SUMMER 2022

Parallax

THE NEWSLETTER OF THE SANTA FE INSTITUTE

"Prairie Bluffs Burning" by George Catlin, 1832. (Image: Smithsonian Open Access.)

As climate changes, so must political economies

On April 30, 2022, the Santa Fe Institute's Science Board hosted its annual symposium. The meeting's topic — political economy and climate change — is central to SFI's new Emergent Political Economies research theme, and will remain a focus of SFI research for the duration of the five-year grant and beyond.

SFI External Professor and outgoing Science Board Co-chair, Dan Schrag,* who led the symposium, said that the program would help us "prepare for the ways that climate change will affect societies around the world." For both Schrag and SFI President David Krakauer, who contributed opening remarks, one factor we must anticipate is how unevenly the effects of climate change will be felt in different economies around the world.

To fuel dynamic thinking in SFI's research network, Schrag invited David Victor and Lint Barrage,* two experts on the interplay between politics, economics, and climate change, as the Symposium's main speakers.

A new theory of change will be central to any large-scale strategy for responding to the global climate crisis, said Victor. His notion of change focuses on finding "ways to control emissions that are politically sustainable." This means, in part, understanding the spectrum of changes people are likely to make. Instead of simply asking individuals to quit flying or eating meat, political leaders must find ways to facilitate technological evolution that can transform our global energy system — and co-evolve in turn.

This, however, means taking on risky projects. "These are not typical investments," Victor explained. Disruptive technologies require large-scale, experimental collaborations between companies, governments, and scientists. Complexity scientists can help investors predict risk and simulate the evolution of technology and policy — then firms and governments can better ascertain the risks worth taking.

Barrage's talk focused on the impediments to climate progress, and the policy tools that can advance it. "Economists overwhelmingly endorse carbon pricing as a key climate policy tool," she said, but have failed to persuade governments, particularly in the United States, to deploy it sufficiently. To motivate change and innovation, carbon must be priced at $40 to $100 per metric ton of CO_2 emissions; right now, around the world, it is priced, on average, at $2. Barrage notes that one consequence of low

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Italian meeting to explore quantitative human ecologies

To address climate change and other societal challenges like rising inequality, human migration, and biodiversity loss, humanity must consider the ecological, economic, and political constraints of our planetary systems.

In late July, the International Centre for Theoretical Physics (ICTP) in Trieste, Italy, will host a workshop to discuss these considerations and foster collaboration across research communities. SFI is hosting the workshop in partnership with ICTP and the Fondazione Internazionale Trieste. Co-sponsorship is provided by the U.S. Mission in Italy. Titled "Quantitative Human Ecology," the meeting will focus on three key sustainability challenges.

The first challenge is that the timelines of policy and nature are out of sync. Policy solutions, both internationally and domestically, do not operate at the same time scales of the physical and ecological processes being transformed by human activity.

"This leads to all sorts of tragedies of the commons," says SFI President David Krakauer, one of the workshop organizers. "It's hard to ask someone to make a decision that hurts them economically but will benefit the planet in 100 years."

Krakauer alludes to the second major challenge: human agency. Individuals tend to make decisions that benefit themselves and their families. This can create tension when collective needs run counter to individual wants, especially when sustainability is not the affordable or convenient option. One example is the continued use of plastic bags in grocery stores despite their known role in polluting both terrestrial and marine ecosystems.

Lastly, it remains difficult to integrate across multiple dimensions of society and ecology. For example, economic inequality and biodiversity are both integral to sustainability, but they function under different theoretical frameworks and require unique solutions.

To address these challenges, the workshop will integrate methods from economics, ecology,

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Language: a window into human minds

The Turkish word *o* is a non-gendered pronoun that translates as either "he" or "she." Yet for a long time, if you plugged the sentence *O bir doktor* into Google Translate, it would come back as, "He is a doctor." Switch *doktor to hemşire* — nurse — and the translation would read, "She is a nurse."

That was a bias in the Google Translate algorithm, and it stemmed from perceptions embedded in language and human minds. While this particular Google problem has been fixed, many others remain.

"Human beings are biased," says SFI External Professor Mahzarin Banaji (Harvard University). "So if you use the output from human minds to train an artificial system, it will by necessity learn the biases inherent in the human data."

It was an issue up for discussion at a June 1–3 SFI working group meeting titled, "Language as a window into mind and society." Banaji, a psychologist, organized the meeting as an opportunity for computer scientists, psychologists, and linguists to learn from each other's work.

The purpose of language is communication — but it's also much more. "We can elevate our mental states by the poems and novels we read," Banaji says. "We can also do terrible things with language. We can hurt people; we can lie and deceive."

Thanks to databases as wide-ranging as the Internet, researchers can now quantify such biases and harms by analyzing billions of words and sentences to determine how society associates certain groups of people based on race, ethnicity, gender, and other characteristics. For example, men are widely associated with engineering, technology, power, religion, sports, war, and violence, whereas women are associated with sex, lifestyle, appearance, toxic language, and profanities.

"This poses a very challenging socio-technical problem," says University of Washington computer scientist Aylin Caliskan, who presented her research on gender bias in word embeddings at the SFI meeting.

Machines use algorithms embedded with implicit bias to make crucial decisions that affect people's lives — everything from job candidacy and university entrance to recidivism prediction.

Caliskan gives an example of a woman applying for a tech job. If her resume contains words that reflect gender — a reference to a women's college or sports team, perhaps — machines may perceive her as a less-than-ideal fit for the job, which historically is associated with men.

"These are not very optimistic research findings," Caliskan says, although awareness of the problem is increasing.

As Banaji says, there is an aspiration that one day we will design machines that make better

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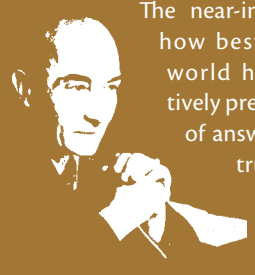
BEYOND BORDERS

PRECISION AND SOUL

We do not have too much intellect and too little soul, but too little precision in matters of the soul.

—Robert Musil



The near-infinite question of how best to describe the world has yielded a relatively predictable taxonomy of answers. At least this is true if we judge this question in terms of the species of avocation/profession, categories of object or artifact, and scholarly departments.

We are told that there are (and worse still that *we are*) scientists, artists, humanists, or electrical engineers, plumbers, and gardeners. The list is long and also disappointing. So much seems to be lost, or perhaps contracted, by the labels.

An alternative and, I think, more liberating approach is to look at the organic shaping of ideas over the course of careers, and thereby trace biographical territories that are explored and the many borders that are crossed in the making of minds. When Robert Musil wrote of precision in his essay, "Helpless Europe," in 1922, he was expressing an opinion that found its most complete expression in his encyclopedic novel, The Man Without Qualities:

"If there is a sense of reality, there must also be a sense of possibility. To pass freely through open doors, it is necessary to respect the fact that they have solid frames. This principle, by which the old professor had lived, is simply a requisite of the sense of reality. But if there is a sense of reality, and no one will doubt that it has its justifications for existing, then there must also be something we can call a sense of possibility. Whoever has it does not say, for instance: Here this or that has happened, will happen, must happen; but he invents: Here this or that might, could, or ought to happen. If he is told that something is the way it is, he will think: Well, it could probably just as well be otherwise. So the sense of possibility could be defined outright as the ability to conceive of everything there might be just as well, and to attach no more importance to what is than to what is not."

In a profound sense, it is the business of science to express as rigorously as it can a sense of possibility. Quantum mechanics has a very nice phrase, "counterfactual definiteness." It describes the perfectly reasonable meaning that can be attached to measurements that have not yet been performed. Einstein made a career out of proliferating thought experiments in a physical universe with very "solid frames" in order to reveal through a sense of possibility that it also has more doors than a Royal Palace.

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CREDITS

EDITOR: Katherine Mast

CONTRIBUTORS: Karen Coates, Carrie Cowan, Anthony Eagan, Natalie Elliot, William Ferguson, Lucy Fleming, John H. Miller, Stephen Ornes, April Reese, Julie Rehmeyer, and Aaron Sidder

DESIGN & PRODUCTION: Laura Egley Taylor

VP FOR SCIENCE: Jennifer Dunne

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

www.santafe.edu

SFI IN THE MEDIA

In April, as the COVID BA.2 variant emerged, **Sam Scarpino** spoke with *The New York Times*, *The Atlantic*, and ABC News about the challenges posed by inaccurate case counts.

Ricardo Hausmann spoke with *Nature* about what Russia's war in Ukraine could mean for energy, climate, and food. He also shared with *The Economist* his insights on European tariffs on Russian energy as a strategic tool.

MIT Press Review cited **Sam Bowles**' research on the Gini coefficient in their story, "The Archaeology of Inequality."

The New York Times considered advancements in AI language comprehension, citing a column published last year by **Melanie Mitchell**.

Australia's ABC Radio National featured a 2019 lecture by **Mark Pagel**, which asked if human tribalism is a curse of our evolutionary past.

