SFI Bulletin

2009, vol. 24

SFI @ 25:
VERY FEW CELLS REMAIN UNCHANGED

ILLUMINATING THE LIVES OF CELLS, GENES, NETWORKS, MARKETS AND PEOPLE

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

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SFI @ 25: Very Few Cells Remain Unchanged

By David C. Krakauer, Professor and Chair of the Faculty

In the infancy of societies, the chiefs of state shape their institutions; later the institutions shape the chiefs of state.
—Charles de Secondat, Baron de Montesquieu,
The Spirit of the Laws, *1748*

SFI has now reached its 25th year. The Institute was imagined and realized by a visionary group convinced of the merits of pursuing general principles rooted in diverse, empirical phenomena. These principles would account for regularities in the complexities of adaptive systems spanning the broadest range of material characters. Through a succession of projects and personnel, SFI has grown to the stature of an internationally respected institute, with an influence significantly greater than its size might suggest, and a reputation reaching far beyond academia into business, government, and policy making.

The Institute has succeeded by pursuing theory in areas where quantitative data is abundant, where new concepts are recognized as being needed, where new computational tools might be exploited, and, equally crucial, areas that the majority of universities and institutes have ignored for falling too far from familiar disciplinary concerns. The strength of SFI has been its continued evolution, combined with a willingness to take risks and suffer the consequences, while striving to move beyond the particular concerns of its genesis. SFI is like a developing body, which remains identifiable through time but in which very few cells remain unchanged.

It is said that imitation is the sincerest form of flattery, and now that SFI's once risky research investments have yielded abundant returns, the concept of SFI is being emulated and recreated in a variety of forms elsewhere. With the shock waves from the breakdown of financial markets penetrating all spheres of society, there is some sense that the vision of SFI is more important than merely new academic or business models, and that it points towards a new framework for risk-prone collaborative research in universities and elsewhere. And at just such a time, SFI itself is reconfiguring.

This year SFI, in common with many other organizations, has been forced to eliminate positions and reduce budgets. In addition, our President, Geoffrey West, is stepping down to assume a faculty position at SFI. Our Vice President for Development, Shannon Larsen, is shifting over to the Business Network, and our Chair of the Board of Trustees, Bill Miller, is stepping down from the chair to re-join the Board. The opportunities these changes offer are great, and the science being generated is more exciting and relevant to our contemporary concerns than it has ever been.

So what is the character of complexity science at SFI? Wary of definitions, let me provide an example from one of my own research interests: the analysis of genomes. Traditionally, genetics was grounded in biochemistry, with a "disciplinary" approach of sequencing DNA and measuring gene activity. As the data increased, researchers catalogued the networks of interactions among molecules, and the genome became represented as a matrix of connections—some activating, others inhibiting. At this point, questions of the stability and complexity of these networks became major concerns, forging a link with ecology, where researchers seek to understand the emergent properties of networks of interacting species. As the functional implications of these "ecological" patterns of activity started to surface, we began to see how the matrix of interactions could give rise to coherent patterns of activity resulting from regular inputs to the system. Thus, the genome became a computational system, and questions of memory storage and information processing now dominate research.

A single mechanistic complex—the genome—thus penetrates at least three frameworks, all of which continue to contribute valuable insights into the way the genome functions, and most important, establish new connections and descriptions that serve as the raw material for subsequent forms of integrated analysis and inquiry. The same type of embedded cross-disciplinarity applies equally well to work on social systems, microbial dynamics, food webs, metabolic networks, and urban systems. This process of scientific construction, building hierarchies of nested representations, is greatly facilitated at SFI by encouraging discussion among diverse groups of scientists expert in wide ranges of subjects. These groups are both interdisciplinary and oriented towards the search for powerful new principles and techniques.

Speaking of the emergence of the great geography and cultures of Mesopotamia, Francis Sales Betten wrote: "This Oasis is the work of the Tigris and Euphrates." There have always been two currents organizing the Santa Fe Institute. One is inter- or trans-disciplinary, searching for solutions to the wealth of problems that lie on the membranes defining the interface of fields. The other is a search for general principles of complex, adaptive systems.

Interdisciplinary observations provide the comparative database upon which to build new synthetic theories. I increasingly see the strength of SFI as an institutional device designed for aggregating people, models, and theories around observations of interest, and when possible, seeking to unify these ideas under a general framework we label, for practicality, complexity theory. At present, complexity theory represents a significant body of ideas and methods of great value for understanding adaptive and historical phenomena from a large variety of domains.

This edition of the Bulletin provides representative insights into the current range of interests at SFI and the manner in which projects are initiated and pursued. The contributions further illustrate the importance of both exceptional individuals and the unique mechanisms for promoting collective and collaborative activity. There is little doubt in my mind that SFI remains the most systematically inclusive and diverse theoretical research environment in the global, academic community in the early 21st century. ◀

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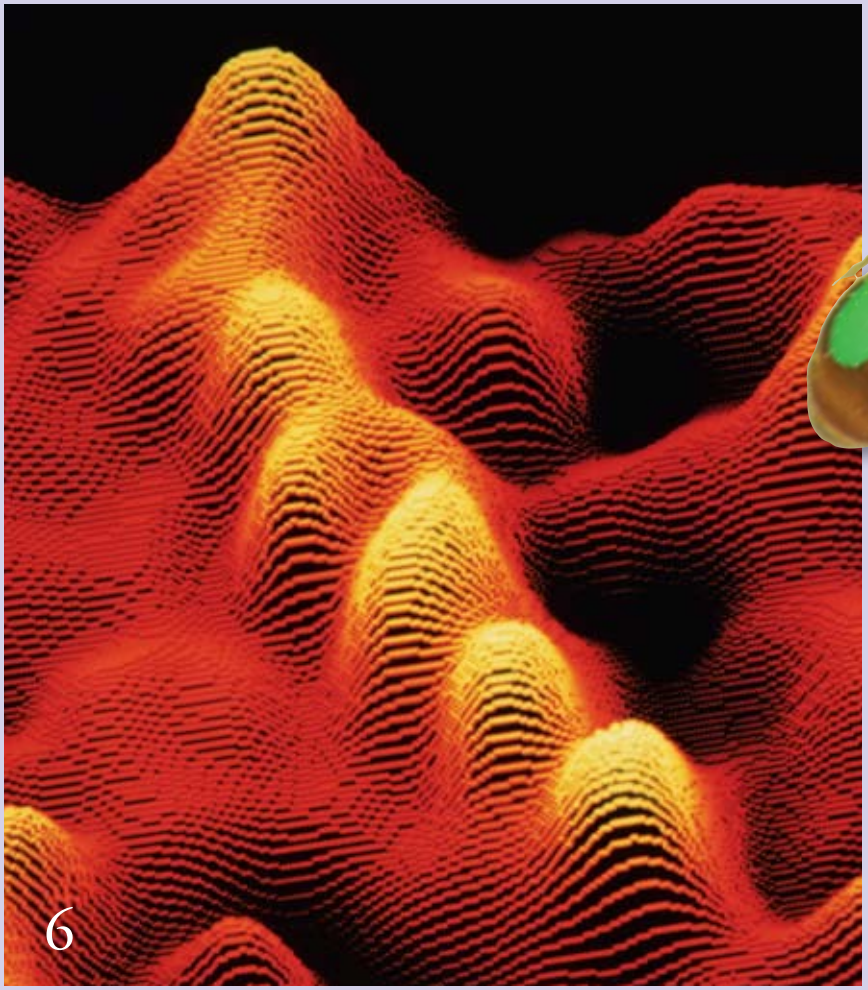

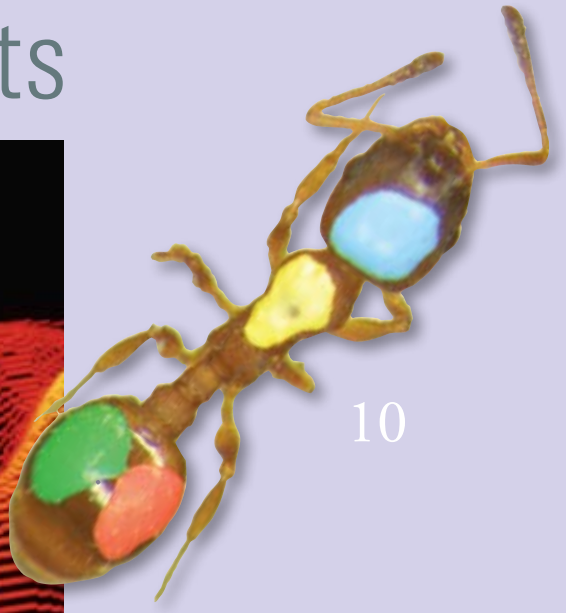

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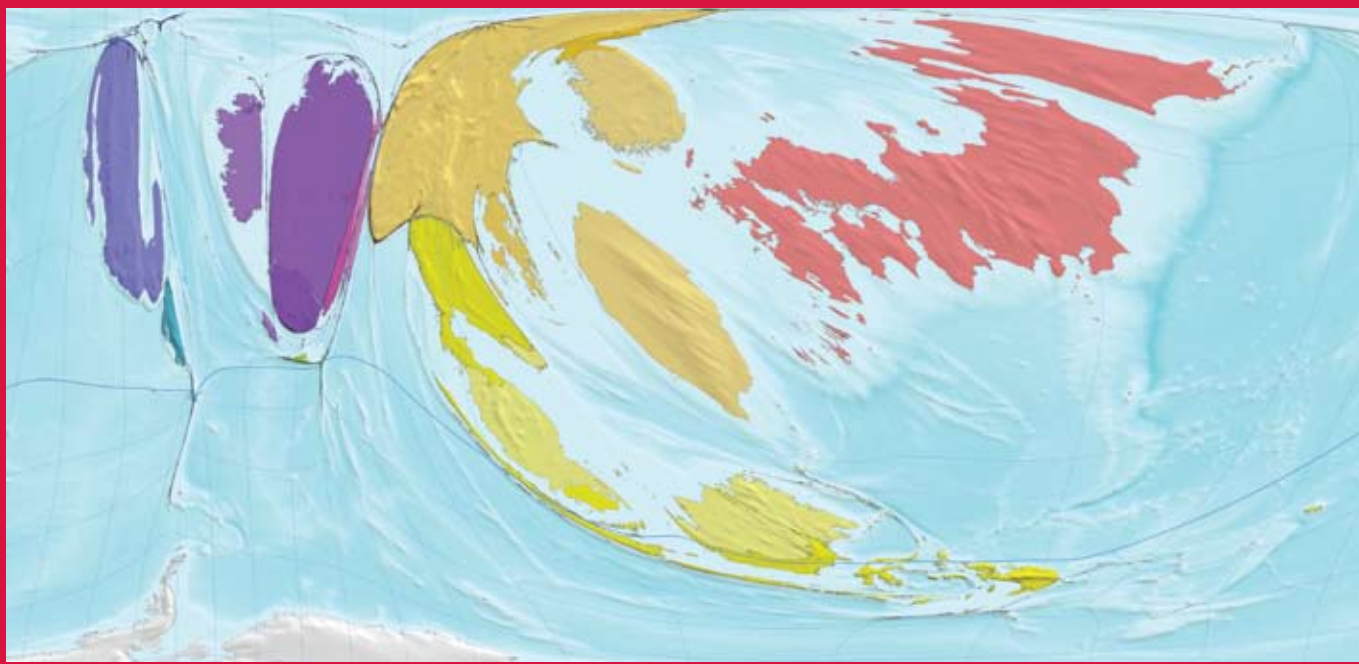

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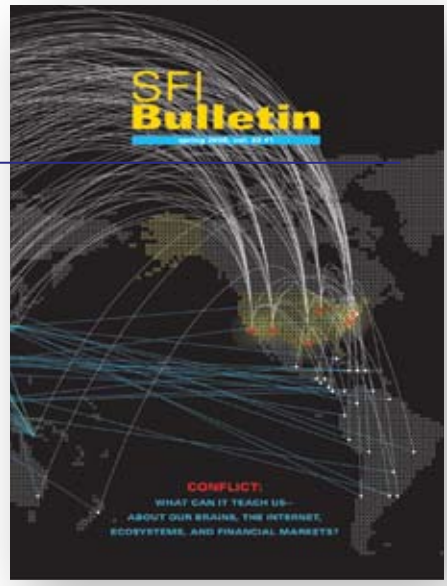
PHOTO CREDITS— TOP RIGHT: PAULA EASTWOOD; CENTER: MAP OF ELECTRONICS EXPORTS FROM *THE ATLAS OF THE REAL WORLD* © 2008 DANIEL DORLING, MARK NEWMAN, ANNA BARFORD. THAMES & HUDSON, LONDON AND NEW YORK.; LOWER LEFT: PAULA EASTWOOD; LOWER RIGHT: VEER.COM/JOEL NAKAMURA

Reader Response

to the Spring 2008 Bulletin



The Endangered Navajo

The article on "When Diversity Vanishes" was superb. I was especially glad to see the point made by Suzanne Romaine about the extinction of languages, that "it's not just languages that are at stake, but forms of knowledge." Many years ago I was talking to a Navajo medicine man who bemoaned the loss of the Navajo language among the young. He said the ceremonies he performed would "not work" if performed in English instead of Navajo. He made the point that the Navajo people would cease to exist "when the last person who speaks Navajo dies," even if there were thousands of registered Navajo tribal members still living on the Rez at that time.

He recognized that culture and language are inseparable; you can't have one without the other. Museums can never be a "vault to preserve human culture" in the way a seed bank can preserve the genetic diversity of crops. You need living, believing, and speaking people to preserve culture; nothing less will suffice.

Douglas Preston
Round Pond, Maine
Author of The Monster of Florence *and several other novels and nonfiction books.*

The Transforming Self

"Know thyself," instructed Socrates. Several centuries later, Shakespeare in *Hamlet* has Polonius exhort his son Laertes, "To thine own self be true, And it must follow, as the night the day, Thou canst not then be false to any man" (or woman, I like to add). Clearly, an underlying assumption is that a coherent "self" exists which is possible of being known and honored. Jon Wilkins' stimulating article "The Conflicted Brain" challenges this notion and asserts that "Every decision we make is argued by at least two distinct evolutionary "selves." I found his argument so interesting that I requested and received an extended conversation with Jon at the Institute in order to learn more about the neuronal and genetic underpinnings of his point of view.

It won't surprise anyone to hear that I came away from this dialogue with yet more questions than answers, and I'm hoping for a "rematch" with Jon. As a counseling psychologist for almost four decades, I have been working away, all this time, with the self of each of my patients. For years I've looked at all this material of human existence and daily lives, as though lived, ostensibly, by the same person who came for her 10 a.m. appointment last week, and is now here again. The unspoken assumption is that she, albeit changed a bit perhaps, is nonetheless still the same person who walked in and sat down in that chair last week. Now, I'm reconsidering a working definition of the self. I recall the dictum that the more things change, the more they remain the same. I'm toying with the notion that the self might be like that, that what is constant is the emergent property of change. Does this make any sense? What do other readers out there think? I would enjoy talking about this, a work-in-progress.

Penelope Penland
Licensed Psychologist living in Santa Fe, NM

Large May Be Smart But Small is Beautiful

Well, if you live long enough most things get turned on their head. British economist E.F. Schumacher popularized the notion of "Small is Beautiful" in his 1973 book by that name, which, as far as economic development is concerned, is largely debunked by your recent article "Cities: Large is Smart."

What Professor Bettencourt et al. call "scaling," *The Economist* recently called "lumping," as in "Lump Together and Like It" (Nov. 8, 2008), based on the World Bank's latest annual *World Development Report*. The article suggests that "third-world cities grow so big and so fast precisely because they generate vast economic advantages, and that these gains may be increasing."

This is refreshing stuff. In the past, green concerns have encouraged anti-development beliefs, which could lead to people frowning on such counter-intuitive findings that Big is Beautiful, as far as cities go. That such concentrated development might not only help pull people out of poverty but be green-friendly as well is definitely a new viewpoint. Humans are funny birds and they just seem disposed to bunking and bulking up—in lumps. And when scale economies run out, well, we just innovate to revitalize.

Despite being an optimist, I still feel mildly queasy when the researchers suggest that cities can "grow indefinitely" through innovation or wealth creation. As the article noted, by 2007 Buenos Aires, Calcutta, Mexico City, and São Paulo were losing, not gaining, population. *The Economist* provided a potential answer when it averred that such cities rise "fast until they [make] up about a quarter of their countries' population, then [stabilize] when the country's income hits about $5,000 per person."

Alas, all growth rates must flag, in spite of Viagra-like innovations. I, for one, after living over five years in both New York and São Paulo, with metro areas around 19 million, moved to a colonial town of 7,000 inhabitants in the interior of Brazil, adding to São Paulo's exodus. Small can still be beautiful, depending on who's looking at it.

Ben Batchelder

Writer/photographer living in Tiradentes, Brazil

Individualized Computing

While reading the article "Malware Wars," I was struck by the repeated biological reference to malware as a quickly evolving "parasite" on the Internet host. Stephanie Forrest and others have pointed out an aspect of computer security that needs more attention: The increasing lack of diversity in the computing environments participating in the Internet is making the chance of large scale "infection" more likely. In computing, it makes little economic sense to support many ways of doing the same thing, so Forrest suggests a means of making each computer's software execution environment unique through the use of special compilers and the scrambling of other system properties such as the names and locations of system files.

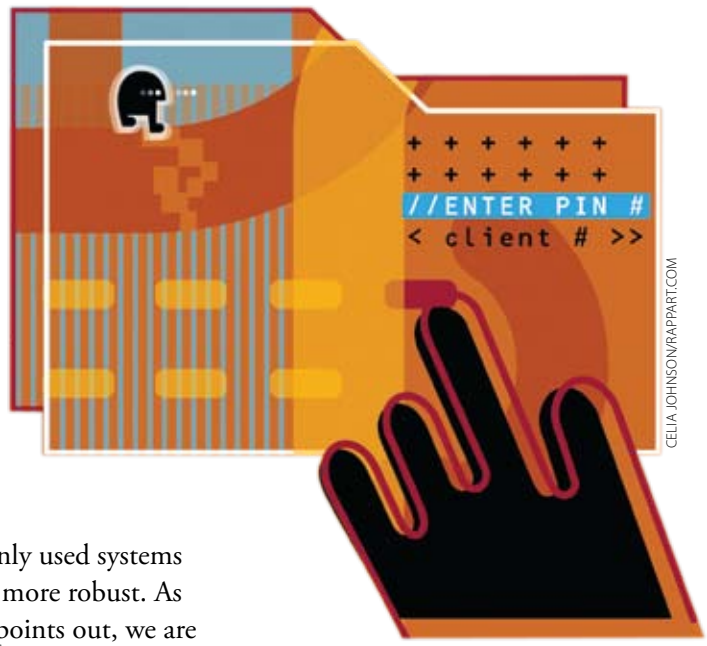
We already naturally have this situation in the differences between the various flavors of the surviving operating systems: Windows, Linux, AIX, HP-UX, Solaris, BSD, etc. For instance, though there are trojans, worms, and viruses for OS X (a BSD variant), these are few and far between. Of course, if Apple had the market share that Microsoft currently enjoys, it is likely that there would be more. But maybe this is the point: having more, less commonly used systems may be ultimately more robust. As Robert Gleichauf points out, we are actually moving toward having more different computing environments participating in the Internet with the rise of portables such as phones and Internet tablets and other so-called net appliances.

