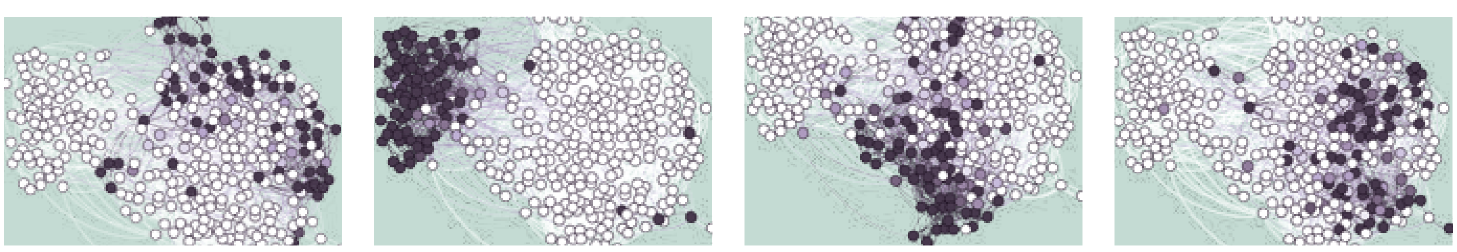
Summer 2017

Parallax

THE NEWSLETTER OF THE SANTA FE INSTITUTE



A new tool for multilayer networks

Sophisticated network analysis means finding relationships that often aren't easy to see. A network may have many layers — corresponding to different types of relationships in a social network, for example — but traditional approaches to analysis are limited. They tend to flatten networks into single layers, or treat layers independently of the others.

A new algorithm from an interdisciplinary team at SFI identifies relationships not only within individual layers, but also across multiple layers. It's the product of a recent project involving an anthropologist, a mathematician, a physicist, and a computer scientist.

SFI Omidyar Fellow Eleanor Power, the anthropologist, says the model is broadly applicable to a variety of network types. "It can also predict missing information," says SFI Postdoctoral Fellow Caterina De Bacco, the physicist of the group.

Power and De Bacco collaborated with SFI Omidyar Fellow Daniel B. Larremore, a mathematician, and SFI Professor Cristopher Moore, a computer scientist and polymath. The group published their work April 24 in the journal *Physical Review E*.

They tested the model on two datasets. The first came from Power, who spent two years collecting data on social networks in two villages in rural India. In her work, layers correspond to relationships like friends, babysitters, or people who would loan money to each other. The model successfully predicted missing connections in her data both within and between layers.

The researchers then analyzed Larremore's genetic data on the malaria parasite, in which the links of the network correspond to shared genetic substrings and layers represent different locations within the parasite genome. In that case, the model's predictive power worsened with more layers — likely because parasites with more genetic diversity can better evade a host's immune system.

De Bacco says the collaborators built the model to be broadly applicable to researchers — in physics and other fields — and have released the code, in a user-friendly format, to anyone who wants it.

Image: Caterina De Bacco (left), Eleanor Power (center), and Cris Moore (right) pose in front of a network that shows division by caste membership. The four black and white networks display membership in four types of social communities for each node.

JSMF awards SFI $2.5 million to study complex time

Time in complex systems operates concurrently at different scales, runs at multiple rates, and integrates the function of numerous connected systems. This is "complex time" as opposed to the simple, regular clock time of physical phenomena. In complex time, aging includes explicitly the coupling between information gain and information loss.

In our lived experience, time always moves in one direction: forward. Stars, organisms, companies and technologies all come into existence, grow old, and then die. Hot things, when left alone, get cooler, and fragile items break when dropped. While quantum mechanics suggests that time may not always move in the way we experience it, there are no physical phenomena that we know of that do not, in some fundamental way, experience the forward-moving arrow of time. The Santa Fe Institute will be pursuing questions about general, universal principles of complex time with support from the James S. McDonnell Foundation (JSMF) through a five-year, $2.5 million grant.

The new grant, titled "Adaptation, Aging and the Arrow of Time," will investigate "how fundamental complexity insights and tools developed by SFI bearing on the 'arrow of time' could transform our understanding and treatment of natural biological and disease phenomena, social systems and technology."

These phenomena are incredibly diverse in range and scale, but still have common mechanisms and processes. This new program will take an innovative approach to studying aging and adaptation in complex systems by considering both the gain and loss of order, and by looking at systems of many scales, simultaneously. By bringing together experts from many different communities to share data and insights across fields, the program aims to conceive of bold, new experiments that will lead to a deeper, shared understanding of the mechanisms of aging.

"This is a very exciting collaboration between the JSMF and SFI. There are few experiences more fundamental than time, and yet when it comes to time's role in complex systems we have barely scratched the surface," says SFI President David Krakauer. "And the implications of a deeper understanding of the relationship between adaptation and aging could change the way we think about disease, cognitive decline, the life and death of companies, and even the future of civilizations. This is a really bold project that will draw on a large network of SFI scientists and new domain experts not yet exposed to the power of complexity science."

This grant builds on the spirit of the JSMF-SFI Founding Program on Robustness and Social Processes, which since 2001 has launched a new field of research and generated numerous books, publications, and ongoing research.

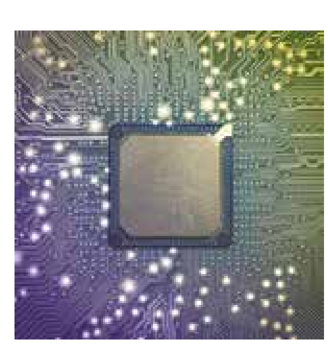
JSMF seeks out scholarly fields that hold promise and potential for future generations, and provides funding for fields such as human cognition and complex systems. More about the James S. McDonnell Foundation. (https://www.jsmf.org/about/)

Cooler computing through biology

Look closely at a computer chip, and you'll see circuits. Zoom in further, and you'll find atoms moving around in patterned ways that correspond to the 1's and 0's of binary code. These collections of atoms consume energy, perhaps provided by a battery, to perform tasks and execute algorithms — and they produce waste heat.

