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Parallax

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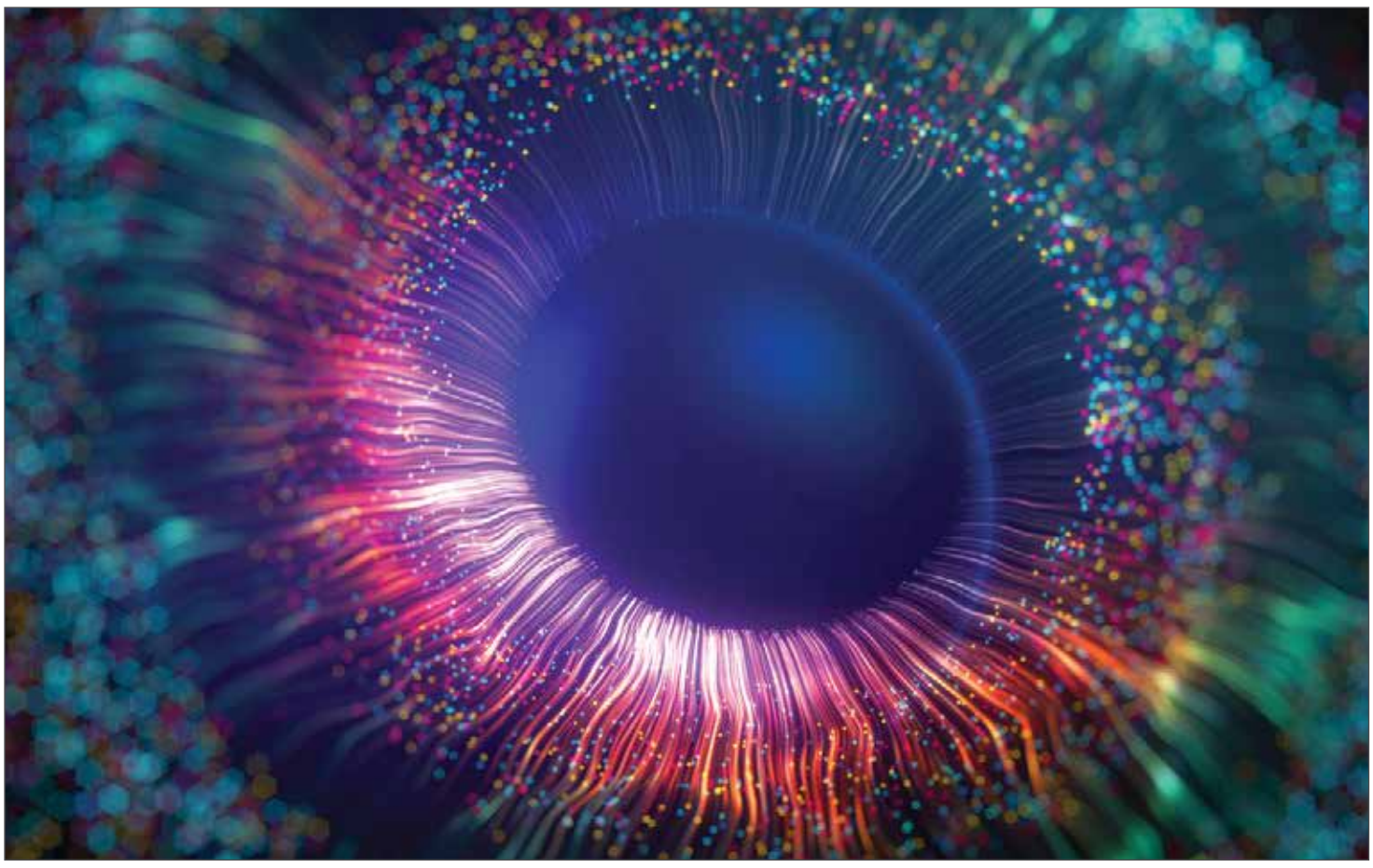

What if life is better understood on the analogy of the eye, a convergent organ that evolved from independent origins? (Image: CG Alex/Shutterstock)

A new theory of life's multiple origins

The history of life on Earth has often been likened to a four-billion-year-old torch relay. One flame, lit at the beginning of the chain, continues to pass on life in the same form all the way down. But what if life is better understood on the analogy of the eye, a convergent organ that evolved from independent origins? What if life evolved not just once, but multiple times independently?

In a new paper, published in the Journal of Molecular Evolution, SFI researchers Chris Kempes and David Krakauer argue that in order to recognize life's full range of forms, we must develop a new theoretical frame.

In their three-layered frame, Kempes and Krakauer call for researchers to consider, first, the full space of materials in which life could be possible; second, the constraints that limit the universe of possible life; and, third, the optimization processes that drive adaptation. In general, the framework considers life as adaptive information and adopts the analogy of computation to capture the processes central to life.

Several significant possibilities emerge when we consider life within the new framework. First, life originates multiple times — some apparent adaptations are actually "a new form of life, not just an adaptation," explains Krakauer — and it takes a far broader range of forms than conventional definitions allow. Culture, computation, and forests are all forms of life in this frame. As Kempes explains, "human culture lives on the material of minds, much like multicellular organisms live on the material of single-celled organisms."

When researchers focus on the life traits of single organisms, they often neglect the extent to which organisms' lives depend upon entire ecosystems as their fundamental material, and also ignore the ways that a life system may be more or less living. Within the new framework, by contrast, another implication appears: life becomes a continuum rather than a binary phenomenon. In this vein, the authors point to a variety of recent efforts that quantitatively place life on a spectrum.

By taking a broader view of life's principles, Kempes and Krakauer hope to generate more fertile theories for studying life. With clearer principles for finding life forms, and a new range of possible life forms that emerges from new principles, we'll not only clarify what life is, explains Krakauer, we'll also be better equipped "to build devices to find life," to create it in labs, and to recognize to what degree the life we see is living.

The fix is in for archeology's 'dating problem'

Archaeologists have long had a dating problem. The radiocarbon analysis typically used to reconstruct past human demographic changes relies on a method easily skewed by radiocarbon calibration curves and measurement uncertainty. And there's never been a statistical fix that works — until now.

"Nobody has systematically explored the problem, or shown how you can statistically deal with it," says SFI Applied Complexity Fellow Michael Price, lead author on a paper in the Journal of Archaeological Science about a new method he developed for summarizing sets of radiocarbon dates. "It's really exciting how this work came together. We identified a fundamental problem and fixed it."

In recent decades, archaeologists have increasingly relied on sets of radiocarbon dates to reconstruct past population size through an approach called "dates as data." The core assumption is that the number of radiocarbon samples from a given period is proportional to the region's population size at that time. Archaeologists have traditionally used "summed probability densities," or SPDs, to summarize these sets of radiocarbon dates. "But there are a lot of inherent issues with SPDs," says Julie Hoggarth, Baylor University archaeologist and a co-author on the paper.

