WINTER 2021–22

# Parallax

THE NEWSLETTER OF THE SANTA FE INSTITUTE

*Bill Miller's historic gift to SFI will fund new faculty and programs,and will allow for expansion of SFI's Miller Campus. (Image: SFI)*

## Bill Miller gives $50 million to SFI

In the largest single donation in its history, the nonprofit Santa Fe Institute will receive $50 million from legendary investor Bill Miller. The gift will advance the Institute's pioneering science of complex systems by growing its research community and expanding the facilities in which it works.

Complexity science seeks to find the organizing patterns at the heart of systems with a multitude of adaptive parts — from economies to ecosystems. Many scientists, including the late physicist Stephen Hawking, predicted that the 21st century would be "the century of complexity," when science would build on the foundational laws of physics by understanding "how the laws fit together, and what happens in extreme circumstances," Hawking said.

"This gift comes at a moment when the world needs radically new ideas and quantitative frameworks to engage with the growing connectivity and complexity of life and the accelerating pace of change in both technology and society," says SFI President David Krakauer. "Bill's gift supports the search for new foundational ideas bearing on our understanding of complex reality, which includes consideration of the planetary future, our increasingly hybrid nature with machines, and potential existential issues around climate, our democracy, and rationality."

Beyond being the largest single donation in SFI's history, Miller's gift is also believed to be the largest gift explicitly dedicated to support the science of complex systems, which is also called "complexity." The Santa Fe Institute is the only stand-alone institute in the world dedicated to advancing the frontiers of this field.

Ecologist Jennifer Dunne, who is SFI's Vice President for Science, remarks that "Bill's gift to SFI is extraordinary and provides us with the means to expand and sustain important research and outstanding researchers in complexity science for many years to come. It demonstrates how he fundamentally resonates with the Santa Fe Institute's quest to bring the most diverse, brilliant, and curious minds together (including his!), to make progress on the most interesting and difficult questions facing our world."

For scientists at SFI, the gift marks a turning point in the mainstream establishment of complex systems science, in the same year the

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## Emergent engineering for an evolving world

When Alexis de Tocqueville observed American democracy for the first time, he was so astonished at what he saw that he made a proclamation: "a new political science is needed for a world altogether new." If Tocqueville had been reborn a twenty-first-century technological visionary, perhaps he would have said something slightly different — something like this: a new kind of *engineering* is needed for a world altogether new.

Over the past three years, SFI's Applied Complexity Network (ACtioN) has had a front-row seat in a series of meetings where SFI researchers have been evolving this new kind of engineering, one better suited to the complex systems that drive the contemporary world. Called emergent engineering, it generates the conceptual frameworks and design principles that practitioners need to carry out engineering projects that engage with adaptive agents.

The inaugural exploratory meeting took place in June of 2019, followed by a virtual roundtable in September 2020, and, later that year, a series of roundtables that homed in on emergent engineering in the organization, and in the market, respectively. To continue developing the theme, in November 2021, SFI hosted a virtual ACtioN Board of Trustees Symposium dedicated exclusively to the subject.

One way to understand emergent engineering is by comparison to classical engineering. Whereas classical engineering works with systems that exhibit (more or less) deterministic patterns (think: the steam engine, Newtonian mechanics, or even a supply chain), emergent engineering engages with agents and systems that evolve and adapt (think: ecosystems, public health care, and cybersecurity).

For SFI President David Krakauer, an illuminating example of emergent engineering is the cochlear implant. As Krakauer explains, "the cochlear implant stimulates neurons directly, and essentially simulates the tonotopic frequencies. The designer of a cochlear implant, therefore, has to

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## SFI applauds first Nobel Prize for complex systems research

SFI researchers cheered this October when the Nobel Prize in Physics was awarded to Syukuro Manabe, Klauss Hasselmann, and Giorgio Parisi "for groundbreaking contributions to our understanding of complex systems.*"

Spanning disciplines and notoriously difficult to define, complex systems science has struggled to achieve the mainstream recognition of older, more established fields. But the acknowledgment from the Nobel Committee, arguably the most prestigious award-granting assembly in the world, has emphasized its importance and beauty.

SFI Professor Jessica Flack hailed the decision as "surprising and entirely overdue" in a Twitter thread that details the deep implications of Parisi's work in social and biological sciences, from starling flocks to neuroscience to the concept of renormalization in particle physics. Though a physicist by trade, Parisi's work modeling spin glasses — a kind of disordered magnet — turned out to be applicable to a variety of other fields where understanding disorder is critical.

"Great news today with the @NobelPrize to legendary Italian physicist Giorgio Parisi," tweeted SFI External Professor Ricard Solé. "His work had a major impact in biology, from molecular evolution to neural networks and the dynamics of complex adaptive systems. Very much deserved."

The study of complex systems, to Parisi, was nothing short of a revolution in physics. "[I]t was necessary to change the general philosophy, by introducing probabilistic concepts and probabilistic predictions," he wrote in 2002. Over the past few centuries, physicists have dismantled the order of Newtonian mechanics, revealing a world that can only be

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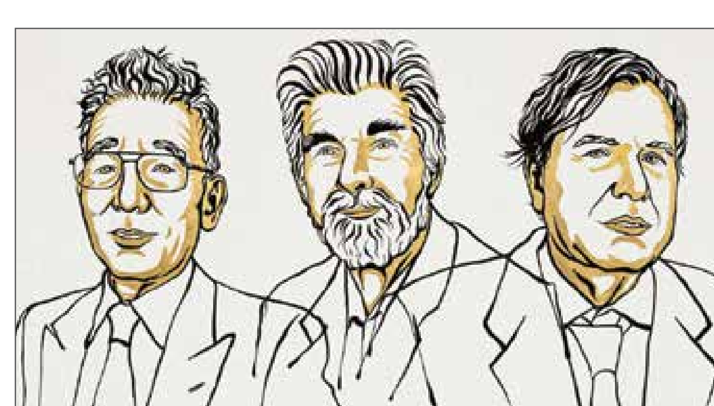

*Syukuro Manabe, Klaus Hasselmann and Giorgio Parisi (Illustration: Niklas Elmehed for Nobel Prize Outreach©)*

# BEYOND BORDERS

## UNIQUENESS AND UNIVERSALITY

One might say that natural history captures the uniqueness of every organism and natural science, their generality. Natural science values parsimony and natural history, profusion. But when is it appropriate to pick one approach over the other — that is, when do the details really matter and when are general mechanisms most important? The honest answer is that we do not know.