Yet experts still don't understand how exactly energy flows in and out of these atoms during computation. To study this, they must figure out how to apply the laws of thermodynamics — the generic rules of heat, temperature, and energy that physicists first used to understand gases and engines — to computers. This August, SFI Professor David Wolpert and other SFI researchers have organized two workshops convening physicists, computer scientists, and biologists to discuss this question. At the workshops, they will discuss how to establish a mathematical language to describe the many microscopic processes that occur during computation.

One practical motivation behind the workshop is that, by pinpointing the physical processes that use or waste the most energy, you can engineer them to achieve higher efficiency. Energy-efficient computers grow increasingly relevant as local governments work to reduce their carbon footprints. "Right now, five percent of energy consumption in the US comes from computation," says Wolpert. Furthermore, industries will need strategies to reduce waste heat in future powerful computers known as exascale computers. "These computers would generate so much heat that they would melt," Wolpert says.



The organizers hope that the multidisciplinary attendees can exchange ideas to inspire new research questions. They've invited biologists because many biological systems — if you think about it — are computers too. Cells, for example, receive inputs, execute algorithms, and even know how to repair themselves. "I'm interested in how well

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BEYOND BORDERS

Several years ago I was asked to speak at a convention of high school teachers and their students on the growing importance and character of interdisciplinary science. This worried me because I have an acquired aversion to all terms "x"-disciplinary, as in x = "multi" and x = "inter". I once tried to short-circuit these unwieldy efforts with x = "trans" and MIT media lab has championed the iconoclastic x = "anti". The problem with these exercises in relabeling is that each modifier ends up bolstering the very concept and value it seeks to undermine — the all-devouring gravitational attraction and tapering force of disciplines.

So I simply asked the students who they would select as crew members for a trip to Mars. Without hesitation they answered: astronaut, engineer, doctor, physicist, botanist, geologist, and even politician. They understood immediately that problems define the necessary breadth of expertise, not single factors, and certainly not disciplines. Necessary ideas for such a mission include consideration of robustness, adaptability, integrated energy resources, the intelligence of the crew-machine environment, metabolic and mental health, and diversity. These are the levels at which complexity science seeks to operate.

Complexity science is, among other things, an honest effort to allow problems, and not history and habit, to define solutions, by searching for the common denominators of a problem, expressing these rigorously, and building connections among ideas and facts that enable new creative frameworks and solutions.

This year SFI, supported by the Miller Omega Program, is spearheading a new initiative, the InterPlanetary Project. The idea is to make the value of complexity science as obvious to the wellbeing of Earth and its future diaspora as the diversity of a Mars crew is to high school students. It seeks to make clear the responsibility that our living generations of Earth need to assume for the long-term health and viability of the biosphere and what might lie beyond it. This ambition is captured by the catchphrase "changing the world one planet at a time."

The InterPlanetary Project is part intellectual mission, part research project, the start of a planet-wide conversation, a festival of ideas in the high desert of the Southwest, and a collaboration in the grand spirit of the World of Tomorrow at a World's Fair. It seeks the ethos captured by the Polish author Stansilav Lem : "A dream will always triumph over reality, once it is given the chance."

— David Krakauer
President, Santa Fe Institute

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Parallax is published quarterly by the Santa Fe Institute. Please send comments or questions to Jenna Marshall at marshall@santafe.edu.

SFI IN THE NEWS

Jessica Flack, SFI Professor, is featured in *Quanta* for her research into the computational rules that groups of organisms use to solve problems.

The Aspen Times highlights **David Pines**, SFI Co-founder in Residence, and his work to encourage scientific thinking in middle schools.

SFI Professor **Sam Bowles** writes for *The Boston Globe* about the global rise of liberalism, and how its embrace of laissez-faire economics is leading to its demise.

Nautilus magazine discusses the work of External Professor **Daniel Dennett** and **Christof Koch** in a story about the search to understand subjective experience and the sensation of consciousness.

Geoffrey West, SFI Distinguished Professor and Past President, published his much-anticipated book, *Scale*, in May. The book receives reviews in nearly a dozen publications including *The New York Times*, *The Economist*, *New Scientist*, *The Wall Street Journal*, and *Nature*.

Doug Erwin, SFI External Professor, tells *The Atlantic* that mass extinctions are network collapse problems and that, despite a lot of popular press toward this idea, Earth is not (yet) in a sixth mass extinction.

SFI Trustee **Cormac McCarthy's** first non-fiction essay, published in *Nautilus* in April, receives reviews in *Quartz*, *The Paris Review*, and *The New Yorker.*

CityLab spotlights massive neighborhood-level analysis by **Christa Brelsford**, a former ASU-SFI Postdoctoral Fellow; **Jose Lobo**, SFI Associate Research Professor; and SFI External Professor **Luis Bettencourt**.

Doyne Farmer, SFI External Professor, tells the *Wall Street Journal* that agent-based models could soon help make market and economic forecasts much like we predict the weather now.

Working group: When physiology computes

A Slinky can hardly be considered a sentient being. Its surprisingly ordered walk down a flight of stairs is purely a marvel of mechanics.

When a person descends a staircase, despite solving roughly the same problem under the same pull of gravity, she owes her success to cognitive processing in the brain…or so we assume.

Not so fast, say researchers at SFI who are working on a theory of embodied intelligence — that is, intelligence that arises from the interplay of brain, body, and environment.

