SANTA FE INSTITUTE

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UPDATE

In Khayelitsha, a shanty town in Cape Town, South Africa, over 500 structures are crowded into a 5.5 acre area, abutting a school with its own 0.8 acre soccer field, emphasizing the heterogeneity of the developing city. The slum's high density and poor road access make providing urban services, such as fire protection and sanitation, challenging and expensive. The data overlay provides a topological measure of how difficult it is to reach each structure from a road. (Image: Christa Brelsford)

Better cities from locally gathered data

Cities give rise to socioeconomic processes that have led to spectacular economic growth and human development in now-rich parts of the world. Such changes, however, were relatively slow to emerge, typically spanning several generations.

Today, the rapid urbanization of the "developing" world demands that problems of sustainable human development are solved faster, "really in the next few decades," says SFI Professor Luis Bettencourt. "But we still lack critical theoretical and practical knowledge about cities and their role in the processes of human development," he says.

Addressing this information crisis through

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RESEARCH NEWS

Symposium revisits economies as complex systems

To mark the Institute's 30th anniversary, SFI's Annual Trustees and Business Network Symposium focuses on an important component of SFI's research portfolio: the investigation of economies, firms, and individual decision-making from a complex adaptive systems perspective.

Chris Wood, SFI VP for Administration and Director of the Business Network, says some of the critical elements of this perspective – or, as some would emphasize, the most notable departures from mainstream economics – include the realizations that:

- economies are rarely, if ever, in equilibrium;
- economies reflect the aggregate of decisions and actions of organizations and individuals at many different scales, from the individual consumer to the giant bank that's "too big to fail" to the actions of federal, state, and local governments to international pressures and opportunities; and
- human decision-makers are rarely the rational, primarily self-interested, utility maximizing "*Homo economicus*" that mainstream economic theories assume us to be.

SFI External Professor W. Brian Arthur summarized this view in a recent SFI working paper: "[T]he economy is not necessarily in equilibrium: economic agents (firms, consumers, investors) constantly change their actions and strategies in response to the outcome they mutually create. This further changes the outcome, which requires them to adjust afresh. Agents thus live in a world where their beliefs and strategies are constantly being 'tested' for survival within an outcome or 'ecology' these beliefs and strategies together create. Economics has largely avoided this nonequilibrium view in

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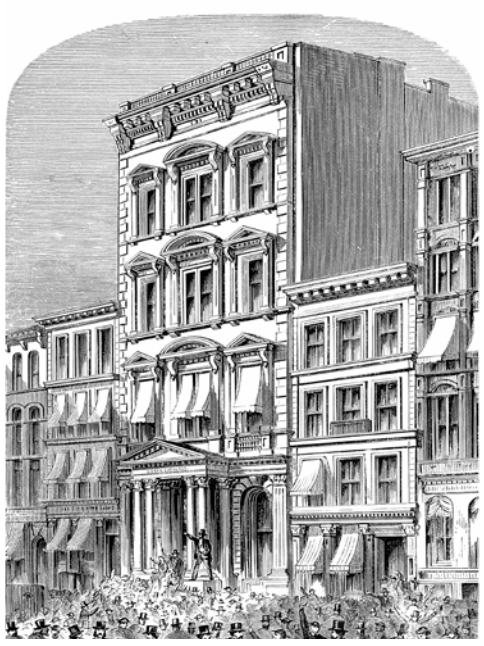

Mob in front of bank during the stock market crash in 1873. Engraved by Arthur Lumley (1837 - 1912) and published in 1874. (Image: public domain, istockphoto.com)

IN THIS ISSUE

RESEARCH NEWS

Weaving new ecological theory

On the heels of a manifesto on the nature of ecological theory, SFI researchers and their collaborators met in Chile in October to discuss its future.

Co-organized by SFI External Professor Pablo Marquet and VP for Science Jennifer Dunne, the working group was the first formal meeting of NETI, the Network for Ecological Theory Integration.

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RESEARCH NEWS

Workshop explores commonalities in network dynamics

A quiet forest scene, where sunlight filters through old-growth evergreens to thick underbrush, belies the system's bustling interconnections. Energy captured by plants, mushrooms, and microbes is directed through insects to songbirds and up to the occasional passing carnivore, and ultimately returns to the forest floor as detritus.

Such a food web is a network exhibiting two kinds of dynamics. Its nutrient flow, where biomass and energy course through a set of feeding relations between organisms, is an example of dynamics ***on*** a network. Dynamics ***of*** a network is when the structure itself changes, for example, when species and their feeding links blink in and out of existence.

Both types of dynamics can operate within a single system and often influence each other. Environmental stresses may

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In the October issue of *New Mexico Magazine*, Mary-Charlotte Domandi, host of the Santa Fe Radio Café, extolls Santa Fe as an "intellectual mecca," with SFI as its brain.

The October 5 *Santa Fe New Mexican* highlights SFI Science Board Member Deborah Gordon's research on ant interactions as complex systems, describing her vision of using ant-inspired algorithms for making sense of data networks.

In a September 8 article for the *Santa Fe New Mexican's* "Science in a Complex World" series, SFI Omidyar Fellow Ben Althouse described how mathematics is helping us understand how diseases spread.

A September 8 article in the *Santa Fe New Mexican* offered a preview of SFI President Jerry Sabloff's 2014 Stanislaw Ulam Memorial Lecture Series, during which he showed how lessons today's archaeologists are learning about the past offer insights that could shape present and future human societies.

In an October 27 "Science in a Complex World" piece in the *Santa Fe New Mexican,* SFI External Professor Andreas Wagner addresses a question that has confounded theoretical biologists: how do evolutionary innovations arise in the first place?

In an interview with SFI Miller Scholar Sam Shepard in the September 7 issue of *The Guardian*, Shepard acknowledges SFI's Cowan Campus as a place where he is surprisingly productive.

On September 4, *the Santa Fe New Mexican* reported on the McKinnon Family's generous donation of $2.5 million to endow and provide administrative support for SFI's education and outreach programs.

In a September 1 *New York Times* article, SFI Professor Luis Bettencourt comments on the need for further analysis before implementing a ride-sharing system for New York City taxi cabs.

Both *Science* and NBCnews.com reported on an analysis of animal depictions on Egyptian artifacts by SFI Omidyar Postdoctoral Fellow Justin Yeakel and colleagues suggesting that the Nile Valley ecosystem has grown progressively less stable over the last 6,000 years.

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The *SFI Update* is published bimonthly by the Institute to keep its community informed. Please send comments or questions to John German at *jdg@santafe.edu*.

