



# SFI Bulletin

2011, vol. 25

TRANSCIENCE: SHARED PATTERNS

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. SFI seeks to catalyze new collaborative, multidisciplinary research; break down the barriers between the traditional disciplines; spread its ideas and methodologies to other institutions; and encourage the practical application of its results.

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Patrisia Brunello at 505/984-8800, ext. 2700 or [pdb@santafe.edu](mailto:pdb@santafe.edu).

#### **Editorial Staff**

John German  
Lesley S. King  
David C. Krakauer  
Andi Sutherland  
Chris Wood

#### **Contributors**

Jenna Marshall  
Matthew Blakeslee  
Julie Rehmeyer  
Dan Rockmore  
John Whitfield  
Krista Zala

#### **Design & Production**

Paula Eastwood  
[www.eastwooddesignsf.com](http://www.eastwooddesignsf.com)

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[CLAYELLISPHOTOGRAPHY.COM](http://CLAYELLISPHOTOGRAPHY.COM)

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# Transcience

## Disciplines and the Advance of Plenary Knowledge

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

*"Everyone takes the limits of his own vision for the limits of the world."*—Arthur Schopenhauer

Scientists, a risk-averse group, tend to eschew announcing their larger aims. After all, it is not entirely licit or proper to say, "we are trying to discern the laws of biology, or why social systems might proceed through sequences of increasing complexity," preferring instead remarks like "we are interested in gene regulation, or how large molecules are synthesized, or why the ancestral Puebloans stored maize." We feel that the larger objectives come across as grandiose and so we retreat into prosaic descriptions of the work we do. In other words, we retreat into disciplinarity, a comfortable and familiar zone of tribal and historical cohesiveness, where the consolation of crowds helps to justify our activities. There is nothing wrong in cleaving to operational particulars, and for those interested in detail, these provide valuable information about what we do. The cost of this maneuver is that it restricts the scope of our inquiries and causes us to lose sight of the numerous extra-disciplinary ideas and methods that have contributed to (and will be required to further) our progress through the thorny branches of science.

As we have systematically overcome our ignorance of the cosmos, we have pushed at the boundaries of natural phenomena, intermittently reaching critical points where the methods of a field have proven inadequate for further progress. New ideas, techniques, and devices imported from other fields have been required to squeeze through explanatory bottlenecks. Sometimes this fusion of fields has been



of sufficient magnitude to warrant the creation of a new discipline (genetics, ecology, etc.), and in time these absorb the insights of others. In this way, scientific disciplines possess something akin to a life cycle, with periods of rapid growth, maturation, sex, and finally senescence and even death. As the pace of life has accelerated, so has the production of disciplines and the rate of their extinction.

Scientists, as a professional order, were not recognized before 1837, when William Whewell coined the term in his *History of the Inductive Sciences*. As for science itself (excepting those who locate its true origins in the European scientific revolution of the 17th century), it is now widely accepted that scientific activities—meaning systematic forms of inductive-deductive process—have been ever present in human society. Best known of the pluralists is perhaps Joseph Needham, who in his *Science and Civilization in China* (first volume appeared in 1954, coauthored with Wang Ling) went to great lengths



INSIGHT FOTO

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The pattern we observe in the evolution of the scientific disciplines is what the late Buckminster Fuller characterized as accelerating acceleration, which implies that new ideas are appearing more quickly than we can possibly reorganize careers and departments to respond to them.

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to demonstrate evidence of science and technology long before the European Renaissance, extending into the early millennia BC in China. These are efforts at locating concepts; however, we seek to explore their transmutation. It is not so much when and where science and scientists first appeared that interest us, but the pace of scientific transformation. The geocentric model of the solar system proposed by Ptolemy in the *Almagest* in the 2nd century remained unchanged right up until the 16th century when Copernicus proposed the more parsimonious heliocentric alternative. From Copernicus to Newton was just over a century, and from Newton to relativity, quantum mechanics, string theory, and dark matter, another couple of centuries.

The idea that all animals are preformed in the embryo (like nested Matryoshka dolls) was the dominant theory

of inheritance for most of our scientific history. Then, in 1865, the monk Gregor Mendel, while breeding peas, initiated the study of genetics. Genetics itself did not exist as a discipline outside of botany until William Bateson in 1894 coined the term in his *Materials for the Study of Variation*. At this point, the study of inheritance became a subject in its own right. In less than a century we have discovered DNA, regulatory RNA, prions, and the epigenome. Most of these are not studied in genetics departments (many of which were closed or renamed over the course of only a couple of recent decades, giving them a half-life of under a century), but rather in molecular biology, bioinformatics, and systems biology departments.

The pattern we observe in the evolution of the scientific disciplines is what the late Buckminster Fuller characterized as accelerating acceleration, which implies that new

ideas are appearing more quickly than we can possibly reorganize careers and departments to respond to them. The solution has been a messy mixed strategy, with new disciplines and journals popping up every year or month, and new ideas shoehorned into awkward groupings within existing departments to cope with the doctrinal flux. I am reminded of Oscar Wilde when he wrote: “Fashion is a form of ugliness so intolerable that we have to alter it every six months.”

We have reached a stage where the pace of discovery and the nature of shared knowledge bring the whole venerable exercise of disciplinary fads into question. I believe we are entering a period of transcience, where it is becoming necessary that training in areas with fundamental mathematical, computational, and logical principles should be emancipated from a single class of historically contingent case studies. For example, statistical physics will continue to be every bit as useful in understanding social phenomena as it traditionally has been in studying properties of condensed matter. The same could be said for suitable modification of computational theory and evolutionary dynamics. One of the significant contributions of SFI in this new landscape has been to show how ideas have a far greater compass than their original purpose suggests. Profound ideas are often characterized by considerable generality. Departments are becoming battlements that defend vested interests rather than idea incubators that advance understanding. Transcience is an expression that seeks to recognize the pursuit of plenary or synthetic knowledge as an institutional priority.

There are those who would argue that without the rigors of traditional disciplinary instruction, we shall be producing researchers capable of little more than shallow metaphor construction. By their reckoning, the correct approach to complex phenomena is to first apprentice ourselves to tried-and-true research projects. This is the

familiar “when I was a lad I got up at 4 a.m. and walked 15 miles to work” line of reasoning. The alternative is not to neglect the details of a system, but to recognize that many of our most pressing problems and most interesting challenges reside at the boundaries of existing disciplines, and require the development of an entirely new kind of sensibility that remains “disciplined” by careful empirical experiment, observation, and analysis. We are not losing depth, but are recognizing the full potential of theoretical

frameworks of significant universality, and that these should not be limited to communities based on their historical development. Ours is a landscape that can support diversity, and those with disciplinary separation anxiety are free to persist as they are.

The sciences of complexity are our best working examples of transcientific research, but remain restricted in part through the association of complexity with

a small class of models. In this issue of the *Bulletin*, we observe the continued maturation of the field of complexity as we accrue more data, hone our intuitions, and extend the scope of our theories. From the study of cities, through conflict, technological innovation, and cognition, we find a multitude of shared patterns amenable to overlapping forms of analysis. This issue is not organized into sociology, biology, engineering, and neuroscience—none of which would provide an adequate classification for the work being described. Readers of the *Bulletin* are fully aware that each of these areas of inquiry will obdurately resist shoehorning into a disciplinary framework, and there is absolutely no good reason to try. Perhaps it is time for our schools, universities, and research institutes to embrace the full implications of this shift in thought, and to redesign curricula and perhaps even demolish a few departments accordingly. We are entering a phase of increasingly transcientific research, and it is time society and academia wake up to the full implications of this reality. ◀

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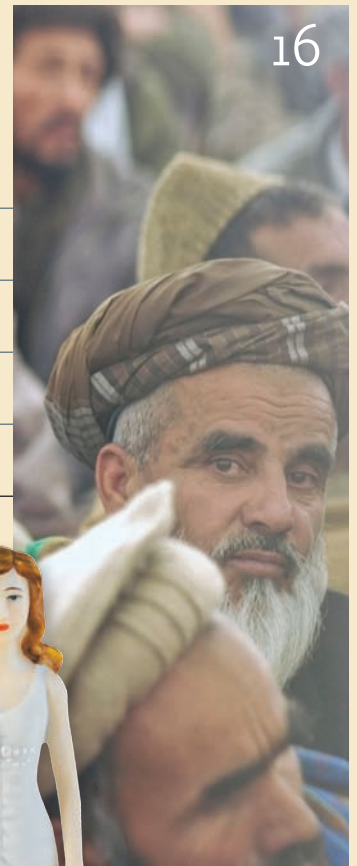


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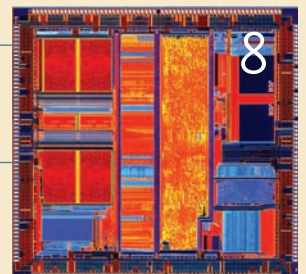
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## FROM ASTROPHYSICS TO ANTHROPOLOGY—

# The Evolving Face of SFI

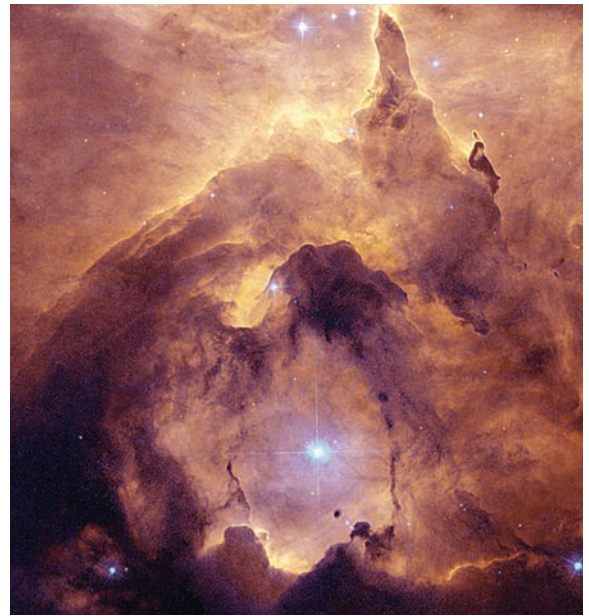
**C**an a scientifically thorough understanding of ancient civilizations provide clues that enrich the lives of our grandchildren?

What chemical reactions might have evolved into life on earth?

By modeling how languages change, can we help preserve the vital elements of a culture?

These are some of the questions SFI's 2010 class of Omidyar Fellows are asking. The nature of their questions, as well as the backgrounds of the people asking them, might look a bit different than in the past, says SFI President Jerry Sabloff.

The 2010 class of four new Fellows, chosen from



more than 200 applicants, includes an astrophysicist trained in chemical physics, a mathematician interested in cultural evolution, a theoretical ecologist looking for universal theories that hold across seemingly different systems, and an anthropologist who hopes to model ancient cultures more fully than in the past.

Sabloff says the changing backgrounds and interests of the 2010 Fellows are indicative of the changing character of the Institute itself.

"SFI is broadening and deepening its interest

and engagement in the social sciences and the humanities, at a time when those fields also are reaching out in search of new tools and methods," he says. "SFI's origins were in physics and mathematics. But, our scientists have always believed that the approaches, methods, and theories within complexity science can shed light on many of the problems and issues in society and the world today."

The four new Omidyar Fellows join the four already at SFI. More information about the Fellows and the Omidyar Fellowship is available at [www.santafe.edu](http://www.santafe.edu). ◀



FIGURINE: CHARLES EDWIN WILBOUR FUND/BROOKLYN MUSEUM; AMOEBA: GARRY DELONG / PHOTO RESEARCHERS, INC.; STAR: NASA, ESA AND J. M. APPELLÁNIZ (IAA, SPAIN)



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**THE SANTA FE INSTITUTE NOW OFFERS A NUMBER OF WAYS** to keep its interested audience informed about complexity science.

Most notably, SFI publishes news on the Institute's home page, [www.santafe.edu](http://www.santafe.edu), and updates it several times a week. To set up automatic delivery of SFI news, navigate to the "Follow Us" section at the bottom of the home page.

Here are some other options for receiving and sharing SFI news:

**TWITTER:** Get short, timely news flashes via Twitter by subscribing to @sfi\_news. Once you are signed up, re-tweet those SFI news stories you like to your own followers.

**FACEBOOK:** If you click the "Like" (thumbs up) button at the top of SFI's Facebook page, you can join more than 1,300 other fans who receive timely SFI

research news posted to their Facebook News Feeds. You can comment on, "like" or share posts with your Facebook friends.

**RSS FEEDS:** Get headlines and links to the latest SFI news via email by subscribing to Santa Fe Institute News (all inclusive), or select news from the Business Network, Education, Events, or Research category.

Just touch the RSS button at the top right of SFI's home page to make your selections.

**EMAIL:** Subscribe via email to the *SFI Update* electronic newsletter (bimonthly) or Activity Announcements (public events in Santa Fe) by clicking the Subscribe button at the bottom left of the SFI home page.

**SHARE:** You can share the individual SFI news articles you like with your friends via Digg, Delicious, LinkedIn, and about 250 other networks by selecting an icon from the sharing menu near the top of each news article.

**VIDEO AND AUDIO:** The Institute's website now offers lectures, colloquia, and other free educational content via SFI's YouTube channel, iTunes U, and SFI's own video library. ◀

## Girls Just Gotta Have Science

In the United States, businesses and institutions have an increasingly difficult time filling positions in science, engineering, and computing—young Americans just aren't pursuing educations in these fields. And, according to a decade of research, the deficiency is growing, with especially low participation from young women, Hispanics, and Native Americans.

