SFI bulletin

Mosaics: Life, Language, and Human Behavior

sfi bulletin

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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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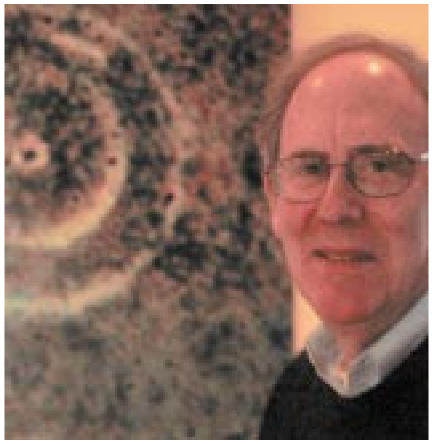
Inside SFI: A Letter from Robert Eisenstein



I'm glad to say that my first six months on the job as SFI's new president have been exciting and fulfilling for me personally. Thanks to the superb work of former President Ellen Goldberg, interim President Robert Denison, and the dedicated faculty and staff of SFI, the Institute is in very good shape.

Most importantly, our recent science retreat in November demonstrated that the intellectual horizons for SFI are unlimited. That meeting focused on summaries and case studies of research in the broad areas of *human social dynamics (including human languages); living systems; networks, robustness and resiliency; and the theory of complex systems.*

One of SFI's longest running and most distinctive research thrusts has been to develop a theory of the common themes that cross real-world complex systems. For despite differences in substrate, there are common principles and mechanisms that underlie the processes by which nature organizes complex systems and how they behave. In other words, there is often simplicity within complexity. When considered over the long term, SFI's theoretical work on this cross-cutting challenge has been remarkably successful.

Fundamental SFI research underway on universal scaling laws in biological and physical systems may lead to important practical applications. These range from medical advances in heart disease and insights into aging, to how such disparate units as corporations and cities grow, to how to create a scalable sustainable environment.

Other novel work in the biological sciences includes emphasis on the flow of information in cells, and on computational paradigms for various cellular activities. Work has also begun on attempts to understand whether or not there are fundamental laws of biology, as there are in physics and mathematics.

SFI's work on robustness—in ecosystems, in physical systems (such as computer and telecommunication networks), and in molecular systems—focuses on these entities as interconnected networks that have the capacity to self-repair and to change and adapt to an altered environment. Can robustness and innovation occurring at the molecular level provide insights as to how communities adapt and change at the societal level? Are there some underlying principles that guide innovation, evolution, and change across the spectrum of biological, physical, and societal conditions?

The Institute's newly launched program in the behavioral sciences seeks to build on the traditional view that individual behaviors interact to produce aggregate social outcomes. This simple statement disguises a wealth of underlying complexity that needs substantive exploration. To pursue this objective, SFI projects currently underway are examining inequality as an emergent property of social interactions; the co-evolution of institutions and behaviors; and the role of innovation in organizational and individual creativity. Computational tools are playing an increasingly important role in the above projects and in most of the Institute's social science research, as they long have in other research areas.

SFI's Evolution of Human Languages (EHL) project explores an especially rich instantiation of human social dynamics, language. Is there a true "mother tongue" to which all existent modern languages can trace their origin? More precisely, what is the genealogical tree or phylogeny of language? It is these sorts of questions, the ones that look to tell a story of a branching journey of the development of languages, that is the goal of this project.

The Santa Fe Institute Business Network continues to grow as an important component of SFI's research community. The companies in this group reflect a cross-section of industry and government entities ranging from finance to automotive companies, and from high tech and manufacturing entities to various federal agencies. Just as experimentalists and theorists discover there is much to learn from each other, business professionals bring interesting questions and perspectives that provide inspiration for our scientific community. It is becoming a wonderful symbiosis.

It is very pleasing to me that SFI has become an integral part of the Northern New Mexico community, adding jobs, providing revenue to the city and the state, and offering a variety of local educational programs. SFI and the Massachusetts Institute of Technology (MIT) have created an "Adventures in Modeling" curriculum to introduce students and teachers to the concepts of complex adaptive systems through the use of StarLogo, a computer-modeling tool that does not require advanced mathematical or programming skills. Since 1998, over 200 teachers and students have attended Adventures in Modeling workshops in Santa Fe, Boston, and around the country. Currently SFI sponsors StarLogo classes in four local high schools, two middle schools, and at the Boys and Girls Club in Santa Fe.

At the other end of the size spectrum, we have been able to expand our activities, through a generous private gift, to many developing nations, including countries in Asia, Africa, Eastern and Central Europe, and Latin America, as well as the former Soviet Union, China, and India. Our efforts include visitor programs (involving junior and senior researchers), students, workshops, and summer schools in these nations. Two-year fellowships are awarded to outstanding graduate students, postdoctoral students, or senior-level researchers who are affiliated with, on a full-time basis, an academic institution within their country of origin.

We are gratified that the Santa Fe Institute approach to complexity science continues to spread beyond the scientific community to a national and global environment. From the early founding meetings to the thousands of people who have now participated in Institute-sponsored workshops, working groups, symposia, colloquia, public lectures, research programs, and summer schools, the Institute casts its net broadly.

The Santa Fe Institute will celebrate its 20th anniversary in May 2004. As befits an energetic and still-young institution, we at SFI will focus hard on possible future opportunities in research and education rather than dwelling too much on past achievements. I look forward to seeing you at our celebratory activities, either here in Santa Fe or elsewhere.

With best wishes,
Robert A. Eisenstein
PRESIDENT

Good Taste in Science: Robert Eisenstein

by Lesley S. King

"Beauty is truth, truth beauty."

—John Keats, "Ode on a Grecian Urn"

APPOLO ON THE DELPHIC TRIPOD
CA 408 B.C. VATICAN MUSEUMS, VATICAN STATE
PHOTO: SCALA/ART RESOURCE, NY

"Physics is an attitude," says Robert Eisenstein, while sitting in his corner office at SFI. "It's an approach, a way of analyzing problems you learn when you study physics. If you can learn it well, you can take it on the road." As the new Institute president, he's well aware of the impact that this ability can have—and has had—when working in the world of interdisciplinary science, particularly in the area of complex adaptive systems.

"If you have a curve," he says, drawing his long arm in an arc through the air, "it's easy to find a function to fit it. It's much harder to find the underlying reasons that make the curve like that."

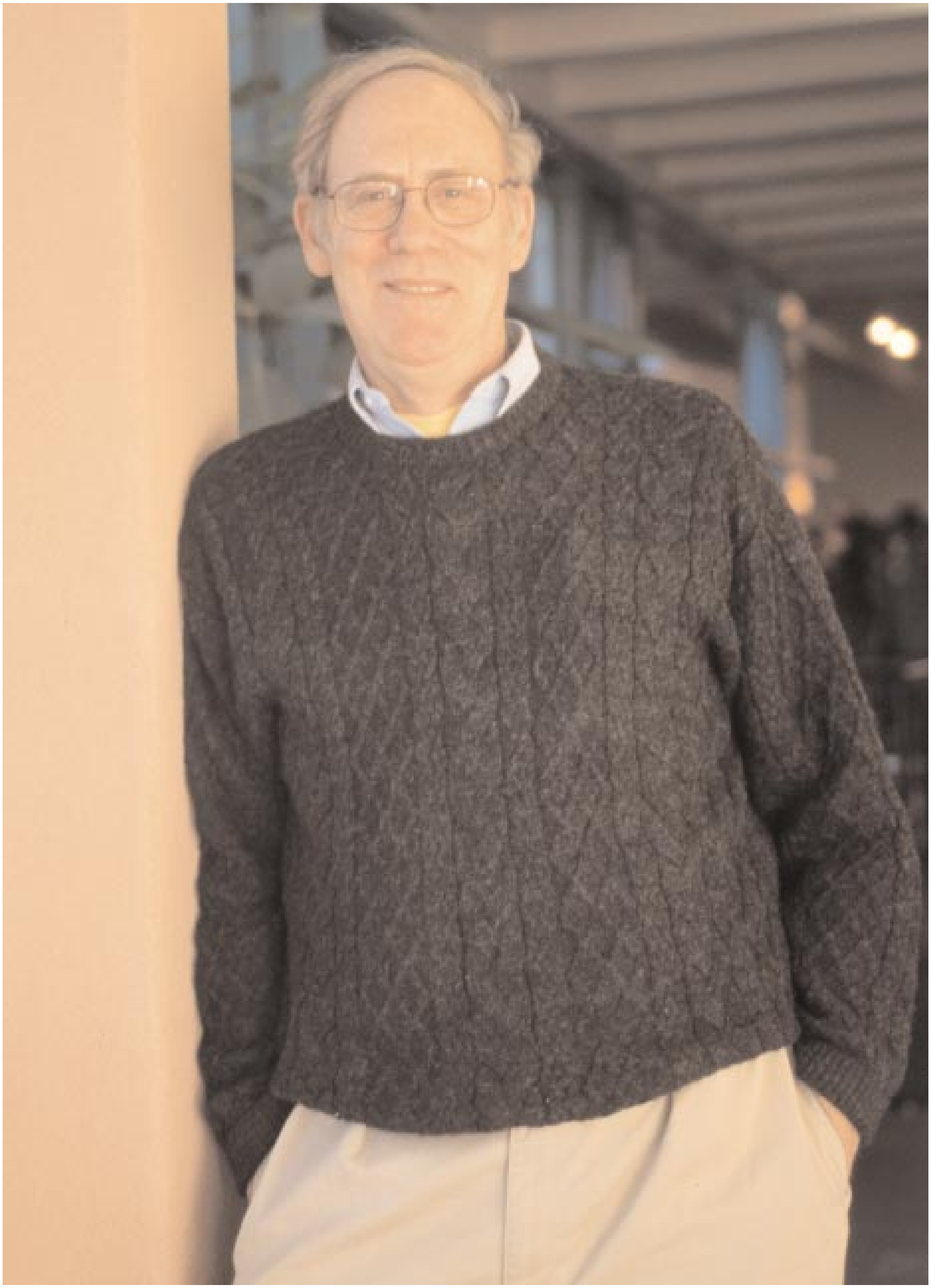
The statement is revealing of what to expect from Eisenstein. Tall, with a low-key approach to the trials of a demanding administrative post, he isn't satisfied with business as usual. Though he has a long-developed appreciation for the work that's gone on here, he's intent on delving deeper or shaking things up a bit, certain that the arc of SFI's lifespan can be even more graceful than it has already been.

The Jazz of Physics

Eisenstein brings a full and varied background to the task. A product of a liberal arts education, he gravitated toward studies in nuclear physics, not because, as one might guess, he had a passion for atomic nuclei, but because of a love of humanism and particularly an appreciation for a man he saw embodying the ideal. Nuclear physicist Charles Bockelman inspired him while at Yale University, where Eisenstein completed his doctoral degree. "He wasn't the smartest man, nor the best scientist," Eisenstein says. "But he was the best human being."

Through time Eisenstein's interest in nuclear physics led him to work with high-energy

PHOTO: JULIE GRABER



physics, where he found his home in science. "It's the study of matter, energy, space, and time—how they interact with each other to form the world." He sits forward, fully engaged. "Why is it that the laws of physics are the same anywhere in the universe?" he asks, passion reddening his cheeks. "Why are there laws of physics?

"The most incomprehensible thing about the universe is that it's comprehensible at all," he adds, quoting Albert Einstein. "Order in the universe is an amazing thing. It's deeply philosophical. The laws are there. They've never changed. They work the same way every time. It is incomprehensible. It's kind of a religious thing in a way."

It's no surprise that Eisenstein did one of his undergraduate theses on John Keats, the 19th-century English poet who spent his brilliant 25-year life celebrating the beauty of the natural world and trying to comprehend and reconcile man's place in it. What's less obvious is Eisenstein's passion for bebop jazz, in particular, the untamed tunes of Thelonius Monk, whose music, Eisenstein says, brings him to a "standstill."

SFI as a Proxy

With his Ph.D. in hand, Eisenstein embarked on a long and rewarding career in academia, first at Carnegie Mellon University, and later at the University of Illinois in Urbana, where he served as director of the Nuclear Physics Laboratory. After 22 years of academic research and teaching, he made a major shift into the public sector, taking a job as director of the Physics Division of the National Science Foundation (NSF), where he later took a leadership role as one of NSF's seven assistant directors. Heading the Mathematical and Physical Sciences Directorate, he and a staff of 135 were responsible for funding—at universities and colleges all over the United States—a wide variety of research projects in the fields of astronomy, chemistry, materials research, mathematics, and physics.

The transition from the less-structured life of academia to a government position wasn't an easy one, he admits. "You're spending the public's money so you have to be careful," he says, concern creasing his brow. "It's also very hierarchical. Quite tense and demanding. When a supervisor needs something today, you get it today. I don't think the public appreciates how hard government employees work." Still, he met the challenge. "When someone gives me a job to do, I try to do it," he says.

Judging from the opinion of Neal Lane, former director of the NSF and currently university professor at Rice, Eisenstein succeeded. "Bob demonstrates all the qualities of a strong, respected leader in science and science policy," says Lane. "He has led, with great distinction, one of the largest components of the Federal Government's programs to support scientific research. He's known for his sound and fair judgment, his keen intellect, his integrity, and his humanity."

Eisenstein brings those qualities to the presidency of an institution he's known for some 10 years. Early on during his tenure at the NSF, he was responsible for directing many of the funds that came to SFI from there. The NSF was at that time the Institute's largest source of research funding. Over the years, it seems, Eisenstein has watched the Institute with an appreciative eye. "It's easy to say you want to do interdisciplinary work, but saying and doing it are different things," he says.

While at the NSF, he saw a number of attempts to bring together disciplines, but they very often failed. "The NSF leadership knew that wonderful things would happen if you brought together, say, physics and biology, so they would form an evaluation panel, but when it came to distributing funds, a physicist would say something like, 'We can't support that, there's too much biology,' and a biologist would say, 'We can't fund that, there's too much physics.' The structure of SFI allowed it to avoid those issues. It really was a proxy for NSF in

Members of an expedition team led by Ernest Shackleton pull a vessel across the ice of Antarctica. (PHOTO BY HULTON ARCHIVE/GETTY IMAGES)

this respect. People could do things here that we had trouble doing there."

His interest in uniting scientific disciplines led him to initiate and maintain a dialog with Ellen Goldberg during her presidency at SFI. "He wanted to find out about SFI first hand," says Goldberg, who was impressed that an NSF director would take such a personal approach. During the seven years Goldberg has known Eisenstein, she's been impressed by various aspects of his leadership. "He had incredible foresight in developing interdisciplinary activities at the NSF," she says. But for her highest praise, she borrows a compliment that George Cowan has awarded discriminately: "He has good taste in science."

Academia with a Twist

After a decade at the NSF, Eisenstein took a sabbatical leave to the Conseil Européen pour la Recherche Nucléaire (CERN), the European Organization for Nuclear Research. There, he worked on the Large Hadron Collider Project, Europe's next-generation particle accelerator. He found the work there very engaging, but the post at SFI seemed to come at a perfect time.

He's ready to be once again in the world of academia, but, he says, "This has a different twist." SFI's connection to the business world, and the way it operates primarily with money from private sources rather than governmental funding, make it much like a business, he adds.

He sees his role here as more challenging than any of the previous ones. "We're responsible for people's livelihood—the people who work here—and we have to generate a revenue stream." His humanistic background shows in other ways too. He would like to see more minorities and women represented within the scientific body of the Institute. "The business of mentoring can really have an impact," he says. "Others see people in those positions and it has a dramatic effect." His concern has not escaped observation. "Bob embraces diversity and that was apparent in his work at NSF," Goldberg says.

As his own role model of leadership, he's chosen Sir Ernest Shackleton, most known for exploring Antarctica. When Shackleton's ship was stranded by polar ice in 1915, he led an awe-inspiring rescue. "He treated everybody equally, of course recognizing differences between what people can do," Eisenstein says. "My goal is to be as hardworking as everybody else at least. I like to be open and allow for discussion, and yet it's important to be efficient." He pauses, as though

"It (SFI) has worked well because of the quality of people. When George Cowan and the other founders created the Institute, they had the idea to find fantastic people, bring them together, and let them generate sparks. That's what happened."

considering Shackleton. "I have expectations, though I don't ask people to do what I wouldn't do myself."

Neal Lane confirms that Eisenstein has met his leadership goals. "You can take Bob's word to the bank," he says. "He is candid, honest, and clear in expressing his views, and dependable in doing what he promises."

Mindful of Its Place in the World

Eisenstein admits that he has a lot to learn in order to do his job well. But he's up to the task. "I've always been kind of a learning junkie," he says. And yet, his previous contact with the Institute has allowed him to quantify and mathemitize its workings to come up with ways to make it even better.

"SFI has been in a leadership role with complex adaptive systems (CAS)," he says. "It has worked well because of the quality of people. When George Cowan and the other founders created the Institute, they had the idea to find fantastic people, bring them together, and let them generate sparks. That's what happened." He adds, "Being in Santa Fe didn't hurt," glancing out the window toward an anvil-shaped thunderhead and the azure Jemez Mountains in the distance.

"It's important for SFI not to let our reputation go to our heads. Leadership might mean something different now than it did then." He pauses, as though knowing he's moving into trickier political territory. "I'm in favor of high-quality interdisciplinary work: whether it involves CAS, matters less.

"SFI must always be mindful of its place in the world," he continues. "We have to be making real contributions, not just be a place where smart people hang their hats." He moves deeper into his purpose. "We must continue to form relationships with other academic institutions and other countries in a true spirit of partnership, not in a sense of noblesse oblige. The challenge is to lead by excellence and example but also in a spirit of collegiality." He cites many examples of areas where such work is already happening: biology and computer science, network theory, linguistics and evolutionary dynamics, to name only a few. But he's not completely satisfied even with those. His search for betterment continues: "I really appreciate good ideas, and I demand excellence. The work that leaves SFI is going to be as good as we can make it."

Lesley S. King is a freelance writer whose articles have appeared in Audubon *and* The New York Times.

New Mexico Adventures in Modeling

Brings Complexity Science and Computer Modeling to Regional Schools

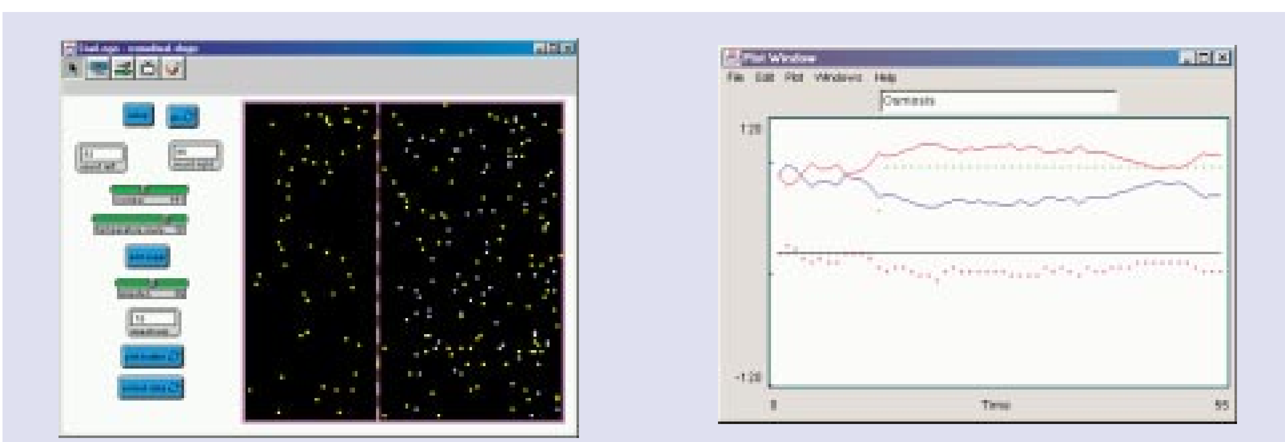
Nearly two dozen middle and secondary school teachers from Santa Fe, Albuquerque, and Northern New Mexico came together at SFI for two weeks this past summer to form what will be an ongoing community of practice. The focus is on how to integrate cutting-edge computer modeling, information technology (IT) tools, and complexity science into local classrooms. With support from the National Science Foundation, the *New Mexico Adventures in Modeling: Integrating Information Technology into the Curriculum through Computer Modeling Approaches* project will for the next three years train New Mexico science, mathematics, and technology teachers at the secondary level (grades 6-12). The teachers will integrate IT concepts and computer modeling—especially of complex adaptive systems (CAS)—into their courses. They will use StarLogo simulation software, participatory simulations with handheld computers, and related computer technologies.

