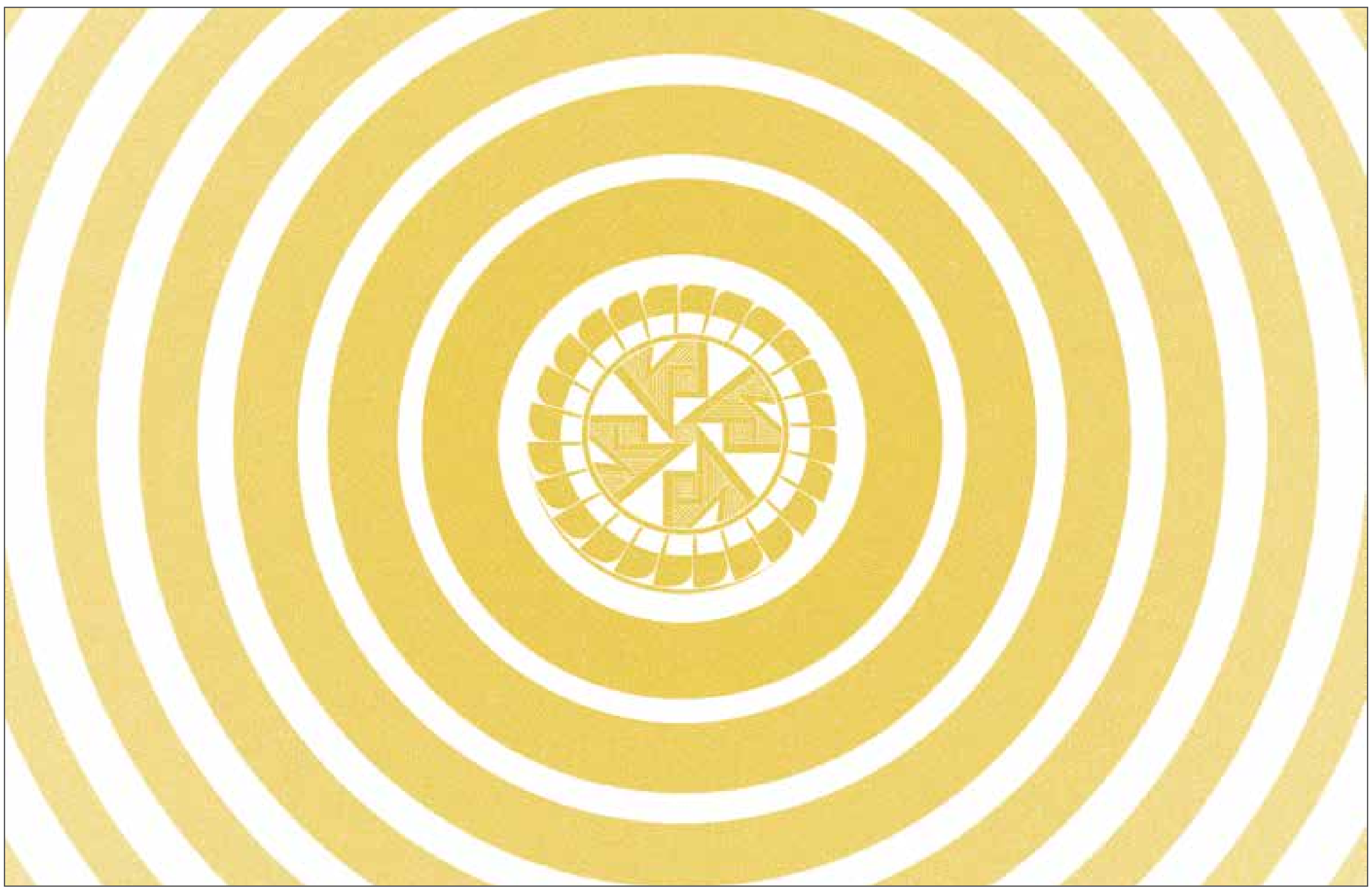
Spring 2020

Parallax

THE NEWSLETTER OF THE SANTA FE INSTITUTE



Transmission: SFI insights into COVID-19

Complexity science offers a wealth of tools for understanding pandemics. At the applied level, epidemiologists use network-science techniques developed at SFI in the early 2000s to track outbreaks, epidemics, and pandemics like Ebola, SARS, influenza, and the novel coronavirus.

Beyond the crucial work of tracking and preventing the spread of biological contagions, complexity science can also shed light on "coupled" problems — the social consequences of pandemic-related misinformation, for example, or the long-term economic repercussions of shutting down global economies.

To present expert perspectives on the complexities of the COVID-19 pandemic, SFI has launched an online series called "Transmission." President David Krakauer, who initiated the series, envisions a collection of short, accessible media created by SFI faculty, on topics related to their scientific expertise.

"Very important work is being done by SFI scientists of direct relevance to the pandemic," Krakauer says, "and the SFI community also has novel insights that might help people deal with the situation more broadly."

He cites SFI researchers who are working to monitor and model the COVID-19 pandemic, to develop vaccines and tests, and to project the socio-economic impact of the pandemic and plot paths to recovery.

The series launched Monday, March 30, with five SFI-authored insights. Krakauer himself penned T-000 (see p.2), which makes the case for eliminating coronavirus through "citizen-based medicine." T-001 by Omidyar Fellow David Kinney takes up the issue of scientists needing to sacrifice a level of certainty in order to provide clear recommendations to policymakers, while External Professor John Harte speaks out against conflicting recommendations on allowable group size in T-002. The third transmission, by External Professor Jürgen Jost and his collaborator Luu Hoang Duc, presents techniques for analyzing inconsistent data on COVID-19 case counts and deaths. T-004, by External Professor Simon DeDeo, asks how we can win "the quarantine end-game," by creating and communicating new guidelines for social interaction.

The series will continue for the foreseeable future, with new insights published every Monday at santafe.edu/transmission.

The Institute responds to the pandemic

In-person gatherings canceled through end of August

With the rapid global spread of the novel coronavirus, SARS-CoV-2, the Santa Fe Institute suspended all public events and scientific meetings and directed all faculty and staff to work remotely beginning Friday, March 13. The State of New Mexico reported its first cases of COVID-19 earlier that week, and the City of Santa Fe reported its first case on Wednesday, March 11.

All SFI gatherings, including community lectures, workshops, symposia, working groups, seminars, meetings of the Applied Complexity Network, summer schools, and the InterPlanetary Festival have also been canceled or rescheduled until after the end of August.

"This is all terrible news and we all desire that the pandemic be controlled more quickly than current projections," wrote President David Krakauer, who made the decision to cancel summer events in consultation with SFI leadership and colleagues at research universities. "However SFI of all places needs to come to terms with the complexity of the situation. And we will adapt quickly if the situation improves."

Answering the call to adapt, some groups and programs have re-organized to convene online (see 'Sustainable investing' and 'Language,' p.2, and 'Meaningful work,' p.5).