In the human case, some computation is outsourced to the body.

Biology provides us with many examples of problem solving that doesn't occur, strictly speaking, in the brain, says Postdoctoral Fellow Keyan Ghazi-Zahedi, who with Professor Nihat Ay is organizing a September working group on "Morphological Computation."

Take the problem of carefully grasping a delicate object such as a dried flower. For a robot, this is a computationally costly problem. Its processors need to compute the locations of its grippers precisely: too little force and the flower slips away; too much and the bud is reduced to dust.

With a human hand, the brain isn't required to do as much computational heavy lifting. Soft tissue in the fingertips, feedback in the finger joints, and tendon friction help the brain solve the problem of gripping with care. This is morphological computation, says Ghazi-Zahedi.

"The traditional view [in robotics] is that all you need is a big computer and then an embodied agent can learn anything," he says. "We're learning that the body is not a burden to cognition. We're starting to understand some of the ways the body, as our interface with the environment, actually contributes to cognition."

Despite morphological computation becoming a widely accepted concept in the short time since its introduction in 2006, it is not at all clear which kinds of morphological processes are computation and which should be understood as pure mechanics.

In recent years, researchers have tried to parse morphological phenomena into categories as a way of determining what is and what isn't computation.

"We believe this is the wrong approach," says Ghazi-Zahedi. "We should be looking for a unifying perspective in the many ways the body contributes to cognition."

This is the goal of the SFI meeting, which brings

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Working group explores ancient Maya understanding of time

Throughout history, different cultures have understood time in very different ways. In the modern U.S., we talk about time as a commodity: we spend it, waste it, or use it wisely. For the Maya, time was a physical presence — the sun, a feathered serpent, a drought or war, the moon — with power to impact humans' lives.

Since 2012, SFI has hosted a series of meetings exploring ancient Maya culture, and two of those meetings have focused specifically on Maya understanding of time. This August 26-28, the Maya Working Group will meet for the fifth time at SFI.

The meeting, "Telling time: Myth, history and everyday life in the ancient Maya world," will explore topics from the materialization of time and how that influenced politics and religion, to the roles of timekeepers, to the buildings and effigies that helped people celebrate time, to what these structures and art can tell us about the way the Maya thought about the future. David Freidel, a Maya iconographer and Washington University professor who has been organizing the Maya Working Groups at SFI since they began in 2012, says the upcoming working group will produce a book — the second to come out of this working group.

Previous meetings led to an edited anthology on Maya E Groups, which are some of the earliest permanent public structures that were ritual centers and astronomical observatories. That book will be published this summer.

This first, forthcoming book "is a coherent edited volume on a subject," says Freidel. "This has been very good, even exemplary, of what SFI can do with working groups. In archeology, this is a very big achievement."

But it's a project that has taken several years to complete. Freidel hopes for a more efficient timeline this second time around. To achieve that, he's asked all participants to draft papers meant to be chapters in the book, and to distribute them to the group weeks before the meeting. As the group discusses the submitted papers during the meeting, Freidel wants to draw out the places of overlap between the papers. "I want them to come away from this meeting ready to revise their manuscripts so that they reference each other," says Freidel.

Under the direction of Briony Barr, participants in SFI's Complex Systems Summer School create an emergent work of art over several hours. By following agent-level instructions (e.g. 'draw with ~25 cm lines of electrical tape when working alone, stack lines horizontally and vary the lengths if you decide to collaborate with others') they produce a system-level pattern of surprising beauty.

Drawing on complexity

Since 2012, artist Briony Barr has been exploring complex systems through her work. In consultation with Andrew Melatos, a physicist at the University of Melbourne, Barr creates different rules, feedback loops, and boundary conditions for collaborative drawings that are real-time versions of agent-based models.

"I've always been interested in using drawing to represent a process of change," Barr says. "It's fascinating to see how very human characteristics such as creativity and interpersonal dynamics, combined with rules over time, produces a whole range of emergent patterns and behaviors."

To view more artwork from the Drawing on Complexity series, visit brionybarr.com

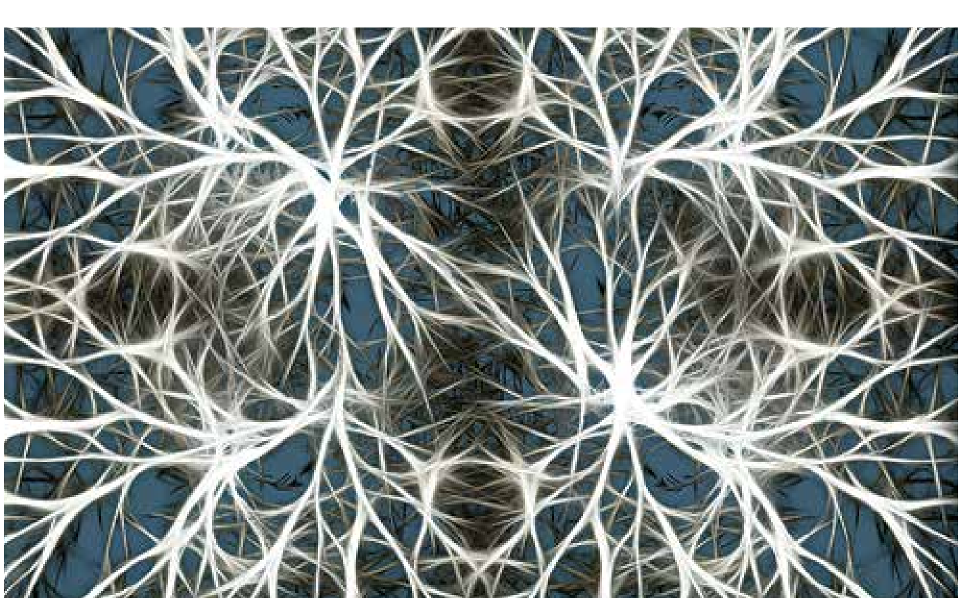
How neurons use crowdsourcing to make decisions

How do we make decisions? Or rather, how do our neurons make decisions for us? Do individual neurons have a strong say or is the voice in the neural collective?

