

SFI Bulletin

spring 2008, vol. 23 #1

CONFLICT:
WHAT CAN IT TEACH US—
ABOUT OUR BRAINS, THE INTERNET,
ECOSYSTEMS, AND FINANCIAL MARKETS?

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

Published by the Santa Fe Institute
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Santa Fe, New Mexico 87501, USA
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home page: <http://www.santafe.edu>

Note: The SFI Bulletin may be read at the website:

<http://www.santafe.edu/bulletin.html>

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PRINTED ON RECYCLED PAPER

Balancing **Convention** **and Risk** to Create Transformation

↓ By Geoffrey West, President

The advent of a New Year is a good time to take a retrospective look at some of the developments and achievements of last year and to speculate on where the Institute might be headed in the coming year. This issue of the *Bulletin* does some of that. It explores many subjects, but a common thread is that of conflict and threat. Topics ranging from the threat of “malware” to the loss of diversity in ecosystems and financial markets are examined from the broad, big-picture viewpoint characteristic of SFI.

One of the more gratifying events of 2007 was the approval of our core umbrella proposal to the National Science Foundation. Our award is unique because, almost without exception, the NSF typically entertains proposals that are for specific, relatively narrow research projects, at least compared to the scale of SFI activities! Our proposal encompasses a mix of questions ranging from anthropology and archaeology, through economics, biomedical sciences and biological sciences, across mathematics, computer science and physics, all the way to the interpretation of quantum mechanics and the wave-function of the universe!

Despite its good intentions and professed commitment to cross-disciplinary, transformative research, the NSF doesn't yet have in place a formal structure for handling such unusually broad proposals. Needless to say, this put ours at some risk. The “normal” mechanism would break ours into 10 to 15 separate proposals, each focused on a specific topic within some sub-discipline, which, of course, is antithetical to a basic philosophy of SFI: transdisciplinary research transcending canonical disciplinary boundaries.

Establishing this and its implications for problems in complexity as a major and exciting component of the research landscape has arguably been SFI's greatest impact. I am delighted to report that the award was a 30 percent increase over the previous one. It is to the credit of the NSF that they were willing to entertain our proposal despite its unique character. I would like to thank them

and all of our researchers who contributed to this effort, and the staff for seeing it to fruition. It's gratifying to know that even though we support research that sometimes doesn't quite fit, we can still be successful when we play on the conventional academic playing field.

Although this award represents less than 10 percent of our funding (indeed, by design, only about one third is derived from government sources), it's extremely important and we value it tremendously. We need that credibility and, by extension, the approval from the academic community, when it comes to soliciting funding from private foundations, universities, and other government agencies.

Regarding research trends in 2007, we've had some tremendous successes, as evidenced by the wealth of SFI publications and reporting about SFI in books, articles in professional journals such as *Nature* and *Science*, and in popular publications such as *Wired*, *New Scientist*, *The Atlantic Monthly*, *The New York Times*, and many more. For example, Samuel Bowles' work on altruism was featured in *The Atlantic* and on National Public Radio. Michael Mauboussin's financial wisdom was also featured on NPR, as was my own work on scaling and lifespan, as well as on cities and innovation, done with my wonderful group of collaborators. Many accolades came to SFI researchers. Among those recognized were Nina Fedoroff, named Science and Technology Advisor to the U.S. Secretary of State, who also received the National Medal of Science; David Sherrington won the 2007 Dirac Medal and Prize from the Institute of Physics; Cormac McCarthy received the Pulitzer Prize for his book *The Road*; and both Duncan Watts and I were featured in *Harvard Business Review's* list of Breakthrough Ideas for 2007 (which meant that two of the 20 such ideas were associated with SFI).

In looking at the future, we have a number of exciting research areas we plan to address. This year we began to recognize that much of the work at the Institute falls under the umbrella of sustainability: e.g., our programs on innovation, robustness, financial markets, networks, and those areas that interface with energy, the environment, and organization. While we are not going to solve or provide detailed models of global warming or sustainable urban infrastructures, we look to provide a holistic, integrated conceptual scientific framework for understanding some of these critical world concerns.

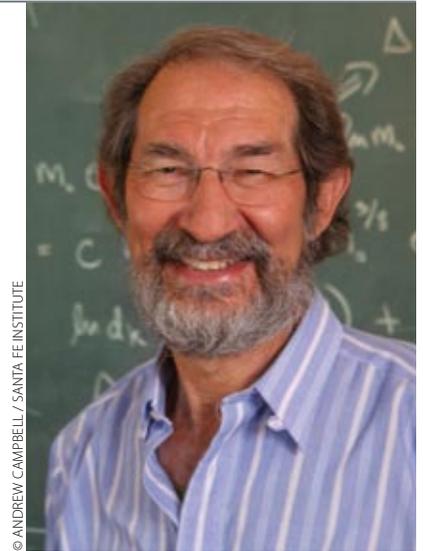
We are also looking at a series of questions that might

be considered outliers on the conventional scientific landscape.

For example, David Krakauer, together with Yale History Professor John Gaddes, is organizing a workshop asking to what extent history can be viewed as a science. This may not be as crazy as it sounds; after all, both astronomy and geology are accepted as "historical sciences." In addition, we are planning to look at law as a complex system. Can we learn something about jurisprudence, about the conceptual framework of law that might impact new emerging legal questions of the 21st century?

Another incipient area of exploration is what we are calling international negotiations and complexity. This arose because people involved in international negotiations approached us stating that the traditional system of diplomacy is broken. They suggested that this system evolved in a "simpler" world of the 19th century where the negotiating paradigm was "linear and Newtonian"; international relations have changed dramatically and can now be characterized as "complex"! Such a line of thinking naturally leads to the Santa Fe Institute. Like all of these new areas of potential investigation we don't yet know if progress will be made by bringing together unlikely combinations of creative people. It is the very nature of SFI to explore such avenues, to see if there might be new insights provided by a "complexity" lens.

A continuous challenge for the Institute is identifying talented people who might be attracted to the spirit of SFI, those exciting minds who really have eclectic, wide tastes, and a passion for some of the big questions that transcend traditional boundaries, and who, at the same time, have the powerful technical tools, background and discipline to execute their ideas. How do we identify those people and get them on board here as resident faculty? Indeed, I believe this is our major challenge, but one we can meet. Our past track record and recent kudos, along with the many awards and publications, offer strong encouragement for our future direction. ◀



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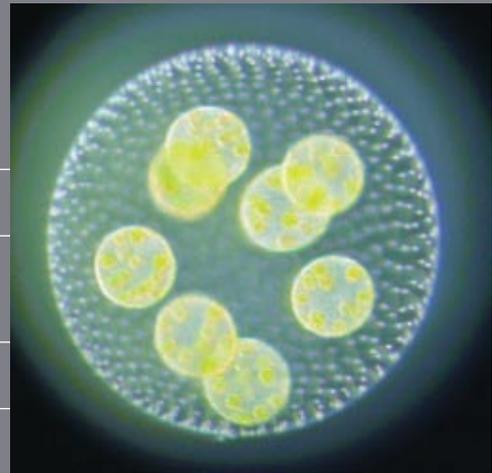
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Cities: Large is Smart

BY JENNA BECK

In an attempt to discover whether cities consume energy in the same way as biological organisms, SFI External Professor Luis Bettencourt, SFI President Geoffrey West, and their colleagues from Arizona State University and the Dresden University of Technology found that the size of a metropolis not only affects energy consumption, but also the pace at which people work, earn, walk, spend, and steal. Their study, published in the April 24th issue of the *Proceedings of the National Academy of Sciences USA*, lays out scaling laws that appear to connect cities of different sizes and in different nations. The most surprising of these laws suggests that a city may have a social metabolism that, as the city grows, increases faster than the population itself.

“A city’s not just a place, just a culture, what people eat, what language they speak,” says Luis Bettencourt. “It’s a space of interaction. When you put more and more people together in a city, some things increase in a very predictable and interesting way.” Using data from international census and statistics bureaus, the researchers compared infrastructure, energy consumption, and a handful of social phenomena for cities large, small, and in between. They found that as a city’s size increases, the infrastructure networks realize economies of scale, while the social phenomena grow faster than the population. In other words, the surface areas of streets and the lengths of electrical cables lag behind a city’s

This satellite image of North America at night illustrates the density of populations in the coastal regions as well as major inland cities, with large stretches of plains, deserts, and mountains remaining dark. Dawn is breaking over the eastern coast of the U.S.A.

PLANETARYVISIONS.LTD / PHOTO RESEARCHERS, INC

research report





Big cities will continue to grow, researchers believe, and understanding such places may help protect them from economic crisis. Here Shanghai's notable sector, The Bund, along the Huangpu River, buzzes with activity.

population growth, whereas income, crime rates, disease transmission, and certain measures of innovation outpace it.

Understanding these phenomena is a timely endeavor. For the first time in history there are roughly the same number of people living in cities as in rural areas, and the United Nations projects that cities will absorb the bulk of the population growth in the next 30 years. Big cities will grow bigger, as will the number of small cities. Between now and 2015, half of the urban growth is expected to come from an increase in

the number of small cities with populations of fewer than 500,000 people.

From an economic perspective, a growing city is usually seen as a healthy one. After all, the world's largest urban centers currently drive the world's largest economies. But while growth can benefit a city's economy, a city's future is by no means ensured. According to the UNFPA State of World Population 2007 Report, there are actually more people moving out of Buenos Aires, Calcutta, Mexico City, São Paulo, and Seoul than are moving in. Furthermore, the economic advantages do

PHOTO ABOVE: © WEIYAN / MASTERFILE.COM

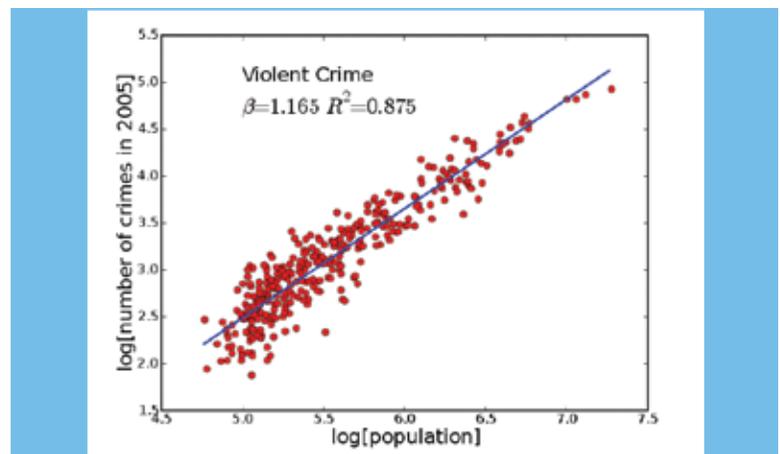
not extend to all urbanites. The report projects that “poor people will make up a large part of future urban growth,” since much of the growth is projected to occur in the developing world, where cities do not generate enough jobs to accommodate their populations. In light of the global urban upswell, questions of how a city grows, how it is sustained and affects the environment, and how, as an environment, it affects its citizens become increasingly important. The scaling laws presented in the researchers’ paper lay down a quantitative base for exploring such questions.

After analyzing datasets from American, Chinese, and European government bureaus, the researchers found three different scaling laws for three categories of data: individual human needs, material infrastructure, and data related to social currency.

Individual human needs included housing, employment, household electrical consumption, and household water consumption. These scaled linearly for cities of different sizes, which suggests that a person’s basic requirements for work, a home, and utilities remain the same whether he lives in New York or Nantucket.

Infrastructure was measured by road surface area, length of electrical cables, gasoline sales, and number of gas stations. The infrastructure scaled sub-linearly as city size increased, which means it didn’t grow as quickly as the population. When more people use fewer roads, gas stations, etc., a city realizes an economy of scale. Large cities, up to a point, are a more economic way of distributing resources than small cities and rural communities. This mirrors a relationship seen in biological organisms, where large animals economize on blood vessels by pumping more blood through proportionally fewer veins and capillaries. Fewer vessels support more mass, but the large animal’s metabolism slackens because the blood is delivered more slowly. When a city grows, the highways deliver more people to and from their destinations, but traffic slows as the roads become congested.

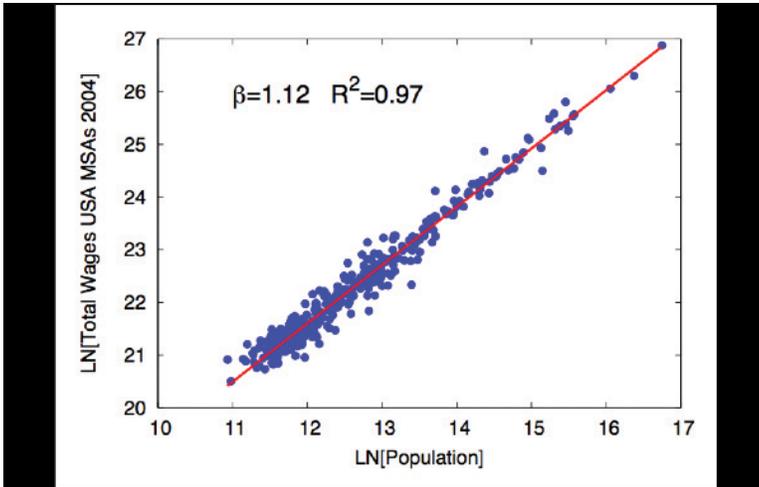
To the researchers’ surprise, the biological parallel failed for the third category of data: social currency. Unlike an animal’s metabolism, which slows with increasing size, as city size increased, the social metabolism sped up. “Superlinear” is the term the researchers use to describe this metabolic growth rate, which, when graphed, maps a steep upward curve rather than a straight line. “It was quite a surprise when we discovered this whole superlinear scaling. Like many things, once you see it and think about it, it seems obvious,” says Geoffrey West. “But it wasn’t obvious at first.” The social currency category included a range of seemingly unrelated measurements. Some of these—number of new patents, inventors, employment in research and development,



Violent crime per capita increases with city size (USA, 2005) as a scaling law.

and creative employment—were loose measures of innovation. Others were measures of consumption: total wages, total bank deposits, gross domestic product, and total electrical consumption. The researchers also took account of such things as the number of new AIDS cases and serious crimes.

As diverse as the social data were, they all scaled superlinearly with roughly the same exponents. This led the researchers to conclude that an underlying social metabolism was driving their growth. “We went into the study trying to



Total wages per metropolitan area indicate increasing per capita returns versus population size.

test the economies of scale theory, first for energy consumption,” Bettencourt says. “It’s only because we kept finding superlinear scaling for energy consumption—and then in everything economic—that it became so obvious that everything social showed increasing returns to population. All these quantities are rates, meaning that their increase per capita with the size of the city is an expression of acceleration of social life.”

As a city grows, its social metabolism speeds up. Individual productivity rises (15% per person when the city doubles) as people get busier. Average walking speeds increase. Businesses, public spaces, nightclubs, and public squares consume more electricity. The city draws in more inventors, artists, researchers, and financiers. Wealth increases, as does the cost of housing.

The superlinear growth rates also suggest that a city can grow indefinitely. When the researchers plugged the scaling exponents into an urban growth equation, they found that cities driven by economies of scale were destined to plateau, whereas those driven by innovation or wealth creation had the potential for unbounded growth. “Should a city have a finite size or should it grow forever? How should it grow? You would argue about it forever if you hadn’t measured,” Bettencourt says.

Sustaining that growth is the city’s chief challenge. To grow indefinitely, a city has to peri-

odically reset its growth rate. Such “resetting” can come from innovations that revitalize the economy, or from outside factors, such as shifts in immigration. The pattern that an ever-growing city falls into is one of successive growth cycles—each one shorter than the last as the size of the city increases. “You’re on this treadmill and you’ve got to go on making these changes, these innovative changes, faster and faster because if you don’t you’ll stagnate and collapse,” West says. “It’s probably hard to have control over these things because a city is embedded in something bigger. My interpretation is that where that cycle ends up might depend upon whether you have a city with a good administration in place, but the general trend and the coarse-grained scale of it is probably determined for you.”

If a growing city does not reset, the growth will collapse when the city exhausts its resources, or when its infrastructure and economy cannot support the population. Bettencourt cautions that a city can also collapse when the dark side of social metabolism accelerates more quickly than the rest: “My intuition, which is something I’d love to measure, is that the bad things can respond more quickly: it’s easy to increase the cost of housing. It’s easy to increase crime. It’s easy to create congestion—it just happens.”

The researchers are now looking into Bettencourt’s intuition about the balance between negative and positive social behaviors. They are also working to determine whether population and economic diversity increases with city size and, if so, whether those factors can help protect a city from economic crisis. “What’s difficult,” adds Bettencourt, “is to create institutions that promote very advanced learning and creativity.” Knowing more about cities just might make the task easier. ◀

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the Revolutionary Lizard

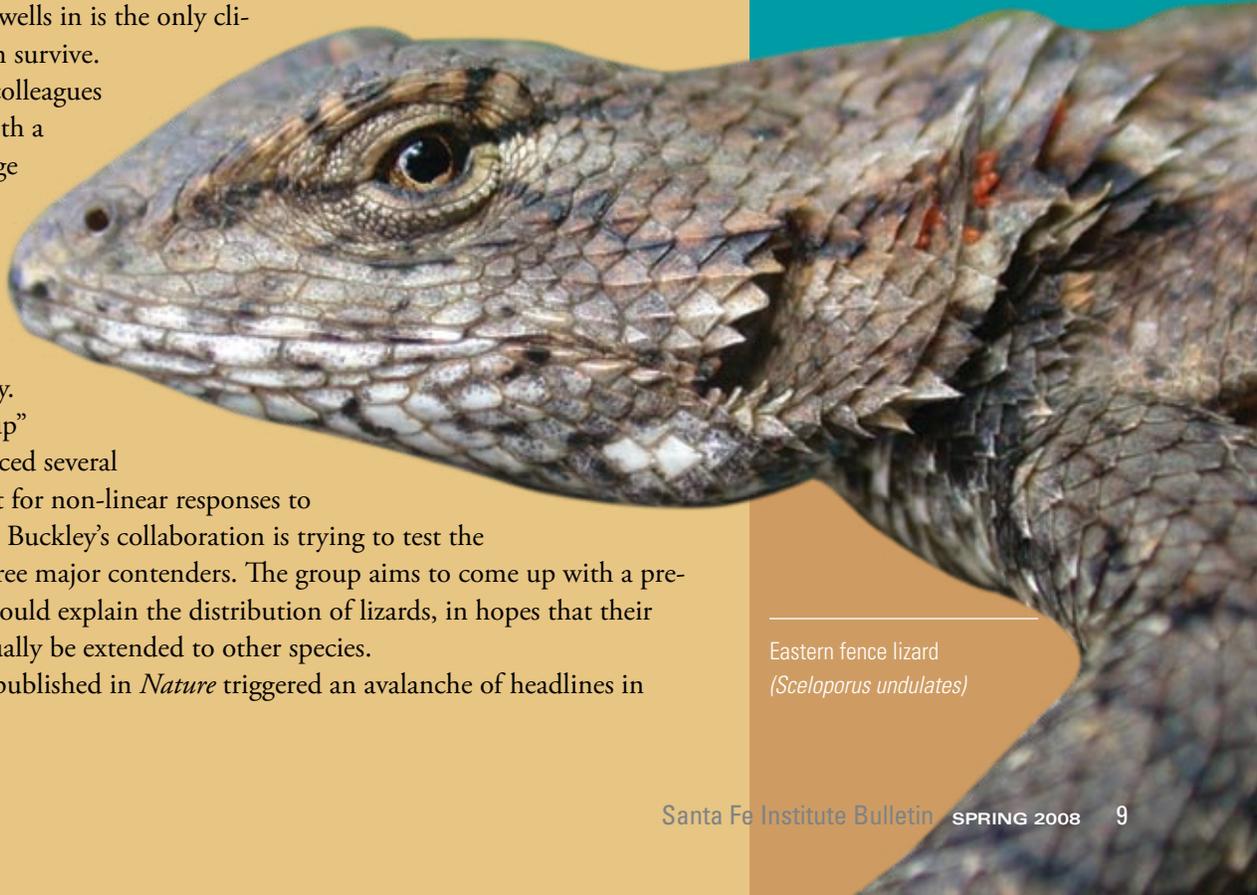
“Who cares about lizards?” Ecology grants usually go to studies of dominant species—large animals that have enough charisma to merit an appearance on *Animal Planet*. So when SFI postdoc Lauren Buckley, along with a group of fellow ecologists, applied for funding to study the eastern fence lizard, she found herself defending the quiet little crawlers. As a result, the humble lizard may change the way ecologists think about global warming.

Buckley and her collaborators are developing a new approach to one of the central objectives in ecology—modeling how wildlife responds to climate change. Most of the current climate-change models fail to explain non-linear migration patterns that have been observed so far, because they assume that as certain temperature zones move north or south, the flora and fauna that inhabit those zones will follow linearly. The models are based on the assumption that the climate an animal dwells in is the only climate in which it can survive.

Buckley and her colleagues hope to come up with a better climate-change model that will predict where organisms can live based on how they forage, reproduce, and use energy. The new, “bottom up” approach has produced several models that account for non-linear responses to climate change, and Buckley’s collaboration is trying to test the relative merits of three major contenders. The group aims to come up with a predictive model that could explain the distribution of lizards, in hopes that their methods will eventually be extended to other species.

In 2004, a study published in *Nature* triggered an avalanche of headlines in

The group aims to come up with a predictive model that could explain the distribution of lizards, in hopes that their methods will eventually be extended to other species.



Eastern fence lizard
(*Sceloporus undulatus*)



INDIANA STATE UNIVERSITY PHOTOGRAPHY SERVICES

Physiological data collection allows ecologists to examine how the variation in physiology across an organism's distribution allows it to live in a diversity of environments. Here, Indiana State University graduate student Joe Ehrenberger loads a fence lizard into a metabolic chamber.

the popular press. “Scientists Predict Widespread Extinction by Global Warming” was the headline that ran in *The New York Times*; “Climate Risk to ‘Million Species’” on *BBC News Online*; and “By 2050 Warming to Doom Million Species, Study Says” on *National Geographic News*. The study estimated the future distributions of plant and animal species using a correlative technique called climate envelope modeling (CEM). The technique infers species’ environmental tolerance from the temperature, precipitation, and seasonality in their present-day surroundings.

Though CEMs are the principle models ecologists use to predict how wildlife will respond to climate change, Buckley and others criticize them for being too simplistic. CEMs assume that the climates in which species currently live are the only climates in which they *can* live,

and that if those climates shift or disappear, the species will follow. Yet there is evidence that species do not simply follow a single set of climactic conditions; data that lepidopterists have collected over the past century indicates that certain butterfly species in Europe have remained stable in the face of a mean temperature increase of 0.8 degrees centigrade, whereas other species shifted northward. An analysis of fossilized mammal remains similarly shows that different species shifted in different directions and at different times during a climate change in the late Quaternary period. CEMs can neither predict nor explain such non-linear behavior.

Buckley’s team of ecologists pursues a new way of modeling. They aim to predict species ranges based on how animals metabolize energy and collectively behave, and in what

temperatures they can gather food and reproduce. Buckley calls it mechanistic modeling. And building a mechanistic model requires not only a new mathematical approach, but extensive data collection and experimentation to ascertain the physiology of the animals in question.

The physiological data for the lizard model will come from a laboratory at Indiana State University. There, ecologist Michael Angilletta and his grad students lower fence lizards into special chambers that measure oxygen consumption. They record the reptiles’ feeding rates, and heat and cool them to find the temperature range at which they remain active. Over the next few years, Angilletta will collect such data from eight different lizard populations.

Once he knows whether lizards collected from different environments have different sensitivities to temperature, he will present the data to Buckley, who will use it to model the species’ environmental ranges. “It takes a lot more time than gathering data from the literature,” Angilletta explains. “The mechanistic modeling is obviously going to take more data because you can’t just get the data from museum records online. You have to collect data on physiology, which is expensive and time consuming.”

The time-consuming data collection will hopefully give

the ecologists a basis for modeling the extent to which the lizards are able to adapt to their environment. Buckley says that the physiological data is important because it indicates the ability of an organism to change: “We’re trying to model the process of evolution, but as a first step, we are examining how the variation in physiology across an organism’s distribution allows it to live in a diversity of environments.”

The group aims not only to produce a good mechanistic model for how lizards respond to climate change, but also to get a sense of how many variables a model needs in order to be predictive. Too few variables make a model inaccurate, while too many make it impractical. Using Angilletta’s data, the group will test three models of varying degrees of complexity, the practical and the predictive. All three of the models represent radical departures from the

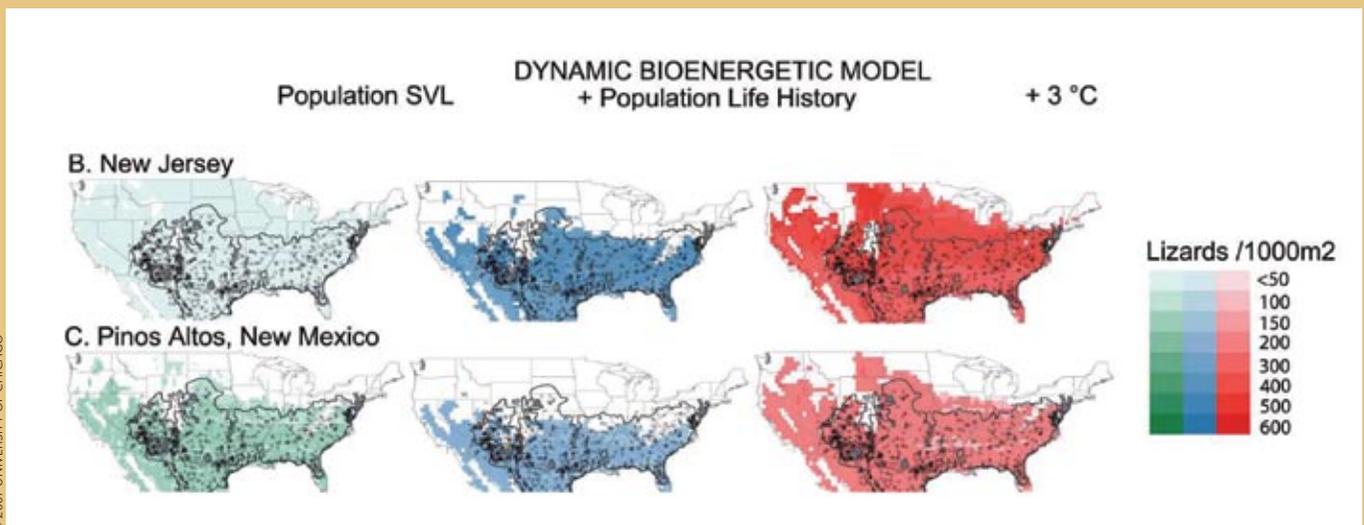
traditional climate-envelope models. Buckley illustrates the radical departure in a paper that will soon be published in *American Naturalist*. In the paper, she compares a mechanistic model with a climate-envelope model by using each to “predict” the current distributions of North American lizards. The maps in the paper reveal a significant difference between the old and new models, and higher overall predictive success for the mechanistic model. Buckley explains that the paper demonstrates that considering a lizard’s biology is important when predicting its distribution. “A central goal of the group’s research,” she writes, “is to incorporate more biology, such as how organisms interact, move, and evolve, into distribution models.”

Buckley is also leading a broader, multidisciplinary collaboration of about a dozen researchers aiming to produce mechanistic distribution mod-

els for organisms as diverse as plants, fish, birds, and mammals. The group will meet twice a year at the National Center for Ecological Synthesis in California and the National Evolutionary Synthesis Center in North Carolina.

They hope the distributional models will be available to other ecologists by October 2009. “All the people who are independently working on mechanistic modeling are going to be in tune with one another, which I think is very cool,” Angilletta says. “If the exercise turns out to be useful and can show that these mechanistic models are more valuable than, say, a climate-envelope model, the way of thinking will spread and other people will go out and tailor the math to their particular systems.” —*Jenna Beck* ◀

BELOW: Range predictions for the fence lizard vary when including population body size (green), population body size and life history (blue), and with a 3° C temperature increase (red).