To address the problem, SFI is leading a three-year education research and outreach program sponsored by the National Science Foundation and designed to attract New Mexico girls. The program, GUTS y Girls, provides Saturday and summer programs in science, technology, engineering, and math (STEM), and information technology (IT) for 300 middle school girls.

"Learning technical and computing skills gives young people the background needed to access higher-paying jobs in these fields," says Irene Lee, SFI's GUTS y Girls principal investigator.

Once-a-month Saturday workshops in Santa Fe offer girls the opportunity to meet female professionals, participate in hands-on design and building projects, and learn about STEM and IT careers. Meanwhile, two-week summer workshops in Santa Fe, Albuquerque, and Las Cruces help girls tackle community-relevant issues using the principles and tools of complexity science.

GUTS y Girls mirrors the successful four-year-old, SFI-led Project GUTS, an



## Girls Just Gotta Have Science

after-school STEM program that has reached more than 900 middle school students. In 2009, 30 New Mexico schools in 15 communities hosted Project GUTS clubs. Each of the clubs meets for two hours a week for 20 weeks during the school year.

The curriculum for Project GUTS, which stands for Growing UpThinking Scientifically, was designed to show young people they can ask questions about the issues that affect them most, develop answers through scientific inquiry, and devise potential solutions by using computational modeling of the intertwined, interdependent systems they encounter. It is a collaboration among SFI, MIT, the University of New Mexico, New

Mexico Institute of Mining and Technology, New Mexico State University, the Santa Fe Complex, the Girl Scouts, the New Mexico Supercomputing Challenge, and Santa Fe Public Schools.

Student projects are decidedly hands-on and minds-on, says Lee. In one popular Project GUTS activity, for example, participants learn about the spread of disease using a participatory simulation on hand-held PDA computers, then build a computer simulation of an outbreak in their own schools. Students incorporate features of each school and its student population and behaviors, then model the spread of infection from person to person based on the

school's layout, how often students come in contact with each other, how many stay home when they are ill, and other variables.

GUTS y Girls was designed to address the gender imbalance seen in Project GUTS—just 34 percent of Project GUTS participants are females—by exposing girls to the wide variety of STEM and IT fields as early as sixth grade, Lee says. “We hope to develop cohorts of girls who can enter Project GUTS clubs together.”

A number of recent studies show that girls tend to take a back seat in collaborative science projects when boys are present, but can thrive in groups of girls. Other research suggests that underrepresented groups tend to become interested in science, and stay interested, when they see others like themselves succeeding.

In view of this, GUTS y Girls enlists women scientists as role models and mentors, engages girls in skill-building activities, and keeps girls and their mentors connected through a virtual clubhouse—a private social networking website specific to GUTS y Girls participants.

The program's research component will study whether this set of activities promotes girls' interest in STEM and IT, and whether social networking can provide an arena for girls to learn more about STEM and IT fields from other women, thereby sustaining their interest and engagement.

“If successful, GUTS y Girls could serve as a national model for attracting and retaining girls in STEM and IT without huge commitments of time from female STEM professionals and scientists,” says Lee. “We hope to leverage social networks to make their time expended mentoring girls stretch a long way.” ◀





# SFI Assesses Templeton Foundation's Complexity Research

RECOGNIZED AS AN AUTHORITY IN COMPLEXITY SCIENCE, the Santa Fe Institute has agreed to assist the John Templeton Foundation with its new funding priority on “the science and significance of complexity.”

Templeton, a major philanthropic organization, funds projects spanning mathematics, natural science, the humanities, and theology in its mission to invest in discoveries relating to the “big questions of human purpose and ultimate reality.” Its vision is derived from the late Sir John Templeton, who believed in the possibility of acquiring new spiritual information through rigorous scientific research and scholarship.

Within its science of complexity program, the Templeton Foundation will fund research into neurocomplexity, complex systems in economics and the social sciences, and genetic and quantum mechanical aspects of the origins of life. The Foundation also is interested in new perspectives, methods, and tools that might enrich scientific and popular understandings of complexity, especially new ways of representing and visually depicting complex processes.

These themes, of course, align with the Institute’s research interests, says SFI President Jerry Sabloff, who views SFI’s role as ensuring that the highest quality inquiries are funded—those describing rigorous, empirically grounded science.

Specifically, SFI will concern itself with the Foundation’s questions of how evolution and self-organization give rise to complexity in living systems, how macro-scale phenomena emerge from micro-scale processes, and ways to measure and represent complexity.



SFI will referee letters of inquiry submitted to the Foundation requesting support of proposed research. The Institute will make recommendations based on the scientific merit of each inquiry. Using those recommendations, the Foundation will invite full project proposals from selected researchers and institutions. At a later stage of the review process, SFI will evaluate full proposals.

“Like SFI, the Templeton Foundation prides itself on an approach based on open-minded thinking combined with scientific rigor,” Sabloff says. “We have a great deal of common ground. SFI will focus on the merits of the science being proposed and leave the spiritual and theological implications to those at the Foundation who are qualified to evaluate such concerns.” ◀





# Tracking Technological EVOLUTION

By Krista Zala

**TECHNOLOGY: IT'S EVERYWHERE.** Even on getaway walks in the woods, we wrap ourselves in revolutionary materials and pack along a breakthrough or two in communications. Technology is so deeply embedded in our culture that, like the air we breathe, we often take its presence for granted and notice only its lack.

Today, in fact, we're living in a Cambrian explosion of technological diversity. Amid the





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SFI External Professor W. Brian Arthur has found that new technologies derive their being from existing ones, evolving similarly to a coral reef that builds itself out of itself.

“One of the biggest questions is how the world is changing through technology,” says Béla Nagy, a statistician and former postdoctoral fellow at SFI. Working with SFI Professor J. Doyne Farmer and former SFI Omidyar Fellow Jessika Trancik, Nagy measures progress across its many forms. “By collecting data about how technology evolves, we’re investigating whether we can predict its future,” he says.

If measuring how fast technology changes sounds like a formidable task, consider the most accessible indicator: cost. The cost of a good reflects how well we apply technology to optimize its production—and it provides a means to compare apples and oranges or VWs to Fords or flat-screen TVs to roller coasters. Historical trends tend to show that cost drops with increased production, in what’s known as a performance curve. Sampling performance curves of various products and abilities, then, offers a means to find trends in improvement.

To do so, Nagy and colleagues created a repository for researchers to donate their data sets. Most donors had collected their data for their own specialized studies, which makes for an eclectic mix of metrics, Nagy says. The website ([pcdb.santafe.edu](http://pcdb.santafe.edu)) features performance curves of wheat and wind power, Model-Ts and monochrome TVs, energy storage and information storage.

Despite the variety, the researchers are finding patterns. “The sources are heterogeneous and the technologies are completely different, but they all seem to support empirical laws,” says Nagy. (Laws in this context are understood as malleable guidelines, not like the more rigid laws of thermodynamics and gravity.) Nagy and colleagues found that Moore’s Law, which predicts that every two years we can double the amount of memory stored in a given size chip, applies in a general way to technological progress: while each product has its own rate, performance curves follow an exponential improvement over time.

merry chaos of touchscreens, jet engines, and MRIs, researchers at the Santa Fe Institute are looking for themes connecting these seemingly unrelated advances. By studying technology’s patterns of development, they are finding laws that govern its progress, modeling how best to direct them, and even sketching a theory of how technologies arise and develop and take their places in society.



“The surprising thing is that we see universalities,” agrees Farmer. “It’s even more surprising for other colleagues, because they don’t believe such laws exist in the first place.”

They hope to expand the database into an Archive of Technology. By ramping up acquisition, catching fleeting data, and running it for decades, Farmer suggests they could apply it to other ambitious ventures such as solving policy questions about government investment strategies.

For now, the performances they’re tracking can potentially keep improving for a while.

“In most cases, technologies are a long way from fundamental physical limits,” says Farmer. For example, we might approach transistors’ physical limits within a decade as we shrink them to a single atom. But by then, if large-scale quantum computing becomes possible, it could change the game completely, as transistors changed vacuum tube systems and as vacuum tubes changed mechanical switch systems. In that case, explains Farmer, the variation on Moore’s Law they are proposing would evolve too, mutating from specifically governing transistors to a more general law of computation power.

Breakthroughs like quantum computing con-

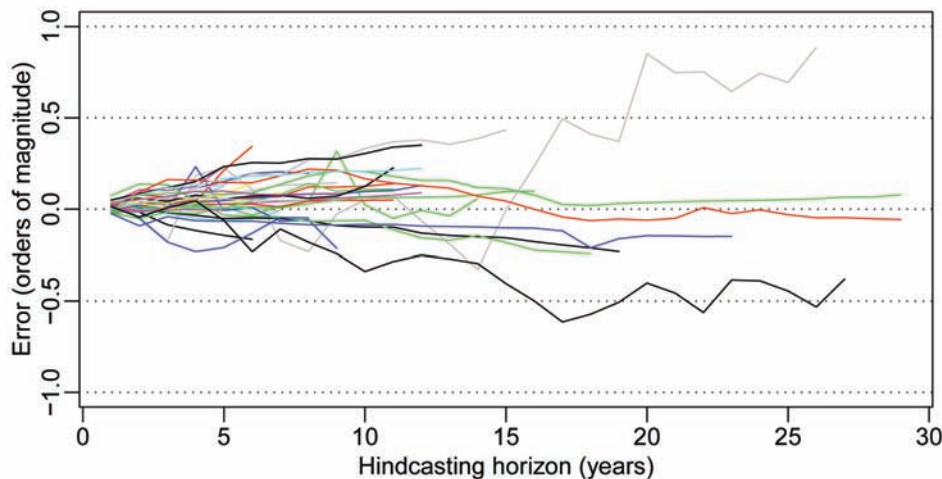
found the patterns of technological evolution. Both vacuum tubes and transistors, for instance, revolutionized computing power and re-launched it on a higher, faster trajectory. But even though the precise type and time of a breakthrough cannot be pinpointed, Nagy suggests that we may one day be able to predict their likelihood, as seismologists do earthquakes.

If quantum computers are built, they are still years and millions of dollars away. And they are just one of thousands of promising projects competing for research and development funding. Limited budgets raise the question of how to fund technological innovation to move societies toward the healthiest possible future. Perhaps the most urgent example lies in the energy sector. With the need to change our energy structure within 50 years to reduce carbon levels, the pressure is on to do so at the lowest possible cost to society.

Unfortunately, “anything that’s cleaner is also more expensive,” explains James McNerney, a PhD student in statistical physics at Boston University and a graduate fellow at SFI. “That’s why people in the energy and climate change world rely on performance curves.” For example, solar power is much pricier than carbon-intensive energies, but

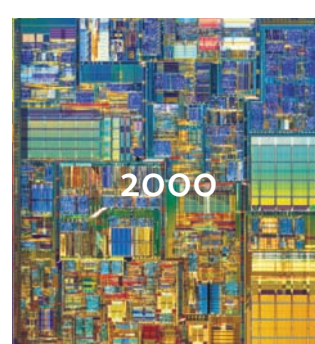
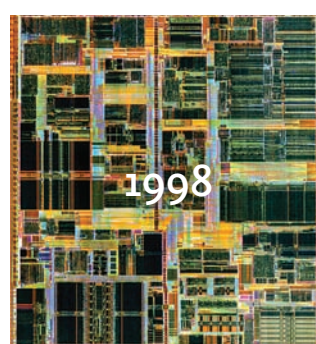
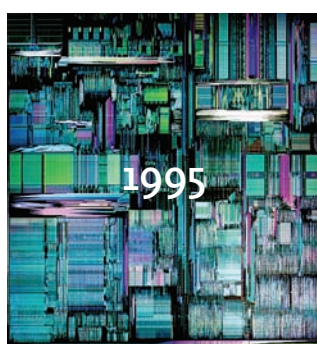
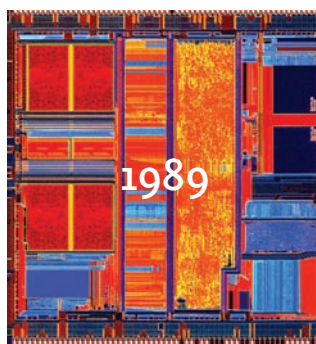
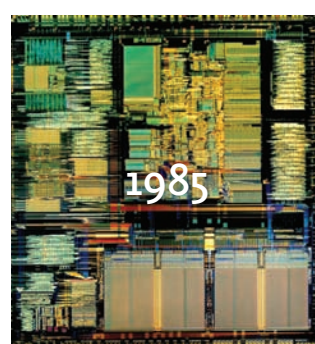
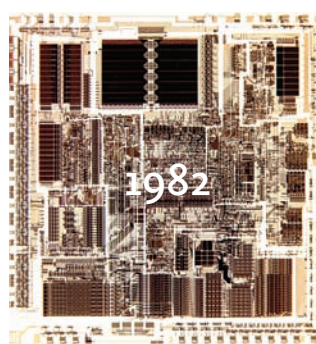
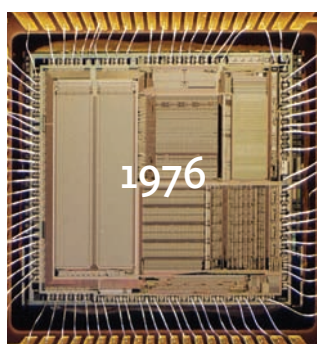
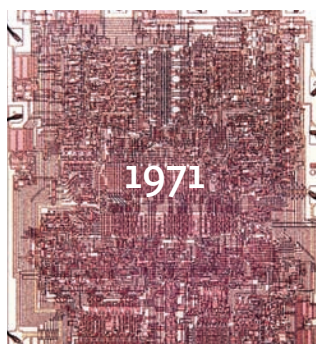
most of its components are getting cheaper. In contrast, nearly half the cost of coal-powered electricity remains fixed (the cost of coal hasn’t changed much in a century, and it hasn’t made economic sense for power plants to squeeze more energy from it since the 1960s) so its curve changes little. When, if ever, will coal meet solar in cost? How much should we invest now in solar power to hasten that event?