ABC News spoke with **Jessika Trancik** global energy consumption and why renewable energy sources are critical for addressing climate change.

Forbes reported on **Dan Larremore** as one the three awardees this year's winners of the Alan T. Waterman Award — the National Science Foundation's most prestigious early-career honor.

Among *Mental Floss's* list of 15 of the most expensive things ever sold was **Cormac McCarthy**'s typewriter, a light blue Olivetti, which sold for over a quarter million dollars in 2009.

Where do space, time, and gravity come from?, *Quanta Magazine* podcast host Steve Strogatz wondered, asking **Sean Carroll** to weigh in on the quest for quantum gravity.

The New York Times Style Magazine takes a meander through the deep cultural and religious significance we humans have ascribed to food, featuring research by **Amy Bogaard** and **Sam Bowles** on the role that oxen in farming played in the rise of economic inequality.

There's more to bees than honey, writes *The Conversation* in a round-up of fascinating bee studies, which included **Orit Peleg**'s research into honeybee swarming behavior.

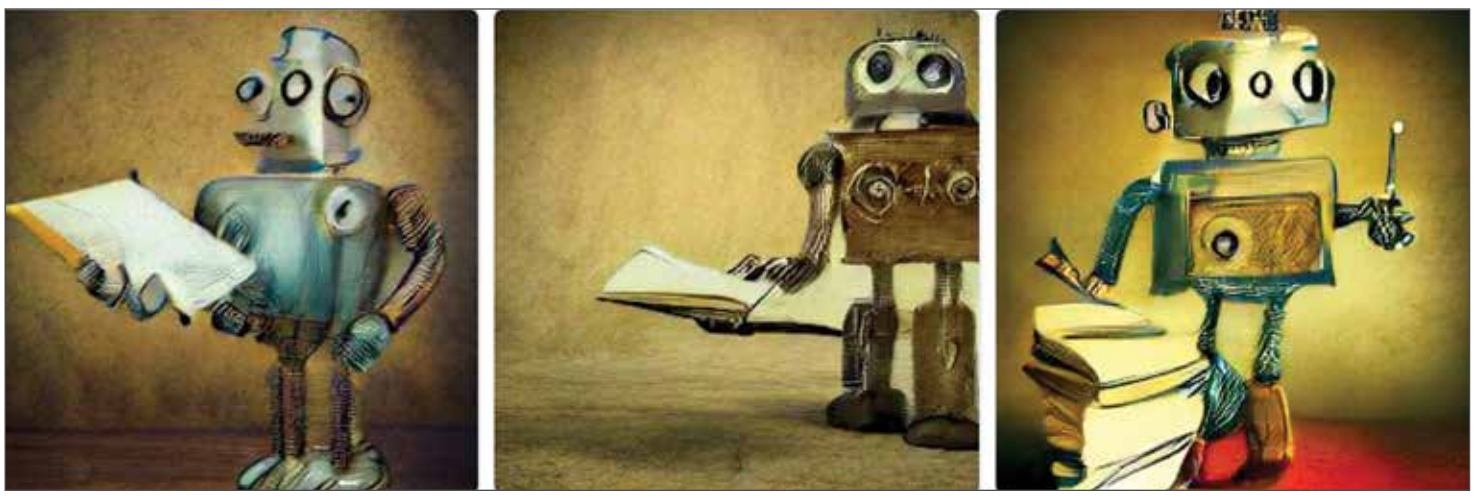
Parachute frogs that use their webbed toes to glide through tropical forests might offer insights into how other animals take to the sky, reports *Scientific American*, citing research by **Mimi Koehl** on dinosaur flight.

The Economist spoke with **Natalie Grefenstette** about the search for extraterrestrial life.

"There is no way to quantify the toll of all this gun violence — not even in a math class," writes **Dan Rockmore** in an op-ed for *Salon* on teaching math in a grieving classroom and broken world.

Bloomberg spoke with **Suresh Naidu** in a report on changes to income inequality in the U.S. during the pandemic.

The Wall Street Journal defends online anonymity, citing research by **Mahzarin Banaji** on its potential for reducing discrimination.



The above images were generated by DALL-E, a text-to-image generator which creates digital images from natural language descriptions. The text prompt for these was "retro vintage steampunk robot writing a book." (image: Laura Egley Taylor/SFI)

Literature's hottest new author: E. Machina?

Imagine a bookshelf that stretches far into the distance, laden with genre fiction: potboilers, romances, thrillers. Farther down, we glimpse the royal blue of a Fitzcarraldo edition.

The catch? Every book has the same author: *E. Machina*. They've all been written by AI.

To SFI External Professor Dan Rockmore (Dartmouth College), we're closer than we think to the world of that bookstore — a world where AI doesn't simply summarize financial reports or baseball games, as it does today, but where its work is even considered literary.

"Why wouldn't somebody one day subject machine-written literature to the same form of literary criticism to which we subject writing by humans?" asks Rockmore. Would that destroy the humanities, or expand their reach? How might it change the ways humans read, write, review, or teach literature?

These are among the questions floated by a working group titled "The Anxiety of the Computational," which will meet at SFI from August 15–17, 2022. Experts in machine learning and stylometry will be joined by literary studies scholars working across various time periods and languages. Together, they will discuss the past, present, and future of "computational poetics" — and the very human anxieties that attend them. Powerful language models such as GPT-3 make distinguishing AI's writing much trickier, and even "human" writing is influenced by algorithms, from auto-fill to AI coaches like Grammarly.

"Best case, [AI literature] opens new kinds of criticism that look more deeply, and *differently*, at the humanities," says Rockmore.

The future of computational poetics may be unpredictable, but we are certain to continue reading text written by AI, from the mundane to the possibly transcendent. After all, as Rockmore's imagined book critic puts it, "*E. Machina has a way of connecting the unexpected with the quotidian…*" That critic, of course, might one day be an algorithm, too.

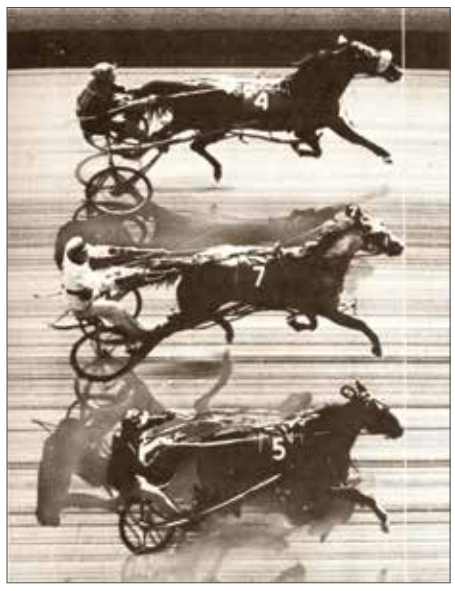
How to rank evaluations, according to physics

The world is rife with rankings and orderings. They show up in tennis — as in the French Open, which ends with a final ranking of champion players. They show up in pandemics — as when public health officials can record new infections and use contact tracing to sketch networks of COVID-19 spread. Systems of competition, conflict, and contagion can all give rise to hierarchies.

However, these hierarchies are observed after the fact. That makes it difficult to know the true rankings of the system: Who was actually the best player? Who infected whom? "You can't go back in time and learn exactly how this thing happened," says SFI Postdoctoral Fellow George Cantwell. One could build a model of the network and compare all possible outcomes, but such a brute-force approach quickly becomes untenable. If you were trying to rank some group with just 60 participants, for example, the number of possible permutations reaches the number of particles in the known universe.

For a recent paper published in *Physical Review E*, Cantwell collaborated with SFI Professor Cris Moore, a computer scientist and mathematician, to describe a new way to evaluate rankings. Their goal wasn't to find one true hierarchy, but to calculate the spread of all possible hierarchies, with each one weighted by its probability.

"We were willing to not be exactly right, but we wanted to get good answers with some sense about how good they are," Cantwell says. The new algorithm is inspired by physics: Ranks are modeled as interacting entities that can move up or down. Through that lens, the system then behaves like a physical system that can be analyzed using methods from spin glass theory.



The first triple dead heat in harness racing, Freehold Raceway, October 3, 1953 (image: Wikimedia commons)

Soon after the start of the COVID-19 pandemic, Cantwell and Moore began thinking about models of how disease spreads through a network. They quickly recognized the situation as an ordering problem that emerges over time, not unlike the spread of a meme on social media or the emergence of championship rankings in professional sports. "How do you order things when you have incomplete information?" asks Cantwell.

They started by imagining a function that could score a ranking on accuracy. For example: A good ranking would be one that agrees with the outcomes of matchups 98% of the time. A ranking that agrees with outcomes only 10% of the time would be lousy — worse than a coin flip without any prior knowledge.

One problem with rankings is that they're typically discrete, which means they follow the whole numbers: 1, 2, 3, and so on. That ordering suggests that the "distance" between the first- and second-ranked members is the same as that between the second and third. But that's not the case, says Cantwell. The top players in a game, worldwide, are going to be close together in terms of skill, so the difference between top-ranked players may be closer than it seems.