The Child and Fortune, Leon Bouillon (19th C./French)



Sleep to Repair

“What probing deep Has ever solved the mystery of sleep?”
—Thomas Bailey Aldrich, *Human Ignorance*

The poet and novelist Thomas Bailey Aldrich

died in 1907, just before the birth of modern sleep research. Since then, researchers have advanced the study of sleep with instruments such as electroencephalograms (EEGs), computerized axial tomography (CAT scans), and magnetic resonance imaging (MRI). Some have even begun to identify the molecular signals that accompany sleep and wakefulness. But Aldrich’s words still ring true, and the basic question of why we sleep remains a mystery. There are many hypotheses that offer explanations for the purpose of sleep, but in the absence of a convincing way to test and compare them, no consensus has emerged.

SFI researchers Van Savage and Geoffrey West have narrowed down the quest for a sleep theory by extending their gaze beyond human beings or any single species. In a study published in the January 2007 issue of the *Proceedings of the National Academy of Sciences USA*, the researchers examined sleep times across 96 different mammals. They were able to test various hypotheses that connected sleep to functions in the body and/or brain, ruling out several with a thoughtful examination of sleep times, animal size, and metabolic rates. Having honed in on a quantitative connection between sleep times and the brain’s metabolic rate, the pair put forth a theory that suggests sleep’s primary function is to repair and reorganize the brain. The theory explains why a mouse sleeps 14 hours a day, an elephant sleeps less than four, and a human being falls in the middle with eight. It also provides a basis for further research into the nature of REM sleep, sleep and aging, and sleep times during development.

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Deep inside the brain, a neuron prepares to transmit a signal to its target. To capture this moment, Graham Johnson based this drawing on ultra-thin micrographs of sequential brain slices.



GRAHAM JOHNSON MEDICAL MEDIA / WWW.FIVTH.COM

The idea for a cross-species sleep study came about when Van Savage was pondering biological time scales for animals of different sizes. He knew that most biological times, such as gestation and lifespan, increase in length for organisms of increasing size. Just to be sure, he went to check the data and found that sleep times didn't fit the pattern: they actually decrease for larger animals. "Sleep scales the opposite of everything else—it was a completely different pattern than you see for other biological times," Savage says. "So that made me fascinated from the perspective that it's different. It was really weird, and the more I got into it, the more I realized that sleep is a fascinating subject." Savage asked Geoffrey West, an expert in biological scaling and his advisor, to join the investigation, and they began to read up on sleep literature.

One of the better-known sleep hypotheses they encountered holds that sleep gives rest to the body and brain. This idea has been met with skepticism because sleeping doesn't conserve much energy. The metabolism only slows 10 to 15 percent during sleep, and for humans, the energy saved from eight hours of sleep versus eight hours of sedentary wakefulness is roughly equivalent to the number of calories in a dinner roll.

Another hypothesis says that sleep protects the brain from overheating. The idea was first propounded by Hippocrates around 400 BC, and while thermoregulatory theories have few living advocates of note, they still crop up in lists of potential explanations for sleep. Savage and West elegantly debunked the heating and cooling theory on the grounds that it didn't account for the drastically different sleep times observed in different animals. They speculated that if the theory were true, heating and cooling rates would depend on metabolism (which heats the brain) and brain size (the amount of brain being heated). Because both bear the same relation to body mass, then the ratio between them remains constant for all animals. The thermoregulatory theory would predict that the amount of wak-

ing time, in which the metabolism would heat the brain, and sleeping time, in which the brain would cool, would remain constant for all mammals. Since the prediction flatly contradicted the observed differences in sleep times across species, Savage and West crossed the thermoregulatory sleep theory off their list.

Yet another sleep hypothesis holds that sleep's function is to repair damage in the body and/or brain. Cellular damage is a secondary effect of metabolism, which slowly harms the very cells it keeps alive. When a cell produces energy, it also releases free radicals—the infamous molecules that age cells and damage DNA. To find out whether sleep might serve to repair the damage wrought by metabolism, Savage and West looked at metabolic rates across species. According to Savage, one of the well-known facts of biologi-

**“O peaceful Sleep! until from pain released
I breathe again uninterrupted breath!
Ah, with what subtle meaning did the Greek
Call thee the lesser mystery at the feast
Whereof the greater mystery is death!”**
—Henry Wadsworth Longfellow

cal scaling is that “smaller and hotter” animals generally live life at a faster pace than “larger and colder” ones. Rodents have quicker metabolisms than primates, which have quicker metabolisms than pachyderms. And since sleep times scale in reverse (pachyderms sleep less than primates, etc.), the researchers surmised that the amount of sleep an animal requires might well be dictated by some secondary effect of metabolism, such as the need for repair.

But how to tell if the repair occurs at the level of the body or the brain? The brain seemed a likelier candidate than the body because neurons, unlike other cells, are not replaced when they die. It seemed reasonable, then, that the body would



© NATUREPL.COM

Hibernating dormouse (*Muscardinus avellanarius*) curled up asleep in nest, Sussex, UK.

invest in a daily repair process for the precious cells, and that such a brain-level process might require unconsciousness. The researchers' quantitative tip-off to the connection between sleep and the brain was that sleep times, which generally decrease as body size increases, tended to scale to brain size rather than body size. A horse is 10,000 times larger than a mouse, but its brain is only 1,000 times larger. And while a horse sleeps less than a mouse, its nightly sleep time is not 10,000 times shorter. Savage and West calculated a mass-specific brain metabolic rate: a rate that, when coupled with an animal's brain size, would predict the amount of time the animal devoted to sleep. The rate they calculated fit with rough empirical measurements of brain metabolic rates, so the brain-level repair hypothesis was still in the running.

Though the researchers had traced sleep's primary function to the brain, they didn't have evidence that the process was repair per se. Another of sleep's functions could be processing memories of the waking day. This cortical reorganization might also be governed by metabolism, because small animals with fast metabolisms move more

quickly and have more sensory input in a given period of time than do large and slow ones. Because processing this sensory input might require sleep, neural reorganization fits the metabolic sleep theory just as well as neural repair. In the end, Savage and West did not choose between repair and reorganization. They suspect that sleep may serve a dual function. "A certain amount of your metabolic energy goes into repair, a certain amount goes into reorganization," West says. "At the level at which the theory was developed, it does not distinguish the proportion."

Yet another intriguing finding that fell out of the research was that the fraction of time spent in rapid eye mo-

ment (REM) sleep is independent of body mass. Elephants sleep less than mice, but devote the same percentage of their total sleep time to REM sleep. "We argue that total sleep time is this effect of metabolism that you have to respond to in some way," Savage says. "But then there's REM sleep and it's not clear if it's repair and reorganization or something else." Savage is now looking for clues about the function of REM by studying sleep times in babies, who sleep more than adults and spend a greater proportion of their sleep time in REM.

West points out that the study could also provide a framework for further research into the connection between sleep and aging, both of which tie into metabolism. "People my age seem to sleep less and I don't know why that is," West says. "I'm sure there are people studying it, but I'm not sure anyone understands why that should be. Now when you get really old, you do sleep more like cats, for 15 hours a day. There are a million reasons people sleep for longer times and there are all sorts of factors that are neglected, so this study forms a baseline for trying to discover what those factors are." —*Jenna Beck* ◀

A History of Sleep Research

Ca 350 BC—Aristotle wrote that sleep results from warm vapors rising from the digestive tract.

Ca 400 BC—In the *Corpus Hippocratum*, Hippocrates hypothesized that sleep protects the brain from overheating.

1907—French scientists Rene Legendre and Henri Pieron kept dogs awake for several days and extracted a toxin from their blood serum. When they injected the toxin of the sleep-deprived dogs into healthy dogs, the recipients were induced to sleep. The book that the researchers published in the wake of the experiment laid out a scientific approach to the study of sleep, and is generally thought to be the foundational text of modern sleep research.

1929—Constantin Von Economo, a doctor who treated encephalitis lethargica patients in the wake of the 1918 flu, observed that patients who suffered brain damage in the hypothalamus and preoptic area, succumbed to long periods of sleep and unconsciousness. He posited that sleep is regulated by a specific location in the brain.

1929—Hans Berger, a German professor of neurology and psychiatry, recorded his son's brain waves by attaching wires to the boy's scalp. He published a report on the "Elektrenkephalogramm," or "electroencephalogram" (EEG) in English.

1935—Alfred Loomis used the electroencephalogram to detect different patterns in the brain activity of sleeping persons, hypothesizing that the various EEG patterns corresponded to various states of consciousness.

1953—The "Father of American Sleep Research," Nathaniel Kleitman, and his student Eugene Aserinsky reported in the journal *Science* that rapid eye movement (REM) occurs during sleep. To accompany their EEG measurements, the researchers devised an electro-oculogram (EOG) to record changes in electrical activity, hence, in movement, around the eyes.

1958—William C. Dement, another of Kleitman's students, connected REM sleep to dreaming and found that both cats and humans sleep in REM and non-rapid eye movement (NREM) stages. Scientists would later discover that almost all mammals have REM sleep. (It was once thought that platypuses and dolphins did not have REM sleep. The notion was contradicted for platypuses in 1999, when a group of researchers constructed an elaborate platypusarium and discovered that platypuses actually have more REM sleep than any other mammals. It is now thought that dolphins may spend a very small fraction of their sleep time in REM.)

1967—Michel Jouvet advanced the modern biochemistry of sleep with the observation that the sleep stages in cats depend on the presence of a neu-

rotransmitter. Jouvet also located the area in the brainstem wherein neurons regulate REM and NREM sleep stages.

1968—Allan Rechtschaffen and Anthony Kales published a standardized method for interpreting EEG recordings.

1974—Harold Zepelin and Rechtschaffen published sleep times in different mammalian species, mostly observed in zoos and laboratories.

1979—An analysis of data from the American Cancer Society found that people who slept less than four, or more than ten hours per night had shorter life expectancies. The results were confirmed with a follow-up study between 1982 and 1988.

1989—By experimenting on rats, Rechtschaffen and colleagues concluded that sleep deprivation leads to death in two to three weeks. Deprivation of either REM or NREM sleep killed the rodents over a slightly longer time span. Today there are over 200 sleep centers and laboratories in the United States. A mass of experimental evidence documents the cognitive and physiological effects of sleep deprivation, and there is a widespread effort to research sleep disorders such as narcolepsy, insomnia, and sleep apnea. Researchers have shown that sleep is essential for some forms of learning and processing memories, and they continue to explore the nature of dreams and cognition during sleep.—*Jenna Beck*

patterns of terror

AARON CLAUSET HAS SPENT NEARLY THREE YEARS MODELING THE STATISTICS OF TERRORISM, but holds little hope that a mathematical model can predict whether a given man will walk a bomb into a given café on a given afternoon. He does believe that in large enough social systems, the capricious behaviors of individuals seem to fade in the face of collective patterns. “A classic question that many historians have asked over the years is, ‘Where does individual control end and statistical behavior take over?’” Clauset says. A physicist and computer scientist by training, he is pursuing that question.

His work to date has led him to conclude that terrorist attacks conform to patterns, at least on a global scale. In February 2007, Clauset, a Santa Fe Institute postdoc, and his partners Maxwell Young (now a graduate student at the University of Waterloo) and Skrede Gleditsch (a reader at the University of Essex) published a study in the *Journal of Conflict Resolution* that made a novel claim: the frequency of severe terrorist attacks, when taken worldwide, seems to follow a remarkably simple equation. The statistical distribution fits severe events like 9/11 to the same curve as more common but less severe ones that kill a dozen or so people. The pattern suggests that such rare and large events are not outliers, as was previously thought, but are somehow interconnected with the smaller attacks. The authors claim that if an underlying connection exists, then taking measures to discourage small-scale attacks might also prevent severe ones.

FIRE © ISTOCKPHOTO.COM; DEBRIS © JENNY MATTHEWS / ALAMY

Qana, South Lebanon: A wedding dress shop destroyed by bombing, August 2006.



The authors claim that if an underlying connection exists, then taking measures to discourage small-scale attacks might also prevent severe ones.

The group also found that the global pattern breaks down at the regional scale. The distribution that described the global terrorist attacks did not hold for terrorist attacks within individual countries, possibly because political quirks, cultural and historical factors, and individual caprice play a greater role in smaller regions. Clauset's group would like to understand how the simple global pattern arises from the complex local conflicts, and to that end they are currently studying a single region of conflict.

The study of social phenomena has enjoyed a quantitative renaissance in recent years thanks to an infusion of methods from condensed matter physics. In 1998, Duncan Watts and Steve Strogatz employed a small-world network, which in mathematics and physics is a kind of graph, to formalize a social theory commonly associ-

ics and computation at the University of New Mexico. The professor, SFI's Cris Moore had taught a unit on power laws just as Young and Clauset's mutual interest in analyzing conflict led them to look into conflict databases. When they found the database of the Memorial Institute for the Prevention of Terrorism (MIPT), they were satisfied that the data was copious and consistent enough for statistical analysis. Clauset and Young looked at the 28,445 terrorist events that had occurred since 1968, restricting their analysis to the 10,878 events that resulted in one or more casualties. When they plotted the severity of events against the frequency, the average number of deaths per terrorist attack (about 5) was a poor indicator of the overall distribution, which included events that killed tens and hundreds of people. The data did not fit a bell curve, as would

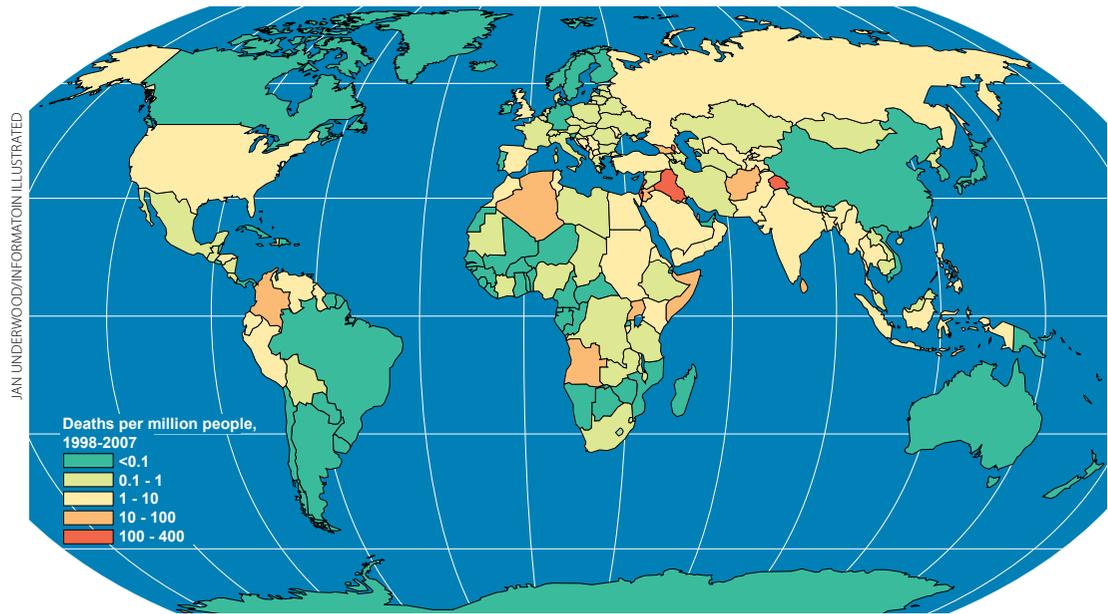
“At a large scale, no single person or group can control very well where the conflict goes, and the statistics, or if you like, the physics, start to take over.”

ated with “six degrees of separation.” Physicist Alberto-Laszlo Barabasi further popularized the physics approach to social phenomenon in 1999 when he claimed to have found a pattern in the distribution of hyperlinks in the World Wide Web. The scientific community took notice, and as more scientists began looking for similarities between complex atomic systems and complex social systems, “physics of society” papers began claiming more space in the top journals. Phase changes, which are typically used to describe the behavior of gasses, fluids, and solids, have been applied to traffic patterns. Power laws, the inverse-square equations that describe gravitation and electromagnetic force, are also thought to fit distributions of wealth, populations of cities, and, now, terrorism.

The inspiration for the terrorism project came after Maxwell Young took a course on phys-

typically distributed events such as heights of people or speeds of cars on a highway. The severe events, like 9/11 and a 1998 car bombing in Nairobi that injured over 5,000, were drastically far from the mean. They made the distribution “heavy-tailed”—and in physics, a heavy tail is the calling card of a power law.

Power laws tend to be exciting to physicists because they are often the direct consequences of other physical laws. They also imply “scale invariance,” which suggests that the small-scale and large-scale events on the curve are generated by the same mechanism. Clauset and Young had to “curb their excitement,” in Young's words, out of recognition that “there are an infinite number of heavy-tailed distributions out there.” In the spirit of caution, the pair developed some new statistical tools for accurately characterizing and testing power law distributions in empirical data.



The power law prevailed as the best fit, with the frequency of events scaling as an inverse power of their severity ($P(x) \sim x^{-2.48}$).

The power law suggested that severe and small terrorist events are interconnected, and that counter-terrorism strategies that succeed on the small scale might succeed in preventing larger events as well.

The challenge that remains is figuring out why terrorism events should follow a power law at all. Skrede Gleditsch, a political scientist and statistician, helped Young and Clauset frame their analysis for a political science audience. “A power law per se is a statistical distribution, and knowing that something fits that is maybe not terribly interesting by itself,” Gleditsch says. “But it might give you some ideas about what kind of processes could generate the distribution.” If severe terrorist events have the same underlying distribution as minor terrorist events, can they be explained by scaled-up versions of the same underlying processes?

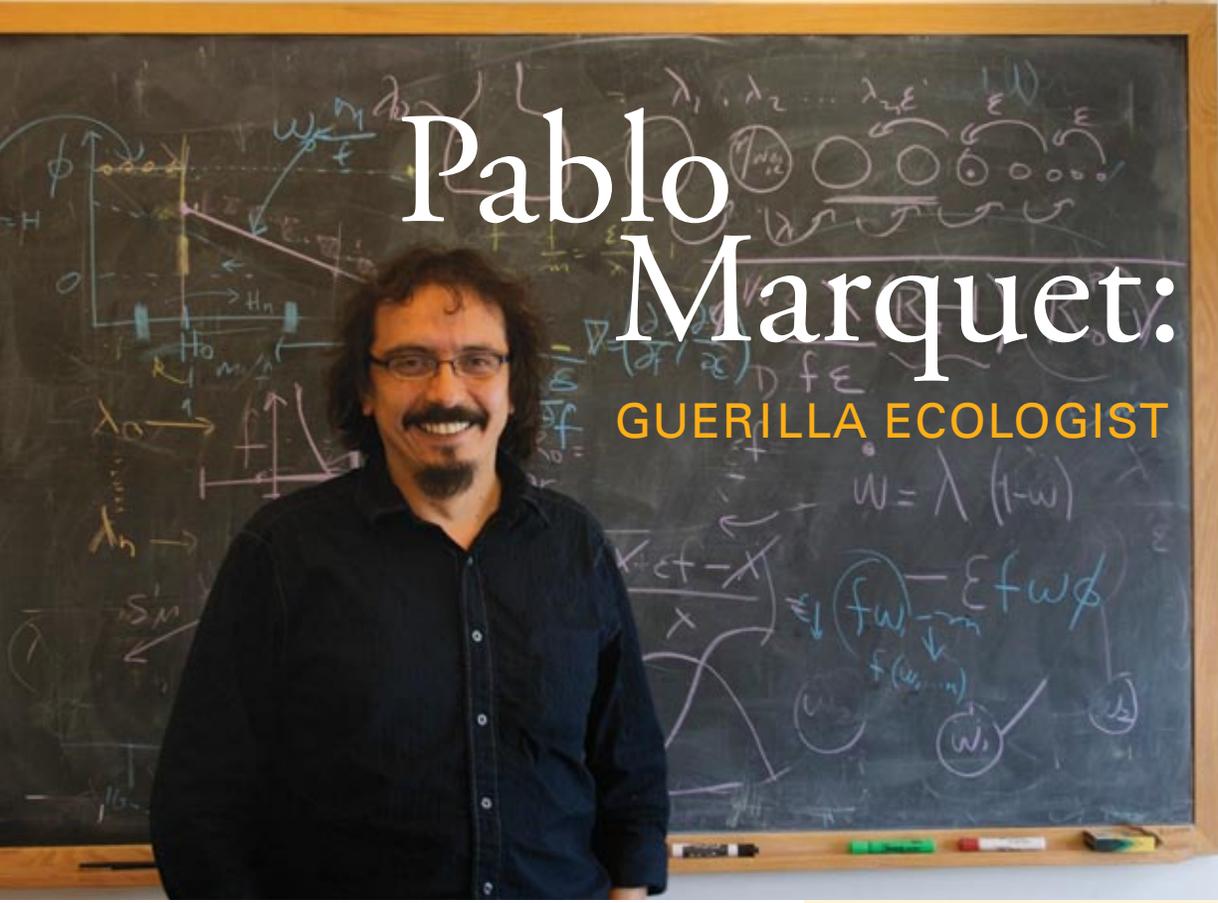
The authors acknowledge the possibility, but do not claim to know what those processes are. “While there are many instances where complex behavior can be plausibly explained by a relatively simple generating mechanism,” Young wrote in an email, “I personally hold out little hope for that in this case.” As a sample explanation, the paper put forth a mathematical toy model that showed the power law distribution as resulting from a game-like competition between terrorists

and states. The paper also calls for new models to convincingly connect the observed distribution to knowledge of the factors that mitigate or contribute to terrorism.

In that spirit, the group is now embarking on a more detailed study of what governs terrorist attacks in a single region. Using the MIPT data and public opinion polls, they are examining the ongoing Israeli-Palstinian conflict. “Instead of looking at the macro level,” Gleditsch says, “we are looking at individual groups so we can try for a more integrative model.” The hope is that learning about the behavior of the complex players in the regional conflicts will lead to a better explanation of the global pattern.

Clauset believes that their success in creating a model will depend on the number of constraints a human system must have before statistics start taking over. He says: “In terrorism, if you look at a small enough scale—say, attacks in Baghdad—at that level it’s extremely strategic, and individual decisions have a large effect on the statistics. But the idea of looking at global conflict or an entire conflict between two sides is that the details matter less and striking statistical patterns emerge. In other words, at a large scale, no single person or group can control very well where the conflict goes, and the statistics, or if you like, the physics, start to take over.” —Jenna Beck ◀

This map illustrates the level of “risk” of terrorist attacks around the globe. “Risk” is defined as the total number of deaths over a 10-year period divided by the nation’s current estimated population.

A photograph of Pablo Marquet, a man with glasses and a goatee, smiling in front of a chalkboard filled with mathematical diagrams and equations. The text 'Pablo Marquet:' is overlaid in large white font on the top half of the image.

Pablo Marquet:

GUERRILLA ECOLOGIST

By
Julie J.
Rehmyer

SFI International Fellow
Pablo Marquet

Nature had called Pablo Marquet years ago by inspiring him to become an ecologist, but now it was calling him in a different way. He rushed through the halls of his crowded university building in downtown Santiago, driven less by his current need than by his excitement. A scientist had just given a lecture that satisfied the frustration Marquet had been struggling with through college.

To Marquet's eye, ecology was filled with all these little studies in little areas giving little results, with no grand theories tying any of them together. But Jim Brown, Distinguished Professor at the University of New Mexico, had just shown how he was turning ecology into a quantitative, predictive science, like physics or chemistry.

Marquet stepped into the restroom and looked out through the smoggy haze at the Andes towering above. He had been even more amazed by what had happened after Brown finished speaking. The great scientists assembled in that room had attacked Brown's theory as a meaningless dead end. But Brown had fought back! He'd defended himself against the combined opposition of the greatest ecologists in North and South America combined.

Marquet had listened to the raging debate quietly. He

was just 21 years old—a college kid, after all—and his English wasn't very good. But now, who should step into the restroom but Jim Brown himself. A thought flashed through Marquet's mind: "Look! I'm here, with this great scientist!" Their eyes met, but Marquet couldn't seem to untie his tongue.

Ideas were already forming in Marquet's mind, however. He was formulating an experiment that would make Brown's theory even stronger.

SNAILS VERSUS MUSSELS: PREDICTING POPULATIONS

What Brown had done was to explore the ecological consequences of a set of beautifully simple mathematical formulas that relate body mass to a remarkable number of biological attributes: metabolic energy, life span, population density, and more. He had also begun to explain why these formulas, called scaling laws, were popping up over and over again throughout biology.

The scientists at the conference had laid into Brown's theories with a number of criticisms, and Marquet thought one of them had some legitimacy. Brown and others had found the scaling laws by pulling together data

TOP: LAURA WARE

Would the laws hold in a real ecosystem, comparing animals that live in direct competition with one another? Would they hold in different ecosystems?

from all kinds of different animals in far-flung regions of the world. Would the laws hold in a real ecosystem, comparing animals that live in direct competition with one another? Would they hold in different ecosystems?

Marquet figured he knew just how to find out. A professor of his was working in two stretches of coastline in Chile that were very similar, except that in one, humans weren't allowed to fish or hunt, and in the other, they were. Marquet realized that these areas were the perfect testing ground for Brown's ideas.

As a community ecologist, Marquet focused particularly on Brown's claim about population density. The theory was almost like a magic trick: give Brown any ecosystem, anywhere in the world, and tell him a particular weight, say 10 grams. Then, Brown said, he could tell you the number of creatures you'd find per acre that weigh 10 grams.

So Marquet wanted to test Brown's claim in his two Chilean ecosystems. As similar as the two regions were, they were a hard challenge for Brown's theory. In the area with hunting, people did all kinds of things that changed which animals prospered and which suffered. For example, people collected giant sea snails to eat, so the area with hunting had fewer snails than the undisturbed area. And that didn't just affect the snails. The mussels prospered when the snails declined, because snails loved to eat mussels. The differences rippled throughout the entire community of animals.

If Brown's laws were really a universal property of living things, then when the snails became rarer, some other creature with the same body size had to prosper. It might be something completely unrelated, like a little bird or a rodent, but the total number of creatures with that body size had to be the same. Similarly, when the mussels prospered, some other small creature—perhaps a barnacle or even an insect—had to suffer. Marquet wanted to find out if that was true.

When Marquet crunched the numbers, the scaling laws

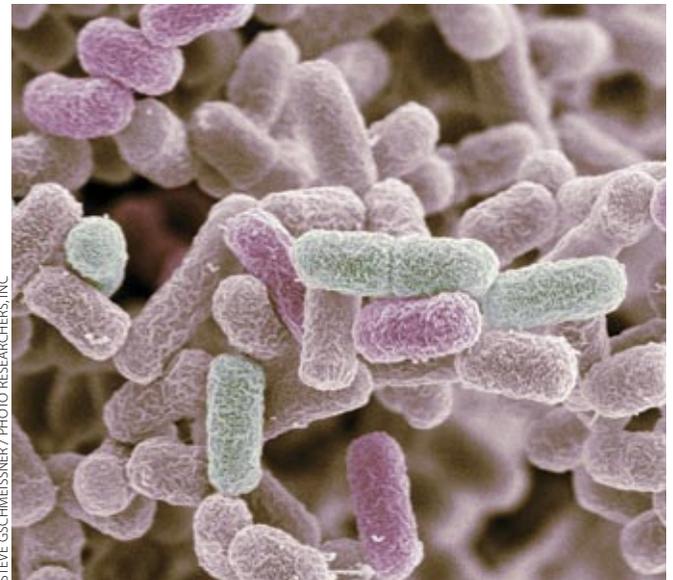
held up just as Brown claimed. "It came out beautifully," Marquet says, "just like the prediction."

Brash kid that he was, he submitted the paper to *Science*. After that, he applied for a Fulbright Fellowship to be a doctoral student with Jim Brown.

Marquet's prediction about his own success was as accurate as his prediction about the abundance of populations. A week after he arrived at the University of New Mexico, the paper appeared on the cover of *Science*. "It was the best presentation any new graduate student could ever have," he says with a smile.

THE BIOTIC BANG

It wasn't long before Marquet was driving through the piñon and juniper highlands between Albuquerque and Santa Fe to attend talks at the Santa Fe Institute. That was the beginning of a life-long association with the place. Marquet has visited periodically ever since, recently as an International Fellow.



STEVE GSCHMEISSNER / PHOTO RESEARCHERS, INC.

In his quest to uncover some of the secrets of how biodiversity develops, Marquet uses bacteria, such as these rod-shaped *E. coli* bacilli.

The International Program at the Institute was begun in 2000 to encourage multidisciplinary collaboration in countries in which little funding is available for such work. The program funds several researchers as International Fellows each year, providing two years of financial support including up to two months in residence at the Institute, developing collaborations with SFI researchers. The Institute also supports fellows in their home countries by providing funds for them to organize workshops or host visitors.

