SUMMER 2021

Parallax

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Text collage of court transcripts drawn from London's Old Bailey (Image: Carrie Cowan)

SFI launches humanities analytics institute

The sciences and humanities are often characterized as disparate cultures. Scientists quantify the natural world, studying patterns produced by the forces of nature. Humanities scholars dissect texts, stories, and human-made artifacts, studying patterns produced by the forces of culture.

As archives of digital texts expand and become widely available, though, digital tools are becoming not only useful but also necessary to advance fields that don't fall under the STEM umbrella. Experts at SFI say the computational and quantitative tools used by scientists have a potentially transformative role to play in advancing the humanities.

This August, supported by a grant from the National Endowment for the Humanities, SFI is launching a new "NEH institute," Foundations and Applications of Humanities Analytics, to introduce early-career humanities scholars to new ways of studying culture using a wide range of computational tools. Leading researchers in the humanities and sciences will draw on models and ideas in information theory, statistics, and computer science for new insights into the dynamics of literature, history, and the arts.

In its first year, the NEH institute will be offered online to a wide audience through SFI's Complexity Explorer platform; in years two and three, a smaller group of students will be invited SFI for an in-person intensive school.

"This institute puts SFI in a position to bridge cultural gaps that don't need to be there," says philosopher David Kinney, an Omidyar Postdoctoral Fellow at SFI who is co-leading the new institute with SFI External Professor Simon DeDeo and SFI Director for Education Carrie Cowan.

"We want to introduce people who study the humanities to new ways of seeing everything from the experience of reading a poem to the arc of global history," DeDeo says.

Recognizing the opportunity to introduce complexity science to a new audience, Cowan enlisted DeDeo and Kinney to design the course, and Susan Carter, SFI Research Development Director, to help secure the NEH grant. U.S. Congressman Ben Ray Luján, who represents New Mexico's Third District, called to congratulate the team.

Cowan says that the program offers a new way to look at humanities research through the lens of complexity.

"The humanities offer a natural place to think about complex systems," she says. "History, for

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Collective behavior must be 'crisis discipline,' researchers argue

Our ability to confront global crises, from pandemics to climate change, depends on how we interact and share information.

Social media and other forms of communication technology restructure these interactions in ways that have consequences. Unfortunately, we have little insight into whether these changes will bring about a healthy, sustainable, and equitable world. As a result, a team of researchers that includes SFI's Albert Kao and Mirta Galesic now says that the study of collective behavior must rise to a "crisis discipline," just like medicine, conservation, and climate science have done, according to a perspective piece published June 21 in the *Proceedings of the National Academy of Sciences*.

"We have built and adopted technology that alters behavior at global scales without a theory of what will happen or a coherent strategy for reducing harm," says Joseph Bak-Coleman, the lead author and a post-doctoral researcher at the University of Washington.

Social media and other technological developments have radically reshaped the way that information flows on a global scale. These platforms are driven to maximize engagement and profitability, not to ensure sustainability or accurate information — and the vulnerability of these systems to misinformation and disinformation poses a dire threat to health, peace, global climate, and more.

No one, not even the platform creators themselves, have much understanding of how their design decisions impact human collective behavior, the authors argue.

"The events of January 6 are a recent example of how aspects of social media networks can influence the public sphere," says Kao, an SFI Omidyar Fellow and Baird Scholar who studies collective behavior in animals.

"We urgently need to understand this and move forward with focus on developing social systems that promote well-being instead of creating shareholder value by commandeering our collective attention," says co-author Carl

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Mobility data reveals universal law of visitation in cities

New research published in *Nature* provides a powerful yet surprisingly simple way to determine the number of visitors to any location in a city.

Scientists from SFI, MIT, and ETH Zürich have discovered and developed a scaling law that governs the number of visitors to any location based on how far they are traveling and how often they are visiting. The visitation law opens up unprecedented possibilities for accurately predicting flows between locations, which could ultimately have applications in everything from city planning to preventing the spread of the next major pandemic.

"Imagine you are standing on a busy plaza, say in Boston, and you see people coming and going. This may look pretty random and chaotic, but the law shows that these movements are surprisingly structured and predictable. It basically tells you how many of these people are coming from 1, 2, or 10 kilometers away and how many are visiting once, twice, or 10 times a month," says lead author Markus Schläpfer of ETH Zürich's Future Cities Laboratory, who began the research at SFI during his postdoctoral fellowship. "And the best part is that this same regularity holds not only in Boston, but across cities worldwide."

The researchers' findings are a result of an analysis of mobile phone data from millions of anonymized cell phone users in highly diverse urban regions across the world, including Greater Boston in North America, Lisbon in Europe, Singapore in Asia, and Dakar in Africa. Schläpfer began the analysis and development of the theory during his time at SFI, working together with senior author Geoffrey West, Distinguished Shannan Professor and Past President, who leads the Cities, Scaling, and Sustainability project. It was later extended to include researchers at the MIT Senseable Cities

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Aerial view of pedestrians in crosswalk (Photo: Shutterstock)

BEYOND BORDERS

DISCOVERING KNOWLEDGE JUNCTIONS TOGETHER

In which SFI President David Krakauer contemplates the trade-offs inherent in exchanging ideas online vs in person

In 1860, Ralph Waldo Emerson wrote in *The Conduct of Life*, part one, on Fate, "How shall I live? We are incompetent to solve the times. Our geometry cannot span the huge orbits of the prevailing ideas. . ." Which sums up my feelings over the last year and a half. It all started in March 2020 with some hope in "geometry" (immunology, epidemiology) and soon hit the insurmountable wall of prevailing ideas and superstitions. And now as vaccines slowly and unevenly restore normalcy, the whole question of the conduct of life looms large. In the same essay Emerson writes (with characteristic prescience): "Will you say the disasters which threaten mankind are exceptional, and one need not lay his account for cataclysms everyday? Aye, but what happens once, may happen again. . ."

I would like to ask how a community such as SFI should "lay its account for cataclysm" and whether the "new normal" — which implies physical disconnection and virtual connection, communal pause and domestic concentration, and attenuated interaction with effortless access — plays into a strategy for complex preparedness.

In order to answer this question there might be some clues in the scientific literature on the evolution of recombination.

Between 1930 and 1932, Ronald A. Fisher and Herman Muller proposed that sexual recombination evolved to accelerate the speed of adaptation by reducing competition among beneficial mutations in separate lineages. Recombination brings beneficial mutations together into one super-genome. Like the ultimate merger of complementary technologies. Importantly, this mechanism is only of value when environments are changing and existing adaptive complexes are not sufficient. Recombination in a fixed environment is a waste of time and energy.

