. "If the best problem-solvers tend to think about a problem similarly, then it stands to reason that as a group, they may not be very effective," Page says.

It's worth noting that this isn't just a trick with averaging. A new book, *The Wisdom of Crowds: Why the Many Are Smarter than the Few* and *How Collective Wisdom Shapes Business, Economies, Societies and Nations*, written by *The New Yorker* columnist James Surowiecki, has recently popularized the idea that groups can, in some ways, be smarter than their members, which is superficially similar to Page's results. While Surowiecki gives many examples of what one might call collective cognition, where groups out-perform isolated individuals, he really has only one explanation for this phenomenon, based on one of his examples: jelly beans. In a long series of experiments, students in psychology classes are asked to guess, for example, the number of jelly beans in a jar. Quite reliably, the average guess of all the students in the class is closer to the real number than the individual guesses, sometimes astonishingly close. The reason this works, Surowiecki says, is that averaging together many independent, unbiased guesses gives a result that is probably closer to the truth than any one guess. While true—it's the central limit theorem of statistics—it's far from being the only way in which diversity can be beneficial in problem solving.

If you think the only way that collective cognition can work is through pooling independent guesses, you will be puzzled about situations where it works when people's guesses are dependent. In particular, you'd expect that if each person's guess is strongly dependent on the last person's guess, then the group should fail miserably. But in Page and Hong's model, remember, each agent starts from where the last one got stuck, so its guess does depend strongly on the previous agent's. Yet these groups not only don't do badly, they do better than they would if each agent acted independently of the others. So while Surowiecki's idea is not wrong, it's incomplete.

It's also important to distinguish this idea from the division of labor, even the division of cognitive labor. Big engineering projects (say, designing a new jet), are often broken down into modules which are nearly self-contained, with well-defined interfaces connecting them. This means that someone can work on the autopilot, without knowing all the details of the engines, just some of its interface properties (for example, the maximum thrust it can deliver), and someone else can work on the engines without knowing the details of the autopilot. This in turn means that engineers can specialize in control or power, solve their individual problems, and then put their individual partial solutions together, with some hope of the result working. Often some tweaking is needed, because the interfaces don't perfectly encapsulate the different modules, but much less than if the project wasn't broken up this way to start with. Specialization is a way of using diversity, because control and power engineers do learn to think differently (as anyone who's had to coordinate both can tell you). But this isn't what's going on in Page and Hong's set-up, where the team is dealing with a single, undivided, perhaps indivisible, problem.

The division of labor is, in part, an adaptation for handling complex problems, but only those which are complex in the straightforward sense of being very large. It relies on finding a way of decomposing the large problem into nearly-separate parts, so that it can be attacked through a strategy of divide-and-conquer, with different people specializing in conquering the various divisions. (This topic, and its relation to hierarchical structure, was explored by Herbert Simon in his classic *Sciences of the Artificial*.) Diversity, in the sense Page is talking about, is another way of adapting to complexity, and specifically to complex problems which are not decomposable into neat hierarchies.

Put strategically, the idea is like this: Agents have only a limited capacity to represent, learn about, and predict their world, and so solve their problems. When the problem or environment is too complex for any one agent, then you should have many weak agents make partial, incomplete, overlapping representations. You'll be better off by doing this and then learning a way to combine them, than by trying to find a single, globally accurate representation, such as a single super-genius agent that can handle the problem all by itself. Collectively, the combined representations of the group of agents are equivalent to a single high-capacity representation. But nobody, individually, has anything like the complete picture; in fact, everybody's individual picture is pretty much wrong, or at best drastically incomplete.

Powerful, high-level capacities which emerge from the interplay of low-level components are a common feature of complex systems, but here as elsewhere, just having the components and letting them interact is not enough. The organization of the interactions is crucial. In the brain, for

"DIVERSITY TRUMPS ABILITY."

instance, this is the difference between coherent thought and delirium, or even epilepsy. In distributed problem solving, social organization is the key to realizing the potential benefits of diversity, and avoiding mutual incomprehension or socially-amplified folly. Improving organization raises performance in diverse groups by making it easier for the agents to utilize each others' abilities and efforts, which can be more important, as we've seen, than improving those individual abilities. Page and Hong's model shows, in a sense, how well the group could do with the right organization, but not how to find that structure.

When political scientists, say, come up with dozens of different models for predicting elections, each backed up by their own data set, the thing to do might not be to try to find the One Right Model, but instead to find good ways to combine these partial, overlapping models. The collective picture could turn out to be highly accurate, even if the component models are bad, and their combination is too complicated for individual social scientists to grasp.

It's already widely appreciated that markets perform this kind of distributed problem-solving. No individual in the market can grasp all the information about goods and services in every economy, much less search over allocations to ensure that supply and demand balance. But the market as a whole not only finds such allocations, it adjusts them as conditions change, and does so by using the diverse local knowledge of the participants. Even though it's appreciated that markets can solve problems individuals can't grasp, it's disconcerting to think this way about something like a scientific discipline, or about more formal institutions, such as governments and businesses. Or, for that matter, law schools. In a provocative mood, Page suggests that Scalia "got things completely backwards." Given the complex interdependencies of the problems we ask the legal system to resolve, it might well be that diversity is the only way to excellence, that "ability is diversity, and to say there's a trade-off is in some sense to misunderstand the nature of ability."

Which is not to say that diversity has no drawbacks. Diversity of heuristics and perspectives tends to be linked to diversity of values and interests. This, as Page says, is where things get tricky. We've been assuming everyone agrees on what makes a solution good or bad, that everyone shares a common set of interests. But, unless everybody values exactly the same thing, and receives exactly the same share of what the group gets, this won't likely be the case. Diverse groups, good at solving problems, will tend to be ones whose members have diverse ideas about which problems they ought to solve. Should a police department catch criminals, deter potential criminals, reduce the harm done by crime, or get the police chief reappointed? The study of how to aggregate differing agents' preferences into a common collective choice brings us back to Kenneth Arrow's "logic of social choice" mentioned earlier.

This is bad news, because the main thrust of the logic of social choice is Arrow's "impossibility theorem." The gist of the theorem is that under certain conditions of rationality and equality, it is impossible to guarantee that societal preferences will correspond to individual preferences when more than two individuals and alternative choices are involved.

The way to avoid the impossibility theorem is for people in the group to agree in their preferences (or not disagree too much). One way to achieve this is to limit the membership to those with the "right" values, but this will in turn reduce the diversity of heuristics and perspectives. Such groups may find it easy to decide what to do, but they're ineffective at doing it. The way to preserve diversity is to reach agreement on preferences. This could be either by reaching new, shared values, or by crafting compromises which satisfy divergent values. These are the cornerstones of democratic deliberation. In the end, perhaps, the logic of diversity explains why democracy is so hard, and so necessary.

WHEN POLITICAL SCIENTISTS SAY, COME UP WITH DOZENS OF DIFFERENT MODELS FOR PREDICTING ELECTIONS, EACH BACKED UP BY THEIR OWN DATA SET, THE THING TO DO MIGHT NOT BE TO TRY TO FIND THE ONE RIGHT MODEL, BUT INSTEAD TO FIND GOOD WAYS TO COMBINE THESE PARTIAL, OVERLAPPING MODELS.