Marquet's presence at the Institute has provided just the kind of cross-fertilization of ideas and approaches that the program intends. "Pablo asks questions and approaches things in a way that I don't think any young scientist who grew up and was trained only in the U.S. or in Britain would have," Brown says. "He is by far the most philosophical of all my former students. His work on ecology is integrated into a worldview that includes the broader science of complexity and a sense of what you might call human ecology, our place in nature."

Marquet has used that philosophical outlook to tackle perhaps the grandest question in ecology: why life first began to diversify. "The physicists try to understand the Big Bang," Marquet says. "Ecologists need a theory to understand the Biotic Bang."

With SFI support, Marquet has organized workshops in Chile, Santa Fe, and Santa Barbara that have gathered ecologists together to puzzle out an approach to the problem. He also worked with another SFI International Fellow, David Storch of the Center for Theoretical Study in the Czech Republic, to organize a workshop in Prague. Marquet, Storch, and Brown edited a book from the conference, entitled *Scaling Biodiversity*, which has just come out this year.

ONE BACTERIUM'S WASTE IS ANOTHER'S FOOD

In his own research, Marquet is working with his former student Juan Keymer and SFI postdoc Miguel Fuentes to understand a simple experiment. In the process, they hope to uncover some of the secrets of how biodiversity developed. Put a single species of bacterium into a flask in some medium that provides food and the bacteria will reproduce madly. If you keep supplying medium for the bacteria to eat, they will continue to prosper, but should

you forget, the bacteria will eat up all the food and then the population will crash.

If you are really neglectful and never pour in more medium, a surprising thing happens: a few bacteria continue to live. Despite the lack of food, the population continues at a very low level. After a while, the population will even begin to grow again. But soon thereafter, it experiences another crash. This boom and crash cycle continues for a while, until it somehow stabilizes into a continuing population of bacteria.

Marquet explains that what happens is that after the bacteria consume the initial medium and mostly die off, a mutant evolves with a remarkable innovation: it is able to consume the waste products of the original bacteria as food. "They're eating the dead bodies of their fellows," Marquet says.

The new mutant thrives until it is outcompeted by a new mutant better able to eat the waste from the previous mutant, and it repeats the cycle. The population stabilizes when mutants coexist and a whole community of bacteria evolves. Marquet, Keymer, and Fuentes are developing a mathematical model to understand this process more thoroughly, with hopes that the process may illustrate secrets behind the initial development of biodiversity.

Marquet has undertaken this line of research while at the Santa Fe Institute, and he sees an analogy in the work for the fruitfulness of the Institute. "At SFI, there are a lot of mutants, so you can create innovation just like the bacteria," he says. "Eventually, we can create a sort of food web where my throw-away insights can be your resources so we can produce something together. At the end of the day, we are like a bacterial biofilm."

Part of Marquet's unique contribution to the SFI community, Brown says, comes from his breadth of interests and ability to make surprising connections. "He reads a lot of literature, really philosophical literature. He'll sometimes say something that will change the whole tenor of conversation and send it in a new, more creative direction. Often it is by analogy, similar to the way that Isabel Allende uses alliteration in her novels."

SCIENCE WITHIN A DICTATORSHIP

Marquet's scientific projects reflect that breadth of interest. At the same time as he works on his speculative



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La Portada, Antofagasta, Chile: When Marquet applied Jim Brown's theory to a coastal region in Chile, the laws held up just as Brown claimed. "It came out beautifully," Marquet says, "just like the prediction."

theory-building, he also tackles an enormous variety of practical ecological problems. He is developing models to understand how climate change is likely to affect Chilean ecosystems. He is collaborating with archaeologists to understand why a hunter-gatherer society in Chile that lived 8,000 years ago had enough energy and resources to make elaborate mummies of their dead. He is also studying the patterns plants form in the Chilean Atacama Desert, which is the driest desert on earth.

Marquet has now returned to Chile, and he is committed to continuing both his practical and theoretical work there. He has been tempted to move to the United States, where he has more colleagues interested in the speculative work that he loves. But he notes: "I have a huge impact in Chile in terms of students, connecting people to my network of colleagues, changing how the system works, bringing new perspectives, and making it easier for people thinking in more theoretical ways. I would probably be just one more scientist in the States or in Europe."

He also recognizes the stamp of Chile in his own ways of working. Chile, he says, is like an island, removed from the rest of the world on one side by the Andes and on the other by the Pacific. Just as creatures on an island tend to evolve into unique forms that are different from creatures

on the continent, Chilean scientists themselves develop unusual patterns of thought.

Marquet grew up during the years of Augusto Pinochet's reign, and he says that in many ways, Pinochet's dictatorship had a very bad effect on science. It limited funding for science and created an atmosphere of fear in which people were afraid to speak their minds. That was part of why he was so astonished by Brown's bold defense at the conference in 1986.

"The process of maturation in science is to find your own voice, finding yourself saying something that you believe in," he says. "That process is a combination of art and science. It's an act of creation, and I think that a dictatorship is not the best environment for creativity."

But he notes that the dictatorship also bred an attitude in the best Chilean scientists that he respects and embraces. "It's guerilla science, with 100 percent passion. I really love that spirit, feeling that what moved you to do this is such a strong force that you will overcome any obstacle." ◀

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

Malware Wars

BY DEVON JACKSON

■ **Vulnerabilities versus patches.** Robustness versus phishing. Botnets versus evolvability. And complexity versus spam. Some of these terms and concepts are central to the work and philosophy of the Santa Fe Institute. Some, though, are more specific to the world of the Internet—as complex a system as any organic one.

The predators and parasites of this system are known as malware. Usually defined as software designed to infiltrate or damage a computer system without the owner's informed consent, malware (a combination of “malicious” and “software”) ranges from computer worms, viruses, and identity theft to spam, spyware, and adware—as well as botnets, distributed denial-of-service attacks, phishing, pharming, and zombies. It's a multi-billion-dollar criminal industry, with its own language (called Eblish—an amalgamation of English, text messaging-speak, email-speak and whatever language happens to be native to the user, say, Nigerian, Mandarin or

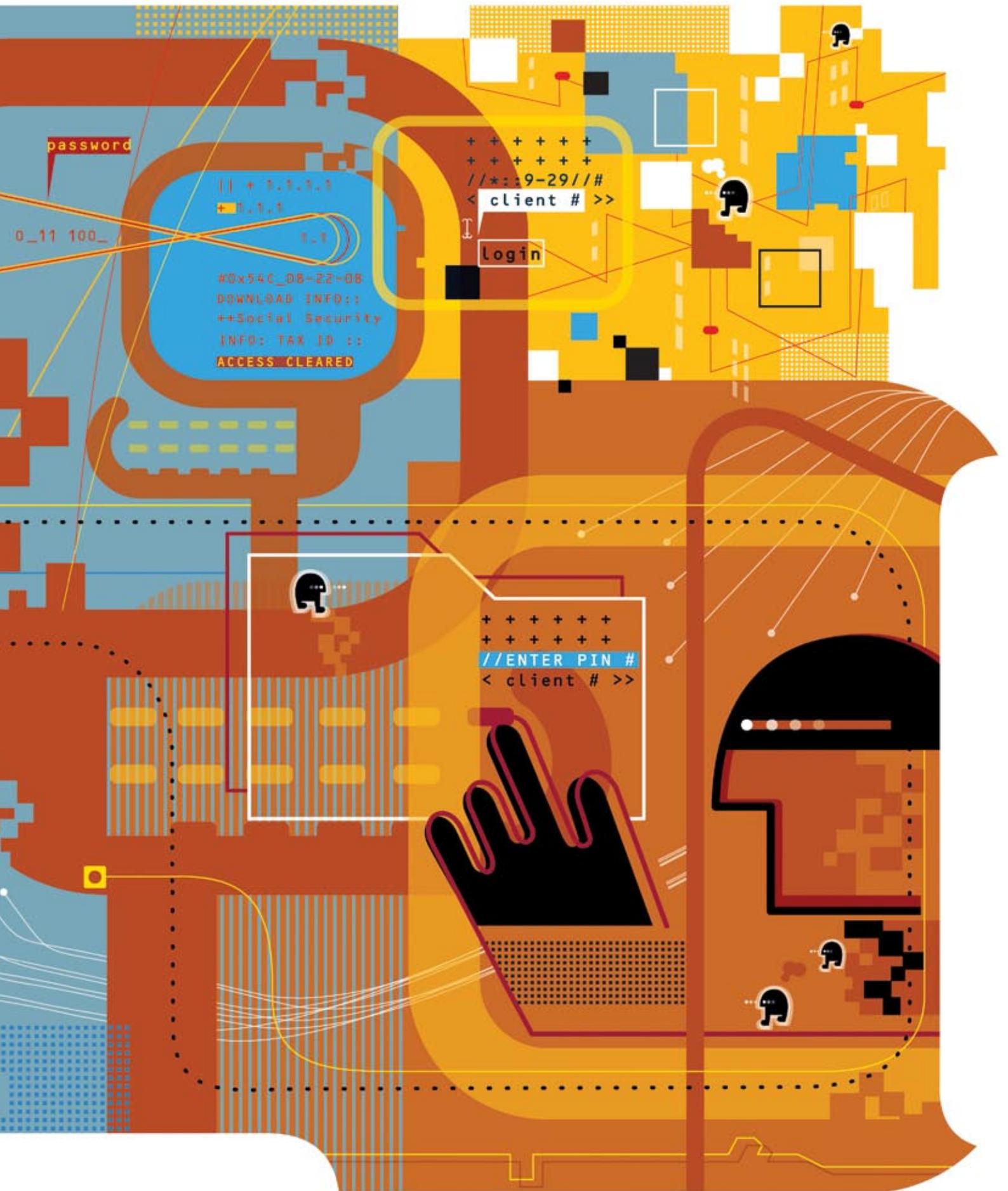
Romanian), and an emerging market economy. Malware's effects reach far beyond computers, and some fear that it threatens to drive the Internet, as most people know it, to extinction. That's why the Santa Fe Institute again agreed to host, for the second straight year, a workshop on how to deal with this potentially disastrous phenomenon.

This year's workshop, like the first, was organized by Matthew Williamson, a principal research scientist at Sana Security, and Eric Davis, a senior policy specialist at Google. The two-day event, entitled “Fighting Modern Malware II,” included participants from academia, private corporations, and the government.

And beyond its economic and social impact, malware is the perfect lab rat for anyone interested in complexity, interconnectedness, and evolution. It's real, and it's global. As SFI Vice President Chris Wood observed, “Malware raises issues of evolvability, robustness, and diversity. It is computation in the wild.”



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password

0_11 100_

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|| + 1.1.1.1  
+ 1.1.1
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#0x54C_08-22-08  
DOWNLOAD INFO: :  
++Social Security  
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ACCESS CLEARED
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+ + + + +  
//*:9-29//#  
< client # >>
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login

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+ + + + +  
+ + + + +  
//ENTER PIN #  
< client # >>
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According to a recent survey, “The 2007 Malware Report: The Economic Impact of Viruses, Spyware, Adware, Botnets, and other Malicious Code,” conducted by *Computer Economics*, a monthly information technology newsletter, the worldwide economic impact of malware is in decline: dropping from a high of \$17.5 billion in damages in 2004 to \$14.2 billion in 2005 to \$13.3 billion in 2006. But *Computer Economics*’ editors cautioned against over-optimism: “Although direct damages of malware may be declining,” they wrote, “the indirect or secondary damages are likely increasing.” As pointed out by Stefan Savage, associate professor of computer science and engineering at the University of California at San Diego and the director of the school’s Collaborative Center for Internet Epidemiology and Defenses (a joint effort between UCSD and the International Computer Science Institute), “We really don’t know precisely how big this problem is, but we know it’s large and growing.”

Hence, a prevailing sense of urgency (if not impending doom) among the workshop’s 18 participants. “My fear is that the horses are already out of the barn and it’ll be impossible to get them back in,” said Howard Cox, the Department of Justice’s Computer Crime Division assistant deputy chief.

“We’re in the third generation of this. The juveniles of yesterday—the hackers and the Defcon wannabes—have turned into adults and have figured out, ‘We can now make money at this thing.’” He noted that the economic incentive makes it almost impossible to stop people from

getting into malware. “We’re dealing with a criminal enterprise equivalent to the Mafia, and one that has no leader,” he added.

Malware’s engineers are moving at warp speed. But the guys in the white hats, as the anti-malware folks sometimes call themselves (or, alternatively, the Jedi Council), have had their hands tied. “These bad guys exist in a world without boundaries,” said former Secret Service agent Robert Rodriguez, a sentiment echoed by Google’s senior staff engineer,

Malware is the perfect lab rat for anyone interested in complexity, interconnectedness, and evolution. It’s real, and it’s global. As SFI Vice President Chris Wood observed, “Malware raises issues of evolvability, robustness, and diversity. It is computation in the wild.”

Niels Provos, an expert on honeypots—computer systems set up as traps for attackers. “The development and acceleration of malware in China and elsewhere has gotten to the point where we can’t keep up,” he said.

“We’re just not adapting quickly enough,” added Pittsburgh-based FBI agent Michael McKeown, who, like Cox, sees a trend toward organized crime and a global network. “We are doomed to be reactive,” warned Savage.

Given that 80 percent of all malware attacks originate outside the U.S., American authorities often find themselves in dire need of cooperation from authorities in the country from which the malware was initiated. And the situation would be easier if other countries had similar laws to those in the U.S., or any laws at all. Many, however, have yet to even outlaw malware, much less understand it. Still, as difficult as it may be to prove that, say, someone in Latvia sent out a virus, it’s Cox’s belief that the laws currently in place are, for the most part, adequate. “We have the laws we need,” says Cox. “What’s lacking is attribution, number one, and getting data from other countries. Beyond that, we also need more reporting of Internet crimes—both from our own private businesses and from our government agencies.”

And, as if to add emphasis to his point about the adequacy of existing laws, Cox recently reported to the group the arrest of Alan Ralsky, the self-proclaimed “King of Spam.” Cox emphasized, “As I stated at the conference, the criminal justice process is not the first line of response in addressing malware, but to the extent that malware is a form of computer crime, this case demonstrates that even kings are not out of reach.”

The Jedi Council Versus the Malwarts

So, in a world where everyone’s vulnerable but no one is accountable, who should be held liable? The browser? The user? The Internet service provider (ISP)? “The decision on where you invest your effort is

In this fictional scenario, an attacker (green) hires bot herders (blue) to give instructions to zombies—computers infected by their malware (white), which hit designated targets.



ABOVE: CATALOGTREE.NET FOR WIRED MAGAZINE

important,” said Savage. “In malware, the problems change so quickly. Last year’s problems are not this year’s problems.” The moving target of malware makes it hard to figure out where to invest one’s efforts—viruses sent over email are not the problem they once were. Instead, attacks sent via browsers and malicious web pages are a growing threat.

Which is why it’s just as important to determine *how* to invest one’s effort. Given that exploiting a weakness is usually easier than patching it up, no wonder the containment, let alone defeat, of malware seems a Sisyphean task. “Our patches to fix up holes is like the whack-a-mole game, only in technological terms,” said Savage.

It’s a problem of scale, as well as speed—one software bug equals mil-

lions of compromised hosts. The bad guys can scale up faster because they have no laws, no rules, and no boundaries. The good guys—banks especially, agreed the Jedis—remain loath to share information with each other, with law enforcement, with their customers, or the public. Competition frustrates cooperation, and intellectual property laws, too, serve to suppress anti-malware innovations.

And the problem with most anti-malware innovations is that they tend to come at the expense of overall ease: one more lock on the door may slow down an intruder but it also slows down the owner when getting in or out—and that newfangled new lock won’t come free, either. “If we introduce frictions (anti-malware actions) into the equation,” said Savage, “then

we introduce them into the transaction cost.” The goal is to put a drag on the bad guys without imposing an equal amount of drag on the good guys. Otherwise, the future looks rather Orwellian. “My fear is that in the effort to secure the industry, we’ll see people’s rights trampled,” said Vincent Weafer, a member of Symantec’s Security Response Team. “And that there’ll be these country-wide firewalls enacted under the guise of security.”

Whatever technological solutions arise out of the workshop, most of its participants more or less agree that economics drives malware. Take the incentives away, devalue them, or redirect malware engineers toward beneficent incentives, and the Internet may survive. “My hope is that we can

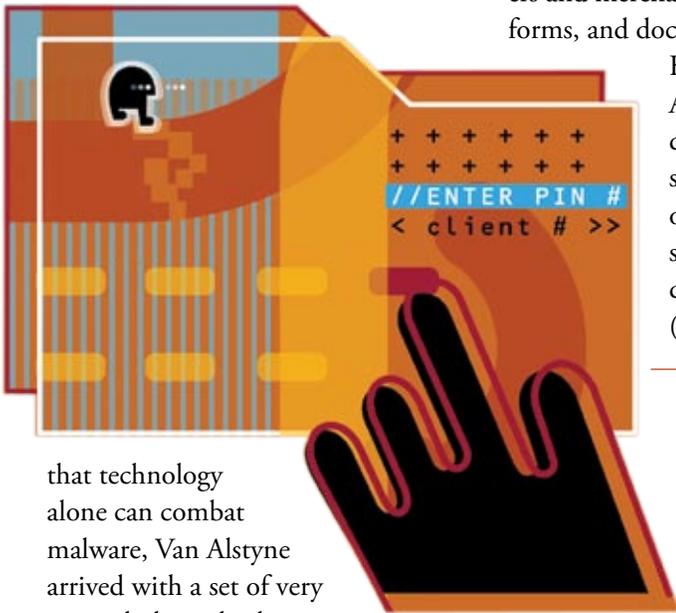
find economic disincentives so that people don't use malware or invest in it," said Ari Schwartz, who works on privacy and government-information issues for The Center for Democracy and Technology, a nonprofit advocacy group that helped various anti-spyware companies form a coalition.

"We need to attack their revenue streams," declared Marshall Van Alstyne, an associate professor at Boston University and visiting professor at MIT who specializes in the economics of information. An avowed skeptic

plained, exists when one party to a transaction has more information than another party. Principles of information asymmetry can be used to force the more knowledgeable party to disclose what they know. This method can help reveal someone's true intentions, for example, when they want a party to read their message or install their applet. Two-sided networks, he explained, are matching markets with two distinct user groups who provide each other with benefits. Common examples include cardholders and merchants on credit card platforms, and doctors and patients on

HMO platforms. Van Alstyne, who helped develop theories of two-sided networks, pointed out that they often have sophisticated fraud-detection techniques (similar to those used

from an observer's perspective than an economist's. He presented some of the mechanics of malware's underground economy. Malware has gone from being a reputation economy—in which people hacked for kudos—to a complex, stratified profit economy, in which people are innovating all the time. "They even try to phish each other and ruin each other's reputations," said Lance James, author of *Phishing Exposed* and an expert on phishing and malware who heads up Security Science Corporation's External Threat Assessment Team. (Phishing uses social engineering tactics as a way to obtain access to user names, passwords, identity information, credit cards, and other personal and corporate data; it also relies heavily on botnets, software robots that run autonomously and automatically, usually on groups of zombie computers controlled remotely.)



that technology alone can combat malware, Van Alstyne arrived with a set of very nontechnological solutions.

In a quick overview of his paper, "An Economic Response to Unsolicited Communication" (i.e., spam—which costs about \$50 billion a year in losses and makes up 92 percent of all email), Van Alstyne outlined a very cogent and rather elegant three-pronged attack, based on the economic principles of information asymmetry, two-sided networks, and externalities.

Information asymmetry, he ex-

plained, exists when one party to a transaction has more information than another party. Principles of information asymmetry can be used to force the more knowledgeable party to disclose what they know. This method can help reveal someone's true intentions, for example, when they want a party to read their message or install their applet. Two-sided networks, he explained, are matching markets with two distinct user groups who provide each other with benefits. Common examples include cardholders and merchants on credit card platforms, and doctors and patients on HMO platforms. Van Alstyne, who helped develop theories of two-sided networks, pointed out that they often have sophisticated fraud-detection techniques (similar to those used

to catch credit card and insurance fraud), that can be applied to fight malware. Lastly, externalities may be useful. An externality is an impact (positive or negative) on any party not involved in a given transaction. Van Alstyne showed how liability laws that are currently in place for other types of cases might be applied with success toward malware problems.

How have hosts fought off parasites in the past?

Hope that the host is robust enough, implied Gleichauf, Savage, and others, to withstand a parasite as nasty and evolvable as malware.

So, proposed Savage and James, the solution may be to attack the malware market, as well as its still intact reputation-based system. They also advocated attacking the malware industry economically, disrupting its efforts to launder its profits.

Is Complexity Science the Solution?

Economic solutions. Technological solutions. Legal factors, industry factors. Phishing, patching, spamming,

friction. Do they work? Will they? Or does it just boil down to so much tilting at windmills? Or might it all simply be part of some grander digital design that's still evolving?

Enter Lee Altenberg, an associate professor in the Department of Information and Computer Sciences at the University of Hawaii who teaches exclusively online and specializes in evolutionary theory and population genetics. He thinks that programs behave enough like organisms that some lessons from nature might be applicable to the Internet and malware. Altenberg gently coaxed the complexity cat out of the malware bag.

A major contributor to the complexity discussion was Robert Gleichauf, a former Ph.D. candidate in anthropology who is now the Chief Technology Officer for Cisco's Security Technology Group. A realist as well as a ponderer, he is anything but blasé about the effects and potential of malware; nor does he see it as a necessary evil, or think that the death of the Internet is imminent. He does, however, believe in leveling mechanisms, and keeps an eye out for events that can lead to large evolutionary swings. "Yes, we need to minimize the impact of perturbations," says Gleichauf, "but, after all, there's a life cycle of information. Things tend to find their stasis point."

"The question is," he continued, "when you factor in the losses against the total amount of money going across the Internet, at what point is the pain of losses so high that you take action?" He asked later on, during one of the workshop's tactical sessions: "How much of malware

crime levels itself out? If you can isolate these upper-tier forces—not the ankle-biters—will they regulate themselves?" And later still, he speculated, "If we stop trying to improve the Internet, our products and all things related to it, maybe they'll stop."

Robustness to the Rescue?

Malware is parasitic on the software, hardware, systems, and users of the Internet. How, then, have hosts fought off parasites in the past? In nature? In other economic systems? What's the proper co-evolutionary response, if any? Hope that the host is robust enough, implied Gleichauf, Savage, and others, to withstand a parasite as nasty and evolvable as malware. Gleichauf, for one, wanted more discussion on robustness. It's his belief that email systems are robust enough to survive. "But that's not so in banking," he said, "which is founded on trust, which doesn't work electronically."

Or do we latch on to a punctuating event—some major shift or development—mused Gleichauf, to escape the parasites? "Is there a punctuated event about to happen?" he asked. "Right now, that's what we're looking for at Cisco: the browser versus the mobile market," referring to the current merging of computer technology with technology that's mobile, such as phones and iPods.

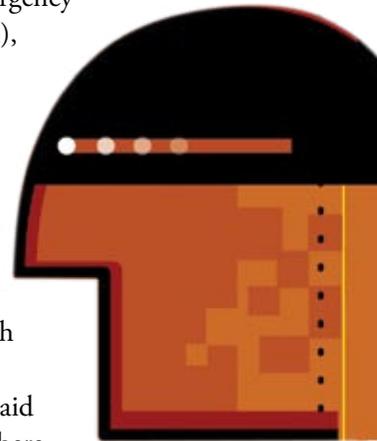
Eventually, the complexity-fueled debate came back to the threat itself. "The rate of evolution for bad guys is so much higher," said Savage. "Malware has such high evolvability, it may evolve to the point where the Internet is no longer useable."

"What we're trying to do," said Gleichauf, "we're trying to maintain the functionality of old systems."

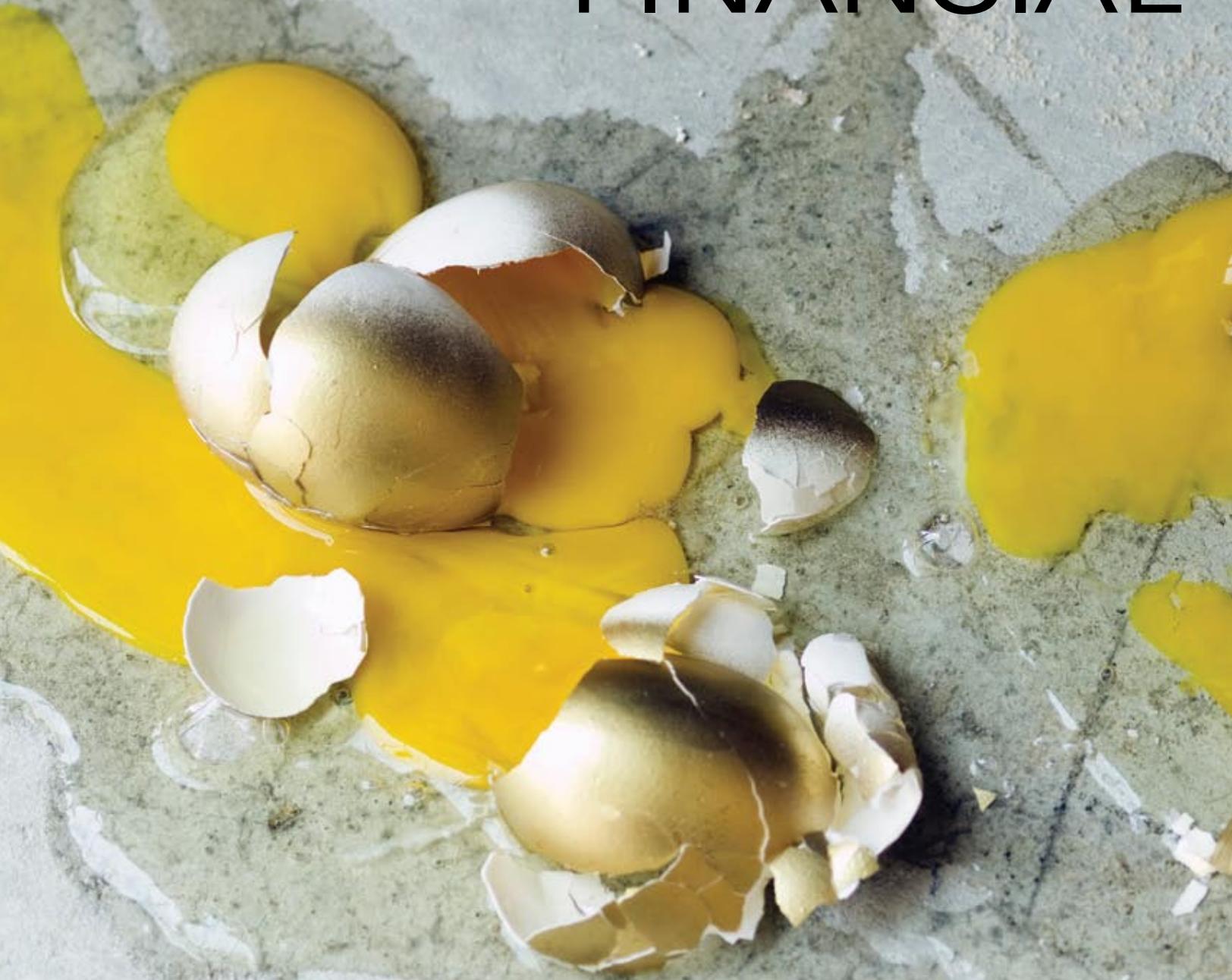
Old, antiquated, not as robust as they need be. And doomed, perhaps, though no one has yet given up. If anything, meetings such as this, and other SFI workshops, which encourage collaboration and cross-pollination, infuse participants with a renewed sense of purpose. In this case, the group will come up with a set of anti-malware action points. They will hold regular meetings, both real and virtual—that will include representatives from the banking industry, the insurance industry, U.S. CERT (the Computer Emergency Readiness Team), Amazon, eBay, Yahoo and/or Earthlink, and Microsoft. Beyond that, they also want to establish a malware research institute.

"My hope," said Davis, "is that there are livable boundaries. That there will be a malware crime rate, that's pretty much unavoidable. But people will know what to do and what not to do." That's the hope anyway. ◀

Devon Jackson is a freelance writer based in Santa Fe. He writes regularly for Southwest Art, and has written for Smithsonian, Outside, The New York Times and many other magazines and newspapers. He is also the author of Conspiranoia!