Radiocarbon dating measures the decay of carbon-14 in organic matter. But the amount of carbon-14 in the atmosphere fluctuates through time; it's not a constant baseline. So researchers create radiocarbon calibration curves that map the carbon-14 values to dates. Yet a single carbon-14 value can correspond to different dates — a problem known as "equifinality," which can naturally bias the SPD curves. "That's been a major issue," and a hurdle for demographic analyses, says Hoggarth. "How do you know that the change you're looking at is an actual change in population size, and it isn't a change in the shape of the calibration curve?"

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Virtual workshop takes a hard think about thinking

Brains are a lot like computers. Both transmit information, transform information (i.e., "solve problems"), store memories, and use circuits that require energy to achieve their functions. Unfortunately, unlike your desktop computer, we don't have detailed schematics for the brain; and its "algorithms"— the step-by-step logical processes underlying its large-scale functions — are largely a black box. Simply put, we don't know how the brain computes.

In July, "Dynamics of the Off-Equilibrium Brain," a virtual workshop led by SFI Professor David Wolpert and University of Pennsylvania Professor Vijay Balasubramanian, began to investigate new ways of understanding how the brain computes using newly developed ideas in thermodynamics and information theory.

Why thermodynamics and information theory? Brains must process tremendous amounts of information and do so while consuming resources like energy efficiently. "Your brain is amazingly more thermodynamically efficient than computers," Wolpert says. Unlocking the relationship between energy and information in the brain could help researchers figure out how computation actually works. In particular, the workshop focused on the fact that the brain is not a static system, as classical theoretical frameworks often assume. Instead, it is an inherently dynamic system.

The workshop was held over two weeks with a daily talk and freeform discussions by Zoom. Attendees and speakers logged in from around the world to spend about three and a half hours each day talking about brains. Participants had backgrounds in neuroscience and physics, and spanned many career stages — their ages ranged from 18 to 80. Participants presented some new research, but dedicated much of their time to figuring out how to even formulate questions for future inquiry.

"Normal workshops and conferences just don't fit the bill — you come and report stuff you've

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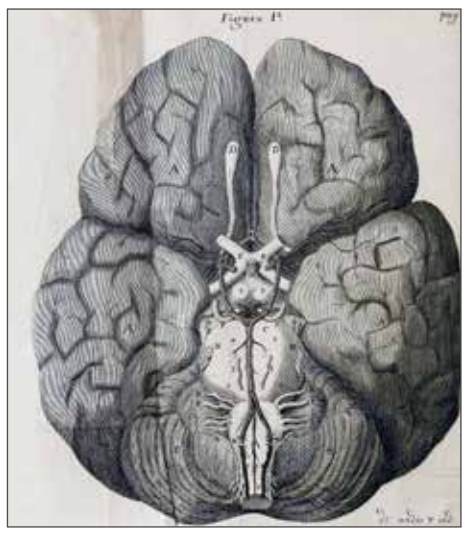

Christopher Wren's engraving of the lower side of the brain from Thomas Willis's Cerebri Anatome, *1664*

BEYOND BORDERS

THE END OF NARRATIVE

In 1992 Francis Fukuyama wrote a long book with a mystifying title: "The End of History and the Last Man." Even before reading the book, the title presented itself as a contradiction —surely there can be no end of history without an end to time? And after reading the book — which was reassuringly more parochial than its title and focused on a Hegelian unfolding of liberalism as the Omega point of institutional order — even the more modest thesis seemed questionable, a position that Fukuyama himself adopted in his later book "Identity: The Demand for Dignity and the Politics of Resentment," in which the stable social equilibrium that Fukuyama had foreseen was disrupted by the unbounded desire for recognition.

But what if we were to alter Fukuyama's title slightly and substitute "narrative" for "history"? I think I could defend the idea of The End of Narrative, by which I mean the concept of historical time that is implied by narrative — a sequence of limited and dominant cause/effect relations required to explain the present in terms of a contingent past.

The period of the late eighteenth century to the mid-twentieth century was characterized by an idea of time in which the socio-cultural clock moved according to a small number of springs, wheels, and pinions. Narrative history is a clockwork history where everything is neatly ordered along a timeline, and where every effect has a reasonable and comprehensible number of causes.

Edward Gibbon, author of the nearly imponderably long and dense "Decline and Fall of the Roman Empire" (and one of the books I most admire precisely because of this) wrote, "…the decline of Rome was the natural and inevitable effect of immoderate greatness. Prosperity ripened the principle of decay; the causes of destruction multiplied with the extent of conquest; and as soon as time or accident had removed the artificial supports, the stupendous fabric yielded to the pressure of its own weight."

For those of us inculcated in entropic reasoning, this quote sounds eerily familiar: the rate and certainty of decay is in direct proportion to complication. Gibbon argued that it was the role of the historian to understand the simple facts, and the best historian is a narrative historian, one "capable of distinguishing these types of fact [dominant causes] in the vast chaos of events."

Georg Wilhelm Friedrich Hegel, an admirer of Gibbon equally fearful of over-complication that "presents a disgusting picture of imbecility . . . [with] passions stifle the growth of all that is noble in thoughts, deeds . . ." articulated a positive, or anti-entropic narrative theory, but this time for all of history: history is the progress of consciousness, in particular the self-consciousness of freedom. And that this comes about through a dialectical form of reasoning in which thesis and antithesis achieve a synthesis whose primary quality is freedom. If Fukuyama's thesis strained credulity, Hegel's synthesis looks utterly preposterous.

Hegelian non-viability did not deter Karl Marx in the mid-nineteenth century from

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SFI IN THE MEDIA

In a September feature article, Scientific American reported on Shannan Professor of Complexity **Geoffrey West** and former Complexity Postdoctoral Fellow **Markus Schläpfer**'s mathematical law for how humans move through cities around the world.

Scientific American also featured External Professor **Thalia Wheatley**'s research on the neuroscience of eye contact, and what it signifies in the context of conversation.

A new research metric (see p.6) co-authored by SFI's **Stefani Crabtree**, with **Corey Bradshaw** at Flinders University, was reported in the Times Higher Education.

Professor **Mirta Galesic** was interviewed on Vox's "Recode Daily" podcast, in an episode about "How social media threatens humanity," describing a PNAS commentary she co-authored with Omidyar Fellow **Albert Kao** and their UW collaborators.

Nature News & Views, Science News, and other outlets featured a recent study by External Professor **Brain Enquist** and collaborators that maps the tragic impact of drought and fire on the species that inhabit the Amazon basin (see p.6).

Chris Kempes and **David Krakauer**'s recent framework on multiple life origins (see p.1) was featured in IFL Science, SYFY Wire, and other outlets, giving it the top media attention score for papers in the Journal of Molecular Evolution.

Quanta magazine quoted External Professor **Joshua Grochow** in the article "How Big Data Carried Graph Theory Into New Dimensions," citing his research and separate research by External Professors **Pamela Yeh** and **Van Savage**.

