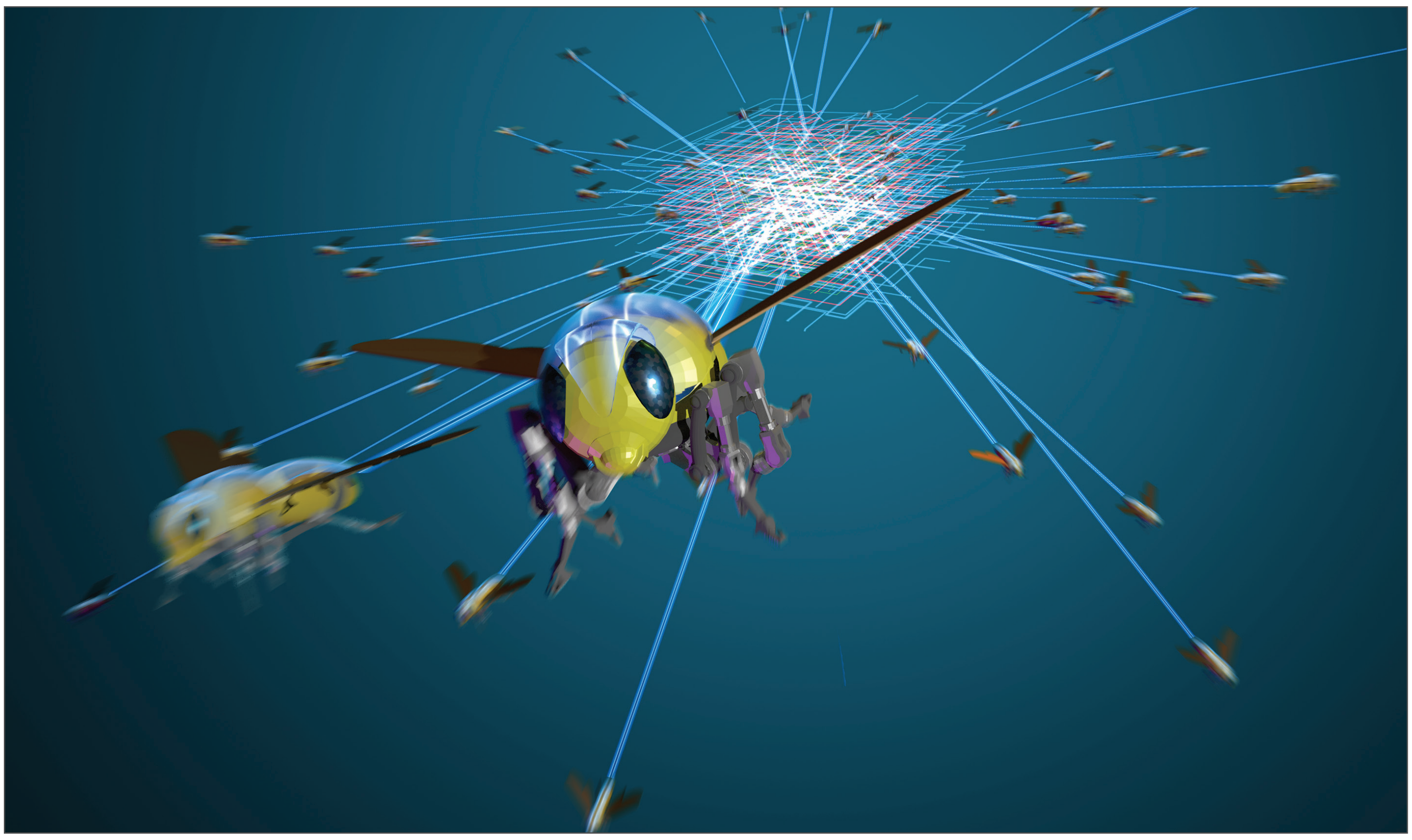
Spring 2019

Parallax

THE NEWSLETTER OF THE SANTA FE INSTITUTE



Robotic bees and computer chip. (Illustration: Jonathan Spencer Kaia Levy)

How do collective effects shape crypto networks?

From currencies like Bitcoin and Ethereum, to user-centric social networks, to new modes of governance, such as Decentralized Autonomous Organizations (DAOs), "crypto networks" consist of individuals who agree to follow a shared set of rules.

They represent a huge natural experiment. Yet in many cases, crypto networks and the currency systems built upon them are designed by trial and error or with game-theoretic toy models — an approach that SFI Professor Jessica Flack says "works well in rarefied settings. But crypto networks don't operate in rarefied settings. They operate in the wild, are built by their users, and have to work at scale."

As such, the entire crypto space is a tangle of rulesets, evolutionary strategies, and economic propositions. What can more subtle, quantitative methods offer the study and design of these networks? What insights can we draw from wild-born, natural systems, such as brains and insect swarms, to better understand and implement collective smarts at a planetary (even interplanetary) scale?

To start addressing these and other pressing questions raised by the proliferation of new crypto networks, SFI will host a workshop on "Collective Crypto" June 13, immediately before the InterPlanetary Festival. Organized by Flack, along with SFI President David Krakauer, Omidyar Fellow Joshua Garland, Trustee Graham Spencer of Google Ventures, and Dan Moroz of Harvard, the workshop will convene a necessarily diverse array of experts from academia and enterprise, bringing software developers and crypto token designers into collaboration with social scientists, evolutionary biologists, collective computation theorists, and systems-thinking venture capitalists.

This group will cast its questions wide: How much agreement is required to produce intelligent collective action? Are there mechanisms that allow consensus to emerge that also maintain diversity of opinion? How might a DAO or public ledger change under the influence of different algorithms for the way agreement is encoded in the network?

Flack sees opportunities for the crypto ecosystem to inform the science of collectives as well. "How can decentralization be operationalized and measured?" she asks. "Is decentralization about how the information is integrated, or about how components contribute to aggregate function?"

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A world worthy to visit: InterPlanetary 2019

The InterPlanetary Festival returns to Earth June 14-16. In anticipation of another transporting experience (see p. 6 for programming), we publish SFI Miller Scholar Laurence Gonzales's firsthand account of the "Origins of Life in Space" panel from the inaugural festival:

I drift past the stage and my attention is caught by [SFI Professor] Chris Kempes. I don't know the man sitting beside him but I soon come to learn that he is Caleb Scharf, Director of Astrobiology at Columbia University, and that gets my attention. He wrote The Zoomable Universe, *a dazzling tour from the scale of the entire universe to the scale of a subatomic particle with beautiful illustrations. I want to hear what he, not to mention Chris, has to say. I sit down and listen to him discussing Frank Drake, who in 1961 made an attempt to estimate "how many communicative species are out there in our galaxy," to use Caleb's words. The so-called Drake equation that resulted from this effort involved such factors as how many new stars form every year. Then Drake asked how many of those stars have planets. The answer is that most every star has planets. The next factor is that about ten to forty percent of those planets resemble earth. The final factor Drake considered was how often, on those small rocky planets, life actually occurs.*

"And that's where we hit a brick wall," Caleb says. And we know nothing about this subject. In fact we don't really know what life is. There is no accepted definition.

