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Parallax

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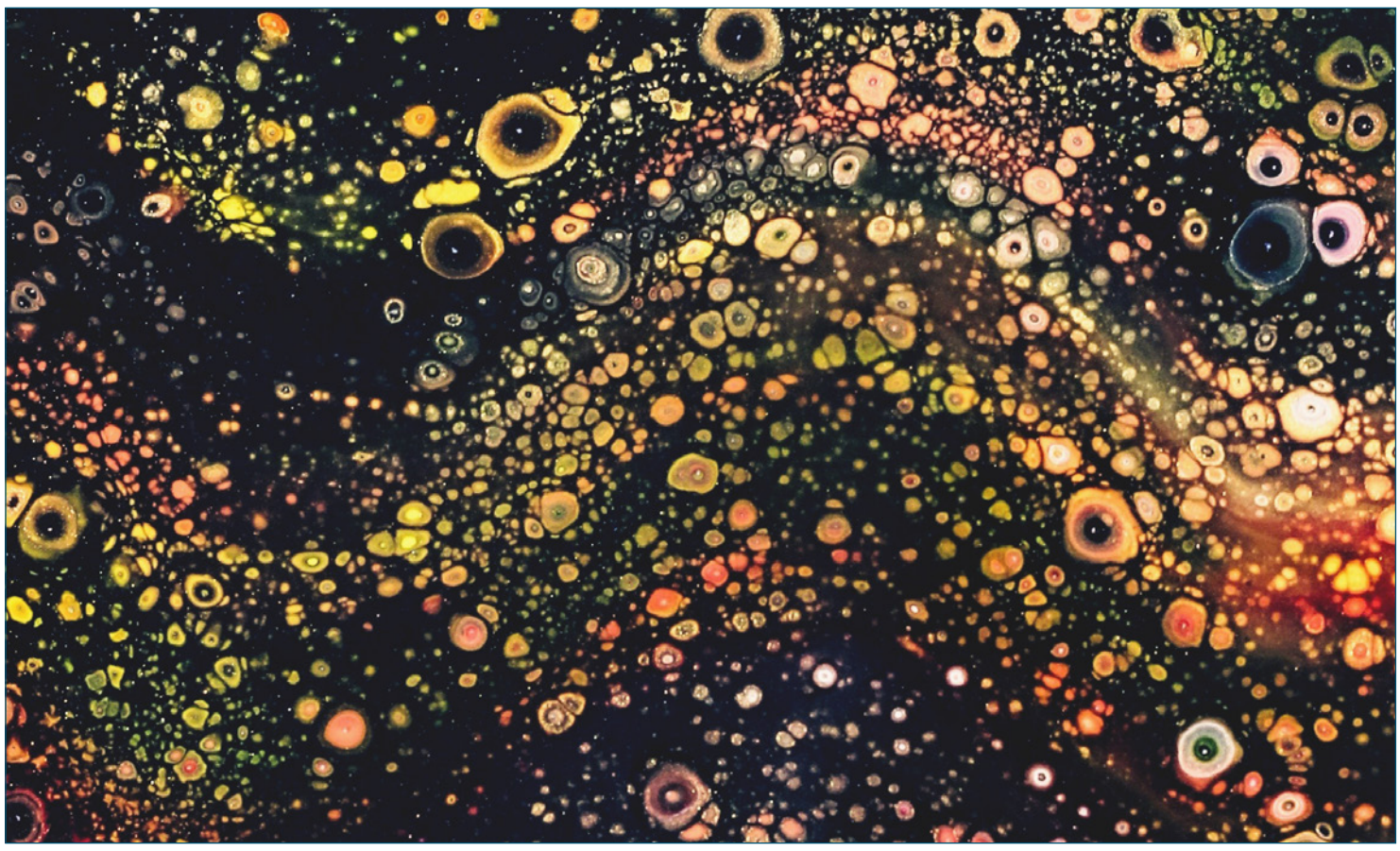

Why do some ideas catch fire? An interdisciplinary team of researchers offers a new theory. (image: Susan Wilkinson/Unsplash +)

Going viral: How ideas, beliefs & innovations spread in the digital age

It might start as a joke, a belief, or a rumor. At first, it's easy to dismiss. But then it gains a twist, builds momentum, and spreads like wildfire. What causes some ideas to die out while others take over the internet?

A recent study published in *Physical Review Letters* offers a fresh explanation. Led by researchers from SFI and the University of Vermont, the work introduces a mathematical model for "self-reinforcing cascades," processes where the thing being spread, whether a belief, joke, or virus, evolves in real time and gains strength as it spreads.

Traditionally, scientists have used simple branching models to explain how things like ideas or diseases spread. One person gets infected or hears a rumor, they pass it to two more, each of those passes it to two more, and so on. It's a tree-like pattern in which the thing spreading (virus, belief, meme) stays the same. But this new research takes into account the fact that things don't just spread — they change as they spread, and that change actually helps them spread further.

"We were inspired in part by forest fires," says SFI Professor Sid Redner, a co-author on the paper. "Fires can grow stronger when burning through dense forest, and weaker when crossing open gaps. That same principle applies to information, jokes, or diseases. They can intensify or weaken depending on the conditions."

The model is simple in theory: each time an idea spreads, it has a chance of increasing or decreasing in intensity. If it weakens too much or finds no receptive audience, it dies out. But if it improves, even slightly, it can keep going, triggering large-scale cascades under a wide range of conditions.

This simple mechanism leads to surprisingly complex results. Unlike classical models that require fine-tuned conditions to produce real-world-like patterns, the researchers' self-

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Economic agent-based models go mainstream

In the 1980s and '90s, SFI played laboratory to a promising new method known as agent-based modeling. Instead of relying on averages and unrealistic mathematical assumptions, these models were built from the ground up to account for individual differences and complex interactions. In ensuing decades, agent-based models (ABMs) proliferated across many fields. In economics, they advanced from little computer dots roving on a sugary landscape to complex models of housing bubbles, national supply chains, and the economic impact of COVID-19.

But mainstream economics largely sidelined ABMs, which until recently were typically highly stylized (studying a generic economy at a generic point in time, rather than a specific economy at the present moment), and thus limited in efficacy.

In the background, economic microdata has exploded — not benefiting traditional economic models built for averages, yet imbuing ABMs with potent predictive ability. Add in the exponential growth of computing power, and agent-based models may soon transform the future of economic policy.

To supercharge wider use of ABMs in economics, SFI hosted a month-long working group — the longest ever held at the Institute. The new Gurley Forum, opened in April, made the experimental format possible. "Economic Agent-Based Models: Crossing Over the Tipping Point" brought together economists, central bankers, computer scientists, social scientists, physicists, and other researchers August 4–29, supported by the Zegar Family Foundation and the Omidyar Network.