All of this leads to a very basic question: How do we encourage diversity in a world that favors economies of scale? Is there a way to make the network infrastructure itself more diverse? Natural systems seem to trade efficiency/redundancy for adaptability and robustness; how can we do the same for our own engineered systems?

Joshua Thorp

Software developer living in Santa Fe, NM

Send comments to grr@santafe.edu or Editor, SFI Bulletin, Santa Fe Institute, 1399 Hyde Park Rd., Santa Fe, NM 87501. Please include your full name, address, and daytime phone number. Published letters may be edited for length and clarity.

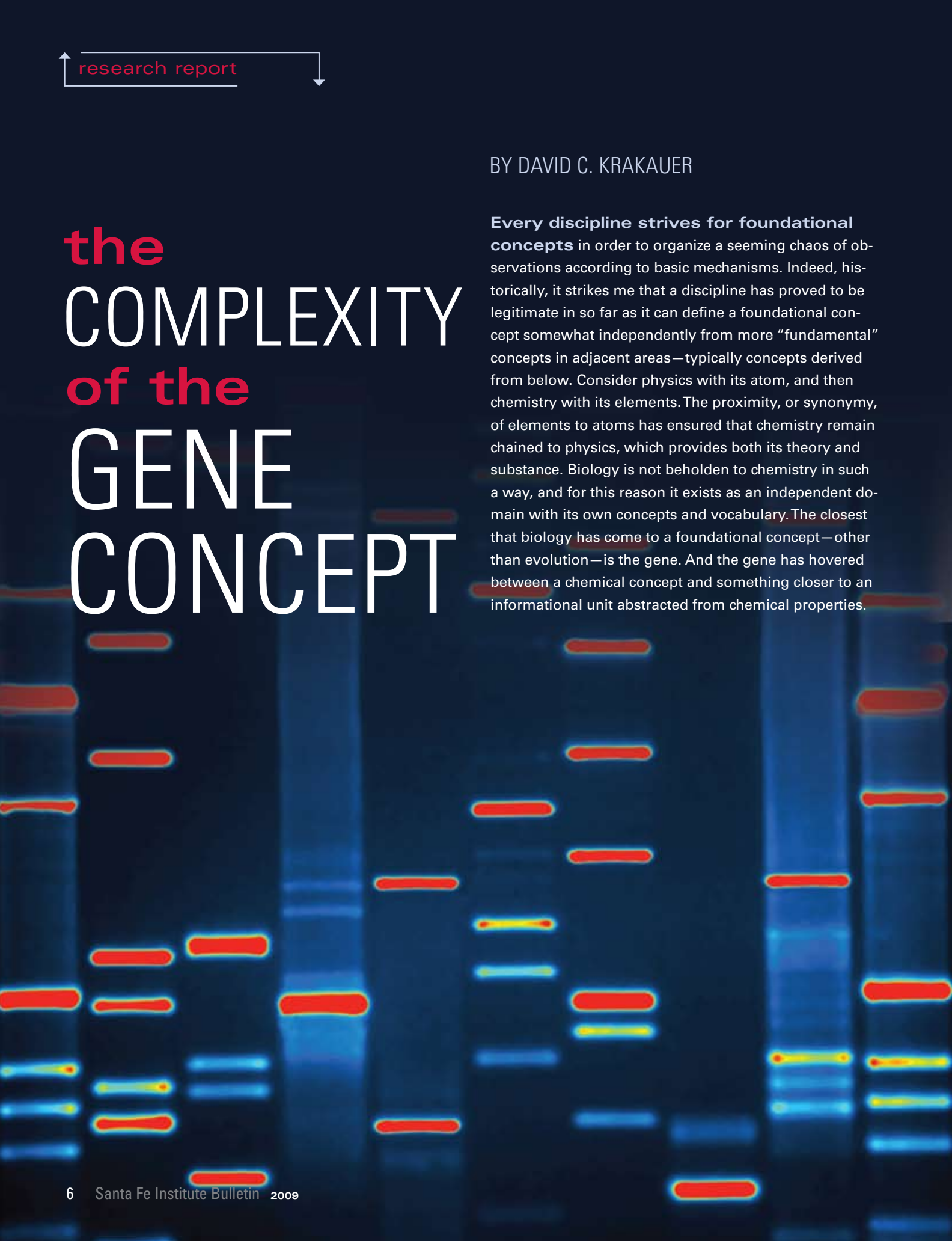


CELIA JOHNSON/RAPPART.COM

the COMPLEXITY of the GENE CONCEPT

BY DAVID C. KRAKAUER

Every discipline strives for foundational concepts in order to organize a seeming chaos of observations according to basic mechanisms. Indeed, historically, it strikes me that a discipline has proved to be legitimate in so far as it can define a foundational concept somewhat independently from more "fundamental" concepts in adjacent areas—typically concepts derived from below. Consider physics with its atom, and then chemistry with its elements. The proximity, or synonymy, of elements to atoms has ensured that chemistry remain chained to physics, which provides both its theory and substance. Biology is not beholden to chemistry in such a way, and for this reason it exists as an independent domain with its own concepts and vocabulary. The closest that biology has come to a foundational concept—other than evolution—is the gene. And the gene has hovered between a chemical concept and something closer to an informational unit abstracted from chemical properties.



The foundational status of the gene concept is evident when we consider how it is used at all levels of biological organization—molecular biology, development, physiology, behavior, medicine, evolution, and even culture. In few of these cases is atomic chemistry the critical property, but rather some kind of discrete, regulatory unit with a heritable, causal influence. The two senses in which the gene is most commonly used are either as a memory molecule or as a determinant of the phenotype—anatomy, physiology, or behavior. From these two usages derives the gene's value in the study of inheritance, and in applied areas such as medicine. And these two qualities fuse when we consider how phenotypic traits are transmitted between generations and how these traits evolve.

In order to evaluate the current state of the gene concept, the Santa Fe Institute recently convened a workshop on the "Complexity of the Gene Concept." The meeting was engendered by the central role of the gene in organizing biological observations and theories, and the failure of the simple, chromosomal model of the gene—first proposed by Thomas Hunt Morgan—in the light of huge quantities of genetic data in digital form. The Morgan model describes the gene as beads on a string, each string a chromosome, and with each bead standing for a DNA nucleotide contributing a quantum of character. What emerged from the meeting were gene concepts grounded in a more compelling view of the relationship between a gene's structure and its function, which often included informational and computational principles.

For such a concept with such widespread influence and acceptance, the gene remains surprisingly slippery. At one level there is just the chemistry, and at another level, there are its effects—the color of the eyes, differential resistance to disease, and the ability to fly or swim. Relating phenotypes and their functions to the materiality of the gene is similar to the challenge of relating the mind to the brain or software to hardware. And these analogies provide a clue as to the nature of the gene. Rather like a computation which can be understood both from the perspective of transistors and of algorithms, the gene can be conceived both as coded information and materially. In striving to define the gene, these two varieties of meaning compete for scientific dominance.

The gene, thought about as a single stretch of contiguous DNA or RNA, transcribed and translated into a unique protein, with unambiguous expression and quantifiable selective value, has always been an ideal rather than a reality. Under most definitions the gene has been presumed to perform three functions: to serve as a unit of inheritance, a regulatory element in developmental dynamics, and an atomic unit of selection. In each case there is a mutable component, well behaved and easily identifiable, that survives cell division, can be turned on and off as a unit through suitable regulatory pathways, and contributes a quantum of fitness to an organism when expressed. The work—contribution to heritable, regulatory or selective variance—in each of these cases is presumed to be done by the gene, and so the gene occupies, understandably, a central position.

These many properties of the gene have contributed to a lively historical debate. Darwin, who was so clear on natural selection, became a little hazy when discussing the units of inheritance. Darwin's first problem was finding a suitable name. In a letter to his son George, at the time

PHOTO RESEARCHERS, INC.

Facing Page: Colorized images from human DNA; Above: Inbreeding has been common among royal families, causing genetic disorders. Married to her first cousin, Queen Victoria (1819–1901) carried the gene causing hemophilia, which passed to her children, and then on to the Spanish and Russian royal families.

LEFT: DNA AS ART, BY DNA11.COM

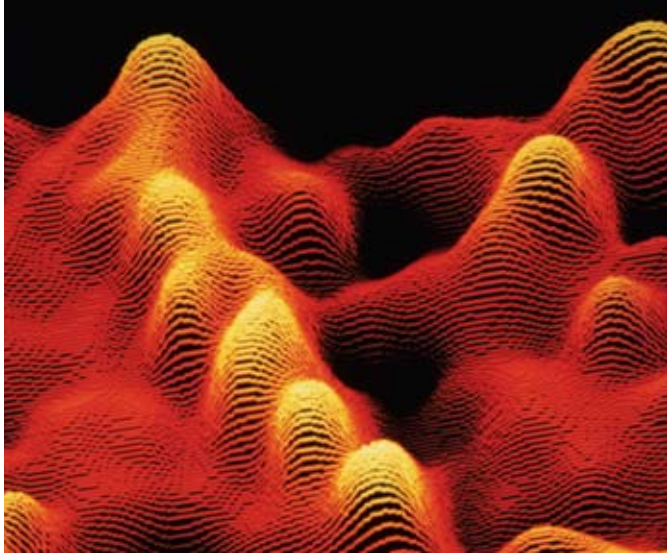


PHOTO RESEARCHERS, INC.

The Center for Human Genome Research created this color-enhanced image, a scanning tunneling electron micrograph (STEM) of a right-handed DNA duplex. The center's goal is to construct a physical map of DNA in 24 chromosomes.

studying mathematics at Cambridge, Darwin requested the advice of a classicist "who could suggest any Greek word expressing cell, and which could be united with genesis." Finally settling on the term pangenesis for his theory of inheritance, which suffered neglect for its complexity, Darwin wrote to the geologist Charles Lyell, "My fear has always been that pangenesis would be a still-born infant, over whom no one would rejoice or cry."

The SFI workshop, hosted by Institute researchers Peter Stadler, from the University of Leipzig, Sonja Prohaska from Arizona State University, Manfred Laubichler also from Arizona State University, and me, and supported by the McDonnell Foundation, sought to synthesize the growing body of somewhat contradictory data bearing on the gene concept. The idea was to bring together researchers for whom genetics is a critical consideration, but among whom the details of analysis vary enough to foster rather different operational definitions of the gene.

Representing bioinformatics, Stadler and Prohaska both expressed concern that annotation and taxonomic identification of genes is being hindered and obfuscated by the traditional, beads-on-a-string concept, which needs to be replaced. They suggest a DNA-based concept of distributed sequences understood in terms of context-dependent mappings onto RNA and protein. From a DNA-editing viewpoint, James Shapiro (Univ. of Chicago) called for the abolition of the gene concept based on its spurious unity and operational disutility. From RNA editing, Thomas Gingeras (Cold Spring Harbor Laboratory) recommended locating the gene concept at the level of the growing set

Darwin wrote to the geologist Charles Lyell, "My fear has always been that pangenesis would be a still-born infant, over whom no one would rejoice or cry."

of RNA transcripts where information is integrated. From the philosophy of biology, Richard Burian (Virginia Tech) was keen to ensure that a new gene concept could accommodate the elaborate roles of single gene sequences in multiple developmental contexts. Kenneth Weiss (Penn State), who has worked on the genetics of disease, emphasized the role that numerous, small mutations distributed over the genome play in defining traits and the value of operational-based definition of ordered sequences rather than genetic units. Douglas Erwin (SFI, Smithsonian) compared the proliferation of gene concepts to the zoo of species definitions and urged a practical approach so as to avoid discord and focus on critical developmental implications. From theoretical chemistry, Christian Forst (Univ. of Texas Southwestern Medical Center) was outspoken in dismissing the gene as an idea that has outlived its usefulness in an age of detailed, microscopic data.

All speakers agreed that a new gene concept needs to deal with the problem of distributed sequences, playing multiple roles in multiple contexts. If the regions of DNA sequence from which an RNA transcript is synthesized are distributed over the entire genome, or if multiple proteins all make use of the same sequence, the work is not performed purely by a sequence gene, but by the constructive processes capable of locating, transcribing, and concatenating all the relevant transcripts into a new sequence which behaves as if it were the traditional reference gene. This implies that most of the interesting dynamics take place in the coordination of the transcripts, and suggests that the gene might better be thought about in terms of input-output functions or mappings: That is, those functions that take as input, or arguments, a heterogeneous set of sequences typically in DNA form, and transform those inputs onto downstream RNA and protein targets that possess the functions that we formerly assigned to "the gene" as a contiguous DNA sequence.

Under this model, the new reference gene is partly a state-

ment about DNA-based memory, and partly a regulatory concept. This is because it suggests that the appropriate units of function, or modules, are those pathways capable of turning distributed DNA sequences into functional RNA transcripts. Mutations to these pathways are associated with modification of the phenotype, and the regulation of these pathways provides the raw material upon which gene regulation and natural selection then operates.

We might think about this modified gene concept in computational terms as some procedural element, or function, instantiated in sequences of code, contributing to one or more adaptive behaviors. The procedure or function describes the set of regulatory operations to be executed in some systematic fashion to generate a stable transcript. The code that furnishes the arguments for the function is the ordered collection of nucleotides stored in an enzyme-readable form distributed over the genome. And the final output of the procedure is the modification of phenotypic variability through contributions to cellular function. The gene is thereby a computational, or algorithmic element, exploiting underlying sequence structures, and is not merely a distributed structure itself.

Thus when we speak of selfish genes we are really speaking of a selfish function and its arguments, and not just an inert sequence of DNA or RNA base-pairs. And when we compare genomes among species, we ought to be comparing them at the level of these functions that are the true source of evolutionary variation, rather than at the level of the sequences which provide the combinatorial raw material for transcript production. One intriguing implication of this approach to the evolution of biological complexity is that it should provide a more satisfying metric than the current one, in which a simple gene-as-sequence has the disconcerting property of making primates and worms virtually indistinguishable at the genomic level, and severely reducing the resolution of cross-species comparison. ◀

David Krakauer is an SFI professor.

The Parade of Memories by Desmond Morris (20th C., British)

COURTESY OF DESMOND MORRIS

BUILDING SMART GROUPS

BY THOMAS D. SEELEY

Many animals, including humans, live in sophisticated societies. As a result, many important decisions are made not by individuals acting alone, but by groups acting collectively. In humans, these group decisions range from some friends choosing a restaurant to a nation electing a government. Likewise, in a school of fish, troop of baboons, or swarm of bees, the group's members have to make decisions about where to go or what to do. The fundamental puzzle is this: How can a group use its members' knowledge to choose an optimal course of action for the group as a whole?

STR/AFP/GETTY IMAGES

Women show their completed voting cards during the 2009 general election in India, the largest democratic election in the world, with some 743 million voters.

The problem of collective decision-making has challenged philosophers and political scientists from Plato onwards. Many have been skeptical about group decision-making. Henry David Thoreau, for example, penned in his *Journal* in 1838: "The mass never comes up to the standard of its best member, but on the contrary degrades itself to a level with the lowest." Likewise, Friedrich Wilhelm Nietzsche wrote in *Beyond Good and Evil* in 1886: "Madness is the exception in individuals but the rule in groups."

The natural world, however, presents us with many examples of clever animal groups—consider a flock of migrating geese deciding when to take flight or a swarm of honeybees choosing a new home. And as James Surowiecki noted in 2004 in his book *The Wisdom of Crowds*, in a human group with the right organization, "the many are smarter than the few." For example, in guessing the number of jelly beans in a jar, the average of a group of independent guesses is often more accurate than the best individual guess.

Recently, John H. Miller, an economist at Carnegie Mellon University and part-time research professor at the SFI, and Nigel Franks and I, biologists specializing in social insects, from the University of Bristol in England and Cornell University respectively, organized a workshop at the Santa Fe Institute on how to optimize group decision-making. The workshop, titled "Collective Decision-Making: From Neurons to Societies," brought together some 20 experts in animal behavior, neuroscience, political science, and engineering to explore common features of natural systems—such as monkey brains, ant colonies, and Vermont towns—that show good collective decision-making. Part of the attraction of this topic is to offer strategies to improve how human organizations make decisions.

The discussion focused on the scenario in which a group makes a single collective choice that is binding for all its members. Examples include human legislative decisions regarding passage of a new law, choices of travel direction in cohesive groups, and visual neurons deciding about the direction of an approaching object. The fundamental question is how to make a decision based on a pool of information that is dispersed across the group's members. The talks at the workshop revealed some astonishing consistencies among the mechanisms of decision-making in primate brains, insect societies, and New England town meetings. In each type of system, every member of the group has limited information and limited intelligence, and yet the group as a whole makes first-rate collective decisions. Furthermore, in each system, the decision-

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These rock ants wear radio frequency identification tags, which allow researchers to determine each individual's role in the collective decision on a new nest site.

making process is a popularity contest—a race between competing accumulations of evidence in support of the various alternatives. The winner is the first to gather enough evidence (support) to cross a critical threshold (quorum). The better the choice, the more rapidly it gains supporters (neurons, insects, or persons), and the more likely it is to be the first alternative to gain enough support to become the community's choice.

It appears that an important feature of all these systems is having the right mix of independence and interdependence between the group members. Individuals generally assess the quality of different alternatives independently. But they are also more likely to support an alternative that is more strongly supported by others. For example, in a "debate" among ants over which rock crevice should be their new home, the individuals that have found a first-class site will advertise it most powerfully and create the strongest positive feedback loop of supporters recruiting additional supporters—those who "shout" loudest, in other words, are most convincing.

Without sufficient independence in evaluating the alternatives, an informational cascade (groupthink) can lead to a bad decision. This happened with the Space Shuttle Columbia disaster in 2003, in which Linda Ham, the leader of the Mission Management Team, did not encourage independent views on the consequences of the foam that struck the shuttle's wing during launch. Similarly, without sufficient interdependence, the decision-making can also be suboptimal, as the group cannot amplify its information about good alternatives. This situation arose in the AIG debacle. Individuals within the corporation knew that selling credit default swaps was risky but could not influence those that chose (foolishly, we now know) to do so. There was not a broad discussion of the wisdom of this decision, hence no opportunity for interdependence.