As they talk, life is exploding all around them. The stage has no back to it, so we can see a green and glowing tree behind the elevated platform where they sit and we can see people walking by with umbrellas against the summer sun and even one of the big Roadrunner locomotives roaring and dinging as it flashes past. It's a typical messy rock-and-roll stage with the very cluttered signature of life all over it, the wires hanging down and the made-in-China chairs with stainless steel frames and the white plastic pitcher of water on the Mies van der Rohe cuboid table and the scattered obscure and heavy-looking items of electronic equip-

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Taking a MACRO view of the microbiome

At first glance, elephants and bacteria appear to have little in common. They differ in size, habitat, life span — everything, really. The two organisms do share at least one trait, though: Both are influenced by the biotic and abiotic environment around them and reciprocate by shaping their surroundings. Whether the focus is an elephant roaming an African savanna or a bacterium residing in the human gut, ecologists strive to understand this dynamic exchange between organism and environment.

However, elephants and bacteria operate at different scales, and are governed by different physical processes. As a result, the fields of macroecology (studying ecosystems of organisms visible to the eye) and microbial ecology (studying ecosystems of microorganisms, such as the human microbiome) have evolved differing theoretical approaches and experimental methods.

"These fields have historically been quite separate," says Carolina Tropini, a James S. McDonnell fellow at Stanford University and soon-to-be assistant professor at the University of British Columbia. "There is a lot of theory that has been developed in both fields, particularly in macroecology, that has not been applied to the microbiome."

Tropini is helping to organize a working group at SFI May 8-9 that will attempt to link the two branches of biology. The other organizers include Britt Koskella, an evolutionary biologist at the University of California, Berkeley; Andrew Hryckowian, a microbiologist at Stanford University; and SFI External Professor Elhanan Borenstein, a computational biologist at Tel Aviv University.

The meeting, "Macroecological Insights into Microbiome Resilience and Function," is intended as a starting point for a continuing conversation between the macro and micro worlds. The event will lay the groundwork for collaboration by identifying common challenges, parallels, and differences in theory and

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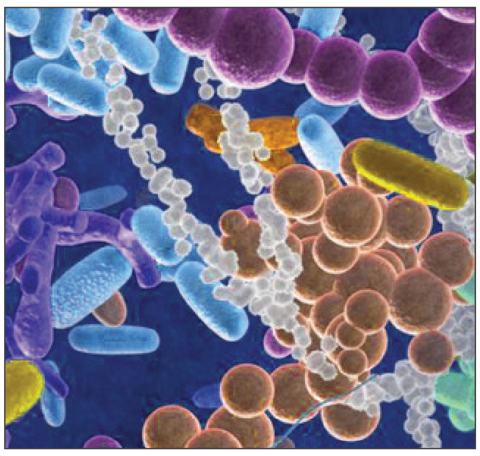

Illustrator's rendering of a microbiome

INSIDE . . . New SFI postdocs . . . Complexity of retail . . . Cells as computers . . . MORE

BEYOND BORDERS

FROM GUTENBERG TO GALAXIES

The 1408 constitution of Oxford strictly forbade the translation of the Bible into English from the Latin. Latin was the official language of the Roman Empire, mastery of which ensured the church maintained centralized control over its flock. In 1525 the theologian William Tyndale, motivated by an egalitarian impulse to disseminate religious ideas, prepared a secret translation of the New Testament in retreat in Germany, drawing on a recent Greek translation compiled by Erasmus of Rotterdam. For his efforts toward making divine wisdom accessible Tyndale was strangled and burned at the stake in the Duchy of Brabant in the Holy Roman Empire in 1536.

The control of knowledge has always been the ultimate means of controlling society. The emergence of Demotic script in northern Egypt in the 7th century BCE was seen as a direct challenge to priestly hieratic, which in turn was a means of easing the writing challenges of the quasi-divine hieroglyphic.

The evolution of languages and writing systems simultaneously expands the popular reach of learned culture while diminishing the sacerdotal control of ideas. And so it is no surprise that the reaction to democratizing knowledge has so often assumed the forms of dismissal, slander, and exile.

What is our responsibility to society as scholars and educators? How should scientific knowledge be shared, reviewed and evaluated in modern society, and extended beyond the reach of insiders, peers, and experts? The development of digital culture has enlarged the space of possible communications media far beyond the printed book, whose vernacular growth following Gutenberg reconfigured the expectations and opportunities of many members of society.

Over the last three years the Santa Fe Institute has established a series of new memetic laboratories to help explore alternative forms of communication and debate around complexity science. These experiments span a range from the established to the eccentric, the passive to the active, and the traditional to the radical: The SFI Press, Complexity Television, and the InterPlanetary Festival. Each one of these new projects analyzes different structures for conveying and debating the insights of complexity science—the domain of networked adaptive agents that dominates the social world.

The SFI Press is set to release five new volumes this year. Complexity Television is wrapping up production of "Episode One: Scale," and the InterPlanetary Festival — codename Stardust — comes to Santa Fe for its second year this June. I will discuss the SFI Press and Complexity Television in forthcoming Beyond Borders. The InterPlanetary Festival launched in 2018 — codename Genesis — attracted ~5,000 people a day in a near-equal balance of genders. Featuring panels of researchers, artists, filmmakers, musicians, designers, writers and investors, the Festival seeks to engender the sentiment of its mission: "To change the world one planet at a time."

Will these experiments prove successful? Will complexity science find new audiences and change the way people think about the world in which we live? Will the maverick rigor of SFI diffuse into collective consciousness and empower new minds and endeavors? Will popular ideas attract people to explore technical foundations? If we knew the answer to these questions we would have no need of experiments. If we were not SFI, we would not be performing these experiments but would be plowing the same furrows that brought us to this point. In the spirit of William Tyndale we would like our ideas to be made available to everyone and we would risk a great deal to make this possible. The signs are not so much exile as affirmation.

— David Krakauer
President, Santa Fe Institute

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SFI IN THE NEWS

Quanta Magazine profiled VP for Science Jennifer Dunne and her pioneering work integrating humans into ecological networks. The March 21 Q&A is titled "She Finds Clues to Future Sustainability in Old Food Webs."

The real college admissions scandal, according to External Professor Scott E. Page, is the "specialization effect," whereby students at wealthy secondary schools have more opportunities to excel through elite sports. His March 21 op-ed appeared online in *The Washington Post*.

In a March 14 interview with *Nautilus* magazine, External Professor James Evans described how dissenting opinions lead to better Wikipedia entries.

