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Parallax

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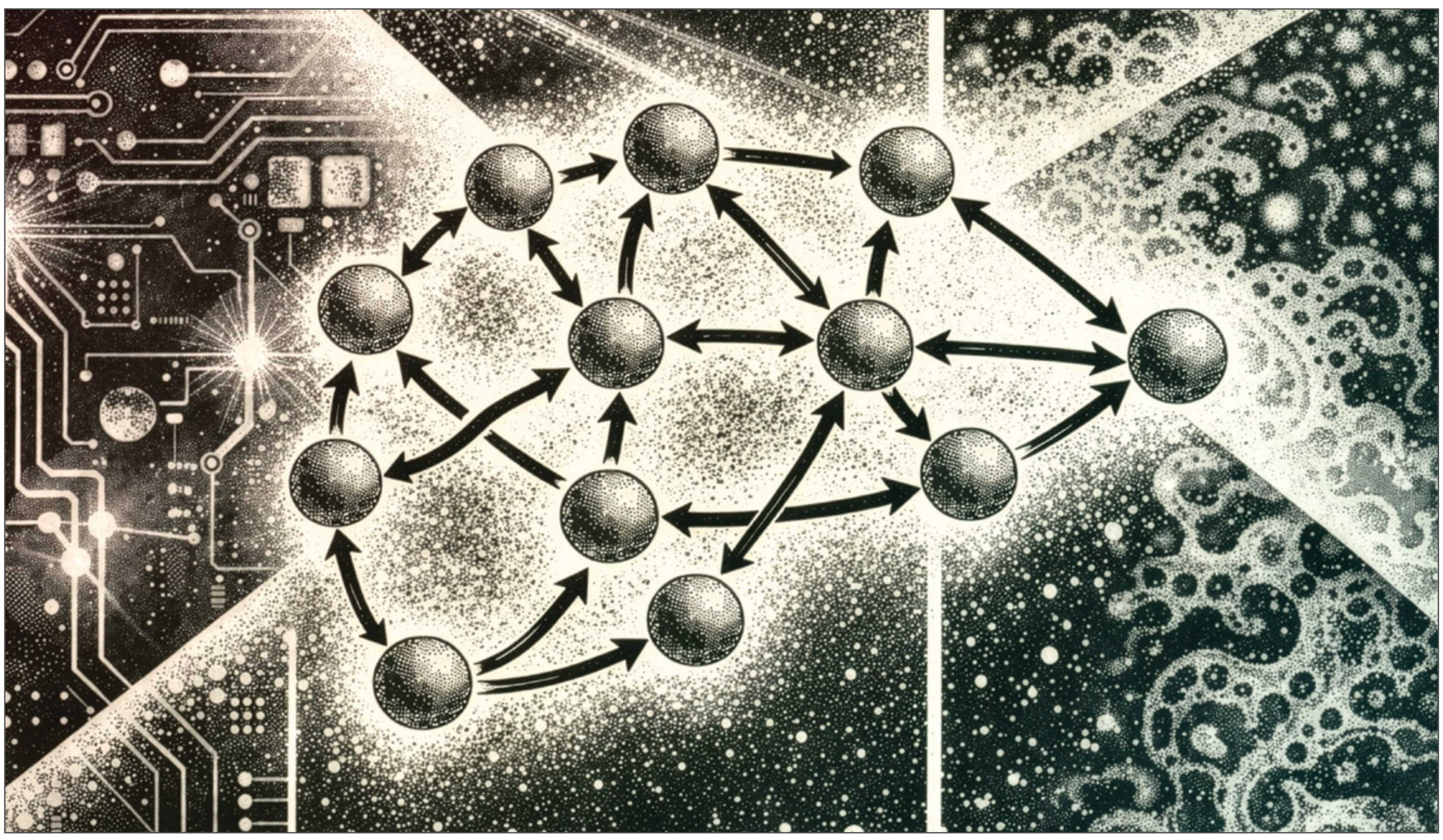

Across very different forms, natural dynamic systems carry out computations, too. (image: AI-generated & hand-edited by Edson de la O/SFI)

What does it mean for a system to compute?

Some computers are easy to spot. Artificial, human-built computers like those found in smartphones and laptops are abstract dynamic systems with observable computational elements like input, output, energy cost, and logical processes.

Other computers aren't so readily recognized. Scientists have argued that many natural dynamic systems — from cells to brains to turbulence in fluids — carry out computations, too. However, it's not always been clear what these dynamic systems are computing, or how they might be harnessed to solve tasks, says SFI Professor David Wolpert.

"The issue is how to define, formally, a set of criteria for identifying what computation(s) a given, arbitrary dynamical system does, in order to give us insights into these computational systems found in nature," says Wolpert. Such criteria, he says, would be powerful tools for investigating what it means to compute, in the broadest sense of the word. They would also reveal connections between "constructed" computers, which would include those found in phones and laptops, and "non-constructed," or natural systems that can carry out computations but remain poorly understood.

A recent paper in the *Journal of Physics: Complexity* offers a way forward. In the paper, Wolpert and Jan Korbel, a postdoctoral researcher at the Complexity Science Hub in Vienna, Austria, describe a novel approach to identifying and studying the computations encoded in a dynamic system. Their framework shows how to map, or connect, computations carried out by a non-constructed system to those carried out by a constructed computer.

For example, a network of chemical reactions can be seen as a kind of non-constructed computer. The input to this system is the initial concentration of chemical reactants. The output is the concentration of the chemicals after the reaction stops. Looking at a reaction this way, says Wolpert, reveals that chemical reactions "encode" a broad set of computational tasks that align neatly with computing operations that are already well known.

A mapping that connects physical systems to computer counterparts will allow researchers to probe the computational behavior of any dynamic system, and provides a way to define computation specifically. "We can say that some system can compute and what a particular instance of their dynamics does in fact compute, because now there's an explicit mapping between an abstract computational device and a real dynamic system," says Korbel.

Wolpert and Korbel have been collaborating on projects related to computing and complexity for years. For instance, in 2022, the two co-organized an SFI meeting focused on the

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Complexity in U.S. law

A century ago, the section of U.S. federal law governing public health and welfare was relatively small and loosely connected to the rest of the legal system. Today, it is one of the largest and most interconnected parts of the United States Code.

That shift is one of many patterns revealed by a new dataset published in the journal *Scientific Data*, which reconstructs the U.S. Code — the official compilation of federal statutory law — from 1926 to 2023. Developed by researchers at SFI and collaborators, the dataset offers the most comprehensive, data-ready picture yet of how federal law has grown, reorganized, and become more interconnected over the past century.