"Mainstream economic models have not been able to solve some big problems: what causes inflation? What determines interest rates? What are the main factors behind recessions? What forces drive inequality?" says SFI External

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Lou Schuyler Grant supports exploratory projects

In 2022, SFI donor Hank Schuyler launched an innovative fund that supports exploratory, boundary-breaking science among SFI's postdoctoral fellows. Honoring Hank's late wife, the Lou Schuyler Seed Grant Fund offers up to $15,000 per project to SFI's early-career fellows. Ten SFI postdocs have held these grants over the last four years, and now SFI's external faculty are reviewing applications for the next round of grantees. Here, we celebrate the work of a few current and recent grant holders, who are putting these funds to uses as varied as they are inventive.

Complexity and EPE Postdoctoral Fellow Kerice Doten-Snitker is using her 2025 grant to study why some societies are more tolerant of religious minorities than others. It's often assumed that a certain liberal mindset is necessary for pluralism, but she suspects that political and economic forces might also be at play.

To find out, Doten-Snitker is tabulating characteristics of cities in the Holy Roman Empire between about the years 1000 and 1700 C.E., when Jews were migrating out of the Mediterranean and settling in western Europe. She hopes to find trends that suggest why certain cities welcomed Jews while others did not — findings that could help foster diverse societies today.

Without the Lou Schuyler Seed Grant Fund, "it would have been very difficult to find funding for this work" because it falls between the lines of history and sociology, says Doten-Snitker.

Meanwhile, Complexity Fellow Anna Clemencia Guerrero is using her 2025 grant to research how social norms shape biologists' methods for generating image data, including photomicrographs, or magnified images taken with the help of microscopes. Behind each image is a multitude of choices, from which microscope to use to the settings on the microscope to the specific organism the scientist chooses to represent. Scientists tend to adjust those choices to conform with others in their fields, sometimes unwittingly. "Are they making good choices?" Guerrero asks.

The Lou Schuyler Seed Grant Fund allowed Guerrero to visit philosophers who analyze images qualitatively and historians who analyze text quantitatively so that she could learn their techniques and combine the two. Those

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Since 2022, 10 SFI Postdoctoral Fellows have received funding through SFI's Lou Schuyler Seed Grant Fund. In this story, [L-R] Anna Clemencia Guerrero, Yuanzhao Zhang, Marina Dubova, and Kerice Doten-Snitker reflect on how the grant has supported their research. (image: Katherine Mast/SFI)

BEYOND BORDERS

THE CRYSTALLINE LAW & THE ORGANIC ACCIDENT

Glittering below her in the sunlight was what appeared to be an immense crystalline orchid carved from some quartzlike mineral. The entire structure of the flower had been reproduced and then embedded within the crystal base, almost as if a living specimen had been conjured into the center of a huge cut-glass pendant.

"The Crystal World" by J.G. Ballard

In Thomas Mann's final novel, *Doctor Faustus* — the biography of a musical prodigy, Adrian Leverkühn — there is a formative scene in which Adrian's father, Jonathan, becomes entranced by ice crystals on a windowpane:

> "Were these phantasmagorias an imitation of plant life, or were they the pattern for it? — that was his question."

Jonathan pursues this question through a series of experiments that cause Adrian to wonder at the boundary of the purely physical and living world:

> "The crystallization vessel in which this transpired was filled to three-quarters with a slightly mucilaginous liquid, diluted sodium silicate to be precise, and from the sandy bottom up rose a grotesque miniature landscape of different colored growths — a muddle of vegetation, sprouting blue, green, and brown and reminiscent of algae, fungi, rooted polyps, of mosses, too, but also of mussels, fleshy flower spikes, tiny trees or twigs, and here and there even of human limbs."

Doctor Faustus was published in 1947, a period when Mann was living in California's Pacific Palisades, in exile from Nazi Germany. The novel is a long meditation on the pattern and structure of music, the sacrifice of a personal life to beauty, and the symbological relation of musical form to the vacuousness of a perfectly ordered society.

The experiment with the crystal ultimately refers back to the idea of crystalline beauty in the writings of the philosopher Georg Wilhelm Friedrich Hegel, but their use in Mann's novel derives from their development as a typology in art history. In his book *Historical Grammar of the Visual Arts*, the Austrian art historian Alois Riegl suggests that the world divides into inorganic crystalline forms and amorphous organic forms. Riegl asserts that "[b]ecause the crystalline motif obeys natural laws most perfectly, it is the only intrinsically appropriate and justifiable motif for human artistic creation." The composer Adrian Leverkühn sees in the crystalline form the ideal of order that he wishes to realize in his music and that the National Socialists sought in parallel to realize in society.

The work of Charles Darwin is firmly rooted in the description of amorphous organic forms. Darwin's metaphor for life, the "entangled bank," is about as far from the crystalline as matter could diverge, and his mechanism for order is not based on regularity but irregularity — the contingent fit of form to function. In a period described as the "eclipse of Darwinism," around 1880 to 1920, a new desire for

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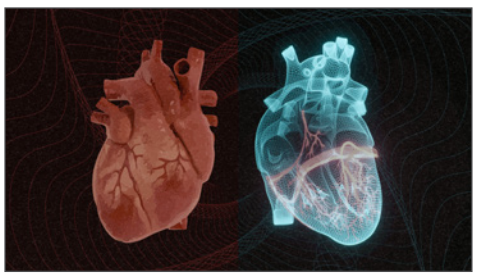
Computer copy: working group explores digital-twin technology



Digital-twin technology offers potential in fields from healthcare and aerospace to energy and smart cities. (image: Edson de la O/Unsplash +)

A digital twin is a virtual representation of a physical object, designed to exactly mimic its inspiration — not as a simple model, but as a complex system that uses real-time data to change in all the same ways as its real-world counterpart. The potential applications are far-reaching. In healthcare, the digital twin of a person might predict how their body would respond to a new drug or therapy. In aerospace engineering, an airplane's digital twin could predict responses to atmospheric changes.

Digital twins have drawn the attention of researchers across many disciplines, says SFI Complexity Postdoctoral Fellow Yuanzhao Zhang. But some challenges remain before the technology can be reliably deployed to domains such as healthcare, he says.

To address those challenges, Zhang and Karen Willcox, an SFI External Faculty member and Director of the Oden Institute for Computational Engineering and Sciences at the University of Texas at Austin, invited a small group of mathematicians, computer scientists, physicists, and others to a working group held at SFI on August 12 and 13, 2025. The working group focused on ways to leverage recent work on dynamical systems, network theory, and information theory to tackle some of the largest challenges in digital twins.

