SPRING 2024

Parallax

THE NEWSLETTER OF THE SANTA FE INSTITUTE

SFI External Professor and former Omidyar Fellow Daniel Larremore (CU Boulder) presenting at the fall 2023 Postdocs in Complexity conference. Recent gifts from the McKinnon Family Foundation and the Darla Moore Foundation support the continuation of SFI's education and postdoctoral programs. (image: Scott Wagner/SFI)

Major gifts support EDU, postdoc programs

In the first major gift of 2024, and as part of SFI's 40th anniversary, the McKinnon Family Foundation and the Darla Moore Foundation have collectively pledged $750K each year for the next five years to support SFI's education and early-career researcher programs. The gift will ensure the financial stability of SFI's Omidyar Fellowship, summer Undergraduate Complexity Research program, and its flagship Complex Systems Summer School.

Throughout its history, SFI has hosted more than 150 postdoctoral fellows. These early-career researchers are selected from around the world and across science for their intellectual curiosity, quantitative rigor, and multidisciplinary creativity. SFI's Complexity Fellows, supported by various private grants, have wide academic freedom to follow independent research questions.

"A Complexity Postdoc at SFI is a highly sought-after position. It comes with tremendous freedoms, and an expectation of pursuing important ideas — dare I say risky ideas — at an early stage in a career," says SFI President David Krakauer. "This is the time when the mind is best prepared for exploration but also the time when our institutions are most conservative. This gift from the McKinnon Family Foundation and the Darla Moore Foundation empowers the pursuit of fundamental science, by extraordinary minds, at a time when they might challenge all that we believe. It is an incredible and important opportunity."

Each year, four new Complexity Postdoctoral Fellows join SFI as Omidyar Fellows. Since 2009, a generous gift from Pierre and Pam Omidyar has covered half the cost for each Omidyar Fellow, while the remaining expenses have been covered by grants and gifts secured each year. Now, a portion of the McKinnon and Moore gifts will be dedicated to covering those remaining monies, offering SFI significant financial relief and reducing the annual hiring volatility into the future.

"We are pleased and excited to support SFI's Postdoctoral Fellows Program," says Darla Moore. "The Fellows represent backgrounds and disciplines that are representative of the wide-ranging, creative exploration of ideas that happens at SFI. We believe in preparing the next generation of scientific minds in understanding complex systems in the hope their continued study will contribute to solving the increasing challenges of our world."

> MORE ON PAGE 6

Carlo Rovelli, theoretical physicist, joins SFI Fractal Faculty

Why do we remember the past but not the future? Why is it that we can decide what to do tomorrow but not what we did yesterday? Theoretical physicist Carlo Rovelli revels in asking such questions about the nature of time — they might seem trivial at first but they force one to look deeper, revealing new aspects of reality. He has been pursuing answers to questions like these for years, and eventually, came across work by SFI Professor David Wolpert on how time works in different memory systems.

"The breadth and the kinds of questions asked at SFI resonate with me," says Rovelli. "There's a focus on fundamentals without being trapped in a research program." Last fall, Rovelli joined the Institute's Fractal Faculty.

In the world of physics, Rovelli is known for his work on loop quantum gravity — a theory that builds on Einstein's general relativity and seeks to understand the quantum aspects of spacetime. The theory shows that the fabric of spacetime is woven by tiny loops built into a network. Beyond the world of physics, he is known as the author of popular science books such as *Seven Brief Lessons on Physics* and *The Order of Time*, which have been translated into more than 40 languages.

Born in 1956 in post-WWII Italy to a family that held knowledge in high regard, Rovelli grew up surrounded by books. During his adolescence, he felt acutely aware of the widespread hypocrisy of the world and rebelled. In his hometown of Verona, he had also to confront a lingering-nostalgia for fascism. He learned not to trust common opinions around him.

"It was not an easy phase, but that's when I learned to question. I wanted to know better and I knew I wouldn't find answers in Verona," he says. He chose to drop out of school. As a consequence, his father cut him off financially.

At age 16, Rovelli hitchhiked from Europe to the Soviet nations and, at the height of the Cold War, learned to be critical of narratives produced by both sides. A few years later, he traveled alone, hitchiking coast-to-coast in the U.S. and Canada, finding jobs when he ran out of money, inspired by the people he met.

"It was a way for me to take my life in my hands, to learn about the diversity of humans, our visions and perspectives," says Rovelli.

To delay being drafted into the military, he enrolled in the University of Bologna. There, he became involved in politics and wrote his first book — *Fatti Nostri*, or "Our Business" — about the '70s uprising in the Italian universities. The book, published in 1977 by a small, politically engaged Italian publisher, became a hit.

> MORE ON PAGE 4

Predicting steps in a random process

Tiny particles like pollen grains move constantly, pushed and pulled by environmental forces. To study this motion, physicists use a "random walk" model — a system in which every step is determined by a random process. Random walks are useful for studying everything from tiny physics and diffusion to financial markets.

But what if the environment itself — and not just the walker — is random? "We can think of a town in which the elevation undulates in a random way, with the walker more likely to step downhill rather than uphill," says SFI Professor Sidney Redner. A fundamental question in this scenario, he says, is to determine the time for the system to move from one arbitrary point to another. This quantity is called the "first-passage time," and researchers have solved it in one dimension, albeit using cumbersome calculations.

In a paper published in *Physical Review E*, Redner, together with SFI Program Postdoctoral Fellow James Holehouse, introduced a new way to efficiently determine all possible first-passage times and their probabilities.

Their approach, which relies on heady math, captures the randomness of both the walker and the environment. In the paper, they describe how to compute a "moment generating function" — a kind of mathematical machine for providing complete statistical information about the distribution of first-passage times.

Their approach could improve predictive analyses in a wide range of processes influenced by randomness, from changing biological populations to migration systems to the dynamics of financial instruments used to study markets. It builds on ideas that Redner first described in his 2001 book *A Guide to First Passage Processes* (for which he's preparing a second edition.)

Researchers typically approach first-passage problems using enormous simulations, which start with initial systems and run through time to predict the time to reach a certain state. "But simulations are a really poor way to study these systems," Holehouse says.

Redner adds, "If you simulate some of these systems, you're guaranteed to get the wrong answer because you need to simulate so many instances of the system that to see the right answer would require a computation time that is beyond the age of the universe."

A new paper offers a mathematical approach to modeling a random walker moving across a random landscape. (image: Qingbao Meng/Unsplash)

BEYOND BORDERS

OUR AGE OF COMPLEX STEAMPUNK

Charles Babbage — Lucasian Professor of Mathematics at Cambridge (follower of Newton), co-founder of the Analytical Society (turncoat champion of Leibniz), life-long advocate of super-natural causes, and designer of unbuilt calculators — made his name in 1832 with the publication of *On the Economy of Machinery and Manufactures*.

Babbage's book was received as the definitive survey on the efficiency and production of machinery designed to supplement or supplant human work. Babbage described the project in his introduction as a review of:

> "the effects and the advantages which arise from the use of tools and machines;—to endeavour to classify their modes of action;—and to trace both the causes and the consequences of applying machinery to supersede the skill and power of the human arm."