"The U.S. Code is more than a set of rules. It's a record of what society has decided is important enough to regulate — and how those priorities evolve as society becomes more complex," says SFI External Professor Hyejin Youn (Seoul National University), senior author on the study.

For SFI Postdoctoral Fellow James Holehouse, co-lead author, the code stood out as a uniquely rich case. "Many countries don't have a single, codified body of law like this," he says. "The U.S. does, and it's about a hundred years old. That gives us a rare opportunity to study how one of the world's largest regulatory systems has changed."

Making the study possible meant first rebuilding the past. Many early versions of the U.S. Code exist only as scanned pages, riddled with errors from early text-scanning software. Co-lead author Dawoon Jeong, a computational social scientist at the Knowledge Lab, University of Chicago, led the effort to clean and reconstruct those records using artificial intelligence in a carefully controlled process.

"Before this, we didn't really have usable data for studying legal change over such a long period," Jeong said. "Once we could reliably recover the old texts, we could finally look at how the legal system evolved as a whole."

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Bridging governance for a complex adaptive power grid

The grid is in crisis. A century-old system for generating, distributing, and regulating electricity cannot cope with coinciding pressures of electrification, decarbonization, enormous demand from data centers, and grid technology updates such as digitalization and artificial intelligence. Even the supply chain is faltering.

"If you want to build a new gas-fired power plant to serve the data center going in down the street, it's going to take you seven years just to get the turbine," says SFI External Professor Lynne Kiesling (Northwestern University).

To address the grid's overarching challenges, Kiesling helped organize a February 19–24 SFI working group on "Converging Technologies, Diverging Institutions: Bridging Governance for the Grid and the Grid's Edge." Building on an April 2025 meeting focused on grid governance, the working group assembled participants from academia, law, industry, and public policy to discuss how technology is upending old ways of managing energy.

For example, the grid once ended at your home electric meter. Now it's acquired a fuzzy edge: third-party extensions like electric vehicles and rooftop solar panels have introduced new actors to the electricity market, plus the chance for significant consumer control.

"Emerging actors in the U.S. grid are almost like new kids in class. We don't know where they should sit! Right now, the popular kids get to decide. The world is evolving, but those traditional grid decision-makers want to hold onto their power and follow the same rules they always have," says Kiesling.

Local working-group participants shared examples of this clash between new actors and old systems in New Mexico. A private equity group is seeking to buy the state's biggest utility, presenting unexpected challenges and opportunities for regulators. Santa Fe-based Microgrid Systems Laboratory is experimenting with innovations on the grid's edge (such as storing electricity at your home, or developing microgrids operated by Indigenous communities)

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An SFI working group met in February to discuss the various coinciding pressures on the U.S. electrical grid and the changes to governance that might be needed to address those challenges. (image: Overhead power lines crossing the Everglades. Greg Stellentin/Unsplash)

BEYOND BORDERS

THE BIOPHYSICS OF PARADIGM CHANGE

How might we detect or measure the acceleration of the world? When pundits, alarmists, and dystopians declare that the world is moving too fast for us to keep track, how is it that they are estimating rates of cultural change and how do they establish that these changes are too fast for individuals and society to respond? We all know the answer: plotting a few exponentials, sprinkling around the word "singularity," and neglecting the science of adaptation.

It is a curious fact of evolution that every organism that measures acceleration — that possesses a working accelerometer — does so in more or less the same way. Each organism contains an organ in which a "proof mass" is suspended on a mechanosensory hair in a fluid-filled chamber. The proof mass is inertial, and upon movement, it lags behind the basement membrane to which the hair is attached. The strain in the hair generates receptor potentials by opening ion channels, which are processed into an estimate of acceleration.

All evolved accelerometers face a series of unavoidable physical trade-offs. The minimum acceleration is bounded by a thermal noise floor: the smaller the proof mass, the harder it is to distinguish real motion from thermal fluctuations. This leads to a design choice through a bandwidth-sensitivity trade-off: For a small mass to counter noise, it needs to be suspended on a very stiff hair, and this limits the ability to detect low-frequency variation. This is why the semicircular canals in the human ear, using relatively massive otoliths, can detect low-frequency rotational acceleration on the order of 0.1Hz, whereas tiny insect campaniform cells can only detect changes two orders of magnitude higher. And all evolved accelerometers need to deal with viscous regimes — where the proof mass is strongly coupled to the surrounding fluid medium and fails to provide any evidence of relative motion.

We can extend these insights in a fairly straightforward way to knowledge and culture. Let's treat the quantity of accumulated and connected cultural knowledge — all of those ideas that are coordinated into a correlated system of verified belief — as analogous to proof mass. Any paradigm change in a field induces a rate of change in the epistemic environment, and this is the acceleration we would like any "cultural accelerometer" to detect.

Just as with evolved accelerometers, there is a need to distinguish noise (misinformation, rumor, error) from signal. We know from Bayes' rule that the prior plays the role of the proof mass: the greater the accumulated evidence for the incumbent beliefs, the greater the inertia in the system. And, we know the rate of updating maps to the stiffness of the mechanoreceptor: a commitment to the status quo reduces sensitivity to genuine signals for change but increases resistance to noise. Additionally, viscous

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How function diversity scales, from cells to companies

A mystery novel, a history book, and a fantasy epic may have little in common in plot or style. But count the words inside them and a strange regularity appears: many new words show up early, then fewer and fewer as the author reuses what has already been introduced.

That pattern, known as Heaps' law, turns out not to belong to books alone. A new study in *PNAS* finds that the same rule also describes the growth patterns in many complex systems, from living cells and corporations to universities and government agencies — and could even be used to predict how they will change in the future.

The study, led by scientists at the Santa Fe Institute and MIT, doesn't just document this regularity; it introduces a mathematical model that quantifies how different systems diversify and specialize. It finds that, while systems vary in how much they invest in creating entirely new functions, once those functions exist, their subsequent growth follows a remarkably universal rich-get-richer process.

Complex systems, from living cells to corporations, follow a remarkably universal growth pattern. (image: "Boekdrukkunst" attributed to workshop of Philips Galle, c. 1589 - c. 1593 via Rijksmuseum)

"What's striking is that these systems weren't designed to follow the same rules," says SFI Program Postdoctoral Fellow James Holehouse, who co-led the study with Vicky Chuqiao Yang, a former SFI Omidyar Fellow now at MIT. "Yet when you look at how they grow, you see the same trade-off between adding something new and building on what already exists."