Eric Klopfer from the Massachusetts Institute of Technology's (MIT) Teacher Education Program and SFI Research Professor Ellen Goldberg head this project. Local program coordinators Irene Lee, Greg Malone, and James Taylor come from Santa Fe schools. In addition to SFI and MIT, other program partners are the University of New Mexico (UNM), The New Mexico Commission of Higher Education (NMCHE), and local schools in the greater Santa Fe area in northern New Mexico. The partnership builds on existing relationships including the Adventures in Modeling partnership between MIT and SFI that has introduced computer modeling and simulation through CAS and its supporting software tools to over 300 teachers in the last five years. It also builds on the existing relationship between the Adventures in Modeling program and Santa Fe schools, and the ongoing professional partnership between UNM and the State of New Mexico that has provided expert professional development practices.

An important part of this project will be the creation of a permanent group of successful "teacher implementers" in local schools. In the process of creating this, organizers and participants will determine what combination of supports, under what conditions, is the most powerful in helping teachers implement IT and computer modeling concepts. They will also work to overcome obstacles to reforming the instruction they provide for their students.

There are clear benefits to using computer modeling and simulation in the classroom since it is a natural way to integrate science, mathematics, and technology. The connections between these disciplines become clear as students are compelled to use their scientific knowledge to conceptualize the models, their technical knowledge to build the models, and their mathematical knowledge to analyze the models. Further, the students' experience pursuing and building their own science projects and models, as they do in this program, will have lifelong implications for how they experience the role of technology in society. The aim is to produce measurable changes in student attitudes about science and technology, their understanding of the nature of scientific systems and studies, and their mastery of the specific scientific systems studied.

For more information about this program, see http://education.mit.edu/starlogo2003/. New Mexico secondary teachers interested in becoming part of this project should contact Paul Brault (paul@santafe.edu) at SFI.



Left: Osmosis and Diffusion Model. Water molecules (yellow) can pass through the semi-permeable membrane while sugar molecules (blue) cannot. Right: A time series plot showing the concentration of water on the right (red) and left (blue) as sugar (green) is added.

Bringing Cities
into Complexity Science

by José Lobo

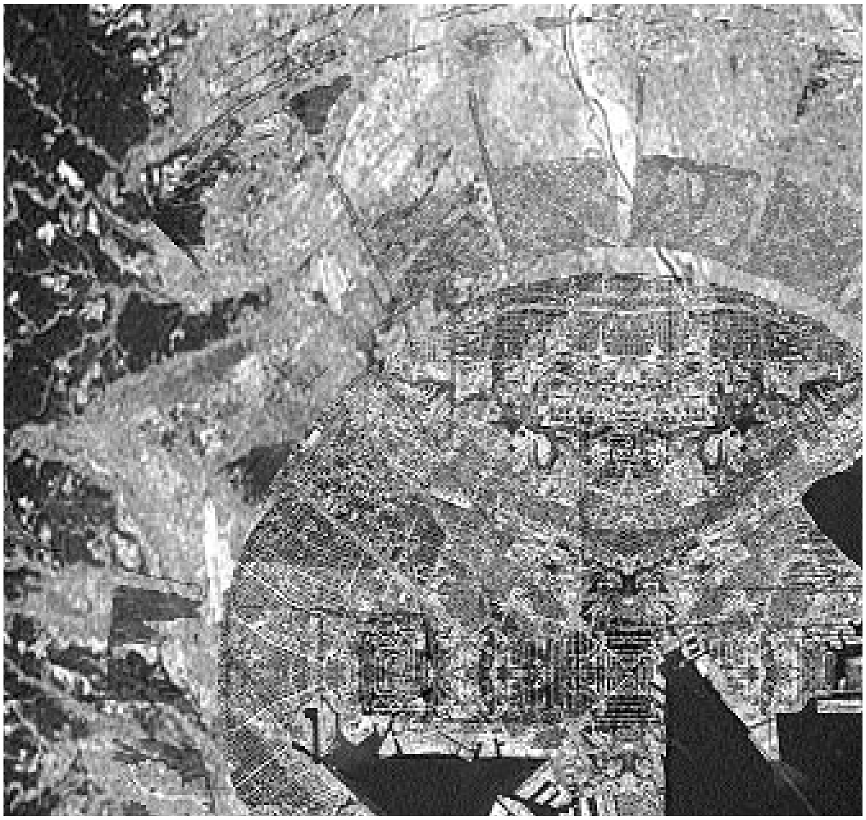
"The chief function of the city is to convert power into form, energy into culture, dead matter into the living symbols of art, biological reproduction into social creativity."

—Lewis Mumford, *The City in History: Its Origins, Its Transformations, and Its Prospects* (1961)

"The biggest and most cosmopolitan cities, for all their evident disadvantages and obvious problems, have throughout history been the places that ignited the sacred flame of the human intelligence and the human imagination."

—Peter Hall, *Cities in Civilization* (1998)

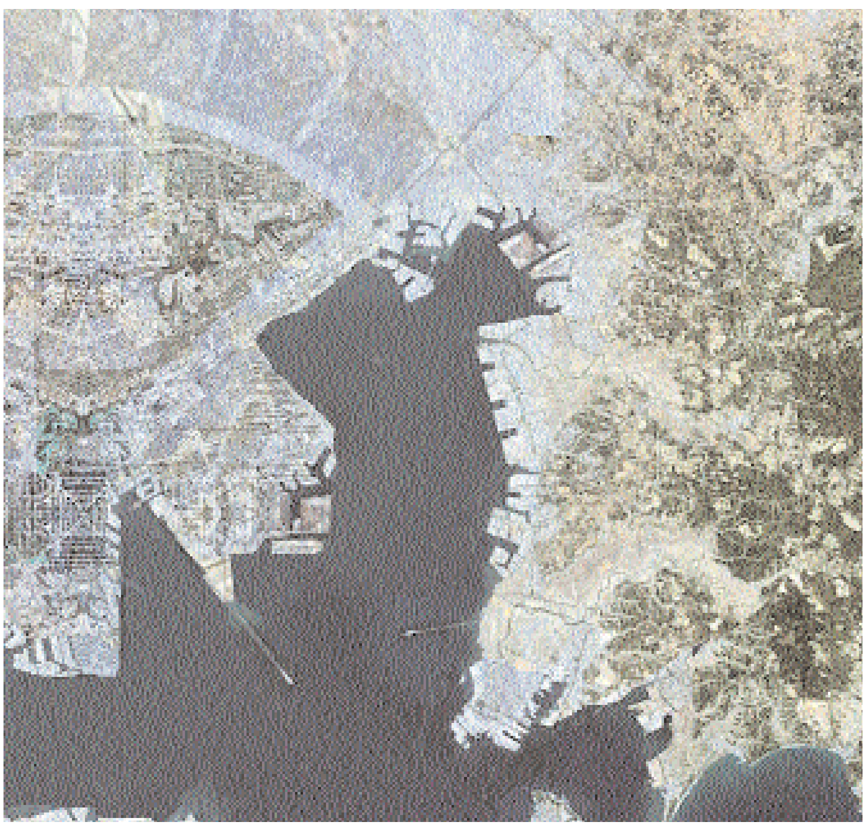
"**Robustness**," minimally understood as the ability to adapt and respond to changing circumstances, is a hallmark of any prosperous human collective. One of the most important of human collectives is a city, and cities vary markedly in their ability to sustain economic growth and prosperity, their agility to adapt to exogenous economic, political, and technological changes, and in their capacity to foster economic, organizational, cultural, and scientific innovation.



ILLUSTRATIONS: ANN LEVY

Some cities—New York, Boston, Barcelona, Amsterdam, Hong Kong, Shanghai, Istanbul, Mexico City, Milano—are able to "come back" after periods of upheaval or decline, while other cities—like Buffalo, Yokohama, Jakarta, Gary, Cleveland, Detroit—are victims of "boom-and-bust" episodes. The Institute's Program on Robustness in Social Processes has sponsored a working group on "Cities and Organizations" to explore these phenomena.

Why would the study of "robust cities" be a useful addition to the Program's scope? To begin with, there is the sheer economic importance of cities: in most countries, the greatest portion of economic activity takes place in urban areas. Historians have long acknowledged the role of cities as incubators of innovation, since the very beginnings of civilization. The cramming of individuals, occupations, and industries into close quarters provides an environment in which ideas flow quickly from person to person, what economists have come to refer to as "knowledge spillovers." Cities also provide a permissive social and cultural environment for the sort of "experimenting" essential for innovation to take place. Given that most of the world's population lives in an urban environment, it is hard to overstate the sociological, political, and demographic importance of cities. Understanding why some cities are robust—seeing robustness as a key determinant of long-term success or failure—is not only an intellectually engaging exercise, but also one rich in public policy implications.



The research agenda of the working group centers on two related questions: What are the social, political, administrative, cultural, technological, and economic characteristics of a city that facilitate innovative behavior on the part of its constituents (individuals and organizations)? Conversely, what are the attributes of a city's citizens that make a city innovative and robust? In biweekly meetings, and several workshops held since the beginning of the year, the working group has brought together researchers (from within and outside the Santa Fe Institute), as well as practitioners and policy-makers (from within New Mexico and out-of-state) to share theoretical and empirical insights, experiences and intuitions on how organizational and locational characteristics interact to foster and facilitate innovation. The working group has also served to inject some of the insights accumulated by urban historians and urban economists into ongoing discussions at the Institute about market formation and organizational innovation. Indeed, one cannot truly understand technological and economic innovation without considering these as spatial phenomena.

SAUL STEINBERG, THE FIVE SENSES, ORIGINALLY PUBLISHED IN *THE NEW YORKER,* MARCH 9, 1998

Are you my mother . . .
Tongue?

by Daniel Rockmore

CONSTRUCTION OF THE TOWER OF BABEL, HENDRICK VAN CLEVE III, CA 1525-1589
PHOTO: SNARK/ ART RESOURCE, NY

The story of the Tower of Babel is the creationist's version of the origin of language diversity: Man, in one of his many hubristic moments decides to build a tower to Heaven. God, realizing that communication is the key to completing any massive public works project, foils the plan by replacing the single common language of the workers with many different languages, thereby making impossible their cooperation, not to mention the scheduling of car pools and the organization of a softball team.

Is there a true "mother tongue" to which all existent modern languages can trace their origin? More precisely, what is the genealogical tree or phylogeny of language? It is these sorts of questions, the ones that look to tell a story of a branching journey of the development of languages, that is the goal of SFI's Evolution of Human Languages (EHL) Project, funded by the John D. and Catherine T. MacArthur Foundation, and spearheaded by SFI Distinguished Fellow Murray Gell-Mann and Russian Academy of Sciences Member (and frequent SFI visitor) Sergei Starostin. The third leader of the project is Dr. Merritt Ruhlen from Stanford University, author of the monographs: "Guide to the World's Languages" and "The Origin of Languages."

The EHL project falls squarely within the discipline of comparative linguistics. The last 200 years or so of the subject have been devoted to the clarification of the most elementary stages of linguistic organization, an effort that has resulted in a partitioning of the roughly six thousand attested languages into several hundred more fundamental "language families," each of which implies the existence of a single language ancestor for its family members.

The standard methodology used to show relatedness involves the identification of a set of phonetic similarities between the words in the respective basic vocabularies (e.g., words for body parts, numerals, natural phenomena, etc.). This is the sort of comparison that supports the existence of a common Germanic language able to account for the English "hundred" and the German "hundert," or uses the Italian "cento" and the French "cent" as evidence for an older ancestral Romance language—actually attested as Latin. The reconstructed protolanguages are then grouped together into families of the next level, in our case forming the so-called Indo-European family. It is estimated that its protolanguage was spoken (in a homeland that is still a matter of dispute) some six or seven thousand years ago. A number of other universally recognized families have similar "time depths." Although many comparative linguists maintain that further classification is impossible because too many changes impede comparison and reconstruction, a few bold scholars go further to find superfamilies composed of several such families, with protolanguages spoken thousands of years earlier. Instead of comparing modern languages they use the reconstructed protolanguages that are naturally closer to each other than their modern descendants.

This is the so-called step-by-step reconstruction, a technique from the Russian school of comparative linguistics first used in the construction of Eurasiatic protolanguage. After several decades of research, the evidence for macrofamilies became overwhelming, and there are many indications that even those can be further grouped together suggesting the existence at some point in time of a single common ancestor.

These achievements are, in the words of Starostin, "pre-science," insofar as they are obtained without mathematical tools. However, it is in the search for deeper levels of organization, and in the investigation of temporal considerations, that the tools of mathematics and statistics truly come to the forefront. Those tools mark a transition from pre-science to science for comparative linguistics, and the starting point of the discipline of "lexicostatistics" or "glottochronology," originally started in the United States by Maurice Swadesh. It is in this domain that SFI is making a big contribution.

It is fitting that Gell-Mann is the person leading this search. The son of the founder of the Arthur Gell-Mann School for Languages (which taught English to immigrants and other languages to Americans), Gell-Mann has been interested in etymologies and language sound systems since childhood.

In essence, what Gell-Mann and

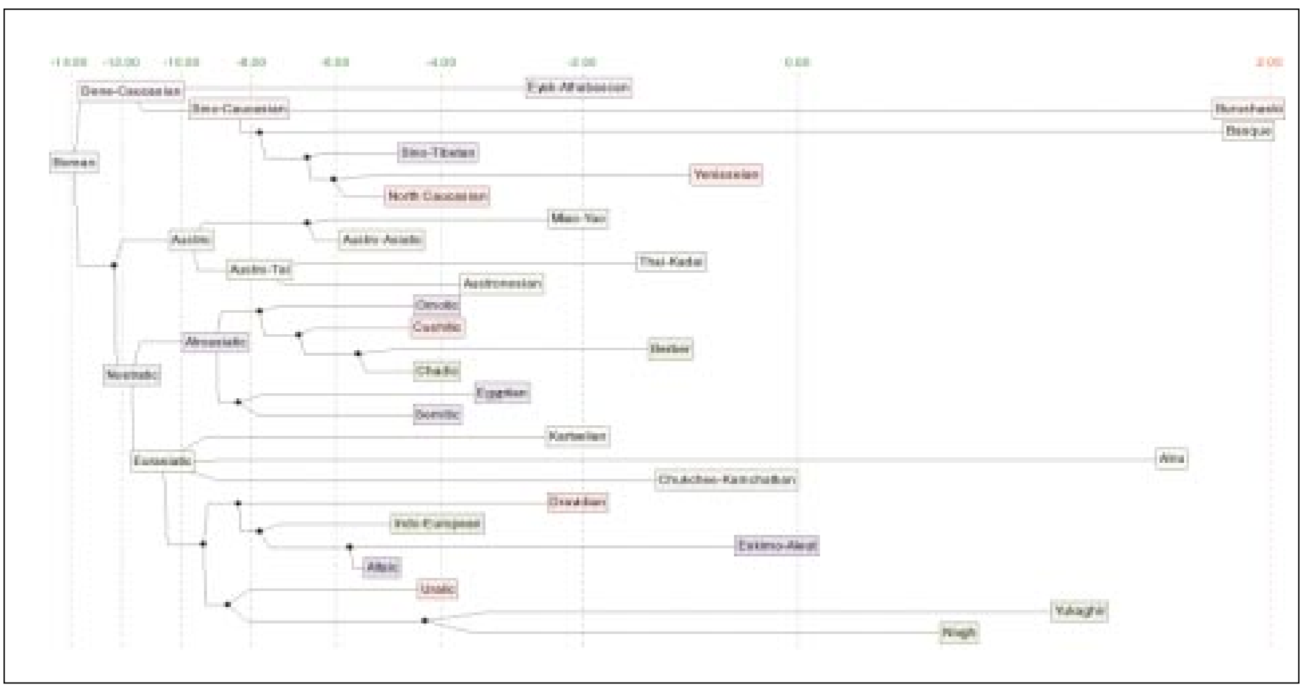


Figure 1: Genealogical tree of the languages of the Old World (with time-scale in millennia), obtained on the basis of comparing lists of the 35 most stable words in various language families of Northern Africa and Eurasia. The margin of error at the deepest points in the tree is on the order of one a millennium.

Starostin seek is the linguistic equivalent of Gell-Mann's Nobel Prize-winning "Eightfold Way," his insightful 1950s reorganization of what was then a "zoo of particles" (over one hundred of them) thought to be the fundamental constituents of nuclear matter. By grouping them according to certain approximate symmetry conditions, and creating new mathematical techniques for their study, Gell-Mann was able to see this apparent confusion of particle types as parts of a more coherent whole. The reorganization suggested a new, more basic fundamental particle which Gell-Mann named the quark, as responsible for this "zoo," and in so doing, he brought our understanding of the story of matter closer to the beginning of time. By fusing his great love of language with his scientific proclivities, he has found what seems to be a promising approach toward the search for the Mother Tongue.

At the heart of the problem is estimating the rate at which languages change, as measured by the changes that occur in the basic vocabulary as it passes from generation to generation, passed on like genes of "cultural DNA." The basic principles underlying the model formulation are that language requires stability to ensure communication between generations, but that nevertheless there is inevitable information drift, resulting in changes during transmission. The latter takes place via a mechanism of replacement, which occurs either through borrowing or through synonymic shift.

Replacement by borrowing occurs when a word is replaced by its foreign equivalent: An example is "mountain," borrowed from French to English, supplanting the old English "berg." Replacement by synonym, "synonymic shift," occurs within a language when a word drifts to a new, but nearly equivalent meaning. An example of this is the current usage of the word "kill," which has its origins in the Germanic word for torture. Keeping in mind the genetic model, these sorts of language mutations are akin to horizontal and vertical replacement (transmission) in genetics, which result in the evolution of a particular genetic sequence.

While the replacement by borrowing is unpredictable, replacement by synonym seems to follow a standard model of genetic drift, the mechanism that many believe is responsible in biology for the species diversity we see today. In the context of language this model provides a means by which the times of language divergence can be estimated. At work here is an implicit assumption of a regular process of change, which Starostin likens to the measurable rate of isotope decay that makes carbon dating the exact science that it is today. The glottochronological version of carbon dating suggests that one word of basic vocabulary is replaced roughly every 200 to 300 years or about five over a millennium. The original model assigns approximately the

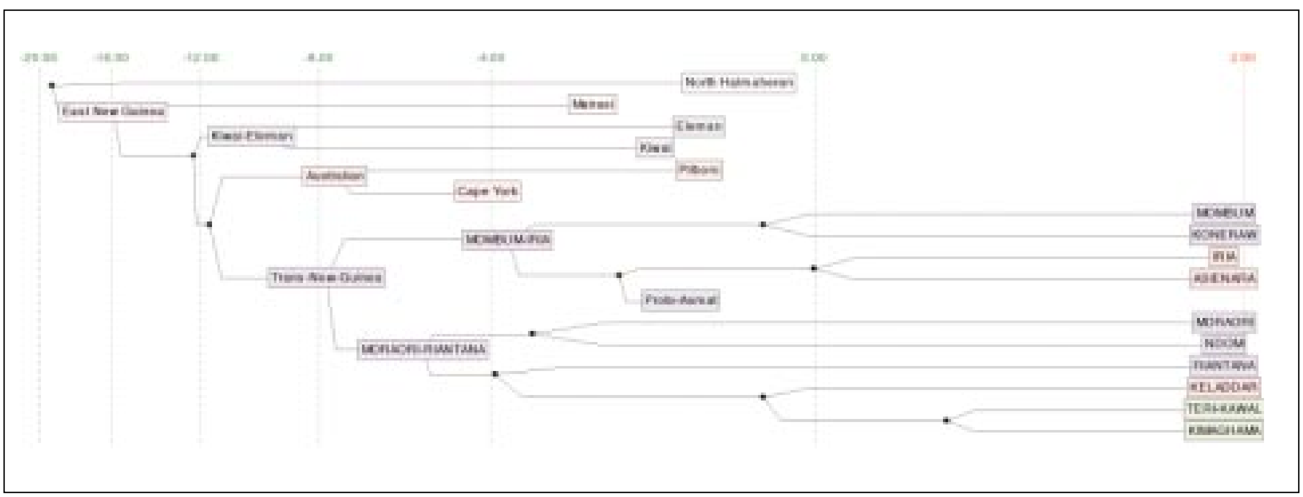
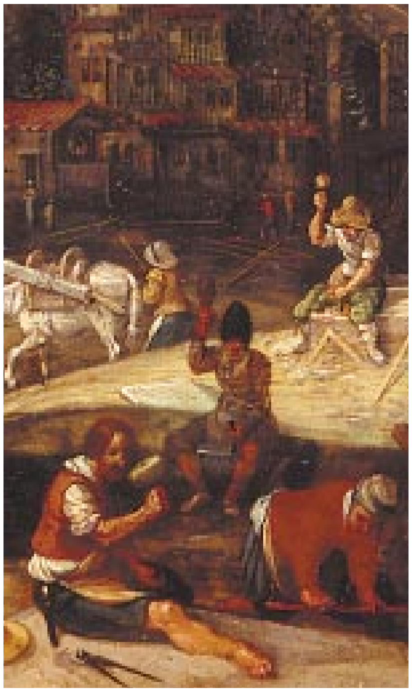


Figure 2: The genealogical tree of several language families of New Guinea and Australia (with time-scale in millennia) also obtained on the basis of the evolution of the 35 most stable words. The classification is far from complete, since most of the languages are not yet processed in a proper way; however, it gives an idea of the time distance and level of divergence of languages in this part of the world.



same probability of replacement to each word in the basic vocabulary. This model is quite naïve and Gell-Mann is leading an effort directed toward tuning the model using more realistic estimates of replacement probabilities of individual words.