RISK IN FINANCIAL



MARKETS—

Learning from Nature

BY JOHN WHITFIELD

On July 19, 2007, the Dow Jones Industrial hit 14,000 for the first time. Less than a month later, it was below 13,000, and was still there three months later. Nor was this a local American difficulty: as of early December the Bank of England had spent £30 billion (\$60 billion) propping up the Northern Rock bank, one of the United Kingdom's most notable lenders, which had invested, and lost heavily in the U.S. subprime mortgage market. The European Central Bank, which is responsible for maintaining stability of the euro, spent \$205 billion propping up markets across the continent.

Not surprisingly, the mortgage crisis and its secondary effects on other markets were on everyone's mind at a forum in New York in October 2007 on modeling risk in financial markets, co-hosted by the Santa Fe Institute and SAC Capital Partners. Why do such crashes happen? And how can we design and regulate markets to reduce the risk of them happening in the future?

Many of the speakers looked to biology for ideas, comparing the behavior of financial and ecological systems, and hoping to learn from the adaptations that life uses to deal with risk and

uncertainty. And one of the hottest questions in biology—and another focus of SFI research—is, what makes ecosystems robust, and what causes them to collapse?

It certainly looks as if finance might have something to learn from biology about stability. Author and hedge fund manager Rick Bookstaber pointed out that despite the U.S. economy as a whole being more stable, with fewer recessions and less variation in gross domestic product (GDP), financial markets have become less so. This destabilization seems to have come from within: Michael Mauboussin of Legg Mason Capital Management and Columbia University reported that four-fifths of the large movements in markets are uncorrelated with outside events such as terrorist attacks, elections, and so on.

One key consideration for both financial and ecological systems is the link between their diversity and their stability. In nature, changes in diversity—for example, when a species is lost from a place—can trigger a cascade of secondary extinctions among species that depended directly or indirectly on the missing species, either for food or to keep their own predators in check.



AP PHOTO / RICHARD DREW

Traders on the floor of the New York Stock Exchange, Monday, August 6, 2007. Stocks fluctuated in early trading that Monday following a sharp pullback the previous Friday.

As humans increasingly dominate and manipulate wild ecosystems, understanding this process takes on a keen practical importance.

And yet what makes for robustness and stability in ecology, and how this relates to diversity, is still unclear. It might be that the flow of insight can go both ways: the goldmine of data on decisions, strategies, and their effects to be found in stock market transactions can tell us something about how, in general, the behavior of many individuals—each pursuing a particular goal, be it money or offspring—creates large-scale dynamics and emergent patterns. SFI researchers, working to take the comparisons between the two systems from the metaphorical to the concrete and quantitative, certainly hope so.

In both biology and finance, diversity can mean lots of different things. Genetic diversity within individuals, and between the offspring of a single individual, seems to be a means of coping with external threats and environmental uncertainty. For example, animals, including humans, prefer

Why do such crashes happen?
And how can we design and regulate markets to reduce the risk of them happening in the future?

the scent of potential mates whose immune-system genes are different from their own; it's thought that this makes for healthier offspring. Queen honeybees mate with many males—at the cost of increased physical wear and tear and exposure to predators—but the resulting increase in the genetic diversity of their brood makes for a more able workforce and a better-functioning nest. And species in harsh and unpredictable environments, such as annual desert plants and shrimp that breed in ephemeral pools, produce offspring that spread their germination or hatching over a number of years. Many ecologists see this as a form of bet-hedging, a means of reducing the variance in their reproductive success.

Such forms of diversity are analogous to one of the central tenets of finance: keep a diverse portfolio. Fund managers try to ensure that the performance of their various holdings is not too closely correlated. They are paying to reduce variance: their whole portfolio will not hit the jackpot at once, but nor will it all go south at once. “Moderation is key,” said Aaron Brown, a risk manager at AQR Capital Management. “The idea is to do a little of a lot [of different things], so that you do well in the good times and survive the bad times.”

But, Brown added, you can't tell which stocks are synchronized until they all move at once. A famous example is the 1998 collapse of the hedge fund Long Term Capital Management (LTCM). The fund sought to risk-proof its investments by assuming a 30 percent correlation between their performances, far higher than that usually seen. But when the Russian economy collapsed, this correlation went up to 70 percent,

and the fund went out of business. LTCM had no exposure to Russian markets, just as Goldman Sachs's Global Alpha Fund, one of those worst hit during recent events (although Goldman Sachs as a whole has done well), kept away from subprime mortgages. The problem was that in both cases, the funds that did hold such mortgages sold other assets that LTCM and Global Alpha held, causing their value to fall. Highly leveraged funds, such as LTCM and Global Alpha, were then forced to sell, which caused the price of their holdings to fall, which forced them to sell more, and so on. LTCM lost \$4.6 billion in four months; Bloomberg, one of the top financial news sources, has reported that Global Alpha might end 2007 \$6 billion worse off than it started, a 60 percent decline.

The network structure of the market may have exacerbated the effects of the problems in the mortgage market. Ironically, the collateralized debt options—where mortgage debt was parceled out and sold on to other investors—that widened the impact of the subprime mortgage crisis were intended to *reduce* risk, by spreading the loans. But this seems to have increased risk, by making the banks overconfident about who they loaned money to. Brown compared subprime mortgages to a contagious person infecting others with their disease. How such contagion spreads through markets is still poorly understood, as is the markets' network structure at all scales, from the transactions within a market to the way that, for example, the mortgage market affects the stock market.

Market structure is not the only network that affects how markets behave. The social network of dealers is also important. Jason Karp, director of research at CR Intrinsic Investors, a division of SAC Capital Advisors, told the New York meeting that traders' strategies are heavily influenced by their social contacts. "People make investment decisions based on a note written on a napkin," Karp told the meeting. Such social connections can also spread damage, he said: influenced by

their friends, traders buy stocks that they know little about, only to sell them at the first sign of trouble, again creating a downward spiral in prices. The crowding in markets caused by this sort of copying behavior is an important, but poorly understood influence on their behavior, he said.

In general, there was a sense at the meeting that diversity is a good thing, that diverse systems should show smaller fluctuations and quicker recovery times, and that loss of diversity augurs trouble. For example, crop monocultures can be wiped out by a single pest or pathogen, and the onset of groupthink in a market—when the wise crowd becomes a Gadarene herd—is thought to herald a crash. Some studies using agent-based models, which simulate the behavior of large groups of interacting individuals, seem to bear out this view.

On the other hand, both Karp and Bookstaber suggested that one source of instability in markets



JOHN M. COFFMAN / PHOTO RESEARCHERS, INC.

The yucca moth (*Tegeticula yuccasella*) is the yucca's only pollinator. Scientists find such dependency in nature can provide insight into what happens in financial markets.

(although this view is controversial) is the increasing number and complexity of financial instruments such as derivatives, which allow investors to speculate on the performance of a market or stock without actually buying that stock. And it is still not clear what diversity actually means,



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Easily influenced by their friends—like sheep—some traders buy stocks that they know little about, only to sell them at the first sign of trouble, creating a downward spiral in prices.

in financial terms. Here, ecology might provide an insight, because it seems that it's not species diversity per se that counts, but what you do with it—robustness or volatility results as much from the form taken by the network of interactions between the different players as from the number of players.

Early theoretical ecologists also thought diversity a good thing. In 1955, Robert MacArthur hypothesized that the more links there were between species, the more stable the ecosystem, as it reduced the destabilizing effects of any one species becoming dominant. A large number of links, he suggested, is easier to achieve in more diverse communities. But in 1972, Robert May turned the field on its head—and launched the modern study of how diversity and complexity influences ecological stability—in a now-classic paper in which he showed that if you add species or links to a randomly structured network of in-

teracting species it becomes less, not more stable, with species more likely to go extinct. Ecologists have spent the past quarter century trying to reconcile May's model with their observations that nature is full of large groups of species interacting in complex ways, and with field and lab studies suggesting that more complex, diverse ecosystems, in fact, show smaller fluctuations in their population sizes.

Ecologists are pursuing a variety of ideas, sometimes conflicting, about what gives rise to stability, which—like diversity and complexity—has been defined in several ways. One significant difference between real ecosystems and May's model is that species interactions are not random. Using data and models drawn from real-life food webs (networks describing who eats whom in ecosystems), researchers including SFI research fellow Jennifer Dunne have found that they show consistent non-random patterns in their degree distribution (how the number of feeding links per species is distributed across the whole set of species). Dunne has shown that highly connected food webs, with many links between the different species, are less likely to experience cascading extinctions from loss of a particular species or set of species, and thus are more robust than simpler, less well-connected webs.

Models also show that food webs, like other networks such as the Internet, are vulnerable to loss of the most highly connected players. But it turns out that in real systems, highly connected species are very unlikely to go extinct. In a study of the food webs of fish and plankton species living in lakes in the Adirondacks, Dunne and colleagues found that the species most vulnerable to extinction are the ones that result in the fewest secondary extinctions. This suggests, at least in the absence of human manipulation, that the structure of ecosystems maximizes biodiversity persistence. Researchers are now trying to deduce what shapes ecological networks into these robust configurations—forces such as natural selection or thermodynamic constraints on energy

flows within the food web might each be at work.

SFI Professor J. Doyne Farmer, who also spoke at the conference, has been exploring the connections between biology and finance for a decade. For example, he compares different strategies—such as value investors, who look for companies whose share price underestimates their true worth, and trend-followers, who bet that a rising market will continue rising, and vice versa—to species. Farmer also draws parallels between the amount of money invested in each strategy to its population size, and the flow of money through a market to the flow of energy through a food web. He has found that the same mathematics used to describe how predators and prey affect each other's population dynamics—thought to be another contributor to the robustness, or otherwise, of ecological systems—can also describe the way that different trading strategies interact with one another.

Recently, Farmer and his colleagues obtained access to transaction data from exchanges in London, Spain, New York, and Taiwan. The Taiwan data set, for example, has tens of billions of trades, with information on who made them. This will allow the team to analyze financial markets in unprecedented detail. In effect, they hope to fast-forward through the past 250 years of the study of species, from basic taxonomy (identifying and classifying the different strategies found in the market), to cutting-edge ecology (understanding the interactions of different strategies, and their effect on the market as a whole). If one strategy increases its profits while another slumps, for example, the former might be said to be preying on the latter. And over periods of months to years, evolutionary changes in strategies and composition of the market may also emerge.

Ultimately, the team hopes to be able to reveal the market's network structures, and to test the idea that diverse markets function better than homogenous ones. This, in turn, could reveal the effect that the rules governing exchanges, such as the charges levied on different forms of trades, have on individual trades, and how this influ-

ences the health of the market as a whole.

Wild fluctuations in markets are difficult to explain with the dominant theory in financial economics—the “efficient market hypothesis”—which assumes that the behavior of markets reflects rational actors making the best use of perfect information. In this case, any volatility reflects accurate adjustments to new knowledge. But there is increasing evidence that perfect rationality cannot explain the behavior of markets, and that some, or much, of their volatility is noise that impedes decision making. Understanding the sources of this noise should help reduce it, and improve markets' performance.

Of course, even the best-regulated market is vulnerable to human error; the subprime mortgage crisis was triggered by old-fashioned bad decisions—loaning money to people who couldn't pay it back.

Of course, even the best-regulated market is vulnerable to human error; the subprime mortgage crisis was triggered by old-fashioned bad decisions—loaning money to people who couldn't pay it back. Most organisms and ecosystems have been around long enough to have experienced repeated cycles of good times and bad, and, as the food webs of Adirondack lakes show, to come to terms with a variety of stresses, so that dealing with risk is an important part of their makeup. They know that bubbles burst and easy money cycles don't last forever. Perhaps the world of finance could learn from life that, in the long term, survival is a more realistic aim than victory. ◀

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

When Diversity Vanishes

BY DON MONROE

Complex systems, from ecologies to economies, do interesting and unexpected things. Much of this rich behavior can be traced to the networks through which the underlying “agents” affect each other. Often, however, diversity of the agents themselves is essential. If they act too similarly, the entire system can cease to function. At the annual symposium of the Santa Fe Institute Business Network, November 1–3, 2007, an array of experts explored this “diversity collapse” in contexts ranging from ecology and the food we eat, to finance and organizational structure.

ECOLOGICAL COLLAPSE

The most dramatic diversity collapses are mass extinctions, which have wiped out much of life five times in Earth’s history. Doug Erwin, of the National Museum of Natural History and SFI, said that one of these, the end-Permian extinction, wiped out “90 to 95 percent of everything in the oceans, about 70 percent of everything on land, and by all accounts was about the best thing that ever happened to life on Earth.” The extinctions made room for later innovation—but not right away. “Eventually the diversity got bigger than before, but it took four million years to even get started.”

In contrast to some observers, Erwin does not believe that we are entering a “sixth wave”

of extinction. “At least if we’re lucky, we’re not,” he said. Nonetheless, “the crisis is real.” Erwin emphasized that there are many types of diversity, which do not have the same impact. For example, individual species on different branches of the tree of life forms can become extinct without substantial effect, but losing the same number of species on a single branch could eliminate that entire branch.

Global extinction reflects the combined changes in smaller, individual ecosystems around the world. Andrew Dobson of Princeton University described what he called “probably the best-studied” ecosystem: the Serengeti National Park in Tanzania. Established in 1951, this park and the surrounding areas provide “a natural example of what happens when we perturb an ecosystem,” he observed. Outside the park, the ecology changes dramatically because of farming and grazing. The difference is most notable at the highest trophic levels in the food chain, Dobson observed.

Dobson contributed to the Millennium Ecosystem Assessment, which framed the contributions of healthy ecosystems, at least in part, in terms of the economic “services” they provide to people. Almost half of the value, Dobson said, comes from the most basic level, including bacteria, and another one third from plants. These lower levels also tend to be more resilient. Higher trophic levels, including grazers and



The Global Seed Vault on the Norwegian island of Svalbard opened in February 2008. Descending almost 500 feet under the permafrost, it is designed to withstand earthquakes, extreme temperature fluctuations, and bomb blasts.

ABOVE: DEAN C.K. COX
predators, are more visible but provide less value, he said. They are also more sensitive to changes, so “monitoring these brittle species gives an early warning” of damage.

“We have a scarily short time scale to understand how ecosystems collapse,” Dobson commented. “Most large natural ecosystems will be destroyed in the next 30 to 50 years. The quality of human life on this planet is dependent on the economic services supplied by those webs.”

Historically, said Mercedes Pascual of the University of Michigan and SFI, ecologists viewed complexity in food webs as an essential feature

of healthy ecosystems that helps them to resist disruption. In contrast, monocultures, such as the endless fields of U.S. Midwestern corn, can succumb to a single pest.

The important work of Robert May in the 1970s, however, showed that complexity actually reduces stability in some mathematical models. Ever since, Pascual said, ecologists have tried to understand “how more realistic structures lead to higher stability.”

Instead of studying small perturbations as May did, Stefano Allesina, of NCEAS, and Pascual looked at major shifts such as the disappearance



© GARY COOK / ALAMY

Natural ecosystems, which have evolved complex webs of interactions, are ideally “managed” by leaving them alone. The images above and on the facing page depict the contrast between the pristine land of the Serengeti National Park in Tanzania and land outside the park, where grazing and other uses have prevailed.

of prey causing a predator to become extinct. They also used food webs taken directly from ecological studies instead of mathematically generated networks. They then determined which pathways are functional and which are redundant, from the perspective of secondary extinction, and found that in real webs about 90 percent of connections are functional, independent of the size of the ecosystem.

As a result, Pascual observed, “Even when secondary extinctions are not observed, the loss of species makes ecosystems more fragile to further extinctions.” There may be little warning of an approaching “tipping point,” in which the entire ecosystem collapses.

Pascual suggested that work by SFI External Professor Ricard Solé may clarify the dynamics of interacting populations contributing to extinctions in these ecological networks. In his model, as species continually become extinct and new ones immigrate into a region, the food web forms a self-organized state, with many of the features observed in real webs.

Although the system as a whole seems static, individual species are not. “Individual populations...are all going up and down like crazy,” Pascual said. These fluctuations at one level may even enhance the stability at a higher level. The extinction of individual species may therefore be a misleading measure of the loss of diversity.

The question of the best level for gauging diversity also arose in work by Katia Koelle (Penn State), Sarah Cobey (University of Michigan), Bryan Grenfell (Penn State), and Pascual on the evolution of flu. Genes evolve continuously, but often with no effect on the “phenotype”: the surface proteins that determine immune response. The researchers modeled genetic evolution coupled with the prevalence in the human population of immunity to particular variants. In this model, viruses multiply rapidly whenever they take on a new phenotype, quickly crowding out other variants. “This pattern of boom and bust is explained by an interaction of genetic drift and selection, and not exclusively one or the other,” Pascual said.



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MANAGED ECOSYSTEMS

If the ecologists are right, natural ecosystems, which have evolved complex webs of interactions, are ideally “managed” by leaving them alone—when possible. In stark contrast, agricultural crop management resembles control theory—an engineering tool developed for much simpler systems—and features simplified ecosystems that depend heavily on external inputs. Much of the corn in the U.S. is grown with petroleum-derived pesticides and fertilizer, and fed to cattle whose excrement then becomes toxic waste rather than nutrition for plants.

An alternative was described by Joel Salatin, who recovered marginal land in Virginia by using cow manure to fertilize the grasses that are the natural food for cattle. But Salatin complained that the many regulations aimed at industrial-scale production present formidable barriers to small farms like his.

In spite of such efforts, local production is likely to be an anomaly in an industrial food system that prizes cheap and abundant food. But

Cary Fowler of the Global Crop Diversity Trust asserted that this system depends on underappreciated diversity of plant varieties.

Even as agriculture has focused on fewer species over the past 12,000 to 15,000 years, Fowler said, “diversity in some sense was increasing,” as farmers in different regions selected variants with different traits. “There are about 120,000 different varieties of rice, each as distinct one from the other as a Great Dane from a Chihuahua,” he commented.

Industrial agriculture, Fowler said, threatens this variation within species, although scientists still cannot agree on how to measure it. In response to new challenges, he wondered, “can we continue to develop our agriculture without diversity?” His answer: “Obviously we can’t.”

The expected global warming in coming decades makes these issues especially urgent. “My guess is we are ill-prepared for this kind of change,” Fowler said. “But if we are prepared, it will be because of the gene banks and the diversity they contain.”

“My guess is we are ill-prepared for this kind of change,” Fowler said. “But if we are prepared, it will be because of the gene banks and the diversity they contain.”



Numerous gene banks have been storing seeds for crops and other plants around the world. Unfortunately, Fowler said, many of them are poorly funded and maintained. He stressed that for a modest cost—an endowment of some \$250 million—“we can conserve the gene pool of our major crops in perpetuity.” As a start in this direction, Fowler’s organization is funding a facility above the Arctic Circle to provide a global seed repository, sometimes called the “doomsday vault.”

VALUING DIVERSITY

No such vault exists to preserve human culture. “The forces of homogenization are rampant,” said Suzanne Romaine of the University of Oxford. She described the rapid extinction of languages, as large ones like Mandarin, Spanish, and English spread at the expense of smaller ones.

As a linguist, Romaine values languages as data for her own work. But she sees linguistic extinction as part of a larger problem. “It’s not just languages that are at stake, but forms of knowledge,” she said. “They can’t be separated from people, their identities, their cultural heritage, their well-being and their rights.” She also stressed that language diversity and biodiversity often disappear together.

In a similar way, shared communication drives a homogenization in computer systems, said Gabriela Barrantes, of the University of Costa Rica and SFI. The dominance of Microsoft in personal computer software is only the most visible example of this diversity collapse, she said.

This uniform computing environment is sensitive to threats, just as monocultures are vulner-

able to agricultural pests. Barrantes and Stephanie Forrest, of the University of New Mexico and SFI, have been exploring how artificial variability in computer systems can slow the spread of malware. In any successful scheme, she stressed, computers must still interoperate with similar performance and cost.

Diversity can be introduced at many levels, Barrantes said. For example, the well-known “buffer overflow” attacks rely on long data spilling into areas of memory intended for programs. Varying the locations of these segments can often thwart the spread of infection between different machines. This kind of artificial diversification is “currently being used in two major operating systems,” Barrantes said.

Diversity collapse in computer systems is probably well ahead of that in ecosystems, Forrest suggested. But she noted that “adding diversity back in is much easier than it would be in the natural world.”

The dominance of Google, eBay, and others shows that “online niches are often winner-take all,” notes Virgil Griffith of the California Institute of Technology and SFI. But Griffith claimed that “promiscuous interoperability” can promote diversity by allowing people to use data for new purposes. “When all-powerful monocultures make data available, diversity flourishes,” Griffith claimed. “The users diversify the monoculture, not the other way around.”

DIVERSE PERSPECTIVES

In finance, diversification reduces risk by spreading money among assets that respond differently during market moves. But during the 1998 international financial crisis, Long-Term Capital Management suffered enormous losses when its ostensibly diversified investments began to react

PAULA EASTWOOD

LEFT: Though much industrial agriculture favors cheap and abundant food, a great deal of diversity, such as these varieties of beans, can still be found.

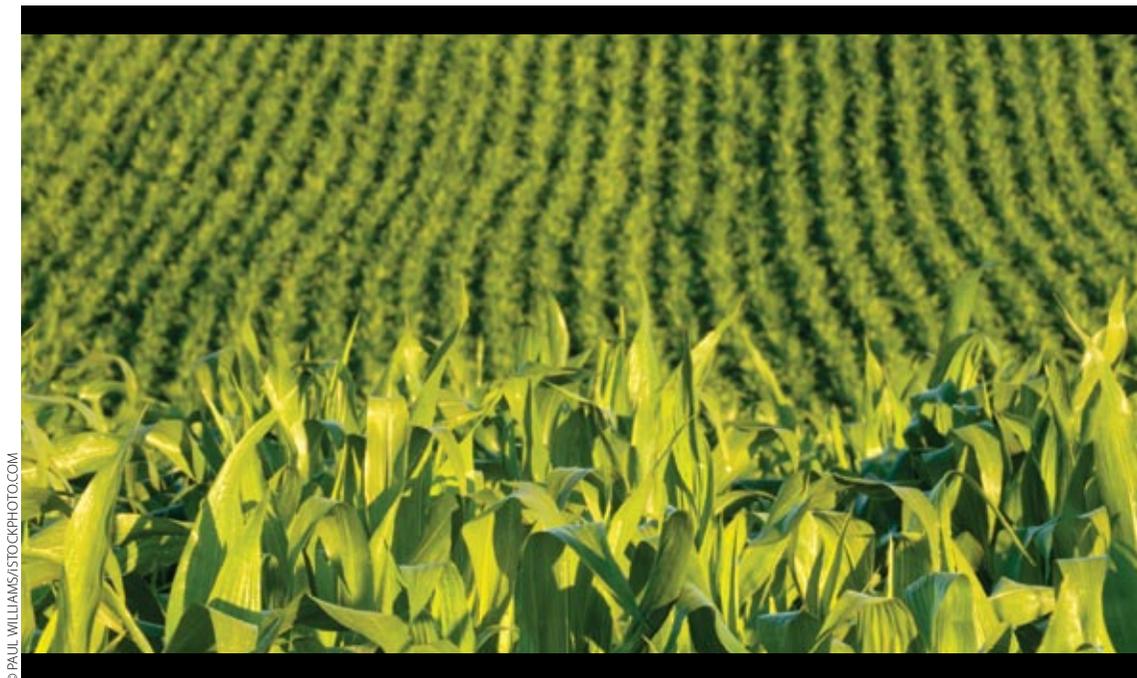
similarly as other investors desperately sold the same assets (see “Risk in Financial Markets” in this issue). “Diversity collapses are really the source of inefficiencies in markets,” asserted Michael Mauboussin, Chief Investment Strategist at Legg Mason Capital Management and an SFI trustee.

Mauboussin reviewed three theories for how markets become efficient, meaning that prices reflect value. The first, in which all investors behave rationally, is unrealistic. A second explanation, which requires only that some investors exploit—and thereby remove—arbitrage opportunities, “has failed us in critical junctures,” he asserted.

Mauboussin contrasted these models with a view of “markets as a complex adaptive system, where prices essentially emerge from the interaction of many agents.” In this view, also called “the wisdom of crowds,” three conditions assure efficiency: diversity among investors, an aggregation mechanism, and financial incentives. Of these assumptions, he said, “the most likely to be violated is diversity,” which may decline imperceptibly until it suddenly collapses.

Scott Page of the University of Michigan and SFI, has compiled many ways that diverse groups outperform individuals. In expert judgment, for example, as in diversified portfolios, the average judgment of a group is always better. “This is not a feel-good statement, this is a mathematical theorem,” Page said. For problem solving, having multiple strategies can help a group evade roadblocks that hamper any one approach.

“In human systems,” Page said, “the thing that really works against cognitive diversity is selection.” The increasingly global marketplace of ideas selects the current “best practices” at the expense of other approaches. “If the world is flat,



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we cannot count on the right amount of diversity existing,” Page said.

Page warned that merely recognizing the advantages of cognitive diversity might not be enough to preserve it. “Diversity’s benefits may be public goods that are not in any one’s interest to maintain.”

One way to maintain diversity is through time-varying selective pressures that prevent one idea from dominating. However, Page showed a simple model in which such churn did not prevent uniformity. He suggested that maintaining diversity also requires diverse selective processes or richer networks, so that the criteria for picking winners varies.

The broad range of speakers at this symposium shows that the Santa Fe Institute is in no danger of diversity collapse, although similar principles apply in very different fields. Still, in the world outside, increasing interconnectedness seriously threatens diversity in both human organizations and ecosystems. ◀

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Complexity in food webs helps them resist disruption. In contrast, monocultures, such as the vast fields of U.S. Midwestern corn, can succumb to a single pest.



Economics and Markets as Complex Systems: A Postcard from the 2007 Complex Systems Summer School

By Daniel Rockmore

Every June, an effervescent and diverse mix of graduate students and post-doctoral fellows, plus a few junior faculty and even a handful of business folk, come to the Santa Fe Institute Complex Systems Summer School (CSSS). The CSSS is a four-week intellectual sprint designed to introduce a new generation of researchers to the ideas and techniques of complex systems. A four-week course can't possibly touch on every aspect of the discipline, so each week is given a theme. The 2007 CSSS began with a week-long introduction to the fundamentals of the subject, outlining its physical roots in chaotic dynamics and the basics of agent-based modeling. Week two provided a deep look at the new science of networks and at ecological systems—all of which was good preparation for the third week's focus on financial markets. Week four touched on allometry and scaling laws in biology—for which SFI has become so well-known—as well as epidemiology and evolution.



In this article we look at some of the ideas explored during “Markets Week.”¹ The markets are a fantastic and data-rich example of a complex system. In fact, part of SFI’s beginnings can be traced to the bringing together of physicists and economists (at the behest and with backing from then Citicorp CEO John Reed) to understand the global financial market as a complex system.

economist Leon Walras (1834–1910). For Walras, the physical forces that could hold an object at rest, the so-called “balance point,” were directly comparable to the “forces” of supply and demand that would eventually balance out to create a market equilibrium price.

As Smith pointed out, the analogy has many flaws—chief of which is that it neglects the possibility for a physical system to move forever about an equilibrium point. To the audience’s delight, Smith introduced the term “analogon” to describe alluring but incorrect (or even dangerous) scientific analogies.²

Although Walras’s analogizing of mechanics and markets was a misstep, it sowed the seeds of an interesting idea. The study of markets through the lens of physics and the tools of relatively sophisticated mathematics began to gain adherents, and the metaphor of mechanics was soon replaced by a new physical analogy, in the form of classical thermodynamics. With its laws describing the behavior of a perfect gas—relating temperature, pressure, and volume through equations of state—the analogy would be one of a market driven toward an equilibrium assignment of goods or an equilibrium price, like a gas in a container compressed by a piston. As Smith pointed out, this comparison also falls prey to analogons, chief among which is the path-dependent nature³ of most economic processes. In recent work with External Faculty Member and New School Professor Duncan Foley, Smith gives the analogy more solid foundations, showing that for “quasi-linear economies”⁴ there is a mapping or dictionary that essentially allows one to use classical thermodynamics to draw rigorous or formal conclusions regarding the market of interest. However, while the technical analogy makes sense, it is, Smith says, debatable as to whether or not these quasi-linear economies are a reasonable model of reality. The lesson is to apply a healthy skepticism at all points of the investigation.