Bloomberg featured SFI's **W. Brian Arthur** on their "Odd Lots" podcast, in an episode dedicated to complexity economics. Arthur was also featured in BloombergQuint and interviewed on The Jim Rutt Show podcast.

BloombergQuint and The Washington Post published an op-ed by External Professors **Eric Beinhocker** and **Doyne Farmer**, on how to save 5 trillion dollars during the energy transition.

Vicky Chuqiao Yang was quoted prominently in PNAS News, in a feature about physicists' approaches to studying political polarization. It was written by Mitch Waldrop, the author of the book "Complexity."

IEEE Spectrum quoted External Professor **Melanie Moses** in an article about the challenges around regulating open-source AI software.

External Professor **Orit Peleg** (see p. 6) was featured in Axios, The New York Times, Science, Physics World, and other outlets for her new research on self-organization in swarms of fireflies. She also wrote a long form essay, "Living orbs of light," for Aeon magazine.

Aeon also published a long form essay by SFI authors **Geoffrey West** and External Professor **Van Savage** about their quantitative theory for why we sleep.

Thomas Ashcraft, SFI's resident artist, was profiled by NASA, where he participates in a citizen science project.

As cities grow in size, the 'rich get richer and the poor get poorer'

Cities are hubs of human activity, supercharging the exchange of ideas and interactions. Scaling theory has established that, as cities grow larger, they tend to produce more of pretty much everything from pollution and crime to patents and wealth. On average, people in larger cities are better off economically. But a new study published in the Journal of the Royal Society Interface builds on previous research that says, that's not necessarily true for the individual city-dweller. It turns out, bigger cities also produce more income inequality.

> . . . poorer city dwellers are missing out on the increased social interactions that are credited with driving innovation and wealth creation in large metropolises.

(Photo: Max Böhme/Unsplash)

"Previous literature has looked at [urban scaling] through a lens of homogeneity," says SFI Omidyar Fellow Vicky Chuqiao Yang, an author on the study. These past studies have shown a per-capita increase in wealth as cities grow. "But we know from other literature, especially in economics, that many societies are unequal and economic outputs are not distributed evenly."

Using data from municipal areas across the U.S., the authors took another look at urban wealth through a lens of heterogeneity. Breaking the income in their dataset into deciles, the team found that, as cities grow larger, the top ten percent of income earners gain an increasingly large portion of the wealth.

"For a long time, what has often been thought about in urban scaling is the whole system," says SFI Professor Chris Kempes, a co-author on this paper who has worked closely on other projects with co-author Geoffrey West, SFI Shannan Distinguished Professor and Past President, to study scaling relationships in systems from cities to biological organisms.

But it's not just wealth that tends to increase as cities grow; the cost of living also increases. So, the authors factored in an adjustment for housing prices. With that adjustment, their analysis showed that, as cities get bigger, the housing costs increase at a faster rate than lower-decile income.

"For the lower decile, there is no proportional increase in wealth. So, the city is not increasing economic benefit, but it's not decreasing it either," says Kempes. "However, since costs do go up, the experience of the poorest individuals gets worse."

Across the world, civilization is undergoing rapid urbanization. More than half the world's humans currently live in urban settings, and in the coming decade, researchers predict the number of megacities — those with 10 million people or more — will quadruple. "There is an urgent need for a quantitative and predictive

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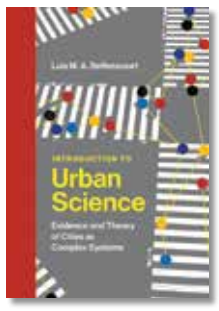
New books by SFI authors

"**Agent-Based Modeling for Archaeology: Simulating the Complexity of Societies**" (SFI Press, 2021) by ASU-SFI Biosocial Complex Systems Fellow Stefani Crabtree, Iza Romanowska, and Colin D. Wren, explains agent-based modeling to archaeologists with little or no experience with the technique. Archaeologists of all specialties will appreciate the examples of agent-based models that are helping to answer some of the field's biggest archaeological questions, and will gain guidance and inspiration to apply the tool in their own work.

"This technology is a couple decades old, but I think there was a need for a textbook to teach people how to do this," says Crabtree, who along with her co-authors teaches workshops on the technique.

And the need for the tool has never been greater, she adds — as evidenced by the book's days-long run as the #1 bestseller on Amazon.com in the archaeology category in August 2021.

"**Introduction to Urban Science: Evidence and Theory of Cities as Complex Systems**" (MIT Press, 2021) by External Professor Luís Bettencourt presents a comprehensive guide to the properties of cities as complex, evolving systems. Most of the world's people now live in cities, and as urban



areas have grown, these centers of government, commerce, innovation, and social interaction have become increasingly complex. The usual tools for understanding them — urban geography, sociology, economics, and so on — no longer suffice. To grasp the totality of today's cities and devise the best solutions to address urban problems, we need a new, interdisciplinary approach that builds upon all of these realms of knowledge and a lot of new data while offering a new way of thinking about cities.

Bettencourt says he hopes anyone who studies cities or teaches urban science will find the book, which draws on decades of SFI research and a course he teaches at the University of Chicago, useful. It provides readers with a solid understanding of the classical models of cities and complex networks before delving into key features of urban areas, from diversity, economic productivity and infrastructure to geography, growth, and institutions, and how they're connected.

"The book makes the point again and again that cities are not just the things you see when you look out the window," Bettencourt says. "Cities are people in action, change, networks."

View of SFI from Ann Nitze hiking trail. (Photo: Kate Joyce/Santa Fe Institute)

SFI welcomes nine new external researchers

The external faculty are central to SFI's identity as a world-class research institute. They enrich our networks of interactions, help us push the boundaries of complex systems science, and connect us to over 70 institutions around the globe.

This year, nine new researchers join us as External Professors.

MONIQUE BORGERHOFF MULDER
Distinguished Research Professor, Department of Anthropology Evolutionary Wing, UC Davis

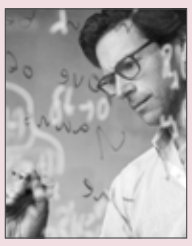
Research interests: *demography, marriage, natural resource management*

MARCO BUONGIORNO NARDELLI
University Distinguished Research Professor, Department of Physics, Division of Composition Studies, University of North Texas

Research interests: *music composition, computational physics, media arts*

TINA ELIASSI-RAD
Core Faculty, Network Science Institute and Professor of Computer Science, Northeastern University

Research interests: *data-mining, machine learning, network science*



JOHN KAAG
Professor and Chair of Philosophy, University of Massachusetts, Lowell

Research interests: *academic philosophy, biological origins of creativity, ethics of drone warfare, philosophy and memoir*

PAUL KRAPIVSKY
Research Professor, Physics, Boston University

Research interests: *dynamics of interacting many-particle systems*

MASON PORTER
Professor, Department of Mathematics, UCLA

Research interests: *applied mathematics, including nonlinear science, nonlinear dynamics and chaos, nonlinear waves, billiard systems, quantum chaos, granular media, nonlinear optics, atomic physics, network science, social network analysis, mathematical biology, synchronization*