Current techniques appear to reliably reconstruct the "protolanguages" in use six to seven thousand years ago. In addition, there is striking evidence for the existence of about ten "superfamilies" responsible for all languages in use today. The analysis reveals some interesting family relations; for example, it indicates that Northeast Asian languages such as Korean and Japanese are closer to European languages than are Southeast Asian languages (e.g., Chinese).

The theoretical (i.e., model building) component of the EHL program is paired with (if not made possible by) a huge empirical component. A part of this component stems from the recently completed *Etymological Dictionary of Altaic Languages,* which gives a comparative study of the Altaic languages, for which Starostin is co-author. See facing page.

The print component of the project is important, but the process of comparison and modeling is primarily focused on the development and management of a growing collection of online language databases. At the head of the database effort is Starostin, whose software package "STARLING" is designed specifically for linguistic database management (see http://starling.rinet.ru). The number of online language databases is increasing steadily. Of great current interest is the effort to digitize all the languages of New Guinea, an effort that will go a long way toward the reconstruction of the Indo-Pacific protolanguage.

The installation at SFI of the entire STARLING project (software, webserver, etc.) is one of the major directions of current work in the EHL project. This, in concert with the mathematical modeling effort, defines the EHL project as another cornerstone in SFI's work at the scientific frontier. Our generation is bearing witness to a long-overdue mathematicization of the life and social sciences, a modern updating of the Tower of Babel tale in which, through the ever-broadening mediation by the universal language of number, scientific knowledge is growing via a renewed unification across disciplines. SFI's work to find the Mother Tongue is yet another instance of the progress propelled by the rewriting of sciences in the Mother Tongue of mathematics.

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ILLUSTRATION: SNARK/ ART RESOURCE, NY

✱**kéro** to fight, kill: Tung. ***kere-, *kerbe-**; Mong. ***kere-**; Turk. ***gEröĺ-**; Jpn. ***kə́r-**; Kor. ***kūr-**.

PTung. ***kere-, *kerbe-** 1 kill 2 to fine 3 to slander 4 to revenge (1 убивать 2 штрафовать 3 клеветать 4 мстить): Evk. *kerbe-* 1, *keremī-* 3, *keremǯu* bi- 4; Man. *keru-le-* 2, *keru-n* 'fine'.

◊ TMC 1, 381, 452, 453, 454.

PMong. ***kere-** 1 to quarrel, to fight 2 to be angry (1 ссориться, драться 2 сердиться): MMong. *kere-* (SH), *kiräldu-* (MA), *keurde-* (IM) 1; WMong. *kere-*, *kereldü-* (L 457) 1, *kereče-* 2; Kh. *xerelde-* 1; Bur. *xerelde-* 1; Kalm. *keṛldə-* 1; Ord. *kerelde-*; Mog. *kerälda-*; ZM *keräldu-* (17-3b); Dag. *xerəldə-*; S.-Yugh. *kerēlde-* 1; Mongr. *kərēdi-* 1 (SM 198), (MGCD *kəreldə-*), *kərū* 'quarrel' (SM 199).

◊ KW 227, MGCD 344, 345.

PTurk. ***gEröĺ-** to quarrel, fight, wrestle (ссориться, драться, бороться): OTurk. *keriš-* (OUygh.); Karakh. *keriš-* (MK), *küreš-* (MK, KB); Tur. *güreš-*; Gag. *güreš-*; Az. *güläš-*; Turkm. *göreš-*; MTurk. *küreš-* (MA), *güreš-* (Sangl.); Uzb. *kuraš-*; Uygh. *küräš-*; Krm. *küreš-*; Tat. *köräš-*; Bashk. *köräš-*; Kirgh. *keriš-*, *küröš-*; Kaz. *keris-*, *küres-*; KBalk. *küreš-*; KKalp. *keris-*, *güres-*; Kum. *küreš-* (dial.); Nogh. *küres-*; Khak. *küres-*; Shr. *küreš-*; Oyr. *keriš-*, *küreš-*; Tv. *xüres-*; Tof. *xireš-*, *xüreš-* ; *xire-* 'to start a fight'; Chuv. *kəreš-*; Yak. *küres* 'wrestling'.

◊ EDT 747-748, ЭСТЯ 3, 79-81, 5, 50-51, Федотов 1, 280. The peculiar variation of *keriš-* and *küreš-* in old sources allows perhaps to reconstruct the original shape **geröĺ-*.

PJpn. ***kə́r-** 1 to kill 2 to curse (1 убивать 2 ругать): OJpn. *koros-* 1, *kor-* 2; MJpn. *kórós-* 1; Tok. *kòros-* 1; Kyo. *kórós-* 1; Kag. *korós-* 1.

◊ JLTT 713.

PKor. ***kūr-** to curse, deprecate (ругать, порицать): MKor. *kūr-*; Mod. *kul-* (arch.).

◊ Nam 62, KED 217. Cf. also MKor. *kòr'ǡp-* 'to be rude, coarse' (Nam 51), modern *kol* 'anger' (KED 156).

‖ EAS 146, KW 227, Poppe 18, 79, Murayama 1962, 110. Cf. **kàra*.

This small excerpt from the Eurasiatic database shows the common Altaic root for "fight, kill," with a phonological reconstruction and a detailed account of its descendants in Turkic, Mongolian, Tungus-Manchu, Korean, and Japanese.

Searching for the Laws of Life

D. Eric Smith and Harold J. Morowitz

We expect that life originated in a steady, reliable environment that was relatively rich with simple but energetic molecules…

Separating Chance from Necessity

The noted contemporary paleontologist and natural historian Steven Jay Gould has said of the history of life that "…any replay of the tape would lead evolution down a pathway radically different from the road actually taken."[1] Should one make such a strong statement about all aspects of life, though? Gould studied the body plans of the major groups of animals that suddenly appeared in the fossil record 570 million years ago, in a period called the "Cambrian explosion." Indeed it seems largely accidental that just this combination should have come to make up the entire animal world, creating a large-scale taxonomy of which only a subpart has survived to this day.

But what about the chemical composition of those organisms, or the way they capture energy to maintain and replace themselves, which we also share? Could that really have taken a different form than the one we see attested today? What about the great events when biological innovations changed the surface chemistry of the earth, like the emergence of photosynthesis that loaded our atmosphere with molecular oxygen, after two billion years in which it had had very little? What of endosymbiosis, when one group of bacteria-like unicells began living as organelles within another? How much of chance is there in these stages of our shared structure and history, and how much of necessity?

For five weeks in the summer of 2003, a diverse group led by Science Board member Harold Morowitz, Postdoctoral Fellow Jennifer Dunne, and Research Professor D. Eric Smith met to examine some of the universal structures and patterns in living systems, from biochemistry to ecology, and to ask which might have arisen from the action of underlying "laws of life." The goal was a set of rules or principles that select living forms from chemistry and geophysics, the way simple rules such as the Pauli exclusion principle generate the periodic table of the elements, and all of chemistry, from a few properties of the proton, neutron, and electron.

The discussion ranged from narrow technical details of core biochemistry, to broad philosophical questions of what should be meant by "laws" in biology. It is clear that, while biology is a natural science whose observations can be quite precise and often quantitative, the biological notion of understanding assigns less importance to predictions about the specific course of the future than is given in chemistry or physics. The roles of accident, individuality, and uniqueness are correspondingly greater in biology, and with these it becomes less clear how to interpret those features of life that we do observe as universal.

While the deeper questions about the ontological role of laws were largely left unresolved, a serious attempt was made to account for the specific universal features of life that are simplest and most primitive, for which the predictive power of biological laws should most resemble that in physics and chemistry. For these very old features, universal occurrence is more likely to indicate that few solutions to biological "function" were possible, and that this is why we have the forms we do. Understanding these structures is also likely to be critical as we try to piece together the origin of living from nonliving matter.

Such a focus on early core chemistry leaves many aspects of biological law unexplored, and even leaves us unable to say anything new about a host of regularities that the group examined, such as the beautiful web-like cell wall that encrusts all bacteria like a Fabergé egg, or the ubiquitous scaling laws in ecology. However, with chemical universals as starting points, the group was able to embed biology in the larger geochemical world, and also to look for the first place where uniquely biological forms of necessity differ from those in physics and chemistry.

A New View of Life's History

A lot has been learned about the earth's early geochemistry and the metabolic history of organisms since the early "chicken soup" models of the emergence of life. In the 1950s, Stanley Miller and Harold Urey showed that a broth of surprisingly complex molecules could be produced from the action of lightning in an atmosphere of ammonia, methane, and water, and this spawned a whole generation of models for the first emergence of proteins, DNA and RNA, and how these might have assembled into the machinery of cells [2].

The investigations were truly revolutionary, because they turned questions about the origin of life into laboratory science, and many of the experiments uncovered valuable pathways for synthesis of

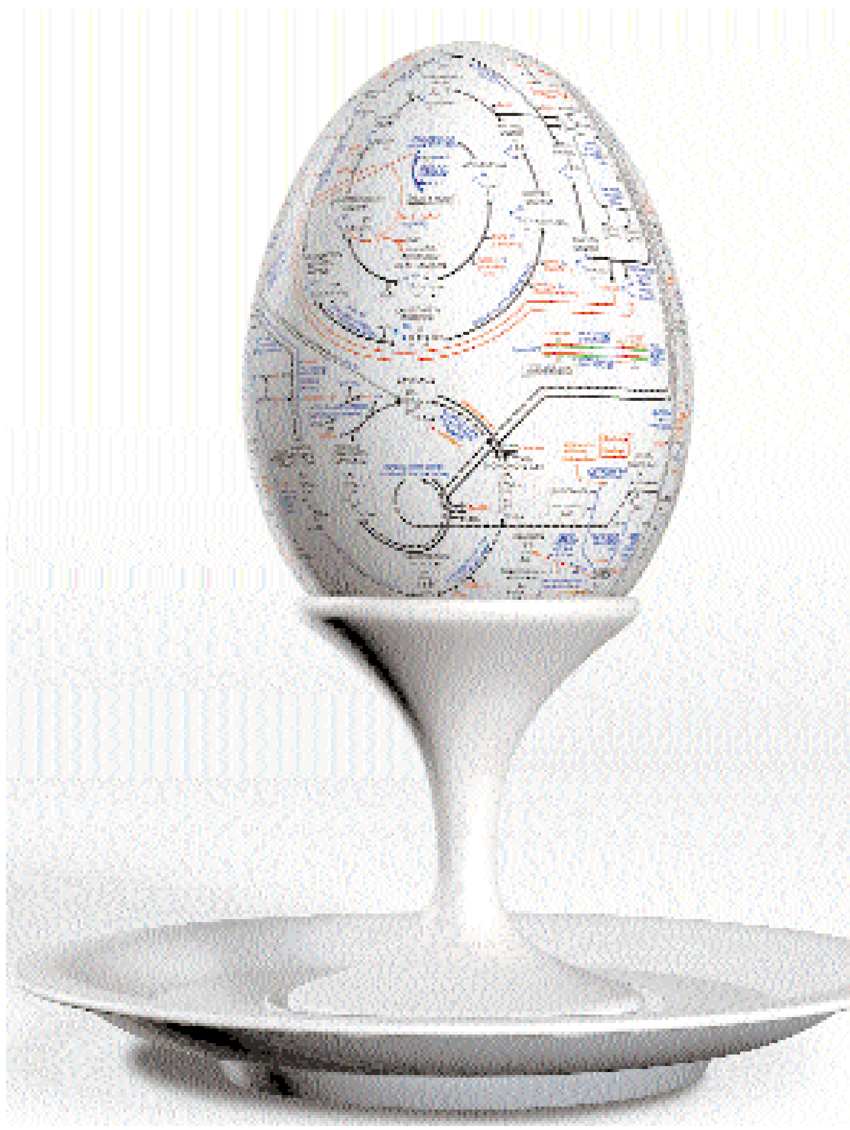

ILLUSTRATION: PATRICK MCKELVEY

these important classes of molecules. At the same time, the enterprise fundamentally lacked structure, and no convincing overall origin stories ever came of it. It tried to account for the detailed combinations of molecules we see today, but could give no deep reasons for why those molecules were important. Was containment in cells necessary to run the metabolism that traps energy to build the cells? Were template molecules like RNA or proteins needed to select the reactions that would then build more RNA or protein? Each of these questions led to a version of the uniquely biological conundrum: "Which came first, the chicken or the egg?"

We are finding now that the four-billion-year history of life is divided chemically into two great periods, each about two billion years long. In the first, while sunlight was prevalent as it is today, living things appear not to have used it the way modern plants or blue-green algae do, and perhaps not at all. They may have drawn all of their power and material from energy-rich molecules bubbling up from volcanoes beneath the oceans. The molecules are simple and familiar—carbon dioxide, molecular hydrogen, carbonic acid (tonic water), hydrogen sulfide (rotten-egg gas), acetic acid (vinegar), or ammonia—but the realization that it is possible to live on those has only followed the discovery of families of modern deep-ocean bacteria that do just that. These remarkable organisms need nothing to eat besides such small molecules and inorganic mineral salts, and can build all of their complex biomass, literally "from the ground up."

Molecules bubbling up from magma are a limited resource, though, and it appears that photosynthesis emerged as a way to trap light to increase this resource pool, as certain purple bacteria do today. Only as a byproduct of storing energy from light in sugars did bacteria first produce oxygen, which could be used later to burn the same sugars to extract the stored energy. The large-scale adoption of this process converted earth's atmosphere to the oxygen-rich form we know today, and introduced a whole new way of life, powered by eating sugars, and metabolizing them with atmospheric oxygen. This was the second great period, in which life expanded to fill every niche on the earth's surface. We have traditionally viewed life inappropriately as if this were its only stage, simply because oxygen renders the older way of life impossible in the surface world where we live.

Life Through the Looking Glass

When things happen in a particular order in history, it is often because the later stages build on the accomplishments of the earlier ones. The very fact that the early origin stories repeatedly run aground on chicken-and-egg paradoxes, where none of the steps seems possible before the others, suggests that we should take the two-stage history of life as an important clue. Can it be that the history of life is also a key to the emergence of the complexity of life?

The results of many different streams of work presented in the "Laws of Life" meetings suggest that this is indeed the case. For the last 20 years, Morowitz has been steadily rearranging the metabolic chart of all modern organisms[3], showing that the chemoautotrophic[1] reactions creating all the major classes of biomolecules originate somewhere on a single reaction cycle through 10 compounds, known as the Citric acid cycle, or Krebs cycle. This observation in itself is compelling, because it shows that the Krebs cycle is a kind of core of synthesis for all of biomass. However, that observation only goes part of the way toward simplifying our view of modern organisms, because for them the Krebs cycle is simply a way to digest sugars with oxygen, to produce energy. The energy digested is not used with the cycle compounds in any direct way to make biomass, and there is no obvious reason the chemicals in that particular cycle should be the starting compounds from which the rest of life is built.

Even more puzzling, the sugars digested by the Krebs cycle are now produced in plants by a separate complicated photosynthetic pathway, involving chlorophyll and many complex structures for managing energy and carbon flow. The molecules that perform photosynthesis perform no direct steps in their own replacement; that all comes from the Krebs cycle. No subset of this complex network of reactions can persist in isolation, because the whole network is required to supply any one of its compounds. At the molecular level, we again encounter chickens and their eggs.

The Krebs cycle, though, contains a telltale clue that modern organisms are not the place to look for its explanation. It is a cycle that takes two three-carbon sugar fragments, digests one of them to carbon dioxide to make energetic hydrogen ions, and returns the other through a so-called anaplerotic[2] reaction chain as a seed to begin the cycle again. Since the sugar is provided externally, this two-into-one cyclicity is not needed to supply materials. Further, from the perspective of SFI science, it is the ultimate paradox. The business of life is to build more life; why is the core engine of synthesis of all life a cycle that turns two copies of a complex molecule into only one? For many decades, a staple in abstract models of the emergence of complexity has been a self-catalyzed reaction that takes in one complex object, and spits out two. The simplest such reaction, of course, is a cycle. The Krebs cycle has all the topology of such a so-called autocatalytic pathway[4], only the reactions run around the cycle in the wrong direction.

The two-stage history of life resolves this deep puzzle, because in the earlier stage, the core biochemistry was a sort of mirror image of what we find in the later stage. We now know that the Krebs cycle is also present in the self-sufficient organisms of the first phase, and is an engine of synthesis in them, just as in us. This is certainly true for the deep-ocean bacteria found today, and we suspect it is has been a property of organisms back to the first cells. In these organisms, though, it runs in the right direction for autocatalysis. In other words, this reverse-direction Krebs cycle regenerates itself from nothing more than environmental small molecules, and then serves as a foundation from which all the rest of biomass is formed. Only after a complex life evolved to use and share sugars was an alternate pathway found to use sunlight for their formation. Then, the same Krebs cycle that had once built them was the most natural pathway to run in reverse, to break them down.

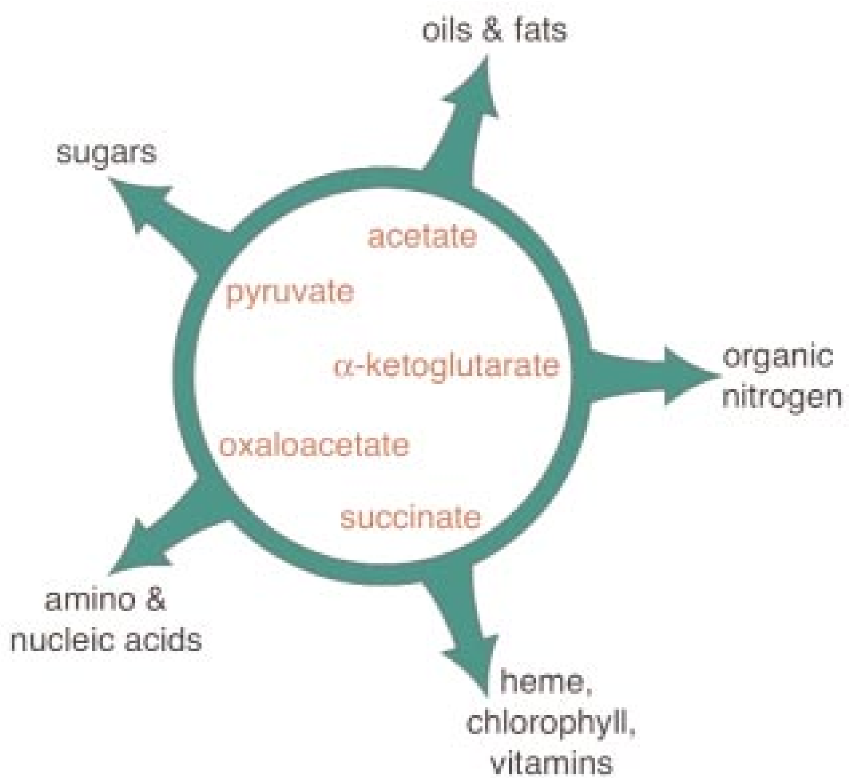

Figure 1: The Citric acid cycle is a core of synthesis for all major classes of biomolecules. Key compounds of the cycle (all organic acids) are shown in red letters, and the types of molecules they generate are shown in black. Other compounds in the cycle that are not direct precursors of biomass are not shown.