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Nonlinearities

From the editor

Each summer, 50-60 graduate students and postdocs converge in Santa Fe for nearly four weeks of scientific nirvana at SFI's Complex Systems Summer School. Typically, one summer's session generates a handful of papers that get published in reputable journals. CSSS 2014 was an outlier! Of the 21 papers written (so far) by participants, 13 have either been published or are awaiting publication.

Not only are the raw numbers remarkable, so are the topics. Here is a sampling of titles. You can read those papers not awaiting publication at bit.ly/12kVkdx.

- "A model for revolution based on multiplex networks" [yes, this is a look at the mathematics of authoritarian regime overthrow]
- "How artificial intelligence can inform neuroscience: A recipe for conscious machines?"
- "Modeling the heart as a communication system" [biochemistry meets info theory and introduces it to physiology]
- "Is evolution a software engineer? A case-based comparative analysis of biological and software systems"

The Ebola outbreak in West Africa is a sobering spectacle. It's also becoming clear there is still too much we don't know about Ebola, and more generally about how diseases spread and how to stop them. If there is a good case for vigorous science and science funding, here it is.

So why don't we know enough about Ebola (after two-dozen outbreaks since 1976)? I suppose we've been parsing a dwindling research budget in smaller chunks and directing what's left toward more urgent questions. Sure, hindsight is 20/20, but it doesn't take a genius to see that a pandemic – perhaps not this one, but some future runaway virus – is *the* greatest threat to human life, and it's a threat we can't hope to isolate in its village or country of origin.

That said, I'm always impressed that when something interesting happens in the world, someone in the SFI circle almost always has something intelligent to say about it. I had a chance to hear SFI External Professor Lauren Ancel Meyers talk in Austin recently about what lessons the seasonal influenza cycle offers our response to Ebola, and how modern, mostly digital tools can improve our abilities to detect any outbreak. Over the last month, amid the finger pointing and fear mongering, Meyers has made frequent appearances in national news outlets, serving as a calm, credible voice and offering mathematical objectivity to the major questions. So have others, including External Professors Marc Lipsitch and Joshua Epstein.

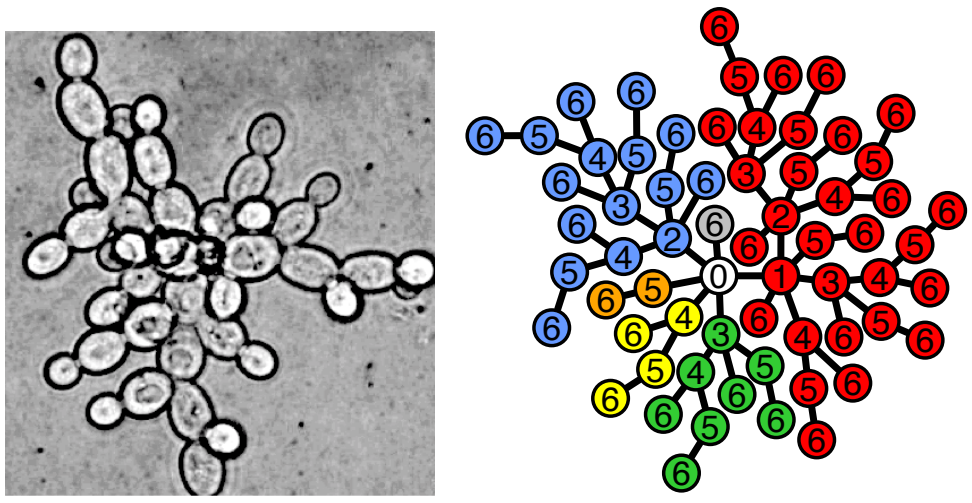
I suppose that's the advantage of an unusually diverse, inquisitive, and interdisciplinary group of experts. Emerging questions – and old unresolved ones too – require new and creative ways of thinking. ■

– John German, jdg@santafe.edu

Geometry-enabled multicelluarity

Geometry and programmed cell death might have helped along the evolution of multicellular life, according to research led by SFI Omidyar Fellow Eric Libby.

Writing in the journal *PLOS Computational Biology*, Libby and colleagues argue that genetically-programmed cell death likely evolved along with multicellularity, laying the foundations for the reproduction of multicellular organisms.



Cross-section of branching yeast (left) and simulated group growth (right) showing where the multicellular organism might cleave. Colors represent growth branches from original parent cell (0); numbers represent generation of each cell's birth.

The team took inspiration for their results from a recent experiment on yeast. In that study, researchers repeatedly grew the yeast *Saccharomyces cerevisiae* in test tubes and selected whatever sank to the bottom for more growth. Because the yeast cells that stuck together tended to sink, larger clusters survived this artificial selection.

So too did rudimentary reproduction: when one cluster got too big, it would simply break apart, forming two distinct organisms. But a more counterintuitive trait evolved as well – individual cells that were programmed to die sooner than their unicellular ancestors.

One reason for this, Libby says, is space. In the multicellular yeast creatures, each cell can split in two, forming new branches along which the organism grows. But if the multicellular organisms grow too large, they'll start to compete with each other for nutrients and eventually crowd each other out. Unabated, that trend would limit the success of the new species. With cells born to die quickly, however, an organism can avoid that fate. Rather than suffocate itself, cells die, breaking one creature into two more manageably-sized ones.

"We must view the group organism as a completely new environment, one in which traits like cell death might have different consequences" for the health of living things, Libby says. ■

Study traces mammal life over 6,000 years of Egyptian history

Artistic depictions of animals on ancient Egyptian artifacts have helped scientists assemble a detailed record of large mammals that lived in the Nile Valley for the past 6,000 years. A recent analysis of this record by SFI Omidyar Postdoctoral Fellow Justin Yeakel and collaborators shows that species extinctions, likely caused by a drying climate and a growing human population in the region, have made the ecosystem progressively less stable.

The study, published in *PNAS*, finds that local extinctions of mammal species led to a steady decline in the stability of the animal communities in the Nile Valley. When there were many species in the community, the loss of any one species had relatively little impact on the functioning of the ecosystem, whereas it is now much more sensitive to perturbations.

The study had its origins in 2010, when Yeakel (then a graduate student at UC Santa Cruz) visited a Tutankhamun exhibition in San Francisco with coauthor Nathaniel Dominy.

"We were amazed at the artwork and the depictions of animals, and we realized they were recording observations of the natural world... we started thinking about how we could take advantage of those records," says Yeakel, the paper's lead author. ■

Working group considers man-made evolution

Biology has gone through countless evolutionary innovations since the dawn of life – the emergence of multicellular organisms is just one – but a deeper understanding of those transitions might come from examining emerging fields such as synthetic biology and evolutionary robotics, argue SFI External Professor Ricard Solé and Professor David Wolpert.