Karl Marx in the much-discussed, unpublished seven-volume *Grundrisse*, or *Foundations of a Critique of Political Economy*, included extensive reflections on automation inspired by Babbage's researches:

> "But, once adopted into the production process of capital, the means of labour passes through different metamorphoses, whose culmination is the machine... a moving power that moves itself; this automaton consisting of numerous mechanical and intellectual organs, so that the workers themselves are cast merely as its conscious linkages."

Babbage conceived of his book as "one of the consequences that have resulted from the Calculating-Engine, the construction of which I have been so long superintending." It was not Babbage's intention to inspire a radical political economy, but to assay the most efficient means of manufacturing calculating engines:

> "This much-abused Difference Engine is, however, like its prouder relative the Analytical, a being of sensibility, of impulse, and of power."

The insights of Babbage and Marx sound as if they were written in the last several months in response to AI.

The life and society of Babbage is exemplary of the nineteenth century and its obsessions with machines, engines, designs, efficiency, scale, populations, evolution, and revolution. Babbage hosted super-sized parties at his home and laboratory at 1 Dorset Street in Marylebone, London. Charles Darwin, Michael Faraday, Lord Kelvin, Charles Lyell, Ada Lovelace, Henry Fox Talbot, and Alexis de Tocqueville all attended. It would not be a stretch to describe Babbage's informal soirées as the founding meetings in the precognition of a possible complexity science.

What we now broadly think of as complexity, the domain of far-from-equilibrium, self-organizing, and selected mechanisms

> MORE ON PAGE 5

CREDITS

EDITOR: Katherine Mast

CONTRIBUTORS: Nora Bradford, Tony Eagan, Rachel Fairbank, Mirta Galesic, Sienna Latham, Leah Magidson, Larry O'Hanlon, Stephen Ornes, Abha Eli Phoboo, Aaron Sidder, Paul Stapleton, Ellis Wylie

DESIGN & PRODUCTION: Laura Egley Taylor, Melissa Latham-Stevens

COPYEDITORS: Sienna Latham, Abha Eli Phoboo

VP FOR SCIENCE: Jennifer Dunne

Funding details for research and meetings available in associated stories at www.santafe.edu/news

Parallax is published quarterly by the Santa Fe Institute. Please send comments or questions to Katherine Mast at katie@santafe.edu.

www.santafe.edu

Larger, diverse cities create less biased citizens

The city you live in could be making you, your family, and your friends more racist. Or, your city might make you less racist. It depends on how populous, diverse, and segregated your city is, according to a new study that brings together the math of cities with the psychology of how individuals develop unconscious racial biases.

The study, published in the latest issue of *Nature Communications*, presents data and a mathematical model of exposure and adaptation in social networks that can help explain why there is more unconscious, or implicit, racial bias in some cities than others. The authors hope that local communities and governments can use the findings to help create more just and equitable cities.

"What I think is most interesting is the implication that there's a piece of systemic racism that has to do with how people learn and the way cities are organized," says psychologist Andrew Stier, an SFI Complexity Postdoctoral Fellow and lead author of the study.

Cities create dense networks of social interaction between people. Because of the interactions with many different people, we need to be constantly adapting to new situations and learning, says SFI External Professor Luís Bettencourt (University of Chicago), a co-leader of SFI's Cities, Scaling and Sustainability project and co-author of the study.

To see how racial biases emerge from how U.S. cities are organized, Stier turned to the enormous database of the Implicit Association Test (IAT). In the popular online test, volunteer participants are given a pairing of White or Black faces with positive or negative words and asked to categorize a single face or word. If they are faster to categorize things when White/good are paired they have a White–good bias and if they are faster to categorize things when Black/good are paired they have a Black–good bias.

Buried machinery in barn lot in Dallas, South Dakota, United States during the Dust Bowl, an agricultural, ecological, and economic disaster in the Great Plains region of North America in 1936. (image: USDA image no. 00di0971)

"People may feel they are not prejudiced, but can unconsciously have a preference for one group or another, and this is revealed by these tests," Stier says.

The researchers took the average IAT bias scores from approximately 2.7 million individuals in different geographic areas and linked them to racial demographics and population data from the U.S. Census to build a model that accounts for how individuals learn biases through their social networks. They found that when these networks are larger, more diverse, and less segregated in cities, implicit racial biases decrease.

The results suggest that there are structural reasons why cities help or deter people from becoming less racially biased. Perhaps the most pronounced reason is the segregation of different racial groups into different neighborhoods. Related to that is the lack of more cosmopolitan public spaces where a diverse range of people can experience positive interactions with one another.

In cities where people can't encounter and interact with people and institutions used by other groups, racial biases create major barriers to equity. These barriers, the authors state, are associated with disparities across essentially all aspects of life including medical care, education, employment, policing, mental health outcomes, and physical health.

Scaling theory reveals patterns in urban waste production

Waste is a natural by-product of life on Earth and of productive human economies. Living systems have evolved to reconstitute waste — creatures like dung beetles fill an ecological niche of breaking down other organisms' feces — but waste is a problem that still plagues human systems.

As the world population continues to grow and rapidly urbanize — two-thirds of humans will be city dwellers by 2050, according to the United Nations — our waste is driving a mounting worldwide crisis. Microplastics blanket the planet and infiltrate our bodies, wastewater pollutes our waterways, and greenhouse gas emissions are driving global climate change.

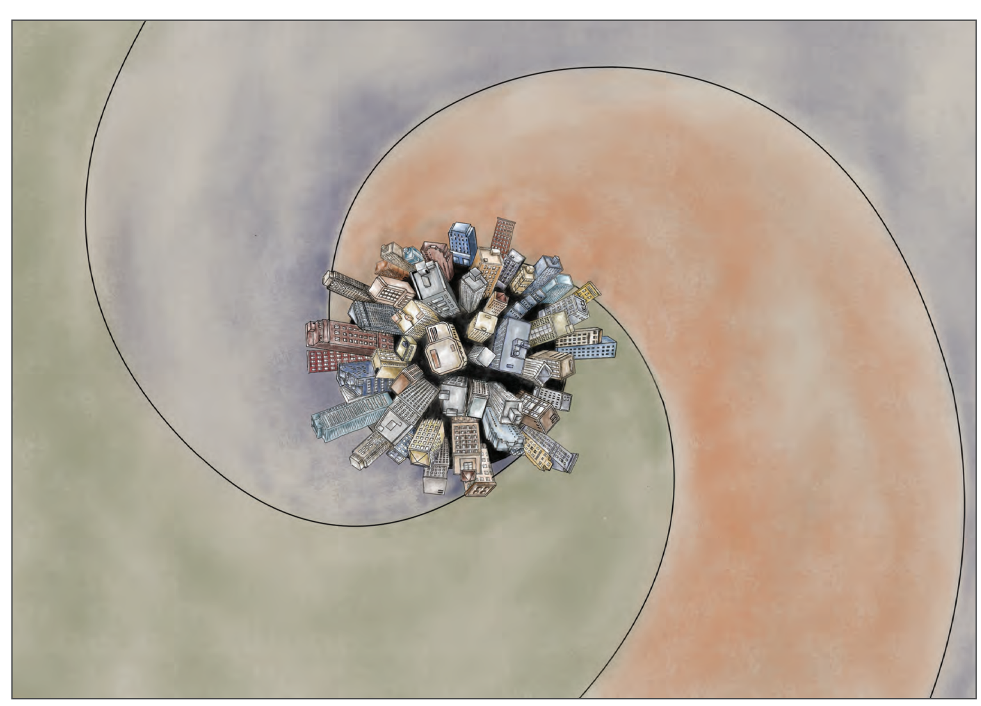
"We, as a society, tend tend to ignore the unpleasant side of our production," says Mingzhen Lu, a former Omidyar Fellow, now an Assistant Professor at New York University.