The centrality of the Citric acid cycle in the metabolic chart suddenly makes sense, and in the autocatalytic direction, it no longer requires complex external pathways for the production of complex “food” molecules. Since the cycle itself is simple, involving only 10 small compounds of carbon, hydrogen, and oxygen, it is also plausible as a primordial structure. This view is strengthened when one studies the internal chemistry of the Krebs cycle reactions, because it actually requires only three types of reactions involving C, H, O, and helper molecules like pyrophosphoric acid and hydrogen-sulfur molecules that may be available in some deep-ocean environments. The rest of the cycle, chemically speaking, comes for free. The important experiments that will be needed, to see how the cycle relates to the origin of life, involve how the reactions proceed without enzymes. Because modern organisms are highly optimized, and use enzymes to fine-tune every internal reaction, there is no easy reconstruction of pre-enzymatic history from them.

Rewriting Origin Stories

These observations about the history of life and the structure of metabolism suggest a new family of scenarios for the origin of life, which is both structured and clearly law-like, in comparison with the chicken soup scenarios. We envision that the earliest life was more like the self-sufficient deep ocean bacteria, than like anything else we know today. It formed around whatever chemical reaction cycles could convert the energy-rich but simple carbon- and hydrogen-containing molecules into structures that would seed their further consumption. The simplest such structure was the reversed Krebs cycle, whose emergence and stability were driven by this metabolic capacity.

For any chemical mixture not tightly regulated by catalysis, the physics and chemistry of finite temperatures ensure that there is a cloud of surrounding reactions, breaking down the chemicals toward lowest energy forms. When the starting chemicals are the intermediates of the Citric acid cycle, these surrounding reactions contain the basic building blocks of sugars, fats, and amino acids that create proteins, and nucleic acids that create DNA and RNA. They also contain the fundamental plate-like molecules that are assembled to make chlorophyll, heme (which is wrapped in different proteins to make myoglobin and hemoglobin), and most of the metal-containing vitamins.

The story is completely reversed from the early scenarios of Miller and Urey. Rather than depend on relatively low concentrations of complex, atmospherically produced molecules, we expect that life originated in a steady, reliable environment that was relatively rich with simple but energetic molecules, as has been suggested by John Corliss[5] and Günter Wächtershäuser [6]. The stability of their chemistry slowly led to a simple but stable non-background chemistry, in which carbon cycling in reverse through the Citric acid compounds carried energy from the small-molecule

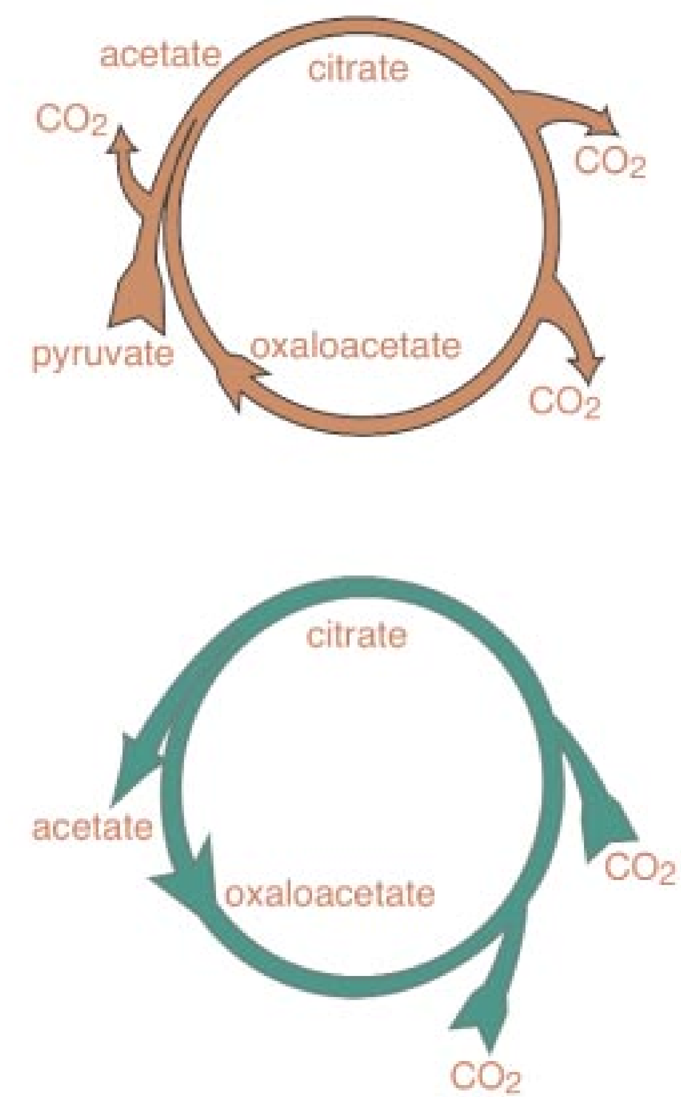

Figure 2: The Citric acid cycle can run in two directions. Top (red) is the oxidizing direction found in modern, sugar-burning organisms. Bottom (green) is the autocatalytic direction that we believe was primordial, and is still found in some deep-ocean bacteria. Pyruvate, a 3-carbon organic acid produced from sugars, loses a carbon to form acetic acid before entering the cycle. Oxaloacetate is a recycled 4-carbon organic acid that seeds the cycle in both directions. Only carbon entry or exit from the cycle is shown; entry or exit of hydrogen and water are suppressed to simplify the figure.

"food" to equally simple, small-molecule "waste," accumulating excesses of the building blocks of biomass as a byproduct. Stability of this rudimentary metabolism was the foundation for long trial and error, in which there was time for the discovery of those useful byproducts that could feed back to enhance the core metabolism, like the polar lipids (partly water-soluble, partly oily molecules) that made cell membranes or the protein-like molecules that are the simplest catalysts. These late-stage successes were not required to support the first metabolism, or to provide the supply that allowed the experimentation to go on.

The thing that makes this origin story law-like, however crudely, is its reliance on the ability to sample over and over again from a chemically "ordinary" environment. Rather than rely on chance reactions among rare molecules, it describes an emergent sequence in which each new level was available to be found, discarded, and found again, in samples from a stable level of structure directly beneath it. Metabolism selected from small-molecule chemistry. Biomass synthesized from a chemically stable metabolism. At each stage, the feature that emerged was the most stable, or most probable, that could be built on the foundation directly beneath it. The ability to identify structures as preferred, even in this probabilistic sense, embeds the lowest levels of biology in chemistry and physics.

What About the Genome?

One of the striking sociological features of biology today is the extraordinary importance placed on the sequencing and interpretation of DNA. The search for chemical regularity in the working group's discussions hearkens back to an older, even pre-Darwinian view of cause for the order of life. The older view says that living things have the shapes they have because, in some absolute sense, those shapes are good for something.

The early theories of visible characteristics[3] were often motivated by social, religious, or political idealisms, and gradually took on an aura of disrepute as scientific argument became more mechanistic, and (some) political ideals more egalitarian. During this transition, Darwin articulated the idea that inheritance with random variation determines what is possible, and competition then selects among the choices it is offered. Where the older arguments for "good shapes" seemed reasonable, Darwin's natural selection offered a way to converge on them, but the original notion of efficient design as a driving force toward good shape was lost in this transition.

In the century since Darwin, the first simple models of fitness with respect to an unchanging environment have given way to more subtle models, recognizing that species create each other's environments and so co-evolve, and mathematical treatments have also made us more aware of how few of the possible forms and ecologies can ever be discovered

The modern biological perspective is much more like one in which, to the genome, "everything is permitted," and the history of life is simply the history of accidents in the absurd races among genes in ecologies.

at random. The idea of efficient design has thus been weakened even further—good solutions to problems can easily go undiscovered, and "Red-Queen" dynamics of co-evolution can cause all the species in an ecology to change in order to keep up with each other, while none of them actually "improves" in any obvious sense of its relation to the environment. The modern biological perspective is much more like one in which, to the genome, "everything is permitted," and the history of life is simply the history of accidents in the absurd races among genes in ecologies.

What does the historical record of the genome say about a metabolism-centric view of life, and about the role of design more generally? When only the genetic history of ribosomes (tiny bodies within cells that build proteins using information transcribed from DNA) had been reconstructed, there appeared to be a clear picture of the family tree of all life. Three major lineages lead to all of the modern organisms, of which two are types of bacteria. The third lineage contains everything else from yeasts to plants and animals. The cleanness of this description led biologists to expect that when a different genealogy from the DNA of nuclei was reconstructed, it would reinforce this ribosomal family tree, and add detail to its earliest divisions.

What happened was rather different[7]. The DNA record muddies the early branches of the family tree, by showing that the early single-celled organisms tried many different strategies for regulating their core biochemistry, and exchanged the DNA that encoded these strategies rather freely across the early family boundaries. The three families still make sense, as identified by strategies for making structural walls and membranes of different types. Moreover, they seem to have all shared the core metabolism discussed above. These chemical features seem more stable, though, than the DNA that determined their regulatory machinery, as if chemistry determined the "right answers" to the cells' problems of metabolism and gross structure, and the DNA largely reified those right answers.

It appears as if the chemical "configuration" of the cells determined these earliest levels of structure, more specifically than the genome did. If this is true, it suggests a change in the emphasis of biology, where absolute preferences for configuration interact with the mutation and selection of the genome, to determine which forms of life can emerge and persist, and which cannot. We are not overturning Darwin's arguments about variation with selection, or returning to the Victorian notions of efficient design. However, we are learning to recognize that genes need not be rigid commitments, for good or ill, and that there may be aspects of life whose form is uniquely determined by the same sorts of thorough sampling that enable us to make specific predictions in physics or chemistry, an expectation that biology seems largely to have lost.

Physical Self-Organization and Biological Law

The group's investigation of primordial metabolism is very much in the spirit of studies of self-organization that have been traditional at SFI. Indeed, the emergence of an autocatalytic metabolism before there were enzymes, if it can be demonstrated, is as much a problem in pure physical chemistry as in biology. Yet clearly cellular life is more than pre-enzymatic metabolism, and biology obeys rules of order beyond those studied in physics. What light, if any, does our study of origin stories shed on these?

A focus on an emergent and self-sustaining core, from which living matter is constructed, alters our view of the many layers of complexity that surround that core in all modern organisms. We see that enzymes for core reactions "pay their way," in improving the efficiency of the metabolic cycles that built them. Photosynthesis enabled primitive, volcanic metabolism to expand and fill the world, by wrapping that metabolism in a chemical "space suit," which could generate food molecules from light. This freed organisms to leave the immediate neighborhoods of hydrothermal vents where they had evolved. Since the photosynthesizing molecules were themselves built from chemicals in the core metabolism, in augmenting it they provided for their own reconstruction.

At all levels of complexity in life, we see a hierarchical structure in which higher, regulatory structures sharpen or direct lower-level constructive processes. When they serve to enhance the processes by which they are created, either individually or cooperatively, they are favored by selection, and become the stable innovations of evolution. Ultimately, every structure experiences some positive or negative bias from its impact on the energy and material extractable from core metabolism. This principle of construction may have no counterpart in physics, and yet may remain law-like and predictive in the biological realm. It is like a feedback between components in a system, except that it operates between levels in a hierarchy. One could call this reciprocity between construction and regulation a "feed-down" relation.

It is tempting to see feed-down as an input to selection all around us, even at the levels of economy and society. In the economy, many activities lead to production, but those that generate capital enable us to change our means of production. For this catalytic effect, we actively work to protect those ways of life that generate and use capital. Similarly, many early states have their origins in piracy, when the pirates realized that they could extract more from local populations by living among them and instituting cooperative public-works projects. Theft became taxation, and the pirates became rulers, but only when their rule led to innovations such as cooperative irrigation, fisheries management, or reduction in internal conflict. We use such criteria today to distinguish legitimate states from other forms, though we still understand only poorly how to encourage legitimacy. An intriguing problem for the future is to see how much of anatomy, ecology, and sociology can be accounted for in terms of feed-down reciprocity (perhaps including some properties of Gould's phyla), and what it can predict about future innovations and change.

The authors wish to thank our co-organizer Jennifer Dunne for reminding us that the laws of life are hierarchical, and must look upward to ecology as well as downward to physics and chemistry.

D. Eric Smith is a Research Professor at SFI, and Harold Morowitz is a member of SFI's Science Board.

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[1] "Autotrophs" are the self-starters of the food chain. The chemoautotrophs are organisms that require no intake of either organic matter or light in order to live. They self-sufficiently generate all of their biomass from inorganic small molecules.

[2] Anaplerotic is a term coined to refer specifically to the pathways that direct carbon in the modern Citric acid cycle into compounds other than fully-degraded carbon dioxide. These include the pathways that return it through oxaloacetate, an organic acid, to seed the next round of the cycle.

[3] Called Phenetics, from Greek phainein, to show.52 (1988) 452-484.

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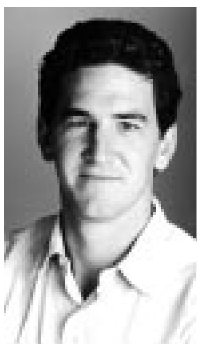

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During a 22-year business career focused on financial and strategic roles, **Gary Bengier** participated in a variety of developing technologies, including the Internet, semiconductor chip design, computer peripherals, scientific instrumentation, and biotechnology. He currently serves on the Board of Directors of Logitech Inc., a maker of computer interface products. From January to November 2001, Bengier served as senior vice president of Strategic Planning and Development for eBay Inc. Prior to that, from 1997 to 2001, he was eBay's vice president and chief financial officer, during which time he led the company's initial and secondary public offerings. Bengier was vice president and chief financial officer of VXtreme, Inc., a developer of Internet video streaming products in 1997. From 1993 through 1996, he was corporate controller at Compass Design Automation, a publisher of electronic circuit design software. Bengier has also held senior financial positions at Qume Corp. and Bio-Rad Laboratories, and spent several years as a management consultant for Touche Ross & Co. He holds a B.B.A. degree in computer science and operations research from Kent State University and an M.B.A. from Harvard Business School.

Adam R. Dell is the managing general partner of Impact Venture Partners, a venture-capital firm focused on information technology investments. Prior to founding Impact, he was a partner with Crosspoint Venture Partners in Northern California and a senior associate with Enterprise Partners in Southern California. Before becoming a venture capitalist, Dell worked as a corporate attorney in Austin, Texas with the law firm of Winstead Sechrest & Minick. He received a B.A. in political economy from Tulane University and a law degree from the University of Texas School of Law. He currently serves on the Board of Directors of XO Communications, MessageOne, and OpenTable. Dell teaches a course at Columbia Business School on business, technology, and innovation, and is a contributing columnist to the technology publication, *Business 2.0.*

Ellen H. Goldberg, Santa Fe Institute (SFI) research professor and co-director of the Santa Fe Institute Consortium: Increasing Human Potential, is responsible for coordinating a longitudinal multidisciplinary study in an attempt to better understand the relationships between growth and maturation of critical neural functions and behavioral development in babies and preadolescents. Goldberg was president of the Santa Fe Institute from January 1996 through January 2003, where she was responsible for overseeing the overall operation of SFI, including financial and scholarly activities in the area of complex adaptive systems. She received her B.S. degree in biology from Russell Sage College and her Ph.D. in genetics from Cornell University Medical College. For her research at Cornell, Goldberg received an "outstanding dissertation award" in which she identified unique cell surface antigens on spermatozoa. Her work on differentiation antigens continued throughout her career in the Department of Microbiology at the University of New Mexico School of Medicine for which she was awarded grants from the National Institutes of Health (NIH) from 1972 through the present. Among many honors, in 2000, Goldberg was appointed chair of the National Science Foundation's Biological Sciences Advisory Committee. She also serves on the Board of Directors for HopeLab Foundation and on the Advisory Board for the Investment Company of America.

James Rutt is currently a researcher in residence at the Santa Fe Institute, studying the application of complexity science to financial markets, social simulations, and artificial intelligence. He was most recently CEO of Network Solutions, Inc., which administers the .COM, .NET, and .ORG domain namespaces on the Internet, where he led the resolution of long-standing issues around Internet governance, led the company through a successful $2.1 billion secondary offering, and ultimately engineered its $17 billion acquisition in 2000 by VeriSign. He has either founded or played a key role in several significant information services and network companies. Starting back in 1980, he went to work for "The Source," one of the first consumer online services, and was intimately involved in developing early versions of e-mail and bulletin boards, and has been credited with having coined the term "snail mail." He has been involved as an early-stage investor and/or advisor to numerous technology-based companies; and is currently a director of MarketSwitch Corporation, Netscan Corporation, Rio Grande Ventures, and Proteus Foundation; and chairman of the board of Analog Design Automation Inc. of Ottawa, Canada, a creator of software for automating the design of analog and mixed-signal integrated circuits (IC) for the semiconductor industry. Rutt received his B.S. degree in management from the Massachusetts Institute of Technology in 1975, and is a member of the Advisory Board of the School of Management at George Mason University in Fairfax, Virginia.

Graham Spencer was a co-founder of Excite.com, where he worked as chief technology officer until the company was sold to @Home in 1999. After leaving Excite, Spencer founded DigitalConsumer, a non-profit political lobbying group dedicated to preserving "fair use" and other freedoms related to digital media. He received his bachelor's and master's degrees from Stanford University.

TRANSITIONS

Postdoctoral Fellows
External Faculty
New International Fellows

Postdoctoral Fellows

These researchers are in residence from one to three years working both on collaborative and individual projects. Here are SFI's new additions:

Nihat Ay comes to SFI from the Max Planck Institute for Mathematics in the Sciences in Leipzig, Germany, where he worked as a staff researcher. He's a graduate of mathematics of the University of Leipzig, where he wrote his dissertation on "Aspects of a Theory of Pragmatic Information Structuring," exploring the question, "Is learning driven by an infomax principle that in some sense improves the information processing abilities of a neural system?" He believes that there is such a principle.

Jung-Kyoo Choi, an economics Ph.D. from the University of Massachusetts, Amherst, returns to SFI. His research concerns the evolutionary dynamics of human behavior and institutions. He uses agent-based modeling and evolutionary game theory to explore the roles of institutions and social structures that favor the evolution of behavioral traits of individuals living in group-structured populations, and on the evolution of social structures themselves.

Michelle Girvan recently received a Ph.D. in physics from Cornell University, where she specialized in dynamical systems on complex networks and models of synchronization and disease spread. Even though her training is in physics, Girvan has been drawn to biological problems. She's concerned about the decline of the Earth's biodiversity. Using computer modeling, she's working to capture key features of ecological networks that relate to diversity and stability.

Fabrizio Lillo, a physicist from Palermo, Italy, is working with J. Doyne Farmer examining financial markets. Lillo is doing an empirical investigation of agent-based models with the aim to "devise data analysis strategies able to capture the behavior of the agents and the role of the environment in which they interact." He holds a Ph.D. in physics from Palermo University.

Yuzuru Sato is a postdoctoral researcher working with James Crutchfield on the Defense Advanced Research Projects Agency (DARPA) Dynamics of Learning Project. His background is in nonlinear dynamical systems and computation theory. The research involves two themes. The first is to investigate the dynamics of learning in individual adaptive agents and the second is to investigate how such agents behave, adapt, and coordinate themselves in collectives. Sato comes to SFI from the Brain Institute of the Institute of Physical and Chemical Research (RIKEN) in Saitama, Japan.