In 1949, Fisher introduced his Theory of Junctions to explore more carefully the conditions under which recombination could evolve. The problem is that in inbred populations (i.e. homozygous at most loci) recombination offers no advantage, as this merely shuffles identical regions of parental genomes. It would be like exchanging books when we have identical libraries. Junctions should only appear in those stretches of the genome where novel recombination can arise. For example, if I collect science fiction and you collect murder mysteries we might surprise each other by swapping books from these genres. And once a solution has been found, the junction can drift out of existence.

Places like SFI are in part recombinational mechanisms operating in the space of ideas. But this is insufficient to ensure novelty. The real challenge — as Fisher pointed out — is the placement of the junctions. It is not only a question of exchanging ideas (most ideas are common knowledge — epistemically homozygous), but exchanging ideas that are novel to both parties. Fisher observed that the evolution of the placement of junctions is a slower process than the recombination events themselves. It takes many generations of trial and error to get the position of the junctions just right. Discovering junctions is the true process of exploration, whereas

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Mandating vaccinations could reduce voluntary compliance

Citizen opposition to COVID-19 vaccination has emerged across the globe, prompting pushes for mandatory vaccination policies. But a new study based on evidence from Germany and on a model of the dynamic nature of people's resistance to COVID-19 vaccination sounds an alarm: mandating vaccination could have a substantial negative impact on voluntary compliance.

Majorities in many countries now favor mandatory vaccination. In March, the government of Galicia in Spain made vaccinations mandatory for adults, subjecting violators to substantial fines. Italy has made vaccinations mandatory for care workers. The University of California and California State University systems announced in late April that vaccination would be required for anyone attending in the fall.

The research, published June 7 in the *Proceedings of the National Academy of Sciences* (PNAS), extends an earlier *PNAS* study by first author Katrin Schmelz, a psychologist and behavioral economist at the University of Konstanz, documenting that a major source of vaccine hesitancy is distrust of government. She found that enforced vaccinations reduce people's desire to be vaccinated, particularly among those with low levels of trust in public institutions. In the new study, Schmelz and economist and SFI Professor Samuel Bowles exploit a large panel survey implemented in Germany during the first and second waves of the pandemic. Despite infections in Germany being 15 times more common in the second wave of both the pandemic and the survey, the researchers observed increased opposition when they asked participants a hypothetical question about how they'd respond if vaccinations were to be legally required (the German government is publicly committed not to require vaccinations). In contrast, there was a higher and undiminished level of support for the voluntary vaccinations now in force.

The authors also draw on evidence from the dynamics of diffusion of novel products and technologies such as TVs and washing machines in the last century. They reason that as those who are hesitant or opposed to vaccination see that others are getting vaccinated, they might change their mind. Learning from

Anti-vaccine protest in front of Scottish Parliament Building in Edinburgh (Photo: Shutterstock)

others' vaccination decisions – "conformism" in psychology – means that even if initial vaccination hesitancy is substantial, as more become vaccinated it may be possible to get to a herd immunity target without mandating vaccines.

They also use experimental evidence from behavioral economics showing that explicit incentives, whether in the form of carrots or sticks, may crowd out intrinsic or ethical motives. Policies that aim to incentivize a desired behavior, such as getting vaccinated, can actually undercut individuals' sense of a moral or ethical obligation to do the right thing. This is evident in the researchers' data. Mandating vaccinations by law directly reduces the desire to be vaccinated. Their model also suggests an adverse indirect effect: enforcement will reduce the extent to which others being vaccinated will induce vaccine hesitators to become willing, as this carries a weaker signal. Schmelz says, "How people feel about getting vaccinated will be affected by enforcement in two ways — it could crowd out pro-vaccine feelings, and reduce the positive effect of conformism if vaccination is voluntary."

Bowles says this should be a caution to governments considering mandated policies: "Costly errors may be avoided if policymakers reflect carefully on the costs of enforcement. These could not only increase opposition to vaccination, but also heighten social conflict by further alienating citizens from the government or scientific and medical elites" Nonetheless, he says government enforcement "may still be necessary if the number wishing to be vaccinated is insufficient to control the pandemic."

Schmelz concludes „Our findings have broad policy applicability beyond COVID-19. There are many cases in which voluntary citizen compliance to a policy is essential because state enforcement capacities are limited, and because results may depend on the ways that the policies themselves alter citizens' beliefs and preferences," adding that "... examples include policies to promote lifestyle changes to reduce carbon footprints or to sustain tolerance and mutual respect in a heterogeneous society."

What we're reading

Books chosen by SFI scholars on the theme of 'The reciprocal forces of creation and destruction'

We at SFI are often asked for reading recommendations, so we feel it is time to make our responses more broadly available to the public.

Beginning with this first installment, future issues of *Parallax* will feature three new recommendations on a specific theme, each from a different member of our community. The books may be new or old, obscure or celebrated, and drawn from any genre. The only condition is that they are accessible to a variety of readers. Since this column is a new creation, for our inaugural theme we have selected "the reciprocal forces of creation and destruction."

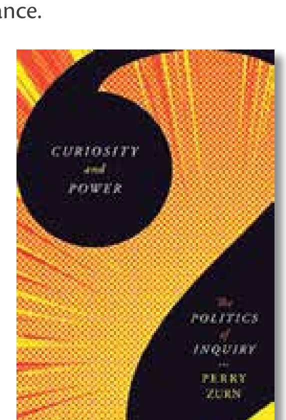
A. Edward Newton, who wrote *The Amenities of Book-Collecting*, once claimed that "the buying of more books than one can read is nothing less than the soul reaching towards infinity." Another distinguished bibliophile, Alberto Manguel, made a similarly hyperbolic statement in his elegy, *Packing My Library*: "Perhaps the books we choose determine our perdition or salvation in the eyes of whimsical gods."

Whether one is striving towards infinity or seeking to avoid perdition, whether one buys books merely for their beautiful domestic aura, for some insatiable encyclopedic urge, or for immediate consumption, we hope this new column will be of some assistance.

Danielle Bassett, SFI External Professor, J Peter Skirkanich Professor of Bioengineering at the University of Pennsylvania

Curiosity and Power: The Politics of Inquiry, by Perry Zurn (University of Minnesota Press, 2021)

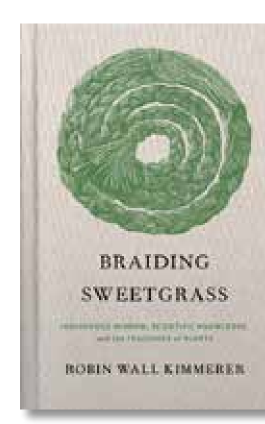
Curiosity is a force for the creation of knowledge, or the unveiling, voicing, freeing, and growth of ideas. Power can be wielded as a force for the destruction of knowledge, or the hiding, quieting, policing, or demise of ideas. When curiosity and power spar, the epistemic cataclysm is of universal proportions.