Lu and SFI Professor Chris Kempes are corresponding authors on a new paper published in *Nature Cities* that explores waste production as a function of urban systems.

"The key question is whether waste is produced more or less efficiently as systems scale up, and how big a recycling burden there is as a consequence," says Kempes.

To address this question, the authors used scaling theory to analyze waste products — municipal solid waste, wastewater, and greenhouse gas emissions — from more than one thousand cities around the world. Scaling theory has been used in biology to describe how organism physiology changes with body mass, and it proved relevant for understanding how waste production scales with the growth of a city.

"Scaling theory allowed us to extract overarching broad stroke patterns and transcend the individuality of each city," explains Lu.



In a new paper, Mingzhen Lu and Chris Kempes explore how three types of waste production — municipal solid waste, wastewater, and greenhouse gas emissions — scale with city size. (image: Elisa Heinrich Mora)

The resulting patterns show distinct differences in waste production as cities grow. Solid waste scales linearly — because it is tied to individual consumption, it increases at the same rate as population growth. In contrast, wastewater production scales superlinearly while emissions scale sub-linearly. In other words, bigger cities contribute disproportionately more liquid waste than smaller cities, but expel fewer greenhouse gasses. The results suggest an economy of scale for emissions as growth typically brings more efficient energy and transportation infrastructure, but a diseconomy for liquid waste.

. . . our waste is driving a mounting worldwide crisis.

Cities tend to deviate from the universal scaling law as they grow wealthier. Cities with higher per-capita GDP generate more waste across the board, which underscores the relationship between waste generation and economic growth. The findings emphasize the need for a new science of waste that can help predict the future state of urban ecosystems and inform policies to reduce waste and enhance sustainability.

Psychology journal's special collections explore human collectives and AI

The journal *Perspectives on Psychological Science*, one of the flagship publications of the Association for Psychological Science, has published two new special issues, both edited by SFI researchers and both taking an unusual approach for disciplinary journals: featuring research from a range of disciplines to address two especially timely topics. One of the special issues dives into the power and perils of human collectives, while the other takes on the rapid advances in AI. Both issues feature voices from diverse disciplines spanning psychology, anthropology, economics, computer science, social science, politics, and physics. The editors hope the special issues will encourage discussion and lead to more interdisciplinary collaborations.

> Collectives are already known to behave differently from individuals . . .

TWO'S A COUPLE. THREE'S A COLLECTIVE.

From orchestras to organized labor, service clubs to soldiers, congregations to crews, humans working in groups can accomplish much more than the simple sum of their members. In recent years that super-power of human collectives has been amplified by the Internet and social media, which allow people to form, join, and act as collectives with unprecedented ease.

Collectives are already known to behave differently from individuals in important ways, write editors SFI Professor Mirta Galesic, SFI External Professor Henrik Olsson of the Complexity Science Hub in Austria, and David Garcia, Professor at the University of Konstanz in Germany, in the editorial for the special issue "The Psychology of Collectives."

Consider, for example, how it feels to watch a sports event alone on TV versus in a stadium with other fans. At home, you could feel disappointed if your team loses. At a stadium, you could come away with hope of future wins and pride in the fan unity. The quality of the experience changes completely. Collectives are also known to shape the emotions and beliefs of individuals, as can be readily seen in religious, political, and many other types of collectives.

Because psychologists have long focused on individuals, they have some catching up to do on collective behaviors, explains Galesic. To help, this special issue includes articles written by scholars from different disciplines that explore how collectives can increase polarization, create echo chambers, affect an individual's willingness to cooperate, and strengthen views that reinforce racial segregation. The publication also offers articles on collective memory, modeling of crowds, how individual minds interact, and technology's influence on collectives.

ALGORITHMS: FRIENDS AND/OR FOES?

These days we're swimming in algorithms, those complex sets of rules or instructions that allow our phones, computers, cars, social media, etc., to operate. Like a lot of new technologies, they have created problems and raised some big, fundamental questions, says Galesic, who is also a co-editor of the special issue "Algorithms in Our Lives," along with SFI Professor Melanie Mitchell and Sudeep Bhatia, an associate professor at the University of Pennsylvania's Wharton School. These big questions include: How do algorithms make decisions? How do humans make decisions? And how do we put these very different kinds of decision-making together?

The chapters in this issue explore the contrasting but interacting nature of how algorithms influence human psychology and, vice-versa, how our psychology influences algorithms. Among the topics explored are how algorithms can be combined with human judgments to improve forecasting of geopolitical events; what makes false, divisive and infuriating content go viral on social media; what children can do that AI can't do (yet); and whether it's reasonable to use psychological tests designed for humans to assess AI.

In these early days of AI, it's common for machine and human decisions to be at odds because humans and algorithms often have different objectives, the editors write. The algorithms for many social media platforms, for example, are designed to maximize clicks regardless of the quality of the content. That can leave people less informed. Other, more consequential, mismatches have been found in the AI used in criminal justice and by mortgage companies that mirror and reinforce society's racial biases and fuel discrimination.

> . . . algorithms can be combined with human judgement to improve forecasting of geopolitical events.

We have a long way to go and more dialogue between disciplines is vital, says Galesic. But for starters, "Psychologists and computer scientists need to come together to better understand the possibilities and challenges of emerging AI technologies," she says. "We need to design algorithms that support healthy development of both individuals and collectives."

Life as a planetary regulator

According to the Gaia hypothesis, which was proposed by the scientists James Lovelock and Lynn Margulis in the 1970s, our planet should have been getting progressively warmer for millions of years, while our oceans should have been progressively more acidic as well. The fact that this hasn't happened suggests a planet-wide complex system that is self-regulating, with planetary life and geological processes working together to stabilize planetary geology and climate. Despite its importance, this idea could not previously be tested due to its planetary scale.