The workshop revealed important avenues for future investigation. Researchers of individual decision-making have shown that people exhibit many unintentional biases when making quick, intuitive judgments. For example, when asked to estimate the gestation period of animal X (elephants, for instance), people tend to say nine months. This is a case of unintentional "anchoring"—tending toward a value that is familiar, even if irrelevant. The problem can be overcome with certain habits of thought, such as being one's own "devil's advocate" to trigger mental deliberations. Are group decisions prone to such analogous biases, and if so, what are the strategies for avoiding them? When a group's debate seems inadequate, could it foster deliberations by weakening positive feedback interactions among its members, or by increasing the critical level of support needed to identify a chosen alternative? Along with such questions, the workshop's participants left with a new appreciation for the commonalities of collective decision-making across a wide range of systems. ◀

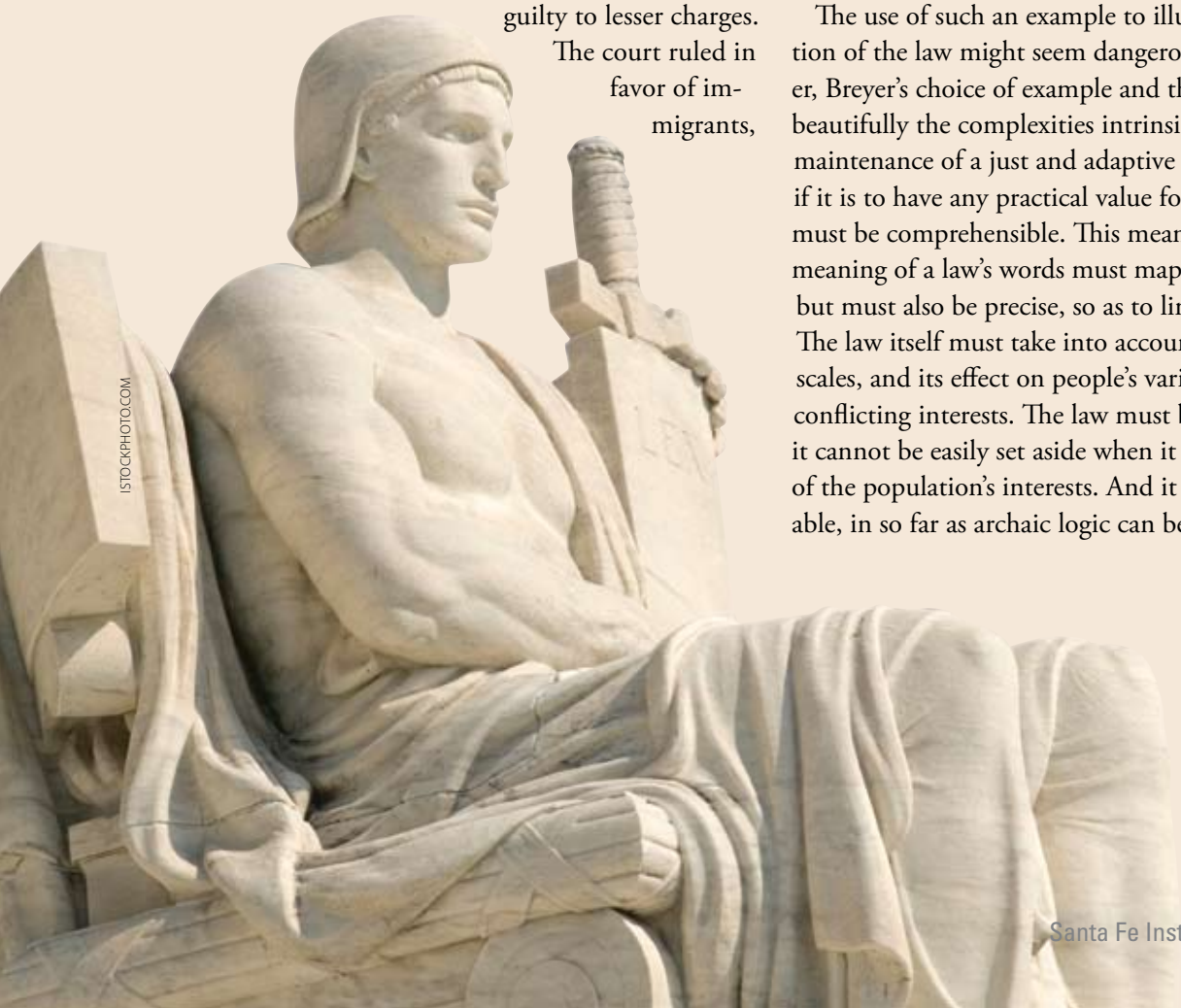
Thomas D. Seeley is professor of neurobiology and behavior at Cornell University.

Engineering Better Legal Systems

BY JESSICA FLACK

In April of this year the Supreme Court of the United States had to decide whether it was constitutional to prosecute illegal immigrants for using falsified social security numbers. The primary issue in Flores-Figueroa v. United States, No. 08-108 was whether an individual could be charged with identity theft even if he or she had not known that the number belonged to someone else. A second issue concerned prosecutors using the threat of these more serious charges as a means of coercing illegal immigrants into pleading guilty to lesser charges. The court ruled in favor of immigrants, stating that the law only applies when an offender has knowingly transferred, possessed, or used, without lawful authority, another person's means of identification. The court argued that the "knowing" requirement meant that the presumed offender understood that the number he was adopting belonged to someone else. Justice Stephen G. Breyer made this point in everyday terms: "If we say that someone knowingly ate a sandwich with cheese, we normally assume that the person knew both that he was eating a sandwich and that it contained cheese."

The use of such an example to illustrate an interpretation of the law might seem dangerously flippant. However, Breyer's choice of example and the case itself illustrate beautifully the complexities intrinsic to the building and maintenance of a just and adaptive legal system. The law, if it is to have any practical value for ordering society, must be comprehensible. This means that the intended meaning of a law's words must map onto everyday usage, but must also be precise, so as to limit manipulation. The law itself must take into account short and long timescales, and its effect on people's varied and sometimes conflicting interests. The law must be robust, in so far as it cannot be easily set aside when it conflicts with a subset of the population's interests. And it must also be overturnable, in so far as archaic logic can be recognized and



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The statue *Authority of Law* sits at the entrance to the U.S. Supreme Court building in Washington D.C., which was constructed in 1935.

CAMERAPHOTO ARTE, VENICE / ART RESOURCE, NY

The Doge Thanking the Great Council During the First Meeting by Gabriele Bella, (18th C./Italian)

abandoned for a more appropriate set of rules.

In more general terms, a good legal system, and well-written laws, must take into account information-theoretic considerations, timescale effects, scaling, heterogeneity of agents and interactions, correlated and hidden variables, contextual effects, and trade-offs between robustness and evolvability—topics that fall under the general remit of "complexity science." Yet none of these issues is considered in a formal quantitative framework when penning legislation or when building structures such as judiciary systems.

The question is whether a better legal system might be engineered using design principles from complexity science. This is a particularly difficult task because the solution must come from individuals within the system, using largely local information. There is no external engineer with access to global information and the ability to experiment on large scales. The question of how to better incorporate insights and methods from complexity science into the study and construction of legal systems served as the basis for a meeting organized at the Santa Fe Institute by SFI Professor David Krakauer, Jenna Bednar from the University of Michigan, and me in March on "Evolution, Complexity and the Law." The meeting, which was funded by the Kauffman Foundation, was attended by an interdisciplinary group of scholars and scientists, including legal scholars and attorneys, political scientists, anthropologists, mathematicians, physicists, and biologists.

Although the problems are formidable, there is reason to be optimistic. The traditional justification for penning legislation and the methods for evaluating its effects have been largely based on argument. Argument is based on informal logic and the use of qualitative precedent, rather than on quantitative data. Partly this is because quantitative data on the scale required have been lacking. Until recently, collecting such data made little sense, as the tools and conceptual frameworks required to analyze such data were not available.

Within the last 15 years, however, researchers have developed methods for the coding and analysis of large, noisy data sets permeated with network effects, largely for the study of genomic and molecular problems. In partic-

ular, these methods allow us to empirically address issues related to the correlated activity of many variables. For example, in biological systems it is now understood that many proteins function differently depending on their connectivity in the cell's network of protein interactions. Highly connected proteins in scale-free networks are more essential to cellular function than weakly connected ones. Although this might seem obvious in retrospect, until computational methods for analyzing the structure of large networks became available, it was assumed that a particular protein was responsible for catalyzing a specific cellular reaction much as it was (and often still is) assumed that there is a gene for X. My own work, in collaboration with SFI researchers Nihat Ay, Simon DeDeo, and David Krakauer, has generated a mathematically rigorous, systematic means for determining in biological systems the types of solutions—such as scale-free wiring versus exponential wiring of networks—that contribute to robustness, as well as when system components are likely to cause problems.

These approaches for disentangling causality and studying robustness and adaptability in complex systems are general enough to be used to study social questions, such as the origins and dynamics of legal systems. This includes isolating the factors that cause laws to succeed or fail, determining the architectures and construction rules that make legal systems robust yet adaptable, and determining the conditions under which it pays to write legislation that is lengthy and operationally precise versus legislation that is concise and colloquially comprehensible.

Progress in engineering better social systems is already being made in a closely related discipline—economics—in work by SFI Science Board member and Nobel Prize Winner Eric Maskin, among others, on "Mechanism Design Theory." The research has shown that game theoretic arenas can be designed around problems to increase the probability of competing participants converging on an a priori-defined desired outcome. The design of the Vickrey auction, for example, gives bidders an incentive to bid the true value of the good being sold. In this auction, bidders submit sealed bids without knowing the bids of others. The highest bidder wins but pays the value of the bid submitted by the second highest bidder. These two rules increase the probability that in an auction for a single, indivisible good, bidders will not intentionally under- or overbid.

Our recent meeting was the first step toward engineering legal systems from the bottom up to produce just outcomes at multiple scales for a diverse set of participants. The second step is to identify a few candidate data sets, and areas for data collection and coding that offer the prospect of complementing traditional styles of legal reasoning and intervention with complexity tools and concepts. One such data set is the distribution of case citations. A group of researchers from the meeting, led by Daniel Katz, a graduate student at the University of Michigan, has been studying why these citations follow a power law—that is, why some cases are heavily cited and others rarely or never. This work will help researchers identify the factors contributing to the origins and evolution of legislation. Another group of researchers, led by David Krakauer, SFI External Professor Dan Rockmore, and Robert Cooter of the University of California at Berkeley, is focusing on the analysis of constitutions, using new statistical methods to track patterns of shifting ideas in the cultural evolution of documents. Armed with the kinds of insights generated by these projects, we can begin to develop a "mechanism design theory" for law. ◀

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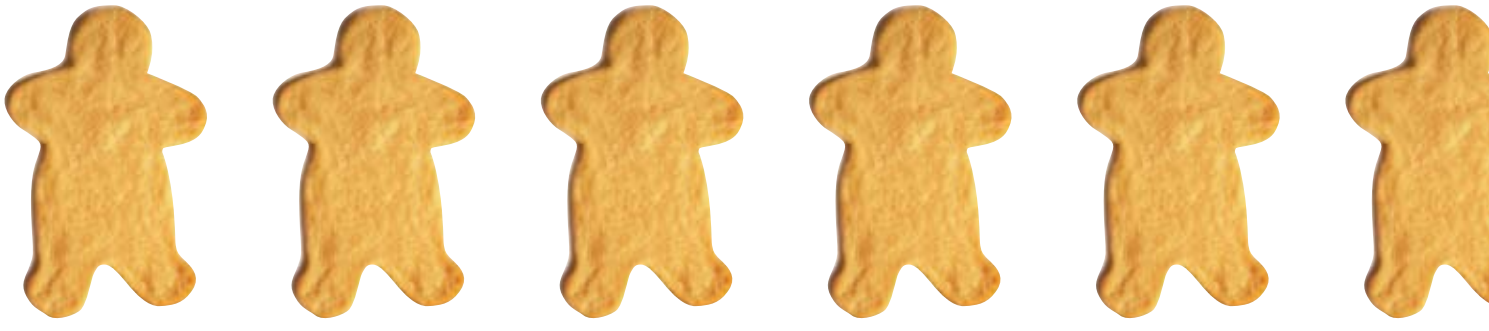
AVERAGE IS NOT GOOD ENOUGH: THE FUTURE OF Individualized Medicine

BY JANET STITES

The first thing to understand about Avidan Neumann is that he is not a medical doctor. However, his impact on the field makes this a benefit rather than a drawback. Armed with a Ph.D. in physics and mathematical biology from Bar-Ilan University in Israel and the École Normale Supérieure in Paris, Neumann has shown how mathematical modeling can help us understand disease. Now, he is doing the same for the individual patient.

Much of his work has been in the field of viral kinetics, in particular the study of Hepatitis C and B, HIV/AIDS, and the use of mathematical modeling of viral dynamics for drug development.

After completing a postdoctoral fellowship at the Weizmann Institute, Neumann worked as a postdoc for four years in the mid-1990s at the Santa Fe Institute and Los Alamos National Laboratory under the guidance of Los Alamos Senior Fellow and SFI External Professor Alan Perelson. Now he is an associate professor on the faculty of life sciences at Bar-Ilan University in Ramat-Gan, Israel, and the head of the Laboratory for Modeling In-vivo Clinical Kinetics there. But the work he did in New Mexico—and his love of the landscape—led him to a position of external professor at the Institute. Over the years, he has often collaborated with SFI faculty and continues to make the long trip to Santa Fe about once a year.



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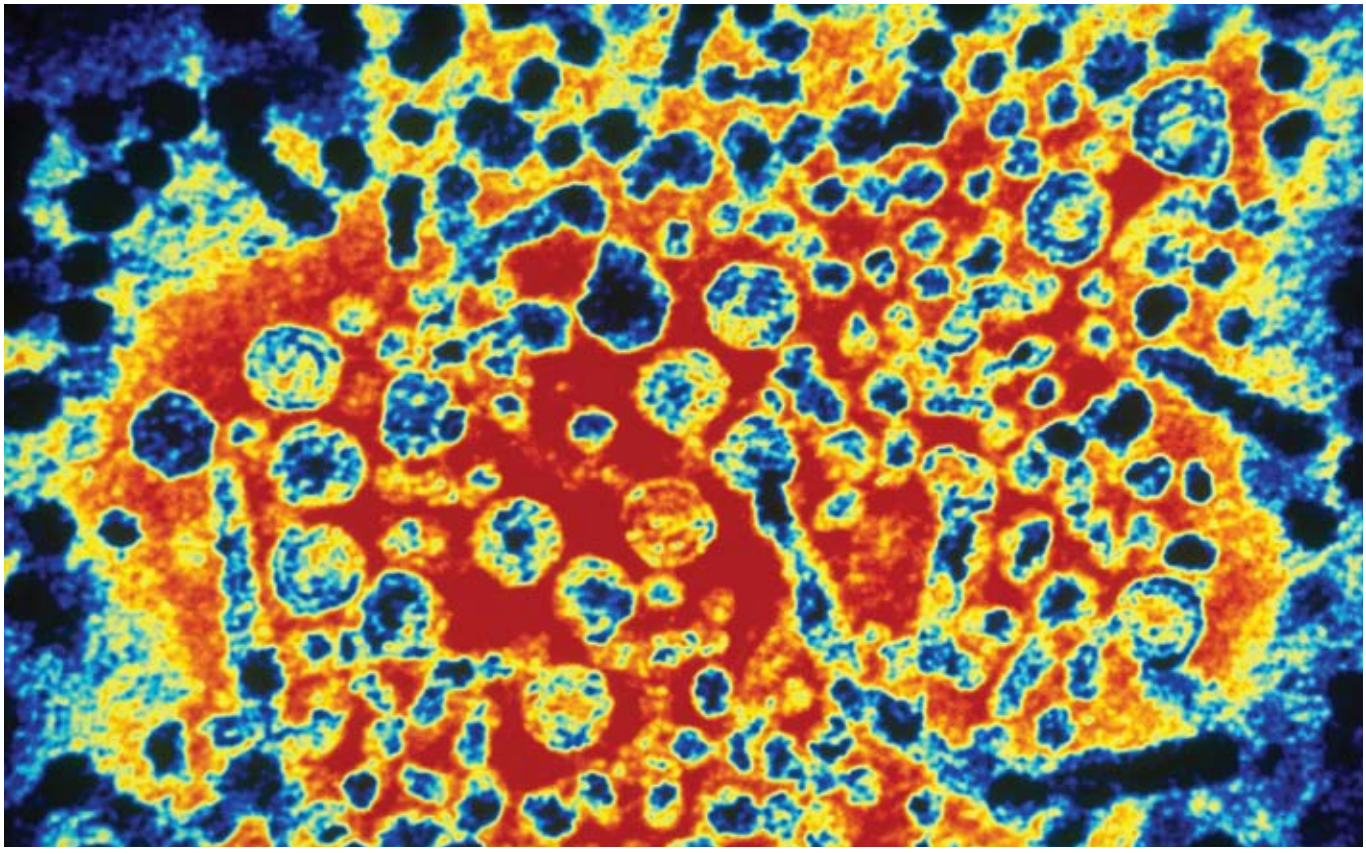

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This color-enhanced transmission electron micrograph shows the Hepatitis B virus, which infects the liver of humans, causing inflammation, vomiting, jaundice and, rarely, death.

He did so last fall to give a talk at the 2008 Annual Business Network and Board of Trustees' Symposium on the topic of individualized medicine. Often this term, also known as personalized medicine, is used in the context of genome science as researchers continue to build links between diseases, drugs, and genes. Neumann's idea for individualized medicine is different in two ways: he wants to personalize drug therapy based on each patient's response, rather than simply considering the mean response to the drug; and he wants to take into account the health history of individual patients, their "clinical kinetics," to allow timely diagnostics of a developing disease.

Battling Mediocrity

Neumann's research focuses on how individualized medicine will affect the future of medicine, but of course the future was shaped by the past. "Until the 20th century, an individual's health was often worsened after a visit from a physician," he says. "For the simple reason that doctors in the 19th century did not wash their hands before seeing a patient."

The 20th century, Neumann points out, brought major advancements in medicine and a steep increase in life expectancy. He attributes this to four factors: the introduction of antibiotics; mass vaccinations which eradicated many diseases; the ability to screen large numbers of drugs by trial and error; and the introduction of sizable clinical trials, which have helped differentiate good therapies from bad.

"The 20th century really helped the average patient," he says. "I like to call it the century of statistical medicine, the medicine of large numbers." For most of the world, particularly the West, this was a good thing. But in Neumann's opinion, it is no longer good enough. He uses results from a

clinical trial of the drug Adefovir to explain.

For background, Adefovir is an anti-viral drug used to treat Hepatitis B. Neumann studied a trial of 340 patients, with a control arm in which 170 received a placebo and an active arm where 170 received the drug. The trial lasted 48 weeks.

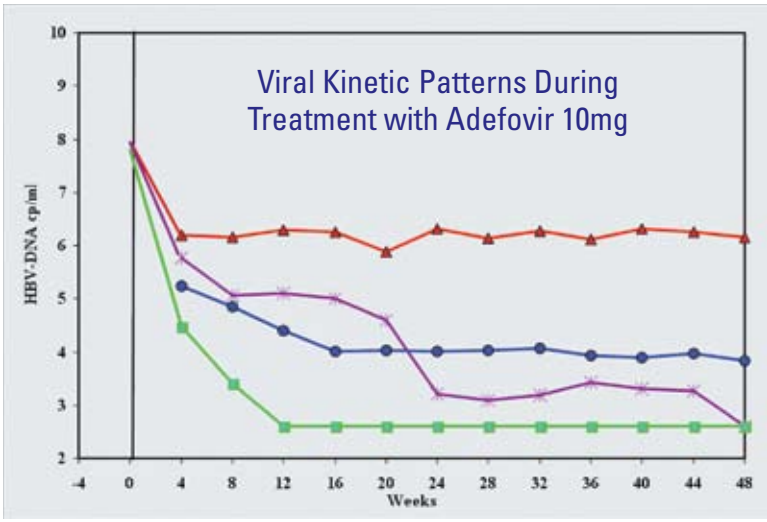
Looking at the median response of each group as a whole, the patients on placebo showed very little change in viral load over time, whereas the patients who received the drug showed a significant decline in the virus. Statistically, this outcome was very unlikely to be chance, Neumann explains, so the FDA approved the drug for Hepatitis B treatment. "This is a median viral kinetics analysis," he says. What drives Neumann is the nagging question: "Is the median kinetics the correct thing to look at?"