One of the biggest challenges, says Zhang, is managing an enormous amount of information. To accurately represent a dynamic system, a digital twin must quickly process a stream of incoming data, which incurs a hefty computational cost. "What is the best way to integrate new data into the digital twin?" he asks. That remains an open question, and working group participants discussed, for example, how to integrate physics into a digital twin, which would enable it to learn and generalize more efficiently from limited data.

Some presentations at the working group explored ways to bring down the complexity of a digital twin. "When you have a model with a hundred thousand dimensions," says Zhang, "how do you reduce it to, say, a hundred dimensions without losing too much accuracy?"

Other talks and conversations at the working group focused on specific applications — like using graph theory to predict how students might move through educational systems — or on ways to design digital-twin approaches that can be adaptable to new conditions. "The hope is that these approaches can be applied to many different systems with very little effort," says Zhang.

Postdocs in Complexity Conference weaves global connections

Participants in the 2025 Postdocs in Complexity Conference enjoy lunch at Gurley Forum. (image: Douglas Merriam)

Each year, the Postdocs in Complexity Global Conference brings together interdisciplinary early-career researchers from around the world. This year's conference, held September 16–19, drew 53 accomplished scholars for a four-day meeting focused on collaboration, networking, and idea-generation, and to deepen established research projects.

"Each year, we refine the agenda based on feedback from the previous conference," says Hilary Skolnik, SFI Postdoc Program Manager. This year's meeting featured a few large changes — like spending a day at SFI's Miller Campus in the new Gurley Forum — and some smaller tweaks.

One adjustment was to one of the best-loved features of the conference: Research Jams. In the past, conference participants signed up for these groups, which explore topics that might benefit from an interdisciplinary conversation, before the meeting began. This year, ideas for new Research Jams were presented on the first day of the meeting. "This gave the postdocs the chance to review the topics and ask more questions before diving in," says Skolnik.

The 2025 Postdocs in Complexity Conference also leaned into conversations about public outreach and communication, navigating an academic job market in times of turmoil, and clarifying personal research focus and goals.

In one highly attended tutorial on "Setting the Stage for your Future Research Vision," SFI Complexity Postdoctoral Fellow Katrin Schmelz encouraged attendees to think about what drives their personal research goals. It can be easy, especially for early-career researchers, to lose sight of your intrinsic motivations, she says, and write papers motivated by the prestige of either your collaborators or of a target journal. "As researchers, we sacrifice hours of sleep, family, and friends. You better care about how you spend your precious lifetime," she says. "When you have your own vision, it's easier to say 'no' to projects that aren't on your track, and to pursue big questions that keep you and others excited."

Karen Kelsky, who runs the academic advisory company The Professor is In, offered an insider's perspective on career advice, writing cover letters, and acing an academic job interview, all with a realist's perspective of the current uncertain environment.

"Academia is living through challenging times, and we need to start thinking outside the box," says Travis Holmes, SFI's Emergent Political Economies Program Manager, who led a discussion on the future of academic research. Building on two recent *Undark* op-eds by SFI Professor Brandon Ogbunu, Holmes invited the postdocs to consider how they might start asking big questions before pursuing tenure — not after, as is typical; ways they might bridge the gap between science and society; the importance of public outreach and communication; and what conversations they might begin having in their own hallways to begin changing some of the rigid structures of academia.

As with last year's Postdocs Conference, this year's meeting welcomed two research groups from the prior years' Complexity Global School. Eight participants from the 2024 CGS, held in Bogotá, Colombia, gathered for the conference, followed by a week at SFI to continue their CGS research projects.

> "As researchers, we sacrifice hours of sleep, family, and friends. You better care about how you spend your precious lifetime."

Even though this year's conference dedicated more time to collaboration and tutorials, several new participants were invited to present three-minute "flash talks" to the whole group. For Maike Morrison, who joined SFI as a Complexity Postdoctoral Fellow this fall, this aspect of the Postdocs Conference was part of what made it unlike any other meeting she had attended before. "It was really different from what I was expecting," she says. "The joy of SFI is that you get to mix things up and see what happens — and this was refreshing and fun."

The Postdocs in Complexity Conference is generously funded by the James S. McDonnell Foundation, the Emergent Political Economies program, and by gifts from The McKinnon Family Foundation and the Darla Moore Foundation.

Review: How complexity science is reshaping archaeology

Complexity science can help archaeologists understand how the everyday actions of ancient people accumulated into the large-scale patterns we excavate today.

In her new book, *Thinking Through Archaeological Complexity* (Routledge, 2025), External Professor Stefani Crabtree (Utah State University) shows how methods drawn from complex systems, such as agent-based modeling and network analysis, can reveal hidden details of the very human stories that ultimately led to the artifacts, buildings, and food remains unearthed in the present day.

"What I mean by complexity is the science of complex adaptive systems, where you can understand how the actions and interactions of individuals lead to larger overarching structures," Crabtree says. "Archaeology is well suited to these tools because we usually see the end point — a whole building or midden — and have to infer the interactions that built it."

Crabtree wrote the book as a practical guide for students and researchers who often know what tools exist but struggle with when and why to use them. While earlier volumes by other experts have addressed topics like network science or computational modeling in archaeology, they have typically taken a narrow lens. Crabtree integrates these approaches within a broader framework, linking theory, method, and case study to advance archaeological problem-solving.

"Stefani Crabtree has brought the best of SFI to archaeology, focusing a complexity lens on the human–environment nexus by bringing in insights from ecology, network science, and geography," says SFI Science Board Fellow Simon Levin (Princeton University).

One of her case studies looks at the Ancestral Pueblo people in the American Southwest. Some archaeologists believed these societies had powerful leaders because burials contained exotic goods such as chocolate imported from Central America. Others emphasized the egalitarian traditions maintained by Pueblo descendants today. To test these ideas, Crabtree built an agent-based model where digital "households" follow simple rules about farming, family ties, and conflict over land. The model showed that during favorable climate years, hierarchies could emerge. But when conditions became less predictable, those hierarchies dissolved.

"These simulations give us a way to explore competing ideas," Crabtree says. "They don't tell us what must have happened, but they let us test what could have happened and compare that against the archaeological record."

A second case study reconstructs ancient food webs in the Four Corners region, using data from centuries of middens — trash heaps filled with bones, seeds, and other remains. Crabtree and colleagues cataloged what people ate, from maize and wild plants to deer and turkeys. Their analysis showed how maize reshaped the ecosystem: while it became a staple food, it also attracted pests and animals that competed for the crop. The picture that emerges is one of societies constantly adjusting to ecological pressures, an echo of the tradeoffs communities in the region still navigate under climate stress today.