SFI researchers are also using online platforms to stay abreast of each others' research (see 'Carrying on,' p.1) and to forge new collaborations aimed at fighting the novel coronavirus (see 'After the first wave,' p.5)

Carrying on with collaborative research

SFI has always prided itself on its ability to bring together top scientists from around the world. Traditionally, they've met in the same room, with catered meals and coffee on tap.

Now, in an effort to help slow the spread of the COVID-19 pandemic, SFI's faculty, postdocs, and staff are making the most of remote work.

Researchers are holding a weekly teleconference to catch up on each others' science. Called "remotely together" in the initial email invitation from Professor Cris Moore, the Wednesday meetings consist of seminar presentations, informal science talks, and, in Moore's words, "the usual . . . lunchtime conversation."

Davis Professor Melanie Mitchell delivered the first seminar on March 18, presenting her current research into how we can evaluate an AI's ability to form abstract concepts. For example, an artificial neural network can accurately identify a picture of a cable bridge, but cannot extend this understanding to the "bridge" of a nose, or a "bridge" between scholarly disciplines. Mitchell presented some classic and state-of-the art problem sets that have been proposed to test this type of abstraction, including one designed by her mentor, Douglas Hofstadter. In classic SFI style, she invited participants to interrupt with questions.

SFI's IT department set up the video conference, and despite a few audio and visual glitches, participants could speak up throughout the presentation. Interlocutors quickly learned to state their names before speaking, so others could identify them.

"The online format took a little getting used to," Mitchell says, "but the essential experience of dialogue and camaraderie went amazingly smoothly."

Toward the end of the presentation, Mitchell returned to the bridge example with a prescient challenge from the field of AI. One explanation for how humans are able to abstract a concept like "bridge" has to do with the way we experience the world as physical, embodied beings. If an AI has never used a plank to cross a stream, or driven the Golden Gate, can it really abstract the ultimate purpose of the object?

Participants unmuted their microphones to applaud, then rallied for an overtime Q&A, approximating the "embodied" experience of lingering in the conference room to continue a lively conversation on a complex problem.

The new look of an SFI meeting **(Photo: SFI)**

INSIDE . . . Citizen-based medicine . . . After the first wave. . . New postdoctoral fellows . . . MORE

TRANSMISSION

Instead of David Krakauer's usual Beyond Borders column, he presents the first transmission in a new SFI-authored series dedicated to complexity and the pandemic. For more, see santafe.edu/transmission

CITIZEN-BASED MEDICINE

Imagine a world where one had the opportunity to prevent cancer. And that this involved no medication and could be developed by every one of us without any special training, entirely from home. And that by preventing the disease for several months, we would provide researchers the window of time required to develop a cure, and doctors, nurses, and hospitals, the relief to effectively deploy it across the global population.

I suspect that we would all stay at home, strive as best us we could to remain productive, and thereby become an active part in one of the greatest prophylactic achievements in the history of public health. The Nobel Prize for medicine would be justly awarded to all the citizens of the world.

This is an impossible scenario for cancer. It is an impossible scenario for effectively all of the top 20 causes of deadly disease in the world. For heart disease, cancer, stroke, and Alzheimer's, we have at best a rather patchy understanding of their origins, how they cause illness, and how we might treat them.

Each of these diseases is correlated, to different degrees, with our genetics, behavioral habits, social systems, economies, and ecosystems. For example, heart disease has a strong genetic component: it is highly dependent on our diets and addictions and our behavior — particularly how active we are. The same factors have an impact on cancer but with a stronger influence from genetics and environmental factors and conditions. And these factors feed back on one another to make isolating a single optimum point of intervention nearly impossible. This is what we describe as Complex Causality. And it makes prevention and treatment of disease very hard.

But the world that we can only dream of for cancer, and for most of the top causes of mortality, is a reality for COVID-19 — we will have a treatment within a couple of years or less and it will work. So why the huge system shock with COVID-19? It has to do with a rather amplified property of causality that reaches out beyond the disease to touch the complex systems of the world.

Unlike these other diseases, in the case of COVID-19 there is a rather unique convergence of causes that reestablishes a kind of simple causality, and these causes are transmission networks. The virus is transmitted initially from animal hosts to humans, typically through diet. Humans then transmit the virus to other humans by contact. These contacts are then transmitted through our transport systems and professional and social lives. This is perhaps the principal reason why the markets and society have been so volatile; the shared factor of transmission is so integral to modern life, it is to such a great extent the foundation of the modern world, that it touches nearly every factor of production. Just as monocultures can generate lethal simplicity in agriculture, transmission has generated lethal simplicity across the globe.

But there is a flip side to this entanglement of complex systems: transmission, unlike the complexity of genetics, and social systems, economies, and ecosystems, can be relatively easily understood, and, by extension, controlled. By following the few simple behavioral rules that we all have come to know well —

> MORE ON PAGE 4

CREDITS

EDITOR: Jenna Marshall

CONTRIBUTORS: Sienna Latham, Caitlin McShea, Katherine Mast, April Reese, Paul Stapleton, Deb Trevino

DESIGN & PRODUCTION: Laura Egley Taylor

VP FOR SCIENCE: Jennifer Dunne

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

www.santafe.edu

SFI IN THE NEWS

As the new coronavirus spreads across the world, SFI scientists are sharing how complex systems and network science can help us understand the social, biological, and economic impacts of an epidemic.

External Professor and Science Board member **Lauren Ancel Meyers** and her team have been featured in multiple media outlets, including *The New York Times*, for mapping the extent to which the novel coronavirus can be spread by seemingly healthy individuals.

In *Vox EU*, Professor **Sam Bowles** and External Professor **Wendy Carlin** outlined "The coming battle for the COVID-19 narrative," arguing that the way we understand and respond to the pandemic brings an opportunity to revive civil society.

In an op-ed for *STAT* news, Omidyar Fellow **Vicky Chuqiao Yang** and former Program Postdoctoral Fellow **Laurent Hébert-Dufresne** argued that misinformation is important public health data, and should be included in network models for pandemics.

Former External Professor **Carl Bergstrom**, an epidemiologist, has also spoken widely about the role of misinformation, and the importance of social distancing, in top media outlets like *CNBC* and *The New York Times.*

Sam Scarpino, a former Omidyar Fellow, described an international data collection and mapping effort in a video for *VICE* news. His lab's work has also been featured in *The Boston Globe* and other media outlets.

External Professor **Thalia Wheatley** reminded *TIME* readers that remote work is still a compromise.

Epidemiologist **Marc Lipsitch**, a former External Professor, has also been quoted in multiple articles and outlets for projecting the trajectory of the pandemic and endorsing containment strategies like social distancing.

Omidyar Fellow **David Kinney**'s Transmission (see p.1) was featured in *The Guardian*, as part of an article that explored how scientists make ethical decisions in times of crisis.

Former Omidyar Fellow **Caroline Buckee** has been featured in *Bloomberg*, *WIRED*, and other outlets for using mobile phone data to help understand and monitor the pandemic (see p. 4).

In a column about the "Transmission" series (see p.1) and the "After the first wave" workshop (see p.4), *The Santa Fe Reporter* invited readers to join scientists in using "knowledge and reason to fight the pandemic."