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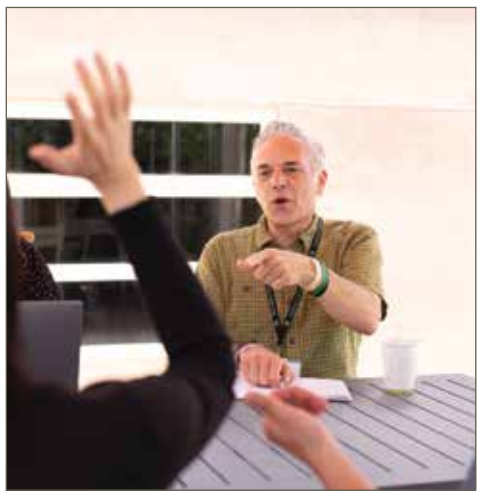











SCENES FROM A SUMMER DAY AT THE SANTA FE INSTITUTE: *Photographer Douglas Merriam recently caught these shots of participants in several of SFI's summer programs: Complex Systems Summer School, Graduate Workshop in Complexity and Computational Social Science, Advanced Graduate Workshop, and the Undergraduates in Complexity Research Program. (photos: Douglas Merriam)*

SFI SUMMER PROGRAMS: BACK IN FULL SWING

UCRs explore real-world problems

In 1993, SFI launched its first summer research program for undergraduate students. This summer, after two years as a remote, virtual experience, the Undergraduate Complexity Research (UCR) program returns to campus — just in time to celebrate its 30th anniversary.

The 2022 SFI UCR students are (back row, left to right): Daniel Cotayo, Yutaro Shimizu, Will Crockett, Quinn Bellamy, Levi Grenier; (front row, left to right): Katherine Li, Diana Citlali Avila Padilla, Charlie Crawford, Brady Dye

Over the past three decades, the UCR program — previously known as Research Experiences for Undergraduates (REU) — has brought nearly 250 students from more than 120 colleges and universities to SFI to conduct independent research. Over the course of 10 weeks, UCR students define and, with the guidance of SFI faculty, carry out a project that reflects their individual interests and priorities.

"Students arrive with a wide range of interests, and won't decide on a research topic until the second week," says SFI Director for Education Carrie Cowan. "The UCR students bring expansive creativity and enthusiasm — and they want their research to have impact in the world."

2006 REU alumna Oana Carja's summer research both provided real-world impact and changed the course of her career. A mathematics student with no prior interest in biology, she joined physicist Tanmoy Battacharya* and biologist Bette Korber* to study HIV. "I still remember walking into Bette's office that first day and being so awed when she told me: "our goal here is to find a vaccine for HIV. Let's see how you can help,'" says Carja. She went on to publish research about human genetics and disease, including HIV, and is now an assistant professor of computer science at Carnegie Mellon University.

Bryan Wilder, a 2013 alum, adds, "I remember SFI for its sheer intellectual vibrance, comparable to nowhere else, generated by scientists who engage honestly and deeply across fields." Wilder is currently a Schmidt Science Fellow at Harvard School of Public Health and Carnegie Mellon University, where he will soon join the computer science faculty. "My research still explores the interface between computation and the social world, following seeds planted that summer."

For many participants, some of the most important things to come from the UCR program are the relationships, which often persist far beyond the program's end. "I return to SFI often, for summer schools, workshops and talks," says Carja. "It still feels like coming home, every single time."

The UCR program has been supported by generous donors, foundations, and federal grants, including NSF Award 1757923 & NSF Award 1745355

**Tanmoy Bhattacharya (Los Alamos National Laboratory): SFI Resident Professor 2007–2017; SFI External Professor 2017–present. Bette Korber (Los Alamos National Laboratory): SFI researcher 1992–2004; External Professor 2004–2013.*

GWCCSS tackles impossible homework

For the past 27 years, SFI's Graduate Workshop in Complexity and Computational Social Science has invited 10 participants from around the world for a two-week intensive. Just a few hours before the workshop begins the participants are grouped into pairs who don't know one another and who study in different fields — sociologists may be paired with economists, anthropologists with physicists, and communications majors with political scientists — and they are given a homework assignment, due the following morning. It's an assignment intentionally designed without an answer.

GWCCSS participants: (back row, from left) Scott Page, Likun Cao, Kesong Cao, Laura Fürsich, Ben Preis, Elic Weitzel, Brandon Freiberg, John Miller; (front row) Qiankun Zhong, Shayla Olson, Herbert Chang, Elaine Yao (photo: Scott Wagner)

All five pairs puzzle over the same question, though the homework assignment varies from year to year and is often built from a real-world conundrum facing someone in the broader SFI community: How might you model a standing ovation? How do jokes travel through a community? What's the best method for passengers to board an airliner? The homework problems are completely open-ended and not something that the students have ever been exposed to in the course of their studies.

In just 21 hours, the teams work to find solutions to the assignment before presenting their research in the morning.

"The students display a remarkable degree of creativity as well as solid scientific insight during these presentations," says SFI External Professor John Miller (Carnegie Mellon University), who coordinates the Graduate Workshop with External Professor Scott Page (University of Michigan). Not surprisingly, no two teams take the same approach to the problem. "The large differences in foci, core assumptions, and analytic techniques, are a critical part of the exercise," says Miller.

During the rest of the workshop, the students draw on the various differences and similarities across each team's approach to the homework to hone their intuitions about what makes a useful model and the value of different approaches to solving the interesting problems in the world. "A side benefit," says Miller, "is that the students also realize that with only 21 hours, including some sleep, they can generate the core of a paper that, with some additional work, could be turned into publishable research."

At times, the question is more important than the answer.

How can non-equilibrium statistical physics be used to uncover fundamental physical constraints of computation in dynamic, highly non-equilibrium systems like computers? (photo: iStock)

Thermodynamics of computation: Central to not cooking the planet

Ten percent of carbon burned on Earth comes from devices like your cellphone, quietly computing even when you aren't looking at it.

Developing a greater understanding of the thermodynamics of computation like that done by your cellphone is critical to reducing energy use. It is also critical to understanding a host of deep, long-standing scientific problems.

The thermodynamics of computation governs the amount of energy used by complex systems that are not at equilibrium because they are constantly processing information and evolving. This includes everything from computers to the human brain, yet research in the field is almost non-existent.

To address the knowledge gap, the Santa Fe Institute is convening a panel of experts Aug. 15–17 for a workshop to identify challenges, opportunities, and priorities to push forward scientific investigations of this topic.

"Advances in non-equilibrium statistical physics over the last 20 years provide us with the tools for the first time to investigate the energetic attributes of non-equilibrium systems which is central for everything from physics to biology to not cooking the planet," said SFI professor David Wolpert. "In other words, we suddenly have this massive opportunity in science as a whole and we have no idea what we will find through that door."

Wolpert, along with former SFI Complexity Postdoctoral Fellow Joshua Grochow, a computer scientist at University of Colorado, Boulder, and other SFI collaborators, plans to discuss how the recent breakthroughs in non-equilibrium statistical physics can be applied to uncover fundamental physical constraints of computation in dynamic, highly non-equilibrium systems like computers.

They will focus on both naturally occurring and artificially distributed computational systems with three chief characteristics: they are distributed, comprising a set of spatially separated non-identical subsystems; the subsystems interact with one another in a hierarchical, modular network; there are substantial thermodynamic costs of communication among, and within, those subsystems.

> We suddenly have this massive opportunity in science as a whole and we have no idea what we will find through that door.

The National Science Foundation–sponsored* event will ultimately inform research to advance fundamental understanding and practical applications such as reversible computing.

Findings from the workshop will be collected in a report to the NSF, posted to the preprint server arXiv, and submitted to the *Proceedings of the National Academy of Sciences.*

** NSF Award 2145170*

Aviv Bergman on sabbatical at SFI

Imagine that we rewound life's tape to a distant past and let evolution play out again. Which species and traits would succeed the second time? Which characteristics would emerge over and over again, invariant to random chance?

Aviv Bergman of the Albert Einstein Institute of Medicine has come to the Santa Fe Institute to develop computational models designed to answer those questions. He points to a few traits we would expect to emerge consistently: Most animal species have bilateral symmetry, for example, suggesting that this feature is likely to be preserved. Another example he points to is that while humans might have evolved to typically have seven fingers rather than five, it's likely that whatever the number is, it would be consistent over nearly all people. Systemic properties like this are robust — in other words, they emerge consistently, even as the underlying system they're part of gets perturbed.

Aviv Bergman. Self-portrait

More generally, Bergman is trying to identify the laws, beyond natural selection, that govern the evolution not just of species but of all kinds of things that evolve: corporations, societies, political and economic structures, and even languages.

> Bergman is trying to identify the laws, beyond natural selection, that govern the evolution not just of species but of all kinds of things that evolve: corporations, societies, political and economic structures, and even languages.

After decades of affiliation with SFI as an External Professor, Bergman is spending six months on campus. "It's a very, very unique environment that enables you to sit back and think about questions that are 'forbidden' to be asked within normal academic environments," he says.