Katherine Collins, Chair of the SFI Board of Trustees, Head of Sustainable Investing at Putnam Investments, and Founder of Honeybee Capital

Braiding Sweetgrass, by Robin Wall Kimmerer (Milkweed, 2020)

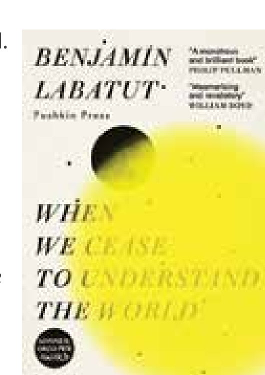
"Despite our fears of falling, the gifts of the world stand by to catch us." This book is science, and also poetry. Robin Kimmerer is a professor of environmental biology and enrolled member of the Citizen Potawatomi Nation, and a combination of science, indigenous wisdom, and sheer love of our natural world shines through on every page. Whether you swim in a sea of digital data or in a pond hidden deep in the woods, you will find beauty, creativity, and wisdom here.



David Krakauer, SFI President and William H. Miller Professor of Complex Systems

When We Cease to Understand the World, by Benjamín Labatut (Pushkin Press, 2020)

Great books are ontological funhouse mirrors. They can return us to the mysteries of childhood or allow us to live another life. Somehow, this book did both for me. Labatut looks at the existential turning points at the end of profound understanding by inspecting the lives of Schwarzchild, Grothendiek, Schrödinger, and many others. He suggests that in our endeavors we are all the epigones of Einstein, devastated by the fog shrouding human creativity.



We would like to thank Ian McKinnon, Vice-Chair of SFI's Board of Trustees, for suggesting this column, and SFI Research Fellow Antony Eagan for compiling the recommendations.

SFI IN THE MEDIA

The *Santa Fe Reporter*'s "Model Citizens" article by journalist Julia Goldberg won a Top-of-the Rockies award in April 2021. The article, originally published in 2020, was inspired by SFI's first pandemic flash workshop, co-hosted by SFI Professors **Cristopher Moore** and **Michael Lachmann**. Goldberg's article quotes External Professors **Lauren Ancel Meyers** and **Sam Scarpino**, and cites SFI's **Complexity Explorer** course on pandemics.

A new preprint by SFI Davis Professor of Complexity **Melanie Mitchell** (see p.3) was featured in *The Wall Street Journal*, in an article about AI in self-driving cars. Mitchell's work was also cited in *Scientific American* and other outlets.

SFI External Professor **Simon DeDeo** appeared on the Mindscape podcast, hosted by External Professor **Sean Carroll** (see p.3). They discussed how to evaluate explanations in science and in other realms of life.

Physics World reported on former Undergraduate Complexity Researcher **Zhijie Feng**'s paper "When will an elevator arrive," which she co-authored with SFI Professor **Sidney Redner**.

Research that simulates the peopling of the Australian super-continent, led by ASU-SFI Postdoctoral Fellow **Stefani Crabtree,** was featured in *The Conversation*, *Gizmodo AU*, *MSN*, *Real Clear Science*, and in the news section of *Science*, among other outlets.

The Washington Post published a blog post by SFI Professor **Samuel Bowles** and his colleague Katrin Schmelz on the unintended consequences of mandating vaccinations (see p.2). The research was also cited in *Bloomberg* and other outlets.

The *Financial Times* interviewed External Professor **Wendy Carlin** about the revolutionary CORE economics curriculum, which she developed with Bowles and other SFI-affiliated contributors.

ASU-SFI Postdoctoral Fellow **Helena Miton**'s research was featured in *Psyche* online magazine, in an essay titled "Looking at portraits with an eye toward cultural evolution."

SFI-initiated research on the "Universal law of human mobility" (see p.1), led by former Complexity Postdoctoral Fellow **Markus Schläpfer** and co-authored by Distinguished Shannan Professor **Geoffrey West**, was featured in *Nature*'s news and views section, *Cosmos*, *Le Monde*, *Der Spiegel*, *Frankfurter Allgemeine*, and other outlets.

Paula Sabloff, SFI External Faculty Fellow, was quoted in *The Washington Post* in an article about yurts.

SFI External Professor **Andy Dobson** was quoted in *WIRED* in an article about zoonotic pandemics.

The Atlantic quoted SFI External Professor **John Krakauer** in an article about a mysterious phenomenon in neuroscience.

MSN featured research led by SFI Program Postdoctoral Fellow **George Cantwell** that elaborates on the famous "friendship paradox" in network science.

SFI Professor **David Wolpert** was quoted in *New Scientist*, in a feature article about thermodynamics, time's arrow, and "biology's great mysteries."

Origins of Life researchers develop a new biosignature

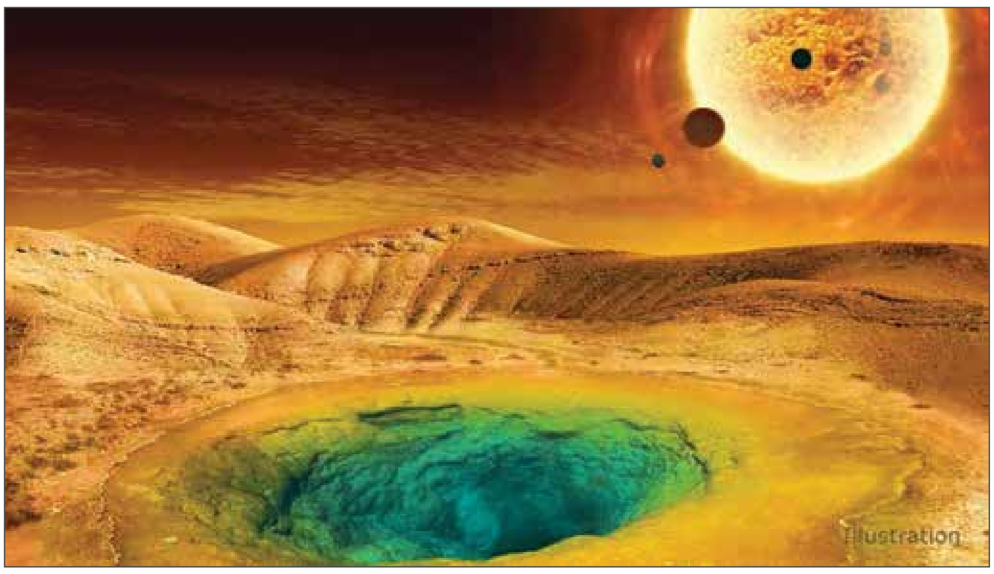
When scientists hunt for life, they often look for biosignatures — chemicals or phenomena that indicate the existence of present or past life. Yet it isn't necessarily the case that the signs of life on Earth are signs of life in other planetary environments. How do we find life in systems that do not resemble ours?