A new toolkit for sustainable investing

The past three years have seen a surge in sustainable investing. Motivated by the intensifying climate crisis, investment firms and their clients increasingly opt for funds that demonstrate Environmental, Social, and Governmental practices known in the industry as "ESG." There's even a framework for evaluating ESG-friendly funds, which often outperform traditional counterparts.

For SFI Trustee Katherine Collins, Head of Sustainable Investing at Putnam, the ESG framework is a good start. But it fails to address a fundamental question:

"What happens when you take a system that is highly mechanized and focused on very short-term feedback and collide it with a system that's long-duration in nature, has a totally different system of feedback, and supports all life as we know it?"

Collins believes the "machine" of finance is just beginning to tune itself to the importance of sustaining the environment on which it depends, but lacks the right tools to do so.

To that end, Katherine and ACtioN member Putnam Investments will co-host a Virtual Topical Meeting beginning in late May to explore how complexity science can inform sustainable investing. The meeting will bring investors together with leading climate and complexity scientists to discuss "The Complexity of Sustainability and Investing."

In addition to Collins, who is Vice Chair of SFI's Board of Trustees, other SFI speakers will include External Professor Jessika Trancik and Science Board co-Chairs Simon Levin and Dan Schrag.

Schrag, a climate scientist who served on President Obama's advisory council for science and technology, notes how rare it is for investors to seek out scientists for advice on sustainability. "Why aren't investors calling me every day to ask about the climate?" he remarked.

One of the group's objectives is to explore what mathematics might look like for sustainable enterprises. "Most of the math of finance is inherently extractive and zero-sum in its calculating," Collins explains. And current frameworks sometimes "miss the forest for the trees."

For example, there are ways for a well-run company to score highly on the ESG framework, even if its product is inherently wasteful and unnecessary — like a sustainably harvested version of the "Thneed" from *The Lorax*. Some companies, by contrast, produce great products but are not well managed.

Katherine Collins

Beyond exploring a better mathematics for evaluating sustainable investments, Collins hopes the group will have time to ask how such tools could be used to address "the problem of improving the interface between systems of money flow and the system of the Earth we're living on."

"We have this golden moment where there's urgency to act in a more complete and thoughtful way, and an openness to take in new inputs and protocols. The goal of this meeting is to make sure we are doing something wise and not something merely clever."

Working group views language as a window into human minds

Most of us share our thoughts, ideas, and beliefs online, and the sheer volume of words now floating in the public sphere presents an unprecedented opportunity for psychologists who study language. What we say and write can reveal more about us than our words alone convey: Within the vast trove of communiqués in cyberspace lie patterns that can provide rich insights into how our minds work. But psychologists who study language and social cognition have struggled to make sense of such huge amounts of data using traditional methodologies. In the field of computer science, recent advances in machine learning have begun to produce tools that could be used to mine these datasets. A two-day SFI working group, now scheduled to convene online in April, will bring together psychologists and computer scientists to explore how the two fields can collaborate.

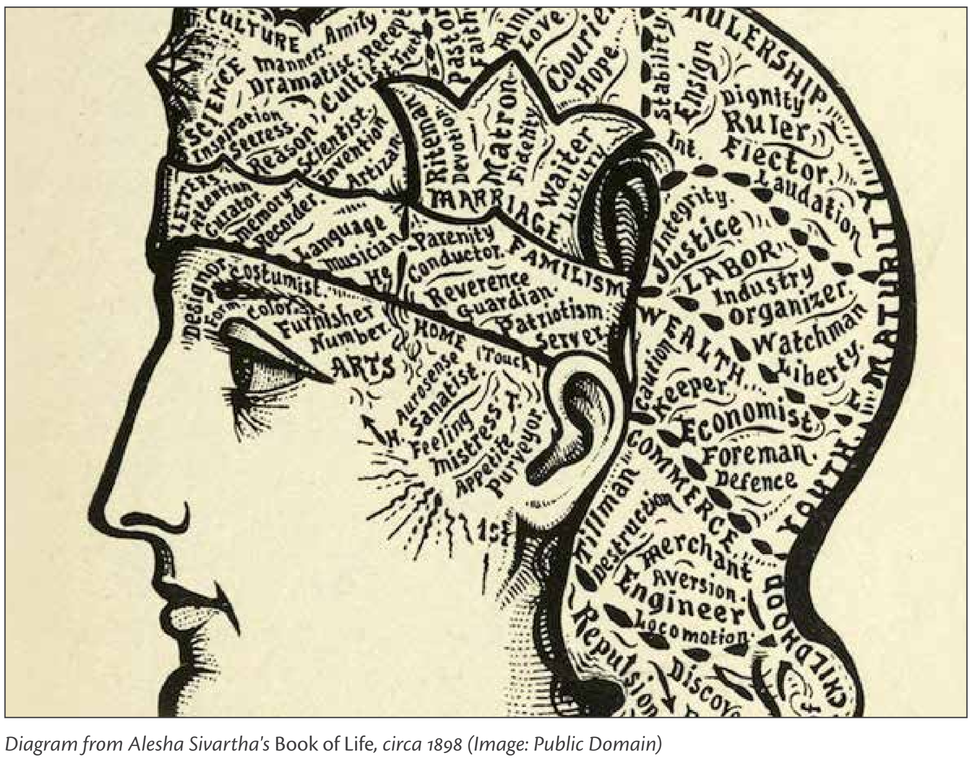


Diagram from Alesha Sivartha's Book of Life, *circa 1898 (Image: Public Domain)*

"You could have all the content in the world, but if you don't have methods [to analyze it], you're stuck," said working group organizer and External Professor Mahzarin Banaji, a psychologist at Harvard. "But we do now."

The collaboration will focus on "the coming together of these large sets of data that contain human expressions of language and methods that are being designed by computer scientists — algorithms — that plow through these massive amounts of words to be able to tell us something about these hidden patterns," she added. At the same time, psychologists will share their own methods for analyzing text, which could help computer scientists refine their algorithms. "We're trying to jump-start a collaborative, interdisciplinary approach, to be able to speak to each other."

In addition to Banaji, the 11-member working group will include researchers with backgrounds in computer science, psychology, brain science, and social dynamics. Among them: Aylin Caliskan, a computer scientist at George Washington University who studies machine learning; SFI Professor Mirta Galesic; and psychologist Jamie Pennebaker of the University of Texas at Austin.

The idea for the working group came to Banaji, who is known for her research on implicit bias, when she read a paper about machine learning. The study got her thinking about what psychologists might be able to learn from computer scientists, especially when it comes to unearthing the layers of

> MORE ON PAGE 5

SFI welcomes new and incoming postdoctoral fellows

The Santa Fe Institute's postdoctoral fellows are selected from around the world and across science for their intellectual curiosity, quantitative rigor, and multidisciplinary creativity. At the Institute they enjoy exceptional freedom to pursue new research questions and collaborate with top minds in SFI's international research network as they prepare to become tomorrow's scientific leadership.