To pursue that synthesis, Solé and Wolpert have organized an SFI working group for December, "Major Transitions in Natural, Synthetic, and Artificial Evolution," that brings together a mix of physicists, biologists, computer scientists, linguists, and even philosophers to ask some basic questions about the nature of innovation and transition.

The meeting will focus on understanding how biological innovations arise in nature, but through a new lens. "Synthetic biology has shown that artificial tissues and organs can be constructed," Solé says.

Three decades ago, it seemed crazy that a character in the film Blade Runner, a genetic engineer named Chew, would specialize in making eyes, but researchers today are starting to do precisely that, Solé says. Meanwhile, robots can develop simple grammars, lie to each other, and identify themselves in the mirror.

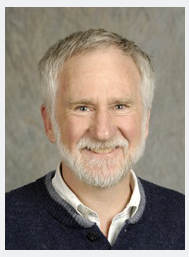
Such research, they say, opens up new possibilities and new questions about the nature of evolution: Is there a unique kind of design principle for living cells? Or might there be alternative evolutionary principles that can be applied to artificial systems but are absent in nature? Is complex language a rare accident, only arising in human societies, or instead might there be other kinds of complex language that become a reality in the future as communicating, evolving robots become more complex?

"By looking at life's human-made counterparts, we hope to better understand some fundamental questions concerning the possible and the actual," Solé says.

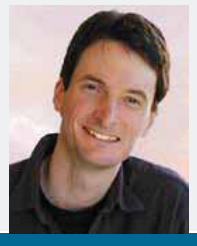
Solé says he hopes the working group will create new ties between SFI researchers and bring new researchers into the SFI circle – and lay some foundations for a new area of research. ■

The emergence of multicellular life, probably in the form of a cyanobacteria around $3.8 billion years ago, was a major biological transition. (Image: istockphoto.com)

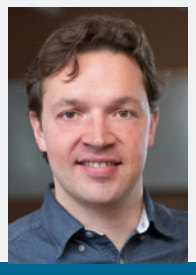
ACHIEVEMENTS



Tim Kohler has been selected to receive the 2014 Alfred Vincent Kidder Award by the American Anthropological Association's Archaeology Division. The Award is given every two years to an outstanding scholar specializing in the archaeology of the Americas. The award will be presented at the 2014 AAA business meeting in Washington, D.C. in early December.



SFI Science Board member and External Professor Alan Perelson and SFI External Professor Mark Newman are among the "World's Most Influential Scientific Minds of 2014," an annual Thomson Reuters recognition of researchers who published the most highly cited papers in 21 prominent scientific fields for the 11-year period from 2002 through 2012. Newman is among researchers cited for papers in physics. Perelson makes the list in the mathematics category.



Former SFI Omidyar Fellow Ruben Andrist has joined Google Zurich as a software engineer in the Group for Machine Intelligence, focusing on natural language processing. ■

SFI Online

Multimedia content available at ***www.santafe.edu***

Video: Zappos CEO Tony Hsieh describes his project to revitalize downtown Las Vegas, with SFI's Geoffrey West joining him on stage for a discussion. Special event in Santa Fe

Video: SFI's 2014 Research Experiences for Undergraduates students describe the results of their summer projects, from "Linguistic divergence in Timor" to "Kickstarting memes and movements." 2014 SFI REU final presentations

Video: SFI President Jerry Sabloff shows how lessons today's archaeologists are learning about the past offer insights that could shape present and future human societies. SFI's 2014 Stanislaw Ulam Memorial Lectures

Audio: SFI Professor Sid Redner reveals an unexpected truth in sports statistics: there is no such thing as a "hot hand," at least in baseball and basketball. Santa Fe Radio Café interview

RESEARCH NEWS

Exploring the thermodynamics of a living Earth

Consider the Moon. Grey. Unchanging. Lifeless, simple chemistry.

Now consider the Earth. Green. Chaotic. Alive, complex chemistry. Seemingly under strong "pressure" to form ever more ordered patterns.

The Earth and the Moon are next-door neighbors in the universe, both receiving plenty of light from the nearby sun. So why has the Moon stayed simple, ignoring all that energy, while the Earth exploits it to such fabulous effect? What general principles underlie the differences in how they have evolved?

Erwin Schrödinger, one of the titans of quantum mechanics, considered this question in posing what is now known as Schrödinger's Paradox. SFI Professor David Wolpert thinks the answer to his paradox might lie in the way biological systems store and transmit information – and information is something one can analyze with well-established theoretical machinery, he says.

So why has the Moon stayed simple, ignoring all that energy, while the Earth exploits it to such fabulous effect?

"When physicists talk about 'information,' what we mean is how much we can infer about the state of one thing by looking at the state of another thing," he explains.

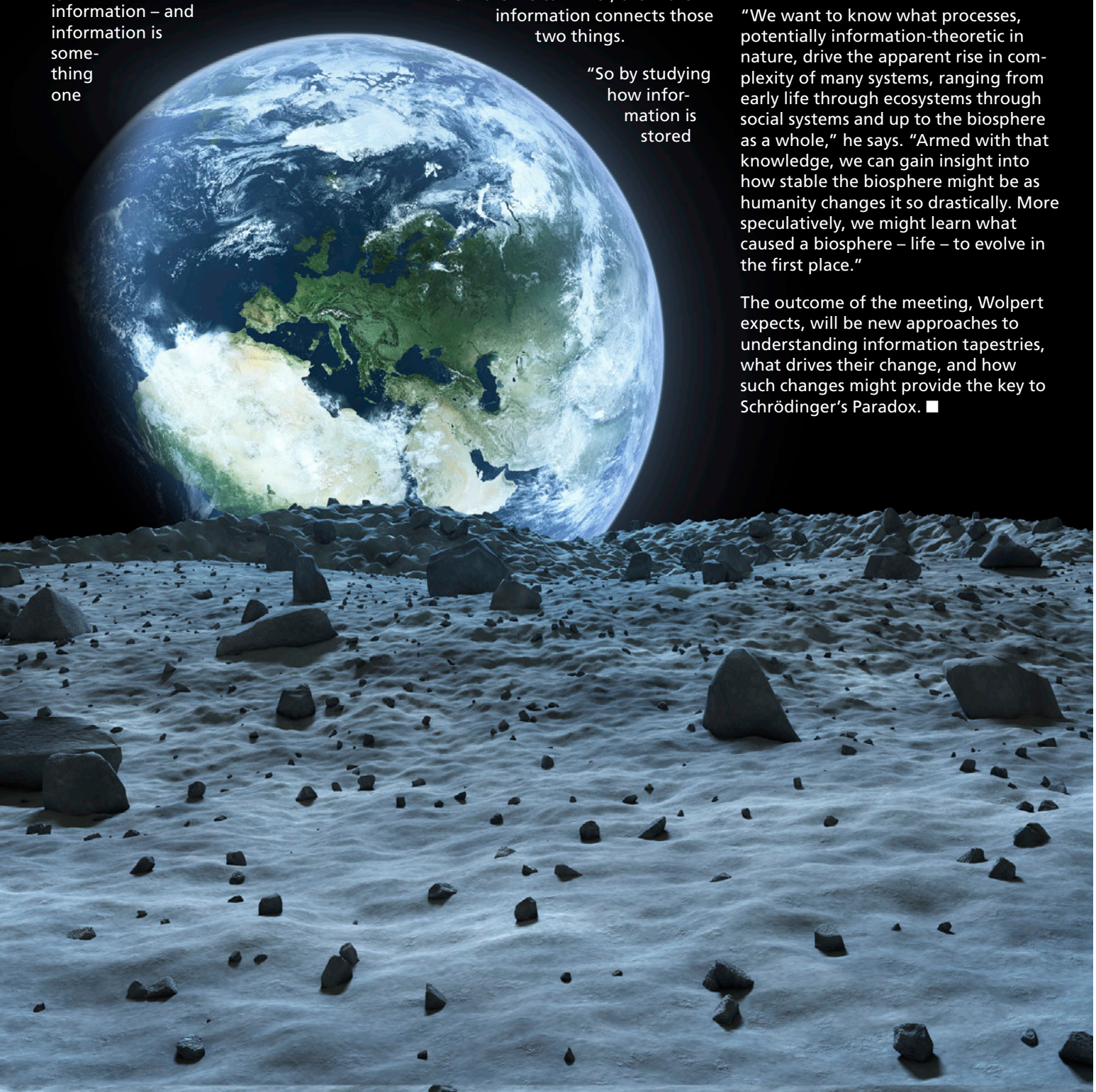
A simple example is how much we can infer about the total biomass of predators in an ecosystem from what we know about the total biomass of prey. The more we can infer, the more information connects those two things.