KATHY POWERS
Associate Professor, Political Science, University of New Mexico

Research interests: *the nature of institutional authority, institutional change, and effects, design of international institutions and law*

DEVIN WHITE
R&D Manager, Autonomous Sensing and Perception group, Sandia National Laboratories

Research interests: *machine intelligence, remote sensing, imaging science, photogrammetry, computer vision, geographic information science, computational social science, complex systems, high-performance computing, and quantitative approaches to understanding prehistory*

HYEJIN YOUN
Associate Professor, Management & Organization Department, Kellogg School of Management, Northwestern University

Research interests:
the *interplay between technological innovation and socio-economic systems*

Stuart Firestein: 'It could be otherwise'

The neuroscientist Stuart Firestein can't point to a single moment when his quest to understand science's long history and uncertain future began, but the fall of 2008 is as good a place to start as any. At the time, Firestein, a Columbia University neuroscientist with a Brooklynite's love of colorful language, was facing a crisis of scientific confidence. He was on stage in an auditorium, teaching "Intro to the Brain" to 200 glazed-eye undergraduates. "Essentially asking them to memorize a 1,414 page, seven-pound textbook," recalls Firestein, laughing at the ridiculousness of the idea. "We don't practice science deterministically, but we sure as hell teach it that way." That disconnect, Firestein realized, goes a long way toward explaining why in America climate change is doubted and vaccine hesitancy rising. The public has lost faith in science. "We're facing a crisis," Firestein says. People distrust the very thing modern society is built upon.

Firestein is an esteemed neuroscientist who specializes in the olfactory system: why and how our brains and noses sense smell. But it's his obsession with the history, evolution, and future of science that brought him to SFI as its newest fractal faculty member. He has already authored two popular books, "Ignorance" and "Failure," that cast science as an unending quest to illuminate ignorance and failure as an essential component in that process. He's now begun a third book he plans to call "Optimism." In it, Firestein will make the case that modern society's optimism, oversimplified as the sense that our future will be brighter than our present, is a direct product of the scientific process.

"Science helps us act on the belief that 'It could be otherwise,'" he says, invoking that tidy phrase to sum up his book's thesis. But he also wants "Optimism" to sound an alarm. Science is impermanent. Unless scientists get better at communicating with the public, it could one day stop marching humanity toward a better version of itself.

When considering how science arrived at this precarious moment, Firestein takes the long view. He starts in the 1600s with the likes of Copernicus, Vesalius, Galileo, Kepler, and the first scientific revolution. Before science, each generation lived essentially the same life as the generation before. Change was so slow as to be imperceptible. After this cognitive revolution, change became palpable and the idea of change accepted as normal. But powerful as this engine of progress was, Firestein notes that it developed into a kind of creeping determinism, a dogmatic certainty about the way the world is governed. Science's optimism suffered. Determinism eliminates possibility. It closes the world. Science was in danger of losing its optimism.

This changed when Darwin's "On the Origin of Species" appeared in 1859."That was the most revolutionary idea since Copernicus," Firestein says. "Darwin showed us that life is nondeterministic—it's random at its base yet also predictable." In Firestein's view, Darwin's ideas changed the very essence of the questions that science sought to answer. Instead of extracting immutable laws from nature, trying to fit our understanding into a clockwork universe, science had to embrace uncertainty and randomness as fundamental forces. It had to embrace the very idea that parts of the universe are unknowable. Firestein thinks of this seismic and ongoing shift as the second scientific revolution. Among its discoveries he counts Ludwig Boltzmann's statistical approach to the second law of thermodynamics, Quantum mechanics, and nuclear energy (and yes, the bomb). Plate tectonics. iPhones. Climate models and mRNA vaccines.

But for all the whiplash progress that the second scientific revolution has delivered, it is critically and maybe even suicidally flawed. "The early scientists of the late Renaissance and Enlightenment — Galileo, Hooke, Voltaire — wrote in common vernaculars or had their works translated into vernacular languages. Voltaire, for example, translated Newton into French making his revolutionary work available to a wide public," Firestein says. Egalitarianism was chief among science's appeals. Post-Darwin, science became more niche and its vernaculars so hyper-specific that a Ph.D. in one field can no longer comprehend a Ph.D. in another. One result of this trend is that scientists talk publicly about their work deterministically. Why? It's easier. But it's dangerous. "We have left the public far behind," Firestein says. "People now think that unsettled science is unsound science when exactly the opposite is true."

> ". . . the sense that our future will be brighter than our present, is a direct product of the scientific process. "Science helps us act on the belief that 'It could be otherwise,'" he says.

After finishing his "Intro to the Brain" course back in 2008, Firestein launched a sort of rebellion against determinism. He started a new course where he invited top scientists to speak about the questions that animated their work. The idea was weirdly profound: a class about what nobody knew. Firestein realized it was the first time he was teaching science as a process rather than an outcome that could be labeled right or wrong. Twelve years later, he's still teaching the course but the stakes now feel higher. Never has America, and much of the world, been more hostile to science. And never has it been so important for science, an institution that helped make the world modern, to bring its optimism back to that world.

So what can be done? That's the question Firestein is coming to SFI to answer. While here, he wants to understand how optimism figures in the working process of scientists working on complexity and uncertainty. And he is interested in hearing their ideas about how their work can be better communicated to the public. "Our forebears did it. We owe it to future scientists and ourselves to do it too," he says. Put another way, Firestein wants science to be talked about in a common vernacular. Because, in this scary moment, he believes that it could be otherwise.

In the Summer 2021 issue of Parallax, we introduced Melanie Mitchell and Sean Carroll as the first two "fractal" members of SFI's faculty. Now, we welcome Stuart Firestein as our third.

Stuart Firestein at SFI. (Photo: Kate Joyce/Santa Fe Institute)

(Photo: Vlad Tchompalov/Unsplash)

New tutorial teaches open science

The best possible science is science that is "open, reproducible, replicable, transparent, and inclusive," says Open Science advocate and SFI Complexity Postdoctoral Fellow Helena Miton.

Miton teaches the newest tutorial on Complexity Explorer, which introduces learners to Open Science and the set of practices it includes. Open Science is a methodological approach throughout the research cycle, from preregistering research questions to publishing final results. Miton hopes her course will be used as a teaching tool to educate the next generation of scientists about the applications and advantages of Open Science.

To that end, Miton's course outlines a "buffet" of techniques — including open methods, open code, open materials and data, preprints, and open access. "I constructed the course with the goal of providing one entry to the whole spectrum of practices in the same place, rather than in a piecemeal fashion, which is how I had to learn them," she says. "After watching the videos, you will have a good foundation in the different Open Science methods and resources for learning how to apply them."