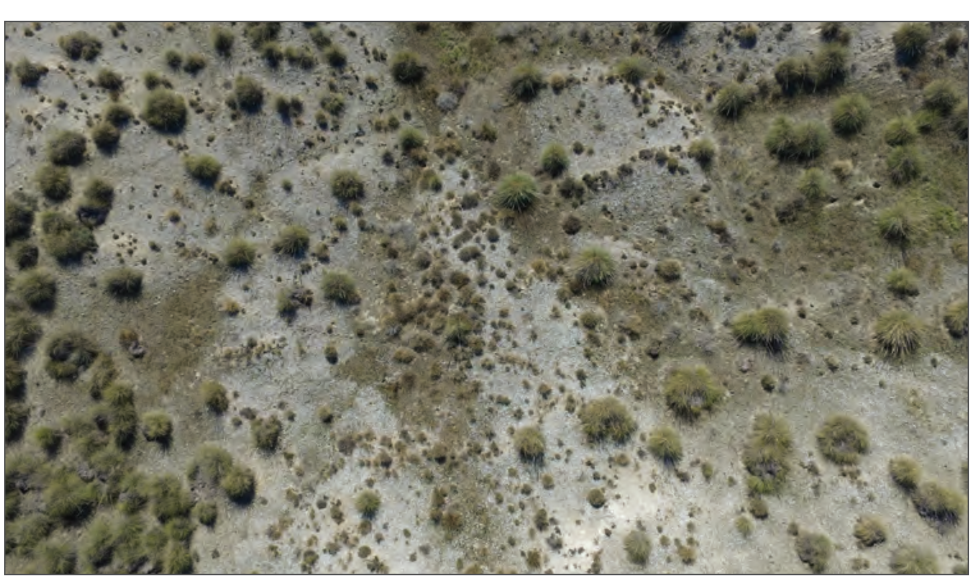
In a recent paper, published in the *Journal of the Royal Society Interface*, SFI External Professor Ricard Solé (Universitat Pompeu Fabra) and collaborators propose an experimental system that will test, on a small scale, the dynamics that regulate planetary processes. Using synthetic biology, they will test two engineered micro-organisms in a self-contained system to see if they can achieve a stable equilibrium.

This proposed setup is inspired by recent research in fermentation, which has typically required finely tuned outside control, to achieve stable, regulated conditions, including a stable pH level. "There's been recent work in trying to see if you can engineer microorganisms for fermentation so that they can self-regulate," Solé says. "That was the key inspiration." This experimental setup, which Solé and several of his students developed during a visit to SFI, has the potential to answer long-standing questions in the field about planetary-wide regulatory systems.

In this experimental setup, one strain will detect if the environment becomes too acidic, counteracting the increasing acidity, while the other strain will detect if the environment becomes too basic, acting to counteract this decreasing acidity. "Because these strains act on the environment, and the environment affects them, this creates a closed causal loop," Solé said. "The idea is to show that under very broad conditions, they will stabilize to a constant pH level, as predicted by the original theory."

A new paper proposes an experimental setup that could test the classic Daisyworld model — a hypothesis of a self-regulating planetary ecosystem — in the lab via two synthetic bacterial strains. (image: Victor Maull, created with Image Designer)

Dryland resilience



This semi-arid steppe in Ciempozuelos, Spain, displays the characteristic vegetative clusters found in drylands around the world. (image: Miguel García-Gómez)

Many complex systems, from microbial communities to mussel beds to drylands, display striking self-organized clusters. According to theoretical models, these groupings play an important role in how an ecosystem works and its ability to respond to environmental changes. A new paper in *PNAS* focused on the spatial patterns found in drylands offers important empirical evidence validating the models.

Drylands make up 40 percent of the Earth's landmass and are places where water is the limiting resource for life. They often display a characteristic clustering of vegetation surrounded by bare soil — patterns that are easy to spot in aerial images. The new study, led by SFI External Professor Sonia Kéfi (CNRS), finds that not only are these spatial patterns caused by the stressful environmental conditions of drylands, but they are also a critical adaptation that allows drylands to function in changing conditions. When a dryland ecosystem tips into a degraded state, the spatial patterns disappear.

"Many people have the idea that 'interesting' ecosystems are places like the Amazon, and that drylands are poor in some way," says SFI External Professor Ricard Solé (Pompeu Fabra University), a co-author on the paper. "But they can be very rich. They are responsible for managing how water is being retained or not in these habitats, and are important for CO_2 exchange." Beyond their ecological importance, drylands are also home to one-third of the world's human population, making them important economically and culturally.

In healthy dryland ecosystems, islands of vegetation create oases where conditions are a bit better than the rest of the landscape. There's more water, more nutrients, and more shade. If an ecosystem's climate becomes drier, those clusters tend to move further apart.

And this, says Kéfi, is a double-edged sword. While improving local conditions, these clusters also create spaces without vegetation — harsh places where a single plant would not survive on its own. If conditions become too harsh, the ecosystem can reach a tipping point into desertification.

> . . . drylands are also home to one-third of the world's population.

Kéfi and her colleagues wondered if aerial images, and their evidence of changes in spatial patterns, could themselves indicate the health or level of degradation in a given plot of land.

"In theory, we could tell something about the ecosystem from the sky — that's what the models predict, in very broad terms," says Kéfi. To test this, the team paired aerial images with soil and vegetation data gathered from 115 dryland ecosystems across 13 different countries. "This on-the-ground data shows us where one ecosystem is healthier or functioning better than other ecosystems." Using the two types of data, the team could test the predictions of the model against real-world observations.

"Our results represent a significant advance in the development of tools for the management and preservation of dryland ecosystems in a warmer, drier world," says Kéfi. "More specifically, changes in spatial vegetation patterns (or the lack thereof) could be used as indicators of degradation."

According to Solé, the study offers, for the first time, real validation that the model correctly predicts the non-linear dynamics of what has been unfolding in dryland ecosystems. "The beauty of this work is that it reveals something that goes beyond the pattern-forming problem. You can talk about ecosystem health in ways that are not metaphoric, and it opens new interesting questions about how to address the future of these ecosystems," he says.

The authors hope their work will make it easier to spot degrading systems that might be approaching a tipping point. And, because vegetation patterning seems to also be key in other natural systems, such as microbial communities or coastal wetlands, their results could have implications for systems beyond arid zones.

Complexity tools for USDA nutritional guidelines

The decision of what to eat, and how those choices impact overall health, has always been complicated. Although nutritional guidelines can often offer guidance, there is no one-size-fits-all approach to a well-balanced diet, with factors ranging from a person's health status, cultural background, and access to resources like farmer's markets or well-stocked grocery stores, to personal dietary preferences.

"There's enormous heterogeneity across people and across contexts," says SFI External Professor Ross Hammond (Washington University/Brookings). "Making one-size-fits-all recommendations is difficult." Given this complexity,nutrition is an ideal area to apply complexity science. In February, the U.S. Department of Agriculture released a commissioned report, which Hammond wrote with a team of other researchers, outlining specific ways that complex-systems science — or "systems science" in the report — could be incorporated in shaping the country's nutritional guidelines.

A new report co-authored by SFI External Professor Ross Hammond lays out several ways tools from complexity science could be applied in updating the USDA's nutritional guidelines. (image: nrd/Unsplash)

The USDA's Dietary Guidelines, updated every five years, offers advice on what individuals should eat and drink. But the impacts of these guidelines go well beyond the personal — they influence school lunches, federal food assistance programs, and the food industry more broadly. "The Dietary Guidelines are the central source for all evidence-based nutrition guidance developed by the federal government and shape hundreds of billions of dollars of annual federal spending," says Hammond.