After his time at SFI, Bergman is launching a new institute, the Albert Einstein Institute for Advanced Study, which aims to solve major problems in the life sciences through much greater integration between pure scientific inquiry and the humanities. He points out that compared to physics, life sciences aren't yet rigorous. "The best way we know how to move forward is, for example, through the creation of narratives. Who is better than creating narratives than philosophers, historians, people in the humanities?"

Thermophiles, Norris Geyser Basin (image: NPS/Neal Herbert)

From life's possible metabolisms to life's general principles

From its inception in 2017, the Santa Fe Institute's Research Coordination Network* (RCN) has been bringing interdisciplinary researchers together to study life's possible origins. This summer, SFI will host two working groups through the RCN: "Feasible but Undiscovered Metabolisms," from July 11–16, and "Multiple Life," from August 22–26.

The first working group will take a comprehensive look at energetically feasible, but unknown metabolisms. "We know that plants do not use all wavelengths of light for photosynthesis — they don't use ultraviolet light as an energy source," notes SFI Professor Chris Kempes, who is a co-organizer for both working groups. "We want to think about where there are energy sources that could be harnessed by unknown metabolisms, and understand better the constraints that dictate the range of possible metabolisms," he says.

The second meeting will shift the focus from specific energetic systems and possible metabolisms to universal principles, explains Kempes. This meeting will take its starting point from a recent SFI paper co-authored by Kempes and SFI President David Krakauer, in which they argue that life is best understood as having originated multiple times. The meeting will be oriented around three sets of questions: How different could the material of life be across diverse origins? What are the laws that constrain life? What principles do we lack that we need to make progress to build or recognize unknown forms of life?

Alongside the meeting, SFI will conduct interviews with invitees to create SFI Press volumes, magazine articles, podcasts, and documentary films. "In the past, these meetings have generated white papers and collaborations within the research community," says Caitlin McShea, Program Manager for the RCN, "but in this meeting, we will add science-fiction writers to the discussion."

Kempes and McShea hope that both the workshop and the multimedia capture will allow SFI's researchers and public audiences to engage with the study of life's origins in an enticing new way.

**National Science Foundation Grant Number 1745355, under the Research Coordination Networks (RCN) program (RoL: RCN for Exploration of Life's Origins)*




Upcoming Community Lectures

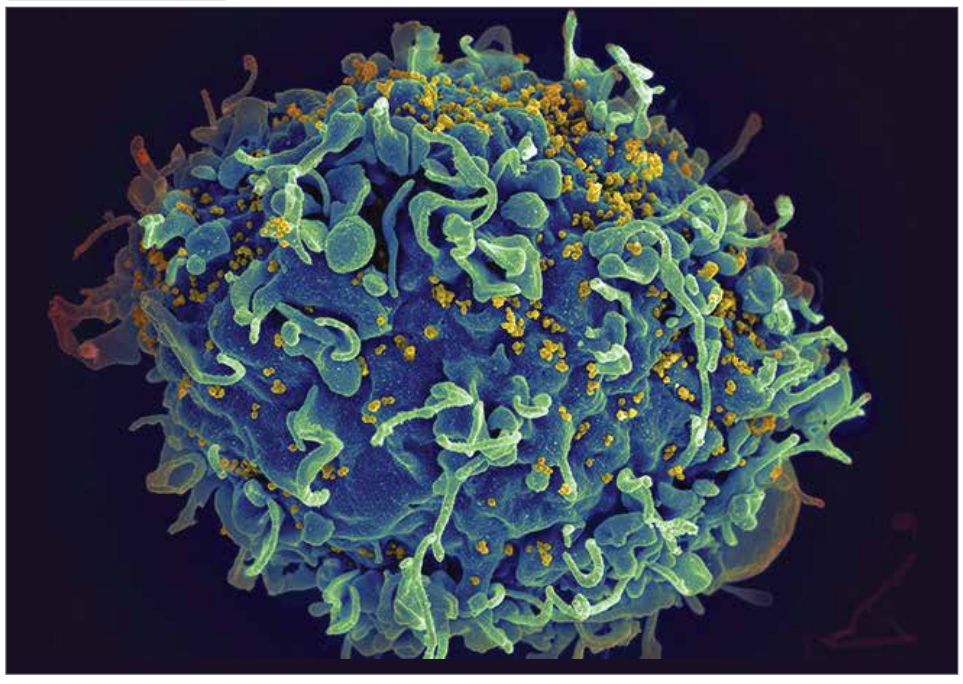
All SFI Community Lectures are presented at the historic Lensic Performing Arts Center in downtown Santa Fe and are free and open to the public. Seating is limited; tickets can be reserved at www.santafe.edu/community.

Those unable to attend in person can live stream these lectures from the Santa Fe Institute's YouTube channel at *santafeinst*

Tuesday, August 2 7:30 pm | Book signing 6:30 pm
ANDREA WULF *Santa Fe Institute*
The Invention of Nature: Alexander von Humboldt's New World

Tues. & Wed., Sept. 20 & 21st 7:30 pm
Stanislaw Ulam Memorial Lectures
STEVEN STROGATZ *Cornell University*
Mathematical Stories:
Tuesday, Sept 20: *The Story of Calculus*
Wednesday, Sept 21: *The Story of Sync*

Tuesday, Oct 18 7:30 pm
"HUMAN SOCIAL NETWORKS"
A panel discussion, featuring:
JESSICA FLACK, *Moderator Santa Fe Institute;*
NICHOLAS CHRISTAKIS *Yale University;*
MATT JACKSON *Stanford University; Santa Fe Institute*



HIV, the AIDS virus (yellow), infecting a human cell (image: ZEISS Microscopy)

What's next for theoretical immunology?

The immune system is almost fantastically complex, and many basic questions remain unanswered about how it manages to keep us safe from intruders without attacking our own tissues. SFI researchers helped pioneer the field of theoretical immunology, seeding a vibrant community of modelers whose work has led to new HIV treatments, better methods to choosing vaccine strains, and improved cancer immunotherapy treatments. The connections have also helped create improvements in computer science, with applications in security, anomaly detection in manufacturing, robotics, and more.

A June 8–10 working group, "Distributed Computing Perspectives on Theoretical Immunology," gathered a diverse community of researchers to revisit classic problems in immunology and ask what new questions have arisen, taking advantage of recent developments in both biology and computer science.

Consider, for example, the now-famous spike protein on the new coronavirus. The immune system recognizes the virus by targeting the spike protein and a few other antigens, ignoring many other proteins on the surface that might serve as red flags for the intruder. This strategy gives the immune system fewer proteins to remember and reduces the chances that it will react to the body's own proteins, creating autoimmunity — with the downside that a few mutations in those key proteins can allow the virus to effectively don an invisibility cloak. This raises questions that an algorithmic mindset might shed light on: How does the immune system decide which proteins to remember? How might we quantify the trade-offs of this strategy compared to alternatives, particularly with pathogens that evolve quickly, like the novel coronavirus or the flu?

Another example of an area ripe for exploration is the analogy between cybersecurity and immunity. By comparing the two systems, the workshop planned to tackle questions including: *When does an effective defense invite increasingly damaging attacks?*

Another example of an area ripe for exploration is the analogy between cybersecurity and immunity. By comparing the two systems, the workshop planned to tackle questions including: When does an effective defense invite increasingly damaging attacks? Can defense be structured to make less damaging attacks advantageous to the attacker? Can some attacks simply be tolerated, so that the attackers face less evolutionary pressure, with the goal of creating an equilibrium in the arms race?

This team of computer scientists, mathematicians, experimental immunologists, and modelers aims to crack these puzzles and more.

This working group was co-hosted by SFI External Professor Stephanie Forrest (Arizona State University), Saket Navlakha (Cold Spring Harbor Laboratory), and Joshua Daymude (Arizona State University)

Illuminating the structure of technology

In the last decade, SFI External Professor Ricardo Hausmann has reflected on the ways that economists conceive of technology. So far, he thinks that they don't have a clear picture. "Technology is, in economics," he says, "what dark matter is, in physics: we don't see it, but we infer its effects."

Hausmann, an economist at Harvard University and co-chair of the SFI Science Board, hopes a June 14–16 SFI workshop, "The Structure of Technology," will help researchers develop better frameworks to capture how technology emerges, takes shape, and shapes the world in turn. The workshop is the first of a series of meetings that are taking place through SFI's Emergent Political Economies grant and research theme.