> "It is remarkable that cells, bureaucracies, and companies, despite obvious differences, all grow their function repertoire with a similar pattern."

In the study, researchers focus on what they call "distinct functions" — the different kinds of work a system performs. In a cell, that might mean different proteins. In an organization, it could mean different kinds of jobs. As systems grow, they do add new kinds of work, but they do so more and more slowly over time.

Using their model, the team analyzed dozens of bacterial and microbial cells, more than a hundred U.S. federal agencies, thousands of companies and universities, and hundreds of metropolitan areas. Across most of these cases, the same pattern appeared: as systems got bigger, the pace at which they added new functions steadily slowed, growing sublinearly.

In practical terms, sublinear growth means that doubling the size of a system does not double the number of functions inside it. Instead, growth increasingly comes from expanding what already exists. A growing organization hires more people into established jobs before creating new titles. A cell produces more of the proteins it already uses instead of evolving entirely new ones.

"It is remarkable that cells, bureaucracies, and companies, despite obvious differences, all grow their function repertoire with a similar pattern," says Yang, an assistant professor at MIT Sloan and the Institute for Data, Systems, and Society. "This suggests that the regularity discovered in Heaps' law applies not only to what humans create, like books, but also to human organizations themselves."

Cities, however, follow a different version of the same trend. They still add new kinds of jobs as they grow, but they do so much more slowly, following a logarithmic pattern rather than the power-law pattern seen in other systems. Even as populations soar, genuinely new job types become increasingly rare.

That difference reflects a deeper structural divide. Cells, firms, and agencies behave like organisms, with clear boundaries and unified goals. Cities, by contrast, resemble ecosystems shaped by the independent choices of individuals rather than centralized control.

Geoffrey West, a co-author and Santa Fe Institute Shannan Distinguished Professor, adds, "There are underlying regularities shaping how complexity builds, even in systems that look completely different on the surface."

This material is based upon work supported by the U.S. National Science Foundation under Award No. 2526746.

Boldness is key to avoiding self-censorship

To maintain the right to self-expression, use it early and often, suggests a recent study. (image: Unsplash+)

Whenever an authority has influence over a population — be it a social media platform moderating user comments, a government imposing laws on its citizens, or an employer placing restrictions on employees — some people will push back against the authority's rules. In a study published in November in *PNAS*, SFI External Professor Stephanie Forrest and her colleagues devised a mathematical model for the give-and-take between dissenters who break the rules and authorities who impose punishments.

"Pick any issue you like. You'll express something in between what you really want, if there's no penalty for doing so, and nothing at all, if the punishment is severe," says Joshua Daymude, an Assistant Professor in the School of Computing and Augmented Intelligence at Arizona State University.

Forrest and Daymude collaborated on the study with Robert Axelrod, the William D. Hamilton Distinguished University Professor Emeritus at the University of Michigan.

Key to the model is a quality the researchers call "boldness": the willingness to risk punishment for the sake of genuine self-expression. As more and more individuals dissent, authorities tend to impose stricter and stricter punishments, and individuals must be increasingly bold if they want to continue to dissent. Without sufficient boldness, they begin to censor themselves for fear of the repercussions.

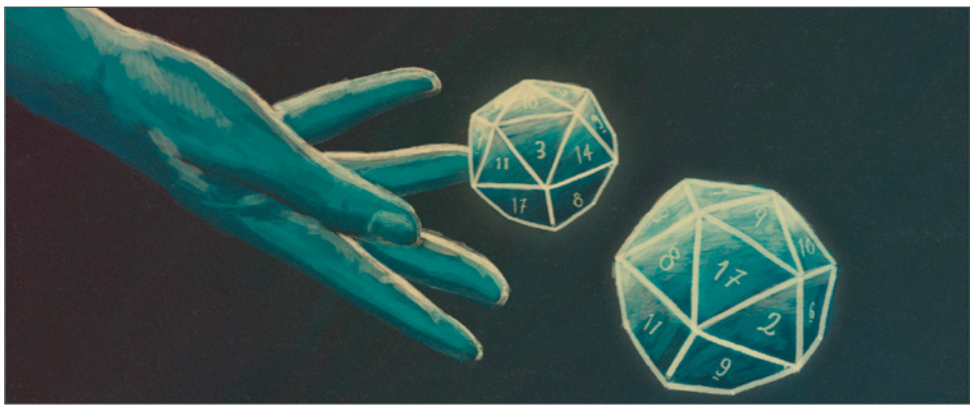
"That's sort of obvious. But what surprised us was that small amounts of boldness are highly effective at delaying self-censorship," says Forrest, who is also a Professor of Computer Science at Arizona State University and the Director of the Biodesign Center for Biocomputing, Security, and Society.

That's because punishments always come with a cost, such as the cost for a social media platform to hire moderators, explains Daymude. If individuals are very bold, then mild punishments impose a cost on the authority without doing anything to change behavior. When enough people dissent early and often, punishments can become too costly for the authority to maintain.

The study comes with caveats: the researchers omitted the impact of people who support the authority — the opposite of dissent. Furthermore, there's no method for predicting what people would have done in the absence of authority, so the researchers lack empirical data with which to test their model. Instead, they offer examples of times their predictions have borne true. For example, during the 2022–23 protests in Hong Kong, people chose to self-censor on Twitter after new laws were passed that increased the severity of punishments.

The model shows that maintaining the right to self-expression "is about boldness," Daymude says. "It's about continuing to take risks to say what needs to be said, under threat of punishment."

Study: Reassessing the scientific method



Choosing experiments randomly can help scientists develop better theories. (image: Edson de la O/SFI)

The race to develop a virtual scientist — an AI creation that conducts every stage of research, from idea to publication — has consumed researchers, start-up founders, and tech juggernauts alike.

It has also illuminated fundamental philosophical questions about the process of doing science. Is the scientific method really the best approach to learning about the world?

A new paper in *Collective Intelligence* applies the scientific method to itself, finding that some common strategies scientists consider gold standards for designing experiments perform worse than random choice. In other words, random exploration may produce better theories than carefully planned experiments.

"These results contradict some common intuitions about the scientific method," says lead author and SFI Complexity Postdoctoral Fellow Marina Dubova.

"The traditional ways we teach people to do experiments seem very premeditated: let's confirm what we know, let's try to falsify a dominant theory, let's resolve a disagreement between two theories. But weirdly enough, we found that such carefully motivated experiments don't seem to guide scientists toward useful theories as well as randomly chosen ones," Dubova explains.

Dubova, a cognitive scientist, collaborated with former SFI Postdoctoral Fellow Arseny Moskvichev and Kevin Zollman of Carnegie Mellon University on the paper.