All SFI fellows participate in a unique training program designed to develop their scientific, communication, and leadership skills. Most go on to hold faculty positions at major universities and research institutions, where they serve as lifelong ambassadors for the philosophies and methodologies of complexity science.

ANJALI BHATT

Human organizations, from business to schools to volunteer networks, each develop their own cultural structures over time. We know that cultural diversity — when individuals in a group hold a variety of values and beliefs — can spur creativity and innovation. It can also lead to conflict. We know less about how cultural diversity emerges or behaves in organizations. Anjali Bhatt, an incoming Omidyar Fellow, uses natural language processing, agent-based modeling, and machine learning to analyze empirical data and build theoretical models to understand the dynamics of organizational cultural diversity. She is particularly interested in how those dynamics change when individuals cross the boundaries of one organization to another.

Bhatt, who holds an AB in physics from Harvard University and is completing a PhD in organizational behavior at Stanford Graduate School of Business, blends organizational and cultural theories, which are grounded in sociology, with the mathematical models of evolutionary biology and the quantitative tools of computational linguistics. Developing a systematic theory for cultural diversity in organizations could help managers who are increasingly being asked to consider cultural change and diversity, and also offer broader social relevance as well. "If we want to understand cultural shifts in society, we might want to understand more about what's happening in organizations," says Bhatt.

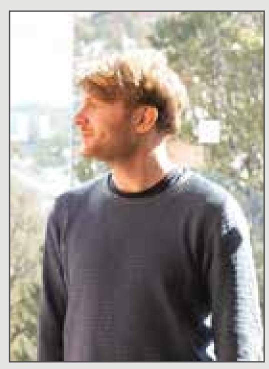
GEORGE CANTWELL

The study of network dynamics, or how large numbers of individual components interact, is foundational to much of the research at SFI. Network theory has offered insight into everything from stock markets and ecosystems to disease spread and human social behavior. But there are still vexing challenges — problems that look simple but which prove to be quite hard — at the heart of network theory and models.

Incoming Program Postdoctoral Fellow George Cantwell, who is completing his PhD in physics at the University of Michigan, recently tackled one well-known flaw in network modeling that has persisted since the 1930s. A common tool, belief propagation, used for calculating network properties, only works on networks with no short loops. But most real-world networks *have* short loops.

That disconnect between models and their ability to rigorously fit to real-world data is the vexing challenge that drives Cantwell's research. He would like to see theoretical research orient toward consequential real-world questions. The questions of greatest import for Cantwell, who also holds a BA in physics and philosophy from the University of Oxford, concern human sociology and psychology. "Many of the hardest and most interesting questions arise in this context," he says. At SFI, Cantwell will be working with Professor Cris Moore on an NSF-funded project aimed at identifying when it is mathematically possible to pull patterns from large, noisy, high-dimensional real-world datasets.

JONAS DALEGE



One of the central features of being human is our ability to develop and maintain beliefs. We each hold ideas about what is true and what is not, what is fair, just, or moral, even what is real. These beliefs are connected as networks in our own minds, and are also connected to the beliefs of other people in our social networks. Past theories have approached individual and social belief networks separately, but Professor Mirta Galesic, External Professor Henrik Olsson, and new Program Postdoctoral Fellow Jonas Dalege, hope to develop a unifying theoretical framework that integrates the two approaches.

Dalege, who holds a PhD in psychology as well as a BSc and MSc from the University of Amsterdam, studies the nature of human attitudes. He has developed a network theory of individual attitudes, describing the complex interactions between elements like feelings, beliefs, and behaviors.

"A central postulate of my network theory of attitudes is that the connections between different attitude elements increase when one thinks about and pays attention to an attitude object," says Dalege. If, for example, you don't care much about politics, positive feelings about a political candidate are unlikely to translate into volunteering for their campaign. In contrast, when politics are very important to you, feeling strongly about a political candidate is much more likely to motivate you to volunteer for their campaign. The more time you spend thinking about the candidate, the more interconnected your beliefs, feelings, and behaviors regarding that candidate become. "Because of this, your overall attitude becomes more stable and extreme," he says.

At SFI, Dalege, Galesic, and Olsson hope an integrated network perspective can help shed more light on why people hold tight to some beliefs while others are more easily changed.

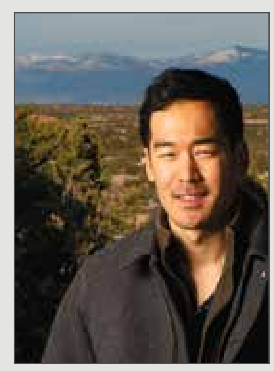
NATALIE GREFENSTETTE

Natalie Grefenstette was still in elementary school when she started wondering about life: how it began on Earth, where it might be elsewhere in the Universe. These questions became her obsession long before she first heard the word "astrobiology." In fact, the still-nascent field of astrobiology was only starting to form as Grefenstette entered college. "So I had to approach it a different way," she says. She studied biochemistry as an undergrad at University College London, looking at how cells and life work on Earth through things like proteins and disease. In 2017, she completed her PhD, also from UCL, in prebiotic chemistry.

The questions that have captured her lately are: How different might life look elsewhere in the Universe? How do we look for life beyond Earth if we don't know exactly what we're looking for? Are there universal laws — perhaps based more in physics than in chemistry — that govern life on Earth and beyond?

Grefenstette joined SFI last June as a Program Postdoctoral Fellow working with SFI Professor Chris Kempes on the NASA-funded Agnostic Biosignatures project. "There aren't many people asking these questions, so I'm lucky to have found this program," she says.

EDDIE LEE



The behavior of social animals, from humans to pigtailed macaques, may look messy and unpredictable at first glance. In recent years, however, concepts from statistical physics have helped reveal surprising patterns and predictable regularity. Eddie Lee, a Program Postdoctoral Fellow working with SFI President David Krakauer and Professor Jessica Flack in the Collective Computation (C4) Group, builds on his background in physics to study social phenomena like the emergence of voting blocs on the U.S. Supreme Court, scenarios where the outcome of an decision comes down to a few pivotal votes, and the spread of armed conflict.

Inspired by Professor Geoffrey West's work in scaling laws, Lee and the C4 group analyzed data from various wars and violent upheavals across Africa over 20 years to study how armed conflict spreads. "The results were remarkable," says Lee. "We were finding universal scaling patterns in the dynamics — the spatial structure, duration, and social statistics — of conflict. It's surprising when you can take something as messy as armed conflict and find such regularity." Now the group is working to build a model that captures those regularities.

Lee has been part of the SFI network since spending a summer on campus as an REU while he was studying physics and biophysics at Princeton University. "One of the drivers through graduate school was coming to SFI," he says. "I always returned to school with lots of ideas." Lee holds an MSc and PhD in physics from Cornell.