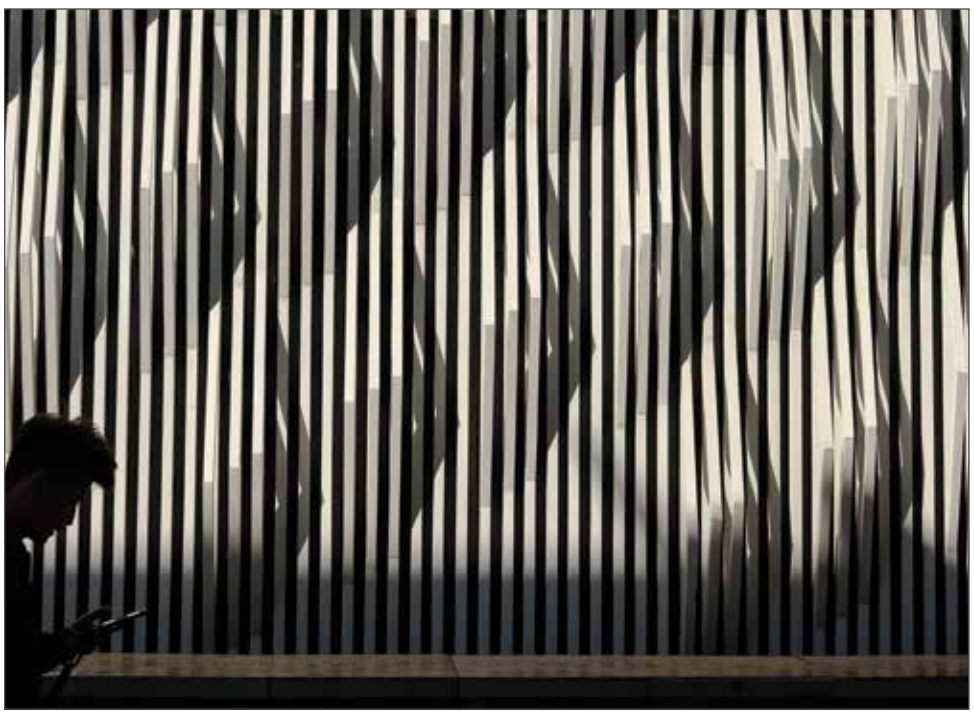
SFI External Professor Hyejin Youn (Northwestern University), who co-organized the workshop with Hausmann, anticipated that the group would look for common patterns in how technological objects — from cell phones to bombs — are formed, as well as for organizational structures that operate on different scales. Technological processes happen simultaneously in different spaces, she says, "in production space, in trade space, in idea space." They are also deeply intertwined with social structures, she emphasizes.

Like Youn, Hausmann is interested in exploring technology in relation to the social world. Humans store technology in three different forms, he explains: in things (like tools), in code, and in brains. Because technology takes different forms in brains, "it forms networks of knowledge," and these networks are themselves complex systems.

A central part of the workshop will involve developing language and mathematics that illuminate the dynamics of technology. For former SFI Graduate Fellow James McNerney, a Harvard research scientist and the third co-organizer of the workshop, this may involve the creation of a lingua franca. "There is a Rosetta Stone that connects machine learning and statistics," he explains. "Similar bridges are possible here, too."

Ultimately, the organizers anticipate that developing new conceptual frames for researchers who study technology in different fields will allow them to build deeper theories.

**Funded by NSF Award 2034026 and the Omidyar Network's Emerging Political Economies grant*



(photo: Tim Jamieson/Unsplash)

POLITICAL ECONOMY OF CLIMATE CHANGE *(cont. from page 1)*

carbon prices is that U.S. patents in green technology have been declining.

The talks sparked a lively discussion. SFI Professor Sam Bowles, for example, argued that changing the structure of global energy systems is not simply a matter of creating new incentive structures. "I have a slogan," he said: "Green incentives are no substitute for green citizens." He emphasized that we need a new economic theory that does not consider human values to be static.

SFI Professor Ricardo Hausmann,* who now joins SFI Professor Melanie Mitchell as Science Board Co-Chair, helped synthesize different threads of the meeting. The choice is not between becoming less prosperous or emitting less CO_2, he summarized. Instead, the process of advancing technologies and policies that reduce emissions can create growth. "I think that the focus should be on making economies prosper while reducing emissions," he said. "The secret of growth is the growth of knowledge."

**Dan Schrag: Harvard University; David Victor: UC San Diego; Lint Barrage: UC San Diego and ETH Zurich; Ricardo Hausmann: Harvard University*

RANKING *(cont. from page 2)*

"You quite often see that lower-ranked players can beat higher-ranked players, and the only way the model can make sense and fit the data is by squishing all the ranks together," says Cantwell.

Cantwell and Moore described a system that evaluates rankings based on a continuous numbering system. A ranking could assign any real number — whole number, fraction, infinitely repeating decimal — to a player in the network. "Continuous numbers are easier to work with," Cantwell says, and those continuous numbers can still be translated back to discrete rankings.

In addition, this new approach can be used for predicting something about the future, like the outcome of a tennis tournament, and also inferring something about the past, such as how a disease has spread. "These rankings could tell us the order of sports teams from best to worst. But they could also tell us the order in which people in a community became infected with a disease," says Moore.

"Even before his postdoc, George was working on this problem as a way to improve contact tracing in an epidemic. Just as we can predict which team will win a game, we can infer which of two people infected the other when they came in contact with each other."

In future work, the researchers say they plan to investigate some of the deeper questions that have emerged. More than one ranking might agree with data but disagree radically with other rankings, for example. Or a ranking that seems incorrect may have high uncertainty but not be inaccurate. Cantwell says he also wants to compare the model's predictions to outcomes from real-world competitions. Ultimately, he says, the model might be used to improve predictions in a wide range of systems that lead to rankings, from infectious disease models to sports betting.

Cantwell says he'll hold on to his money — for now. "I'm not quite ready to start betting on it," he says.

ITALIAN MEETING *(cont. from page 1)*

physics, epidemiology, social science, and more.

"The point of this conversation is to try and come up with interoperable standards — or a science-based consensus — for sustainability," adds Krakauer. "Sustainability is not the domain of any one discipline."

Krakauer is organizing the workshop with SFI Science Board member Simon Levin (Princeton University), Matteo Marsili, a research scientist at ICTP, and several other Italian scientists. The organizers' intent is that the workshop will spur new cross-discipline collaborations.

"We are trying to build partnerships among scientists, humanists, and decision-makers who wouldn't normally be talking to each other," says Levin. "The nature of the problems has changed, so the nature of the solutions has to change too."

LANGUAGE *(cont. from page 1)*

decisions than humans do. After all, language is a reflection of humanity's wondrous potential.

"Some of the gifts that evolution has given our species, such as language, are so basic and so familiar to us that we just fail to be gobsmacked by it as we should be," she says. "We should be just astounded by the capacity, and its role in improving judgment and decisions."

BEYOND BORDERS *(cont. from page 2)*

In the spirit of expanding our sense of possibility, SFI and the SFI Press are starting a new magazine of interviews, featuring our Miller Scholars (artists, historians, and humanists) and Fractal Faculty (distinguished sabbatical researchers) in collaboration with our partners at *Santa Fe Magazine*. It will be called *ExtraTerritorial*. We are borrowing the title from George Steiner's book of the same name in which he describes the paths of linguistic nomads defying the borders of cultural identity. Through interviews that connect the zigzag of a life to the accretion of ideas we hope to lend some precision to matters of the soul.

— David Krakauer
President, Santa Fe Institute

Researchers look at the paradox of masking and disease

Much research has been done on the effectiveness of masks to mitigate the spread of infectious diseases. However, standard infection models tend to focus only on disease states, overlooking the dynamics of a complex paradox: While masking reduces transmission rates and consequently disease prevalence, the reduction of disease inhibits mask-wearing — thereby promoting epidemic revival.

To investigate this bi-directional relationship, a team led by researchers at the University of Virginia*, developed a multi-contagion framework and intertwined a threshold model for mask-wearing behavior, or "social contagions," with an epidemic model. The threshold model accounts for various behavioral mechanisms that influence mask-wearing, such as peer pressure, fear of infection, elite influence, and prosociality.

In their paper, "Understanding the coevolution of mask wearing and epidemics: A network perspective," published in the *Proceedings of the National Academy of Sciences*, the researchers posit that the final epidemic size (or attack rate) of a disease exhibits a critical transition when populations assume the disease spreading is more infectious, triggering a sustained massive response of mask adoption which sharply decreases the final epidemic size.

While masking reduces transmission rates and consequently disease prevalence, the reduction of disease inhibits mask-wearing — thereby promoting epidemic revival.

The conundrum is that when disease rates are low, mask-wearing becomes an afterthought, and a less infectious disease could cause a higher attack rate than its more infectious counterparts.

Results highlight that without proper enforcement of masking, reduction in the disease transmission probability via other interventions — such as mass vaccination — may not be sufficient to reduce the final epidemic size. This was the case in a resurgence of COVID-19 cases in the U.S. after vaccinations when the number of new daily cases jumped by approximately an order of magnitude from early June 2021 to early September 2021.

"Interdisciplinary models are absolutely critical for helping refine our assumptions," says SFI Complexity Postdoctoral Fellow Stefani Crabtree (Utah State University), who contributed to the research. "The findings have helped me to not bow to peer pressure. I'm still masking at grocery stores and in crowded areas because, even though I am vaccinated, I know it will help."