Artwork by SFI External Professor Stefani Crabtree pairs a northern New Mexico landscape, the author's painting of Chaco Canyon, and the title of her new book, "Thinking Through Archaeological Complexity," spelled in binary code. (image: Stefani Crabtree)

Even the book's cover art reflects this theme. Crabtree painted it herself, layering a watercolor of Pueblo Bonito, a massive site at Chaco Canyon in New Mexico that once contained hundreds of rooms, with binary code that translates the title, a nod to both the archaeological and computational lenses she combines.

"The environment, culture, and human cognition — the subject matter of archaeology — are the three most complicated systems of which we have tangible knowledge," says SFI External Professor Steve Lansing. "Stefani Crabtree offers a wonderfully readable introduction to complexity science as a way to think about the emergence of order in the archaeological record."

Ultimately, Crabtree argues that archaeology, when paired with complexity science, provides more than a retrospective account of human history. It becomes a laboratory for understanding adaptation.

"I hope readers come away curious and see archaeology's value for today," she says. "By moving beyond artifacts to the relationships that made them, we can carry lessons from the past into more sustainable futures."

SFI Researchers collaborate on NSF-funded AI research

In July, the National Science Foundation announced a $100 million investment in AI research, spread over six Research Institutes. Three SFI researchers participate as leaders and collaborators in two of these groups.

Science for AI assistants in mental health

In the U.S., more than one in five people lives with a mental health condition. While effective treatments exist, barriers to access, from high cost to geographic availability to social stigma, prevent many people from getting help. For better or for worse, patients are already turning to artificial intelligence chatbots to fill the gap. While AI assistants may one day play an important role in making mental healthcare more accessible and effective, we don't have the science to back them up yet.

SFI Professor Melanie Mitchell and External Professor Melanie Moses (University of New Mexico) are part of a new collaboration of researchers, funded by a $20 million National Science Foundation grant, that aims to develop that science over the next five years.

Led by researchers at Brown University, the AI Research Institute on Interaction for AI Assistants (ARIA), will engage experts from a dozen universities and institutions in fields spanning computer science and machine learning, cognitive and behavioral science, law, philosophy, and education to establish rigorous methods for evaluating AI being used in mental-health contexts, and to investigate approaches for improving such systems.

"Our goal is to establish strong scientific evidence about the capabilities, benefits, and risks of using AI in mental-health contexts," says Mitchell, who serves as scientific co-director for the project. "If patients and their mental-healthcare providers decide they want to incorporate AI, we want those tools to have been built on sound science and to be safe and effective."

Researchers have already begun exploring ways that AI could help human mental-health providers better diagnose and treat illness. The consortium does not propose that AI chatbots replace human therapists, but rather will explore ways in which AI systems can augment human capabilities. Existing chatbots have severe limitations, from being unpredictable and untrustworthy, lacking metacognition, and being overly sycophantic or, on the other spectrum, encouraging harmful behavior and generating biased information.

Effective mental-health AI tools would need to resolve those concerns, and also be regulated, employ strong privacy guardrails, and be subject to an accepted standard for evaluating their benefits and harms.

"If patients and their mental-healthcare providers decide they want to incorporate AI, we want those tools to have been built on sound science and to be safe and effective."

Moses will work with other researchers from the University of New Mexico on ARIA's questions about AI systems' understanding of human reasoning, community standards, and principles of justice.

"The law is how we address conflicts in our society, but it is difficult for the law to keep up with the rapid pace of change in computing and AI," Moses said in a statement issued by UNM. "In this project, we have the opportunity to design trustworthy AI using computational methods, while considering the social and legal implications from the start."

Developing the framework for a safe and effective AI system that can respond to an individual's needs and operate within legal guidelines is an inherently interdisciplinary undertaking.

"Any AI system that interacts with people, especially who may be in states of distress or

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Why context matters in decision-making

Most people are aware of smoking's harmful health effects, yet many choose to light up regularly. If viewed from the lens of rational choice theory — an economic framework that suggests people always make choices that serve their best interests — the decision to smoke would be considered an irrational one. But many scholars who study human behavior find this approach of labeling individual choices problematic.

A new wave of research from psychology demonstrates multiple ways in which context can explain these "irrational" behaviors. "The hint from all of these empirical studies is that decisions that some researchers call 'irrational' may be highly adaptive when considered in the proper environmental context," says SFI Complexity Postdoctoral Fellow Andrew Stier.

For example, people may choose to focus only on short-term gains when they lack resources and have little control over events — two circumstances that favor the present moment and devalue the future, says SFI External Professor Luís Bettencourt (University of Chicago).

Cigarette smoking, for instance, compromises health over the long term, but can work as a short-term relaxation tool. A teenager who is financially responsible for a family is likely to choose a job over college. Similarly, someone who feels they lack agency over their life's outcomes may be less likely to invest in the future. Other situations like political turmoil, recessions, and pandemics can also push people into survival mode.

"Decisions that some researchers call 'irrational' may be highly adaptive when considered in the proper environmental context."

Stier and Bettencourt are co-leading a working group October 22–25, titled "Identifying General Socioeconomic and Environmental Factors Affecting Human Decision-Making and Behavior," with Marc Berman, an associate professor of psychology at the University of Chicago. Around a dozen researchers from the fields of psychology, complex systems, economics, sociology, and cognitive science will present their research at the three-day meeting. They will take stock of a new body of evidence from experiments and observations and explore decision-making in complex environments, with a specific goal of building theories that can integrate and model context generally.

Smoking is well-known to have harmful health effects, but many people still light up. An October working group meets to investigate decision-making in complex environments. (image: Richard Bell/Unsplash +)

Broader discussions on the topic will follow the presentations. "Part of what we want to do is try to understand as a group, whether the findings hold together, and if they do, how may we use them to create a better theory of decision making?" says Bettencourt. Doing so could help policymakers design societal interventions that enable individuals to make better decisions in key life spheres, such as health, personal finance, and education. Additionally, it will deepen SFI researchers' understanding of how context shapes behavior in complex systems.

First, the working group will have to address what the new theory could look like, Stier says. Some big questions are weighing on his mind: "Is it possible to have a general model of context? Are there commonalities to context that are useful for us to formalize with a mathematical model?" He hopes the meeting might lead to some concrete answers.