Solar power’s multiple sophisticated technologies uncover another quandary: the more elements a product has, the more opportunities for improved efficiency and lower price points. But, in the same way that a big organization is often slower to change than a



Like Moore’s Law, Wright’s Law offers a functional form for expressing the relationship between experience and production. This graph tracks 37 technologies, each with a history of at least 15 years. The price history in the first 10 years is used to forecast prices in the following years. These are forecasts with the benefit of hindsight, hence referred to as hindcasting. The horizontal axis represents this hindcasting, which is the difference between the 10th year and the target year of the hindcast. The vertical axis shows the difference between the predicted and the actual price on a logarithmic scale (base 10).

CHART: COURTESY OF BELA NAGY/SANTA FE INSTITUTE



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small one, the complexity of a technology can slow its rate of evolution. To find out what slows the rate, McNerney and colleagues recently modeled the interactions between components of a system, looking at how changing any given part affects the rest. They discovered that the number of components may matter far less than their connectivity: the more interconnected the parts, the slower the evolution of the whole.

Though it may be tempting to concentrate efforts on less-interconnected technologies with more potential for quick evolution, there's danger in focusing too narrowly.

"No single technology is going to solve our energy problems," points out Trancik, an assistant professor at MIT's Engineering Systems Division. Trancik studies the driving forces of innovation and their influences on the global energy mix, particularly amid new demands arising from climate change concerns. To address climate change, we have a few policy options, she explains: we can invest in research and development, raise the price of carbon through a tax or cap, or create guaranteed markets where energy companies must draw a given percentage of their power from certain low-carbon technologies.

Drawing from the performance of energy

The increasing complexity of these Intel computer chips illustrates a general principle of technological progress: while each product advances at its own rate, performance curves follow an exponential improvement over time.

options today and how each has changed, Trancik models how best to invest in their technological development. Whether it's a carbon tax or a breakthrough in photovoltaics, a change in one energy source ripples through the market, affecting the competitiveness of other options. From capital costs and conversion efficiency, to demand- and supply-side dynamics, there's no shortage of factors to consider. Such complexity means no single answer emerges, but seeing how the myriad drivers affect innovation and carbon emissions is essential for making informed decisions.

The generalization of Moore's Law that Trancik, Farmer, Nagy, and McNerney are finding in performance curves raises the question of whether technology conforms to a set of principles in its overall evolution. Not surprisingly, another SFI thinker has explored just that.

Economist, engineer, and mathematician W. Brian Arthur (SFI External Professor and visiting researcher in the Intelligent Systems Lab at the Palo Alto Research Center) has worked for much



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Novel technologies come into being by combining ones we already have: the laser printer is put together by combining the operations of a laser, computer, and Xerox machine.

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Understanding technological advancement has become urgent, especially in the energy sector. SFI researchers are exploring competing energy sources to help society move cost-effectively toward a healthy future.

of his career on the economics of technology. His curiosity about how economies arise led him to realize he needed to ask where technologies come from. A dozen years later, he has laid out the principles and mechanisms to an evolutionary theory of technology in his 2009 book, *The Nature of Technology: What It Is and How It Evolves*.

In it, he explains that all technologies are put together—are constructed—from existing technologies. Novel technologies come into being by combining ones we already have: the laser printer is put together by combining the operations of a laser, computer, and Xerox machine. This doesn't mean of course that the MRIs and jet engines of today are combinations of the pottery and arrows of 10,000 years ago. From time to time new phenomena are captured and harnessed into use. X-rays, for example, were discovered in 1895 and

consequently enabled the innovation of X-ray radiology. Similarly, the principles of quantum mechanics, discovered more than a century ago, are just now being summoned for quantum computing.

All novel phenomena are taken from somewhere in nature. Even behavioral changes, like the collective social agreement that a piece of paper has monetary value, arguably have natural roots. This ongoing agglomeration of old elements with the occasional addition of new phenomena to constantly form new technologies is what Arthur describes as combinatorial evolution: new technologies derive their being from existing ones, or, as he puts it, technology—the collection of all technologies—evolves by building itself out of itself. Arthur compares this process to a coral reef building itself out of itself. And as with a reef, innovation is a far more social process than the stories

of lone inventors would have us believe.

Clearly, designers can combine technologies more freely than animals can speciate. But once a new technology exists, its variants encounter plenty of Darwinian selection that determines whether it finds a niche in the economy or is consigned to the curio cabinet of civilization.

Where, then, might we be headed with our turbo engines and DNA microarrays, our gene splicing and space stations? Arthur hopes we apply them to improve the human condition by relieving suffering and extending qualities of life. Ultimately, despite all the delights and horrors it can evoke, technology itself is neutral. It's up to us how we use it. ◀

*Krista Zala is a science writer living in Victoria, B.C. She can be reached at [kristazala@gmail.com](mailto:kristazala@gmail.com).*



# FRACTALS

## Parts That Reflect the Whole

Read more at [www.santafe.edu/news](http://www.santafe.edu/news).



**THOSE WHO KNOW THE SANTA FE INSTITUTE** know we concern ourselves, on a theoretical level, with the often-unseen structures, patterns, and connections in complex adaptive systems. This focus on the underlying nature of things demands that we avoid the temptations of immediate, tangible outcomes.

Yet, in the 18 months since I arrived as SFI's President, I have witnessed substantial, and expanding, appreciation for the

Institute's science, not only among scientists but among policy makers and the public as well. Why? Because, I believe, the science of complex systems is the most productive way to understand our world, which grows more complex every day.

The pages of the *SFI Bulletin* highlight some of the ways complex systems science is making sense of relevant problems in the world around us. Each requires a transdisciplinary approach in which the tools of physics, the natural sciences, the social sciences, and the humanities all contribute. This SFI way of thinking—of doing science—and of addressing complex systems, has explanatory power across the realm of human experience. Inevitably, from this process emerges very real outcomes.

—**Jerry Sabloff**, *President of the Santa Fe Institute*

External Professor **JOHN GEANAKOPOLOS** argued in a paper released in August 2010 by the Federal Reserve Bank of New York that in moments of financial crisis, central banks should lend at more generous terms than the market. This would break the self-reinforcing increase in collateral requirements that can result from a market shock—a phenomenon he has termed the “leverage cycle.”

During SFI's 2010 Ulam Lecture series in September, External Professor **Mark Newman** highlighted the emerging field of network science and showed how networks are illuminating never-before-seen relationships and patterns in society and the world.

External Professor **Dirk Helbing** and collaborators modeled traffic flow and found that self-organizing traffic lights that communicate and make decisions in coordination with other intersections could significantly reduce city traffic congestion.

External Professor **Bette Korber** and Professor **Tanmoy Bhattacharya**, both researchers at Los Alamos National Laboratory, are part of an international team preparing for the first human trial of a new kind of HIV vaccine they helped design using computational models. The candidate “mosaic” vaccine employs many sets of synthetic, computer-generated sequences of proteins to prompt the immune system to respond to a wide variety of circulating HIV strains.

Despite 100 million years of evolutionary divergence, three lineages of mammals—placentals (wombed mammals), marsupials (pouched mammals), and monotremes (egg-laying mammals)—all allocate the same proportional amount of energy to reproduction and offspring development, concluded a study led by Postdoctoral Fellow **Marcus Hamilton**. The work supports the notion that many properties of living things change in mathematically predictable ways with organisms' body sizes—a phenomenon known as allometric scaling.

External Professor and Science Board member **Melanie Mitchell's** book *Complexity: A Guided Tour* (Oxford University Press, 2009) received the Phi Beta Kappa Society's 2010 Book Award in Science. The award recognizes outstanding contributions by scientists to the literature of science.

Professor **SAM BOWLES** and External Professors **HERB GINTIS** and **ROGER BOYD** devised a model of coordinated punishment in human societies that captures a phenomenon missing from other behavior models and experiments: The total social cost of punishing a slacker declines as the number of punishers increases.

A future quantum computer running Shor's 1994 factoring algorithm could break many of today's public-key cryptosystems, including those used for secure online transactions. Professor **Cris Moore** and collaborators showed, however, that the 1978 McEliece cryptosystem is immune to attack by all Shor-like algorithms, providing strong evidence that the McEliece system, which is implementable in today's computers, is destined to remain secure even if quantum computers can be built.

Distinguished Professor **GEOFFREY WEST's** and External Professor **LUIS BETTENCOURT's** search for the hidden laws underlying the growth and dynamics of cities received widespread press coverage in 2010. Articles appeared in *Nature*, *The New York Times Magazine*, *The Washington Post*, *New Scientist*, *Science News*, and on hundreds of blogs. Several radio and TV interviews with the researchers also aired.

A diverse group of experts met at SFI in April 2010 to study ecophylogeny, an emerging tool for ecological network research that combines ecology with evolutionary history to find relationships between ecological organization and relatedness among its species. Professor **Jennifer Dunne**, who co-organized the working group with External Professor **Jessica Green**, said ecophylogeny can provide a new framework to understand impacts of invasions, species loss, and habitat loss, which can better inform conservation.

A research team including External Professor **Harold Morowitz** and Professor **D. Eric Smith** modeled how molecular structures involving transition metal elements and ligands might have catalyzed the synthesis of basic biochemicals that acted as building blocks for more complex molecules, leading ultimately to life on Earth. Their work was part of a Frontiers in Integrative Biological Research (FIBR) grant from the National Science Foundation.

Determining what is genuine and what is not has long been a problem for art curators. It is estimated that 20 percent of the worldwide art market is fake. External Professor **Dan Rockmore** has developed a statistical technique that helps spot art forgeries.

SFI and Princeton University Press published the first two volumes in their collaborative series "Primers in Complex Systems," intended for non-specialists at the advanced undergraduate level or above. *Ant Encounters: Interaction Networks and Colony Behavior*, by Science Board member **Deborah Gordon**, examines ant behavior from the complex systems perspective. *Diversity and Complexity*, by External Professor **Scott Page**, shows how diversity makes fundamental contributions to system performance in complex adaptive systems.

**SFI's first three Miller Scholars came to the Cowan Campus in 2010: renowned philosopher of science, consciousness, and evolutionary theory **Daniel Dennett**; physicist **Seth Lloyd** of MIT, whose research centers on the interplay of information with complex systems, especially quantum systems; and actor-playwright-director **Sam Shepard**. Former SFI Board Chair **Bill Miller** underwrites the Miller Scholars program to bring to SFI high-profile intellectuals to catalyze cross-disciplinary interactions.**

SFI and the Santa Fe Symphony Orchestra explored the intersection of science and music in “Voyages of Discovery: The Planets.” The October 2010 concert interspersed the works of Claude Debussy and Gustav Holst with projection images of the solar system assembled by Dr. Jose Francisco Salgado of Chicago’s Adler Planetarium. Salgado and Omidyar Fellow **Simon DeDeo** provided accompanying commentary.

A very small number of biased, complacent, or incompetent referees can significantly undermine the ability of the scholarly peer-review system to select the best scientific papers, according to modeling by External Professor **Stefan Thurner** and collaborator **Rudolph Hanel**.

**SFI Professor SAM BOWLES’ January 2011 multidisciplinary workshop on the coevolution of human behaviors and social institutions examined sea changes in social behaviors, such as the emergence of property rights following the onset of agriculture, and how changes in individuals’ behaviors influence the behaviors of social institutions and vice versa.**

Recent advances in biology, linguistics, and computer modeling, along with new archaeological finds, prompted SFI to host a September 2010 meeting that took a fresh, transdisciplinary look at the peopling of the Americas. Participants included geneticists, physical anthropologists, linguists, a mythology expert, and archaeologists.

President Barack Obama in September 2010 announced his selection of External Professor **CARLOS CASTILLO-CHAVEZ** to the President’s Committee on the National Medal of Science. Meanwhile, External Professor **DAN SCHRAG** and sabbatical visitor **CHRISTINE CASSEL** are members of the President’s Council of Advisors on Science and Technology.

**Professor J. Doyne Farmer’s project—with collaborators and External Professors John Geanakoplos and Robert Axtell—to develop agent-based models of the economy was covered in *The Wall Street Journal*, *The New York Times*, *The Economist*, *Newsweek*, *Harvard Business Review*, and on CNBC.**





# Unraveling THE Tangle of Foreign Policy

**H**ow do you help a developing nation form a stable government and meet its people's basic needs? It's a tough question to answer, especially when the country is beset by conflict and chaos, fractured by tribal, ideological, and religious division, and destabilized economically and politically.

Bill Frej seeks to answer that question. Frej, the former mission director for Afghanistan at the United States Agency for International Development (USAID), is spending a year in Santa Fe as SFI's first Diplomat in Residence, working with researchers to explore the interface between science and national policy. At a more applied level, he hopes to use SFI-style thinking to unravel foreign policy dilemmas relating to the complex systems that are Afghanistan, Pakistan, and the Middle East in general.

Here are some of his thoughts:

**BULLETIN:** You've been a USAID official in Afghanistan during the war, in Indonesia during and after the 2004 tsunami, in Poland after the fall of the Iron Curtain, and in many other places. You've also spent time in the White House as a National Security Council director during the buildup to the Iraq war. You've seen some major transitions in foreign policy. What have you learned?