Neumann took a closer look, analyzing the individual data to verify if it was indeed accurately reflected in the median results. "If you look at the individual kinetic profiles," he says, "we see several distinct kinetic patterns, rather than only one median pattern."

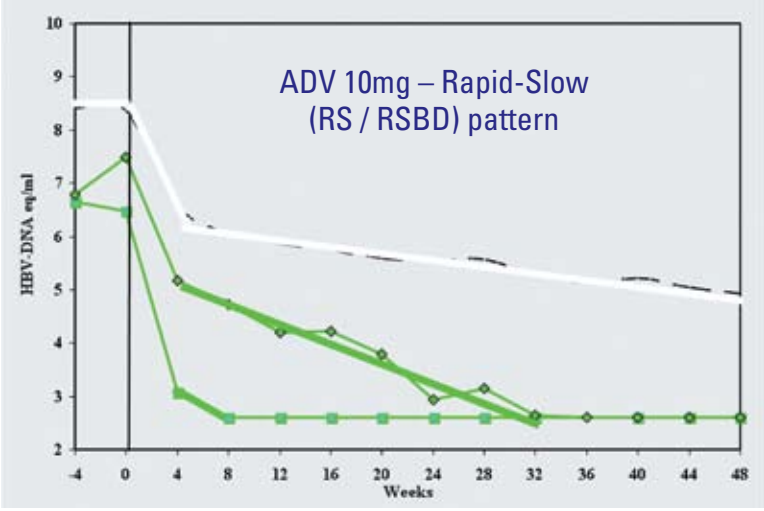
Indeed, about a quarter of the patients that took the placebo had no response at all, similar to the median. However, more than half of the placebo patients had major oscillations in their viral load. "What is clear is that the pattern generated by the median is incorrect," Neumann says. "We really have to look at individual kinetics to understand what is happening here." He further points out that many patients had "flares" in ALT, which is a marker of liver damage, indicating the immune system is killing infected liver cells, just before the decline in the virus.

For those that received the drug treatment, Neumann found that upon closer individual inspection, the first phase of treatment matched the median line. However, after the initial decline, many patients stopped responding. Other patients' viral load continued to decline in a slow second phase and stopped responding after a few months. Still others had a continuous decline of the virus, until the viral load was undetectable. But theirs was a rapid decline, not the slow average decline shown by the median.

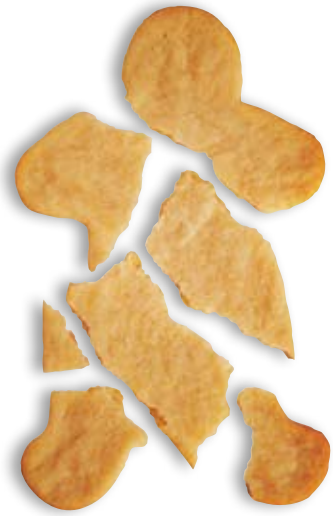
"In general, if we look at the distribution of the individuals' decline instead of the median, we can actually see four different patterns," Neumann says. His previous work helped measure the median response, but now he's moved



The FDA approved the drug Adefovir based on the median effect on patients. However, when Neumann looked closely, he saw that, after an initial rapid decline, four different patterns of response to the drug emerged.



In this graph, though the disease in both patients (green) showed an initial rapid decline with the Adefovir, one continued to respond in a slow second phase, while the other stopped responding. Both patients' responses differed from the median (white)



"You remember when people just died of old age?" he asks. "That's not allowed to be put on a death certificate anymore. It's illegal."

beyond it. "I believe the median analysis is a mediocre approach to medicine. Can we optimize treatment based on those individual patterns of kinetics?"

Further analysis of the patients who received the placebo in the first year of the trial, but received Adefovir in the second year, revealed that the individual kinetic patterns during the first year—flat versus oscillatory—predicted which patients would respond to treatment and which not. Even more important, it was possible to identify a number of points—the beginning of a flare, for example—at which starting therapy allowed for highly successful treatment.

Redefining Health

According to Neumann, in the 21st century and beyond, medicine will redefine sickness and health. He points out that lifespan in the Western world is now more than double what it was in Medieval Britain: 66 years, rather than 30. In the U.S. the average lifespan is 77, with estimates it will rise to 85 by 2050. "You remember when people just died of old age?" he asks. "That's not allowed to be put on a death certificate anymore. It's illegal."

Neumann suggests we start to look at lifespan, not beginning at birth, but when people reach 65. "If people live to 65, they are expected to live another 20 years," he says. "We no longer expect to die of old age. This has to change the way we look at medicine."

When people do reach old age, Neumann points out, most are dealing with multiple ailments. What's more, some have chronic diseases which become drastic at some point. "We have to ask: Is 'healthy' a person with no symptoms or is 'healthy' a person who does not need therapy?"

His solution is to use individualized medicine for early diagnostics. The use of genomics-based personalized medicine poses a problem in this regard. Diagnostics based on the sequence of a patient's genes can be done early, but they only give a probability for the disease to occur sometime in their life. For example, you might find that you have an 80% chance of developing cancer sometime in the next 30 years. "What can you do with such information?" he asks.

Instead Neumann suggests using what he calls clinical kinetics to allow for timely diagnosis of diseases as they develop. "We need to look at how various clinical markers change over time for each patient, and based on that—possibly including genomic data as well—be able to make a specific, individualized diagnostic at real-time," he says. "That will allow us to find out when a patient is developing a disease and treat it before it becomes serious."

Treatment, he adds, will have to remain fluid and responsive, finding a starting point, but then tweaking therapy based on the patient's response. In addition, he explains, the example of Adefovir shows that *when* to start a therapy is as important as what drugs to give.

Neumann warns against physicians relying too much on genomics. "There are limitations," he says, "because of the confounding effects of multiple genetic factors. Moreover, a patient's history—immunological and metabolic—is important. We are more than just the sum of our genes." ◀

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

CELLUCIDATE: Modeling by Community

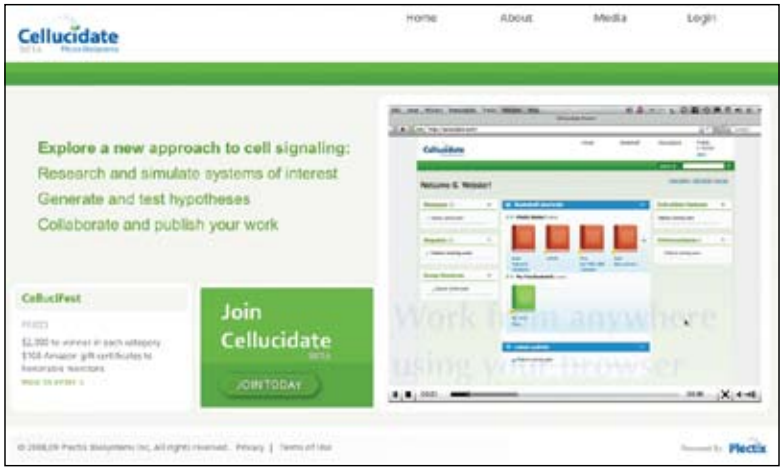
BY JOHN WHITFIELD

"CELLUCIDATE," SAYS SFI EXTERNAL PROFESSOR WALTER FONTANA, IS "FACEBOOK FOR PROTEINS." It allows biological molecules, via the people who study them, to form connections, find out what they have in common, and keep track of one another. And, he says, it can do the same for the scientists, helping them to communicate and collaborate. "It's also Facebook for researchers that deal with proteins."

More precisely, Cellucidate is a platform, accessed through the World Wide Web, for modeling and simulating networks of cell signalling. These molecular interactions between proteins and genes control and coordinate the workings within a cell and its communication with other cells to ensure every component does the right job as part of the whole body. It doesn't quite have Facebook's social networking reach yet: a beta version of cellucidate.com had a soft launch in December 2008, and as of April 2009, the site had 300 registered users. But what it lacks in numbers, the project makes up for in intellectual ambition: the website describes itself as "Gutenberg for models." Once someone has come up with a model, they can share it with the site's other users, who change it, critique it, or plug it into their model of a different part of the cell-signalling system.

PHOTO: NARISSA ESCANLAR

Walter Fontana explores ways to make models perspective-generating instruments; Background pattern: This depiction of a "hairball," by Funahashi H. Kitano and colleagues, conveys a sense of the complexity inherent in networks governing cellular information processing.



Through the Cellucidate website, researchers can work with the complexity of cells. Such a task is especially daunting because the facts keep changing (and growing), which requires that such networks be easy to edit and update.

And when new data comes along—as it does at an alarming rate, thanks to automated, high-throughput methods for analyzing protein interactions—the model can be updated. The whole business is intended to be simple enough to democratize the modeling process, allowing people with different backgrounds and different skills to talk to one another, and to help researchers focused on the workings of a single molecule see the bigger picture. "Cellucidate allows a community of researchers to look at the same facts in the same way," says Fontana. "It's capable of tracking knowledge scattered across the research community."

In many ways, this echoes Fontana's larger research goal. He has spent his entire career exploring different disciplines. His Ph.D. advisor at the University of Vienna, for example, was theoretical chemist Peter Schuster, an SFI external professor. With Schuster, Fontana trained in chemistry and molecular biology. But since his teens he had also harboured an interest in evolution, sparked by Jacob Monod's classic 1970 book *Chance and Necessity*. "It showed me that chemicals don't just change color in a beaker, or explode, or make smells," he says. "They organize information, and read and write. It was an epiphany." Working with Leo Buss of Yale University, a leader in evolutionary developmental biology, or evo-devo, Fontana pursued these evolutionary interests, looking at the links between biological information, form, and function at the molecular level, using models that were at times conceptual and at times very realistic, such as how sequences of RNA molecules relate to their structure.

In the early 1990s, Fontana spent two years at SFI as a postdoctoral fellow. He returned toward the end of that decade, giving up tenure at the University of Vienna to spend six years as a research professor at the Institute. The move allowed him to escape the problem of extracting space and money from institutions and funding agencies set up along traditional disciplinary boundaries. It's a dilemma all too familiar to researchers who not only straddle disciplines, but also bridge conceptually and empirically driven research.

PLATFORM WITH MANY USES

As well as supporting individual researchers, Cellucidate may aid pharmaceutical companies. Many diseases are the consequence of malfunctions in cell signalling. "Signalling systems are the basis of virtually all cancers," says Fontana. And such systems are the target of many potential drugs. The pharmaceutical industry is always looking for any edge in the search for drug targets or possible side effects, and modeling signalling might help them.

Subscriptions from such companies will likely form the basis of Cellucidate's paid users, though currently, registration for the platform is free. Eventually, it will have to make money for its parent company, a start-up co-founded by Fontana called Plectix BioSystems (www.

plectix.com). For paying customers, Cellucidate will include layers of privacy to allow commercial users to work in confidentiality. But Fontana envisages that most models will remain open-source projects—as will the underlying software—with a view toward maximizing benefits of the networks between proteins, models, and researchers.

But Cellucidate is more than a tool and a business. It's the embodiment of Fontana's attempts to build links between computing and cell biology. Fontana, who moved to Harvard Medical School's Department of Systems Biology in 2004, believes that computation should be what he calls the "third pillar" of systems biology besides chemistry and physics. This means going beyond using computers to crunch data, and even beyond trading metaphors between these disciplines, as with genetic algorithms or DNA computing. Instead, Fontana sees computer science as a basic science that will become increasingly important to biology, as a source of ideas, formal techniques, and explanations.

UNRAVELLING THE HAIRBALL

Even within a single cell, the systems created by signalling molecules are head-spinningly complex. There are about a dozen major systems controlling processes such as metabolism, DNA replication and repair, growth, and cell division. Each has a large number of components, and all of them overlap and interact. One of the main products of systems biology up until now has been diagrams that map the components and connections of a particular system. You can get an idea of what these look like by the fact that Fontana calls them "hairballs"—if you weren't a systems biologist, all you'd take from looking at such a diagram is that the cell is a very, very complicated place.

And yet even the hairballs don't capture the reality. They are static, like a subway map, when in fact the links in signalling networks are constantly changing, winking on and off, varying in strength, and feeding back on one another.

All in all, a cell may have more potential states than there are stars in the universe. "The number of possible objects that the hairball can in principle enable is astronomic—it could be 10^{40}," says Fontana. Even seemingly identical cells can, within seconds, drift into very different states. Understanding such processes requires new tools: "There's no way that you can represent the dynamics of that map with traditional methods."

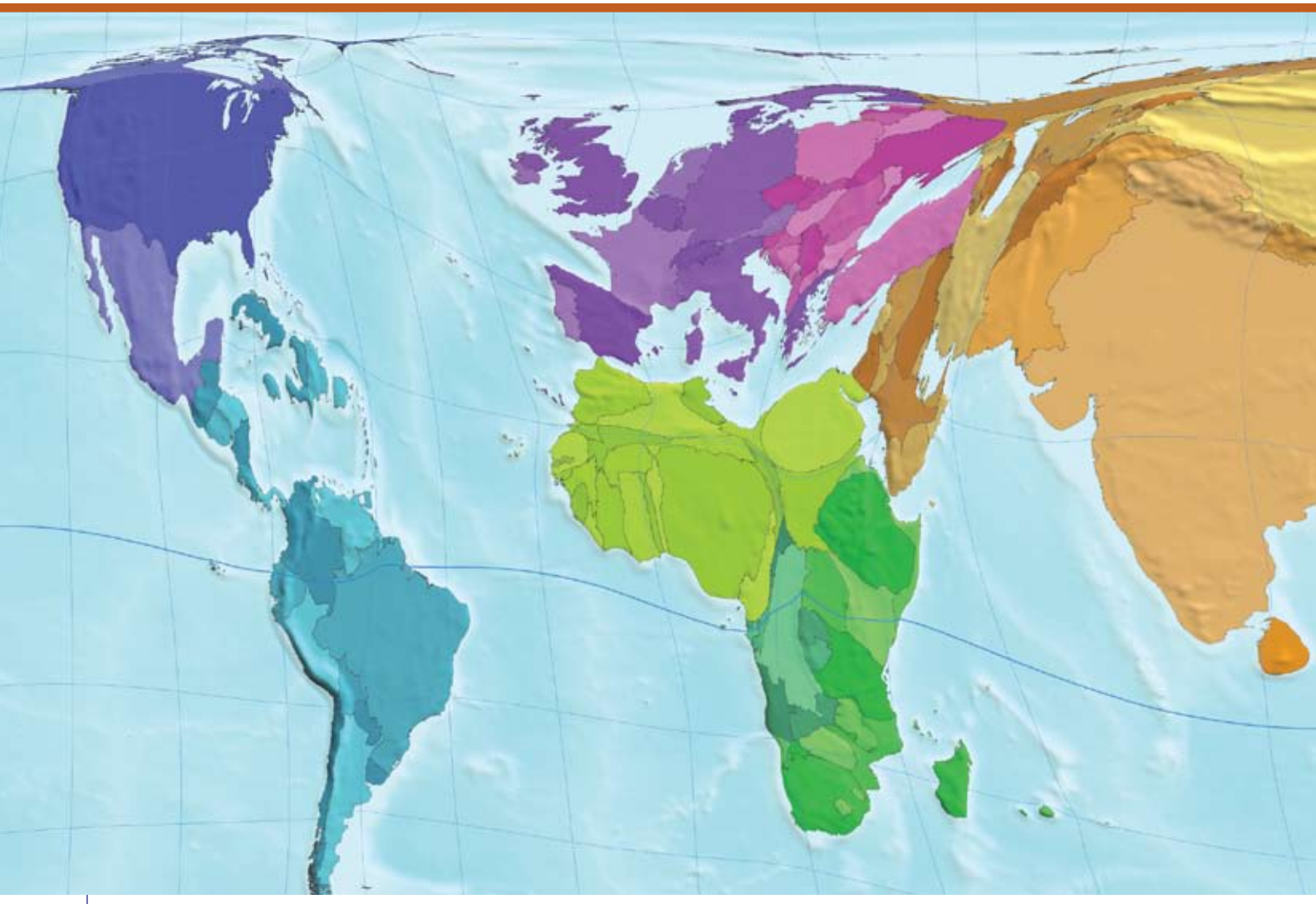
But, he points out, the signalling processes within a cell have a lot in common with computational systems such as the Web (or the brain). They also share properties with distributed computing projects, such as traffic control, where local communication between many autonomous components gives rise to coherent behavior at the system level.

Fontana taught himself computer science, and he devised Cellucidate in collaboration with a group of specialist computer scientists in an attempt to make sense of this complexity, and let other people do the same. The system uses plain English to describe which proteins bind to what. Then, using a computer language called Kappa, it turns these descriptions into a model of cell signalling that is also a program, thus making the connection between cell signalling and computation explicit. When this program is run, it becomes a simulation that provides an idea of how this signalling system plays out at a cellular level. (You can see a demonstration video at www.cellucidate.com.) It's still a work in progress. "The software engines are really good," Fontana says. "Now the question is how to make the best interface."

GROPING TOWARD KNOWLEDGE

As one of the founding professors in Harvard Medical School's Department of Systems Biology, Fontana believes that life is getting easier for interdisciplinary researchers; although, he stresses, that doesn't mean that everyone has the same scientific worldview. Still, Fontana continues to promote modeling, especially a type that owes more to computation than physics. But getting others in systems biology on board can be an uphill struggle. "People are very sceptical about modeling. They say we can't model, because we don't know everything yet." But this, he says, "is precisely why we need to model." Rather than describing something we already understand, a tool such as Cellucidate helps in approaching understanding. "The model is becoming more of a reasoning instrument," he says. "It's a way of arguing and groping towards consensus knowledge." ◀

John Whitfield is a London-based science writer and author of In the Beat of a Heart: Life, Energy, and the Unity of Nature. *From September through December 2007, he was science writer in residence at SFI.*



MARK NEWMAN: Exploring the Physics of Connection

BY JULIE J. REHMEYER

"All men are caught in an inescapable network of mutuality," Martin Luther King said in 1963. "Whatever affects one directly affects all indirectly. I can never be what I ought to be until you are what you ought to be…This is the interrelated structure of reality."

As profound as King's statement is, it's not exactly scientific. Mark Newman pondered this same interconnectedness in the late 1990s—with a physicist's eye. Yes, he thought, networks are big and important and have great moral implications, but how do they work?

Newman's thoughts were inspired in

THE ATLAS OF THE REAL WORLD, © 2008 DANIEL DORLING, MARK NEWMAN, ANNA BARFORD. THAMES & HUDSON, LONDON AND NEW YORK.

In this cartogram, Newman and his colleagues use population density to shrink or grow each country, illustrating world population distribution.

the classic Santa Fe Institute way: tea-time conversations with someone in an entirely different field. Postdoctoral Fellow Duncan Watts told him about his thesis, where he showed that the neurons of the worm *C. elegans*, the power grid of the western U.S., and the collaborations of film actors all formed networks that were alike.

Their chats made Newman realize that Watts' network theory might be able to shed new light on the web of connections between human beings. Then he could go beyond the observation that people influence one another to work out *how* they do so. That understanding might allow him to predict things people need to know, like how fast the flu will spread, who's a terrorist, and how robust the Internet is.