One way to think about this question is to ask how many of my neurons you would have to observe to read my mind. If you can predict I am about to say the word "grandma" by watching one of my neurons then we could say our decisions can be attributed to single, perhaps "very vocal," neurons. In neuroscience such neurons are called "grandmother" neurons after it was proposed in the 1960's that there may be single neurons that uniquely respond to complex and important percepts like a grandmother's face.

On the other hand, if you can only read my mind by polling many of my neurons then it would appear the decision a collective one, distributed across hundreds, thousands, or even millions of neurons. A big debate in neuroscience is whether single-neuron encoding or distributed encoding is most relevant for understanding how the brain functions.

In fact, both may be right. In research recently published in *Frontiers in Neuroscience*, ASU-SFI Assistant Research Professor Bryan Daniels, SFI Professor Jessica Flack, and SFI President David Krakauer tackle this problem using data recorded from the neurons of a macaque monkey tasked by the experimenter with making a simple decision.



In an area of the brain involved in the decision-making process, Daniels and colleagues find that as the monkey initially processes the data, polling many neurons is required to get a good prediction of the monkey's decision. Then, as the time for committing to a decision approaches, this pattern shifts. The neurons start to agree and eventually each one on its own is maximally predictive. Hence at first the "neural voice" is heterogeneous and collective, but as the neurons get close to the decision point, the "neural voice" becomes homogeneous and, in a sense, individualistic, as any neuron on its own is sufficient to read the monkey's mind.

Daniels says a possible explanation for this odd behavior is that the system has two tasks to solve. It must gather good information from noisy data and it must use this information to produce a coherent decision. To find regularities in the input it polls many individual neurons, as the crowd's answer is more reliable than any single neuron's when the data are noisy. But, as Krakauer says, ultimately a decision has to be made. The neurons agree on an answer by sharing their information to come to a consensus.

This explanation echoes results in other collective systems, from animal societies to systems studied in statistical physics. Flack says this commonality suggests a general principle of collective computation: It has two phases — an information accumulation phase that uses crowdsourcing to collect reliable information and a consensus phase that allows the system to act

SFI and ASU to offer online MS in complexity

SFI and Arizona State University soon will offer the world's first comprehensive online master's degree in complexity science. It will be the Institute's first graduate degree program, a vision that dates to SFI's founding.

"With technology, a growing recognition of the value of online education, widespread acceptance of complexity science, and in partnership with ASU, we are now able to offer the world a degree in the field we helped invent," says SFI President David Krakauer, "and it will be taught by the very people who built it into a legitimate domain of scholarship."

ASU contributes to the partnership its degree-granting accreditation and its powerhouse online education platform EdPlus, with its 30,000-student enrollment and 150 degree offerings. It also offers faculty experts in various areas of complexity research. SFI contributes its global network of complexity researchers, many of whom are the recognized giants in the field, as well as its position as the world headquarters for complexity science and education.

SFI also "has the disciplinary breadth and leading ideas that other universities offering complexity degrees can't offer," says ASU President's Professor Manfred Laubichler, an SFI external professor who is leading the university's faculty collaboration on the project.

The curriculum builds on existing free online courses offered through the Institute's highly successful Complexity Explorer, which has, in a few short years, enrolled more than 36,000 students in 15 complexity-based courses and tutorials.

"One of SFI's goals is to help develop the next generation of scientists and students ready to understand the complex realities we'll face in this century," says SFI Director of Education Paul Hooper. "This first SFI degree program gives us an opportunity to amplify the impact of the science, and to define the field."

The degree planners envision 30 credit hours comprising 15 two-credit-hour courses: five in the fundamental concepts of complexity (e.g., generalized evolution and collective computation), four in the methods of complexity science (e.g. networks, game theory), four electives (e.g. economics or cities), two independent study options, and an original research project. The first degree cohort is expected to be admitted in fall 2018 or spring 2019.

Both institutions are looking to the future. "This collaboration with ASU allows SFI to do what it has always done best: encourage integrative scientific and educational opportunities with integrative ideas, across fields and across institutions," says Hooper.

Manfred Laubichler (Image: ASU)

For ASU, says Laubichler, the program is an example of the "global classroom," a vision for higher education in which common online courses are among the listings at multiple universities. "Breaking the place-bounded nature of graduate education may prompt synergies we can't anticipate, such as collaborations, cohorts, student projects, and summer schools across borders," he says.

ACHIEVEMENTS

A 2014 SFI Complex Systems Summer School alumna, **Sarah Laborde**, recently helped host a CSSS-inspired workshop in N'Gaoundere, Cameroon. During the first week of May, graduate students from Cameroon gathered with an international team of researchers for an interdisciplinary dive into the complex social-ecological systems of West Africa. Laborde and colleagues from Ohio State and Maroua University hope to encourage regional environmental researchers and planners — and current graduate students anticipating careers in the field — to consider the complex dynamics of social-ecological systems as they develop and implement environmental policies.

This September, an award-winning stage adaptation of **Laurence Gonzales**' book *Flight 232: A Story of Disaster and Survival* (Norton, 2014), will be remounted by The House Theatre of Chicago following a sold-out run in 2016. The play draws on the interviews and research conducted by the SFI Miller Scholar for his critically-acclaimed book surrounding the events of July 19, 1989 when a DC-10 headed for O'Hare with 296 aboard was paralyzed mid-air. "United Flight 232" is a reflection on how to comprehend tragedy and celebrate human ingenuity in the face of overwhelming challenges.