MINGZHEN LU

Beneath our feet, out of our sight, is a world of complex interactions. Plants, fungi, and microbes work together symbiotically to make resources like carbon, nitrogen, and other nutrients available to one another. "This very cooperation has propelled the evolution of all land plants and all terrestrial ecosystems ever since plants colonized land," says incoming Omidyar Fellow Mingzhen Lu, a biogeochemist who holds a PhD in ecology and evolutionary biology from Princeton University and a BS in geosciences from Peking University. While these symbiotic relationships, as well as competition between individuals, can be viewed on a hyper-local scale, they also play dynamic roles in global ecology. Lu draws on principles from economics to build theoretical and computational models to help describe the complexity and variety of these dynamics across the world.

With the view of the Earth as complex system, Lu also studies regime shifts in biomes: how human activity impacts the boundary between the highly diverse Fynbos, a shrubland ecosystem, and the surrounding less diverse forest in South Africa's Cape Floristic Kingdom; what the thawing of the Arctic tundra and its underlying permafrost could mean for future atmospheric carbon; and how the warming-induced Arctic vegetation shift from grass to shrubs will impact the Earth system.

"The future trajectory of our planet depends on the intricate feedbacks among the Earth's natural components but is increasingly dependent on the behavior of human society," says Lu. At SFI, Lu hopes to continue to expand the application of complex systems research on ecological questions, with a particular eye toward the impacts of human activities. "A complex-systems approach is crucial to understanding the problems we are facing as a society, and perhaps more importantly, how we can inform policy and decision making to act upon these problems."

ANDRÉS ORTIZ-MUÑOZ

Category theory, a recent development in mathematics, provides a framework to link ideas from various mathematical subfields. It has proven useful in revealing unexpected similarities between apparently different concepts and has suggested ways to merge concepts from two different domains to apply to a third. Researchers have applied it, with profound impacts, to the study of linguistics, programming language theory, and theoretical physics.

One area with few existing applications of category theory are the life sciences, but incoming Omidyar Fellow Andrés Ortiz-Muñoz, who holds a BS in mathematics and physics from the University of Texas at El Paso and is completing a PhD in biology at CalTech, sees ample opportunities to venture into this unexplored space.

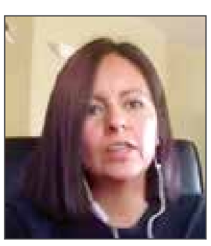
Chemical reaction networks — theoretical, applied mathematical models that describe chemical systems — are convenient, but minimal, tools for understanding how systems of interacting molecules behave. One limitation of CRNs is that they are agnostic to the molecules' internal structure. Category theory could help researchers build a more robust theory of chemical reaction networks that is more faithful to the structural richness of biological molecules.

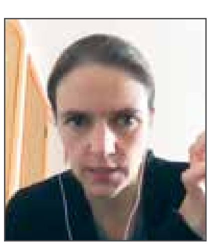
Ortiz-Muñoz, who participated in the 2018 Complex Systems Summer School at SFI, plans to draw on existing projects at SFI to inform his research. Research into the thermodynamics of computation, particularly of biological systems; the concept of emergence; and how a better understanding of molecular computation could inform our understanding of the origins of life are all ideas he hopes to explore during his fellowship.

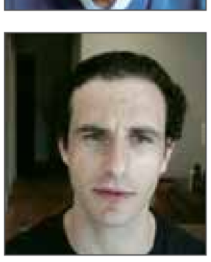
Postdoc portraits by Doug Merriam/Santa Fe Institute

'The Great Wave off Kanagawa' by Katsushika Hokusai, c. 1829-1833 (Image: Metropolitan Museum of Art)

Flash Workshop: After the First Wave







From top: After the First Wave participants Sam Scarpino, Lauren Ancel Meyers; Sara del Valle, Caroline Buckee, Rajiv Sethi, and Glen Weyl

An epidemic spreads faster than wildfire. Unmitigated, it will reach a large fraction of the population before abating, causing hundreds of millions of deaths even with a mortality rate of just 1 percent. For the first time in history, a worldwide effort is underway to stop the spread of a pandemic through stay-home orders and social distancing. This unprecedented response spares human lives and healthcare systems, but it also leaves us in an unstable situation. Unlike an unmitigated pandemic, which burns through the susceptible population and eventually burns out, a mitigated first wave preserves a population of unexposed, susceptible individuals. This means that when social distancing guidelines are relaxed, the epidemic can once again spread worldwide and bring us back where we started.

So, what happens after the first wave?

To explore this question, SFI convened an online workshop on March 31 with leading epidemiologists from its collaboration networks. Sam Scarpino, a former SFI Omidyar Fellow and network scientist at Northeastern University who is mapping the real-time spread of the COVID-19 pandemic, co-organized the two-hour "flash workshop" with Professors Cris Moore and Michael Lachmann.

"Some places like South Korea and China are past the first wave," Scarpino opened, "and in the U.S. we are still on the upswing. Part of the reason we're having this conversation now is so we can both prepare for what's coming and also so we can re-deploy to areas that will be experiencing their first wave."

In the first 90 minutes of the workshop, four speakers presented their research on the COVID-19 pandemic and its potential economic consequences. External Professor and Science Board member Lauren Ancel Meyers, based at University of Texas Austin, and Sara del Valle of Los Alamos National Lab, spoke about their teams' efforts to support public health decision-making by simulating how the pandemic would spread under different scenarios, such as school closures and social distancing at various stages in the outbreak, and for various lengths of time. Both speakers' models showed significant secondary waves.

Caroline Buckee, a former SFI Omidyar Fellow now at Harvard's Center for Communicable Disease Dynamics, started by enumerating key parameters we don't yet understand for COVID-19. For example, although we have published case counts from around the world, the widespread shortage of tests and lack of testing data means we still haven't grasped just how many people in the population actually carry the infection, with or without showing symptoms. Buckee went on to describe her team's work analyzing mobility data from cell phone carriers, which can reveal whether and to what extent people are following social distancing guidelines. She emphasized that a crucial aspect of this work is passing reports on to lawmakers in a way that protects the privacy of the users, and prevents demographic groups from being targeted.

In the final presentation, External Professor Rajiv Sethi (Barnard College, Columbia University) and his collaborator Glen Weyl (Microsoft, RadicalxChange Foundation) looked at the economic implications of containing the pandemic. Citing the massive unemployment that has already resulted from social distancing, they proposed a new containment strategy, "mobilize and transition," that would reduce COVID-19 mortality while easing the economic decline.

The workshop then opened up discussion for an hour to more than 130 SFI-affiliated researchers, which Scarpino called "one of the most exciting groups of people I've seen on a Zoom call."

Bigger-picture, socioeconomic consequences featured prominently. Professor Mirta Galesic raised concerns about societal tipping points that often occur in times of crisis. Former External Professor Carl Bergstrom at the University of Washington followed up by remarking on the importance of maintaining the public's trust through consistent messaging. Former SFI Postdoctoral Fellow Laurent Hébert-Dufresne at the University of Vermont questioned the best way to ease out of social distancing, while Professor Sam Bowles and External Professor Simon DeDeo at Carnegie Mellon raised related points about the need for new social norms.

Lachmann, Moore, and SFI President David Krakauer are in the process of organizing a follow-up flash workshop on April 14 on the social, psychological, and economic mechanisms to mitigate pandemics, capitalizing on the Institute's pioneering work in these areas.