Newman became one of the first physicists to apply network theory to social connections. And as his collaboration with Watts blossomed, so did network theory.

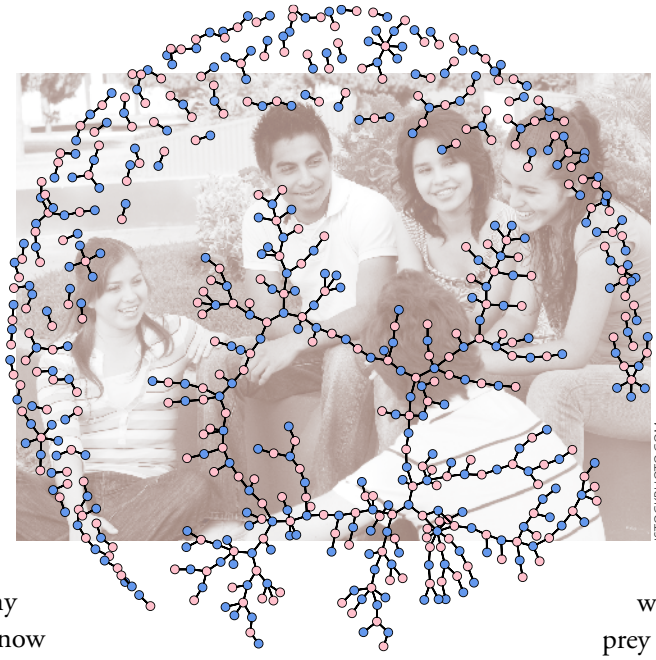
Newman was ready for just this kind of project. He had arrived at SFI as a refugee from traditional physics. Statistical physics, he'd come to believe, had become a victim of its own success. The important problems it could easily solve had been worked out long ago. Now, a theoretician like him had to either labor for decades to chip away at the big, fundamental problems, or settle for secondary issues. But Newman wanted to answer questions that mattered, and he didn't want to wait decades for the answers.

Network theory was littered with rich theoretical questions with important practical payoffs. For example, when a hospital in Evansville, Indiana, experienced an outbreak of pneumonia, the Center for Disease Control (CDC) turned to Newman and his collaborator Lauren Ancel Meyers. The CDC had tested all the hospital's patients and staff for the illness. It knew each patient's ward, roommates, and which doctor and nurse treated them. Could Meyers and Newman figure out how the illness had spread, and how to stop it?

The pair built a network in which each patient and staff member was a node, and those nodes were connected when two people were known to have had contact. Then they worked out how the bug must have spread. It was astonishing: The data showed that patients were nearly certain to pick up the bug any time they had contact with an infected staff member. An infected staff member, then, was enormously dangerous, spreading the disease from ward to ward throughout the hospital. And yet the staff almost never seemed sick. Even when they were carrying the bug, they kept the symptoms at bay. To control the outbreak, Newman and Meyers realized, the hospital had to treat the staff.

Network theory was the key to cracking the case. "There's a long history of mathematical work in epidemiology," Newman says. "People had considered how a disease affects an individual, and they had also considered how diseases spread using the connections between individuals. What had received rather little attention were

NORMAN JOHNSON



In some of his earlier work with networks, Newman mapped this network of dating patterns in a U.S. high school. The nodes are students, color-coded blue for boys and pink for girls, and the connections show who dated whom.

the patterns of connections between individuals. If you don't know the patterns of connections, then it's hopeless to predict how quickly the disease will spread or how many people will get infected." He's now applying similar methods to understanding the spread of HIV, using data from random phone surveys of people's sex lives.

To solve such puzzles, Newman draws on years of work developing a theoretical understanding of how networks function. He started decoding the secrets of networks through a community that was close to home: scientists. Scientists leave a paper trail of their collaborations through joint publications, and Newman used that data to create a big network graph that encapsulated how scientists work together. And that picture looked like…well, a nasty, giant hairball.

To make sense of it, Newman had to build some mathematical tools. He started by asking how spread out the network of scientists is, picking two random scientists—say, a Finnish ecologist and an Australian high-energy physicist—and connecting them as directly as possible through their chain of collaborations. How many "degrees of separation" are there? He calculated that it was usually just five or six.

To probe deeper, Newman considered how we informally make sense of networks. The social networks in high schools, for example, are dominated by cliques: the jocks, the geeks, the Goths. So Newman developed a clique-detector, a tool to detect subcommunities that are tightly interconnected. When he tested it on collaborations among physicists, the communities he found corresponded to the discipline's traditional subfields, like astrophysics or particle physics. This suggests that traditional subfields are a good reflection of what people actually do.

Divisions like astrophysics and particle physics are still pretty crude. Among astrophysicists, for example, there are observational astrophysicists, and among those there are radio astronomers, and so on. So recently, Newman has worked with SFI Postdoctoral Fellow Aaron Clauset and SFI Professor Cris Moore to create a tool that automatically detects whole hierarchies of communities.

In addition, their tool does something extraordinary: predicts missing links. It computes statistics about the hierarchical structure of the subcommunities, and then it generates thousands of other simulated networks with different links but the same structure. If a particular link is common in these "sister" networks, the researchers figure it's likely to be in the original network too. This can be invaluable when studying, say, food webs, where the links show predator-prey relationships and validating each link can take months of fieldwork. The tool successfully predicted missing links in three real-world networks: a food web, a terrorist network, and metabolic interactions.

"Mark is singular in combining theoretical strength with fearlessness about wrestling with real-world data," Moore says. "In networks, there have been theoretical models that aren't very realistic, and there are also people with huge datasets they don't know what to do with. No one has done more to build a bridge between them than Mark. He's helped make the field of networks both theoretically deep and grounded in real data."

Newman's focus on data, Moore says, has been influential at SFI even outside of network theory. In the early days at SFI, researchers were fascinated by simple models that generated complex behavior that looked qualitatively similar to the real world, but they struggled to figure out how to make those connections quantitative. As Newman's postdoctoral fellowship at SFI extended into

a research faculty position and then regular visits, his focus on testing his tools on data has led the way in a broad shift at the Institute toward a data-driven approach, even in fields far removed from network theory.

Newman has also formed a bridge between sociologists, physicists, and computer scientists in network theory. In the last 10 years, physicists and computer scientists have developed revolutionary techniques, but most don't know the rich ideas the sociologists have come up with over decades. Newman takes sociological ideas and makes them quantitative. "Mark is like an archaeologist," says Albert-László Barabási, a fellow network scientist at the University of Notre Dame. "He finds these pieces of gold spread around the communities." Now Newman is writing a textbook on network theory that draws together sociology, physics, and computer science.

"Mark is singular in combining theoretical strength with fearlessness about wrestling with real-world data," Moore says.

His work goes beyond network theory. A friend once sent him a postcard showing "A Texan's View of the United States." Texas dominated the middle, and all the other states were squished around the edges. California was marked "uninhabitable," and New England, "Damn Yankee Land." Newman chuckled over it and set it aside, but it got him thinking about people's internal maps of the world. For example, people often visualize Michigan as being in the middle of the U.S., even though it's far closer to the East Coast. Was there some rigorous way, he wondered, to depict these distorted maps?

He filed the question away for a few years, until he and SFI Postdoctoral Fellow Michael Gastner were collaborating on a project to map out the physical location of computers on the Internet. Computers tended to be where the people were, so their map was essentially a map of population. But then they wondered, did some areas have more computers per person than others?

One way to tell would be to squish the areas of the map with few people and expand the areas with more people, creating a map with uniform population density. If computers were plotted on that map, variations would show up.

To do this, they imagined that each person in the U.S. was a molecule of gas. If you release a gas in a room, it will spread out according to well-understood statistical rules. Newman and Gastner applied those rules to people, allowing them to warp the boundaries of their states with them as they moved. In the resulting maps, the crowded west coast and northeast were swollen and the sparsely populated Rocky Mountain and high plains states shriveled.

And smack dab in the middle of the map was Michigan, just as people tend to imagine. Newman realized he was looking at the mental map he'd been envisioning for years!

Newman and Gastner applied their technique to create a "cartogram" of the 2004 national election data. Typical maps of the election results make it seem as if George W. Bush won by a landslide, with a great mass of red, Republican-voting states in the middle of the country and a much smaller area of blue, Democratic-voting states on the west coast and in the northeast. In Newman and Gastner's cartogram, though, the states form a nearly even balance between red and blue.

Recently, Newman teamed up with a group at the University of Sheffield to apply his method to all kinds of international data. In a cartogram of people affected by natural disasters, China, India, and Southeast Asia mushroom, while the U.S. shrinks to near-invisibility. On the other hand, the U.S. is bloated in a cartogram of extinct species, sharing the stage with the tiny island of Mauritius. Newman and his collaborators published these cartograms last October in a book titled *The Atlas of the Real World.*

Colleagues describe Newman as a giant in the field, and they talk about the enormous impact his work has had. Newman himself is just grateful. "It's rewarding to be working in a field where people actually care about what you're doing." ◀

Julie J. Rehmeyer was SFI's very first undergraduate intern. She went on to do graduate work in mathematics at MIT and to teach at St. John's College. She is now a freelance writer and the mathematics columnist for Science News.

THE SMALL

WORLD of FINANCE

BY DANIEL ROCKMORE

The story is one of easy credit paving the way for a global economic crisis. No, it's not today's news. In fact, it's the news of about 20 years ago. At that time, it wasn't the microloans of ill-advised individual mortgages that formed the first tier of a financial house of cards, but instead, the bad paper of huge loans to developing nations. Much as today, the perspectives and proposed fixes ranged far and wide, but from a complexity science point of view, one reaction stands out.

It is that of John Reed, then CEO of Citigroup, whose company held billions of dollars of bad loans. To address Citigroup's predicament, and to better understand the dynamics of a highly interconnected network of economies, Reed decided that ideas and points of view from beyond neoclassical economics were needed. Perhaps, he thought, the more holistic, yet still rigorous, view of the scientists at the fledgling Santa Fe Institute—a point of view summarized in the phrase "complexity science"—would provide a framework for a deeper understanding.

In his book *Complexity*, Mitch Waldrop describes how Reed backed an SFI meeting of economists, physicists, and even a stray biologist or two. In so doing, Reed helped to foster a wide-ranging conversation about economics, physics, and the other sciences that continues at the Institute to this day, yielding insights into economies and markets, and influencing the way that practitioners and people view them.

Two decades later, the dramatic economic downturn of the past months has once again highlighted the interdependence of the financial markets (in truth, we seem to be "reawakened" to this interdependence every few years). Even more so than the events that brought Reed to SFI, today's crisis reveals an economic and financial system that is complexity in action: the result of interconnections and interdependence at many scales among numerous elements and sectors of the world-wide economy. As governments try to mitigate this crisis and to insert new capital and regulations into the financial infrastructure, the world economy as a complex adaptive system needs to be articulated, studied, and addressed.

The network-centric view of the economic crisis befits an age in which network science, a discipline that grew out of the work of many SFI researchers, most notably Duncan Watts and Mark Newman, plays such a prominent role. In the late 1990s, Watts and his colleague Steven Strogatz developed the first comprehensive model of the "small world phenomenon," which brought to widespread public attention the 1960s experiments of Stanley Milgrim. Today we see and study networks in all sorts of places—the network of neurons that makes up the brain, the hyperlinked network of the World Wide Web, social networks of interpersonal relationships, networks of genetic interrelations that give rise to disease and development, metabolic networks that detail the chemistry that gives life to a cell, and ecological ones that encode the delicate interdependence of species in an ecosystem.

Most relevant to the economy, of course, are the networks of finance that map how value, capital, credit, and risk circulate among market participants. The opaque and dense network of creditor/obligator relations that underlies the financial world has been exposed in the failures and

Opposite page: Evolution has given plants and animals robust and self-regulating circulation networks—and planners try to do the same for roads. Mapping the connections of financial networks might offer similar benefits for the economy.

OPPOSITE PAGE—LEAF VEINS: PAULA EASTWOOD; MAP: U.S. DEPT. OF TRANSPORTATION, FEDERAL HIGHWAY ADMINISTRATION

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A simple stoplight offers a metaphor for the dynamic interplay between regulation and innovation that is central to the history and development of many complex adaptive systems.

near-failures of Bear Stearns, Fannie Mae, Freddie Mac, Lehman Brothers, AIG, and many lesser-known hedge funds. A cascade of extinctions has spread through the ecosystem of the markets along lines of credit and risk, linking the institutions in which we park our money. Even the instruments themselves are a form of network—the value of a derivative object is linked to the value of some other object, which may in turn be linked to even another instrument or asset, and so on and so on.

The network of value is thus also a network of risk. And as we've seen, no matter how risk gets pushed around the network, eventually, like a game of financial Whack-A-Mole, it has to poke its head up somewhere. The unpredictability of this game and the assumed, but almost completely hidden complexity of this network have paralyzed credit sources, causing the economy to grind its gears. Credit makes the world go round. There's a basic necessity to understand its journey, to see the network and map its connections so we can comprehend the consequences of

Even within the hard constraints adaptations to survive, even thrive,

adding a new connection. This would create the transparency needed to reveal the multiple levels of obligation and exposure that are set up in any credit-based deal in a network of credit.

Such a map could, of course, be a consequence of some form of regulation. Regulation also plays a role in many of the healthy networks that we see in life, such as our circulatory and respiratory systems, the networks of plant life and root systems in a forest, the course of rivers, or even various road systems. Each of these can be thought of as branching networks of pipes for resource delivery in which the tubes keep getting smaller (up to some point). Explaining this interplay is part of the well-known work of SFI researchers Geoffrey West, Jim Brown, Van Savage, and others on "allometry"—the way that the form and function of living things change with their size. The network structure seen so frequently in living systems, with multiple levels of branching leading to branches of decreasing thickness, turns out to be the most efficient way to distribute a resource, such as blood in animals or water in plants, throughout a region. Implicit here is the idea that for these systems there is a natural "scaling law" in the movement of resources in the organism.

More recently, West and his colleagues have found that the same kinds of scaling laws can apply in social and economic settings. It would be interesting to see if these arguments provide insights into the recent crisis. For example, did the relaxation of financial regulations and the accompanying expansion of credit produce an unsustainable deviation from a "natural" allometric hierarchical progression of capital flow? Did we, in other words, overload the economy's pipes?

Such a "deviation" may have almost killed off the economic organism that it was meant to sustain. Perhaps each of the individual actors that sits at the branchpoints of the financial network needed to have something pushing back on their

imposed on life by physics and chemistry, evolution has created extraordinary in the harshest circumstances.

natural inclination to pipe through as much capital as possible. In living things, the physics of the system does this job. Maybe in a financial network, some sort of regulation or local penalty could effect the necessary behavior modification. Interestingly, this kind of analogy suggests that perhaps markets and economies have under some conditions a maximal sustainable size. From energetic and structural considerations you can show that we can't have a 50-foot woman—maybe something similar is true of economic systems.

This kind of dynamic interplay between regulation and innovation is central to the history and development of many complex adaptive systems throughout biological, physical, social, and economic life. At times, regulation fosters innovation (e.g., the imposition of standards in technological development, or genetic response to environmental factors). In other instances, regulation can squelch innovation. Innovative responses can respect regulations or attempt to circumvent them. The responses generate new regulations that generate their own responses, and so on.

In this process of co-evolution, some systems flourish while others wither. With respect to markets, some folks argue that regulation stifles innovation. They stress that relaxed regulation is inextricably tied to the ability to create the "liquidity" so necessary to keep the markets fluid. Again, living networks might indicate otherwise. Even within the hard constraints imposed on life by physics and chemistry, evolution has created extraordinary adaptations to survive, even thrive, in the harshest circumstances. It would be interesting to explore what lessons we might learn by considering innovation and regulation across a broad spectrum of phenomena.

In sum, the financial network is a living complex adaptive system of millions or even billions of dimensions. In particular, financial networks have embedded in them the problem that their basic interacting units are people, an organism whose behavior is highly unpredictable—much more than the most complicated quantum effect. The idea that the old rules can manage this adaptive organism is preposterous. Like a monster from a bad bio-horror movie, it's already evolved to anticipate and then exploit the usual fixes. Its complexity begs for an analysis that brings to bear our understanding of the mechanisms that drive other living systems. It is huge, but it is highly likely that, like other living systems, its evolution and dynamics are driven by a relatively few fundamental principles that we now must try to tease out. Our economic and social future depends on it. ◀

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SFI'S CURRENT EFFORTS TO VIEW THE ECONOMY AND FINANCIAL MARKETS FROM A COMPLEX SYSTEMS PERSPECTIVE are summarized by two additional articles in this issue: "Aftershocks of the Financial Earthquake" by former SFI Science Writer in Residence John Whitfield, and "On Time and Risk" by former SFI Postdoctoral Fellow Ole Peters. Others have recently appeared in major journals and news publications: "End the Obsession with Interest" in *Nature,* and "Matters of Principal" in *The New York Times,* both by John Geanakoplos; "Leverage: The Root of All Financial Turmoil," a news article in *Science,* reported on work by Stephan Thurner, J. Doyne Farmer, and John Geanakoplos; "The (Unfortunate) Complexity of the Economy" in *PhysicsWorld,* by Jean-Philippe Bouchaud; and "Managing Economic Crisis in the Computer-Age," in *Nature* (in press), by J. Doyne Farmer and Duncan Foley.

AFTERSHOCKS of the Financial Earthquake

BY JOHN WHITFIELD

When your scientific puzzle is someone else's catastrophe—as applies, for example, to seismologists studying earthquakes—the excitement of a new research opportunity must conflict with compassion for the sufferers. That's a conflict that many economists likely are feeling at present. As the credit crunch turns into a global recession, the emphasis is on disaster relief—rescuing the victims and repairing the damage. But besides influencing all our lives, the global financial system is also a source of questions and insights as rich and complex as the Earth's tectonic plates. And as with an earthquake, anyone surveying the wreckage is going to have a head full of what, how, and why.

The idea that mainstream economic theory does not do a great job of describing and predicting actual economic events will not be news to anyone who follows the Santa Fe Institute's output. Ever since the Institute was founded, its researchers have sought to find more accurate and realistic alternatives to the idea that the behavior of financial markets is driven by the smooth and optimal assimilation of new information, and that the people doing the buying and selling are working with perfect rationality to maximize their returns. It's a quest that has drawn in just about every theme of the Institute's work, including, but not limited to, fields such as networks (see Daniel Rockmore's piece in this issue), emergence, the dynamics of human behavior, and the interaction of history and determinacy.

The 1906 San Francisco earthquake continues to serve as a strong metaphor for the power of tectonic destruction.

Conventional economics at least has the advantage of being relatively simple. It's like looking under the streetlight for your car key, not because that's where you dropped it, but because that's where you can see. The problem is, financial markets aren't simple—quite the reverse. "The economy really is a complex system—all the pieces are built on each other," says SFI Professor J. Doyne Farmer. But, he adds, conventional economics has rarely treated markets as such, with the result that their behavior is still extremely poorly understood.

Farmer has spent decades using ideas from physics and computer science to try and invent a flashlight that will illuminate areas untouched by mainstream economics. At the moment, he and his colleagues Stefan Thurner at the University of Vienna and John Geanakoplos at Yale—both SFI external professors—are working on simulations to analyze what many see as one of the key contributors to the crisis in the markets—debt, and its financial equivalent, leverage. That might be a dirty word right now, but it shouldn't be, says Farmer: "A lot of good things run on leverage—we really need it to make markets work," as shown by the impact that the drastic drop in lending has had on the real economy. But these good things come at a price. "On the other hand, there's risk associated with leverage. As soon as it's there, you have problems."