In separate research, Evans and his collaborators published a February 13 *Nature* paper examining the role of team size in science. Their finding that small teams tend to disrupt fields, while large teams tend to develop them, was reported in *The Atlantic*, *The New York Times*, and *The Conversation*.

On February 12, the *Santa Fe New Mexican*'s "Radio café" podcast aired an interview with External Professor Ross Hammond about the synergistic epidemics of obesity, undernutrition, and climate change. His recently co-authored commission and policy brief in *The Lancet* made headlines in CNN, BBC, Reuters, *The Guardian*, and other major news outlets.

Incoming postdoc Stefani Crabtree and her collaborators were featured in *The New York Times* on February 8 for their study of how Aboriginal Australian hunters played a key role in stabilizing ecological networks in Australia's Western Desert. Their recent study is part of SFI's larger ArchaeoEcology project, co-led by Dunne and Crabtree.

GWCSS at 25: The 'best department in the world'

This summer marks the 25th anniversary of SFI's Graduate Workshop in Computational Social Science and Complexity. The annual two-week workshop, held this year June 16-28, brings together a group of advanced graduate students and a small faculty for an intensive two-week experience.

To learn what makes this annual event so special — and how it has evolved over a quarter century and more than 275 participants — we sat down with co-directors and founders John Miller and Scott Page. Both are SFI External Professors, and Miller also chairs SFI's Science Steering Committee.

Q: How did this annual event start?

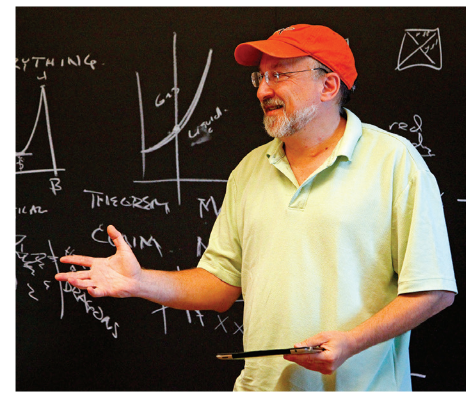
A: We were very young! In 1994, we took the idea that science advances funeral by funeral to heart, and we decided the best way to enhance the emerging field of computational social science and complexity was to create a workshop for the rising generation of new scientists. Thankfully, SFI has always had a long-term perspective on creating new science, so starting a workshop for graduate students was welcomed, even though it might take a decade or more to see the results.

Scott Page

Q: What's the secret to this workshop's longevity? What makes it stand out?

A: The program has always focused on graduate students who have completed their coursework but haven't yet started their dissertations. This allows us to leverage the students' previous training and focus on getting the new ideas we explore incorporated into their dissertations. Dissertations eventually lead to research papers and scientific talks, often setting the path for future careers — and even new students.

We have always started the workshop with a very open-ended homework problem to be completed by the next day with a randomly assigned teammate. These problems have ranged from modeling a standing ovation to a bike race. Each year we draw on SFI resident faculty and fellows to give talks and introduce the students to the SFI way of doing science. And the last half of the workshop is devoted to individual projects that are presented at a conference on the last day.



John Miller

Q: After all these years, what keeps you excited about this workshop?

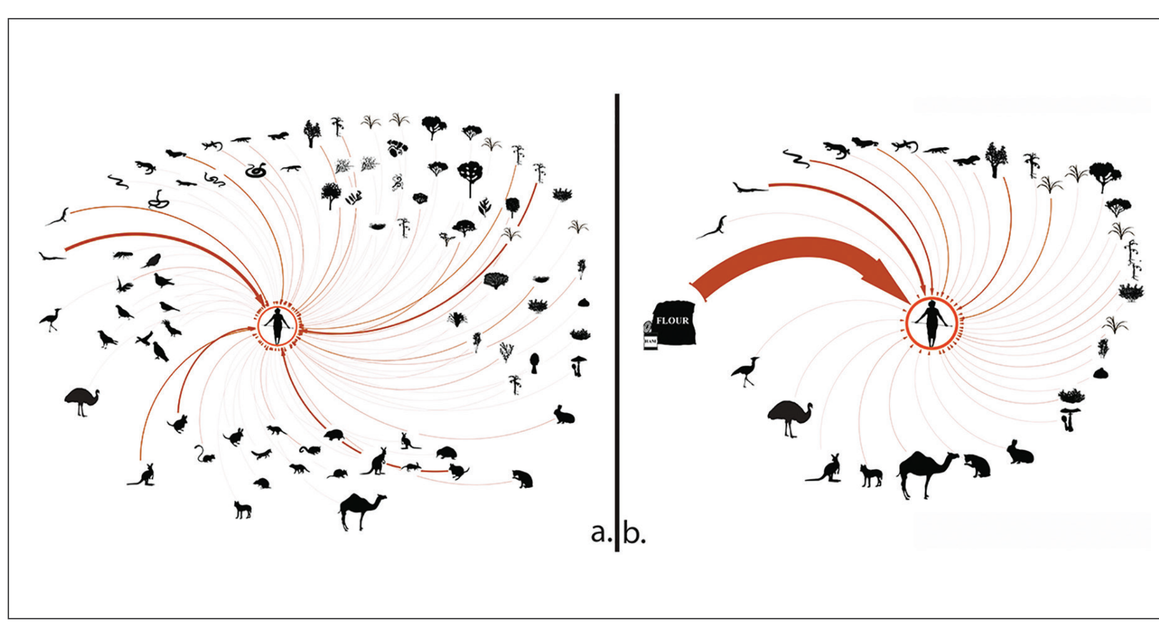
A: Every year in Santa Fe, albeit only for two weeks, we assemble the best department in the world in computational social science and complexity. The students are amazing and, for most of them, it's the first time they're surrounded by other colleagues who, regardless of their field (and there are a wide variety), have similar interests in complex systems. A wonderful and collaborative research culture quickly develops among the participants.

Q: What has surprised you the most?

A: We often find ourselves visiting former students in their faculty offices and see their "awards" from the workshop taped to their office walls. That's so cool. We feel as though SFI reminded them that science should be fun!

Study: Human impact on ecosystems yields unexpected insights

When the Australian government relocated Martu hunter-gatherers from their Western Australia lands in the 1960s, no one could have predicted the massive impact their absence would have on the desert ecosystem. A new study led by Stefani Crabtree, a Santa Fe Institute Visiting Researcher (Center for Research and Interdisciplinarity, Crow Canyon Archaeological Center) and incoming postdoctoral fellow (see p. 4), and co-authored by Rebecca Bliege Bird and Douglas W. Bird of the Pennsylvania State University, shows the critical role humans play in food webs, providing important clues to managing resilient ecosystems around the globe.