**BILL FREJ:** One of the areas I've been focusing on in my career is conflict. My time in a number of conflict-prone countries has been sobering and has raised many questions. How do you work to prevent conflict in these countries? I think the academic establishment as a whole can really lend focus to this question. Clearly Afghanistan is a world locus of conflict.

LAURA WARE

The work the U.S. is doing there both on the civilian and military sides is key to peace and stability in the world. It is critically important that we understand this issue and this place much better than we have in the past.

**BULLETIN:** What did you take away from your 15 months in Afghanistan, just prior to coming to SFI?

**FREJ:** The Afghan people want the same things we want. They want education for their children and healthcare for their families. They want peace and security. But they are caught among a number of outside forces, and they have been for the past 35 years: the Russian invasion, a major civil war, the entrenchment of Al Qaeda and the Taliban, and a war that began in 2001 that is still being fought 10 years later.

Geopolitically that country is being acted on by forces from all sides. The Iranian influence is very heavy in the west, the central Asian influence is very heavy in the north, and Pakistan and India are to the east. I think Afghanistan could again become a safe haven for terrorism. And when you have nuclear powers to the east and, potentially, to the west, Afghanistan becomes very important not only for the U.S. but for the world.

**BULLETIN:** In the foreign policy arena, where are the opportunities for complexity thought to have an impact?

**FREJ:** Certainly foreign policy today is a very complex endeavor. In terms of global sustainability, conflict, and urbanization, complexity science can contribute. Specifically with Afghanistan and Pakistan, there is nothing from a policy maker's perspective more complex than those two countries: their interactions internally among tribes and cultures, their interactions with their external neighbors, and their interactions with the

world community. The whole overlay is complex as well, with terrorists trying to affect their way of life. These are all critical issues that need to be better assessed, better analyzed. From my personal perspective, we need different tools to help make and define foreign policy.

**BULLETIN:** Why did you choose to spend a year at the Santa Fe Institute at this point in your career, at this point in the evolution of U.S. foreign policy?

**FREJ:** I hope to utilize the intellectual power of this preeminent institution and the people working here to look at foreign policy in Afghanistan through a different lens. The faculty here at SFI, as well as many academics, including those that USAID is reaching out to, can be a very positive force in looking at the problem through a more scientific, evidence-based, responsible lens than in the past. The findings can help the policy makers define our next steps.

Afghanistan's culture is also extremely complex because it is based on a tribal structure. It seems a lot of the work being done here on tribes—the work that SFI Professor Paula Sabloff and SFI President Jerry Sabloff are doing, for example—can really help contribute to a better understanding of the roles tribes play in helping define a country's



In 1996 the Taliban regime banned education for Afghan girls, but now schools are open to them, though many obstacles still exist.

culture, direction, and political context. I would hope to be able to reach out to the anthropological elements, the social science elements, of SFI to help define foreign policy in the future.

Also, I think the conflict team that has been established here under the guidance of Faculty Chair David Krakauer and Professor Jessica Flack [see page 28] can help us look at conflict in a different way. This research-based, modeling-based focus can be very useful to exactly what is going on in Afghanistan, Iraq, and the Middle East generally today. There is a great deal of value in looking at animal behavior, and at societal behav-

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“Managing 520 staff and a \$4.5 billion budget in Afghanistan, I really never had the luxury or the time to sit back and reflect on what we’re doing, what adjustments we could make in the way we operate.”

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ior, and using the new insights that come from that conversation. There is a real conflict going on in Afghanistan. Men and women are getting killed every day. Civilians are getting killed every day. Looking at this more holistically can be extraordinarily helpful to both the civilian and military policy makers.

**BULLETIN:** What do you, coming from the policy arena, bring to the theoretical research table?

**FREJ:** Scientists through their research can tell you the true state of play. Policy makers can use that truth to help formulate foreign policy. I think the intersection between these two worlds is very important, and I hope to work with the researchers here to help define a better connection between theory, truth, and policy.

Another important contribution I hope to make

is “ground truthing.” There is a project going on here right now interpreting some extremely involved data from Afghanistan. Some of the faculty here have come to me and said, “Is this really what’s happening? Does this really make sense?” And I’ve been able to offer some insights.

**BULLETIN:** Why SFI and not an academic think tank?

**FREJ:** I’ve been coming to Santa Fe for 30 years, and I’ve always been intrigued by the work being done at SFI. When I was looking for a next assignment, and when I saw how the Institute had begun to take a more focused interest in the social sciences and in informing policy, I couldn’t think of a better place to be.

At the same time a major change was going on in the U.S. government and at USAID. President Obama has a keen interest in using science and research to help formulate policy, both domestic and foreign. The new administrator of USAID, Dr. Rajiv Shah, is a medical doctor with a very strong scientific background. He wants to build a much stronger scientific and technical capacity for USAID. In September I was in Washington for USAID’s first evidence-based summit, and the focus was counter-terrorism and insurgencies. So things are changing, and I was lucky enough to be able to make arrangements with both USAID and SFI to come here to tackle some key questions.

**BULLETIN:** What are your impressions of this place?

**FREJ:** Managing 520 staff and a \$4.5 billion budget in Afghanistan, I really never had the luxury or the time to sit back and reflect on what we’re doing, what adjustments we could make in the way we operate. The environment here, the time to think, to read, to look at the data, to share ideas, is very conducive to a much broader perspective on world issues, on how we can really make a difference. Coming out of a long foreign service career, that luxury is something special. This is the first time I’ve experienced this kind of environment since my early academic career when I was at UC Berkeley in the early ’70s.





**BULLETIN:** What projects are you spending time on?

**FREJ:** I'm planning a working group and a workshop. The first will look at how short-term civilian and military interventions can lead to long-term sustainable development programs in conflict-prone countries, focusing initially on Pakistan and Afghanistan. We'll bring together academics and senior policy makers with SFI faculty and spend three days drilling down into these issues. I hope we'll begin to find ways to inform the policy-making process for our colleagues in Washington.

The second major issue in Afghanistan right now is the judicious use of unexploited natural resources, estimated at between one and 13 trillion dollars. This is a phenomenal foundation for economic growth in that country. But the question some of the senior ministers in Afghanistan now have is whether their country becomes another Angola or Congo, two countries that have not done a very good job of using their natural resources for the benefit of their own people. Or does it become a Botswana, a country that in terms of diamond exploitation *has* benefitted its people.

The policy makers want to make the right decisions. There is no legal framework in place. There is no regulatory framework in place. Afghanistan

Frej will coordinate a workshop on how Afghanistan can use its abundant natural resources to benefit Afghans.

is getting pressure from China and Iran both to do more in terms of resource use outside of a framework of law and regulation. They need a framework that will benefit the people of that country, not line the pockets of a few. So we will focus the second workshop on how Afghanistan uses its resources for the benefit of Afghans.

**BULLETIN:** What do you hope the outcome of your year at SFI will be?

**FREJ:** This is an extraordinarily talented group of people. Some of the work that is underway here is really groundbreaking and clearly at the cutting edge of what the top minds in the world are thinking today. The theoretical research being done here is critically important. Most notable is the clear definition of how conflict impacts the entire world from many different perspectives, and how this can help us look at foreign policy through a different lens, and then also help define foreign policy. Hopefully while I am here there will be a uniting of science and policy that will contribute to making this world a much better place. ◀

A blurred, high-angle photograph of a crowd of people walking in a bright, open space, possibly a city square or a large indoor arena. The image is heavily motion-blurred, creating a sense of a busy, fast-moving environment. The colors are predominantly light blue and white, with some darker silhouettes of people. The overall effect is one of a bustling, dynamic urban scene.

# What Cities

## Can Tell Us About Companies

## When Geoffrey West arrived in the United States from England at the end of 1961, one corporation seemed to

embody American dynamism and expertise: General Motors. “That was when I first heard the phrase ‘what’s good for GM is good for the country,’ ” he recalls. And now GM is recovering from a near-death experience, saved only by the U.S. government’s \$50 billion in survival aid.

But perhaps Rick Wagoner, who resigned as the company’s CEO shortly before it filed for bankruptcy protection in 2009, shouldn’t feel too bad. All companies die. “I can walk into Google and know, despite the fact that it seems all-powerful and it looks as if we’ll still be Googling in 1,000 years, it probably won’t be around in 25 years,” West adds.

The question of what makes businesses mortal set West, a distinguished professor and past president of SFI, off down a path that he hopes will lead to a general theory of social organization. Ultimately, this theory might explain the startling regularities seen in human institutions and societies due to underlying structures of the social networks that make up their fabric. It may also help us understand what makes some social institutions robust and successful, and help us move toward sustainability in the face of climate change, pollution, resource depletion, and other environmental threats.

Back in the mid-1990s, West asked a similar question—why do people live for about a century, and not 10 years, or 1,000? The quest to answer it lured him away from his previous career in high-energy physics and toward a theory that explains why the measurable properties of living things, such as their lifespans, growth rates, and reproductive capacities, change in predictable ways with their size. West, together with his collaborators and SFI External Professors James Brown and Brian Enquist, explained this in terms of the changes imposed by increasing size on the geometry of

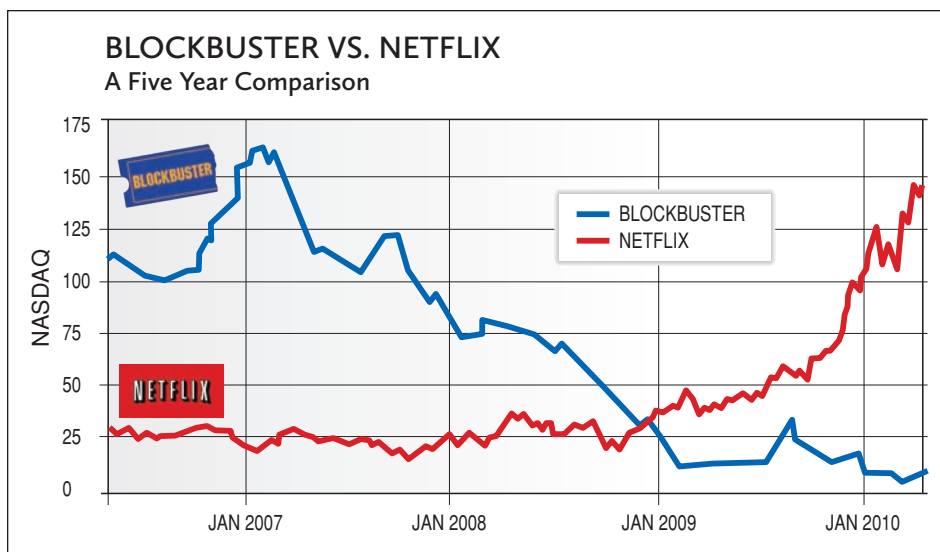
an organism’s transport networks, such as blood vessels. The bigger you are, the more slowly your networks deliver resources to your cells. As a result, your life runs more slowly: you live longer, grow more slowly, and have fewer offspring.

Whether companies show similar scaling behavior—whether, for example, you can predict when a firm will go out of business from its turnover—is an obvious question. But it was inaccessible, because the data for companies are proprietary and prohibitively expensive. So West turned instead to something for which ample data are freely available: cities. Unlike companies and people, cities are remarkably robust. They seem able to stick around in perpetuity, and those like Carthage that have disappeared are rare enough to be remarkable.

West joined forces with a cross-disciplinary team comprising urban economist José Lobo (Arizona State University), complex systems researchers Christian Kühnert (Dresden University of Technology) and Dirk Helbing (Swiss Federal Institute of Technology, Zurich), and theoretical physicist Luis Bettencourt (Los Alamos National Laboratory), the latter two also external professors at SFI. The team began analyzing every variable relating to urban life that it could get its hands on and examining how each related to the population of U.S. cities. “We discovered what I think is an extraordinary result,” says West. “Cities scale. They satisfy simple power laws.”

In some respects, cities and organisms scale in the same way. The bigger the organism, the less food per pound it needs, because each of its cells burns energy relatively slowly. Likewise, the bigger the city, the less infrastructure per person it needs. Large cities, for example, have fewer roadways, less electrical cable, and fewer gas stations per person than small ones. City dwellers use less energy and produce less carbon dioxide, on average, than small-town folk. For all these variables, the





The dramatic rise and fall of these two leading DVD rental companies raises the question of what makes businesses mortal. The answer may contribute to a general theory of social organization.

infrastructure per person declines steadily as a function of the city's population raised to the power of about 0.8. That means that although Houston, population 2.25 million, has ten times as many people as Baton Rouge, it only has about six times as much infrastructure.

But in other ways cities and living things are quite different. Some things do not slow down as cities get bigger. In particular, the researchers found that variables related to social life scale superlinearly. That is, they become proportionately larger as the city's size increases. That goes for economic and intellectual activities such as wealth, wages, and the number of higher education institutions and patents produced. The average household income in Houston in 2008 was \$44,315, whereas in Baton Rouge it was \$37,869. The same goes for crime and disease—which, much as we might not like it, are also forms of innovation. It even goes for the speed at which people walk. Again, the scaling is consistent across the whole range of variables, with an exponent of about 1.15. In other words, plunk a small-town person into a city twice as large, and she will become 15 percent wealthier, 15 percent more innovative, and 15 percent more likely to be victimized by crime.

The paper that unveiled these results, published in *Proceedings of the National Academy of Sciences* in 2007, speculated that the scaling was, as in organisms, a product of networks—in the case of cities, the social networks between people. Since then, West hasn't had as much time as he would have liked to pursue this line of thought—being SFI president, and helping the Institute survive the financial crisis, slowed his research. But since stepping down as president, he has immersed himself in the question.