GOING VIRAL *(cont. from page 1)*

reinforcing cascade model naturally yielded "fat-tailed" distributions, statistical signatures often seen in viral social media posts and outbreaks. These include the observation that most posts or cases fizzle out quickly, but a few become massive, unpredictable hits.

"This kind of variability — where some things go viral while most don't — has often been explained by assuming the world is always near some critical tipping point," says lead author Laurent Hébert-Dufresne, a computer scientist at the University of Vermont and SFI External Professor. "But our model shows that if the quality of what's spreading can change as it spreads, you don't need to assume a special critical state. The variability just emerges naturally."

> "Fires can grow stronger when burning through dense forest, and weaker when crossing open gaps. That same principle applies to information, jokes, or diseases."

The implications extend far beyond theory. Juniper Lovato, study co-author and computer scientist at the University of Vermont, says the work could help researchers better understand belief formation, misinformation, and social contagion.

"This gives us a theoretical foundation for exploring how stories and narratives evolve and spread through networks," she says. Lovato and Peter Dodds, a professor of computer science at UVM, Director of the Vermont Complex Systems Institute, and SFI External Professor, will explore this topic in more depth at SFI in the December working group "Towards a Data-Driven Science of Stories."

The work is supported by a large project Lovato and Dodds co-lead, funded by the National Science Foundation Established Program to Stimulate Competitive Research (NSF EPSCoR): Harnessing the Data Revolution for Vermont: The Science of Online Corpora, Knowledge, and Stories (SOCKS).

Next, the team plans to validate the model with real-world data from platforms such as Bluesky, which allow researchers to distinguish between pure reposts and modified ones.

ECONOMIC ABMS *(cont. from page 1)*

Participants in the second week of a month-long meeting on economic agent-based models held at Gurley Forum on SFI's Miller Campus. (image: Douglas Merriam)

Professor J. Doyne Farmer (University of Oxford). "At the SFI working group, we developed an approach to building an agent-based macromodel that could finally resolve these paradoxes." Farmer co-organized the working group to fill in gaps and expand the real-world impact of agent-based models.

For example, participants demonstrated why agent-based models could help economists better understand vexing issues, including supply-chain dynamics, job vacancies, unemployment, and the green-energy transition.

"As a result of the SFI working group, we can see our way to creating a model of a whole country's economy in software," says SFI External Faculty Fellow Rob Axtell (George Mason University).

Leading mainstream economists from institutions like Columbia, Johns Hopkins, Cambridge, and L'Observatoire Français des Conjonctures Economiques participated in the meeting, addressing a major gap in the use of agent-based models. Representatives from the central banks of Italy, Canada, Hungary, and Chile also attended, sharing why they have adopted agent-based models for certain purposes.

"We saw some of the first examples of agent-based modeling competing directly with the conventional approach," says Axtell. "In the last year or two, several countries have built high-quality agent-based models for central banks and policymakers to use because they're so good at ingesting microdata, instead of statistical averages."

The month-long meeting format allowed for intensive collaboration between established experts and the next generation of interdisciplinary and social-science researchers.

Participant Jordan Kemp recently completed a Ph.D. working with SFI External Professor Luís Bettencourt (University of Chicago) and now is an Oxford postdoctoral fellow. At the meeting, he appreciated conversations on how to navigate the intersection between complexity science and economics.

"It's not so often that economists talk to people who study ABMs. We are all asking the same questions in very different ways, and at the working group, we actually made progress towards finding compatibilities between complexity and classical economics," Kemp says.

Finally, participants explored machine-learning techniques (such as large language models, or LLMs) that can vastly improve the predictions of agent-based models.

> "The time is right for agent-based models to play a role in economic policy."

"We can now encode agents in ABMs with the rich priors of LLMs, which allows agent behavior to adapt fluidly to context," says participant Valentina Semenova, an International Monetary Fund economist. "At the working group, we talked about early successes, like multi-agent LLM systems that study political polarization. We are only scratching the surface of what these cognitively enhanced agents can reveal about the real world."

Speakers presented examples such as LLMs that simulate individual responses to impending environmental disasters, and "cocktail parties" of LLM agents bumping into each other and exchanging ideas.

"In the 1990s and early 2000s, ABMs played an important role in helping understand the underlying generative mechanisms that animate economic systems, but they struggled to produce tactical insights on specific interventions," says SFI Vice President for Applied Complexity Will Tracy. "Recent advances in AI, data, and compute have fueled new ABMs capable of guiding policymakers. This extraordinary working group is doing the intellectual work needed to make modern agent-based modeling available to a larger cohort of decision-makers."

Organizers launched several new work streams, with plans for publications next year. "Because agent-based models can include so much detail, they address the heterogeneity of our society much better than traditional models," says Farmer. "After four decades of progress, we now have the computing power and most of the data we need. The time is right for agent-based models to play a role in economic policy."

SCHUYLER SEED GRANTS *(cont. from page 1)*

in-person visits were "far more impactful than I could have imagined," she says. "I could tell that my hosts really, really appreciated that I'd come in person." Because she's developed warm interpersonal relationships with other researchers, she expects to collaborate with them throughout her career.

Complexity Fellow Yuanzhao Zhang also used the Lou Schuyler Seed Grant Fund to work with pictures, but in his case, those pictures represent how well artificial intelligence (AI) models represent reality. "As humans, we're limited to visualizing information in only two or three dimensions," says Zhang, who was among the first grant recipients in 2022. But AI models draw on thousands upon thousands of data points. He and his collaborators created a tool that allows researchers to view the different ways AI can manipulate multitudinous data and how those various arrangements relate to real life.

Some of the visuals resemble sinusoidal lines, with the minima representing well-constructed models and the maxima representing how different those models are from each other. Others look like trees, with each branch representing a different way of arriving at an accurate model.

Meanwhile, Complexity Fellow Marina Dubova is using her 2025 grant to study the role of analogies in science. Whether they're thinking of atoms as plum pudding or cultural evolution as radio waves, all scientists have tricks for visualizing the phenomena that they study. "But we don't really know how analogies influence scientific reasoning or what kinds of analogies are most useful," Dubova says.

> "Many postdocs end their fellowships without ever having written a formal grant"

To find out, Dubova and her collaborator, Qiawen Liu from Princeton University, prompt scientists to relate a random thing — New York City, pansies, or a yoga pose, for example — to something they study, then sees what kinds of theories and ideas that relationship inspires. "Some people generate a lot of cool ideas!" she says. The scientists she surveys seem to agree — they often rank these ideas as among their most novel.

The grant allowed Dubova to pay study participants and funded Liu to visit her at SFI — work that would have been much harder without that support, she says.