Cosma Shalizi is a postdoctoral fellow at the University of Michigan's Center for the Study of Complex Systems.

TRANSITIONS

Crutchfield and Fontana Accept UC Davis and Harvard Appointments

Research Professor **Jim Crutchfield** moved in late 2004 from SFI to California as a professor of physics at the University of California, Davis, and to help create that campus's new Center for Computational Science and Engineering (CSE). Crutchfield has been associated with SFI since 1991 working in the areas of nonlinear dynamics, solid-state physics, critical phenomena and phase transitions, chaos, and pattern formation. His research at SFI focused on computational mechanics, the physics of complexity, evolutionary theory, machine learning, and distributed intelligence

CSE's founding director is SFI alum John Rundle. The new CSE at Davis will develop into a graduate program in complex systems over the next three to four years and then a full academic department over the next six to seven years with graduate and undergraduate curricula in scientific computation and complex systems; we look forward to seeing CSE students here at SFI in the future!

In September 2004 Research Professor **Walter Fontana** moved from Santa Fe to join Harvard University as a professor of systems biology at the newly created Department of Systems Biology at the Harvard Medical School. Fontana's research focuses on novelty in evolution including RNA folding and evolutionary dynamics, Abstract Chemistry, and self-rewiring signaling networks. He notes, "I first set foot on SFI's premises in 1989, 15 years ago. Since then I have had a virtually uninterrupted sequence of associations with this place or state of mind, as Harold Morowitz aptly put it—first as a "hang-out while at LANL, then as a postdoc, as External Faculty and as Resident Faculty."

Both Walter and Jim have made seminal contributions to the Institute's research. We plan to continue this productive association and expect that both will contribute substantively to SFI's future development as SFI External Faculty professors.

SFI Names International Fellows from Argentina, Columbia, and Mexico

The International Program has named three new International Fellows to 2004–2006 terms. Fellows are invited for short-term visits to the Santa Fe Institute where they have the opportunity to participate in the Institute's many educational programs, workshops, and symposia.

Miguel Fuentes is currently a researcher at CONICET statistical physics group at Centro Atomico Bariloche in Argentina. He will initially be working on a project with David Krakauer on mathematical models in biological systems. Fuentes was a visiting fellow with the Consortium of Americas for Interdisciplinary Sciences at the University of New Mexico and attended lectures at SFI.

Francisco Sanin is a political scientist from the Universidad Nacional de Columbia specializing in the study of political violence and, in particular, the microfoundations of civil wars. Francisco is currently collaborating with SFI Resident Faculty member Elisabeth Wood and will be combining visits to SFI with research visits to Yale University.

Jorge Velasco-Hernandez is a mathematician currently resident at the Instituto Mexicano del Petroleo. He has broad interests in mathematical models of population dynamics, ecology, and epidemiology but will be focusing his time at SFI working with SFI External Faculty member Simon Levin on epidemiological issues such as mixing patterns among individuals, interactions among strains, and spatial aspects of disease dynamics.

SFI Community Mourns Death of Lee Segel

External Professor **Lee A. Segel**, of the Weizmann Institute of Science, passed away on January 31, 2005. His brief intense battle with illness came unexpectedly, during what had been the prime of an early retirement.

Segel did his undergraduate work at Harvard, and received a Ph.D. in applied mathematics from MIT in 1959. After two years in the Aerodynamics Division of the National Physical Laboratory in England, he joined the Mathematics Department at Rensselaer Polytechnic Institute. Until 1968, Segel worked mainly on problems in nonlinear stability theory, but his major focus switched to theoretical biology starting with a sabbatical at the Sloan-Kettering Institute and Cornell Medical School in 1968–9. He joined the Department of Applied Mathematics and Computer Science of the Weizmann Institute in 1973.

He was one of the earliest promoters of the need for close contact between theoretical and experimental biology and was a forefather of the field now known as theoretical immunology. At his death, he was director of the Institute's annual Summer Workshop on Mathematics and Biology, a NIH-supported program that explores concrete examples of how mathematical modeling can improve biological understanding.

Segel wrote many papers in mathematical biology and was the author of a handful of books based on his teaching at the Weizmann Institute. His work led to the creation of new mathematics and computational tools for investigating riches of biological behavior and his research on pattern formation and morphogenesis has been seminal in launching a burgeoning field at the intersection of biology, mathematics, and computation.

ILLUSTRATIONS: ANNE LEVY

TRUSTEES

SFI's Board of Trustees is drawn from leaders in business and finance, the academic world, and the public sector. Here are the newest additions to an accomplished roster:

Christopher Davis, Davis Selected Advisors, has more than 15 years experience in investment management and securities research. He joined Davis Advisors in 1989 after working as a securities analyst, and now leads the portfolio management team for the Davis Funds. Davis received his M.A. from the University of St. Andrews.

William Enloe has served as the chairman and chief executive officer of Los Alamos National Bank since 1994. Mr. Enloe has been employed by Los Alamos National Bank since 1971 and served as the president and chief executive officer from 1978–1994; vice president from 1975–1978; cashier from 1973–1975; and as a loan officer from 1971–1973. Additionally, he has served as chief executive officer and chairman of the board of Title Guaranty since May 2000.

Enloe serves as a member of the boards of directors of the State Private Equity Investment Committee, the Association of Commerce and Industry, Los Alamos Economic Development Committee, Los Alamos Technical Associates, Inc., MIOX Corporation, and as a member of the Los Alamos National Laboratory Foundation, the Industrial Business Development Advisory Board, the American Banker's Association Government Relations Council, and Quality New Mexico Judges Panel.

William Melton, president of Melton Investments, has been an entrepreneur and investor in the high-tech industry for over 30 years. In 1981, he founded VeriFone, Inc., the transaction automation company that made credit authorization terminals ubiquitous on retail merchant counters. From 1991 to 1999, Mr. Melton was an early investor in and board member of America Online. Additionally, Mr. Melton was the initial funder of Transaction Network Systems (TNS), founder and CEO of CyberCash, and an initial funder of other high-tech companies including Prio (sold to Infospace, Inc.) and Maxager Technology. Melton is currently an active investor and board member of several early stage venture capital companies. He holds a master's degree in Asian Studies and Chinese Philosophy.

Jerry Murdock is a managing director and the co-founder of Insight Venture Partners. Since Insight's inception in 1995, he has played a leading role in defining the company's investment strategy and has been primarily responsible for the development of many of the firm's portfolio investments. Prior to Insight, Murdock founded the Aspen Technology Group to provide strategic consultancy services to clients including Warburg Pincus, Andersen Consulting, EDS, TRW Corporation, and numerous high-technology companies and private equity investment firms.

Murdock currently serves as a director of Quest Software, Peace Software, CallWave, Inc., Dorado Software, Inc., KWI, Inc., and Digital Harbor, Inc. Previously he served as a director of Click Commerce, Convergent Group (acquired by Schlumberger), McKinley (acquired by Excite) and SeeBeyond Technology Corp. Mr. Murdock also led Insight's investment in Illuminet (acquired by Verisign).

Murdock graduated with a degree in Political Science from San Diego State University and subsequently worked at the Georgetown Center for Strategic & International Studies (now known as CSIS) where he was a contributor to the export competitiveness project.