Biological scaling emerges

because living transport networks (like the circulatory system) have a fractal-like structure, meaning that a small part looks the same as a larger part, which looks the same as the whole. This is called self-similarity. West has found that if you assume the same for social networks, and posit social life as a self-similar network where constant and intense interactions at the family level give way to links with, say, friends, colleagues, acquaintances, bosses, and public officials, then a superlinear pattern of increasing group size leading to greater social productivity results. In the next year, he hopes to make some progress toward conceptualizing what is actually flowing in these networks, be it information, money, or some combination of these and others.

Superlinear scaling sounds great—the more the merrier. But there's a catch. A superlinear power law produces a curve that tips ever upward, and terminates in a point where, for a city, a finite number of people are producing an infinite amount of activity, consuming an infinite amount of resources in the process. That's called a "finite-time singularity," and it's impossible. What would really happen at such a point would be a crash, after which everyone goes back to being hunter-gatherers, suggests West.

Technological innovation, however, can push

the reset button, returning a society to a gentler point on the curve and allowing it to start growing again. “When you have a major innovation—such as the discovery of iron, or coal, or oil, or the invention of computers—it completely changes the culture and resets the clock,” says West.

But there’s another catch. To keep dodging the singularity, each innovation must come quicker than the last. So, at the risk of caricaturing human progress, the Stone Age lasted more than two million years, with each of its subdivisions—lower, middle, and upper Palaeolithic—being shorter than the last. That ended when the Bronze Age began about 5,000 years ago. The Iron Age followed about 2,000 years after that,

and things have been speeding up ever since. The gap between each cycle of innovation shrinks in a systematic way, determined by the exponent 1.15 in the equation for social scaling.

“Not only does the pace of life get faster as society gets larger, you’re forced to make major changes in an accelerated fashion,” says West. That, in other words, is why your smartphone seems obsolete by the time you’ve got it out of its packaging. Life doesn’t just feel like it’s speeding up. It really is.

At some point, West notes, we are going to need an industrial revolution every half hour to keep on our current course. “That’s clearly not sustainable. The treadmill is going to run so fast that

Unlike companies and people, **cities are remarkably robust**. They seem able to stick around in perpetuity, and those like **Carthage** that have disappeared are rare enough to be remarkable.



Researchers have found patterns in cities: While Corvallis, Oregon, for example, has produced more patents than any other U.S. city, Las Vegas is among the nation’s least intellectually productive.

you'll fall off." In other words, it's hunter-gatherer time again. Can we stop growing, and maintain a developed society without sliding backward? "To my amazement, economists haven't answered that question," says West. The lack of intellectual understanding, not to mention the political will to act on what we do know, is daunting. "I've become a terrible pessimist," he says. "Every time terrible things happen I'm beginning to see them as mini indicators. That may just be paranoia, but the financial collapse, and the fact that we're still in it, may be the beginning of a sign that we'd better be doing something. I think that this problem, if it's soluble, is one that we needed to have started thinking about at least 50 years ago. I fear for my grandchildren."

Not that this pessimism has translated into inertia. West and his colleagues' work seems to be accelerating towards a singularity in its own right. There's new data to analyze: SFI has made a deal with Compustat, a leading commercial database of company information, to gain access to its numbers for a bargain price. Preliminary

any other U.S. city. Others go the opposite way: by the same measure, Las Vegas is the nation's least intellectually productive city. And a city's performance remains constant through time. "If they're a good city in 1950, they're still overperforming to the same degree today," says West. "And if they're a lousy city, they're still a lousy city, no matter what the urban planners have done. The most amazing case, to me, is San Jose. The city was overperforming before Silicon Valley grew up, and after the [tech] crash it relaxed back to where it was, but it still overperformed. What is going on in San Jose, culturally, that ensured that if Silicon Valley started there it was going to be a good place to incubate?"

You can imagine that's the kind

Not only does the **pace of life get faster** as society gets larger, you're forced to make major changes in an **accelerated fashion**, says West. Life doesn't just feel like it's speeding up. **It really is.**

analysis shows that companies scale too: "If you tell me what the assets of that company are, I can tell you most of the things about that company—how many employees, how much it pays for taxes, all these variables that we've now looked at," says West. There are also new theoretical avenues to pursue: West believes the tools of thermodynamics and information theory will help us understand how information and resources flow through social networks.

And there are new puzzles. Those regularities in cities hide a lot of variation. Some places overachieve—Corvallis, Oregon, for example, lies higher above the curve for patent production than

of question policy makers would like answered. But before you begin making recommendations, West says, you need a theoretical understanding of where such patterns come from. He is cautiously optimistic that such an integrated theory is possible, and that as well as helping policy makers in their quest to create sustainable communities, it will give archaeologists, anthropologists, economists, and geographers new questions and tools. A meeting in Italy in July 2010 brought 15 people from across the academic spectrum together to imagine what form such a project might take. The meeting was funded by the Rockefeller Foundation, which provided seed funding to work







ISTOCKPHOTO.COM

out the questions and may also fund a larger project to pursue the answers and their implications.

The universality of social scaling laws shows that energy, finance, transport, and crime are all parts of the same whole, and manifestations of the same underlying dynamics, says West. To make our society sustainable, we must see them as such.

“Until we have an integrated approach, I don’t think we can attack these problems. We need to get people thinking in a much more integrated way. That’s what I think SFI is trying to do.” ◀

*John Whitfield is a London-based science writer. He is currently working on a book about reputation.*

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A city photo taken with a slow shutter speed illustrates the high velocity of contemporary life. West says such a pace is “clearly not sustainable.”





# REAL-WORLD ECONOMICS RISING

By John German

ONE INSIDER HAS CALLED ECONOMICS A PROFESSION THAT HAS “LOST ITS LICENSE OF EXPERTISE.” Not only did most mainstream economists fail to see the financial crisis coming, they might have helped fuel it, unwittingly, through strategies fashioned from a rigid adherence to neoclassical economic theories and models.

Those models, which feature an implicit assumption that all actors make informed and rational choices most of the time, are inadequate for describ-

ing the complex adaptive systems that make up the world’s economies today, says SFI Professor J. Doyne Farmer. What’s worse is that because they don’t have reliable models, economists and policy makers tend to draw on common sense and loose analogies with past crises in dealing with emerging ones, he says.

“The leaders of the world are flying the economy by the seat of their pants,” Farmer says.

He and SFI External Professors Robert Axtell and John Geanakoplos believe they have a better way.



They want to build an agent-based model of the entire U.S. economy, one that accounts for the behaviors of individual actors in markets and in the systems that influence them.

Traditional top-down econometric models use past data to forecast future trends, so they fall short when facing an unprecedented crisis. General equilibrium models, the other kind of traditional model, assume that economies and markets fluctuate around and return to a perfect, stable, crisis-free equilibrium—the “at rest” condition of a system in which competing influences are balanced.

Agent-based modelers don’t make assumptions about how the whole economy behaves. Instead they build an economy’s behavior from the bottom up, assigning particular behavioral rules to each decision-making agent in their simulations. This enables, for example, more life-like representations of the copy-cat behavior that leads to “herding” among investors. Agents may learn from experience or switch their strategies according to majority opinion. Or they might aggregate into institutional structures such as banks and firms. Just like real life.

And because an agent-based model is built from the behaviors of individual actors, which aggregate into behaviors of groups of actors, such a model can incorporate the interactions among different sectors of the economy—such as housing and finance—at different scales, something the traditional models don’t do very well.

Agent-based modeling might seem like the obvious choice, but infusing complexity thought and new models into mainstream economics isn’t as easy as simply making a case for it. “Economists tend to reject any model that doesn’t employ an equilibrium,” Farmer says.

But some are listening. Farmer and Axtell have begun to form alliances with economists who think the field

needs a re-think. At an April 2010 conference in Cambridge, England, organized by The Institute for New Economic Thinking (INET), participants agreed that many of the assumptions on which the current models are based—such as efficient financial markets and rational expectations—aren’t rational.

Farmer asked the crowd, which included four Nobel laureates and many prominent economists, to shed the dogma that says markets self-stabilize, and instead create much more complex models based on actual “rational” behavior—that of agents making decisions with incomplete information in complex, changing environments. Farmer says the response was generally positive, with some expressing skepticism that agent-based model-

ing could succeed at such a complex undertaking.

But that concern is being addressed as well. At a June 2010 conference on the topic in Washington, D.C. sponsored by the National Science Foundation, participants explored the potential uses of massive data sets and enormous computing power available today.

Although Farmer’s calls haven’t yet penetrated the din of Wall Street, the chorus of voices is getting louder. Kenneth Arrow, a former SFI visiting scholar and 1972 Nobel Prize winner in economics, who co-designed the best-known mathematical proof of a market-clearing equilibrium, has said publicly

that his profession has taken the wrong lessons from his work. He added that investors, savers, and consumers are simply burdened with too much faulty or incomplete information to make truly rational decisions most of the time.

“Using agent-based models to model the complexity of real economies, instead of pencil and paper to model imaginary, highly idealized economies, will drive a fundamental breakthrough in the usefulness of the discipline of economics,” Farmer says. The research continues to gain momentum. Recently INET funded Farmer’s team to develop just such a model. “We are going to do it with economists or without them,” Farmer says. Changing the view of the whole field is not going to be easy.” ◀

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Farmer asked the crowd to shed the dogma that says markets self-stabilize, and instead create much more complex models based on actual “rational” behavior—that of agents making decisions with incomplete information in complex, changing environments.

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SFI Professor J. Doyne Farmer, along with SFI External Professors Robert Axtell and John Geanakoplos, hope to build an agent-based model of the entire U.S. economy.

# the Complexity of Conflict

BY DAN ROCKMORE

This sequence of events below was captured on video by Jessica Flack while she was collecting data on social dynamics at the Yerkes Regional Primate Research Center. It shows a fight erupting between an adult female pigtailed macaque and a juvenile. A second juvenile intervenes on behalf of the first. The female responds with aggression and then retreats. Many fights involve only two or three animals. However some can grow to include as many as thirty animals, consuming almost a third of the group.

The PowerPoint slide shown to General Stanley McChrystal around the time he took charge of the conflict in Afghanistan depicted a mass of interests and threats, a *New York Times* article reported. It included topics such as “tribal governance,” “infrastructure services and economy,” and “military tactical strategies” among many others, all tied together with a chaotic web of arrows that looked as orderly as a bowl of spaghetti. The image could be described with two words: “It’s complex,” but five words offer more precision: “It’s a complex adaptive system.”

As a step toward understanding conflict as a complex system, in May 2010

SFI’s Business Network and the New America Foundation (NAF) co-sponsored in Washington D.C. a one-day symposium, “Seeing Conflict in a New Light.” That new light was the illumination that comes from bringing ideas of complexity science study to this notoriously opaque phenomenon.

## Conflict and Complex Systems—A Thumbnail History

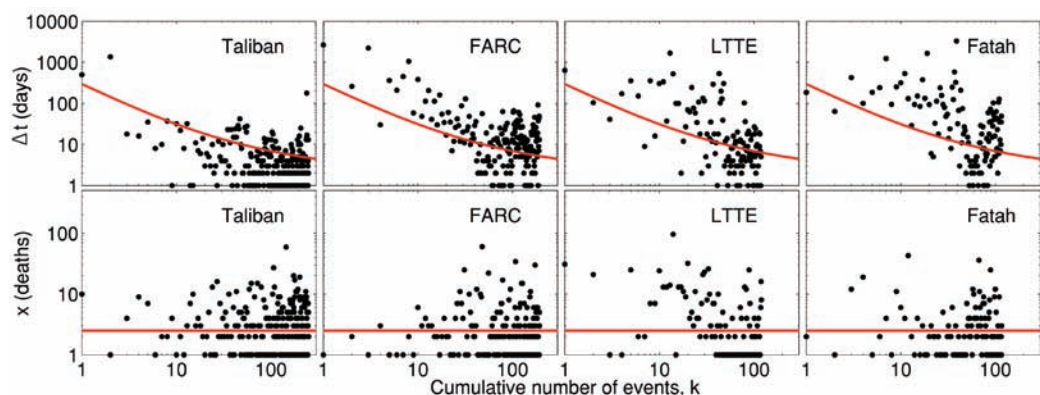
The conjunction of complex systems and conflict is hardly a shotgun marriage. Conflict is a lens through which many complex systems phenomena can be seen. It occurs on the scale of cells, individuals, and







Abu Nidal Organization (ANO) Abu Sayyaf Group Al-Aqsa Martyrs Brigade Al-Shabaab Ansar al-Islam  
 Communist Party of the Philippines/New People's Army (CPP/NPA) Continuity Irish Republican Army Gama'a  
 al-Islamiyya (HUII-B) Harakat ul-Mujahidin (HUM) Hizballah (Party of God) Islamic Jihad Group Islamic Movement  
 of Israel (JI) Kahane Chai (Kach) Kata'ib Hizballah Kongra-Gel (KGK, formerly Kurdistan Workers' Party, PKK)  
 Liberation Tigers of Tamil Eelam (LTTE) Libyan Islamic Fighting Group (LIFG) Moroccan Islamic Combatant Group (GICM) Mujahideen



This graph illustrates the attacks of the four most prolific terrorist groups in the world. The upper cells show the delay in days between consecutive attacks, while the lower show the severity of attacks, both as a function of the cumulative number of attacks. The trend lines show the model, illustrating that terrorist groups tend to accelerate their attacks according to a power-law function as they gain experience, but later attacks are no more deadly than earlier ones.