In 1766 James Christie hosted his first auction on the Pall Mall in London. Included in the sale were a pair of sheets, two pillowcases, and two chamber pots. It is hard to imagine anything more particular than an auction lot. In the same year Daniel Bernoulli, a 66-year-old professor of botany, physiology, and physics (yes, all three) at the University of Basel published "Essai d'une nouvelle analyse de la mortalité causée par la petite vérole" — his mathematical treatment on increased mortality due to infection with smallpox — that blight of sheets and chamber pots.

Bernoulli's paper is the ur-type, type-specimen, or structurally, the Bauplan for many mathematical models of epidemics decanted from the late 18th century up to the present. Bernoulli envisaged a population of susceptible hosts that die at a constant rate, and a population of immune individuals who have been fully vaccinated following a single infection. Infected susceptible populations who do not transition into the immune state experience an elevated death rate. Bernoulli sought in his work to account for the increased mortality due to infection.

The model assumes that all susceptible individuals experience the same rate of infection, a constant case fatality rate, and that all immune individuals die at the same rate. For the sake of generality, the model assumes extreme homogeneity.

Shortly after Bernoulli introduced his model — and prior to its first publication — his lifelong rival, Jean Le Rond d'Alembert, criticized his work for, ironically, its excessive complication, providing a more parsimonious model of greater generality for estimating mortality, albeit with reduced relevance to infectious disease.

In 1927 Kermack and McKendrick significantly extended Bernoulli's model to include a dynamical transmission process (dropping the assumption of a constant rate of infection), allowing infected individuals to infect susceptibles, and making mortality and recovery rates a function of the duration of infection.

The Kermack and McKendrick paper introduced for the first time a threshold level of infection below which epidemics die out and above which the epidemic grows — the idea of the basic reproductive number or R0 which has haunted our imaginations and dreams for the last two years.

Over the course of a century, these models have been subjected to a large number of variations and augmentations — to such a degree that it would be fair to conclude that we now possess a natural history not of epidemics but of general models for epidemics. Which at some level must suggest a contradiction.

The pursuit of the most parsimonious model has been replaced by the pursuit of

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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.*

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## SFI IN THE MEDIA

In October, *The Washington Post* credited **Bette Korber** as one of the first to recognize that SARS-CoV-2 is mutating.

*New Jersey Monthly* reported **Andy Dobson**'s prediction of another pandemic if habitat loss and wildlife trade are not curbed.

**Sam Bowles**' and Katrin Schmelz's June 2021 PNAS paper on opposition to COVID-19 vaccination in Germany has been reported extensively in media outlets including ZDF public television, *Der Spiegel*, and *Deutsche Welle*.

*Discover* magazine cited **Marten Scheffer's** research on the human climate niche, which tends to average 50 to 60 degrees Fahrenheit. The magazine also spoke with **Scott Ortman** for their round-up of five ancient cities that no longer exist.

*The Economic Times* interviewed **Eric Beinhocker** on the critical need for businesses to go net-zero greenhouse gas emissions.

**Seth Blumsack** spoke with *Wired* about the current limitations of electrical grids and the additional challenges they will face as more energy is produced from renewable sources.

*Axios* and *The Atlantic* both reported on **James Evans**' PNAS paper showing that larger scientific fields progress slowly.

Rebutting an assertion that America is running out of new ideas, **David Krakauer** told *The Atlantic*, "I see no evidence that people are less ingenious. I see the problem as moving their genius into the world."

*Vice* cited **Josh Wolfe** and his insights about the dot com bubble in their feature "The 'To the Moon' Crash is Coming."

*MarketWatch* and *The Irish Times* featured new research by **Andrew Lo** on which investors are most likely to panic sell. (Answer: married, middle-aged men).

**Michael Mauboussin** discussed how to read stock prices with *Bloomberg*'s Opinion podcast.

In *Fast Company*, Dan Schulman, CEO of PayPal, recommended **Sean Carroll**'s book *Something Deeply Hidden* as one of his favorite 2021 reads. The book also garnered mention in an *Aeon* essay.

*The New York Times* quoted **Albert Kao** in a story about worm blobs and collective behavior.

In an essay for *Quanta*, **Melanie Mitchell** discusses why it has been difficult to develop a true test of a machine's knowledge and ability to understand.

In December, shortly after the first Omicron variant case was detected in the U.S. **Samuel Scarpino** told *The Boston Globe*, "it's just a matter of time before it shows up in most places in the U.S." He went on to speak about the variant with outlets including *The Atlantic*, *Bloomberg*, *Reuters*, *The New York Times*, *Politico*, and *The Wall Street Journal*.

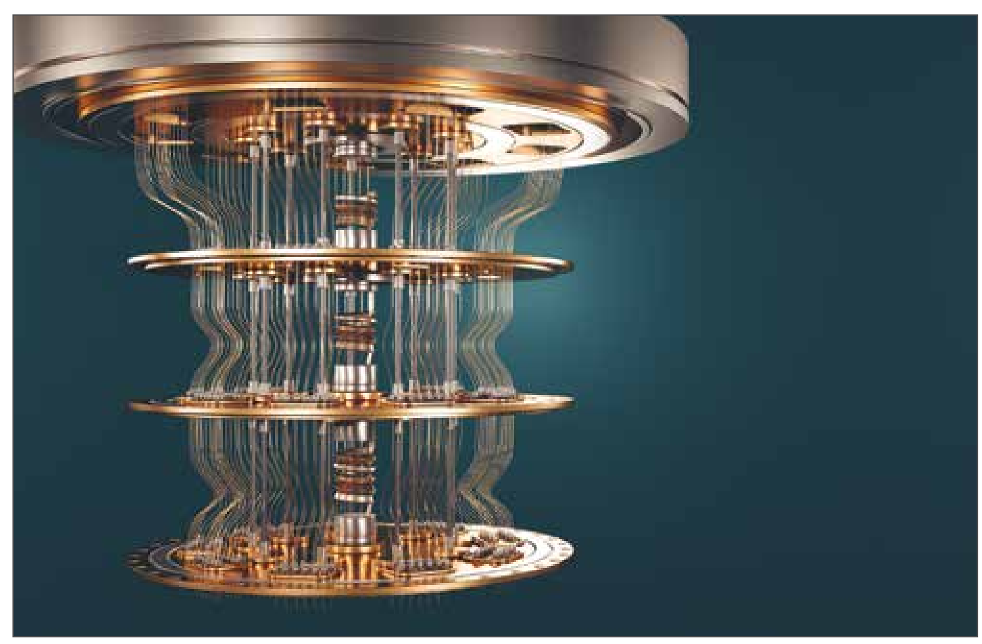
**Lauren Ancel Meyers** also offered insights into the spread and threat of Omicron in multiple outlets including *The Texas Tribune*, *The Atlantic*, *NPR*, and *USA Today*.