The constriction of the Martu foraged diet between the nomadic period (a) and the contemporary period (b) for the summer-season food web. (Image: Stefani Crabtree et al)

"Until 1964, the indigenous Martu people lived traditional, nomadic lives, hunting large monitor lizards for sustenance," Crabtree explains. "By lighting fires to expose their prey, they effectively created fire breaks each winter that protected the land from summer lightning fires. Their hunting methods also helped other species of plants and animals thrive, just as they dampened predators and suppressed harmful invasive species."

In the decades when the Martu were taken out of this food web, the ecosystem shifted significantly, with increased wildfires, reduced biodiversity, and the growth of invasive species — including the camels now wreaking havoc in Australian deserts. Comparing the 1960s food web to the modern food web — and showing all species as nodes on a network — demonstrates that the Martu were the "knitters" of their ecosystem, and that their removal had devastating results.

Exploring the role of humans within the food web is a fairly radical approach. "Ecologists typically look at ecosystems as separate from people, but to understand ecosystem health, we have to understand the people within the ecosystems," Crabtree says. "Using these kinds of well-resolved cases, where we have good snapshots of what people were like in the past and what they're like now, we'll be able to better understand our place in these ecosystems."

Rebecca and Douglas Bird, who have been living and working with Australian Aboriginal communities for 17 years, believe there has been far too little research on the part humans play in our ecosystems. According to Rebecca Bird, "Indigenous people like Martu, who have lived in the same region for millennia, have likely played an important role in shaping the assembly of plant and animal communities. It's important that we recognize that role, both for issues of environmental justice, and for understanding how best to go about restoring ecosystems to some prior state. Most attempts to reintroduce extinct mammals in the region have failed."

ERRATUM: *A photo caption in the previous issue erroneously described the Sanak Nearshore food web as "the only" detailed, complex food web to explicitly include humans. The food web should have been described as "the first."*

ACTioN event scopes the complexity of retail

At first glance, the workings of the retail world may seem simple: Companies sell goods that people want, and consumers buy them. But behind the must-have products and slick advertisements is an intricate network of supply chains, investors, markets, data, and consumers that together influence whether a retailer succeeds or fails. Complexity science, it turns out, has much to offer the retail sector — particularly as more historic brands go into bankruptcy, and the industry's disequilibrium increases.

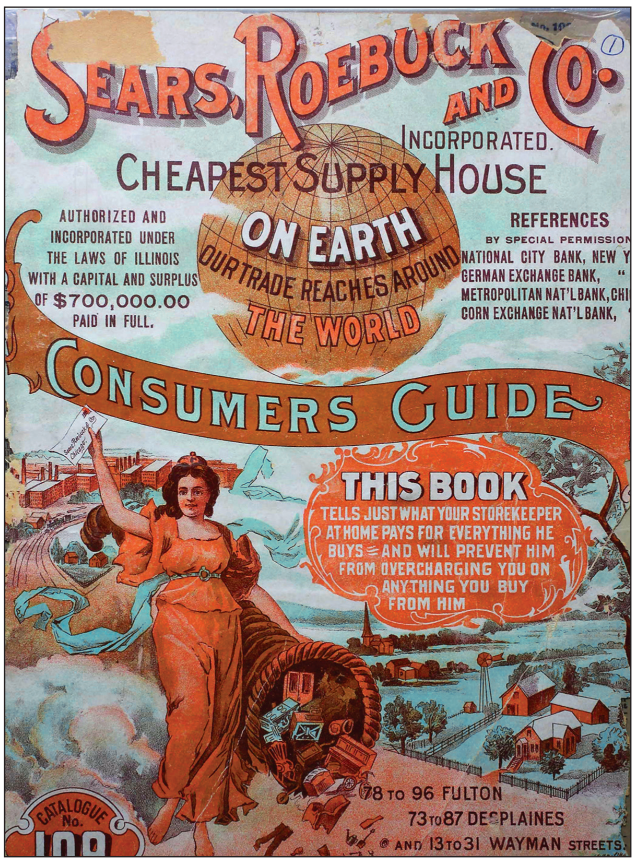
Especially useful to the retail industry is network theory. "If you think about a physical retailer, it really is very well described by a network — you have to get goods to those places as efficiently as possible," says Michael Mauboussin, Chairman of SFI's Board of Trustees and Director of Research at BlueMountain Capital Management. "The traditional retailers have moved into e-commerce, and e-commerce has moved into physical stores," Mauboussin notes. This shift makes a network analysis of the retail sector more challenging, but also increases the potential impact of this approach.

Another area where complexity science could benefit the retail sector is in understanding how companies scale. SFI Distinguished Shannan Professor Geoffrey West's work on scaling and company mortality could be applied to the retail sector, for example. "I'd be really curious to see [if] mortality in retail is any different than in any other industry," Mauboussin says. "Is birth, or death, different than in other industries — and if so, why? That's important if you're an investor."

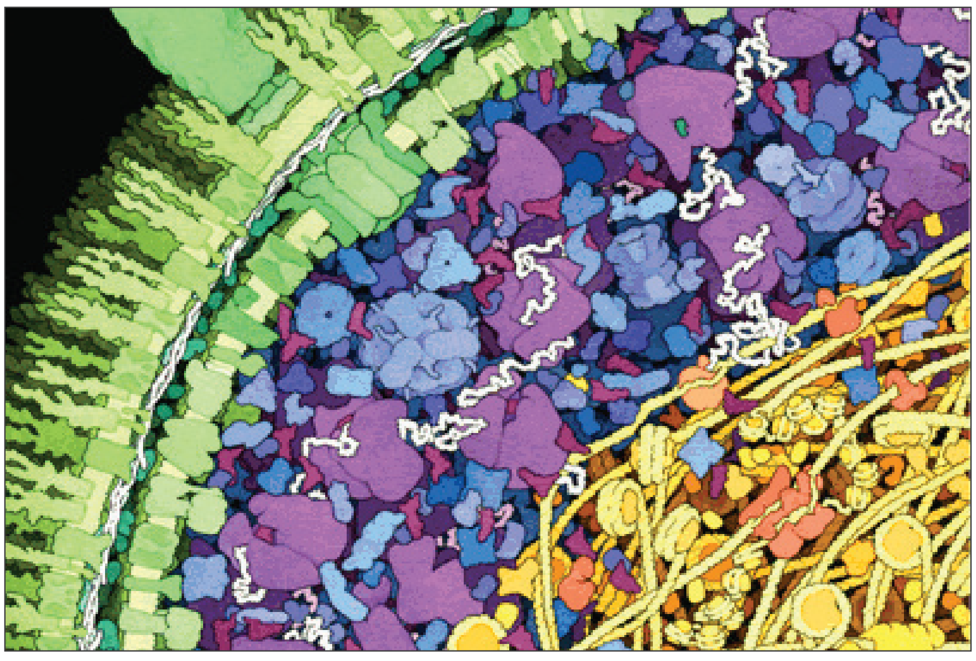
"I'd be really curious to see [if] mortality in retail is any different than in any other industry," Mauboussin says. "Is birth, or death, different than in other industries — and if so, why?"