Sam Bowles, an SFI professor, was recognized by the American Political Science Association for his book *The Moral Economy: Why Good Incentives Are No Substitute For Good Citizens* (Yale University Press, 2016). The book argues that markets and institutions can stifle instinctive moral behavior by incentivizing self-interest. The APSA awarded Bowles an honorable mention for the Robert E. Lane Award for the best book in political psychology published in the past year.

Workshop in N'Gaoundere Cameroon

Working group explores cheating, the system

Groups of organisms, from microbes to humans, harbor cheats: individuals who don't contribute to the common good but still benefit from the work of others. This classic social evolution dilemma was at the heart of a five-day working group that met for the second time in early June. The group built on the models developed in their first meeting last summer, exploring ways to model interactions between organisms and a public good, where both can diffuse in space.

The models developed in the working group identify four ways organisms can interact via a single compound: ways that help others through producing a common good or removing waste, and ways that harm others through producing toxins or consuming public goods. Whether or not a cheat disrupts the whole system depends on a variety of factors.

"One way to model this social dilemma is to abstract away the environment," says Eric Libby, an Omidyar Fellow and co-organizer of the working group. Such models would only consider the dynamics between producers and cheats. "Our working group was primarily interested in what happens when you explicitly measure that public good along with the organisms, and allow chemicals and organisms to diffuse or move."

Modeling the environment — the public good — and the dynamics of movement through space are actually quite important, says Libby. For instance, using traveling wave models, the group documented how movement can allow less productive but faster-moving organisms to surpass and eventually outnumber more productive but slower members of the population.

Including environment and movement in social evolutionary models may be important for better understanding diseases like cholera, says Libby. "When they first invade, *Vibrio cholerae* secrete molecules that make you sick. But when their population increases, they can detect this by quorum-sensing molecules they generate, and leave your system," he says. "These models are a way of understanding what we believe to be more like real microbial ecologies where societies are deciding between these different types of strategies."

SFI ON THE arXiv

Marathon science event looks at trends in world records

Santa Fe Institute's postdocs have completed the second annual 72 Hours of Science, a 3-day-long marathon of research, data analysis, modeling, and writing for publication. Riffing on the structure of the 48-hour Film Festival, 72 Hours of Science — 72h(S) for short — explores the limits of what novel science a group of diverse researchers can produce in a short, focused timeframe. In a rented house tucked in the hills outside of Santa Fe, this year's group decided to explore the data-rich arena of world records.

SFI Postdoctoral Fellow Artemy Kolchinsky pitched the winning idea, which the group selected from 13 wildly different topics. While he knew he'd come with a strong idea in mind, but he was still surprised when it became the overall favorite, he says. "It was fascinating to watch the idea acquire a momentum and trajectory of its own."

One of the first major changes in trajectory came as the group reviewed the existing literature. "We quickly realized that there was more that had been done on this topic than we'd known about going in," says Eleanor Power, SFI Omidyar Fellow. "It was a good sign that we were on the right track, but we had to pivot on a tight timeframe — we digested what had been done and developed a new tack and set of questions to pursue."

On the final morning, with two hours left before their 1 p.m. deadline, the house was quiet save for fervent clicking of keyboards. Everyone had their laptops open, simultaneously editing the same Google doc or rendering the final set of figures. With seconds to spare, they posted the resulting 22-page paper to the arXiv preprint server.

To complete this project, the team had divvied up the work into smaller groups. Some gathered records from sports and games, biological evolution, and technological development. Others took a deep dive into the data of marathon races.

"If you think about records as extreme behavior, something pushing the boundary for a process, that allows you to think about records across lots of different domains. The question then is, for all of these different records, how do you start to put those into meaningful categories? The hope is that those records can tell you something about ultimate limits," says SFI Omidyar Fellow Chris Kempes.

SFI Omidyar Fellow Dan Larremore was part of the group analyzing marathon data. "If you want to understand how records are set, you need to know about the mechanisms that are generating exceptional individuals," he says. This deep dive into marathon records revealed that record-setting data alone can obscure the bigger picture. For instance, a line highlighting the times achieved by marathon winners shows incremental, periodic improvement over nearly 50 years, with new records set only nine times. Meanwhile, a snapshot of the top 100 times in those same races paints a different picture, with periods of rapid, consistent improvement and a narrowing of the time distribution among the top finishers overall. Looking at the broader dataset of people who came close to winning provides a better picture of the record-setting process.

SFI postdocs, post-72h(S)

Keyan Ghazi-Zahedi, SFI's newest postdoc, who arrived at SFI just a week before 72h(S), says: "It was on the one hand very professional, but I also had fun. That's something really hard to balance."

SFI President David Krakauer congratulated the team after the paper was published. "It's an inquiry into the limits and possibilities of human performance through an actualized experiment on the limits of human concentration!"

What algorithms can't tell us about community detection

Many who study networks care about groups of interconnected nodes. These groups, called "communities" or "modules," represent real-world relationships like friend groups on Facebook, businesses in a supply chain, and even species within a food web. The challenge is to identify whether, and ultimately where, these structures exist within a mass of data.

In a recent paper, Jess Banks, a Ph.D. candidate in mathematics at UC Berkeley and a former Santa Fe Institute undergraduate intern, Robert Kleinberg, Associate Professor of Computer Science at Cornell, and SFI Professor Cristopher Moore set out to test under what conditions a computer algorithm can verify the absence of community structure in a network. Without an algorithm that can do this, network scientists can't tell whether the communities they find are statistically significant — that is, they can't tell real communities from fake ones.