**Marc Lipsitch** discussed the nuances of understanding COVID-19 infections with *The New York Times* and *Scientific American*.

# Strengthening the second law of thermodynamics

According to the second law of thermodynamics, the total entropy of a closed process can increase or stay the same but never decrease. The second law guarantees, for example, that an egg can wobble off a table and leave a mess on the floor but that such a mess will never spontaneously form an egg and leap back on the table. Or that air will escape a balloon but never, on its own accord, inflate it. Since at least the 19th century, physicists have been investigating the role of entropy in information theory — studying the energy transactions of adding or erasing bits from computers, for example.

The thermodynamics of computation is a research focus of SFI Resident Professor David Wolpert, and for the last few years, he's been collaborating with Artemy Kolchinsky, former SFI Postdoctoral Fellow, to better understand the connection between thermodynamics and information processing in computation. Their latest exploration of the topic, published in *Physical Review E*, looks at applying these ideas to a wide range of classical and quantum areas, including quantum thermodynamics.



*Two computers might carry out the same calculation but differ in entropy production because of their expectations for inputs — a "mismatch cost." This fundamental relationship extends even more broadly than previously thought, including to the thermodynamics of quantum computers . (Photo: Shutterstock)*

"Computing systems are designed specifically to lose information about their past as they evolve," says Wolpert.

If a person inputs "2+2" into a calculator and then hits "enter," the computer outputs the answer: 4. At the same time, the machine loses information about the input since not only 2+2 but also 3+1 (and other pairs of numbers) can produce the same output. From the answer alone, the machine can't report which pair of numbers acted as input. In 1961, IBM physicist Rolf Landauer discovered that when information is erased, as during such a calculation, the entropy of the calculator decreases (by losing information), which means the entropy of the environment must increase.

"If you erase a bit of information, you have to generate a little bit of heat," says Kolchinsky.

Wolpert and Kolchinsky wanted to know: What is that energy cost of erasing information for a given system? Landauer derived an equation for the minimum amount of energy that is produced during erasure, but the SFI duo found that most systems actually produce more. "There's a cost that appears beyond Landauer's bound," says Kolchinsky.

The only way to achieve Landauer's minimum

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# When is a basin of attraction like an octopus?

Mathematicians who study dynamical systems often focus on the rules of attraction. Namely, how does the choice of the starting point affect where a system ends up? Some systems are easier to describe than others. A swinging pendulum, for example, will always land at the lowest point no matter where it starts.

In dynamical systems research, a "basin of attraction" is the set of all the starting points — usually close to one another — that arrive at the same final state as the system evolves through time. For straightforward systems like a swinging pendulum, the shape and size of a basin is comprehensible. Not so for more complicated systems: those with dimensions that reach into the tens or hundreds or higher can have wild geometries with fractal boundaries.

In fact, they may look like the tentacles of an octopus, according to new work by Yuanzhao Zhang, physicist and SFI Schmidt Science Postdoctoral Fellow, and Steven Strogatz, a mathematician and writer at Cornell University. The convoluted geometries of these high-dimensional basins can't be easily visualized, but in a new paper published in *Physical Review Letters*, the researchers describe a simple argument showing why basins in systems with multiple attractors should look like high-dimensional octopi. They make their argument by analyzing a simple model — a ring of oscillators that, despite only interacting locally, can produce myriad collective states such as in-phase synchronization. A high number of coupled oscillators will have many attractors, and therefore many basins.

"The geometry is very far from anything we know," says Strogatz. "This is not so much about what we found as to remind people that so much is waiting to be found.

"When you have a high-dimensional system, the tentacles dominate the basin size," says Zhang.

Importantly, the new work shows that the volume of a high-dimensional basin can't be correctly approximated by a hypercube, as tempting as it is. That's because the hypercube fails to encompass the vast majority — more than 99% — of the points in the basin, which are strung out on tentacles.

The paper also suggests that the topic of high-dimensional basins is rife with potential for new exploration. "The geometry is very far from anything we know," says Strogatz. "This is not so much about what we found as to remind people that so much is waiting to be found. This is the early age of exploration for basins."

The work may also have real-world implications. Zhang points to the power grid as an example of an important high-dimensional system with multiple basins of attraction. Understanding which starting points lead to which outcomes may help engineers figure out how to keep the lights on.

"Depending on how you start your grid, it will either evolve to a normal operating state or a disruptive state — like a blackout," Zhang says.

# Some colleges are mammals, others are cities

Higher education in the United States spans five orders of magnitude, from the tiny institutions like the 26-person Deep Springs College in the high desert of eastern California to behemoths, like Arizona State University's city-sized 130,000. A new study by SFI researchers examines how scale affects factors like tuition, research production, and teaching salaries. The research, published in *PLOS ONE*, is the first to systematically look at interconnected scaling effects in U.S. higher education.

"Community colleges, in particular, are much more like organisms," says West. "They emphasize efficiency, and they deliver on that and they're mean and lean, and big universities are rich and fat and getting fatter."

"The power of the paper is quantifying [scaling effects], and putting it into . . . a serious scientific framework," says Geoffrey West, a theoretical physicist, former President of SFI, and SFI's Distinguished Shannan Professor of Complexity.

West and co-author Chris Kempes, SFI Resident Professor, have previously examined how scaling laws dictate tree height, animal sleep, bacteria, and even cities. Scaling effects govern all aspects of organisms (and organism-like entities such as cities) from their metabolism and growth to their longevity. Large mammals, for example, use energy more efficiently than their smaller counterparts because the vascular system scales sublinearly: the bigger they are, the less the infrastructure to circulate blood costs.

To tackle the question of scaling in higher education, the researchers divided institutions into categories, such as for-profit colleges, community colleges, private research universities, and public research universities. The team, which included Ryan Taylor and Xiaofan Liang, co-first authors who participated in SFI's Undergraduate Complexity Research program in 2017, found that institutions were optimized for their function. For instance, in accordance with their goal to offer an affordable education to students, community colleges were very efficient; as they grew in size, tuition decreased and faculty salaries grew less.

*College of DuPage, in DuPage, Illinois (Photo: Jimmy Tompkins/Unsplash)*

The largest community colleges spent less than half as much per student as the smallest ones did.

On the other hand, as prestigious research universities grew in size, tuition and faculty salaries increased, while research production dramatically increased. Kempes, who co-led the project with former SFI Postdoctoral Fellow Marion Dumas, noted that this superlinear growth — "everything is getting bigger, better, faster" was similar to the way cities follow scaling laws.

"Community colleges, in particular, are much more like organisms," says West. "They emphasize efficiency, and they deliver on that and they're mean and lean, and big universities are rich and fat and getting fatter."