J. Leighton Read, M.D., became a general partner at Alloy Ventures in 2001, after 14 years as a biotechnology entrepreneur and investor. He co-founded Affymax NV, under the direction of Dr. Alejandro Zaffaroni. He founded Aviron, where he served as chairman and CEO until 1999 and director until its sale to MedImmune in early 2002. He received a B.S. from Rice University in Psychology and Biology (1973), an M.D. from the University of Texas Health Science Center at San Antonio (1976), and completed internal medicine training at the Peter Bent Brigham Hospital in Boston, where he held appointments at the Harvard Medical School and School of Public Health. He has served as director for a number of other biotechnology companies, on the executive committee of the Biotechnology Industry Association, and has won several awards as co-inventor of technology underlying the Affymetrix GeneChip™.

Peter Schwartz is a co-founder and chairman of Global Business Network (GBN), a Monitor Group Company. GBN is a membership organization specializing in scenario thinking, strategic conversation, and futures research. Schwartz is also a venture partner of Alta Partners in San Francisco, and serves on the advisory boards of numerous organizations and companies ranging from The Highlands Group to USC's Institute for Creative Technologies. Before founding GBN in 1987, Schwartz headed scenario planning for the Royal Dutch/Shell Group of Companies in London and directed the Strategic Environment Center at SRI International. Schwartz is the author of *Inevitable Surprises and The Art of the Long View*. He is also the co-author of *The Long Boom, When Good Companies Do Bad Things* and *China's Futures*. He received a B.S. in Aeronautical Engineering and Astronautics from Rensselaer Polytechnic Institute.

William J. Spencer was named chairman emeritus of the International SEMATECH board in November 2000 after serving as chairman of SEMATECH and International SEMATECH boards since July 1996. He came to SEMATECH in October 1990 as president and chief executive officer. He continued to serve as president until January 1997 and CEO until November 1997. During this time, SEMATECH became completely privately funded and expanded to include non-U.S. members.

Spencer has held key research positions at Xerox Corporation, Bell Laboratories and Sandia National Laboratories. Before joining SEMATECH in October 1990, he was group vice president and senior technical officer at Xerox Corporation in Stamford, Connecticut from 1986 to 1990.

Spencer received an A.B. degree from William Jewell College in Liberty, Missouri, an M.S. degree in Mathematics, and a Ph.D. in Physics from Kansas State University.

EXTERNAL FACULTY

An important driving force of SFI's scientific life is its network of external researchers, affiliated with universities and research institutions throughout the world.

Seven individuals—**Jim Crutchfield, Walter Fontana, Alfred Hubler, George Gumerman, Timothy Kohler, Peter Schuster**, and **Martin Shubik** —well known to the SFI community (either as Resident Faculty or former External Faculty members) recently were added to this roster.

Other recent additions:

Robert Axtell is a senior fellow at Brookings Institution whose work focuses on dynamic models of social and economic systems, environmental economics and regulation, global change science and policy, and industrial organization and economic geography. Current projects include industrial ecology and agent-based modeling, social influences and smoking behavior, firm dynamics, market volatility, and discount rate policy.

Timothy Buchman is professor of surgery at Washington University School of Medicine, with specific expertise in trauma and intensive care, practices that present some of the most dramatic situations of complex systems failure and recovery. His research agenda is focused on the role of noise or "biological variability" in interacting organ systems.

Arizona State University Biomathematics Professor **Carlos Castillo-Chavez**' research focuses on the role of dynamic social landscapes in disease evolution. He has also worked on the role of dispersal and disease as enhancing mechanisms of ecological diversity. He is currently working problems at the interface of homeland security and disease invasions (natural or deliberate) and on models for the spread of social "diseases" such as alcoholism and Ecstasy use. Carlos Castillo-Chavez directs the Mathematical and Theoretical Biology Institute, which offers research opportunities at the interface of the biological, computational and mathematical sciences.

The current research of **Eric Heller**, professor of physics at Harvard University, is in the area of chaotic phenomena in quantum mechanics, on mesoscopic physics, and on areas relevant to quantum computing. His publications include works on scattering, cold atom collisions, and quantum dots (a proposed technology for quantum computing). Heller leads a large research group and collaborates closely with chemists and experimentalists.

Kunihiko Kaneko, professor

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of pure and applied sciences at the University of Tokyo, is one of the leading complex systems researchers in Japan. As an Ulam Fellow at the Center for Nonlinear Studies at Los Alamos National Laboratory in the early 1990s, Kaneko pioneered a class of models known as "coupled map lattices" for pursuing the structure and mechanisms of complex phenomena. He has developed globally coupled maps (GCM) and in recent years has considered the origin of life with a computational model developed from GCM.

Bette Korber, staff scientist at Los Alamos National Laboratory, is an internationally recognized AIDS researcher. She applies computational methods to study human retrovirus evolution and diversity, focusing on international variation and vaccine design. Her work brings together immunology, virology, genetics, mathematics, and computing technology. The Los Alamos HIV sequence database that she has overseen for close to a decade provides a basic resource for HIV researchers, facilitating the investigations of thousands of scientists in the field.

Michel Morvan is a professor at Ecole Normale Supérieure in Lyon, France. Morvan's interdisciplinary activities began with a study of the lattice structure of the states of sandpile models, creating a formal mathematical structure for self-organized criticality. Recently his work has focused on how one can do complex systems research in a mathematically principled way, and especially understanding when simulations are robust under different conditions. Morgan is playing a pivotal role in building complex systems activities in Europe including recent EU-sponsored Thematic Institutes and invitational workshops involving young complex systems researchers.

Steen Rasmussen has pioneered several methods and applications for self-organizing processes in natural and artificial systems including abstract self-programmable matter, molecular dynamics (MD) lattice gas simulations for molecular self-assembly, rational and evolutionary protocell design, as well as novel simulations for large-scale socio-technical systems. He is currently the (acting) team leader for the Self-Organizing Systems team at Los Alamos National Laboratory. He also leads the Los Alamos Astrobiology program working on experimental and computational protocells. In addition he is one of the principal investigators on the new European Union sponsored Programmable Artificial Cell Evolution (PACE) program and he was one of the founders of the Artificial Life movement.

David Sherrington is Wykeham Professor of Physics and Head of Theoretical Physics at University of Oxford. Sherrington is a condensed matter theoretical physicist best known for his seminal contributions to the theory of spin glasses. Sherrington is one of the world's experts in the application of statistical mechanics to complex problems in physics and biology; he and his co-authors have worked on modifications of the minority game including noise, and have demonstrated how statistical mechanics may be applied in this context. He is also currently interested in emergent behavior in neural networks and in cognitive processes.

James Sidanius received his Ph.D. in political-psychology at the University of Stockholm, Sweden in 1977 where he also taught for 10 years. He joined the Psychology Department at UCLA in 1988 and is currently a fellow at UCLA's Center for the Study of Society and Politics. Sidanius is author of some eighty scientific papers in the general field of political-psychology. This work includes study of the interface between political ideology and cognitive functioning; the political psychology of gender, group conflict, and institutional discrimination; and evolutionary psychology. Sidanius is co-author of several books including *Social Dominance: An Intergroup Theory of Social Hierarchy* and *Oppression and Racialized Politics: Values, Ideology, and Prejudice in American Public Opinion*.