Mask-wearing plays a critical role in curbing rates of disease transmission. (photo: Yoav Aziz/Unsplash)

In their study, the researchers described mask-wearing as a "complex contagion" whose adoption requires multiple interactions and sources of reinforcement to produce the "contagion" and help model behavioral adoption (switching from masked to unmasked and vice versa). This is opposite to disease transmission for which a single contagion would be enough to transmit the disease.

While mandatory masking may be viewed as cumbersome and expensive, mathematical models incorporating individual adaptive human behavior during epidemics have shown the essential role of continuous reinforcement of masking in minimizing epidemics.

"An even larger issue to tackle is how polarized our society is," says SFI Science Board Member Simon Levin (Princeton University), a co-author on the paper. "I have never in my lifetime seen individuals so divided over something I consider commonsense public health measures."

**Authors include a prestigious international team of researchers from the University of Virginia; University of Amsterdam; Princeton University; Northeastern University; Utah State University; Santa Fe Institute; Stockholm School of Economics; and Cornell University.*

Adapted from the University of Virginia's press release, Researchers Show Mask-Wearing is Critical in Suppressing and Epidemic (June 23, 2022).

Exploring and expanding the boundaries of music

Bach's Well-Tempered Clavier, a collection of fugues and preludes, is regarded as one of the greatest works in the history of classical music. Caught up in its emotional power, the last thing on your mind might be the music's intricate compositional mechanics. But those complexities have long captivated composer and physicist Marco Buongiorno Nardelli and physicist Miguel Fuentes,* both SFI External Professors.

Almost three years ago, the pair formed an SFI working group to apply network theory to the study of music in hopes of learning more about its complex structures and patterns — and how these new insights could expand the possibilities for composition. The first in-person meeting of the group, "Complexity and the Structure of Music II: Universal Structures and Evolutionary Perspective Across Cultures," was held at SFI May 17-20, 2022.

The meeting aimed to expand the boundaries of our understanding of music by pooling the expertise of researchers from even more disparate backgrounds than the first gathering, held via Zoom in December 2020, Fuentes says. "We are trying to take a step forward and bring in more people to open up the discussion."

The event launched with a pre-meeting public concert held at SITE Santa Fe on May 16 with performances by working group participants Buongiorno Nardelli, David Stout, Dmitri Tymoczko,* and other artists.

"It was a very interactive, very creative, complexity-based event in which all these people that were invited, who are all very bright in their own field, kind of played around with this idea of music complexity," Buongiorno Nardelli says.

While the working group initially discussed musical elements like harmony and structure that are common in Western music, it plans to explore musical structures and people's experience of music in non-Western cultures as well, adds Fuentes, whose work with the group includes developing ways to quantify the degree of complexity in different elements of a piece of music, such as structure or tempo changes. "We will need to produce another set of tools just to analyze non-Western music," he says.

The group's work has already attracted an unusual amount of public attention — an unexpected side benefit that organizers hope will lead to a greater appreciation of the complexity embedded within the music that moves us. Some videos of the working group's inaugural meeting have tallied more than 1,500 views. "For such an academic topic, it's somewhat astonishing," Buongiorno Nardelli says.

**Marco Buongiorno Nardelli (University of North Texas); Miguel Fuentes (Argentine Society of Philosophical Analysis); David Stout (University of North Texas); and Dmitri Tymoczko (Princeton University)*

The working group brought together network and complexity scientists, musicologists, music theorists, composers, performers, and neuroscientists to explore the intersections of music and complexity from as many angles as possible. (image: Stefano Ciociola/Unsplash)

What we're reading

Books chosen by SFI scholars on the theme of Myths

What is a myth? Like so many other seemingly simple terms, "myth" cannot be accurately defined, but we all know one when we see one: Prometheus, Narcissus. The Fall from Eden. Nonetheless, two twentieth-century authors have made compelling points about myth which, taken together, may capture something essential.

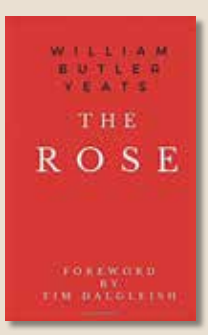
C.S. Lewis, in his book An Experiment in Criticism, wrote that myth is "a particular kind of story which has a value independent of its embodiment in any literary work…the first hearing is chiefly valuable in introducing us to a permanent object of contemplation."

Half a century later, in his book The Soul of the World, Roger Scruton ventured that myth "is a fiction, although a fiction that illustrates the truth." A myth, then, is a pre-logical conception of human truth that is an eternally relevant, inexhaustible source of art and ritual, one that forever remains beyond the grasp of science. Often, the greatest myths involve deep contradictions that fill in the negative space that science has yet to penetrate.

In this edition of "What We're Reading," we celebrate myths old and new. Each selection deals with those permanently captivating "true fictions" that shape our lives and ground our self-understanding — those completely mysterious, permanent objects of contemplation.

MAELL CULLEN
SFI Postdoctoral Fellow

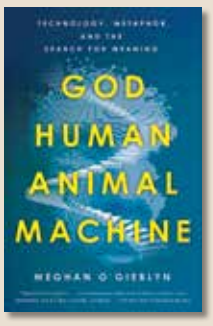
***The Rose*, by W.B. Yeats**



In a period of political turmoil, a young man in the throes of unrequited love explores modern futility through Irish mythology. In the wake of Cuchulainn's battle with the sea, you may consider going with Fergus, the wandering King, and abandoning your sense of self entirely.

STUART FIRESTEIN
SFI Fractal Faculty
(Columbia University)

***God, Human, Animal, Machine: Technology, Metaphor, and the Search for Meaning*, by Meghan O'Gieblyn**



O'Gieblyn is an original voice in the chatter over free will, immortality, the singularity, and all the rest of the topics du jour. Although of an atheist bent, her stance does not renounce the importance of religious yearning. Instead, her work is a recognition that our present technological ambitions — AI, immortality, robotic everything — are a reflection of the same desires and beliefs about life as those of early monotheistic cultures. The comparisons she is able to draw are both jarring and enlightening.

CAITLIN MCSHEA
Director: InterPlanetary;
Program Manager:
Miller Omega, Origins
of Life, Complex Time

***The New Science*, by Giambattista Vico**

When a community tries to understand the world through a shared rhetoric, a "culture of the best humanity" arises. This "poetic work" as Vico describes it is the first step towards wisdom, and it manifests itself historically in myth-making. For Vico, the constituents of myth — memory, imagination, imitation, and wonder — are the necessary pre-conditions for rationality.

SFI welcomes new postdoctoral fellows

VERONICA CAPPELLI

Many researchers at SFI are driven by a curiosity to understand the laws that underlie various forms of life. Work spearheaded more than two decades ago by SFI's Geoffrey West, Brian Enquist, and Jim Brown has illustrated that organisms' biological functions are governed by scaling laws. Other researchers have gone on to discover that human social life, from cities to organizations, follows similar rules. "These laws apply, with their own specificities, across domains," says Veronica Cappelli, an SFI Applied Complexity Postdoctoral Fellow. "What I find extraordinary is our ability to infer these higher-level laws governing processes that are incredibly complex and cognitively distant from us. Observing the presence of scaling behavior across such a wide variety of domains, from biological to social, evokes a sense of unity and connectedness in a seemingly chaotic world."

Following an M.Sc. in economics and social sciences and an M.Phil. in statistics from Bocconi University, Cappelli completed her Ph.D. in economics and decision sciences at HEC Paris in 2020.

Long captivated by the beauty of mathematics and fascinated by the human mind, Cappelli studies decision theory, researching the laws that underlie human thought, specifically in an organizational context. "I believe that it is important to understand and model behavior of economic agents correctly," she says. "Trying to understand these laws of behavior is the first step in designing optimal policies including, for instance, those that incentivize firms to act in ways that benefit society." *Arriving Aug., 2022.*

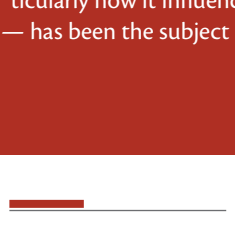
ARSENY MOSKVICHEV

Our sophisticated use of language is a key part of what makes us human. As far as we know, no other animal is capable of, say, using an apples-and-oranges analogy to help explain the difference between two things or of summarizing the key points in a Ph.D. dissertation.

New Program Postdoctoral Fellow Arseny Moskvichev is fascinated by how people use language and abstraction to communicate and share knowledge. Moskvichev, who received his Ph.D. from UC-Irvine, where he worked closely with advisor Mark Steyvers, is particularly interested in using insights from cognitive science and machine learning to advance language capabilities in artificial intelligence systems. His dream, he says, is to see Natural Language Processing AI models become capable of having meaningful conversations and even change their beliefs.

At SFI, Moskvichev will work with Professor Melanie Mitchell to solve the problem of how to measure abstraction and the analogy-making capabilities of AI systems.