Critically, this efficiency doesn't seem to come at any cost to completion rates — by that measure students are still graduating at the same rate, even though they're saving money. Using data from mid-career salaries of graduates from 1984 to 2014, the researchers were also able to compare the return on investment for institutions. Again, community colleges punched above their weight, competing with more expensive schools in terms of how tuition grows compared with graduate salaries as schools become larger.

Why exactly institutions of higher education follow the trends they do is still not clear. One mechanism, West suggests, is that institutions are trying to optimize education and research. Some schools also choose specifically to stay at a certain size. In future work, Kempes hopes to separate a genuine scaling effect of size and category from a strategy.

While the current paper does not address policy implications, the authors note that it suggests institution success should be measured relative to scale. An institution that seems to underperform might in fact be overperforming for its size — not unlike a mammal, or a city.

# When does reputation lie?

Consider two stories: the first, about a boy who gets all the attention. He's the cool kid in class who comes from a well-known family. He seems to soar through life. When he errs, few seem to care. The more popular he is, the more beloved he becomes. The second: a girl who can't thrive. She tries and tries, to no avail. She's smart and kind, but she has few friends. The more she's shunned, the more discouraged she becomes.

*Researcher Eleanor Power's recent work draws on her ethnographic work among South Indians who practice acts of religious devotion such as firewalking. (Photo: Shutterstock)*

Does the boy merit his standing? Or does his status ensure his success? Is the girl trapped in a system that holds her down? Or is reality somewhere in between?

These are questions explored in a new paper that grew from hallway conversations among former SFI Postdoctoral Fellows Eleanor Power and Marion Dumas (both of the London School of Economics and Political Science) and their colleague Jessica Barker (Aarhus University and the Alaska Department of Health and Social Services). The trio developed an analytical and agent-based model to assess the interplay of reputation, social prominence, and social capital. The research draws from Power's ethnographic work among South Indians who perform intense acts of religious devotion such as firewalking and body piercing in gratitude toward a Hindu goddess.

Power recognized that religious participation is tied to status and the strength of one's social support networks. The more devoutly you behave, the greater your reputation. But not all is equal: some low-status villagers — particularly women and Dalits — don't get the same benefits from their actions. And their mistakes — say, tripping over hot coals — can be seen as divine punishment.

Power had a hunch that her observations reflected the influence of status on the costs and benefits of people's religious actions. Her colleagues told her, "I think you can model that," Power says.

Their research reveals a world neither black nor white. Quality is often recognized and rewarded, as expected. But sometimes people don't merit the prominence they maintain, while others, stuck in a "reputational poverty trap," lack the social support needed to succeed. As Power says, their work "speaks to the messiness of the world."

The paper, "When does reputation lie? Dynamic feedbacks between costly signals, social capital and social prominence," appears in a special issue of *Philosophical Transactions of the Royal Society B*, co-edited by Power and dedicated to multidisciplinary research on cooperation and reputation. "What's unique about it, in a very SFI sort of way, is the diversity of approaches," she says. "These are core concepts of the behavioral sciences that are being pursued along multiple avenues."

# Complexity's power to safeguard humanity's future

Will the 21st century be humanity's greatest, or our worst? According to the award-winning new documentary "Solutions," which was filmed on location at the Santa Fe Institute, the answer depends on the decisions we make in the next couple of decades, and on our ability to work across disciplines and continents to find revolutionary solutions.

"Solutions," which made its U.S. debut at this year's United Nations Association Film Festival (UNAFF) in Palo Alto, CA on October 31, captures a gathering of some of the world's leading thinkers at SFI. Over 10 days, 20 visionary scientists and innovators examined the growing gap between physical technologies like automation and AI, and social institutions like governments and healthcare systems. Warning that "When society is detached from reality, bad things happen," the film serves as an urgent call to action.

The SFI workshop gave rise to a global research project that aims to sketch out solutions for humanity to survive some of its most pressing challenges. Climate change, democracy in decline, economic inequality, and weaponized narratives transmitted through social media are just a few of

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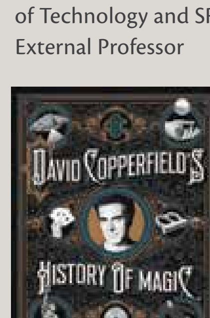
# What we're reading

## *Books chosen by SFI scholars on the theme of 'Deception'*

Despite the obvious human yearning for truth, we also appear to have an equivalent yearning for deception. As Friedrich Nietzsche succinctly put it in *Beyond Good and Evil*, "Whatever is profound loves masks." The pleasures and benefits of deception are apparent in almost every arena of life. From theater, the arts, and Plato's "noble lie," to masquerades, camouflage, and cosmetics, so many of our inventions and pastimes involve disguise, concealment, or subterfuge. Of course, this is true in the world of flora and fauna as well, where the stakes of deception reach existential proportions.

Whereas the last installment of What We're Reading was devoted to the art of Detection, for this edition we have selected the opposing theme of Deception. Whether detailing the history of the magicians who captivate us, informing us about the deceptively omnipresent fungi which "make our worlds, change our minds, and shape our futures," or constructing a situation in which routine perceptions melt away, the books here afford readers a glimpse behind the veils of everyday certitude. If good literature amplifies the tension between our love of deception and our quest for illumination, we hope these three works may be considered exemplary.

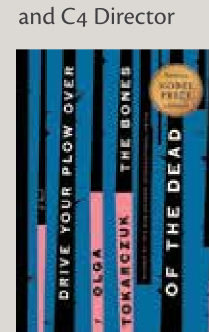
**SEAN CARROLL,** Research Professor of Theoretical Physics at the California Institute of Technology and SFI Fractal Faculty and External Professor




**"David Copperfield's History of Magic" (Simon & Schuster, 2021) by David Copperfield, Richard Wiseman, and David Britland**

*David Copperfield has assembled a unique museum devoted to the history of magic, from the 16th century through Houdini to today. But the collection isn't public — can't give away the secrets! Instead, we have this new book, a sumptuously illustrated tour of the most important milestones in the history of illusion.*

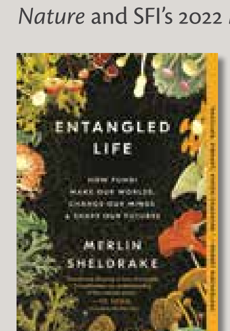
**JESSICA FLACK**, SFI Resident Professor and C4 Director




**"Drive Your Plow Over the Bones of the Dead" (Penguin Random House, 2019) by Olga Tokarczuk, translated by Antonia Lloyd-Jones**

*Is perception velvet or gauzy? Without having felt perception fray, without experiencing the vertigo that comes with the labyrinth dissolving, to ask this question is purely an intellectual exercise. Tokarczuk's Janina — translator of William Blake, guardian of forest animals, and a person in whom there is "a fire burning like a neutron star" — compels her readers to question not just perception but causality, and to feel the complicated possibility of velvet.*

**ANDREA WULF**, Author of *The Invention of Nature* and SFI's 2022 Miller Scholar




**"Entangled Life" (Penguin Random House, 2021) by Merlin Sheldrake**

*Few books have blown my mind like Merlin Sheldrake's magisterial* Entangled Life. *I'm not sure if I've ever learned so much from a single volume. Sheldrake invites his readers into a magnificent new world — after which nothing looks quite the same any more.*

# Complexity Scientists on the COVID-19 Pandemic

The COVID-19 pandemic tested our institutions and societies, from the global to the local, in unprecedented ways. The sheer speed of the novel coronavirus's spread meant that scientists, public health officials and medical professionals were left scrambling to understand it in real time, as the death toll rose. It may be one of the most complex and challenging public health crises the world has ever known.