To determine what makes experiments succeed, the authors built an agent-based model. This technique from complexity science enabled them to represent human scientists as individual actors, or "agents," in a computer program. Next, the authors created a statistical "ground truth" for the scientist-agents to explore. (For a fictional alien species, the ground truth would be all the alien characteristics like height, weight, brain size, and behavior in response to testing.)

Within the computer program, the scientist-agents conducted a series of experiments, forming and refining theories based on the results. They also shared their observations and theories with other agents, simulating how real-life scientists learn socially through publications or conferences.

The model revealed that the most informative, predictive scientific results emerged when scientist–agents randomly collected data — not when they selected experiments to confirm, falsify, or resolve disagreement between theories.

One of the most interesting findings was that agents selecting theory-driven experiments grew convinced they were succeeding, even though they weren't. When the scientist-agents communicated with each other, they managed to give plausible accounts (represented mathematically) of the ground truth, and rated the success of their theories highly. They never found out their accounts were often wrong.

"The agents were able to develop an illusion of progress. Using theory-motivated experimentation strategies, agents collected a narrower set of data, which made it less likely for them to encounter observations that challenged their theories," Dubova says.

It's too early for human scientists to ditch carefully designed experiments for random experimental roulette, Dubova is quick to point out. However, scientists would do well to check their epistemic assumptions. "There is a vicious cycle you can enter, where you collect data using what you think is a good strategy and grow confident in your success, but actually, you're not learning much about the world," she says.

What's the benefit of a brain?

Researchers are examining how the high-energy cost of the brain may be balanced by the evolutionary advantages of intelligence. (image: Unsplash)

The brain runs on about 15-20 watts, less than most light bulbs, but has still managed to evolve a voracious appetite for energy. In humans it accounts for only about one-fiftieth of weight but consumes about 20% of our daily energy. "That is an off-the-charts fitness cost," says SFI Professor David Wolpert. "Nothing else even comes close." Intelligence must confer some survival advantage to sustain such a formidable energy share, says Wolpert, but until now, researchers haven't rigorously examined that trade-off.

In February, Wolpert and SFI External Professor Van Savage, a mathematical biologist at UCLA, hosted the SFI working group "Evolutionary Consequences of Energetic Cost of Intelligence." The meeting brought together 15 neuroscientists, evolutionary biologists, physicists, and other experts to develop multi-disciplinary strategies aimed at modeling the evolutionary tradeoffs of intelligence.

Wolpert says SFI-affiliated researchers have long been interested in extending the mathematical tools used by evolutionary biologists to neuroscience, and the meeting offered a chance to introduce experts in those communities to each other's ideas.

The gathering opened with a challenge: to clearly define concepts like energetics, evolution, and intelligence. The first two weren't so difficult, says Savage, as physicists could reasonably describe what's known about how the brain uses energy, and evolutionary biologists could describe methods for identifying evolutionary advantages of phenotypes. "But intelligence was very difficult to define," he says.

"We started with a little bit of locking horns," agrees Wolpert. They debated whether intelligence was unique to humans or something broader, like the ability to do nonrandom things in the environment that would increase their ability to acquire energy. They found common ground in the core concept, however: whatever model they used, it had to incorporate how living systems use energy while reflecting the real-world limitations of time and size encountered by an intelligent system.

"The meeting was really useful to figure these issues out," says Savage. "You can do a lot of intelligent things in an energy-efficient way if you have unlimited time. But in reality, you don't have unlimited time."

By the end of the meeting, says Wolpert, the researchers had established both a clear articulation of the importance of understanding this evolutionary trade-off and begun to chart a road forward. They're drafting a perspective paper on the subject, he says, and researchers are now collaborating on projects aimed at laying down a mathematical foundation. The participants are eager to keep the conversation advancing, he says. "I'm getting emails from people who are saying things like, unfortunately, I couldn't sleep all week because there are so many ideas percolating in my head."

This meeting was partially funded by a grant from the Robert Wood Johnson Foundation.

Smart parts for smart wholes

Interest in artificial intelligence is driving a proliferation of research into the nature of intelligence. Researchers at SFI are using it as an occasion to revisit classic problems and to make progress on some frontier questions around complex-adaptive systems.

"We have all these cases where some complex whole that displays intelligent capabilities is built up of parts that are themselves intelligent," says SFI External Professor Jacob G. Foster, a professor of informatics and cognitive science at Indiana University Bloomington. "How do you build smart wholes from smart parts?"

The success or failure of collective intelligence can make or break a society's response to challenges requiring large-scale coordination, such as climate change and COVID-19. A better understanding of intelligence could help institutions coordinate more effectively in the future, says SFI Professor Melanie Mitchell.

To explore these questions, Foster and Mitchell convened an SFI working group on March 19–20. This was the first in-person meeting of leaders on "Building Diverse Intelligences Through Compositionality and Mechanism Design," a project funded by the Templeton World Charity Foundation.

The working group explored themes of compositionality — a property of parts that means they play well together — and mechanism design, or how parts can be made to interact and overcome incentive conflicts to produce a desirable collective behavior.

With expertise in fields like biology, computer science, engineering, and cognitive science, the researchers working on this project explore intelligence from different angles using a diverse array of formal models and model systems. They are united around central questions like, "What is the compositional structure — and what are the mechanisms — for taking these pieces and bringing them together in ways that make the whole more than the sum of the parts?" says Mitchell.

Compositionality is especially relevant in exploring AI systems' ability to solve problems using abstraction and analogy. "AI has problems with generalizing outside of what it's been trained on," says Mitchell, whose group is exploring how AI can combine disparate pieces of knowledge in novel scenarios.

When it comes to agentic AI, having "a wider set of design principles for thinking about how to coordinate the behaviors of artificial agents, or humans working with artificial agents," would be beneficial, Foster adds.

In addition to artificial intelligence, group members are investigating model systems such as scientific institutions, brains, evolutionarily designed soft robots, and communities that work together to solve puzzles.

"AI has problems with generalizing outside of what it's been trained on."

The group plans to synthesize their knowledge in position papers that put forth formal frameworks for understanding compositionality and mechanism design, with the goal of offering researchers a lens they can apply to new systems of interest. They intend to reconvene next year to share progress.

Gathering to explore their research in-depth allowed attendees to identify overlaps in their work and stimulate collaboration. "Everyone I talked to came away from this meeting with a real buzz from the excitement of talking about these ideas together," Foster says.

ACtioN Academy engages industry leaders on AI & complexity

Conversations about AI seem to have infused every field of inquiry, but are those conversations focused enough to be productive?