The NASDAQ (National Association of Securities Dealers Automated Quotations), the largest electronic screen-based equity securities trading market in the U.S., lists approximately 3,200 companies

Beware the “Analogon”

The compressed form of the CSSS lets participants see the interrelations among different complex systems, be they ecologies, economies, societies, or brains. But good science requires more than analogies. Identification must lead to investigation, careful consideration, and brutally honest evaluation to see where an analogy holds, where it is useful, and where it falls apart.

Appropriately, Markets Week began with a cautionary tale of the use of scientific analogy in the study of economics and markets. “Neoclassical economics,” the modern paradigm of markets in which price emerges out of the competing pressures of supply and demand, has been interpreted in the light of contemporaneous physical discoveries and theories. SFI Research Professor Eric Smith gave a wonderful thumbnail sketch of this history—which becomes something of a pre-history of econophysics. This dialogue is generally thought to have begun with the French

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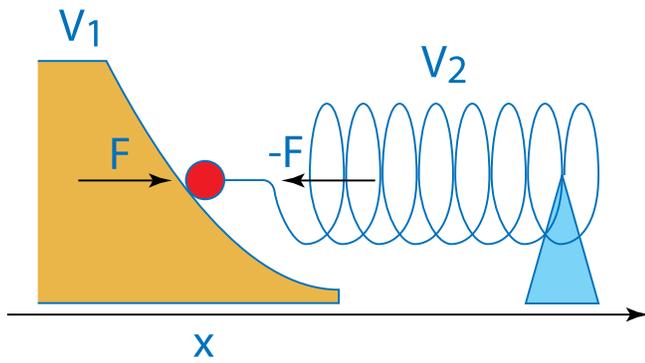
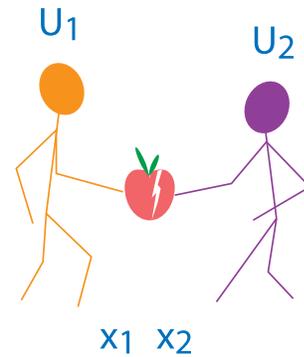


Figure 1: A cartoon comparison of forces on a ball rolling down a hill that will result in its equilibrium position at the bottom versus the “forces” of supply and demand that result in an equilibrium price for a good.



Nevertheless, the thermodynamics analogy is alluring, and closer to what you might call the complex systems ethos, of an emergent structure born of relatively simple interactions among a multitude of individuals. In thermodynamics, these are the trillions upon trillions of particles of varying energies, bouncing around some container according to the laws of classical mechanics, collectively giving rise to temperature and pressure. In the markets, it is a variety of many competing participants, from individuals to institutions, working in the marketplace, which gives rise to price.

Of course, particles in a box have no agency, and the degree of agency assigned to market participants is a critical component of any market model or simulation. The spectrum ranges from the “zero intelligence” model, which mirrors the random motions of particles in a box, to the traditional “homo economicus”—the fully rational and omniscient actor capable of optimizing behavior in light of total information. An interesting interpretation of “rationality” is to consider how much of market dynamics derives from institutional constraints as opposed to individual preference. In this view, zero intelligence means a dynamics completely driven by the rules of the marketplace, while homo economicus is a way to get at a model in which purely internal (“personal”) concerns create social allocations without institutions. Presumably, reality lies somewhere between these two extremes, but even zero intelligence can provide a fair amount of insight into some aspects of price dynamics. In particular,

Smith showed how even a rule-based marketplace accompanied by the inevitable mismatches that occur in the random arrival of buyers and sellers with random ranges of requirements and constraints (the “continuous double auction”) is able to replicate many of the characteristic statistics of the price dynamics of the actual marketplace while simultaneously exposing various dependencies of the dynamics of order flow.⁵ We may be closer to zero intelligence than we know...

The dynamics and market effects of order flow were also in part the subject of the lectures of Smith’s colleague (and sometimes co-author), SFI Research Professor J. Dooyne Farmer. Farmer discussed the interplay of order flow and market impact—the effect that a trade has on the price of the thing traded. He also explored what a science of finance and markets might look like, pointing out where current theory (one that puts the paradigm of equilibrium at the center of all considerations) falls down and explaining the importance of simulations based on more realistic assumptions.⁶

Both zero intelligence and full rationality have the advantage of enabling (in many cases) analytic solutions for their models. At intermediate levels of rationality, mathematical proofs are relatively rare. Instead, we can turn to the world of agent-based simulations and artificial markets. In these *in silico* markets, a large population of participants (the agents) trades a generally small number of assets. The agents have a range of strategies—behavioral rules dependent on their risk aversion and the state of the market—which is some simple function of market observables. These agents generally have “bounded rationality”: they know something about the global

situation, know something about history, and have some simple update rule for making trading decisions and evolving their strategies. In outline, this is similar to the many program trading formats widely used today—they are constrained by partial market information and have hard temporal constraints for executing their strategies. The agents' (and programs') strategies reflect traits such as degree of risk aversion, market depth, and memory of past market behavior. The fun (i.e., surprise) in these models lies in the strategies' evolution—poorly performing strategies go the way of the dodo, while productive strategies persist and possibly adapt, finding trading niches. Questions abound: Do various populations and update rules generate a market equilibrium? How sensitive are the dynamics to the changes in parameters? Are there recognizable regimes of behavior in the parameter space?

The CSSS was treated to four lectures on agent-based markets by SFI External Professor and Brandeis Professor of Economics, Blake LeBaron. LeBaron was one of the developers of the Santa Fe Institute Artificial Stock Market, which was among the early agent-based markets. LeBaron went over a good deal of the basics on how these markets are constructed, and discussed some more recent work in which he and his colleagues have built artificial markets with heterogeneous “investors.” These models generate market dynamics that replicate much of the behavior usually associated with the time series of a given stock price, such as distributions with “fat tails”⁷ the “persistence” of trading volume,⁸ the so-called “long memory” of volatility (meaning that price fluctuations persist), and correlations between volatility and volume. In particular, LeBaron finds connections between persistence and the modification of individual strategies via imitation of known successful strategies in an order-driven market.

Markets—A Top-Down Networks View

Agent-based models are “bottom-up”: the system's laws of interaction are specified, with the

hope that this seed will grow into the dynamics of the whole system. The art is not to simplify too much—remember Einstein's admonition: “Make everything as simple as possible, but not simpler.” Alternatively, we might also take the system as it is, consider it from the “top-down” and try to characterize the emergent phenomenon of interest. Once again, this involves choices.

Understandings of a complex system are achieved when top-down and bottom-up approaches meet. In the case of an individual equity, replicating various properties of the price series (long tails, long memory, correlated volatility) in simulation hints that the model may be on the right track. A variety of basic statistical tools can measure the distance between simulation and reality. But what happens when we turn our attention to an actual market—say, a collection of assets whose behaviors are necessarily correlated—where strategies must account for the interrelation of a wide range of complicated assets. From 10,000 feet, a view of “the market” might look something like the cartoon in Figure 2—in which capital flows between the different “submarkets” of equities, bonds, etc.

The market is a network of large markets, which are in turn themselves networks of markets and so on and so on, until we arrive at some sort of tradable “atom.” Any bottom-up model would ultimately need to reproduce this kind of hierarchical structure, a structure that seems to be both characteristic of financial markets, but also a general feature of many complex systems.

How to articulate this structure in a mathematical way? This was the topic of three lectures by Greg Leibon of Dartmouth College. Leibon showed how tools from statistical learning can analyze the correlation structure of the equities market, or the “network of equities,” and reveal the hierarchical structure described above. The core object of study was the weighted network of equities, in which two equities are connected by an edge whose strength reflects the degree of correlation in the time series of normalized daily

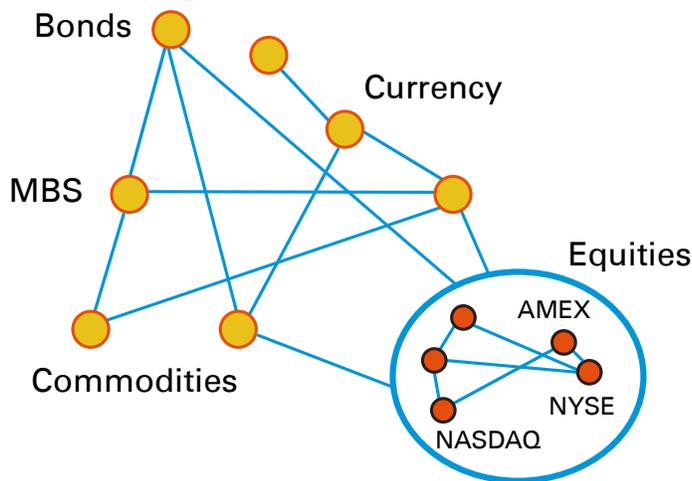


Figure 2: Model of the market network in which capital flows between the different “submarkets.”

close prices over 15 years.⁹

Leibon’s analysis treats the equities network as a spring model, in which pulling or pushing on one piece can send shocks to other pieces. Given this mechanical toy composed of thousands of masses (equities) and almost 2.5 million springs (correlations), the goal is to try to uncover collections of equities that generally move as one and then to try to understand the degrees to which subsets of the market are in phase or out.

A similar problem confronts a chemist or molecular biologist trying to understand (predict) the properties of a complicated molecule. These fields use the mathematics of “spectral analysis”—a subject that derives its name from studying the response of a substance to various kinds of radiation—to reveal the properties of molecules from the (slightly modified) network of connections that describe them. In a similar fashion, the same mathematics can reveal the structure of the equities network. In both cases, the “large” modes of the molecule—the perturbations that cause the most dramatic resonances—indicate the existence of large neighborhoods or clusters that effectively move together. Finding the large modes lets Leibon know how many big clusters to look for. What is of interest here is that “neighborhoods” of the market emerge in an unsupervised fashion, corresponding to labeled sectors such as technology, energy, and so on. Also striking is that the

analysis can automatically recognize some known dynamics of the market, such as the cyclic flow of capital between sectors.

While some of the clusters reflect or replicate a traditional view of the market, comprising mainly equities from a single “traditional” sector, other clusters are highly mixed, suggesting that new kinds of hybrid sectors have emerged or evolved in our era of highly diversified, multinational, publicly traded entities. A new structure can suggest new markets, new derivative products, new opportunities for investment, as well as new strategies for ameliorating risk.

Each cluster can then be viewed as its own submarket, ready to be analyzed just like the original market. The process is then iterated until one reaches a submarket that is effectively completely decorrelated. The result is a more highly textured and geometric view of the correlation structure of the market. It suggests a “null model” of the correlation structure of the market that is much more interesting and sensible than a strawman “random” assortment of correlations or correlation matrices.

By analyzing the correlation structure of the market as a network, market analysis has been turned into a geometry problem (Leibon trained as a geometer and topologist). And the visual form of this network reduces the data of thousands of 1,000-dimensional time series to a three-dimensional representation that contains a good deal of the original information.¹⁰

Identifying this clustered and hierarchical structure is in a sense a data-driven form of equities classification. In Leibon’s final lecture, he showed how “Bayesian nets” and more generally “graphical models,” probabilistic tools for modeling complicated (i.e., highly non-independent) multivariate distributions, could then use this understanding as training data to solve the problem of classifying unknown or new data streams as (behaving like) members of a given sector (traditional or not). These tools can also be turned upside down to generate time series that behave

like a member of a given sector. While such a “generative model” still doesn’t account for all other kinds of market dependencies and interactions, it still provides a more sensible model of behavior for price series movement, given sector information. This is a first step toward some sort of meso-scale artificial market working at a level above participants and strategies.

These lectures were the material that made up Markets Week, but of course the subject matter was discussed in other weeks too. The compressed timescale of the CSSS causes the subjects to wash over one another, making participants think about possible connections and relations. For example, discussions of niche development, innovation, and evolution carried over to discussions of emergence in markets. Could the new work in food-web dynamics and extinction patterns give insights into risk management—or vice versa? Do the methodologies of functional neuroimaging and the hierarchical structure of neuroanatomy map onto the measurements and structures of economies and markets? Analogies or analogons? Only time and a lot of careful thought will tell. ◀

Daniel Rockmore is John G. Kemeny Parents Professor of Mathematics at Dartmouth College where he is also Chair of the Department of Mathematics and Professor of Computer Science. He is an External Professor at SFI and Director of the Complex Systems Summer School. This article benefited from the helpful comments of Robert Savell and Eric Smith.

1 Copies of the slides of almost all lectures from the 2007 CSSS as well as some related readings can be obtained at http://www.santafe.edu/events/workshops/index.php/CSSS_2007_Santa_Fe-Readings

2 Smith and his co-author SFI External Professor Duncan Foley attribute “analogon” to a 1949 paper of J. Lisman. Coupled with “ridiculousgram,” Mark Newman’s name for the indiscriminate use of obfuscating network diagrams, we now have a growing vocabulary for modes of bad science.

3 In this context, path dependence for an economic process can be thought of as the idea that the equilibrium that is achieved (e.g., price) would depend on the manner (process) by which the price comes to be

determined. For example, historical “accidents” could very well play a part. In the physics of an ideal gas, it would be the fact that work (for example) is a path-dependent function of the state variables pressure, temperature, and volume. The analogons arise when we try to find analogies for the state variables in an economic process and then “derive” path dependence—or the lack thereof.

4 A quasi-linear economy is one in which the utility function of the participants (how much they value any particular assignment of “goods,” including money) breaks up into a sum of the cash on hand plus a utility function of the non-cash goods alone.

5 “Order flow” refers to the continual influx of buy and sell orders into the marketplace for a particular equity.

6 See also Farmer, J. D., D. E. Smith, and M. Shubik. “Is Economics the Next Physical Science?” *Physics Today* 58(9) (2005): 37-42

7 The notion of “fat tails” makes reference to an underlying probability distribution and the fact that there is a relatively large probability for the occurrence of large deviations from the mean, in contrast to normally distributed (bell-curve) phenomena. With respect to the markets, this is reflected in high volatility, so that the existence of fat tails makes risk management much more difficult.

8 Persistence (or hysteresis) refers to the ability to see the effects of moving large amounts of a stock well beyond the time of the actual sale or purchase—like a slowdown in traffic that persists well past the time of an accident.

9 A direct analysis of the simple time series of close prices results in all sorts of spurious identifications of correlation or the lack thereof. A standard first normalization is to consider the series of relative changes. In addition, we transform the data in order to take out market effects—that is, general effects due to the movement of capital between markets.

10 This is the content of a paper in preparation: G. Leibon, S. Pauls, D. Rockmore, and R. Savell, “Hierarchical structures in the equities market.”

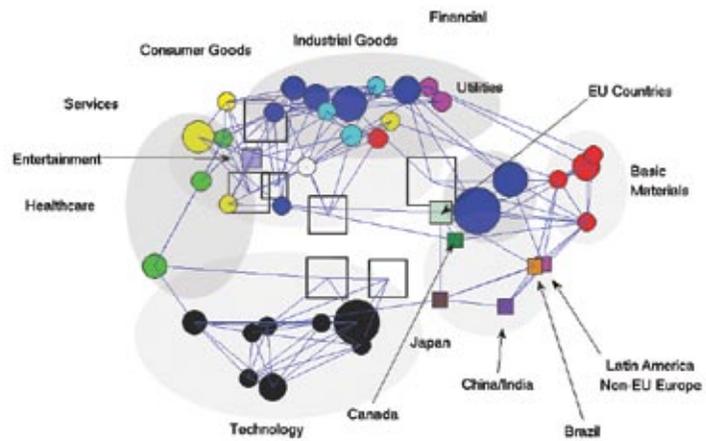


Figure 3: Network structure of the equities market after cluster analysis and dimension reduction. Labels reflect dominant sector or classification (e.g., country). Node size is proportional to cluster size. Unfilled squares indicate highly mixed (i.e., not easily identifiable) clusters. Connections are made for the (relatively) closest cluster centroids.

VISUAL UNDERSTANDING

By Melanie Mitchell



LEFT: © WATT / JAMIE7 ANIMALS ANIMALS ENTERPRISES

Consider the pictures above. What concept do all three images represent?

Of course there are any number of different concepts these images represent, such as “animals,” “mammals,” “things with limbs,” and “multiple objects,” but most people would very quickly answer “mothers and babies,” or something similar, perceiving that more abstract concept to be the intended meaning of this juxtaposition.

How does the mind so quickly translate an array of pixels of different light intensities and colors into an abstract *meaning*? Visual understanding of this kind is a great mystery for neu-

roscentists and psychologists studying how the brain accomplishes this translation, as well as for computer scientists who are trying to build programs that automatically determine semantics from pictures. Although science has uncovered many of the brain and perceptual mechanisms underlying low-level vision, very little is known about how the brain accomplishes higher-level, more abstract perception. Similarly, while modern computer vision systems have impressive performance in some specific domains, there are no systems able to recognize instances of visual categories or understand the contents of visual scenes with anywhere near the generality and robustness of human perception. Our current lack

of understanding of how low-level visual inputs can be translated into high-level conceptual descriptions has been termed the “semantic gap.”

Garrett Kenyon, a theoretical neuroscientist at Los Alamos National Laboratory (LANL), and I, a computer and cognitive scientist, recently organized a workshop on this topic at the Santa Fe Institute. The workshop, entitled “High-Level

relationships among these segments (e.g., spatial adjacency or color similarity) are encoded.

High-level vision is the process of translating these lower-level perceptions into the recognition of objects and their conceptual relationships, yielding a coherent description of the image as a whole. This information processing is not wholly one way: it is generally believed that the different

levels of processing continually communicate with one another in both a feed-forward and feedback manner. Not only does information from lower level processing influence higher levels, but higher-level processing, involving stored knowledge, can guide lower-level perception in tasks such as segmentation. The ability to fluidly integrate the different levels is a major source of visual understanding in humans and other animals.

The talks and discussions at the workshop concerned scientific and technological enigmas at different levels of visual processing. The first

The mind quickly translates an image into abstract meaning: These pictures of a humpback whale with her calf, a human mother and child, and a swan and her cygnets easily conjure the concept of “mother and child, or children.”



Perception and Low-Level Vision: Bridging the Semantic Gap,” brought together a small group of prominent neuroscientists, psychologists, computer scientists, and theoretical biologists to discuss the semantic gap from an interdisciplinary perspective and to see if a set of common principles of visual understanding could be discovered from the collective knowledge of the participants.

Visual perception can be roughly categorized into different levels of information processing. In *low-level vision*, primitive visual features such as color, contrast, texture, edges, and contours are extracted from the collection of photons that impinge upon the retina. Subsets of the image are identified as separate “segments” and relation-

set of speakers—mainly computational neuroscientists—described recent research on how the brain performs low-level vision. Bartlett Mel of the University of Southern California and Ilya Nemenman from LANL each spoke about the lowest level of the visual system: individual neurons. Their common message was that neurons are surprisingly complex, both with respect to the information encoding and processing they (and their subunits, such as dendrites) can perform and with respect to how information is communicated between individual neurons. In light of data recently obtained from detailed probes into individual cells, novel brain imaging techniques, and realistic computer models, classical theories

in neuroscience are being radically redrawn. Neuroscientists are now rethinking paradigms that were once generally accepted; results from recent experimental studies are undermining notions such as the static “receptive fields” of neurons, the transmission of information among neurons via the simple counting of spikes, and the role of dendrites as “passive” conductors of electrical signals. As Tom Stoppard wrote in his play *Arcadia*, “It’s the best possible time to be alive, when almost everything you thought you knew is wrong.”

Collective information processing by groups of neurons was a key topic for other participating brain scientists, including Garrett Kenyon, Pam Reinagel (University of California, San Diego), John George (LANL), Fritz Sommer (Redwood Center for Theoretical Neuroscience), and David Field (Cornell). The question of how such neuronal groups represent information is currently being hotly debated in neuroscience. Particularly significant controversies that were discussed concern (1) the existence and role of correlated

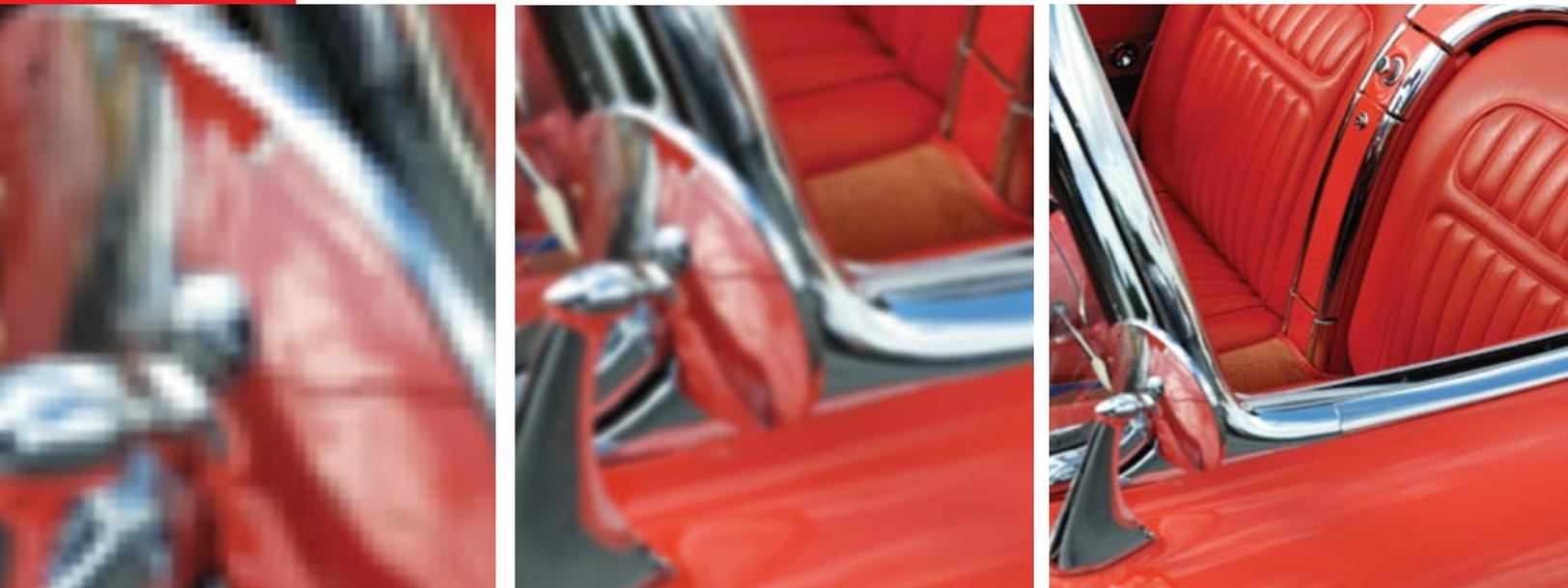
spiking in neural populations; (2) the nature and advantages of distributed and sparse representations, in which sensory information is encoded with only a small number of active neurons at any given point in time; (3) methods for measuring statistical and information-theoretic properties of natural visual inputs and inferring their implications for how the brain efficiently encodes visual information; and (4) the role of feedback connections from higher brain levels.

FOR THE THEORISTS IN THE GROUP,

the experimentalists’ talks drove home the difficulty of obtaining and interpreting data about the brain, which is perhaps the most complex of all natural systems. The theorists, on the other hand, underscored the increasing importance of computer modeling in neuroscience.

With respect to understanding sensory information processing or any other brain process, computational neuroscientist Tony Bell (Redwood Center for Theoretical Neuroscience) asked, “What level of description should we be focusing

BELOW © ISTOCKPHOTO.COM



Visual perception can be categorized into different levels of information processing: Low-level vision takes in primitive visual features such as color and texture, while high-level vision translates these perceptions into recognition of objects and their conceptual relationships, yielding a coherent description of the whole.



RIGHT: © BIGSTOCKPHOTO.COM



RIGHT: © STEVE GERR/ISTOCKPHOTO.COM

on?” He challenged the group with his assertion that “the fact that information flows all the way up and down the reductionist hierarchy...has significant implications for the way neuroscience (and presumably other areas of biological information processing) should be done.” The group discussed some examples of information flow to and from levels as low as genetic regulation, and several in the group strongly disagreed that it is important to include such levels when studying information processing in the brain.

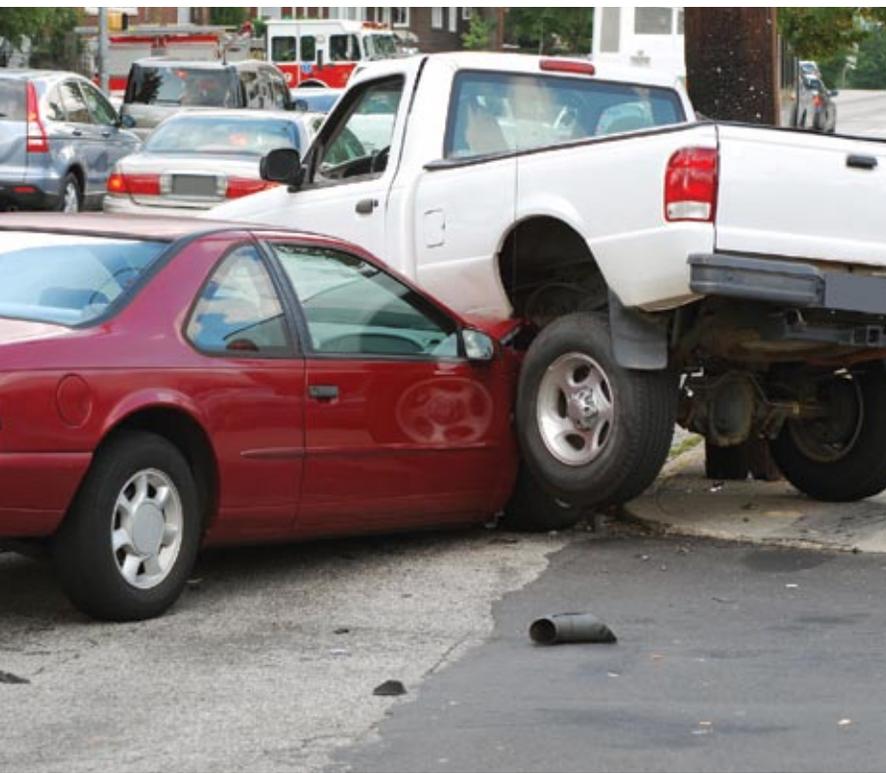
Higher-level visual behavior was a second focus of the workshop. How do humans and other animals use vision in real life, and what can be understood from studying human visual behavior from a psychophysical and psychological perspective? Psychophysicist Simon Thorpe, from the Centre de Recherche Cerveau et Cognition in France, described a surprising set of experimental results showing that humans are able to do some complex visual recognition tasks much faster than had been previously thought. For example, Thorpe’s experiments have shown that most people can identify whether or not a picture contains an animal in less than 200 milliseconds. These results call into question the role of feedback connections in visual recognition, since 200 milliseconds is not enough time for signals to propagate to higher brain levels and for those higher levels to send feedback. However, it seems that the brain clearly must use feedback connections

for *something* in vision—there are about 10 times as many feedback as feed-forward connections in the visual cortex. Much discussion (some rather heated) concerned the role of feedback information and what kinds of experiments could tease out its function.

Visual *attention* is one area where feedback from higher levels seems essential. Psychologist Todd Horowitz, from Harvard Medical School, addressed the issues of what constitutes visual attention and whether it is needed to bridge the semantic gap. In particular, when viewing a scene, what do we pay attention to and how does that affect our ability to remember the scene later on? Horowitz presented experimental results that indicated that people require focused attention to encode the “gist” of visual scenes in terms of objects present and spatial layout, and in particular, that focusing on the layout is more important than focusing on the objects for remembering a given scene.

Neuroscientist and psychophysicist Peter König (University of Zurich), zeroed in on a particular form of visual attention: the control of eye movements in response to the information content of input stimuli and “top-down” feedback. Computer scientist Dana Ballard (University of Texas at Austin), presented a computer model for “multi-tasking” in visual attention, which his group tested by having it navigate in a virtual reality simulation.

Experiments have shown that people can identify whether or not a picture contains an animal in less than 200 milliseconds.



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People require focused attention to encode the “gist” of visual scenes. Interestingly, the scene’s layout may be more important to memory than the objects themselves.