In the new report, Hammond and his coauthors outline six main strategies for incorporating complex-systems science into nutritional guidelines and offer a roadmap for creating a more nuanced, multifaceted approach to shaping nutritional policies. One strategy suggests including systems-science experts in the development of dietary guidelines, allowing new kinds of evidence and analytical tools to be included in the process. Another proposes using computational modeling tools from systems science to inform how dietary guidelines are implemented; this process often includes a range of factors, including everything from our agricultural systems, supply chain issues, and environmental considerations. "That is a deeply complex-systems kind of question, because you are invoking lots of different moving pieces," Hammond says.

As Hammond notes, nutritional guidelines don't exist within a vacuum, but rather are informed by a number of different social, cultural, and environmental factors. As a result, the number of Americans who follow the dietary guidelines is currently quite low, with the numbers remaining stagnant for decades. Systems science can offer insight into some of the main barriers that are preventing Americans from following dietary guidelines; offer more nuanced and flexible guidelines on diet to accommodate a wide swath of personal and cultural preferences; and identify potential strategies that can help move Americans towards healthier eating patterns.

"Rather than a one-size-fits-all recommendation, what if we were able to have personalized recommendations that would suggest which are the things you could do right now, that would be easiest for you, that would move you in the right direction?" Hammond says. "What is the one thing that you could do, that would really help?" Thanks to advances in systems science, we are getting closer to making this a reality.

Second Complexity Global School to convene in Colombia

This summer, SFI and the Universidad de los Andes (Uniandes) will host the second Complexity Global School. From July 21 through August 3, 60 students from Latin America, Western Europe, the Caribbean, the U.S., and Canada will convene in Bogotá, Colombia. The school is part of SFI's Emerging Political Economies program and is supported by the Omidyar Network.

SFI launched the first Complexity Global School (CGS) in 2023 with two partnering institutions — the Indian Institute of Technology, Bombay, and the University of the Witwatersrand in South Africa — who hosted simultaneously. Last December, 30 South Asian students gathered in India and 30 African students gathered in South Africa to explore ideas at the intersection of complexity science and political economy. During the two-week school, students interacted with their local cohort as well as the students and instructors at the other location.

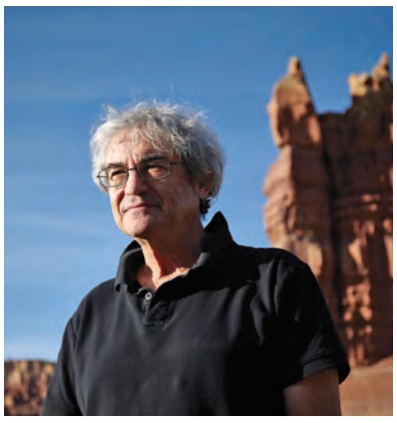
"The CGS structure was complexity science put into practice," says Olufemi Oloba, a student at Afe Babalola University in Aye, Nigeria who attended at the South African site. "While discussions occasionally surpassed our understanding, they centered on invaluable topics, leaving us to delve deeper into those of interest."

Complexity Global School highlights methods, models, and new frameworks to analyze complex phenomena in various social, economic, and political spheres. These multiple lenses help students reimagine the fundamental paradigms that organize political economies, fostering a deeper understanding of their complexities and empowering innovative solutions to address today's most pressing challenges.

Modeled after SFI's flagship Complex Systems Summer School, CGS features lectures, informal interactions, and project groups that work together to identify interesting research topics. The groups continue to work on their projects remotely for several months after the in-person component concludes.

"One activity of reckless idea generation challenged us to break free from the constraints of our academic training and explore unconventional solutions," says Somya Srivastava, a student at Indian Institute of Technology, Delhi who attended CGS in Bombay. "This experience helped me understand the importance of interdisciplinary collaboration in questioning dominant narratives."

CARLO ROVELLI *(cont. from page 1)*



Carlo Rovelli at the sandstone formations near Abiquiu, NM. (image: Kate Joyce for SFI)

But times were changing and his generation's radical dreams of a world without weapons, class divisions, boundaries, and wars, were fading. Rovelli turned to books for solace and fell in love with science.

He studied quantum mechanics, mostly on his own, occasionally sitting in class for an exam or journal activity. He asked his professors for books to read. If they recommended one, he would buy three on the same topic. He wanted to learndifferent perspectives and spent hours doing calculations. Enamored by the ideas of Einstein and quantum physics, he decided to study quantum gravity. Rovelli signed up for a Ph.D. but theuniversity had no professors well versed enough in the subject to teach him. So, Rovelli came up with a course to systematically teach himself everything about quantum gravity.

"I wanted to immerse myself in the subject. I didn't care about publishing papers and getting a job, which is why it was a long time before I published anything," he says. After his Ph.D., he received a scholarship from the Italian government and moved to the University of Rome, where he was given a little office in a basement and forgotten. From that basement, he wrote letters to theoretical physicists elsewhere working on quantum gravity asking if he could visit them.

One of his visits was to Chris Isham, a leading figure on quantum gravity. Another was to Abhay Ashtekar who created Ashtekar variables to explain a different way of understanding how gravity works in the universe. A crucial visit was to meet Lee Smolin at Yale.

Rovelli and Smolin became friends, hanging out to solve equations and discuss ideas late into the night. Together, they started loop quantum gravity, a quantum theory of gravity that, unlike other theories of gravity, didn't rely on a fixed background. They used loops, which are closed paths, to describe the behavior of gravity on a tiny scale. They gave talks in the U.S., Europe, and Asia that generated enormous interest, and Rovelli began writing his first papers.

Rovelli was finally being noticed. Back in Italy, universities now offered him a job, but he decided to join the University of Pittsburgh's physics department. There, he worked with pioneers in general relativity, such as Ted Newman, and engaged in discussions with philosophers of science, such as John Earman. It was a decade before he returned to Europe and, together with Smolin, developed the ideas of loop quantum gravity into a fully formed theory.

"The quest for quantum gravity is to ask what time and space are. The main result, which took so long to develop, is that if you take general relativity, apply quantum mechanics, and calculate, what comes out is the granularity of space — there is no continuous space. This, I consider to be a physical result of loop quantum gravity," says Rovelli. The theory has not been empirically verified yet, but it represents a possible solution to the problem of quantum gravity.

"Studying quantum mechanics is about relationships, systems, structures, and orders that make the world," says Rovelli. As in, meaning is created in relation to surroundings and is not inherent in individual things. He sees quantum mechanics as a way to challenge how we perceive reality and so he stays on course to question temporality, entropy, and the asymmetry of time in our universe. After all, who knows what the future holds?

Colophon: Updates from the SFI Press

Press works to visualize complexity

What does the emergence of a new paradigm look like? How might we visualize the history of complexity? Since beginning work on *Foundational Papers in Complexity Science* four years ago, project editor David Krakauer and the SFI Press team have grappled with these questions. How, we've wondered, could we do justice to this collection of 88 papers and accompanying commentary while also ensuring that the visuals we create enhance the experience of both expert readers and those encountering complexity for the first time?