"Because AI is like a giant octopus with tentacles going everywhere, people want to write big hot takes. But more than enough people are waxing philosophic about the future of the world," says SFI External Professor Scott Page (University of Michigan). "Something that SFI faculty do instead is address questions in a really careful way." Last December, Page led a small group of industry professionals to consider such a question: when does AI add value to a decision?

It was the first virtual seminar for ACtioN Academy, a yearlong SFI program helping industry leaders explore how complexity science applies to their work. The inaugural cohort met in October in New York and will reunite for in-person and online seminars throughout the year.

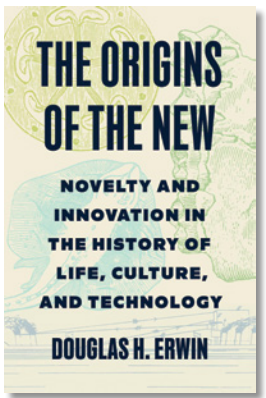
During Page's seminar, he introduced a recent paper, "Replace, Augment, Disrupt: AI & Organizational Decision-Making." Then participants discussed why you must reason through a decision before you can assess AI's suggestions — and how to fix misalignments when you and an AI disagree.

"My research studies when and how diversity improves decision-making, and this ACtioN Academy discussion was a classic example. It was great to have a conversation with smart people outside academia. I had a deep, applied follow-up call with a participant," says Page. "Those interactions — between practitioners and scientists — are the lifeblood of ACtioN."

Page's talk grew out of a series of SFI Applied Complexity events on measuring AI impact in the real world. This coming June, Google DeepMind will co-host their second multiday session with SFI, where researchers, regulators, and policymakers will discuss "AI and Multiscale Human Intelligence."

"Building community among rigorous and diverse thinkers has always been part of SFI's secret sauce," says SFI Vice President for Applied Complexity Will Tracy. "Regular ACtioN programming does this broadly, but ACtioN Academy is helping us forge deep connections among a small group of diverse practitioners. So far, this experiment is off to a roaring start."

Review: *The Origins of the New*



The built and natural worlds around us are full of examples of diversity from small, incremental evolutionary changes. Keyboard designs offer slightly different key spacing and press stiffness; two species appear almost identical, save for a slight change in body size But sometimes, something entirely original appears. So, how do radically different entities come to be? How does the world produce true novelty?

In his book, *The Origins of the New*, SFI External Professor Doug Erwin argues that the generation of novelty, and not just the mundane speciation that we are familiar with, is a central topic in science.

Erwin situates novelty as something much deeper than the constant generation of endless diversity, and through a meticulous account of the major debates in the study of evolution, illustrates that novelty has been both under-appreciated and dealt with through incomplete theories.

Erwin's scope is not simply organisms. He spans the earliest evolution of life on Earth, through the major transitions to the current world of radical transformation in human language, culture, and technology. His polymathic powers are on full display in this book, and there is a huge amount to learn bibliographically, conceptually, historically, biologically, and culturally.

Along the way to developing his own framework, Erwin illustrates how ideas come in and out of favor, rescues forsaken characters and their descendant ideas from history, and with great precision and subtlety, shows that it is often only aspects of theories, rather than entire theories, that are right or wrong.

Erwin is exceptionally fair to the long arc of arguments made by figures both past and contemporary, and he even includes an assessment of his own proposals.

Such a fair adjudicator of knowledge and theories is a wonderfully rare find. Erwin is a very well-known paleontologist and the former curator of the Burgess Shale at the Smithsonian. He holds unusual expertise in both traditional fossil excavations and evaluations and the frontier of molecular biology, particularly with respect to development and regulation. In *The Origins of the New*, he uses both areas of expertise to illustrate ideas through detailed examples, and his conceptual framework for novelty manages to be both general and ambitious while being grounded in an array of convincing facts.

> Potentiation . . . is essential to explain the history of life. Without this framework, other theories of innovation and novelty are incomplete.

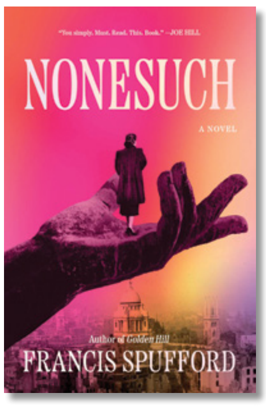
In his framework, Erwin argues for the central role of potentiation — small evolutionary events that open up radical new spaces and set the stage for a future novelty. Potentiation, he argues, is essential to explain the history of life. Without this framework, other theories of innovation and novelty are incomplete.

Erwin also shows how novelty is a frontier in complexity science with a loopy and impossible-to-predict character — a consideration that matters centrally for cells and societies alike.

The coarse stratigraphy of this wonderful book covers a broad scope of concepts, embedded in which are gems of case studies, facts, and fascinating historical asides. Enjoy this book for the overarching concepts and the page-by-page fascinalia!

Review by SFI Professor Chris Kempes.

Francis Spufford publishes *Nonesuch*



Francis Spufford, SFI's newest Miller Scholar, is a prolific author whose writing often straddles the line between fiction and nonfiction. His history *Red Plenty* incorporates fictitious narrative, and novels like *Cahokia Jazz* are so deeply researched that they amount to counterfactual historical theses. His new novel, *Nonesuch*, published March 10, is no exception; in this historical fantasy thriller, the fate of the world rests on one woman's ability to interpret and manipulate complex systems as she navigates the relationships between politics, economics, WWII, and magic.

As Britain declares war against Germany, Iris Hawkins balances her duties as a financial secretary in a brokerage firm — a position she hopes to leverage into personal wealth — with her duty to humankind: she's been drafted by angels into an occult war against the British Union of Fascists, who are poised to activate London's secret network of divine power to alter time to engineer Hitler's triumph.

> In this historical fantasy thriller, the fate of the world rests on one woman's ability to interpret and manipulate complex systems

The angels Iris encounters are, by turns, amalgamations of wings, comic-book characters, animated collections of rubbish and typewriter ribbon, and tessellating streams of luminescent data. The angel who warns Iris of the fascist plot can't quite decide on the right terms to explain the physics of it all: somehow through the triangulation of voluminous ether, quantum tunneling, and black magic, Iris can — and must — reach "Nonesuch Place," where time itself is malleable and the past can be changed, before the fascists exploit it to their own ends.