"So by studying how information is stored in a biological system, how it flows within the system, and the dynamics of how this flow changes in time," he says, "we can start to uncover the tapestry of information in such systems – and, just maybe, start to understand what pressures that tapestry to grow ever more complex."

With former SFI Omidyar Fellow James O'Dwyer and SFI VP for Science Jennifer Dunne, Wolpert is co-coordinating a two-day, invitation-only working group, "Information Theory, Ecosystems, and Schrödinger's Paradox," in mid November. Scientists specializing in ecosystem modeling, phylogenetic tree reconstruction, cell biology, algorithmic information theory, computation, and statistical physics will gather at SFI to look closely at how life orders itself, and then try to reconcile biology's underlying order with thermodynamics.

"We want to know what processes, potentially information-theoretic in nature, drive the apparent rise in complexity of many systems, ranging from early life through ecosystems through social systems and up to the biosphere as a whole," he says. "Armed with that knowledge, we can gain insight into how stable the biosphere might be as humanity changes it so drastically. More speculatively, we might learn what caused a biosphere – life – to evolve in the first place."

The outcome of the meeting, Wolpert expects, will be new approaches to understanding information tapestries, what drives their change, and how such changes might provide the key to Schrödinger's Paradox. ■



> *Economics* continued from page 1

the past, but if we allow it, we see patterns or phenomena not visible to equilibrium analysis."

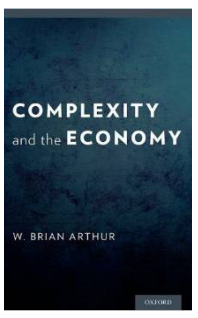
The Symposium addresses a number of other threads of SFI's work on economics, including the development of cooperation versus competition in ancient societies, income and wealth inequality in modern economies, network effects in economic behavior, and international development and the diffusion of technological knowledge.

Looking forward, the Symposium will address alternative approaches to structuring the investment industry and new perspectives on improving capitalism as we know it.

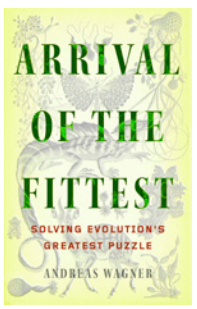
The keynote address will be presented by Nobel laureate and SFI Science Board member Kenneth Arrow, who has long been a part of SFI's community. Invited speakers include a range of former and current SFI faculty, affiliates, and collaborators: Sam Bowles, University of Siena and SFI; Eric Beinhocker, Institute for New Economic Thinking, Oxford; Doyne Farmer, Institute for New Economic Thinking, Oxford, and SFI; John Geanakoplos, Yale University and SFI; Nick Hanauer, Second Avenue Venture Partners; Ricardo Hausmann, Harvard University and SFI; Tim Hodgson, Towers Watson; Alan Kirman, Aix-Marseille Université; and David Wolpert, SFI.

The invitation-only event falls within a few days of the 30-year anniversary of the second of two SFI founding workshops in late October and early November 1984, "Emerging Syntheses in Science," at which Arrow and several dozen invited scientists formulated the corpus of SFI's original research portfolio, including SFI's founding research program "Complexity and the Economy," begun in 1987. ■

BOOKS BY SFI AUTHORS



Complexity and the Economy (Oxford, 2014) by W. Brian Arthur describes complexity economics, from the field's origins in a 1987 conference at SFI, through its development as SFI's first research program, its foundational papers, and its rising importance during the recent revisiting of economic theory.



Arrival of the Fittest: Solving Evolution's Greatest Puzzle (Penguin Group, 2014) by Andreas Wagner answers a longstanding challenge to Darwinian evolution – how chance mutations could possibly result in the efficient and marvelous structures life forms use to survive. Wagner shows how robustness, long a subject of interest at SFI, helps solve the problem. ■

Modeling pilots behaving strategically

It's a jungle up there. More than 87,000 commercial flights take off and land in the U.S. every day. Add to that countless flights by military and private aircraft, all piloted by human beings relying on limited information and a mind-boggling array of technology.

Despite all that traffic, the national airspace is remarkably safe. But what happens when thousands of unmanned aerial systems (a.k.a. drones) join the mix? In particular, what rules and procedures should govern drones, controlled by human operators on the ground through noisy communication links (links that sometimes drop out entirely), to ensure that current safety standards are met?

The FAA has these questions and more on its plate as it prepares to issue new rules that open the skies to unmanned systems in the next few years. Science might help.

SFI Professor David Wolpert is leading a three-year, NASA-funded project to develop new computational models that offer quantitative predictions of air safety as the national airspace gets increasingly congested with planes, onboard pilots, remote drone pilots, automated technologies – and a great deal of new uncertainty.