Now, almost two years after the global rise of COVID-19, which has claimed more than five million lives worldwide so far, researchers are beginning to reflect on the pandemic's many lessons. *The Complex Alternative: Complexity Scientists on the COVID-19 Pandemic*, a new book from the SFI Press, offers reflections and recommendations from more than 60 members of the Santa Fe Institute community.

In this elegantly designed book — a tome of varied perspectives on the wide-ranging implications of the COVID-19 pandemic — researchers from across the sciences weigh in on topics ranging from modeling transmission to decision-making in the face of uncertainty, to how wildlife responded to suddenly empty cities.

This collection of articles, written for a general audience, underscores the importance of resisting simple answers in combatting a phenomenon as complex as a global pandemic and instead recognizing its inherently messy nature. Much of what went wrong during the pandemic can be attributed to overly simple, one-size-fits-all "solutions," such as questionable remedies or the singular efficacy of isolation, SFI President and William H. Miller Professor of Complex Systems David Krakauer and Shannan Distinguished Professor and Past President Geoffrey West write in the book's introduction. While there is often great comfort in embracing simplicity, "there can also be a certain naiveté in the excessive elegance that sometimes accompanies simplicity. And of greater concern is the danger in the desire for expediency — to explain every event or phenomenon as if it had a single cause and to flatten reality into a linear chain-like narrative whose future is as predictable as its past is comprehensible." The book, they add, "disavows simple explanations and solutions in favor of a concerted effort to come to terms with the whole matrix of the pandemic and all its messy parts."

As we struggle to grasp the full magnitude of the damage the pandemic has wrought, *The Complex Alternative* offers a wealth of nuanced insights into what we've learned — and makes an important contribution to the conversation about what we must do to better prepare for the next one.

**SECOND LAW** *(cont. from page 2)*

loss of energy, he says, is to design a computer with a certain task in mind. If the computer carries out some other calculation, then it will generate additional entropy. Kolchinsky and Wolpert have demonstrated that two computers might carry out the same calculation, for example, but differ in entropy production because of their expectations for inputs. The researchers call this a "mismatch cost," or the cost of being wrong.

"It's the cost between what the machine is built for and what you use it for," says Kolchinsky.

In past papers, the duo has proven that this mismatch cost is a general phenomenon that can be explored in a variety of systems, not only in information theory but also in physics or biology.

In past papers, the duo has proven that this mismatch cost is a general phenomenon that can be explored in a variety of systems, not only in information theory but also in physics or biology.

They've found a fundamental relationship between thermodynamic irreversibility — the case in which entropy increases — and logical irreversibility — the case in computation in which the initial state is lost. In a sense, they've strengthened the second law of thermodynamics.

In this latest publication, titled "Dependence of integrated, instantaneous, and fluctuating entropy production on the initial state in quantum and classical processes," Kolchinsky and Wolpert demonstrate that this fundamental relationship extends even more broadly than they'd previously thought, including to the thermodynamics of quantum computers. Information in quantum computers is vulnerable to loss or errors due to statistical fluctuations or quantum noise, which is why physicists are searching for new methods of error correction. A better understanding of mismatch cost, Kolchinsky says, could lead to a better understanding of how to predict and correct those errors.

"There's this deep relationship between the physics and information theory," says Kolchinsky.

**MILLER GIFT** *(cont. from page 1)*

field received its first Nobel Prize in Physics.

"2021 has been a defining year for complex systems," Krakauer says. "In October, the Nobel Prize was awarded to Giorgio Parisi for his work on physical models for complex systems, which built on the work of SFI researchers including Phil Anderson and David Sherrington."

In 1984, SFI became the first research institute dedicated to the rigorous analysis of complex systems. Over the past 37 years, this pursuit has yielded transformative methods and insights that have been applied to sustaining cities and ecosystems, preventing pandemics, and predicting bubbles and crashes in financial markets.

"Bill Miller's continuing generosity and support over the years has been absolutely pivotal for SFI and, as a consequence, for promoting and sustaining the kind of science and scholarship that is playing an increasingly central role not just across academia and business but in how we understand the messy world around us and address the enormous challenges we face," says Geoffrey West, SFI's Past President and Distinguished Shannan Professor of Complexity. "His latest gift has gone one extraordinary step further in ensuring long-term support of complexity science, transdisciplinary collaboration, and addressing the really big questions; in a word, ensuring the support of the science for the 21st century."

In the decades to come, SFI plans to use Miller's gift to attract more of the best minds in the world to the frontiers of complex systems science. The Institute hopes to grow a critical mass of researchers to advance both a fundamental theory of complex systems, and to supercharge individual research themes like complexity economics, the interface of complexity science and machine learning, mathematical and philosophical foundations of complexity science, foundations of natural and artificial intelligence, the theory of sustainable urban and large-scale social systems, and the theory of information processing systems like cells and brains, which are an iconic example of "emergence" in complex systems.

*Bill Miller (courtesy photo)*

Miller credits his 30-year involvement with SFI* for inspiring four major decisions in his investment career which significantly contributed to his fortune. But for Miller, the new gift to SFI isn't about repayment or monetary investment — it's a bet on the future of humanity.

"My long affiliation with SFI has been among the most rewarding of my life, both personally and professionally," says Miller. "SFI scientists have been and remain at the forefront of the most exciting and important scientific problems and challenges we face. I am delighted to be able to contribute to the critically important work SFI is engaged in."

**Miller, whose formal name is William H. Miller III, first visited SFI in 1991 and joined its board in 1995. He has since served SFI as Chair, Vice-Chair, and Chair Emeritus of the Board of Trustees. He is currently the founder of investment firm Miller Value Partners. He spent 35 years at global investment firm Legg Mason.*

**NOBEL PRIZE** *(cont. from page 1)*

described by equations that account for uncertainty and randomness.