Fortunately, Iris is good at evaluating systems. Underutilized and unnoticed in her day job at the brokerage firm, she discerns patterns in the wartime stock market that allow her to square humanistic and patriotic duty with her own ambitions for self-sufficiency, entering into a lucrative and noble financial conspiracy with her boss. She is also romantically entangled with a brilliant and shy signals operator, Geoff, who helps her navigate an unindexed storeroom of occult paperwork to support her nightly anti-fascist crusade. His technical knowledge of waves and signals, developed in his work with the nascent BBC television broadcasts, is in high demand for building Britain's early RADAR systems and is equally indispensable to Iris's metaphysical war, as the angels are made of energy and signals.

In his previous novels, Spufford's fascination with the complexity of cities is used to bring readers into vibrant settings like the speculative eponymous Indigenous metropolis of *Cahokia Jazz* and the historical embryonic New York City of *Golden Hill*. The London of *Nonesuch* is equally complex and warped, not only by the magical interrelationships of angel-possessing statues, but in the mundane and increasingly common rigors of industrial cities bombarded from the air: blackouts, rations, shock waves, fires, deaths.

Iris's worldliness and curiosity are her keys to saving Britain. Undaunted by the need to decipher the occult writings overcrowding her boyfriend's attic, or the declining markets on the teletype, Iris takes stock of what is in front of her, making and testing bold hypotheses about the war economy and London's network of statuary angels, with little regard for her own safety or reputation. She has no problem jumping from a roof to an invisible bridge, or cornering John Maynard Keynes at a dinner to interrogate her financial theories. She's the sort of person who would probably have a pretty good time at SFI.

ACHIEVEMENTS

The Society for Industrial and Applied Mathematics has named SFI External Professor **Mark Newman** the awardee for the 2026 John von Neumann Prize for his contributions to the theoretical and algorithmic foundations of network science and their application to real-world systems.

SFI External Professor **Aaron Clauset** was elected to the American Academy for the Advancement of Sciences. The University of New Mexico's School of Engineering also recognized Clauset this spring with its 2026 Distinguished Alumni Award.

SFI External Professor **Santiago Elena** was elected as a fellow of the American Academy of Microbiology, joining 62 other fellows in the class of 2026.

The German Physical Society awarded SFI External Professor **Laurent Hébert-Dufresne** its 2026 Young Scientist Award for Socio- and Econophysics.


Mark Newman


Aaron Clauset


Santiago Elena


Laurent Hébert-Dufresne

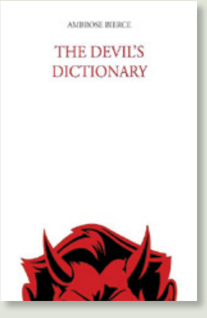
What we're reading

Books on the topic of lexicons

April 23 is a special day for bibliophiles. Shakespeare was born on April 23, 1564, and he died exactly 52 years later, on April 23, 1616. Every year, admirers around the world commemorate his birth and death simultaneously. In 1995, UNESCO initiated World Book Day, to be held each year on April 23, a tradition that holds strong three decades later. Thanks to Shakespeare, April 23 is also English Language Day, a ritual instituted by the United Nations "to celebrate multilingualism and cultural diversity as well as to promote equal use of all six official languages throughout the Organization."

Shakespeare's influence penetrates down into the very structure of modern and contemporary English. No one quite knows how many of our words and phrases he coined, but by the count of most scholars, roughly 1,700 English words appear for the first time in his poetry and plays — including such common ones as "bedroom" and "lonely." He also formulated many now seemingly routine English phrases like "heart of gold" and "forgone conclusion." This is to say nothing of such commonplace idioms like "to be or not to be?" "to thine own self be true," and "what's in a name?"

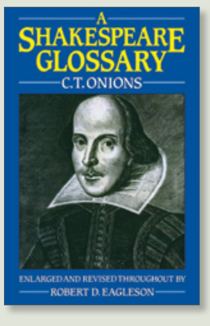
With a nod to Shakespeare's facility and inventiveness with the complexities of English itself, and with full awareness that he remains the supreme master of the most commonly spoken language in the world, we recommend three must-have English lexicons inspired wholly or in part by his work — each of which will delight lovers of words, wit, precision, satire, miscellany, or mere entertainment. In place of a précis, we provide two entries from each as examples of the pleasures to be found within its pages.



The Devil's Dictionary
Ambrose Bierce

EMOTION (n.) A prostrating disease caused by a determination of the heart to the head. It is sometimes accompanied by a copious discharge of hydrated sodium chloride from the eyes.

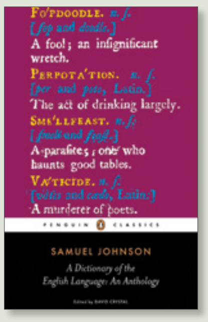
YEAR (n.) A period of three hundred and sixty-five disappointments.



A Shakespeare Glossary
C.T. Onions

BEEF-WITTED (adj.) Brainless as an ox, thick-headed. *Troilus and Cressida*, 2.1.13 "thou mongrel beef-witted lord!"

SPONGY (adj.) 1. Resembling a sponge in absorptive qualities; (hence) drunken. *Macbeth* 1.7.71 "His spongy officers. 2. Wet, moist. *The Tempest* 4.1.65 "spongy April."



A Dictionary of the English Language
Samuel Johnson

LEXICOGRAPHER (n.) A writer of dictionaries; a harmless drudge, that busies himself in tracing the original, and detailing the signification of words.

OATS (n.) A grain, which in England is generally given to horses, but in Scotland supports the people.

SFI Press launches *The Economy as an Evolving Complex System IV*

Think of the economy as a giant web where every person, company, and country is linked. When something big happens — a pandemic, the rise of artificial intelligence, or a climate-driven disaster — it doesn't just hit one strand. The shock ripples across the entire web, creating effects in real time that are hard to predict.

That's the central theme of *The Economy as an Evolving Complex System IV* (SFI Press, 2026), the two newest volumes in a series launched at SFI nearly four decades ago to rethink economics through the lens of complexity science. Rather than assuming markets always balance neatly, these books treat the economy as a living system that grows, changes, and reacts in ways that are hard to predict.

"The economy isn't a machine that always returns to balance," says R. Maria del Rio-Chanona, co-editor and an assistant professor in the computational economics and finance section at University College London. "It's a complex system where shocks can spread quickly, and our goal is to give policymakers tools that reflect that reality."

The project's thirty-one chapters, divided between two volumes, act as a guide for researchers, students, and policymakers seeking better ways to understand and manage an increasingly turbulent economy, highlighting how a new generation of tools for capturing complexity are reaching maturity and moving into practice. Agent-based models, for instance, use data on workers, firms, and households to simulate how economies behave under stress. The volumes show how these models are no longer confined to theory: policymakers and central banks are already using them to forecast GDP during crises, manage housing bubbles, and prepare workers for the AI transition.