Complexity science could also offer insights into one of the most elusive aspects of retail: How trends start and spread. One study, co-authored by former SFI Postdoctoral Fellow Duncan Watts, highlights how preferential attachment behavior can impact the popularity of songs. Newer work, co-authored by SFI External Professor Stefan Thurner, examines the interplay between elite-driven "top-down"changes in tastes and "bottom-up" changes driven by less socially prominent groups.

SFI will delve more deeply into the complexity of retail in a September 12 Topical Meeting in San Francisco, CA. The meeting is organized by SFI's Applied Complexity Network (ACtioN) and will be hosted by Shopify. More information about SFI's Applied Complexity Network and the September 12 meeting can be found online at santafe.edu/ACtioN



The mail-order catalogue of Sears, Roebuck and Co. dominated retail in the 20th century.


Cross-section of an Escherichia coli cell (Illustration: David S. Goodsell)

A living inspiration? Working group to investigate cells as computers

Computers guzzle energy. A big chunk of the money spent on computers pays for power, and an estimated four percent of the total energy consumed in the United States is used to keep our computers computing. Physicists have long been interested in understanding the physical laws that describe that tradeoff: What's the thermodynamic cost of processing information?

This isn't just a question for physicists, though. It resonates with living systems, too, which have evolved to perform specific jobs with access to only limited resources. "Our brain requires quite a bit of food whether we think anything useful or not," says computer scientist and SFI External Professor Peter Stadler. Similarly, cells carry out biochemical reactions that might be regarded as information processing, akin to computing.

Artificial, human-built digital computers are always out of equilibrium: They need a steady source of power to keep running. So it goes with cells. Without energy, they stop functioning and die – so equilibrium, for a living thing, is death. In the last decades, breakthroughs in the rigorous study of systems far from equilibrium — a field called nonequilibrium statistical physics – have led to the development of new tools. Now, researchers from a range of disciplines can better analyze such systems, whether they're used on our smartphones or keeping organisms alive.

Notably, recent studies suggest that cells carry out some biochemical "calculations" at a level of efficiency orders better than modern, artificial computers. That comparison raises a number of provocative questions. Do efficient biological systems look like any existing ideas in computer science theory? How did they evolve such efficient ways of computing, and what can we learn from them?

"Thinking of biological systems as computing or information-processing entities immediately begs the question, What do they actually compute? It's an open question," says Stadler.

In an effort to start probing those questions, Stadler and SFI Professor David Wolpert have organized a working group, "Thermodynamic and Computational Efficiency in Cellular Chemical Reaction Networks," to be held at SFI April 23-24. They've invited researchers from a range of disciplines — chemistry, physics, molecular biology, mathematics, computer science — who are interested in investigating the connection between energy and information processing, or computing.

The meeting may help researchers gain insights into whether or not living cells should be seen as inspirational for future low-power devices. Are cells more like vending machines with simple inputs and outputs and limited functionality? Or do their functions speak to a broad range of calculations?

"One potential outcome," says Stadler, "might be that biological systems are a very bad model for building computers."

Viewpoints collide in social reactors working group

"Urban scaling explains everything!"

It was a message pounced on by popular reviewers in 2017 with the publication of *Scale* by SFI Distinguished Shannan Professor Geoffrey West. But in academic circles, the theory has moved far beyond what West popularized in his book — and it has also provoked heated debates.

"Many researchers, and especially urban economists, have loudly rejected the work," says José Lobo, faculty in the School of Sustainability at Arizona State University. "The criticisms have been serious and have accumulated."

So far, the debate has been conducted in slow volleys through the pages of top journals. But this spring, dissenting voices will come together for the first time.

SFI's collaborative ethos often centers discussion that reaches across disciplinary lines. This meeting, which will be held at SFI May 15-17, extends that open-mindedness even further, inviting to the table some of the theory's most prominent critics.

Urban scaling theory is most famous for highlighting the disproportionate growth in economic output and innovation when a city grows linearly in population. These "superlinearity" findings, while easily hyped, are not necessarily novel, and detractors assert that urban scaling theory adds little to existing approaches by urban economists and economic geographers. Others question the robustness of reported scaling results or point out that it fails to identify its underlying generative processes.

"It is not often that SFI convenes a meeting at which criticism of SFI-sponsored work is explicitly aired and confronted," says Lobo, who is the event's organizer and convener. The three-day summit will keep one-way presentations to a minimum, instead directing time to mutual listening.

One looming question hits at the heart of urban studies itself: what exactly is a city?

"What is the thing people are studying? A built environment, or a social network?" asks External Professor Scott Ortman (CU Boulder). Ortman leads SFI's Social Reactors Project, which conceptualizes cities not as physical spaces so much as "social reactors," hubs of human interaction that fuel technological change.

"This debate is raging at the moment," says Lobo. It's "a crucial one, for if we are to advance in our understanding of urbanization we need to be clear that we are measuring the right thing."

"The most important tasks of the working group," says Lobo, are "to clearly place urban scaling work in the context of the rich work that has been done on urbanization and the origin of cities by many disciplines, assess the empirical strength of the reported scaling results, [and to] clarify just what is it that we have learned from the urban scaling work."

In doing so, the working group will build on one of SFI's signature strengths: putting dynamic thinkers not in the same journal but in the same room to clarify what urban scaling adds to an ongoing, urgent conversation with implications for cities past, present, and future.

Crypto networks *(cont. from page 1)*

Krakauer emphasizes the urgency and scope of this conversation, adding, "We're going to be forced now to conceive of fundamentally new institutions that more accurately reflect empirical reality. We see this in the blockchain/cryptocurrency debate, which started out as a very local means of decentralizing banking services, and has become an entirely new way of thinking about accountability and trust."

Cutting through the hype is a priority if these novel systems can be implemented as the platforms for vital social functions they were designed to be — and SFI, ever the home to maverick, discipline-blurring research is an ideal place to ask these questions.

Microbiome *(cont. from page 1)*

methodology across research areas. Eventually, the group aims to produce a synthesis paper.

"The ultimate goal is to understand the complexity of natural systems," says Tropini. "The real world is not divided into disciplines or scales, so it's possible we require a connection between macroecology and microecology."

The scientists plan to discuss experimental, theoretical, and computational approaches in macroecology and microbial biology. They will also explore concepts of ecosystem resilience and function and how they change in the face of invasive species. Additionally, the meeting will tackle the challenges of defining species, particularly in microbiomes, and how species interactions shape ecosystems.

GARLAND AND BERDAHL AUTHOR ONE OF MOST-DOWNLOADED CHAOS PAPERS OF 2018


Joshua Garland


Andrew Berdahl

The AIP journal *Chaos* has announced that "Anatomy of leadership in collective behavior," co-authored by SFI Omidyar Fellow Joshua Garland, former Omidyar Fellow Andrew Berdahl, and their collaborators, is among the most-downloaded papers of 2018.