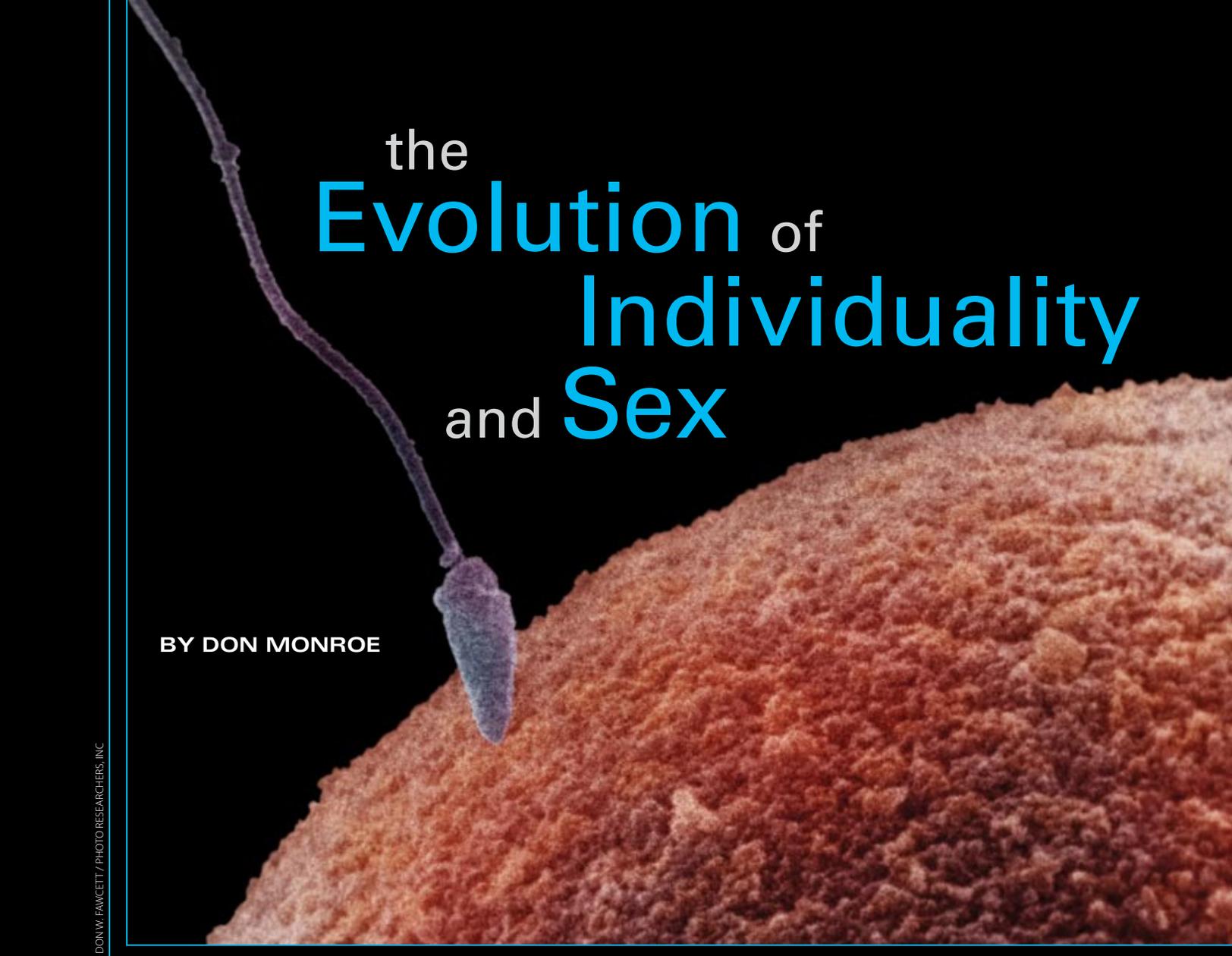
Ballard, along with several other participants, argued for the importance of studying vision in the context of the rest of the body. He stressed that the visual system and motor system are tightly interconnected, and constrain one another so as to make the computation of behavior tractable. Psychologist Shimon Edelman, of Cornell University, emphasized that vision scientists, in modeling abilities such as object recognition, should not lose the phenomenological aspect of vision—that is, visual phenomena that do not involve categorization and recognition, including our first-person experience of what it feels like to “see.” Psychologist Rob Goldstone, from Indiana University, described a different notion of embodiment: the effects of visual perception on reasoning and abstract problem solving. Goldstone reported on experimental results that indicated that even the most abstract of tasks—mathematical reasoning—is affected by visual input, such as the layout of the problem on the page. His point was that, just as vision scientists need to take

the rest of the body into account, psychologists studying abstract reasoning cannot ignore the effects of visual perception that “leak” into such reasoning.

New approaches to classical problems in computer vision and pattern recognition were proposed by computer scientists Lakshman Prasad and James Theiler, both from LANL, and myself. Ideas from “left field” were presented by theoretical immunologist Tom Kepler, of Duke University, who explored possible analogies between the visual system and the immune system, which itself must perform sophisticated, unpredictable, and ongoing tasks of pattern recognition and response. I described how my own work on high-level visual pattern recognition and analogy has been inspired by the immune system and other complex systems with pattern-recognizing abilities.

In the last decade or so, research on both natural and computer vision has become rather narrow and specialized; work on the fundamental problem of how different levels of vision are integrated has been largely neglected. In my view, the main benefit of the workshop was the opportunity for scientists studying widely diverse aspects of vision to communicate to one another the recent major advances and controversies in their areas. On the one hand, learning more about the daunting complexity of the visual system in processing sensory data, juxtaposed with the extraordinary abilities of the mind to glean abstract meaning, only made the gap seem wider. On the other hand, the talks and discussions at the workshop gave all the participants a new appreciation for the scope of the problem and its requirement for interdisciplinary collaboration, a sense of where the most promising directions are, and (at least for me) plans for new collaborations and many fresh ideas to take home and ponder. ◀

Melanie Mitchell is Professor of Computer Science at Portland State University, and External Professor at the Santa Fe Institute.



the Evolution of Individuality and Sex

BY DON MONROE

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“As far as we know, life began once, four and a half billion years ago, and since then has been passed down like a family heirloom from parent to offspring,” says Richard Michod, head of the Department of Ecology and Evolutionary Biology at the University of Arizona. Along the way, life has repeatedly devised novel ways to organize and reproduce itself as it evolved from primitive self-replicating molecules to complex societies of multicellular organisms.

The persistence and enhancement of our genetic legacy is all

the more striking when contrasted with our frail and mortal bodies. In fact, eliminating inferior individuals is crucial to the biological evolution that drives new innovations. As an evolutionary biologist, Michod has explored this process both theoretically and experimentally.

At a September SFI Business Network meeting in Washington, D.C., Michod spoke about “Cooperation and Conflict during the Evolution of Individuality and Sex.” The talk came within the larger theme of the meeting: “Conflict, Cooperation and Creativity in Complex

SEM (Scanning Electron Microscope) of a single sperm penetrating an egg at the point of fertilization: Researchers are finding that sex has important biological purposes beyond procreation.

Systems.” Organized by SFI Research Fellow Jessica Flack, and William Glenney, Chief of the Naval Operations Strategic Studies Group, the meeting focused on identifying the types of conflict that lead to creative new solutions.

Michod described a continuing cycle—more accurately a spiral—of cooperation leading to new types of conflict, which in turn lead to higher levels of cooperation and the emergence of novel traits. “Basic properties of the living world emerge out of this cycle of cooperation and conflict,” he said.

He described several stages along this spiral, starting with the innovation of the cell. Drawing on his own experiments in colony-forming algae,

some of which catalyze the replication of DNA, but in the beginning there was probably only a single molecule. The prime suspect is RNA, which can both replicate its internal structure and act as a catalyst.

Simply replicating is not enough, however, because some errors always happen during copying. Some three decades ago, theoretical biologists suggested that cooperative networks of genes (presumably RNA at first) that promote each other’s production could keep errors from accumulating. As long as the error rate is below some threshold, Michod said, such networks, known as heterocycles, “maintain themselves stably through time.”

Although free-floating genes can cooperate in this way, “it’s a poorly

fates of its constituents, Michod said, “it enforces cooperation on them,” because cells with selfish mutants do worse than cells with cooperative genes. “The cell is the perfect example of a conflict mediator.”

Michod only briefly mentioned another milestone, the appearance of eukaryotic cells that comprise all multicellular organisms as well as many single-celled organisms. Biologists widely agree that the DNA-containing mitochondria—the structures in animal cells that provide energy—and chloroplasts—which perform photosynthesis in plants—were once separate species. Even the nucleus, the defining feature of eukaryotic cells, may have arisen from such interspecies cooperation.

Michod described a continuing cycle—more accurately a spiral—of cooperation leading to new types of conflict, which in turn lead to higher levels of cooperation and the emergence of novel traits.

he clarified the conflicts leading to multicellular life and to sexual reproduction. This cycle of innovation illuminates not only the nature of life on Earth, but more general principles of how conflict and cooperation can foster innovative approaches to problems.

Cells as Conflict Mediators

In the primordial chemical soup, Michod said, “the first individuals were things like molecules and genes replicating through some kind of prebiotic chemistry.” Current organisms use DNA to specify proteins,

defined life, these cycles of genes,” Michod observed. “Cheating was rampant.” A gene that undergoes a “selfish” mutation, so that it propagates at the expense of its partners, will eventually take over. “Pretty soon there’s only taking, no giving, and the whole cycle goes extinct.”

Faced with this conflict between its constituents, Michod said, “there’s a need for some kind of conflict mediation.” The membrane-enclosed cell solved this problem. “What the cell does is align the interests of all the members inside.” By linking the

Altruistic Cells

In the laboratory, Michod recapitulates the more recent development of multicellularity by studying colony-forming algae. Poised at the crossroads between a single-cell and multicellular lifestyle, these primitive plants illustrate the conflicts that push life one way or the other.

“A single cell has immediate and effective interaction with its environment,” Michod said, making it easy to get resources and get rid of wastes. “The problem is simply that a single cell has to do everything.” A cell has

to devote resources to every aspect of survival, and addressing one task can impede another.

“There are often tradeoffs between the effects of a trait on different necessary components of fitness,” Michod observed. In the alga *Volvox carteri*, for example, cells cannot reproduce while they maintain the hair-like flagella that let them move in response to their environment. An individual cell cannot benefit from having flagella without sacrificing reproduction.

“Division of labor in the group is a way to break through this tradeoff that governs the life of single cells,” Michod explained. In fact, many *Volvox* species form colonies with a few germ cells dedicated to reproduction while other “soma” cells retain the flagella that let the entire colony move.

Although specialization clearly benefits the colony as a whole, Michod pointed out, the soma cells must act altruistically, because they forgo the chance to reproduce themselves. “Altruism is widely appreciated to be the central problem of social behavior, and it’s also fundamental to the evolutionary transition to multicellularity. It takes fitness from one level and gives it to another, from the cell to the colony.”

One evolutionary explanation of altruism, known for decades, is based on kin selection: it makes sense for an individual to sacrifice its life for others, as long as those others share enough of its genetic heritage. The genetically identical algae cells clearly meet this requirement. However, Michod’s team is still clarifying why only some *Volvox* species—generally

those that form larger colonies—display this altruistic behavior.

The researchers also identified the molecular mechanism by which *Volvox* cells specialize. They found that the genetic “switch” that determines whether a cell becomes a germ or soma cell is adapted from a mechanism that already existed in single-cell algae. That mechanism—like the calorie-restriction response that extends life in many animal species—acts to delay reproduction in favor of extended survival when resources are limited.

There are limits to this strategy for resolving conflict between cells, Michod noted. Since the soma cells do not divide at all, they can never go on to make larger structures. The way in which conflicts are mediated, he noted, “can have effects on the future evolvability of the lineage.” In contrast, our own cells continue to divide. Even when they are not destined to become reproductive cells, they continue to specialize, forming the various complex tissues in our bodies.

Sex: Evolution’s Raw Material

Finally, Michod discussed the evolutionary role of sexual reproduction. In many species, such as humans, sex is

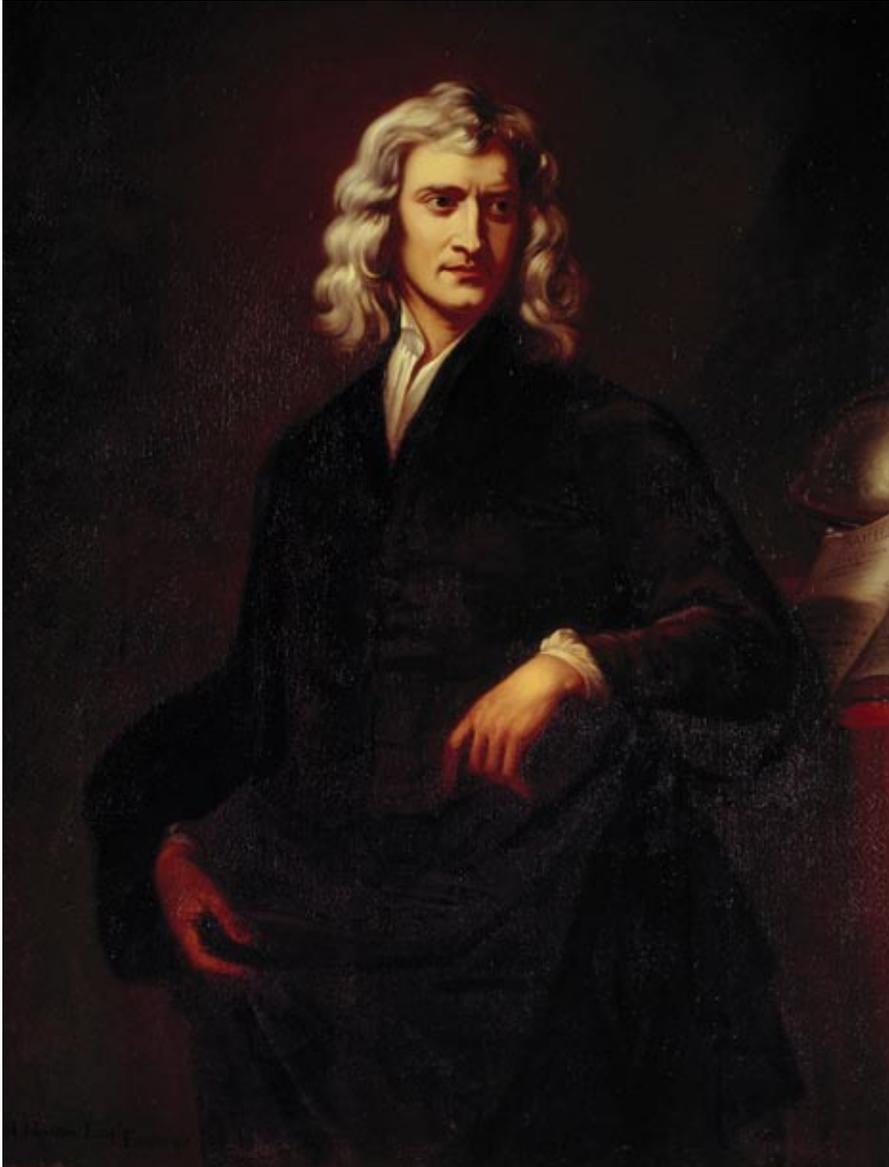
tied to reproduction. But other species, including large animals like some lizards, reproduce asexually, while other species exchange genetic material independently of reproduction, Michod noted. “The idea that sex is necessary for reproduction doesn’t hold up.”

From an evolutionary perspective, Michod said, “the most obvious thing about sex is its cost.” Extravagant displays like those of the male peacock appear to be unnecessary and wasteful, but help meet the challenge of finding a choosy mate. Sex also exposes the body to the risk of infection.

“What are the benefits that offset all these costs?” Michod asked.



Sex has an evolutionary cost, as evidenced in the extravagant display of the male peacock



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Curiously, creative people, such as Isaac Newton (1642–1727), are often misfits who don't reproduce, raising questions about their repeated appearance in the population.

“Biologists differ strongly on what they think are the major benefits of sex, and there’s no real agreement on the whole problem.” They agree, however, that the mixture of traits between individuals provides raw material for evolutionary change. Like altruism, this explanation involves a transfer of fitness between levels, in this case between individuals and their species.

Sex also corrects genetic damage, Michod said. Damage to the DNA of one partner can be repaired by undamaged DNA from the other partner. In this way, sex recovers an error-correcting feature that had been present in early genetic networks. This feature was lost somewhat when life began forming cells, because “damages and mutations get trapped on the inside,” Michod observed.

“Sex repairs DNA,” he said, helping to explain how “the cells in our body get old and die, but our germ line goes on forever.”

Further insight into sex comes from species that can reproduce either sexually or asexually. There is general agreement, Michod said, that “in such organisms sex is induced by stress.” He suggested that the stress acts by affecting the balance between the oxidation and reduction reactions that fuel life. “Stress universally upsets this balance,” he said, resulting in a buildup of reactive oxygen species that can damage DNA. “Sex is a way of coping with this damage,” Michod commented, because it repairs DNA. Indeed, he and collaborator Aurora Nedelcu of the University of New Brunswick found that exposing algae to antioxidants prevents their sexual response to heat stress.

Like other evolutionary changes, sex helps to solve problems introduced by earlier innovations, but it introduces new problems. These include biological and behavioral manipulation of the mating process, such as genes that limit the resources that males devote to offspring. “There are all kinds of conflicts that are set up because of sex,” Michod observed. “You solve one set of conflicts but then create other sets of conflicts. It’s the raw material that leads to continued evolution.”

Harnessing Social Conflict

Other presenters at the meeting identified the types of conflict that lead to creative new solutions. Flack set the stage by describing conflict-mediation mechanisms in three very

different arenas: policing of conflict by dominant chimpanzees, elaborate election procedures in Renaissance Venice, and co-option of “jumping genes” to build the adaptive immune system. In each case, she said, “either the arms race between the components or the implementation of the robustness mechanisms, resulted in new problems, which in turn generated the evolution of new solutions to maintain stability. So we get this ratcheting up of complexity in all of these systems.”

In the context of the whole meeting, Michod’s research provides intriguing examples of innovative mechanisms for mediating conflicts, which could also apply to human situations. Good managers, for example, well know the value of aligning the interests of individuals with those of the whole team, as the cell does for its genetic networks. Similarly, division of labor was applied in manufacturing long before it was recognized in *Volvox*. Enlightened managers have also encouraged (non-sexual) “cross-fertilization” between teams to stimulate new ways of thinking.

Still, there are risks to using evolutionary conflicts as a metaphor for human behavior. For one thing, biological evolution acts only through the persistence of genetic changes in offspring, while cultural evolution transmits new ideas rapidly between unrelated individuals and organizations. Perhaps more sobering, biological evolution works only because

individuals or species that use inferior strategies are killed off. Hopefully, directly adopting the best practices of others can help organizations avoid this fate.

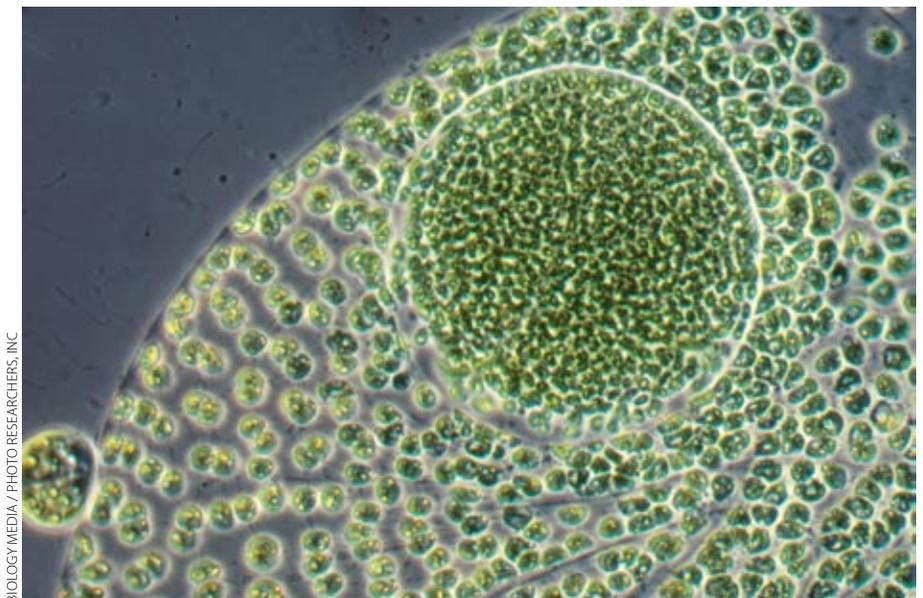
The other speakers at the meeting offered highly varied insights into the roles of conflict at the social level. Dean Simonton, Distinguished Professor and Vice Chair of the Department of Psychology at the University of California at Davis, for example, extended evolutionary ideas to individual creativity in two distinct ways. Creative geniuses are often misfits who do not reproduce, he said, so their repeated appearance in the population demands an evolutionary explanation, perhaps like those that Michod described for altruism. Simonton also described “secondary Darwinism,” the social and personal influences that encourage susceptible individuals to generate the wide-ranging ideas that underlie creativity.

Uniquely creative individuals were clearly critical in the development

of both atomic and thermonuclear weapons. Richard Rhodes, author of the Pulitzer Prize winning *The Making of the Atomic Bomb* and many other books, contrasted these two mega-projects, saying that, although external conflict was a primary driver for both, conflict within the project was much more destructive for the hydrogen bomb. Aaron Clauset, a postdoctoral fellow at SFI, discussed more modern conflicts, analyzing patterns in terrorist attacks. He concluded that although the attacks of September 11, 2001 were unusually large, they are best seen as part of the “long tail” of a power-law distribution of event sizes, rather than as historically unique events.

The tension between conflict and cooperation leads to innovation in a variety of situations, and researchers are still struggling to describe the many ways this happens. One day, perhaps, they may be able to systematically analyze and even predict this evolution. —Don Monroe ◀

Volvox alga, a kind of green algae, reproduces both asexually and sexually. Such behavior raises questions about the purpose of sex.



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The Conflicted Brain

BY JON WILKINS

When I played third base in Little League, ground balls used to come at me fast. Invariably, once a year, one would hit me in the eye, or nose, or mouth. In those cases, I would be positioned in front of the ball, but then, at the last moment, I'd flinch and look away. The ball would then bounce up and hit me in the face.

The problem was that different parts of my body were trying to achieve two different goals. My legs placed my body in front of the bouncing ball—with the goal of catching it. My face, on the other hand, was trying to get out of the way. If my entire body had committed to getting away from the ball, I could simply have moved aside and let the ball through. Better yet, if my entire body had committed to catching the ball, I would have kept watching it, and would have had my glove in the right position to catch it; keeping my eye on the ball metaphorically would have saved me from doing it literally.

Most people recognize this type of conflict: the feeling of being pulled internally in two directions. It's the tiny angel and tiny devil sitting on our shoulders, urging us to take disparate actions—we want to lose weight, but we also want to eat that donut. Recent research suggests that this sensation may have a basis in real mechanis-

tic and evolutionary conflicts within our brains.

Brain-imaging studies suggest that different brain regions come into conflict with each other over certain decisions. At the same time, many genes that are expressed in the brain show evidence of having been in a long-term evolutionary conflict with each other. It is possible that when we feel as if we are of two minds, it is precisely because different sets of our own genes have effective control over different regions of our brains, and these different brain regions are exerting antagonistic influences on the decision-making process.

The idea of conflict in the mind is old. What is new is that we are beginning to understand some of the mechanisms through which these conflicts play. This new understanding undermines our preconceptions about human intelligence and our notions of the “self.” In fact, it may turn out to be misleading to talk about the notion of individuals having a single “self” at all.

BATTLE OF THE NEURONS

On the basis of recent neuroeconomic experiments, researchers have suggested that difficult decisions might be made by a type of “voting” process within the brain. Typically, an experimen-

tal subject performs some behavioral task while his or her neural activity is monitored. This type of procedure has been used for decades to identify regions of the brain that are particularly active during specific cognitive or behavioral tasks.

One recent set of studies focuses on decision-making in difficult moral dilemmas. Subjects face a hypothetical situation: a train is rushing toward five people who are tied to the track. The only way to save those five people is to kill a different person (for example, by throwing him or her in front of the train). On the one hand, people sense that five lives are more valuable than one. On the other hand, there is something morally and emotionally distressing about the idea of actively participating in the death of the one person.

In the study, the subjects show increased activity in a region of the brain called the anterior cin-

these two responses are localized in distinct sites within the brain. It is as if one set of neural circuits is screaming out, “You must act! The lives of the five people on the track outweigh a single life!” while another set of circuits screams, “It is wrong to kill this man! The ends do not justify the means!” The decision that is ultimately made depends on which of the two sets of circuits screams louder.

WHY CAN'T WE ALL JUST GET ALONG?

Why might decision-making in the brain be structured like this? Is decision-making through competition adaptive, or is it a maladaptive byproduct of an evolutionary process? Most evolutionary explanations fall into one of two categories. These explanations assume (often implicitly) either (1) that this conflict is an adaptation, or (2) that it is a historical artifact. While there may well be some truth to either or both of these assumptions, both are rooted in a naïve understanding of natural selection that fails to capture the nuances of the evolutionary process. After briefly explaining these two simple classes of explanation, I will introduce a third possible explanation, one based on recent advances in molecular biology and evolutionary genetics: that this apparent neural conflict reflects a genuine evolutionary genetic conflict.

The first class of explanation assumes that competition is a powerful and robust way to make choices in a noisy and complicated world. Imagine that you face two choices, A and B. The brain receives a constant stream of information from the environment, most of which is irrelevant to the decision at hand. It must collect and evaluate the relevant information and follow the better of the two choices. One possible solution is to establish one apparatus that filters this stream and gathers all the evidence favoring choice A. A second apparatus would be dedicated to collecting evidence favoring B. Each would then produce a signal proportional to the weight of this evidence. If the signal favoring choice A outweighs

This new understanding undermines our preconceptions about human intelligence and our notions of the “self.” In fact, it may turn out to be misleading to talk about individuals having a single “self” at all.

gulate cortex, associated with conflict resolution. Subjects also show increased neural activity in other regions. Some of these regions (such as the medial frontal gyrus and the posterior cingulate gyrus) are associated with the emotional response to the situation. Other regions (including the parietal lobe) are associated with higher cognitive functions—the “reasoning” part of the brain. Interestingly, the subjects who say that they would sacrifice the one to save the five show relatively higher levels of activity in this “rational” part of the brain. The subjects who would refuse to act show relatively more activity in the more “emotional” regions of the brain.

We are a long way from a complete understanding of this type of decision process. However, one possible interpretation is that the situation elicits two conflicting responses, and that

that favoring B, choice A is followed, and vice versa.

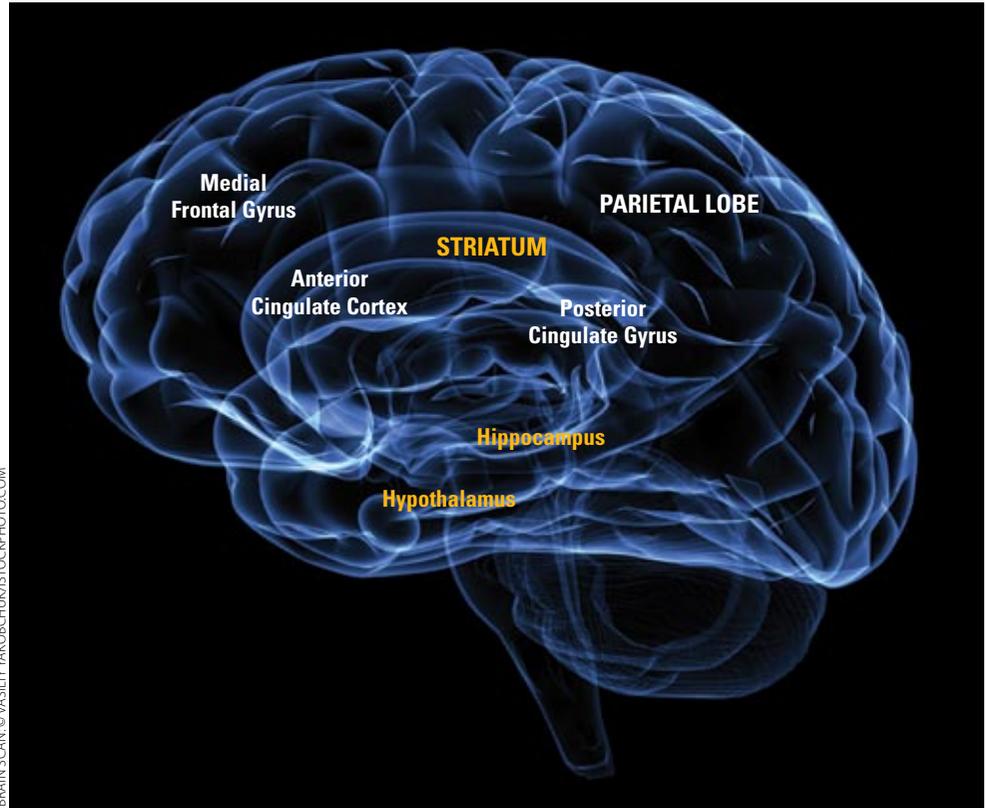
This is like the principle upon which the Anglo-American criminal justice system is based. In principle, the goal is to reliably determine guilt or innocence on the basis of available evidence. The mechanism by which we attempt to reach an unbiased verdict, however, is an antagonistic interaction between biased advocates. One party is charged with gathering and presenting all of the evidence that the defendant is guilty. Another party collects the evidence that would exonerate the defendant. A third entity—the judge and/or

jury—assesses which of the two has presented a more compelling case and rules accordingly.