Miton sees Open Science as one of many ways to improve science, and she applies the principles in her own work. "A lot of people agree on Open Science in theory but are reluctant to put it into practice because they believe it requires extra effort. As a researcher, I find that Open Science approaches have many advantages and provide a different way to organize my workflow that isn't any costlier. These approaches give structure and robustness to my research process."

In addition to enhancing her own research, Miton appreciates the collective benefits of Open Science. Open Science contributes to diversity in science, in part, she says, "by shifting away from traditional economic incentives, like the power of publishers, and rethinking how researchers are evaluated. The goal is to make sure that scientific knowledge is accessible to all."

The course on ComplexityExplorer.org is free and open to all.

BRAIN WORKSHOP *(cont. from page 1)*

already done," says Balasubramanian. "I felt that this workshop was fundamentally different. The entire two weeks was about trying to figure out how to express new concepts that we didn't previously know how to formalize."

One fundamental question discussed at the workshop: What exactly is computation in the brain? According to Balasubramanian, much of what classical neuroscience calls computation is actually communication — sending information from here to there. But as Wolpert says, "If all the brain did was transmit information accurately, you'd do well to scoop out all the goo in your skull and replace it with fiber optic". Computation, on the other hand, requires transforming information.

That's where non-equilibrium thermodynamics comes in. While all parts of the body spend energy synthesizing new proteins, the brain's job is to compute. Determining constraints on the energy used to perform that computation could provide answers to questions such as why humans have as many neurons as we do — 86 billion, on average. Applying know-how from thermodynamics about noise and entropy, the measure of disorder in a system, could help formulate better theories about how the brain does its job.

Another goal of the workshop was to delve more explicitly into the brain-computer analogy. Neuroscientists talk a lot about circuits at various scales, but the discussions often fall short of explaining holistically how the brain functions as a computer. "We have circuit diagrams of which brain areas talk to which brain areas, and what's going on within each brain area—but I challenge you to find one person on the planet who can explain to you in detail how your behaviors arise from those divisions," Balasubramanian says. By framing questions with additional computer science concepts like "architectures" — the rules which bridge the gap between hardware and software — and "algorithms," he and Wolpert hope to push inquiry further.

Part of the reason classical neuroscience simply hasn't been asking some of these questions is because tools to measure the activities of neurons have been limited, and hence the inquiry wasn't feasible. Only recently have experimentalists been able to take data from large numbers of neurons at the same time. It's at these scales, above individual neurons and below entire regions of the brain, that the processes are murkiest, and where the workshop's participants centered their discussions.

Following the workshop, attendees have split off into smaller working groups to tackle problems raised during the sessions. They hope to eventually produce theories of the brain that experimentalists can check against reality.

A new model for group decision-making shows how 'followers' influence outcomes

From small committees to national elections, group decision-making can be complicated — and it may not always settle on the best choice. That's partly because some members of the group do research on their own, and others take their cues from the people around them.

That distinction is readily observed around election time. "Many voters couldn't tell you the policy platforms for the candidates they're voting for," says Vicky Chuqiao Yang, an SFI Omidyar Fellow and Peters Hurst Scholar. "Many individuals are uninformed, and they're most likely to rely on information they get from others."

Social scientists have long sought ways to study the phenomenon of group decision-making, but that's a tricky undertaking. Researchers in a range of disciplines have tried to tackle the problem, with parallel efforts often leading to conflicting conclusions. Most existing models examine the effect of a single variable, which means they don't capture the whole picture.

"The outcome of collective decision making is the result of complex interactions of many variables," says Yang, "and those interactions are rarely taken into account" in previous work.

To overcome that challenge, Yang recently led the development of a mathematical framework that captures the influence of multiple interactions among members of a group. "You can plug in multiple effects and see their behavior and how they manifest in the group at the same time," she explains.

Those effects include the influence of social learners. The model predicted, for example, that decision-making groups have a critical threshold of people who get their information from others. Below that threshold, the group chooses the high-quality outcome. Above it, the group can end up choosing the better or worse option.

The model also predicted a significant role for "committed minorities," or people who refuse to change their minds, no matter the evidence. These committed minorities can be bolstered, Yang says, by social learners, though every group is different.

> The model also predicted a significant role for "committed minorities," or people who refuse to change their minds, no matter the evidence.

The mathematical model is both simple and general and can accurately reflect the multitude of moving parts within a system. Yang's collaborators include psychologist and SFI Professor Mirta Galesic, economist Ani Harutyunyan at the Sunwater Institute, and Harvey McGuinness, an undergraduate at Johns Hopkins University and former student researcher at SFI. (The whole project began, said Yang, with a question from McGuinness.) The group reported on the framework in a paper published in *Proceedings of the National Academy of Sciences.*

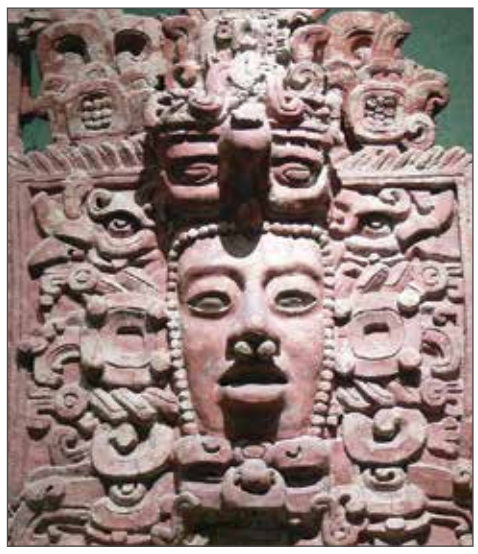
Yang says she hopes the model will help bring together parallel work from different disciplines. These disciplines have found separate effects at work in collective decision-making, "but we don't yet have a holistic understanding that gives a recipe for good collective decision making," she said. "Our work brings us one step closer to it."

RADIOCARBON DATING *(cont. from page 1)*

When she discussed the problem with Price several years ago, he told her he wasn't a fan of SPDs, either. She asked what archaeologists should do instead. "Essentially, he said, 'Well, there is no alternative.'"

That realization led to a years-long quest. Price has developed an approach to estimating prehistoric populations that uses Bayesian reasoning and a flexible probability model that allows researchers to overcome the problem of equifinality. The approach also allows them to combine additional archaeological information with radiocarbon analyses to get a more accurate population estimate. He and his team applied the approach to existing radiocarbon dates from the Maya city of Tikal, which has extensive prior archaeological research. "It serves as a really good test case," says Hoggarth, a Maya scholar. For a long time, archaeologists debated two demographic reconstructions: Tikal's population spiked in the Early Classic period and then plateaued, or it spiked in the Late Classic period. When the team applied the new Bayesian algorithm, "it showed a really steep population increase associated with the Late Classic," she says, "so that was really wonderful confirmation for us."

The authors produced an open-source package that implements the new approach, and website links and code are included in their paper. "The reason I'm excited for this," Price says, "is that it's pointing out a mistake that matters, fixing it, and laying the groundwork for future work."