The paper explores how leadership arises in groups of animals like schooling fish, flocking birds, and herding caribou. Rejecting simplistic "follow-the-leader" explanations, the authors develop an "anatomy of leadership" that relies on several principal components from how leadership arises in a group to how distributed, long-lasting, and far-reaching a particular leadership scenario is.

DEDEO WINS COZZARELLI PRIZE

SFI External Professor Simon DeDeo and co-authors are recipients of the 2018 Cozzarelli Prize, awarded by the Proceedings of the National Academy of Sciences, for their paper "Individuals, institutions, and innovation in the debates of the French Revolution." Each year, The Cozzarelli Prize recognizes six papers published within PNAS for their "outstanding scientific quality and originality."


Simon Dedeo

DeDeo and colleagues' study used machine learning techniques to parse transcripts and assess speech patterns during the French Revolution as a makeshift assembly emerged to form a new government. The analysis of these speeches reveals how new ideas emerged and took root — or floundered.

New SFI Complexity and Program Postdoctoral Fellows

SFI postdoctoral fellows are selected for their rigorous, quantitative research across disciplines. Four Complexity Postdoctoral Fellows and two Program Postdoctoral Fellows join SFI in 2019. Complexity Postdoctoral Fellows are supported by Omidyar Gift funds as well as the ASU-SFI Center for Biosocial Complex Systems. Program Postdoctoral Fellows are supported by research grants.

GIZEM BACAKSIZLAR

In the past few years as social movements around the world have ignited, online social platforms have helped them spread, and have led to protests and sometimes to conflict. Gizem Bacaksizlar is intrigued by how groups of people make decisions to take action on social issues, and how widespread use of smartphones, access to the Internet, and the speed of social media has inflamed anger. She uses agent-based modeling, natural language processing, and system dynamics for her work in computational social science.

Bacaksizlar earned her Ph.D. in complexity and software and information systems at the University of North Carolina at Charlotte. She joined SFI as a postdoctoral fellow in February 2019 and works with SFI Professor Mirta Galesic to investigate how emotions and opinions spread in online networks. Their project scrapes data from news sites ranging from *The Atlantic* and *Mother Jones* to Breitbart and The Hill to assess how different outlets cover a single social event, such as the 2016 Unite the Right rally and counter-protests in Charlottesville, Virginia. They also gather data from those news sites' comments sections and from Twitter to analyze how individuals are sharing and interacting with the information online.

TYLER MARGHETIS

Human beings have a high capacity for abstract thought. We speak and write using metaphors, conceive of untouchable objects like the number five and the future, and create musical improvisation. This cognition occurs in a variety of nested complex systems — our own brains, through our bodies interacting in space, and across the sociotechnical systems we inhabit. And it sometimes undergoes radical revolutions: An individual might have a religious conversion or mathematical insight, or an entire culture can shift how it uses language over time. Cognitive scientist Tyler Marghetis researches how human imagination and abstract thought emerges, what triggers regime shifts, and why it settles into new stable regimes. "What I'm doing now and am excited to do in the future is to articulate a complex systems science of certainty and conviction, of insight and loss of faith, of mathematical discovery and artistic improvisation to get a traction on the regimes and revolutions of abstract thought," he says.

Marghetis holds a Ph.D. in cognitive science from the University of California San Diego and is currently a postdoctoral research scientist at Indiana University, Bloomington. He plans to join SFI in September 2019 as an Omidyar Fellow.

STEFANI CRABTREE

It may seem that the problems modern society faces — from climate change to mass migration — are intractable and also unprecedented. However, the archaeological record holds countless examples of humans responding to similar challenges, and of societies discovering solutions. Stefani Crabtree approaches archaeology with a computational and complex systems lens, using data and modern modeling techniques to study how humans have interacted with their ecosystems — as part of the food web and as environmental managers — and how they assessed and dealt with risk. She also looks for ways to detect social transitions and to describe the common ways that societies interacted with their landscapes across the globe and throughout history. "We are poised at a crossroads as a civilization, plagued by many of the same issues that our ancestors faced," she says. "An understanding of our past will help us make informed decisions about our future."

Crabtree holds two Ph.D.s — one from Washington State University and another from the Maison des Sciences de l'Homme et de l'Environnement at the Université de Franche-Comté. She has worked extensively with SFI as a visiting researcher, collaborating with VP for Science Jennifer Dunne on the Archaeoecology Project, and as a panelist for the 2018 InterPlanetary Festival. She will join SFI as an ASU-SFI Fellow in June 2019.

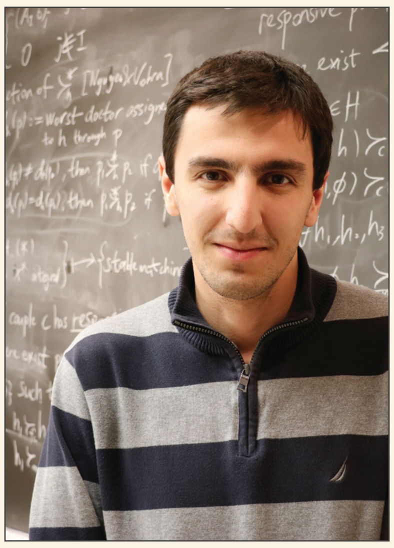
HELENA MITON

There are two main features that make human culture unique among other organisms. First, what emerges as culture is highly non-random; of all the objects, language modifications, and behaviors that emerge within human cultures, only a few small subsets become cultural phenomena. Second, as cultural elements evolve and are shared over time, it allows us to achieve things that no one individual could accomplish alone. Incoming Omidyar Fellow Helena Miton's work aims to explain these two features by combining fine-grained empirical data and a theoretical grounding in cognitive science. Her projects have explored the stability of widespread maladaptive medical practices like bloodletting and anti-vaccination beliefs, and the cultural transmission of complex visual and graphical patterns, including coats of arms and writing systems. She plans to use complexity science tools to develop mathematical models of cultural evolution, models that could better account for the complexity of real-world cultural phenomena. Helena is completing her Ph.D. in cognitive science at the Central European University in Budapest, Hungary. She will join SFI in January 2020, and she plans to explore the role of institutions in fostering and transmitting innovations.

DAVID KINNEY

To understand complex phenomena — to untangle the ways multiple variables work on a system and identify the mechanisms underlying a behavior — scientists build statistical models. But first, they must decide which details to include in their models, and which to leave out. This level of fine- or coarse-graining differs among the disciplines and depends on the specific research question being addressed. For instance, a doctor can infer that smoking led to a patient's lung cancer, and can choose a course of action accordingly without documenting every time the patient picked up a cigarette. However, research into, say, quantum physics requires much higher granularity. "When we face chemical, biological, or economic choices, information about the quantum-level details of the relevant systems may not be worth anything to us as agents. Therefore, this information can be left out of our explanatory models," says David Kinney, who is completing his Ph.D. in the philosophy of science and formal epistemology at the London School of Economics. Kinney's research also looks for better ways to graphically express probabilities and uncertainty in modeling high-dimensional systems, including interval-valued probabilities and algorithmic measures of complexity.