"SFI and its broader network have a unique ability to bring epidemiologists and economists together to explore how we can recover from both the pandemic and its economic cost," Moore says.

Video from the workshop can be viewed on our YouTube channel: youtube.com/user/santafeinst

SFI's undergraduate research program

'Meaningful work with social impact'

Jake Jackson

Elisa Heinrich Mora

For students who participate in SFI's Undergraduate Complexity Research program, the 10-week residential opportunity* not only develops their research skills, it opens their minds to new concepts and builds lasting relationships.

We recently caught up with two students who attended the 2019 session: **Jake Jackson**, a Brown University senior, and **Elisa Heinrich Mora**, a Minerva School at KGI senior from Asunción, Paraguay. Both were drawn to SFI's work on urban scaling, and each has big plans for their future.

Q: What got you interested in this program and in complexity science?

Elisa: Since high school, I was interested in the idea of multidisciplinary approaches to solve problems, but I never had a name to put to it. Then I started reading about SFI, and I knew this is exactly what I wanted to do! I wanted to work with physics and math, but also to do meaningful work with social impact. I read papers about cities and slums by Luis Bettencourt — highlighting issues we see every day in Paraguay. This made me realize there is very little knowledge about those type of systems, so I really wanted to work on that.

Q: Can you tell us about a highlight of your time at SFI?

Jake: It's cliché but it's true: what makes the program is the relationships with the cohort. It was the second-to-last weekend, and a lot of us were watching the sunset on a big rock by St. John's College, playing music and talking. It was a beautiful experience. From a research perspective, there were so many meetings where we were just blasting through ideas, and we'd leave the room in an hour and a half completely drained but excited at the next thing to pursue.

Q: What did you take away from the experience, and how will it help guide you going forward?

Elisa: I want to keep doing complexity science. I think I'm going to take some years to do a pre-doctoral to have some experience, but then I want to do my PhD. I see myself as not constrained anymore — I'm very excited to do research, but I'm also excited to see how I can apply all these ideas into helping specific programs or policies.

Q: What would you tell another undergrad researcher about this program?

Jake: I would say absolutely do it, it's the best experience you can have in undergrad. It's a very diverse set of people, backgrounds, and interests, yet there's a common way of thinking. This makes for incredible conversations and opportunities to grow with each other in a really meaningful way.

**Due to social distancing guidelines in place for the COVID-19 pandemic, the 2020 program will take place virtually. SFI faculty and postdocs will mentor undergraduates remotely for 10 weeks, ending with virtual presentations of their summer research to the SFI community.*

The 2019 complexity research undergraduates at the Santa Fe Opera

Transmission *(cont. from page 2)*

quarantine, maintaining social distance in public, practicing appropriate hygiene, and developing new habits for home-work when possible — every citizen can play a meaningful and significant part in eliminating this scourge.

We use our understanding of the common factor of transmission to our advantage: continue to mobilize the largest information-transmission network the world has ever seen – our technologies of communication — to enable the collective action needed to eliminate the transmission of the virus. Strategic isolation is our anti-viral flash-anti-mob.

And we recognize the extraordinary economic sacrifices that are being made to make citizen-based medicine a reality — position economic relief as fair sharing in the reward for the unprecedented scale of teamwork required to rid the world of a terrible disease. If we can transmit insight at the speed of light then we should do the same for compassion and support. If the economy is going to rebound anywhere near as fast as it declined, we need to understand the complex nature of transmission, in aligning emotion, reason, science, policy, and economies toward recovery as effectively as these alignments produced collapse.

By using transmission to our advantage, we can control coronavirus through citizen-based medicine.

— David Krakauer
President, Santa Fe Institute

Interacting contagions call for complex models

When disease modelers map the spread of viruses like the novel coronavirus, Ebola, or the flu, they traditionally treat them as isolated pathogens. Under these so-called "simple" dynamics, it's generally accepted that the forecasted size of the affected population will be proportional to the rate of transmission.

But according to former SFI postdoc Laurent Hébert-Dufresne at the University of Vermont and his co-authors Samuel Scarpino at Northeastern University, a former Omidyar Fellow, and Jean-Gabriel Young at the University of Michigan, the presence of even one more contagion in the population can dramatically shift the dynamics from simple to complex. Once this shift occurs, microscopic changes in the transmission rate trigger macroscopic jumps in the expected epidemic size — a spreading pattern that social scientists have observed in the adoption of innovative technologies, slang, and other contagious social behaviors.

Interacting contagious diseases like influenza and pneumonia follow the same complex spreading patterns as social trends. The findings, published in *Nature Physics*, could lead to better tracking and intervention when multiple diseases spread through a population at the same time.

"The interplay of diseases is the norm rather than the exception," says Hébert-Dufresne. "And yet when we model them, it's almost always one disease in isolation."

The researchers first began to compare biological and social contagions in 2015 at SFI, when Hébert-Dufresne was modeling how social trends propagate through reinforcement. The classic example of social reinforcement, according to Hébert-Dufresne, is "the phenomenon through which 10 friends telling you to go see the new 'Star Wars' movie is different from one friend telling you the same thing 10 times."

Like multiple friends reinforcing a social behavior, the presence of multiple diseases makes an infection more contagious that it would be on its own. Biological diseases can reinforce each other through symptoms, as in the case of a sneezing virus that helps to spread a second infection like pneumonia. Or, one disease can weaken the host's immune system, making the population more susceptible to a second, third, or *nth* contagion.

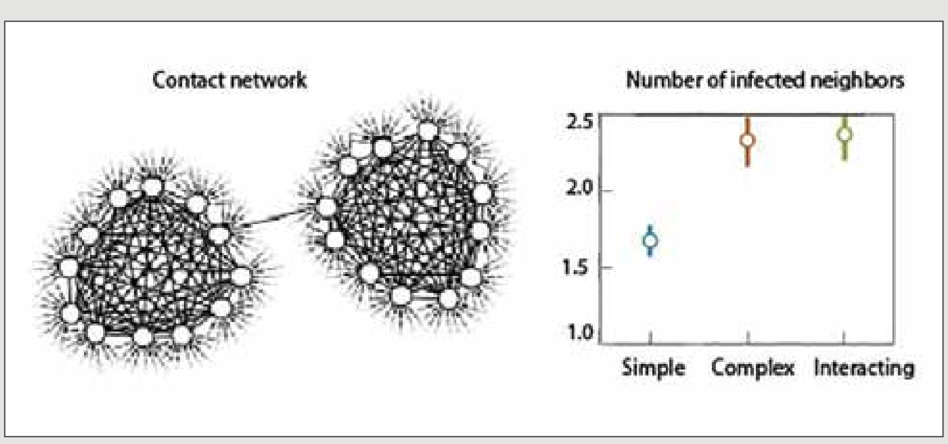
When diseases reinforce each other, they rapidly accelerate through the population, then fizzle out as they run out of new hosts. According to the researchers' model, the same super-exponential pattern characterizes the spread of social trends, like viral videos, which are widely shared and then cease to be relevant after a critical mass of people have viewed them.