Maya mask from Early Classic period circa 250 - 600 AD. (Photo: Joyce Kelly 2001 An Archaeological Guide to Central and Southern Mexico)

This paper is just the first step. Next, through "data fusion," the team will add ancient DNA and other data to radiocarbon dates for even more reliable demographic reconstructions. "That's the long-term plan," Price says. And it could help resolve a second issue with the dates as data approach: a "bias problem" if and when radiocarbon dates are skewed toward a particular time period, leading to inaccurate analyses.

But that's a topic for another paper.

BEYOND BORDERS *(cont. from page 2)*

subjugating the dialectic into his own historical materialism, in which materials replace ideals in the dialectic of proletariat versus capitalist state. As with Hegel, Marx understood history through a rather simple narrative as progressive liberation toward socialism.

As a frequent inhabitant of used books stores, one of the more common species of neglected volumes is James George Frazer's "The Golden Bough." The third edition was finished in 1915 and runs to twelve volumes, but the full set is a rare sighting (unlike the single volume — a diminished abridgement). Frazer argues that beneath the complexity of modern life there are a series of patterns that define a unified existential narrative: that all individuals and societies are bound to celestial cycles, and these are symbolized by a king who is the incarnation of a dying and reviving god — one who dies at the harvest and is reincarnated in the spring. For Frazer, life was not progressive by cyclical and thereby cultural reflection of the mechanics of Newton and Poincare. The most obsessive, periodic historian was Arnold Toynbee, who I also tend to excavate in the rubble of disregarded book stores and who also wrote twelve volumes of panoramic world history between 1934 and 1961. Toynbee, unlike Frazer and like Gibbon and Hegel, endogenized historical change. Creative minorities arise that challenge controlling authority. These go on to become dominant minorities, which through positive acts of creation establish a new society. This cycle repeats — like a clockwork mechanism — creating an endless periodic history.

After Toynbee, this kind of narrative history strikes us as no more realistic than the "Star Wars" trilogy — or more properly, "Asimov's Foundation," which is entirely lifted from Toynbee with a bit of Boltzmann thrown in as scientism. In our own time, narrative reasoning — outside of artwork — is either quaintly ingenuous, wishful thinking, or ideologically motivated moonshine. Complex reality emerges through a kind of complex time, in which a multiplicity of causal factors at many scales lead to an endless series of events. One way to apprehend this complexity is through methods or frameworks that can deal with irreducible complexity, either with coarse-graining observations and understanding how much information is being lost, or by working within methods that eschew easy explanations in terms of patterns and schemes that provide a means of classifying varieties of historical sequence.

The end of Narrative would not be a bad thing. It would free us from the teleologies of ideology and force us to come to terms with the hardships and disparities that civil society is built to redress — a process that is endless.

— David Krakauer
President, Santa Fe Institute

(Photo: Martin Bilek/Shutterstock)

Researchers look to human social sensors to better predict trends

Election outcomes are notoriously difficult to predict. In 2016, for example, most polls suggested that Hillary Clinton would win the presidency, but Donald Trump defeated her. Researchers cite multiple explanations for the unreliability in election forecasts — some voters are difficult to reach, and some may wish to remain hidden. Among those who do respond to surveys, some may change their minds after being polled, while others may be embarrassed or afraid to report their true intentions.

In a new perspective piece for Nature, in a special issue devoted to computational social science, SFI researchers Mirta Galesic, Jonas Dalege, Henrik Olsson, Daniel Stein, Tamara van der Does, and their collaborators propose a surprising way to get around these shortcomings in survey design — not just in the world of politics, but in other types of research as well. While it's widely assumed that cognitive bias clouds our assessment of the people around us, their research and that of others suggests that in fact, our estimations of what our friends and family believe are often accurate.

"We realized that if we ask a national sample of people about who their friends are going to vote for, we get more accurate predictions than if we ask them who they're going to vote for," says Galesic, who is the corresponding author. "We found that people are actually pretty good at estimating the beliefs of people around them."

That means researchers can gather highly accurate information about social trends and groups by asking about a person's social circle rather than interrogating their own individual beliefs. That's because as highly social creatures, we have become very good at sizing up those around us — what researchers call "social sensing."

When people are selected to represent a particular group, their perceptions, combined with new computational models of human social dynamics, can be used to identify emerging trends and better predict political and health-related developments in particular, the team writes. This approach, combining elements of psychology and sociology, can even be harnessed to devise interventions that "could steer social systems in different directions" after a major event, such as a natural disaster or a mass shooting, they suggest.

"I really hope human social sensing will be included in the standard social science toolbox, because I think it can be a very useful strategy for predicting and modeling societal trends," Galesic says.

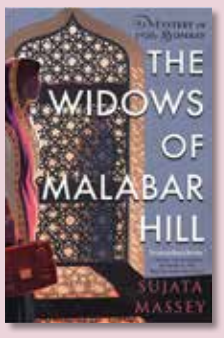
What we're reading

Books chosen by SFI scholars on the theme of 'Detection'

In a short story from 1936 entitled "Poirot and the Triangle at Rhodes," Agatha Christie's famous Belgian detective travels to the Greek isles for a holiday: "A holiday, especially, from crime," as he tells himself. Within just a few days of his arrival, however, a woman is murdered with a poisoned gin cocktail. Hercule Poirot is quick to solve the mystery, but his inescapable role as crime-solver is made abundantly clear to him. The story concludes with Poirot sighing the words, "It seems that I am never to get a real holiday." Some individuals, it seems, are destined to be constant detectives.

This claim is not limited to criminologists. As Stefani Crabtree suggests in her recommendation below, all "-ologists"—psychologists, anthropologists, biologists, and so on—are detective types who apply their logic to the subject matter at hand while simultaneously searching for a pre-existing logic embedded within the phenomena under examination. Detection uses human logos; that is, in an effort to find a corresponding logos within some slice of the increasingly observable world.

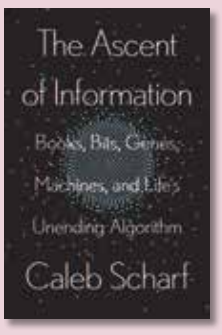
For this edition of What We're Reading, our theme is detection. Each of the books here concerns those individuals among us who, like Hercule Poirot, are constant detectives, forever following clues in the quest to understand the mysteries around us and within us.



STEFANI CRABTREE, Assistant Professor of Socio-Environmental Modeling at Utah State University and ASU-SFI Biosocial Complex Systems Fellow

"The Widows of Malabar Hill" (Soho Press, 2018) by Sujata Massey

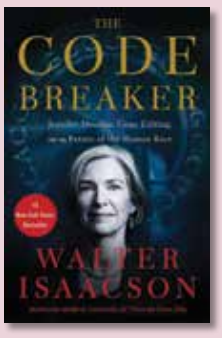
My professor at the Sorbonne said every scientist should read detective novels to teach us how to follow the 'clues' that lead toward scientific truths. Sujata Massey's detective series follows Perveen Mistry, the first female lawyer in Bombay, as she solves crimes perpetrated against women. Set in the 1920s, these works examine the shifting politics of India and explore the ways women can be powerful agents of change.