In an informal, post-Nobel seminar, physicist Dan Stein, an SFI External Professor and Science Board Fellow, explained how Parisi's work on spin glasses fit into that story — with a twist. In a ferromagnet such as a fridge magnet, each atom acts like a tiny bar magnet and points in the same direction. The atoms in a spin glass lack a tidy magnetic organization, but in their disorder, Parisi found a "hidden order."

Before Parisi, SFI External Faculty Fellow David Sherrington and his collaborator Scott Kirkpatrick published a solvable model of a spin glass in 1975, for which Parisi found the equilibrium solution in 1979. The Sherrington–Kirkpatrick model was itself inspired by previous work by Sam Edwards and SFI co-founder Phil Anderson (also a Nobel Laureate in physics), which had used a mathematical trick of calculating spin-glass properties by creating replicas, effectively enabling the averaging of physical observables over many copies of the system. Parisi realized all these replicas were connected in a highly non-trivial manner, similar to descendants in a family tree: they all came from a single higher-energy state.

"Parisi is one of the leaders of spin glass theory," wrote SFI Professor Cris Moore. "This [award] joins several people associated with SFI, including Phil Anderson and (more remotely) Dan Stein. Parisi created something called the replica method, which lets us find phase transitions in systems with "glassy" landscapes. A version of this theory is what Lenka Zdeborova, Pan Zhang,† Florent Krzakala, and my other collaborators — including George Cantwell† and Caterina De Bacco† — use to study problems in high-dimensional inference, including community detection in networks."

Though spin glasses remain esoteric magnetic materials, the mathematical approaches physicists like Anderson and Parisi developed to understand disordered systems spread rapidly to other disciplines, from economics to ecology.

The prize is a reminder that climate, too, is an example of a complex system — one that humanity depends on understanding. Manabe and Hasselmann, who split the prize with Parisi, are climatologists. Parisi also studied the complexity of the climate, a recent comment in *Nature* pointed out, as do SFI researchers Daniel Schrag‡ (Harvard University) and Elizabeth Bradley‡ (University of Colorado Boulder), Joshua Garland†, and others.

At a press conference, after the prize was awarded, Parisi directly addressed the issue of climate change: "It's clear that for the future generation, we have to act now in a very fast way."

**The individual recipients of the 2021 Nobel Prize in Physics are not affiliated with SFI, which is the first research institute dedicated to complex systems science and is generally acknowledged as the global leader in the field.*

*†Pan Zhang, Caterina De Bacco, and Joshua Garland are former SFI Postdoctoral Fellows. George Cantwell is a current Postdoctoral Fellow.*

*‡Daniel Schrag is an SFI External Professor, the Science Board co-chair, and a Science Steering Committee member. Elizabeth Bradley is an SFI External Professor and Science Board member.*

**ENGINEERING** *(cont. from page 1)*

be cognizant of both electronic engineering and also neurophysiology. Contrast that with a hearing aid, which is just an amplifier." The brain of a person who's received a cochlear implant bypasses the old auditory system and effectively learns a new language.

The forums at SFI where complexity scientists and practitioners discuss emergent engineering frameworks illustrate the field's adaptive character. As Casey Cox, ACtioN Director, explains, "one of the things that we've noticed as we've conducted our meetings is that this is a research area where practitioners and complexity scientists have much to offer each other." For Cox, there's a dynamic relationship between science and practice that is integral to the field.

At SFI and in the world, engineering continues to evolve. In the fall of 2022, ACtioN is planning an in-person conference in Santa Fe that aims to elucidate further the field's principles. Ultimately, Krakauer plans for emergent engineering to become a full research theme at SFI and expects that the Santa Fe Institute will take the lead in shaping this new kind of dynamic science.

**BEYOND BORDERS** *(cont. from page 2)*

exceptions. Many publications are now based on pointing out one or more ways in which simple models fail. We now include our "chamber pots and sheets" in order to better fit contingent data sets. The most recent agent-based models for COVID-19 include age structure and population size, transmission networks for households, schools, workplaces, long-term care facilities, and communities, as well as detailed viral dynamics. The mathematician d'Alembert would have been stupefied by the complications.

The fact is we do not know how best to justify or choose between the complicated unique simulation and the simple universal analysis. For Bernoulli and Kermack and McKendrick the objective was to identify the most salient causal links in a chain of mortality. For modern agent-based models the objective is to provide a near real-time simulacrum for the pandemic to guide policy-making. And still none of these models include realistic psychological reactions, and very few embed the epidemic within a political economy.

Enrico Fermi recollected a conversation with John von Neumann who declared that "with four parameters I can fit an elephant, and with five I can make him wiggle his trunk." All of us trained in the mathematical natural sciences are drilled with that quote and until recently have avoided any suggestion of models that wiggle. It is now clear that the intellectual austerity of d'Alembert and von Neumann has in certain domains become obsolete. It will be a significant challenge for complexity science to do a better job of justifying the unique versus the universal.

*— David Krakauer*
*President, Santa Fe Institute*

*PNAS Special Feature*

# A look at the dynamics of political polarization


The challenges society will face in the coming decades will require cooperation, but trends toward partisanship, populism, and polarization around the globe could impact our ability to work together to meet those challenges. In a special feature in the *Proceedings of the National Academy of Sciences*, researchers from various fields explore these trends as systems-level phenomena.

"In viewing political systems as complex adaptive systems, we can gain a new understanding of the forces that shape current trends, and how that knowledge might affect governance strategies going forward," writes SFI's Simon Levin with special feature co-editors Helen V. Milner and Charles Perrings in their introduction. "Extreme polarization is a dangerous phenomenon that requires greater scientific attention to address effectively."

The 11 papers and additional perspectives in the special issue include contributions by SFI's Stephanie Forrest, Jenna Bednar, and Scott Page, and came out of a series of "Dialogues in Complexity" workshops co-hosted by Forrest and Levin with Andrea Graham and Ann Kinzig. The articles represent collaborative research between political scientists and complex-systems theorists.

"Polarization is a process and that is what complexity theory can best help us understand," write Levin, Milner, and Perrings. "The main goal of the Special Feature is to deepen our understanding of the dynamics of political polarization and related trends, and especially the interplay among these processes at multiple scales, from the local to the international."

*Affiliations and Funding: Andrea Graham (Princeton University); Ann Kinzig (Arizona State University); Simon Levin (Princeton University); Helen V. Milner (Princeton University); Scott Page; and Charles Perrings (Arizona State University).*

*Dialogues in Complexity workshops supported by funding through Arizona State University.*


*Northampton, MA. USA 5/2/2020 Pro trump supporters rally in Northampton MA to protest corona virus lockdown and Trumps reelection while a counter protester drives by. (Photo: Shutterstock)*

# Preventing extreme polarization of political attitudes

Encouraging interactions between people on opposite ends of the political spectrum may not be the best way to foster tolerance in a polarized nation.