"Agent-based models and network tools allow us to see things standard equations miss," says co-editor Marco Pangallo, a research scientist at the CENTAI Institute. "They capture diversity and feedback loops and let us realistically test what might happen in complex situations. That's what makes them so powerful for designing real-world policy."

The emphasis on application is what makes the new books stand apart from their predecessors, according to co-editor François Lafond, an economist at the University of Oxford who authored a chapter on forecasting technological progress. "Earlier volumes were more about proving that complexity ideas could work in principle," he says. "These show how they're being used today by central banks, regulators, and researchers to tackle real problems."

For the authors, the most exciting aspect of this shift from theory to practice is that the field can now be judged by objective results rather than abstract debates. With richer data, stronger computing power, and realistic synthetic populations of households and firms, researchers can finally test whether their models outperform traditional ones. They hope the books will give readers confidence that methods from complexity economics are ready to shape real decisions about the economy's future.

"For years it was all theory," Lafond says. "Now we can simulate supply chains or labor markets, let the models run, and then check against reality. The world is messy, and so are our models — but that's exactly why they work."

Paperback copies of the two books that comprise *The Economy as an Evolving Complex System IV* are available for purchase through Amazon, and individual chapters are available for free download at sfipress.org.

WHAT DOES IT MEAN TO COMPUTE? *(cont. from page 1)*

thermodynamics of computing systems, and in the summer of 2025, Korbel attended an SFI working group on stochastic thermodynamics and computer science.

Their collaboration crosses borders, too: both attended an October 2023 meeting on the nature of computing, hosted by the Complexity Science Hub. It brought together researchers from a range of fields to share recent insights and results from investigations into how various systems can be seen to compute. Those fields included fluid dynamics, neuroscience, and cellular automata — mathematical models that evolve according to simple rules.

"They were very different things," says Korbel. During the meeting, the researchers looked for definitions and rules that could describe computational commonalities.

The paper is part of a special issue of *Journal of Physics: Complexity*, which features the work by Wolpert and Korbel, and is devoted entirely to the broad question, "What does it mean for a system to compute?" The other papers included in this special issue also highlight work by researchers at the fall meeting in Austria, focused on unmasking computation in its many guises.

U.S. LEGAL CODE *(cont. from page 1)*

The resulting dataset captures legal complexity on three levels: textual change, including word counts and vocabulary growth; hierarchical structure, showing how titles branch into chapters and sections; and networks of cross-references linking different areas of law.

Taken together, the data reveal how U.S. law shifts in response to events and priorities. The growing role of public health, from disease control to food safety, and the creation of Title 6 (Domestic Security) after 9/11, shows how major events reshape the legal system.

The team emphasizes that the dataset is a foundation rather than a conclusion. Future work will focus on modeling why some legal domains change quickly, how growing interdependence affects adaptation, and whether legal complexity can keep pace with societal complexity.

"As rules grow and institutions come under pressure," Holehouse says, "it's increasingly important to understand how these systems evolve before we try to change them."

Based upon work supported by the U.S. National Science Foundation under Award No. 2526746.

Page one of Jacob Shallus' officially engrossed copy of the U.S. Constitution signed in Philadelphia by delegates of the Constitutional Convention in 1787. (image: Wikipedia)

COMPLEX POWER GRID *(cont. from page 1)*

— proving it's possible to reduce rigid hierarchy in energy decision-making.

"Traditionally, grid problem-solving has been piecemeal: people's electric bills go up, and we laser-focus on fixing one specific part of the system," says SFI External Professor Seth Blumsack (Penn State), working group co-organizer. "But in this moment of deep structural change for the grid, piecemeal solutions aren't enough. At the working group, we tried to zoom out and say, how is the grid system organized as a whole? How can we address whole-systems problems?"

A complex-systems approach can avoid the pitfalls of the piecemeal. Working-group participants considered foundational complexity concepts like SFI External Professor Brian Arthur's recombination as it relates to innovation, and Stuart Kauffman's fitness landscape applied to regulation.

"What does a research agenda for a 'complex adaptive grid' really look like?" Blumsack asks, borrowing a phrase from Microgrid Systems Laboratory's David Breecker. To hash out such an agenda, more than a dozen researchers and practitioners have agreed to continue meeting and are preparing a journal commentary paper.

"Using the complex-systems approach, we want to introduce practitioners to new ways of thinking about stuff they've been doing every day for decades. We hope that encourages them to make regulatory changes that would create a more resilient, adaptive grid," says Kiesling.

This meeting received support from SFI's Emergent Engineering theme (which is sponsored by the Robert Wood Johnson Foundation Grant #81366) and Emergent Political Economies program.

THE COLOPHON: UPDATES FROM THE SFI PRESS

Publishing with the SFI Press

Like all publishers, the SFI Press receives a variety of book proposals and submissions. But our approach to publishing is unconventional relative to popular, university, and academic presses, and we can only accept submissions from scientists affiliated with SFI.

Since 2017, the SFI Press has published books explicitly aimed at making complexity science affordable and accessible to everyone. This means producing inexpensive reprints of canonical works like former External Professor Wojciech Zurek's *Complexity, Entropy, and the Physics of Information* (2023), originally published in 1990, alongside new work, including textbooks aimed at archaeologists, psychologists, and other social scientists. Sometimes our books are tied to SFI-hosted workshops or working groups. Our latest publication, *The Economy as an Evolving Complex System IV* (2026), for example, is the product of a 2023 meeting co-organized by SFI External Professors Eric Beinhocker and J. Doyne Farmer, both professors at Oxford University, along with INET economist colleagues.

SFI Press books capture a moment in the complexity-science landscape, documenting that work for contemporaries and preserving it for future researchers to navigate those ideas with new perspectives and insights.

We welcome proposals exclusively from SFI's research community and encourage creative, collaborative approaches to complexity. All submissions, from monographs to edited volumes, follow a consistent process: SFI Press editor-in-chief David Krakauer reviews submitted proposals with members of our editorial advisory board. Once a proposal is approved, authors and editors begin working with the SFI Press team.

From this point, our process varies depending on the needs of the individual book. Monographs and textbooks undergo review by other SFI researchers, while edited volumes are typically cross-reviewed by contributors as well as the editors.