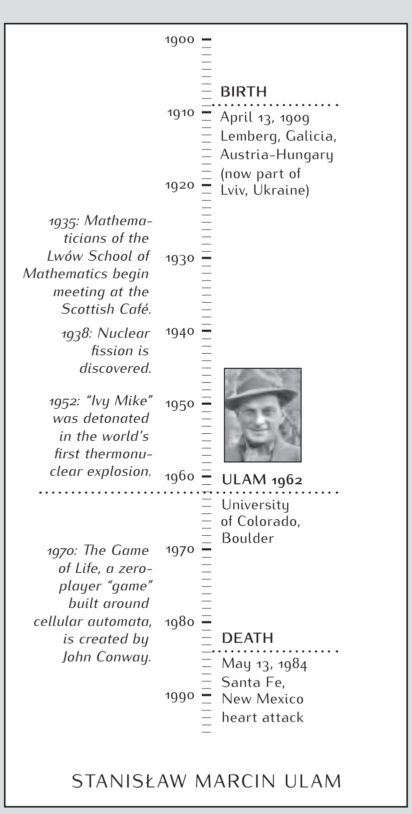
In the case of this four-volume set, the magnitude of the contents led us toward simplicity: a visual template that gives readers insight into these disparate chapters and their authors. The books will feature a dot motif developed by SFI Press Production Assistant Zato Hebbert, an artist, coder, and sculptor. In this visualization, each foundational paper is represented by a dot, with its placement signifying the year it was originally published. The dot-papers contained in a given book are highlighted to indicate contents across the four volumes.

We believe that the visual presentation of our books should complement the science they contain and communicate. The process of developing art for SFI Press volumes is painstaking and iterative, requiring the team to be nimble, resourceful, and responsive to the needs of each book. We typically explore dozens of ideas before landing on the right approach for a particular text.

"It's fun to explore ways in which we can add meaning to the experience of reading the books," Hebbert says. "With art, a certain level of ambiguity and abstraction allows readers to make their own associations."

We've applied a similar treatment to the authors of these papers. Each chapter opens with a timeline drafted by Laura Egley Taylor, who oversees design for the SFI Press, documenting the life of each author, when the paper was written, and relevant scientific, technological, and broader world events that impacted the work.

Although these volumes presented a unique challenge, all SFI Press books reflect our commitment to artwork that is not only beautiful, elegant, and unexpected, but also meaningful. To learn more, visit the project website at FoundationalPapersInComplexityScience.org.



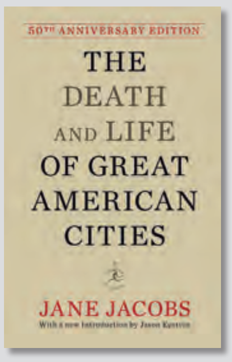
Left: *The draft design for the spines of the* Foundational Papers *series.* **Above:** *Timelines like this one for the life of Stanisław Ulam will be used to introduce each chapter.*

What we're reading

Books selected by SFI researchers on the topic of The Metropolis

"It is a complex order…This order is all composed of movement and change, and although it is life, not art, we may fancifully call it the art form of the city and liken it to the dance—not to a simpleminded precision dance with everyone kicking up at the same time, twirling in unison and bowing off en masse, but to an intricate ballet in which the individual dancers and ensembles all have distinctive parts which miraculously reinforce each other and compose an orderly whole."

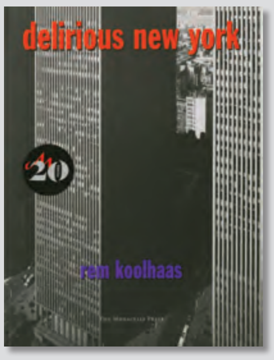
So writes Jane Jacobs in her classic book about urban planning, *The Death and Life of Great American Cities*. Long before the Santa Fe Institute was founded, writers like Jane Jacobs, Georg Simmel, Charles Baudelaire, and Gustave Flaubert were describing urban kinetics and theorizing about the city as a complex system. Similarly, the pages of Charles Dickens, James Joyce, Robert Musil, or Virgina Woolf, offer insights into many topics currently being researched at SFI, from traffic, to waste production, to overlapping time scales, emergent engineering, epidemics, the energy grid, niche construction, economics, language, and group decision strategies. With the recent publication of several papers about cities by SFI researchers, our theme for this installment of "What we're reading" is The Metropolis.



The Death and Life of Great American Cities, published in 1961, remains magnificent and relevant. Opening as an attack on top-down urban planning, it shifts into a panoramic encomium to emergent city life, with chapters devoted to the role of diversity, the uses of sidewalks and parks, the need for concentrated areas, the consequences of rigid borders, the role of slums, and the evolving nature of money and transit. Of particular note is a chapter entitled "The Need for Small Blocks," in which Jacobs provides primitive but perfectly explanatory models of how fluidity and commerce increase as block size decreases.

Around the same time, Carlo Emilio Gadda became one of the first great European novelists to involve a specific character as a mouthpiece for urban complexity thinking. His 1957 book, *That Awful Mess on the Via Merulana*, describes Rome as a "system of systems" while simultaneously investigating a gruesome murder. The title alone hints at its intersecting themes: while "Via Merulana" pinpoints thoroughfare in a definite region of the city, the word "mess" — *pasticciaccio* in Italian — signifies a tangled situation without an identifiable cause. As the protagonist Don Ciccio puts it, "unforeseen catastrophes are never the consequence or the effect, if you prefer, of a single motive, of a cause singular; but they are rather like a whirlpool, a cyclonic point of depression in the consciousness of the world, towards which a whole multitude of converging causes have contributed." Don Ciccio himself stresses that urban activity is always a knot or a muddle, and his ability to solve crimes entails a deep understanding not only of psychology, sociology, forensics, and history, but also of geology, botany, mineralogy, and viticulture — all of which and more contribute to the tangled criminality of Roman life under Mussolini's dictatorship.

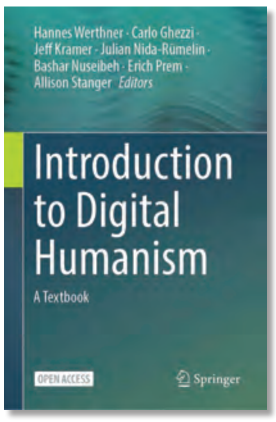
Echoing Gadda's detective, the architect Rem Koolhaas suggests that a metropolis is a "mountain range of evidence with no manifesto…" His magnificently learned and unique book, *Delirious New York* (1973) is a "retroactive manifesto," as he calls it, designed to excavate the inarticulate social decisions that coalesced to make New York what it is, flaws and all. Complete with beautiful illustrations, maps, photos, and archival documents, *Delirious New York* shares with the books of Gadda and Jacobs an obsession with how all urban phenomena are greater than the sums of their parts, with every success or catastrophe being the result of an intricate, unchoreographed ballet, where "the suspense in the spectacle comes from the constantly escalating intensity of the performance."