External Faculty

The driving force of the SFI's scientific life is its network of external researchers, affiliated with universities and research institutions throughout the world. Here are the most recent additions:

Lisa Curran, assistant professor of tropical ecology and natural resource policy at the Yale School of Forestry and Environmental Studies, has spent over 18 years conducting terrestrial ecological research, primarily in South and Southeast Asia. She has also done interdisciplinary research and teaching on ecosystem dynamics, forestry policy, and land use with anthropogenic change in tropical forest regions, primarily in Indonesian Borneo. She's a director of the Tropical Resources Institute, an organization devoted to supporting tropical studies worldwide.

Nina V. Fedoroff did her undergraduate work at Syracuse University, graduating summa cum laude with a dual major in biology and chemistry. She attended the Rockefeller University, where she earned her Ph.D. in molecular biology. She joined the faculty at the University of California, Los Angeles (UCLA), and carried out research on nuclear RNA. Later, working in the laboratory of Donald Brown, Fedoroff pioneered DNA sequencing, determining the nucleotide sequence of the first complete gene. In 1978, Fedoroff became a staff member at the Carnegie Institution of Washington and a faculty member in the Biology Department at Johns Hopkins University. Her research focus changed to the isolation and molecular characterization of maize transposable elements. In 1995 Fedoroff joined the faculty of the Pennsylvania State University as Willaman Professor of Life Sciences. From 1995 to 2002, she served as the director of the Biotechnology Institute and she organized and served as the first director of the Life Sciences Consortium (now the Huck Institute for Life Sciences), a seven-college organization devoted to the promotion of multidisciplinary research and teaching in the life sciences. In 2002, Fedoroff was named an Evan Pugh Professor at Pennsylvania State. Fedoroff's current work is directed at understanding the genetic organization and molecular dynamics of plant stress and hormone responses and makes use of DNA microarray expression profiling, reverse genetics, and theoretical approaches to the analysis of large data sets.

Hillard S. Kaplan, professor of anthropology at the University of New Mexico, has researched a range of cultures, from the Tsimane of Bolivia to foragers in Rondonia, Brazil. His work focuses on the human life course with the goal of understanding physical and psychological development and aging, the determinants of age-specific fertility and mortality profiles, and the demographic and economic implications of life course variation. The research program is both theoretical and empirical. From a theoretical perspective, it synthesizes evolutionary biology and economics in the development of new models of human life history evolution. Empirically, it spans hunting and gathering societies, forager-horticulturalists, and modern urban settings in both the developed and developing worlds. The work has resulted in publications such as "The co-evolution of intelligence and longevity and the emergence of humans," (with Arthur Robson) in the *Proceedings of the National Academy of Sciences,* and "An Evolutionary and Ecological Analysis of Human Fertility, Mating Patterns, and Parental Investment," (with J. Lancaster) in *Fertility Behavior in Biodemographic Perspective,* among others. Kaplan holds a Ph.D. from the University of Utah.

Among many accomplishments, **John S. McCaskill** pioneered the field of information processing in adaptive biomolecular systems, linking automata theory with physical chemistry to attain a deeper understanding of living systems and their evolution. A theoretical chemist, and graduate of Oxford, he's currently head of the New Research Division for Biomolecular Information Processing for GMD (German National Research Center for Information Technology), part of Fraunhofer Gesellschaft.

Lauren Ancel-Meyers, assistant professor of integrative biology at the University of Texas, Austin, has had a relationship with SFI since she came here as a Complex Systems Summer School student. Most recently, she's been working on mathematical models that attempt to explain the quick spread of SARS. The models are being used by Canadian public health workers to predict which strategies will work best to control the spread of the virus. Ancel-Meyers was a presenter at the 2002 Complex Summer School at SFI, lecturing on "Modeling Evolution: Integrating Computation, Experimentation, and Theory," and also at the 2002 workshop on the "Evolution and Measurement of Robustness in Organisms."

Martina Morris, professor of sociology and statistics at the University of Washington, is also a director for the Center for Studies in Demography and Ecology. She's interested in the analysis of social structure and population dynamics. Her research is interdisciplinary, intersecting with demography, economics, epidemiology and public health, and statistics. Examples from her current projects include the study of partnership networks in the spread of HIV/AIDS, a micro-simulations study of the effect of concurrent partnerships on HIV spread in Uganda, and comparing results to those in countries such as Thailand and the U.S. Another examines the impact of economic restructuring on inequality and mobility. She's also researching the development of relative distribution methods for statistical analysis.

Mercedes Pascual, assistant professor in the Department of Ecology and Evolutionary Biology at the University of Michigan, is a theoretical ecologist and biological oceanographer interested in population and community dynamics. Current collaborative projects address the dynamics of cholera in relation to climate variability and the modeling of planktonic food webs in the Western Equatorial Atlantic. She received her Ph.D. from the Joint Program of the Woods Hole Oceanographic Institution and the Massachusetts Institute of Technology. She was awarded a U.S. Department of Energy Alexander Hollaender Distinguished Postdoctoral Fellowship for studies at Princeton, and more recently, a Centennial Fellowship in Global and Complex Systems from the James S. McDonnell Foundation. She's currently affiliated with the Center for the Study of Complex Systems at the University of Michigan and participates in the Program on Health Effects of Global Environmental Change at Johns Hopkins University.

Alan Charles Swedlund, from the Department of Anthropology at the University of Massachusetts, Amherst, has most recently assessed the status of paleo-Indian remains, including the Kennewick Man discovery. He's also analyzing the "Changing Risk Factors in Mortality in the Historical U.S." He's on the editorial board of *American Anthropologist* and a research associate for the New Mexico Museum of Indian Arts and Culture and Laboratory of Anthropology.

2003-2005 SFI International Fellows

The International Program has selected the 2003-2005 class of International Fellows from among over 100 applications. This will be the fourth class of Fellows since the program's inception in 2000, and the applicant pool was the strongest the program has seen.

Himanshu Agrawal is an assistant professor at the School of Information Technology, Jawaharlal Nehru University, New Delhi, India. His interests lie in multidisciplinary research encompassing physics and biology, bioinformatics, biophysics, and statistical physics. Specifically, he is interested in employing the methods of statistical physics in identifying the genetic networks forming the regulatory core of complex biological systems. As an International Fellow, Dr. Agrawal hopes to extend his work on synthetic gene networks, especially those associated with gene-linked malignancies such as cancer.

Ernesto Altshuler is profesor auxiliar in the Physics Faculty at the University of Havana, Cuba. He is engaged in experimental and theoretical research in a number of cross-disciplinary areas. One of his main fields of work has been the study of avalanche dynamics in different scenarios, ranging from superconducting vortices to real piles of beads. Altshuler is especially interested in the role that self-organization plays in these scenarios. He is primarily concerned with identifying and characterizing spontaneous symmetry-breaking in physical and biological systems ranging from piles of sand to ants escaping an anthill under conditions of panic.

Elena Alvarez-Buylla is the head of a large laboratory at Universidad Nacional Autonoma de Mexico, whose members combine experimental, evolutionary, and dynamic modeling approaches to questions concerning the genetic interactions that govern plant development. She is interested in dynamic non-linear models that may be used to integrate data on genetic regulation of plant development and morphogenesis. Alvarez-Buylla is a biologist by training but has used mathematical models to model data sets in fields ranging from population dynamics in tropical rainforests to molecular genetics and the evolution of plant developmental mechanisms.

Claudia Codeço is an associate researcher at the Scientific Computation Program, Oswaldo Cruz Foundation (Fiocruz), in Rio de Janeiro, Brazil. Fiocruz is the Brazilian equivalent of the United States' Centers for Disease Control. Codeço's research focuses on the theoretical aspects of population ecology and evolution of host-pathogen systems and the epidemiology of infectious diseases. Her background in modeling includes traditional compartmental models, individual-based models and stochastic matrix models, with applications to dengue, yellow fever, and other tropical diseases. Her current research interest is the ecology and evolution of host-vector-parasite systems and the design of control strategies for infectious diseases, especially dengue and yellow fever. Codeço is most interested in defining strategies to model the effect of small-scale processes on large-scale events.

Arkadiusz (Arek) Majka is currently a Ph.D. student at the Interdisciplinary Center for Mathematical and Computational Modeling (ICM) at Warsaw University, Poland, and of the Polish-German Graduate College, operated by ICM and Heidelberg University. Arek graduated from the Physics Department at Warsaw University. His master's thesis concerned plasma flow in magnetic tubes embedded in the atmosphere of the sun. He focused on energy equation and thermodynamic formalism in order to describe flow dynamics and heat exchanges. Majika's interests, however, extend beyond physics, and following his master's degree, he began working at ICM on more interdisciplinary problems. He is interested in applications of physics to the social sciences, decision sciences, and economics. He is seeking a thermodynamic formalism for economic systems. Majika's recent research is related to choice models, which are of great importance in many branches of economics, psychology, the behavioral sciences, cognitive science, political science, and the social sciences.

Carlos Rodriguez-Sickert recently accepted a position as an assistant professor in the Department of Sociology of the Catholic University of Chile. Rodriguez-Sickert uses game theory to explore the question of trust in human interaction. His past work has led to the development of a conceptual framework to analyze problems of trust as a specific form of social exchange, and to the exploration of devices that might improve social outcomes under such settings. As an International Fellow, Rodriguez-Sickert will devote his energy to the dynamic interplay between the material sanctions that operate against deviant behavior (both institutional sanctions and peer-to-peer enforcement mechanisms) and the intrinsic moral dispositions of the agents who conform to a particular community. His specific aim is to build a theoretical model that could explain how adherence to moral norms, which go against the material self-interest of the agents who adhere to the norm, can emerge and stabilize.

Balazs Vedres is an assistant professor at the Department of Sociology and Social Anthropology, Central European University. His research interests include economic sociology, economic transformation, social networks, and historical and discourse analysis methods. In his most recent research project (with SFI External Faculty member David Stark), Vedres has developed methods to chart the historical transformations of network structures in the Hungarian post-socialist transformation, building on a combination of optimal matching and social network analysis methods. His recent publications concern the interdependence of strategizing agents and evolving network structures in large-scale social change, in the areas of business networks, political discourse, and civil society organizations.

Prince Andrew, Duke of York, Visits SFI

PHOTO: JANE BERNARD

In October 2003, His Royal Highness Prince Andrew, Duke of York, visited SFI. As Special Representative for International Trade and Investment, he was in the region supporting United Kingdom companies trading internationally and encouraging foreign investment. His goal was to learn more about SFI and its research activities.

During a ceremony, Bob Eisenstein, Ellen Goldberg, Geoffrey West, and Murray Gell-Mann addressed the dignitary. Robert Ghanea-Hercock, of BTexact Technologies, also spoke. Ghanea-Hercock is a member of the SFI Business Network who was in residence at the Institute, as the SFI Business Network Fellow.

Eisenstein was pleased with the visit's outcome. "Prince Andrew listened to an hour of presentations on various aspects of SFI science," he said. "When they were finished, he asked questions, and they were good ones. He also had a nice interaction with the staff and students."

2003 REUs

Supported by the National Science Foundation, SFI's Research Experience for Undergraduate Students program hosts a small number of motivated and talented undergraduates each summer. The 2003 REUs brought curiosity and expertise to their projects. Each worked with a faculty mentor on an individual project focusing on some aspect of the computational properties of complex systems.

John Albers is majoring in mathematics and atmospheric and oceanic science at the University of Wisconsin, Madison. His interests include the study of applied mathematics, fluid dynamics, complex systems, and computational mechanics. While at SFI he worked with Research Professor James Crutchfield exploring multiple agent dynamical systems. Albers' residency was partially supported by DARPA.

Samuel Arbesman, of Brandeis University, majors in computer science and biology. He's interested in the field of conceptual computer science, the study of theories and concepts of computation and their relationship to other areas. "For example," he writes, "I'm interested in the field of artificial life, which seeks to abstract the fundamental characteristics of biological life and to try to tease out their parallels within machines, with the eventual goal of creating digital organisms." While at SFI, he collaborated with Research Professors Walter Fontana and David Krakauer.

Rahall Deb, a computer science and engineering major at the Indian Institute of Technology in New Delhi, brought a range of interests to SFI. He's done work with player bargaining for IBM Research in New Delhi and helped with designing a prototype of a network photocopy machine for Xerox India. While at SFI, he worked with Research Professors Samuel Bowles, J. Doyne Farmer, and John Miller on the project entitled "Modeling Players in Games Using Evolving Automata."

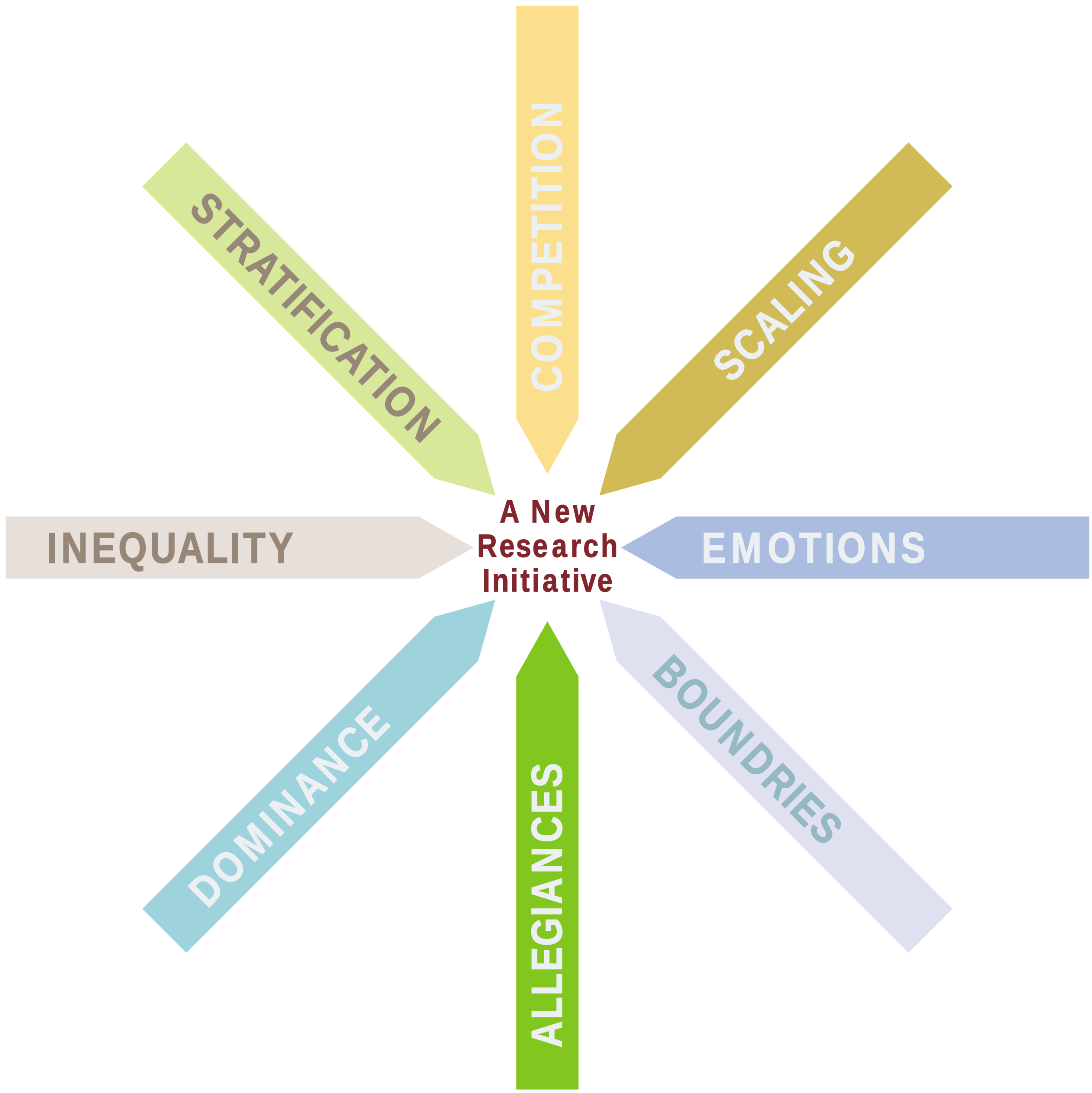
Miriam Goldberg, pursuing a special major in emergent behaviors and economic and social systems in the Economics Department at Yale, is interested in ways in which large social and economic phenomena arise from interactions of the individual behaviors of large numbers of people. Further she's exploring how these systems of people can sometimes exhibit behaviors that are not straight-forwardly representative of the individuals comprising them. While at SFI, she worked with Samuel Bowles and John Miller on a computational model of microfinance.

Selah Lynch, a physics and computer science major at Lehigh University in Pennsylvania is interested in studying extremes, which has led him to research into various granular systems. At SFI, he worked with James Crutchfield on computational mechanics, particularly modifying current software for ?-machines.

Meredith Root-Bernstein studies biolinguistics (the biological study of communication and language) at Princeton. Her interests lie in exploring the dynamics of evolving communication systems in animal populations. While at SFI, she worked with David Krakauer exploring the origin of communication in animal populations.

Erik Talvitie, a computer science and mathematics major at Oberlin College in Ohio, is interested in artificial life, especially understanding the common thread that binds complex systems together. "It amazes me that a famous system for modeling the flocking of birds can be nudged ever so slightly to produce behavior that looks qualitatively like molecules forming a crystal," he writes. While at SFI, Erik collaborated with James Crutchfield, and produced a paper titled "Can a Fly See Checkerboard?" in which he uses computational mechanics to explore many possible approaches to pattern discovery.

Matthew Tanner, of Princeton, studies operations research and financial engineering. He's interested in probability models such as Markov chains and queuing theory, especially with a focus on applications to experiment design as well as both parametric and non-parametric regression. While at SFI, he worked with John Miller and Research Professor Eric Smith on evolving signals, determining whether the ability to affect the environment by dropping and receiving signals can allow simple agents to better solve a coordination problem.



Probing the Mystery of Human Behavior

Many challenges to human well-being—global warming, the spread of HIV-AIDS, terrorism—are social in nature. So, too, are many opportunities for enhanced well-being—alleviation of global poverty, extending opportunities for learning, increasing tolerance of racial and other diversity. Understanding these challenges and addressing them requires knowledge, not only of the workings of the physical world, but also of how people act and how individual behaviors interact to produce outcomes for society as a whole. The physical sciences have made immense contributions to human betterment. By contrast, the contribution of the behavioral sciences appears modest, and inadequate to the contemporary challenges.

All decisions are collective decisions even when they seem to be individual decisions.

In fact, much in-group cooperation is based not on ill will toward outsiders, but on expectations of reciprocity from fellow group members

Recent intellectual developments have created both the environment and the tools necessary to address a number of foundational weaknesses of the behavioral sciences. From these developments arose the SFI Founding Workshop: Research Priorities in the Behavioral Sciences, in August 2003. At the Santa Fe campus some of the world's top researchers in biology, physics, anthropology, economics, neuroscience, psychology, sociology, and archeology convened to discuss the outlines of the new initiative. It's supported by an endowment given to the Institute by George Cowan, one of SFI's founding fathers, and coordinated by Samuel Bowles, SFI Arthur Spiegel-Endowed Research Professor.

The group faces a tough challenge, said Bowles during opening remarks. He stressed that the work that comes out of this initiative—even the most abstract theory—eventually needs to be useful to the world. Bowles said that the program will draw on past contributions of the SFI research community—especially the modeling of evolutionary processes, agent-based computer simulations, and non-linear dynamical systems—and extend those methods into some novel areas. "Until recently, mathematical approaches in the social sciences have been heavily influenced by an overly simple and empirically untenable economic model that has held sway since the middle of the last century," said Bowles, an economist by training. "Worse still, disciplines were walled off from one another. SFI is uniquely placed to contribute to improvements in this area."

During the workshop, each of the 35 participating scientists gave a brief capsule of his or her research and visions for the future of the behavioral sciences, followed by discussion. Below is a sampling of a few of the talks.

A Brain Tug-of-War: The Neuroscience of Social Emotions

Joshua Greene, of Princeton University's Center for the Study of Brain, Mind, and Behavior, discussed his work applying neuroscience to study decision making. Greene examines the brain to determine what parts of it are active when subjects are making personal versus impersonal moral judgments. With the use of functional neuroimaging technology, he tracks the cerebral blood flow of people as they take actions in the face of hypothetical moral dilemmas. Among his many findings are that distinct parts of the brain are active when subjects make decisions using their emotional versus cognitive faculties. "There's a tug-of-war between the different brain systems and different responses," said Greene. He's even able to map the emotional backlash that occurs after subjects make cognitive decisions, scientifically pinpointing specific emotions such as regret.