CHRIS KEMPES, Professor, Santa Fe Institute

"The Ascent of Information: Books, Bits, Genes, Machines, and Life's Unending Algorithm" (Penguin Random House, 2021) by Caleb Scharf

One term for our current period in history is the 'information age.' Perhaps that era should be extended all the way back to the very origins of life itself, since life is fundamentally about information maintenance, transformation, and propagation. Caleb Scharf's new book addresses related ideas, and "dataomes" more broadly, in biology and society. This book has relevance for thinking about life-detection beyond Earth since, as many of us at SFI hold, the search for life is about recognizing certain types of information dynamics.

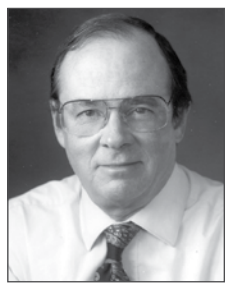


IAN MCKINNON, Vice-Chair of the SFI Board of Trustees and Founding Partner of Sandia Holdings, LLC

"The Code Breaker" (Simon & Schuster, 2021) by Walter Isaacson

This book chronicles the pioneering work of biochemist Jennifer Doudna in gene-editing and leveraging the CRISPR technology. Doudna, who won the Nobel Prize in Chemistry in 2020 for her contributions to genetics research, is a fascinating figure to observe as she navigates the promise, as well as the ethical peril, of the on-going revolution in life sciences.

In Memoriam



MERRITT RUHLEN

Stanford linguist Merritt Ruhlen, a long-time Santa Fe Institute collaborator who co-founded the Evolution of Human Languages project (EHL), passed away on January 29, 2021.

Ruhlen was well known for his work tracing lexical similarities across all the major language families of the world — so-called "global etymologies." Drawing on these similarities, he made the case that these language families can be traced back to a single "mother tongue" — a claim that built on the legacy of Ruhlen's mentor, Joseph Greenberg, and other comparative linguists before him.

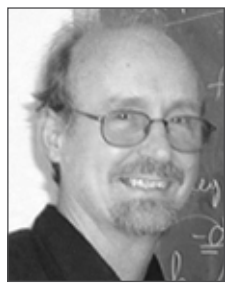
In 2001, Ruhlen worked closely with SFI co-founder Murray Gell-Mann and renowned linguist Sergei Starostin (George Starostin's father) to co-found EHL, hosting its foundational meetings at SFI.
The project's primary purpose is to trace the historical relationships between the world's ~6,000 spoken languages, and to "organiz[e] them into a genealogical tree similar to the accepted classification of biological species," according to the project website.

RICHARD LEWONTIN

Richard Lewontin, 92, a revolutionary geneticist, evolutionary biologist, and longtime member of the SFI Science Board, passed away in his home in Massachusetts on July 4, 2021.

Lewontin delivered a critical jolt of complexity to the field of population genetics. Through fieldwork, new laboratory techniques, computation, and innovative statistical methods, his work pushed genetics past the simplistic assumption that all phenotypic variations are driven by isolated mutations on single genes.

Throughout his scientific career, Lewontin was an outspoken critic of popular accounts of racial differences, which invoked biology to lend credibility to assertions that complex phenotypic traits, like IQ, were simply pre-determined by DNA. He believed strongly that what science did and how discoveries were evaluated and used depended on the structure of the social system in which the science was carried out; that is science and society are in the same messy complex system.



DOUGLAS WHITE

UC Irvine anthropologist Douglas White, a former SFI External Professor, passed away on August 22, 2021.

White was widely regarded for his research into human relationships, communities, and cultural roles as dynamic, complex networks. He was the co-author or editor of five books; founded and co-chaired the Social Networks Ph.D. at UC Irvine and chaired the Social Dynamics and Complexity research group, and was president of the Social Science Computing Association. Committed to making scientific research open and accessible, White founded two open-access e-journals: *World Cultures* in 1985, and *Structure and Dynamics* in 2005.

Using rigorous mathematical modeling to approach classic anthropological questions of human interactions — particularly regarding kinship, marriage, and divisions of labor — White helped advance the practice of network analysis in anthropology. In addition to his innovative approaches to human networks, White was admired for the spirit with which he approached his work and colleagues.

Read the full obituaries for Ruhlen, Lewontin, and White at www.santafe.edu/news

CITIES *(cont. from page 2)*

theory for how larger urban areas affect a wide variety of city features, dynamics, and outcomes," write the authors.

The questions in this study were initially raised by co-authors Cate Heine, Elisa Heinrich Mora, and Jacob J. Jackson, who together spanned two cohorts of Undergraduate Complexity Researchers at SFI.

According to West, the new results emphasize that inequality is primarily an urban phenomenon, arising from underlying social dynamics "that desperately need to be addressed." He speculates that poorer city dwellers are missing out on the increased social interactions that are credited with driving innovation and wealth creation in large metropolises.

> "What was a huge surprise in this research was that, as the city grows, there's no advantage to people in the bottom 10-20th percentiles."

"What was a huge surprise in this research was that, as the city grows, there's no advantage to people in the bottom 10-20th percentiles. As you go down the income deciles, the value-added for city-dwellers got less and less in a systematic way... so much so that, in the bottom decile you get nothing at all. There's even evidence that you're losing quality of life," says West. "Here we found that rich are getting even richer than we thought and the poor are getting even poorer than we thought."

ACHIEVEMENTS

SFI Complexity Postdoctoral Fellow **Helena Miton** received Central European University's 2021 award for Best Dissertation. Each chapter of Miton's dissertation presents a study that stands alone as a contribution to a question in cultural evolution and supplies evidence for the robustness of the framework she outlines for empirical research in cultural evolution.

The Complex Systems Society will award a 2021 Junior Scientific Award to SFI External Professor **Orit Peleg,** an assistant professor within the University of Colorado's Department of Computer Science and BioFrontiers Institute. Peleg's research aims to understanding how biological communication signals are generated and interpreted. Peleg uses insect swarms as a model system to identify how organisms harness the dynamics of communication signals.

ATLANTIS series traverses space, science, and art

Space has always been the place where the imagination reaches beyond the world as we know it. What happens when we stretch deep into space science and set our imaginations adrift?

Welcome to ATLANTIS, a new creative editorial series released by the Santa Fe Institute's InterPlanetary Project, which sails through space research and engages with the scientific and philosophical questions that emerge on the voyage. The series is co-created by science writer Natalie Elliot and SFI's Caitlin McShea, Director of the InterPlanetary Project, who post under the pseudonym "ATLANTIS" – a (fictitious) space-faring ship named after the lost city, "which was said to drown for its hubris, and then rose again to champion the humane use of science," the creators write.