In the past, regulations governing air traffic have typically relied on subjective expert opinion or on the anecdotal results of crash investigations. What's missing if we want to update those regulations, says Wolpert, is a quantitative, predictive framework that acknowledges that aircraft are controlled by human beings interacting with one another.

This suggests a role for game theory, he says. "A near-miss in the sky is the quintessential game of chicken. Do I swerve left or right? I have to guess what the other pilot is thinking, and the other pilot makes guesses about what I am thinking."

But modeling airborne events presents a challenge traditional game theory can't address: airborne events take place not in a series of discrete time steps, with lockstep stages of which human moves when. Rather they occur in continuous time, with events, actions, delays, and reactions occurring in a partially random sequence, at random times.

According to Wolpert, such randomness in the sequence and timing of events is best modeled with techniques from a different field, stochastic process theory. "We need to merge game theory and stochastic process theory, creating a completely new field," he says.

To begin, Wolpert and colleagues from Stanford and Los Alamos National Laboratory are working with the U.S. Forest Service. The goal is to investigate what procedures would be best for using drones to help fight forest fires.

"More generally, we think we can contribute to the assessment of potential air safety issues of the entire national airspace as it gets more crowded and starts to include drones," he says. "Our new approach could be of interest in a number of other areas as well, from cyber security to regulations of financial markets."

"When you become sensitized to it, it's hard not to see randomness in the sequence of human actions in almost all scenarios where people interact," he adds. ■

To study Ebola's spread, understand human mobility

In a letter in *Science* on October 24, SFI Omidyar Fellow Sam Scarpino and co-authors stress the importance of human mobility patterns in understanding the spread of Ebola. The authors write that "modeling efforts are limited in the absence of good mobility data." Analyses of existing mobile phone data and air travel data have produced initial maps of Ebola's movement, but more data are required to inform transmission models, which are necessary for planning appropriate interventions as the outbreak evolves.

When humans bred with Neanderthals

A *Nature* paper co-authored by SFI Professor Michael Lachmann decodes the genome of a 45,000-year-old human from Siberia. The researchers analyzed DNA from a fossilized femur found on the banks of the Irtysh river near the settlement of Ust'-Ishim. It is the oldest modern human bone found outside of Africa and the Middle East. The man it belonged to possessed a quantity of Neanderthal DNA similar to that of present-day Europeans and east Asians, though in larger segments along the genome. The lengths of the fossil's Neanderthal DNA segments revealed a new and better estimate for when interbreeding between Neanderthals and modern humans might have occurred. The analysis indicates that the two groups interbred 7,000 to 13,000 years before the man lived, or 50,000 and 60,000 years ago.

Trade relations offer stability against war

In a paper published on arXiv.org on October 5, SFI External Professor Matthew Jackson and co-author Stephen Nei model military and trade networks since 1820 in the first game-theoretical study of international alliances. The model combines network theory with game theory to ask whether countries' military and trade alliances provide stability against armed conflict. The model shows that the rapid increase in trade alliances since the 1960s increased the stability of international networks. The study also suggests that while modern networks are far more stable due to the increased number of trade alliances, no network of interconnected nations can be wholly immune to war.

Mergers lead to business ecosystem imbalances

Business mergers and acquisitions bring about significant imbalances in the functioning of economic systems, and the threat of monopoly looms large, according to an analysis of economic data published in *Proceedings of the Royal Society A*.

Drawing on approaches from complexity and evolutionary biology – and analyzing historical business data from a variety of industries and geographies and from the 1830s to the present – SFI Distinguished Professor Geoffrey West and colleagues from Imperial College London and PricewaterhouseCoopers show that the cumulative history of mergers and acquisitions of companies (i.e., ancestry) is a key characteristic underpinning the dynamics of business ecosystems.

They conclude that a universal mechanism leads to imbalanced business ecosystems in which a few very large but sluggish "too big to fail" entities, and very small niche entities, prevail. ■

> *Building better cities* continued from page 1

improved data and data collection is the focus of three-day workshop at SFI in November, "Acting Locally, Understanding Locally: Scaling Up Community Collected Data in Developing Cities."

Co-organized by Bettencourt, ASU's Jose Lobo, and SFI's Joe Hand, the meeting brings together researchers, community and nongovernmental organizations, open-source software developers, and representatives from the United Nations, World Bank, and various philanthropic foundations.

The need for data is particularly critical – and lacking – at the local level inside cities, says Bettencourt, where strong heterogeneity and inequality necessarily underlie urban planning and human development.

"The technology to collect, organize, and share local urban data is getting really good and it will only get better," he says. "But the organization is lacking. We want to create a vision for acquiring data easily and learning from it fast."

Born out of the SFI researchers' interactions with local community organizations as part of the Neighborhood, Slums, & Human Development project, the workshop seeks ways to build an international community dedicated to collaborative local data collection, especially in poor neighborhoods in developing cities.

"We want to create information bases and tools for large-scale collaboration, and create free open platforms for people to collect the data, upload it, and share it with others," says Bettencourt. "We want to create an infrastructure that's light and easy to use, and have the means to share knowledge about people's local conditions – sort of like Wikipedia for neighborhoods, but with a strong data and scientific foundation." ■

Jose Lobo (center) teaches local members of Slum Dwellers International in Bolivia to collect data on an SFI-designed mobile phone app. (Image: Joe Hand)

RESEARCH NEWS

How to know whether brute-force computation is the best we can do

The connection between the complexity of mathematical proofs and the complexity of algorithms is deeper than previously thought, according to SFI Omidyar Fellow Joshua Grochow and his collaborator, University of Toronto computer scientist Toniann Pitassi.

Their recent work, presented by Pitassi at the IEEE Symposium on Foundations of Computer Science on October 20, could help researchers better understand a central problem in computer science, known as P versus NP.

"Prior to our paper, the proof system approach to proving that P is not NP was an infinite endeavor," Grochow says.

For decades, the fundamental issue computer scientists face hasn't been just how to make algorithms run faster, but whether it's always possible to improve on brute-force algorithms.

Take the traveling-salesperson problem, which calls for finding the shortest route connecting several cities. The brute-force method is to compute all possible routes and see which is shortest, but as you add cities, the problem grows exponentially: with 5, 10, or 15 cities, there are 120, 3.6 million, and 1.3 trillion different routes to check, respectively.

The P versus NP question asks whether there are fundamentally faster solutions, not just to the traveling-salesperson problem, but to any of thousands of important computational problems. If P doesn't equal NP, then for many problems brute force is essentially the best we can do.

A related problem is whether there are relatively short – meaning not exponentially-long – proofs of mathematical statements. If there aren't, then P doesn't equal NP, answering a million-dollar question, says Grochow. Because there are many different mathematical proof systems, or dialects, proving that claim is a tall order.