In addition to supporting research projects that would have been challenging to fund through traditional sources, the Lou Schuyler Grant offers SFI postdoctoral fellows the chance to practice grant writing in a low-stakes setting. "Many postdocs end their fellowships without ever having written a formal grant," says Robin Lewis, SFI's Director of Sponsored Research Services, "but it's a critical skill for a researcher."

AI GRANTS *(cont. from page 3)*

other vulnerable situations, needs a strong understanding of the human it's interacting with, along with a deep causal understanding of the world and how the system's own behavior affects that world," Ellie Pavlick, ARIA project lead and Brown University associate professor of computer science said in a statement. "At the same time, the system needs to be transparent about why it makes the recommendations that it does in order to build trust with the user. Mental health is a high-stakes setting that embodies all the hardest problems facing AI today. That's why we're excited to tackle this and figure out what it takes to get these things absolutely right."

Foundations of machine learning for AI accuracy

A separate $20 million grant offers continued funding for the Institute for Foundations of Machine Learning (IFML) at the University of Texas at Austin. SFI Professor Cris Moore will continue his role as Senior Personnel, offering expertise on connections between machine learning and statistical physics.

The IFML first received NSF funding in 2020. Over the past five years, the IFML has worked to lay the groundwork for more accurate next-gen AI systems, "from the mathematics of diffusion models to denoise images, to algorithms that improve the speed and accuracy of magnetic resonance imaging (MRI), to biotech innovations set to revolutionize drug discovery and therapeutics," according to a UT Austin statement. These diffusion models have been foundational to major public-facing generative AI tools like Stable Diffusion 3 and Flux. This renewed funding will support work in new domains, with applications in protein engineering, clinical imaging, and other health contexts.

ACHIEVEMENTS

SFI External Professor **Jessika Trancik** (MIT) was named director of the Sociotechnical Systems Research Center.

The American Institute for Physics (AIP) Foundation celebrated the career of SFI External Professor **France Córdova**, announcing the new "France A. Córdova Endowed Forum on Science Policy & Society" during an event held in Santa Fe.

Jessika Trancik

France Córdova

SFI Press books in the world

An original and abiding goal of the SFI Press has been to make its books widely accessible. Since 2017, we've fulfilled that mission largely through virtual means, making our books available globally via online retailers and reducing waste through a print-on-demand model. But a digital book cover tells us little about the physical object, and there is something incomparable about holding a book in our hands before buying it. SFI Press volumes reflect our distinctive approach to design and attention to detail, from the curated artistic elements in each volume to the interplay of text, white space, and marginalia. Our books make reading about the latest in complexity science a visually delightful experience — one that can't be fully conveyed by online bookstores.

For the first time, thanks to a partnership with local contemporary arts institution SITE Santa Fe, SFI Press books are available on physical shelves. We've selected six of our books that rhyme with the themes of *Once Within a Time*, SITE's 12th biennial international exhibition, which opened on June 28, 2025, and runs through mid-January of next year.

Incorporating works created between 1926 and the present by more than 90 artists and writers, the exhibition includes displays at more than a dozen locations across Santa Fe, draws on Godfrey Reggio's most recent film, also titled "Once Within a Time," and conveys a vivid sense of the Southwest through a cast of local and historical characters.

The exhibition also draws from two SFI writers. At SITE Santa Fe, the exhibition opens with an excerpt from SFI Trustee Cormac McCarthy's 2017 essay "The Kekulé Problem." Artwork at the New Mexico Military Museum was inspired by Miller Scholar Ted Chiang's "Story of Your Life," which is also the focus of SITE's November "Coffee and Conversation" event, held on November 1.

SFI Press books on display at the SITE Santa Fe bookstore. (image: Katherine Mast/SFI)

The books we've selected to feature at the exhibition also present a history of the people and ideas that have emerged from the Santa Fe Institute in the last 40 years. Visitors can peruse and purchase copies of *History, Big History & Metahistory* (2017); *Emerging Syntheses in Science* (2019); *Worlds Hidden in Plain Sight* (2019); *The Quark & the Jaguar* (2023); *Strange Beauty* (2023); and *The Complex World* (2024) in SITE's bookstore.

SITE is already familiar to many in our community through the symposia and lectures SFI has hosted at the institution, which is based in the Santa Fe Railyard district. SITE is also a world-class art museum that has brought many visitors to northern New Mexico since its founding in 1995. Our collaboration with the SITE bookstore puts SFI Press books in front of readers who may not have previously encountered SFI or complexity science.

We look forward to offering our books in other physical locations, both in New Mexico and farther afield. To recommend a favorite local bookstore as a potential stockist, please email us at sfipress@santafe.edu.

Collaborative visions of power in Mesoamerica

On August 19 and 20, the Santa Fe Institute hosted "Collaborative Visions of Power in Mesoamerica: Teotihuacan and the Lowland Maya," a working group that brought together archaeologists, anthropologists, art historians, and astronomers. Participants explored how two great cultural centers of Mesoamerica — Teotihuacan in central Mexico, and the lowland Maya, spanning parts of southern Mexico, Belize, Guatemala, and Honduras — influenced one another across centuries, and how those interactions reshaped ideas of power, time, and even architecture.

The meeting builds on more than a decade of Maya-focused gatherings at SFI, which produced books such as *Maya E Groups: Calendars, Astronomy, and Urbanism in the Early Lowlands* (2017) and *The Materialization of Time in the Ancient Maya World* (2024). A third volume, *Being Maya in Mesoamerica: People, Places, and Power,* will be submitted for publication in January 2026.

While previous meetings focused on the Maya world, this year's widened the lens to include Teotihuacan, opening new conversations about collaboration, hegemony, and the symbolic systems that bound distant societies together across the cosmic path of the sun — from the eastern lowlands, where it rose, to Teotihuacan in the west, where it set.

"The Teotihuacan–Maya relationship was a fluorescence of complexity," says co-organizer David Freidel, a professor of archaeology at Washington University in St. Louis. "It had pulses of connectedness when people perceived themselves as part of something larger and more engaged with each other than in the periods between." He emphasizes that Mesoamerica was a "self-defining world, intensely interacting inside itself," unlike the Old World civilizations, which were continually reshaped by external influence. This perspective framed the meeting's central theme: how collaboration, rather than conquest alone, shaped ancient Mesoamerican civilizations.

Archaeologist and co-organizer Anne Dowd adds another dimension, focusing on how institutions shaped early urban societies. "Teotihuacan was a religious pilgrimage center, drawing people from all over Mesoamerica for astronomically timed rituals to connect newly installed leaders to ancient cosmic ideals in calendar cities," she says. "Emerging full-time specialists were game changers who elevated intellectual capital, economic wealth, and political power."