Banks posed the research as a thought experiment: "If I generate a random network with no community structure 'baked in,' will it have communities by chance? If not, can an algorithm certify that it doesn't?"

After generating random networks with no real community structure, the researchers put one particular algorithm to the test — the simplest algorithm in a popular class called "the Sum of Squares hierarchy." They decided to investigate the algorithm's ability to verify the absence of dissasortative community structures, which, like competitive businesses, are characterized by a lack of connections with each other. In computer science, this corresponds to the classic Graph Coloring problem, where nodes connected by an edge are required to have different colors.

By studying the behavior of this algorithm, the researchers uncovered a blind spot. If a network is too sparse, with too few connections, the algorithm cannot tell whether or not it has communities. Using some clever mathematics, they proved that the algorithm can be fooled into thinking that communities exist even when they don't.

"If we care about doing good science, and honestly testing our hypotheses, then verifying the absence of structure in the data is just as important as being able to find it when it is there," Banks says.

"We're all looking for patterns in data," Moore adds. "But just like humans, our algorithms often find patterns that aren't really there. We need to understand the fundamental limits on our ability to tell whether patterns truly exist, so we'll know when we need more and better data before we can draw any conclusions."

Going forward, the researchers' method could be used to test other, more powerful algorithms in the same hierarchy.

Cooler computing *(cont. from page 1)*

evolution has come up with solutions for energy efficiency for computation in single cells," says Chris Kempes, an SFI Omidyar Fellow and co-organizer.

Kempes' example involves the microscale of life, but the workshops will span many scales. For example, Wolpert is interested in discussing a strategy the human brain uses, known as approximate computing: when your brain is sloppy but still gets the job done. If you're crossing the street, your brain doesn't need to register the color of every car passing by. "Your brain can be imprecise because there's no big outcome if you screw up," Wolpert says. Approximate computing saves energy, and researchers want to learn how the brain does it and how they can implement similar strategies in computer algorithms.

The goal of the workshops is to think about computation from a fresh angle by combining perspectives from multiple disciplines. Physicists know the rules that govern collections of atoms; computer scientists know how to design algorithms; biologists know how organisms function. "We hope there will be a bunch of new questions we haven't even thought of," Wolpert says.

When physiology computes *(cont. from page 2)*

together a dozen or so experts from robotics, mathematics, philosophy, engineering, biology, and physics.

Ultimately, Ghazi-Zahedi says, such discussions might open the door to a formal treatment of the phenomenon, even quantification of cognitive contributions in biological systems — a goal of his own research. It also might help reduce the burden on programmers and designers trying to create artificially intelligent robots.

Pacing social and technological change

As technology changes the world at an accelerating pace, concerns arise about how well society is prepared to deal with these developments.

An early August working group, "Envisioning New Modes of Cultural and Technological Change," seeks to examine the challenges posed by a growing disconnect between technological change and societal institutions, and to propose possible solutions to some of these issues.

"Cultural change is lagging technological change," explains organizer and SFI External Professor Doyne Farmer, Co-Director, Complexity Economics, The Institute for New Economic Thinking at the Oxford Martin School. "That manifests itself in lots of ways. Institutions aren't adapting fast enough. How do we deal with social media, reality bubbles, fake news, automation, rapid formation of digital monopolies, and increasing inequality driven by these things? These are issues we think center around that basic problem."

Social media and the rise of fake news, a subject of discussion since the past election season, provides one area for further examination in the working group. New technologies are replacing older ones in shaping people's views of the world, but without a corresponding mechanism to regulate or balance the changes.

"Facebook operates under different regulations than Fox News, is treated in a different way, even though it's operating in a similar domain," says Farmer.

Facebook presents another change accompanying technology: large companies that require few employees and where increasing size doesn't significantly increase costs, promoting monopolistic conditions.

Plus, some of the issues dominating Facebook newsfeeds in the last election, such as the decline of the coal industry and loss of manufacturing jobs, are discussed in terms of immigration policy or government regulation, when the largest driver is really technological change.

"It's important to have workshops like this to identify problems, find ways to deal with them, and improve the narrative," says Farmer. "There are a lot of areas in which things are changing and society is not adapting or is adapting in dysfunctional ways."

Is wealth disparity an Old World problem?

A three-day working group at SFI will meet August 23-25 to explore a leading theory about wealth disparity variation between the Old and the New worlds.

Archaeologists use household size as a measure of historic wealth. Since around 4,000 B.C., many societies across Eurasia showed significant Ginis, indicating wide wealth disparities. Some members of those societies amassed a lot of wealth while others had little.

In a workshop last year, a group of archaeologists compared this Old World data to assessments of the New World—societies from North- and Meso-America. What they found surprised them, says SFI External Professor and Science Board Member Tim Kohler: New World societies had much smaller wealth disparities than those in the Old World.

The prevailing theory about why this difference exists revolves around large draft animals like sheep, goats, cattle and pigs, which were domesticated by around 8,000 B.C.

"In the Old World, draft animals like oxen make it possible to do an extensification of farming," says Kohler. Land owners could begin to farm larger areas further from their residences. "This can tie wealth to income. It's expensive to maintain a team of oxen, but if you have them, you can till your own land and you can also rent them out." And because farming extensification is land-hungry, it can create a class of landless peasants.

"None of this ever happens in the New World before the arrival of Columbus. There was no landless peasantry, and there were no large, traction animals," says Kohler.

Kohler plans to invite specialists to the August meeting to test the robustness of the theory. The working group will also explore what models might work best to describe this phenomenon and identify what additional data might help clarify the theory.

ACtioN and Web of Science join forces to advance applied complexity

When a highly-networked research institute joins forces with a vast web of citation data, new insights are bound to emerge.