Kinney plans to join SFI as an Omidyar Fellow in September 2019.



MEHRDAD MOHARRAMI

Random graphs are one tool researchers can use to make rigorous predictions about real-world networks that either lack data or provide an unwieldy data set. These models have been used for many years and in a variety of fields, but there are still plenty of opportunities to address open questions and mathematical challenges, and to develop theoretical proof and rigorous analysis for how and why these models work. Mehrdad Moharrami, who is completing his Ph.D. in electrical engineering at the University of Michigan, is looking for ways to address these questions and to provide a rigorous analysis for the models already in use. Moharrami is a familiar face at SFI — during a three-month internship in the fall of 2018, he worked with SFI Professor Cristopher Moore on two research projects concerning Bayesian inference and discovering patterns hidden in high-dimensional data.

As a postdoctoral fellow, he will continue exploring these questions with Moore. He plans to arrive at SFI later in 2019.

Audience members listen attentively to a panel at the 2018 InterPlanetary Festival. (Photo: Kimberly Corante)

ment, some with odd and alien-looking antennae that give no hint of their function--and thick cables and great tangles of extension cords running everywhere. But as the wind blows, the cottonwood seed is swarming through the air between the audience and the speakers as if to make a mockery of their very conversation: This is life, this spermy, erratic, random, yet astonishingly certain drive toward reproduction.

Love is blind.

God is love.

Stevie Wonder is blind.

Therefore Stevie Wonder is God.

There's your Drake equation for you.

Chris gives a discourse on what life might be and also a general idea of the problem of answering Drake's final question. Once a large planet or asteroid hit the earth and created the moon, the impact effectively sterilized the earth and if there had been any life it was all gone, Chris said. But then it took only half a billion years for life to arise again in the form of simple one-celled creatures. That, he said, was encouraging as far as Drake's final necessary number is concerned. On the other hand, it took a full billion years for those cells to become eukaryotes and acquire (create?) nuclei. So maybe it's not such an easy transition. Remember, these are all necessary steps on the road to "communicative species," which even eukaryotes are decidedly not. Or are they?

Caleb in turn points out that we have no first principles, no fundamental theory of life in the way that we have such theories in physics. We know to a first approximation why shit happens in the world outside of biology. Where living things are involved, we do not. So we have no tools comparable to the ones in physics to predict the probability that life might arise. However, he points out, we do have another route to the answer and that is simply to figure out how to count the instances of life occurring in our galaxy. This might have been a silly suggestion just a few years ago, like suggesting that the way to understand the human brain was to expose it and watch its gears turn.

To use the whole galaxy and perhaps the whole universe as our kindergarten in becoming InterPlanetary Citizens with a decent record of stewardship of our own world that would make us worthy to visit (or be visited by) another world.

Of course, that's exactly what technologies such as Magnetic Resonance Imaging have allowed us to do, and when it comes to exoplanets, as planets outside of our solar system are called, we have now begun to develop the technology not only to see planets around other stars but to measure what's in their atmosphere.

Chris says, "We now have a much greater sample of environments in which we might be able to look for what we call biosignatures — signatures of life." In other words, we are systematically working toward detecting whether or not someone is passing gas on another planet. That's the only way to put it that captures its essence. We're looking for methane. And oxygen, too. And some other stuff.

In 2020 NASA plans to launch the James Webb telescope, which will greatly increase the probability of detecting methane on distant planets. And Caleb believes that within a year or two of that launch, we could begin to see signs of life. And within a decade, we should be able to say something about the probability of life anywhere at all.

Chris brings it full circle to point out that what we learn about the dynamics of exoplanets can inform our quest to manage our own planet more intelligently with respect to such issues as the use of resources and a changing climate. And therein he captures the essence of the InterPlanetary Project itself: To use the whole galaxy and perhaps the whole universe as our kindergarten in becoming InterPlanetary Citizens with a decent record of stewardship of our own world that would make us worthy to visit (or be visited by) another world. And perhaps by having all of these potential citizen scientists witnessing all of this science here at the InterPlanetary Festival each year we can gently nudge the great ship of humanity in the direction of making it a slightly more urgent business to avoid destroying the world.

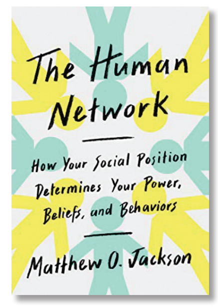
Caleb says that he's an astrophysicist and so to his mind planets are stupefyingly complex, while "stars are simple. We can figure out the basic functioning of stars with just a few lines of equations and a little bit of physics. Planets are insanely complex."

But he says the opportunities are dazzling for this new research into exoplanets, offering us the possibility of looking deep into a planet that is the equivalent of our own world when it was an infant of a billion years old. We can also find one that represents our world a billion years in the future and inform ourselves of where we are going.

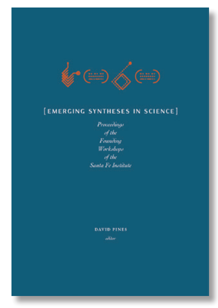
"This festival is in most respects about the future, our future as a species." And then he reflects that, "In about a billion years' time, it's all going to be over for life on the surface of the earth." And a kind of collective sigh passes through the audience as we realize that we are hurtling toward oblivion, learning and dancing as fast as we can here in this lemonade sunshine of our youth.

[From *The Factory of the Impossible*, a forthcoming book by Laurence Gonzales]

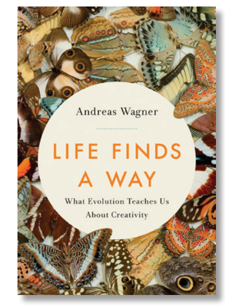
New books by SFI authors



The Human Network: How Your Social Position Determines Your Power, Beliefs, and Behaviors (Pantheon, 2019) by SFI External Professor and Science Board member Matthew O. Jackson draws from psychology, behavioral economics, sociology, and business to take a complex systems-approach to understanding how human social networks, which hold a primary role in our daily lives, impact our personal beliefs and actions, and inform broader political and economic practices.