Leverage, as its name suggests, is an amplifier. By borrowing to invest, you increase your returns. But when things go wrong, you increase your losses.

THE CALIFORNIA HISTORY ROOM, CALIFORNIA STATE LIBRARY, SACRAMENTO, CA

PROFESSOR BUTTS STEPS INTO AN OPEN ELEVATOR SHAFT AND WHEN HE LANDS AT THE BOTTOM HE FINDS A SIMPLE ORANGE SQUEEZING MACHINE. MILK MAN TAKES EMPTY MILK BOTTLE(A)PULLING STRING(B) WHICH CAUSES SWORD(C)TO SEVER CORD(D) AND ALLOW GUILLOTINE BLADE(E) TO DROP AND CUT ROPE(F)WHICH RELEASES BATTERING RAM(G). RAM BUMPS AGAINST OPEN DOOR(H)CAUSE ING IT TO CLOSE. GRASS SICKLE(I)CUTS A SLICE OFF END OF ORANGE(J)AT THE SAME TIME SPIKE (K)STABS" PRUNE HAWK"(L)HE OPENS HIS MOUTH TO YELL IN AGONY, THEREBY RELEASING PRUNE AND ALLOWING DIVER'S BOOT(M)TO DROP AND STEP ON SLEEPING OCTOPUS(N). OCTOPUS AWAKENS IN A RAGE AND SEEING DIVER'S FACE WHICH IS PAINTED ON ORANGE, ATTACKS IT AND CRUSHES IT WITH TENTACLES, THEREBY CAUSING ALL THE JUICE IN THE ORANGE TO RUN INTO GLASS(O).
LATER ON YOU CAN USE THE LOG TO BUILD A LOG CABIN WHERE YOU CAN RAISE YOUR SON TO BE PRESIDENT LIKE ABRAHAM LINCOLN.

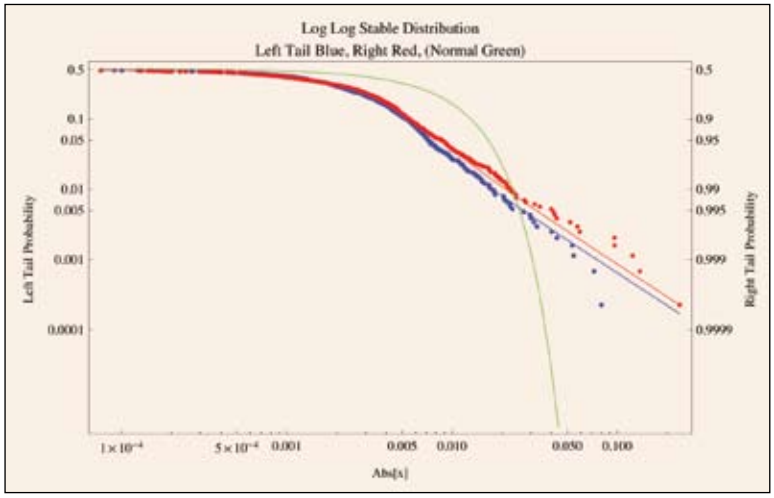
And when one part of their portfolio declines, heavily leveraged investors are forced to liquidate other assets, driving those prices down, and creating a spiral of declining value that can spread through markets. In simulations, Farmer and his colleagues have found that adding leverage to a market changes the distribution of returns, creating what are known as heavy tails in the price movement. These reflect an increased probability of extreme events—that is, you become more likely to both hit the jackpot and lose your shirt.

What's needed, says Farmer, is an actuarial understanding of the risks associated with leverage, which could be used to regulate the amount that investors are allowed to borrow—in a similar way that anyone taking out a personal loan is expected to offer evidence of their ability to repay it, and often to provide a down payment. That understanding is currently lacking. "Until we understand what the right amount of leverage is and how to regulate it, we'll be repeating these mistakes," he says.

What Farmer and his colleagues do is often called "econophysics." It uses vast data sets and sophisticated mathematical models to get a view of how history and environment affect the dynamics of markets. At the other end of the spectrum of unconventional economic ideas are behavioral and experimental economics. These take ideas from evolution and psychology to look at why individual behavior often deviates from conventional economic rationality, and the social consequences of such actions. SFI Professor Sam Bowles, using experimental and real-world evidence, has shown that economic incentives sometimes backfire, as they are a signal of distrust—it can be more effective to appeal to a person's sense of duty and ethics than to try to bribe or fine them into activity.

Such experiments usually examine interactions between individuals, or in small groups. But you can apply the same ideas at a larger scale, says Duncan Foley, an SFI external professor based at the New School in New York. Foley has taken the ideas of behavioral economics and applied them to the interactions between banks. In the boom before the bust, he says, banks trusted one another in their dealings, because they believed that they held adequate reserves. This kept the interest rates for inter-bank lending low, and created an equilibrium state where banks lent freely to one another without collateral. "At the good

Adding leverage to a market changes the distribution of returns, creating "heavy tails" in the price movement, and so increasing the probability of large gains or losses.



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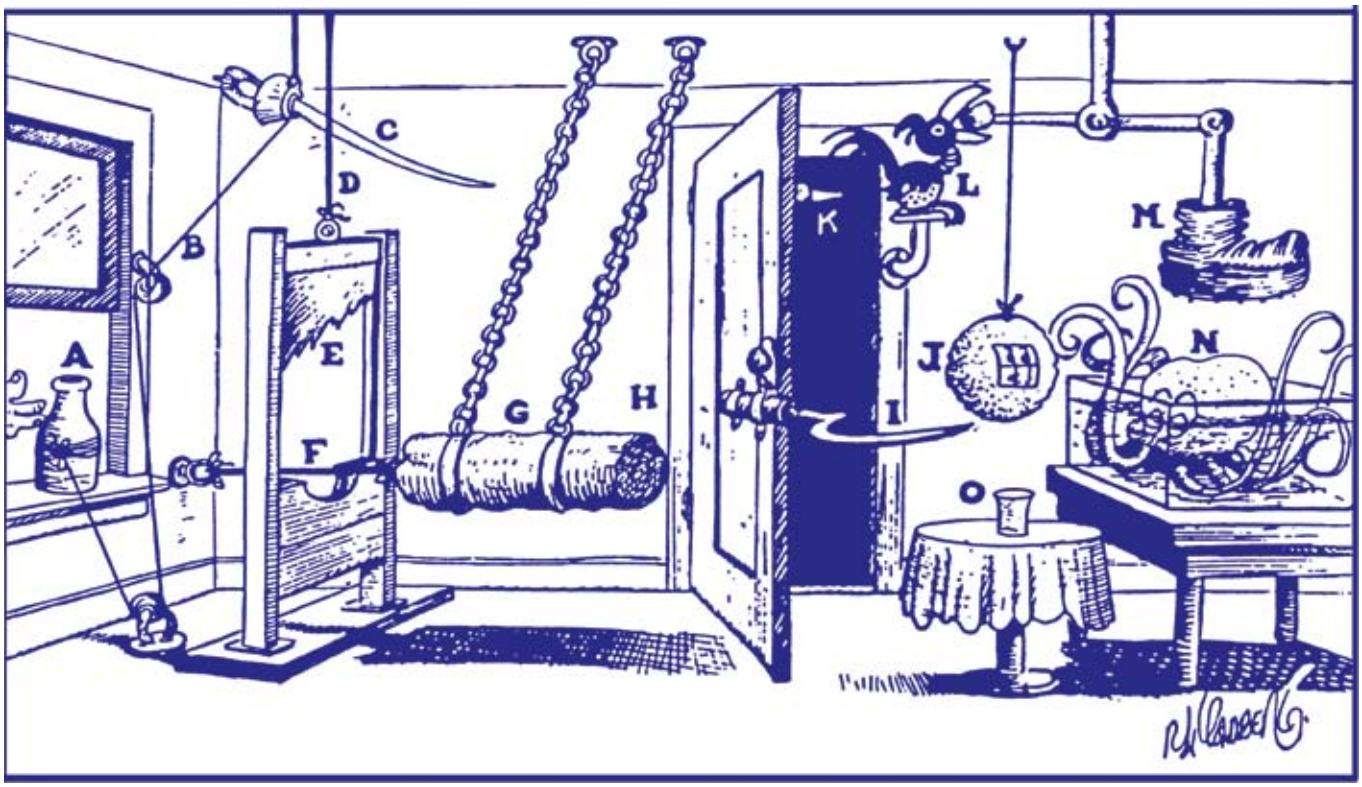

equilibrium, everyone takes it more and more for granted, and puts the balance sheet in a more and more leveraged position," says Foley.

This increasing leverage, however, was like pressure building on a fault line. And it wasn't the only source of pressure. Money from cash-rich nations such as China, Russia and Saudi Arabia poured into the United States, pushing the economy away from industry and towards financial services, triggering a consumption binge and inflating domestic asset prices. Even without sub-prime mortgage lending, a quake was inevitable, says Foley. "It's a mistake to think that the system would have gone on indefinitely. If it hadn't been mortgage-backed securities, it would have been credit card debt, or something else."

In the past 18 months, says Foley, as it became clear that the banks did not have the cash to back up their promises, the trusting equilibrium of easy lending gave way to a much more expensive equilibrium, where trust has vanished, in a similar way that behavioral economics has found that a few cheats can undermine a large group of co-operators. "If any one institution refuses to deal with its counterparts on trust, it forces all the others to devote capital to collateralization," he says. Likewise, the real economy has shifted from an equilibrium where consumers spend and borrow, creating liquidity for others, to one where everyone holds onto their money, which threatens to keep the economy in its trough.

One difference between seismologists and economists, of course, is that the latter ultimately hope to prevent the disasters they study. And although the financial system is complex, some of the suggested fixes are quite simple. Both Farmer and Foley argue that a good first step would be to increase transparency, requiring investors to reveal the amount of leverage they have taken out, if not their actual positions. SFI Visiting Professor Ole Peters, who elsewhere in this issue explains how considerations of time can help optimize risk, has looked at this issue. He believes that many of the bonus schemes offered to fund managers, where the rewards for doing well were far greater than the penalties for failure, encouraged excessive risk-taking. One solution he suggests is to make the incentives in markets the same for traders and investors by requiring that traders invest in their own funds. "If you're managing a fund and all your money is

invested in that fund, whatever is optimal for the fund is optimal for you," he points out, adding that "perhaps the crucial step is to start using the concept of objective optimality." This level of risk truly maximizes the return on an investment, not the level that seems like a good idea to a gung-ho fund manager angling for a massive reward.

Meanwhile, Foley suggests that the world financial system needs stronger controls on exchange rates. Something upon those lines was suggested by John Maynard Keynes at the 1944 Bretton Woods Conference, in which the allied nations made arrangements for global finances after World War II. But the United States was unwilling to give up the sovereignty that such controls would require—leading to the weaker World Bank and International Monetary Fund. This, says Foley, contributed to the problems of today, because it meant that the dollar became the de facto global currency and the United States found itself managing global demand, meaning that when its economy began to quake, the whole globe felt the aftershock.

Even with such a system, rebuilding isn't going to be easy. The markets may have moved into a new stable state: "It's a rather tough situation for policymakers to deal with," says Foley. "The good equilibrium may no longer be there at all." And even though many commentators and policymakers are calling for tighter regulation of financial markets, the appropriate stringency of regulation isn't at all clear. "If you regulate for the worst case, you over-regulate. But if you regulate for the normal case, you don't protect the system from collapse."

Regardless of what fixes we attempt, we need new ways to monitor and understand the system, says Farmer. The simple models of conventional economics are not up to the job. "We've got no model that deals with, for example, the fact that the financial system affects the production sector of the economy, yet that's what's causing the recession," he says. And taking complexity out of the markets isn't an option. Sophisticated financial instruments are here to stay, and can be a force for good. "We're not going to go back to banking in gold," he says. The only thing we can do, he concludes, "is to recognize the complexity and tackle it head on." ◀

John Whitfield is a London-based science writer.

finance

ON Time AND Risk

BY OLE PETERS

Let's say I offer you the following gamble: You roll a dice, and if you throw a six, I will give you one hundred times your total wealth. Anything else, and you have to give me all that you own, including your retirement savings and your favorite pair of socks. I should point out that I am fantastically rich, and you needn't worry about my ability to pay up, even in these challenging times. Should you do it?

The rational answer seems to be "yes"—the expected return on your investment is 1,583 1/3% in the time it takes to throw a dice. But what's your gut feeling? Perhaps you are quite happy with your present situation; maybe you own a house and a nice car and a private jet—would you be one hundred times happier if you were one hundred times richer? And how much less happy would you be if you suddenly had nothing?

This example illustrates a common flaw in thinking about risky situations, one that can make us blind to excessive risks and which appears to have been a factor in the financial markets in recent years. As we will see, the calculation of the enormous expected return essentially assumes that you have dealings with parallel universes. Consequently, financial models can fall prey to the assumption that traders will regularly visit the parallel universe where everything comes up sixes. An analysis of risk and return that prohibits such eccentricities gives rather different answers. We will start with an outline of the classical treatment of risky problems, then offer an alternative, and finally discuss the practical consequences of both perspectives.

Daniel Bernoulli, the man who explained why helicopters fly a few hundred years after Leonardo da Vinci drew them and a few hundred years before they took to

Considering the course of time, your ability to play the game

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tomorrow depends on the consequences of today's decisions.

ART GALLERY OF NEW SOUTH WALES, SYDNEY, AUSTRALIA/THE BRIDGEMAN ART LIBRARY

Diogenes by John William Waterhouse. Oil on canvas (1882). Living in a tub on the streets of Athens in the 4th–3rd century B.C., Diogenes was a beggar who made a virtue of extreme poverty.

the skies, contemplated pretty much our gamble, when, in 1738, he offered his answer to what economists now call the St. Petersburg paradox. The paradox asks how much a rational person should pay for a lottery ticket that offers a very low chance of a tremendous win.

He pointed out that mathematics alone does not capture the situation. It produces numbers for us like 1,583 1/3%, but it cannot give those numbers meaning, for the fundamental reason that how much I own is irrelevant—what matters is what use my possessions are to me. I might require an expensive, life-saving operation next week, which limits my ability to take risky gambles. Or my name could be Diogenes, and when offered riches I yawn and mumble something about shade and sun, wave a hand and turn around in my tubular abode. St. Exupéry's Little Prince comes to mind, who stares in bewilderment at the business man who is counting the stars that he owns.

Bernoulli argued intuitively that the increase in the usefulness—utility—of my total wealth from a small gain should be inversely proportional to the wealth I already have. If I'm rich already, another dollar won't make much difference (although he also acknowledges exceptions, such as a rich man in prison whose utility increases more due to the extra ducats required to buy his freedom than that of a poorer man given the same amount). Mathematically expressed, this assumption amounts to a so-called logarithmic utility function. Utility functions had already been established before 1738 as a concept to reflect risk preferences and became the standard answer to problems where investments are characterized by an expected return and an uncertainty in that return.

Bernoulli's answer, logarithmic utility, reconciles the mathematics with our gut feeling—the expected utility (or logarithm) of your wealth after playing my game is negatively infinite, a strong warning against taking the gamble. But because his perspective is intuitive, it is vulnerable to modifications. Arguing on the basis of usefulness, different types of utility functions, designed to include rare exceptions like the rich prisoner, are no less valid than the logarithm he proposed. After all, these functions are supposed to reflect personal choices and circumstances. Thus, invoking the individuality of human beings, Bernoulli's peers emphasized that the full treatment of the problem is outside the realm of reason. But this sounds more like a cheap excuse than an answer to the problem—and what's more, an excuse to choose a utility function that gives the answer I want.

A less vulnerable perspective that, strangely, remained on the fringes of economic theory, was

If you find yourself in this situation, by all means, play the game. But if you're a mere mortal, I'd advise you not to do it.

pointed out 218 years after Bernoulli's treatment of the problem by John Larry Kelly in 1956. I offer you the same bet as before. This time, following Kelly, we will make do without utility and instead focus on the irreversibility of time. Since we're considering a situation with randomness, we're interested in some expected, or average performance. Playing the game repeatedly, we might expect the performance over many rounds to converge to this average.

Why might we expect this? If I ask you to roll your dice 100 times and tell me how many sixes you got, your answer will be somewhere around 17. Alternatively, we could measure the expected number of sixes by giving one dice to each of 100 people and let everyone roll once. In this instance, we will find a similar number of sixes—again, around 17. Whether we look at a time average (you rolling your dice many times) or an ensemble-average (many people each rolling a dice once)—as the number of trials increases the fractions of sixes will converge to 1/6.

It seems trivial that the two differently computed averages should be the same—trivial enough for mathematical physicists to question it. Ludwig Boltzmann, in about 1884, coined the term "ergodic" for situations with identical time averages and ensemble averages. Not every situation is like this, however; there exist "non-ergodic" situations as well, and these are often as counterintuitive as the ergodic situations seem trivial.

So do we have to be more careful when we talk about expected returns and average performances? There are two averages, not one—two ways of characterizing an investment, two quantities with different meanings. Let's consider each in turn, ask which one is relevant in our case, and see if they are identical.

First the ensemble average: When economists, or Bernoulli, speak of "expected return," they typically mean an average that is calculated as the sum over all possible outcomes, weighted by the probabilities of these outcomes. An example is the 1,583 1/3% per round expected return of our game.

Probing a little deeper, we discover that this calculation uses the conceptual device of an ensemble of infinitely many identically prepared systems, or copies of our universe. The ensemble average simultaneously considers all possible paths along which the universe might evolve into the future. The fraction of systems from the ensemble that follows some scenario is the probability of that scenario, and summing the possible outcomes and weighted with their respective probabilities amounts to taking an average over all possible universes.

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Daniel Bernoulli, an 18th-century Dutch-Swiss mathematician, pioneered work in probability and statistics.

Herein lies the danger: If we don't actually play many identical games at once, then such an average only has practical relevance if it is identical to the quantity we're interested in, often the time average. There may be many possible paths from here into the future, but only one will be realized. In our game, you are risking your entire wealth, which obviously cannot be done many times simultaneously, so the ensemble average is not really the relevant quantity. Technically, it stems from a gedanken experiment involving other universes.

Now the time average: Perhaps it is identical to the ensemble average, and it doesn't matter which one we use. In other words we ask, is the situation ergodic? Considering the course of time, your ability to play the game tomorrow depends on the consequences of today's decisions, and next month's ability depends on the 30 daily outcomes in between. The ability of one player in the ensemble to play the game, on the other hand, does not depend on other players' luck. For this reason the ensemble average return is different from the time average—maliciously so: The time average performance of a single investment is always worse than the ensemble average. So unfortunately, the situation is not ergodic.

In our initial treatment of the game, the fact that I asked you to risk everything you own didn't impress the mathematics—it produced an expected return that seemed to strongly recommend playing the game. The reason this ensemble average didn't respond to the fact that you were most likely about to lose everything is this: The ensemble includes those few lucky copies of yourself whose enormous gains would easily make up for your likely loss.