In groundbreaking new work, a team led by SFI Professor Chris Kempes has developed a new ecological biosignature that could help scientists detect life in vastly different environments. Their work appears as part of a special issue of the *Bulletin of Mathematical Biology* collected in honor of renowned mathematical biologist James D. Murray.

The new research takes its starting point from the idea that stoichiometry, or chemical ratios, can serve as biosignatures. Since "living systems display strikingly consistent ratios in their chemical make-up," Kempes explains, "we can use stoichiometry to help us detect life." Yet, as SFI Science Board member and coauthor Simon Levin explains, "the particular elemental ratios we see on Earth are the result of the particular conditions here, and a particular set of macromolecules like proteins and ribosomes, which have their own stoichiometry." How can these elemental ratios be generalized beyond the life that we observe on our own planet?

The group solved this problem by building on two lawlike patterns—two scaling laws, that are entangled in elemental ratios we have observed on Earth. The first of these is that in individual cells, stoichiometry varies with cell size. In bacteria, for example, as cell size increases, protein concentrations decrease, and RNA concentrations increase. The second is that the abundance of cells in a given environment follows a power-law distribution. The third, which follows from integrating the first and second into a simple ecological model, is that the elemental abundance of particles to the elemental abundance in the environmental fluid is a function of particle size.

While the first of these (that elemental ratios shift with particle size) makes for a chemical biosignature, it is the third finding that makes for the new ecological biosignature. If we think of biosignatures not simply in terms of single chemicals or particles, and instead take account of the fluids in which particles appear, we see that the chemical abundances of living systems manifest themselves in mathematical ratios between the particle and environment. These general mathematical patterns may show up in coupled systems that differ significantly from Earth.



Artist's conception of where life might be found on a distant planet. (Illustration: NASA)

Ultimately, the theoretical framework is designed for application in future planetary missions. "If we go to an ocean world and look at particles in context with their fluid, we can start to ask whether these particles are exhibiting a power law that tells us that there is an intentional process, like life, making them," explains Heather Graham, Deputy Principal Investigator at NASA's Lab for Agnostic Biosignatures, of which Kempes is also a part. To take this applied step, however, we need technology to size-sort particles, which, at the moment, we don't have for spaceflight. Yet the theory is ready, and when the technology lands on Earth, we can send it to icy oceans beyond our solar system with a promising new biosignature in hand.

Junior women's caucus responds to gender imbalance in physics

This June, an SFI working group tackled a persistent disequilibrium in physics.

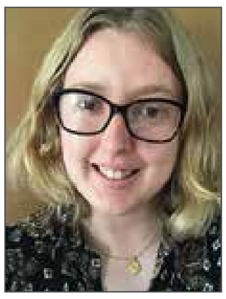
Women physicists are outnumbered, earning only 20% of Ph.D.s and only 10% of full professorships in U.S. colleges and universities. This gender imbalance was brought into sharp relief during the inaugural, virtual Workshop for Stochastic Thermodynamics in 2020, when Jenny Poulton, a postdoctoral physicist at Imperial College London, was the first woman to speak.

"By day three of this conference, not one woman had asked a question or given a talk," Poulton recalls, "and someone put up a slide about online conferences potentially being beneficial to women." She chuckles. "So I made a bit of a fuss."

This year, as part of the 2021 virtual workshop hostd by SFI (see p.4), Poulton spoke at the conference and also organized a follow-on working group — the first meeting of the Junior Women's Caucus in Stochastic Thermodynamics. Designed for women physicists at the Ph.D. and postdoctoral levels, the working group aimed to give participants the opportunities many early-career researchers find most helpful, such as networking, journal-reading, tutorials, and access to senior academics in the field.

"I've been part of women's groups before where the focus was on going to schools and doing outreach — and those things are very admirable," Poulton says. "But I wanted this group to be of direct advantage to the women who are involved."

The paucity of women in stochastic thermodynamics reflects a broader trend in physics, and more broadly in science, technology, engineering, and mathematics (STEM). The "leaky pipeline" metaphor refers to a well-documented phenomenon where fewer and fewer women participate as STEM scholars move from undergraduate, to graduate, doctoral, postdoctoral, and faculty positions.



Jenny Poulton

The pipeline problem looks especially pronounced in stochastic thermodynamics, which is an emerging field within physics. There is no particular reason for this field to have a worse gender bias than physics in general. Because it's a small field, Poulton says, the very small number of women might just be a product of random chance. This makes it harder to conclude that the bias toward men is truly representative of the field over time. But "even if we are as good as the rest of physics then that's pretty poor levels of representation."

SFI Professor David Wolpert, who is the senior advisor who worked with Poulton to co-organize the working group, sees both moral and practical reasons for advancing more women into senior positions in physics, despite there being "only so much one can do" at further reaches of the pipeline.

"There's a moral imperative," Wolpert says, "but there's also a purely selfish one. I want to have the broadest pool of people to interact with because that's what will help my own scientific research."

What defines 'us vs. them' in U.S. political discourse?

When political discourse in the U.S. turns to immigration, "us" and "them" are categories bandied about with little thought paid to their definitions. It's implied: "us" often refers to white, English-speaking Americans, who may only be a generation or two removed from a family history of immigration themselves.

This type of rhetoric, or "boundary rhetoric," creates categories of belonging and exclusion between the in-group "us" and the out-group "them." Over time, boundary rhetoric in political discourse may affect who is accepted, who is marginalized, and who receives access to important resources.

A new project, funded by the Russell Sage Foundation and led by SFI Program Postdoctoral Fellow Tamara van der Does, alongside SFI Professor Mirta Galesic and Indiana University Professor Dina Okamoto, will analyze around 500,000 congressional speeches from Senate and House proceedings to create a larger picture of the use of boundary rhetoric over nearly the last century of American political discourse.

A Day Without Immigrants, Washington, DC (Photo: Ted Eyton/Wikimedia Commons)

By examining boundary rhetoric in the congressional record, the researchers seek to contextualize the relationship between the identities that define people's lived experiences and how policy makers discuss and shape those identities as they make laws.