The same complex patterns that arise for interacting diseases also arise when a biological contagion interacts with a social contagion, as in the example of a virus spreading in conjunction with an anti-vaccination campaign. The paper details a 2005 Dengue outbreak in Puerto Rico, where failure to accurately account for the interplay of Dengue strains reduced the effectiveness of a Dengue vaccine. This in turn sparked an anti-vaccination movement — a social epidemic — that ultimately led to the resurgence of measles — a second biological epidemic. It's a classic example of real-world complexity, where unintended consequences emerge from many interacting phenomena.

Although it is fascinating to observe a universal spreading pattern across complex social and biological systems, Hébert-Dufresne notes that it also presents a unique challenge. "Looking at the data alone, we could observe this complex pattern and not know whether a deadly epidemic was being reinforced by a virus, or by a social phenomenon, or some combination."

"We hope this will open the door for more exciting models that capture the dynamics of multiple contagions. Our work shows that it is time for the disease-modeling community to move beyond looking at contagions individually."

A follow-up workshop on interacting contagions has been tentatively scheduled for November 2020, at SFI.



The contact network used in the authors' simulations (left), alongside number of infected neighbors for simple biological contagions, complex social contagions, and interacting contagions (right). For full figure and caption, see Hébert-Dufresne, L., Scarpino, S.V. & Young, J. Macroscopic patterns of interacting contagions are indistinguishable from social reinforcement. Nat. Phys. (2020).

Language *(cont. from page 2)*

meaning embedded in the torrent of words flowing across the Internet.

"Although I don't study language, I've always been interested in how language reflects our beliefs and values and on the other hand how we use language to shift the way we think," Banaji said.

Originally scheduled to meet in Santa Fe, the working group, "Language as a Window into Human Minds: Explorations with Computer-Resident Language and Naturalistic Conversation" will be held online, April 23.

ACHIEVEMENTS

"The ergodicity problem in economics," a perspective piece written by External Professor **Ole Peters** (London Mathematical Laboratory) received one of the highest Altmetric attention scores for 2019. The scores are calculated based on the number of mentions a paper receives in news outlets, social media, and blog posts.

As of April 2020, the paper's Altmetric score is over 1,000, making it the highest-scoring paper in the journal *Nature Physics*.

RESEARCH NEWS BRIEFS

Illustration from Nathaniel Hawthorne's 'Tanglewood Tales' c. 1921 (Image: Virginia Frances Sterrett/Public Domain)

THE SCIENCE OF STORIES

From ancient myths to modern novels, good stories capture our attention. Aristotle famously observed that a plot has a beginning, middle, and end — what other patterns might be at play?

In a new issue of *PLOS One* dedicated to the "science of stories," SFI Professor Mirta Galesic and her fellow guest-editors, Peter Dodds (University of Vermont), Mohit Iyyer (UMass Amherst), and Matthew Jockers (Washington State University), collect examples of emerging computational approaches that could add a new dimension to narrative analysis. When compared to qualitative techniques, computational approaches can render "detailed, moment-by-moment analysis of semantic and emotional narratives, their internal dynamics, and their similarities and differences when compared to stories of other authors, cultures, and times."

SYNTHETIC BIOLOGY FOR TERRAFORMATION

Saving endangered ecosystems like tropical forests and drylands — and the ecological services they provide us — is one of the biggest challenges of modern times. As the loss of these systems accelerates, some scientists have proposed an unusual remedy: using synthetic biology to change ecological communities in ways that prevent their demise. But as SFI External Professor Ricard Solé and six colleagues detail in the journal *Life*, "ecological engineering" is rife with risks and presents a host of scientific and ethical challenges that need to be carefully considered. What would it take to successfully alter an environment — from the gut microbiome to the biosphere — to make it more hospitable to certain life forms?

THE THERMODYNAMICS OF COMPUTING WITH CIRCUITS

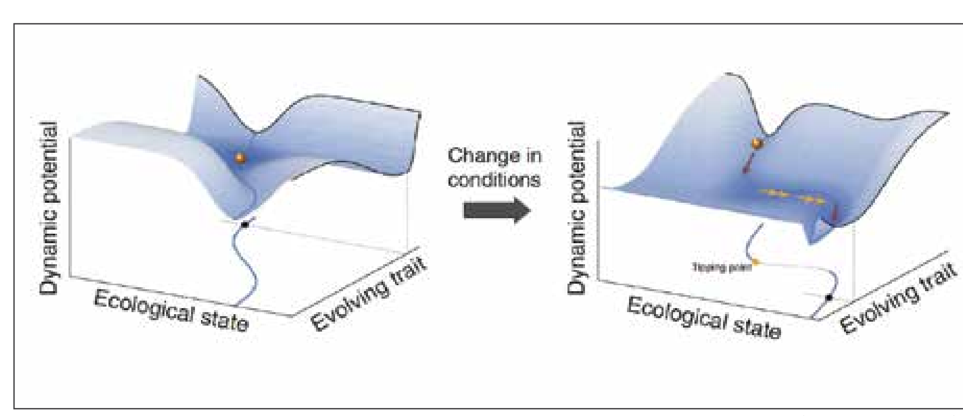
The circuits that make up the brain of a computer require a lot of energy to operate — so much so that running computers accounts for ~5 percent of U.S. energy consumption. And with demand for computing power increasing with the rapid technological advances that bring us ever-smarter cell phones, laptops, and other devices, there's tremendous interest among manufacturers and scientists in developing more energy-efficient computer systems. A new paper by SFI Professor David Wolpert and Program Postdoctoral Fellow Artemy Kolchinsky in the *New Journal of Physics* describes one of the major problems that computer scientists will need to overcome to achieve that goal: how the topology of a circuit limits which parts of it can interact — and how those limitations affect the thermodynamic costs of operating the system.

IF CANCER WERE EASY, EVERY CELL WOULD DO IT

Instead of asking why we get cancer, Leonardo Oña of Osnabrück University and SFI Professor Michael Lachmann use signaling theory to explore how our bodies have evolved to keep us from getting *more* cancer. Their evolutionary model, published in *Scientific Reports*, reveals two factors in our cellular architecture that thwart cancer: the expense of manufacturing growth factors and the range of benefits delivered to cells nearby. Individual cancer cells are kept in check when there's a high energetic cost for creating growth factors that signal cell growth. To understand the evolutionary dynamics in the model, the authors emphasize the importance of thinking about the competition between a mutant cancerous cell and surrounding cells.

DID ANIMALS RISE WITH OXYGEN?

Oxygen is essential for life — all animals need it for at least some part of their life cycle. But Earth was not always the oxygen-rich planet it is today. Determining how and when the world became oxygenated enough to support animal life has been a challenge in the field of geobiology. A study, which grew out of an SFI working group, published in the journal *Geobiology* by SFI External Professor Douglas Erwin and colleagues, critiques six prominent arguments in the debate over the timing and role of oxygenation in the rise of animals and identifies key research questions that need to be answered.



Two evolutionary spaces illustrate how a small change in environmental conditions with few immediate effects opens up a gradual path toward regime change (Figure: André de Roos).