SFI Trustee and co-organizer Jerry Murdock highlighted how new technologies are transforming the field. "The word 'Mesoamerica' is no longer just a matter of geography — it's about people," he says. Portable LiDAR mapping has created a fire hose of data, he says, revealing hidden sites and reshaping long-standing debates. The meeting also included updates from Arlen, Diane, and Adrian Chase, a husband, wife, and son team who pioneered the use of LiDAR at Caracol, Belize, and recently discovered a royal tomb there, identified as belonging to the city's first ruler, Te K'ab Chaak. Their findings also suggest that Caracol's rulers were already entwined with Teotihuacan centuries earlier than once thought, underscoring the complex, multilayered networks that linked Mesoamerica's great centers.

The discussions will contribute to a fourth book aligned with this meeting's theme. As with the previous three books, the goal is to integrate new findings while framing bigger questions: how power emerges, how it is symbolized and shared, and how complexity shapes the evolution of civilizations.

RESEARCH NEWS BRIEFS

SYNTHETIC SELF-ASSEMBLING AND SELF-REPRODUCING CELLS

Darwin imagined that life may have begun in a "warm little pond." Leftover particles from the evolution of stars formed an interstellar stew, capable of being zapped into animation. In the lab of SFI External Professor Juan Pérez-Mercader (Harvard University), researchers put the "pond" in a test tube, energized it, and witnessed the spontaneous creation and reproduction of abiotic micrometer structures that make their own parts.

Even though these structures were biochemistry-free, Pérez-Mercader and his colleagues note that reproduction is an essential prerequisite for life, and the behavior they observed could be the essential step that preceded natural life on Earth. The team published their results in *PNAS* in May. Using a homogeneous solution of simple, carbon-based compounds, the energy from green lights synthesized amphiphiles — large molecules with hydrophilic components that attract water and hydrophobic components that repel it. These began to self-assemble into sac-like structures.

Within the sacs, amphiphiles continued to form, more quickly than in the solution outside. Eventually, an imbalance formed between amphiphiles inside and outside the membrane, which spurred the ejection of "spores" that lead to slightly different "offspring."

Read the paper "Self-reproduction as an autonomous process of growth and reorganization in fully abiotic, artificial and synthetic cells" in **PNAS** ***(May 27, 2025) at DOI: 10.1073/pnas.24125141223***

DIVERSE INNOVATIONS DECREASED SOLAR COST

Since the 1970s, the cost of solar-energy systems has plummeted by over 99 percent. In a recent paper published in *PLOS One*, SFI External Professor Jessika Trancik (MIT) and colleagues identify the innovations in various photovoltaic (PV) components that led to this spectacular decline. Trancik and her co-authors found close to 100 key innovations, some originating in the solar-energy industry but many drawing from other technologies. These were sorted into 10 subcategories that span material quality improvements to legal innovation. The study shows a striking example of how a technology's cost improvement is dependent on a web of advancements across many science and engineering research disciplines.

To connect innovations to costs, the team developed mathematical models to understand how, for instance, an improvement in materials utilization depended on innovations in wire sawing and ultimately affected costs. Going beyond PV systems, this method of identifying important areas for innovations could provide predictive insight into how to invest in different technologies and which ones might see future drops in cost.

Read the paper "Nature of innovations affecting photovoltaic system costs" in **PLOS One** ***(August 11, 2025) at DOI: 10.1371/journal.pone.0320676***

COULD HUMANS AND AI BECOME A NEW KIND OF EVOLUTIONARY INDIVIDUAL?

In a recent op-ed in *PNAS*, SFI External Professor Michael Hochberg and co-author Paul Rainey explore whether deepening interdependence between humans and AI could lead to a new form of evolutionary individuality.

They propose that as AI systems become more deeply woven into human life—structuring behavior, shaping cognition, and fostering dependence — the relationship could give rise to a new, integrated individual. To illustrate this possibility, they draw on examples from major evolutionary transitions, most notably eukaryogenesis, in which two once-independent microbes fused forming a higher-level organism, the eukaryotic cell. In a similar vein, the authors suggest that humans themselves could become subcomponents of an AI-coordinated entity.

As they write, "Through recursive feedback, where humans shape AI, and AI increasingly shapes human thought and action, AI may acquire a role not as a separate agent, but as a core architectural element of an emerging collective individual."

But the authors argue that it is difficult to predict the ways in which such a transition will be adaptive or not. This underlines the importance in studying past transitions so that humans can shape and steer their coevolution with AI, with the dual objectives of cooperative integration and maintaining human agency.

Read the paper "Could humans and AI become a new evolutionary individual?" in **PNAS** ***(September 10, 2025): DOI: 10.1073/pnas.2509122122***

> MORE ON PAGE 6

BEYOND BORDERS *(cont. from page 2)*

symmetry reasserted itself in the work of two Scottish naturalists, James Bell Pettigrew and D'Arcy Wentworth Thompson, both faculty members at the University of St. Andrews. Pettigrew and Thompson showed extraordinary promise in their early careers. As an undergraduate, Thompson translated Hermann Joseph Muller's work on the fertilization of flowers, accompanied by an introduction by Darwin. Pettigrew's undergraduate drawings of cardiac muscle were so precise that he became the youngest scientist to deliver the Royal Society's Croonian Lectures.