AARON CLAUSET

societies, over microseconds and millennia, in environments ranging from the intercellular battles that accompany the body's fights against disease and aging, through the struggle for resources in ecosystems or societies, and to the gamesmanship of the marketplace, boardroom, or playing field. The ways one engages in conflict can be examined from various perspectives, such as through game theory and optimization (making the most—with respect to some property or criteria—of a complicated situation), which are cornerstones of complex systems analysis.

The first appearances of what one might consider a complex systems

approach to the study of conflict can be found in the work of Lewis Fry Richardson (1881—1953). Richardson was a polymath and, in retrospect, something of a one-man Santa Fe Institute. His early work was in fluid dynamics and meteorology, taking on the notoriously difficult problem of numerical weather prediction, and as such, butting heads with the infamous “butterfly effect.” This phenomenon—in which a small cause in a complex system can have a large effect elsewhere in the system—he encountered decades before the birth of modern nonlinear dynamics and chaos theory.

His belief in the power of science and mathematics coupled with his

Quaker upbringing and experiences of World War I eventually led him to turn his data-driven attentions to a quantitative study of conflict, with the goal of bringing a dispassionate and thus (in his mind) necessarily irrefutable voice to the analysis of societal and international violence. His first attempt at this gave us the eponymous Richardson equations, a pair of coupled linear differential equations relating the rates and current levels of arms expenditures between two mutually antagonistic nations. Richardson saw arms





Armed Islamic Group (GIA) Asbat al-Ansar Aum Shinrikyo Basque Fatherland and Liberty (ETA) Communist al-Islamiyya (Islamic Group) HAMAS (Islamic Resistance Movement) Harakat ul-Jihad-i-Islami/Bangladesh Liberation Movement of Uzbekistan (IMU) Jaish-e-Mohammed (JEM) (Army of Mohammed) Jemaah Islamiya organization, KADEK) Lashkar-e Tayyiba (LT) (Army of the Righteous) Lashkar i Jhangvi Liberation Tigers of Tamil Eelam (LTTE) Medin-e Khalq Organization (MEK) National Liberation Army (ELN) Palestine Liberation Front (PLF)

expenditures as a measurable proxy for bellicosity, and his work shows that even under fairly simple assumptions, arms races can have a variety of dynamics.

Richardson's later work attempted to understand the influence of various national characteristics on the proclivity to violence. In trying to incorporate real (as opposed to numerical) boundary conditions—such as the length of a country's borders—into the mix, he was led to the discovery of fractal dimension, yet another statistical foundation of complex systems.

Of all this, Richardson's *magnum opus* in conflict analysis was *Statistics of Deadly Quarrels*—a compendium and analysis of data measuring the violence in society from roughly 1820 to 1950, ranging in scale from homicides to world wars, but excluding natural disasters. In conflict, as in many phenomena, while the individual events appear “random,” statistical structure emerges at the large scale. Careful analysis of the numbers led to the discovery of what some now call Richardson's Law of conflict, which is that the distribu-

tion of casualties has the form of a power law. Among their interesting features, power law distributions possess a “heavy tail,” meaning that events far out in the distribution still occur with some significant probability or frequency. For example, we've all experienced of late the heavy tail of stock price movements.

### Viewing Violence as Business

Aaron Clauset (University of Colorado, Boulder, and a former SFI Omidyar Fellow) uses Richardson's Law as a jumping-off point for his research of terrorism. Clauset's first work on the subject of conflict was with Maxwell Young in the Department of Computer Science at the University of New Mexico. The research resulted in a Richardson-like analysis of the terrorism casualties as collected in the National Memorial Institute for the Prevention of Terrorism database. It showed the power law statistical regularity in the casualty data.

Power laws are ubiquitous in the statistical analysis of many complex systems phenomena, exhibiting a

simple structural relationship in the observed distribution of events—in this case that the probability an attack has a given number of casualties is approximately a fixed power of the number of casualties. Trying to understand models of conflict that create this kind of distribution can lead to understandings about the mechanisms of conflict.

While this structure is interesting, it is only a first step, for it suggests the much more important question of “What is the source of this regularity?” Clauset and Young show that this structure is consistent with a model of “competition” between the insurgents and the nation-state in which the magnitude of the attack as well as the probability of intervention by the nation-state are proportional to the time taken to prepare the attack.

At the May meeting Clauset spoke about new work with Kristian Gleditsch, a researcher at the University of Essex and the Centre for the Study of Civil War in Oslo, Norway. The two find that the timing between attacks by various organized violent actors decreases according to





alestinian Islamic Jihad (PIJ) Popular Front for the Liberation of Palestine (PFLP) PFLP-General Command (PFLP-GC) Jihad fi Bilad al-Rafidayn (QJBR) (al-Qaida in Iraq) (formerly Jama'at al-Tawhid wa'al-Jihad, JTJ), al-Zarqawi in the Arabian Peninsula (AQAP) al-Qaida in the Islamic Maghreb (formerly GSPC) Real IRA Revolution (FARC) Revolutionary Organization 17 November Revolutionary People's Liberation Party/Front (DHKP-Indo) Sendero Luminoso, SL) United Self-Defense Forces of Colombia (AUC) Harakat-ul Jihad Islami (HJI)

a power law in the group's experience, while the size of the attack is independent of their age. This focus on the maturity of the organization with attendant hypotheses regarding its functional capabilities has interesting analogies in the business world with respect to the inception, growth, and success of companies. In this framework the terrorist groups are cast as start-up companies whose primary product is political violence, "valued" in the currency of casualties. Most striking is their finding that the "development curves" (relating organizational age to time between events as well as number of casualties) bear a striking similarity to the production curves in manufacturing relating production costs with cumulative number of items produced.

### Calculating Probabilities of Conflict

SFI Professor Jessica Flack brings a biological and evolutionary approach to the problem, taking the point of view that a broader perspective is necessary for the articulation of more

general, even universal, principles of conflict. In addition, the investigation of conflict in settings outside the human realm can allow for the rigorous testing of hypotheses regarding the nature of conflict.

Flack has for many years been studying primate societies, in par-

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ticular analyzing a macaque colony at the Yerkes National Primate Research Center, a part of Emory University located outside of Atlanta. Flack sees the macaque collective as a model system for the study of many aspects of social dynamics, including conflict. As opposed to the coarse kinds of casualty data that usually form the basis of conflict studies, the constant close

surveillance of the primate micro-society provides scientists with an extraordinarily detailed and highly resolved dataset of interactions and outcomes. Flack and her colleagues have been able to examine this data to produce a general analytic framework for the study of conflict.

Flack's recent work, in collaboration with SFI Professor and Faculty Chair David Krakauer and Omidyar Fellow Simon DeDeo, applies the tools of *inductive* game theory (a methodology created by them) to "discover" strategies of conflict in the macaque society (48 adult macaques) from time series that encode their behaviors over several observation periods. It is precisely in this ability to extract strategies as opposed to positing them *a priori* that distinguishes (in part) inductive game theory from classical, or *deductive*, game theory.

The time series of conflict dynamics abstracts the macaque behavior into the basic data of who participated in conflict, their roles in the conflict, and the start and stop times of the conflicts. The focus on participants

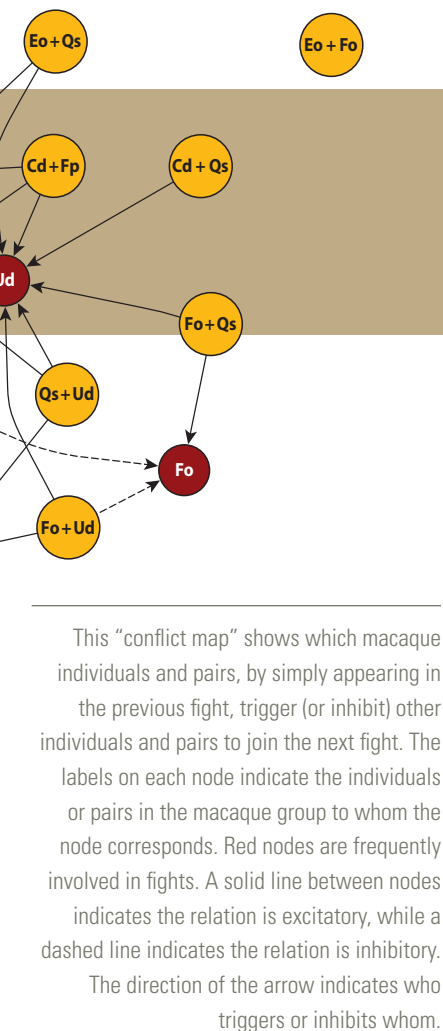


and (PFLP-GC) Tanzim Qa'idat  
 (awi Network) al-Qa'ida al-Qa'ida  
 ary Armed Forces of Colombia  
 /C) Revolutionary Struggle Shining  
 (UJI) Tehrik-e Taliban Pakistan

and timing yields some surprising conclusions mainly related to the role of memory in conflict. The data enables the calculation of the (conditional) probabilities that any given subset of actors engages in a next conflict, given that some other specified subset engaged most recently in a conflict. For example, the figure on the right shows significant pairwise effects with an arrow from individual A to individual B if the presence of A in a conflict is a “significant” indicator for the presence of B in the next conflict. This probabilistic approach enables Flack and her colleagues to separate out the significant (and sometimes overwhelming) role of memory in conflict from various “externalities” such as resource competition. This has obvious relevance for many of today’s most violent conflicts. The results are enabled by the creation of an elegant formal language for specifying the dynamics of conflict. This produces a rigorous framework for the testing of hypotheses about conflict generally (e.g., replace macaque with insurgent group) that can be used to articulate strategic paradigms in human conflicts.

More broadly, Clauset’s and Flack’s research can be seen as evidence for the power of the tools of statistical learning in the analysis of conflict data. In my closing statement at the NAF conference, I picked up on this theme, noting that statistical learning is the modern instantiation of what is often referred to as “pattern recognition”—that is, the automatic (i.e., computer-guided) discovery of structure in data. I discussed the various ways these methods have been applied in a variety of areas, including textual and behavioral analysis, and how they might then find further use in conflict. When turned on its head, these tools also enable the discovery of anomalous behavior in the data stream, akin to the search for the canary in the coal mine that might presage a violent action.

Richardson is quoted as seeing war as primarily “chaos,” though partially “restricted by geography and mod-



fied by infectiousness.” In the work of Clauset and Flack and others in the SFI community, we see that these complex systems references are more than metaphor. ◀

*Dan Rockmore is the John G. Kemeny Parents Professor of Mathematics and chair of the Department of Mathematics at Dartmouth College. He is a member of SFI’s Science Steering Committee.*





# WEDDING BIOLOGY TO

BY JULIE REHMEYER

**L**AURA FORTUNATO WAS BORN INTO AN OLD ITALIAN FAMILY, with traditions and customs dating back centuries. But the strong hand of modernity has been pressing against those customs, sometimes extinguishing them (such as the extravagant dowries brides' families used to pay) and sometimes adapting them to new times (such as the ongoing but lessening squabbles over land and inheritance).

Fortunato accepted these changes as the natural way of the world, as children do—until she studied biology in college. Long-term studies of the mating strategies of deer, for example, led her to ask similar questions about the mating strategies in her family. Why, she began to wonder, had they paid those dowries? Why do some societies have very different customs? How had all these variations come about? Her professors didn't seem to

have the answers, and she was struck: "We understand more about deer than we do about people!"

When she became an anthropologist in graduate school at University College London, the mystery—and the sense of scientific missed opportunity—deepened. By historical, international standards, Europe was *strange*. In 83 percent of the world's societies, men are permitted to have multiple wives at once, a shocking custom by European standards (though adultery barely raises an eyebrow in some quarters). Furthermore, in other parts of the world new couples typically joined either the husband's or the wife's family household rather than forming their own, as had been the practice for hundreds of years in many European societies. Why was Europe different?

There were certainly some theories. For example, anthropologists have commonly argued that monogamy came about because of Christianity.

PAULA EASTWOOD



But Fortunato found this explanation wanting, since a Babylonian legal document restricted polygyny 2,000 years before Christianity. Evolutionary biologists had their own story: For any individual fellow, they've said, it's always better to have multiple wives, because he'll have more kids. But if one guy has lots of wives, other men will inevitably end up with none—and might not like that much. The strife that goes along with this kind of competition is damaging to society as a whole. So as societies became bigger and required more cooperation, the biologists have argued, monogamy became more common.

"I wasn't very happy with those explanations," Fortunato says. "For one thing, no one has tested them. And this whole theory is based on whether a mating strategy is good for men only. Women are treated as completely passive."

So Fortunato, now an Omidyar Fellow at SFI, set out to bring some careful science to these questions. First, given all the extra-marital fooling around that can happen in monogamous societies, she knew that marriage and mating just aren't the same thing. So the first question was, how does marriage affect evolution? The key, she thought, was inheritance: the legitimate children are the ones who get the goods when a man dies.

And for inheritance, the number of wives a man has matters, since his property will have to be split between each of his families. In Europe, where people have traditionally farmed small plots of land intensively, a polygynous man's children could end up with too little land to support themselves—a big evolutionary problem. But in Africa, where land was historically plentiful, inherited land was inessential and polygyny worked out fine.

# ANTHROPOLOGY





Monogamous, neolocal societies (purple) cluster together on the evolutionary tree, while monogamous, dowry-giving societies (red) are scattered. This means the monogamous, neolocal societies have a common ancestor from which both practices originate. Thus the practices might not be inherently related, instead just happening to occur together because they were both adopted by a common ancestor.