The second common explanation is that this conflict is an artifact of the evolutionary history of our brains. Our brains evolved through modification of an earlier primate brain, which was derived from an earlier mammalian brain, and so on. The human brain is necessarily descended from a long line of brains, each of which had to function well enough in its own environment to allow its bearer to survive and reproduce. Thus we have inherited a neural architecture that evolved in a very different context. It may simply be that when a complex organ is constructed in this way, by layering new functions on old, certain conflicts and incompatibilities will inevitably arise.

This second class is being invoked when researchers talk about conflicts between the “reptilian” and “mammalian” or the “emotional” and “cognitive” parts of the brain. In this scenario, our ancestors had a brain with certain heuristic rules that it used to navigate the world. Our modern brains contain regions that are homologous to those ancestral brains. We also have other

BRAIN SCAN © VASILY YAKOBCHUK/ISTOCKPHOTO.COM



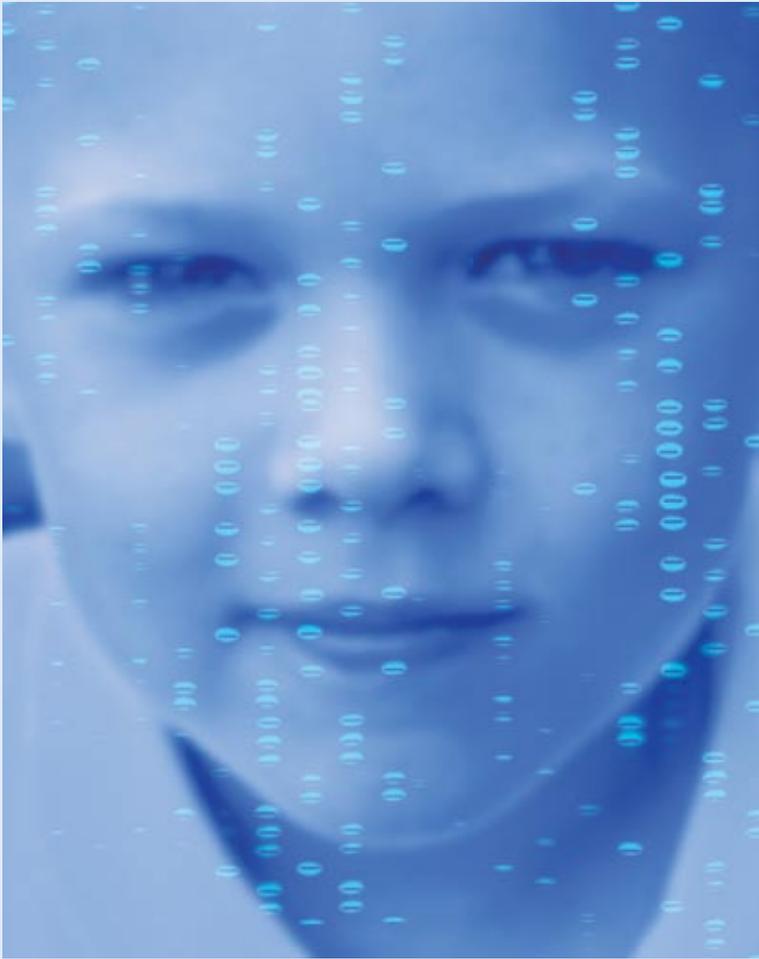
regions that have evolved more recently, regions with their own set of heuristic rules. Sometimes, the old and new rules contradict each other. In this case, the conflict is not conceived as adaptive, but rather as an unfortunate limitation resulting from the historical path followed by evolution.

Now I’ll suggest a third possible class of explanation—that the conflict is in some sense real. What I mean is that the conflict represents the direct outcome of natural selection, but that natural selection is acting differently on different parts of the brain. The apparent conflicts between regions of the brain are a manifestation of an underlying genetic conflict.

IMPRINTED GENES

We now understand that a conflict exists between the maternally and paternally inherited sets of genes within each of us. About one percent of genes in mammals (including humans) are subject to *genomic imprinting*. In the case of these imprinted genes, the gene copy, or *allele*, that came from your father functions differently from the allele that came from your mother, even if the

White text indicates locations of brain regions mentioned in the neuroeconomics studies. Orange text locates the human structures corresponding to the mouse brain regions mentioned in the genetic chimera experiments.



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This DNA autoradiogram superimposed over a child's face shows a pattern of bands produced during DNA analysis. It may represent genetic individuality, paternity testing, or biometric identification.

two alleles have identical DNA sequences. These functional differences are the result of *epigenetic* (meaning “on top of the genes”) modifications to the DNA that are established in the germ line, and propagated through developments.

During *spermatogenesis* (the production of sperm), imprinted genes are marked with particular chemical modifications. During *oogenesis* (the production of eggs), these same genes are marked with different modifications. The offspring therefore inherits two functionally different alleles. When this individual grows into adulthood and has offspring of its own, these marks will be erased and reset on the alleles that it passes on to the next generation.

Why would a complicated mechanism like this exist? The most prominent explanation suggests that genomic imprinting is the outcome of an evolutionary conflict between these maternally and paternally derived alleles. The key to this

conflict is the fact that natural selection acts to maximize the number of allele copies that are passed on to future generations. These copies can be passed on directly through the survival and reproduction of the individual organism carrying those genes, or through the reproductive success of related individuals who carry an identical copy of the allele. Since the maternally and paternally derived alleles are related to different individuals (e.g., cousins on your mother's side versus those on your father's), the strategy that maximizes the number of copies passed down differs between the two alleles.

PARENTAL CONFLICTS IN THE BRAIN

Our understanding of imprinted genes in the brain is still in its infancy. However, observations involving *genetic chimeras* (made up of two sets of cells with different genomes) suggest that our maternally and paternally derived genes are in conflict over how large particular brain regions should be.

Normal mammalian development requires the presence of both maternally and paternally derived complements of alleles. In mice, it is possible to make *gynogenetic* embryos (which contain two maternally derived sets of genes) or *androgenetic* embryos (which contain two paternally derived sets of genes) by removing the nucleus (containing the DNA) from one cell and injecting it into another. These uniparental embryos fail to develop beyond the first few rounds of cell division, since they have inherited two inactive copies of many imprinted genes (and are receiving double the normal dose from the rest).

However, it is possible to combine these cells with cells from a normal, biparental embryo. These mixed, or chimeric, embryos develop relatively normally. The inclusion of gynogenetic and androgenetic cells appear to have complementary effects on the development of the brain. When a chimera contains gynogenetic cells, those cells are overrepresented in particular brain regions, including the striatum, the hippocampus, and the

neocortex. These regions (evidently favored by maternally inherited alleles) are involved in many higher cognitive functions, such as planning and problem solving.

In the other type of chimera, the androgenetic cells are overrepresented in different regions, including the mediobasal forebrain and the hypothalamus. The regions favored by these paternally inherited alleles participate in behaviors such as food seeking, mating, social aggression, and the expression of emotions.

Another set of observations concerns a genetic disorder called Turner syndrome. Girls with Turner syndrome inherit only one copy of the X chromosome (as opposed to the normal two). These girls suffer from a variety of problems, and generally perform less well than chromosomally normal individuals on various cognitive tasks. Relevant here is that there are significant differences in the extent to which different cognitive skills are impaired, depending on the parental origin of the single X chromosome. If the X chromosome is paternally, rather than maternally, inherited, the girls exhibited better verbal ability, social cognition, and behavioral inhibition.

These are only two of the experiments that suggest that imprinted genes affect the development of different brain regions, and the development of different sets of skills. Other experiments suggest conflicts over how much care to provide for offspring and how to value risk. If the neuroeconomists are right, some of our decisions may be determined by comparing the relative intensity of activity in two or more regions of the brain. Imprinted genes might effectively tip the scales to favor one type of decision over another by influencing the relative size of these different brain regions.

WHAT DOES IT ALL MEAN?

Based on the type of effects we see in other systems affected by genomic imprinting, we can speculate about how this conflict might have affected our brains.

First, we expect to find an escalatory “arms race” between different brain regions. If maternally derived genes are expanding one region to bias decisions in a particular way, paternally derived genes will counter by augmenting regions with the opposite effect. Eventually, we might expect this to produce an increase in overall brain size. In fact, this may have happened: over the past hundred million years, the size of the mammalian brain has increased disproportionately relative to body size.

We also expect this conflict to increase fragility. Different sets of genes are pulling hard in opposite directions; a mutation in any one of these genes can result in a dramatic shift in the system. Imprinted genes have been linked to many human behavioral dysfunctions, including schizophrenia, ADHD, autism, and bipolar disorder. These disorders may be much more severe

It is perhaps time to stop thinking of the human brain as evolution’s crowning achievement and the physical embodiment of the “self.” Rather, our brains are casualties of millions of years of internal conflict.

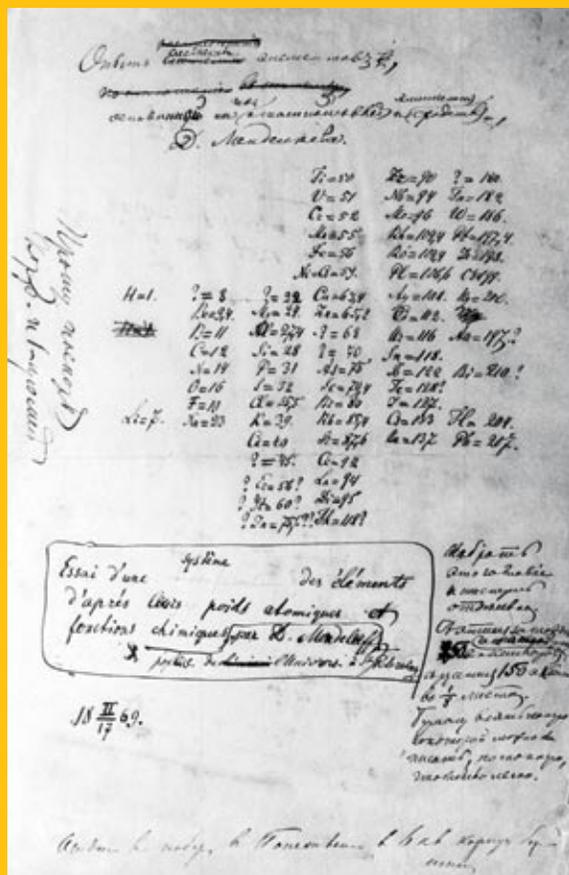
and/or more common than they would be in the absence of genomic imprinting.

As humans, we routinely engage in a wide variety of self-destructive behaviors. We cheat on our diets. We don’t exercise. We smoke and gamble and get addicted to a wide range of substances. It is perhaps time to stop thinking of the human brain as evolution’s crowning achievement and the physical embodiment of the “self.” Rather, our brains are casualties of millions of years of internal conflict. Every decision we make is argued out by at least two distinct evolutionary “selves.” We may eventually discover that multiple personality disorder is simply the most extreme manifestation of a dynamic that governs even the most mundane behaviors in each of us. ◀

Jon Wilkins is an SFI professor.

Cherry Picking the Periodic Table: A New View of Life

By James Trefil



This is the first version of the periodic table, drawn in 1869 by Dmitri Ivanovich Mendeleev. He left gaps in the table for new elements, which were indeed later discovered, vindicating his theory.

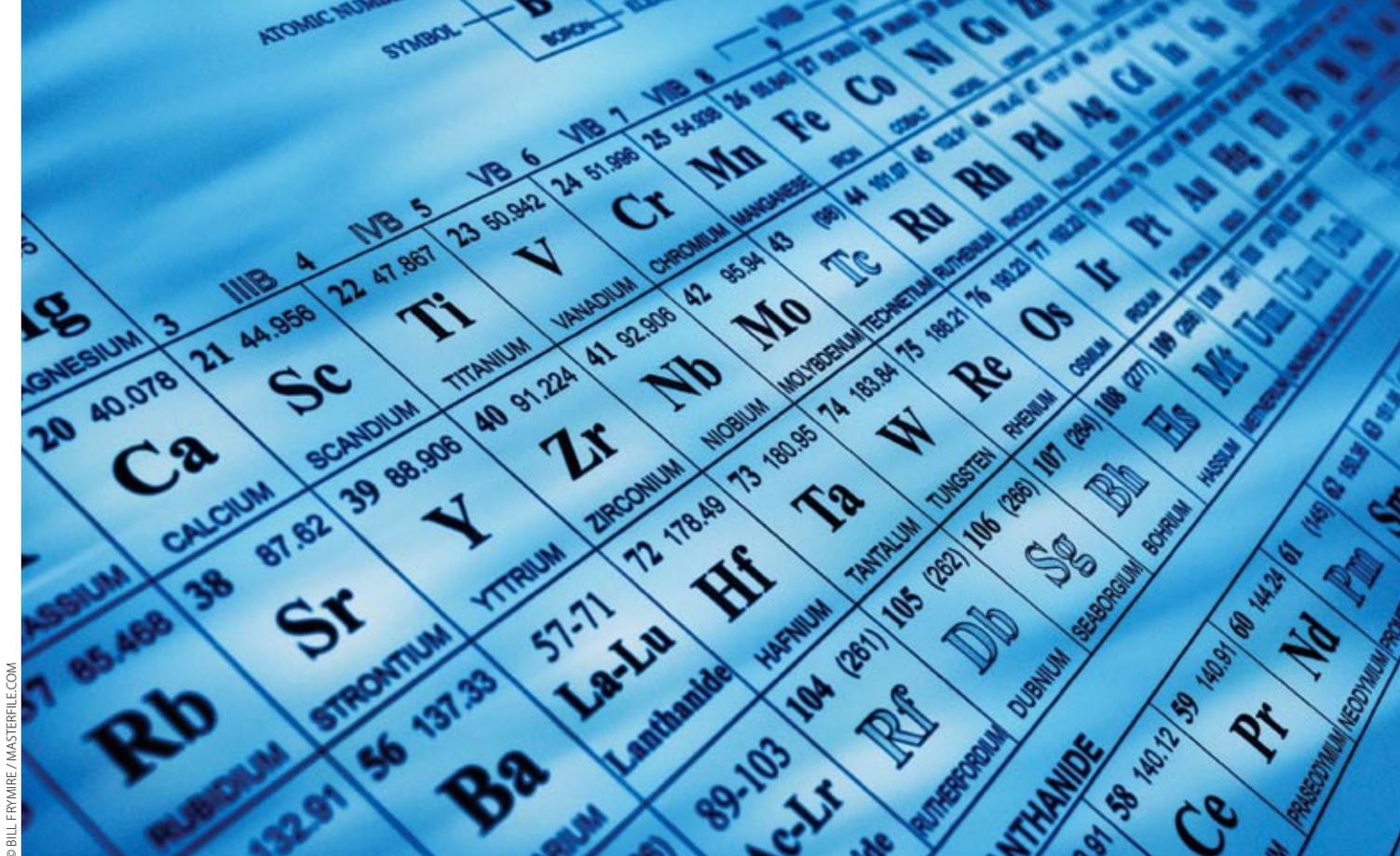
The periodic table of the elements is a beautiful thing. It was first written down in 1869 by the Russian chemist Dimitri Mendeleev, a professor in St. Petersburg. Mendeleev had an interesting life—born as one of 14 children to a family in Siberia, he was such a precocious student that the entire family moved to St. Petersburg so that he could attend the university. Later, after his work had achieved international attention, he went through a divorce and remarriage. Technically, this made him a bigamist in the eyes of the Orthodox Church, a situation which is supposed to have prompted the Czar to declare, “Mendeleev may have two wives, but I have only one Mendeleev!”

The periodic table is one of those organizational schemes that demonstrates the fact that the universe has an underlying simplicity, despite its apparent complexity. It lists all of the known chemical elements (118 and counting at this time)

in an orderly way. Read from left to right in any row and the elements progressively increase in atomic number. Look at the entries in any column and you find elements with similar chemical properties. Mendeleev arrived at this way of organizing the elements after years of trying to make sense of the seemingly chaotic assortment of chemical elements that had turned up in the 19th century. He had no idea why the table seemed to make sense, or why it predicted the existence of then unknown elements such as germanium and scandium (they showed up as gaps in his orderly arrangement). Understanding why the table is the way it is would have to wait for a half century—for the discovery of the structure of the atom and the development of modern quantum mechanics. Nevertheless, the table gives us a list of the basic building blocks from which the universe is made.

And today, if new ideas put forward by Harold Morowitz of George Mason University and

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the Santa Fe Institute are right, the periodic table may turn out to play an important role in addressing another fundamental question—the question of how life evolved on our planet. To see what Morowitz is getting at, we have to remember that, at bottom, life is based on chemistry, so that when we talk about evolution, we are really talking about how things arranged themselves so that certain atoms attached themselves to each other and interacted with other groups of atoms. To know how life developed, in other words, we have to start by knowing how atoms and molecules came to interact with each other as they do in living systems.

And that’s where the periodic table comes in. Think of it as a kind of giant Home Depot, with bins that contain all the materials necessary to build

everything around us, including living systems. Each bin is labeled with the name of an element—hydrogen, carbon, ytterbium, and so on. Some of the bins, like hydrogen, are huge, holding a significant amount of all the material in the universe. Other bins, like ytterbium, are small, and represent less abundant substances. But large or small, what’s in these bins is the stuff from which the entire universe is made. The question that Morowitz wants to ask is simple: Why does life seem to use some building materials more than others? Why, in other words, does life seem to require more from some “bins” in the periodic table than from their neighbors?

There are actually two parts to this question. The first part asks what elements actually appear in living systems, the

second asks why those particular elements are used and not others. Let’s start with the first part. In the table below, we see some common chemical elements, together with the percentage (by weight) in which these elements are found in the universe at large, in the Earth’s crust, and in the human body (which we will take as a proxy for living systems in general).

Two things leap out at us from this table. The first is that a massive winnowing of elements took place when the Earth formed—the mix of elements on our planet isn’t much like the mix in the universe at large. More importantly for this discussion, though, we can see that yet another winnowing took place when living systems formed, because elements found there (carbon and iron, for example) are not particu-

This contemporary version of the periodic table has the elements arranged in blocks set in columns.

BELOW: Like a grocer adjusting his pile of fruit to suit his customers' needs, nature has, over time, shifted the mix of atoms in living systems to make them better competitors.

larly common even on Earth. In fact, scientists have long known that living systems are made almost entirely of a few elements—carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur (a convenient mnemonic is CHNOPS). To these we add some elements common in seawater, like sodium and calcium, and a few trace elements, and that's pretty much it. So why, Morowitz asks, are these the chosen "bins"?

For some elements, the an-

swer is obvious. For example, one of the basic requirements of life is that there has to be some way to transfer information from one generation to the next—the job done by DNA in living systems on Earth. Carbon is an atom that can be formed into long, complex chains, and hence can be used to form the backbone for information-carrying molecules. Go down one row in the periodic table and we find silicon, an atom that has properties similar to carbon and, one would think, could serve as the basis for an alternate form of "DNA." Indeed, silicon-based life has been a staple of science fiction for years. Unfortunately, when you look at the properties of silicon in detail, it just won't work. For one thing, the bonds formed between silicon atoms tend to be weak, and even when chains are formed, they tend to be unstable in the presence of water and oxygen. This makes them poor choices for an alternate biochemistry.

For other elements, however, the reason for the choice is less obvious. Morowitz proposes a simple answer to this question: fitness, or, in his words, "fine tuning." To understand how this works, think of a simple analogy. Imagine that you are a grocer who wants to make a pile of citrus fruit for your customers. You start with crates of lemons, oranges, grapefruits, limes, and so on. Imagine fur-

ther that each piece of fruit has little Velcro patches that allow it to attach to others.

In the beginning, you might just put together a pile from the biggest box—all oranges, for example. You would quickly learn, however, that your customers wanted more than oranges, and you would start arranging your piles of oranges so that you could fit in grapefruit and lemons. Later, you might learn that the Velcro on the ordinary grapefruits was too strong, so that customers had a hard time taking them off the pile, but that the Velcro on pink grapefruit didn't create this problem. Over time, then, your pile would come to have only pink grapefruit. Eventually, driven by the desire to maximize your sales, the pile might come to have proportions of citrus quite different from the proportion in the boxes from which the pile is made.

In the same way, Morowitz argues, over billions of years living systems have fine-tuned their molecules in response to their environment, driven by the inexorable pressure of natural selection. Like the grocer adjusting his pile in response to customer demand, nature has, over geological time, shifted the mix of atoms in living systems to make them better competitors.

That life should be based on the CHNOPS atoms isn't too hard to understand—they are reasonably common on Earth



© PAULA EASTWOOD

and form multiple chemical bonds easily. In terms of our analogy, they come in big boxes and have big Velcro patches. But once we get past these simple atoms, Morowitz's "fine tuning" begins to operate with a vengeance. In the chemical maelstrom we call the cell, tiny differences in the efficiency of a chemical reaction can have a huge effect on the ability of the cell to reproduce. And just as a slight customer preference for lemons in our analogy will quickly produce more lemons in the citrus pile, a slight advantage in reaction rate will allow the cell that has it to outcompete, and eventually eliminate its competitors.

Morowitz points to an interesting example of this effect. It turns out that all mammals require selenium as a trace element (it forms part of complex molecules that govern the processes by which toxic materials are removed from cells, increasing the efficiency of those processes). Selenium is below oxygen and sulfur in the periodic table, which means it has similar chemical properties, but it is relatively rare (it's concentration in the Earth's crust is only one ten-millionth that of oxygen). Nevertheless, because some ancestral organisms containing selenium were slightly better at surviving than those that were not, today we all need it. In fact, a rare heart condition in humans called

Keshan's syndrome is caused by a lack of the element. And oddly enough, there are even a few obscure bacteria in which experimenters have found that selenium can be replaced by tellurium, the next element in that column in the periodic table. This kind of experiment may eventually tell us something about how life works its way down the periodic table.

The necessity of trace elements in living systems can sometimes lead to surprising situations. For example, a number of years ago in Australia, sheepherders were puzzled when large numbers of their flocks sickened and died when grazing in a particular area. Investigators eventually found that the soil in that area was severely depleted in cobalt, an element that plays a role in the chemistry of vitamin B12. Plants can thrive without cobalt, but mammals cannot, as the sheepherders learned to their cost. (Feeding the sheep cobalt supplements eventually solved the problem.)

"What we learn from the periodic table," Morowitz says, "is that life is always conducting chemical experiments, trying to find that small advantage. It doesn't matter how difficult it is to find the element you need—life will make the effort

to incorporate it."

This way of looking at life and the periodic table is new—as you read this, SFI scientists have been thinking about it for only a few months. Thus, it is difficult to imagine where it will lead. We know that each atom, each obscure element, has a story to tell us about how it came to be incorporated into living systems. At the very least, when we know these stories we will have filled in another piece of the marvelous tapestry of evolution. And maybe—just maybe—in uncovering these stories, we'll find something completely new and unexpected. That's the beauty of basic research.

Stay tuned! ◀

James Trefil is Clarence J. Robinson Professor of Physics at George Mason University and a member of the FIBR project. His latest book is Why Science?

NEBULA: EARTH CORE: COURTESY OF NASA/JPL; BODY: © DENIS AGLICHEV/ISTOCKPHOTO.COM

ELEMENT	UNIVERSE	EARTH CRUST	HUMAN BODY
H Hydrogen	74	1.5	10
He Helium	24	0	0
C Carbon	.005	0.01	18
O Oxygen	.01	46	65
Fe Iron	.001	6.2	<.05
Ca Calcium	.0007	4.6	1.5

Common chemical elements together with the percentage (by weight) in which they are found in the Earth's crust, and in the human body. It's evident that a massive winnowing of elements took place when the Earth formed, and yet another took place when living systems formed.



2008 SFI Community Lectures

SFI has exciting lectures lined up for this year. The March talk explores how genetic aspects of the brain influence our behavior. April and May presentations focus on cutting-edge topics in information and computing. Summer events are devoted to art and science—dance, the visual arts, and music. In the autumn we consider various aspects of human social behavior.

Los Alamos National Bank provides major underwriting for this program.

Wednesday, March 19, 7:30 pm; James A. Little Theater

Jon Wilkins, Professor, Santa Fe Institute

3/19

Devil or Angel: Genetic Conflicts in Brain and Behavior

The genes that we inherit from our mothers and fathers favor two different sets of behavior, and clash both during brain development and in real-time decision-making. This talk will discuss the causes and consequences of this conflict, as well as what these discoveries mean for our understanding of the human mind and our notion of the unified “self.”

The following lectures in April and May are underwritten by RedfishGroup, Santa Fe. Both lectures take place at the Armory for the Arts, 1050 Old Santa Fe Trail.

Wednesday, April 23, 7:30 pm; Armory for the Arts

Seth Lloyd, Professor, Mechanical Engineering, and Principal Investigator, Research Laboratory of Electronics, Massachusetts Institute of Technology; author, *Programming the Universe: A Quantum Computer Scientist's Takes On the Cosmos*

4/23

Programming the Universe

Is the universe a giant computer? If so, how does it compute? It has been known since the nineteenth century that every atom in the universe carries with it bits of information, and that every time two atoms collide, those bits flip. The universe is carrying out a computation at the most microscopic level. This talk discusses the implications of the computing universe, ranging from quantum computation and quantum gravity, to the problem of free will and the ultimate future of life.

Wednesday, May 14, 7:30 pm; Armory for the Arts

Peter Norvig, Director of Research, Google Inc.

5/14

Practice Makes Perfect: How Billions of Examples Lead to Better Models of Language, Pictures, and Other Things

A computer might not learn in the same way that a person does, but it can use massive amounts of data to perform selected tasks very well. In this talk, Norvig explores the way that a computer can correct spelling mistakes, translate from Arabic to English, and recognize celebrity faces about as well as an average human—and can do it all by learning from examples rather than by relying on programming.

Monday, June 2, 7:30 pm; James A. Little Theater

Liz Bradley, Professor, Computer Science, University of Colorado, Boulder

David Capps, Professor, Dance, Hunter College

6/2

Con/cantation: Chaotic Variations

Bradley and Capps present a dialog between computer and dancer in a performance piece revolving around a simple movement phrase, its mathematical refraction, and its reconstitution into a structure inspired by the theme and variation form. They describe the piece as “an unfurling of the possibilities of order, kinetic logic, and cause and effect.”

This lecture is underwritten by the National Dance Institute of New Mexico.

Wednesday, July 16, 7:30 pm; James A. Little Theater

Charles Falco, UA Chair of Condensed Matter Physics and Professor of Optical Sciences, University of Arizona

7/16

Art, Optics and Human Vision

Falco—working with painter David Hockney—has identified a variety of optical evidence within a number of paintings demonstrating that artists as early as Jan van Eyck used optical projections as aids for producing portions of their images. While making these discoveries, Falco and Hockney developed new understanding about how more recent artists, such as Monet, Pissarro, and others, have created some of their iconic images.

This lecture is underwritten by Gerald Peters Gallery.

Wednesday, August 13, 7:30 pm; James A. Little Theater

Dimitri Tymoczko, Arthur Scribner Bicentennial Preceptor and Assistant Professor, Music, Princeton University

8/13

The Geometry of Consonance: Music and Mathematics

Musical chords live in interesting geometrical spaces called “orbifolds”—spaces that contain unusual twists and strange “singularities,” analogous to the black holes of general relativity. Tymoczko provides an accessible, multimedia introduction to this new way of thinking about music.