In fact, a new study in the *PNAS* special feature suggests extreme polarization can be avoided when two sides of a stubbornly intolerant population have low exposure to each other.

SFI External Professor Stephanie Forrest, a computer scientist (Arizona State University), and coauthors Joshua Daymude, a postdoctoral researcher (Arizona State University), and Robert Axelrod, a professor of political science (University of Michigan), created an agent-based model to study ideological polarization that is unique in its simplicity.

In their Attraction–Repulsion Model (ARM), each individual agent is assigned two rules governing their behavior. In essence, the rules dictate that individuals move closer to or further away from extreme positions based on their attraction or repulsion to others' ideological positions.

"We tried to make the simplest model possible that captures what we thought were realistic assumptions," Daymude said. "It enables us to ask questions like what happens over time when the agents are more or less tolerant of others' ideological positions or more or less likely to be exposed to differing viewpoints."

Using the model, the researchers showed that a high level of intolerance was the key component of runaway polarization, especially when it was enhanced by high exposure between dissimilar individuals.

"While it at first may appear contrary to practical experience, our model suggests strictly limiting exposure to dissimilar views could be an effective mechanism for avoiding rapid polarization," Daymude said.

Another interesting finding of the study was that extreme polarization could be avoided when individuals were assigned a preferred ideological position based on economic self-interest and acted in favor of this assigned position.

"Even a small amount of self-interest can dramatically reduce polarization," Forrest said. "This is perhaps the most promising result of the model because it suggests a direction for policy intervention by which this polarizing dynamic could be moderated."

# Understanding the emergence and perils of polarization

We can't understand polarization unless we analyze it as a complex system, argue SFI External Professor Scott Page (University of Michigan) and co-author Delia Baldassarri (New York University) in a commentary for the special feature in *PNAS*.

Polarization occurs both in ideology (beliefs about the world and appropriate policies) and emotion (distrust and disconnection between the groups), and it is the feedback loops between these two types of polarization that make it such a difficult problem to solve. Positive feedback loops — where divergence creates more divergence — build polarization in the first place; negative feedback loops stifle attempts to build bridges across groups.

> Polarization occurs both in ideology . . . and emotion . . . and it is the feedback loops between these two types of polarization that make it such a difficult problem to solve.

Different models of polarization highlighted in the special feature shed light on particular aspects driving it. One model assumes that people become more like those who agree and diverge from those who disagree. That simple force transforms an ordinary array of varying opinions into two camps. A second model highlights the role that technology plays in enabling this movement, making it easier to link with those with similar views and to avoid those who disagree. And a third views polarization as a result of the overwhelming complexity and multidimensionality of the issues voters face: Incapable of deciding issue by issue, citizens look to elites and political leaders to simplify, and party leaders have incentives to build loyal, ideologically clustered networks of supporters.

Getting out of our polarized state, which according to some models will demand more effort than was required to get into it, will hinge on a deep understanding of the multiple forces that got us where we are now. The different theoretical explanations these models provide offer a start on that.


*IRVING, TEXAS, USA-MAR 2, 2018: Yard sign at residential street near library for primary election day in Dallas county. (Photo: Shutterstock)*


*Washington, D.C., USA. 24 March 2018. Thousands of students and supporters gather along Pennsylvania Avenue to rally against and protest school gun violence. (Photo: Shutterstock)*

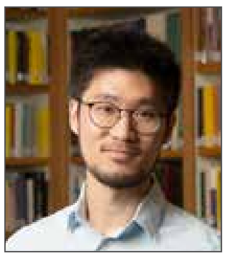
# Polarization, diversity, and democratic robustness

Polarization is dangerous for democracy. Though the U.S. Constitution was designed to harness rivalry with a diverse, redundant, and modular set of institutions, if that rivalry curdles into the belief that your competitors are your enemies, those institutions may not be strong enough to hold a nation together.

In a Perspective piece in the *PNAS* special feature, SFI External Professor Jenna Bednar (University of Michigan) argues that polarization poses three perils in particular.

The first problem is that people tend to gather with those who think similarly and avoid those who think differently, accentuating a distaste for those who differ. Second, elites can manipulate the public through fear, persuading their followers that others pose an existential threat — and then that fear can feed on itself, beyond all control. And third — and most dangerous, Bednar argues — is that the positions of the population become simplified, with less room for individual variation in beliefs. This can happen, for example, when each group polices the beliefs of its members and punishes those who don't conform with the established party line. This creates a loss of diversity in opinions that imperils democracy just as species diversity loss imperils ecosystems.

## ACHIEVEMENTS



SFI Schmidt Science Postdoctoral Fellow **Yuanzhao Zhang** was one of three recipients of the 2021 Emerging Researcher Award from the Complex Systems Society.

External Professor **Sara Walker** (Arizona State University) received the Stanley L. Miller Early Career Award from the International Society of the Study of the Origin of Life. Walker's research focuses on developing new theories for understanding what life is, and identifying universal laws of life that could apply to life throughout the universe.

External Professor **Jean Carlson** (UC Santa Barbara) was named a fellow of the American Physical Society, acknowledged "for the development of mathematically rigorous, physics-based models of nonlinear and complex systems that have significantly impacted a broad range of fields including neuroscience, environmental science, and geophysics."

## COMPLEXITY'S POWER *(cont. from page 3)*

the clear indicators that technological advances are pushing us to the brink of a major societal transition. With perspectives from luminaries in economics, public policy, history, law, biology, engineering, business, and beyond, "Solutions" presents citizens and societal decision-makers with what SFI External Professor Steen Rasmussen calls "a laundry list" of takeaways that highlight the power of complex-systems thinking to address the challenges of the 21st century.

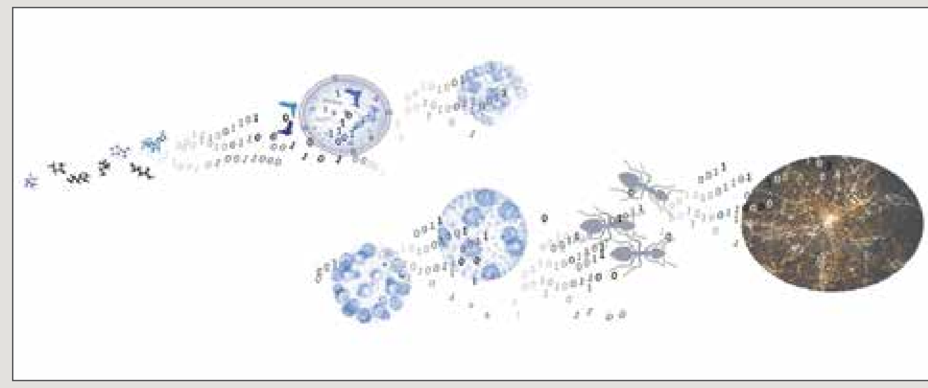
> "Solutions" presents citizens and societal decision-makers with what SFI External Professor Steen Rasmussen calls "a laundry list" of takeaways that highlight the power of complex-systems thinking to address the challenges of the 21st century.