The pair developed an algebraic proof system and showed that if that system doesn't have short proofs, then the algebraic versions of P and NP, known as VP and VNP, are not equal. But, says Grochow, the result is "significantly stronger than that," and should help researchers learn more about the P versus NP problem. ■

(Image: istockphoto.com)

Are quarantines confounding Ebola containment?

A study published in *PLOS Currents: Outbreaks* by SFI External Professor Carlos Castillo-Chavez and co-authors models the rapid evolution of the Ebola virus and efforts to contain it. By applying a time-series analysis and other statistical methods to World Health Organization data for Ebola in West Africa, they found that in Liberia and Guinea, the transmission rate accelerated when military-enforced quarantines were imposed – suggesting a rethinking of the nuances of mitigation strategies.

Ecologists need 'efficient theory' to make sense of all the data

Ecologists are awash with data and have the tools to find patterns in it. But understanding those patterns requires simple, mathematical approaches. The 16 co-authors of a July 16 report in *BioScience* term such approaches "efficient theory," which builds on first principles and a small number of assumptions. SFI-affiliated authors include lead author Pablo Marquet, Jim Brown, Jennifer Dunne, Brian Enquist, Jessica Green, John Harte, James O'Dwyer, and Geoffrey West.

How hosts and parasites co-evolve

In a paper in *PNAS*, SFI External Professor Michael Hochberg and collaborators examined co-evolution patterns among the host bacterium *Pseudomonas aeruginosa* and a panel of bacteriophages (viruses that infect and replicate within a bacterium). Their study finds that pathogen identity affected co-evolutionary dynamics and suggests that these dynamics are associated with the nature of the receptor used by the viruses for infection.

When microbes join forces, useful new compounds emerge

In a paper in *PLOS Computational Biology*, SFI External Professor Elhanen Borenstein and co-authors show that when living together, communities of microbial species commonly produce novel, potentially useful compounds that single species growing alone do not. They begin to define the mechanisms and time signatures of such "emergent biosynthetic capacities" and present a computational framework for modeling, exploring, tracking, and predicting this phenomenon in simple two-species communities.

Weighing the pros and cons of fracking for oil and gas

In *Physics Today*, SFI External Professor John Rundle and co-authors review the practice of fracking – injecting large volumes of low-viscosity water into shales to extract oil and gas – and consider the pros and cons. Although the relatively new technique of superfracking has dramatically increased natural gas recovery, the authors note, it also raises significant technical and environmental concerns.

Modern forests shaped by extinction event

In *PLOS*, SFI External Professor Brian Enquist and colleagues suggest that the asteroid that probably spelled extinction for the dinosaurs could be responsible for modern forest landscapes favoring deciduous trees over evergreens. The team analyzed more than 1,000 fossilized plant leaves and classified their survival strategies. They found that slow-growing plants such as evergreens prevailed before the extinction event, while fast-growing, fast-flowering deciduous plants displaced them after the collision.

What influenced the prevalence of violence in ancient societies?

In a July 2014 paper in *American Antiquity,* SFI External Professor Tim Kohler and co-authors plot eight centuries of violence in two pre-Hispanic societies in the American Southwest, finding that violence generally declined (even as population increased markedly) in one region, and that violence increased (as population increased and maize production fluctuated) in another region. Scott Ortman, a former SFI Omidyar Fellow, is a study co-author.

Culture influences strategy in online coordination game

People strategize better with those from their own culture and they are poor at predicting the behavior of those from different cultures, suggests a new study led by SFI External Professor Matthew O. Jackson and published in *PNAS*. Subjects in India and the United States using an online strategy game had fundamentally different strategies and different expectations of the other players, the study found.

RESEARCH NEWS

Workshop takes stock of niche construction research

Under our feet, bacteria influence the microstructure of soil, tipping advantage toward their offspring. Beneath the waves, a coral reef's stony additions create architecture for other species to call home.

On the human side, recent studies suggest that a pregnant woman's food choices can affect her child's food preferences. The child's consequent ecological niche (in terms of diet) triggers gene regulation, ultimately creating epigenetic effects.

Niche construction, in both ecology and culture, is the focus of a growing number of recent research and theoretical developments, according to SFI External Professor Marcus Feldman. "Fifteen years ago there were not many papers," he says. "Now there are hundreds, and [niche construction] is poised to explode as a subfield within ecology. It's a very good time for us to stand back and look at the whole field and how it's been going over the last few years."

To explore the current landscape, Feldman, Kevin Laland, Lucy Odling-Smee, and Doug Erwin are convening a workshop, "Frontiers in Niche Construction: From Theory to Application in the Biological and Social Sciences," at SFI November 10-12. The meeting involves some two-dozen researchers whose fields relate to, or are impacted by, the biological sciences.

Evolutionary theory's modern synthesis will be among the topics of discussion. It was developed in the middle of last century, says Feldman, before we knew about epigenetics, microbiology, or developmental biology – and pertinent mathematical theory was in its early days – which raises the question of how to fold these new and complex fields into the synthesis, and whether it's worth doing, he says.

Another question is whether the field "is sufficiently complex that it could serve the purpose of a program at SFI," he says. "We'll discuss it with resident faculty and postdocs at SFI to see whether it tickles their fancy enough to make it a regular thing." ■

› *Network dynamics* continued from page 1

eradicate a species, for example, forcing the food web to reconfigure and redirect its energy flow.

Some changes are insignificant, others cataclysmic; it depends in part on the number and kinds of connections that particular species has, as well as its population size and those of other species.

Much network data and analysis, whether for food webs or power grids, focuses on structure – which only provides a snapshot of how networks are organized. Increasingly, researchers have access to richer dynamical data, which in turn requires new kinds of analyses and models.

"This is a wide-open field," says SFI Professor Cris Moore. He and SFI Professor and VP for Science Jennifer Dunne are convening a week-long workshop, "The Dynamics Of and On Networks," in December to explore ways to use such data "to understand how a network's structure and its dynamics are related to each other," Moore says.

Ecologists, engineers, power grid experts, mathematicians, and physicists will consider approaches to investigating and modeling a network's resilience to stressors, how communities join or split apart in a social network, and the optimal interconnectivity in a system.

The invitation-only meeting runs December 1-5 at SFI. ■

INSIDE SFI

Five journalists selected for fellowship

Five journalists have been selected for the 2014-2015 SFI Journalism Fellowship in Complex Systems Science.

The fellowship is generously supported by SFI Board of Trustees Chair Emeritus Bill Miller. It identifies accomplished reporters who have demonstrated an interest in complex issues and offers them an immersive experience in complex systems science at SFI.