Books by SFI Authors

INTRODUCTION TO DIGITAL HUMANISM EXPLORES THE INTERCONNECTEDNESS OF AI AND HUMAN LIFE

In our rapidly digitizing world, humans have been handing over increased responsibility to AI and other digital tools. We're creating art and writing with Dall-E and ChatGPT, and asking algorithms to weigh in on important decisions like judicial sentencing and financial loans. A new textbook co-edited by SFI External Professor Allison Stanger (Middlebury College) explores the implications of allowing algorithms to make decisions for us and the best practices for integrating algorithms into our lives.



The free, open-source *Introduction to Digital Humanism* invites a human-centered approach to digital technology and weaves ethics, philosophy, and history into conversations about our modern age. In this multidisciplinary book of nearly 40 chapters, various authors delve into a wide range of digital advances and their consequences — both constructive and concerning — for humanity. For instance, one chapter explains the hidden labor involved in AI, involving countless underpaid workers cleaning, labeling, and preparing data for AI training. Another chapter explores the threat various technologies pose to our privacy, as many companies collect and commodify our personal data. The book evaluates fundamental intersections between AI and aspects of our society, like labor rights and democracy, and then anticipates how relinquishing our decision-making to AI could change the way we work, exacerbate existing inequalities, and threaten our democracy.

"Obviously, this is a rapidly evolving topic, but to the extent possible, we tried to emphasize the issues that are evergreen," says Stanger. "Contemplating how best to uphold human dignity in the face of rapid technological innovation is the lodestar of the project."

While aimed at students and teachers, the book covers many topics of current interest to policymakers, such as facilitating access to digital resources, protecting human agency, and improving user privacy. The book is arranged into three parts. The first, "Background," covers the history and philosophical roots of digital humanism, computing, and the digital revolution to the social responsibilities and gender perspectives scientists and technologists need to consider moving forward. The second section, "Digital Humanism: A System's View," covers general considerations in developing and changing technology with humanity in mind, such as facilitating access to technology and creating trustworthy AI. The final section, "Critical and Societal Issues of Digital Systems," delves into specific, pressing issues raised by advancing technologies like recommender systems and cryptocurrencies.

Each chapter tackles a unique aspect of digital humanism and provides discussion questions and further reading suggestions. Whoever may be reading, they are sure to walk away with a better idea of how to use technology to create a sustainable, equitable, and responsible future. For humans to coexist with technology, it is imperative that we keep humans at the center of new policies and new inventions. This book offers the necessary tools to do so.

NEW BOOK OFFERS THOUGHTFUL APPROACH TO MODELING COMPLEX SOCIAL SYSTEMS

We are often puzzled by human social phenomena. Why does misinformation sometimes spread so easily while scientific facts have trouble taking hold? Why is it so difficult to cooperate on problems that obviously threaten humanity, such as climate change? Why are people willing to risk their lives, and the lives of their families, rather than getting vaccinated? All of these phenomena are emerging from complex cognitive-social systems that can be difficult to understand using only verbal reasoning. To better understand their structure and dynamics, it is helpful to generate and manipulate them computationally.

Indeed, there are many computational models of various aspects of social systems, but still relatively few are done by social scientists. While cognitive scientists, sociologists, political scientists, anthropologists, historians, economists, and other social scientists possess deep knowledge about critical aspects of human cognitive-social systems, they often have little experience with computational models.

Now, a new book by SFI External Professor Paul Smaldino (University of California, Merced) offers a uniquely helpful, comprehensive, and approachable solution. In *Modeling Social Behavior: Mathematical and Agent-Based Models of Social Dynamics and Cultural Evolution* (Princeton University Press, 2023), Smaldino provides an excellent introduction to agent-based modeling for social scientists and anyone else interested in modeling cognitive-social systems. Notably, the book also integrates the use of computational agent-based models with classic mathematical approaches from dynamical systems and game theory.

The book helps novices to build and experiment with their own models quickly and easily, and inspires seasoned modelers to re-examine their assumptions and interpretations. Smaldino provides numerous examples of models of various social phenomena, from segregation, contagion, belief dynamics, and cooperation, to the science of science and social networks. Each chapter includes examples in NetLogo, an easy-to-learn but powerful modeling platform. Smaldino's writing is engaging, witty, and full of fun and useful real-world examples.

Importantly, Smaldino provides meta-level commentary on the philosophy of models — their relationship with reality, how they are analogous with maps, their limitations and advantages, and best practices for designing and interpreting agent-based models. Readers will therefore not only master the practice of modeling, but also get deep insights into the way models should be done. And, this book is just pure fun; readers will think about large modeling problems in the company of cubist chickens and cool dinosaurs. Smaldino's book is a wonderful thinking and teaching resource for anyone who strives for a deeper understanding of the bewildering social complexity around us.

BEYOND BORDERS *(cont. from page 2)*

of adaptation, grew directly from the work of Babbage's guests and contemporaries. The age of steam provided the phenomenological set of necessary elements for complexity: thermodynamics, uniformitarianism, evolution, and computation. Their union would be pursued in the twentieth century through the work of Alan Turing, R.A. Fisher, Norbert Weiner, John von Neumann, Claude Elwood Shannon, the Santa Fe Institute, and others.

This work cannot be described as physics, biology, or sociology, but a larger endeavor to make sense of the principles governing purposeful matter. We follow in the footsteps of the belligerent Babbage, with a troublemaker's attitude to mechanisms, making a stand for steampunk:

"Chaos was my philosophy. Oh, yeah. Have no rules. If people start to build fences around you, break out and do something else."
— *"Johnny Rotten" John Lydon, the Sex Pistols*