Still, he said, there's much to learn. "The business of predicting interesting behavior from neural activity is barely explored." He added that this is because there aren't many circuit-level models of high-level brain function. "We know how neurons work, how neurons can, in principle, carry out complex computation, but we know very little about how the brain's actual neurons work together to carry out the brain's most interesting business," he said.

Emory University's James Rilling, an anthropologist, uses functional neuroimaging to explore the neural basis of human social emotions among subjects in experimental games such as the Ultimatum and the Prisoner's Dilemma games. These games are simple enough that they can be implemented within the confines of the fMRI scanner, but yet rich enough to provoke many of the emotions all of us experience in our everyday lives. Through the process he and his colleagues have been able to map the brain's response to being treated fairly and unfairly. One of the findings shows that blood flow increases to the anterior insula cortex when players are mistreated. This region has been implicated in negative emotional states such as anger and disgust and may even relate to a form of moral disgust in this situation. He said that defining such intricacies within the brain could lead to deeper understandings.

"Our understanding of human brain function can be enhanced by a consideration of the process responsible for designing our brains, that is, by an approach that is informed by evolutionary theory," he said. In this vein, he sees a promising research direction in probing the neural basis of those aspects of human behavior that have been under strong evolutionary selective pressure. "We should focus on psychological solutions to perpetual problems that impacted the ability of our ancestors to survive and reproduce, or to promote the survival and reproduction of their genetic relatives," he added.

The workshop provided a launch pad for further interaction between Rilling, Greene, and others studying brain functioning and ongoing research at SFI. They will explore the evolution of social emotions and other motivations supporting civic-minded behaviors observed both in real, contemporary life, and in behavioral experiments conducted among today's hunter-gatherers and simple horticulturalists.

Choosing Allegiances: Race, Ethnicity, and Nations

Psychologist Toshio Yamagishi, from Japan's Hokkaido University, brought important findings exploring in-group and out-group behavior. Previous experimental findings on inter- and intra-group behavior have been interpreted to show that, as he stated, "We discriminate based on categorizing because our brain has a system of processing information based on categorization." But, surprisingly, this doesn't always happen. In fact, much in-group cooperation is based not on ill will toward outsiders, but on expectations of reciprocity from fellow group members. When this is precluded by the structure of the experiment, Yamagishi finds that people often act fairly toward out-groups even when they hold a low opinion of them. Thus stereotyping need not lead to one group taking advantage of another. His findings are consistent with the view that most of in-group-favoring behavior is a byproduct of an evolutionary-founded psychological mechanism to promote mutual cooperation within groups.

UCLA anthropologist Robert Boyd interpreted in-group and out-group relationships drawing both on ethnographic material and on mathematical models of cultural and genetic evolution. He argues that "primordial groups are not really primordial." In fact, he said, throughout history people have traveled across ethnic boundaries and chosen their allegiances depending on political and economic exigencies. However, people do attend to symbolic markers such as language, ideology, and shared history, and these factors affect which groups are able to elicit cooperation, a fact apparent today in such groups as business firms, army regiments, and academic disciplines. Gaining a deeper understanding of those group workings could aid in our understanding of the factors contributing to such conditions as racial tensions and high levels of group performance.

Haves & Have-Nots: Stratification, Dominance, and Inequality

Christopher Boehm, an anthropologist and primatologist at the University of Southern California, explores the causes of hierarchy among humans and other primates. He explained that hunter-gatherer cultures have hierarchical tendencies, but they can and often do alter the system to create egalitarian societies. Human hunter-gatherers, like chimps and other primates, learned how subordinates can band together to limit the power of the alphas. We see modern-day manifestations of these tendencies in a system such as a democracy and in a policy such as progressive taxation. Further, Boehm presented what he calls "genetic building blocks of hierarchical behavior," which include benefits for both dominant and submissive actors. "Domination gets you stuff," he said, "while submission keeps you from getting hurt." Another human reaction to existing in dominance hierarchies is a tendency of subordinates to resent being dominated. It is for this reason that subordinate coalitions are formed to damp the power of alphas.

Polly Wiessner, from the University of Utah, also shed light on the discussion of hierarchy. First she presented studies of !Kung or Ju/'hoansi Bushmen of Namibia and Botswana. These Bushmen are hunter-gatherers who are strictly egalitarian and who have formed informal and formal means of risk sharing. Their egalitarian system demands both equality of opportunity and equality of outcome. The former means equal access to resources, goods, and status and the latter means equal attained status for all adults. Through working with them for three decades, Wiessner found that today their egalitarian system still has benefits in promoting cooperation.

By contrast, two decades of studies among the Enga of Papua New Guinea have shown a different outcome. Over a period of some 240 years, the Enga began the transition from an egalitarian system to a hierarchical one. What sparked the transition was the introduction of the sweet potato along local trade routes. This allowed for a substantial surplus production for the first time in Enga history. Thus competition fueled the system and allowed some hierarchy to emerge. Comparing the Enga history to the African Bushmen, Wiessner noted, "If the Bushman allowed for inequality of outcome, their situation might be quite different today."

Exploring the intricacies of hierarchical systems, UCLA's Jim Sidanius, a psychologist, traces how race and gender interact as causes of inequality in the contemporary U.S. One study traced the returns in hourly earnings for additional years of school completed for whites and blacks. One of his many findings showed that white males made more money the more education they received, whereas the return for black males with more education was substantially less. However, these differences didn't exist between white and black women. The findings stressed the importance of studying race and sex differences in economic success jointly rather than separately. Sidanius concluded that there are numerous reasons for the persistence of inequality. "It's important to understand the many levels of concerns that cause such inequalities."

Predictions through Modeling: Empirical Applications of Complexity Science

SFI Distinguished Research Professor Geoffrey West, who is also at the Los Alamos National Laboratory, discussed scaling laws and social organization. He and a research team have found that in spite of its extraordinary complexity and diversity, many of the most fundamental and complex phenomena in biology scale with size in a surprisingly simple fashion. The work is based on the fundamental observation that, as he said, "Regardless of size, almost all life is sustained, and ultimately constrained, by space-filling, fractal-like hierarchical branching networks, which are optimized by the forces of natural selection." He explained further that the scope of the theory comes over 30 orders of magnitude, ranging from molecular and intra-cellular levels up through the smallest unicellular organisms to the largest animals and plants to ecosystems.

West and his team are applying these notions to social organizations. They're working to formulate a general quantitative theory of such networks based on a set of universal principles. The work addresses many problems. One main one is defining what a social organization is and how information flows within it. Another is coming up with appropriate scaling laws for social organizations. Yet another is determining what constraints must be satisfied by the architecture of the structures that channel social flows of information, matter, and energy. And finally, finding out what kinds of historical processes might result in anything like efficiency maximization for the social structures that regulate the flow of information, matter, and energy, and how these processes might be modeled.

SFI McKinsey Research Professor J. Doyne Farmer, another member of the resident faculty at SFI, presented work in which he and a research team use financial markets as a highly constrained environment to probe human behavior. The group borrowed ideas from statistical physics to model the "continuous double auction," which is the most widely used exchange mechanism in financial markets. In the auction people place orders to buy or sell; transactions happen when the buying prices are higher than the selling prices. Mainstream studies have focused primarily on the behavior of the agents, who are generally assumed to be highly rational. Farmer's group is taking the opposite approach.

"We make an extremely simple agent model—so simple we just assume that the agent's behavior is completely random," he said. "The great advantage of this is that it allows us to make a more realistic model of the real market institution, and to treat its dynamics in a realistic way. Although the institution of the continuous double auction might seem like a simple thing, its consequences are surprisingly profound and subtle." The random agent model allows Farmer and his team to flesh out what is really essential about the institution. "What's really surprising is that this results in very good predictions for real markets," said Farmer. "It seems that at least in many respects, the market institution is more important than the agent behavior."

Participants at the workshop pointed out that the zero intelligence random agent model inverts the usual approach in economics, which pays scant attention to institutional details, but endows individuals with elaborate cognitive abilities.

Networks and Social Interaction

In his discussion on networks and collective behavior, Duncan Watts, a physicist turned sociologist from Columbia University, showed how individual and institutional behavior relate to each other. He discussed two classes of collective behavior: problem solving and decision making. In the first, the collective has to solve a problem. As an example, he gave New York City, where there's an administrative body, firms, groups, and thousands of organizations that manage to operate in a relatively effective way solving the problem of keeping the city functioning.

In collective decision making, each individual is either cooperating or defecting by making choices. These might include deciding whether or not to vote, or which car to buy. "Individuals think they're making decisions themselves, but when you look at the aggregate, you see the regularities," he said. "All decisions are collective deci-

"Domination gets you stuff, while submission keeps you from getting hurt."

sions even when they seem to be individual decisions." Understanding both of these processes could help in determining how networks function and thus could help stop failures within systems, such as the August 2003 East Coast blackout that occurred at the time of the founding workshop.

Martina Morris, a statistician and sociologist from University of Washington, presented eye-opening research on partnership networks and HIV. Her work explores the prevalence of HIV, helping to explain what drives global variation in the disease's transmission. Most studies have assumed number of partners as the determining factor in transmission. And, indeed, it is a factor, but Morris' analysis of data from Uganda and Thailand shows the situation is more complex than that.

Exploring core group dynamics using agent-based simulations and network theory, she found that concurrency is crucial to the rate of disease spread. In Uganda there's a high rate of concurrency, meaning many people have more than one sexual partner at the same time, and the overlap between the two partners is typically quite long—on the order of one to three years. In countries such as the U.S., concurrency is much less common, and in Thailand, though concurrency is also common, the duration of the overlap between the two partners is very short—typically one night. In fact, the disease spread is less in Thailand than in Uganda mainly because rather than having many partners, men tend to go to prostitutes for extra-marital sex. The difference between the two scenarios (Uganda and Thailand) was the duration of the overlap in partnerships.

Such research has direct implications for policy makers combating HIV, she said. First, a goal would be for people to not simply have fewer partners, but to have them one at a time. She also said, in order to delve further, data collection needs refining. As well, the findings show that new methods of analysis are effective. "It's not just the number of partners, nor the level of concurrency, but the detailed timing and sequence," she said. This is what makes simulation methods so important, as they are the only methods that make it possible to investigate this kind of detailed network dynamic.

Good Ideas that Catch On and Make a Difference

During the workshop, five informal working groups formed to consider further collaboration, covering the following topics: Emotion, Cognition, and Behavior; the Robustness Variation of Sex Differences; Insiders, Outsiders, and Group Boundaries; Inequality as an Emergent Property of Social Interactions; and Institutional Innovation and Persistence. Further, since the close of the Workshop, three events have been arranged. One during the fall of 2003 was convened by SFI External Faculty members Peter Hammerstein and Hillard Kaplan, along with SFI Research Professor Elisabeth Wood. The workshop held at the Institute for Theoretical Biology at Humboldt University in Berlin explored sex role differences in humans and other animals. Another in February 2004 at SFI will be convened by SFI External Faculty members Herbert Gintis and Ernst Fehr along with Joshua Greene to examine the neuroscience of social emotions. A working group of primatologists, economists, anthropologists, and others will meet in July 2004, also at SFI, to discuss inequality as an emergent property of social interactions.

Bowles concluded the workshop by urging the scientists onward to create very tangible results. "It isn't just having a good idea that counts," he said. "It's coming up with good science that catches on and makes a difference."

Metaphors
Ladders of Innovation

by David Gray and Michele Macready

Though often dismissed as mere rhetorical window dressing, metaphors play an important role in innovative thinking. In particular, the *cognitive* use of metaphor can reveal potentially fruitful connections and novel ways of seeing that lead to new insight. There are many modes of metaphorical thinking, and an analysis of its operation in science, as in other domains, requires attention to the intention of the metaphor, its essential structures, and the different types of impact it can produce.

PHOTO: JULIE GRABER

A Necessary Ladder

A two-day workshop organized by SFI and the Strategy Institute of the Boston Consulting Group (BCG) last April brought together practitioners and academics from a number of fields with a common interest in the topic of metaphor. SFI participants Walter Fontana, José Lobo, and Jim Rutt gave presentations on the use of metaphor in their respective areas of chemistry, economics, and business. Paul Humphreys and Nicholas de Monchaux of the University of Virginia presented, respectively, a philosophical account of metaphor and its use in shaping visions in architecture. Tiha von Ghyczy of University of Virginia's business school and the BCG Strategy Institute, together with Michele Macready and David Gray, also of BCG, reported on the Strategy Institute's effort to build an online "gallery" of multi-disciplinary metaphors to inspire business thinkers, and reflected on the potential of employing large sets of metaphors as aids to creative thinking. The meeting explored the use of the cognitive metaphor as an important element in innovation in all these disciplines. The road to novel theoretical work consistently winds through a forest of metaphors.

Complexity science is premised on the assumption that seemingly disparate phenomena, both natural and social, evolved and constructed, can be understood using a common conceptual framework. The signature concepts used to talk about complex systems—emergence, adaptation, networks, evolvability, phase transitions, self-organized criticality, fitness landscapes, robustness, learning, edge of chaos, even the very notion of complexity itself—remain more metaphorical and suggestive than definitional and precise. And how else could physicists, biologists, chemists, economists, anthropologists, ecologists, computer scientists and historians engage in meaningful scientific dialogue without the ferocious exchange of metaphors?

Reliance on metaphors is by no means unique to complexity science, of course, but is instead prevalent in every field of scientific inquiry, especially in its early stages. Nor is the importance of metaphors confined to rarefied reasoning: the use of metaphors shapes our basic perception and understanding of the world. And yet scientists often distrust metaphors. Metaphors are not models and are thus not susceptible to the sort of direct application and rigorous testing that are the gold standard of scientific verification. As such, metaphors are sometimes viewed as incomplete—or worse, shoddy thinking. While acknowledging their appeal, many regard metaphors merely as ladders which, to paraphrase Ludwig Wittgenstein (no slouch himself when it came to the use of metaphors), once used to climb to a conceptually novel place must then be discarded.

At SFI, concerns for the proper role of metaphors and a respect for the difficulties in transitioning from metaphors to models have been present from the beginning and continue to animate discussion, from the 1992 "Integrative Themes Workshop"[1] to a recent workshop on the "Robustness of Coupled Natural and Human Systems." Plenty of Wittgensteinian ladders continue to be erected and kicked away in complexity science. At the Strategy Institute the cognitive use of metaphors in developing innovative strategies has been at the center of recent work.[2] The insights gained have already started to make an impact on practical work for clients.

Yet, the prevailing view systematically under-appreciates the critical operation of metaphor in cognition—whether in science, the arts, or in business. A metaphor is not merely a flawed and fuzzy model. Nor is it a final answer. A useful metaphor is an *invitation to hard work* that can be indispensable to innovation. Metaphors and models are not locked in a battle for relevance but can be seen as successive ladders, stacked one upon the other, which continue to underpin good thinking. W. Brian Arthur acknowledged this state of affairs at an SFI conference a few years ago when he said: "I have a very strong belief that science and thinking progresses not so much by theorems but by metaphors. Metaphors are what we absorb, that go in deep, that we digest, perhaps also consciously forget. But two years later you start to write about evolution in the economy and (suddenly you find yourself) deeply informed about how it takes place."

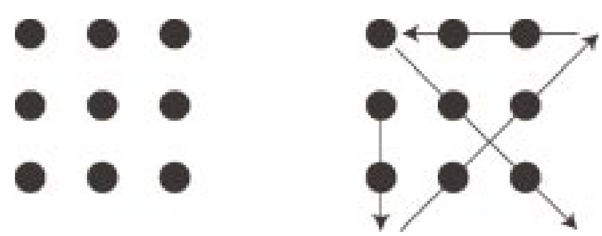
One goal of the April workshop was to discern some of the essential aspects of metaphors that make such unlikely, playful connections so highly productive. What constitutes the "appropriateness" of a metaphor, and where do good metaphors come from? More fundamentally, are there ways to improve our prowess as metaphorical thinkers, and can the novel topologies created by the mixing of metaphors, such as occurs regularly in cross-disciplinary work at both institutes, increase their power? This paper is an attempt to address some of these thorny questions and draws heavily upon conference presentations for insights and examples.

Metaphorical Reasoning

Metaphors appear almost everywhere in our conscious experience. While the classical use of the term applies primarily to a literary device, metaphors can also be visual or even auditory or olfactory (say, comparing something to the aroma of baking bread or apple pie). The organization of the PC "desktop," with its folders and file cabinets, is built on a metaphor. And what are we to make of so-called "metaphors of use" that let us see that, for certain purposes, a dime is a screwdriver? What is it that makes all these things potential metaphors?

"A metaphor," writes philosopher Nelson Goodman, "is an affair between a predicate with a past and an object that yields while protesting."[3] This rather louche, metaphorical definition highlights an essential feature of the metaphor: an intrusion from one domain into another. The metaphor borrows language, symbols, logic, and associations from one field and imposes them upon another to which they do not properly belong. Thus, the notion of a "war on poverty" suggests a transfer of structures and associations from the military domain to the social. The fit may be uncomfortable and endured only under protest, as Goodman notes. It is the incommensurability of the metaphor that is often its salient characteristic: if taken literally, all metaphors are patently false if not absurd. Melville's declaration that "Christ was a chronometer"[4] is a stark example. A liaison that does not involve some transgression of boundaries is no metaphor.

Thus the fit of the metaphor will always be inexact, and it is around these jagged edges that much of its innovative potential lies. A metaphorical intrusion smoothed by time and long wear is apt to become a dead metaphor or cliché: "Achilles heel" no longer jangles with associations of its original source but is used quite unreflectively to denote a fatal weakness. For most in the business world, the exhortation to "think outside the box" evokes no connection to the brain-teaser that spawned the phrase. These metaphors have died into literalness and thus lost their power to catalyze thinking.



The player must connect all 9 dots with four straight lines without lifting the pencil from the page. The solution requires thinking outside the (non-existent) box created by the square arrangement of the dots.

We should note that language is thick with the corpses of dead and dying metaphors. Scratching the etymological surface of most words reveals their metaphorical roots: the "corporation" derives from the *corpus*—a living body, and "strategy" from *strategos*—a military general. We are quite justified in using words literally without constantly acknowledging the underlying metaphors, but unearthing these foundations can sometimes be revealing. Unquestioned, implicit metaphors continue to exert a strong effect on the structure of language and thus on the structure of thought itself. For instance, bringing to light the mechanical metaphor implicitly embedded in a lot of business thinking (which continues to spawn new sub-metaphors, like "alignment," "toolkits," and "reengineering") can cause us to reconsider whether we are operating with the right picture in mind. Attention to metaphor allows us to engage in a useful archeology of clichés.

Anatomy of a Metaphor

Linguists use the terms *source* and *target* to designate the linked domains of the metaphor. The target is the main topic of discourse (e.g., the development of scientific ideas)—the thing we wish to understand—and the source is the interpretive device that sheds light on the target (e.g., political revolutions). Typically, we would expect the source domain to be the more familiar to us, the one closer to understanding or intuition, which therefore allows it to elucidate the more obscure target.

Many metaphors, however, draw upon source domains of considerable complexity: for example, laminar flow as a metaphor for business supply chains. Among business practitioners the invocation of laminar flow is likely to produce a lot of blank faces, while the supply chain (itself a metaphor!) will be quite familiar. In this case, the effectiveness of the metaphor is not immediate but requires a great deal of education to make it work.

The example highlights an important feature of metaphor--its power to *defamiliarize* the familiar. We think we know something about supply chains: the interlinked system of companies, individuals, and goods that provides inputs to manufactured products. The effectiveness of the metaphor borrowed from physics lies in its power to unhinge this knowledge--is it a chain? or is it more like a smooth flow of liquid? or is it a web?--in a way that allows new thinking to penetrate. We need not discard the existing picture, but the effective metaphor causes us to add new dimensions to the conceptual space. We may, therefore, wish to replace the notions of "familiar" and "unfamiliar," substituting "known"and "unknown." In some sense, the cognitive flow of the metaphor will always be from a domain of knowledge to one of nescience, but this does not necessarily correspond to the intuitive familiarity of these realms.