But of course, a man has to be pretty sure that his wife's kids are really, genetically, his for it to make evolutionary sense for him to hand his property down to them. Fortunato realized that this means both spouses may be acting strategically: Men are more willing to transmit their property to their wives' children if they're confident she's been faithful, and women are more willing to be faithful if they believe it will lead their husbands to leave property to their own children. Indeed in some societies, men will

sometimes transfer their property to their sisters' children—and those societies tend to be ones in which women are more promiscuous.

Fortunato and Marco Archetti of Oxford University coded these insights into a game-theoretic model and found that these forces were sufficient to make monogamy a good strategy for both parties. "Evolutionary anthropologists tend to think that males always have a great advantage in having multiple wives," Fortunato says, "but our model shows that monogamy can be good for both males and females."

Fortunato then wondered why dowries (a gift from the bride's family to her) and neolocality (the custom that a newly wedded couple establishes their own household) were common in monogamous societies but rare in polygynous ones. Anthropologists had assumed that those customs

ILLUSTRATION: PAULA EASTWOOD

cause each other in some way, but she wondered if they were part of a historical accident instead: Societies that were both monogamous and gave dowries or both monogamous and established their own households might have been the ones that spread, taking both practices with them even though they weren't inherently related.

Since customs like monogamy don't leave a trace in the fossil record, she could only use the traces of the past in the present. Language is one such trace: People who descended from common ancestors tended to have related languages. So Fortunato built evolutionary trees of societies based on their languages and tracked which societies were monogamous, gave dowries, and were neolocal.

A statistical pattern jumped out: The monogamous, neolocal societies clumped together on the evolutionary tree, whereas the monogamous,



In some cultures, especially in places with plenty of land, polygyny—here depicted as a harem—works as a marriage strategy.

dowry-giving societies were scattered all around. That meant that the monogamous, neolocal societies had a common ancestor who they probably got both practices from. So the practices might not be inherently related, instead just happening to pop up together because they had both been adopted by this common ancestor.

But since dowries and monogamy occur together even in distantly related societies, it seems likely that they're deeply connected in some way and evolve together.

This has the remarkable implication that the nuclear family itself may not have been an evolutionary inevitability, Fortunato says. History might have played out differently, with monogamous couples joining one of their parents' households, for example. "That means it's possible that things could change," she says, "and families could organize themselves quite differently."

Fortunato hopes to do more than just understand marriage. She wants to transform anthropology into a science. "Anthropology lacks the sound, systematic theoretical framework that biology has through evolutionary thinking," Fortunato says. She believes that the evolutionary perspective can allow anthropologists to assemble diverse bits of knowledge into a compelling whole. Others are becoming convinced that it could happen, too.

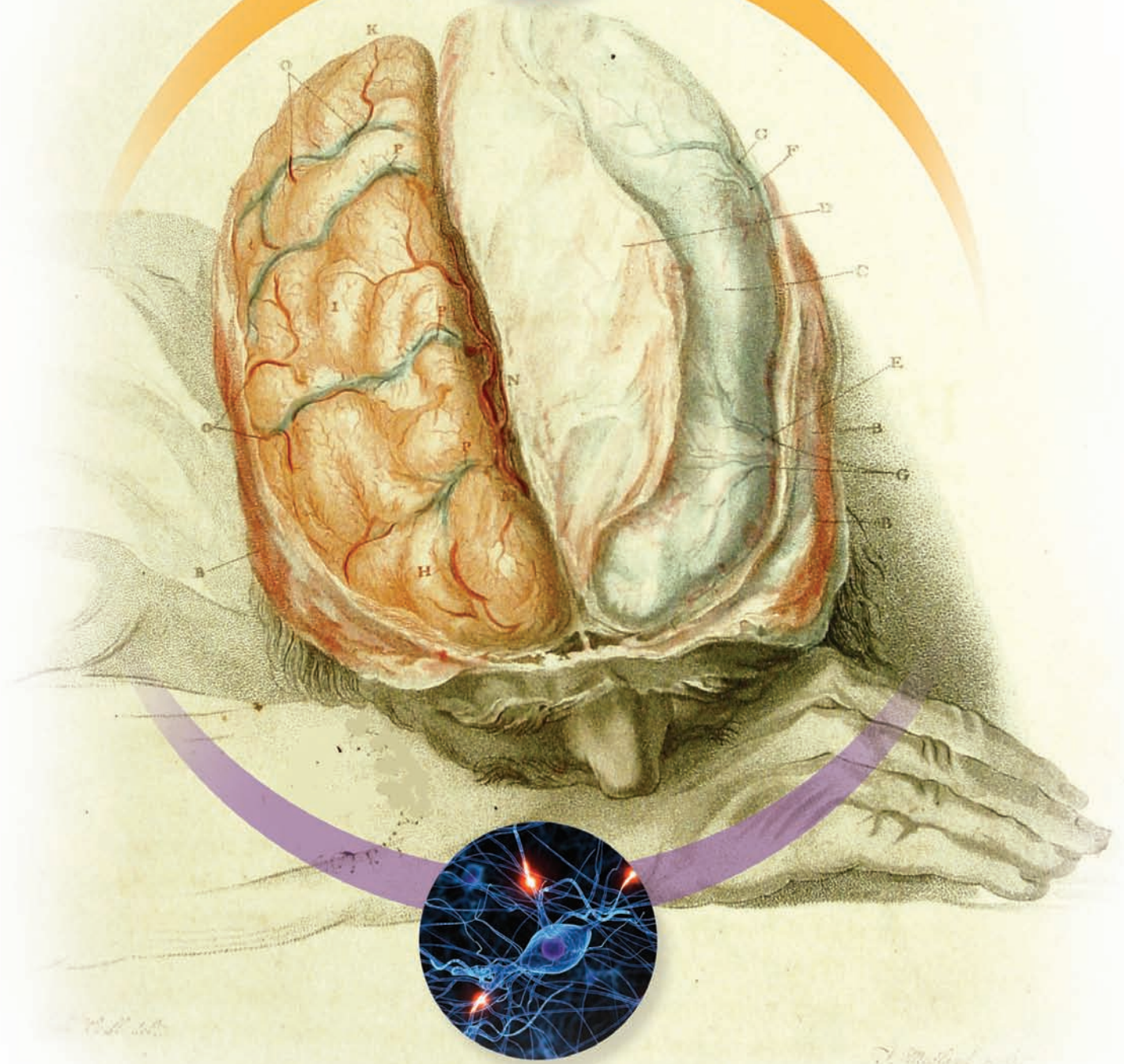
"These methods have the potential to revolutionize anthropology," says Stephen Shennan, who helped supervise Fortunato's PhD at University College London. "Anthropologists have been asking about things like monogamy and dowries since the 19th century. We finally have the possibility of getting real answers." ◀

*Julie Rehmeyer is a freelance math and science writer based in Berkeley, CA, and Santa Fe, NM, who writes regularly for Wired Magazine and Science News. She is a former mathematician and tutor at St. John's College. She was SFI's first undergraduate intern.*





Plate 1.



# The SPLIT PERSONALITY of COGNITION

By Matthew Blakeslee

SCIENTISTS AT THE SANTA FE INSTITUTE ARE HAVING A FRESH THINK ABOUT COGNITION OUTSIDE THE BOX—THE BOX, IN THIS CASE, BEING THE INDIVIDUAL BRAIN.

“Most cognitive science still emphasizes the individual brain,” explains Professor and Faculty Chair David Krakauer. “But there are two directions cognitive science can move that are quite different from the focus on individuals.”

One direction is to expand its scope up, toward the social level, Krakauer says. The term for this is “distributed cognition,” something that occurs wherever knowledge, skills, and decision making are distributed across populations of individuals in societies and organizations.

The other direction for cognitive science is to narrow its scope down to the sub-components of the individual brain—to the level of cells, molecules, and circuits. Cognitive scientists can then ask at what points, and by what degrees, do the collective actions of mindless neurons and small-brain structures increasingly add up to a full-fledged, intelligent self.

Krakauer is organizing five groups that will interact over the coming year. The theme of these groups is captured under the umbrella of *Emergence in Decision Making and Cognitive Systems*, one of four focus areas at SFI. (The other three focus areas are scaling, risk, and conflict.)

Krakauer’s workshops will explore various ways to understand cognition when it is distributed across

scales both higher and lower than the individual brain. Three of the groups will be based at SFI; the other two will be centered at other institutions in California.

Two of the working groups are devoted to game theory, a behavior-oriented branch of mathematics that analyzes strategy, decision making, and reward seeking. Game theory has found applications in many fields, notably in economics, international relations, and evolutionary science. Game-theoretic analysis can illuminate optimal strategy, the expected payoff of a given action, and predictions about the likely strategies of competitors and allies.

Game theory is an elegant edifice, Krakauer says, but it is sometimes criticized as being too rarefied and abstract. At its core, it posits an idealized decision-making agent who has a highly streamlined and optimized psychology. This model is sometimes mockingly referred to as *Homo rationalis*, the Platonic ideal of a fully rational, self-interested, utility-maximizing individual. *Homo rationalis*’s ability to derive and execute the mathematically optimal strategy for any given “game” is all well and good, but as everyone knows, flesh and blood *Homo sapiens* often deviate from it. They might buy lottery tickets, invest in socially responsible mutual funds (which do not maximize their profits), get swept up in dot-com and housing-bubble manias, dash the chess board to the ground and sulk home.



A baseball player in a white pinstriped uniform with red accents, including a red cap with a white 'R' logo and red sleeves. He is holding a brown leather baseball glove in his left hand and a white baseball in his right hand. The background is dark, and there is a purple horizontal bar at the top of the image.

R

When you design a system you may not know where every agent is going to be at every point in time...So you need to somehow come up with a sufficiently **general, flexible program** that will lead to a desirable outcome. The logic is, I don't know the particulars, but if I set it up right, the **outcome will be reasonable.**

The game theory working group **Reasoning and Beliefs in Strategic Settings: New Foundations from Empirical Data** is led by former Omidyar Fellow and extramural fellow Willemien Kets, from Tilburg University, the Netherlands. The group aims to modify game theory to make it more psychologically realistic—to bring it more in line with how decision making actually happens in the real world.

“One of their questions,” Krakauer explains, “is whether within the existing framework of Bayesian game theory [the branch of game theory concerned with how agents learn and adapt their strategies] there might be ways to incorporate elements of real neuroscience, psychiatry, and cognitive science into the mix. In a sense, to make it more complicated”—but in a good way.

As part of their contribution to this workshop, Krakauer, SFI Professor Jessica Flack, and SFI Omidyar Fellow Simon DeDeo are approaching the problem with a slightly more radical method. Rather than attempting to fix game theory with tweaks and half-measures, they plan to cast the whole edifice aside and rebuild it from scratch.

“Game theory never came out of social data,” says Krakauer. “It came out of the mathematics of parlor games—poker—and then was generalized to real-world situations in a kind of abstract, toy-model sense. So our question is, what if we started again, but this time with the social data itself? Could we do any better [than classical game theory] at making sense of how strategic interactions are carried out by real people?” The new edifice they hope to build has been dubbed *inductive* game theory.

The second working group with a game-theoretic orientation, **Decentralized Control in Systems of Strategic Actors**, is being organized by David Wolpert (NASA’s Ames Research Center), SFI Professor D. Eric Smith, and Robert Ecke,

Director of the Center for Nonlinear Studies at Los Alamos National Laboratory. This group uses as its springboard the work of SFI Science Board member Eric Maskin, who is based at the Institute for Advanced Study in Princeton and who won the Nobel Prize in Economics in 2007 for his development of mechanism design theory.

The interest here is in designing behavioral settings that channel agents’ collective behavior in desired directions. In a sense, Krakauer says, it inverts the usual way game theory gets applied: Rather than analyzing the behaviors and strategic incentives of the agents engaged in a given game, mechanism design seeks to construct a set of game rules and a game environment up front that, once set in motion, guarantees certain group dynamics or kinds of outcome. Mechanism design theory has broad application, including to auction systems, voting systems, market regulation, industrial processes, and emergency procedures.

“When you design a system,” Krakauer explains, “you may not know where every agent is going to be at every point in time, what goals each one will be pursuing, or what information each one is going to have access to. So you need to somehow come up with a sufficiently general, flexible program that will lead to a desirable outcome. The logic is, ‘I don’t know the particulars, but if I set it up right, the outcome will be reasonable.’”

The third working group, **The Role of Entropy in Language, Communication, and Behavioral Sequencing**, is co-organized by Krakauer, philosopher and linguist Mark Johnson from the University of Oregon, and linguist Katherine Demuth of Macquarie University in Sydney. This group is interested in exploring human communication and behavior in terms of information theory (the mathematics of encoding and transmitting information), entropy (ambiguity or information loss during communication), and formal grammars (rule sets for manipulating information-bearing symbols such as numbers, words, gestures, and actions).

Its ultimate achievement, Krakauer says,

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A baseball pitcher provides a strong metaphor for the complexity of cognition. The whole game centers on his interaction with the other players as well as his physical skill in handling the ball.



would be to build a bridge between classical Chomskyan linguistics and the motley hoard of language-related neuroscience data that are still in search of a strong unifying theory. These two approaches still stand largely at odds. The Chomskyans have an elegant and rigorous logico-mathematical theory of grammar, but their theory is completely silent on (as well as historically indifferent to, and even contemptuous of) the question of how the living brain might actually instantiate it. In another camp are cognitive scientists who demand a biologically grounded, neurodynamical account of human language and social behavior. At present, Chomsky is Chomsky and neurons are neurons, and never the twain have met. By forcing these estranged bedfellows together, the scientists will address a host of difficult questions about how language, communication, and decision making

“His whole career, Mike has been very interested in the problem of the unitary sense of consciousness,” Krakauer says. “If there is no homunculus [no “pilot” controlling the brain from a central command center], how is it that cells in a distributed network somehow conspire to make a decision that they all seem to agree with—and that you, as a sensible conscious entity, think you made?”