"I was talking to my colleague Vicky Chuqiao Yang* and she mentioned this data set on congressional speeches," explains van der Does, "and I thought it would be interesting to see how policy makers discuss different groups and create these categories. After World War II, boundary rhetoric was used to justify the internment of Japanese Americans by categorizing them as un-American. Boundary rhetoric is used to justify policies that exclude people."

Although the research uses computational methods, it will be guided by a deep understanding of the sociological theory underlying symbolic boundaries around immigration.

"This approach offers the opportunity to computationally test sociological theories in a large data set over a long period of time," says Galesic. "[We can ask] what kinds of social and economic circumstances create a perceived threat for the majority group? How does that contribute to the in-group/out-group rhetoric?"

The researchers hope that gaining a new perspective on boundary rhetoric in policy, and its source within changing demographics and political shifts, will contribute to a more nuanced picture of the U.S. as a "nation of immigrants."

**Yang is an SFI Omidyar Fellow and Peters Hurst Scholar.*

Branching fractal patterns are woven throughout the new mural by artist Joerael Numina on SFI's Cowan Campus. (Mural: Joerael Numina, Photo: Scott Wagner/Santa Fe Institute)

First 'fractal faculty' seek foundational insights

A fractal looks the same at different scales. Similarly, the concept of a fractals can be used as a metaphor to describe the experience of many SFI researchers who may stay for days, weeks, or years, yet partake of the same, undiluted culture of spontaneity and collaboration.

In his previous column for our spring issue, SFI President David Krakauer introduced the Institute's new Fractal Faculty program as a natural extension of our fractal-like organization. "Whereas faculty at universities exist at preferred scales of both space and time (appointments to a physical department with labs of a given size and in residence for a given duration of tenure)," he wrote, "a fractal faculty member [at SFI] can be scale-invariant and live at many scales of space and time, from months to years and consequently at many spatial scales spanning New Mexico to Madagascar!"

Echoing Krakauer's introduction of the program, we now introduce the first two "fractal" members of SFI's faculty, both of whom join us in Santa Fe this summer as SFI moves toward full re-opening.

MELANIE MITCHELL, SFI DAVIS PROFESSOR OF COMPLEXITY

Melanie Mitchell's life changed on the New York City subway. During her post-college stint as a high-school math teacher in Manhattan, every subway ride was an opportunity to conquer a few more pages of Douglas Hofstadter's *Gödel, Escher, Bach*. Reading it, she became fascinated with the way math, art, and music could help explain the emergent properties of intelligence. She realized she wanted to work with Hofstadter and become an AI researcher.

Several decades later, Mitchell has achieved that goal and more. Her research has explored the limits of analogy-making machines, the particle physics of cellular automata, and the rules of genetic algorithms.

Combined with a lifelong love of science and logic puzzles, Mitchell's drive to "think about how we think" made Hofstadter's research group a natural first step in her AI career. In the mid '80s, she worked to build Copycat, a computer program that looked for analogies between strings of letters. For example, if the string *abc* changes to the string *abd*, what is the analogous change to the string *mrrjjj*?

"It's amazing what you can do in this very constrained domain," Mitchell says. In Hofstadter's group, the maxim was that constraints could breed creativity.

While Copycat wasn't particularly computationally expensive, one thing that set it apart was Mitchell's brilliant visual interface that showed the computer's actions in real time. For many computer scientists, Copycat provided immensely valuable insight into the thinking process of AI — and humans as well.

At the University of Michigan, Mitchell also began to branch out into biologically-inspired AI with John Holland, one of SFI's earliest professors. Holland was the inventor of genetic algorithms, computer methods inspired by Darwinian evolution. He had developed a theory that predicted how these algorithms would solve problems. But when Mitchell and fellow Michigan graduate student Stephanie Forrest (now a member of SFI's external faculty) looked, they found something amiss.

"We tried to probe his theory by coming up with the simplest example that, according to his theory, genetic algorithms would absolutely excel at — and we showed that it wasn't the case," Mitchell says. Holland's idea was that genetic algorithms would have a high fitness, or success, if they combined fit components together, like adding up multiple genes which all increase height.

It turns out, just like biology, algorithms also suffer from a problem called hitchhiking: maladaptive genes located near fit genes on the chromosome can get carried along simply by association.

The research would lead Mitchell to SFI in the nineties, where she spent much of the decade as the director of SFI's Adaptive Computation program, where her goal was to make computational systems "more lifelike" by bringing in

insights from natural adaptive systems such as insect colonies and immune systems, as well as biological evolution. At SFI, Mitchell worked with researchers across a breadth of fields, from population geneticists to physicists.

Since moving up to Oregon in the early aughts, Mitchell has remained an external faculty member at SFI, writing books about complexity and artificial intelligence. Her research over the past decade has moved back to AI, trying to understand image recognition from the perspective of analogy-making.

What Mitchell wants to know is how our version of object recognition differs from a computer's — how both top-down and bottom-up perspectives can be continually combined to enable visual analogies.

Though her research spans multiple disciplines, Mitchell finds unifying connections throughout.

"In adaptive systems like evolution, there's this balance between what's called exploration and exploitation," Mitchell says. Exploitation meaning repeating what works and exploration meaning trying new strategies. Individuals have to do some of both to succeed. Too much exploitation and you get stagnation; too much exploration and you lose stability. This isn't just the case for carbon-based organisms — Copycat and other AI programs also need to balance exploitation and exploration to succeed.

Lately, Mitchell has been working on an even more general principle — one at the heart of *Gödel, Escher, Bach*. "If you look at that book, it's really about intelligence. About how something like intelligence can emerge from a non-intelligent substrate of, say, neurons interacting with each other," she says.

This year, along with SFI External Professor Melanie Moses, Mitchell is investigating foundations of intelligence by hosting a series of interdisciplinary workshops to answer questions like where it can exist and whether human intelligence is the same as computer intelligence or the intelligence of a swarm. By bridging disciplinary divides in how intelligence is understood, they hope to discover the next frontier in AI research.

In other words, she's still thinking about thinking.

SEAN CARROLL, SFI EXTERNAL PROFESSOR

In 2011, Sean Carroll was sipping coffee on a boat traveling between Bergen, Norway, and Copenhagen, when it occurred to him that there was no better model for how life emerged from chaos than his favorite hot drink. Or, as he put it later, "why complexity increases with time and then decreases — in contrast to entropy, which increases monotonically." The boat was hosting FQXi's physicist conference, and when the theoretical computational scientist Scott Aaronson, who was on board, heard Carroll's question, he fell in love with what he called Carroll's beautiful idea. After recruiting undergraduate Lauren Ouellette as a collaborator, he and Carroll released a paper that tried to quantify the process that led to the creation of the universe as we know it. They modeled how cream mixes with coffee. Since then, Carroll has been fixated on an idea: if complexity arising out of increasing entropy can shed light on the state of our universe, what else might the process explain?