Sergei Starostin is a Russian scholar at the Moscow University for the Humanities, who is also affiliated with Leiden University in the Netherlands. A member of the Russian Academy of Sciences, his reconstructions of language phyla at great and shallow time depths include a reconstruction of Proto-Kiranti and Tibeto-Burman for the Himalayan Languages Project of Leiden University. Starostin is the co-author of the recent *Etymological Dictionary of Altaic Languages* and is a founding member (along with Murray Gell-Mann and Merritt Ruhlen) of SFI's Evolution of Human Languages Project, a program devoted to tracing the genealogical tree or phylogeny of human language.

Steven Strogatz is a professor in the Department of Theoretical and Applied Mechanics and the Center for Applied Mathematics at Cornell University. He is the author of the textbook *Nonlinear Dynamics and Chaos: With Applications to Physics, Biology, Chemistry, and Engineering* and the trade book *Sync: The Emerging Science of*

Spontaneous Order. Strogatz' seminal research on human sleep and circadian rhythms, scroll waves, coupled oscillators, synchronous fireflies, Josephson junctions, and small-world networks has been featured in *Nature*, *Science*, and *Scientific American*, among other publications.

Joseph Traub is the Edwin Howard Armstrong Professor of Computer Science at Columbia University. He was founding chairman of the Computer Science Department at Columbia from 1979 to 1989 and founding

chair of the Computer Science and Telecommunications Board of the National Academies from 1986 to 1992. From 1971 to 1979 he was head of the Computer Science Department at Carnegie Mellon University. Traub is the founding editor of the *Journal of Complexity* and an associate editor of *Complexity*. He is the author of some 120 papers and nine books including

The work of **Colleen Webb**, assistant professor of biology at Colorado State University, focuses on theoretical evolutionary ecology, coevolution, species interactions, resiliency, quantitative genetics, genomics, nonlinear dynamics, and spatial models. Currently, she is studying how ecosystem level characteristics, such as modularity, enhance the robustness of ecosystems to disturbance (resiliency), and whether these higher level characteristics can evolve from selection at the individual level. From 2001 to 2003 Webb held a joint Santa Fe Institute/Yale University postdoctoral fellowship, working on the robustness of ecosystems.

Kenneth Weiss is Evan Pugh Professor of Biological Anthropology and Genetics at Pennsylvania State University. Weiss has been a leader in the use of genetic variation to ask and answer anthropological and evolutionary questions about humans. His work spans paleodemography as well as the genetic basis of diseases. At Penn State, Weiss has developed his lab with specializations in mammalian models of complex traits and in the genetics of human disease. He is the author of numerous publications including a widely-read column in the journal *Evolutionary Anthropology*.

Douglas White is a professor of anthropology and graduate director of social networks at the University of California at Irvine. Trained at the University of Minnesota, White has done field research of Ojibwa Indians, and societies in Veracruz and other parts of Mexico. White's research interests focus on social structure/networks, modeling social systems and dynamics, and mathematical anthropology. His co-edited books include *Kinship, Networks and Exchange* (1998) and *Research Methods in Social Network Analysis* (1991). White's current modeling work is on large-scale longitudinal studies of human populations and the network dynamics of changing institutional configurations.

SFI Postdoctoral Fellows Bieda and Choi Move to New Institutions

SFI Postdoctoral Fellow **Mark Bieda** has taken a position in the Farnham Laboratory at the UC Davis Genome Center. This new organization conducts research on the phenotypic consequences of genetic variation through an approach that combines comparative, functional, and structural genomics. While at SFI, Mark's work focused on the evolution and development of single neuronal properties, genomic analysis of neural genes, and analysis of poxvirus interactions with the immune system.

Jung-Kyoo Choi is now at the School of Economics and Trade at Kyungpook National University in South Korea. Choi's work at the Institute focused on the evolutionary dynamics of human behavior and institutions. He studied the formation, evolution, and spread of cooperative norms, and various institutions within communities that support these norms.

Borenstein is 2005 Steinmetz Fellow

Elhanan Borenstein, a graduate student at Tel-Aviv University, has been selected as the 2005 Steinmetz Fellow. The Steinmetz Fellowship, awarded to Complex Systems Summer School (CSSS) alumni, supports a one-month research residency at the Institute. Its aim is to provide the opportunity to CSSS students to further pursue research projects in complex systems and to participate in SFI scientific activities.

Borenstein's research interests focus on artificial life and evolutionary computation, the interaction between imitation and evolution, cultural evolution and social behavior, and models of gene-meme co-evolution. During his stint at SFI, Elhanan will work on developing a conceptual computational/mathematical model for genotype-phenotype mapping.

PHOTO: PATRICK MCFARLIN

Understanding Communication—From Interstellar to Intercellular and Beyond

By Rebecca E. McIntosh

While considering how best to approach the subject of communication for a recent Santa Fe Institute Annual Business Network Meeting and Symposium, SFI Research Professor David Krakauer contemplated orders of magnitude. What would it be like to approach the subject of communication networks from the most vast expanses, such as space, to the most minute, such as quantum mechanics? Thus, the structure of the Symposium was set, taking members on a journey of discovery through many fields of research, and revealing that although the networks may differ greatly, some principles remain generally applicable: whether examining communication between planets, between primates, or within cells in a human body, understanding the flow of information is key.

Krakauer set the stage by defining many models of communication networks, both traditional and innovative, including the canonical information theoretic principle of a sender (or node) giving specific information to a receiver (another node) through a channel or link. What complicates the situation, though, is that in most cases, multiple nodes are in fact sending and receiving information simultaneously, which necessitates integration over multiple channels and filtering out different sources of noise. This problem becomes even more complicated when communicating through multiple networks, as is common in biology and social systems. Furthermore, in some networks, most nodes are equally effective, while certain "key" nodes, if they were disrupted, would drastically change communication throughout the network. The meeting aimed to emphasize the need for a new, non-equilibrium network information theory applicable in many research areas.

Krakauer explained that because the problem of integrating across multiple information sources is common in many types of communication networks, be they natural or engineered, the conference should explore networks by common structure and function, rather than by discipline. To further emphasize this, the presentations were arranged according to network scale, illustrating the important property of self-similarity, such that no matter how large or small the networks, many of the fundamental properties persist. This way, he explained, representatives from different areas of expertise could converge on the subject, making contributions and applying new insights to their respective fields.

Somewhere Out There

The first presenter, Seth Shostak, from the SETI (Search for Extraterrestrial Intelligence) Institute began by addressing the topic of interstellar communication. He explained that SETI has worked to develop ways to detect sentient life on other planets by looking for signs of radio or optical communication. In order to do so, SETI has used a large radio telescope in Puerto Rico, an optical telescope at the Lick Observatory, and is currently developing an array of 350 radio telescopes in California.

Discussing the likelihood of life existing on other planets, Shostak explained that most scientists in his field agree that statistically life probably does exist out there somewhere. In fact, he noted, there are more stars in our galaxy alone than grains of sand in North America, that many are not unlike our sun, and that more than 130 planets have already been detected. However, even though planets with biology—even very old ones—could be common, the matter of whether or not there is intelligent life on them is, of course, a separate question. "It's not entirely clear that if I give you a bit of time, you get intelligence," joked Shostak.