"Solutions" brings viewers into the room with complexity scientists, offering the opportunity to experience how people with diverse areas of expertise can come together to diagnose global problems and search for answers. These conversations are complicated and sometimes uncomfortable, but always riveting.

"We all believe we want to change the world," says participant Doyne Farmer, an economist and SFI External Professor. "It's not just an empty academic exercise."

Directed by award-winning filmmaker Pernille Rose Grønkjær, "Solutions" was selected for UNAFF by a 24-member jury for its relevance and potential to captivate audiences. The documentary has already been lauded as a "must-see" in academic circles and won the Grand Prize at the 2021 Prague Science Film Festival. It has also been accepted to film festivals in Australia, Canada, France, Germany, the Netherlands, Norway, and Russia, and is in the running for several more awards.

## RESEARCH NEWS BRIEFS



**Information across the life spectrum.** *The figure illustrates a conceptual framework for how living systems might be considered as a gradation of examples of the same physical phenomenon with the key difference being the structure of information. It remains an open question whether an ordering of living systems on such a scale is possible, and if so what measures would characterize the scale. The complex systems in the figure represent a set of abiotic chemical compounds, the biochemical interactions within a cell, Volvox colonies composed of up to 50,000 cells, group behavior of ants' colonies, and a social structure embedded in a city — these are not comprehensive but illustrate how such scaling of systems representing different degrees of "aliveness" might look. (Figure 1: From: "Informational architecture across non-living and living collectives," Theory in Bioscience)*

### INFORMATIONAL ARCHITECTURE ACROSS NON-LIVING & LIVING COLLECTIVES

The intensifying search for life on other worlds begs an important question: Will we recognize life when we find it? A living thing on another planet may look quite different than any organism on Earth. One way to determine what alien lifeforms may be like is to compare various characteristics of the living and non-living systems we know — characteristics such as how collective behaviors are exhibited in each system. New work co-authored by SFI External Professor Sara Imari Walker offers an innovative way to determine the differences in collective behaviors between living and non-living systems: comparing their information architecture, or how information is stored and processed. The paper, published in a special issue of *Theory in Biosciences* on quantifying collectivity edited by SFI's Jessica Flack and Manfred Laubichler, aims to help improve the way collective behaviors are quantified — and leave us better prepared to recognize life on other planets, if and when we find it.

***Read the paper at doi.org/10.1007/s12064-020-00331-5***

### INNOVATIONS ARE DISPROPORTIONATELY LIKELY IN THE PERIPHERY OF A SCIENTIFIC NETWORK

The advancement of everything from science to education relies in large part on the ability to come up with new ideas. But under what conditions is innovation most likely? To help answer this key question in the science realm, SFI External Professor Manfred Laubichler and colleagues developed a framework to identify the origins of innovation across one field: evolutionary medicine. They conducted an automated analysis of more than 6,000 documents, including every paper in the field published before January 2018, measuring the novelty and acceptance of the ideas. The team then determined whether they fit within well-established lines of inquiry or fell on the periphery. The authors found that most innovations occurred at the fringe — suggesting that skirting the status quo "could be beneficial to creating novel and lasting change." The analysis was published in a November special issue of *Theory in Biosciences* on quantifying collectivity, edited by Laubichler and SFI Resident Professor Jessica Flack.

***Read the paper at doi.org/10.1007/s12064-021-00359-1***

### SLOWED CANONICAL PROGRESS IN LARGE FIELDS OF SCIENCE

In recent years, many academic disciplines have seen steady growth in the number of papers published as the fields aim for more researchers, funding, and output. But more papers don't necessarily mean a commensurate expansion of ideas. In fact, as SFI External Professor James A. Evans and co-author Johan S. G. Chu propose in a recent study in *PNAS*, too many papers can lead to stagnation rather than advance. The authors examined 1.8 billion citations referenced in 90 million papers across 241 fields. The sheer volume of papers can mean that new ideas can get lost in the sea of information, and as the annual number of papers in a field grows, the diversity of citations shrinks, with authors tending to cite already well-cited papers.

"Rather than causing faster turnover of field paradigms, a deluge of new publications entrenches top-cited papers, precluding new work from rising into the most-cited, commonly known canon of the field," the authors write. "The more-is-better, quantity metric-driven nature of today's scientific enterprise may ironically retard fundamental progress in the largest scientific fields."

***Read the paper at doi.org/10.1073/pnas.2021636118***

### FEEDBACK CONSIDERATIONS FOR BIODIVERSITY–ECOSYSTEM RESEARCH

In some parts of our lives, we are aware that humans, animals, and plants interact to shape the biodiversity of ecosystems in dynamic ways. Yet in other parts of our collective lives, we aren't benefiting fully from a scientific understanding of biological feedback.

In *The Proceedings of the Royal Society B*, SFI External Professor Mary I. O'Connor (University of British Columbia) and colleagues argue that public policy would benefit greatly if it were informed by the science of biological feedback. The research team investigated seven outstanding knowledge gaps, which can be addressed through an ambitious multidisciplinary research agenda, to clarify the ecological consequences of biodiversity feedbacks. Ultimately, the authors hope that by proposing better models of biological feedback, their work will help initiate a new feedback loop in scientific–political collaboration.

***Read the paper at doi.org/10.1098/rspb.2021.0783***

### CHANGING SOCIAL INEQUALITY FROM FIRST FARMERS TO EARLY STATES IN SOUTHEAST ASIA

In a study published in the *Proceedings of the National Academy of Sciences*, SFI External Professor Amy Bogaard (University of Oxford) and colleagues documented the distribution of valuable artifacts across Southeast Asian gravesites over an era that spans from the arrival of farming to the emergence of early states. Using the Gini coefficient to measure the concentration of wealth for each collection of sites, the researchers determined which kinds of historical events caused spikes in inequality. They found that during the Bronze Age, inequality rose when groups of elites held restricted ownership of valuables like copper-based axes and jewelry. Additionally, the arid climate that prompted a shift to wet-rice farming gave rise to the first political states, and with them, new inequality.

***Read the paper at doi.org/10.1073/pnas.2113598118***

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WINTER 2021–22
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