Carroll now sits at Richard Feynman's old desk as a research professor of theoretical physics at the California Institute of Technology. He wasn't trained in complexity studies. He's a physicist and a well-known writer and public commentator. He made his mark in the field in the late nineties and early aughts by contributing to the science of dark energy and dark matter, those mysterious and still unseen forces that, as Carroll posited, are very likely the driving engines behind the universe's accelerating expansion. Carroll's best known for his popular work in science communication, which you might sum up as testing every major theory in existence — from evolution to God — against the laws of physics. He believes the natural world is governed by natural laws.

Tall, red-headed, and with that rare ability to speak off the cuff like he's reading from a prepared script, you may recognize Carroll from any number of outlets. He was on the Colbert Report, explaining the Higgs-Boson discovery. He's talked to Google employees about why time always flows toward the future, debated the existence of God with esteemed Christian theologian William Lane Craig, and written four popular books, one a bestseller called *The Big Picture*.

Carroll identifies himself as a physicist, but *intellectual omnivore* is just as apt. "I chase ideas that interest me," he says. "The most exciting thing I can do is learn." Now, transitioning from an external professor to a fractal faculty member at the Santa Fe Institute, he's trying to learn how to build a framework that allows for the seamless connection of foundational physics — quantum mechanics, spacetime, the Core Theory — to higher level phenomena like the evolution of neural networks. "We need to better understand and elucidate the nature of the levels of reality: what they are, how they relate to each other, and how different levels can be investigated for different purposes," he says. He believes the path to this understanding lies through complexity.

Carroll insists that studying complexity is an extension of his 25-year physics career, not a diversion. To illustrate his point, he goes back 13.77 billion years to the birth of the universe. Our best theories predict that plasma was then evenly dispersed throughout space. You could take one particle and randomly swap it out for any other particle and nothing would change. Remember the coffee? In this state, the universe was black coffee with separate cream — low entropy and low complexity. Then the Big Bang blew and what was low entropy began transitioning to higher entropy. In Carroll's model, cream was mixed with the coffee and complexity bloomed.

Then the Big Bang blew and what was low entropy began transitioning to higher entropy. In Carroll's model, cream was mixed with the coffee and complexity bloomed.

Over time, matter self-organized into systems and sub-systems, such that it was no longer possible for one particle to swap out with another without radically changing the reality. Stars formed. Planets shaped. And once Earth existed, atoms became cells that spawned life that eventually produced the very consciousness occupying our minds. Carroll sees the universe's fate mirroring that of the coffee's: when the cream is fully mixed, entropy will be high but complexity low. Matter will be too widely dispersed to foster complexity. And when that happens 100 trillion or so years from now, life will necessarily fizzle. "Those swirls of cream mixing into the coffee," Carroll wrote in a passage in his book the *Big Picture*. "That's us. Ephemeral patterns of complexity, riding a wave of increasing entropy from simple beginnings to a simple end. We should enjoy the ride."

At SFI, Carroll and his colleagues are asking whether it's possible to quantify the process of how complexity appears when low entropy transitions toward high entropy. There is no law that says it has to — so why does it? If the conditions that allow for the formation of complexity can be understood, maybe the thermodynamic arrow of time — increasing entropy in the universe — can be used to explain cause and effect here on Earth? Maybe we can better explain the origin of spacetime? The origins of life? The origins of consciousness? Maybe, Carroll hopes, he can even apply the principles that explain complexity's rise to social forces relevant to this moment in time, like why democracy forms and why it breaks. The answers to these questions and others may lie in his next cup of coffee.

Electricity surges between two lumps of coal. (Photo: Shutterstock)

A surge of interest in stochastic thermodynamics

Almost 900 confirmed participants joined "WOST II" — the second annual virtual workshop that focuses on stochastic thermodynamics and its application to many issues involving complex systems.

A young field, stochastic thermodynamics is a fast-developing branch of statistical physics that is revolutionizing our ability to analyze systems far from thermodynamic equilibrium. It grew out of investigations into nano-scale systems that are larger than micro-scale systems — whose entropy cannot change with time — but smaller than macro-scale systems, whose entropy can increase but never decrease.

Most complex systems, like economies or ecosystems, rest squarely in the realm of the "macro." However, SFI Professor David Wolpert, the workshop's co-organizer, points out that even though stochastic thermodynamics grew out of analyses of nano-scale systems, the theorems of stochastic thermodynamics apply to any system, no matter what its size, so long as it evolves according to a "Markov process." In particular, many of those theorems apply even if the system has no obvious thermodynamic interpretation. For example, many of the theorems of stochastic thermodynamics apply to the dynamics of opinion networks in social systems, and to genomes evolving according to the "stochastic replicator dynamics" of evolution, just as much as they apply to the heat engines and chemical reaction networks that they were designed to investigate.

During the first meeting, which convened online in 2020 and was hosted by Complexity Science Hub Vienna and co-hosted by SFI, senior physicists in both stochastic thermodynamics and complex systems presented possible connections between their fields. This year's SFI workshop continued to explore these connections and again brought together the most prominent researchers in the field. In addition, the agenda in 2021 showcased the work of early-career scientists, who were invited to apply to give 10-minute "lightning talks" throughout the five-day meeting.

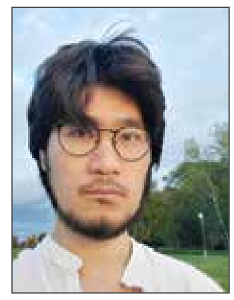
"We had 15 lightning talk slots for postdocs and grad students, and received 136 applications," says Wolpert. "That's a more selective acceptance rate than [the journal] *Nature*!"

The presentations fell into five broad areas where stochastic thermodynamics is currently being applied: physics and chemistry, biophysics, "active matter" (such as molecular motors that consume energy and are out-of-equilibrium), quantum stochastic thermodynamics, and quantum information theory. Each topic had its own dedicated day on the agenda, which kicked off with a day of tutorials on May 17.

Unlike in-person SFI workshops, which are limited to 50-60 participants by the occupancy of the Noyce conference room, the online format allowed the organizers to draw from a much larger pool of global researchers.

"One of the great things about having a virtual workshop is that it allows us to include people without the funding to attend an in-person conference, and to reach out to people in the third world, many of whom have a hard time participating in the central research streams of modern science," says Wolpert.

SFI welcomes two new postdocs



YUANZHAO ZHANG

Synchrony — when individuals within coupled systems move nearly identically together — can be found in many living and nonliving systems from the cells that control the beating of our own hearts to the periodic emergence of some cicadas to pendulum clocks and metronomes mounted to a common base.