Shostak explained that our ideas about what extraterrestrial intelligent beings might be like are probably rather naive. Given the fact that the Sun is a relative newcomer to the galaxy, other intelligent life forms, if they exist, could very well have mastered artificial intelligence and produced thinking machines. Any aliens that we might get a signal from, could, in fact, be machinery, not protoplasm.

Shostak emphasized that sending information between stars is relatively easy, and therefore by eavesdropping on the communication networks throughout the galaxy, scientists might detect advanced life if it's really out there. "We're not trying to figure out what E.T. is saying," he said. "We're just trying to see if the transmitter is on."

Also discussing large-scale networks, Chris Wallace, of Northrop Grumman Mission Systems, presented the audience with a glimpse of the satellite communication systems around the planet and how they are used. This network of communication has layers in space, within Earth's atmosphere, on the ground, and in the water. Each layer has many capabilities. For instance, with data from some of the space satellites (in the upper layers of the system), it is possible to view the Earth clearly enough to identify different species of trees.

Wallace showed how networks of satellites communicate with networks of aircraft, which then pass information to networks on the ground—which could include individuals in the military. Wallace described the use of coordinated systems in military operations and even showed the Symposium participants examples of how this information could be of use to soldiers on the ground in Iraq. He explained that soldiers in one area are able to use satellite information to locate soldiers in other areas (not visible to them) and to monitor and communicate about each group's position. Naturally, one of the key components in this network is that not all nodes are privy to the information, and that it must be kept secret, especially from the enemy.

Power Structures in Communication—"Knocking Out" a Primate

Another type of communication discussed was status-signaling interactions among nonhuman primates. Jessica Flack, a postdoctoral fellow at SFI, explained the role of communication in the "organizational mechanics" and robustness of animal social organizations. Flack is interested in how power structures, which emerge from status-signaling interactions, influence intra- and inter-organizational heterogeneity in conflict management performance and style, and how conflict management mechanisms, in turn, influence social network structure.

Using ethological techniques that include video and voice-recording of primate social interactions in large, captive groups of macaques (monkeys found mainly in Asia) and chimpanzees (apes found in west, central, and east Africa), Flack collects data on status signaling interactions, conflicts, interventions by third parties, reconciliation, and pro-social behaviors including grooming and play. It turns out that the macaque social group studied by Flack and her colleagues has a log-normal power distribution, in which a few individuals receive many status signals from many individuals. These individuals are responsible for a large majority of effective conflict management. This conflict management, called policing, occurs when third-parties impartially intervene into ongoing disputes among group members, thereby terminating the conflict. Although policing is relatively rare, occurring in only about 15 percent of disputes, Flack hypothesized that it plays an important role in organizational robustness. To test this hypothesis, Flack and colleagues performed a "knockout" study. Knockout studies are common in the field of developmental genetics, where researchers infer the function of genes by disabling them and assessing changes to organismal phenotype following knockout.

Using this same logic, Flack temporarily and repeatedly removed powerful individuals responsible for effective policing and asked how social network structure and social system variables, like levels of aggression and reconciliation, changed when the policing mechanism is disabled. In the absence of policing, aggression increased, pro-social behavior decreased, and social networks fragmented – indicating that the presence of powerful policers plays an important role in organizational plasticity and robustness by promoting positive interactions among relatively unfamiliar individuals and maintaining network structures that promote information flow through the system. The upshot of all of this is that organizational robustness, as measured through changes to social network structure, is made possible by effective conflict management, which in turn is made possible by a power structure that emerges from a status communication network.

How Cells Communicate

Further down the spatial scale of the networks, David Krakauer discussed his work with External Faculty member Walter Fontana, of Harvard's Systems Biology Institute, on networks of communication within cells. These networks, which typically consist of modified proteins, are not only essential to the cells' ability to communicate with each other, but they also make up the primary mechanism by which a message that reaches a cell can then be transmitted to the nucleus within the cell. These signals frequently induce DNA to express copies of genes that will be translated into proteins, which modify communication networks or perform more general functions for the cells. The two types of regulatory networks Krakauer discussed were signal transduction networks (protein-protein interactions) and gene regulatory networks (protein-gene interactions).

In describing how signal transduction pathways function, Krakauer explained that in response to a stimulus, proteins floating in a cell are able to spontaneously come together to create a network or pathway. This is in contrast to engineered networks that typically exist as a fixed topology. The self-assembling property of biological regulatory networks present new theoretical challenges in biological information theory. One example is the cascade network, in which a set of proteins work as a relay of connections in order to pass a message from the exterior of a cell to the nucleus. The cascade circuit has been observed to have many computational properties, including amplification, filtering, and integration. In contrast, ionic signaling pathways occur when a protein (or ligand) attaches to the outside of the cell causing the release of charged particles that then affect many different proteins within the cell. The ionic interactions are more diffuse, which Krakauer likened to the systemic modulation of nerve cells by circulating hormones, as opposed to the precise connections between nerve cells in the brain. The ionic signals are like a cloud, and the cascade is a network.

The importance of these cell communication pathways can be illustrated through examining certain diseases. For instance, the protein interferon is produced by HIV-infected cells to warn other cells (by binding to a receptor upstream of a signaling pathway) to enter into a virus-activated state, thus making them less susceptible to infection. However, there can be substantial variation in this response. For example, some people have large amounts of interferon and are thus less likely to get HIV, and males and females vary in their interferon pathways. Viruses can attack these signaling pathways, disrupting the flow of information and crippling the host response.

Another example of the importance of cell communication has been found in cancer research. It is understood that certain signal pathways are disrupted in cancerous cells with mutations to proto-oncogenes. These pathways are normally used to induce a cell to proliferate, but in cancerous cells they are prevented from turning off, causing the cell to proliferate uncontrollably. Conversely, it is normal for cells to be regularly signaled to commit suicide and die, termed "apoptosis" (especially when defective), but in many cancer cells, the pathways that instruct the cell to enter apoptosis are disrupted and the cell immortalized. The disruption of these networks can be likened to memory loss in the nervous system, whereby adaptive states are erased through the action of mutations, and hence disease becomes a form of molecular network amnesia.

Quantum Communication

Carlton Caves, of the University of New Mexico, captivated the audience with a discussion of quantum information theory and quantum key distribution. As mankind continually advances its methods of communicating, through satellite and computer networks, one of the biggest challenges continues to be security of the communicated information. Secret information, such as issues of national security or even bank account details, is constantly being transmitted. To protect this information from the prying eyes of hackers, communication is encrypted; the sender and receiver share a security code or key used for encryption, without which decryption is practically impossible. However, this merely changes the emphasis of the security. Caves addressed the question: how are the security keys, packets of information themselves, kept secure when transmitted over open networks?

Caves used the example of secret communication between two parties, Alice and Bob, to illustrate concepts of quantum key distribution. Essentially, Alice wants to send information to Bob so that they can share a secret code. The scheme proposed uses lasers to create individual photons, which Alice can send through two channels. The photons represent binary information (0 or 1)—characterized by their polarization. This is done in two ways, vertical-horizontal polarization or diagonal left-to-right and right-to-left polarization. When Bob receives the photons in the first channel, he measures the polarization of each, using a randomly selected coordinate set, sometimes vertical-horizontal, and sometimes diagonal. Alice will then send, through the second channel, the correct orientation of the coordinate set used to generate the polarization of the photons, but not their digital values (0 or 1). Comparing results, Bob can discard measurements where the incorrect coordinate set was used, therefore leaving the correct digital values. This digital sequence becomes their secret key, and can be used as a "one-time pad" to send secure information.