2008 SFI Community Lectures

Tuesday, Wednesday and Thursday, September 16, 17, 18
7:30 pm; James A. Little Theater

Samuel Bowles, Professor, Santa Fe Institute; Professor, Economics, University of Siena

Stanislaw Ulam Memorial Lectures: A Cooperative Species—How We Got to Be Both Nasty and Nice

Humans are remarkably cooperative animals. We frequently engage in joint projects for the common benefit on a scale extending beyond the family to include total strangers. We do this even when contributions to the project are costly and yield little private benefit. Examples include upholding social norms even when a transgression would not be noticed, engagement in warfare, and actions to preserve the natural environment.

Lecture 1. A cooperative species (or are we just afraid someone may be looking?)

Drawing on archaeological, genetic, climatic, and other information about the conditions under which our distant ancestors lived, Bowles will show why standard explanations of human cooperation are inadequate.

Lecture 2. Altruism, parochialism, and war: Rambo meets Mother Teresa

Bowles uses computer simulations to generate artificial histories of humanity over tens of thousands of years, tracing alternative trajectories that could explain how we got to be both nasty and nice.

Lecture 3. Machiavelli's mistake: why policies designed for "wicked men" fail

The final lecture will show why taking account of our ethical dispositions and the conditions necessary to both enhance and empower cooperative motivations is essential if we are to face the challenges of environmental sustainability, control of epidemic disease, the governance of the information-based economy, and political violence.

9/16,17,18

Tuesday, October 7, 7:30 pm; James A. Little Theater

Frans B. M. de Waal, Director, Living Links, Yerkes Regional Primate Research Center; Professor, Psychology Department, Emory University

Our Inner Ape: On the Possibility of Empathy in Other Animals

De Waal explores expressions of empathy in animals, especially nonhuman primates, and presents a "Russian doll" model of how animals perceive others. The model comes from a core emotional linkage arising from a direct mapping of another's behavioral state onto the subject's representations. This "Perception-Action Model" provides the basis for an increasing distinction between self and other, so that the other is recognized as the source of felt emotions.

This lecture is underwritten by Wayne and Barbara Coleman.

10/7

Wednesday, November 5, 7:30 pm; James A. Little Theater

Daniel Gilbert, Harvard College Professor of Psychology at Harvard University and Director of Harvard's Hedonic Psychology Laboratory; author, *Stumbling on Happiness*

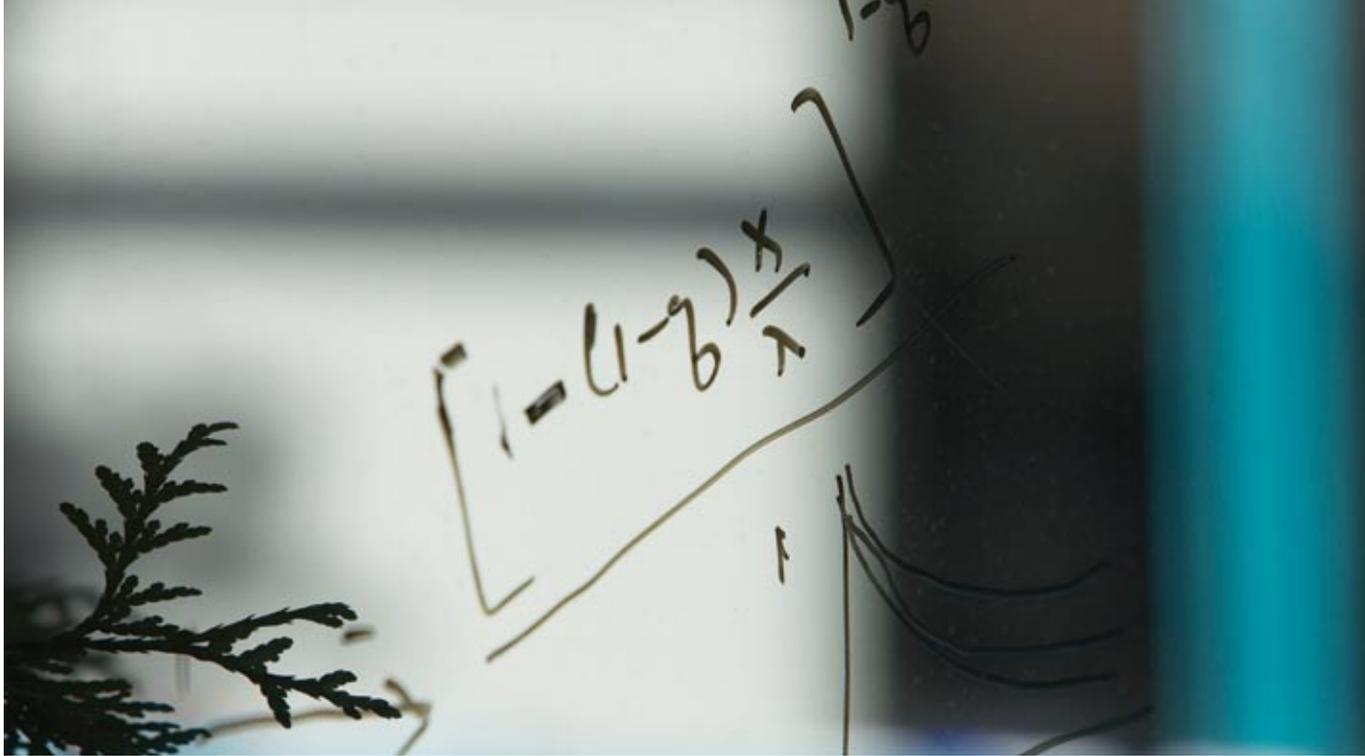
Stumbling on Happiness

People want to be happy. To achieve this they must do two things. They must predict how they will feel in a variety of possible futures, and they must act to bring about the best of these and avoid the worst. Gilbert describes what science has to teach us about why we seem to stumble on (and not upon) happiness.

11/5

All lectures begin at 7:30 p.m. Most lectures are Wednesday nights—with the exception of June, September, and October. (See schedule above.) April and May lectures take place at the Armory for the Arts, 1050 Old Pecos Trail, Santa Fe; all other lectures take place at James A. Little Theater, 1060 Cerrillos Road, Santa Fe. Admission is free but seating is limited.

For a more expanded explanation of the talks, visit www.santafe.edu/events/talks-public-lectures.php or call 505/984-8800.



TRANSITIONS

External Faculty

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

David Ackley received a Ph.D. from Carnegie Mellon University, and then went on to be a member of the Cognitive Science Research Group at Bellcore. Currently, he is professor of computer science at the University of New Mexico. His ongoing research interests center on artificial life models and real artificial life; current research emphases include genetic algorithms and programming, distributed and social computing, robust self-aware systems, and computer security.

Sander Bais From quantum field theory to string theory, Sander Bais's research focuses primarily on problems in theoretical high-energy physics. He has, however, "made interesting excursions to adjacent fields like condensed matter theory and physics

of the early universe" and explored novel applications of information entropy with the Santa Fe Institute's J. Doyne Farmer.

A science writer by hobby, Bais frequently contributes to Dutch newspapers and magazines. He has authored two books for a general audience, one that walks the reader through a handful of physics equations that "marked turning points in our thinking about nature" and a pictorial guide to relativity that was published this year.

Bais lives with his family in the Netherlands, where he works as a professor at the University of Amsterdam's Institute for Theoretical Physics.

Carl Bergstrom An expert on information and evolution, Carl Bergstrom has modeled the spread of antibiotic resistance in hospitals, mapped the flow of information through scientific communities, and co-authored a paper with his father on parent-offspring conflict. He is an associate professor of biology at the University of Washington.

Bergstrom enjoys learning about

other fields and collaborating with other researchers to tackle parallel problems across different disciplines. He is "thrilled to be affiliated with the Santa Fe Institute," as he considers it to be "the leading place in the world for interdisciplinary interaction in the sciences."

In his free time, Bergstrom studies the art of bonsai.

Luis Bettencourt works for the theoretical division of Los Alamos National Laboratory. He says it's "a great thrill to be involved with SFI, which has pioneered the scientific environment essential for progress in interdisciplinary research areas."

Bettencourt's professional interest lies in discovering themes in complex systems where new data and mathematical theory can test classic ideas and develop predictive insights. His current projects include analyzing data from living neural networks, working with epidemiological data streams to predict the evolution of emerging infectious diseases, and understanding human social dynam-

ics through the study of urban organization. He is also conducting an empirical investigation of Santa Fe coffee shops.

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

D'Souza has been a regular visitor to SFI since 1996, when she attended the Complex Systems Summer School as a Ph.D. student studying cellular automata. She recently came full circle when she attended the China Complex Systems Summer School in 2006 and 2007 as a lecturer and helped organize the SFI-sponsored residency month at the Institute for Complex Systems in Valparaiso,

Chile. As a member of the External Faculty, she welcomes the opportunity to further contribute to the vitality and intellectual energy of SFI.

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

Brian Enquist is a broadly trained plant ecologist and associate professor at the University of Arizona. His lab investigates how functional and physical constraints at the level of the individual (anatomical and physiological) influence larger scale ecological and evolutionary patterns. In particular, the lab focuses on two core areas: (1) Highlighting and deducing general principles, scaling rules, and the physical constraints influencing the evolution of organismal form, function, and diversity; and (2) Understanding the larger scale ramifications (ecological, evolutionary, and

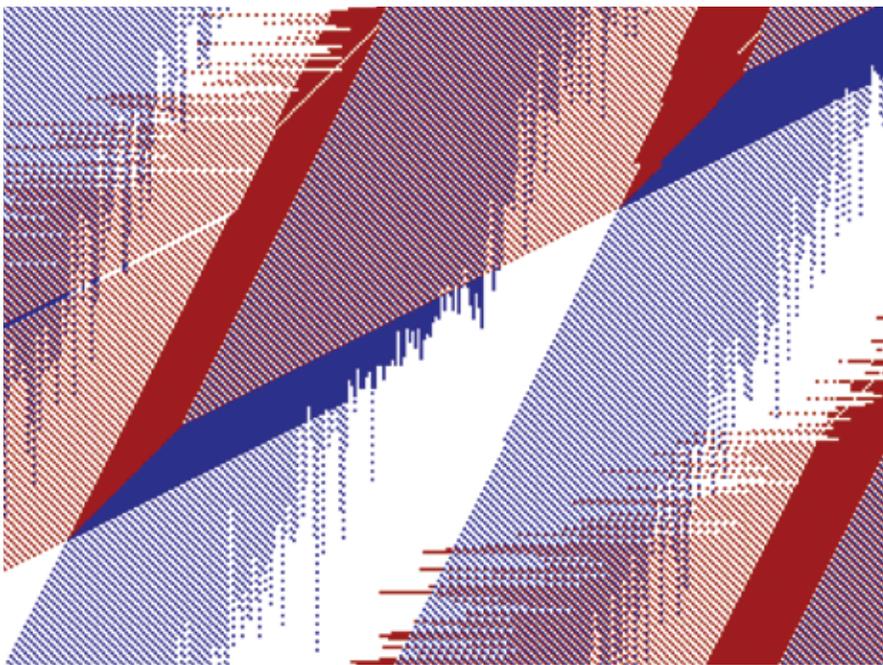
ecosystem) of these rules/constraints. In order to address these critical issues, the lab uses both theoretical, computational, biophysical, and physiological and ecophysiological approaches. Research in the lab can be summarized into four distinct yet interrelated areas: (1) The evolution of form and functional diversity; (2) The origin of allometric relationships (how characteristics of organisms change with their size) and the scaling of biological processes from cells to ecosystems; (3) The evolution of life-history and allocation strategies; and (4) Community ecology and macroecology.

Enquist first came to the Santa Fe Institute in 1997 as a student in the Complex Systems Summer School.

Duncan Foley is a non-mainstream economist who came to SFI in 2001 for a workshop on the management of common-property resources. He has since been thinking about the range of ways physics concepts and methods can be applied to economic problems, the general area sometimes called "econophysics." He believes that the Santa Fe Institute "can provide a forum where physicists interested in economic systems can learn more about economic history, the history of economic thought, and what is known about the actual functioning of economic institutions."

Foley, Leo Model Professor of Economics at the New School for Social Research, also has a strong interest in the relation of evolutionary thinking to economic behavior, in statistical theory and information, and in the complex neurological system that gives rise to circadian rhythms. He hopes his work in these areas will intersect with the thinking at SFI.

Matthew Jackson, a professor of economics at Stanford University,



COURTESY OF RAISSA D'SOUZA / UC DAVIS

Raissa D'Souza's research on emergent patterns in a model of flow and jamming: Bands of red particles moving eastward and blue particles moving northward self-organize and delay the onset of the jamming phase transition.

is currently putting the finishing touches on a book about social and economic networks. He also co-edits a monograph series and a journal of games and economic behavior. Highlights from his past studies include examining the incentives for countries to go to war and exploring a system by which Andorran farmers mutually insure each other against fires.

Jackson “looks forward to working with other researchers at SFI and studying how social network structure impacts beliefs, decision making, and behavior.”

Jon Machta, a statistical physicist, works with phase transitions, non-equilibrium systems, pattern formation and the computational power of physical processes. He is interested in the interface between computer science and statistical physics both from the practical angle of algorithm development and for the insights that computational complexity theory provide in understanding and characterizing the emergence of complexity in physical systems.

Machta is a professor at the University of Massachusetts, where he has been head of the Physics Department for the past five years. He has greatly enjoyed his visits to SFI and “looks forward to the closer connections as an External Faculty member and new arenas in which to work.”

Stephan Mertens Trained as a theoretical physicist, Stephan Mertens claims an identity as a “migrant who wanders back and forth between physics, mathematics, and computer science.” He has worked on phase transitions in computational problems, algorithmic complexity, pseudorandomness, and on parallel computing.

Mertens is currently working with SFI professor Cris Moore on a book

entitled *The Nature of Computation*, and hopes that SFI will become his intellectual home for the next couple of years.

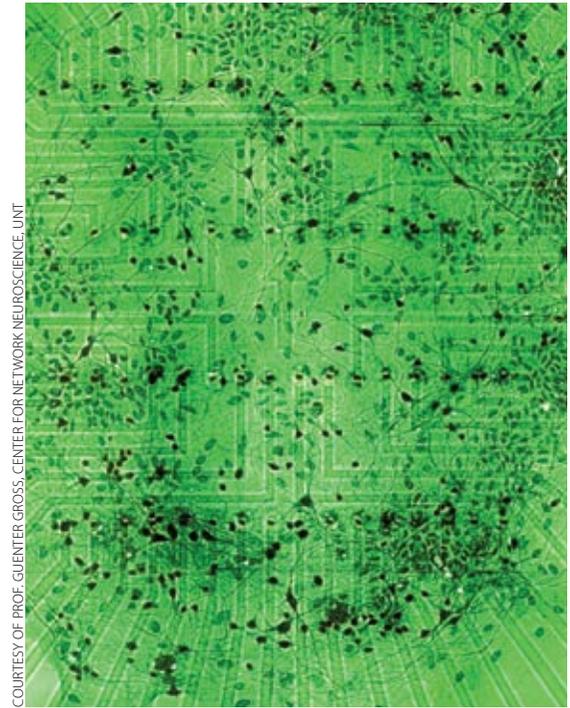
Maya Paczusi founded the Complexity Science group at the University of Calgary in 2006. Through collaboration, the group seeks to combine theory, technological advances, and the best available data to models of distributed information networks (such as global computing), structure of complex networks (such as protein interaction), complex dynamical systems, and social and economic phenomena.

In September 2007, Paczusi presented some of her transdisciplinary research on signaling-metabolic networks in a lecture for the ENRAGEing Ideas workshop. The lecture addressed the challenges of developing cancer treatments, and how network theory and nanoscience could combine to address them.

Paczusi has committed to “increase communication between different scientific disciplines and between science and the general public.”

Mark Pagel, editor-in-chief of the journal *Evolutionary Bioinformatics* and a professor of biological sciences at the University of Reading, hopes to collaborate with SFI faculty in studies of “assembly rules” for protein networks, on ideas of redundancy and evolvability, and on studies of language and cultural evolution.

His past work includes statistically inferring the structure of dinosaur genomes, studying the evolution of the prion proteins that cause mad cow



COURTESY OF PROF. GUENTER GROSS, CENTER FOR NETWORK NEUROSCIENCE, UNL

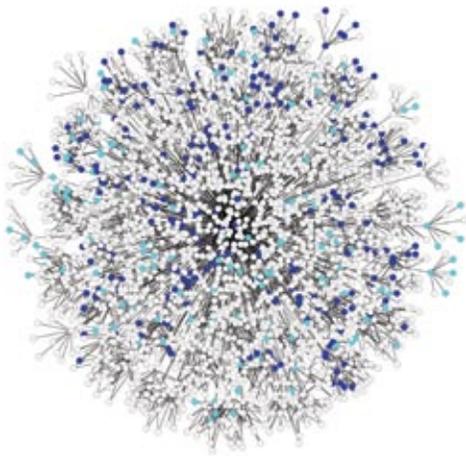
Luis Bettencourt’s work on neural networks: Analysis of patterns of electrophysiological activity in cortical tissue grown *in vitro* provides a window into collective information processing mechanisms in the brain.

disease, and contriving a theory to explain why human infants don’t look like their parents. The reason, he says, is “they have evolved to avoid detection in the event that the domestic father is not the biological father.” Interestingly, he is married with two children.

Sidney Redner, a Boston University physics professor, cut class for the entire 2004–2005 academic year. He spent his truancy at the Los Alamos Center for Nonlinear Studies as the distinguished Ulam Scholar. This jaunt in the Southwest brought him to the Santa Fe Institute, where he was introduced to like-minded researchers.

As a practitioner of statistical mechanics and network theory, he appreciates that SFI is “a place where his brand of research is in the focus rather than in the margins.”

Redner has modeled aging and immortality in cell proliferation, the



COURTESY OF S. CILIBERTI

Andreas Wagner's work with the evolution of molecular networks: Each circle corresponds to a transcriptional regulation network, a network of genes that can turn each other on and off.

effect of zealotry on elections, and can tell you exactly why soccer and baseball are more competitive than football.

Cosma Shalizi came to the Santa Fe Institute in 1998 to work in the Evolving Cellular Automata Project; the Computation, Dynamics and Inference group; and the Dynamics of Learning group. With a background in statistical physics of complex systems, most of his current work draws on information theory, which he considers to be "an invaluable tool for proving probabilistic results."

He says his name really is Cosma, and swears that it is "one of a small number of Italian masculine names ending in A." When not writing books or teaching at Carnegie Mellon University, Shalizi likes to contemplate Talking Heads lyrics and optimize the information on his website for retention in the pineal gland.

Stefan Thurner, a "wannabe concert clarinetist" and the head of the Medical University of Vienna's Complex Systems Research Group,

hopes to use his physics background to broaden the concept of statistical mechanics in order to make it more suitable for predicting complex systems. Since his first invitation to the Santa Fe Institute in 2000, Thurner has analyzed magnetic fields of human brain activity, developed a statistical method for calculating gene expression, and studied banking networks and financial asset price dynamics.

He believes that "any progress in handling complex systems resides in finding ways of treating their intrinsically large number of variables simultaneously," and that "shamelessly generalizing and advancing statistical mechanics is a promising starting point for a better understanding of social and economic systems that are way too complicated for the classic, reductionist approach to science."

In his free time he raises funds for a school-building project in South America.

Constantino Tsallis Born in Athens but currently living in Brazil, physicist Constantino Tsallis specializes in complexity and nonextensive statistical mechanics. He is credited with introducing the notion of what is known as "Tsallis entropy" and "Tsallis statistics" in his influential 1988 paper "Possible generalization of Boltzmann-Gibbs statistics" published in the *Journal of Statistical Physics*. Tsallis recently spent two full years at SFI as a visiting researcher, which he describes as "a wonderful period in my personal and scientific life when I had the opportunity of interacting with great scientists."

As a member of the External Faculty, he would like to "participate in all possible manners of the SFI scientific life." He hopes to visit SFI again, collaborate with various resident members, and possibly organize workshops.

Andreas Wagner heads a laboratory at the University of Zurich's Department of Biochemistry. The Wagner Lab pursues the study of evolution at all levels, from individual genes to communities of organisms. Wagner himself is examining the evolution of molecular networks.

As a member of the SFI External Faculty, he hopes "to advance the frontier of our understanding of evolution by interacting with the best minds that study complex systems." ◀

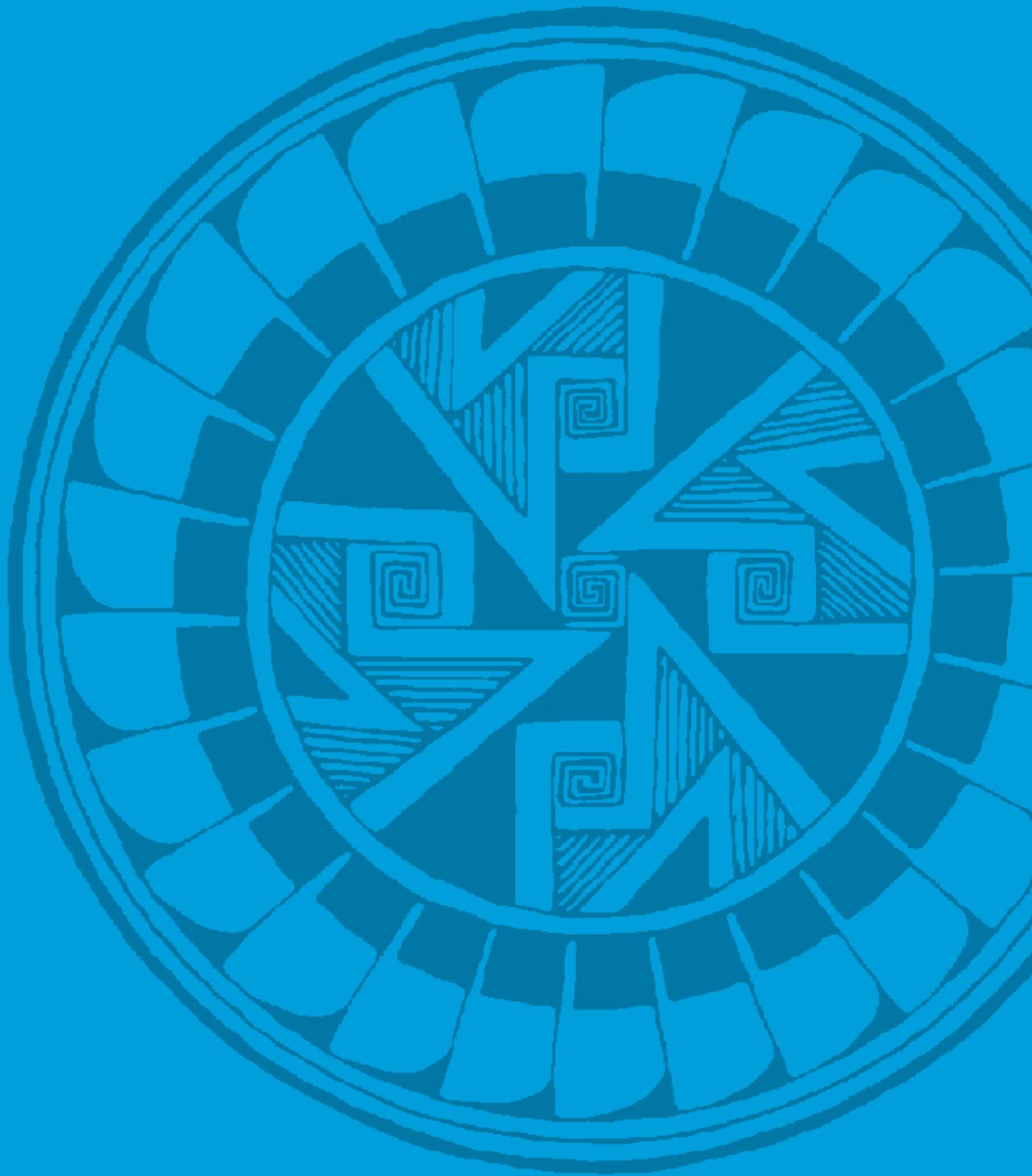
Robert O. Anderson 1917-2007

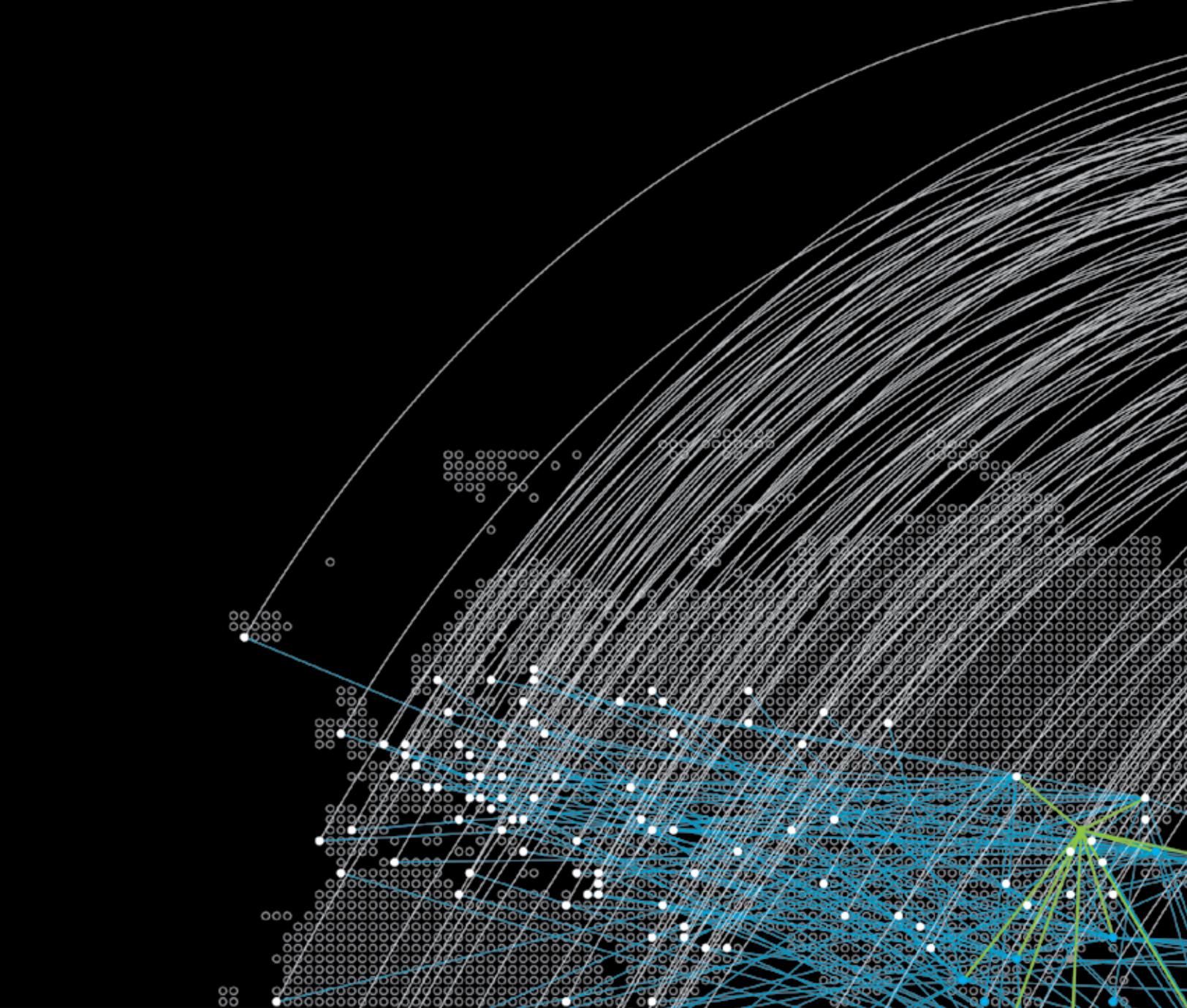
Robert O. Anderson, Chairman of the SFI Board of Trustees in the early 1990s, died in November 2007.

In addition to his leadership role at SFI, Anderson served on the Board of Regents of New Mexico Tech and was Distinguished Professor of Petroleum Engineering there. The Robert O. Anderson School of Management at the University of New Mexico was named as a tribute to him in 1974. He was a Life Trustee of the California Institute of Technology, the University of Chicago, and the International Institute for Environmental Development in London.

Besides being active in the oil business, Anderson's other business interests included cattle raising and feeding operations, mining and milling, and general manufacturing.

Anderson received numerous awards for his tireless efforts in support of public, charitable, and political affairs.





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