ATLANTIS sets sail to explore the theories and technologies that drive the hunt for extraterrestrial life, the complex challenges of interplanetary recycling, and the ways that the narratives of space exploration are constructed — to name but a few subjects it traverses. Traveling with Shakespeare and David Bowie, to Mars's Jezero Crater and Jupiter's moons, the inquiring authors hoist the Jolly Roger of their imaginative ship, which reads, "if this be science, there is art in't." In other words, they show the many ways that the playful voice of art can sound out the most fascinating insights of science.

New dispatches are released about every three weeks. The series is hosted on **Aliencrashsite.org.**

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Virtual topical meeting takes stock of market risk and social media

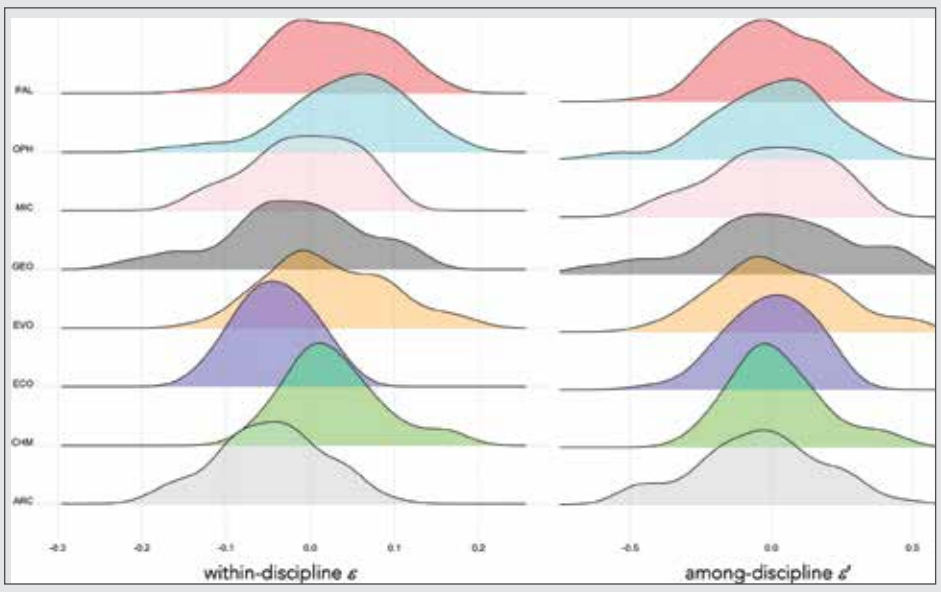
In an age where it's easier to get on social media than off of it, we still know shockingly little about how the scope, speed, and structure of online communication forums impacts beliefs about stock market investing.

This October, SFI partners with UBS to host a virtual topical meeting titled "Technology and Risk: Will Speedier and Deliberate Communication Bring Higher Levels of Risk?" Members of SFI's Applied Complexity Network can continue a discussion that began in 2020 on "Beliefs, Narratives, and Market Structure," now in year that's seen a sensational "meme-stock" rally of GameStop (January 2021), a surge in uranium mining company shares (September 2021), and the preliminary outing of a major Amazon merger (August 2021), all fueled by online exchanges over social media.

Attendees will learn from three scientists researching belief dynamics, communication technology, and market risk. SFI Professor Mirta Galesic, an expert in the emerging field of belief dynamics, will discuss how her team is using quantitative and computational techniques to predict social trends. Filippo Menczer, a distinguished professor of informatics and computer science at Indiana University who develops tools for combating social media manipulation, will explore how community structure impacts the spread of ideas. Finally, Valentina Semenova, a doctoral mathematician working with SFI External Professor Doyne Farmer at the University of Oxford, will present her preliminary analysis of how social contagion, or "hype," on Reddit's WallStreetBets forum drives large fluctuations in stock trading."Belief dynamics is one the most exciting areas of research we're developing at SFI right now," says Will Tracy, SFI's Vice President for Applied Complexity who is co-hosting the event with Juan-Luis Perez, the Global Head of Research at UBS. "Because meme stocks had such an outsized impact on market behavior this year, it seemed important to revisit last year's topic, and continue this conversation."

Following the presentations and Q&A sessions, the researchers will sit for a panel discussion on the implications of technology-driven communication on asset valuation and risk.

RESEARCH NEWS BRIEFS



Left panel: Distribution of within-discipline residuals of the relationship between Arel and loge years publishing by discipline (ARC = archaeology, CHM = chemistry, ECO = ecology, EVO = evolution and development, GEO = geology, MIC = microbiology, OPH = ophthalmology, PAL = palaeontology), each comprising 60 researchers. Right panel: Distribution of among-discipline residuals. From "A fairer way to compare researchers at any career stage and in any discipline using open-access citation data," by Bradshaw et al in PLOS ONE. (Figure: Corey Bradshaw)

A NEW TOOL FOR COMPARING RESEARCHERS

A new study co-authored by ASU-SFI Biosocial Complex Systems Fellow Stefani Crabtree, led by Corey Bradshaw at Flinders University, presents a tool to assess research performance more fairly than the pervasive H-index score, which is commonly used to make hiring decisions in academia.

Called the Epsilon Index, named for the Greek letter used to symbolize residuals in statistics, the new metric takes into account the many differences in the research space to deliver a fairer comparison. The tool is freely available as a ready-made app — simply punch in a few data for a sample of researchers from open-source databases like Google Scholar, and it does the heavy lifting to produce the result, enabling comparison of researchers at any stage of their career and from any discipline on the same scale.

Read the paper at doi.org/10.1371/journal.pone.0257141

STUDY SHOWS IMPACTS OF DEFORESTATION AND FOREST BURNING ON AMAZON BIODIVERSITY

A new study in Nature, co-authored by SFI External Professor Brian Enquist and others at the University of Arizona, provides the first quantitative assessment of how environmental policies on deforestation, along with forest fires and drought, have impacted the diversity of plants and animals in the Amazon.

Researchers created biodiversity maps of the Amazon region representing more than 14,500 plant and vertebrate species, then used observations of forest fires and deforestation from the last two to quantify the cumulative impacts on the region's species.

Since 2001, they found, up to 73,400 square miles of Amazon rainforest have been impacted by fires, affecting 95% of all Amazonian species, including many threatened species.

Read the paper at doi.org/10.1038/s41586-021-03876-7

GETTING IN SYNCH ON A BUDGET

Synchronization is critical for the function of many distributed systems — whether it's computers or power grids or neuronal populations — but doing it using the least amount of energy and resources possible can be a daunting task.

In a paper published in Nature Communications in June 2021, SFI Postdoctoral Fellow Yuanzhao Zhang and former SFI External Professor Steve Strogatz report using temporal network models to show that allowing connection patterns to change over time makes it possible to synchronize a system more efficiently.

The researchers' temporal network design is "open loop," so it's versatile and expected to work for a wide range of systems.

Read the paper at doi.org/10.1038/s41467-021-23446-9

For more research news briefs, visit santafe.edu/news