Moskvichev holds a B.Sc. in psychology and an M.Sc. in neuroscience from St. Petersburg University, as well as a Ph.D. in cognitive studies and an M.Sc. in statistics from UC-Irvine. *Arriving summer 2022, supported by NSF EAGER Award 2139983.*



KELLE DHEIN

When we think of the information age, the first thing that typically comes to mind is computers and the easy access to information of any kind that they allow. Rarely do we question what information is. But in the realm of the philosophy of science, the concept of information — particularly how it influences how biological studies are designed — has been the subject of debate for decades.

Complexity Postdoctoral Fellow Kelle Dhein hopes to shed new light on this debate by exploring how particular concepts of information influence present-day research in the behavioral sciences. He'll draw on his background in the history and philosophy of science to explore how researchers who study experimental animal behavior use concepts about information to compare human and non-human systems. His project at SFI, "Humans, Animals and Machines: Behavior in the Information Age," will build on Dhein's past work on how scientists use concepts of information to justify certain claims about behavior.

Dhein, a member of the Diné (Navajo) tribe, is also interested in Indigenous data sovereignty and is a consulting bioethicist at the Native BioData Consortium. He holds a Ph.D. in history and philosophy of science from Arizona State University and undergraduate degrees in biology, philosophy, and anthropology, also from ASU. *Arriving Sept., 2022., supported by the Ford Foundation.*

JAMES HOLEHOUSE

How do the regulatory systems of governments change as they grow? Do bigger governments require more or fewer bureaucrats per capita? Are more efficient bureaucracies possible? Program Postdoctoral Fellow James Holehouse is fascinated by how complex systems, from governments to cells, change over time.

Working with SFI Professor Sidney Redner under an NSF Rules of Life grant, Holehouse joins a team of SFI researchers working on these questions. The project relies on toy models — ones simple enough to be studied analytically but which include the most important aspects of a regulatory mechanism. "A well-posed toy model would allow us to answer questions across a range of topics," says Holehouse. "For example, how many air traffic controllers are required for a given number of planes? Or how many 'regulatory genes' are required for a genome of a given size?"

Holehouse holds a Ph.D. in mathematical biology and an M.Phys. in theoretical physics, both from the University of Edinburgh, and comes to SFI following an internship at Cambridge Econometrics where he develop a stochastic modeling toolkit to study economic systems. At SFI, he'll draw on the principle of network motifs to explore what conditions support stability in a regulatory network, and whether network structures in larger regulatory networks are similar to structures in smaller ones. *Arriving Oct., 2022., supported by NSF Award 2133863.*

PEDRO MÁRQUEZ-ZACARÍAS

In biology, hierarchies are everywhere, from Linnaean taxonomy — the system we use to classify living things — to the social organization within a pod of gorillas. Biological hierarchies are often explained by the Major Evolutionary Transitions (MET) framework, which holds that evolutionary processes gave rise to life's hierarchies.

But this framework has some missing pieces, Complexity Postdoctoral Fellow Pedro Márquez-Zacarías suggests. One is its lack of a formal notion of biological autonomy — an idea central to our understanding of living systems. Another is understanding the role of life cycles in how hierarchies persist across generations.

At SFI, Márquez-Zacarías will examine these shortcoming by exploring two key questions through the lens of multicellular evolution: How do organisms acquire autonomy? And what are the elemental processes of a given life cycle?

Márquez-Zacarías, an evolutionary biologist, also plans to study an entirely different evolutionary topic: language. He will explore why the Purépecha language, which is spoken in his hometown of Urapicho, México, is a "language isolate," meaning it has no evolutionary relationship to any other language.

Márquez-Zacarías holds a Ph.D. in quantitative biosciences from the Georgia Institute of Technology. *Arriving Oct., 2022., supported by the Omidyar Network.*

DANIEL MURATORE

The COVID-19 pandemic is a cruel reminder of the profound impact viruses can have on human health. Equally important is the effect viruses have on ecosystems. In oceans, for example, just one teaspoon of seawater harbors millions of viruses. They are the most abundant biological entity on Earth, and they may play a key role in the carbon cycle. Yet quantitative data on their impacts are still sparse, so global ecosystem models do not account for them.

SFI Complexity Postdoctoral Fellow Daniel Muratore hopes to help fill that gap in understanding. They study how marine viruses influence the movement of carbon from the surface to the deep ocean — a major carbon reservoir. To decode how viruses affect microbes and nutrient cycles in the ocean, they use methods from a variety of disciplines, including theoretical ecology, machine learning, microbial ecology, and biogeochemical modeling.

At SFI, Muratore, who is equally at home collecting samples from the open sea as analyzing large data sets at a computer, plans to build on their experience unlocking the secrets of marine microbes and carbon cycles to come up with a theoretical framework for understanding the role of viruses in the "export" of organic matter to the deep ocean. They also aim to create new collaborations among theorists and empiricists to help further understanding of the variability in carbon fluxes at a global scale. Ultimately, Muratore hopes this work will help improve global ecosystem models — and our understanding of Earth's response to the changing climate. *Arriving Sept., 2022, supported by the Omidyar Network.*

JACK SHAW

The climate and biodiversity crises are stressing wildlife species around the world in unprecedented ways. Some are migrating up mountainsides to escape the heat. Others are turning to new kinds of prey to make up for the loss of their preferred food sources. But one limitation in studying how animals are dealing with these twin crises — and will in the future — is that a warming world will bring changes that humans have never seen. A species' evolutionary past, however, can help shed light on its fate in the face of future environmental change. Helping to fill in these crucial data gaps is the focus of Complexity Postdoctoral Fellow Jack Shaw's work at SFI.

Shaw's previous research focused on identifying how the lack of fossilized soft-bodied organisms — few of which survived the ravages of time for today's scientists to find and study — skewed our understanding of ancient food webs. At SFI, using network analysis, he is building on that knowledge of ancient creatures to help advance our understanding of how previous mass extinctions and climate change events have shaped animal communities, with the goal of using those insights to better predict how modern-day animals might respond to future environmental changes.

Shaw holds a Ph.D. in earth and planetary sciences from Yale and a B.A. in geology and philosophy, politics and economics at Lafayette College. *Arriving Sept. 2022, supported by the Omidyar Network and a Paleontological Association Grant Award.*

Ricardo Hausmann named Science Board Co-chair

SFI External Professor and Science Board member Ricardo Hausmann (Harvard University) was named Co-Chair of SFI's Science Board at the board's 2022 spring meeting.

The Science Board's main role is to advise the President and Board of Trustees on the Institute's scientific strategy. Hausmann joins SFI Professor Melanie Mitchell, who has co-chaired the board since 2019 with External Professor Daniel Schrag (Harvard University).

"I am excited to serve as Co-Chair of the Science Board of SFI, a truly unique place," says Hausmann. "I have benefited enormously from its approach, which has been profoundly influential in my thinking. I hope to be able to pay back some of the intellectual debt I owe the institution."

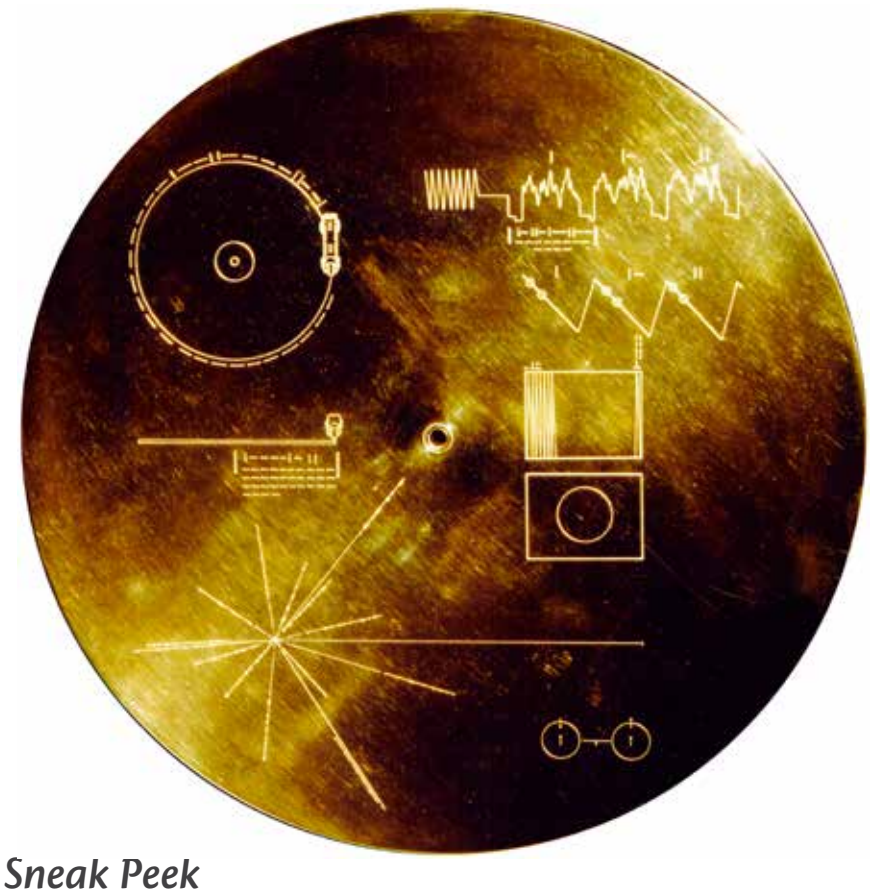
Since 2000, Hausmann has been a professor at Harvard University's Kennedy School of Government, where he is the Rafik Hariri Professor of the Practice of International Political Economy. In 2006, he founded Harvard's Growth Lab, a group of some 50 full-time researchers that work on the issues of inclusive and sustainable growth, covering theory, empirics, and policy work with governments across the world. He has been an External Faculty of SFI since 2011 and a member of the Science Board since 2019.