This is a huge and enduring puzzle in neuroscience: Coherent thoughts and coordinated behaviors arise from the noisy chatter of billions of nerve cells, and there is no central controller anywhere to be found. The group will examine this problem through a couple of approaches. One is to look at how neural activity gets coordinated over multiple scales of space and time. The other is to look at brain development, and try to see how coordination mechanisms get established while the system is first setting itself up.

Coherent thoughts and coordinated behaviors arise from the noisy chatter of **billions of nerve cells**, and there is **no central controller** anywhere to be found.

work at the neural, individual, and social levels.

The last two working groups are collaborations with cognitive scientists in California.

Krakauer is co-organizing the working group **Distributed Computation and the Emergence of Mind** with neuroscientist Mike Gazzaniga at his home institution, the University of California at Santa Barbara. Gazzaniga is best known for his longtime study of split-brain patients—people who have had severed the major fiber tract that connects the left and right halves of the cerebral cortex. Such patients become split into two quasi-selves that are no longer quite unified, and neither of which is quite whole. The severed selves can have different skills and opinions, and can even hold contradictory beliefs. Yet they will often go to absurd lengths to rationalize and claim credit for the behaviors and choices of the other hemisphere—as though they were striving to hold on to a sense of undiminished free will.

The last working group, **The Road to Cognitive Dynamical Systems**, will be held at the Salk Institute in La Jolla, California. In addition to Krakauer, its organizers are Josh Bongard of the University of Vermont, Simon Haykin of McMaster University, Canada, Jose Principe of the University of Florida, Terry Sejnowski of the Salk Institute, and Steve Zucker of Yale University. Their aim is broad and deep, says Krakauer: “If we think of decision making in dynamical systems terms—feedback loops, interacting sub-assemblies, coordination over different time scales—can we find a *unified framework* for studying all things cognitive, everything from robotics and neuroscience to behavior and social science?” The agenda is “explicitly general” and highly ambitious, Krakauer admits, but that is all in keeping with the spirit of the Santa Fe Institute. ◀

*Matthew Blakeslee is a science writer who lives in Santa Fe.*

# ↑ TRANSITIONS ↓

## BOARD OF TRUSTEES

*SFI's trustees are drawn from leaders in business, finance, and academia. Here are the newest additions to an accomplished roster:*

**John Chisholm** has three decades of experience as a technology executive and entrepreneur. A pioneer in online marketing research, in 1992 he founded and served as Chairman/CEO of Decisive Technology (now part of Google), publisher of the first online server software; and of CustomerSat (now part of MarketTools), a leading provider of customer feedback systems. He holds an MBA from Harvard, and MS and BS degrees in electrical engineering and computer science from MIT.

A fellow at the Stanford University Graduate School of Business and an accomplished leader and founder of organizations and publications for the arts, **Kay Taylor Burnett** currently serves as the CEO of a small energy development company and the president of a small nonprofit foundation. She also serves on the board of Marfa Public Radio, whose purpose is to help bring public radio to the vast Trans-Pecos region. This is her second appointment to the Board of Trustees.

**Henry Lichstein** is managing partner of Dryad Partners, his consulting company. He takes interim CEO/CFO roles, consults for technology-based companies, and serves on boards. Educated at MIT with degrees in electrical engineering, economics, and management, he worked for 30 years developing technology, among other duties, for Citibank. He has served on many boards, including ones for Teradata, Lucix, and Intelligent Optical Systems.

**Michael Mauboussin** and **William Sick** have been reappointed to the Board of Trustees after serving a one-year mandatory hiatus.

## 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:*

**Derek Smith** is professor of Infectious Disease Informatics at the University of Cambridge and a senior fellow at the Fogarty International Center at the National Institutes of Health. His



research focuses on pathogen evolution, in particular the evolution of influenza viruses. He examines to what extent this evolution is predictable, and helps determine public and animal health measures against influenza and other evolving pathogens.

**Geoffrey West** is a distinguished professor and past president of SFI, and a senior fellow at Los Alamos National Laboratory. Perhaps best known for understanding the origins of universal scaling laws that pervade biology from the molecular level up through organisms and ecosystems, he is currently extending these ideas to understand quantitatively the dynamics of cities, corporations, and global sustainability.

**Peter Wolynes** holds the Francis Crick Chair in the Physical Sciences at the University of California, San Diego. His research focuses on mathematically characterizing energy landscapes that operate in glasses, liquids, and biomolecules, and in protein-folding kinetics. He is beginning to study how these landscapes affect biological processes such as genetic network regulation and gene recognition.

## Newly Appointed Co-Chairs:

A professor of biological sciences at Stanford University, **Marcus Feldman** uses mathematical modeling techniques to study problems in evolutionary biology. In addition to his teaching and research, he is editing two journals and working on books about gene culture co-evolutionary theory, niche



construction in evolutionary biology, and the sex ratio issue in China. Feldman often works with fellow SFI researchers to shed light on biological and social phenomena by applying concepts of evolutionary biology in novel ways.

**Stephanie Forrest** is chair of the Computer Science Department at the University of New Mexico, and has long been a member of the SFI community. Her research interests include computational immunology, genetic algorithms, and biologically inspired approaches to computer security. Her recent work focuses on automated software repair using evolutionary methods.

### SCIENCE STEERING COMMITTEE

*This group meets bimonthly to advise the SFI administration on science issues. SFI welcomes these new members:*

SFI external professor and professor of systems biology at Harvard Medical School, **Walter Fontana** heads a research group whose theory section develops a new formalism and associated computational methods for studying distributed systems of molecular interaction that orchestrate cellular behavior. The experimental section of his group uses the nematode *C. elegans* to determine quantitatively how genes influence life-span distributions and how physiological processes change with age in individuals.

**Mimi Koehl** is a professor of integrative biology at the University of California, Berkeley, where she studies the physics of how organisms interact with their environments. She aims to elucidate basic physical rules about how body structure affects mechanical function in nature. In her research, she emphasizes field work and laboratory experimentation and combines techniques from fluid and solid mechanics with those from biology.

**Melanie Mitchell**, a professor of computer science at Portland State University, teaches and researches computation in complex systems. Like others in the complex systems commu-

nity, she is fascinated with commonalities across natural systems such as brains, insect colonies, the immune system, cells, the global economy, and evolution. Her work aims to understand how those systems perform computation, and how to use this knowledge to develop new computation techniques.

**Dan Rockmore** is a professor of mathematics and computer science at Dartmouth College, where he also chairs the department of mathematics. His research interests include applied and computational harmonic analysis, image processing relative to the study of art, medicine, complex systems, machine learning, financial markets, and the evolution of culture.

Science Board co-chairs **Marcus Feldman** and **Stephanie Forrest** also serve, ex-officio, on the Science Steering Committee.

### SFI PROFESSORS

*SFI Professors form the backbone of the Institute's research. They are in residence for renewable terms of three to five years.*

The following three have been promoted to Professor:

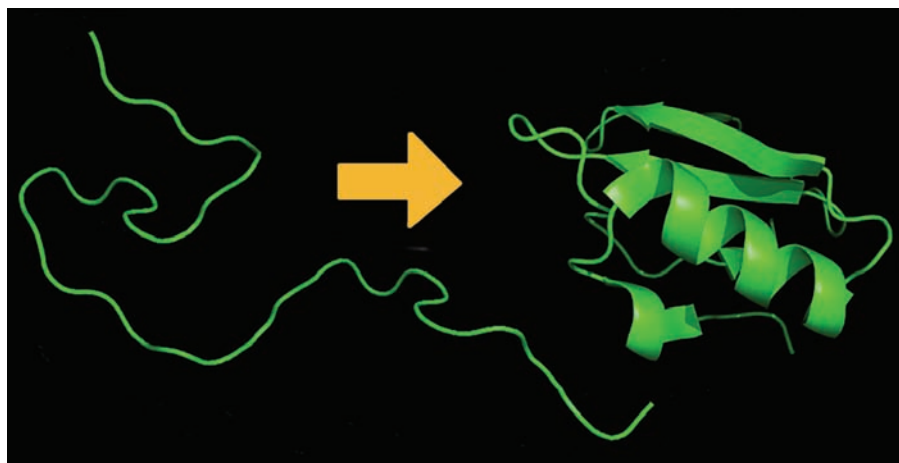
Co-founder of the Pacific Ecoinformatics and Computational Ecology Lab, **Jennifer Dunne** studies the organization, function, and stability of ecosystems in terms of complex species interaction. Her research seeks to identify fundamental patterns and principles of ecological network structure and dynamics at multiple spatial and temporal scales.

**Jessica Flack** codirects the Construction Dynamics Group at SFI, which seeks to build a computational theory to account for the origins of hierarchy and aggregate structure in evolutionary processes. Research foci include the emergence of multiple time scales in social processes and their role in uncertainty reduction and robustness, conflict and conflict management as drivers of complexity, and heuristics for component estimation of system state.

A cognitive anthropologist, **Paula Sabloff** has conducted research in Mongolia, Mexico, and the U.S. She is currently working on Mongolians' changing ideas about democracy and capitalism, asking whether democracy is a universal goal or a conceit of U.S. foreign policy. She also is collaborating with former Omidyar Fellow Tanya Elliot on a cognitive model that can be applied to populations rather than a single brain.

Also at SFI as a professor:

**Geoffrey West**, former SFI President, continues his SFI affiliation as Distinguished Professor and Science Board member.



A member of the SFI Science Board, Peter Wolynes researches protein-folding kinetics, among other topics. Here, a polypeptide folds from a random coil into its characteristic and functional three-dimensional structure.

## EXTERNAL PROFESSORS

*An essential component 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:*

The chair of the Systems and Computational Biology Department at Einstein University College of Medicine, **Aviv Bergman** pursues some of the classic questions of evolutionary biology through his research into complex genetic systems. The research program at his laboratory focuses on the quantitative aspects of evolutionary and developmental biology and uses data from experimental studies in molecular genetics.

**David Campbell**, a leader in the field of nonlinear science, received the American Physical Society's Julius Edgar Lilienfeld Prize for contributions to complex systems study. Campbell is the founding editor-in-chief of the flagship journal *Chaos* and the current provost of Boston University.

An eminent archaeologist of the American Southwest, **Linda Cordell** is currently a senior scholar at the School for Advanced Research on the Human Experience. Her research interests include archaeological method and theory, the archaeology of settlement dynamics in agricultural communities, and human responses to climate change in arid regions.

**Steve Frank** is a professor of ecology and evolutionary biology at the University of California, Irvine. His current research focuses on how the dynamics of genetical, biochemical, and cellular mechanisms determine complex phenotypes, such as cancer and parasite virulence.

**John Harte**, a professor of ecosystem sciences at the University of California, Berkeley, currently has two main research topics. He measures and models ecosystem-climate feedback dynamics, and he applies the MaxEnt principle from information theory to the prediction of patterns in the abundance, distribution, and energetics of species across taxa, habitats, and spatial scales.

The Moffett Professor of Biology and Director of the Center for Biocomplexity at Princeton University, **Simon Levin** researches patterns in ecosystems. He seeks these patterns in evolutionary mechanisms that operate in organisms, in infectious diseases, and in the interface between basic and applied ecology.

Formerly the chief scientific advisor to the UK government and president of the Royal Society, **Lord Robert May** holds professorships jointly at Oxford University in the department of zoology, and at Imperial College London. His current research explores the rates, causes, and consequences of extinction.



Seal of Mongolia: Professor Paula Sabloff researches Mongolians' changing ideas about democracy and capitalism.

An assistant professor at the David Geffen School of Medicine at the University of California, Los Angeles, **Van Savage** uses mathematical models to understand how diversity is organized, constrained, and controlled in biological systems. His research applies to diverse subjects, from the structure of vascular networks in plants, animals, and tumors, to the time scales and purpose of sleep across species, to ecosystem and invasive species' responses to climate change.

**John Schellnhuber** is the founding director of the Potsdam Institute for Climate Impact Research and a long-standing member of the Intergovernmental Panel on Climate Change. He has contributed to the fields of condensed matter physics, complex systems dynamics, climate change research, earth system analysis, and sustainability science, and is an expert on climatological tipping points.

Physicist **Wojciech Zurek** is most known for developing the quantum theory of decoherence and elucidating its significance for the quantum-to-classical transition. He currently works at the Los Alamos National Laboratory as a lab fellow in the theory division.

## POSTDOCTORAL FELLOWS

*Several SFI research programs host postdoctoral fellows and researchers. Below is a list of the newest fellows.*

*To find out about each of them and their research, go to [www.santafe.edu/about/people](http://www.santafe.edu/about/people).*

**Fabio Caccioli**  
**Bryan Daniels**  
**Marcus Hamilton**  
**Hyejin Youn**

## OMIDYAR POSTDOCTORAL FELLOWS

*The Omidyar Fellows Program was established at SFI in late 2008 with a gift from eBay Founders Pierre and Pam Omidyar. Below is a list of the current Fellows. To find out more about each of them, go to [www.santafe.edu/about/people](http://www.santafe.edu/about/people).*

**Rogier Braakman**  
**Nathan Collins**  
**Simon DeDeo**  
**Laura Fortunato**  
**Anne Kandler**  
**James O'Dwyer**  
**Scott Ortman**  
**Jeremy Van Cleave**



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