A common assumption is that synchrony thrives under homogeny — when each individual oscillator within the coupled system is identical to all the others — and that diversity hinders synchronization. While the assumption that individual oscillators could be identical works in theory, incoming Omidyar Fellow Yuanzhao Zhang has focused his research on the more realistic assumption that oscillators will contain some amount of variation. What he found, during his Ph.D. in physics at Northwestern University, suggests that diversity is not only possible in synchronized systems, it might be critical to their success.

For instance, the rhythmic processes in our own bodies, from the beating of our hearts to our circadian sleep-wake cycles, depend on the synchronized behavior of thousands of cells. "Given the importance of keeping these cells in sync, one would expect natural selection to minimize their variance in key attributes," says Zhang. "However, data suggest that such cells can be more heterogeneous than expected." At SFI, Zhang plans to continue exploring the role and effect of cellular diversity on synchronized and coordinated biological processes.

Zhang also holds an M.Sc. in applied mathematics from Northwestern University and B.Sc. in mathematics from Zhejiang University. For the past year, he has worked as a Schmidt Science Fellow at Cornell University with former SFI External Professor Steven Strogatz, and he plans to arrive at SFI in the fall of 2021.

ALESSIO LAPOLLA

Randomness and complexity can be found everywhere in the world from the game tables in Las Vegas to the stock exchange in Wall Street. Often, a probabilistic description is the only way to understand a complex system. Alessio Lapolla finds the mathematical structures developed in the field of statistical mechanics to be beautiful and plans to use them to unravel the erratic behavior found in sports, economics, and many-body physics.

Laoplla obtained his B.Sc. in physics and M.Sc. in theoretical physics from the University of Padua in Italy, and recently completed his Ph.D. in statistical biophysics at the Max Plank Institute for Biophysical Chemistry in Göttingen, Germany.

Already in his career, Lapolla has "established important new techniques and obtained novel insights" into the difficult many-body problem, writes Ralf Metzler, a theoretical physicist at the University of Potsdam. And, in a recent paper published in Physical Review Letters, Lapolla and co-author Aljaž Godec describe a counterintuitive observation of asymmetrical relaxation; that is, on the nanoscale, cold objects become warm more quickly than warm objects get cold.

At SFI, Laoplla will work with Professor Sid Redner as a Program Postdoctoral Fellow. He plans to arrive in October 2021.

HUMANITIES *(cont. from page 1)*

example, is all about the complex intersection of culture, environments, wars, and everything else. Why not represent that at SFI?"

The organizers say the course has three primary goals: To introduce these tools to humanities scholars; to drive the innovation of new scholarship; and to build a community of scholars who can continue to collaborate in the future.

"We want to teach people the different ways that scientists think," says DeDeo. "There are a lot of humanities scholars who don't think of themselves as particularly technical types but who are interested in engaging with this material."

Foundations and Applications of Humanities Analytics runs August 2- November 30, 2021. Register online at complexityexplorer.org

COLLECTIVE CRISIS *(cont. from page 1)*

Bergstrom, a professor of biology at UW and a former member of SFI's external faculty.

Collective behavior and other complex systems are fragile. "When perturbed, complex systems tend to exhibit finite resilience followed by catastrophic, sudden, and often irreversible changes," the authors write.

While there are studies and disciplines that focus on complex systems in the natural world, "we have a far poorer understanding of the functional consequences of recent large-scale changes to human collective behavior and decision making," they add.

Averting catastrophe in the medium term (e.g., coronavirus) and long term (e.g., climate change, food security) will require rapid and effective collective behavioral responses — yet it remains unknown whether human social dynamics will yield such responses.

The situation parallels challenges faced in conservation biology and climate science, where insufficiently regulated industries optimize profits while undermining the stability of ecological and Earth systems.

Historically collective behavior has best been understood as when animals or people exhibit coordinated action without an obvious leader. This includes how fish school to evade predators or when a crowd spontaneously breaks into applause or becomes silent.

That thinking has evolved over the past decade, the authors write, from a phenomena to a contemporary view of collective action as a framework that reveals how interaction among individuals gives rise to collective action.

MOBILITY DATA *(cont. from page 1)*

Laboratory under the leadership of the architect Carlo Ratti.

Universally, they found that the number of visitors to any urban location scales as the inverse square of both travel distance from home and the visitation frequency. Like the gravitational pull of a large planet, an attractive city plaza with fine museums and famous shops draws relatively more visitors from more distant locations, though less frequently than those coming from nearby locations, their relative numbers being predictably determined by the inverse square law. A further surprising consequence of this new visitation law is that the same number of people visit the location whether they are coming from, say, 10 kilometers away three times a week, or from 3 kilometers away 10 times a week.

> ...they found that the number of visitors to any urban location scales as the inverse square of both travel distance from home and the visitation frequency.

While previous research has used mobile phone data to study human movement from the perspectives of individual people — where they go, when, and how often — this is the first systematic study to focus on the frequency of visits from the perspective of places, using mobile phone data to understand the relative attractiveness or utility of an urban area.

"There's an optimization problem going on here in terms of the amount of energy people are using, the distance they're traveling, and the number of trips they're making," says West. "When we travel for leisure, we choose our destinations. During everyday life, those choices are more forced because we have to go to work, say, five times a week, pick up the kids two times, etc. But there's this remarkable conservation inherent in the visitation law — namely, the average amount of energy that people allocate to travel is the same whether they try to do it across different distances or at different frequencies."

Schläpfer says the new paper can give urban planners "a baseline for understanding which locations in their cities are over- or under-performing," in terms of the number of people they attract. It can inform planners about where to add amenities like parks and restaurants, or how much public transportation is needed for new urban developments.

The law of visitation joins a growing body of research on the science of cities, which SFI researchers and their collaborators have pioneered since 2007, when they first uncovered universal laws governing growth, innovation, and the pace of life in cities.

"All of the problems that we face, especially climate change, are generated in cities because that's where the people are," West says. "So understanding cities, and how people move within them, plays into fundamental questions about the future of life on this planet."

BEYOND BORDERS *(cont. from page 2)*

recombination is largely a smart mechanism of exploitation. This is like the difference between the interdisciplinary and the transdisciplinary. In the former we know what ideas to exchange, whereas in the latter we need to find them.

The remote exchange of ideas (from home, online), allows for the recombination of ideas. The challenge is identifying those ideas we need to recombine to discover something novel. As Fisher discovered, this meta-process of discovering the unique books to share in each of our libraries, is incredibly time consuming and requires a high level of population-level trial and error. This is the kind of experimentation that in-person collaboration supports. It goes beyond sharing ideas towards discovering which ideas are worth sharing.