But Hausmann has not just been an academic: his professional experience includes stints as Minister of Planning and member of the board of the Central Bank of Venezuela, as well as Chief Economist and Director of Research of the Inter-American Development Bank. He has helped governments in over 40 countries hone their economic growth strategies.

Ricardo Hausmann.

"Ricardo brings a unique combination of deep practical experience and rigorous systems thinking to issues of political economy," says SFI President David Krakauer, "And he is a mensch. What more could we ask for?"

Vice President for Science Jennifer Dunne adds, "I am delighted that Ricardo Hausmann is joining the leadership of our distinguished Science Board. His enormous scholarly and real-world impact on international development and economics is deep, broad, and fundamentally informed by complexity science approaches. As SFI begins our new program on Emergent Political Economies, funded by the Omidyar Network, Ricardo is poised to provide and elicit the best possible perspectives and advice on that and other SFI research initiatives."



Sneak Peek

InterPlanetary: Voyager to launch in October 2022

This October 22 & 23, SFI will reprise the InterPlanetary Festival. In partnership with SITE Santa Fe, this year's festival offers an intimate setting with limited seating, and content simulcast in theaters throughout Santa Fe and streamed online.

As in years past, SFI researchers and invited InterPlanetary intellectuals will explore deep questions in complexity science while also enjoying classic science-fiction film screenings, book signings, experimental musical performances, keynote lectures, bespoke beverages, and a late-night, dark-matter dance party.

The final itinerary is still being confirmed, but here's a sneak peek of the panels, films, and speakers already on the docket:

Panels: When Will We Need a Theory of Intelligence? • Will Space Limit Human Performance? • Complex Conceptions of Time • Life and its Objects • The Complex Space of Political Economies

Films: *Ikarie-XB 1* • *Colossus: The Forbin Project*

Speakers: David Krakauer • Melanie Mitchell • Jessica Flack • Brandon Ogbunu • Ashton Eaton • Nina Lanza • Carolyn Porco • Sara Walker • Caleb Scharf

Parallax

SUMMER 2022

THE NEWSLETTER OF THE SANTA FE INSTITUTE

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ACHIEVEMENTS

SFI External Faculty Fellow **Wendy Carlin** was elected to the American Academy of Arts and Sciences.

SFI Research Development Director **Susan Carter** received a Mentoring Award from the National Organization of Research Development Professionals.

SFI Board of Trustees Chair **Katherine Collins** received a Harvard Gomes award.

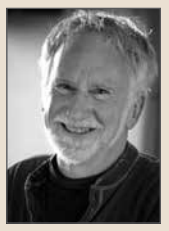
SFI External Professor **Tim Kohler** was elected to the National Academy of Sciences.

External Professor **Mark Newman** was named a Fellow of the Royal Society.

Wendy Carlin

Susan Carter

Katherine Collins



Tim Kohler

Mark Newman

RESEARCH NEWS BRIEFS

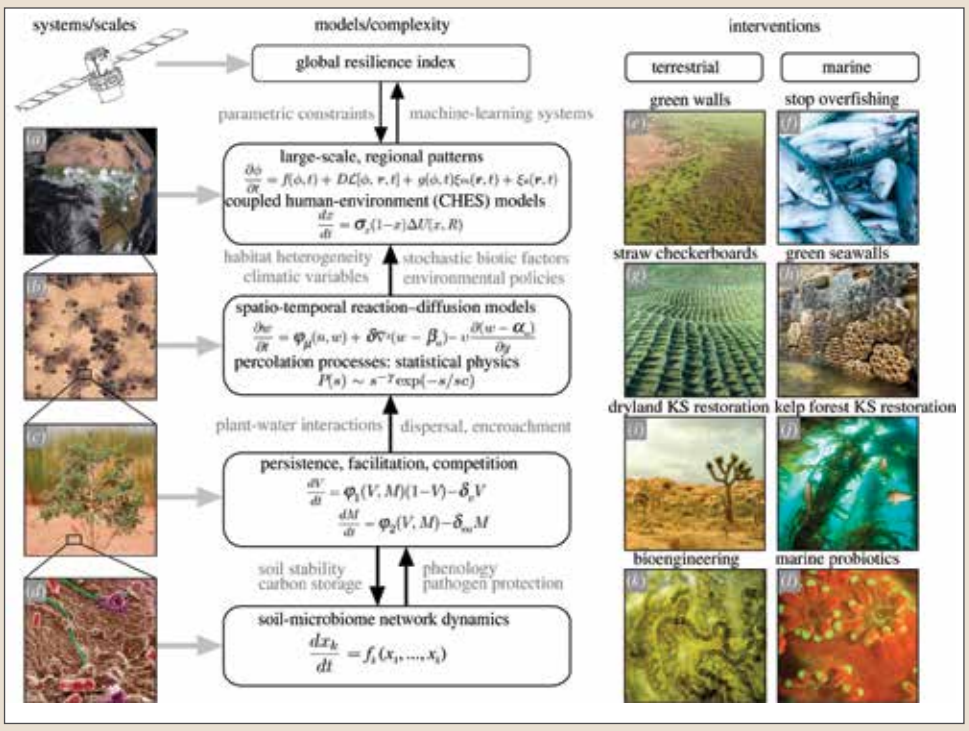


Figure 2 from "Ecological Complexity and the Biosphere: The Next 30 Years." *Scales, models and interventions — Our understanding of different patterns and processes in ecosystems, from molecules and cells to the global climate can be explored by a diverse range of mathematical models (central column). Each model addresses a different scale and answers a specific question about that scale.*

ECOLOGICAL COMPLEXITY AND THE BIOSPHERE: THE NEXT 30 YEARS

In 1972, the report *Limits to Growth* showed that business as usual on a planet with limited resources and a rapidly expanding human population can only end up in unsustainable growth and collapse. The report was inspired by systems science, a precursor to today's complexity science. Now it's time to update that work using the tools developed over the last half-century, as SFI External Professor Ricard Solé (Universitat Pompeu Fabra) and Science Board member Simon Levin (Princeton University) write in the introduction to a special issue of *Philosophical Transactions of the Royal Society B.* The themed issue explores the role that complex-systems science will play in our understanding of the crucial changes facing Earth's biosphere in the next three decades.

We can now develop far more granular models, incorporating geographical variation, with scales ranging from soil-microbiome networks to plant-water interactions to coupled human–environment systems. And the development of complex-systems science allows us to better model tipping points, a key feature of climate change and environmental collapse, as well as potential intervention scenarios.

Read the paper at doi.org/10.1098/rstb.2021.0376

UNIFIED REPRESENTATION OF LIFE'S BASIC PROPERTIES

One of the great goals in physics is to discover whether gravity and the three other fundamental forces in the Universe — strong, electromagnetic, and weak — can be united into a single force, and many superstring and grand unified theories have been created that assume this is possible. But no such grand unified theory has ever been proposed that would unite the characteristics of life — until now.

SFI External Professor Juan Perez-Mercader (Harvard University), together with Alberto Muñuzuri (Universidad de Santiago and Harvard University), started with four fundamental characteristics all living systems possess: they handle information, metabolize, self-reproduce, and evolve. They created equations describing each of these processes and then combined them into three. They could then examine the various solutions to these equations on a computer, and for particular parameter values, they could watch the phenomena we see in living systems emerge, including the generation of a cell membrane, competition between individuals, chemistry-driven motion, and adaptation.

Read the paper at doi.org/10.1016/j.plrev.2022.03.003

INSTITUTIONAL DYNAMICS AND LEARNING NETWORKS

In human cultural life, change often happens in a few notable ways. Some human institutions, like fashion and political opinions, seem to be in constant flux. Others, such as beliefs and scientific theories, change so slowly as to appear static, before suddenly and dramatically shifting course. A new paper in *PLOS ONE* by SFI's David Krakauer and Jessica Flack with co-author Phillip Poon offers an underlying framework to describe these changes, both fast and slow.

The authors identify three major types of change: stasis, then rapid flip; persistent volatility; and slow change over time. Under the surface of all three types are hidden dynamics. For instance, in the U.S., it appeared for decades that there was little support for gay marriage; opposition seemed static. However, recent studies have revealed that many people supported gay marriage, but kept their opinions hidden because they believed they were in the minority. Understanding why change happens requires understanding "how individuals read and influence the collective view," the authors write.

Read the paper at doi.org/10.1371/journal.pone.0267688