As with the inaugural 2013-2014 fellowship, SFI's second fellowship class is selected from a diverse and highly competitive field of candidates, notes SFI President Jerry Sabloff.

"These five exceptional journalists from around the world and from across the spectrum of media and coverage specialities take us another step toward our goal of offering one of the world's signature news media fellowships," he says.

The 2014-2015 fellows are:

Kevin Allison is a Chicago-based journalist and commentator focused on the intersection of business, science, and markets. Since 2011, he has covered topics ranging from climate change to corporate takeovers for *Breakingviews*, Reuters' financial commentary service. Allison plans to spend August 2015 at SFI.

Catalina Arevalo is a Madrid, Spain-based science writer and multimedia communicator. For the last decade she has worked as a correspondent, editor, and producer for the world's largest Spanish-language news organization, EFE, covering climate change, energy, biodiversity, and sustainable development. She plans to spend January and June 2015 at SFI.

Christie Aschwanden is a science journalist whose work has appeared in *Smithsonian, Popular Science, New Scientist, Discover, Science* and NPR.org. She writes a health column for the *Washington Post* and is a frequent contributor to the *New York Times*. She plans to spend May 2015 at SFI.

Rhitu Chatterjee has worked as a public radio and science journalist for nearly a decade. She currently lives in New Delhi. You can hear her stories on PRI's "The World" and NPR's "All Things Considered" and "Morning Edition." She plans to spend April and May 2015 at SFI.

Laurence Gonzales is the author of the bestselling nonfiction book *Deep Survival: Who Lives, Who Dies, and Why* and its sequel, *Surviving Survival: The Art and Science of Resilience*. He has won many awards, including two National Magazine Awards. He plans to spend November 2014 at SFI. ■

New online forum connects SFI alumni

For the first time, alumni of SFI's postdoctoral programs, summer schools, and graduate and undergraduate programs have an online forum for keeping up with fellow alums and maintaining their involvement with the Institute.

SFI's new Alumni Community website was launched in October 2014. The new forum features an alumni map, notable alumni profiles, job opportunities in complex systems, SFI news, and upcoming SFI events. Most important, it allows users to find other alums and form complexity-focused collaborative research or social groups.

"Our former students and fellows are an enduring part of the Institute's community," says Ginger Richardson, McKinnon Family Vice President for Education and Outreach. "They make continuing contributions to our research, serve as ambassadors for the Institute, and often help teach and lead future programs. Our new site enables alums to engage more deeply with SFI and with each other."

The forum's goal, says its coordinator Hilary Skolnik, is "to help our alumni stay involved with SFI, and give them a central place to connect and network with other researchers and students. We hope it will provide alumni with opportunities to continue some of the conversations they began at SFI."

Richardson says she hopes the forum evolves new kinds of interaction and collaboration. "Our alumni community is really the corpus for the larger complexity science community," she says. "I can imagine alums organizing meetups in their communities, beginning online discussions relevant to complexity science, and forming collaborations around new complex systems questions. We've even discussed reunions and complexity festivals. This forum opens the door to interactions we haven't dreamed of yet."

Alumni who wish to sign up for the new community can find it at alumni.santafe.edu, or follow the link from the LEARN page at www.santafe.edu.

Alumni are encouraged to enter the alumni T-shirt design competition; details can be found on the alumni community website. ■

Three new online courses have begun

SFI's Complexity Explorer began offering three free online courses on September 29. You can enroll and begin taking these free online courses any time during the course window.

- "Introduction to Complexity," taught by SFI External Professor Melanie Mitchell, September 29-December 14
- "Nonlinear Dynamics," taught by SFI External Professor Liz Bradley, September 29-December 14
- "Mathematics for Complex Systems," taught by a rotating roster of SFI scholars

The latter offering, "Mathematics for Complex Systems," says Mitchell, "is not so much a 'course' as a set of mathematics tutorials we are developing, covering the math topics most relevant to complex systems science." It will be updated throughout the year, and enrollees will receive email notification when new units are posted. ■

> *Ecological theory* continued from page 1

Marquet, Dunne, and their NETI colleagues recently coauthored a paper on their vision for what they call "efficient theory" in ecology: mathematical theories that economize on assumptions and maximize predictive power. Now, says Dunne, the team has turned its attention to the problem of integration; that is, how to build more broadly applicable theories from less comprehensive ones.

"Our recent article in *Bioscience* took on the task of defining what theory is in ecology and what it should ideally look like and do," Dunne says. Among other things, Marquet and co-authors argued that ecological theory should be mathematical, based on first principles with few additional assumptions, and broadly predictive. Furthermore, they wrote, theory should be understood as an easily testable approximation of nature – in other words, it is critically important to compare theory with real world data.

This framework makes it easier to build unified theories of ecology. "We now want to get back to the 'integration' part of the equation," Dunne says.

A variety of efficient theories, such as metabolic scaling, neutral theory, and MaxEnt, address and predict overlapping ecological questions using various approaches. "The synthesis of these diverse lines of research, as well as other lines of inquiry pushing toward theory status, like work on ecological networks, hold the promise of a more general theory that can address a broader range of ecological questions and phenomena," she says.

Marquet, Dunne, and colleagues have already planned two more meetings, one at SFI in 2015 or 2016, with a third to follow in Prague. ■

McKinnon Family's $2.5M gift supports SFI's Education programs

The McKinnon family in September made a generous gift of $2.5 million to support SFI's Education & Outreach programs.

The gift creates a permanently endowed fund to continue and expand SFI-sponsored educational activities and their administration. These programs include a variety of summer schools, internships, mentorships, and online courses and resources that provide complexity training and engagement for students of all ages and stages of education.

"With this gift we can bring our wide-ranging expertise to thousands of complexity enthusiasts and learners in New Mexico and beyond," says SFI President Jerry Sabloff. "We are extremely grateful to the McKinnons for their confidence in and support for our science and education programs."

"We are honored to partner with you in helping to take SFI to the next level," says Ian McKinnon, an SFI Trustee and longtime Institute supporter.

In recognition of the gift, SFI has renamed the position of Vice President for Education and Outreach the "McKinnon Family Vice President for Education and Outreach."

The gift is among the largest in the Institute's history from a private donor. ■

Murray Gell-Mann accepts Germany's prestigious Helmholtz Medal

In a special ceremony September 25 at the Institute, SFI Distinguished Fellow Murray Gell-Mann received Germany's prestigious Helmholtz Medal for his achievements in physics and the sciences. The Medal is the highest honor of the Berlin Brandenburg Academy of Sciences and Humanities. The ceremony featured an introduction and welcome from SFI President Jerry Sabloff, followed by words of recognition from Gell-Mann's SFI colleagues Jim Hartle and Geoffrey West. Here, Gell-Mann thanks friends, colleagues, and the Academy in a brief acceptance speech.