That's the principle behind SFI's new partnership with Clarivate™ Analytics, the company that develops the Web of Science, the world's leading citation-based research tool used by more than 7,000 institutions around the globe. The partnership not only gives SFI researchers access to cross-disciplinary research from over 33,000 journals, it also creates a spot for Clarivate™ in SFI's Applied Complexity Network (ACtioN), which helps leaders employ complex systems research to solve complex challenges.

With a mission to help "the world's leading innovators reduce risk and accelerate the pace of discovering, protecting and commercializing new ideas," Clarivate™ is a natural fit for ACtioN and for SFI. As Clarivate's Senior Director of Innovation, Jason Rollins knows first-hand how critical applied research is, and sees a win-win proposition in the partnership.

"Major research labs around the world use our citation network as a dataset to do large-scale analysis and make big, bold predictions — connecting patent data to census grant funding data, for example, to understand emerging trends in innovation," Rollins explains. "All of that substantially overlaps with the idea of complexity science, which SFI has very much led the way in formalizing and codifying."

SFI's librarian Margaret Alexander sees Web of Science as a critical first step for scientists who are bombarded with ideas from disciplines that are new to them.

"The whole concept of the Web of Science is to create a network that links authors who cite one another no matter where they work – and that concept is integral to how SFI works," Alexander says. "Bibliographic products evolve, disappear, morph and transform. The Web of Science is timeless and manages to migrate along with all the electronic changes happening in libraries. And for a tiny library—that needs to support big ideas—such as ours, it's our best tool."

Clarivate™ Analytics accelerates the pace of innovation by providing trusted insights and analytics to customers around the world, enabling them to discover, protect and commercialize new ideas faster. Formerly the Intellectual Property and Science business of Thomson Reuters, Clarivate™ owns and operates a collection of leading subscription-based businesses focused on scientific and academic research, patent analytics and regulatory standards, pharmaceutical and biotech intelligence, trademark protection, domain brand protection and intellectual property management. Clarivate™ Analytics is now an independent company with over 4,000 employees, operating in more than 100 countries and owns well-known brands that include Web of Science™, Cortellis™, Derwent™, CompuMark™, MarkMonitor® and Techstreet™, among others.

RESEARCH NEWS BRIEFS

Fractal Balinese rice terraces

GENE NETWORKS TRACE PLANT ADAPTATIONS TO COLD AND DROUGHT STRESS

Recent advances in technology have allowed scientists to probe the molecular nature of life, analyzing thousands of genes at a time and recognizing patterns of gene interaction. In a recent paper published in *Proceedings of the Royal Society B*, SFI Omidyar Fellow alum Samuel Scarpino and co-authors explore gene co-expression networks that have evolved to help plants withstand drought and cold.

The authors identified two unique gene expression networks — one adapted to cold and one to drought — in Arabidopsis thaliana, which is part of the Brassicaceae/Cruciferae family along with cabbage and broccoli.

THE EVOLUTION OF LOSSY COMPRESSION

"In complex environments, there are costs to both ignorance and perception," writes SFI External Professor Simon DeDeo in the *Journal of the Royal Society Interface*. "An organism needs to track fitness-relevant information about its world, but the more information it tracks, the more resources it must devote to perception." DeDeo and co-author Sarah Marzen explore this trade-off with rate–distortion theory, a tool from information theory. Their results suggest that well-adapted organisms will evolve to a point where they can barely distinguish objects that are maximally similar.

FRACTAL PLANTING PATTERNS YIELD OPTIMAL HARVESTS WITHOUT CENTRAL CONTROL

In Bali's famed rice terraces, farmers must manage water resources collectively. Planting rice fields synchronously is beneficial for pest management, but limited water resources mean downstream farmers must adjust their planting schedule accordingly. Thus, management of rice terraces extends from villages to an entire watershed. What results is a near-optimal harvest strategy without any central control, write SFI External Professors Stephen Lansing and Stefan Thurner in a paper in *PNAS*. This successful result shows that under certain conditions, it is possible to reach sustainable situations that lead to maximum payoff for all parties even when every individual makes free and independent decisions.

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UPCOMING COMMUNITY EVENTS

"Painting and Optics in the 17th Century," discussion and screening of "Tim's Vermeer," with Tim Jenison, Farley Ziegler, and Jessica Flack, Tuesday, August 1, 6:30 p.m., The Lensic Performing Arts Center

What makes Vermeer a *great* artist? Some would say that Vermeer's use of color sets him apart, that his unabashed use of expensive and natural pigments resulted in rich expressions of everyday life, more beautiful and perfect than the thing itself. Some say that it was his innate capacity to achieve uncanny realism without any formal training, whatsoever. Others will argue that his poetic use of light and shadow to highlight certain compositional elements makes him unique. Tim Jenison will tell you that Vermeer was a great artist because he utilized a system of optical technologies to create his works.

This is a special screening of the documentary "Tim's Vermeer," which chronicles Tim Jenison's obsessive pursuit to prove that Vermeer's works were a product of scientific innovation, a claim that has caused quite a stir in the art world. Afterwards, the producer of "Tim's Vermeer," Farley Ziegler, Tim Jenison himself, and SFI Professor Jessica Flack discuss the film, the space for science in and around art, and what constitutes a real painting.

"The Future of the Planet: Life, Growth and Death in Organisms, Cities and Companies," with Geoffrey West, Tuesday, August 29, 7:30 p.m., The Lensic Performing Arts Center

Why do we stop growing, live for 100 years, and sleep eight hours a day? Why do all companies and people die, whereas cities keep growing and the pace of life continues to accelerate? Are cities and companies "just" very large organisms? And how are all these related to innovation, wealth creation and the sustainability of the planet?