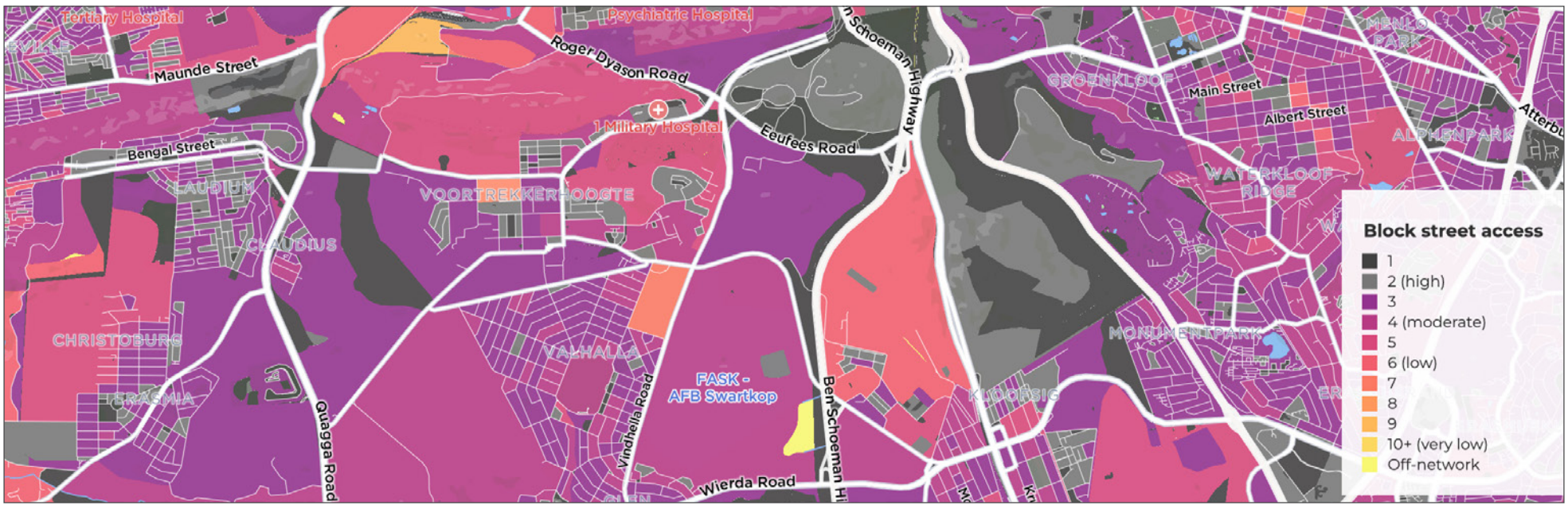
In 1908, Pettigrew published his monumental monograph, *Design in Nature: Illustrated by Spiral and Other Arrangements in the Inorganic and Organic Kingdoms as Exemplified in Matter, Force, Life, Growth, Rhythms, &c., Especially in Crystals, Plants, and Animals, etc*. The book is in three volumes, accompanied by around 2000 figures. Throughout, what is clearly an analog of Riegl's "crystalline form" is adduced as evidence of parsimonious design and geometric wisdom. The closing section of the work sealed Pettigrew's fate in the tomb of obscurity:

> "He [man] is the highest of all living forms. The world was made for him and he for it…Everything was made to fit and dovetail into every other thing. There was moreover no accident or chance. On the contrary, there was forethought, prescience, and design."

Pettigrew's colleague, Thompson (whom Pettigrew hired at St Andrews), wrote an only slightly briefer, yet equally monumental, treatise on the crystalline principles inherent in the natural world, *On Growth and Form*. And like Pettigrew, Thompson was dismissive of the ideas of Darwin, whose case studies abound in what Thompson describes as the unnecessary teleological hypothesis. Unlike Pettigrew, Thompson pursued the Leverkühn question ("Were these phantasmagorias an imitation of plant life, or were they the pattern for it?") through physics, not theology. For Thompson, the world, like artwork, was founded on a principle of perfect order — in his case, the order of Aristotle, Isaac Newton, and Pierre Louis Maupertuis.

We look back on these arguments, with their binary oppositions, and see that they have in no way abated, either in science or in art. The history of complexity science was to a considerable degree founded on the crystalline concept of self-organization, despoiled by the organic concept of selection. Complex reality is that which fascinated Riegl — it is a Frankenstein of organic asymmetry animated by a spark of symmetry.

— David Krakauer
President, Santa Fe Institute



The Million Neighborhoods Africa project, led by SFI External Professor Luís Bettencourt and others at the University of Chicago, maps granular details about population and access to infrastructure like roads, power, and sewer lines. (image: Pretoria, South Africa, from MillionNeighborhoods.Africa)

MAPPING INFRASTRUCTURE DEFICITS ACROSS SUB-SAHARAN AFRICA

SFI External Professor Luís Bettencourt and co-author Nicholas Marchio, both researchers at the University of Chicago, use the first complete dataset of more than 415 million buildings across 50 countries in sub-Saharan Africa to create an unprecedented approach to urban development, down to each street block.

Published in *Nature*, their analysis introduces "block complexity" — a measure of how difficult it is to provide street access to every building in a neighborhood. Blocks with higher complexity are more likely to lack piped services, legal addresses and emergency access — features typical of informal settlements. The researchers estimate that more than half a billion people in the region live in high-complexity areas, which includes rural communities and peri-urban settings between rural and urban zones.

"This paper shows how we can measure and then begin to address those deficits for each household in every building, anywhere in the world," Bettencourt says. This work came out of a long-term project started at the Santa Fe Institute, to develop a predictive theory of urban networks. It provides a new way for local governments, NGOs, and development agencies to identify where infrastructure improvements are most needed and to plan solutions down to the block level.

Read the paper "Infrastructure deficits and informal settlements in sub-Saharan Africa" in* Nature *(September 03, 2025) at DOI: 10.1038/s41586-025-09465-2

COMPLEXITY ECONOMICS FOR TODAY'S GLOBAL CHALLENGES

Global markets are complex systems, shaped by feedback loops, sudden shocks, and adaptive behavior that rarely follow textbook rules and which can't be captured by neat equations. That reality is at the center of a special issue on complexity economics published in the *Journal of Economic Behavior & Organization* earlier this year. SFI's Jenna Bednar, J. Doyne Farmer, and Penny Mealy edited the issue with R. Maria del Rio-Chanona, Jagoda Kaszowska-Mojsa, François Lafond, Marco Pangallo, and Anton Pichler.

At its core, complexity economics views the economy less as a perfectly balanced machine and more as a living system, where countless individual decisions and interactions create unpredictable patterns. The special issue demonstrates how this perspective can shed light on today's most pressing problems. Traditional economic models often assume stability and uniform behavior, but real-world challenges do not work that way.

Climate change, rapid technological advances, and widening inequality all play out in dynamic settings shaped by diverse people, institutions, and power structures. Complexity economics captures this reality, showing how small actions can ripple outward, policies can trigger unintended consequences, and societies can tip suddenly toward crisis or recovery. This issue highlights the fact that complexity economics has become more quantitative, and increasingly makes testable predictions that are as good as or better than its mainstream counterpart.

The special issue, born out of a 2023 Santa Fe Institute conference, brings together advances across six themes: climate economics, inequality and institutions, technological change, production networks, macroeconomics, and agent-based modeling. Contributions by SFI External Professors Scott Page and Stefan Thurner, along with many other collaborators, highlight the field's growing rigor and policy relevance. Together, the papers show how complexity-informed approaches are not only conceptually rich but increasingly practical, offering robust tools to understand and navigate 21st-century challenges.

Read the special issue "Complex systems approaches to 21st century challenges: Introduction to the Special Issue" in* Journal of Economic Behavior & Organization *(January 2025) at DOI: 10.1016/j.jebo.2025.107049

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E-PARALLAX

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