Following Bernoulli, we reconciled the tempting expected return with our intuition by introducing utility. But this is not necessary—we simply need to recognize that we used an inappropriate average, implicitly treating the game as if we could interact with those parts of the ensemble that did not materialize (i.e., parallel universes) and realize the average return over all universes. If you find yourself in this situation, by all means, play the game. But if you're a mere mortal, I'd advise you not to do it. The time-average growth rate for this game, just like the expected logarithmic utility, is negatively infinite—if you don't believe me, play it a few times in a row. Instead of different changes in utility, the time perspective emphasizes that, as time goes by, we cut off different numbers of branches of potential universes reaching from the present into the future. The difference in perspective is subtle but has far-reaching consequences.

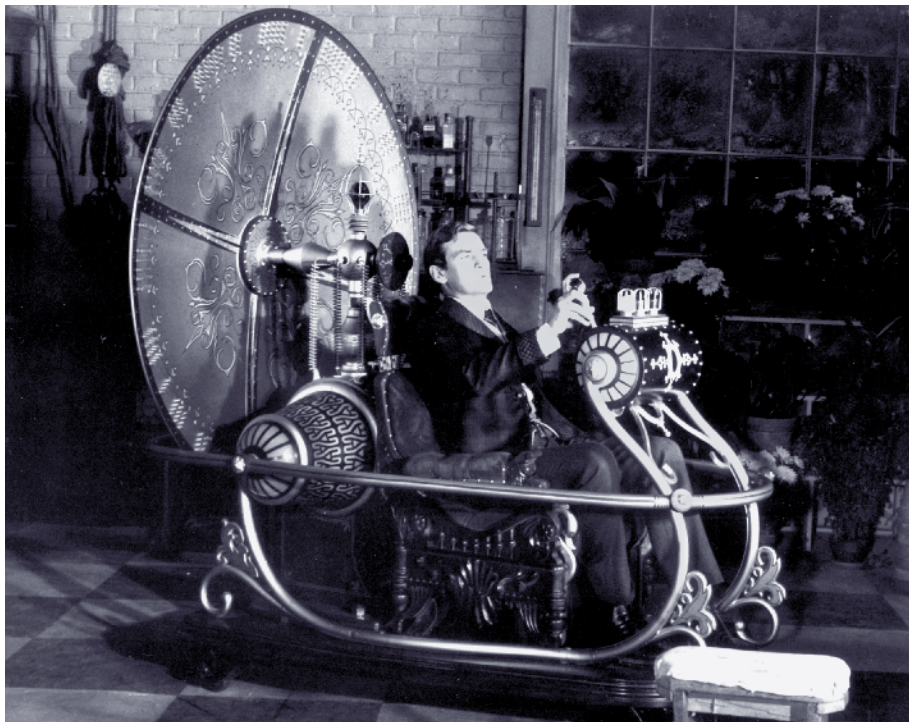
We've considered an extremely risky game for illustration, but none of the above arguments are specific to it. In general, the time perspective reveals an upper limit on risks that may be considered sensible. For example, suppose I offered you a similar but different game: You get to roll a dice and whatever you wager, I will give you 100 times your wager if you throw a six. This situation is different because you can hold back some of your wealth in case you lose. In fact, the time perspective will tell you to invest about 16% of your net worth and keep playing the game, adjusting the wager to that same fraction after every round. It also tells you that over time you will realize a growth rate of about 33% per round. Crucially, *if you choose to risk more than this, you will gain less* (of course you will also gain

Today's risk management often solely relies on investors specifying their risk preferences, or, synonymously, their utility functions, without explicitly considering the effects of time.

less if you risk less than 16% of your wealth).

A time-based approach provides insights into how to regulate credit rationally: how much an investment should be leveraged, the loan-to-value ratio at which a mortgage becomes a gamble, and the appropriate requirements for margins and minimum capital.

The literature on portfolio theory and risk management largely uses a combination of ensemble averages and utility, neglecting time or at best encapsulating its effects in a utility function. In this approach, time irreversibility, the unshakable physical motivation for refraining from excessive risk, is replaced by arbitrarily specifiable risk preferences. Following the establishment of the corresponding academic framework (roughly from the 1970s), regulatory constraints that were largely based on common sense were progressively loosened.



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From the 1960 movie, *The Time Machine.* Most current risk strategy acts as though there are many possible paths from the present into the future, but really only one will be realized.

In an investment context, the difference between ensemble averages and time averages is often small. It becomes important, however, when risks increase, when correlation hinders diversification, when leverage pumps up fluctuations, when money is made cheap, when capital requirements are relaxed. If reward structures—such as bonuses that reward gains but don't punish losses, and also certain commission schemes—provide incentives for excessive risk, problems arise. This is especially true if the only limits to risk-taking derive from utility functions that express risk preference, instead of the objective argument of time irreversibility. In other words, using the ensemble average without sufficiently restrictive utility functions will lead to excessive risk-taking and eventual collapse. Sound familiar?

Considerations of time alone cannot capture an investor's or a society's risk preferences. These preferences will always depend on individual circumstances and include motivations, for example moral motivations, that are indeed beyond the reach of mathematics. But time considerations do place objective upper bounds on advisable risks, and go a long way towards rationalizing our intuitions.

Today's risk management often solely relies on investors specifying their risk preferences, or, synonymously, their utility functions, without explicitly considering the effects of time. My bank asked me the other day what risk type I am, apparently expecting a reply like "I like a good gamble," or "I always wear my bicycle helmet." When I replied with a statement regarding time and answered, truthfully, that I'm the type who likes to see his money grow fast, they thought I was joking. ◀

Ole Peters, a visiting scientist at SFI, is a research associate in the Department of Mathematics at Imperial College London. He is affiliated with the Grantham Institute for Climate Change at Imperial College and is a frequent visitor to the Climate Systems Interaction Group at the University of California, Los Angeles.

JOEL NAKAMURA /VEER.COM

Growing Up Thinking Scientifically

SFI EDUCATION PROGRAM SPREADS ITS WINGS

BY
IRENE LEE

America's competitive edge in the global economy is measured by the skill and versatility of its labor force, and its capacity to nourish research and innovation. The Bureau of Labor Statistics projects that between 2006 and 2016, more jobs will be created in science, technology, engineering, and mathematics (STEM) than in any other field. The ability to fill these positions depends on an education system capable of producing a steady supply of young people prepared in science and math. Unfortunately, current reports show that the U.S. has a dearth of such students; fewer than one-third of 4th grade and 8th grade students perform at or above a level called "proficient" in mathematics, and 12th graders perform below the international average for 21 countries on a test of general knowledge in mathematics and science.

The SFI education programs recognize that an understanding of complexity science and computational thinking will be an important part of all sciences in the 21st century. In order to address the defining problems of this century, such as climate change, loss of biodiversity, energy

consumption, and spread of virulent disease, scientists and researchers will need an understanding of the interrelatedness of systems and of underlying patterns that transcend single disciplines. Future scientists and researchers will need to know how to harness computational resources to model and understand these daunting problems.

The Santa Fe Institute's Project GUTS: Growing Up Thinking Scientifically, aims to address this situation and produce students who can apply computational methods and analysis to complex systems issues. Thus the program has introduced complexity science and agent-based modeling to middle-school students (ages 12–14). Project GUTS provides diverse groups of students the opportunity to learn by using engaging materials and technology tools to investigate complex systems topics of interest to their local communities. The aim is to recruit the next generation of scientists and engineers, especially from previously underrepresented populations such as women and minorities.

Project GUTS was implemented as a 20-week series of after-school club meetings and two-week summer workshops. Each after-school club consisted of between 5 and 24 students, a school teacher serving as a club leader, and a Project GUTS facilitator. Following a four-week introduction to complex systems and agent-based modeling in the computer language StarLogo TNG, clubs followed six-week units on topics in complex systems: opinion dynamics, shared resource management, and social networks. Within each unit, students were introduced to the topic, participated in hands-on activities, and ran experiments on computational models. At the conclusion of each unit students created their own models of a community-relevant application of the topic. For example, as part of the opinion dynamics unit, students investigated the relative impacts of having a strong opinion leader versus having eager adopters of new opinions in a school setting.

Project GUTS has three goals for its students: to attract diverse participants through targeted recruitment and by providing relevant content, a comfortable context, and a flexible program; to prepare students for careers in STEM fields by developing fluency with the concepts of complex systems and computational tools and techniques; and to retain students in STEM disciplines by supporting them from middle to high school as young scientists.

How is the program doing? In the second year of working with students, Project GUTS reached 344 students in 24 after-school clubs; two-fifths were 7th-graders, with the remainder split almost equally between the sixth and eighth grades. Twelve clubs were established in Santa Fe and 12 new clubs were spawned in other areas of New Mexico including Taos, Peñasco, Albuquerque, Chaparral, Carlsbad, and Los Alamos. Attendance was generally high, with two-thirds of participating students attending at least 75 percent of club meetings. In addition to addressing student needs, the project has engaged teachers in its clubs, exposing them to complexity science, technology tools, and pedagogy. Twenty-four teachers who served as Project GUTS club leaders attended 20 hours of professional development sessions over the course of the school year.

Preparation for the future of the STEM program was measured by students' fluency with the

GREG MALONE

Students learn about sharing resources while playing with the Rabbit Farm model in Starlogo The Next Generation (TNG). Starlogo is an agent-based simulation language that can be used to model behavior of decentralized systems.

concepts of complex systems and their ability to use computational tools to experiment, manipulate, visualize, and interpret data. Students rated themselves high in their ability to select real-world problems to model, write their own computer models, use computer models to test hypotheses, and interpret data from computer models. However, their understanding of complex systems was limited. "Complex" and "complicated" systems were often confused, and there was a lack of discernment of different levels of dynamics (individual versus aggregate), pointing toward a need to refine the curriculum to address these misunderstandings.

The program has met up with a few roadblocks, and there is much to improve. Notably, Project GUTS has not yet developed metrics and instruments to assess students' gain in understanding of complex systems. Project GUTS also seeks to improve its outreach and recruitment of young women and retention of young Hispanic males. The program will continue to seek ways to engage such students in STEM through a combination of efforts. The project has applied for future funding that will bring it to a wider audience both regionally and nationally. A proposal has been submitted to the National Science Foundation's (NSF) Innovative Technology Experiences for Students and Teachers Program for a girl-focused version of Project GUTS; and another has been submitted for funding through NSF's Broadening Participation in Computing program to develop near-peer mentoring.

It is clear that the project is succeeding in attracting students, and that the core concept—integrating community-relevant investigations with an engaging modeling tool in which to conduct inquiry—is valid. Additionally, Project GUTS has succeeded in providing program-level and curricular support that enables distal club leaders to run clubs without a GUTS facilitator present. Most importantly, Project GUTS has created a community of teachers, students, and researchers who are interested in and committed to continuing with the program, and thus to better addressing the needs of the U.S. in this century. ◀

Irene Lee is the principal investigator of Santa Fe Institute's Project GUTS: Growing Up Thinking Scientifically. Her research interest is in exploring the use of new technologies and computational methods, from agent-based modeling to network visualization, as tools to teach and learn about complex adaptive systems.

In this Rabbit Farm model in StarLogo TNG, students supervise a farmer, grass, and rabbits, gaining an understanding of the complexity of resources management. Students also deconstruct the model and build their own based on management of a local resource.

94%
NO

"Is what you learn in Project GUTS similar to the science you learn in school?"

6%
YES

SUSAN E. R. STEIN

SFI External Professor Elizabeth "Liz" Bradley (second from front), a new SFI Science Board member, researches nonlinear dynamics and artificial intelligence at the University of Colorado at Boulder's Department of Computer Science. She rowed in the Four With Coxswain in the 1988 Olympic Games.

TRANSITIONS

BOARD OF TRUSTEES

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

The chairman and former CEO of DivX Inc., **Jordan Greenhall** co-founded the San Diego company behind the digital data compression application DivX that enables reasonable quality video transmission over the Internet. Before DivX, Greenhall was vice president at MP3.com, where he developed and implemented the company's business and content development model.

He currently invests in start-up technology companies such as Musinaut, Takelessons, OneRecovery, SparkWords (née SpinSpotter) and OpenCandy. Greenhall is actively interested in questions surrounding Transmedia, culture production, and the singularity and frontiers of science and philosophy.

Mari Kooi founded and currently serves as CEO of Wolf Asset Management International LLC, which manages over a billion dollars in assets for institutional clients around the world. Her career began in physical commodity trading, and she gained experience in alternative markets during her 18 years as a trader, trading manager, and president of Cargill Asset Management. Kooi also founded and presides over the New Mexico Financial Services Task Force, a not-for-profit group dedicated to improving New Mexico's financial services industry.

Several art organizations have benefited from Kooi's governance, including the Minnesota Museum of American Art. Kooi is known to many as the author of the "Sopa Piranha," a market commentary which reaches thousands of people quarterly in the hedge fund industry.

SCIENCE BOARD

This group of scientists and educators, drawn from a wide variety of fields, oversees the general direction, integration, and quality of the Institute's research. These are the newest members:

Elizabeth "Liz" Bradley, a member of the SFI External Faculty, researches nonlinear (chaotic) dynamics and artificial intelligence at the University of Colorado at Boulder's Department of Computer Science.

Her nonlinear dynamics projects range from handling Internet attacks to controlling vortex formation in fluid flows. In her artificial intelligence work, she has built systems that help engineers make mathematical models and geologists deduce the age of landforms. Bradley has also combined artificial intelligence and nonlinear dynamics to generate human movement sequences through chaos and machine learning. She has received a National Science Foundation National Young Investigator award, a Packard Fellowship, a Radcliffe Fellowship, and the 1999 student-voted University of Colorado College of Engineering teaching award. Bradley also rowed in the Four With Coxswain in the 1988 Olympic Games.

Distinguished Professor Donald Saari, a new SFI Science Board member, directs the Institute for Mathematical Behavioral Science at the University of California, Irvine. In his spare time, he cruises local beaches in his buggy and plays Santa Claus for department Christmas parties.

David Gross, the director of the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara, won the 2004 Nobel Prize in Physics for discovering asymptotic freedom. Gross, along with Frank Wilczek and H. David Politzer, showed that the nucleus of an atom can never be broken into its quark constituents because the attraction between quarks grows stronger as they are pulled away from each other. This asymptotic freedom is essential to understanding the nuclear strong force, one of the four basic forces of nature, which Gross has also played a central role in defining.

In addition to work with asymptotic freedom and the strong force, Gross has significantly contributed to superstring theory. With collaborators, he originated "Heterotic String Theory," the prime candidate for a unified theory of all the forces of nature.

One of the nation's experts in applied and theoretical statistics, **Sallie Keller-McNulty** teaches at Rice University where she is the William and Stephanie Sick Dean of the George R. Brown School of Engineering. She researches uncertainty quantification, computational and graphical statistics and related software and modeling techniques, and data access and confidentiality.

Prior to joining Rice in 2005, Keller-McNulty led the Statistical Sciences Group at Los Alamos National Laboratory for seven years. She was also professor and director of graduate studies in the Department of Statistics, Kansas State University; served as director of the statistical design and analysis unit for the Kansas State University Institute of Social and Behavioral Research; and was an adjunct professor in the Computer and Information Sciences Department. She is a former program director for statistics and probability in the Division of Mathematical Sciences at the National Science Foundation.

She is fellow and past president of the American Statistical Society, fellow of the American Association for the Advancement of Science, and a National Associate of the National Academy of Sciences.

In her research and leadership positions, Keller-McNulty has developed a great appreciation for the need for interdisciplinary research to find solutions for today's complex problems.

Arthur Lander directs the University of California at Irvine's Center for Complex Biological Systems, where he researches the strategies that organisms use to control fundamental processes of growth and pattern formation. Combining mathematical modeling, live cell imaging, and experimental genetics, his laboratory investigates how layers of complex molecular and genetic circuitry enable the major events of development and regeneration to proceed robustly in the face of internal noise and external uncertainty. Projects in the lab focus on morphogens—secreted molecules that form gradients in space from which cells obtain positional cues—and feedback regulators of cell growth and differentiation, and make use of a variety of model organisms including mice, fruit flies, and zebrafish.

Initially trained as a molecular biologist and physician, Lander relishes the diversity of perspectives that comes from collaborating with mathematicians, engineers, and physicists, and is passionate about drawing biology students into such work. His other passions include playing jazz and cooking—he can frequently be found teaching a course on the chemistry and biology of food and cooking.

Richard Lenski's long-term evolution experiment with *E. coli* has provided experimental evidence for many of the central concepts of evolutionary biology. Twelve populations, initially identical, have been evolving in his Michigan State University laboratory since 1988, where Lenski and his students have observed the dynamics of their phenotypic and genomic change for over 45,000 generations. The cultures have demonstrated adaptation, diversification, and the origin of new functions. Lenski also studies evolution in action using digital organisms—computer programs that replicate, mutate, compete, and evolve

a computational metabolism.

Lenski was a National Science Foundation Presidential Young Investigator. He has held fellowships from the John Simon Guggenheim Memorial Foundation and the John D. and Catherine T. MacArthur Foundation. He is a fellow of the American Academy of Arts and Sciences and a member of the National Academy of Sciences.

Eric Maskin shared the 2007 Nobel Prize in Economics for developing the theory of mechanism design. Given particular social or economic goals, mechanism design examines whether or not it is possible to construct institutions (mechanisms) that attain those goals.

Maskin has contributed to many other areas of economics as well, including game theory, general equilibrium theory, social choice theory, and contract theory.

He is married with two children and lives in Princeton, New Jersey, where he works as a professor of social science at the Institute for Advanced Study.

A former SFI resident professor, **Melanie Mitchell** now works for the Computer Science Department at Portland State University, where she teaches and researches computation in complex systems. She has also held faculty and professional positions at the University of Michigan, Los Alamos National Laboratory, and the OGI School of Science and Engineering at Oregon Health & Science University.

Mitchell's first introduction to the field of complex systems came in 1989 when, as a graduate student, she participated in a conference on emergent computation. There she met a group of like-minded scientists who saw the need to move beyond traditional, reductionist science in order to understand irreducibly complicated natural phenomena. Many of those scientists were affiliated with the Santa Fe Institute.

Like others in the complex systems community, Mitchell is fascinated with commonalities across systems such as brains, insect colonies, the immune system, cells, the global economy, and biological evolution. Her work aims to understand how natural systems perform computation, and how to use ideas from natural systems to develop new kinds of computational systems.

Mark Newman's research focuses on networked systems such as computer networks and social networks. He has covered topics as diverse as the spread of computer viruses on the Internet, the spread of human diseases over social networks, the pattern of collaborations between scientists in different fields, and the networks formed by committees in the U.S. House of Representatives.

Newman received a Ph.D. in physics from the University of Oxford in 1991 and conducted postdoctoral research at Cornell University before coming to the Santa Fe Institute in 1996, first as a postdoctoral fellow and later as a member of the resident faculty. In 2002 he left Santa Fe for the University of Michigan, where he is currently Paul Dirac Collegiate Professor of Physics and a professor in the Center for the Study of Complex Systems.

Newman is known for co-authoring the widely acclaimed *Atlas of the Real World*, in which the sizes of states and countries are pictured in proportion to their population, health, wealth, resource consumption, exports, and other variables. To read more, see "Mark Newman: Exploring the Physics of Connection" earlier in this issue.

Martin Rees teaches cosmology and astrophysics at the University of Cambridge, where he serves as Master of Trinity College. He holds the honorary title of Astronomer Royal and also Visiting Professor at Imperial College London and at Leicester University. His current research interests are high energy astrophysics, cosmic structure formation, and general cosmological issues.