With a staff of just three, the SFI Press takes a nimble, personalized, deeply collaborative approach to our publications, emphasizing rigor, accessibility, and beauty. Because our books are sold at cost — with each reader effectively subsidizing the printing of their copy — we do not offer royalties. Authors retain the rights to their work; they can choose to make some or all of their work freely available online or reprint chapters elsewhere, if desired.

It's a privilege to support SFI science and work with researchers committed to complexity science and interdisciplinary conversations. Questions? Please reach out to us: sfipress@santafe.edu.

The SFI Press team. [L-R] Zato Hebbert, Ellis Wylie, and Sienna Latham. (image: Kate Joyce)

BEYOND BORDERS *(cont. from page 2)*

regimes are those in which the zeitgeist is absolutely dominant — social pressures of various kinds induce a lock-step between individual and collective knowledge flow.

Just as insects detect high-frequency impulses at low sensitivity, and mammals detect low-frequency impulses with high sensitivity — a binding trade-off no life form can overcome — human society, with its high proof mass, has evolved to detect low-frequency changes with high sensitivity. Technologies offer the possibility for an invertebrate complement, responsive to high-frequency changes. And yet we have been building AI systems with fixed weights that are, in effect, an extreme version of the mammalian otoconial layer — mineralized once and rarely replaced. The proof mass doesn't just resist change — it cannot change until retraining.

Now might be the right time to learn from the adaptive capabilities of crustaceans. The crustacean proof mass — statolith — is discarded at every molt and replaced. Each individual picks up sand grains and places them in the statocyst to rebuild its proof mass. If you give a shrimp iron filings instead of sand, it builds a ferromagnetic statolith and then orients to a magnet instead of gravity. The proof mass is expendable, replaceable, and reconstructed from environmental materials. The crustacean doesn't carry its reference frame across molts — it rebuilds it from whatever the current environment provides. Now that's a model for sustainable technology.

— David Krakauer
President, Santa Fe Institute

COMMUNITY LECTURES 2026

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Art: Detail of "The Peabody Group #32." Al Taylor. 1992. Courtesy of the National Gallery of Art.

I **Crossroads Democracy | A Panel Discussion** — 14 Apr
David Krakauer (Moderator/SFI); Jenna Bednar (UMich/SFI); Sam Bowles (SFI); Hahrie Han (Johns Hopkins University); Katrin Schmelz (SFI)

II **The Indefinite Sublime: Tom McCarthy on *Moby Dick*** — 12 May
Tom McCarthy (Author and SFI Miller Scholar)

III **The Beautiful Engineering of Us: From Neurons to Collective Minds** — 23 Jun
Thalia Wheatley (Dartmouth and SFI External Faculty)

IV **Why Your Brain Hates Losing** — 21 Jul
Colin Camerer (Caltech)

V **31st Annual Stanisław Ulam Memorial Lecture Series** — 25 & 26 Aug
Josh Tenenbaum (MIT)

VI **Neurotechnology and the Recovering Brain** — 20 Oct
John Krakauer (Johns Hopkins University and SFI External Faculty)

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RESEARCH NEWS BRIEFS

Using census data and demographic modeling, the study suggests that polygyny often coexists with high rates of marriage among men. (image: Edson de la O/SFI)

DOES POLYGYNY REALLY EXCLUDE VAST SWATHS OF MEN FROM MARRIAGE?

A new study co-authored by SFI External Professor Laura Fortunato (University of Oxford) challenges a long-standing claim that polygynous marriage, where men have multiple wives, creates a surplus of men with no prospect of ever marrying. A large contingent of unmarried men is widely believed to lead to negative social outcomes, including interpersonal violence and, in extreme cases, civil conflict.

The research was published in *PNAS* in October with co-authors Hampton Gaddy at the London School of Economics and Rebecca Sear at Brunel University London. Combining demographic modeling and recent census data from 30 countries across Africa, Asia, and Oceania, as well as U.S. census data from 1880, the team found that polygyny often coexists with high rates of marriage among men. This pattern contradicts the idea that polygyny leaves large numbers of men without wives.

For example, across over 84 million individual records in the 30-country sample, the researchers found a negative association between the prevalence of polygyny and that of unmarried men at the sub-national level in nearly half of the censuses, and a positive association in less than 10%. The researchers posit that, where polygyny is allowed, cultural norms promoting marriage are likely to offset demographic and other constraints that may otherwise limit men's opportunities to marry.

Read the paper "High rates of polygyny do not lock large proportions of men out of the marriage market" in PNAS (August 27, 2025). DOI: 10.1073/pnas.250809122

DISENTANGLING THE BOLTZMANN BRAIN HYPOTHESIS: MEMORY, ENTROPY &TIME

In a recent paper, SFI Professor David Wolpert, SFI Fractal Faculty member Carlo Rovelli, and physicist Jordan Scharnhorst examine a long-standing, paradoxical thought experiment in statistical physics and cosmology known as the "Boltzmann brain" hypothesis — the possibility that our memories, perceptions, and observations could arise from random fluctuations in entropy rather than reflecting the universe's actual past.

The paradox arises from a tension at the heart of statistical physics. One of the central pillars of our understanding of the time-asymmetric second law of thermodynamics is Boltzmann's H theorem, a fundamental concept in statistical mechanics. However, paradoxically, the H theorem is itself symmetric in time. That time-symmetry implies that it is, formally speaking, far more likely for the structures of our memories, perceptions, and observations to arise from random fluctuations in the universe's entropy than to represent genuine records of our actual external universe in the past. In other words, statistical physics seems to force us to conclude that our memories might be spurious — elaborate illusions produced by chance that tell us nothing about what we think they do. This is the Boltzmann brain hypothesis.

The authors develop a formal framework to clarify how the Boltzmann brain hypothesis, the second law of thermodynamics, and the related "past hypothesis," depend on assumptions about which moments in time are treated as fixed when analyzing the evolution of the universe's entropy. Some analyses condition on the universe's present state, while others assume a low-entropy beginning (at the Big Bang). But physics itself does not say which of these choices is correct.

Anchored in what the authors call "the entropy conjecture," the paper shows that many standard arguments in these debates rely on subtle forms of circular reasoning, in which assumptions about the past are used to justify conclusions — such as the reliability of memory or the direction of entropy — that are then invoked to support those same assumptions. Rather than resolving these debates, the paper makes their underlying structure explicit. Separating physical laws from inferential choices, the authors offer a clearer basis for evaluating long-standing debates about time and entropy.

Read the paper "Disentangling Boltzmann Brains, the Time-Asymmetry of Memory, and the Second Law" in MDPI Entropy (December 3, 2025). DOI: 10.3390/e27121227

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E-PARALLAX

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