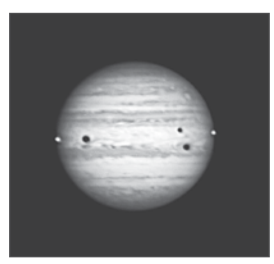
RE-THINKING 'TIPPING POINTS' IN ECOSYSTEMS AND BEYOND

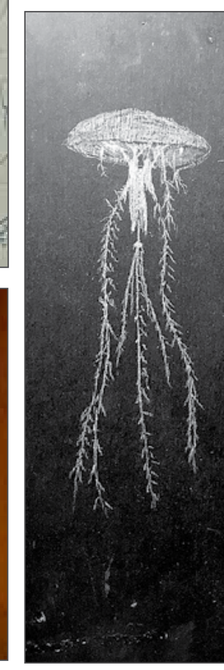
When a grassland becomes a desert, or a clearwater lake shifts to turbid, the consequences can be devastating for the species that inhabit them. These abrupt environmental changes, known as regime shifts, are the subject of new research in *Nature Ecology & Evolution* which shows how small environmental changes trigger slow evolutionary processes that eventually precipitate collapse.

Until now, research into regime shifts has focused on critical environmental thresholds, or "tipping points," in external conditions — e.g., when crossing a certain temperature threshold triggers a sudden shift to desertification. But the new model by Catalina Chaparro-Pedraza and SFI External Professor André de Roos, both at the University of Amsterdam, reveals how a small change in the external environment, with little immediate impact, can induce slow evolutionary changes in the species that inhabit the system.

Understanding the role of evolutionary processes in regime shifts could also shed light on other complex, interdependent systems, like stock markets, which the authors demonstrate in a further analysis of data from the 2008 financial crisis.

> MORE ON PAGE 6





Pictured above (clockwise, from top left): *A panorama interior photograph of Heliotown II (Photo: Ashcraft); Ashcraft presenting a "Jellyfish Sprite" during an SFI seminar (Photo: Michael Garfield); Bacteriophage portal coin (Photo: Ashcraft); Chalk drawing of jellyfish (Ashcraft); Dioramas inside Heliotown II (Photos: Karol Jalochowski, Laura Egley Taylor); Diorama showing miniature Heliotown II (Photo: Laura Egley Taylor); Triple moon Jupiter transit (Photo: Ashcraft); Heliotown II exterior (Photo: Ashcraft); Whimsical display of the Thinkers' Gum lab within Heliotown II (Photo: Laura Egley Taylor); Juvenile coyote inspects jackalope decoy (Photo: Ashcraft)*

The wonderful world of Thomas Ashcraft

Explore. Examine. Discover. Report.

What does a meteor sound like when it hits the atmosphere? Ask Thomas Ashcraft, who is SFI's artist and citizen scientist in residence.

Ashcraft has been profiled in *The New York Times* for detecting and photographing "sprites," fleeting, almost subliminal, luminous events that occur above super-strong lightning strikes.

At SFI, he has converted a tiny building into a mysteriously atmospheric *wunderkammer* (wonder room) called "Heliotown II." The building, formerly a pool house, is now home to a series of tiny dioramas that attempt to expand space and time.

Ashcraft was a farmer in the Ozarks in the 1980s, but something called him to Santa Fe. First, he started studying the sun and from there he "followed his nose." Now he has a laboratory set up on his property near Santa Fe, where his radio observatory monitors the complex sounds that space dust makes colliding with the atmosphere, and a Jupiter observatory that operates in cooperation with NASA. A video camera runs 24/7, capturing meteor strikes and fireballs through an automated system that also records their sounds.

A few years ago he became interested in what was going on at night around his house, so he started recording the nocturnal scene and was "surprised at how dynamic the night time was." He put a couple of trail cameras up at the SFI Cowan Campus with a jackalope decoy in the foreground. Most of the animals passing, such as coyotes and deer, would stop in their tracks to investigate it, then mark it, or, as Ashcraft puts it, "They were leaving pee-mails for each other."

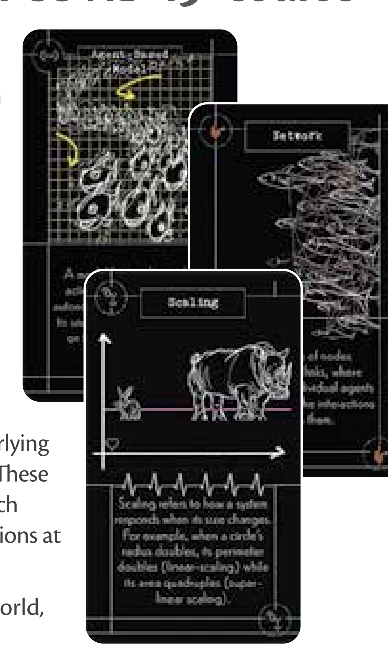
"I was discovering an invisible world right outside SFI's windows," he says. This fascinating collection of trail cam videos offer viewers a rare glimpse of SFI's non-human inhabitants. They can be viewed on his website, heliotown.com.

"I have the poet's license to go anywhere," Aschraft says. "In essence, what it comes down to for me at this phase of my life as a naturalist and scientific-instrument builder are four words: Explore. Examine. Discover. Report."

A whole-planet project:

InterPlanetary's "Complexity of COVID-19" course

The microscopic SARS-CoV-2 virus is dismantling systems across all scales; among the many disruptions caused by the COVID-19 pandemic, the 2020 InterPlanetary Festival has been cancelled as an in-person event. However, its mission to spread intuition about complex systems continues through a new at-home course.



Launched in early April, the online "Complexity of COVID-19" course is a resource for families and communities to think through the broad-reaching consequences of this pandemic in real time. Every Wednesday, the InterPlanetary team will release a course packet containing summaries of the COVID-19 Transmissions (see p.1), a link to that week's episode of the Complexity Podcast, some recommended extra-curricular readings, Complexity Cards that introduce learners to key concepts underlying the proposed insights, and a quiz for assessing comprehension. These course packets offer roughly two hours' worth of curriculum each week, and aim to provide an opportunity for thoughtful discussions at home until we're able to de-quarantine and reconvene.

Reducing disease is a whole-planet project. Let's change the world, one planet at a time.

For more, visit interplanetaryfest.org/complexity-of-covid-19-course/

Research Briefs *(continued from page 5)*

FROM FLUIDS, TO EARTHQUAKES, TO INFECTIOUS DISEASE

Catastrophic events in both nature and society tend to happen in bursts. Think earthquakes, wildfires, stock market crashes. Modeling these events can help scientists figure out how they progress. A recent paper in *Physical Review Letters* by University of California-Davis physicist and SFI External Professor John Rundle and colleagues explores a new model that helps explain burst dynamics. The team's model, based on the idea of "invasion percolation" — how fluids flow into a porous area — could be used to solve problems in earthquake dynamics, statistics, and understanding infectious disease clusters.

Parallax
Spring 2020
THE NEWSLETTER OF THE SANTA FE INSTITUTE

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