Rees's awards include the Gold Medal of the Royal Astronomical Society, the Balzan International Prize, the Bruce Medal of the Astronomical Society of the Pacific, the Heineman Prize for Astrophysics, the Bower Award for Science of the Franklin Institute, the Cosmology Prize of the Peter Gruber Foundation, the Einstein Award of the World Cultural Council, and the Crafoord Prize (Royal Swedish Academy). He is currently on the Board of Trustees of the National Museum of Science and Industry, the Institute for Public Policy Research, and the Princeton Institute for Advanced

CHRISTIAN D'SOUZA

External Professor Raissa D'Souza, a new Science Steering Committee member, works as a professor of engineering at U.C. Davis, where she is helping launch their Complex Systems Center. An avid rock climber, she hopes one day to scale El Capitan in Yosemite National Park.

Study, and has served on many bodies connected with education, space research, arms control, and international collaboration in science. In 2005 he was appointed to the House of Lords and elected president of the Royal Society.

He has authored or co-authored more than 500 research papers, mainly on astrophysics and cosmology, as well as seven books (five for general readership), and numerous magazine and newspaper articles on scientific and general subjects.

Distinguished Professor **Donald Saari** directs the Institute for Mathematical Behavioral Science at the University of California, Irvine. While he was still a physical scientist deeply interested in the evolution of the universe via the Newtonian N-body problem, Saari became irresistibly drawn to the challenges of the social sciences thanks to his many conversations with students and faculty from these areas. His main research now focuses on modifying dynamical concepts to create new ways to address social and behavioral concerns.

Saari is the past chief editor of the *Bulletin of the American Mathematical Society* and serves on the editorial boards of several journals on analysis, dynamics, economics, and decision analysis. He is particularly proud of receiving over 10 awards for teaching, being honored twice during his time at Northwestern University with a "Most Influential Professor" award, and, for over 20 years, serving as Santa Claus for departmental Christmas parties.

Phil Anderson, Marcus Feldman, Murray Gell-Mann, John Holland, David Lane, Alan Perelson, and **Dan Stein** have been reappointed to the Science Board from hiatus.

SCIENCE STEERING COMMITTEE

This group meets bi-monthly to advise the SFI administration on science issues. SFI welcomes these new members:

Trained as a statistical physicist, applied mathematician, and theoretical computer scientist, **Raissa D'Souza** currently works as a professor of engineering at U.C. Davis, where she is helping launch their Complex Systems Center. Her research focuses on building mathematical models of feedback and interaction in layered networked systems.

D'Souza has visited SFI regularly since 1996, when she attended the Complex Systems Summer School as a Ph.D. student studying cellular automata. She returned to the Complex Systems Summer School as a lecturer in 2006 and 2007, and helped organize the SFI-sponsored residency month at the Institute for Complex Systems in Valparaiso, Chile. She is now a member of the SFI External Faculty.

An avid rock climber and aspiring blue water sailor, D'Souza intends someday to count scaling El Cap and sailing to French Polynesia among her accomplishments.

A member of the resident faculty, **J. Doyne Farmer** is one of the preeminent scientists in the SFI community. He has broad interests in complex systems, and has researched dynamical systems theory, time series analysis, and theoretical biology. At present his main interest is developing quantitative theories for financial markets and the evolution of technologies.

Farmer began his career as part of the "chaos cabal" at U.C. Santa Cruz, a group of physics graduate students who did early research in what came to be known as chaos theory. He went on to apply the laws of physics to beat the game of roulette, then worked for Los Alamos National Laboratory's theoretical division, and launched a quantitative stock trading firm called "Prediction Company."

In addition to his current work for the Institute, Farmer serves on the editorial boards of the journals *Quantitative Finance* and *Artificial Life.* He sits on the steering committee of a public policy institute in Santa Fe and served 10 years as a board member of a non-profit dedicated to preserving wildlands in the Southwest.

Charles Stevens, an SFI external professor, heads the Molecular Neurobiology Laboratory at the Salk Institute. He researches mechanisms responsible for synaptic transmission, and ultimately aims to discover the mathematical architecture of neural circuits. In his lab, Stevens studies brain slices and cell cultures gathered from fish using a combination of molecular biological, electrophysiological, anatomical, and theoretical methods. When neural design principles are identified, the lab then checks to verify whether the same principles hold in mammals.

Stevens holds both an M.D. and a Ph.D. in biophysics, with undergraduate training in psychology.

EXTERNAL PROFESSORS

The driving force of 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:

Morten Christiansen co-directs the Cognitive Science Program at Cornell University, where he is an associate professor of psychology. His research focuses on the interaction of biological and environmental constraints in the processing, acquisition, and evolution of language, which he approaches using a variety of methodologies, including computational modeling, corpus analyses, psycholinguistic experimentation, neurophysiological recordings, and molecular genetics. Christiansen has authored more than 90 scientific papers and has edited volumes on connectionist psycholinguistics, language evolution, and, most recently, language universals.

Outside of work, he likes to run, ski, and hike with his family.

Vincent Danos teaches at the University of Edinburgh, UK. He is also Directeur de Recherches CNRS with the Équipe Preuves, Programmes, Systèmes. Danos's expertise in computer science and interest in biology have led him to accomplish path-breaking work towards new forms of modeling biological networks.

Danos serves on the editorial boards of the journals *Transactions on Computational Systems Biology, Logical Methods in Computer Science,* and the *International Journal of Software and Informatics.* He spent 2006 and 2007 as a visiting professor at

NARISSA ESCALAR

Pablo Marquet, a new external professor, teaches and researches ecology at the Catholic University of Chile and at the Center for Advanced Studies in Ecology and Biodiversity, also in Santiago, Chile. He has investigated a broad range of ecological and evolutionary phenomena, including this curious volcano door.

Harvard Systems Biology, while also working for the Plectix company in Boston.

In his free time, Danos writes non-narrative novels considered by specialists as generally unsuitable for publication.

A professor of ecology and evolutionary biology at Princeton University, **Andrew Dobson** studies the ecology of infectious diseases. His research focuses on the community ecology of infectious diseases in a variety of endangered and fragile ecosystems: the Serengeti in East Africa, the coastal salt marshes and grasslands of California, and the forest fragments of Malaysia and Bangladesh. He also tracks the emergence of conjunctivitis in New England house finches, and investigates the interaction between climate variability and the transmission of malaria and cholera in India and Bangladesh.

Dobson has received the Wildlife Trust Conservation Award, the "Deutsche Umweltstiftung" prize for environmental reading, and serves on the editorial boards of *Trends in Ecology and Evolution,* the *Journal of Helminthology, Frontiers in Ecology, PLOS-Biology,* and *EcoHealth.*

Santiago Elena's scientific interests relate to the evolutionary biology of microbes. A research professor at the Spanish National Research Council's Instituto de Biología Molecular y Celular de Plantas, he focuses on studying the mechanisms that generate and maintain the genetic variability of RNA viruses in crops. He has also been exploring the endless potential of digital organisms as model systems for evolutionary studies, and is developing in silico and mathematical hierarchical models of the entire viral infectious cycle.

Elena serves on the editorial boards of *The American Naturalist,* the *International Journal of Evolutionary Biology, The Open Genomics Journal, The Open Virology Journal, BMC Evolutionary Biology,* and *Infection, Genetics and Evolution.*

Elena says his only aspiration in life outside of science is to bring happiness to his wife and three kids.

Jessica Green applies theoretical, computational, and empirical approaches to study biodiversity and biogeography across life's domains. She is particularly interested in the causes and consequences of microbial diversity, and exploring patterns and principles that may be common to microbes, plants, and animals. Her lab uses interdisciplinary approaches at the interface of environmental genomics, ecology, phylogenetics, mathematics, and informatics.

Green is a professor at the University of Oregon's Center for Ecology and Evolutionary Biology. She has recently received a grant from the Moore Foundation to develop new approaches for analyzing vast quantities of metagenomic data, and a grant from

MARIE RUNDLE

New External Professor John Rundle directs the California Institute for Hazard Research at U.C. Davis, where he explores the dynamics of earthquakes. Though he generally works with computer models, his animal friend Konrad, at the Lone Pine Koala Sanctuary in Brisbane, Australia, may prove helpful.

the Sloan Foundation to study the impact of sustainable design on the indoor air environment.

Outside of science, Green spends time with her two young boys, Max and Mauro, and her roller derby team, the Flat Track Furies.

Pablo Marquet teaches and researches ecology at the Catholic University of Chile and at the Center for Advanced Studies in Ecology and Biodiversity, also in Chile. His research program focuses on the search for the general principles that underlie the seemingly endless diversity and variability of ecological systems. Marquet has investigated a broad range of ecological phenomena and evolutionary phenomena, from the implications of the body size of organisms in marine and terrestrial communities to metapopulation dynamics, scaling, food webs, and climate change. He continually tries to apply research results from his laboratory to problems related to the conservation of biological diversity, such as the optimal design of networks of protected areas in the dynamic context imposed by changing land-use patterns and climate change.

Marquet has received many professional and academic honors, including a Guggenheim Fellowship. He is currently a member of the editorial board of the journals *Theoretical Ecology* and *Conservation Letters.*

Juan Perez Mercader's fundamental interest lies in using theoretical physics to gain knowledge of the universe and life. In 1998 he co-discovered Gravito-magnetism, a property of spacetime predicted by Einstein and others in 1918, which Mercader detected and measured. He also explained from first principles the hierarchical structure of the universe, predicted the disintegration of the proton, and explained the fractal distribution of galaxies. Mercader currently directs the Center for Astrobiology in Spain, which was launched by the NASA Astrobiology Institute.

Mercader has received honors and awards from numerous institutions, including the Gravity Research Foundation of Massachusetts, NASA, the Association of Spanish Scientists, the Spanish Armed Forces, and the community of Andalusia.

An ornithologist by hobby and lover of popular science, Mercader spent eight years in Spanish National Radio (Radio 1) contributing to two weekly programs devoted to science.

A specialist in complex economics, **Kazuo Nishimura** directs the Institute for Economic Research at Kyoto University. He contributes prolifically to the field of economic theory, and also works to improve mathematical education in Japan and abroad. He is currently the president of the International Society for Education and the managing editor of the *International Journal of Economic Theory.*

Nishimura is widely known as a gadfly to Japan's public education system, as he periodically surveys university students' math skills to test the quality of their primary-school instruction. To address the problem of declining math skills among many Japanese students, he co-authored a series of self-learning textbooks for elementary school students, which resulted in dramatically improved test scores in schools that adopted the texts.

He has received publication prizes from the Japan Mathematical Society, the Mathematical Society of Japan, and the University of Rochester, from which he also received an award for excellent scholarship. He was awarded an honorary doctorate from the University of Aix-Marseilles III, and has held visiting appointments at universities in Austria, France, and the United States.

John Rundle directs the California Institute for Hazard Research at U.C. Davis. His research focuses on understanding the dynamics of earthquakes through numerical simulations, pattern analysis of complex systems, dynamics of driven nonlinear Earth systems, and adaptation in general complex systems. More

simply, he makes computer models of earthquake faults so he can learn to predict seismic events. He hopes to be able to make earthquake forecasts a year or two in advance for geographical locations in California.

Rundle serves on the editorial boards of the *Earth and Planetary Science Journal,* the *ARI, Bulletin of Istanbul Technical University,* and *Computing in Science and Engineering.* He has received awards and recognition from the American Physical Society, the American Geophysical Union, the Southern California Earthquake Center, the Geosciences Research Program (U.S. Department of Energy), NASA and the Jet Propulsion Laboratory, the International Association of Seismology and Physics of the Earth's Interior, and Sandia National Laboratories.

Rajiv Sethi teaches economics at Barnard College and is a faculty fellow at Columbia University's Institute for Social and Economic Research and Policy. His recent research deals with segregation in neighborhoods and social networks, stereotyping in economic interactions, disparities across groups in crime victimization and incarceration, and the transmission across generations of group inequality. He has also worked on the evolution of social norms and interdependent preferences, decision-making under bounded rationality, and the dynamics of asset prices in financial markets.

Sethi is currently on leave at the Institute for Advanced Study, where he is conducting collaborative research with Muhamet Yildiz on communication, beliefs, and public disagreement. He holds editorial positions with the *Journal of Economic Behavior and Organization* and the *Journal of Public Economic Theory.*

In his free time he likes to visit wildlife sanctuaries and blog about music.

Erica Jen and **Stuart Kauffman** have returned to their external professorships after taking hiatus.

OMIDYAR POSTDOCTORAL FELLOWS

Three young researchers have been accepted as SFI's first incoming Omidyar Fellows. The Omidyar Fellows Program was established at SFI in late 2008 with a gift from eBay Founder Pierre Omidyar, an SFI Trustee. The program aims to attract scholars from the social, physical, and natural sciences to spend two to three years as postdoctoral fellows at SFI delving into the major questions facing science and society. The addition of the 2009 cohort brings the total number of SFI Omidyar Fellows to 13; ten current postdoctoral fellows were renamed as Omidyar Fellows this year. The three new 2009 Omidyar Fellows are:

Simon DeDeo's education includes postdoctoral fellowships at the Institute for the Physics and Mathematics of the Universe, University of Tokyo; and the Kavli Institute for Cosmological Physics, University of Chicago. He holds a Ph.D. in astrophysical sciences from Harvard University, a masters in applied mathematics and theoretical physics from Cambridge University, and an A.B. in astrophysics from Harvard University. He is a past short-term visitor to SFI.

DeDeo's research examines ways to use astrophysical and cosmological phenomena to test novel ideas in fundamental physics. At Princeton, he demonstrated ways to use neutron stars to test the nature of gravity and new tools for extracting information on how the universe condensed from a primordial state into the galaxies and larger structures we see today. At the universities of Chicago and Tokyo, he extended this work to show how more radical theories of space-time structure could be tested with the universe as laboratory, while collaborating with experimenters to develop new techniques optimized for such tests.

His work at SFI extends the "historical reasoning" of cosmology to the biological sciences, where he will bring the philosophies and methods developed for studies of unrepeatable cosmological phenomena to biological systems governed by the unrepeatable accidents of development and evolution.

In his non-scientific work, DeDeo writes and reviews poetry.

Laura Fortunato holds a Ph.D. in anthropology from University College London (including one year of cross-disciplinary training in biology), a masters (MRes) in anthropology from University College London, and a dottore in biological sciences from the University of Padova. She is a past participant in SFI's Complex Systems Summer School in Beijing.

Fortunato's research examines the evolution of human social organization, focusing on the social norms regulating kinship and marriage, including the differing norms among societies (monogamy vs. polygyny, for example) and how these variations arose. She combines theoretical and statistical methods used in the study of nonhuman social systems with theory and data from the historical and social sciences, including anthropology, linguistics, and archaeology.

Her future research will investigate how societies' organizations of relatedness and reproduction explain the evolution of unique features of our species' social behavior, such as our predisposition to cooperate in large groups of unrelated individuals. In her free time, Fortunato applies insights from her research to investigate the social dynamics of characters in Italian opera.

Jeremy Van Cleve's education includes a Ph.D. in biology from Stanford University and a B.A. in mathematics and biology from Oberlin College. He participated in SFI's 2001 Research Experiences for Undergraduates summer program and, as a high school student, received a 1999 SFI prize for scientific excellence.

He is broadly interested in applying analytical and simulation methods to problems in evolutionary and ecological theory. As part of his dissertation research, he has studied the evolution of genomic imprinting, exploring interactions of genetic dynamics with population structure and, through models, the evolution of behaviors that increase the payoff of a social partner.

Van Cleve's SFI research will extend his thesis work through exploration of epigenetic phenomena and their role in adaptation and developing theory that builds on the recent explosion in empirical data from epigenetics.

More information about the **Omidyar Fellows Program** can be found at www.santafe.edu/education/fellowships-postdoctoral.php. ◀

2009 SFI Community Lectures

Since its founding, SFI has been at the forefront of increasing understanding of our world in all of its complexity. In this, our 25th anniversary year, our public lectures are devoted to asking deep questions about the big challenges that face our world, fostering insight into the future direction of scientific and humanistic knowledge.

Tuesday, Wednesday and Thursday, September 15, 16 and 17, 7:30 pm; James A. Little Theater, New Mexico School for the Deaf

Free Admission

Stanislaus Ulam Memorial Lecture Series: *Adventures in the Simple and the Complex—A Tribute to Murray Gell-Mann*

9/15,16,17

Three lectures honor the lifelong work of Murray Gell-Mann, one of the founders of SFI and currently a Distinguished Fellow at the Institute. Among Gell-Mann's contributions to physics was the "eightfold way" scheme that brought order out of the chaos created by the discovery of some 100 kinds of particles in collisions involving atomic nuclei. In 1969, he received the Nobel Prize in Physics for his work on the theory of elementary particles. Gell-Mann's current interests extend to historical linguistics, archaeology, natural history, the psychology of creative thinking, and other subjects connected with biological and cultural evolution and with learning. He is now spearheading the Evolution of Human Languages program at SFI.

Host: Geoffrey B. West, President and Distinguished Professor, Santa Fe Institute

Speakers: Chris Llewellyn-Smith, Director, United Kingdom Atomic Energy Authority, Culham Science Center

Mark Pagel, Professor of Biological Sciences, University of Reading

Daniel Schrag, Sturgis Hooper Professor of Geology, Professor of Environmental Science and Engineering, Professor in the Department of Earth and Planetary Sciences at Harvard University; Member, President's Council of Advisors on Science and Technology; External Professor, Santa Fe Institute

These lectures take place at the James A. Little Theater, 1060 Cerrillos Road, Santa Fe. Admission is free but seating is limited.

Saturday, November 14, 8:00 pm; Lensic Theater

Tickets $20 to $46. Half-price student tickets and senior discounts are available.

Special Anniversary Event in Cooperation with the Santa Fe Symphony
Voyages of Discovery: The Parallel Lives and Inventions of Darwin and Mendelssohn

11/14

This is a year of anniversaries: the 400th anniversary of Santa Fe, the 25th of the Santa Fe Symphony and the Santa Fe Institute, and the 200th of the births of Charles Darwin and Felix Mendelssohn. To commemorate these events, the Santa Fe Institute and the Santa Fe Symphony present an ambitious evening of science and art celebrating Voyages of Discovery. In 1831, at the age of 22, Darwin set forth on the Beagle as the ship's naturalist. On the Galapagos Archipelago, Darwin made observations and formed impressions that would revolutionize humanity's place in nature. Mendelssohn made similar travels in 1829 across the Hebrides Archipelago, and was inspired by this voyage to compose the Hebrides Overture. The evening will be organized into brief presentations covering their parallel lives, given by noted lecturers from the world of music and SFI. Intermixed with this will be performances from Mendelssohn's works, and readings from the correspondences of each written during their travels.

This program is made possible by the generous support of Sydney and Andrew Davis.

The Special Anniversary Event takes place at the Lensic Theater, 211 W. San Francisco St. Purchase tickets at 505/983-1414 or the Santa Fe Symphony website: www.santafesymphony.org.

The SFI Community Lecture series is made possible by support from local businesses and individuals. Los Alamos National Bank provides major underwriting for this program. For updates on the series, visit the events page on our website: www.santafe.edu/events/publiclectures. To arrange for sign language interpretation, please call 505/946-2749.