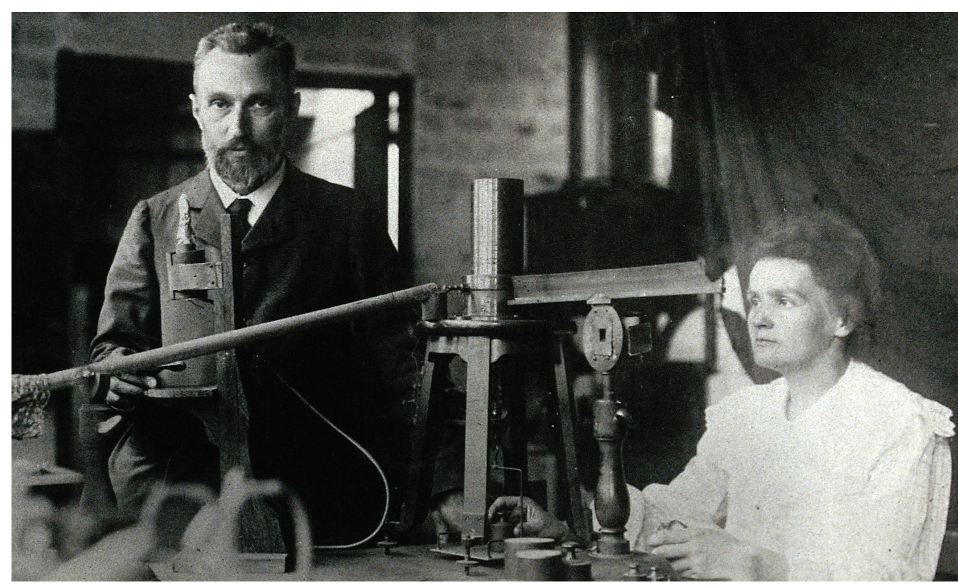


Emerging Syntheses in Science (SFI Press, 2019), edited by SFI co-founder David Pines re-enlivens the debates and ground-breaking research that, in the 1980s, formed the foundation for the Santa Fe Institute. First published in 1988, this new edition includes fresh essays by SFI President David Krakauer and Distinguished Shannan Professor Geoffrey West, the late David Pines, and Stephen Wolfram, a participant in the founding meetings. The volume also includes never-before-published transcripts from the founding meetings held in 1984.



Life Finds a Way: What Evolution Teaches Us About Creativity (Basic Books, 2019) by SFI External Professor Andreas Wagner compares the tools of biological evolution with those of human innovation to make sense of the creative process happing in our minds all the time. Similar mechanisms underlie the processes of a musician rearranging musical phrases, a DNA strand coding multiple proteins, and a moth darkening over time. And as with genetic drift and DNA recombination, human creativity requires exploration and failure in order to find success.

RESEARCH NEWS BRIEFS



Above: Pierre and Marie Curie in the laboratory, circa 1904

LARGE TEAMS DEVELOP; SMALL TEAMS DISRUPT

Modern trends in science and technology favor large teams of researchers, but we may be losing out on novel thinking in this movement away from small teams or individual research. In a study published February 13 in *Nature*, External Professor James Evans and co-authors analyzed more than 65 million papers, patents, and software products from the past six decades and discovered clear trends: large teams tend to draw on recent, popular research, building upon existing knowledge, while small teams are more likely to disrupt science by introducing new ideas. "Both small and large teams are essential to a flourishing ecology of science and technology," write the authors.

COMPLEXITY EMERGES FROM SIMPLE NETWORK

In a new experiment in the "science of sync," External Professors Raissa D'Souza, James Crutchfield, and their collaborators showed how complexity emerges from a toy network of nanoelectromechanical oscillators. Despite each network node being connected only to its immediate neighbor, the researchers observed nodes synching with their neighbors' neighbors — an emergent state. Their paper, published March 8 in *Science*, could eventually inspire technologies for intervening in heart arrhythmias or managing modern infrastructure.

ENERGY OVERSUPPLY UNDERLIES MULTIPLE CANCER RISK FACTORS

Obesity, diabetes, and chronic inflammation are well-established risk factors for cancer — new research published January 21 in *Evolution, Medicine & Public Health* offers an intriguing theory why. External Professor John Pepper and co-authors suggest that an over-abundance of energy to cells super-charges their growth. Healthy tissue has a built-in limiter that keeps cell-proliferation in check, but an energy overload can overwhelm those guardrails. The team used a computer model of cell evolution to simulate what happens to tissue during energy overload, offering a new explanation for how cancer evolves in many high-risk populations, and for why healthy diets and regular exercise can reduce cancer risk.

CHALLENGING THE FUNDAMENTAL ECONOMIC ASSUMPTION OF EQUILIBRIUM

One of the fundamental assumptions underlying most economic models is equilibrium — the idea that market forces tend toward a stable common point, and that people behave rationally. A paper published in *Science Advances* on February 20 by External Professor Doyne Farmer and co-authors suggests that this basic economic assumption may be an unrealistic one in many situations. Drawing from game theory and prior modeling on biological and social systems, the authors show that in simple games, players do behave rationally and consistently converge at an equilibrium. But in more complicated games where there are too many possible moves and counter-moves for players to predict the end-results, there is no equilibrium. "There are many real-world situations where the number of possible actions is large and where payoffs are likely to be anticorrelated," write the authors. In these situations, that fundamental assumption could be dangerous.

SCALE FREE NETWORKS ARE RARE

In research published in *Nature Communications*, External Professor Aaron Clauset and his co-author Anna Broido from CU Boulder challenge a two-decade-old theory that many real-world networks are "scale free," and therefore follow a power law distribution. Drawing from a database of networks from various scientific domains, the researchers applied statistical tests to more than 900 networks, searching for evidence of scale-free architecture. About 4 percent of the networks studied passed the strongest test for being scale-free. Close to half of real-world networks did not meet a more liberal definition.

2019 InterPlanetary Festival

June 14-16 at the Railyard Park in Santa Fe, New Mexico

The mission: To change the world, one planet at a time

SFI's InterPlanetary Festival returns to Earth for three days of celebration and complexity science! Join luminary thinkers, creators, and scientists including celebrity physicist **Sean Carroll**, author and urban designer **Nicholas de Monchaux**, essayist **Cyree Jarelle Johnson**, chef and restaurateur **Mark Miller**, Nebula Award-winner **Rebecca Roanhorse**, and sci-fi novelists **Daniel Abraham** and **Ty Franck**, co-authors of "The Expanse" series under the pen name **James S.A. Corey**.

Speakers include (left to right, from top): Carroll, de Monchaux, Johnson, Miller, Roanhorse, Abraham, and Franck.

View complex challenges through an interplanetary lens in our provocative series of panel discussions — *Building Life From Scratch, Creative Black Futures, Diverse Intelligences, Extremophile Cities, Time,* and *Vintage Space Technologies.*

Geek out on moon suits, watch classic sci-fi film screenings, and enjoy musical performances by **The Family Stone, Itchy-O, Lindy Vision, The Lost Aliens, The Sticky, That1Guy**, and **Tone Ranger**.

Left to right, from top: The Family Stone, Itchy-O, Lindy Vision, The Lost Aliens, The Sticky, That1Guy, and Tone Ranger.

For an up-to-date lineup, and to register for this free event, visit ***interplanetaryfest.org***

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