When economists, computer scientists, and archaeologists at SFI started researching agent-based models for Southwestern demographic shifts, they did not know in advance what ideas they each needed. They had to discover — after numerous fruitless exchanges — where to place their epistemological junctions. Once they had done so, the whole Artificial Anasazi project took off. In order to decide how best to conduct our research life into the future, it is worth bearing in mind the lessons of evolution — when uncertainty is at a maximum we need time together to discover ideas worth sharing. Thenceforth we might each live on our own island and transmit these ideas by pigeon post, secure in the value of their originality

— David Krakauer
President, Santa Fe Institute

Santa Fe Symphony TV (Photo: The Santa Fe Symphony Orchestra & Chorus)

'Science of Sound' series brings music and math to young learners

When SFI Professor Cristopher Moore participated in the PBS documentary "The Majesty of Music and Math" in 2018, he knew he wanted to continue exploring — and sharing — the interconnectedness of music and science. With that inspiration, Moore collaborated with the Santa Fe Symphony to create "Science of Sound: Experiments at Home," a series designed to show young learners how music and science come together to enrich human experience. And for both viewers and participants, the result is pure joy.

Featuring principals from the symphony's string, brass, and woodwind sections, along with some very talented students (including Moore's daughter Rosemary), the series shines a light on the remarkably fun interplay between music and science.

The first three episodes, available now on Santa Fe Symphony TV, cover everything from the physics of the tuba to hearing what a clarinet might sound like on Mars and Venus. Students can also participate at home with projects like creating an orchestra with bottles and water, making a reed instrument with a straw, and building a simple string instrument.

Like many scientists and mathematicians, Moore, a self-described "bad amateur piano player," has always had a love for music — a passion that blossomed when he joined a young composers' club in college.

"There's a lot in common between music and math in how they bring us joy and engage both mind and soul," Moore says. "We like to hear patterns and hum along, but if the music is too predictable or too chaotic, we lose interest. This balance between pattern and surprise is the sweet spot for our brains, and that's where the expression of the musician and inventiveness of the composer come into play."

The Science of Sound series was made possible with the support of executive producer Penelope Penland, writer/producer Fedor Kossakovski, and Thornburg Investment Management.

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ACHIEVEMENTS

In February, the National Science Foundation announced that former SFI Omidyar Fellow **Joshua Grochow**, now an assistant professor at CU Boulder, would receive its most prestigious grant for junior faculty members — a Faculty Early Career Development, or CAREER, award, which will fund the next five years of his research. With the award, he will be pursuing ideas that emerged during his conversations at SFI, by investigating ways to use and optimize mathematical tools that probe higher-order interactions.

On its official web page for "Music & Mathematics," the American Mathematical Society features two videos from SFI Professor **Cristopher Moore**'s Majesty of Music and Math series, with New Mexico PBS and the Santa Fe Symphony Orchestra.

RESEARCH NEWS BRIEFS

Indigenous superhighways of ancient Australia (Image: Megan Hotchkiss Davidson/Sandia National Laboratories)

FIRST AUSTRALIAN POPULATIONS FOLLOWED FOOTPATH 'SUPERHIGHWAYS'

By simulating the physiology and decisions of early way-finders, an international team of archaeologists, geographers, ecologists, and computer scientists led by Stefani Crabtree, ASU-SFI Complexity Postdoctoral Fellow and Assistant Professor at Utah State University, has mapped the probable "superhighways" that led to the first peopling of the Australian continent some 50,000-70,000 years ago. Their study, published in *Nature Human Behaviour*, is the largest reconstruction of a network of human migration paths into a new landscape. It is also the first to apply rigorous computational analysis at the continental scale, testing 125 billion possible pathways. The results suggest that there are fundamental rules humans follow as they move into new landscapes and that the researchers' approach could shed light on other major migrations in human history, such as the first waves of migration out of Africa at least 120,000 years ago.

Read the paper at doi.org/10.1038/s41562-021-01106-8

HOW THE PANDEMIC EXPLOITED SOCIOECONOMIC DISPARITIES

In Santiago, Chile, low-income people were more likely to contract and die from COVID-19 than residents in other parts of the capital city, according to new research published in the journal *Science*.

In analyzing incidence and mortality data collected by government agencies, as well as testing capacity and delays, the research team, which included SFI External Professor Pablo Marquet and former Omidyar Postdoctoral Fellow Caroline Buckee, found significant socioeconomic disparities in access to health care across the 34 municipalities that comprise the Greater Santiago area. The team also found behavioral differences: Using anonymized mobile phone data, the researchers determined that while people in more affluent areas largely remained sequestered during lockdowns, those in economically depressed areas tended to be more mobile. That finding is consistent with previous studies of New York City neighborhoods, and "supports the hypothesis that people in poorer regions cannot afford to stay at home during lockdowns," the authors wrote.

Read the paper at doi.org/10.1126/science.abg5298

LIFE STAGE DIFFERENCES SHIELD ECOLOGICAL COMMUNITIES FROM COLLAPSE

A new study by ecologist and SFI External Professor André de Roos shows that differences between juveniles and adults of the same species are crucial for the stability of complex ecological communities. The research, published in *Proceedings of the National Academy of Sciences*, represents a major advance in ecological modeling at a time when biodiversity is declining and species around the world are rapidly going extinct.

Using computer simulations, de Roos was able to model both the number of total species in a community and key variations within the same species, accounting for differences between juveniles and adults. He says these differences arise not only because adults reproduce, while juveniles grow and mature, but also because juveniles, being of smaller body size, are generally more limited by food availability than adults and run a much greater risk of being captured by predators. These differences lead to variations over time in the ratio of juveniles to adults, which tip the entire community from instability to stability.

Read the paper at doi.org/10.1073/pnas.2023709118

COMPLEXITY HOLDS STEADY AS WRITING SYSTEMS EVOLVE

A new paper in the journal *Cognition* examines the visual complexity of written language and how that complexity has evolved. Using computational techniques to analyze more than 47,000 different characters from 133 living and extinct scripts, co-authors Helena Miton, an Omidyar and ASU-SFI Complexity Postdoctoral Fellow, and Oliver Morin of the Max Planck Institute for the Science of Human History, addressed several questions around why and how the characters of different writing systems vary in how complex they appear. The study suggests that the main driver of characters' complexity was which linguistic units (e.g., phoneme, syllable, entire word, etc.) the characters encode. They were surprised to find little evidence for evolutionary change in complexity: scripts that were invented in the past 200 years used characters of similar complexity to those that have been around for longer.

Read the paper at doi.org/10.1016/j.cognition.2021.104771