SANTA FE INSTITUTE
New Science. New Horizons.
1984-2014

Three decades of reflection and relevance

We had an amazing year!

In 2014, SFI's 30th anniversary year, our scientists advanced our understanding of civilization's sustainability with new research on both early human societies and modern cities. We examined creativity through the lenses of cognitive science, psychology, education, defense, healthcare, the arts, and neuroscience to better understand its critical role in scientific inquiry and human progress. And we brought the wonder of complexity science to future generations through our many education programs, from online courses to summer schools and afterschool programs – which are now reaching schools nationwide.

We also celebrated our 30th anniversary fully. We honored our founders and early scientists and the deep influence they've had across the spectrum of fields in the sciences and the humanities – both through their work here at SFI and through the many spinoff complexity research centers they've helped create. We witnessed our Omidyar Fellows and Postdoctoral Fellows explore compelling questions that are now leading to innovative and practical solutions to stubborn problems, such as understanding how diseases like Ebola spread, or how much total energy could be needed to sustain a growing global human population.

We've also made crucial gains in fundraising. We secured one of the largest gifts in the Institute's history; the generous gift from the McKinnon Family endows SFI's top Education and Outreach position. We met our 2014 Omidyar Challenge goal, and we set a record in new memberships in our President's Circle giving group.

These are important successes that ease the budgetary strain in some areas, but we cannot rest. You might not be aware that SFI has never had an endowment to support our general operations. That means we must re-raise the bulk of the Institute's annual budget year after year, and I'm now looking to our year-end needs – and to 2015. Your annual giving allows us to host scientific meetings, welcome hundreds of visiting researchers, and offer colloquia and public events – all the scientific vitality you expect from SFI. Your continued support, this year, next year, and down the road, is what makes SFI science happen. Please think of us in your year-end giving plans.

Best regards,

Nancy Deutsch, Vice President for Advancement

SFI@30
MY STORY

Jennifer Dunne
Vice President for Science
Santa Fe Institute

"I arrived at SFI as a postdoctoral fellow during a blizzard in early 2001, and at a crucial turning point in my career. SFI turned out to be the perfect place to switch from disciplinary plant ecology to transdisciplinary computational ecological network research. Opportunistic interactions with the huge diversity of SFI-affiliated scientists allowed me to pursue novel research questions and to define new frontiers. I never would have guessed back then that I'd eventually oversee science activities at SFI. It's been more fun than I should probably admit to help shape the dynamic, curiosity-driven, free-range intellectual culture here!"

New Science. New Horizons.
YEAR-END GIVING

The end of the year is the perfect time to ask ourselves a critical question: Have I done all I can to support the causes I care about, set an example for others, and maybe even make a difference in the world? If the answer is "not yet," consider the value of your contributions to SFI. Whether you're passionate about SFI's spirit of inquiry, fascinated by one of SFI's Big Questions, or determined to build a legacy that benefits future generations, SFI offers you many opportunities to make a difference.

New Science. New Horizons., SFI's 30th anniversary campaign, has raised more than $25 million toward our $30 million goal. Contributing now allows you to optimize your tax position this year while helping SFI build for the future. Make the most of your 2014 charitable giving goals by donating cash or securities to any of these funds:

President's Circle Membership: $1,000 per year – Annual giving club with special programming for members.

The Murray Gell-Mann Fund: A special fund honoring Dr. Gell-Mann. The Fund supports the full breadth of SFI science to ensure that Gell-Mann's work – and that of the Institute he helped build – continues for future generations.

Education Scholarships: $3,500 will fully fund a deserving, young complexity scholar for 2015.

There also are opportunities to establish a permanent legacy, from named buildings and open spaces to endowed funds supporting science, education, and outreach. We welcome multi-year commitments and gifts of appreciated assets to fund your chosen program.

Contact the Office of Advancement at 505.946.3678 to discuss how you can help us attain new horizons.

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November / December 2014

UPDATE

SANTA FE INSTITUTE

Upcoming community events

SFI Community Lecture, Wednesday, November 12, 7:30 p.m., James A. Little Theater (1060 Cerrillos Road) – Why we kill: Violence as socialization. Acts of serious violence – often committed by seemingly average people – leave us only to ask "why?" Culture, genetics, and low self-esteem are often cited, but growing evidence points to brutalization experienced in childhood, often at the hands of parents or peers. Ginger Rhodes and Richard Rhodes explore the work of criminologist Lonnie Athens, whose "violentization" model identifies a four-stage process by which almost any human being can be socialized into someone who will assault, rape, or murder. They looks at the history of violence, question the association of violence with mental illness, test Athens' theory on real-life cases, and make a strong argument for early intervention. Richard Rhodes is the author of 25 books including *The Making of the Atomic Bomb*, which won a Pulitzer Prize in nonfiction. Ginger Rhodes is a licensed clinical psychologist in private practice in San Francisco specializing in trauma treatment. The two co-edited the 1996 book *Trying To Get Some Dignity: Stories of Triumph Over Childhood Abuse.*

SFI's 2014 Community Lectures are made possible through the generous support of Thornburg Investment Management. Lectures are free and open to the public, but seating is limited. To watch a lecture as it happens, visit SFI's YouTube page; participate in the discussion live on Twitter at #sfi_live.

Science On Screen, Tuesday, November 25, 7:00 p.m., CCA (1050 Old Pecos Trail) – "Eternal Sunshine of the Spotless Mind" with Chris Wood. SFI VP and neuroscientist Chris Wood presents this Oscar-winning cult classic that follows a man struggling to come to terms with his ex-girlfriend's decision to surgically remove all memories of their relationship from her brain. Kate Winslet, Jim Carrey, Tom Wilkinson, Mark Ruffalo, Kirsten Dunst, David Cross, Jane Adams, and Elijah Wood star in this mind-bending tale of heartbreak and the human mind.

Science On Screen, Wednesday, December 17, 7:00 p.m., CCA (1050 Old Pecos Trail) – "Alien" with Eric Libby. "In space, no one can hear you scream." Ridley Scott's unbeatable 1979 sci-fi horror classic follows a spacecraft invaded by a maleficent creature bent on relentless parasitic reproduction. SFI Omidyar Postdoctoral Fellow Eric Libby, a biologist with a wicked wit and a fascination with how cells mutate and evolve into new organisms, delivers the context.

Science On Screen is a collaboration of SFI and the Center for Contemporary Arts. During each showing, an Institute scientist presents a favorite film, offering personal perspectives and insights from the world of science. It's an idea-rich spin on the movies. For tickets and prices, call the CCA Box Office at 505-982-1338.