We should note that the transfer (the word *metaphor* itself comes from the Greek roots meaning "to carry across," i.e., transfer) can work in both directions. The linking of neurophysiology and computation is a commonly cited example of such a "boomerang" metaphor. While the initial borrowing of language and concepts flowed from brains to computers, the favor has been returned in the form of computer theory as a source of metaphors for neurological processing and, more generally, for information processing in biological processes. It may be more proper to speak of "ricochet" metaphors--once fired off, the trajectory and related combustions touched off by the cognitive metaphor may be difficult to predict! Darwin was clearly influenced by the works of political economists like Malthus and Smith in developing his principle of natural selection. A century and a half later we see the emergence of an army of researchers eagerly applying biological insights to the workings of markets. Likewise, the authors of a new book [6] relating the strategic insights of military theorist Carl von Clausewitz to business note that they are merely returning the metaphor: Clausewitz himself proposed that war could best be compared with commerce, since both are social conflicts of human interests and activities.

Metaphor and Analogy

Analogy is closely linked with metaphor and, indeed, we may think of these two notions as interchangeable: both point out likenesses in particulars between things that are otherwise dissimilar. In the way we propose to use the term, analogy is a *component* of metaphor that refers to the correspondences between domains—the structures or associations that form the core of the link between source and target. Without some degree of analogical mapping, the metaphor will be stillborn. A metaphor, however, goes beyond analogy by including all the ill-fitting facets of the linked entities—the fractures and fault lines—in the picture. The metaphor comes to life where analogy leaves off.

At this point, we raise again the vexed question of metaphors and models. In some cases we want to make a sharp distinction between these two things, while in others they seem to live in harmony. The question arises with particular force in the sciences where metaphors (e.g., plum puddings or solar systems as images of the atom) seem to shade into models that shape experimental design. The metaphorical origins of scientific models have been long noted: "Perhaps every science must start with metaphor and end with algebra, and perhaps without the metaphor there would have been no algebra."

Yet models have certain recognizable properties distinct from metaphors, most notably a degree of formalization that the metaphor lacks. We want models for specific purposes and we demand of them a certain rigidity that preserves the essential relationships between the model and the modeled. We might ask whether the mechanism of the model necessarily involves an appeal to the formalization of mathematics. A ship model, for example, provides a formal mapping to the actual bark by means of a mathematical correspondence, say 1 cm = 1 meter. A financial model similarly purports to capture the essential activities of a firm and their relations to one another using the formal structures of mathematics.

Figure 1 below illustrates the differing intentions of model and metaphor. The widening body on the left represents the "complexification" accomplished by the metaphor. For example, "...Juliet is the sun" brings in a host of potential structures and associations (e.g., of light, warmth, rising and setting, perhaps also eclipse?) that vastly complicate our picture of an otherwise unremarkable teenager from Verona and leaves that object forever altered in our understand-

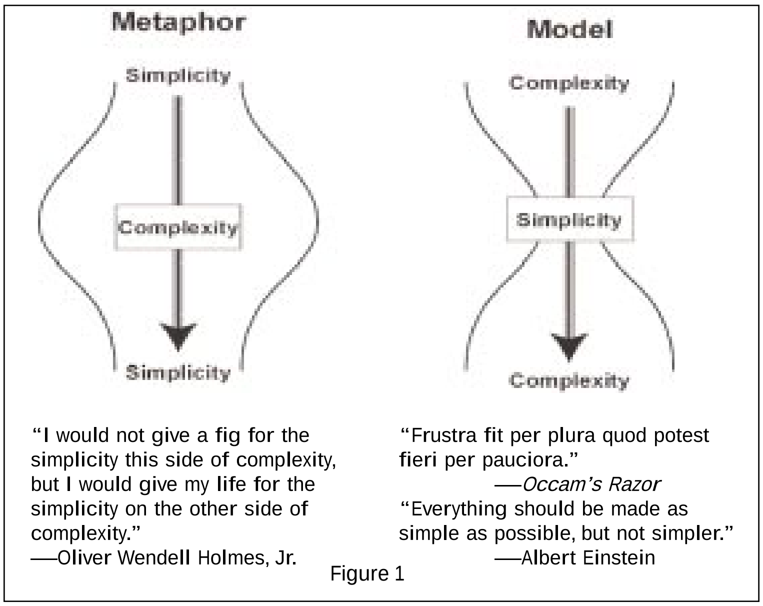


Figure 1

ing. The pinched figure on the right represents the opposed mechanism of the model that seeks to make tractable a potentially vast body of inputs and data through necessary simplification. This simplification is far from the final word, however, as analysis of results gives birth to new types of complexity.

This picture may seem to imply a fundamental opposition between metaphor and model. But this need not be so. One attempt to cut this Gordian Knot is simply to identify models with analogy, which would lead us to say that a model is a special kind of metaphor--one that has been pared down to the hard core of direct correspondence we can map between the two domains. This leaves the door open to further revision of the model through a metaphorical process but also lets us make formal demands of the model that may lead to its "falsification" or rejection if it fails to deliver on its promised correspondence to reality. Figure 2 is an attempted illustration of this relationship that stresses the analogical properties of the model while allowing for an ongoing reciprocity between model and metaphor.

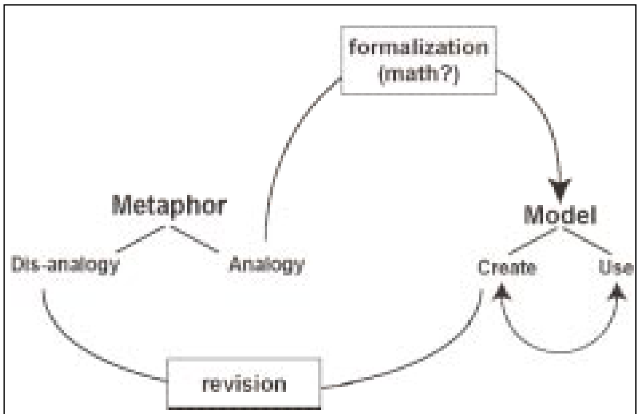


Figure 2: Metaphor and Model

DIALECTICAL TAXONOMY

The metaphor appears in so many guises and incarnations that a formal representation of its workings would seem very nearly futile. Instead, our analysis leaves intact all the inherent tensions. This description incorporates a sort of dialectical pairing of aspects of metaphor without attempting an ultimate synthesis. The progression is described in three stages: the intention, the structure, and the impact of the metaphor.

Intention of the Metaphor

In large part, intention makes the metaphor. There is no reason *a priori* why two such unrelated domains as ant foraging behavior and airline baggage handling should ever meet. The metaphor arises in the deliberate pairing of these two things. Although some things strike us as ìfoundî metaphors, the fact and the nature of the linkage derives more from the intention of the metaphor maker than from inherent structures. Intent must be appropriate to the context in which the metaphor is used and largely determines its success. Thus the particular application of metaphor in the business sphere in which the Strategy Institute operates may differ from its use in the SFI context of scientific research.

Much of the discussion of literary metaphors, going back to Aristotle, deals with them as *rhetorical* devices whose purpose is to convince the reader through an especially apt linkage. The rhetorical metaphor relies on economy of expression and aesthetic impact. The source domain of the rhetorical metaphor should be familiar and intuitive and the analogy between the linked entities immediately compelling. We distinguish from this the *cognitive* use of metaphor that forces a departure from the familiar. The intent of the cognitive metaphor is novelty, and we encounter it primarily as an opening to further inquiry. The linkages may be far from intuitive--for example, a proposed rapport between the intangible structures of proof theory in logic and chemistry[8]. But the intention is to force a cognitive reevaluation that lets us see in new ways and ask different questions.

Thus two alternative intents of the metaphor are revealed: *invitation* and *persuasion.* We are invited by the cognitive metaphor to delve into the intricacies of the source domain, test the strength of the bridge to the target, and hunt for important fractures in the analogy. It is an invitation to become a co-creator of the metaphor. The rhetorical metaphor is more `concerned with persuading us to a certain view.

This points to a further pairing of intentions related to the use of metaphor—*synchronizing* and *disarming.* Metaphors often become shorthand for certain ideas and are thus useful in aligning understanding or expectations. A manager who uses military terminology to describe business situations takes advantage of the synchronizing power of the metaphor, so that the difference between a “flank maneuver” and a ìfrontal assaultî on a competitor is quickly understood. Alternatively, metaphor can disarm expectationsówe may choose the metaphor of laminar flow or neo-Darwinian evolution precisely because it is unfamiliar. With the metaphor comes an unaccustomed vocabulary for describing phenomena in the target domain that forces a reexamination of what we know.

A final dimension of intention involves the use of the metaphor for *creating* versus *distilling* knowledge. The purpose may be to produce a new lens that allows an alternative view of the area we seek to understand. Here, the disjunctions and fault lines of the metaphor can be especially productive and drive us to search out or create structures that appear to be missing in the mapping between source and target domains. The distilling function of metaphor, on the other hand, is less about creating new knowledge than encapsulating wisdom--often gained through long experience--into a form that can be communicated to others.

These dichotomies reflect two categories of metaphorical intentions: learning and communicating. While the distinction is not absolute--we may learn much in seeking to communicate insights through metaphor--there is a natural split in the foregoing pairings. The learning function of metaphor emphasizes extended engagement with the source domain as a way of shaking up received thinking. It is more likely to focus on the fractured edges of the analogy, seeking novelty in the interstices where the fit is most uncomfortable. Rhetorical, persuasive, synchronizing, and distilling uses of metaphor are more geared toward capturing and communicating subtle insight to others.

Intention

Learn	Communicate
• Cognitive	• Rhetorical
• Invitation	• Persuasion
• Disarm	• Synchronize
• Create	• Distill

Structure of the Metaphor

The building blocks of metaphor--source, target, mapping, analogy, fracture--have been discussed in some detail above. But a number of tensions surrounding the structure of metaphor arise in its application. One such tension pertains to what might be called the “level” of the metaphor: does it act as a *governing* paradigm or in an illustrative, *subsidiary* role? A grand, governing metaphor offers a holistic interpretation of the target domain. Some governing metaphors may be unacknowledged-—though no less extensive or influential for that reason. Implicit images of firms as machines or as organisms are pervasive in business discourse[9] and shape our understanding and expectations of action, authority, and change. But not all metaphors make such claims to completeness. When Wittgenstein uses a toolbox to illustrate the diversity of language, or Adam Smith speaks of the intercession of an invisible hand in the market, our enlightenment does not depend upon acceptance of a larger schema.

Indeed, we often find that effective metaphorical thinking involves not just one *grand schema* but a *mixing of metaphors.* While such promiscuity is deemed poor style in the literary metaphor, its cognitive use is enriched by a proliferation of viewpoints. This raises some fascinating questions about the topology of large sets of metaphors: the strength, valence, mutability of connections among the source domains. The metaphorical space suddenly expands geometrically. What is lost, perhaps, is the coherence that a single schema, rooted in a particular domain, makes possible. Again, the intent of the metaphor--as a discovery device versus a communication tool--may dictate the effective structure.

A final reflection on the structure of metaphor deals with the trade-off between *depth* and *shallowness.* The domain acting as the source for the metaphor is rarely taken in all its complexity but is, at best, a snapshot—a frozen picture that provides the basis for the metaphorical transfer. Thus, the structures of biological evolution have been taken seriously as a metaphor in economics at least since the 1950s but the picture of evolution that economists work with is typically limited.[10] Our understanding of the source can and should be continually revisited and revised. But to be effective for the metaphor it must have an *appropriately moderate* number of dimensions. Too much complexity renders the metaphor unmanageable. For the pedantic astrophysicist intent on solar flares and burning helium the comparison of Juliet to the sun will be unrevealing. There is a sense in which all metaphors are shallow and must remain so. We can seek expertise in the target domain but, in the metaphor, we approach the source domain as amateurs.

But as curious amateurs! Unlike the model, which demands a degree of closure and completeness, the process of metaphor has no defined terminus. The original evolutionary metaphor in economics may be updated to include empirical manifestations of epistasis in fitness landscapes or insights from the sequencing of the genome. These revisions may provide valuable extensions of the metaphor—although this is by no means guaranteed. The depth of the metaphor lies in its open-endedness.

PHOTO: JULIE GRABER

Impact of the Metaphor

The outcome of a metaphor will partially depend on its original intent. In some cases, the metaphor may prove immediately effective, while in others considerable effort may be required for it to bear fruit. Its impact may come either in "working" the metaphor or in *using* it. To use a metaphor means to apply the insights, language, equivalences, and other associations of the source to shed light on the target. We do this all the time. Generations of physics students have used the familiar notion of water moving through pipes as a way of conceptualizing the much more intangible flow of electrical current. The parallels break down at some point, but it is a useful early device for learning. We use the metaphor as a kind of "wrapper" to give us a mental grip on a slippery substance.

The effect of working the metaphor is rather different. The impact comes more in its creation than in its eventual application. Working the metaphor means plunging into the intricacies of source and target domain and building the bridge between them span by span. The metaphor that emerges may not be intuitive or easily applicable (e.g., *NKC* landscapes as images of economic ecologies) but the process of generating it may trigger unanticipated insights. The benefit arises from the different perspective one adopts in plumbing the intricacies of the metaphor.

This also raises the question of just who is using or working the metaphor: i.e., the metaphor's community. Is the metaphor the property of an *individual* or of *a group?* Take, for example, a metaphor that publicly shaped U.S. foreign policy for decades: the "domino effect." This theory expressed the fear following World War II that, if one country were to fall to Communism, its neighbors would fall with it (like a row of dominoes). Whatever the merits or limitations of this mechanistic metaphor, there is no doubt that it had many adherents who used it in forming and communicating ideas. Creation and refinement of a metaphor is often the work of a group. The emerging model of the atom in the first half of the 20th century benefited from the metaphorical contributions of multiple minds: Thomson's plum pudding, Rutherford's solar system, Bohr's water droplet, etc., that invited a whole generation of physicists to continue this theoretical exploration.

On the other hand, there are private metaphors that lead to insight for one particular mind. An example of this type of heroic metaphor might be Albert Einstein's thought experiment in which he imagined how the world would look to him riding a beam of light (as if it were a train or a horse). The change of perspective that the metaphor allowed made possible the later development of his theories of relativity without demanding, however, that others adopt the light-riding metaphor themselves.

While most of the discussion has been about the logical transfer of structures between target and source domains, an analysis of metaphors that did not take into account the emotional and intellectual associations that attach to them would be incomplete. Metaphors do not come without baggage, and their impact may have as much to do with these ancillary factors as with their formal content. Indeed, it has been proposed that the cascade of associations, both positive and negative, triggered by the metaphor is its content. These associations are not only inescapable but integral to the impact of the metaphor. For example, the effectiveness of military metaphors in business may have primarily to do with the penumbra of associations--camaraderie, loyalty, sacrifice, determination, etc.--that surrounds warriors. There is thus a dualism between the *logical content* and the *cascade of associations* of the metaphor in assessing its impact.

In highlighting the various strands and tensions of the metaphor, we have raised more questions than we have resolved. At the least, we hope to have made clear how pervasive metaphor is and how multifarious its use. In particular we wish to recognize the essential role of *cognitive* metaphors in creative thinking. As with physical ladders, metaphors must be used with care, planted firmly, and adjusted to the task at hand. And whether we then quietly put them aside or continue to build on these edifices, we will always need to resort to ladders for climbing to new conceptual heights.

David Gray and Michele Macready

more reading

Metaphor and Knowledge: The Challenges of Writing Science (SUNY Press) is a new book by Ken Baake, assistant professor of technical communication and rhetoric at Texas Tech University. The book offers a history of rhetoric and metaphor in science, delving into questions about how language constitutes knowledge. The book grew out of Baake's 1997 science journalism and technical writing internship at the Institute.

[1] See George Cowan, David Pines, and David Meltzer, eds., *Complexity: Metaphors, Models and Reality* (Addison-Wesley Publishing Company, 1994).

[2] See Tihamer von Ghyczy, "The Fruitful Flaws of Strategy Metaphors," *Harvard Business Review* (September, 2003), 86-94 for a discussion of cognitive metaphors in business innovation.

[3] Nelson Goodman, *Languages of Art. An approach to a theory of symbols* (Indianapolis/Cambridge: Hackett Publishing Company Inc., 1976), 69.

[4] Pierre, "Chronometricals and Horologicals," (Plinlimmonís Pamphlet, 1852).

[5] See Thomas Kuhn, *The Structure of Scientific Revolutions* (University of Chicago Press, 1962).

[6] See Tiha von Ghyczy, Bolko Oetinger, and Christopher Bassford, eds., *Clausewitz on Strategy: Inspiration and Insight From a Master StrategistóA Publication of the Strategy Institute of the Boston Consulting Group* (New York: John Wiley & Sons, Inc., 2001).

[7] Max Black, "Models and Archetypes," *Models and Metaphors: Studies in Language and Philosophy* (Ithaca, New York: Cornell University Press, 1962).

[8] See Walter Fontana and Leo Buss, "The Barrier of Objects: From Dynamical Systems to Bounded Organizations," *Boundaries and Barriers: On the Limits to Scientific Knowledge*, eds. John Casti and Anders Karlqvist (Addison-Wesley, 1996), 56-116. http://www.santafe.edu/~walter/Papers

[9] See Gareth Morgan, *Images of Organization,* 2nd ed. (Thousand Oaks: Sage Publications, 1997).

[10] Armen Alchian, "Uncertainty, Evolution, and Economic Theory," *The Journal of Political Economy* 58, no. 4 (June 1950): 211-221, is widely regarded as an early influential article in this vein.

Business as *Un*usual

by Janet Stites

A decade after its launch, SFI's Business Network has taken on a life of its own, acting as an agent to disseminate the theories and research of SFI researchers to the business community and, in turn, bringing back information to SFI. That is why a group of money managers meeting this fall in Newport, Rhode Island, have added the phrase "complex adaptive systems" to their financial dialogues; why a research director at one of the nation's premier-funds management firms is reading evolutionary theory at night after she puts her children to bed; and why SFI's External Faculty member David Stark's name and theory of "explore and exploit" are surfacing in a presentation given by a pharmaceutical executive.

Where did it start and where is it going? Network members are an elite group of self-selecting, open-minded business people from some of the world's largest and most forward-thinking companies. It has grown from an initial complement of five companies in 1992 to a current membership of over 45 companies and government research groups, each of whom contributes $30,000 or more annually to support SFI's basic research agenda.

In return, Business Network members are invited to participate in SFI conferences and workshops, giving them the opportunity to network and interact with SFI scientists and look for ways to use SFI research at their own companies, while SFI benefits from the influx of new ideas.

This is a concept Michael Mauboussin considers daily. As Chief U.S. Investment Strategist of Credit Suisse First Boston (CSFB), Mauboussin is charged with the task of absorbing and digesting data and information at record pace, and then sculpting it into information the bank's investment team and clients can use—not for their own edification or to impress their friends—but to simply beat the market and make money.

CSFB joined the Business Network in 1997, and additionally, the company supports the research of J. Doyne Farmer, McKinsey Research Professor at SFI and founder of the Prediction Company. But Mauboussin, in his own work, is leveraging core concepts from SFI into his research, beginning with thinking of capital markets as complex systems. He began by studying W. Brian Arthur's theories on increasing returns, but continues to widen his scope absorbing what he can on evolutionary biology and network theory and more.

After the 2003 East Coast blackout, Mauboussin put in a call to Columbia University and SFI External Faculty member Duncan Watts, who is an expert in network theory, to get his thoughts on the outage. "The blackout was essentially caused by a cascading failure in a large network," Mauboussin said. "I wanted to see what we could learn from that failure about networks and see how we could apply it to the financial markets."

Mauboussin is also known for his annual "Thought Leader Forum" during which he draws on the work of SFI researchers. This year, the event, held in Newport, Rhode Island, featured Harvard-based geochemist and SFI External Faculty member Dan Schrag, who spoke about climate change. As well, Eric Bonabeau, former SFI postdoctoral fellow and founder and chief scientist of Icosystem Corporation, and Alpheus Bingham, a vice president with Eli Lilly and a member of the SFI Business Network, spoke at the Forum. In the past, SFI-affiliated speakers have included W. Brian Arthur, J. Doyne Famer, John Holland, Duncan Watts, and Geoffrey West, among others.