Although life is probably the most complex and diverse phenomenon in the universe, many of its characteristics scale with size in a surprisingly simple fashion: for example, metabolic rate (the 2,000 food calories you need each day) scales in a systematically predictive way from cells to whales, while time-scales, from lifespans to growth-rates, and sizes, from genome lengths to tree heights, likewise scale systematically. Remarkably, cities and companies also exhibit systematic scaling: wages, profits, patents, crime, disease, and roads all scale in an approximately "universal" fashion.

In this SFI community lecture and book signing, SFI Distinguished Professor Geoffrey West presents the origin of these scaling laws and their compelling implications for explaining the lifecycles of companies, social connectivity, aging and death, tumor growth, urbanization and slums, innovation, and the possibility of a grand unified theory of sustainability.

"The Complexity of Economics," a panel discussion with Rob Axtell, Colin Camerer, Michael Kearns, and Ian McKinnon, co-hosted by Thornburg Investment Management, Tuesday, September 12, 7:30 p.m., The Lensic Performing Arts Center

For up-to-date information, visit www.santafe.edu/engage/community

Stanislaw Ulam Memorial Lecture Series, "Debt and its Discontents," with John Geanakoplos, Tuesday & Wednesday, September 25 & 26, 7:30 p.m., The Lensic Performing Arts Center

Debt, default, and forgiveness have been at the heart of almost every major financial boom, bust, and recovery. Without debt, growth is nearly impossible. Yet too much debt is catastrophic. Why is it that out of all economic variables, debt causes the most trouble?

In two lectures over two nights, SFI External Professor John Geanakoplos, the James Tobin Professor of Economics at Yale University, describes debt in history, in literature, and in economic theory, including his own theory of the leverage cycle, culminating in an explanation of the American mortgage crisis of 2007-2010 and the European sovereign debt crisis of 2010–2016.

The Music Lesson (Lady at the Virginals with a Gentleman), early 1660s. (Image: Royal Collection Trust/ © Her Majesty Queen Elizabeth II 2017)

The October InterPlanetary Series, October 13-17

What will it take to become an InterPlanetary civilization? Following up on the inaugural InterPlanetary panel discussion of July 18, 2017, the InterPlanetary celebration expands with a city-wide science fiction film festival and special presentation at SITE Santa Fe's FUTURE SHOCK exhibit. For up-to-date information on events in the InterPlanetary Project series, visit www.santafe.edu/ InterPlanetary.

"The Past, Present, and Future of the Anthropocene," with Manfred Laubichler, Tuesday, October 17, 7:30 p.m., The Lensic Performing Arts Center

The Anthropocene, a new epoch in earth history, reflects the unprecedented ways in which one species — Homo sapiens — has shaped our planet. To many, the Anthropocene began with the Great Acceleration, a period of exponential growth in just about any measurable parameter from population size to energy consumption to the number of new chemicals introduced into the biosphere and patents registered. But what enabled our species to have such an influence? What co-evolutionary and historical processes led to the Anthropocene? Does the Anthropocene represent a phase transition within coupled natural-social-cultural-technological systems? And what is the future of the Anthropocene?

In this SFI community lecture, part of the InterPlanetary Project, a panel of historians, biologists, earth scientists, and artists explore this unique moment in our planet's history, its past, and its future.

SFI's 2017 Community Lectures are made possible through the generous underwriting of Thornburg Investment Management, with additional support from The Lensic Performing Arts Center.

Tickets for this event are free, but reservations are required; to reserve tickets, visit http://tickets.ticketssantafe.org. Watch lectures live on SFI's YouTube page.

RESEARCH NEWS BRIEFS

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BIG DATA, SCIENCE, AND CIVIL LIBERTIES

Data-driven and algorithm-based decisions increasingly affect every corner of our lives. Companies, universities, police departments, and banks use these algorithms to decide who to hire, admit, target for investigation, or select to receive a loan. Because these algorithms are part of such important decisions in our biggest social institutions, it is critical that researchers and developers make sure these algorithms do not become instruments of discrimination or threats to social justice, writes Elizabeth Bradley, SFI External Professor and Science Board Member, in a white paper for the Computing Community Consortium committee of the Computing Research Association. To assure that, civil rights experts and data scientists — people who are rarely well-versed in one another's fields — will need to work together on cross-disciplinary research.

RECONSTRUCTING ANCESTRAL PUEBLO FOOD WEBS

Most food webs map interactions between plants and animals but omit humans, but that's beginning to change. A new paper published in *Journal of Archaeological Science* explores food webs in the Ancestral Puebloan Southwest, specifically looking at how human activity impacted the region's food web. Major changes in the food web arose from the human introduction of corn, and from hunting and tree harvesting. The paper began as collaboration from the 2011 Complex Systems Summer School, where co-authors Stefani Crabtree and Lydia Smith worked with SFI Professor Jennifer Dunne in her Complex Systems Summer School lectures. Crabtree and Dunne are now collaborating on work that builds on this research.

TO WIT, TU-VOUS: WHY SOME CONVENTIONS STAND THE TEST OF TIME

Linguistic conventions, such as the French tu-vous distinction, often signify social inequality. In new research published in the journal *American Economic Review*, SFI Professor Sam Bowles with collaborators Suresh Naidu and Sung-Ha Hwang investigate why some such conventions fade over time while others persist as stubbornly as inequality itself.

They found that convention switching depends on two factors: the likelihood of any agent to defy the convention and the size of the group. As a material example, a landowner with a 50-50 policy and hundreds of potential workers can replace any worker who asks for a greater share, whereas a pool of three workers is, over time, much likelier to have a majority ask for more.

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