The crux of this encryption scheme is the use of individual quantum objects, photons, to transmit the information. Quantum mechanics dictates that an observation cannot be made without perturbing the state observed. In the case of photons, they cannot be seen without being absorbed (or destroyed), thus only Alice and Bob share the key and can determine if someone is trying to eavesdrop. Furthermore, once they have a secret key, Alice and Bob can send data back and forth using the key to encrypt it.

Caves explained that although this technique is still very much a theory, there are some products already available to help individuals create secret keys. Traditionally, research efforts have been based upon quantum information being transmitted with lasers, computers, and fiber optic cables; however, research (including some at the Los Alamos National Laboratory) is now being conducted to try sending these keys through the atmosphere.

Other conference speakers included Peter Monge, of the University of Southern California, who explored the theory of communication networks. Some celebrities also visited the proceedings. James Surowiecki, writer for *The New Yorker* and author of *The Wisdom of Crowds – Why the Many Are Smarter Than the Few and How Collective Wisdom Shapes Business, Economies, Societies and Nations*, spoke on collective reasoning. Also on hand was New Mexico Governor Bill Richardson, who presented a few points about communication in politics and declared November 5th as "Santa Fe Institute Day" in New Mexico.

Rebecca E. McIntosh is a science writer living in Santa Fe.

PHOTO: COPYRIGHT CORBIS

Seeking Security in a Hostile Environment

By Rebecca E. McIntosh

PHOTO: COPYRIGHT CORBIS

A major theme of the early part of the 21st century seems to be security—how to create it and maintain it. Though the primary focus has been on national security, a quieter foe relentlessly threatens our daily life. In November of 2004, members of the Santa Fe Institute Business Network held a topical meeting to discuss this very issue: security of electronic information. The Adaptive and Resilient Computing Security (ARCS) meeting illuminated the scope of this growing problem, but also showed that although solutions are daunting, many can be found in examining the natural world around us.

The ARCS meeting, which was held on November 3 – 4, 2004, at the Santa Fe Institute, was the third of its kind, and included experts and Business Network members from around the world in the field of computer security. It was chaired and organized by Robert Ghanea-Hercock of British Telecom and Matthew Williamson of Sana Security Inc. By focusing on adaptive and resilient technologies, the conference emphasized approaches inspired by studying biological systems, including contributions on topics such as self-healing networks, machine learning, and immunological models.

Alessandro Vespignani, of Indiana University's School of Information, opened with a keynote address about the epidemiology of computer viruses and attacks, making clear the parallels between a study of biological viruses and computer ones. Epidemiology, a term usually reserved for public health circles, is the study of how disease epidemics propagate around the world. Vespignani drew analogies from the basic models epidemiologists use to map a virus throughout its course of infection. For example, a virus first spreads freely, infecting each individual it contacts, but it can eventually reach a threshold and slow down either because a vaccine has been developed or because too many individuals have died, thus stopping further spreading. The virus eventually reaches an endemic or steady state.

Vespignani pointed out that this research has not generally been able to predict epidemics, rather it helps to understand how they spread, and that understanding can be applied to computer security. Although they are similar, computer viruses don't behave exactly like biological ones. For instance, they may not always reach an epidemic threshold. However, these models do offer a way to visualize the spread of disease and the effectiveness of vaccination.

Vespignani said that the "patching" methods that are often used are not the most effective. He emphasized that even if vaccinations are developed early on in an outbreak, the virus can still linger for years. In the world of computers, this is a significant problem. New viruses are constantly appearing, and patching software is immediately developed to protect computers from these threats. However, customers rarely realize that although they may be updating their computer systems with the latest patches, they are still susceptible to an attack from a virus that circulated years ago and everyone has since forgotten.

One reason the patching strategy is ineffective is because it is random. Certain individuals are diligent in updating their virus software and installing patches when needed. However, there are plenty of people who don't bother, and this allows the viruses to spread. Instead, he proposed that targeted immunization of a few key computers would be much more effective in keeping the viruses from infecting too many machines. He emphasized that knowledge of the network can be helpful in identifying these "key" players. Every computer has a different susceptibility because of its location. Because some computers may serve as gateways between a small network (all the computers in a company) and the rest of the Internet, they are key when it comes to protection.

"You take advantage of this heterogeneity, and just by protecting a few individuals, one can protect the entire system," said Vespignani. Vespignani discussed the need to understand the flow of information in computer networks in order to later identify where vaccination is most effective. For instance, biological epidemiologists study the populations of the world and their susceptibility, as well as the modes through which they interact. When thousands of people from hundreds of countries converge into the close quarters of crowded airports, the flow of disease is accelerated, as the individuals are in close contact and therefore more likely to share germs. Similarly, when the distance between computers is shortened by connecting many of them to a few centralized machines, infection problems may be exacerbated. The epidemic is accelerated when "there is a strong correlation between the degree of the nodes and the flow of information," Vespignani said. The most interesting direction of research, said Vespignani, is to "find the interplay between the flow of information on networks…and the physical pathway of the exchange."

Taking Aim

Other speakers further emphasized the importance of targeted immunization. Hong Li of Intel Corporation spoke of the Internet as a network of fully connected networks. Her network of networks model showed not only that there are roughly six degrees of separation between networks, which coincides with "small world" characteristics, but it also showed the value of recognizing isolated networks such as a network of computers in a company that are all protected by a firewall.

"The maximum number of hops between two nodes is five," said Li, again demonstrating a "small world effect." The research she presented showed a virus spreading among the network of networks through direct paths (not e-mails) when the computers are interacting and sending information packets to other machines on the network. For instance, sending a request to Google requires one's computer to generate packets of information to transmit to Google's computer and vice versa. Because every action the computer performs involves this type of exchange of packets, malicious packets of virus information can sneak into the system. Li examined the computers, or nodes, in her networks and their susceptibility to viruses. The nodes were described as being infected, infectable (susceptible) or immune (patched). Li demonstrated, as Vespignani had discussed, that if certain gateway nodes are protected, the virus didn't propagate the same way.

Kihong Park, of Purdue University, talked about proactive and reactive defenses against distributed denial-of-service (DDoS) and worm attacks in the global Internet, which is known to exhibit power-law connectivity. His research showed the effects of filtering data packets based on knowledge about addresses for DDoS and content signatures for worm protection. Park explained that the packets flow through the Internet from computer to computer, based on addresses stating what computer they are from and where they are going. Typically, these addresses, or IP addresses showing the computers' locations, are looked at by routers to identify where the packet is going—and the "from" address is usually ignored. Park stressed the value of strategically placing filters at transit sites, as opposed to leaf sites, to specifically look at "from" addresses to determine whether or not the sender of the packet is spooling for DDoS attack prevention and content-based signatures for worm containment. In the case of worms, Park and his colleagues show that very small (1.5%) filter deployment suffices to effect containment, facilitated by the power-law connectivity of the Internet. Feasibility of this approach is demonstrated by prototype systems built using Intel IXP network processors that perform worm filtering at gigabit (billion bits per second) wire speeds.