Mauboussin remembers fondly the moment he learned about the Santa Fe Institute. "I was at an Orioles baseball game with Bill Miller (chief executive officer of Legg Mason Funds Management Inc.) in 1995," he says. "He told me I must be involved with SFI."

One ant will run off to the side and look into a different spot, adding to the colony's overall robustness. When we do our own research, we keep in mind that we need to look everywhere.

Bill Miller is a catalyst for many members to join the Business Network. Baltimore-based Legg Mason has been a member since the early 1990s under his leadership. A tireless advocate of the Institute and a vice chairman of the SFI Board of Trustees, Miller has embraced many of the theories imparted by SFI researchers. His own staff has followed suit.

Lisa Rapuano, director of research at Legg Mason Funds Management Inc., was somewhat confused when Miller first started sending her home evenings with books on evolutionary biology and network theory. But then she started attending the Business Network meetings at the Institute, and the disparity between finance and science began to wane.

When asked, Rapuano is initially hard pressed to come up with concrete anecdotes in which the firm has used research and information garnered from their time at the Institute. "You can't think of it in linear terms," she says. "What we have learned is to look at the market as an adaptive mechanism. We need to look for tools than aren't conventional. We need to develop a pool of alternative mental models to think about the market, companies, and economies."

Rapuano explains their strategy this way: "When we take our people out to SFI for the first time, they usually say, 'O.K. That was interesting, but what am I supposed to do with the ideas on Monday?' We tell them, 'Nothing.' We tell them to absorb the ideas and let them enlighten their thinking."

For one example of how participating at SFI has enlightened Legg Mason's research theory, Rapuano points to the concept of "Random Search." "If you think about the way ants behave, they have a set of simple rules to go out and look for food," Rapuano says. "But one ant will run off to the side and look into a different spot, adding to the colony's overall robustness. When we do our own research, we keep in mind that we need to look everywhere. It might be as simple as a situation where you've typed in the wrong ticker, and instead of moving on, you stop and take a look at that company."

Similarly, Rapuano says the firm has incorporated the theory of "weak links" into their philosophy. "Research has shown that people get jobs through social networks—not usually through their friends, but through their friend's friends," she says. "So, this is called a 'weak link.'"

"We try to look for what kind of connections make things happen," she says. "We go to conferences that aren't investment conferences." Making an even bigger commitment based on the "weak links" theory and network theory in general, the firm decided to sublet some space to a Baltimore hedge fund, betting they might garner something valuable from the liaison.

Perhaps the most important idea the researchers at Legg Mason have embraced is one of the most simple, yet fundamental to the work at the Institute: "We believe the market is a complex adaptive system with zillions of agents, with selfish objectives and excess," Rapuano says. "Return is difficult. You have to have a constant philosophy, but you must have an adaptive strategy. We need to be adaptive."

Rapuano, who tries to attend the Business Network meetings every year, says that she now looks for information not just from the SFI researchers, but also from her Business Network peers. "There are really smart people at the meetings," she says. "You might sit next to the guy from Lilly and learn something you didn't know about pharmaceuticals."

Indeed, if that person is Alpheus Bingham, then you are most certainly likely to learn a great deal about pharmaceuticals. Bingham, a vice president of Eli Lilly and Company, has a way of putting a face on the otherwise intractable industry. In turn, Bingham has sifted through the myriad of information he gathers from the Institute and incorporated it into his work at Lilly.

Over the five years Bingham has been active in the Business Network, he believes it has helped him to reshape the structure in which corporate problems and challenges are framed. "It's allowed us to see alternatives that may have been less visible if stuck in traditional viewpoints," he says.

On the practical side, through connections made at SFI, Eli Lilly has incorporated agent-based modeling into its R&D processes, partnering with Eric Bonabeau's Icosystem to build modeling software, which helps the company track the progress of its research, and better understand its revenue flow. On the theoretical side, Bingham has been influenced by the theories of SFI-affiliated scientists such as Stuart Kauffman and David Stark.

A scientist himself, with a Ph.D. in organic chemistry from Stanford University, Bingham is an ideal executive to be involved with the Business Network. He has long been incorporating technology into the research process; he is a visiting scholar at the National Center for Supercomputing Application at the University of Illinois, and former Chairman of the Board of Editors of *Research Technology Management Journal.* He believes the challenge for SFI's Business Network members is to find broader applications of complexity principles, to tap into the potential of the science. "Companies need to develop applications beyond simply using agent-based modeling programs," he says.

Perhaps no one, or no one company, has garnered as much from its affiliation with the Institute as Roger Burkhart, technical consultant to Deere & Company, who has graced the halls of the Institute for more than a decade.

Deere & Company joined the network in 1992. "We had begun developing the use of genetic algorithms for assembly-line scheduling and had developed an interest in adaptive techniques for both manufacturing and investment trading," Burkhart explains.

Two years later, Deere & Company "lent" Burkhart to SFI to participate for more than half-a-year on Chris Langton's Swarm Simulation team, which was developing the now well-known agent-based modeling and simulation platform Swarm, for modeling interactions of adaptive agents. Burkhart continues to help administrate the independent non-profit Swarm Development Group (www.swarm.org).

Having become somewhat of a computer-based modeling evangelist, Burkhart's own projects explore the use of shared computer models across people and organizations, in such areas as product design and agricultural production. "One example," Burkhart explains, "would be integration of geospatial data from machines with agricultural production records to develop crop plans for a farmer. Many partners help collaborate with the farmer to develop and execute the plans, from input suppliers—seed, fertilizer, and chemicals—to agronomic consultants to output marketing channels."

Of late, the Business Network has become increasingly more reciprocal in nature. Many of the members gathered at the Institute last June for a topical meeting at which the Network members, not the scientists, had the microphone, addressing how they are applying research and information from SFI to their businesses.

Speakers represented a variety of industries—pharmaceutical, aviation, manufacturing, automotive, national laboratories, and, of course, high-tech—but were united in one goal of learning to harness the tools of complex adaptive systems research to help them with their own businesses.

Presenters included Bingham and Burkhart, as well as representatives from Intel, Sandia National Laboratory, Argonne National Laboratory, The MITRE Corporation, and Alidade Inc., among others.

Recently appointed SFI President Bob Eisenstein was impressed with the exchange of ideas. For the success of the program he credits the work of SFI staff members Suzanne Dulle and Susan Ballati. "Many problems studied at SFI are also problems of interest to the business community," he says. Eisenstein plans to make no major changes in the Business Network except to focus on bringing in more international firms. "We already have a significant foreign presence," he says. "But we want to connect to businesses in countries such as China and India as well."

One aspect of the Network Eisenstein wants to continue to emphasize is that the exchange is mutually beneficial. "We learn from the members just as they learn from us. Their input is valuable to us. In fact, sometimes there are problems they want to solve that turn out to be interesting problems for us. It's really a two-way street."

Visiting SFI Researcher José Lobo, who has been affiliated with the Institute since 1993, attended much of last spring's topical meeting, listened to the Business Network members' presentations, and participated in much of the dialogue. "There is a growing awareness among SFI researchers and the leadership of the Institute that the Business Network represents a great intellectual source that has remained largely untapped," says Lobo. He cites examples of intellectual exchange between Network members and SFI researchers. One notable one is in the area of biologically inspired software design, a project involving SFI Researcher Walter Fontana and physicist Ann Bouchard from Sandia National Laboratories.

Lobo also describes a new working group on Organizational Design, which was started by Bingham, Roger Burkhart, and SFI Researchers John Miller (also of Carnegie Mellon University), Jim Rutt, and Lobo. The group plans to host a session at the next Business Network meeting and has written a paper on the topic. "We hope that this group can evolve into a full-fledged research project at SFI," Lobo says.

Ultimately, SFI and its Business Network are very young organizations. Central to the Network's continued growth is an acceptance of complexity theory as a valid tool for business applications. In an odd way, the Internet boom and bust and ongoing sluggish economy has opened a door for new ideas and cutting-edge research like that coming out of the Institute.

CSFB's Mauboussin echoes this when reflecting on his tenure in the Network. "Since I first joined the Business Network, I have seen my peers open up to new ideas and begin to search for new formulas," he says. "The point is that we can't think about things in the same way anymore. I'm not saying SFI has the answers. I don't know. But I think there are potentially important ideas in the study of complexity."

Janet Stites is a freelance writer based in New York. She has written for OMNI Magazine, Newsweek, *and* The New York Times.

WORK WITH A SFI MENTOR ON AN INDIVIDUALIZED RESEARCH PROJECT IN COMPLEXITY SCIENCE.

Research Experiences for Undergraduates

DESCRIPTION Undergraduate students work with faculty mentors on an individual project focusing on some aspect of the computational properties of complex systems. SFI's broad program of research is aimed at understanding both the common features of complex systems and at comprehending the enormous diversity of specific examples. Projects focus on adaptive computation; physics, mathematics, information science, and computational aspects of complexity; economics as a complex, adaptive system; and the life sciences including modeling of the immune system, theoretical neurobiology, genetic data analysis, theoretical ecology, and models of protein folding.

This program is highly individualized. Each student works with one or more faculty mentors on a specific mutually-selected project. Participants are expected to be in residence approximately 10 weeks, between mid-May and mid-August.

SUPPORT Interns receive living stipends (from which housing costs are deducted) during their stay, along with some support of round-trip travel expenses from their home institution. The Institute will make appropriate, affordable, shared housing and transportation arrangements in Santa Fe for REU interns.

ELIGIBILITY Support for this program is provided by a grant from the National Science Foundation (NSF) through the Research Experiences for Undergraduates program. Open to U.S. citizens and permanent residents only. For the purposes of this program an undergraduate student is a student who is enrolled in a degree program (part-time or full-time) leading to a bachelor's degree. Students who are transferring from one institution to another and are enrolled at neither institution during the intervening summer may participate. 2004 graduating college seniors are not eligible for this program; nor are graduating high school students who have not yet enrolled as undergraduates.

Mathematical or computational skills or experience (particularly knowledge of the rudiments of the Unix operating system and/or a programming language such as C) are favorably considered.

TO APPLY Provide a current resume, official transcript, and a statement of your current research interests and what you intend to accomplish during your internship. Also, please arrange for three letters of recommendation from scholars who know your work.

ONLINE: You may submit most of your application materials using our online application form at http://www.santafe.edu/reu04.html. We strongly encourage you to apply online in order to expedite your application

POSTAL MAIL/COURIER: Applications sent via postal mail will also be accepted. Include your e-mail address and fax number. Do not bind your application materials in any manner. Send application packages to: Summer Research Opportunities for Undergraduates; Santa Fe Institute; 1399 Hyde Park Road; Santa Fe, New Mexico 87501

TRANSCRIPTS AND LETTERS OF RECOMMENDATION: Transcripts must be official. If you apply by postal mail, transcripts and letters of recommendation may be included in the application package in sealed envelopes, or they may be sent directly to the address above. Letters of recommendation can also be e-mailed directly from the author to paul@santafe.edu.

DEADLINE: All application materials must be postmarked or electronically submitted no later than February 20, 2004.

Women and minorities are especially encouraged to apply.

For further information about the program, please visit http://www.santafe.edu/reu04.html or contact Paul Brault, (505) 946-2746 or paul@santafe.edu.

The Santa Fe Institute is an equal opportunity employer.

Celebrating 20 Years—
1984 to 2004

This year the Santa Fe Institute celebrates its 20th anniversary as a basic theoretical research institute, focused on problems and issues in the physical and social sciences that are complex in nature.

Practical applications have emerged in various fields of study, and have had a positive impact on all our lives—from ecosystems to sustainability, economics to health. The Santa Fe Institute Public Lecture Series, established in 1994, provides the SFI research community an opportunity to present to the public recent information on these applications. We hope you will join us in the celebration of this banner year!

Thurs. 1.22.04

7:30 p.m. at the James A. Little Theater

Jeffrey Sachs

Director, The Earth Institute at Columbia University

Explaining the Persistence of Extreme Poverty in a World of Unprecedented Wealth

The biggest question in global economics is why the rich countries continue to achieve economic growth while the poorest of the poor remain trapped in poverty. The puzzle is stark because the rich and poor are connected in economic networks of trade, international production, and finance. The real reasons for the widening income gaps seem to lie in a deep and highly nonlinear interaction involving physical geography, demography, and economic organization. The poorest of the poor are caught in a "poverty trap" involving adverse geographical conditions interacting with population dynamics and economic structure.

Wed. 2.18.04

7:30 p.m. at the St. Francis Auditorium

Maria Zuber

Head, Department of Earth, Atmospheric and Planetary Sciences, MIT; Fellow, Radcliffe Institute for Advanced Studies, Harvard University

The Carbon Cycle, Climate Variability, and the History of Water on Mars

The surface of Mars preserves the record of a past climate in which liquid water was stable and apparently abundant, which is in stark contrast to the present cold, desert-like environment. Zuber will explore the planetary-scale control of climate through study of the linkage between Mars' internal dynamics and atmosphere-cryosphere system, and the relationship to the carbon cycle on Earth. She will also address concerns such as the origin and fate of the planet's early, thick carbon dioxide atmosphere and a possible northern hemisphere ocean.

Wed. 4.28.04

7:30 p.m. at the James A. Little Theater

Charles M. Falco

Professor, Optical Sciences, University of Arizona

Through A Looking Glass: Rethinking 600 Years of European Art

Recently, renowned artist David Hockney observed that certain drawings and paintings from as early as the Renaissance seemed almost "photographic" in detail. In this talk Falco shows a wealth of optical evidence that he and Hockney discovered during an unusual, and remarkably productive, collaboration between an artist and a scientist. These discoveries convincingly demonstrate optical instruments were in use—by artists, not scientists—nearly 200 years earlier than previously even thought possible, and account for the remarkable transformation in the reality of portraits that occurred early in the 15th century.

Wed. 5.26.04

7:30 p.m. at the James A. Little Theater

Mercedes Pascual

Associate Professor, Department of Ecology and Evolutionary Biology, and Center for the Study of Complex Systems, University of Michigan; External Faculty, SFI; Literature, Science, and the Arts: Biology Department, University of Michigan

Disease-Climate Couplings in a Nonlinear World

One fundamental property of complex systems is nonlinearity. Mathematical models for the dynamics of disease provide some of the best examples in ecology of nonlinear systems. Pascual addresses this problem for the dynamics of cholera in South Asia and its relationship to climate variability, including the El Niño Southern Oscillation. She ends with other challenging questions on complex ecological systems that arise as the result of their large number of interacting components, involving not just pathogens but also predators.

Wed. 6.23.04

7:30 p.m. at the James A. Little Theater

Robert A. Eisenstein

President, Santa Fe Institute

The Santa Fe Institute —Celebrating 20 Years of Scientific Excellence

For the past 20 years the Santa Fe Institute has been the leading center for research into complex adaptive systems and other kinds of hybrid scientific themes. A unique research and education center, the Institute hosts resident scientists and distinguished guests from around the world for collaborative research activities, discussions of new interdisciplinary themes, and a wide variety of seminars, colloquia, and educational activities. Join President Robert Eisenstein as he explains the mission of the Institute, talks about some of its past accomplishments, and points to possible future directions for Santa Fe Institute-style research.

Wed. 7.21.04

7:30 p.m. at the James A. Little Theater

Seth Lloyd

Professor, Mechanical Engineering Department, MIT; External Faculty, SFI

Measuring Complexity

What is complexity and what is it good for? This talk reviews various attempts to measure complexity, and shows how different measures of complexity can be useful in different contexts. Applications to engineering, finance, physics, and cosmology will be presented.

Wed. 8.18.04

7:30 p.m. at the James A. Little Theater

Hillard Kaplan

Professor of Anthropology, University of New Mexico; External Faculty, SFI

Babies, Brains, and Lifespans: The Bioeconomics of the Human Life Course

Compared to other primates and mammals, humans are distinctive in many ways. Most important of these distinctions are our exceptionally large brain and the abilities it confers, a very long lifespan, an extended period of juvenile dependence, multi-generational resource flows and grandparents who help support our reproduction, and male provisioning of females and their offspring. This talk offers an explanation of our unique constellation of characteristics, their evolution, and why they are related to one another.

Tues., Wed., & Thurs., 9/7, 8, 9/04

Eleventh Annual Stanislaw Ulam Memorial Lecture Series

Held each evening, 7:30 p.m. at the James A. Little Theater

Henry Wright

Curator of Archaeology, Museum of Anthropology, University of Michigan; External Faculty, SFI

Raising Civilization

Eight thousand years ago, the ancestors of humanitylived in a world of kin and ritual in which the exploitation of many by a few was held in check. In a millennium or less villagers were incorporated into larger polities focused on sprawling urban centers and ruled by emergent elites. Efforts to explain this fundamental transformation accelerated during the 20th century but no explanation is sustained by extant evidence. These lectures will focus on two cases, the ancient example of Mesopotamia and the more recent example of Madagascar, exploring efforts to propose and test new kinds of understandings.

Wed. 11.17.04

7:30 p.m. at the James A. Little Theater

Martina Morris

Blumstein-Jordan Professor of Sociology and Statistics at the University of Washington; Director of the Center for Studies in Demography and Ecology, and Director of the Behavioral Core of the University of Washington's Center for AIDS Research; External Faculty, SFI

Partnership Networks and HIV: Global Consequences of Local Decisions

Over the past two decades, the epidemic of HIV has challenged the public health community to rethink the framework for preventing infectious diseases. For HIV and other sexually transmitted infections, however, there are at least two people involved in the behavior. This may not seem like a big difference, but in fact, it changes everything. It means that individuals do not have the same kind of control over their level of risk.

This talk will review the remarkable breakthroughs in recent research that have emerged to confront this challenge. In about 10 years, the study of partnership networks has changed the way we sample populations, the questions we ask them, the way we visualize the resulting data, and the way we analyze it.

The lectures are made possible through contributions from community supporters, and 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 the James A. Little Theater on the campus of the New Mexico School for the Deaf, 1060 Cerrillos Road, Santa Fe, or occasionally at the St. Francis Auditorium at the Museum of Fine Arts, 107 West Palace Avenue. For the most current information about the location of 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.

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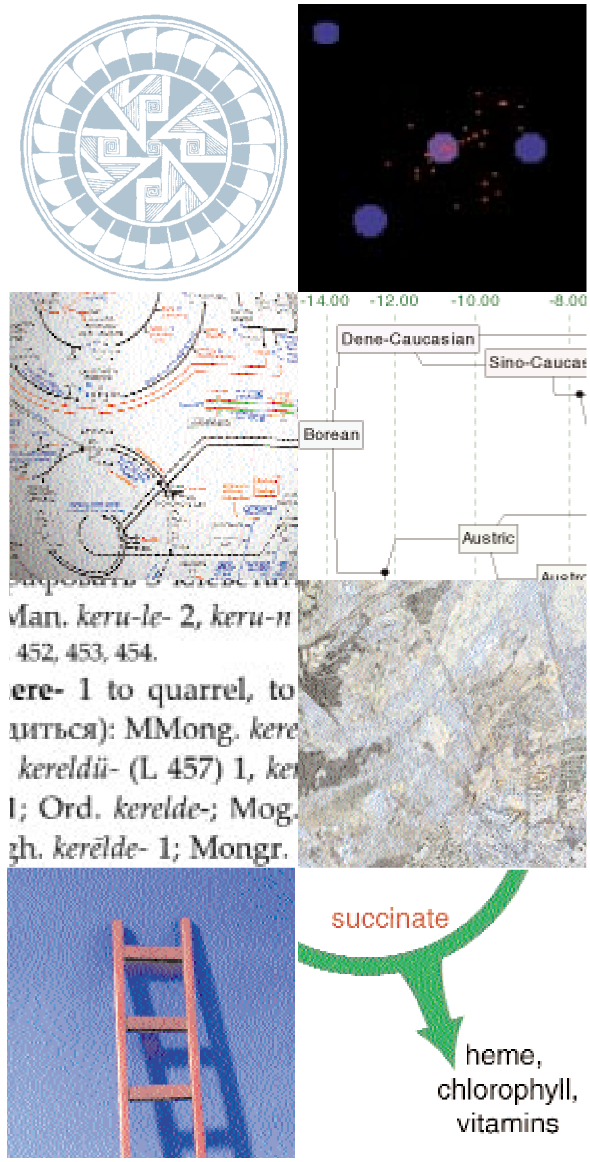

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