— *David Krakauer*
President, Santa Fe Institute

NEW GIFTS *(cont. from page 1)*

L-R: Darla Moore and Ian McKinnon

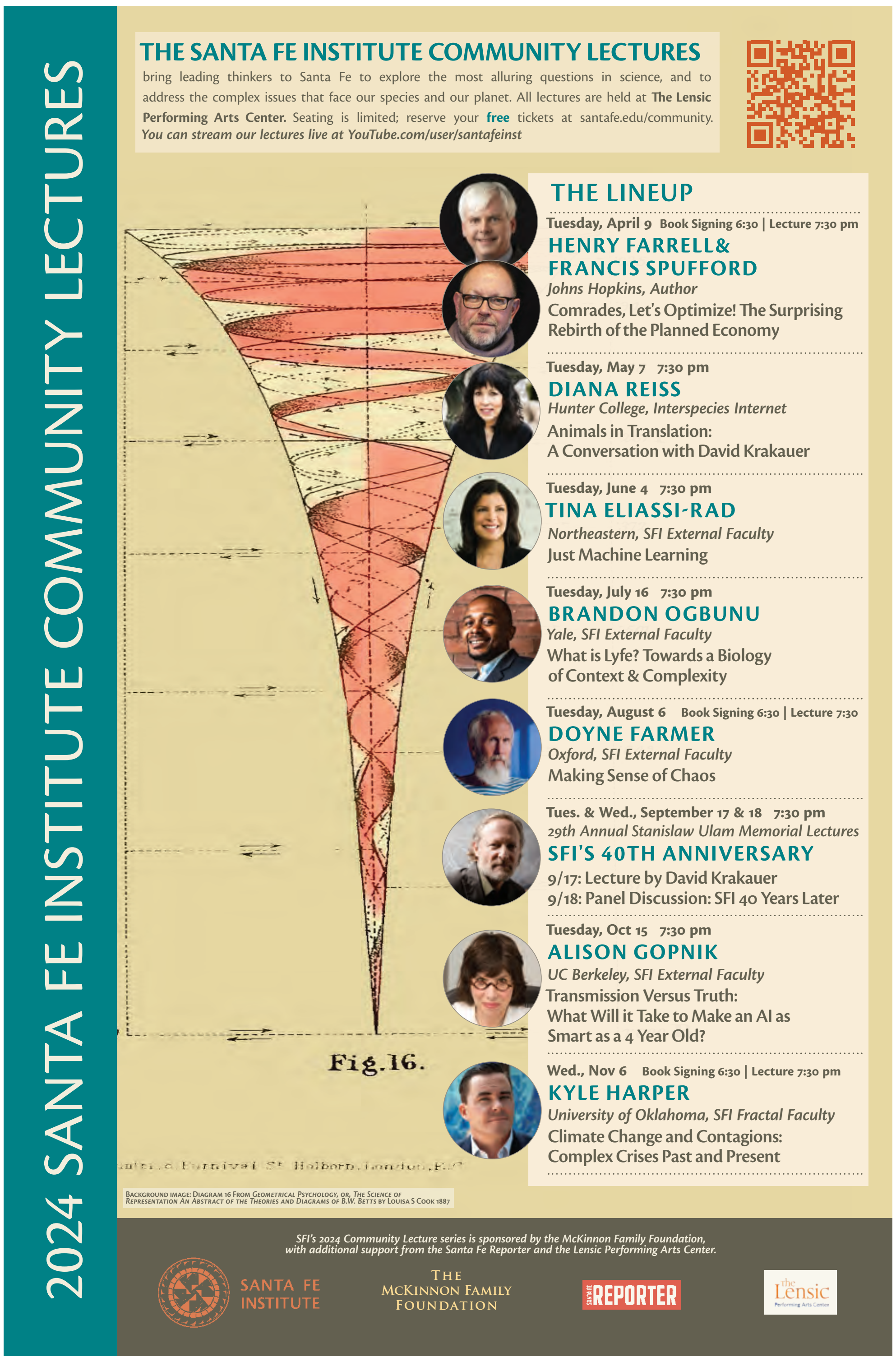
The new gift will also cover the full cost of SFI's Undergraduate Complexity Research program, which brings nine students to Santa Fe each summer for a 10-week immersive experience beside SFI mentors. Many UCR participants have gone on to pursue graduate degrees in areas they were introduced to at SFI, and often maintain research collaborations with other students and their SFI mentors.

And, the gift will supplement scholarships for many students enrolled in Complex Systems Summer School. The four-week intensive offers some 50 graduate students, postdoctoral fellows, and professionals the chance to transcend disciplinary boundaries, take intellectual risks, and ask big questions about complex systems.

"The McKinnon Family Foundation embeds a long-standing focus on education and New Mexico, so this gift to the Santa Fe Institute for complex-systems education and early-career research opportunities fits particularly well with that mission," says Ian McKinnon. "One of the aspects of SFI which has always stood out to me is the way analytical rigor in its research approach is coupled with an appreciation for, and embrace of, the ineffable beauty of the complex adaptive systems which surround us. To the extent that this gift is targeted toward education and early career research, our hope is that we will help to empower new generations of complexity scholars who will apply that rigor and sense of beauty across a broad range of dimensions."

> . . . our hope is that we will help to empower new generations of complexity scholars . . .

The challenges that society faces today, from the future of work, to responding to novel pandemics, growing social and political polarization, and rapidly developing "intelligent" technologies are all rooted in complex adaptive networks. "Given that addressing some of the most thorny global challenges requires an approach rooted in complex-systems science," says McKinnon, "we believe programs like the ones we are helping to fund will yield great returns for society in ways we can now only imagine."



This year's Community Lecture Series began on April 9 with a talk by Henry Farrell and Francis Spufford. Reserve free tickets for upcoming talks to join us in person at the Lensic Performing Arts Center in Santa Fe, or follow the livestreams online. More details at ***www.santafe.edu/community.***

RESEARCH NEWS BRIEFS

ANCIENT ROMAN PANDEMICS CONNECTED TO CLIMATE CHANGES

Recent climate changes have been linked to a lengthening laundry list of troubles, including famines, social turmoil, and disease outbreaks. Now the same sort of connections have been found between climate shifts and crises in the heartland of the ancient Roman Empire.

In a recent paper in *Science Advances*, SFI Fractal Faculty Kyle Harper (University of Oklahoma) and coauthors use plankton buried in millennia of marine sediments from the Gulf of Taranto (the arch in Italy's boot) to track the air temperatures and precipitation from 200 BCE to 600 CE with a resolution of three years. It's the first climate data from that period found so close to the center of the Empire. They found that colder periods after 100 CE are associated with records of pandemic diseases. The shifting climate caused the outbreaks in several ways, they explain, including changes in nutrition, conflicts over resources, and the varying populations of disease-carrying animals like mosquitoes and rodents.

Read the paper "Climate change, society, and pandemic disease in Roman Italy between 200 BCE and 600 CE" in* Science Advances *(January 26, 2024) at doi.org/10.1126/sciadv.adk1033

DEFINING A CITY USING CELL-PHONE DATA

Humans are becoming more urban, with more than half of the world's population now living in cities. This rapid growth poses unique challenges to both the study and governance of cities — a challenge made harder because we lack a single common definition of "city." Cities are often defined by political or administrative units or by built-up areas identified via satellite imagery. The best definitions depend on observing people's mobility between home, work, and other activities —data traditionally collected via surveys, which are expensive, incomplete, and limited to a few nations. New technologies now offer a more complete picture.

In a recent *Perspective in Nature Cities*, SFI Professor Geoffrey West, External Professor Luís Bettencourt (University of Chicago), and co-authors propose that the geolocated data from the world's more than 7 billion cell phone users could be used to map out city limits.

Cell phone data accurately reveal people's presence, movements and social interactions over space and time; these data are becoming the most widespread proxy for drawing city limits. Pairing cell phone data with other datasets, such as remote-sensing imagery and census data, could further improve accuracy and help advance the science of cities as complex systems and their role in global sustainability.

Read the paper "Defining a city — delineating urban areas using cell-phone data" in* Nature Cities *(January 11, 2024) at doi.org/10.1038/s44284-023-00019-z

E-PARALLAX

Sign up for our monthly e-newsletter at **www.santafe.edu/subscribe**

SPRING 2024
Parallax
THE NEWSLETTER OF THE SANTA FE INSTITUTE

1399 Hyde Park Road
Santa Fe, New Mexico 87501
505.984.8800
www.santafe.edu