SPAM

Slamming the Spam

Although many attacks on computer networks are direct, and many users are effective in protecting their systems with the latest technology—it seems almost everyone is still susceptible to junk e-mail or spam, which can certainly transmit viruses, or can just be annoying. Christian Renaud of Cisco Systems, a worldwide leader in networking for the Internet through the development of software, hardware, and service systems, talked about how spam not only can present a physical problem, but can make people lose faith in doing business on the Internet.

Renaud explained Cisco's policy of both content inspection and path/sender-based filtering, which is similar to Park's approach of filtering packets. By placing digital signatures or keys on Cisco employees' e-mails that identify the sender, Cisco's servers can identify whether or not the sender is "authorized" to send e-mail from Cisco computers, or authorized to send e-mail to Cisco computers. In order to maximize the effectiveness of such a system, Renaud explained that other companies would need to adopt a signature/key system.

Renaud also discussed the importance of preserving certain characteristics about e-mail such as the ability to send it to anyone and to have it be relatively anonymous. He explained the necessity of developing this system in conjunction with systems that recognize behavior. For instance, if an individual's e-mail system is taken over by a virus, and made to send millions of malicious e-mails (becoming a so-called zombie), the system would need to recognize the abnormal sudden increase in sending and stop it—even if the e-mails had the appropriate signature keys.

Queuing Up

Taking a slightly different approach, Miranda Mowbray of Hewlett-Packard Bristol (a research facility of Hewlett-Packard in Bristol, England) explained that her research was prompted by many complaints that filtering junk mail, before delivering it to employees, was simply causing too long a delay. Mowbray and Matthew Williamson of Sana Security Inc. (who previously worked at HP Bristol) worked on mitigating this problem by creating separate queues for mail to enter the content scanner: one for junk mail and one for regular mail. This way, the mail in the regular queue would take a shorter amount of time to reach the recipient, and junk mail would have the long queue. In order to determine what mail belonged in which queue, they studied the IP addresses and found some interesting trends.

By monitoring e-mail for a period of two months, they found that junk e-mail does not all come from the same server, but a server that sends junk e-mail will likely send more junk. Essentially, they had expected to find a few servers that would spew lots of junk e-mail, but in reality, the junk was coming from all over the place. However, they did find that servers that sent junk, were likely to send more junk, and servers that sent good e-mail, were likely to send more good e-mail. This enabled them to track down junk servers by monitoring IP addresses that identified the server that sent the mail. The system then scans the IP addresses in order to determine whether the mail came from a good server and should enter the short queue, or whether it came from a junk server and should enter the long queue. Since the Hewlett-Packard server only needs to remember five IP addresses from each server in order to accurately assess the server's tendencies, the whole system could then adapt: if a server sent one junk e-mail, but then ten good e-mails, it would no longer be categorized as a junk server.

"Once you've sent me three good e-mails in a row, then you're a good guy again and you get fast access to the content scanner," said Mowbray. This way you don't have to keep records of all the IP addresses. Also, it's somewhat foolproof. If good e-mail happens to fall into the junk queue, it is still scanned and delivered—just delayed longer than the mail in the regular queue.

Friend or Foe?

One of the most innovative techniques in adaptive and resilient computer security involves machine learning. Researchers studying the immunology of biological systems have noticed the value of self and non-self recognition. Immune systems often depend on this principle: if something does not appear to be "self" or normal, it must be an attacker.

Steve Hofmeyr, of Sana Security Inc., discussed anomaly detection and building an adaptive system, specifically through looking at the order of instructions, or system calls, sent from the computer's operating system to various programs or disk drives. These system calls are the computer's primary way of communicating with its different parts in order to perform tasks. Understanding these instructions can help illuminate what behavior is considered normal for each individual computer and user.

"You've got to be able to collect and define the normal very easily, and you've got to be able to track changes or adapt to changes effectively," said Hofmeyr. There is also a difference in monitoring behavior verses data. Because data, such as packets and e-mails, can be spoofed or misinterpreted, it is not a reliable source to use. By focusing on system calls, the security software can learn sets of tasks and pathways that are normal for the specific computer and therefore can recognize that any deviation from this behavior is worrisome.

Of course, Hofmeyr explained the importance of building this normal behavior in a production environment. He also pointed out that if the computer is infected with a virus while one is observing its "normal" behavior, this approach would be problematic. And he stressed the goal of trying to make the system automated in its response to attack.

Justin Balthrop, a graduate student at the University of New Mexico, described another system that uses learning of normal behavior to detect attacks. RIOT (Responsive Input Output Throttling) is a system he helped create (also with Matthew Williamson) that includes detectors that are designed to learn the user's behavior and to observe all network connections made by the computer. The detectors have an immature state during which they are learning normal behavior. Once they have matured, they are capable of recognizing when the computer is connecting to a network in a way that is not "normal," and therefore blocking such connections.

However, the user has the ability to override the detector's decision to block a certain activity. By viewing a scrollbar that shows each connection or program that is being blocked or slowed, the user can decide to allow a connection to take place, thus sending the detector back to an immature state so that it does not block the same action again. This makes the entire system adaptive.

Learning to Cope

David Patterson's keynote address provided a good summary for the conference as he reflected on the idea of computer security as a whole. Predominantly, Patterson, from U.C. Berkeley, emphasized the overall value of recovery of data and information after a virus attack. Patterson's philosophy boiled down to a quote by the head of the Israeli Labor Party, Shimon Peres: "If a problem has no solution, it may not be a problem, but a fact—not to be solved, but to be coped with over time." Therefore, Patterson explained, attacks are always going to happen, and finding ways to recover quickly and without too much disruption is the best way to cope.

Patterson said that most delays in recovery are caused by human error and that most errors are immediately self-detected. He explained that humans have patience thresholds when dealing with their computers. For instance, humans are willing to wait quite a few seconds, perhaps even a minute, for a website to load. Thus, Patterson proposed taking advantage of small windows of time such as those during which the computer could conduct repairs without really disrupting the user (a minute or less). These quick repairs, which sometimes include "micro-reboots" when sections of the computer need to restart, can help solve problems within the system before they get too big. Rather than waiting and having long system outages, repairs could be broken down into smaller chunks of time, thus causing less anguish for the user.

Recovery-oriented computing, as Patterson put it, requires building tools to help operators design rapid-recovering-based systems on benchmarks created from real failure data. Along with the "micro-reboots" discussed above, he also encouraged processes to create "undo" mechanisms within computer systems. Patterson ended with a very realistic analogy: he reminded audience members that locks are not considered either breakable or unbreakable, but rather rated by how long it takes to break them.

Rebecca E. McIntosh is a science writer living in Santa Fe.

2005 SFI Community

WEDNESDAY, JUNE 15

Mark Newman

Associate Professor of Physics and Complex Systems, University of Michigan, Ann Arbor; External Faculty, Santa Fe Institute

The Internet, Epidemics, and Kevin Bacon: The Emerging Science of Networks

There are networks in almost every part of our lives. Some of them are familiar and obvious: the Internet, the power grid, the road network. Others are less obvious but just as important. The patterns of friendships or acquaintances between people form a social network, for instance, and boards of directors join together in networks of corporations. The workings of the body's cells are dictated by a metabolic network of chemical reactions. In recent years, sociologists, physicists, biologists, and others have learned how to probe these networks and uncover their structures, shedding light on the inner workings of systems ranging from bacteria to the whole of human society. This lecture looks at some new discoveries regarding networks, how these discoveries were made, and what they tell us about the way the world works.

WEDNESDAY, AUGUST 10

Robert P. Kirshner

Clowes Professor of Science, Harvard University

The Accelerating Universe: A Blunder Undone

Supernova explosions halfway across the universe show that cosmic expansion is not slowing down due to gravity. Instead, to the surprise of all astronomers, it is speeding up. We attribute this astonishing cosmic acceleration to a "dark energy" that pervades all of space. Albert Einstein anticipated this discovery in 1917, when he stuck a "cosmological constant" into his equations of general relativity. Some called this Einstein's greatest blunder and it has been theoretical poison ivy since the 1930s. Now we find that something just like Einstein's cosmological constant is needed to explain modern observations. This discovery points to something missing in our understanding of gravity, right at the heart of theoretical physics. This talk will show the evidence for cosmic acceleration, describe what we know about the dark energy, and outline future observations that will reveal more about this strange new component which makes up two-thirds of the universe.

The lectures are made possible through support from community supporters, and they are underwritten by Los Alamos National Bank. For information on how you can help support the Public Lecture Series, please contact Ann Stagg at 505-946-2724, or annstagg@santafe.edu.

There is no admission charge, but seating is limited. The talks are generally held at 7:30 p.m. at the James A. Little Theater on the campus of the New Mexico School of the Deaf, 1060 Cerrillos Road, Santa Fe.

For more current information about a particular talk, visit our website at http://www.santafe.edu/sfi/events/publiclectures.html or call 505-984-8800.

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

Lectures

TUESDAY – THURSDAY, SEPTEMBER 20 – 22

The Twelfth Annual Stanislaw Ulam Memorial Lecture Series

Marcus W. Feldman

Burnet C. and Mildred Finley Wohlford Professor of Biological Sciences, and Director, Morrison Institute for Population and Resource Studies, Stanford University; Science Board, Santa Fe Institute

Molecules, Machines and Mathematics: Issues in Biological and Social Evolutionary Theory

The lectures begin with a description of what the various genome projects have shown about the patterns of genomic variation in modern humans. Advances in computational and mathematical analyses have helped to formulate what will be described as the standard theory for the evolution of modern humans. For some populations, recent history and genetic patterns have an extremely interesting concordance.

The lectures continue with a discussion of how, for biological evolution, in many cases it is incorrect to view organisms as evolving "to solve a problem." Following a suggestion by Richard Lewontin, a new framework has been developed for biological evolution that replaces the notion of adaptation by one of niche construction, according to which there is symmetry between organism and environment, with feedbacks between these forming the driving force of evolution. For cultural evolution, a similar framework can be developed with some culturally transmitted traits forming a "cultural" environment that permits or prevents other social or, indeed, biological changes from occurring. Feldman will present an important example from the epidemiology of infectious disease in the presence of antibiotic therapies.

The Bulletin of the Santa Fe Institute is published by SFI to keep its friends and supporters informed about its work.

The Santa Fe Institute is a private, independent, multidisciplinary research and education center founded in 1984. Since its founding, SFI has devoted itself to creating a new kind of scientific research community, pursuing emerging synthesis in science. Operating as a visiting institution, SFI seeks to catalyze new collaborative, multidisciplinary research; to break down the barriers between the traditional disciplines; to spread its ideas and methodologies to other institutions; and to encourage the practical application of its results.

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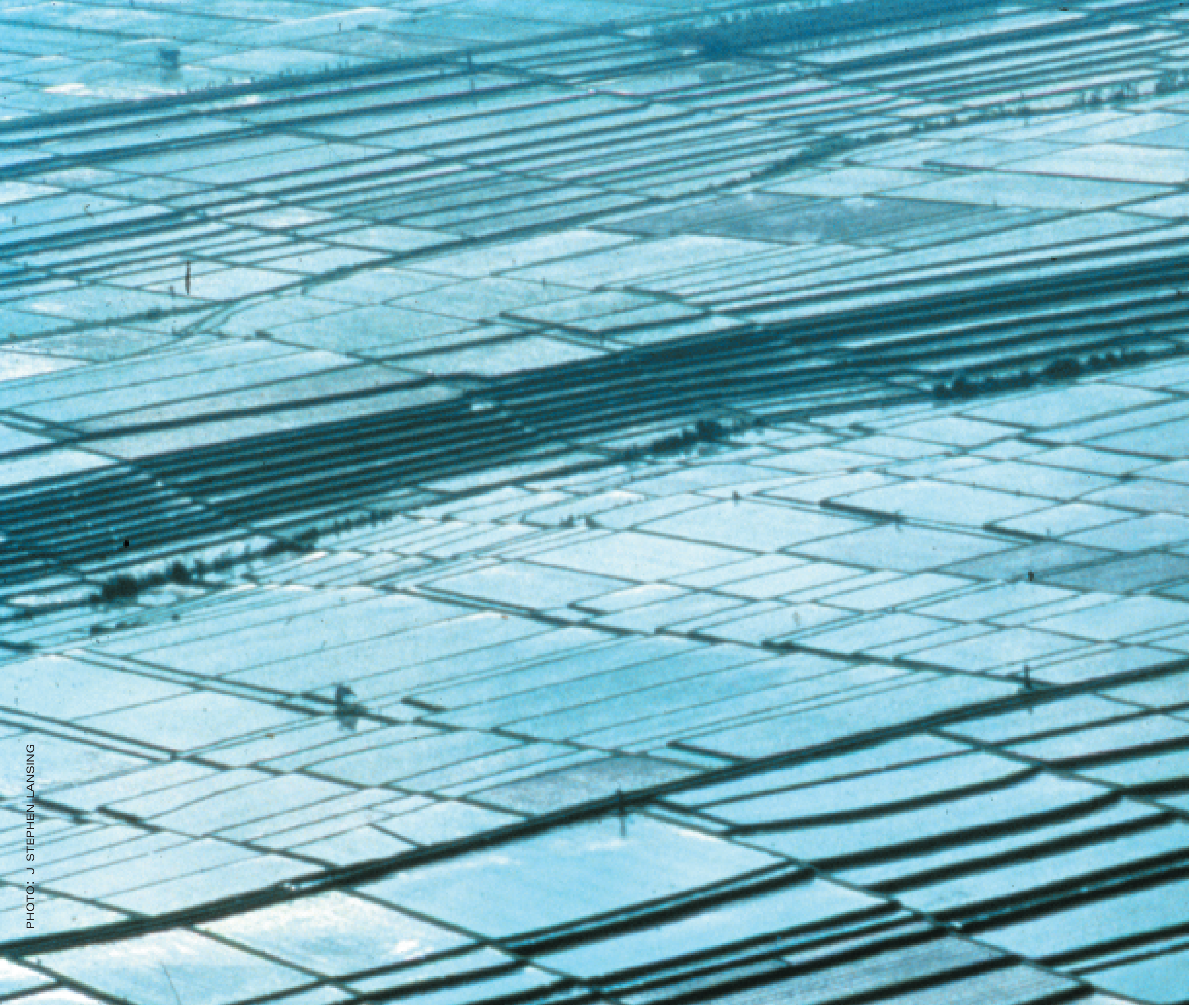

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